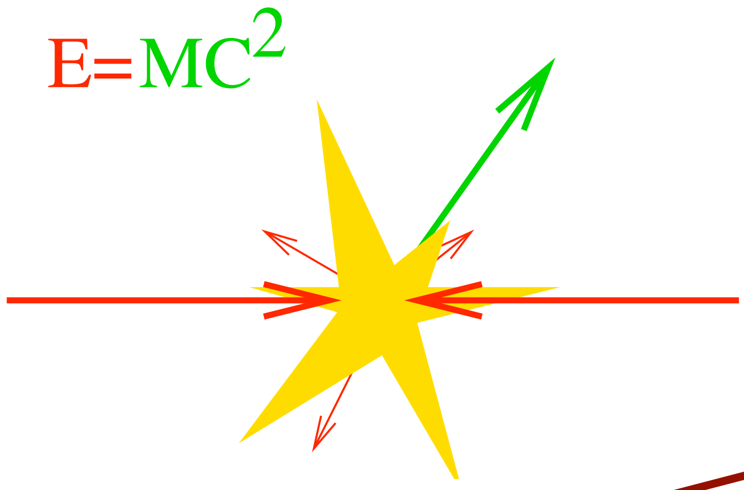
Heavy Flavour Physics

Jonas Rademacker (University of Bristol, LHCb)

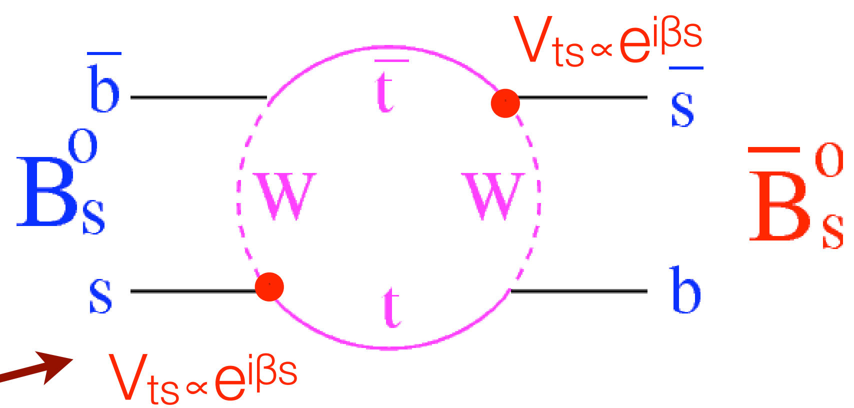
presenting selected heavy flavour results from

Two Roads to New Physics

Direct observation



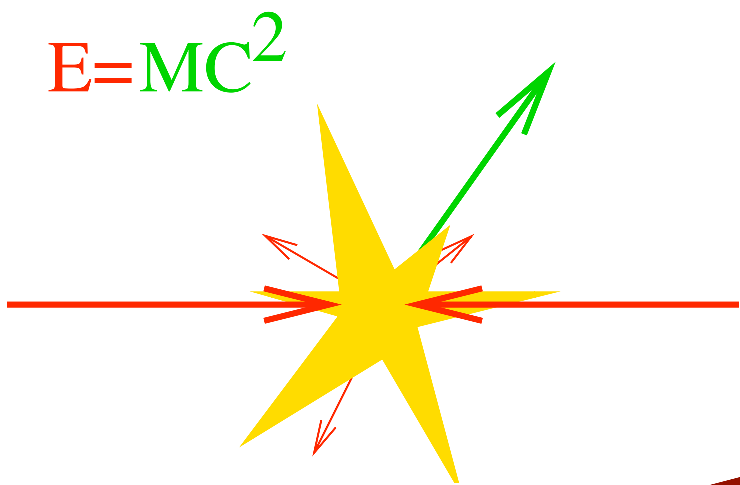
Effects of virtual particles



This approach is sensitive to particles far heavier than those directly produced in a collider. It is what flavour physics is about.

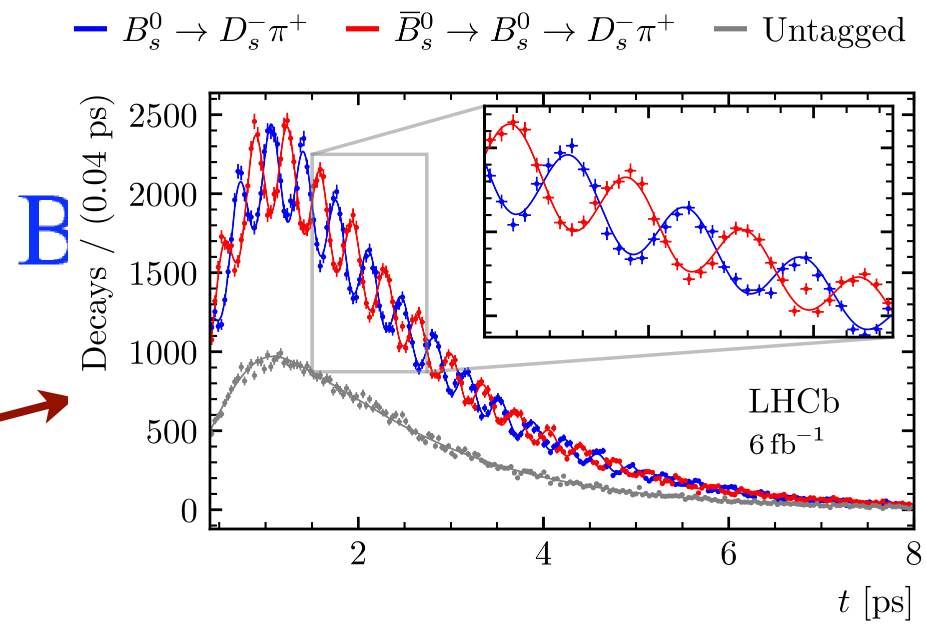
Two Roads to New Physics

Direct observation



Effects of virtual particles

LHCb: Nature Phys. 18 (2022) 1, 1-5



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Flavour physics as a tool to discover New Physics

- Quark Flavour physics is the precision study of quark transitions.

- Sensitive to new particles that can be much heavier than those directly produced.

- Very successful in the past:

  - Charm quark predicted based on the suppression Flavour Changing Neutral Currents (FCNC).

  - Top/bottom quark predicted based on the observation of CP violation.

  - Only serious indications of physics beyond SM today stem from this approach.

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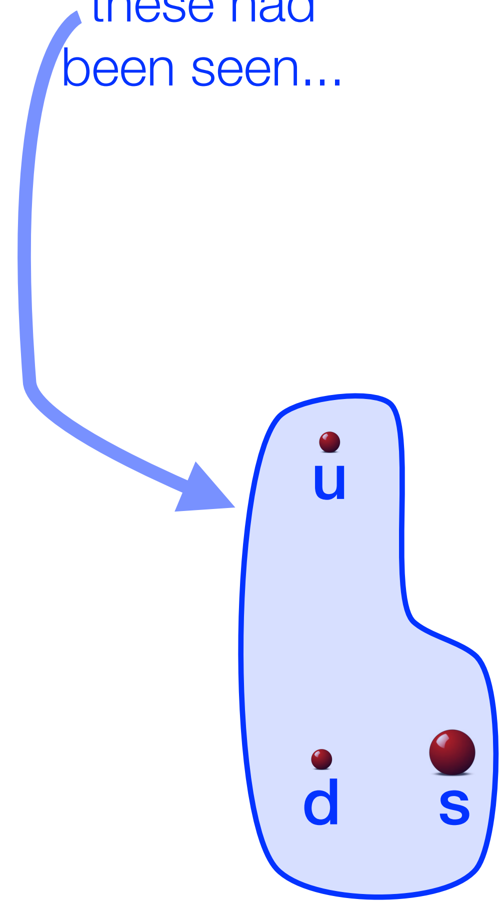
at a time when only these had been seen...



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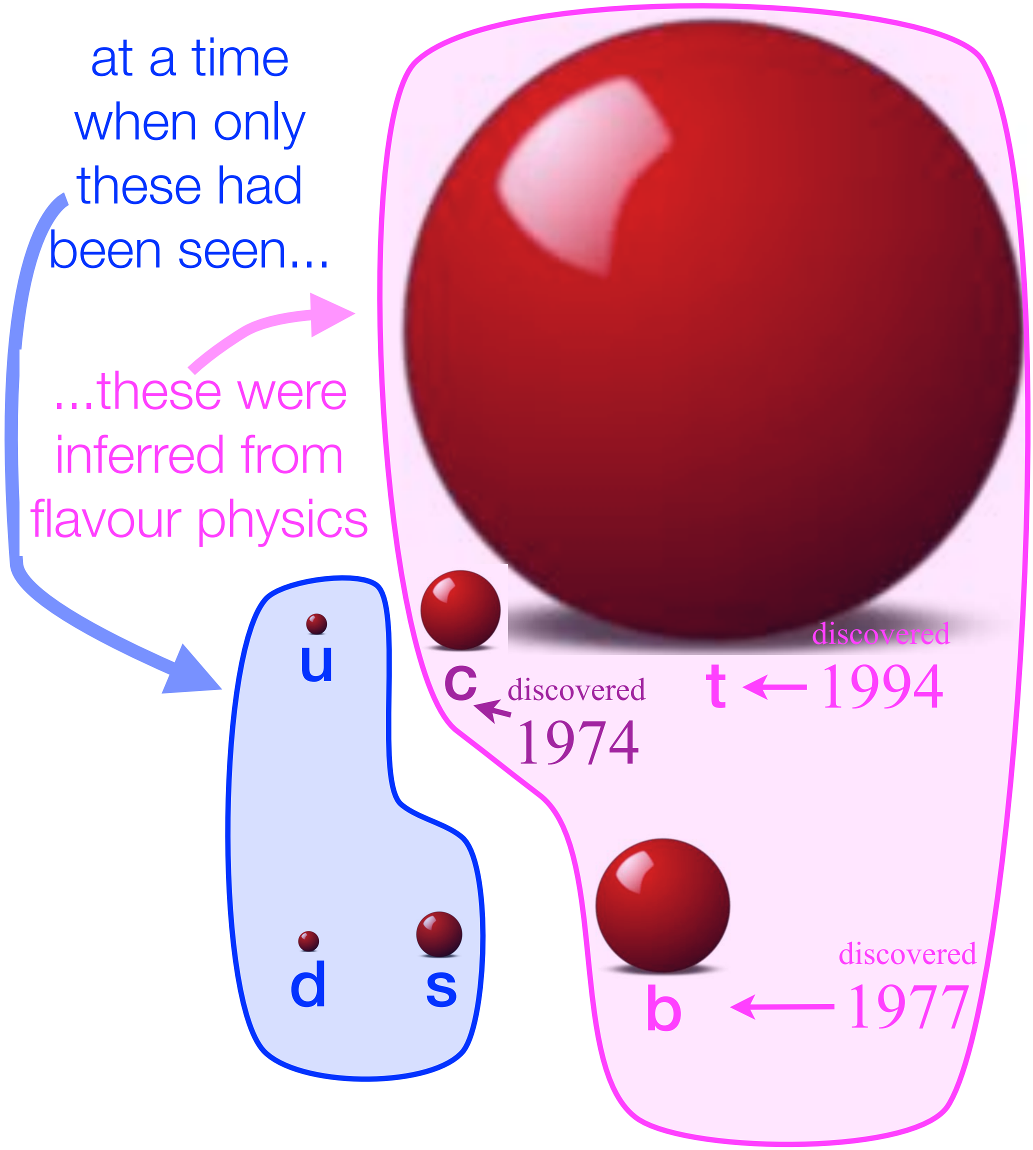
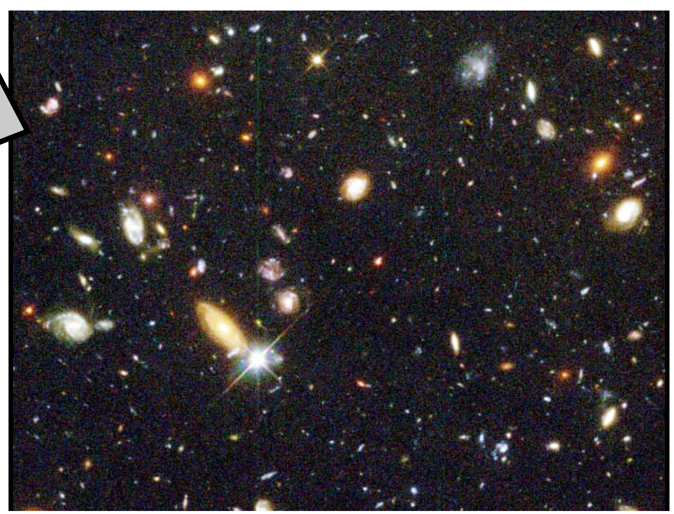


CP violation and New Physics

- While there is O(10%) agreement between the Standard description of CP violation, and measurements, there is a huge discrepancy between CPV in the SM and CPV in the universe.

Universe with SM CPV, only

Real universe



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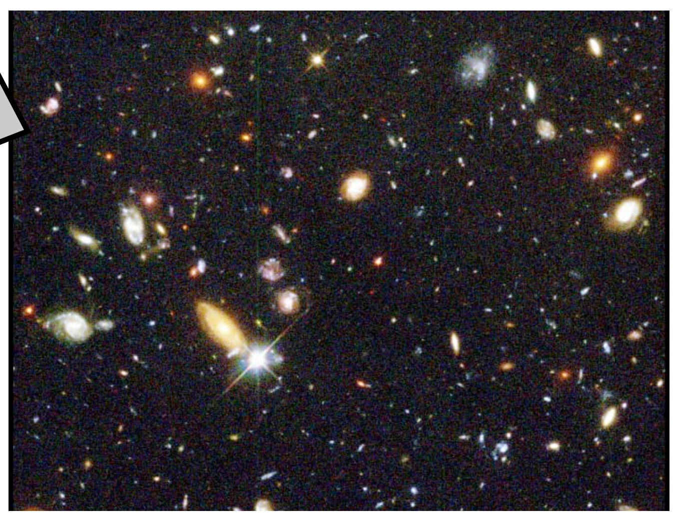
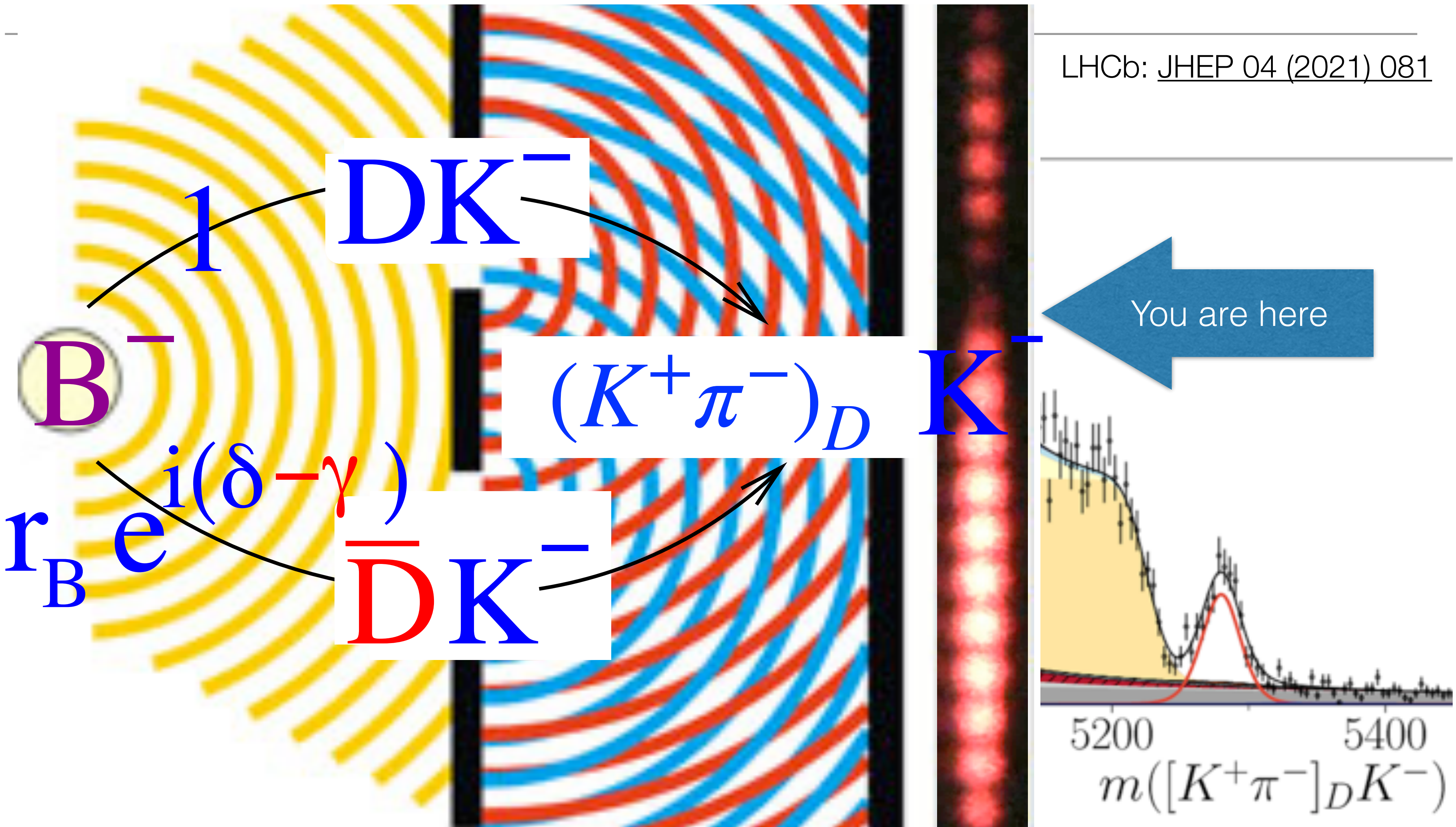


There **must** be new sources of CP violation.

CP violation is an interference effect

LHCb: JHEP 04 (2021) 081



Gronau, Wyler Phys.Lett.B265:172-176,1991, (GLW), Gronau, London Phys.Lett.B253:483-488,1991 (GLW) Atwood, Dunietz and Soni Phys.Rev.Lett. 78 (1997) 3257-3260 (ADS) Giri, Grossman, Soffer and Zupan Phys.Rev. D68 (2003) 054018 Belle Collaboration Phys.Rev. D70 (2004) 072003

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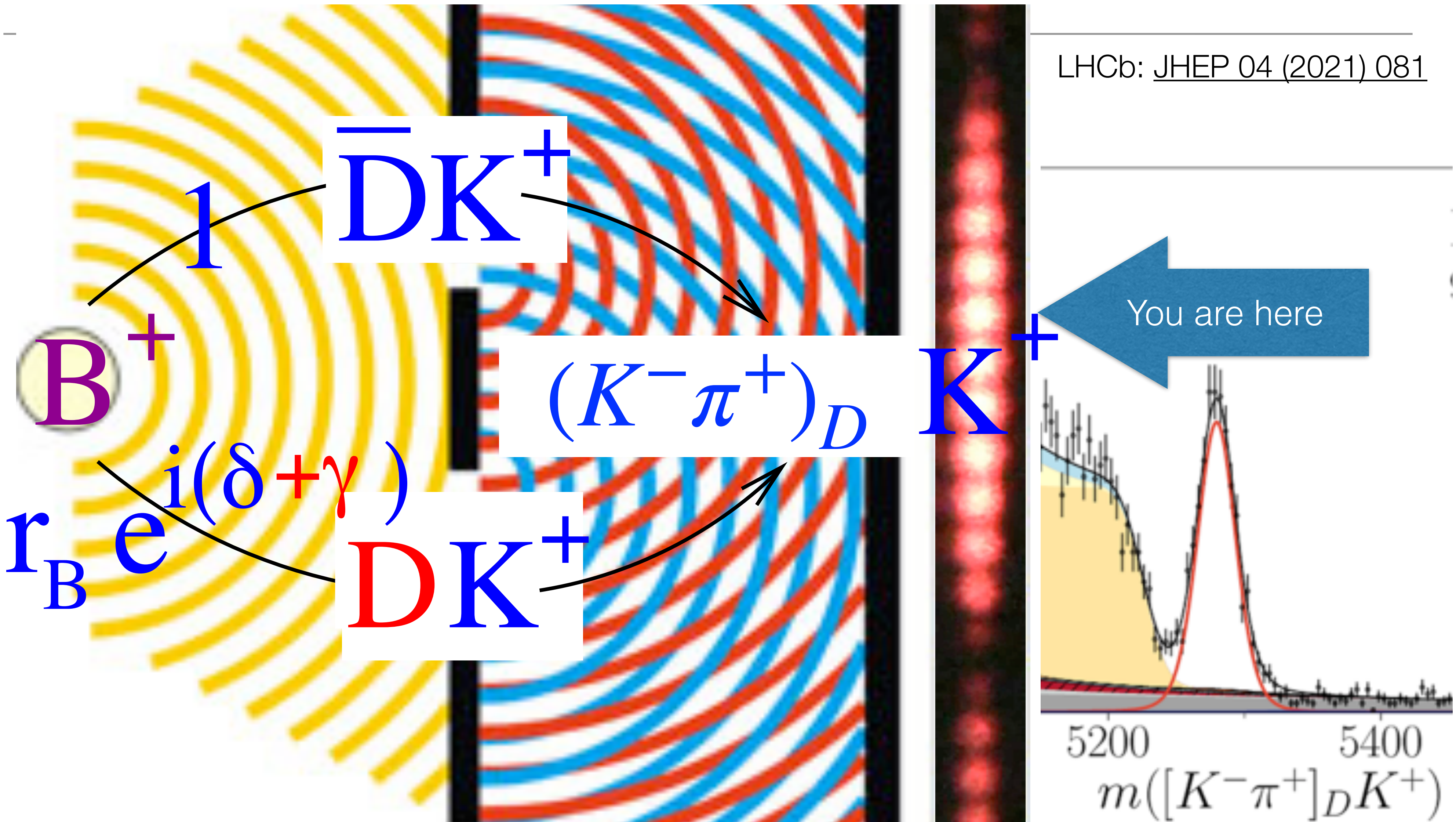

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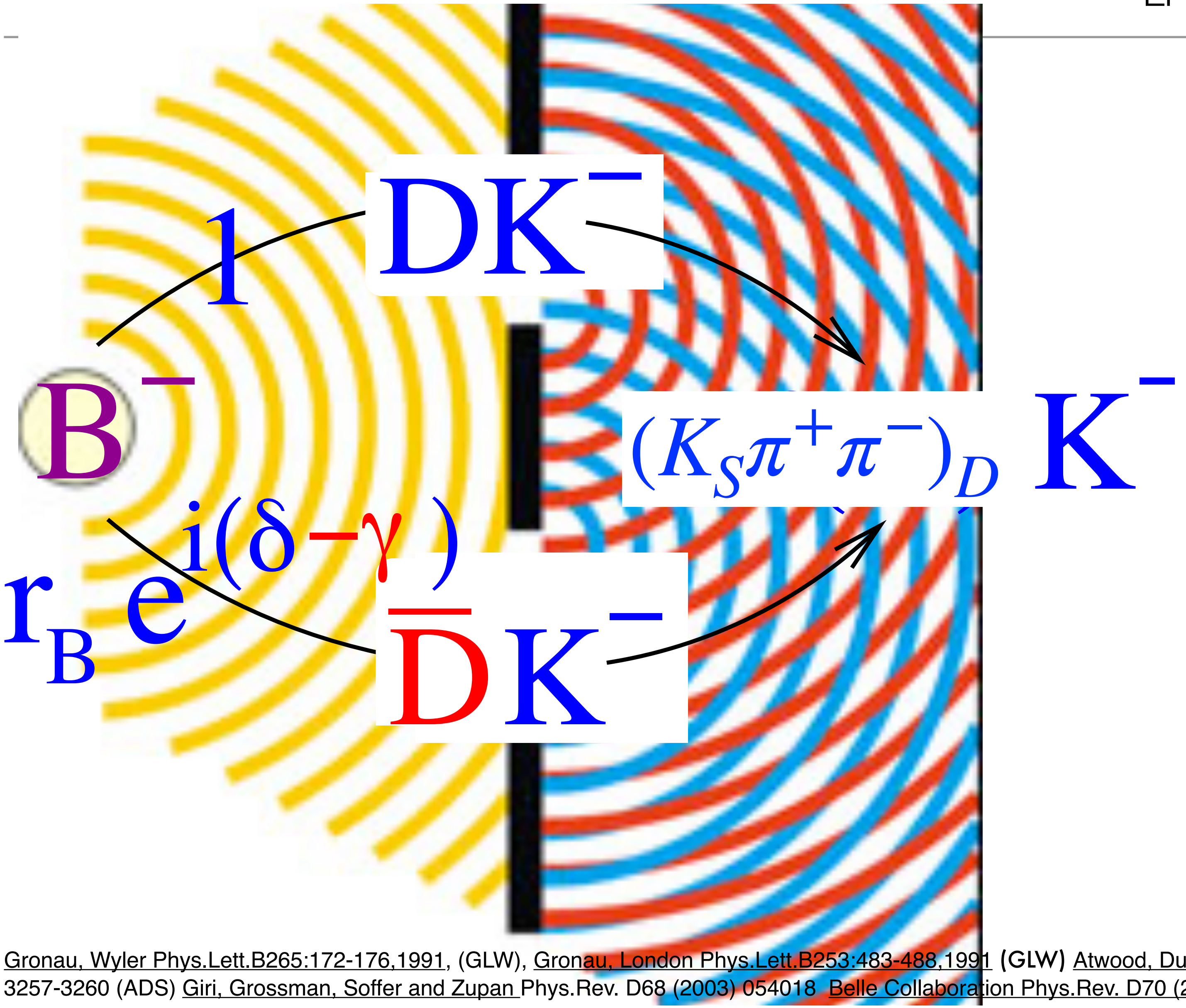
LHCb: JHEP 02 (2021) 169



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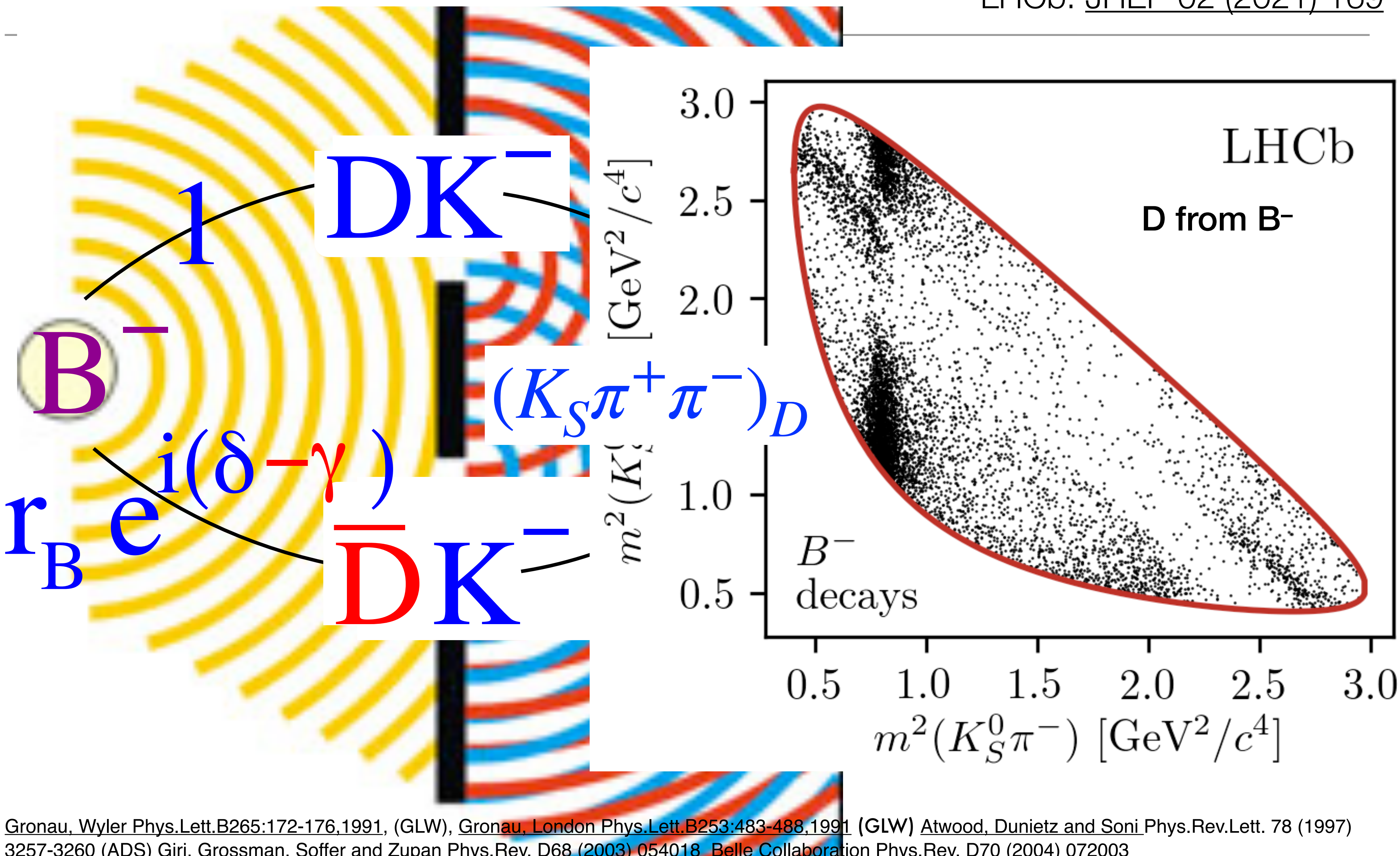

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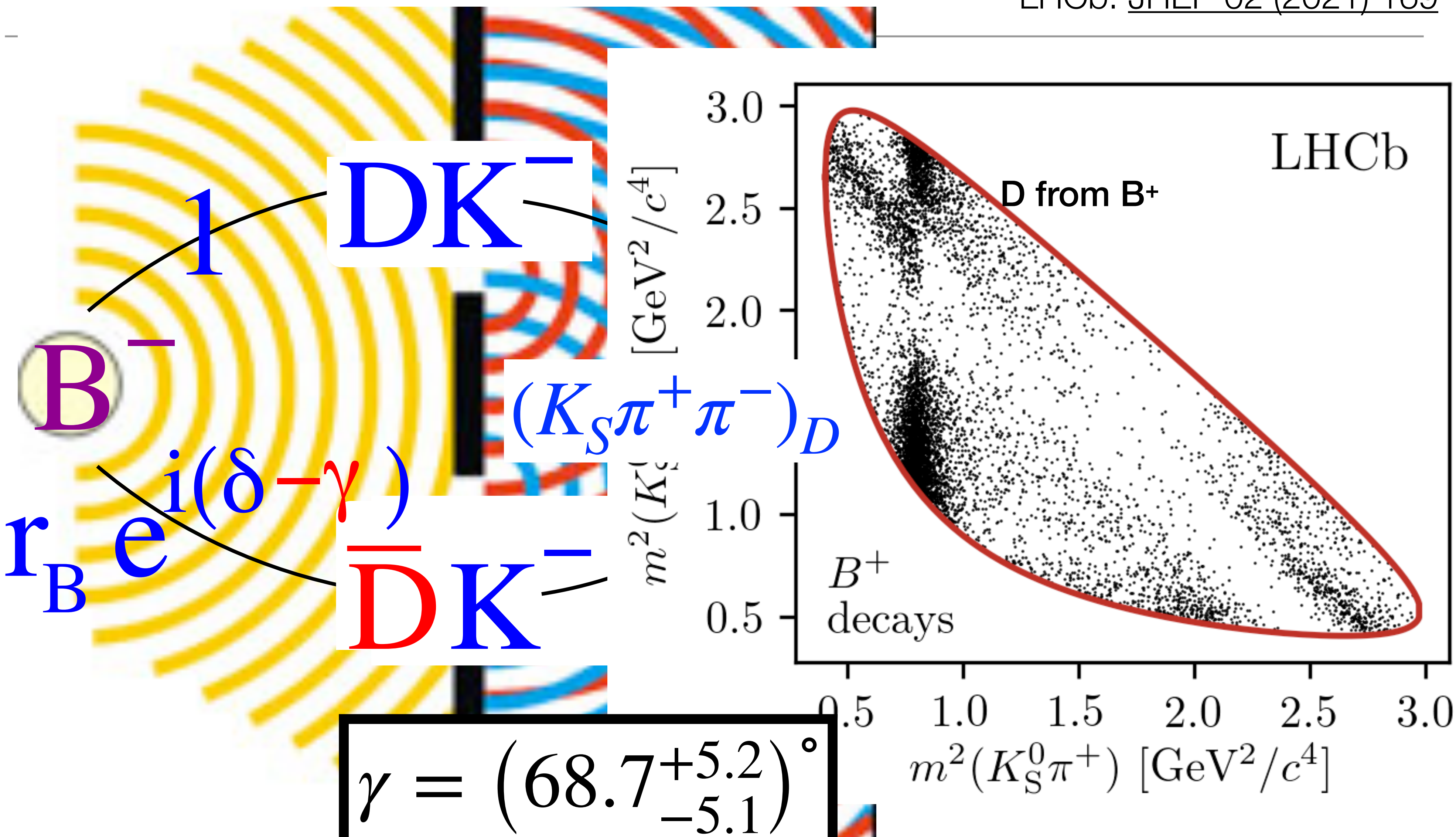

$$\gamma = \left(68.7^{+5.2}_{-5.1}\right)^{\circ}$$

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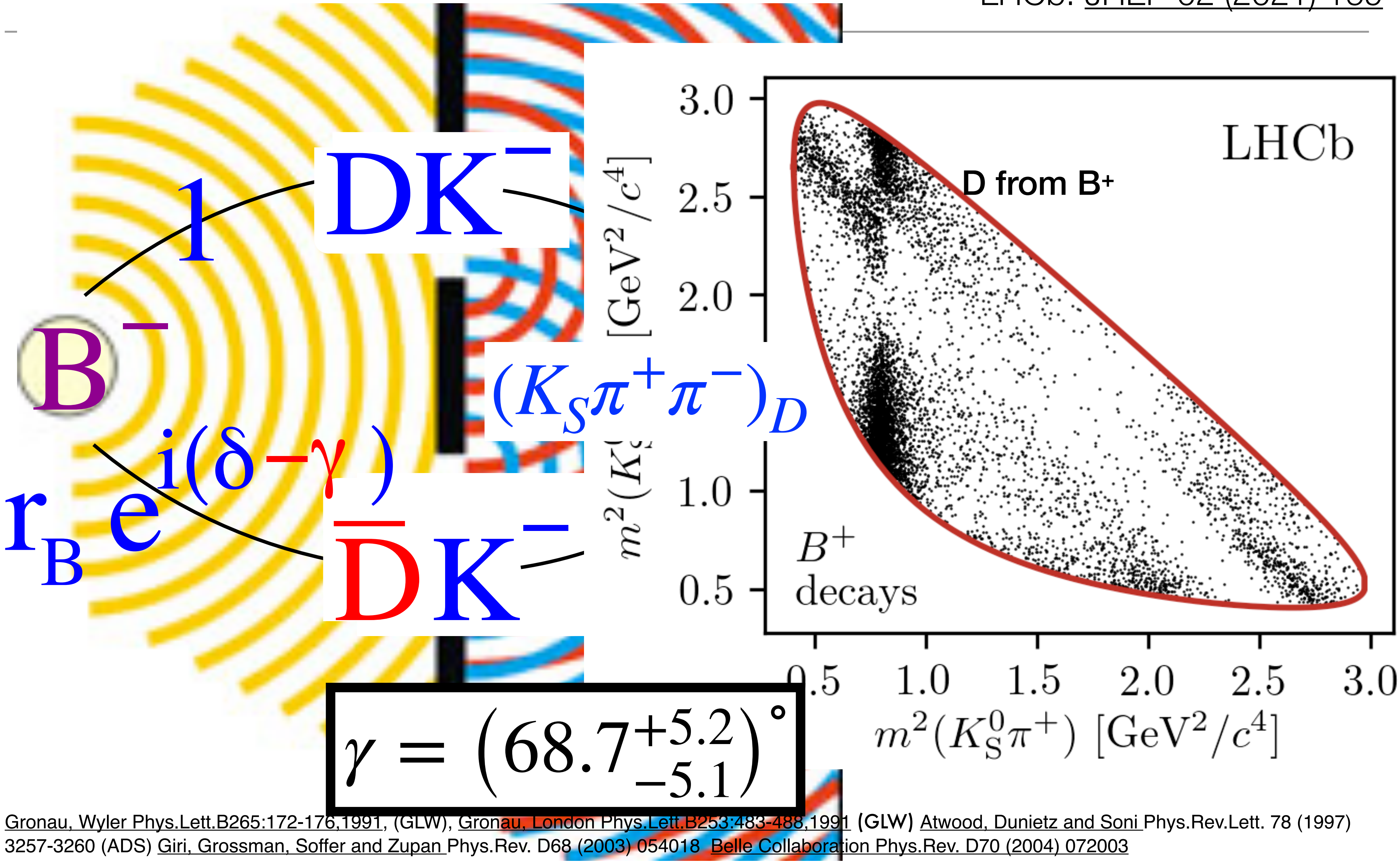

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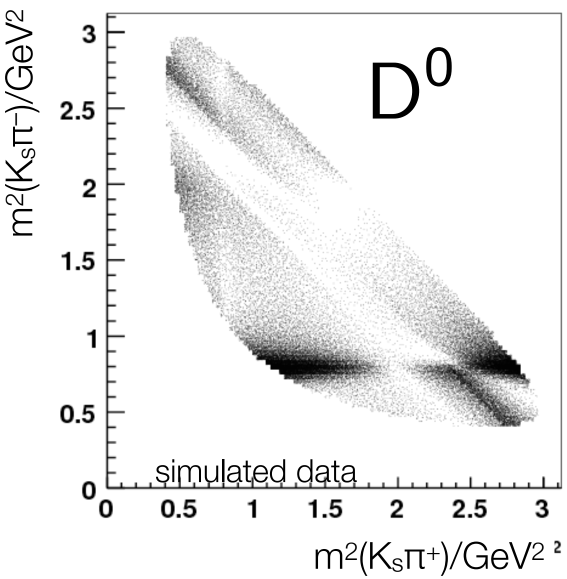
CP and flavour tagged D° at the charm threshold

ψ'' → $\bar{D}_{flavour} \to K^+ e^- \nu_e$

ψ'' → $D_{flavour} \to K_S \pi^+ \pi^-$



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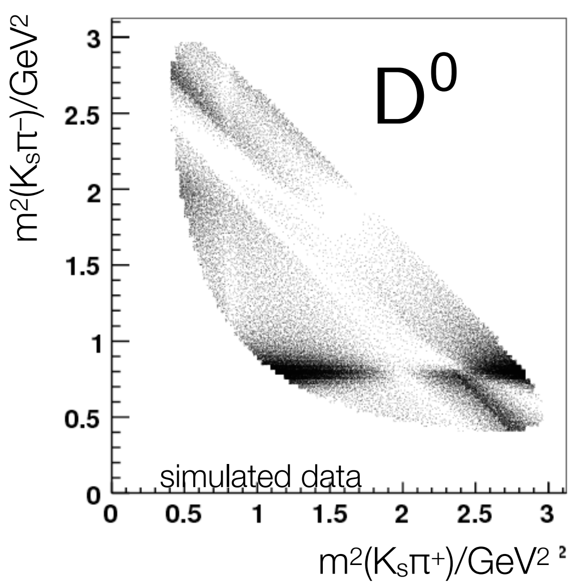
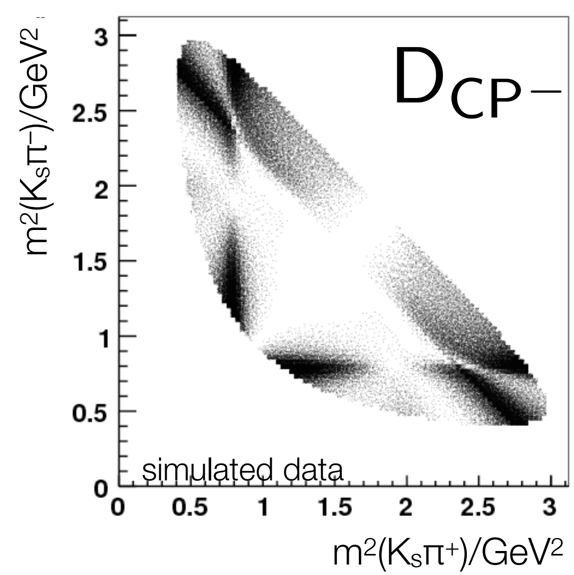


$\psi'' \to D_{CP+} \to KK$

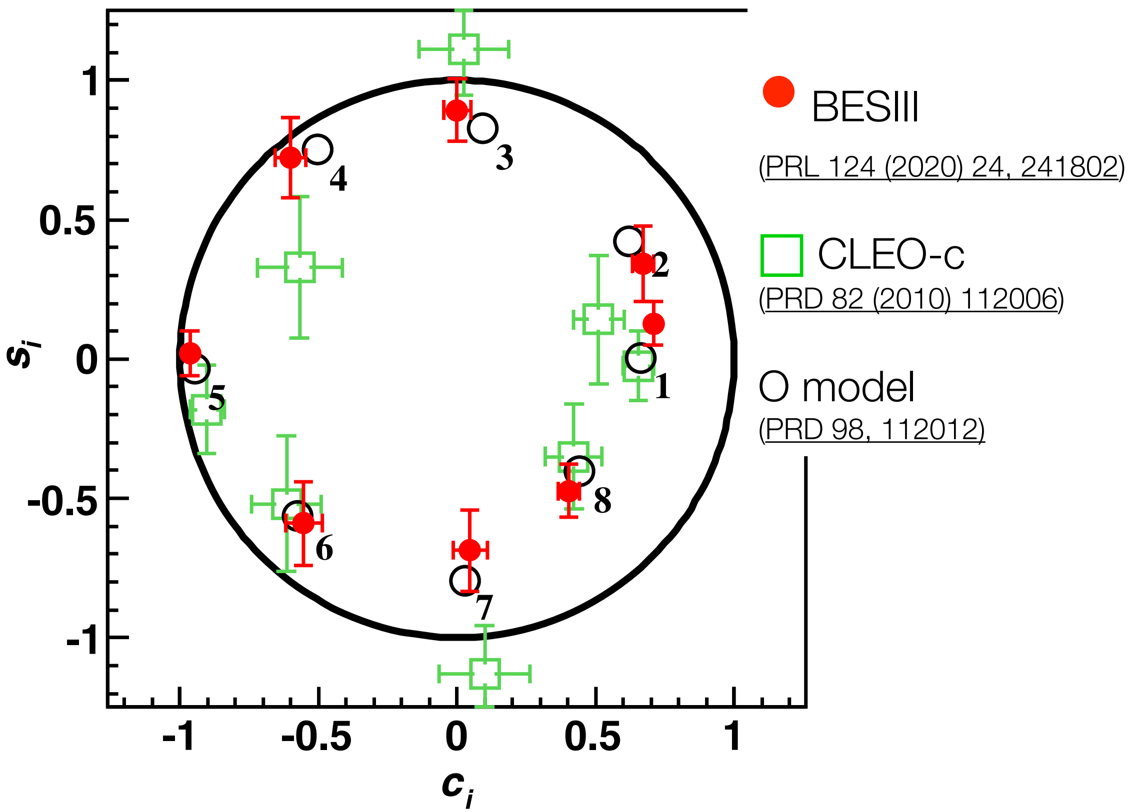
$\psi'' \to D_{CP-} \to K_s \pi^+ \pi^-$

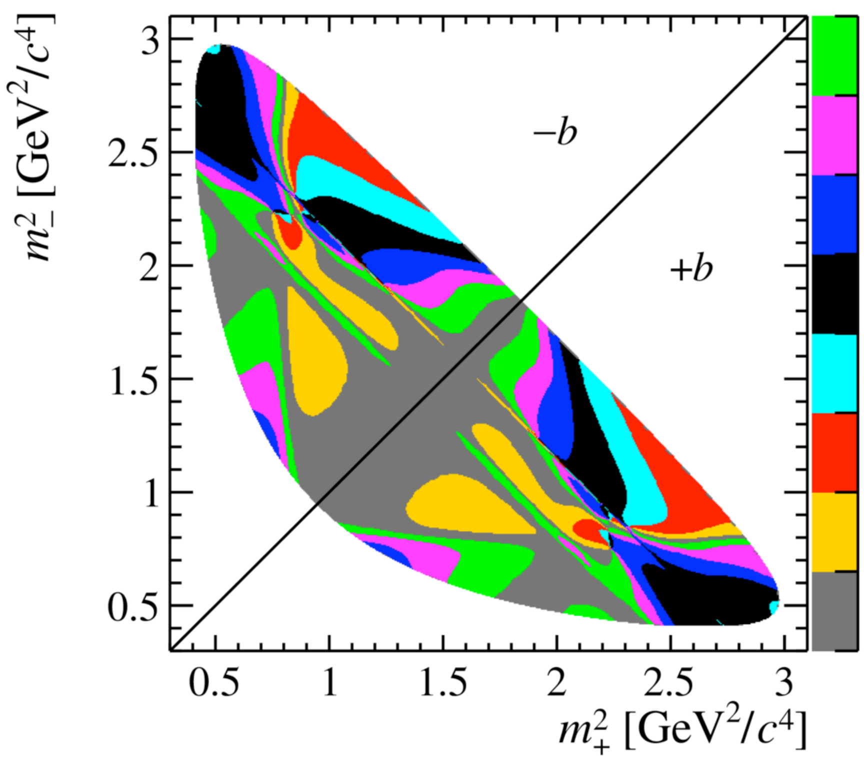


Measurements of $Z_i = c_i + is_i = Re^{-i\delta}$ at BES III

BESIII: PRL 124 (2020) 24, 241802

in $D^0 \to K_S\pi^+\pi^-$





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BESIII: JHEP 05 (2021) 164

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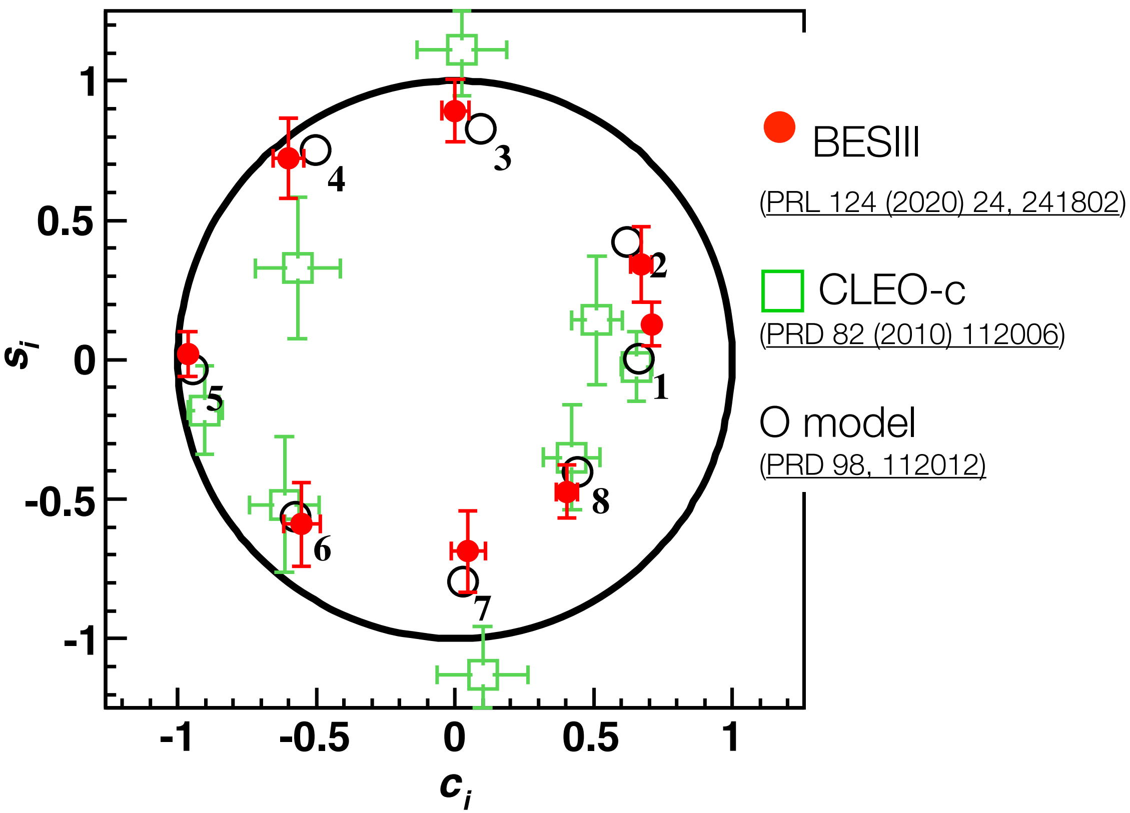
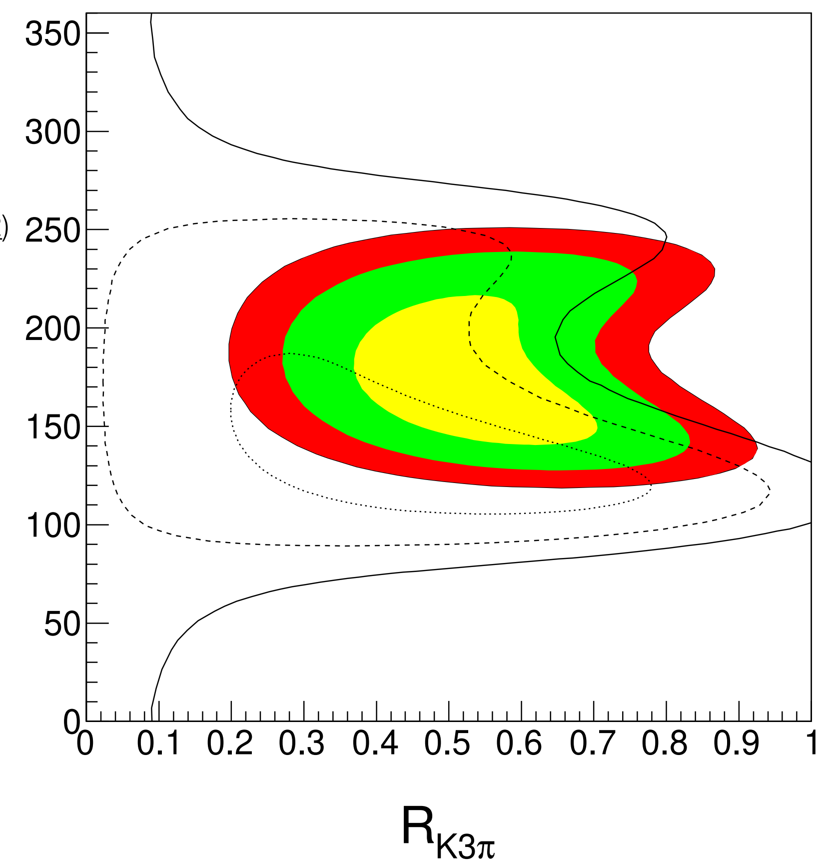
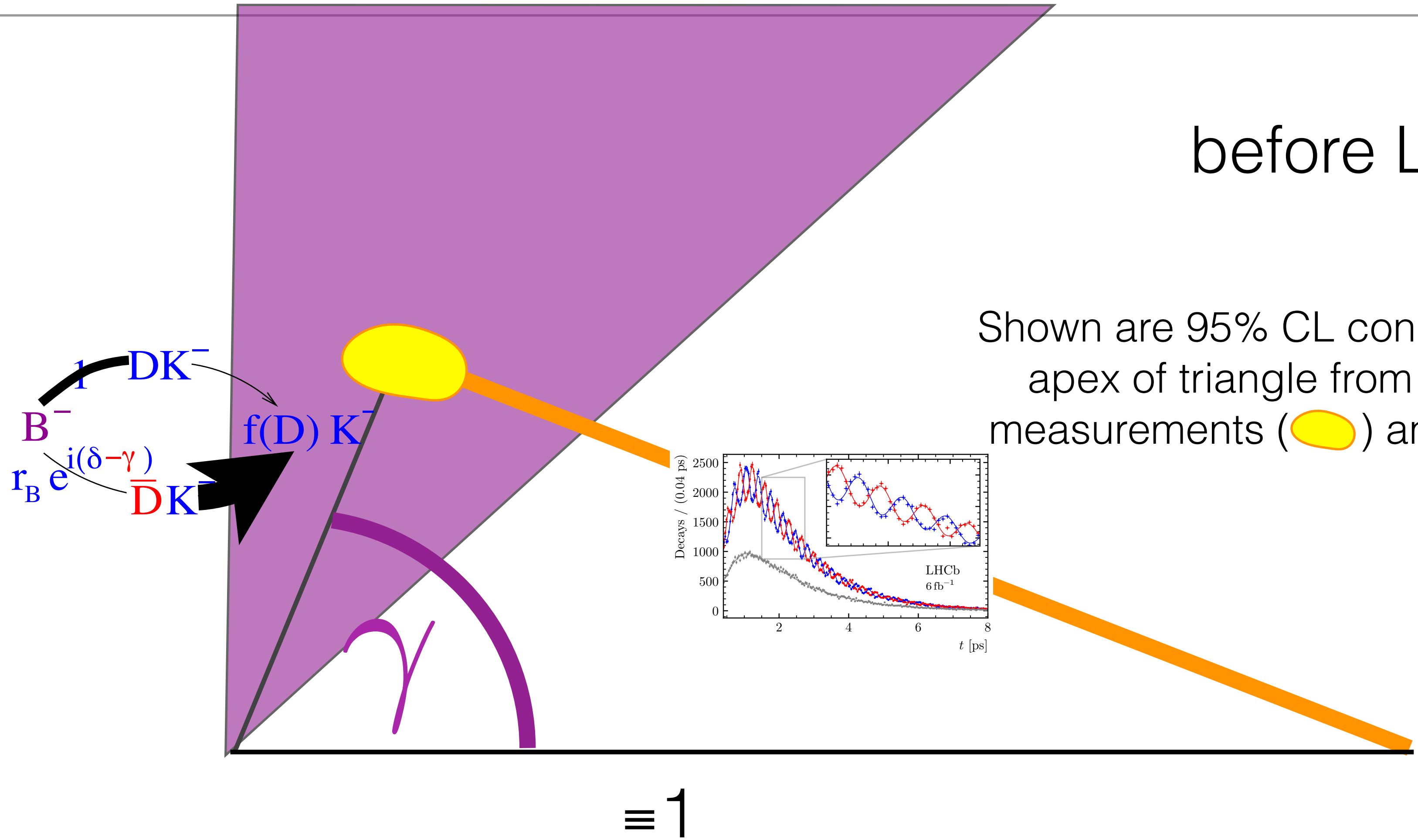


in $D^0 \to K\pi\pi\pi$



See also Jake and Richard Lane's and Ben Westhenry's talks in the today and Wednesday afternoon's parallel.

Unitarity triangle

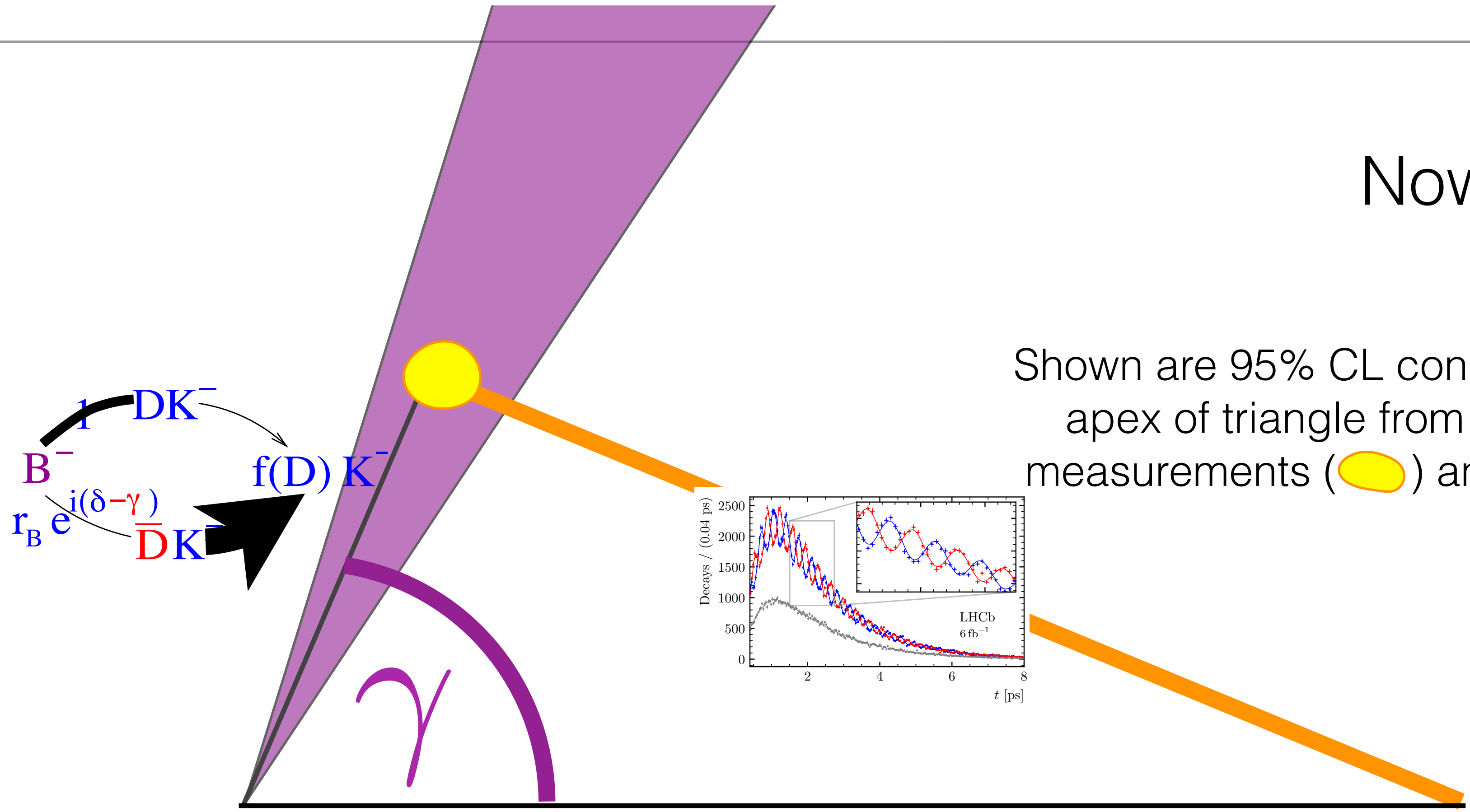


before LHCb

Shown are 95% CL constraints on apex of triangle from various measurements ( ) and γ ( )

CKM Fitter (2012): $\gamma = (66 \pm 12)^{\circ}$

Unitarity triangle



≡1

Now

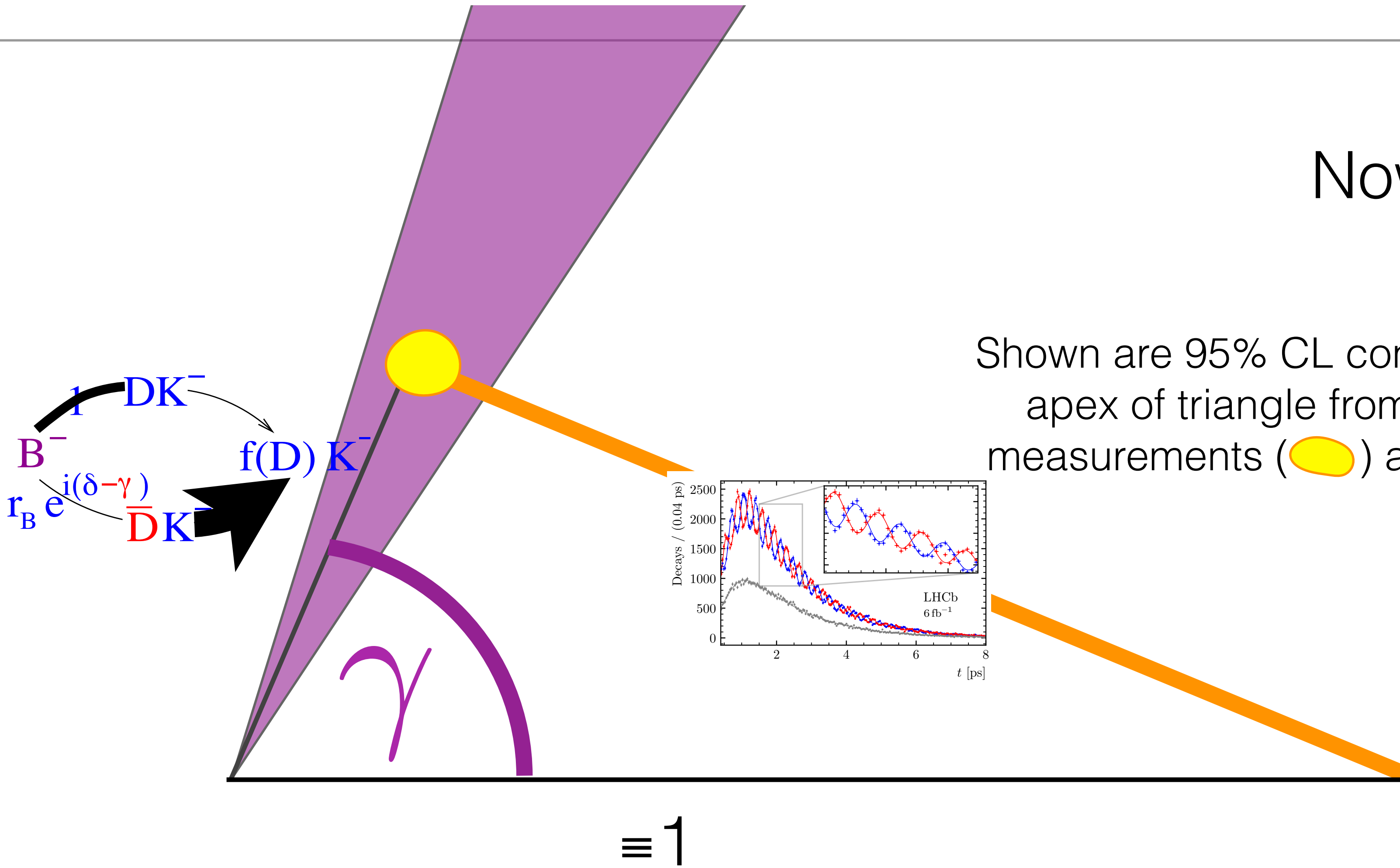
Shown are 95% CL constraints on apex of triangle from various measurements ( ) and γ ( )

LHCb: $\gamma = \left(65.4^{+3.8}_{-4.2}\right)^\circ$

LHCb: JHEP 12 (2021) 141

Unitarity triangle

Now



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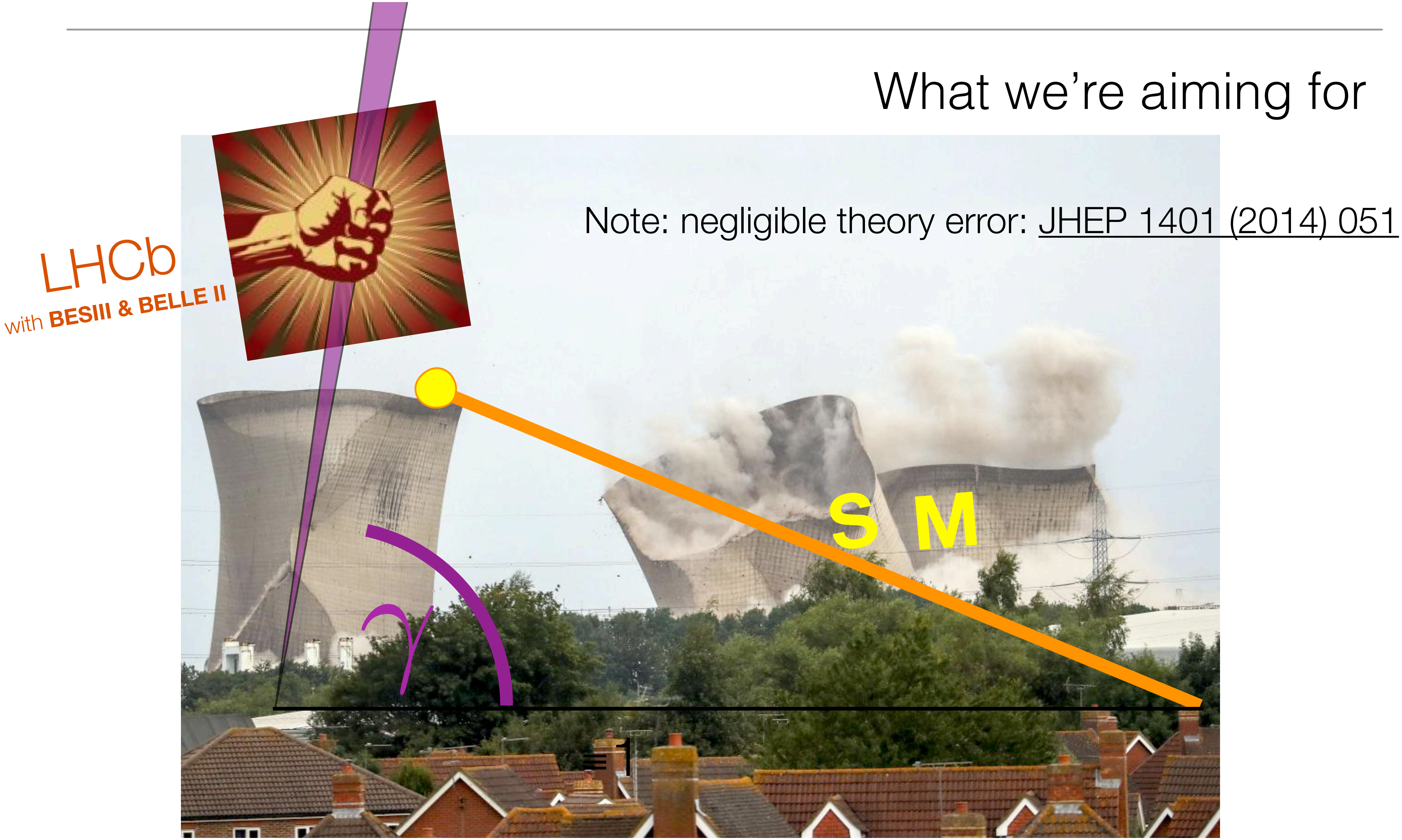
Unitarity triangle

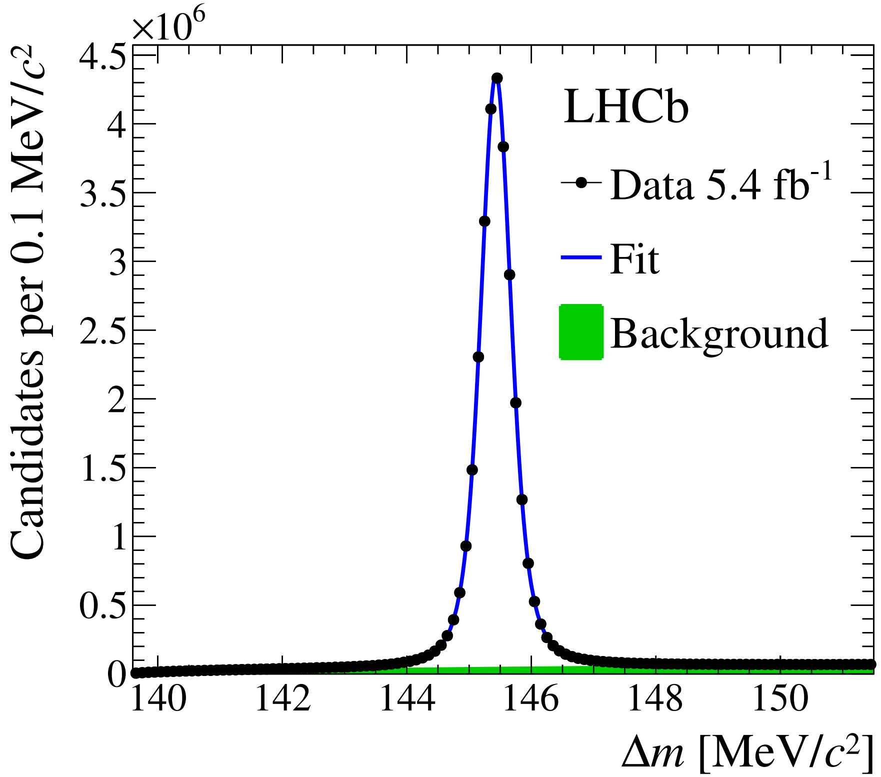
What we're aiming for



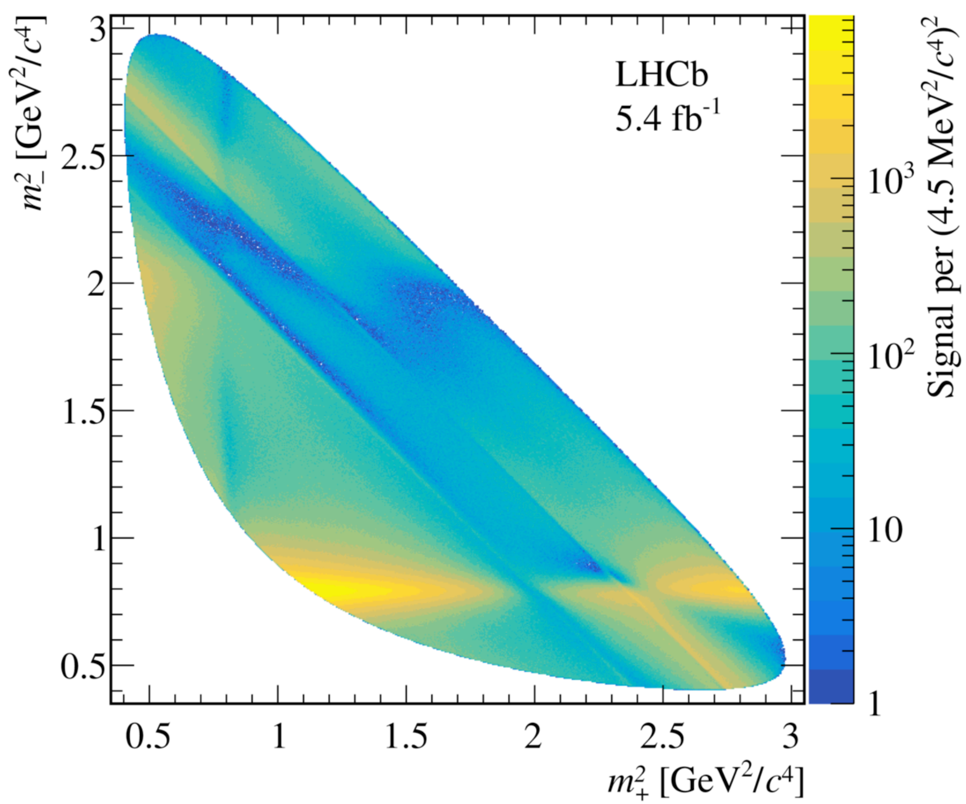
Model-independent analysis of charm mixing in $D^0 \to K_S \pi^+ \pi^-$

LHCb: PRL 127 (2021) 11, 111801

Uses same input from CLEO-c and BES III as for γ to remove amplitude model dependence



$m(D^*) - m(D)$ in $D^{*+} \to D^0 \pi^+, D^0 \to K_S \pi\pi$

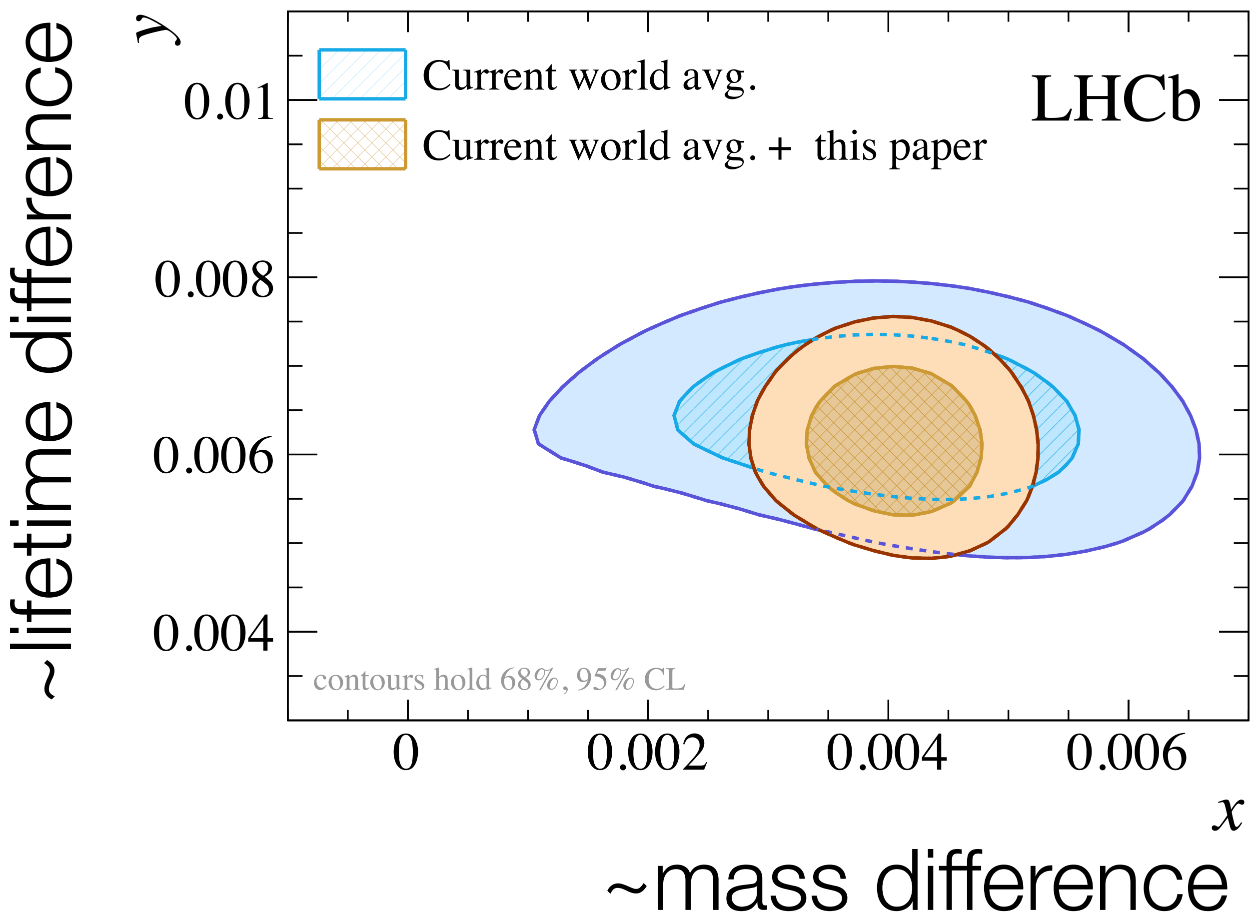


This is real data, not simulation. 30.6M signal events

First observation of mass difference between charm CP eigenstates.

LHCb: PRL 127 (2021) 11, 111801

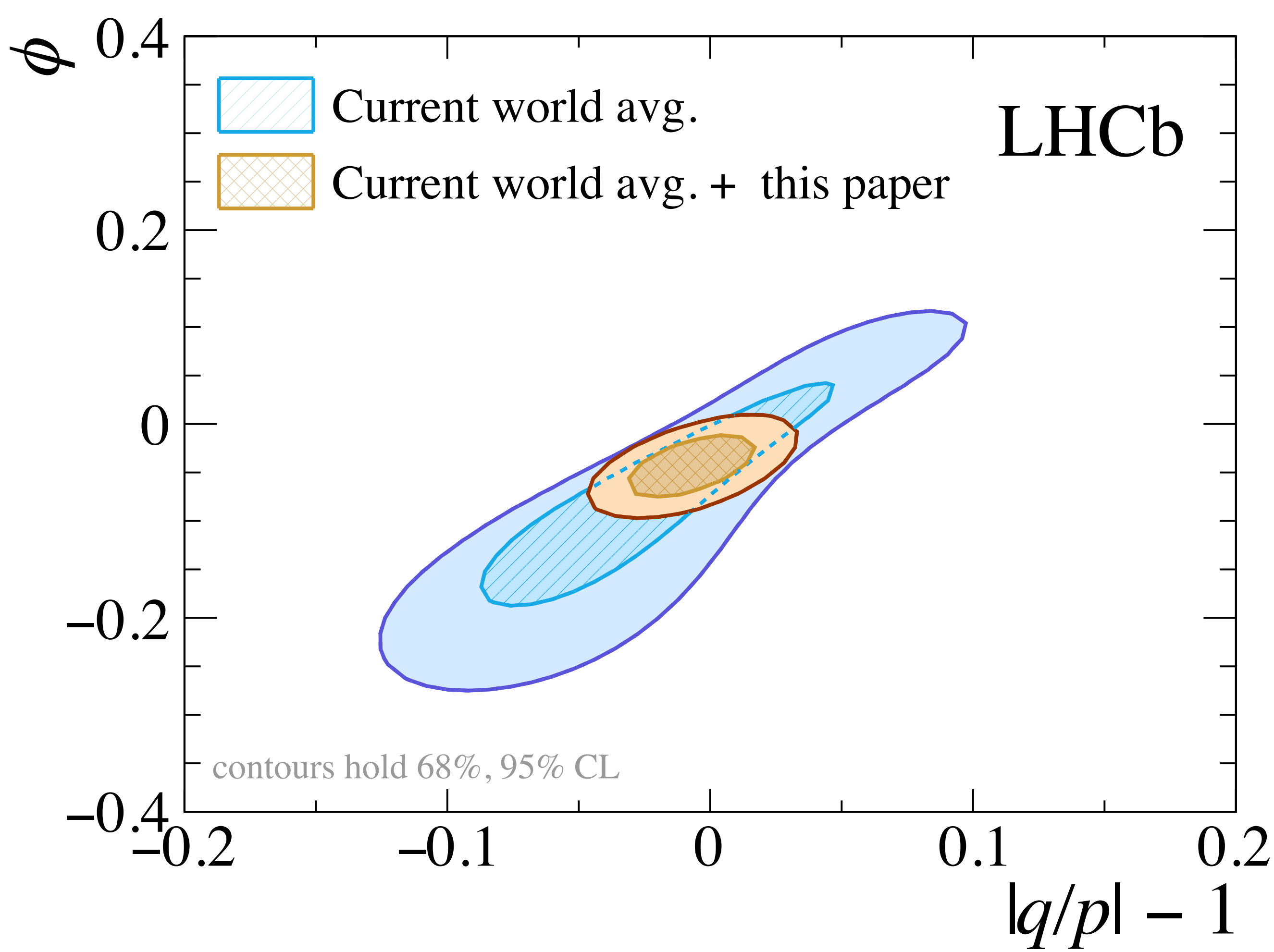
LHCb: $x = 3.98^{+0.56}_{-0.54}$, $x \neq 0$ at 5σ CL - first observation!



CP violation

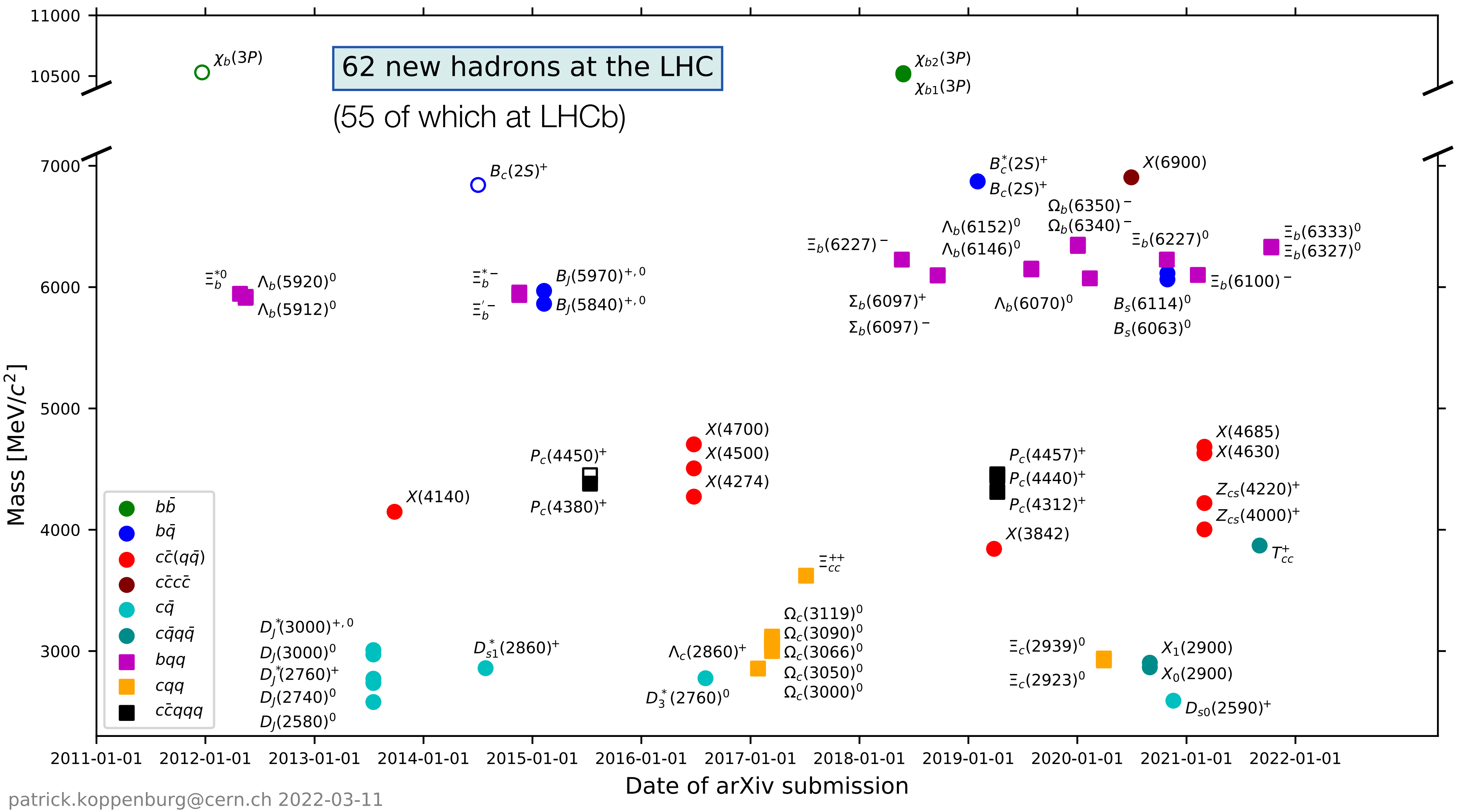
LHCb: PRL 127 (2021) 11, 111801

CPV in the interference between mixing and decay



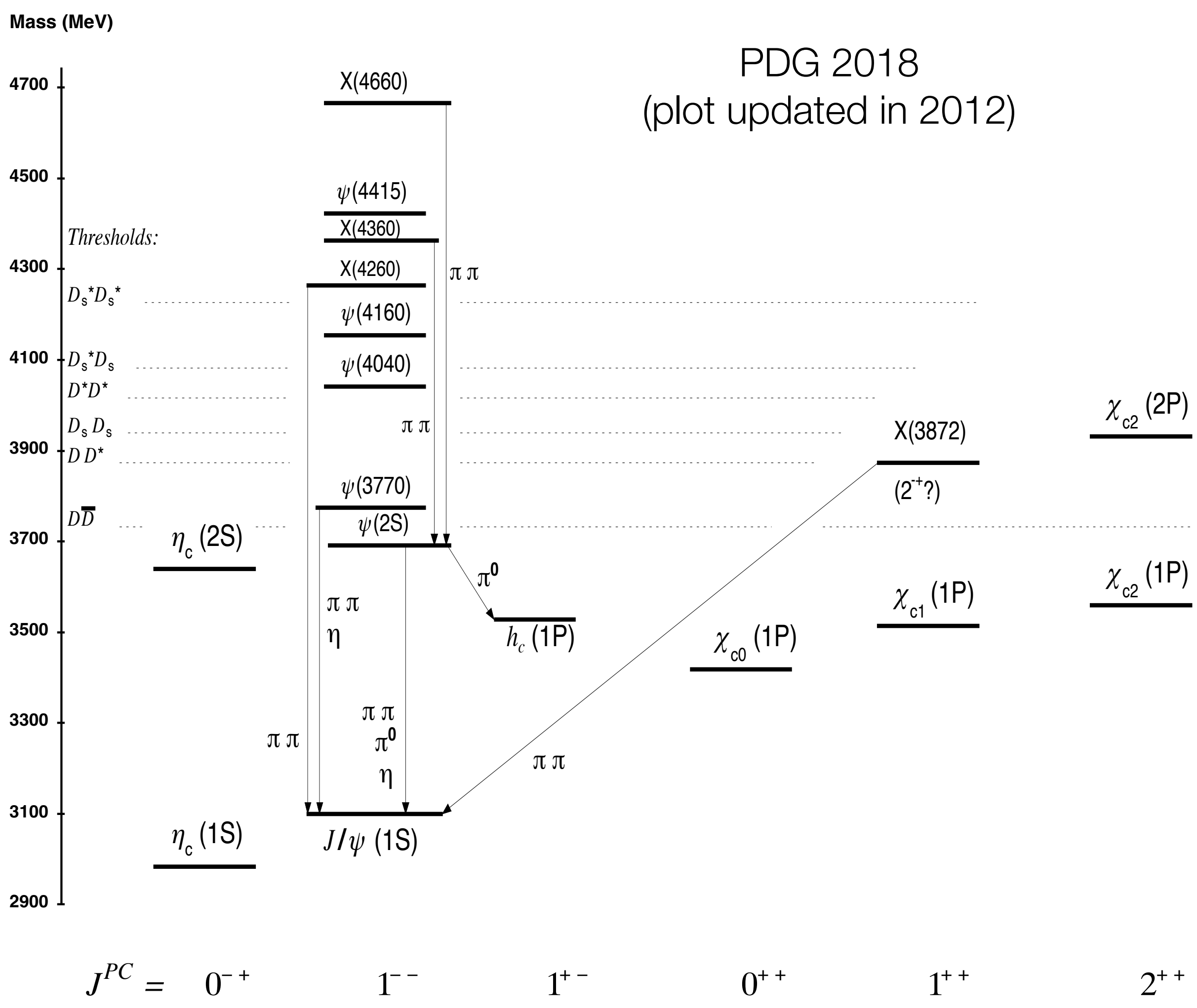
CPV in charm mixing

New Particles

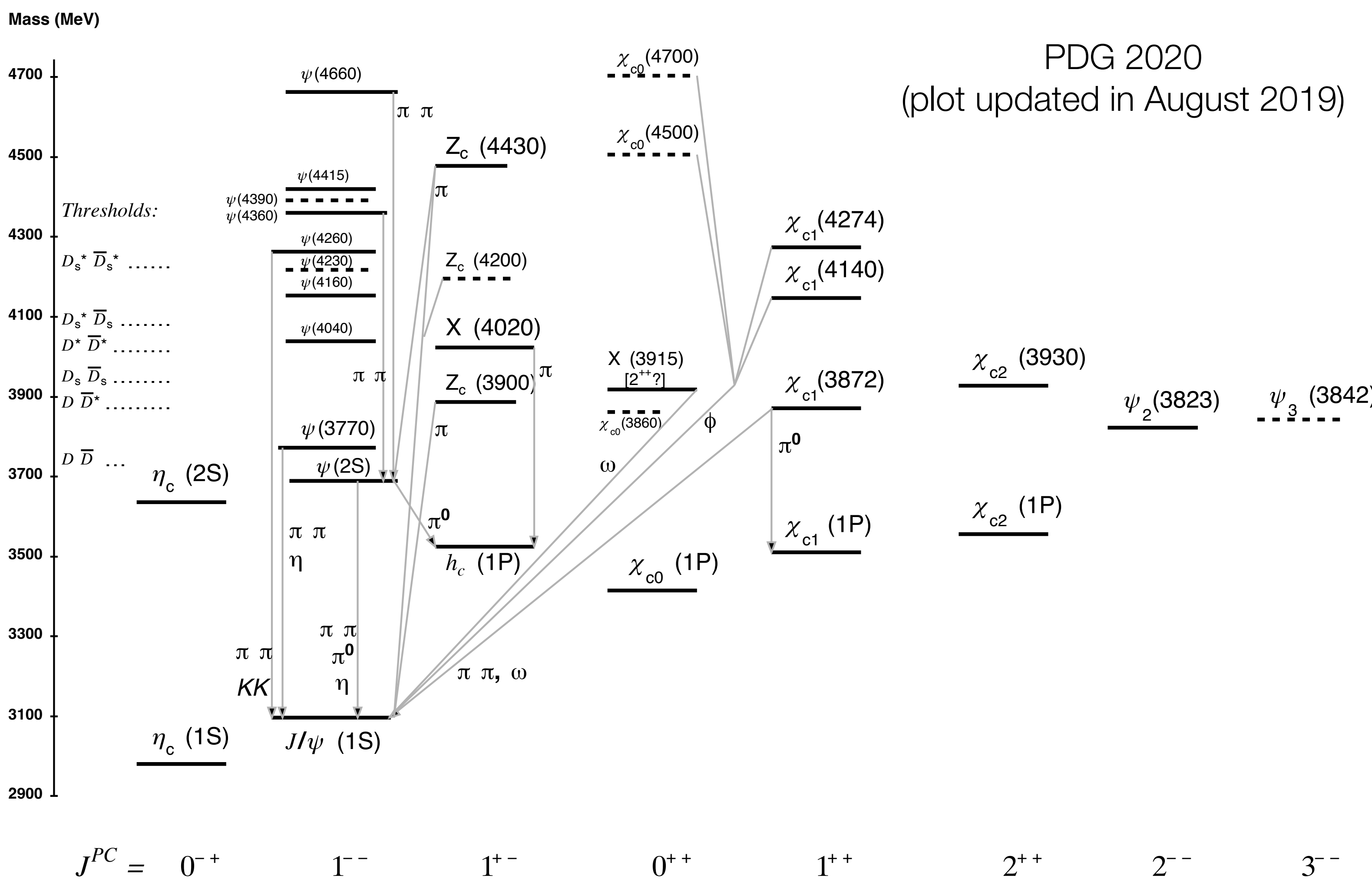


Plot by Patrick Koppenburg: https://www.nikhef.nl/~pkoppenb/particles.html

Charmonium

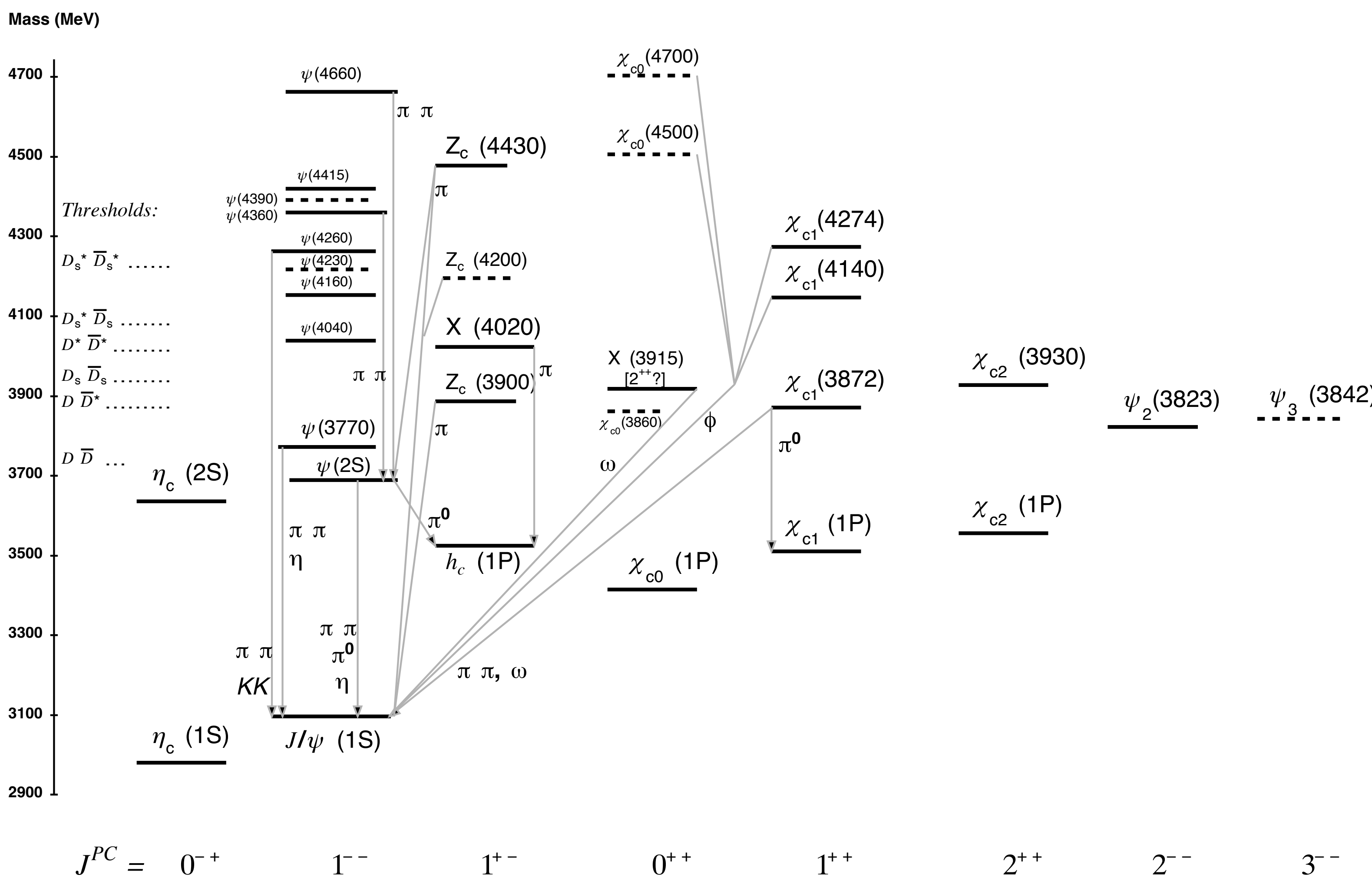

Mass (MeV)
PDG 2018
(plot updated in 2012)
4700
4500
4300
4100
3900
3700
3500
3300
3100
2900
Thresholds:
Ds*Ds*
Ds*Ds
D*D*
Ds Ds
D D*
DD̄
X(4660)
ψ(4415)
X(4360)
X(4260)
ψ(4160)
ψ(4040)
ψ(3770)
ψ(2S)
ηc (2S)
ηc (1S)
J/ψ (1S)
hc (1P)
χc0 (1P)
χc1 (1P)
χc2 (1P)
χc2 (2P)
X(3872)
(2-+?)
π π
π0
η
JPC = 0− + 1− − 1+ − 0+ + 1+ + 2+ +

Charmonium

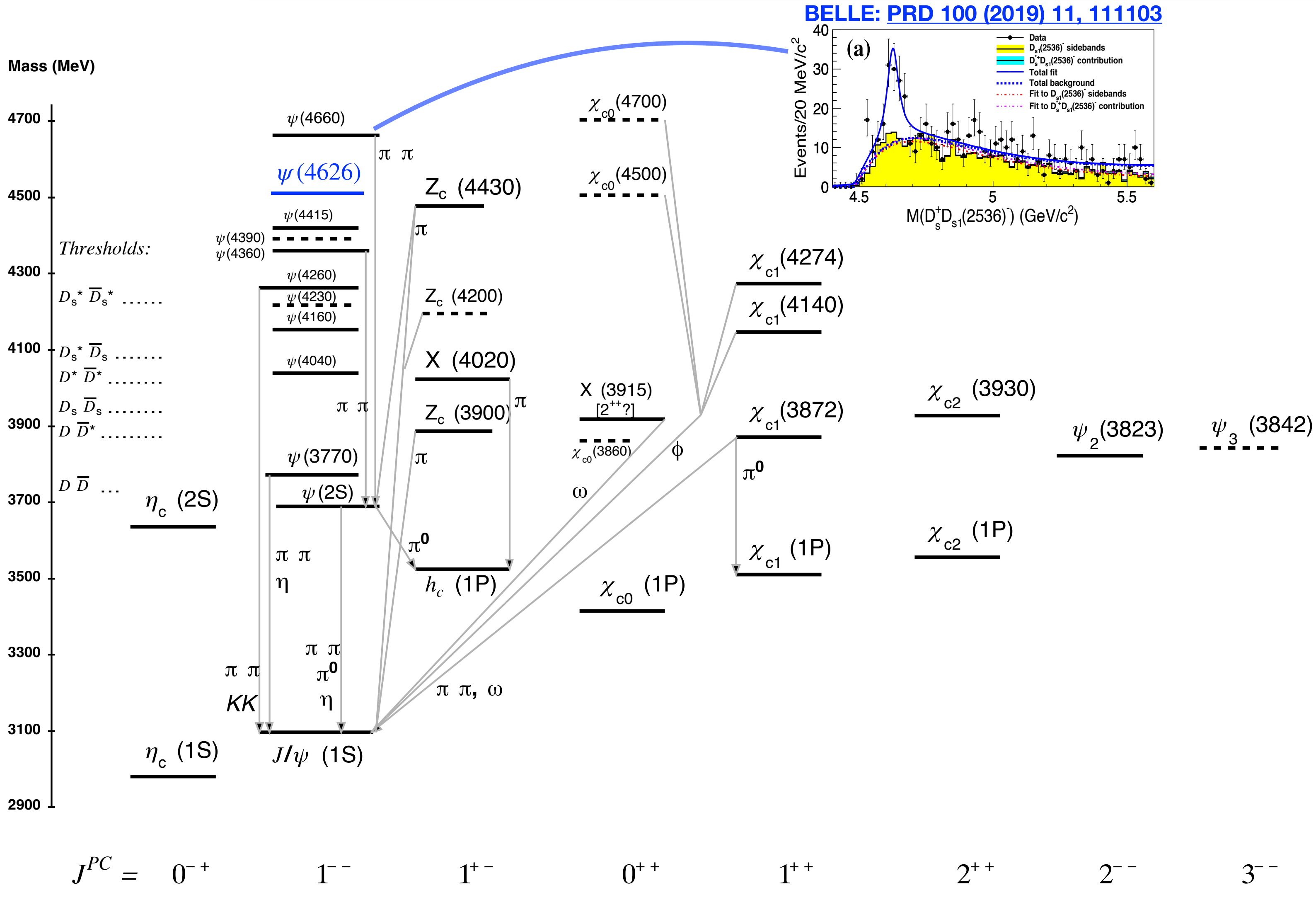


Mass (MeV)
PDG 2020
(plot updated in August 2019)
Thresholds:
ψ(4660)
ψ(4415)
ψ(4390)
ψ(4360)
ψ(4260)
ψ(4230)
ψ(4160)
ψ(4040)
ψ(3770)
ψ(2S)
J/ψ (1S)
η_c (2S)
η_c (1S)
Z_c (4430)
Z_c (4200)
X (4020)
Z_c (3900)
h_c (1P)
χ_c0(4700)
χ_c0(4500)
X (3915)
[2^{++}?]
χ_c0(3860)
χ_c0 (1P)
χ_c1(4274)
χ_c1(4140)
χ_c1(3872)
χ_c1 (1P)
χ_c2 (3930)
χ_c2 (1P)
ψ_2(3823)
ψ_3 (3842)
J^{PC} = 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{--} 3^{--}

Charmonium

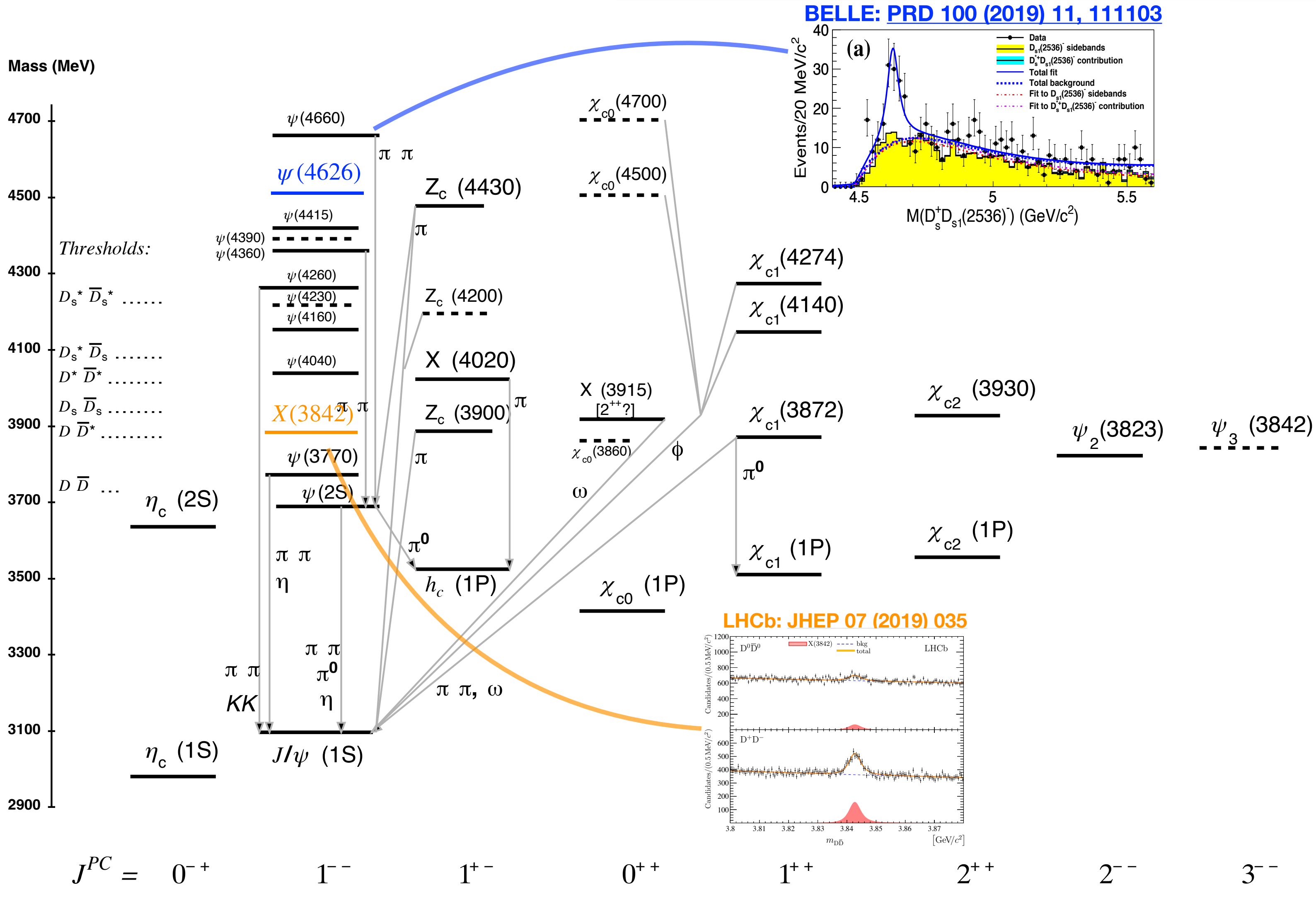

Mass (MeV)
4700
4500
4300
4100
3900
3700
3500
3300
3100
2900
Thresholds:
$D_s^* \overline{D}_s^*$
$D_s^* \overline{D}_s$
$D^* \overline{D}^*$
$D_s \overline{D}_s$
$D \overline{D}^*$
$D \overline{D}$
$\psi(4660)$
$\psi(4415)$
$\psi(4390)$
$\psi(4360)$
$\psi(4260)$
$\psi(4230)$
$\psi(4160)$
$\psi(4040)$
$\psi(3770)$
$\psi(2S)$
J/ψ (1S)
η_c (2S)
η_c (1S)
Z_c (4430)
Z_c (4200)
X (4020)
Z_c (3900)
h_c (1P)
$\chi_{c0}(4700)$
$\chi_{c0}(4500)$
X (3915)
[2++?]
$\chi_{c0}(3860)$
χ_{c0} (1P)
$\chi_{c1}(4274)$
$\chi_{c1}(4140)$
$\chi_{c1}(3872)$
χ_{c1} (1P)
χ_{c2} (3930)
χ_{c2} (1P)
$\psi_2(3823)$
ψ_3 (3842)
π π
π
π π
η
KK
π^0
ω
φ
π π, ω
J^{PC} = 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{--} 3^{--}

Charmonium



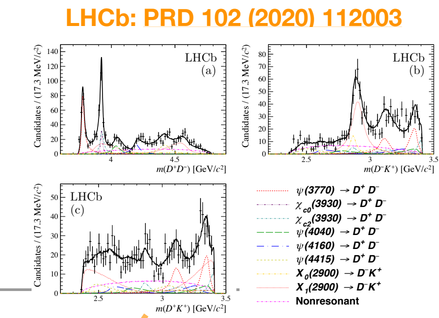
BELLE: PRD 100 (2019) 11, 111103
Mass (MeV)
4700
4500
4300
4100
3900
3700
3500
3300
3100
2900
Thresholds:
ψ(4660)
ψ(4626)
ψ(4415)
ψ(4390)
ψ(4360)
ψ(4260)
ψ(4230)
ψ(4160)
ψ(4040)
ψ(3770)
ψ(2S)
J/ψ (1S)
η_c (2S)
η_c (1S)
Z_c (4430)
Z_c (4200)
X (4020)
Z_c (3900)
h_c (1P)
χ_c0(4700)
χ_c0(4500)
X (3915)
[2^{++}?]
χ_c0(3860)
χ_c0 (1P)
χ_c1(4274)
χ_c1(4140)
χ_c1(3872)
χ_c1 (1P)
χ_c2 (3930)
χ_c2 (1P)
ψ_2(3823)
ψ_3 (3842)
π π
π
π^0
η
KK
ω
φ
π π, ω
J^{PC} = 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{--} 3^{--}

Charmonium

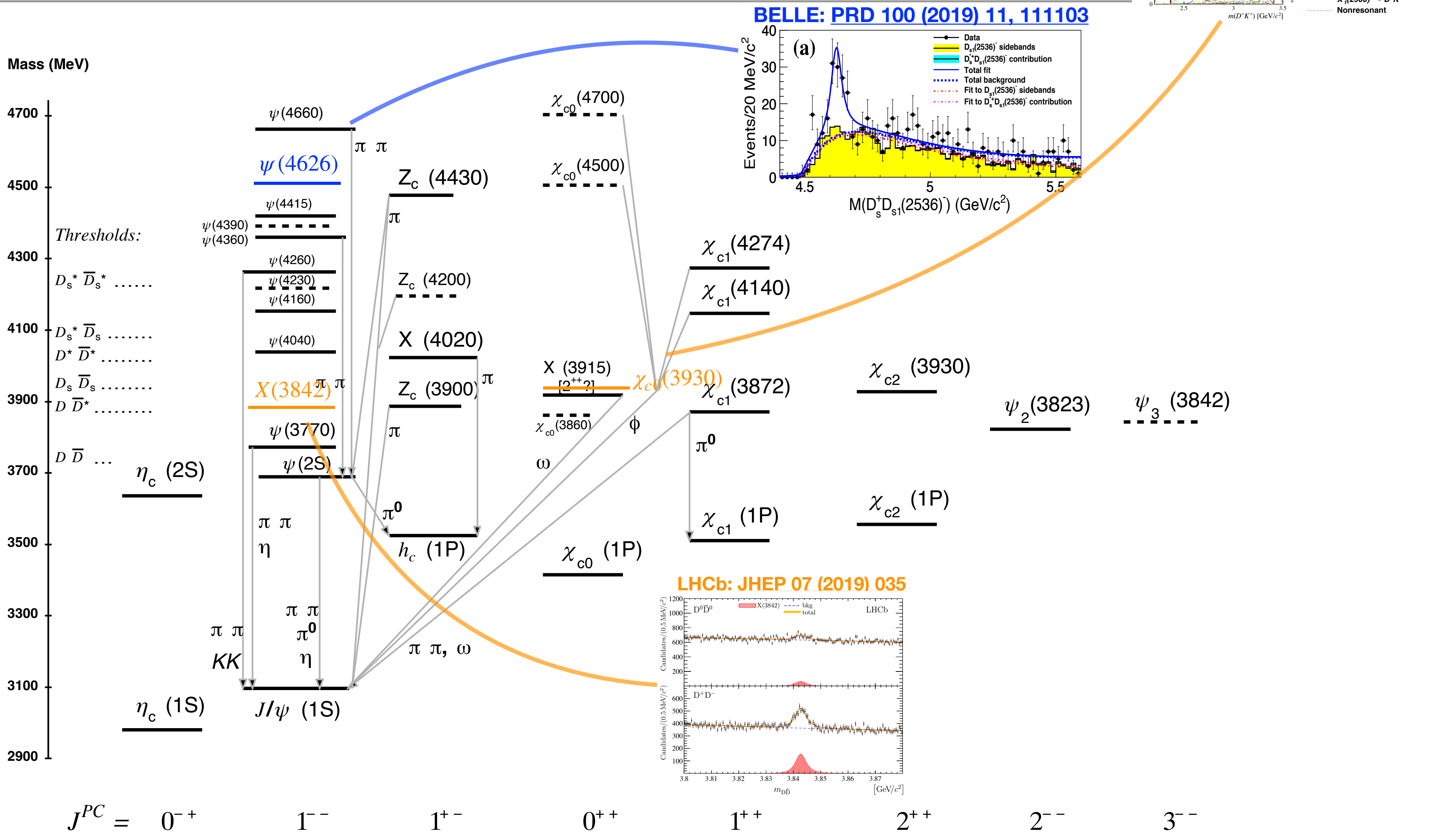


BELLE: PRD 100 (2019) 11, 111103
LHCb: JHEP 07 (2019) 035
Mass (MeV)
Thresholds:
ψ(4660)
ψ(4626)
ψ(4415)
ψ(4390)
ψ(4360)
ψ(4260)
ψ(4230)
ψ(4160)
ψ(4040)
X(3842)
ψ(3770)
ψ(2S)
J/ψ (1S)
η_c (2S)
η_c (1S)
Z_c (4430)
Z_c (4200)
X (4020)
Z_c (3900)
h_c (1P)
χ_c0(4700)
χ_c0(4500)
X (3915)
[2++?]
χ_c0(3860)
χ_c0 (1P)
χ_c1(4274)
χ_c1(4140)
χ_c1(3872)
χ_c1 (1P)
χ_c2 (3930)
χ_c2 (1P)
ψ_2(3823)
ψ_3 (3842)
J^PC = 0−+ 1−− 1+− 0++ 1++ 2++ 2−− 3−−
M(D_s^+ D_s1(2536)^-) (GeV/c^2)
Events/20 MeV/c^2

Charmonium

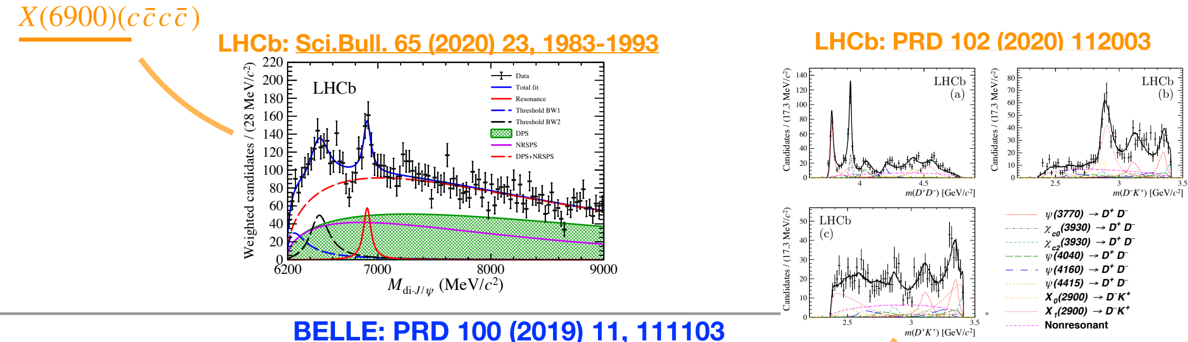


LHCb: PRD 102 (2020) 112003
LHCb (a)
LHCb (b)
LHCb (c)
Nonresonant

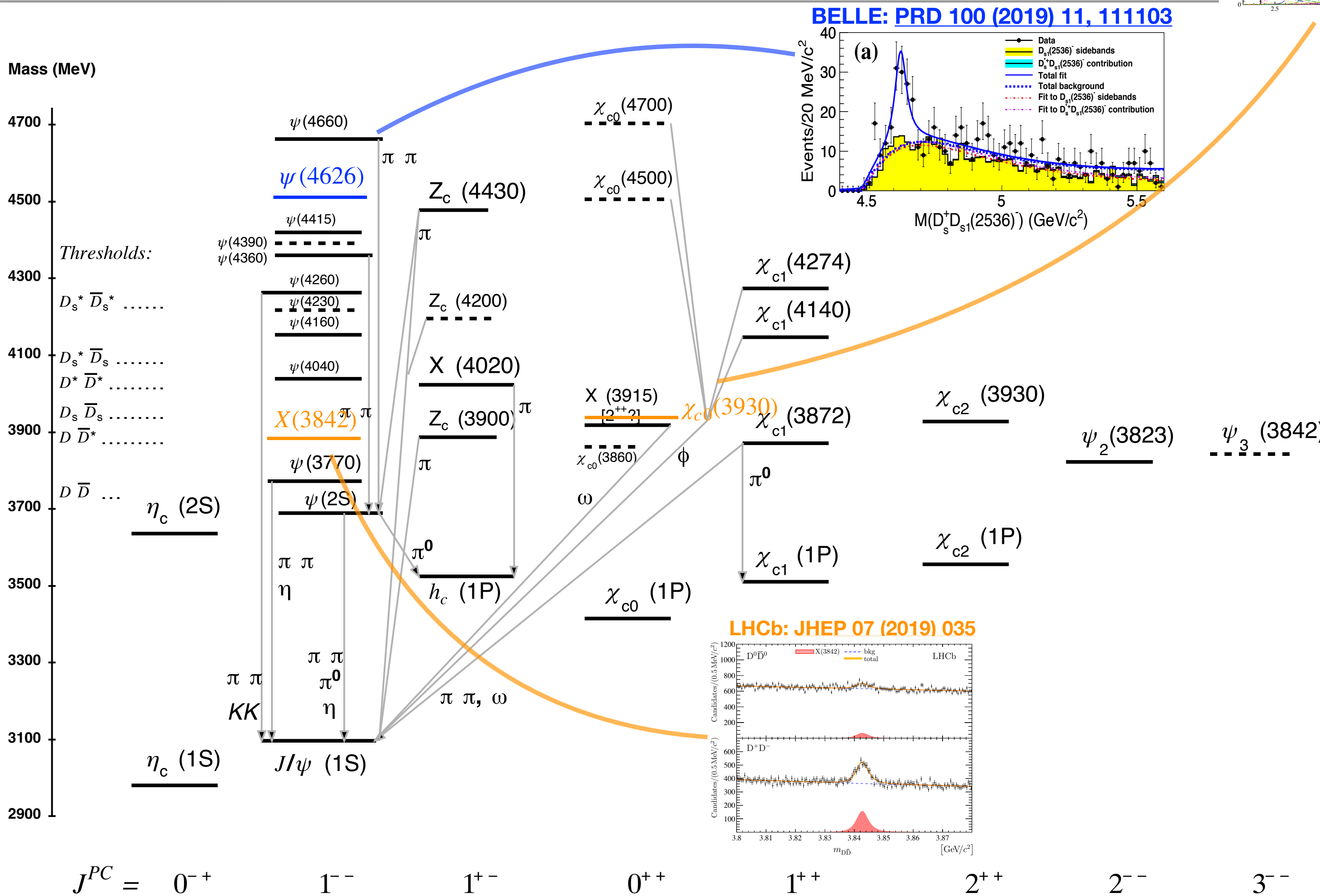


BELLE: PRD 100 (2019) 11, 111103
Events/20 MeV/c²
M(D$_s^+$D$_{s1}$(2536)$^-$) (GeV/c²)
Data
Total fit
Total background
LHCb: JHEP 07 (2019) 035
Mass (MeV)
4700
4500
4300
4100
3900
3700
3500
3300
3100
2900
Thresholds:
$D_s^* \bar{D}_s^*$
$D_s^* \bar{D}_s$
$D^* \bar{D}^*$
$D_s \bar{D}_s$
$D \bar{D}^*$
$D \bar{D}$
$\psi(4660)$
$\psi(4626)$
$\psi(4415)$
$\psi(4390)$
$\psi(4360)$
$\psi(4260)$
$\psi(4230)$
$\psi(4160)$
$\psi(4040)$
$X(3842)$
$\psi(3770)$
$\psi(2S)$
J/ψ (1S)
η_c (2S)
η_c (1S)
Z_c (4430)
Z_c (4200)
X (4020)
Z_c (3900)
h_c (1P)
$\chi_{c0}(4700)$
$\chi_{c0}(4500)$
X (3915)
$\chi_{c0}(3930)$
$\chi_{c0}(3860)$
χ_{c0} (1P)
$\chi_{c1}(4274)$
$\chi_{c1}(4140)$
$\chi_{c1}(3872)$
χ_{c1} (1P)
χ_{c2} (3930)
χ_{c2} (1P)
$\psi_2(3823)$
ψ_3 (3842)
J^{PC} = 0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{--} 3^{--}

Charmonium

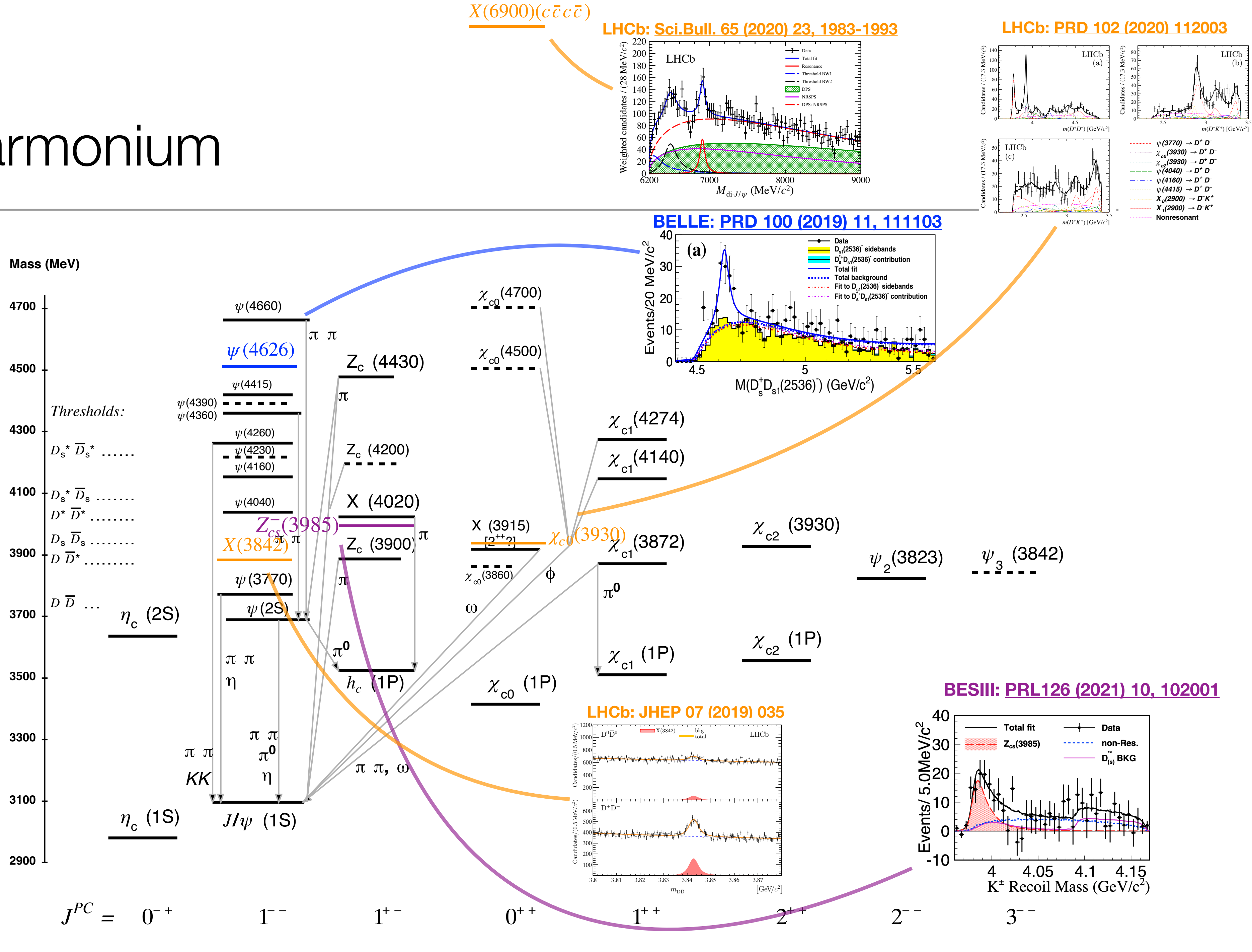


X(6900)(cc̄cc̄)
LHCb: Sci.Bull. 65 (2020) 23, 1983-1993
LHCb
Weighted candidates / (28 MeV/c²)
M_di-J/ψ (MeV/c²)
LHCb: PRD 102 (2020) 112003



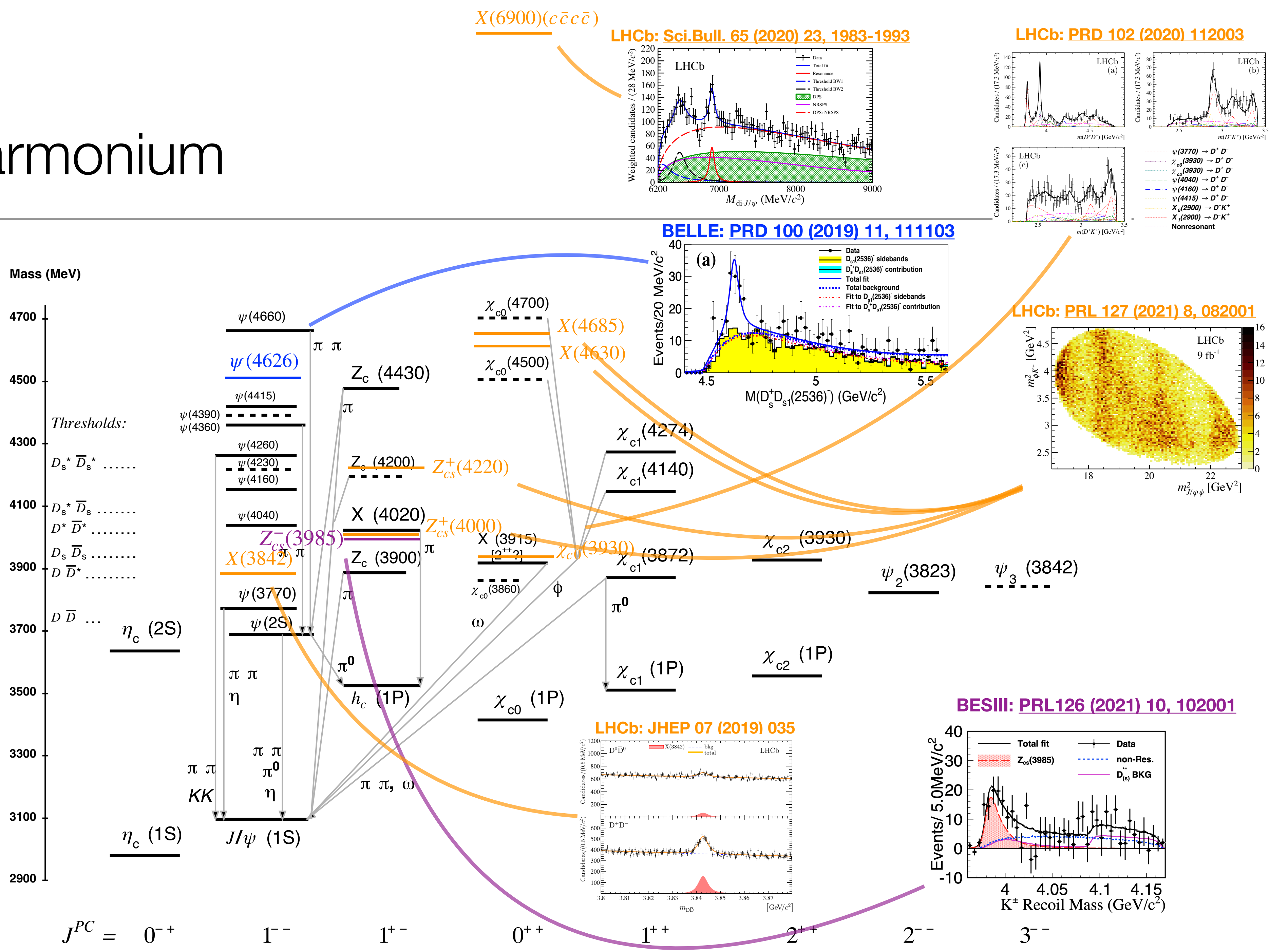
BELLE: PRD 100 (2019) 11, 111103
Events/20 MeV/c²
M(D_s^+ D_s1(2536)^-) (GeV/c²)
Mass (MeV)
4700
4500
4300
4100
3900
3700
3500
3300
3100
2900
Thresholds:
D_s* D̄_s* ……
D_s* D̄_s ……
D* D̄* ……
D_s D̄_s ……
D D̄* ……
D D̄ …
η_c (2S)
η_c (1S)
ψ(4660)
ψ(4626)
ψ(4415)
ψ(4390)
ψ(4360)
ψ(4260)
ψ(4230)
ψ(4160)
ψ(4040)
X(3842)
ψ(3770)
ψ(2S)
J/ψ (1S)
Z_c (4430)
Z_c (4200)
X (4020)
Z_c (3900)
h_c (1P)
χ_c0(4700)
χ_c0(4500)
X (3915)
[2^{++}?]
χ_c0(3930)
χ_c0(3860)
χ_c0 (1P)
χ_c1(4274)
χ_c1(4140)
χ_c1(3872)
χ_c1 (1P)
χ_c2 (3930)
χ_c2 (1P)
ψ_2(3823)
ψ_3 (3842)
π π
π
π⁰
η
KK
ω
φ
π π, ω
LHCb: JHEP 07 (2019) 035
J^{PC} = 0⁻⁺ 1⁻⁻ 1⁺⁻ 0⁺⁺ 1⁺⁺ 2⁺⁺ 2⁻⁻ 3⁻⁻

Charmonium



X(6900)(cc̄cc̄)
LHCb: Sci.Bull. 65 (2020) 23, 1983-1993
LHCb: PRD 102 (2020) 112003
BELLE: PRD 100 (2019) 11, 111103
LHCb: JHEP 07 (2019) 035
BESIII: PRL126 (2021) 10, 102001
Mass (MeV)
Thresholds:
ψ(4660)
ψ(4626)
ψ(4415)
ψ(4390)
ψ(4360)
ψ(4260)
ψ(4230)
ψ(4160)
ψ(4040)
X(3842)
ψ(3770)
ψ(2S)
J/ψ (1S)
η_c (2S)
η_c (1S)
Z_c (4430)
Z_c (4200)
X (4020)
Z_cs^-(3985)
Z_c (3900)
h_c (1P)
χ_c0(4700)
χ_c0(4500)
X (3915)
χ_c0(3930)
χ_c0(3860)
χ_c0 (1P)
χ_c1(4274)
χ_c1(4140)
χ_c1(3872)
χ_c1 (1P)
χ_c2 (3930)
χ_c2 (1P)
ψ_2(3823)
ψ_3 (3842)
J^PC = 0^-+ 1^-- 1^+- 0^++ 1^++ 2^++ 2^-- 3^--

Charmonium

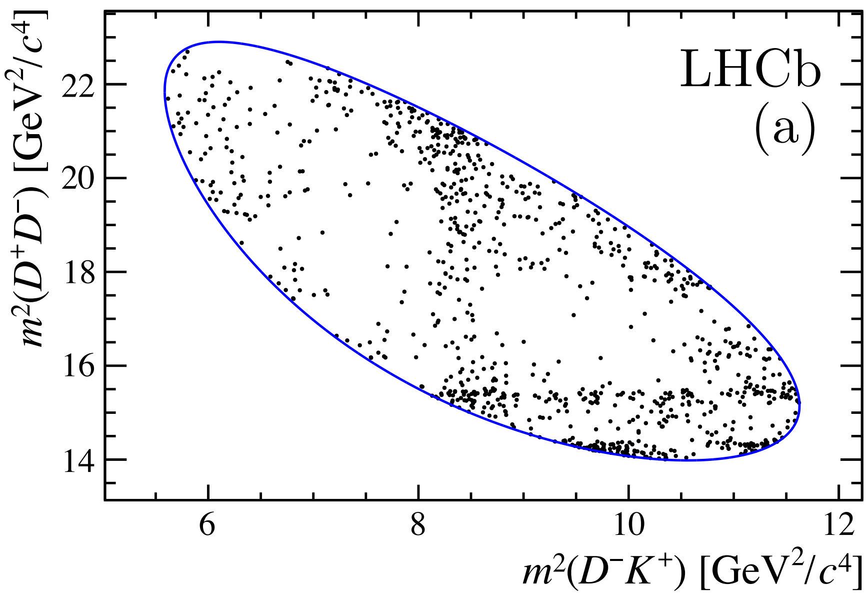


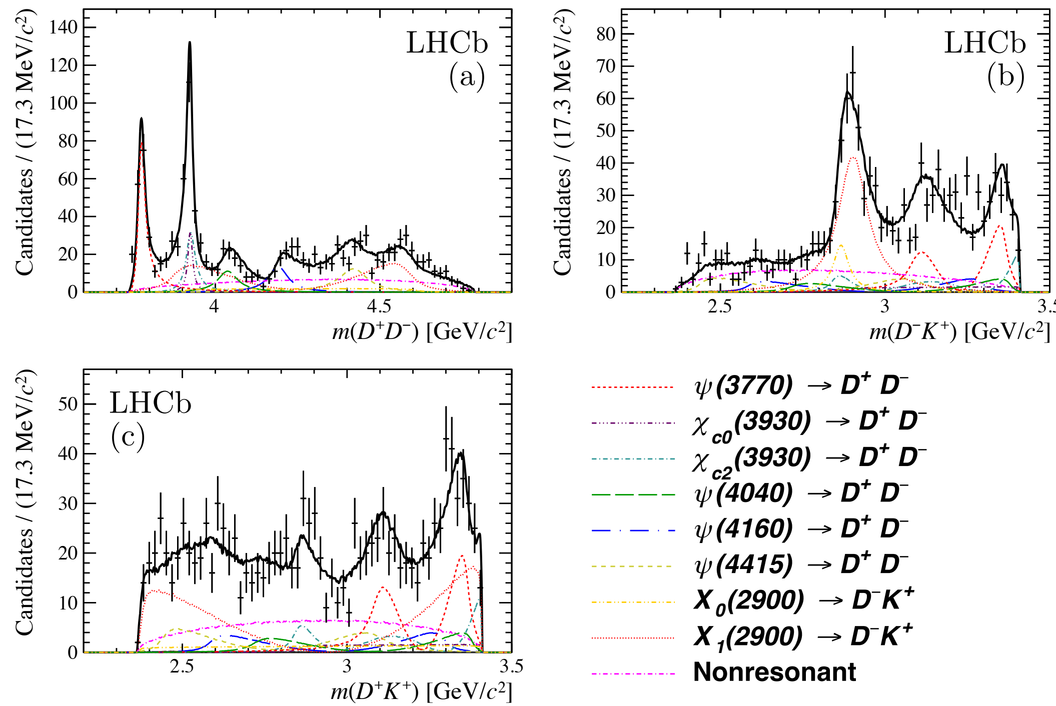
X(6900)(cc̄cc̄)
LHCb: Sci.Bull. 65 (2020) 23, 1983-1993
LHCb: PRD 102 (2020) 112003
BELLE: PRD 100 (2019) 11, 111103
LHCb: PRL 127 (2021) 8, 082001
LHCb: JHEP 07 (2019) 035
BESIII: PRL126 (2021) 10, 102001
Mass (MeV)
Thresholds:
ψ(4660)
ψ(4626)
ψ(4415)
ψ(4390)
ψ(4360)
ψ(4260)
ψ(4230)
ψ(4160)
ψ(4040)
X(3842)
ψ(3770)
ψ(2S)
J/ψ (1S)
η_c (2S)
η_c (1S)
Z_c (4430)
Z_c (4200)
Z_cs^+(4220)
X (4020)
Z_cs^+(4000)
Z_cs^−(3985)
Z_c (3900)
h_c (1P)
χ_c0(4700)
X(4685)
X(4630)
χ_c0(4500)
X (3915)
χ_c0(3930)
χ_c0(3860)
χ_c0 (1P)
χ_c1(4274)
χ_c1(4140)
χ_c1(3872)
χ_c1 (1P)
χ_c2 (3930)
χ_c2 (1P)
ψ_2(3823)
ψ_3 (3842)
J^PC = 0^−+ 1^−− 1^+− 0^++ 1^++ 2^++ 2^−− 3^−−

Really strange: First tetra flavour

LHCb: PRL 125 (2020) 242001
LHCb: PRD 102 (2020) 112003

$B^+ \to D^+ D^- K^+$ Dalitz Plot

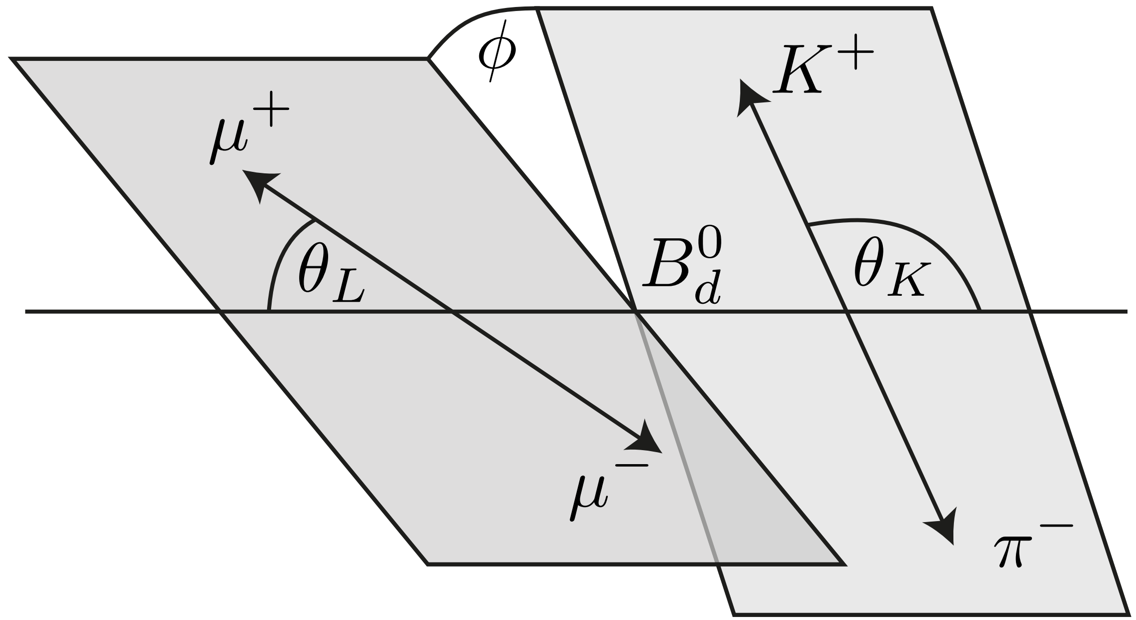




Best fit with two new D^-K^+resonances, $X_0(2900)$, $X_1(2900)$, which have minimal quark content $\bar{c}d\bar{s}u$.

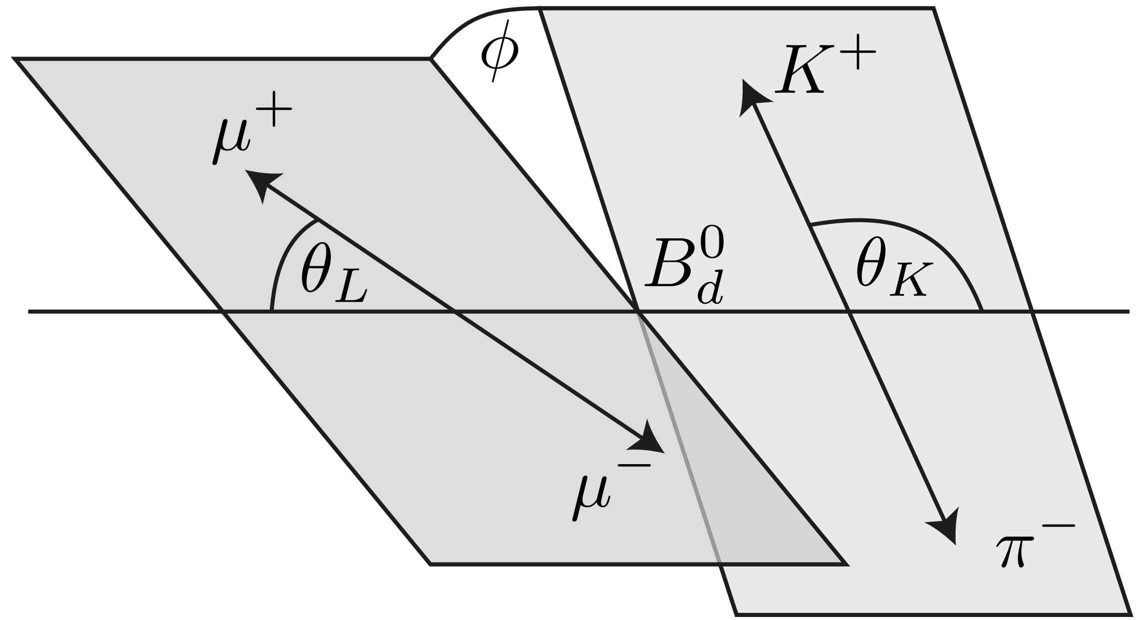
Flavour anomalies

$B^0 \to K^{*0}\mu^+\mu^-$



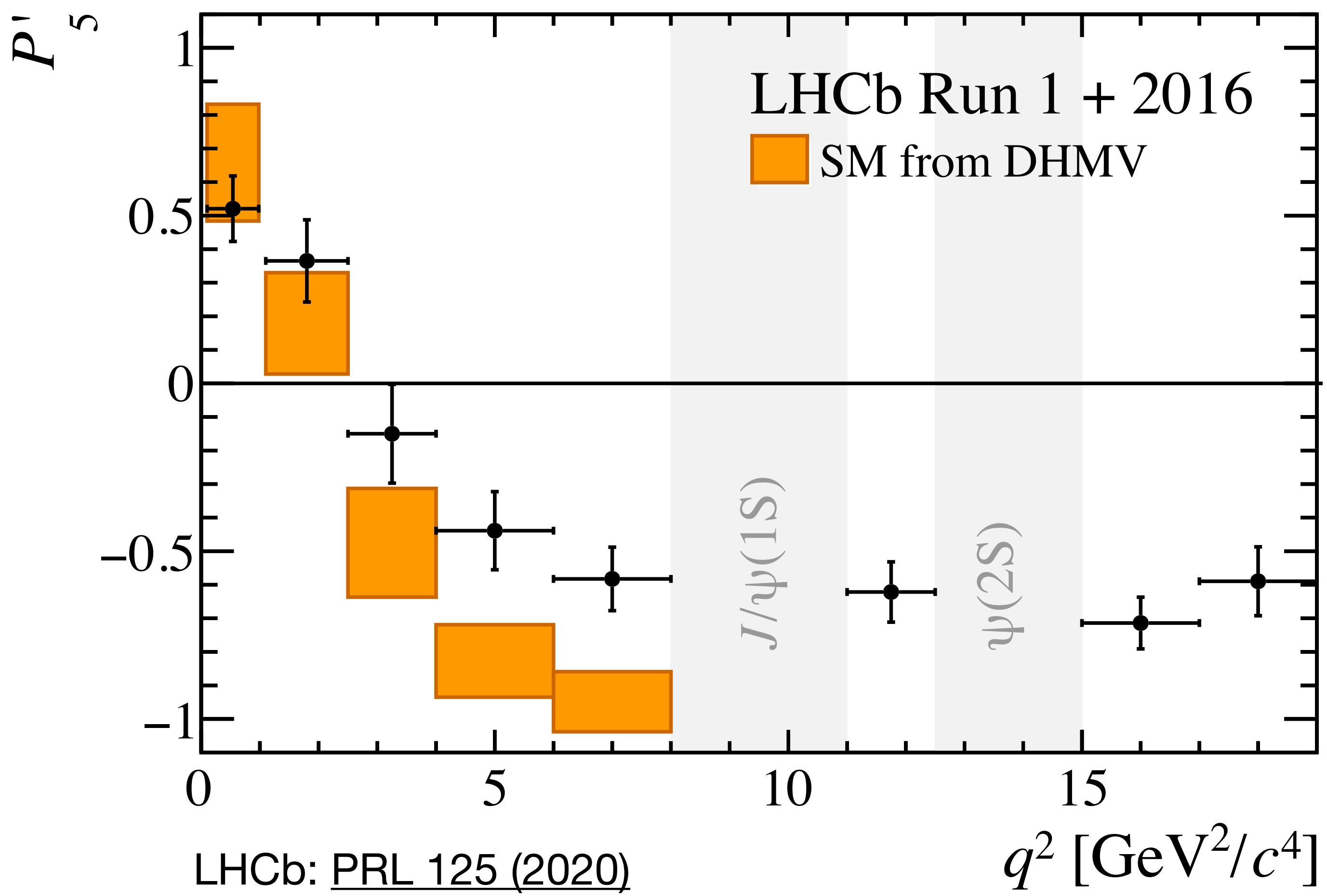
$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_\mathrm{L})A_{Re}^\mathrm{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$B^0 \to K^{*0}\mu^+\mu^-$



$$\frac{1}{\Gamma}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + \frac{1}{2}(1-F_\mathrm{L})A_\mathrm{T}^{(2)}\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi +$$
$$\sqrt{F_L(1-F_\mathrm{L})}P_4'\sin 2\theta_K\sin 2\theta_\ell\cos\phi + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_5'\sin 2\theta_K\sin\theta_\ell\cos\phi +$$
$$(1-F_\mathrm{L})A_{Re}^\mathrm{T}\sin^2\theta_K\cos\theta_\ell + \sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_6'\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}P_8'\sin 2\theta_K\sin 2\theta_\ell\sin\phi + (S/A)_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

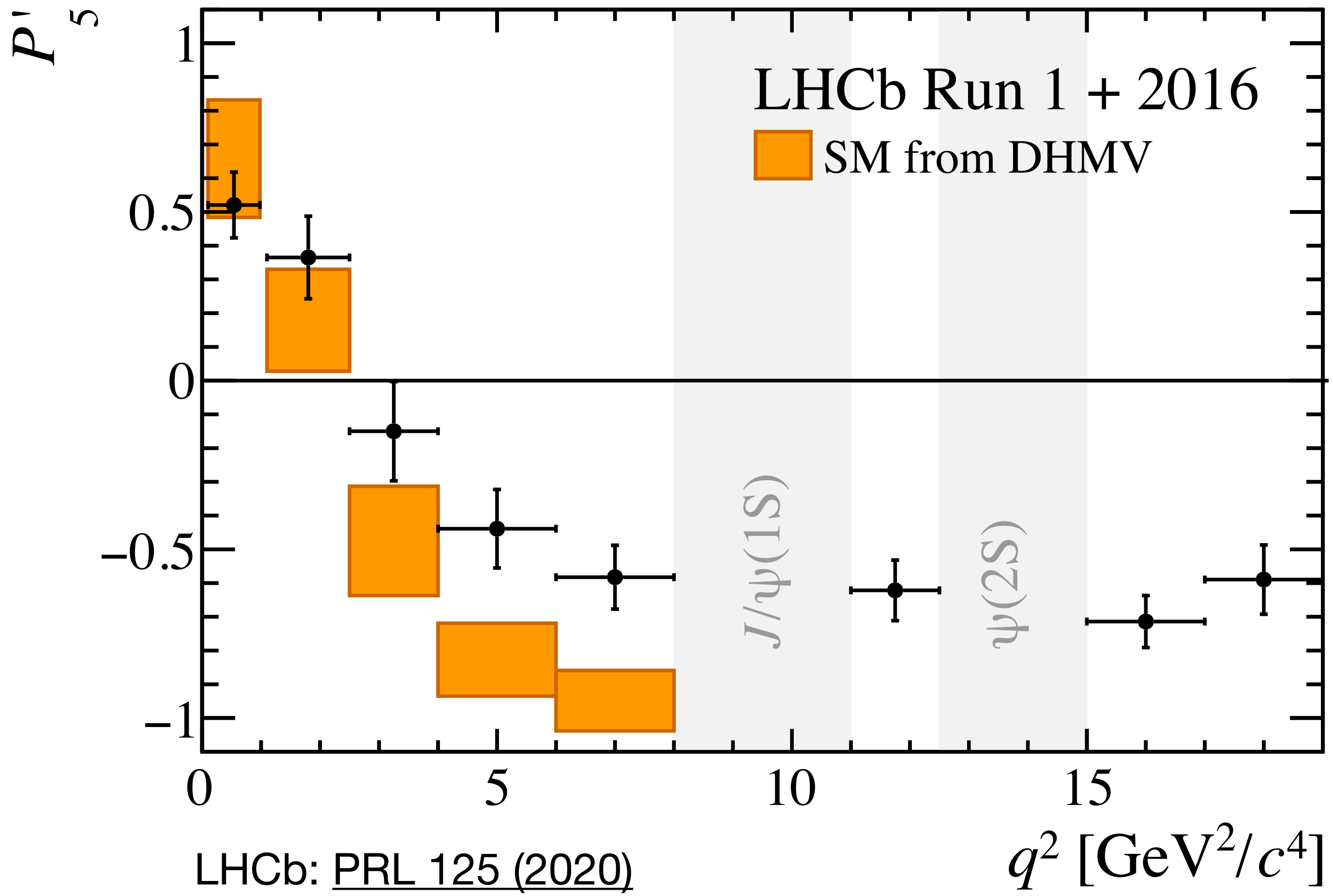
$B^0 \to K^{*0}\mu^+\mu^-$: P'5



LHCb: PRL 125 (2020)

See also Matthew Birch's talk in the today's parallel session after lunch

$B^0 \to K^{*0}\mu^+\mu^-$: P'5

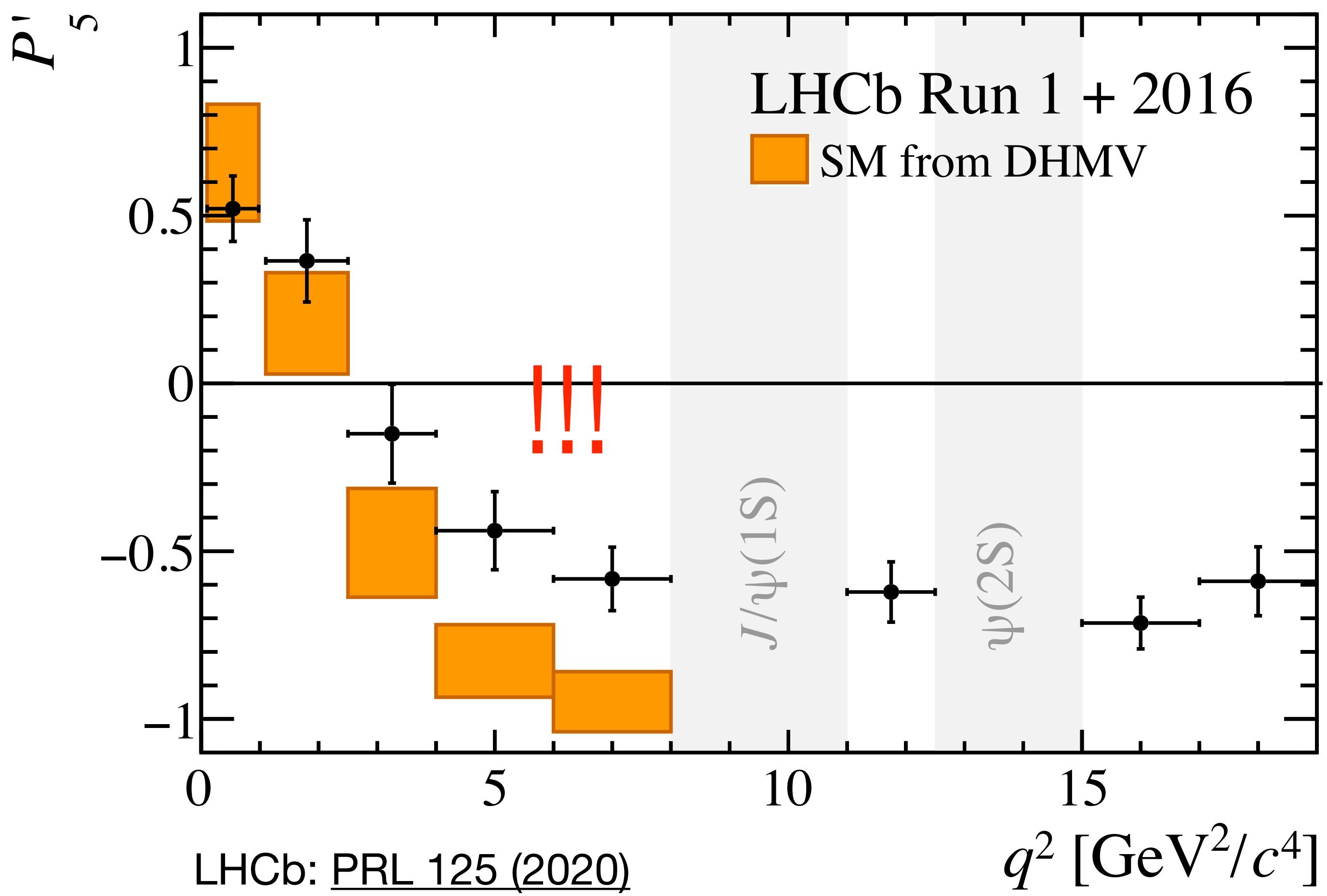


LHCb: PRL 125 (2020)

Theory: JHEP 05 (2013) 137

See also Matthew Birch's talk in the today's parallel session after lunch

$B^0 \to K^{*0}\mu^+\mu^-$: P'5

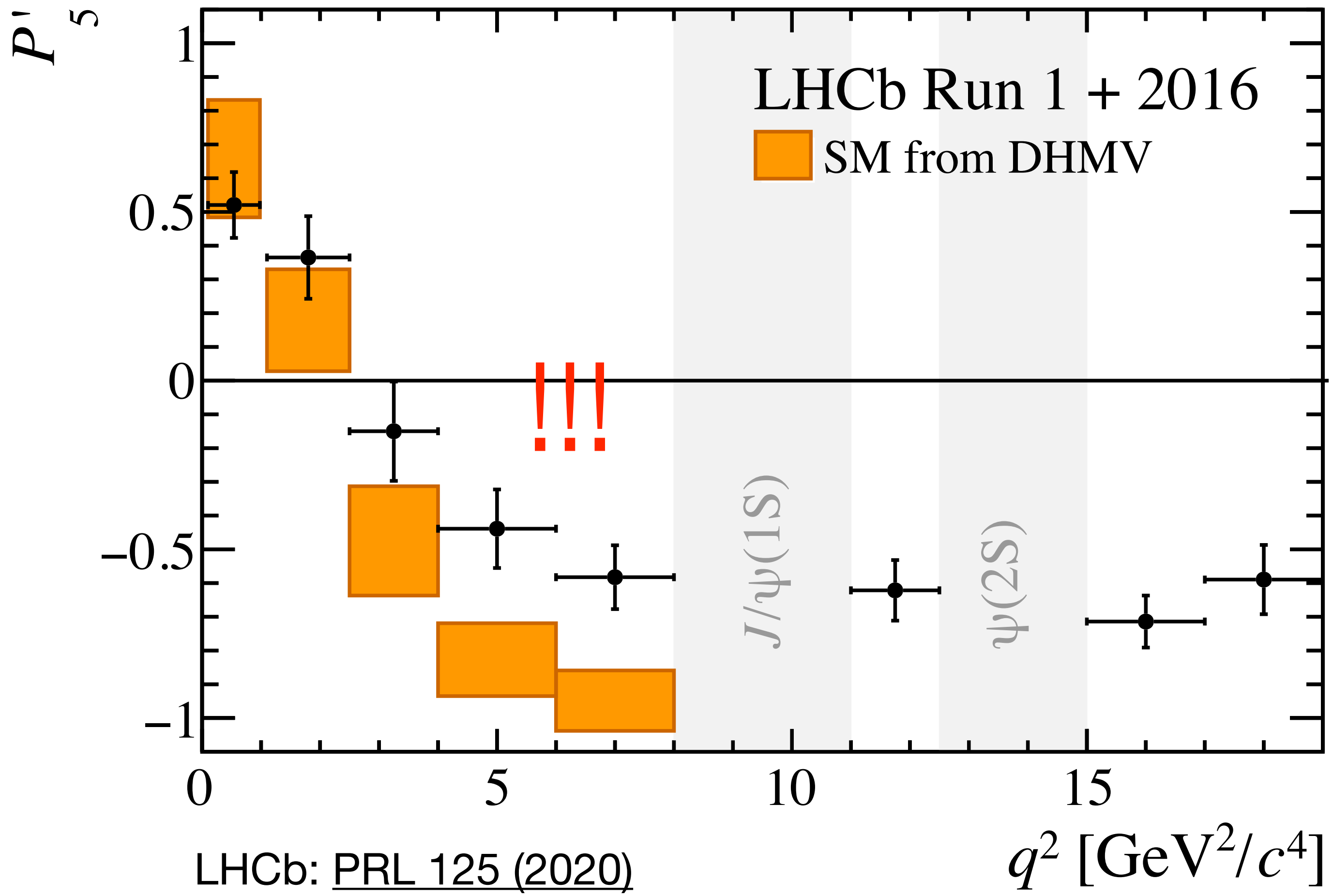


LHCb: PRL 125 (2020)

Theory: JHEP 05 (2013) 137

See also Matthew Birch's talk in the today's parallel session after lunch

$B^0 \to K^{*0}\mu^+\mu^-$: P'5



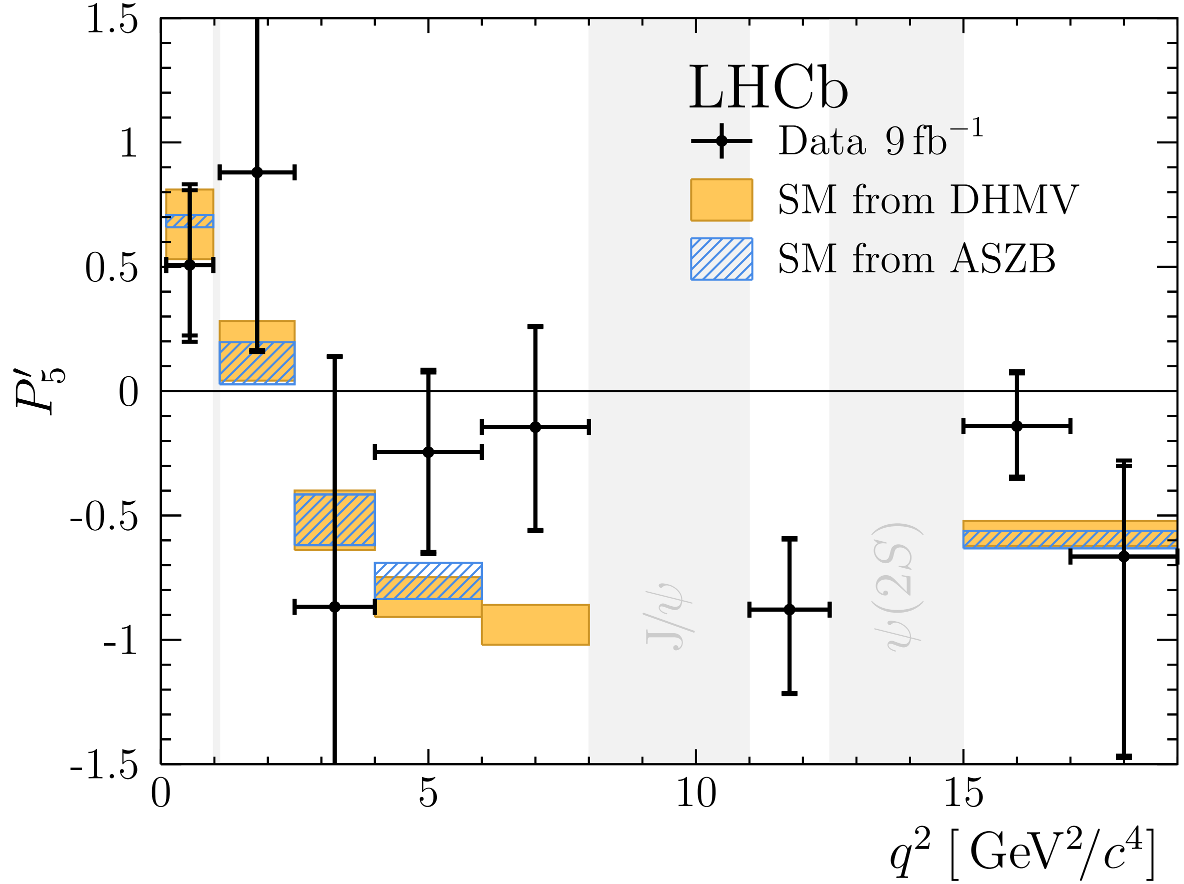
LHCb: PRL 125 (2020)

Theory: JHEP 05 (2013) 137

See also Matthew Birch's talk in the today's parallel session after lunch

- Deviation from SM: 3.3 σ global significance.

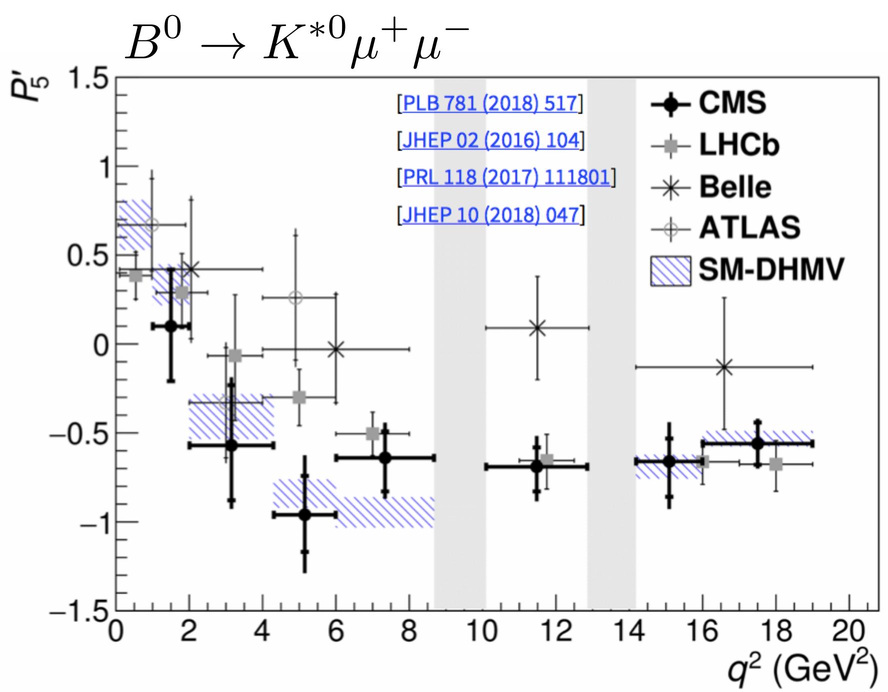
$B^+ \to K^{*+}\mu^+\mu^-$: P'5



LHCb: PRL 126 (2021) 16, 161802

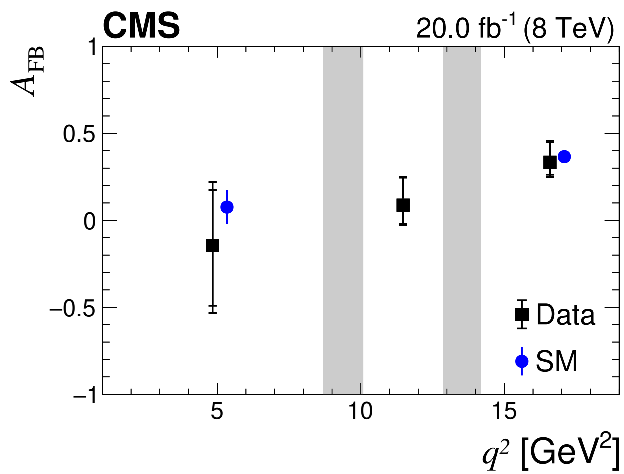
$B^{(0,+)} \rightarrow K^{*(0,+)}\mu\mu$ at CMS, ATLAS, BELLE

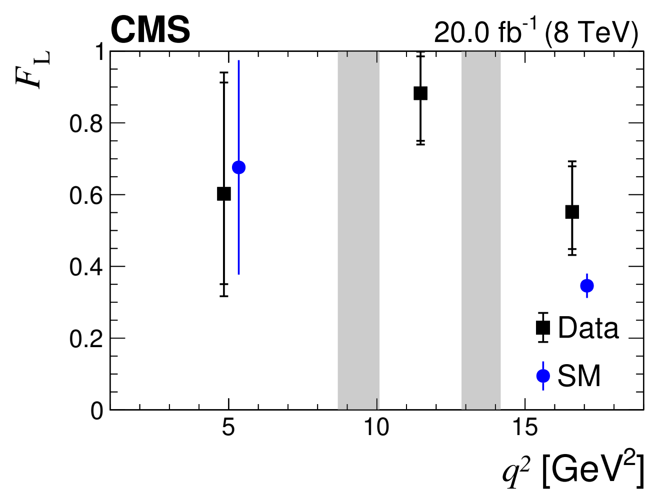
$B^0 \rightarrow K^{*0}\mu^+\mu^-$



PLB 781 (2018) 517 - 541

$B^+ \rightarrow K^{*+}\mu^+\mu^-$





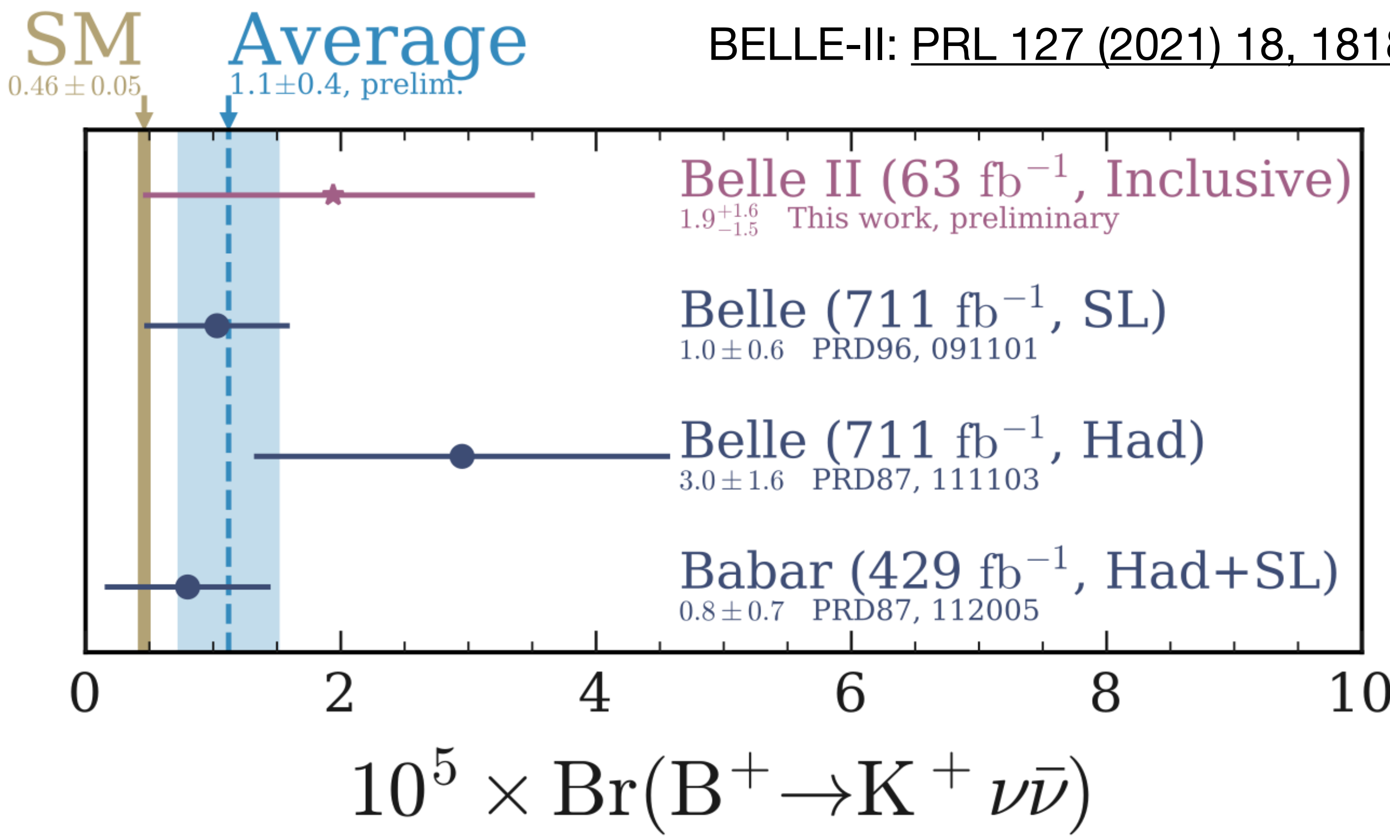
CMS: JHEP 04 (2021) 124

Looking forward to the results from CMS "B-parking" dataset

For more on flavour physics at ATLAS, see Ondrej Kovanda's talk in Tue morning's parallel session

$B^+ \to K^+ \nu \bar{\nu}$

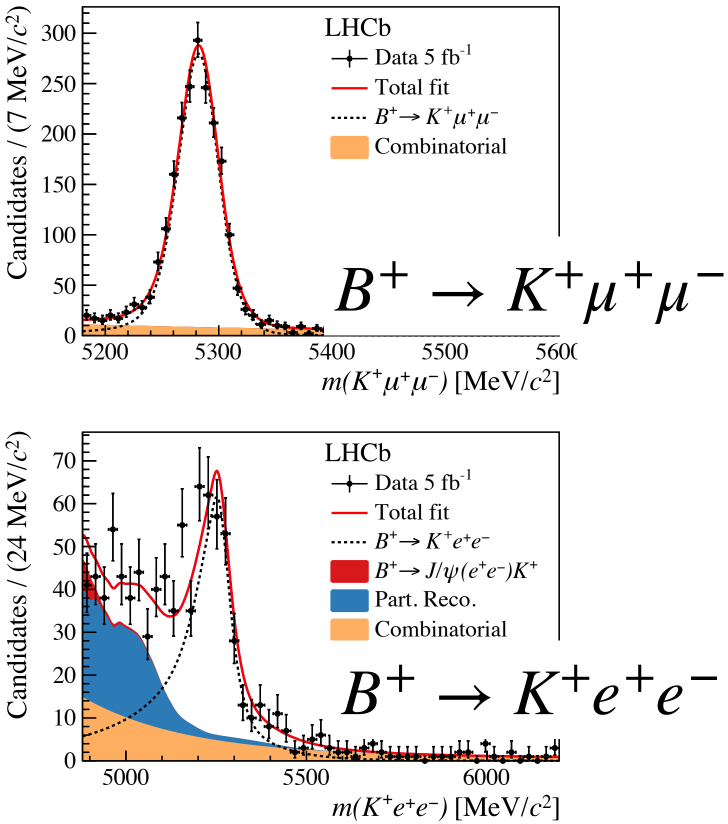
BELLE-II: PRL 127 (2021) 18, 181802



$B^+ \to K^+\mu^+\mu^-$ vs $B^+ \to K^+e^+e^-$

LHCb : Nature Phys. 18 (2022) 3, 277-282

$$R(K) = \frac{\mathscr{B}(B^+ \to K^+\mu^+\mu^-)}{\mathscr{B}(B^+ \to K^+e^+e^-)}$$, theoretically "clean" as hadronic effects cancel



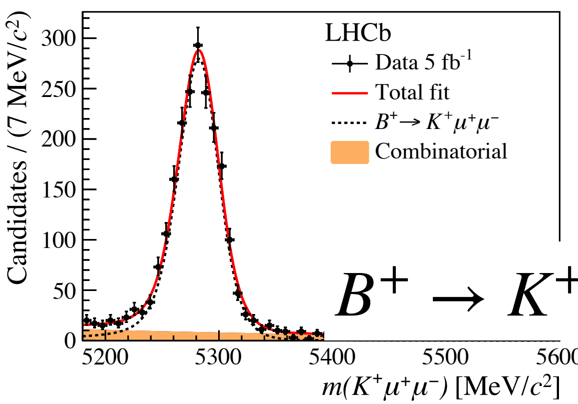
+ further samples (different data taking periods, trigger lines)

$B^+ \to K^+\mu^+\mu^-$ vs $B^+ \to K^+e^+e^-$

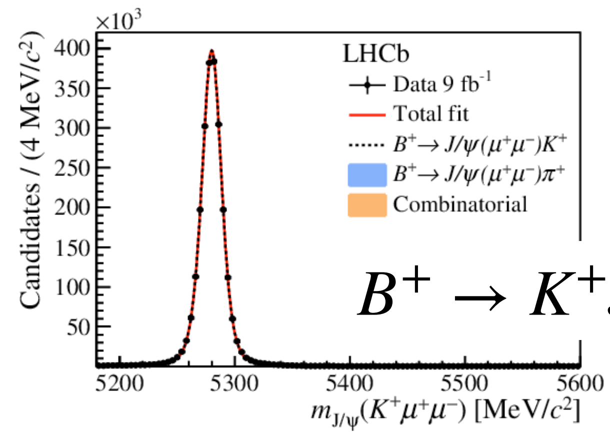
LHCb : Nature Phys. 18 (2022) 3, 277-282

$$R(K) = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+J/\psi(\mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+J/\psi(e^+e^-))},$$

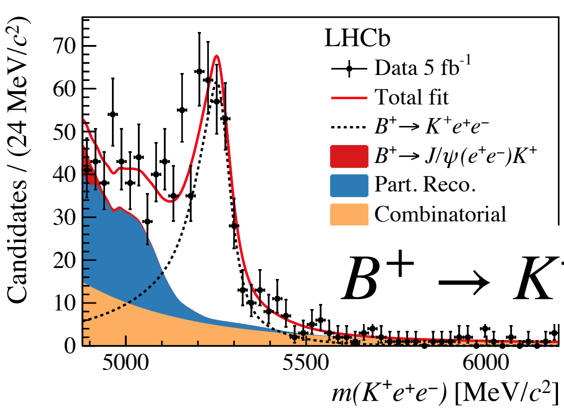
theoretically and experimentally “clean” as hadronic effects and detector effects cancel



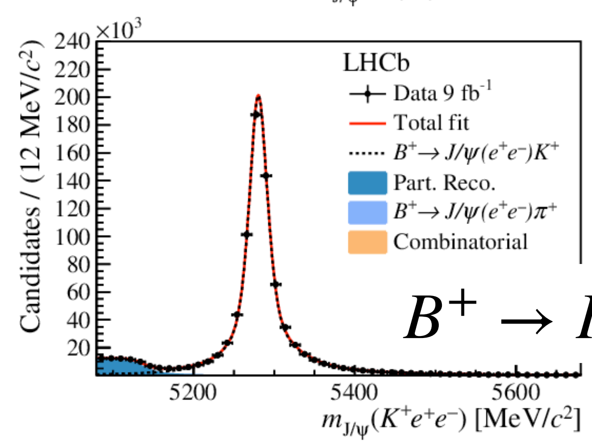
$B^+ \to K^+\mu^+\mu^-$



$B^+ \to K^+J/\psi(\mu^+\mu^-)$



$B^+ \to K^+e^+e^-$

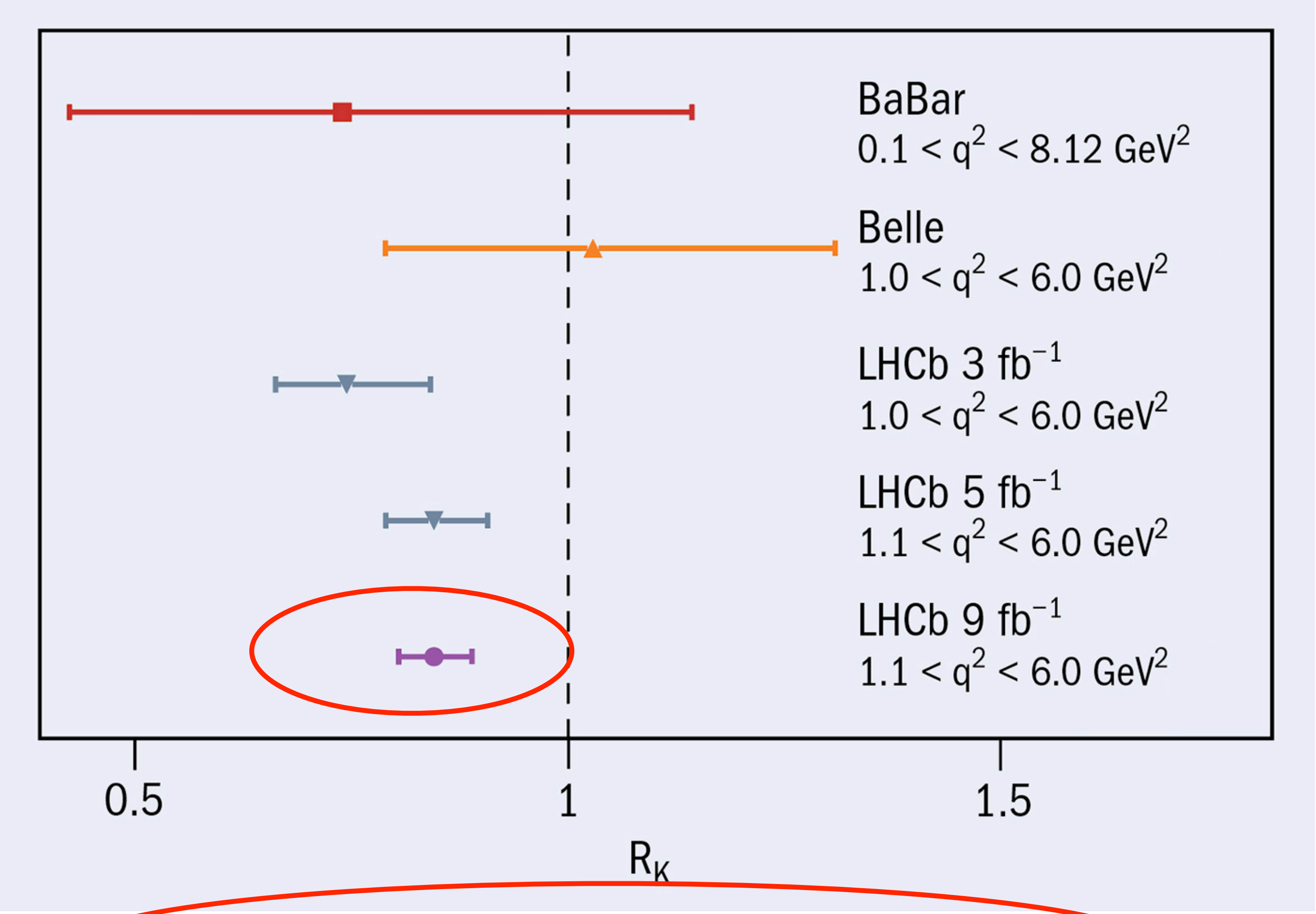


$B^+ \to K^+J/\psi(e^+e^-)$

+ further samples (different data taking periods, trigger lines)

R(K): $B^+ \to K^+\mu^+\mu^-$ / $B^+ \to K^+e^+e^-$

LHCb : Nature Phys. 18 (2022) 3, 277-282



3.1σ deviation from SM

Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$

Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$

- $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$

Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$
- $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$
- $B_s \to \phi\mu^+\mu^-$

Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$
- $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$
- $B_s \to \phi\mu^+\mu^-$
- $B^+ \to K^{*+}\mu^+\mu^-$

Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$
- $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$
- $B_s \to \phi\mu^+\mu^-$
- $B^+ \to K^{*+}\mu^+\mu^-$
- $B^+ \to K^{0+}\mu^+\mu^-$

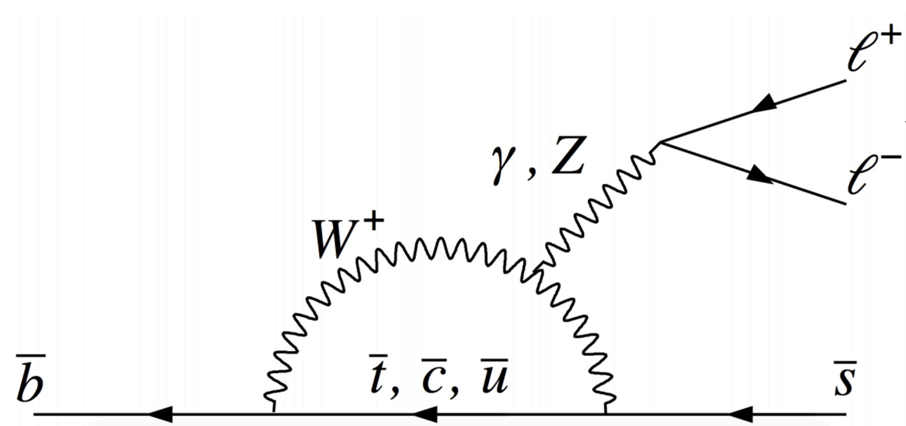
Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$
- $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$
- $B_s \to \phi\mu^+\mu^-$
- $B^+ \to K^{*+}\mu^+\mu^-$
- $B^+ \to K^{0+}\mu^+\mu^-$
- $\Lambda_b \to \Lambda\mu^+\mu^-$

Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$
- $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$
- $B_s \to \phi\mu^+\mu^-$
- $B^+ \to K^{*+}\mu^+\mu^-$
- $B^+ \to K^{0+}\mu^+\mu^-$
- $\Lambda_b \to \Lambda\mu^+\mu^-$

all involve same process:

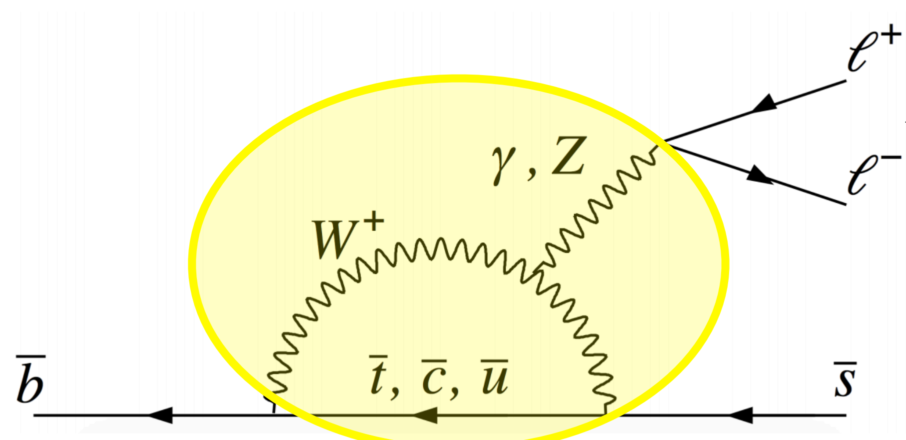


ℓ = e or μ

Deviations in

- $B \to K^{*0}\mu^+\mu^-$ and $B \to K^{*0}\mu^+\mu^- / B \to K^{*0}e^+e^-$
- $B^+ \to K^+\mu^+\mu^-$ and $B^+ \to K^+\mu^+\mu^- / B^+ \to K^+e^+e^-$
- $B_s \to \phi\mu^+\mu^-$
- $B^+ \to K^{*+}\mu^+\mu^-$
- $B^+ \to K^{0+}\mu^+\mu^-$
- $\Lambda_b \to \Lambda\mu^+\mu^-$

all involve same process:

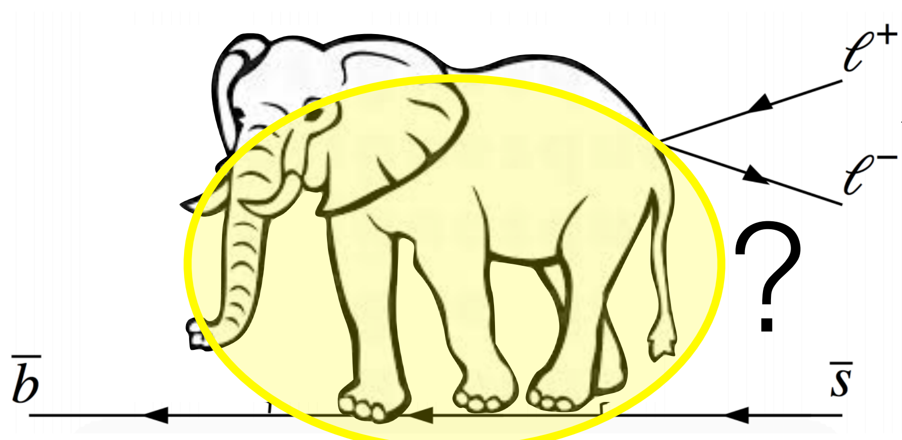


ℓ = e or μ

Deviations in

- $B \to K^{*0} \mu^+ \mu^-$ and $B \to K^{*0} \mu^+ \mu^- / B \to K^{*0} e^+ e^-$
- $B^+ \to K^+ \mu^+ \mu^-$ and $B^+ \to K^+ \mu^+ \mu^- / B^+ \to K^+ e^+ e^-$
- $B_s \to \phi \mu^+ \mu^-$
- $B^+ \to K^{*+} \mu^+ \mu^-$
- $B^+ \to K^{0+} \mu^+ \mu^-$
- $\Lambda_b \to \Lambda \mu^+ \mu^-$

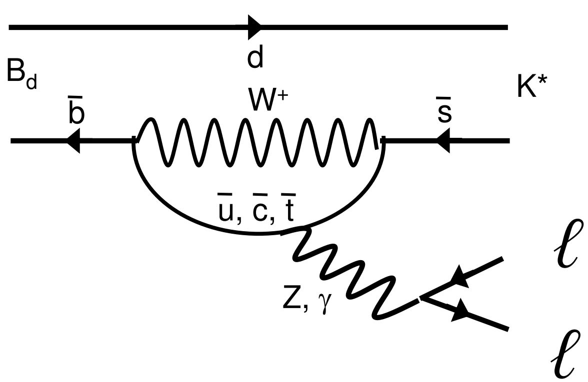
all involve same process:

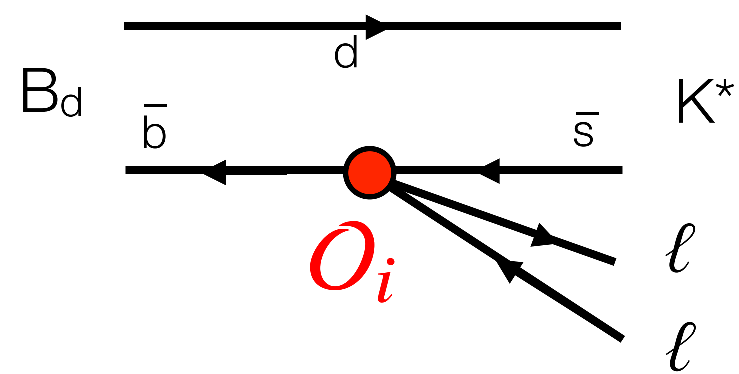


ℓ = e or μ

Putting it all together

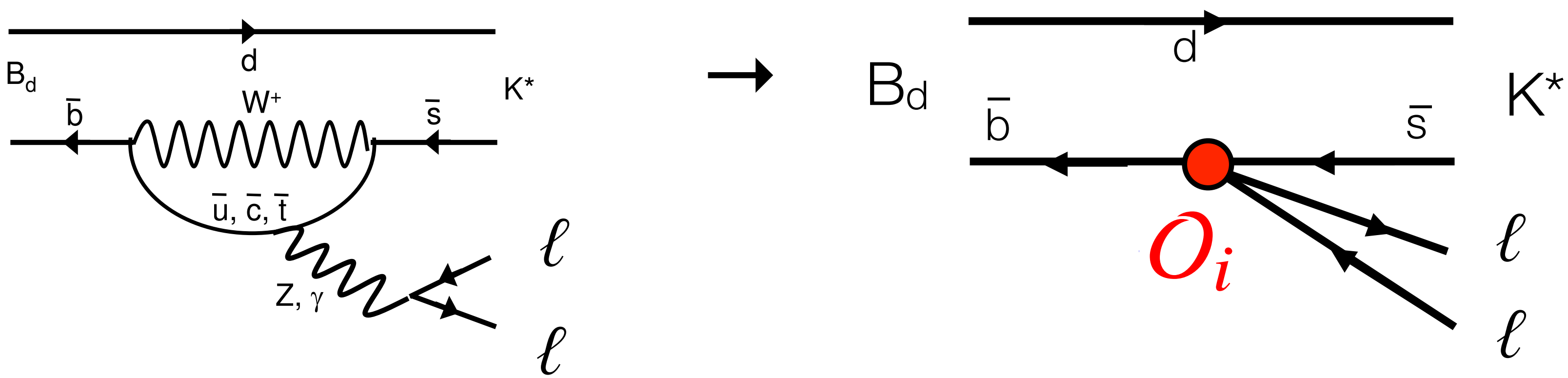
$$\mathcal{H}_{\text{eff}} \approx -\frac{4G_F}{\sqrt{2}} \sum_i V_{tb} V_{ts}^* C_i O_i$$





Putting it all together

$$\mathcal{H}_{\text{eff}} \approx -\frac{4G_F}{\sqrt{2}} \sum_i V_{tb} V_{ts}^* C_i O_i$$



NP can modify C_i and add new operators

O_9: Vector

Vector

Vector in mirror

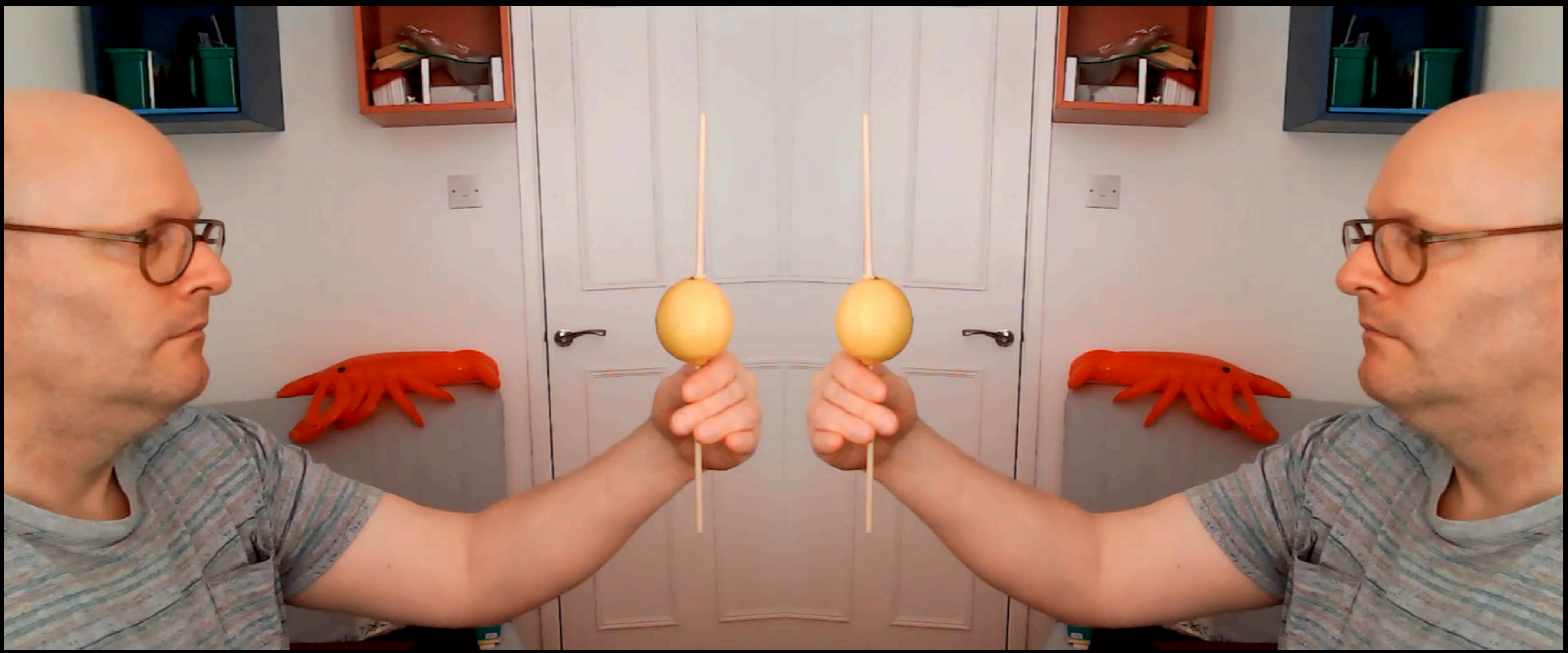
O_9: Vector

Vector | Vector in mirror

O_{10}: Axial Vector

Axial vector

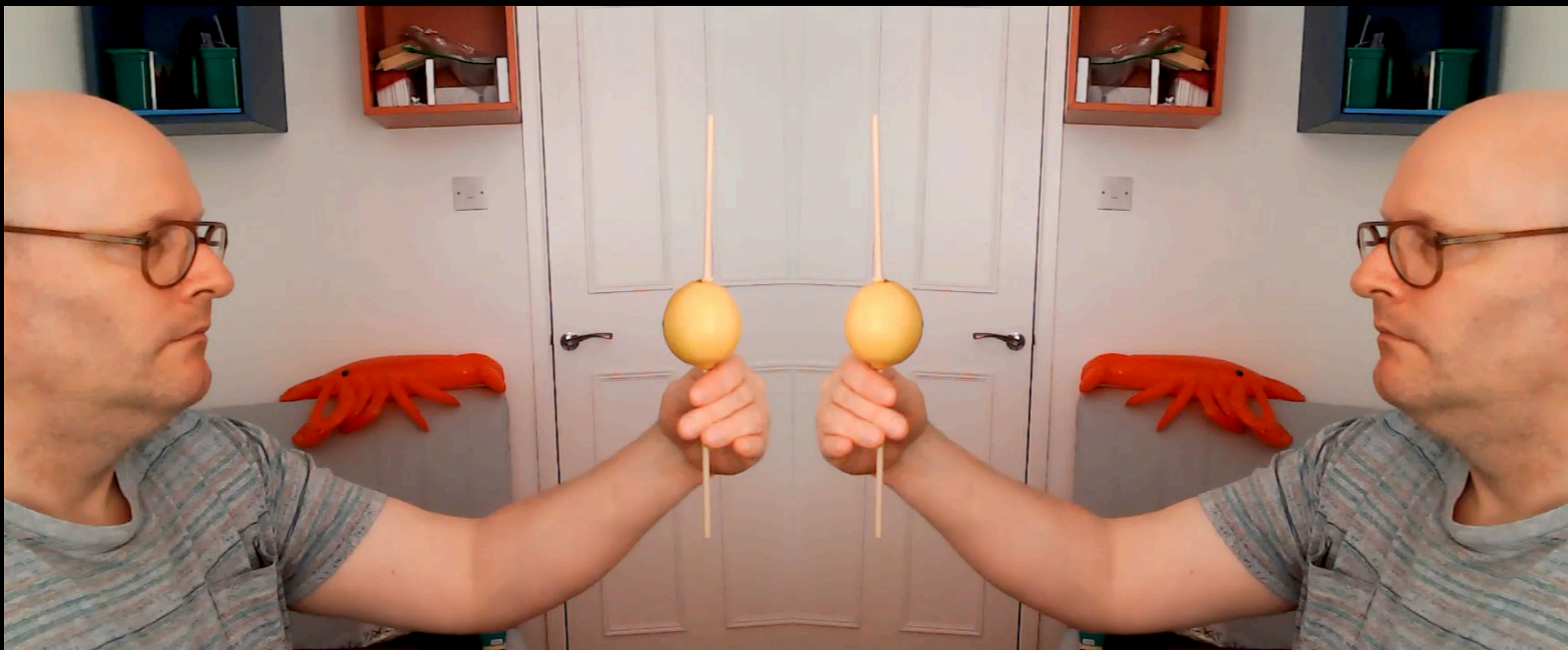
Axial vector in mirror



O_{10}: Axial Vector

Axial vector

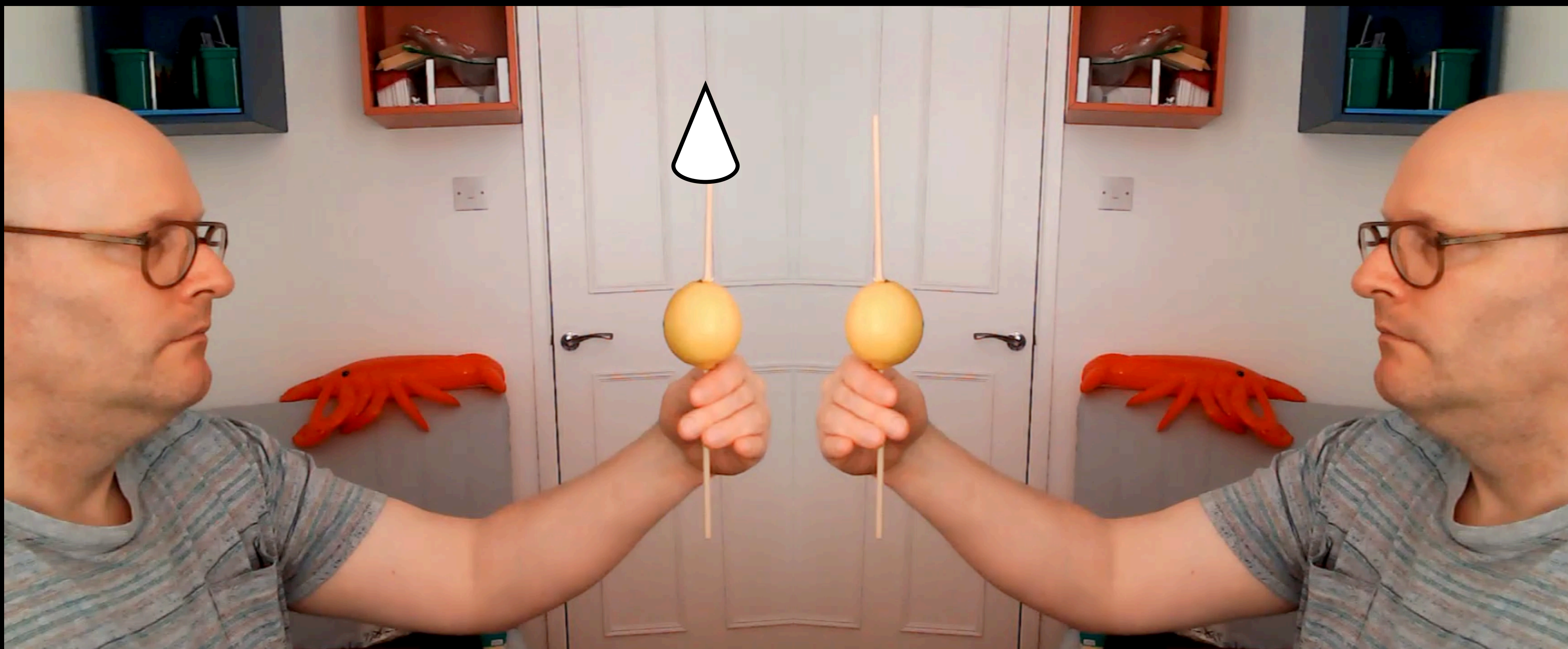
Axial vector in mirror



O_{10}: Axial Vector

Axial vector

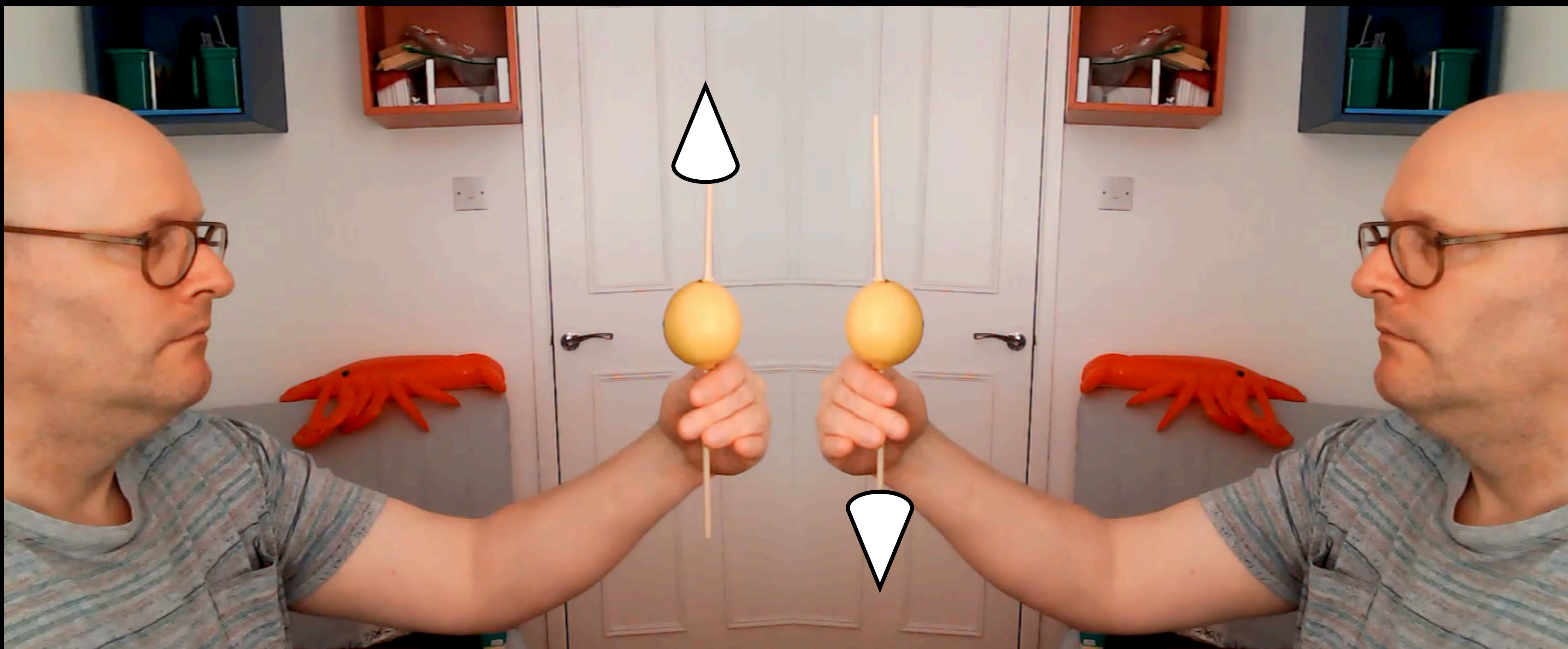
Axial vector in mirror



O_{10}: Axial Vector

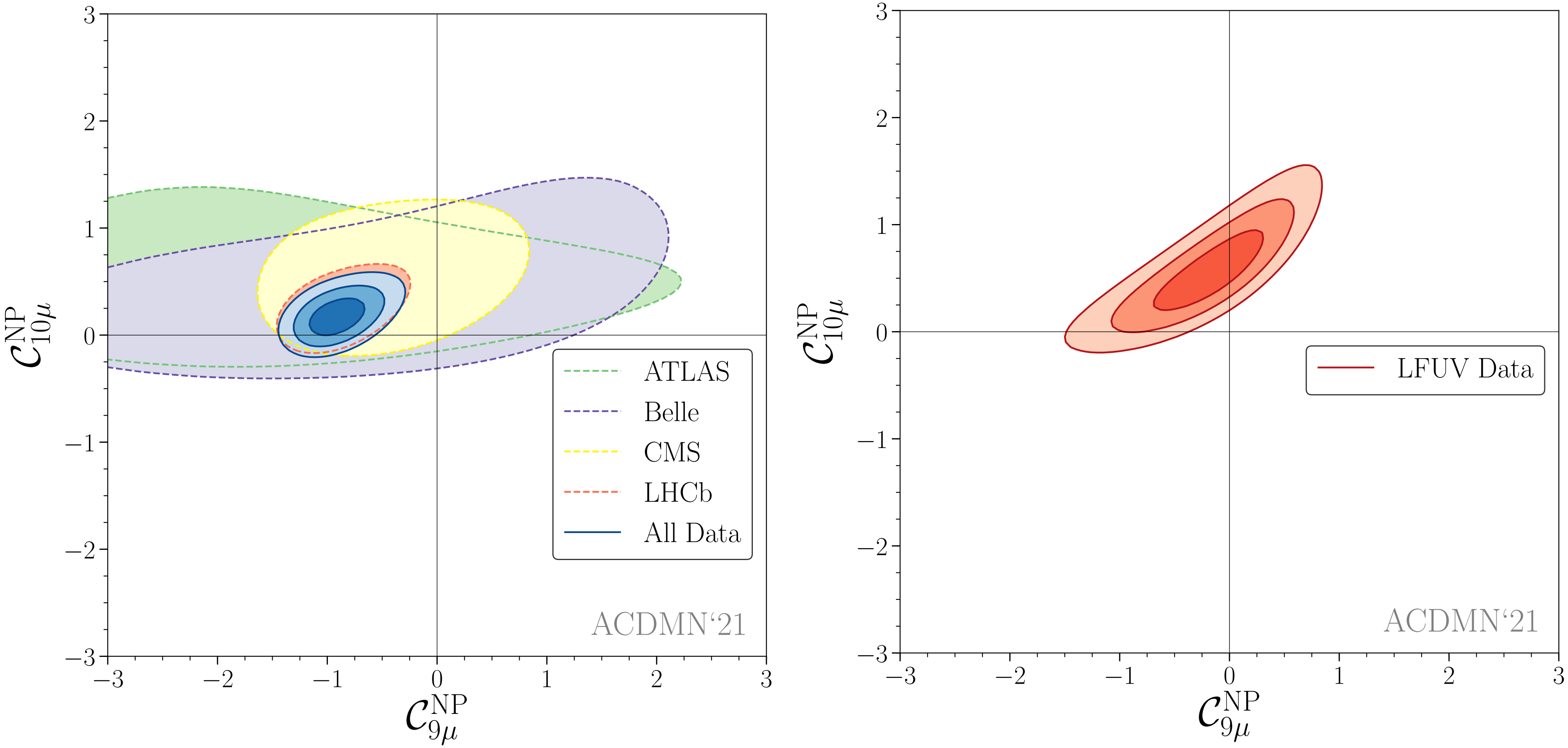
Axial vector

Axial vector in mirror



Constraints on C_9, C_{10}

arXiv:2104.08921 (2021)



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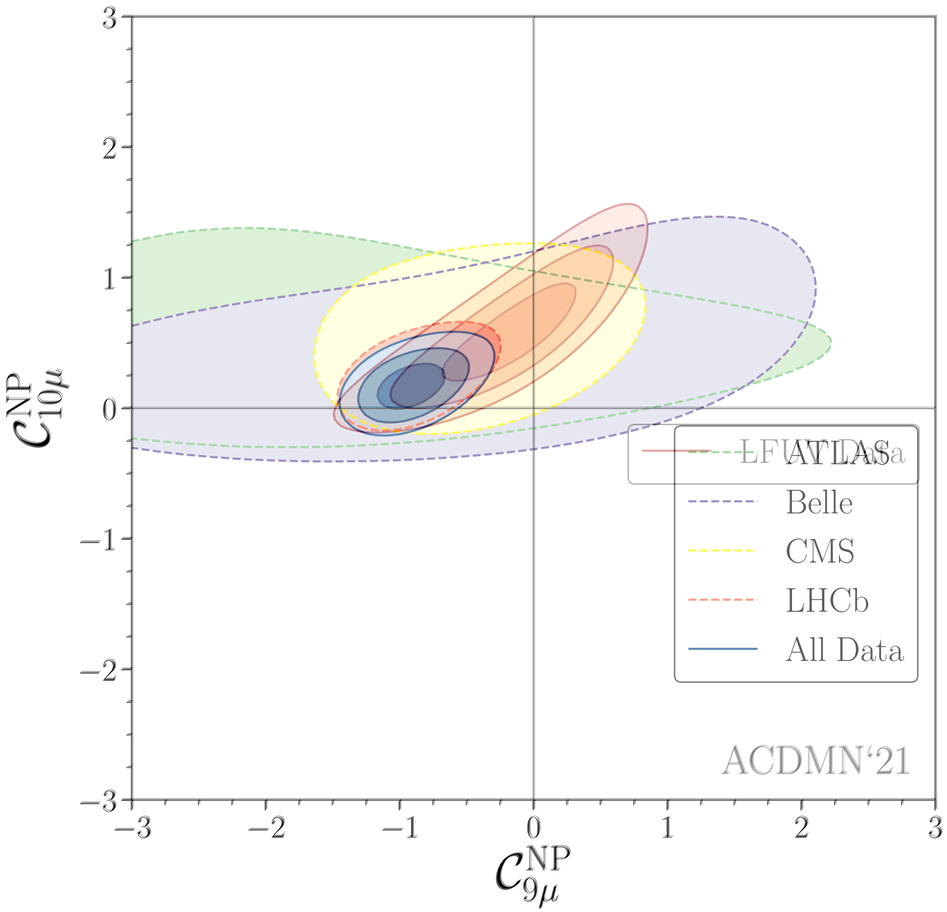


This paper, combining of all inputs: 7σ deviation of C_9 from SM.

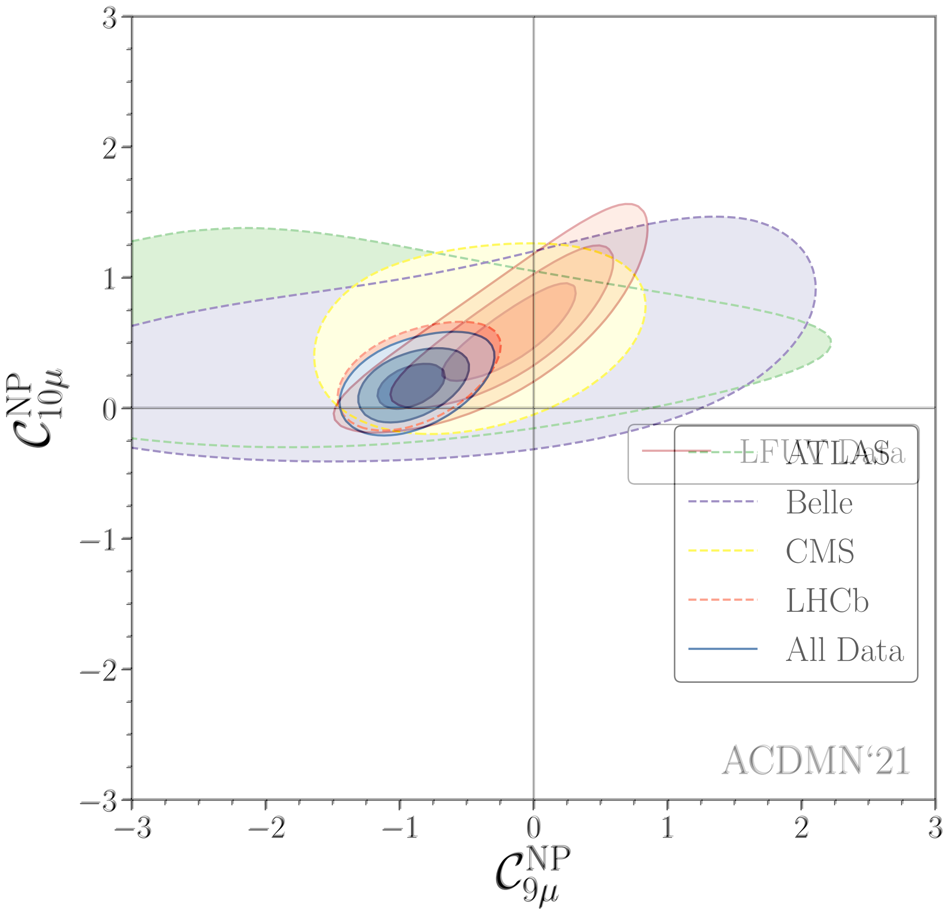
Conservative combination, using only subset of inputs (those save against hadronic effects), careful treatment of look elsewhere effect: 4.2σ.
PLB 822 (2021) 136644 and arXiv:2110.09882 (2021)

Extraordinary claims require extraordinary evidence…. but we have reason to be "#CautiouslyExcited"

Constraints on C_9, C_{10}

More on rare decays in Paula's HEPP-prize 2020 talk on Wed morning.

arXiv:2104.08921 (2021)



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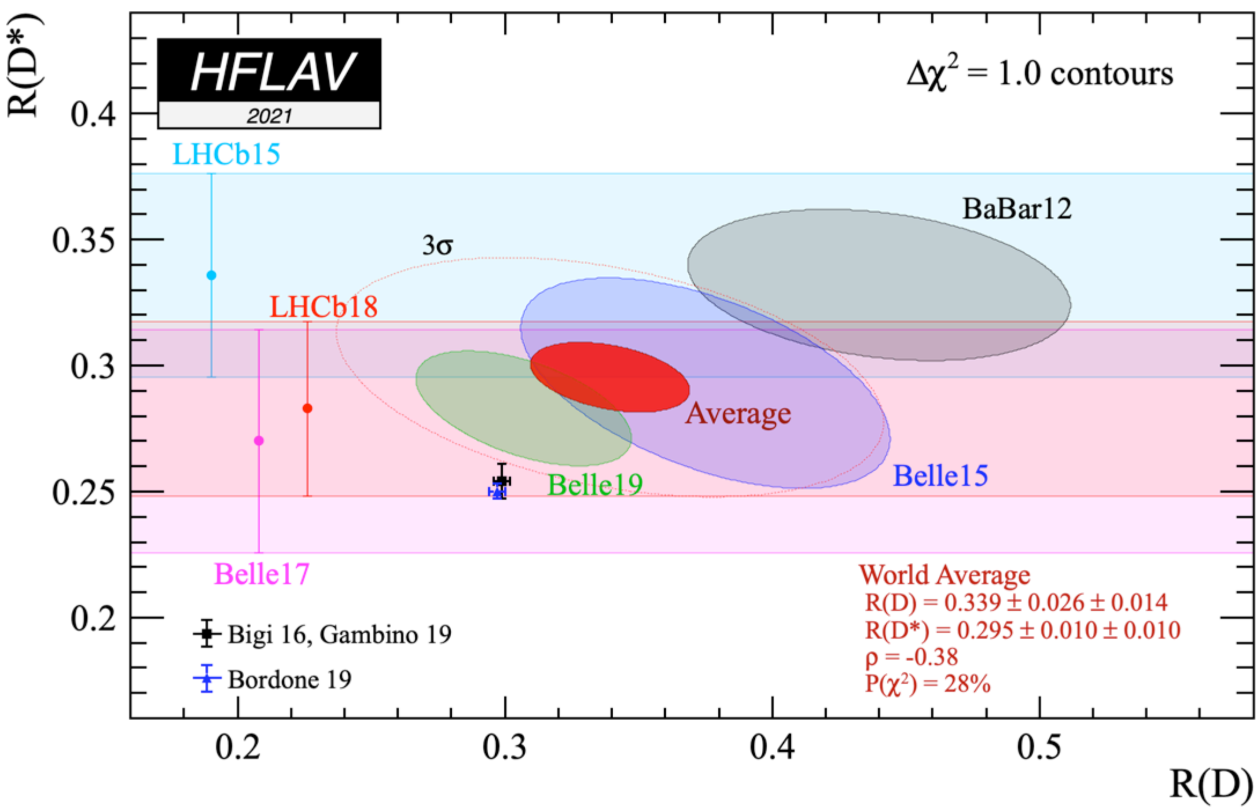
Extraordinary claims require extraordinary evidence…. but we have reason to be "#CautiouslyExcited"

$R(D), R(D^*)$

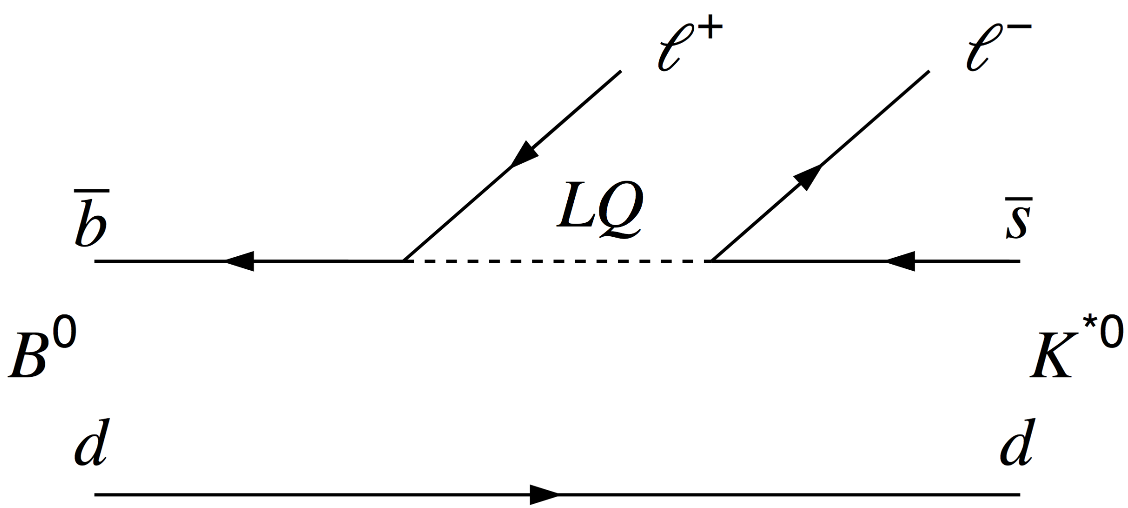
$$R(D) = \frac{\mathscr{B}(B \to D\tau\bar{\nu}_\tau)}{\mathscr{B}(B \to D\mu\bar{\nu}_\mu)}$$



See also Luke Scantlebury-Smead's talk in the today's parallel session after lunch

Interpretation of flavour anomalies

Is it a leptoquark?



e.g.: JHEP 08 (2021) 050, JHEP 1711 (2017) 044,
Phys.Lett.B 800 (2020) 135080, arXiv:2203.10111 (2022),

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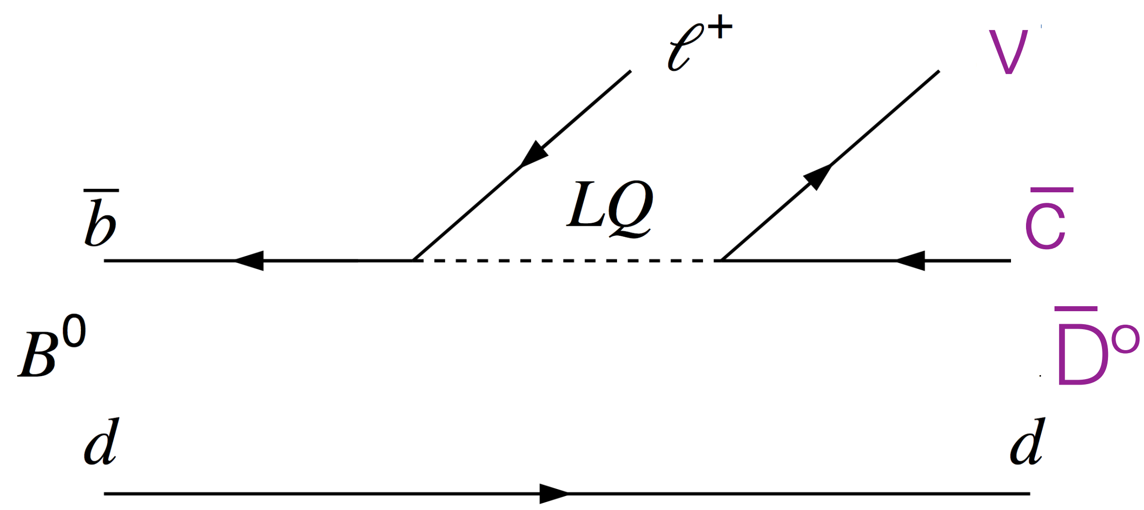


e.g.: JHEP 08 (2021) 050, JHEP 1711 (2017) 044,
Phys.Lett.B 800 (2020) 135080, arXiv:2203.10111 (2022),


A what??


A what??
When the first platypus were sent to Europe, European scientists didn’t believe such an oddity could really exist, until the evidence became overwhelming
By TwoWings - Own work (NB : this is a scanned photography since it had been taken with an analog camera), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3532075

LFUV in -onia?

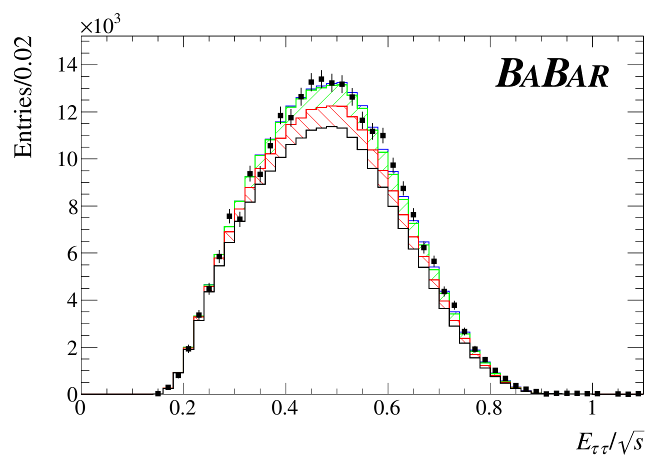
BaBar: PRL 125 (2020) 241801

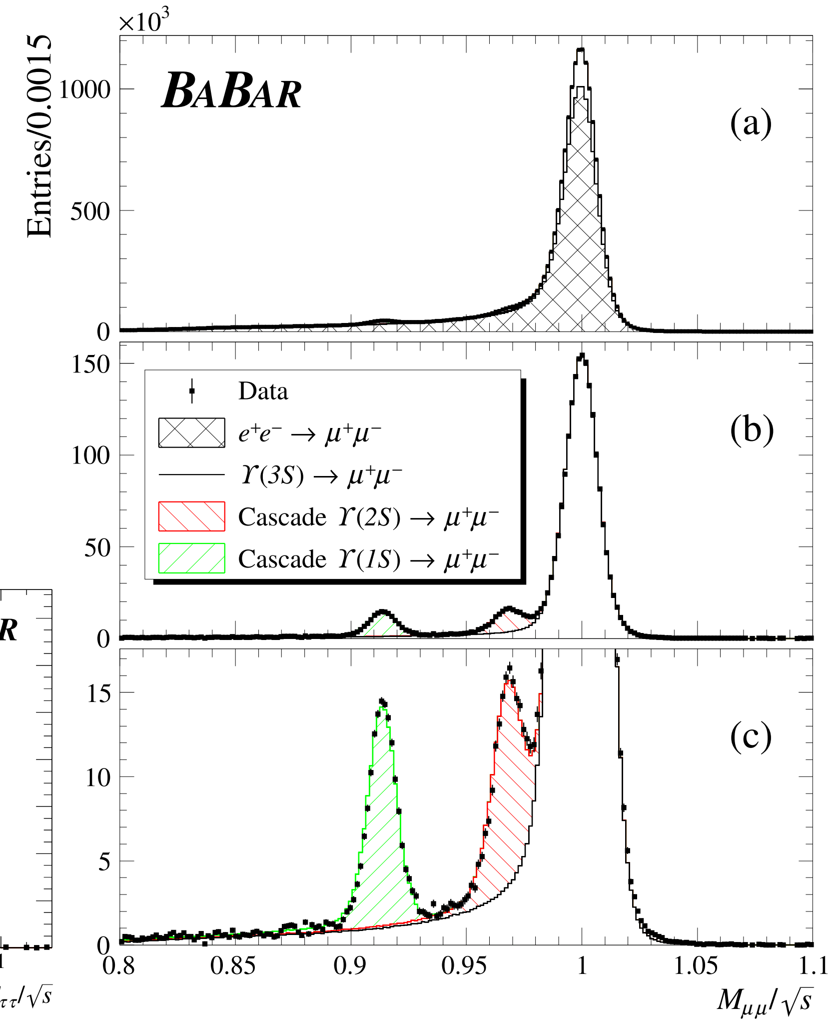
$$\mathscr{R}_{\tau\mu}^{\Upsilon(3S)} = \frac{\mathscr{B}(\Upsilon(3S) \to \tau^+\tau^-)}{\mathscr{B}(\Upsilon(3S) \to \mu^+\mu^-)} = 0.966 \pm 0.008 \pm 0.014$$

Within 2 σ of SM value, 0.9948

Order of magnitude improvement in uncertainty over only previous measurement by CLEO, PRL 98 (2007) 052002

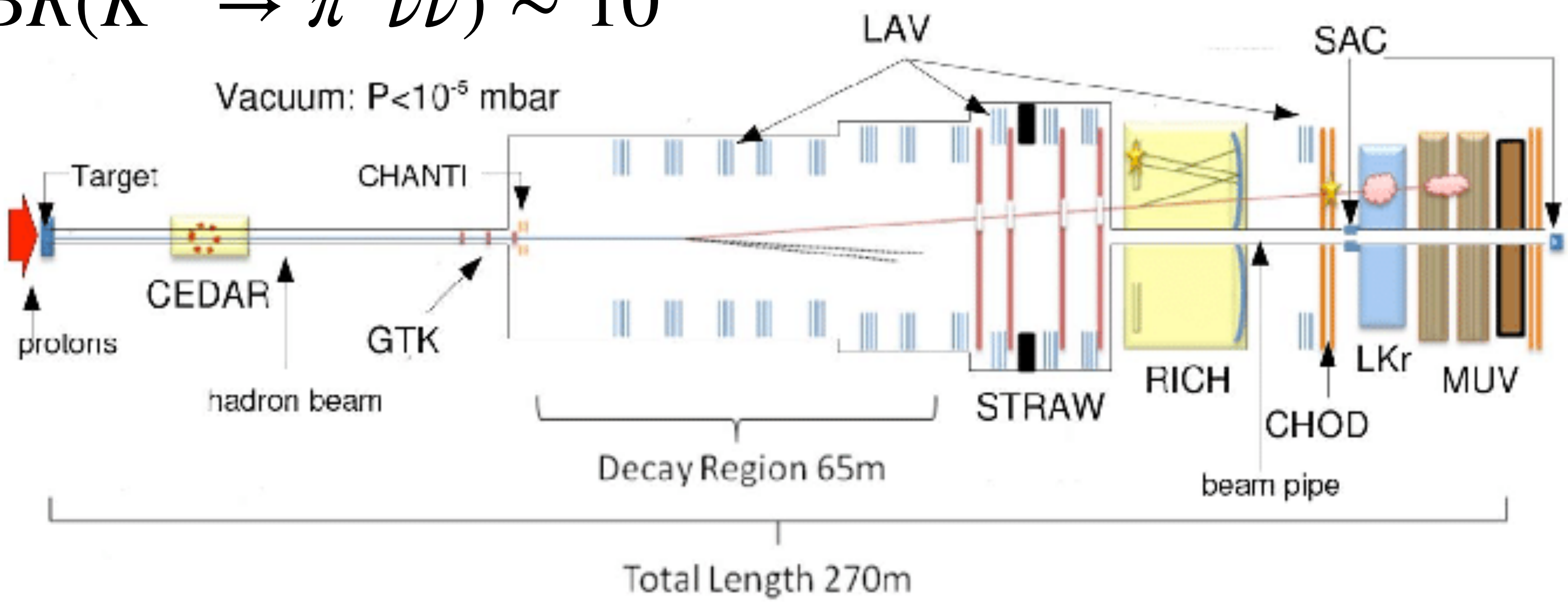
Relates to $R\left(D^{(*)}\right)$, see JHEP 06 (2017) 019





NA62 - optimised for very rare decay $K^+ \to \pi^+ \nu \bar{\nu}$

$BR(K^+ \to \pi^+ \nu \bar{\nu}) \sim 10^{-10}$



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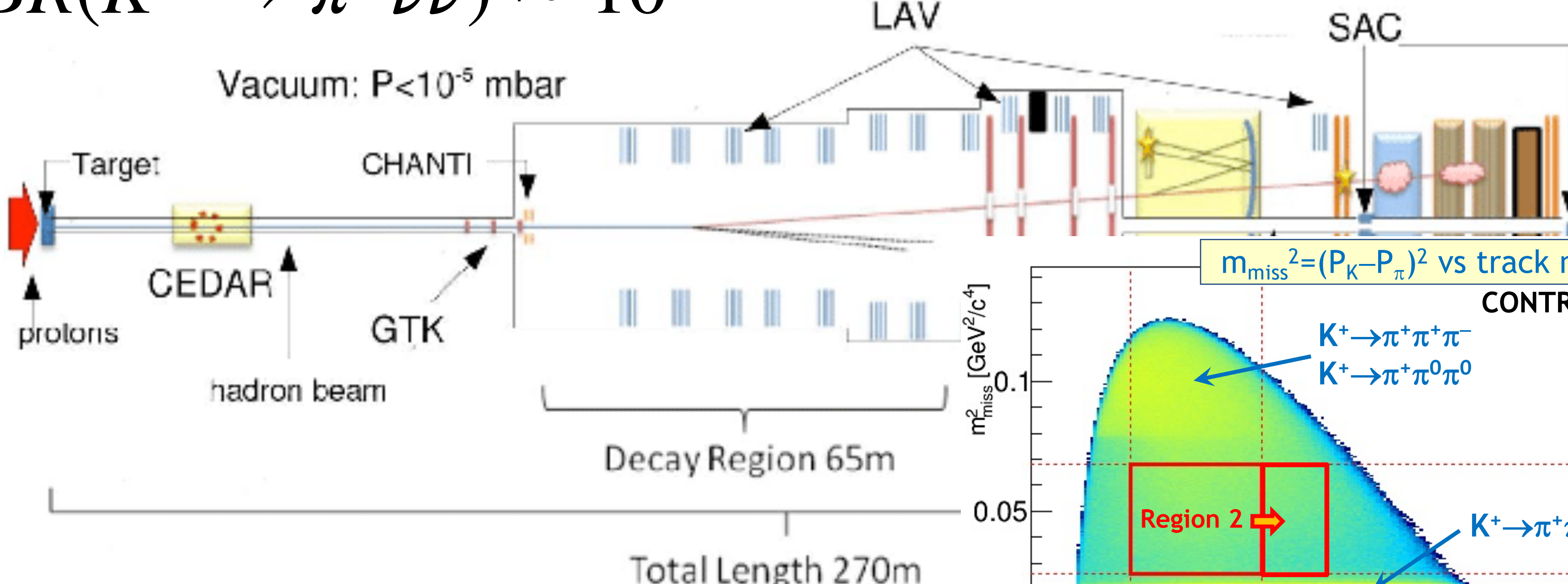
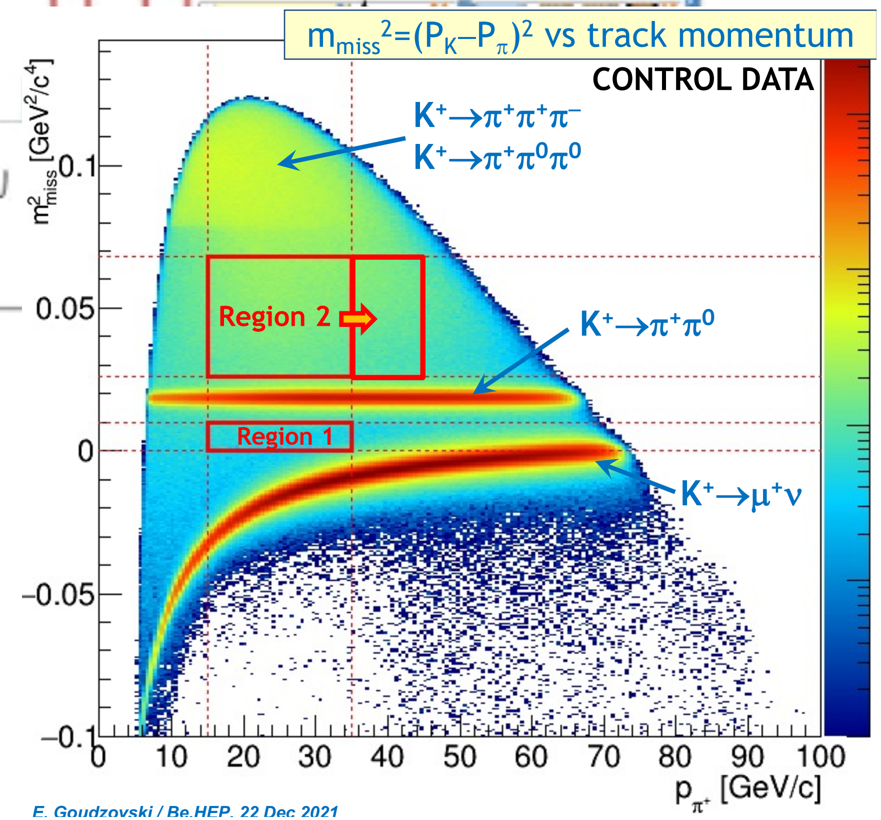




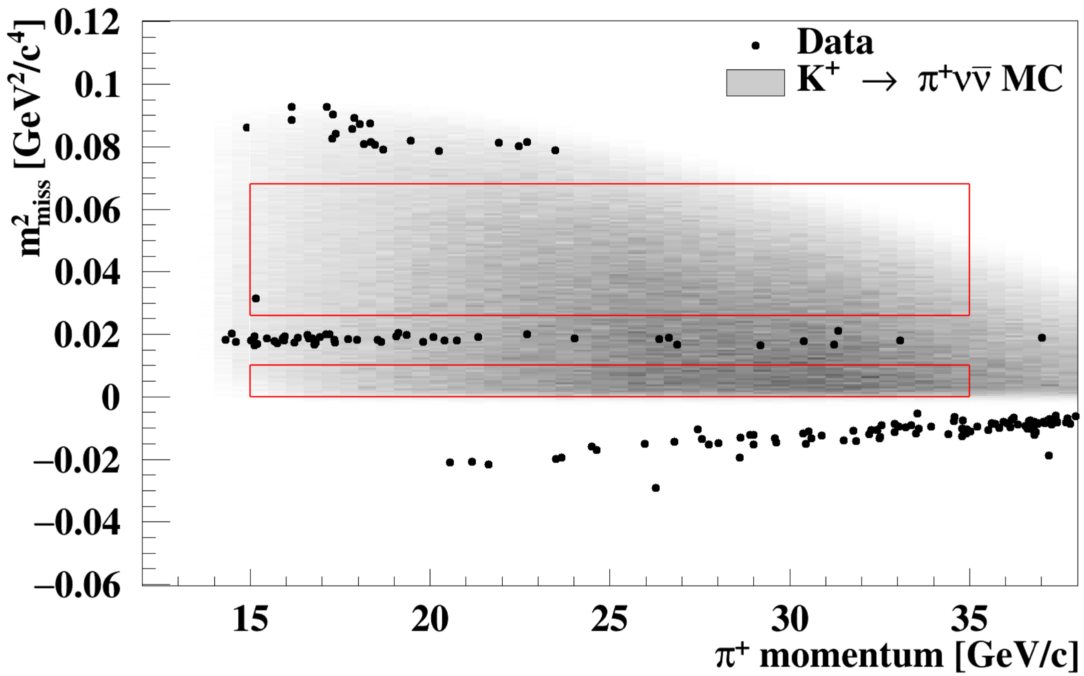
NA62: [Phys.Lett.B 791 (2019)](#)

NA62: [JHEP 11 (2020) 042](#)

NA62: [JHEP 06 (2021) 093](#)

NA62: $K^+ \to \pi^+ \nu \bar{\nu}$

2016 data: 1 signal candidate



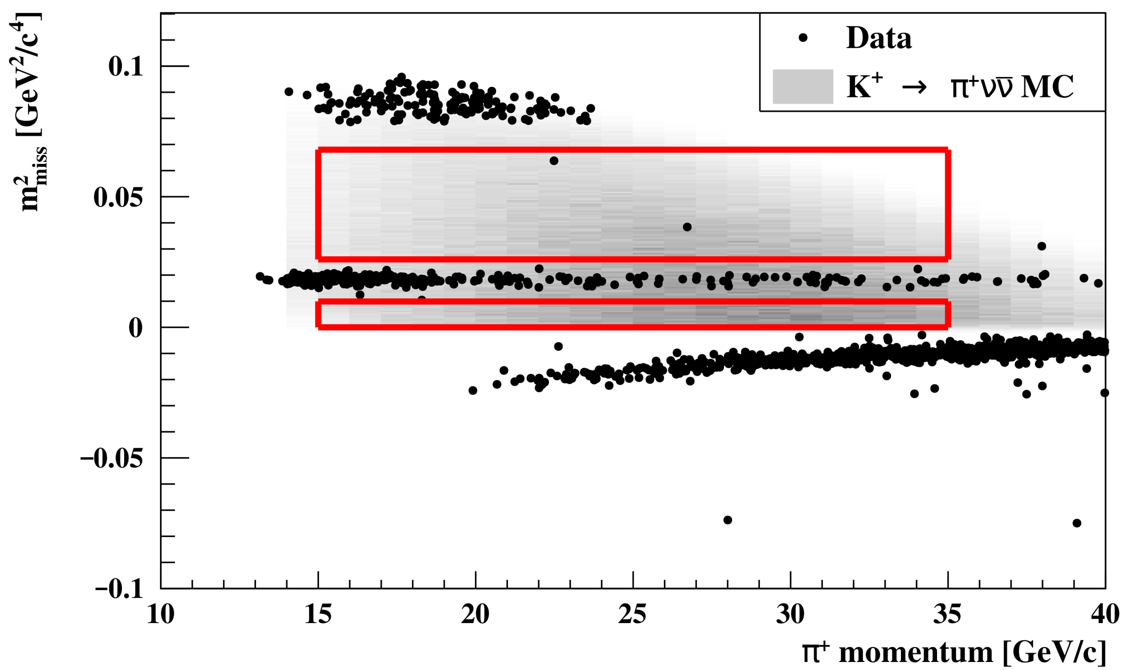
NA62: $K^+ \to \pi^+ \nu \bar{\nu}$

NA62: Phys.Lett.B 791 (2019)

NA62: JHEP 11 (2020) 042

NA62: JHEP 06 (2021) 093

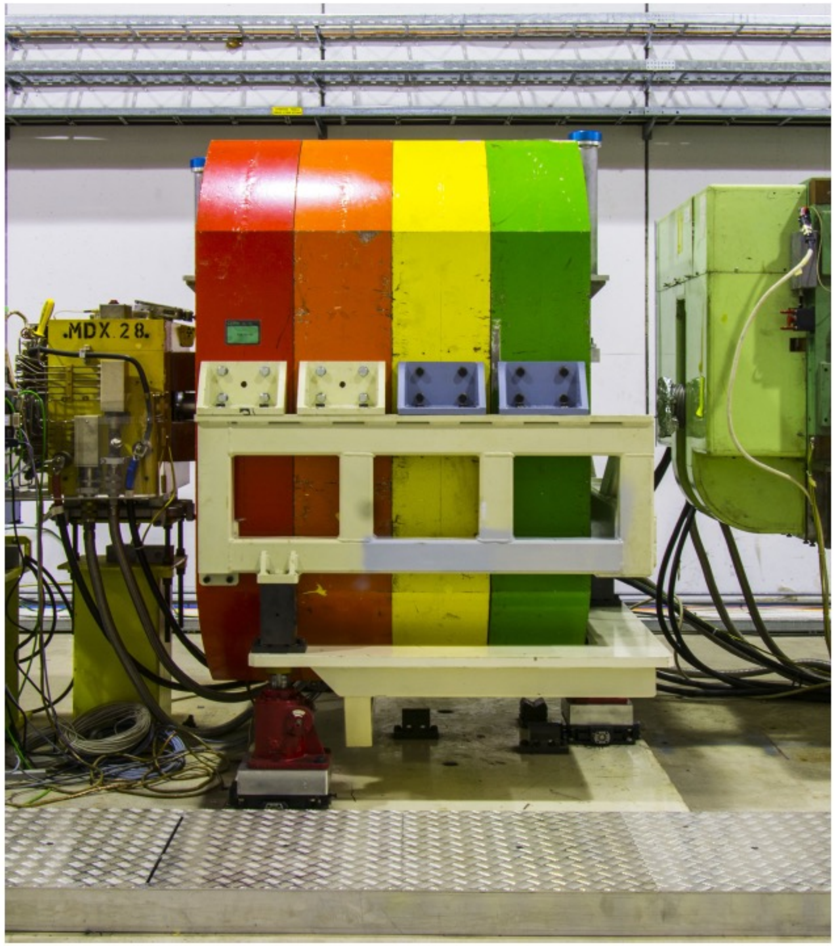
2017 data: 2 signal candidates



NA62, better, more beautiful collimator since 2018

The old collimator

Current collimator (since June 2018)



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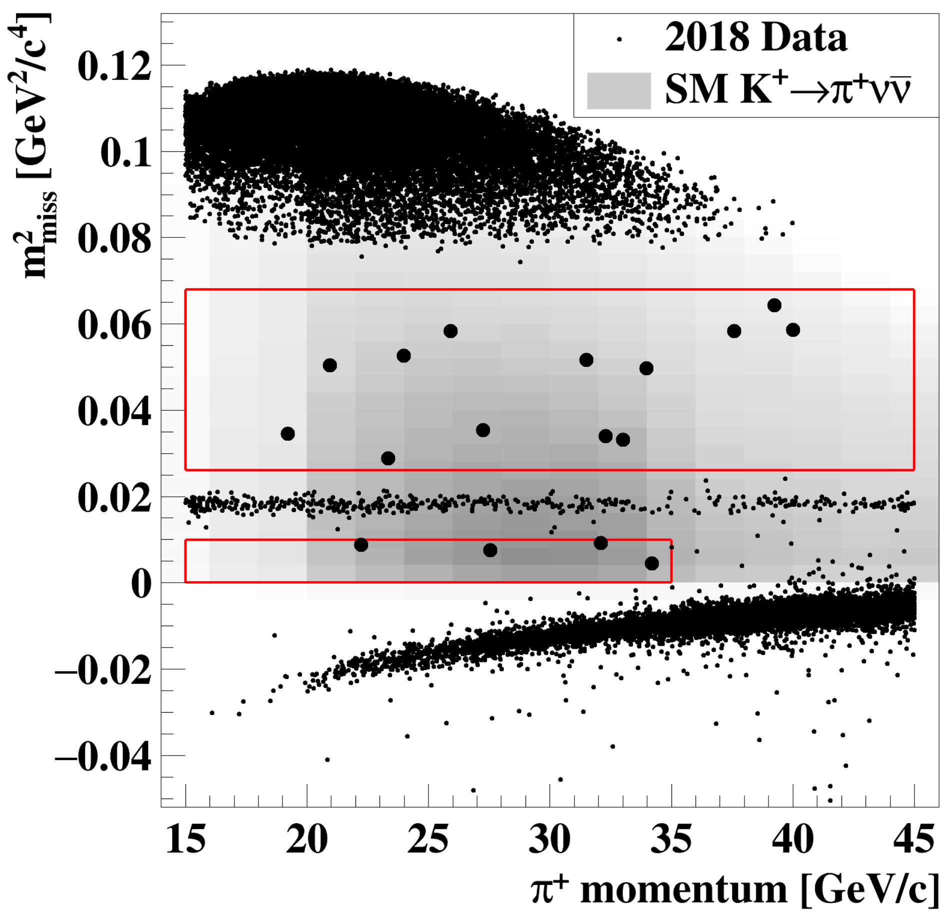
NA62: Phys.Lett.B 791 (2019)

NA62: JHEP 11 (2020) 042

NA62: JHEP 06 (2021) 093

2016, 2017 and 2018 data:
20 signal candidates (expect 7 background events)

$$\mathrm{BR}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$$



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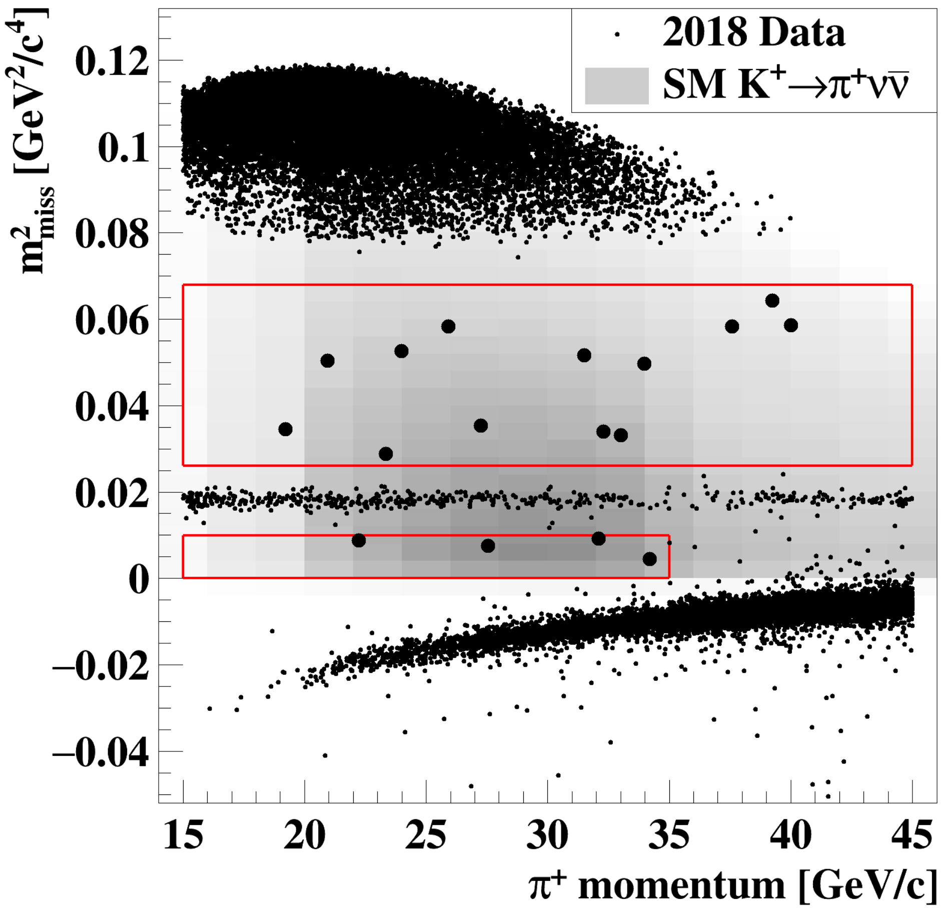

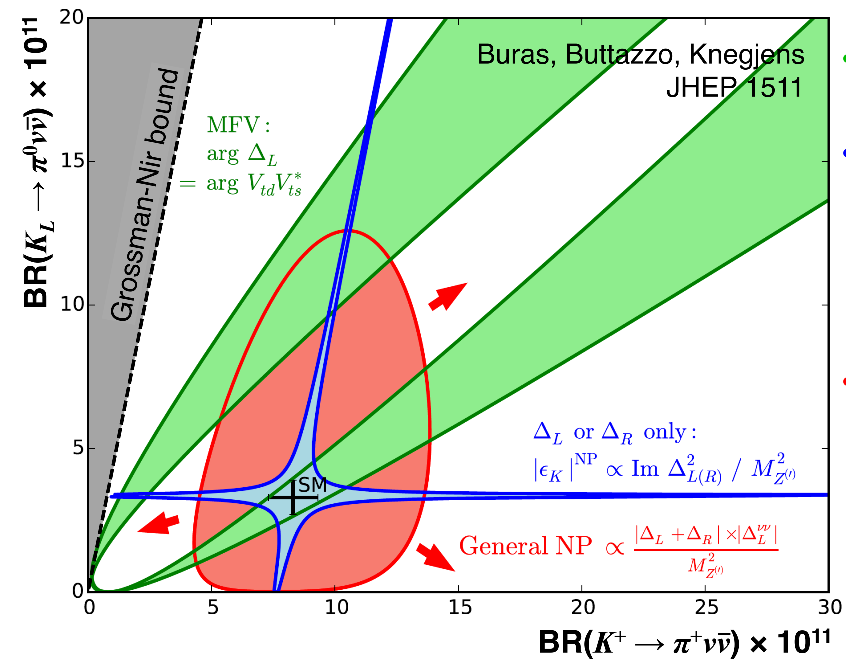

- Models with CKM-like flavor structure
  - Models with MFV
- Models with new flavor-violating interactions in which either LH or RH couplings dominate
  - Z/Z′ models with pure LH/RH couplings
  - Littlest Higgs with T parity
- Models without above constraints
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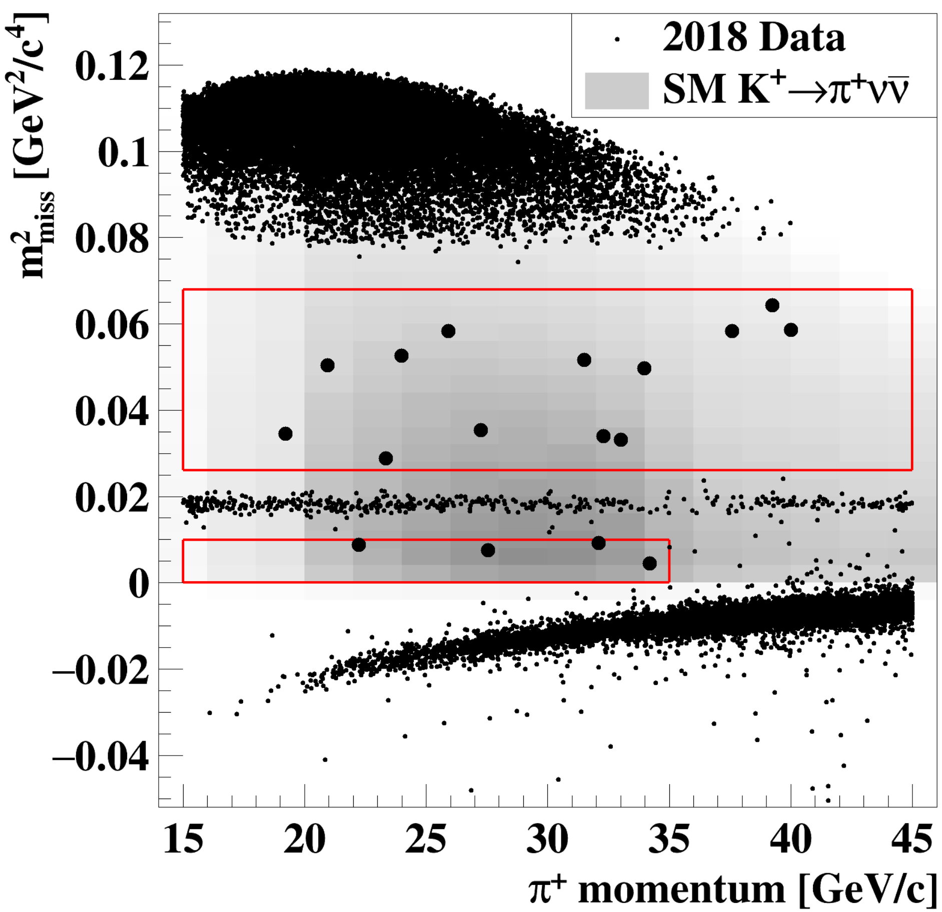

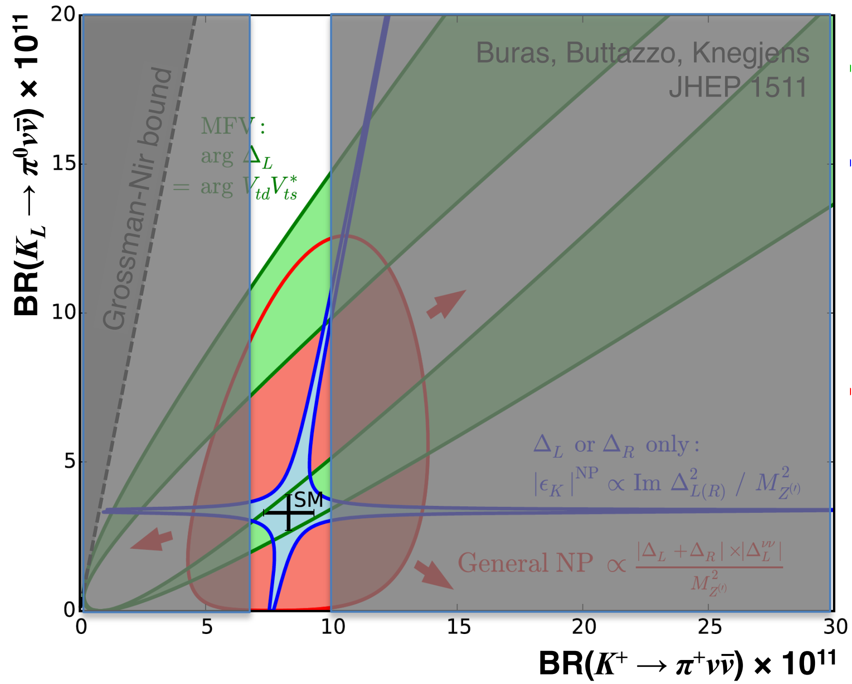

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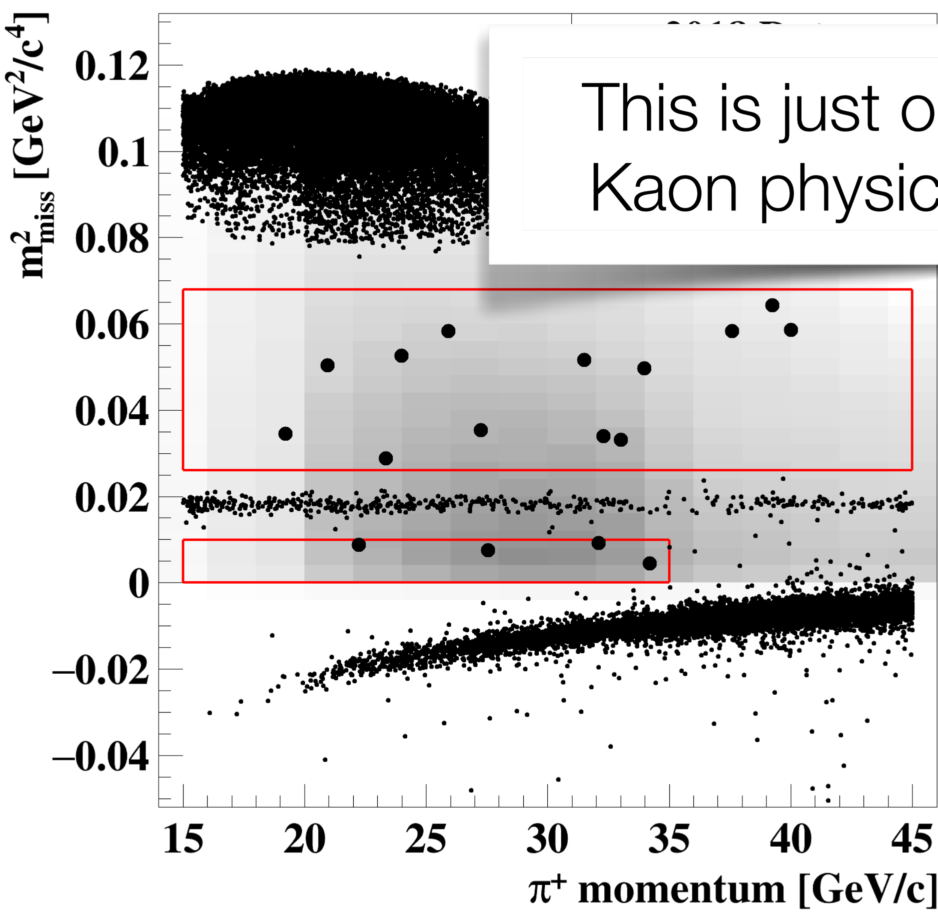
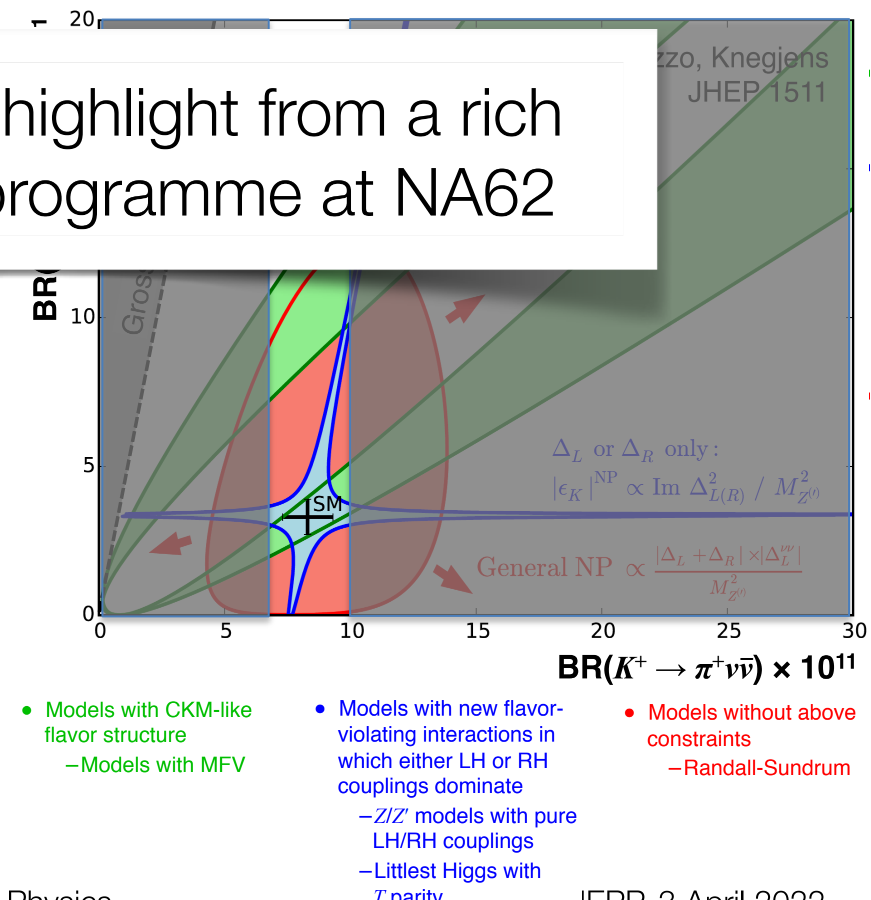
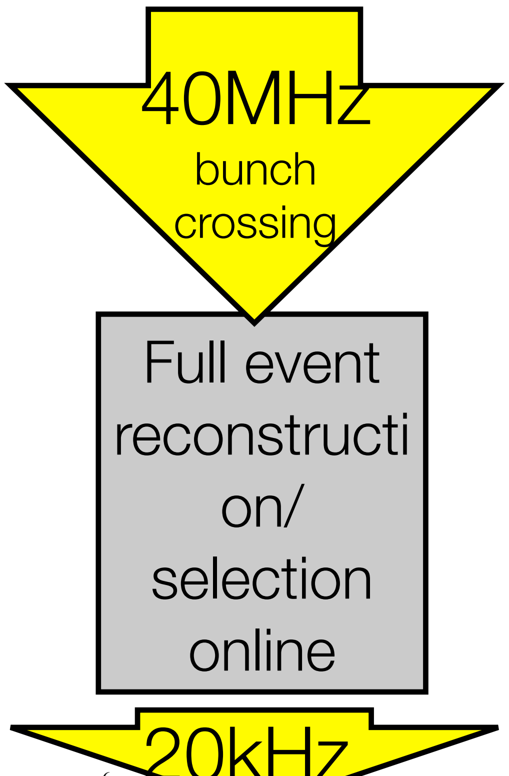
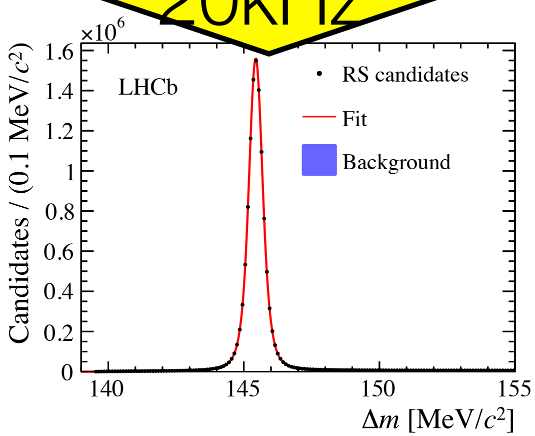


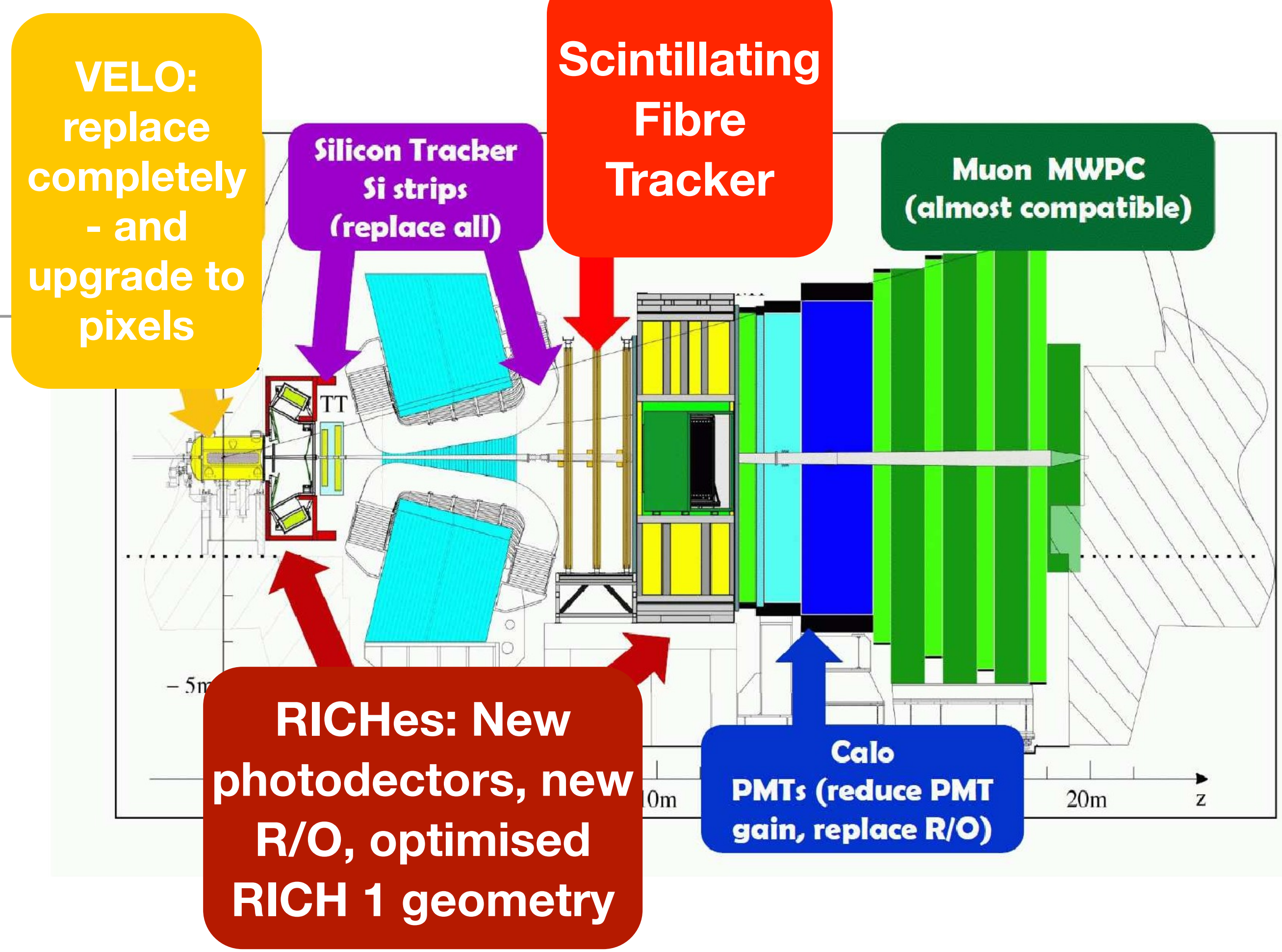


This is just one highlight from a rich Kaon physics programme at NA62

LHCb upgrade





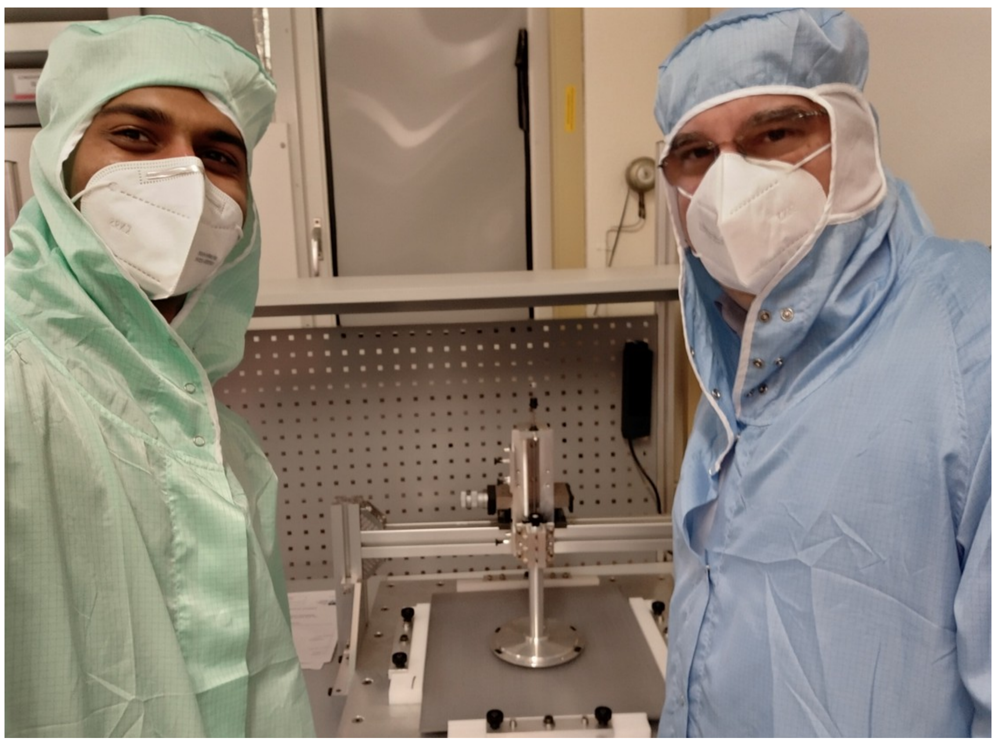


Essentially a new detector running at increased luminosity.
Not just more lumi: Triggereless operation with online reconstruction and selection at 40MHz means more signal per fb^{-1}

See also Dylan White's poster this evening

Upgrading LHCb during COVID

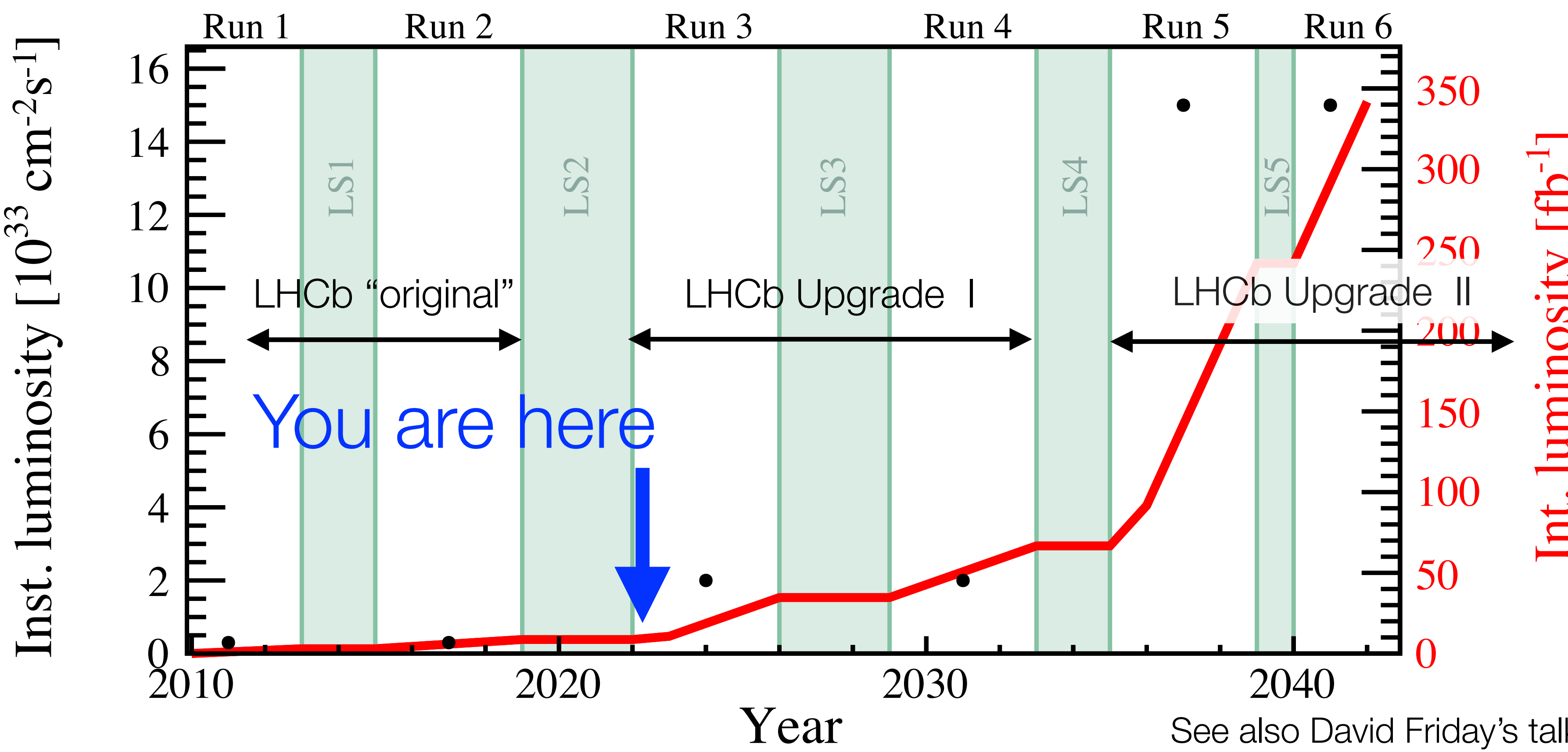
UK has major responsibilities for the LHCb upgrade especially in VELO and RICH - delivered in difficult circumstances.



See also Gianluca Zunica's talk in the today's parallel session after lunch

LHCb upgrades: Moving beyond discovery

- We appear to be on the brink of establishing physics beyond the SM, and flavour is the main window to it. To understand what that NP is, we will need to *measure the heck out of flavour.*



See also David Friday's talk in the today's parallel session after lunch

LHCb upgrades: Moving beyond discovery

See Sudan's talk today at 16:15

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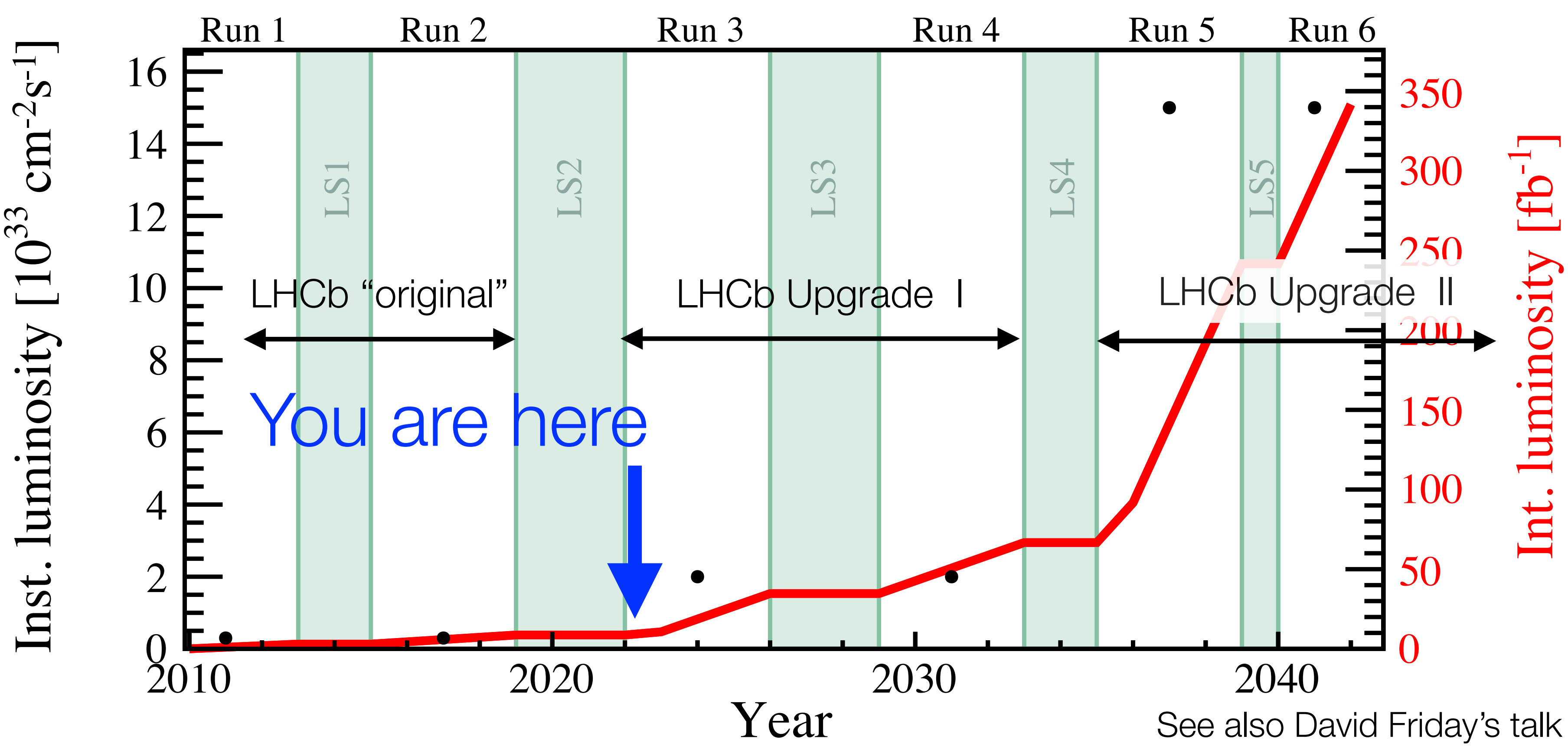

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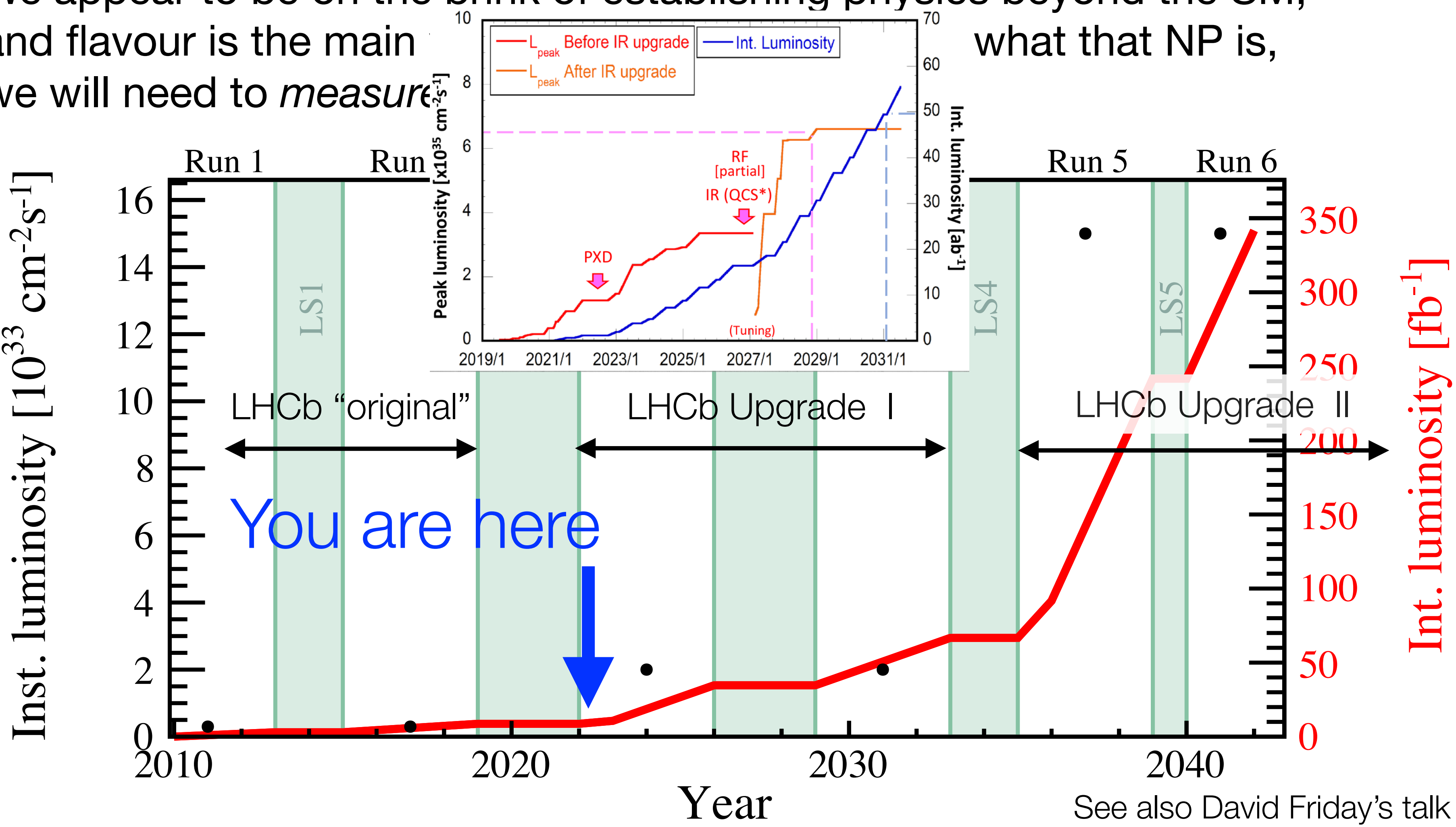

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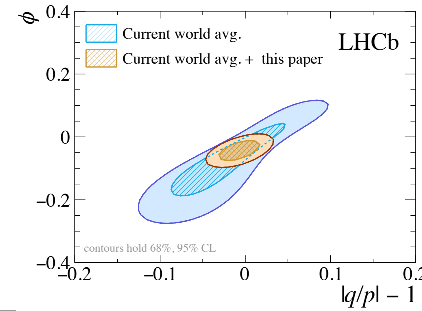
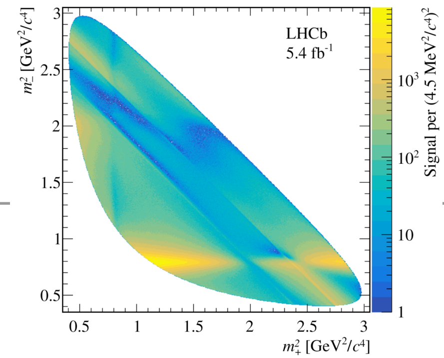
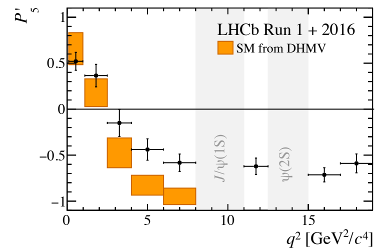
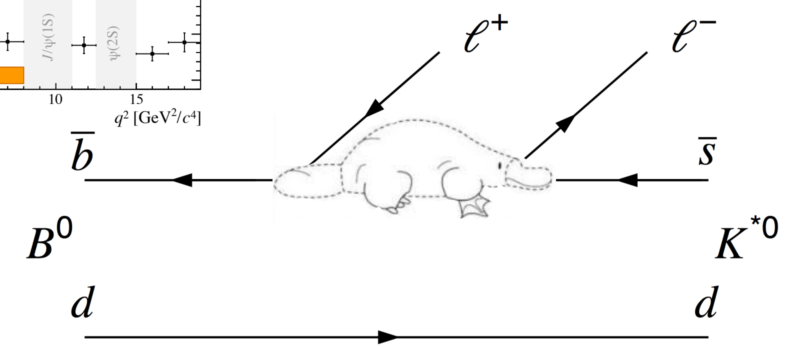
Summary

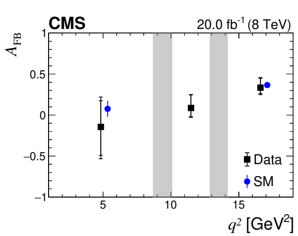
- Flavour provides a unique window onto mass scales far beyond those reached in LHC collisions.
- The beautiful data accumulated over the past years give powerful constraints on models, with indications of physics beyond the SM that are intriguingly consistent across related decay modes.
- Precision is key. We badly need the huge clean datasets to be accumulated with the upgraded detectors.
- The future of flavour is luminous!

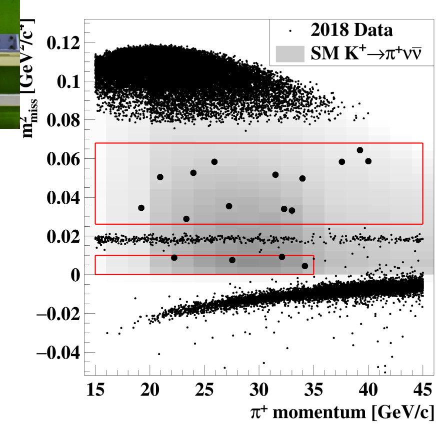


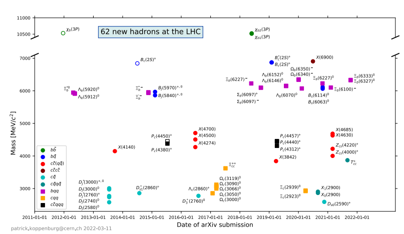






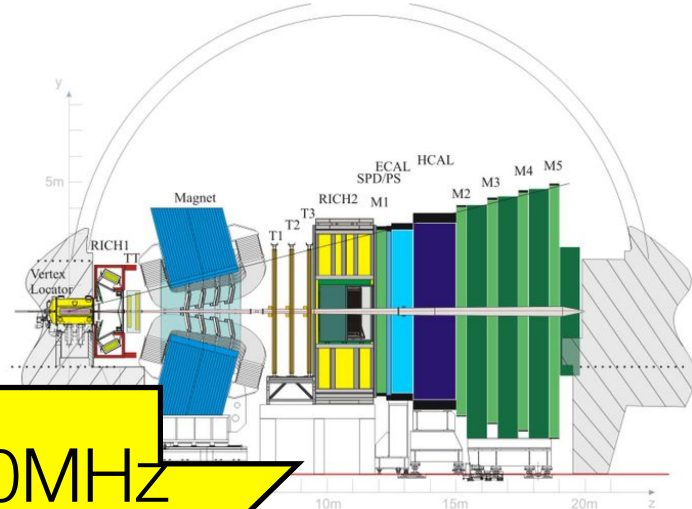






The end

LHC Run 1



40MHz bunch crossing

L0 hardware trigger

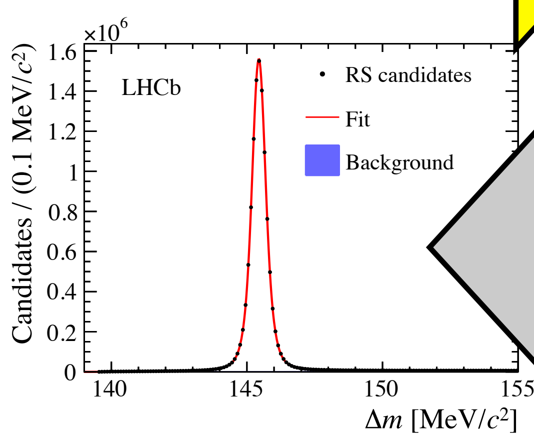
1MHz

Software trigger

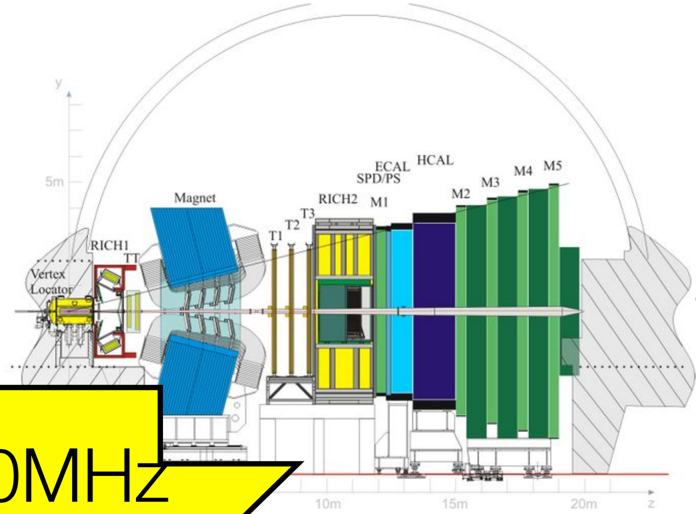
5kHz

Alignment & calibration

Offline reconstruction



LHC Run 2 (2015-2018)



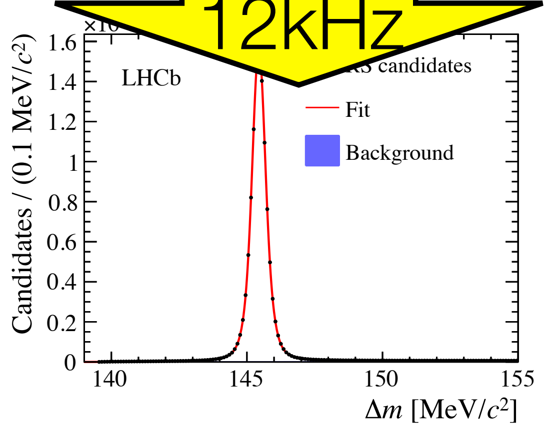
40MHz bunch crossing

L0 hardware trigger

1MHz

HLT1→ alignment & calibration →HLT2

12kHz



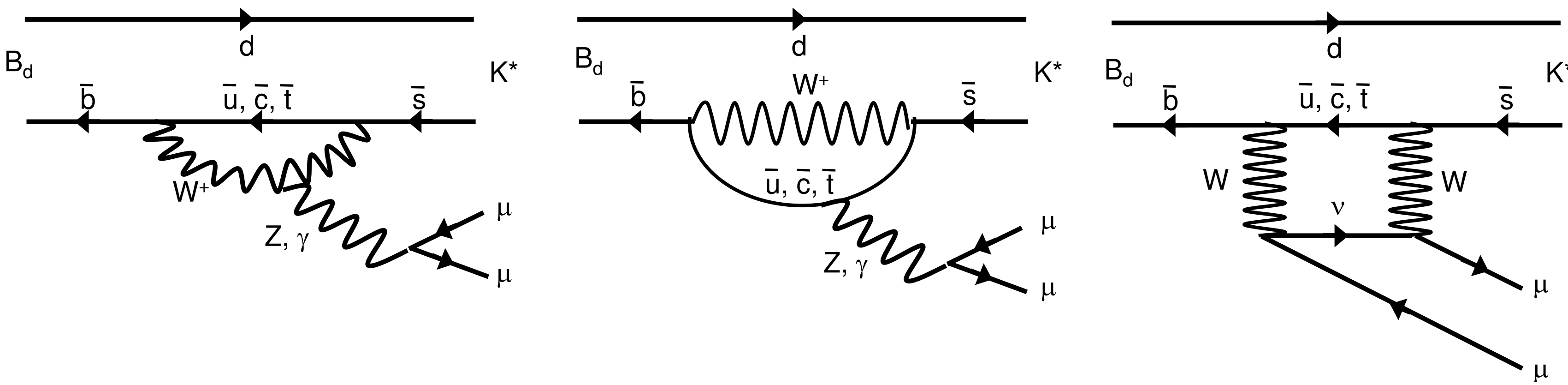
better trigger
& doubled cross section

LHCb upgrade physics reach - selected examples

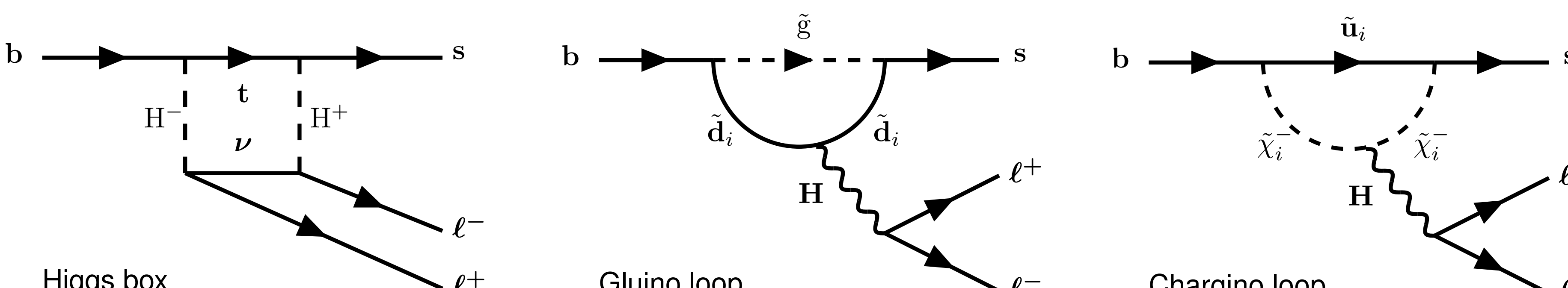
Observable	Current LHCb (up to $9\,\mathrm{fb}^{-1}$)		Upgrade I ($23\,\mathrm{fb}^{-1}$)	Upgrade I ($50\,\mathrm{fb}^{-1}$)	Upgrade II ($300\,\mathrm{fb}^{-1}$)
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9,10]	1.5°	1°	0.35°
ϕ_s ($B_s^0 \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29,30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_{\mathrm{S}}^0\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	69%	[40,41]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \to \mu^+\mu^-$)	—		—	—	0.2
$A_{\mathrm{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$A_{\mathrm{T}}^{\mathrm{Im}}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}_{\phi\gamma}^{\Delta\Gamma}(B_s^0 \to \phi\gamma)$	$^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B_s^0 \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62,64]	0.007	0.005	0.002

B→K*μ⁺μ⁻

FCNC, rare in the SM (BR ~10^{-6})



sensitive to New Physics in loops, e.g.



Higgs box   Gluino loop   Chargino loop

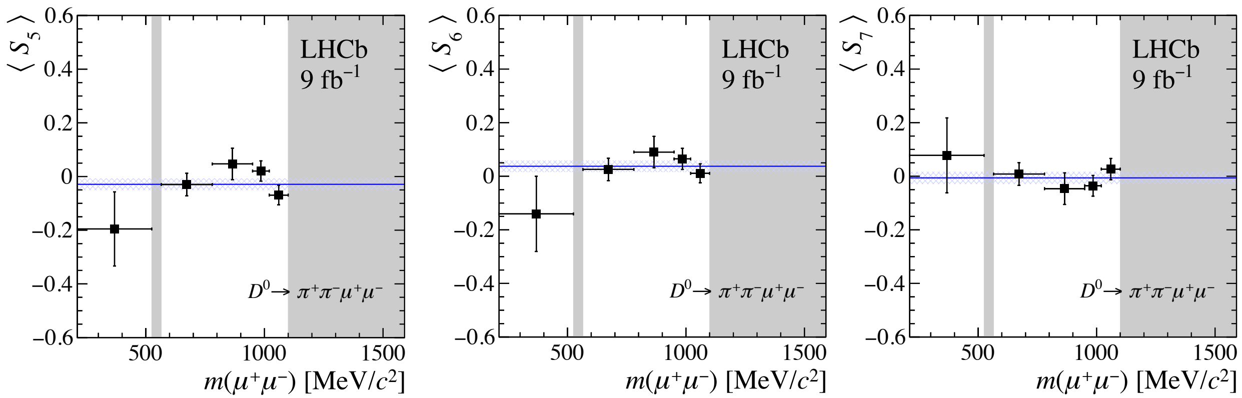
$D^0 \to \pi^+\pi^-\mu^+\mu^-, D^0 \to K^+K^-\mu^+\mu^-$

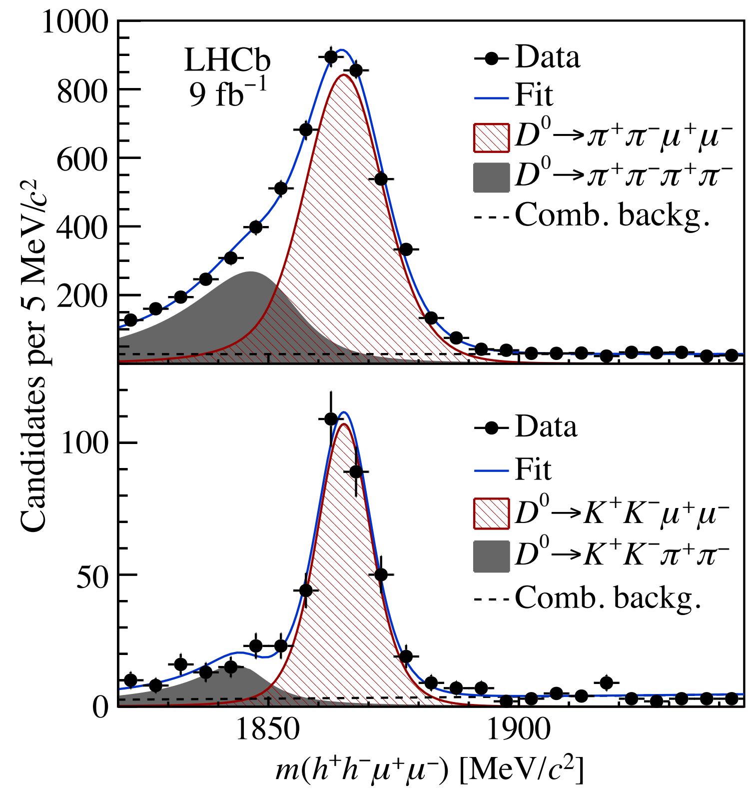
LHCb: arXiv:2111.03327 (2022)

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 9.6 \times 10^{-7}$$

$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) \sim 1.5 \times 10^{-7}$$

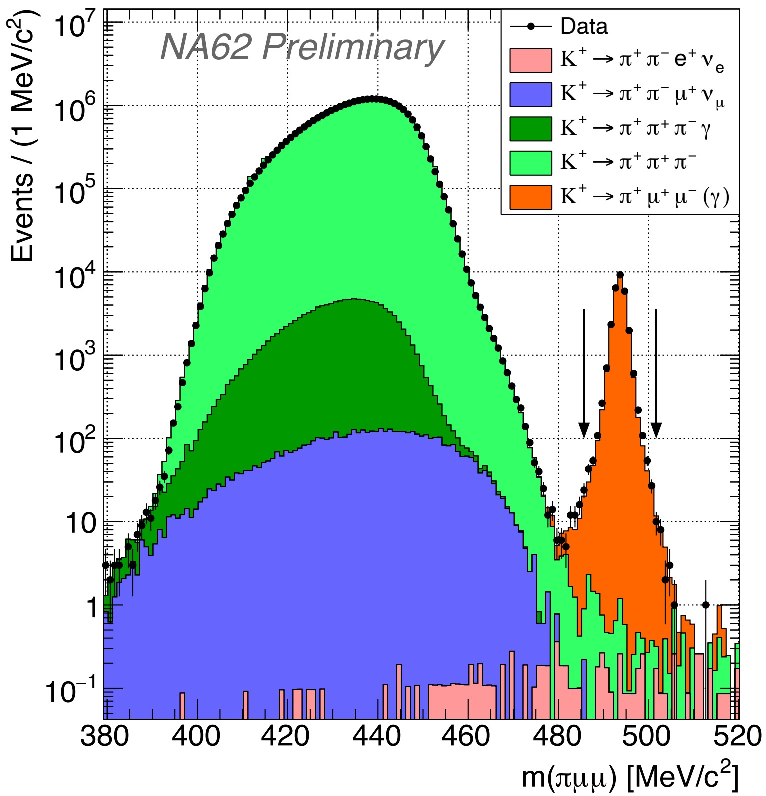
Find enough of them at LHCb for angular analysis:

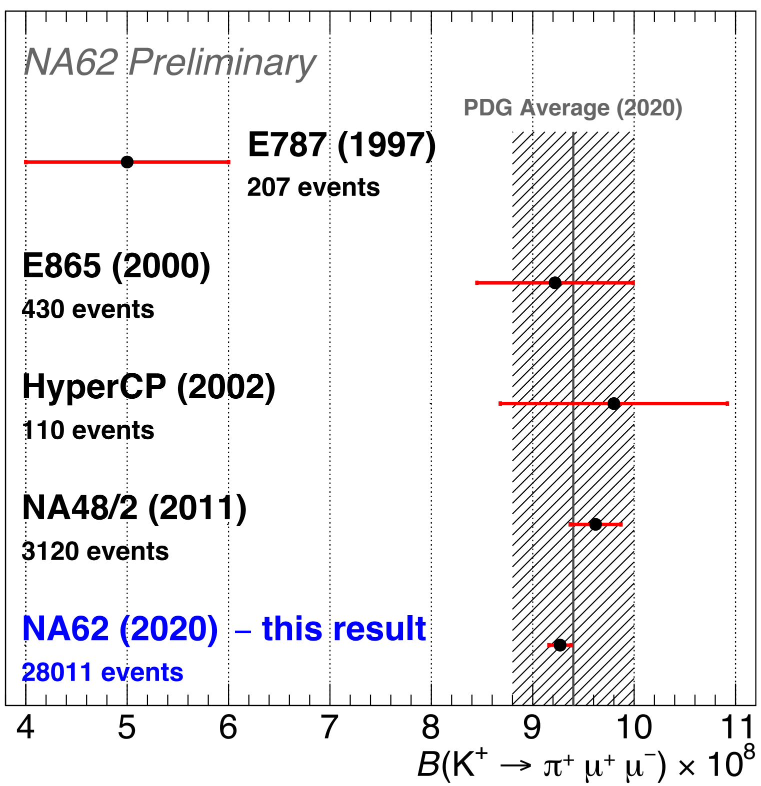




Angular analysis (above, 3 examples of many, many parameters measured) shows no discrepancy with SM

NA62 $K^+ \to \pi^+\mu^+\mu^-$

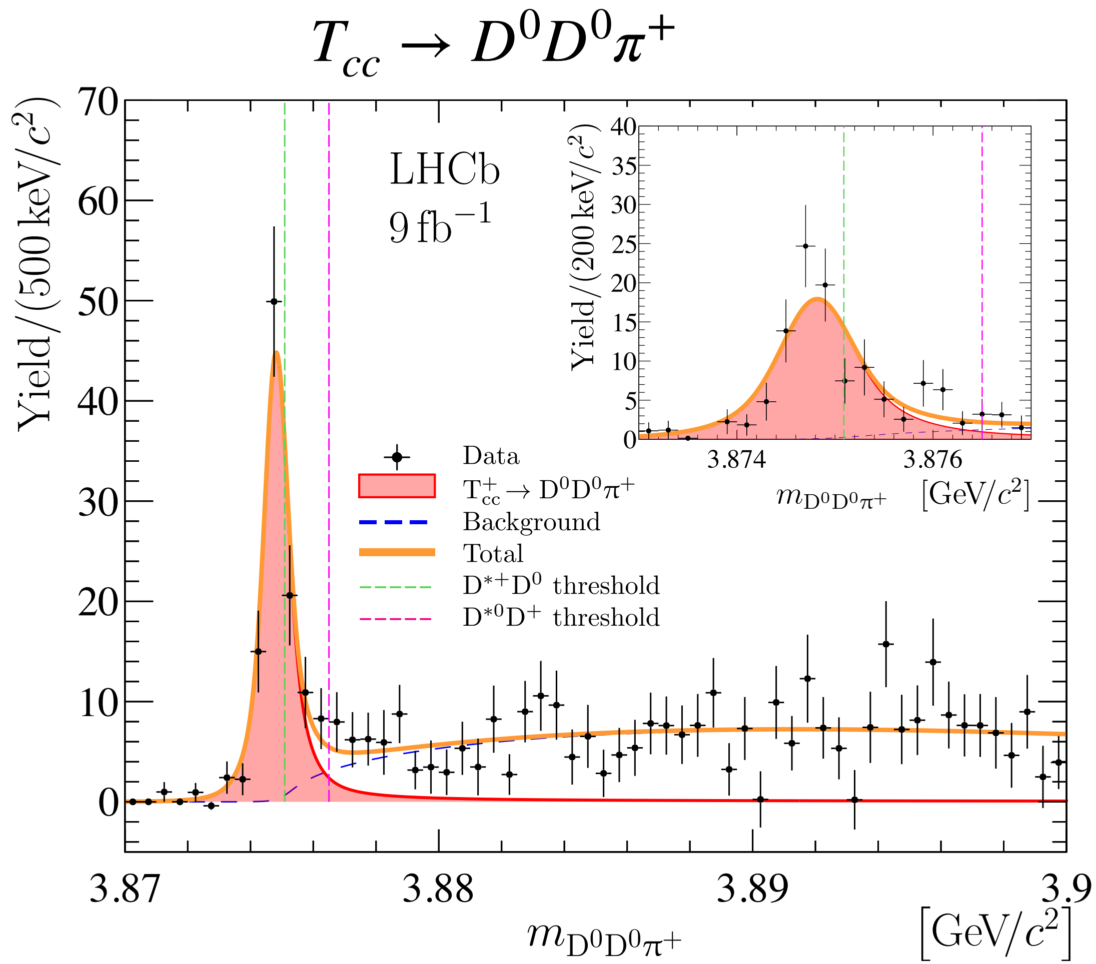




$$\mathcal{B}(K^+ \to \pi^+\mu^+\mu^-) = (9.27 \pm 0.11) \times 10^{-8}$$

T_{cc}

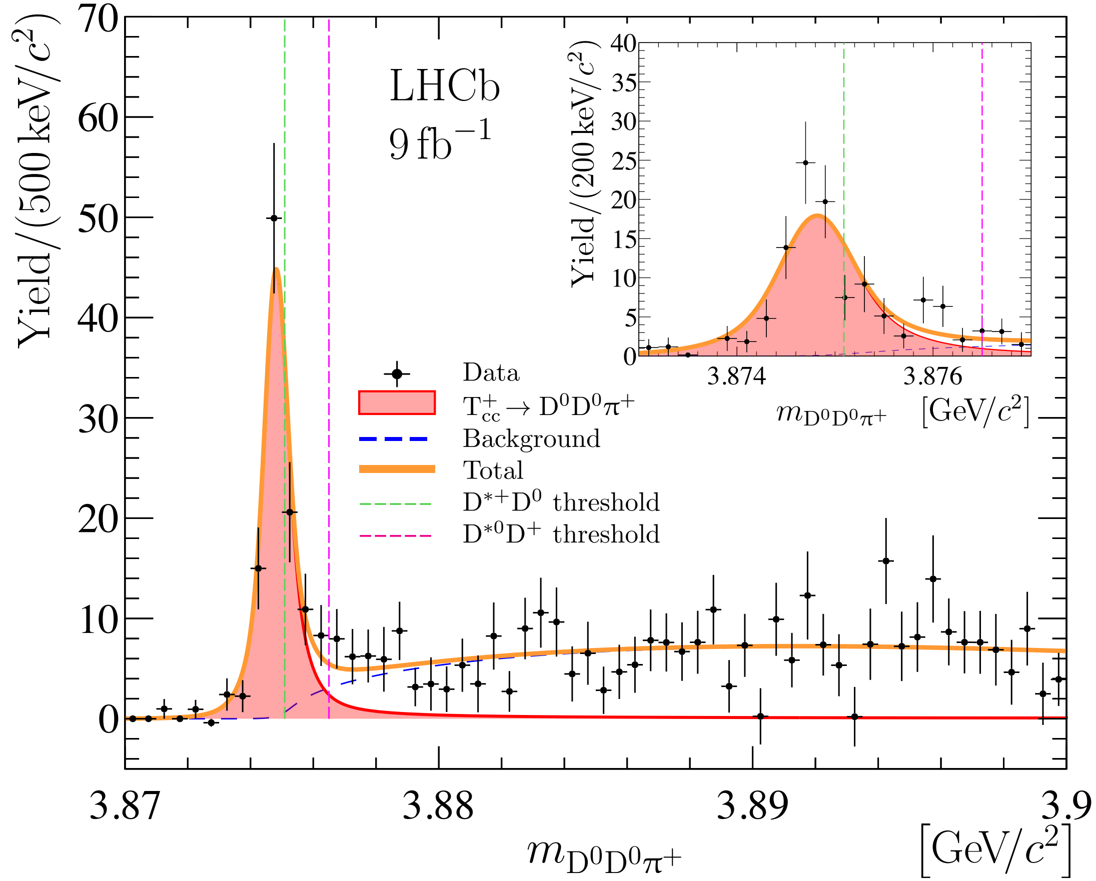
LHCb: arXiv:2109.01038 (2022)



minimum quark content: $cc\bar{u}\bar{d}$ - doubly charmed

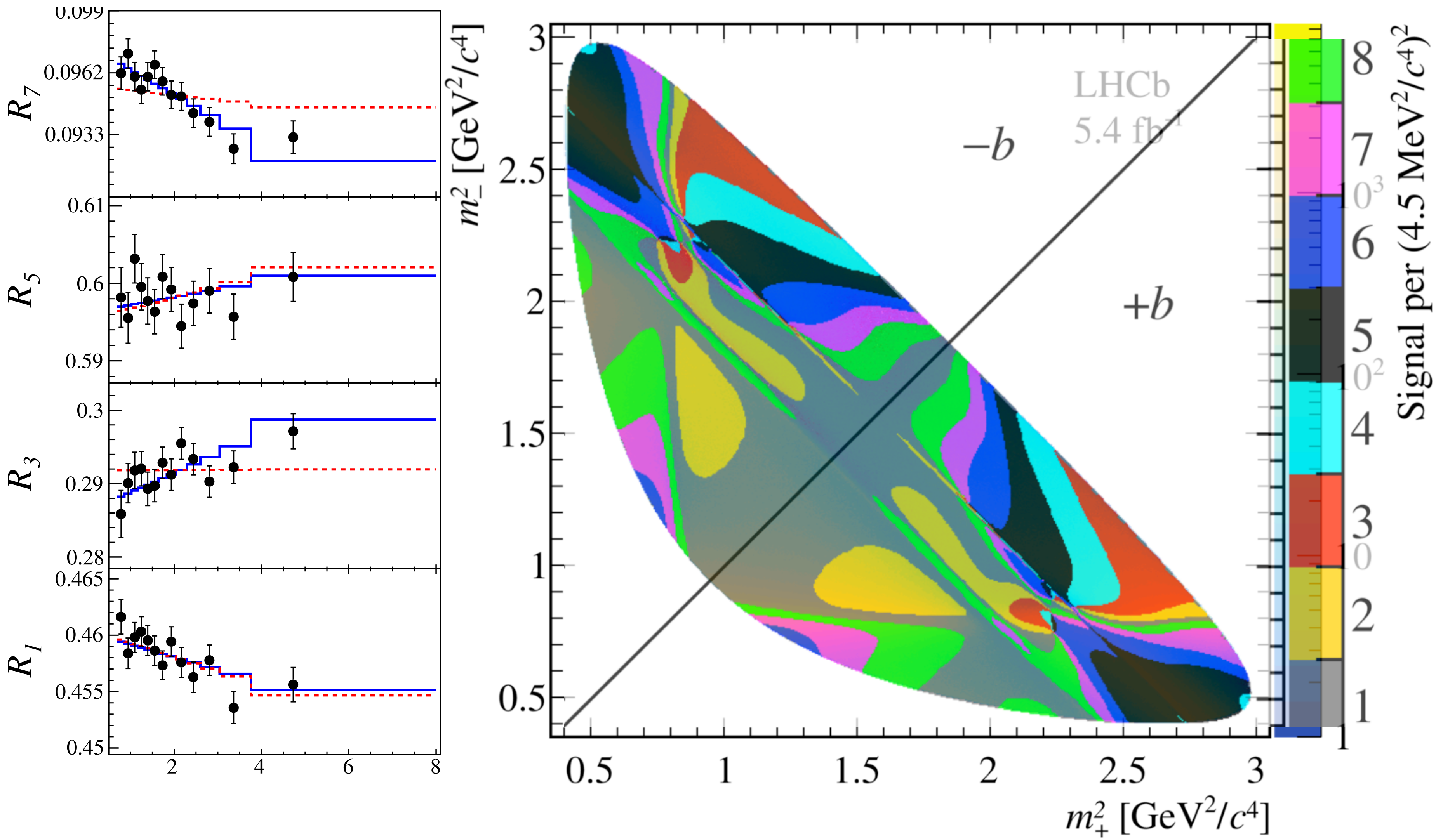
T_{cc}

$T_{cc} \rightarrow D^0 D^0 \pi^+$

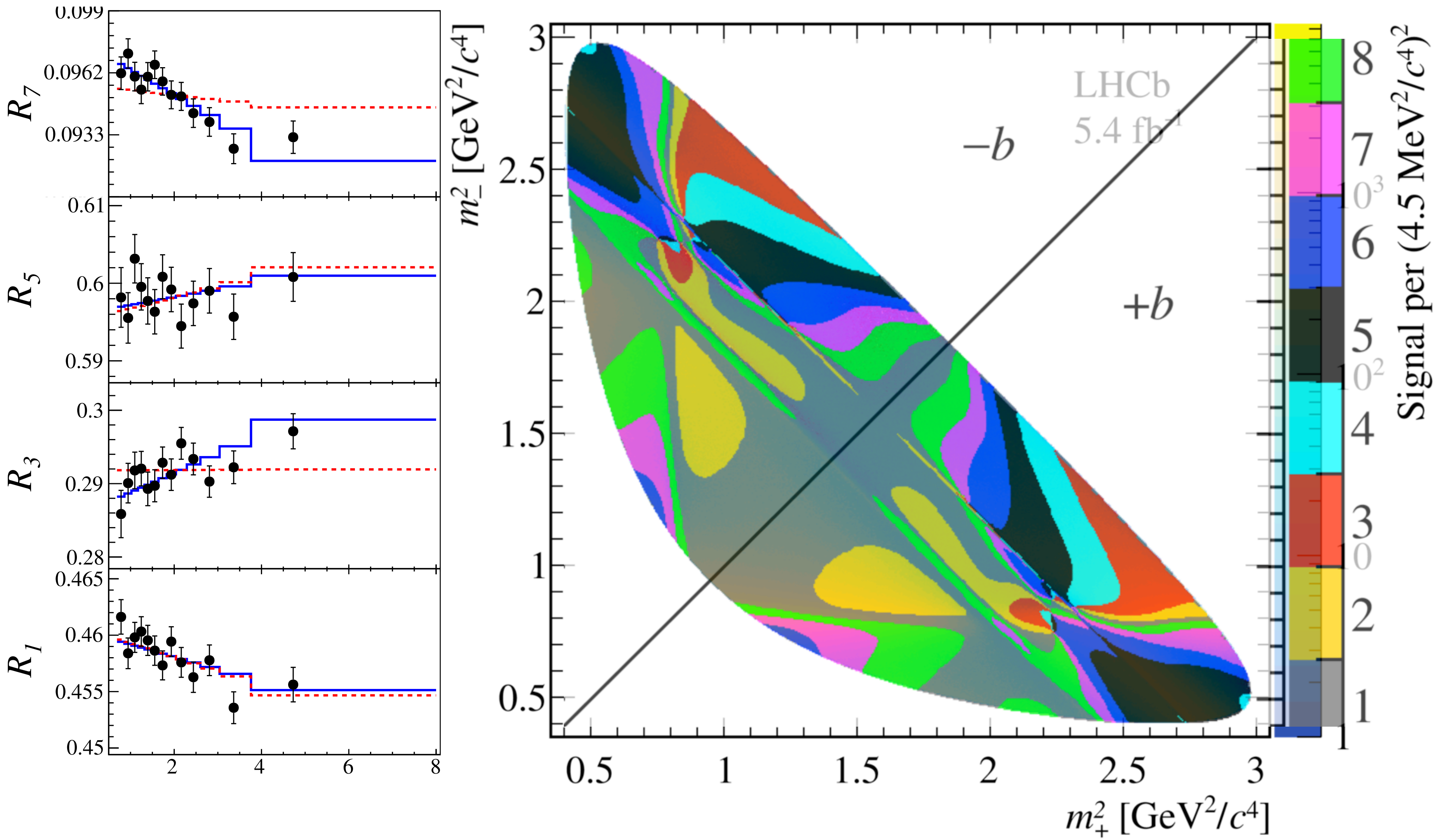


minimum quark content: $cc\bar{u}\bar{d}$ - doubly charmed

LHCb: PRL 127 (2021) 11, 111801

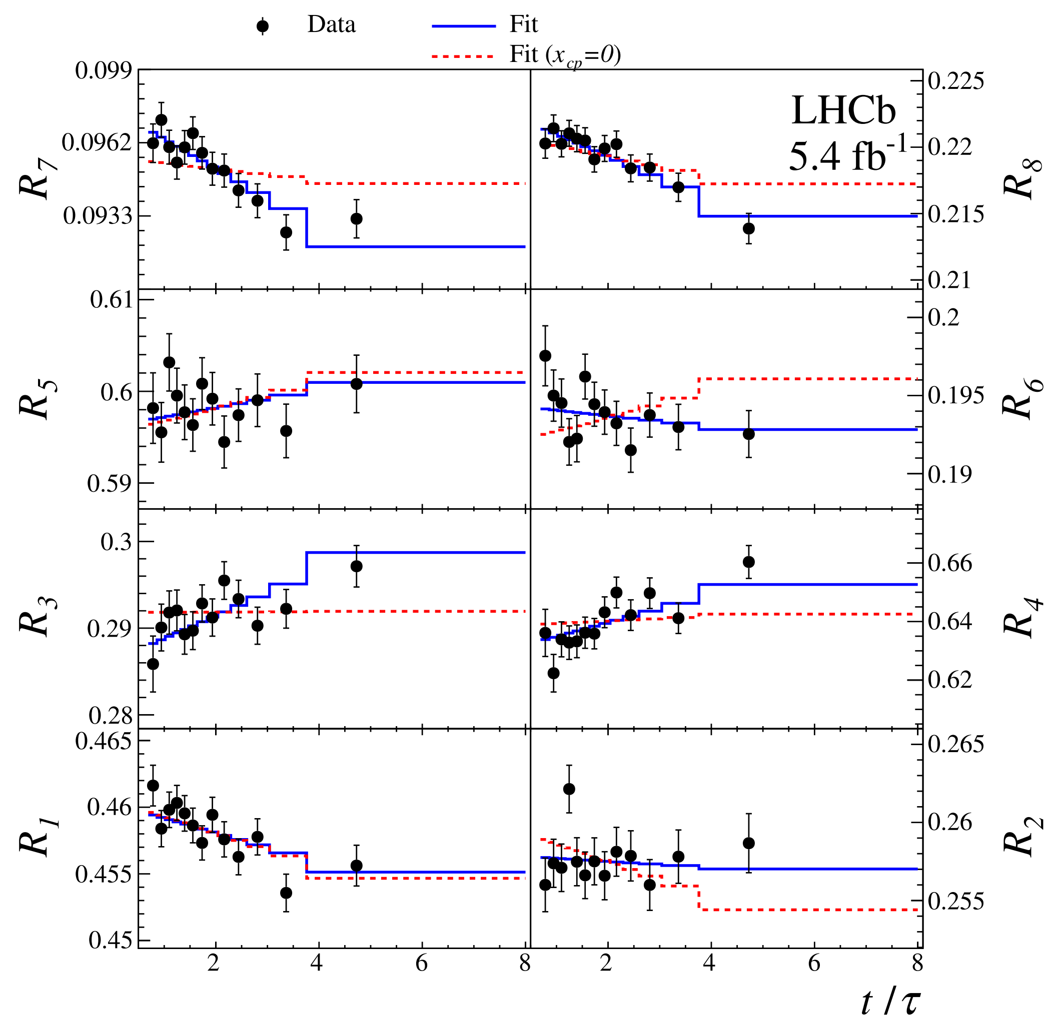


This is data, not a simulation!

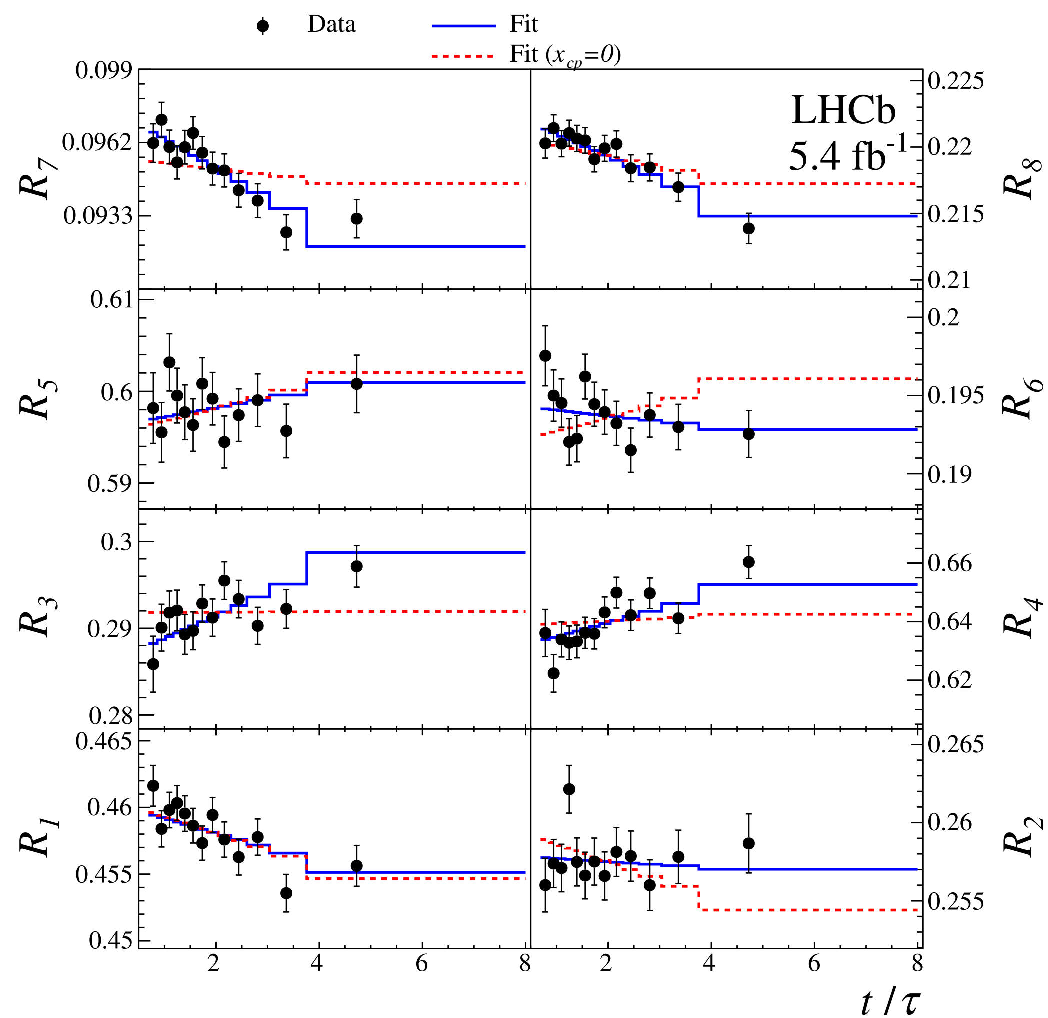


This is data, not a simulation!

LHCb: PRL 127 (2021) 11, 111801



time→


Data
Fit
Fit (x_{cp}=0)
LHCb
5.4 fb^{-1}
R_7
R_8
R_5
R_6
R_3
R_4
R_1
R_2
0.099
0.0962
0.0933
0.225
0.22
0.215
0.21
0.61
0.6
0.59
0.2
0.195
0.19
0.3
0.29
0.28
0.66
0.64
0.62
0.465
0.46
0.455
0.45
0.265
0.26
0.255
2
4
6
8
$t\,/\,\tau$

time→

Resonances in the $J/\psi\eta$ system

- X_C': C-odd partner of $\chi_{c1}(3872)$
  - Predicted by many theoretical works
    [JPS Conf. Proc. 13 (2017) 020023, EPJ Web Conf. 137 (2017) 06002, …]
  - Searched for by Belle and BarBar

BarBar	$\mathcal{B}(B^+ \to X_C' K^+) \times \mathcal{B}(X_C' \to J/\psi\eta) < 7.7 \times 10^{-6}$	Phys. Rev. Lett. 93 (2004) 041801
Belle	$\mathcal{B}(B^+ \to X_C' K^+) \times \mathcal{B}(X_C' \to J/\psi\eta) < 3.8 \times 10^{-6}$	PTEP 2014 (2014) 043C01

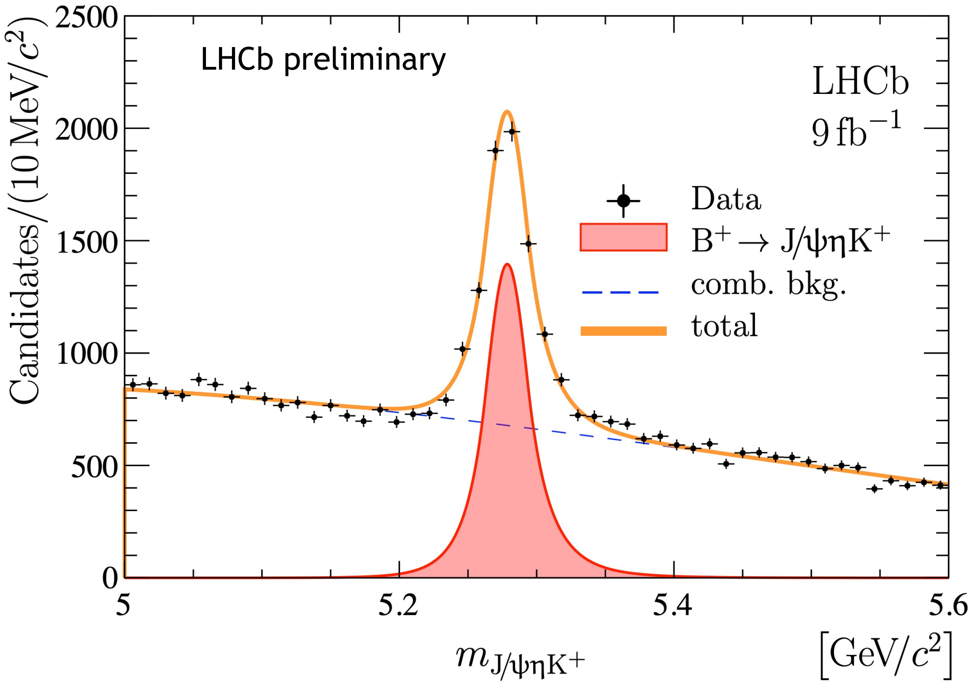
- Other charmonium-(like) states

$B^+ \to J/\psi\eta K^+$ dataset

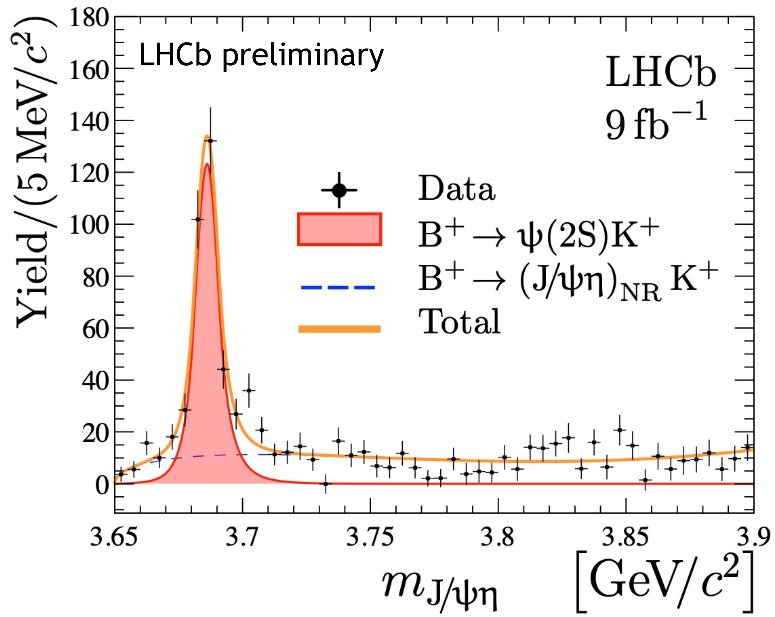
LHCb-PAPER-2021-047, in preparation

- Full LHCb data, $\mathcal{L} = 9\ \text{fb}^{-1}$
- $B^+ \to J/\psi\eta K^+, J/\psi \to \mu^+\mu^-, \eta \to \gamma\gamma$

$N_{B^+}: (5.39 \pm 0.16)\times 10^3$



Clear signature of $\psi(2S) \to J/\psi\eta$



20

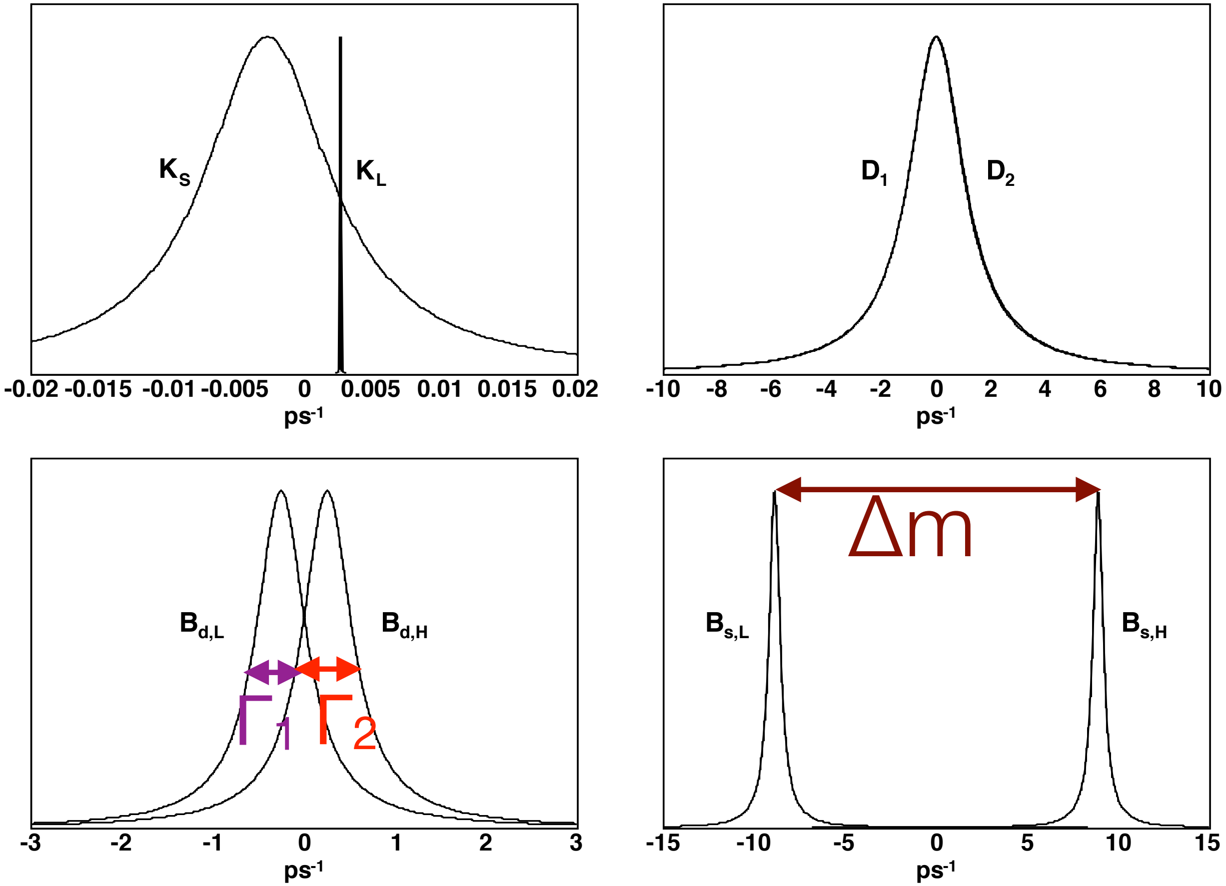
Mixing in neutral meson systems

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

$$\Delta\Gamma = \Gamma_2 - \Gamma_1$$

$$\Delta m = m_2 - m_1$$

$$\Gamma = \frac{1}{2}\left(\Gamma_1 + \Gamma_2\right)$$



$$P(M^0 \to \overline{M}^0)(t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m\, t\right)\right)$$

Mixing in neutral meson systems

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

$$\Delta\Gamma = \Gamma_2 - \Gamma_1$$

$$\Delta m = m_2 - m_1$$

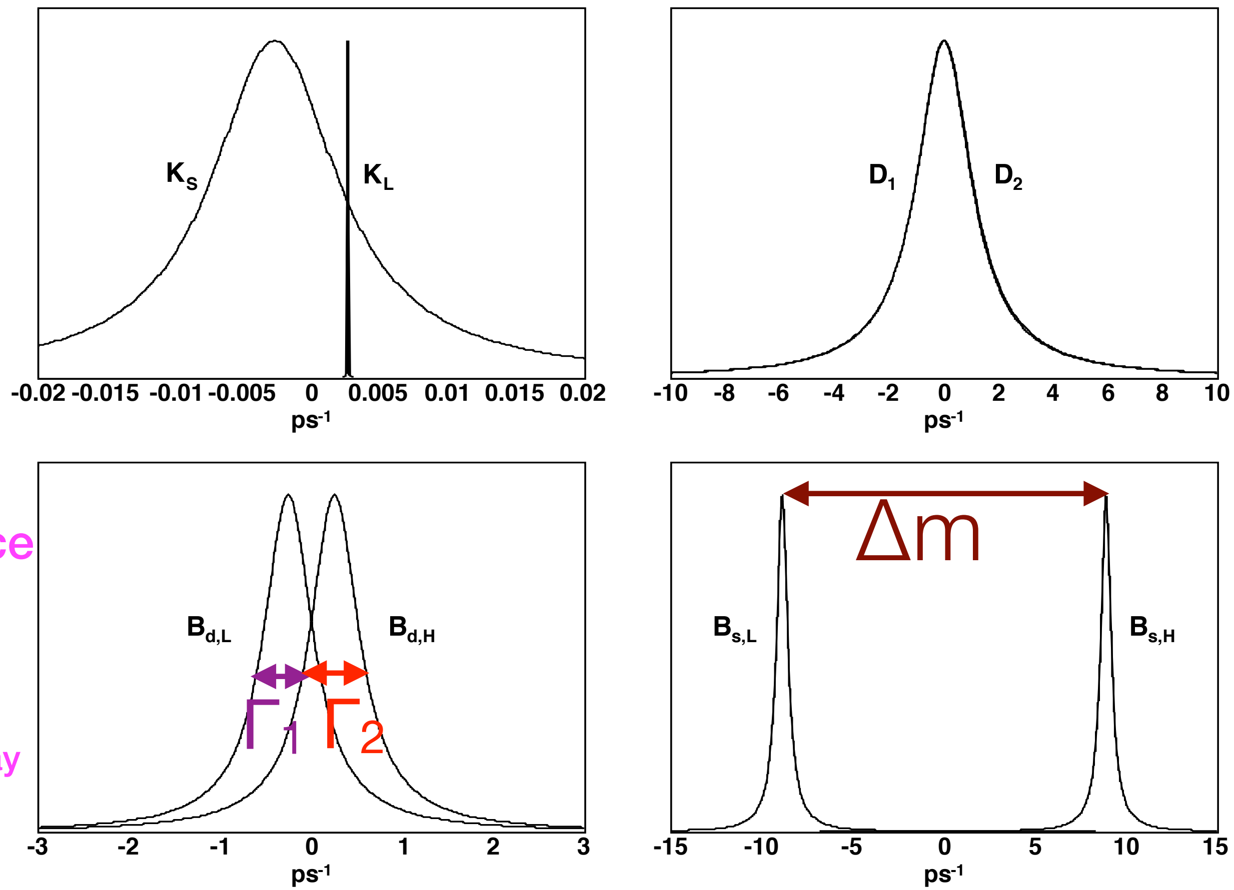
$$\Gamma = \frac{1}{2}\left(\Gamma_1 + \Gamma_2\right)$$

$$\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}$$

CPV in interference between mixing and decay

(if phase is non-zero relative to phase of decay diagram)

CPV in mixing if not 1



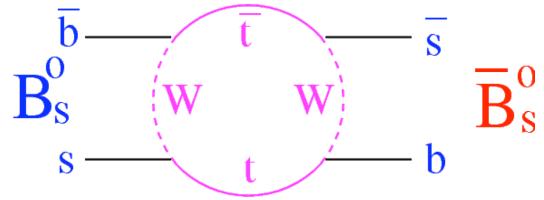
$$P(M^0 \to \overline{M}^0)(t) = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left(\cosh\left(\frac{\Delta\Gamma}{2}t\right) - \cos\left(\Delta m\, t\right)\right)$$

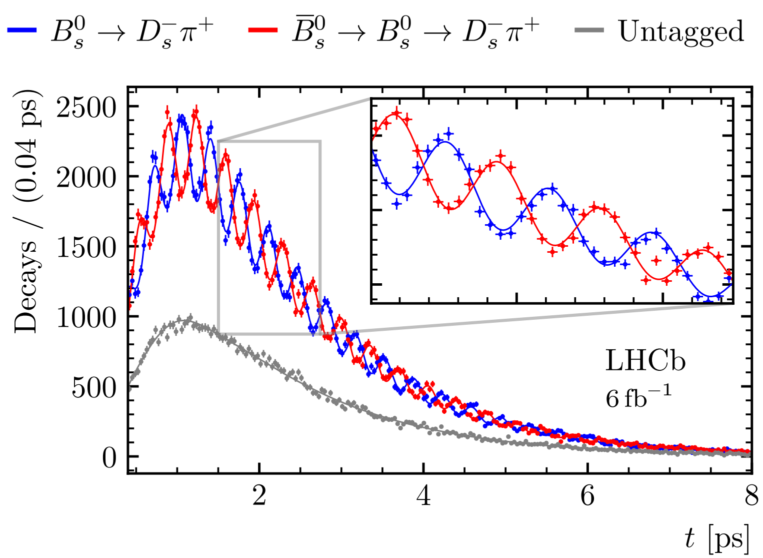
Nature Phys. 18 (2022) 1, 1-5

Oscillations

B_s oscillations at LHCb

- the Bs mixing plot and result





$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ ps^{-1}$$

world's most precise measurement of Δm_s

Nature Phys. 18 (2022) 1, 1-5

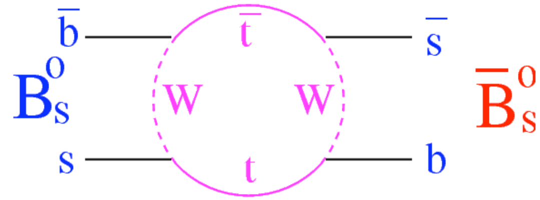
Oscillations

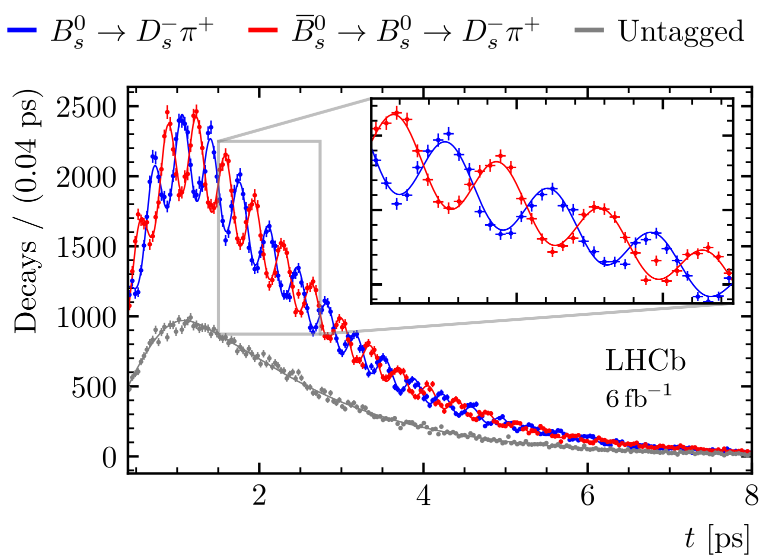
Phys. Rev. Lett. 110 (2013) 101802

Phys. Rev. Lett. 111 (2013) 251801

B_s oscillations at LHCb

- the Bs mixing plot and result





$$\Delta m_s = 17.7683 \pm 0.0051 \pm 0.0032\ ps^{-1}$$

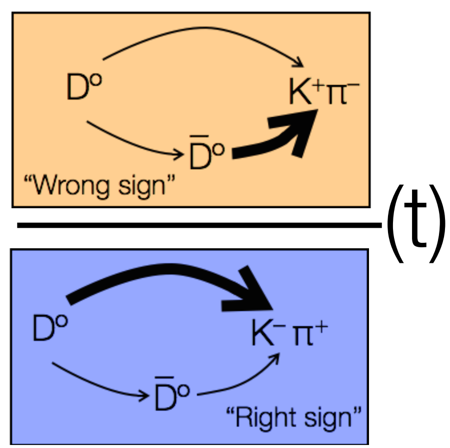
world's most precise measurement of Δm_s

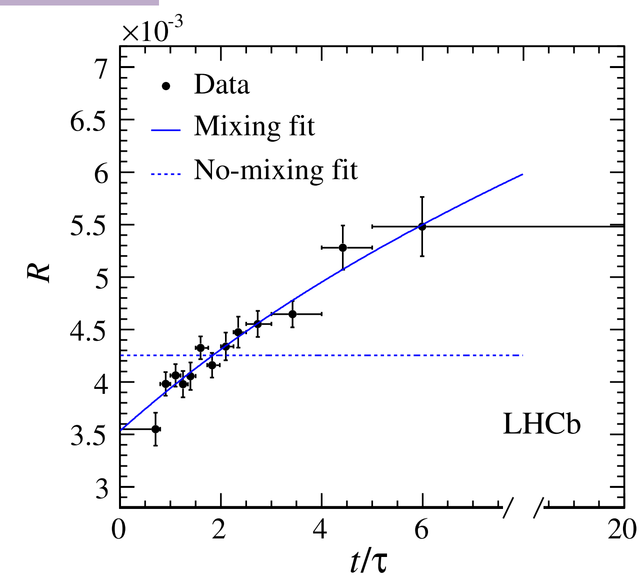
D° oscillations at LHCb

numerator: mixing amplitude D°→D̄°→K⁺π⁻ significant

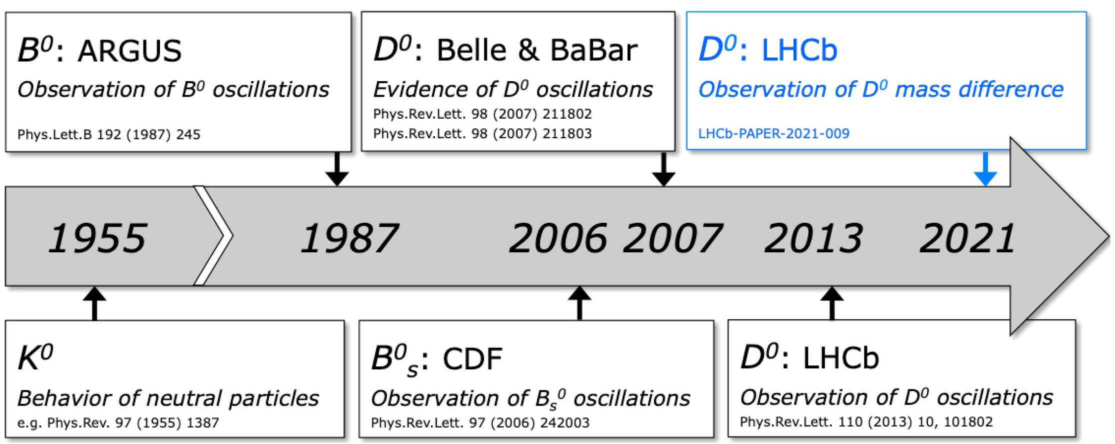
denominator: for normalisation (mixing negligible)

$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)}(t)$$

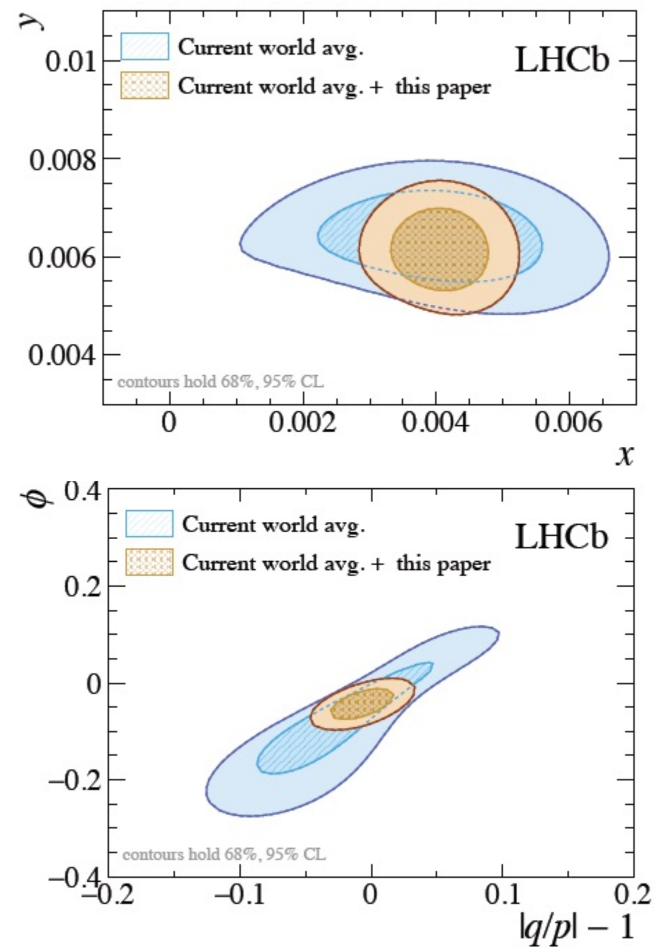


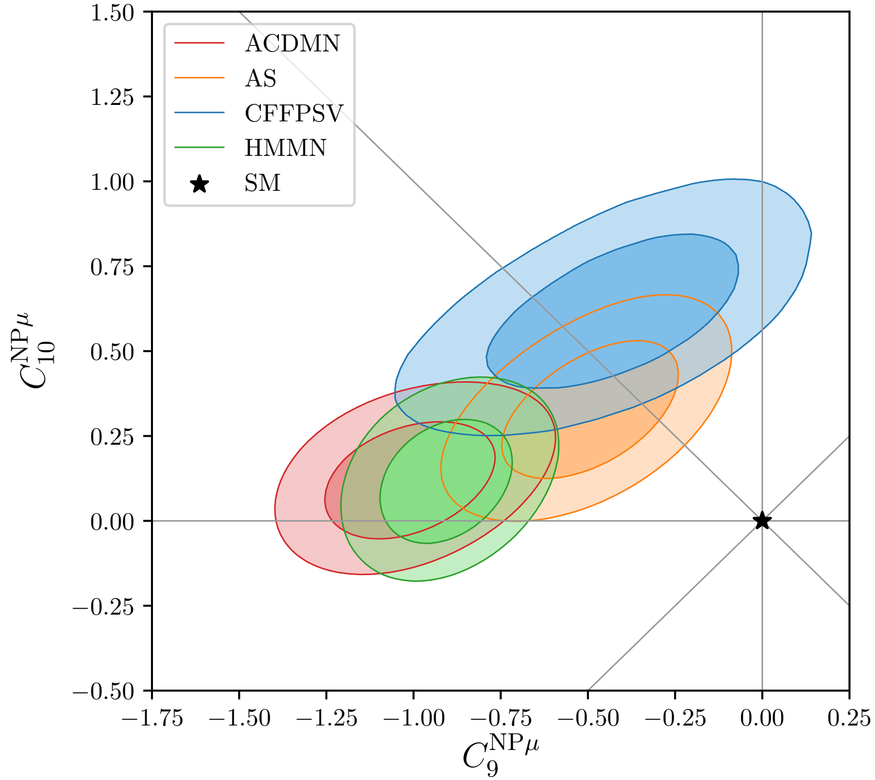


D mixing

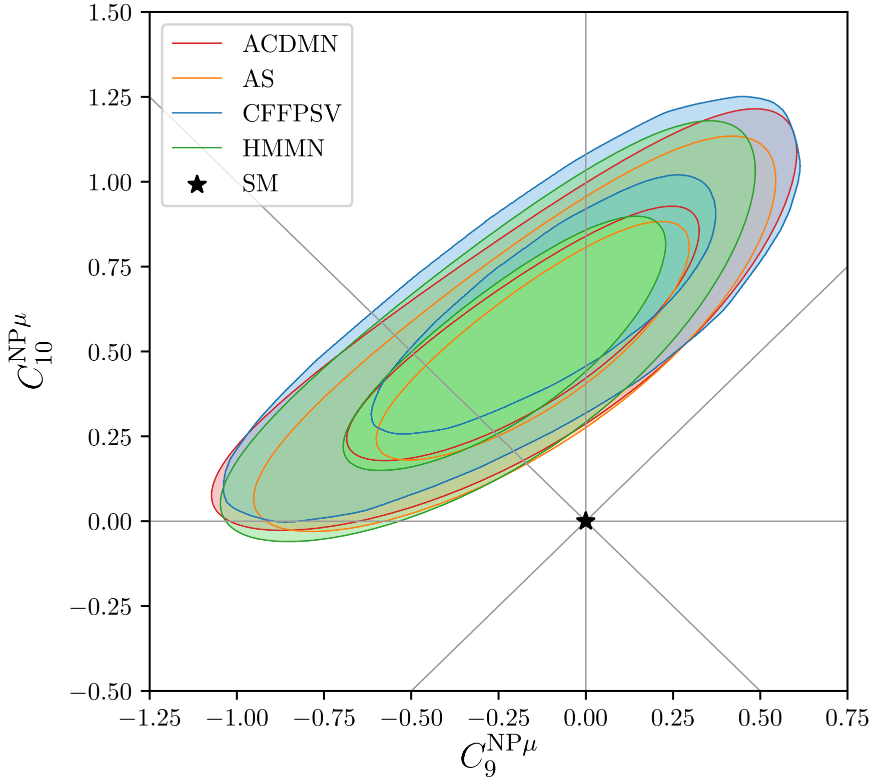


PRL 127 (2021) 11, 111801





global fit



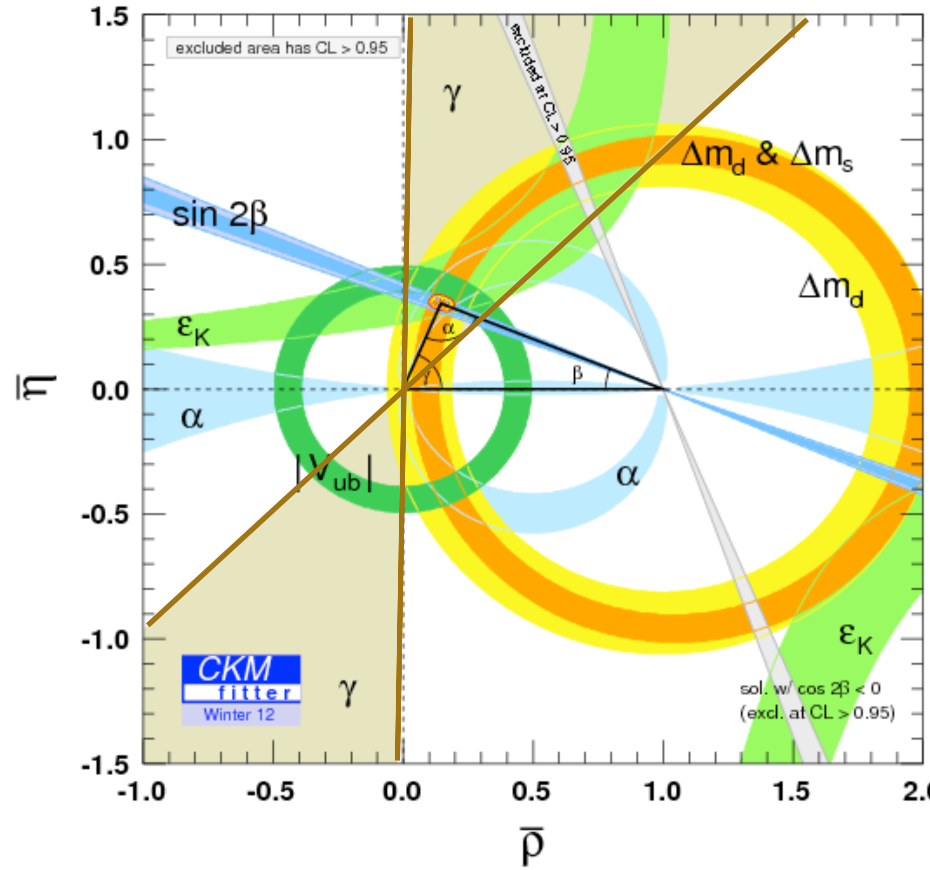
fit to LFU observables + $B_s \to \mu\mu$

technique & 2011 data: Phys. Lett. B726 (2013) 151
2012 data: LHCb-CONF (2013-006)

LHCb's γ combination

World averages by CKM Fitter

- LHCb combines inputs from
  $B^\pm \to (hh')_D K^\pm$
  $B^\pm \to (K_S\pi\pi)_D K^\pm$
  $B^\pm \to (K_SKK)_D K^\pm$
  $B^\pm \to (K\pi\pi\pi)_D K^\pm$
- Result:
  $$\gamma = (67.2 \pm 12)^o$$
- More channels available, including $B^\pm \to D\pi^\pm$, $B^0 \to DK^*$.
- Most recent addition: $B^\pm \to (K_SK\pi)_D K$



previous world average (Moriond 2012): $\gamma = 68^\circ \pm 12^\circ$

LHCb's γ combination

technique & 2011 data: Phys. Lett. B726 (2013) 151
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  $B^\pm \to (K_S\pi\pi)_D K^\pm$
  $B^\pm \to (K_S KK)_D K^\pm$
  $B^\pm \to (K\pi\pi\pi)_D K^\pm$
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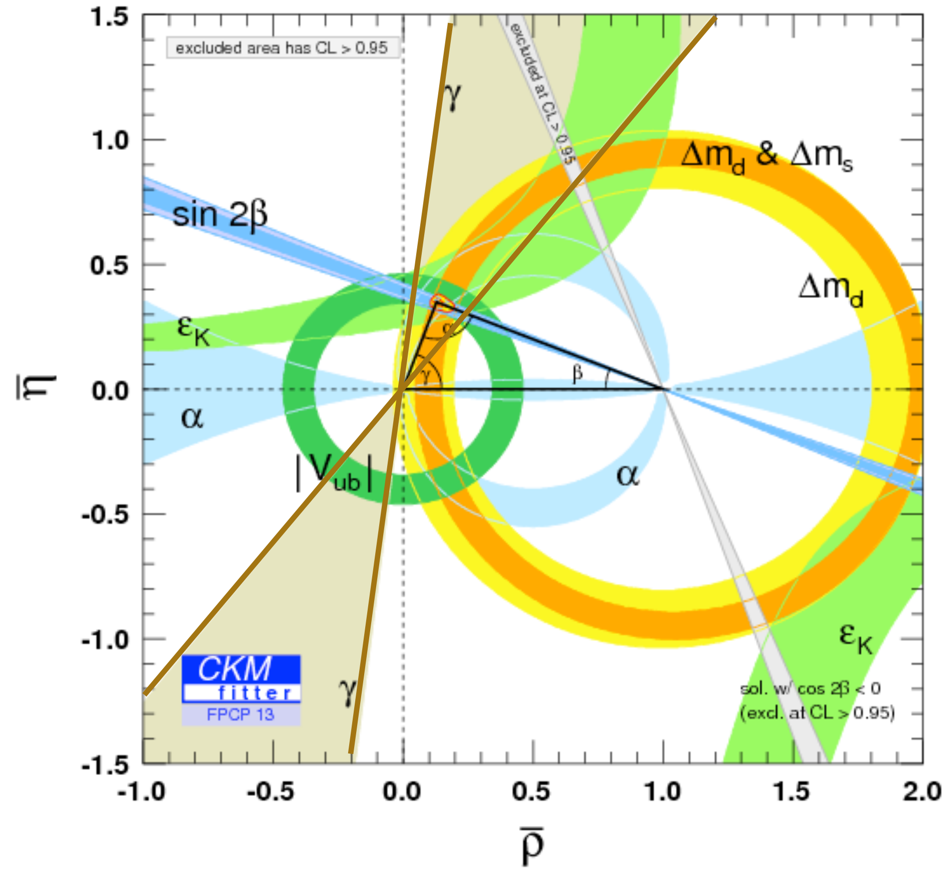


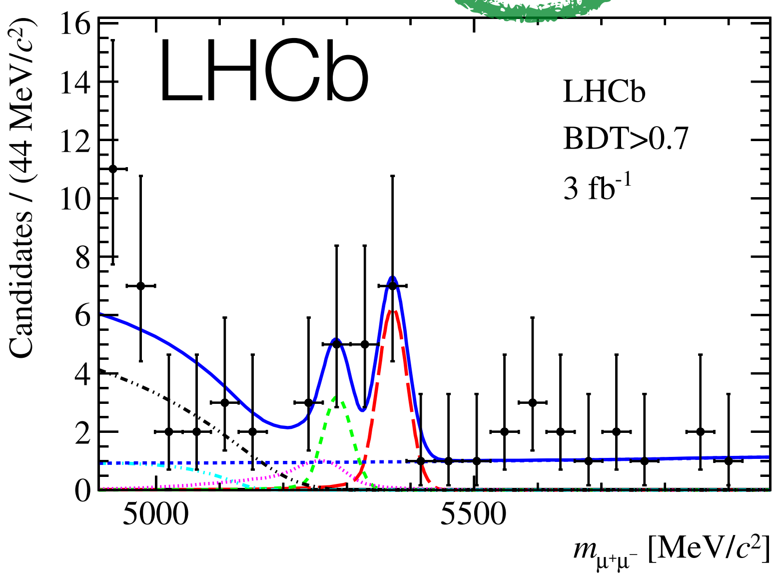
previous world average (Moriond 2012): $\gamma = 68^\circ \pm 12^\circ$

LHCb: γ=67.2°±12°

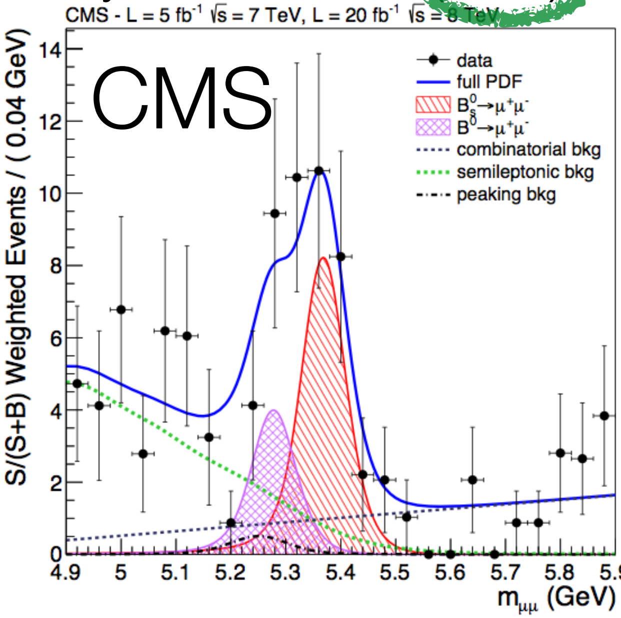
$$\gamma = 68^\circ {}^{+8.0^\circ}_{-8.5^\circ}$$

$B_{(s)} \to \mu^+\mu^-$

Phys.Rev.Lett. 111 (2013) 101805



Phys.Rev.Lett. 111 (2013) 101804



…by many orders … SUSY ∝

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9^{+1.1+0.3}_{-1.0-0.1}) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.7^{+2.4+0.6}_{-2.1-0.4}) \times 10^{-10}$$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.7^{+1.0}_{-0.9}) \times 10^{-9}$$

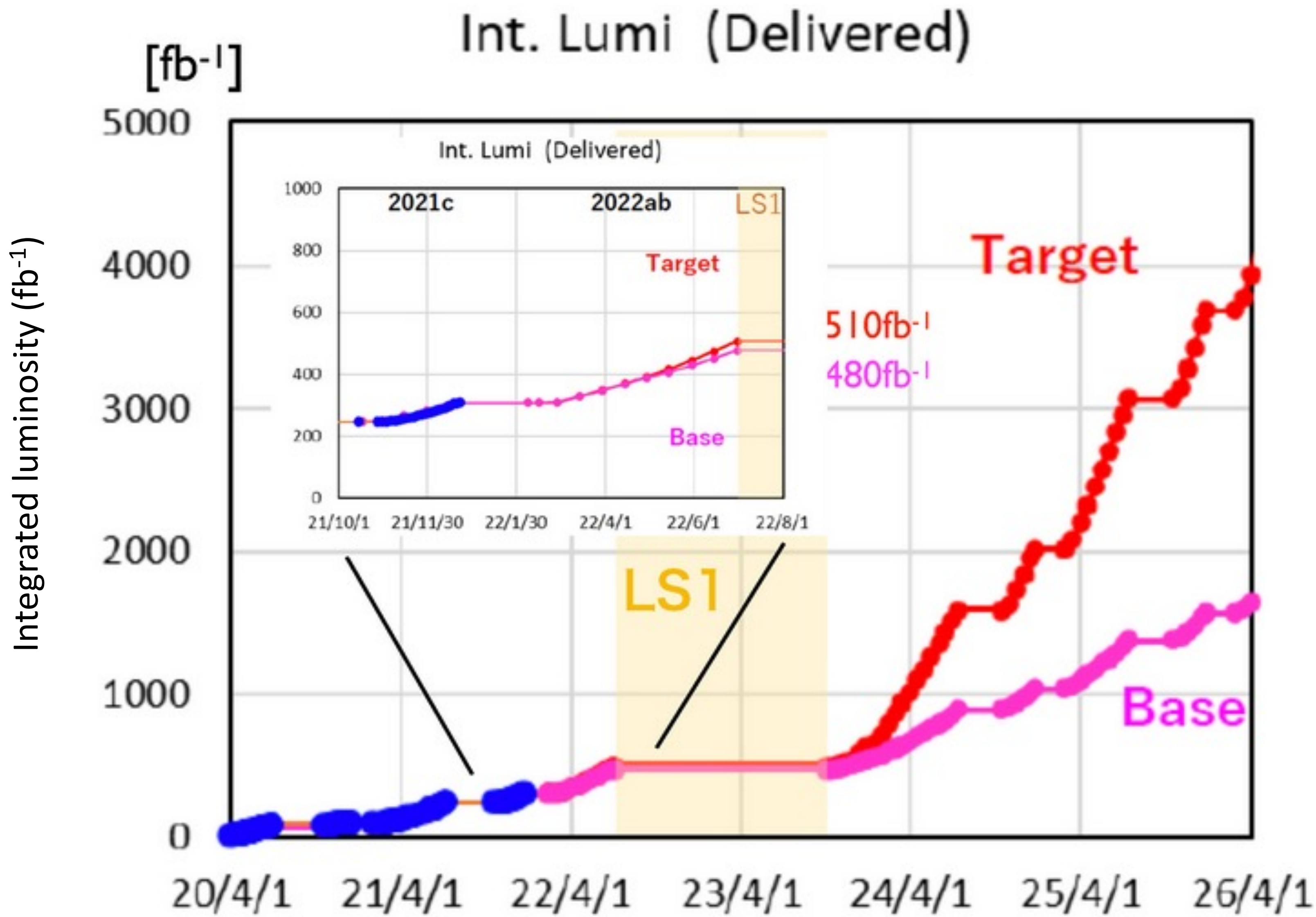
$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$$

[LHCb-CONF-2013-012] [CMS-PAS-BPH-13-007]

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9} \quad \mathrm{SM:} (3.2 \pm 0.2) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \to \mu^+\mu^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10} \quad \mathrm{SM:} (1.0 \pm 0.1) \times 10^{-10}$$

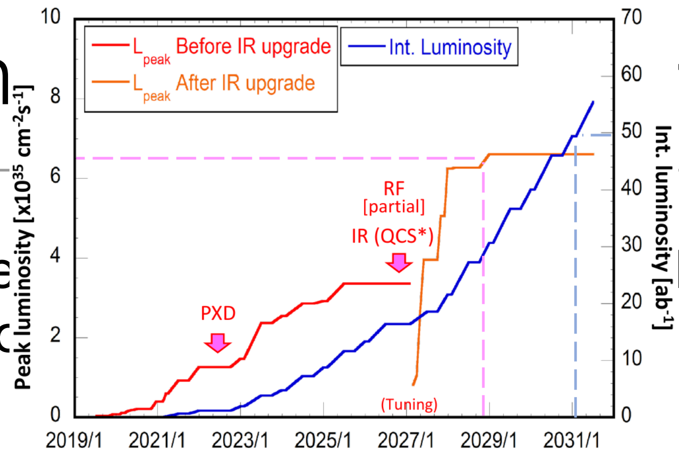
BELLE II

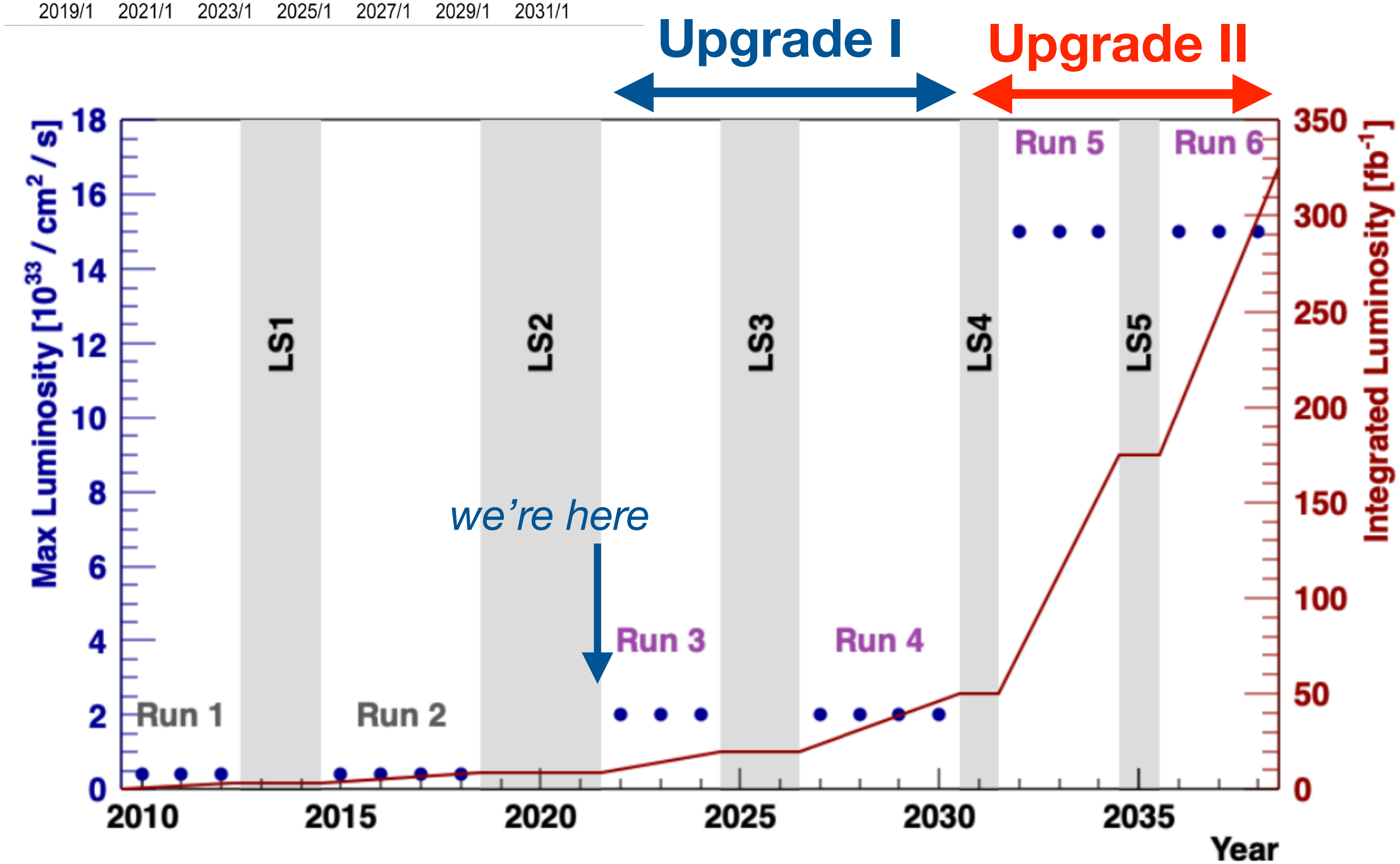


Int. Lumi (Delivered)
[fb-1]
Integrated luminosity (fb-1)
5000
4000
3000
2000
1000
0
20/4/1
21/4/1
22/4/1
23/4/1
24/4/1
25/4/1
26/4/1
LS1
Target
Base
510fb-1
480fb-1
Int. Lumi (Delivered)
1000
800
600
400
200
0
2021c
2022ab
LS1
Target
Base
21/10/1
21/11/30
22/1/30
22/4/1
22/6/1
22/8/1

“Movin … y”

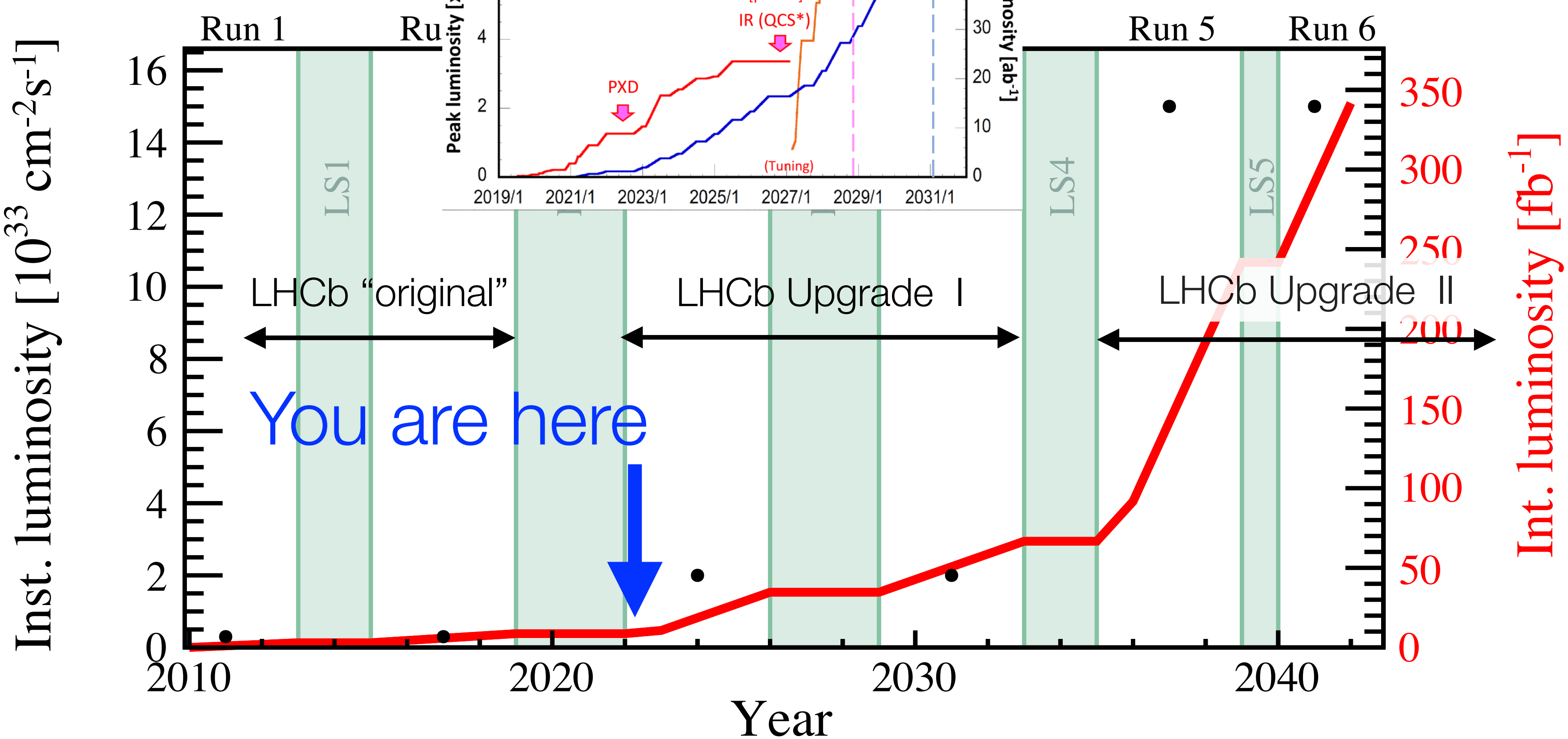
- We appe … blishing physics beyond the SM, and flavo … To understand what that NP is that lies … *measuring the heck out of flavour.*





Moving beyond discovery

- We appear to be on th… ics beyond the SM, and flavour is the mair… d what that NP is that lies beyond the SI… e *heck out of flavour.*



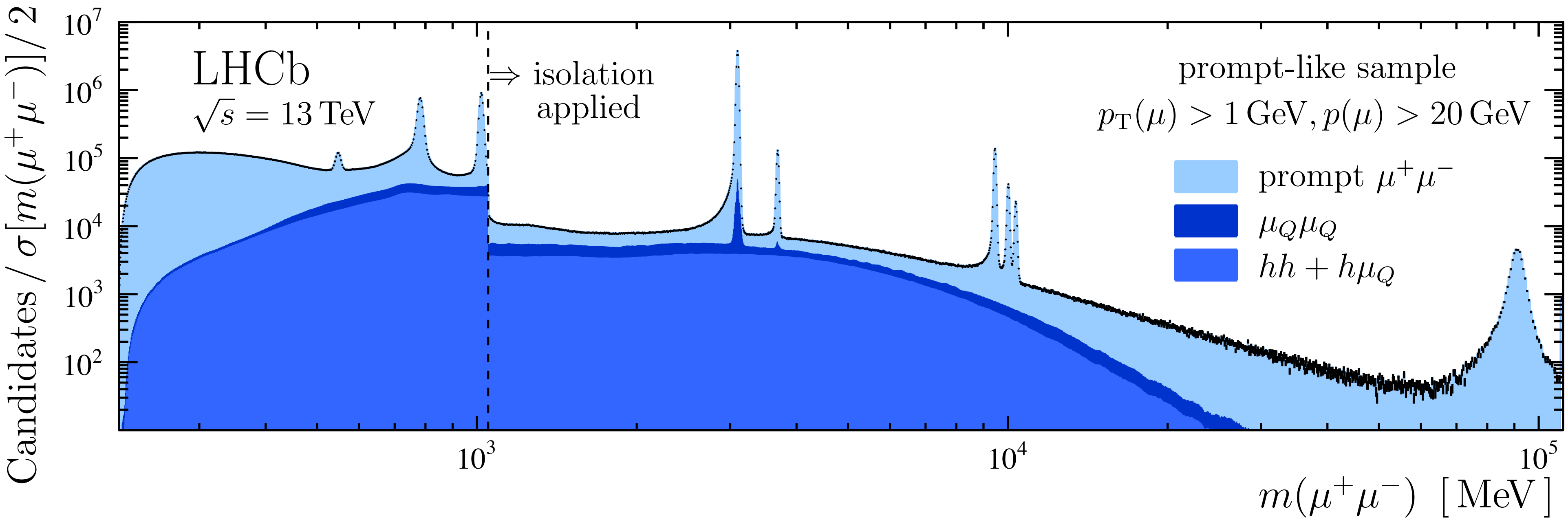
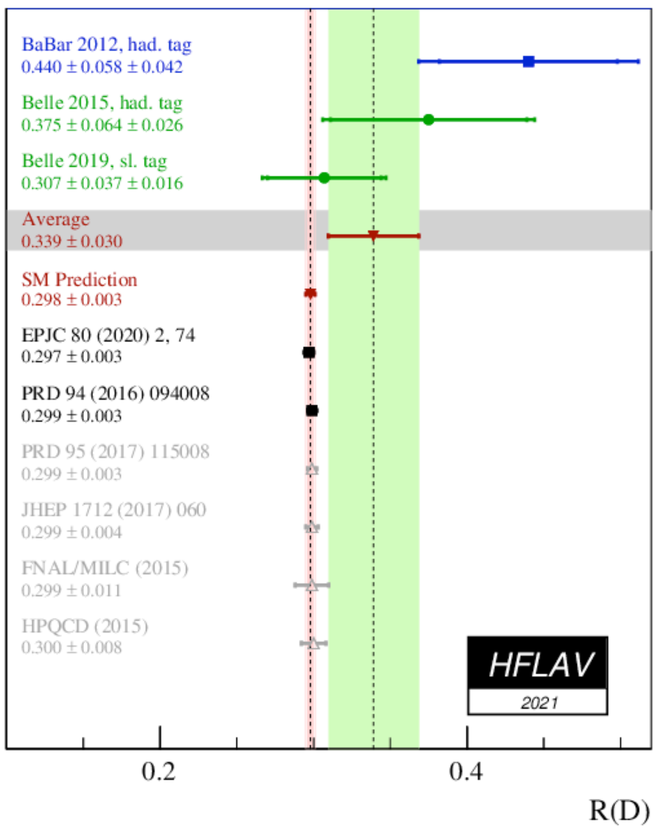
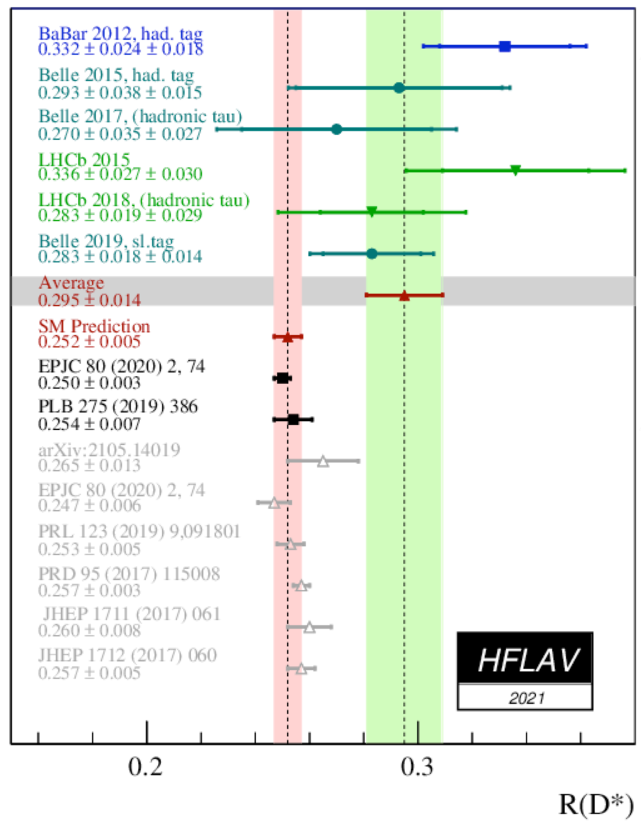
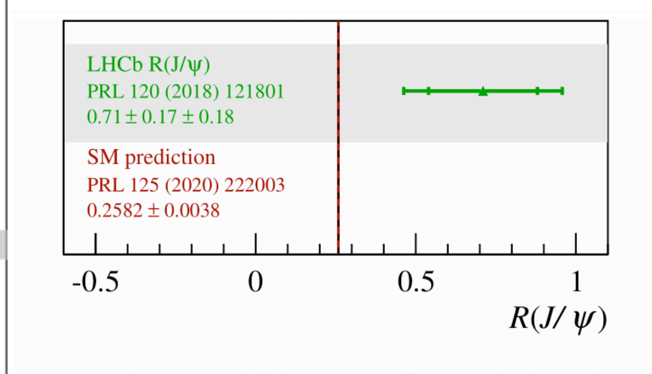
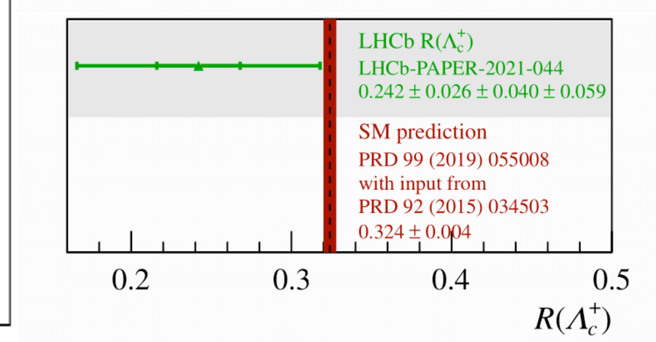


Figure A.1: Dimuon mass distrib. In the dark photon search at LHCb [446]. Note that the heavy-flavour background has been greatly suppressed.

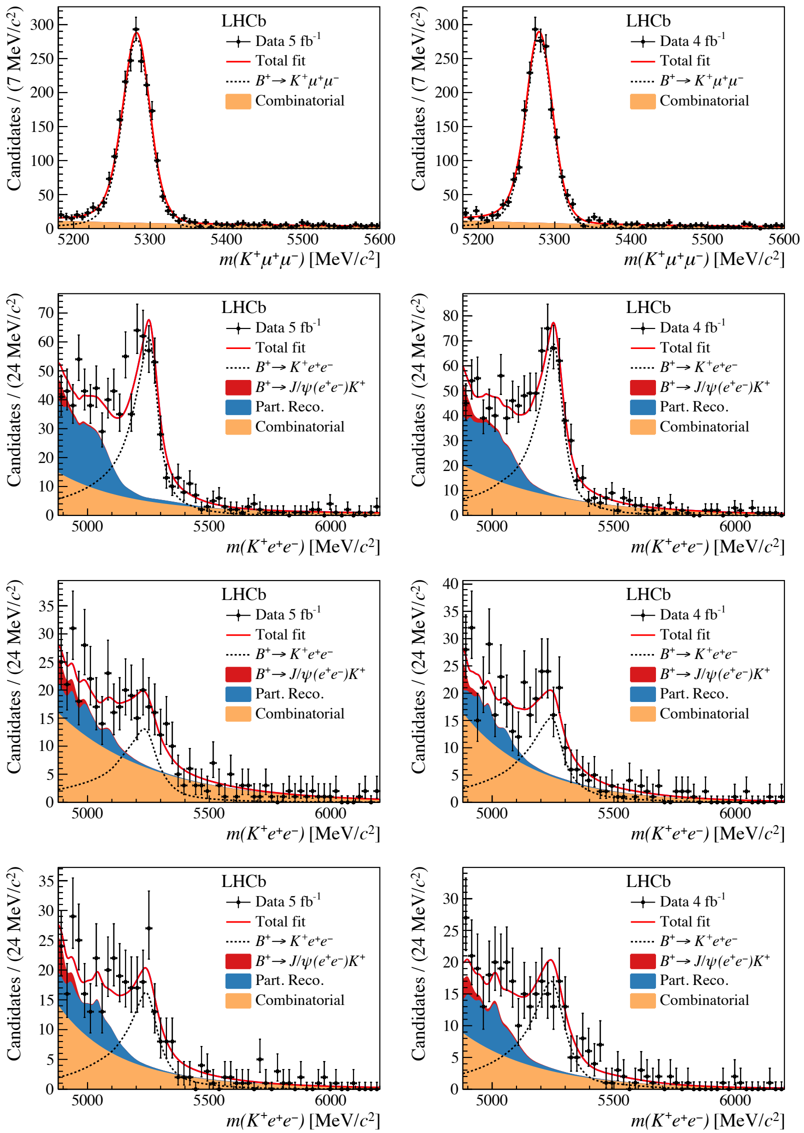

BaBar 2012, had. tag
0.440 ± 0.058 ± 0.042
Belle 2015, had. tag
0.375 ± 0.064 ± 0.026
Belle 2019, sl. tag
0.307 ± 0.037 ± 0.016
Average
0.339 ± 0.030
SM Prediction
0.298 ± 0.003
EPJC 80 (2020) 2, 74
0.297 ± 0.003
PRD 94 (2016) 094008
0.299 ± 0.003
PRD 95 (2017) 115008
0.299 ± 0.003
JHEP 1712 (2017) 060
0.299 ± 0.004
FNAL/MILC (2015)
0.299 ± 0.011
HPQCD (2015)
0.300 ± 0.008
HFLAV
2021
0.2
0.4
R(D)


BaBar 2012, had. tag
0.332 ± 0.024 ± 0.018
Belle 2015, had. tag
0.293 ± 0.038 ± 0.015
Belle 2017, (hadronic tau)
0.270 ± 0.035 ± 0.027
LHCb 2015
0.336 ± 0.027 ± 0.030
LHCb 2018, (hadronic tau)
0.283 ± 0.019 ± 0.029
Belle 2019, sl.tag
0.283 ± 0.018 ± 0.014
Average
0.295 ± 0.014
SM Prediction
0.252 ± 0.005
EPJC 80 (2020) 2, 74
0.250 ± 0.003
PLB 275 (2019) 386
0.254 ± 0.007
arXiv:2105.14019
0.265 ± 0.013
EPJC 80 (2020) 2, 74
0.247 ± 0.006
PRL 123 (2019) 9,091801
0.253 ± 0.005
PRD 95 (2017) 115008
0.257 ± 0.003
JHEP 1711 (2017) 061
0.260 ± 0.008
JHEP 1712 (2017) 060
0.257 ± 0.005
HFLAV
2021
0.2
0.3
R(D*)


LHCb R(J/ψ)
PRL 120 (2018) 121801
0.71 ± 0.17 ± 0.18
SM prediction
PRL 125 (2020) 222003
0.2582 ± 0.0038
-0.5
0
0.5
1
$R(J/\psi)$

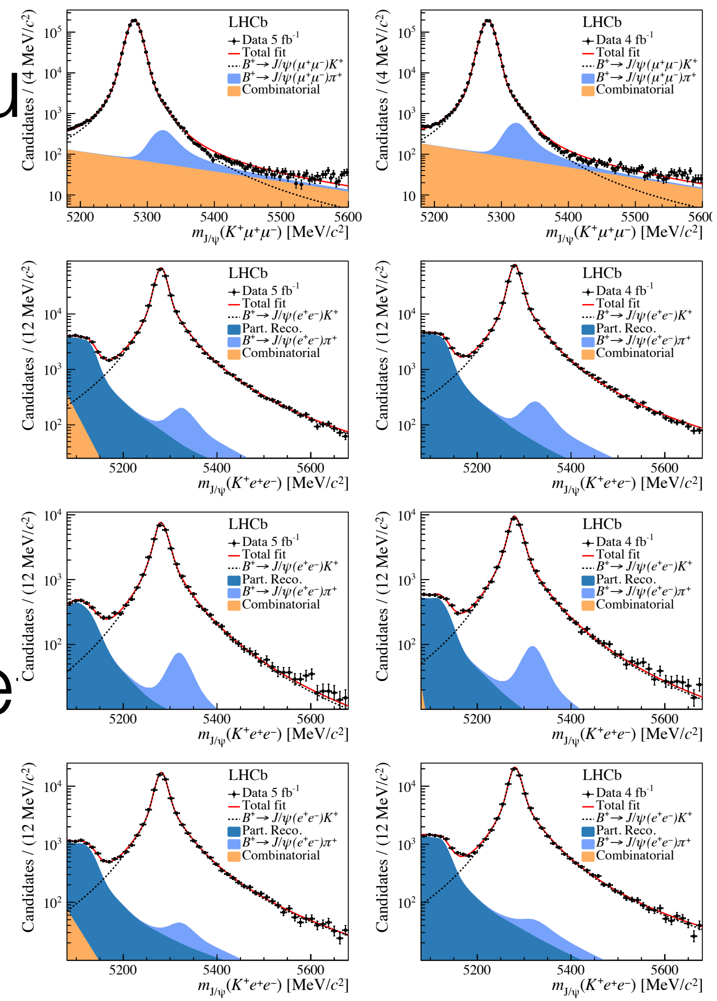

LHCb $R(\Lambda_c^+)$
LHCb-PAPER-2021-044
0.242 ± 0.026 ± 0.040 ± 0.059
SM prediction
PRD 99 (2019) 055008
with input from
PRD 92 (2015) 034503
0.324 ± 0.004
0.2
0.3
0.4
0.5
$R(\Lambda_c^+)$

B→Kμ⁺μ⁻ vs B→Ke⁺e⁻



B→Kμ⁺μ

B→Ke



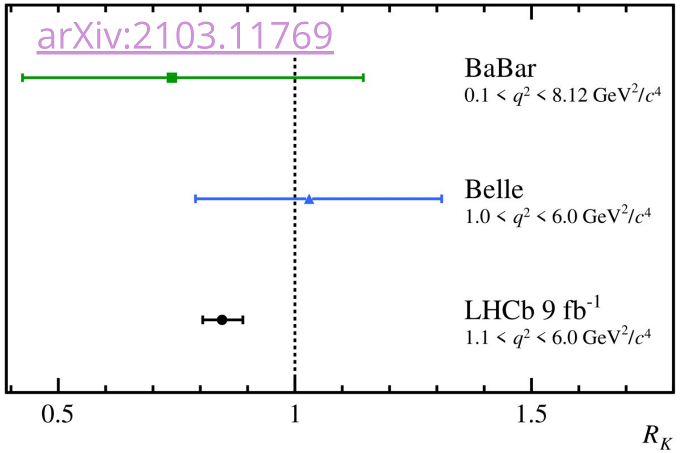
Summary & conclusions

See talk by D. van Dyk and recent Anomaly WS for interpretation of results

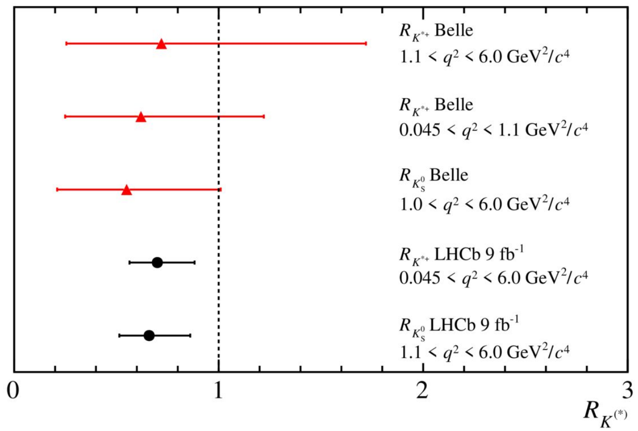
Rare b → sll decays provide stringent tests of NP

Recent results hint at breaking of LFU in b → sll

arXiv:2103.11769



arXiv:2110.09501



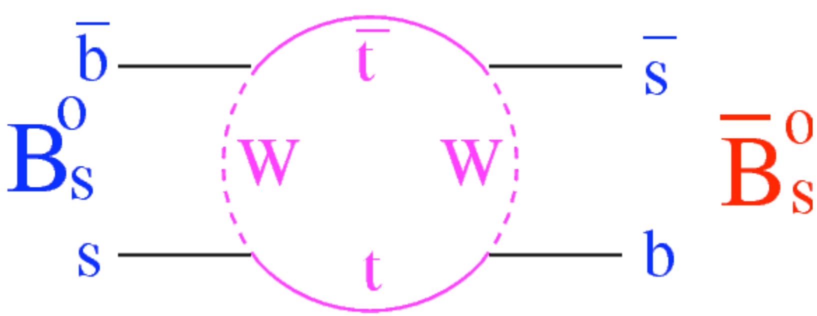
New J.Phys. 15 (2013) 053021

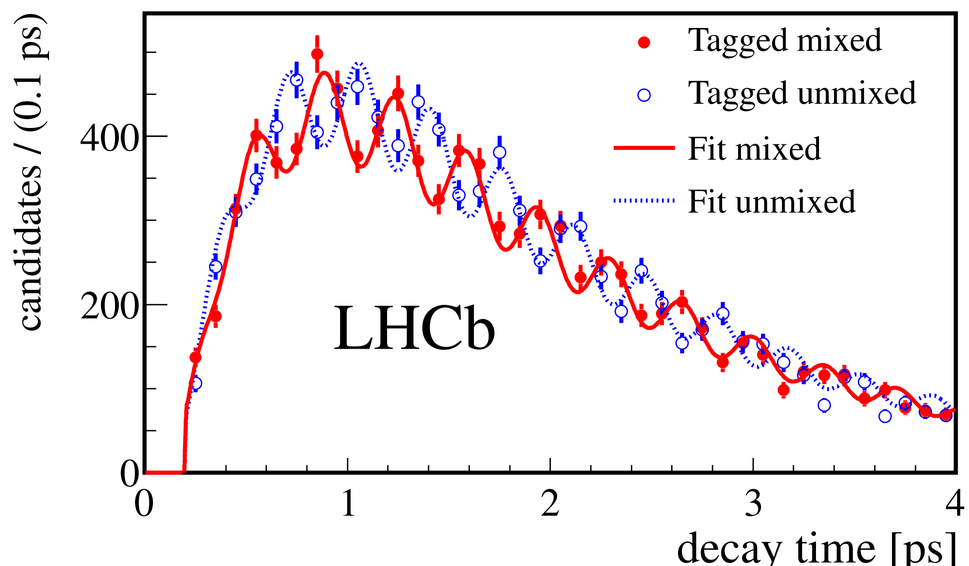
B_s Oscillations

(1st observed by CDF, Phys.Rev.Lett. 97 (2006) 062003, Phys.Rev.Lett. 97 (2006) 242003.)

- the Bs mixing plot and result

B_s oscillations at LHCb





$$\Delta m_s = 17.768 \pm 0.023 \pm 0.006 \;\; ps^{-1}$$

world's most precise measurement of Δm_s

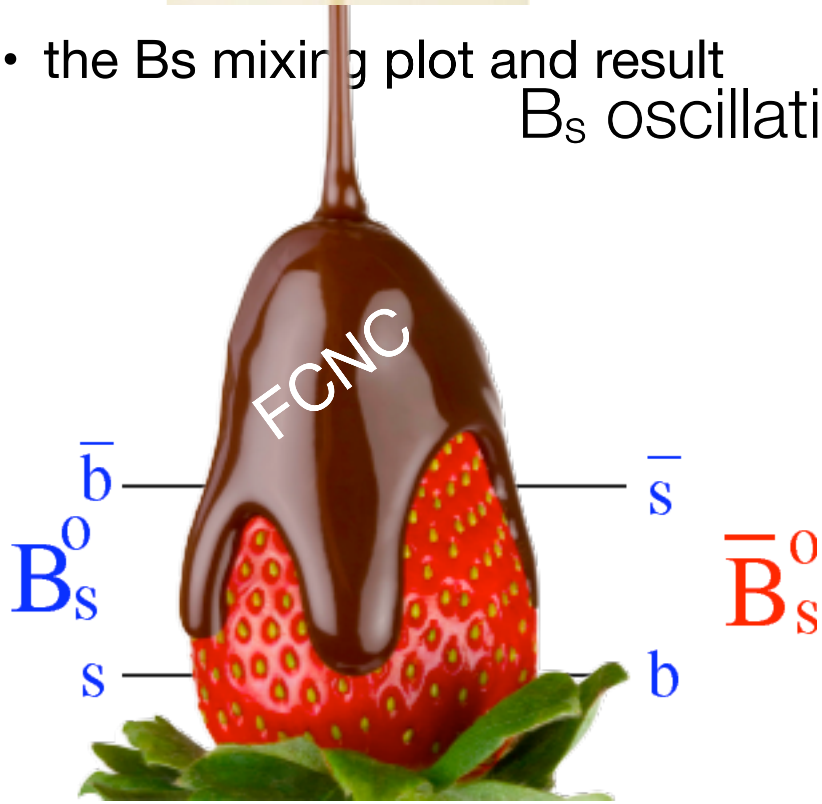
Bs O

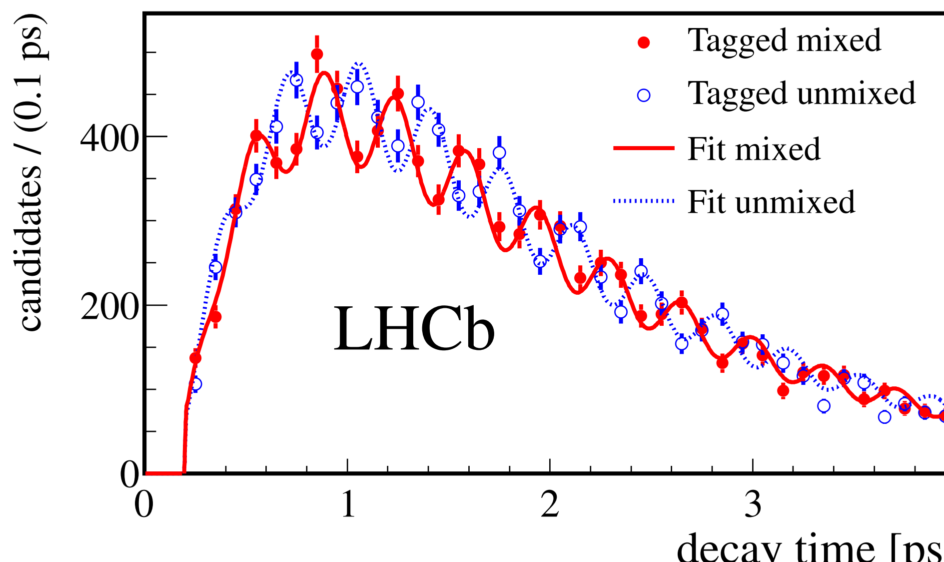
New J.Phys. 15 (2013) 053021

(1st observed by CDF, Phys.Rev.Lett. 97 (2006) 062003, Phys.Rev.Lett. 97 (2006) 242003.)

- the Bs mixing plot and result

Bs oscillations at LHCb





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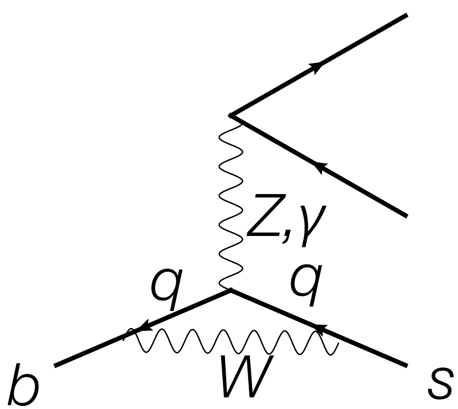
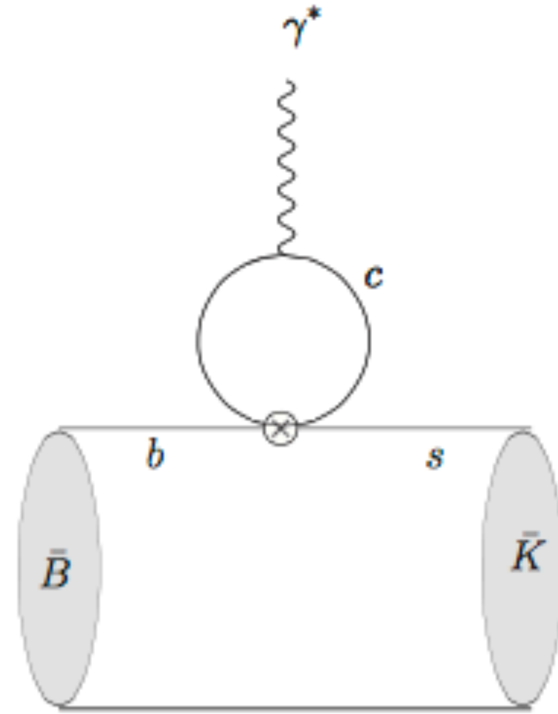
Charm loops





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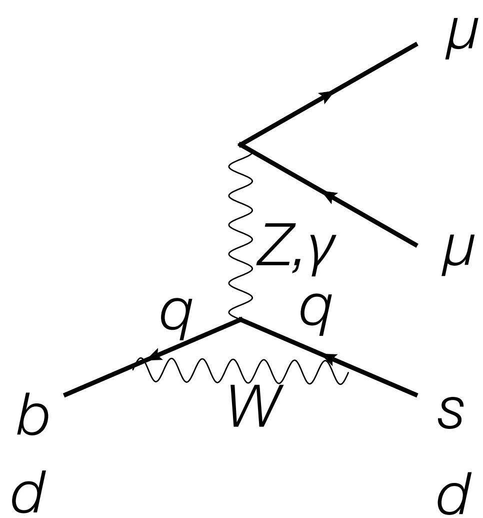

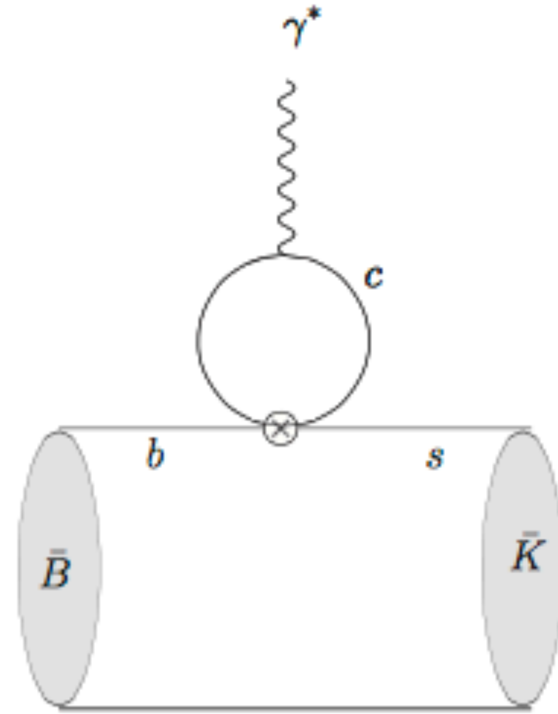

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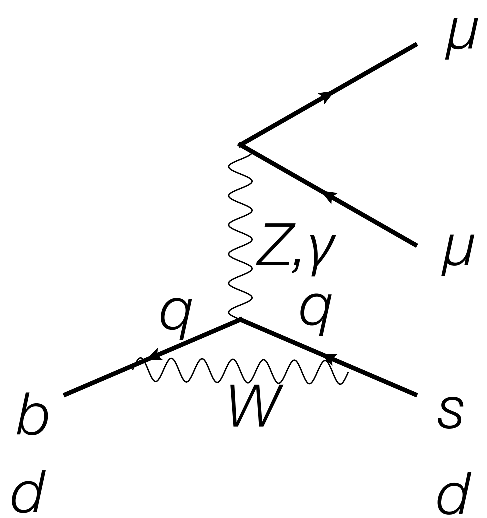
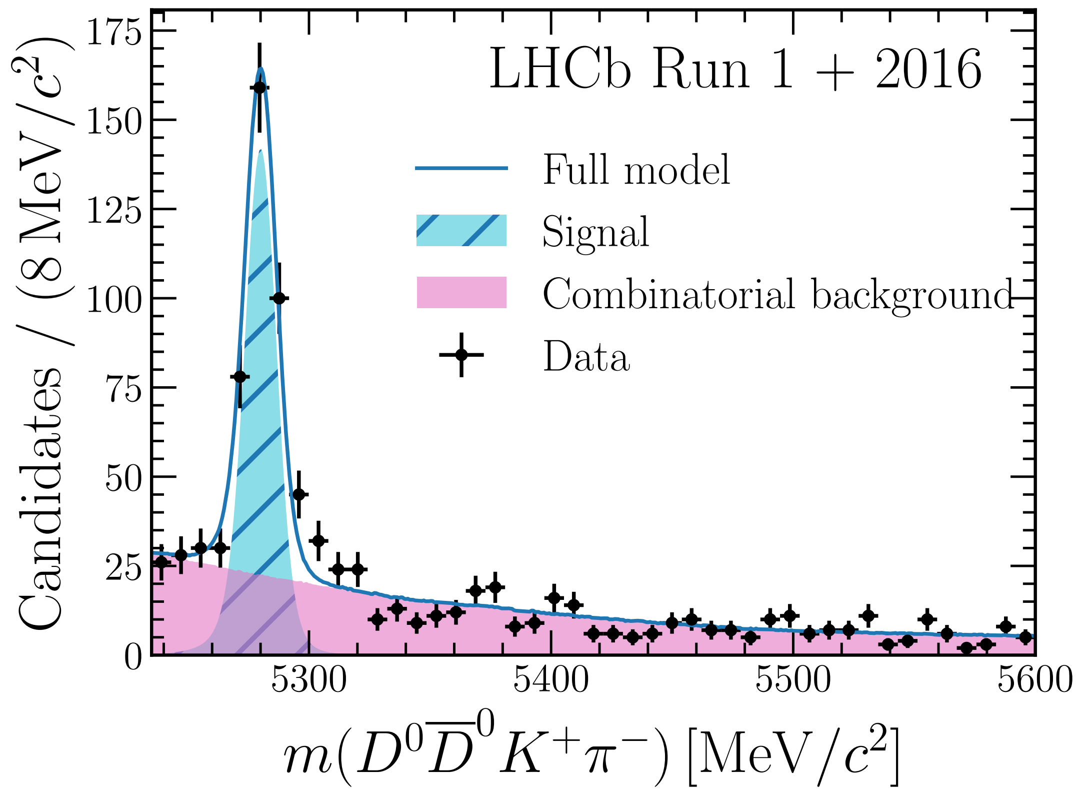




First observation of the decay: Phys.Rev.D 102 (2020) 5, 051102

A selected list NP-sensitive flavour variables

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [244, 258]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Eur.Phys.J. C73 (2013) 2373

A selected list NP-sensitive flavour variables

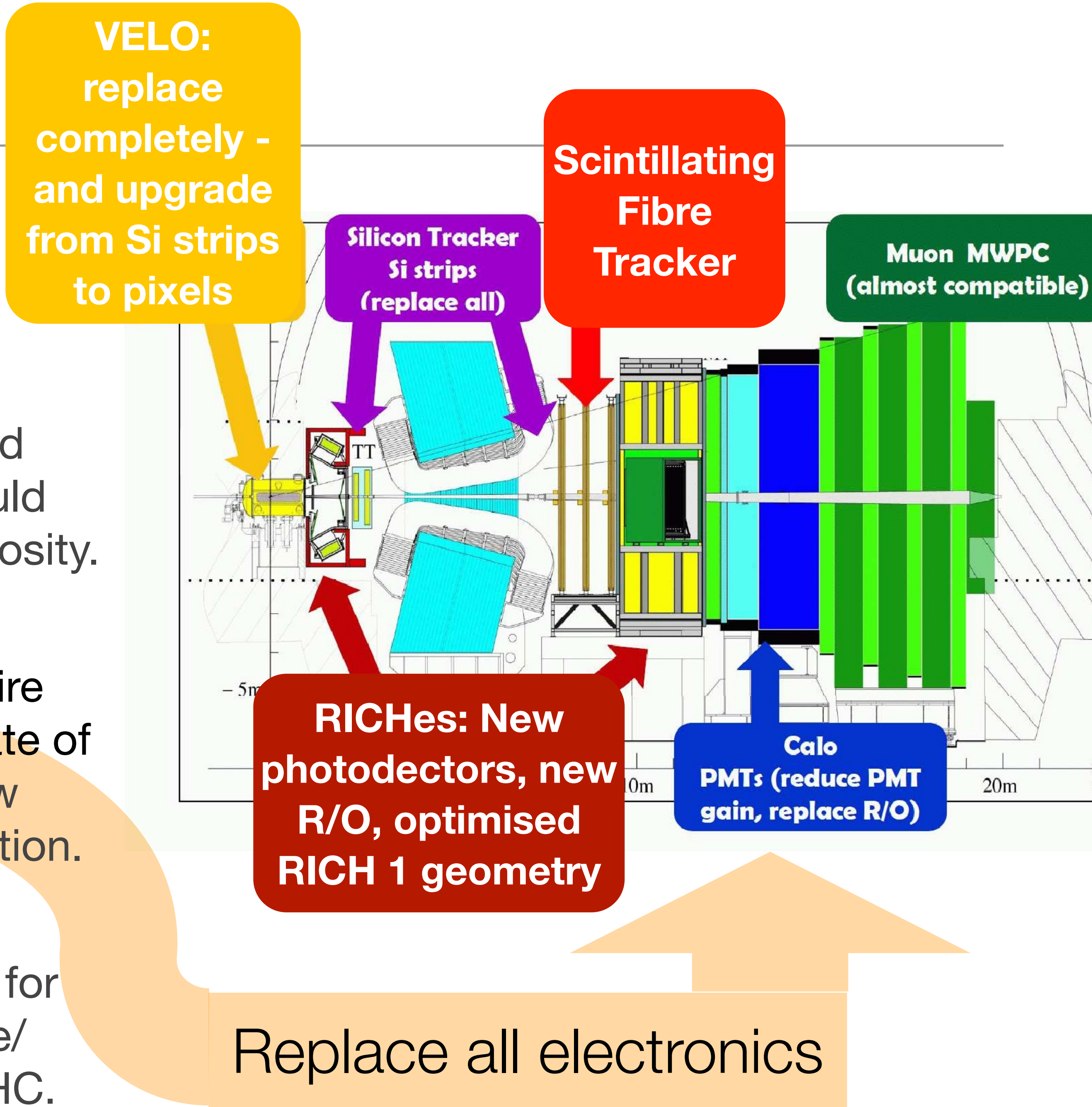
Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing					~ 0.003
					~ 0.01
					0.03×10^{-3}
Gluonic penguins					0.02
					< 0.02
					0.02
Right-handed currents					< 0.01
					$0.2\,\%$
Electroweak penguins					0.02
					$7\,\%$
					~ 0.02
					$\sim 10\,\%$
Higgs penguins					0.3×10^{-9}
					$\sim 5\,\%$
Unitarity triangle angles					negligible
					negligible
					negligible
Charm CP violation					–
					–

- Plenty of theoretically clean channels with high sensitivity and discriminating power for New Physics models
- Theoretical uncertainties in many cases far better than current experimental sensitivity (and improving).
- Lots of room for New Physics to hide - and opportunity to find it!
- Need (even) better experimental precision to fully exploit flavour physics' sensitivity to physics beyond the SM.

Eur.Phys.J. C73 (2013) 2373

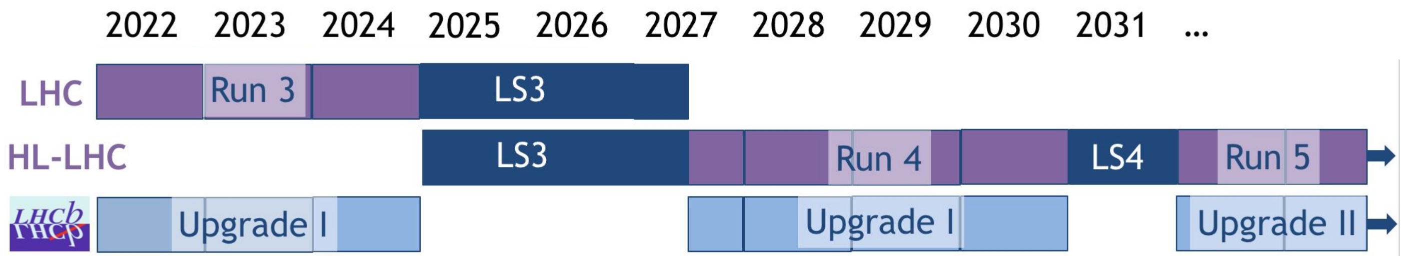
The LHCb upgrade

- Higher luminosity ⟹ higher precision ⟹ better NP reach.
- Trigger is at the heart of the upgrade. Current trigger would "choke", the signal yields would not increase in line with luminosity.
- For upgrade, read out the entire detector at bunch-crossing rate of 40MHz, fully customisable s/w trigger, with full event information.
- Doubles the trigger efficiency for hadronic modes. Most flexible/ customisable trigger at the LHC.

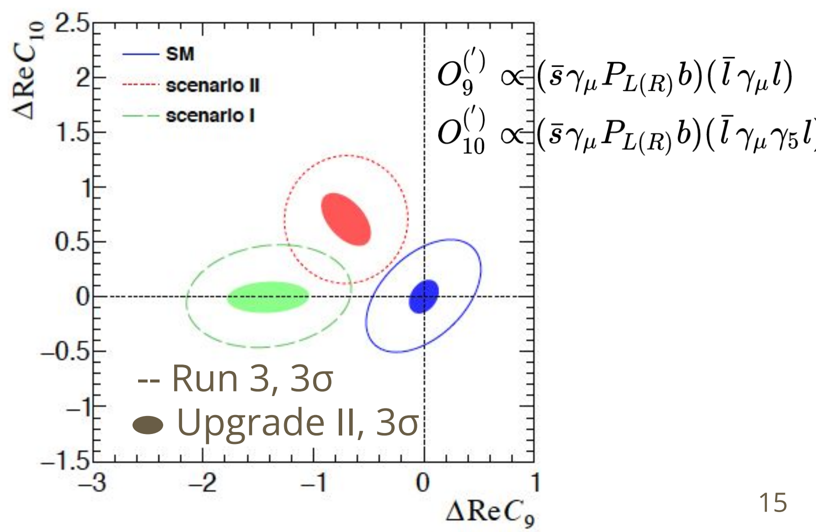


LHCB-PUB-2018-009

Future prospects for LFU tests at LHCb

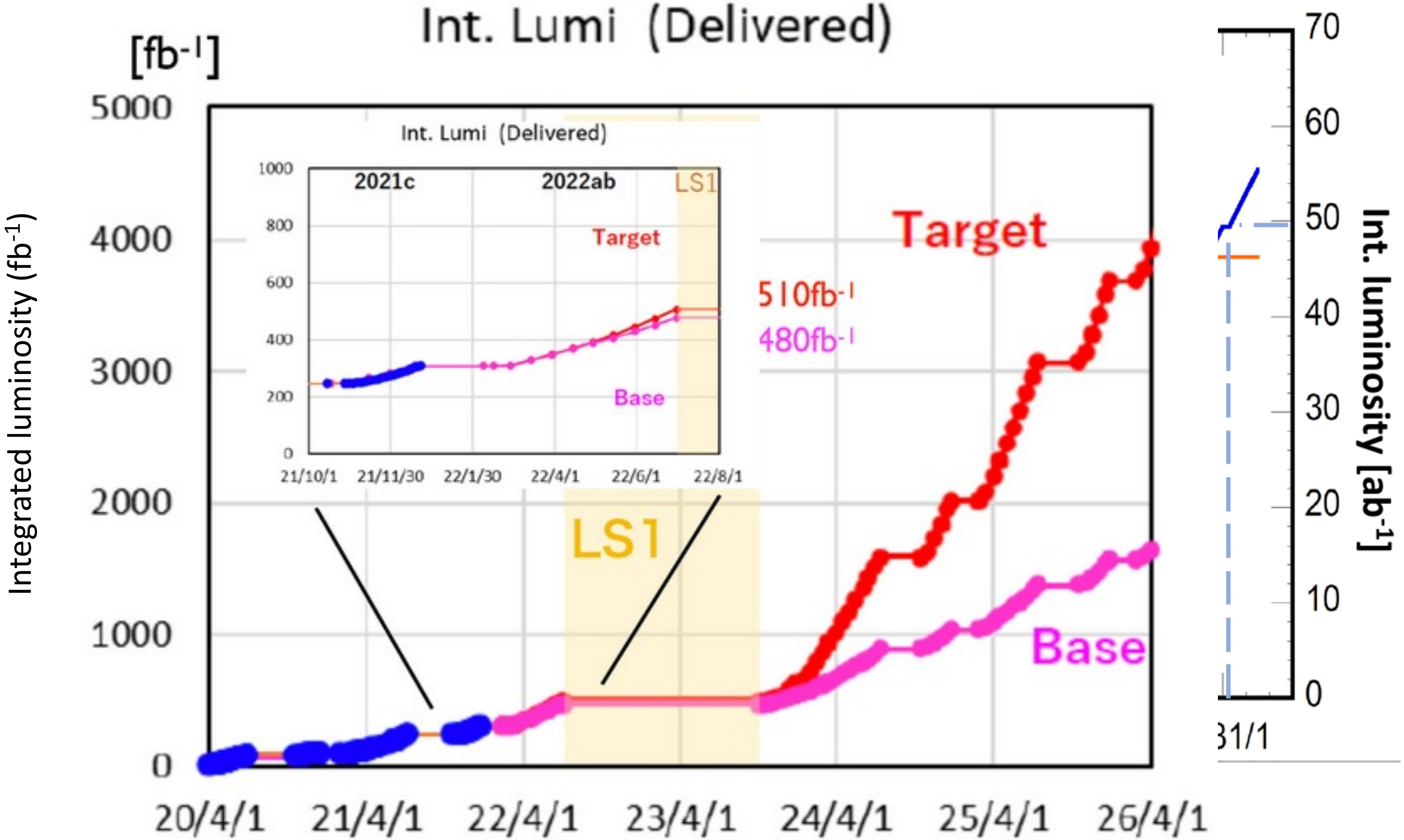


		Run 3	Run 4	Upgrade II
R_X precision	$9\,\text{fb}^{-1}$	$23\,\text{fb}^{-1}$	$50\,\text{fb}^{-1}$	$300\,\text{fb}^{-1}$
R_K	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	0.052	0.031	0.020	0.008
R_ϕ	0.130	0.076	0.050	0.020
R_{pK}	0.105	0.061	0.041	0.016
R_π	0.302	0.176	0.117	0.047

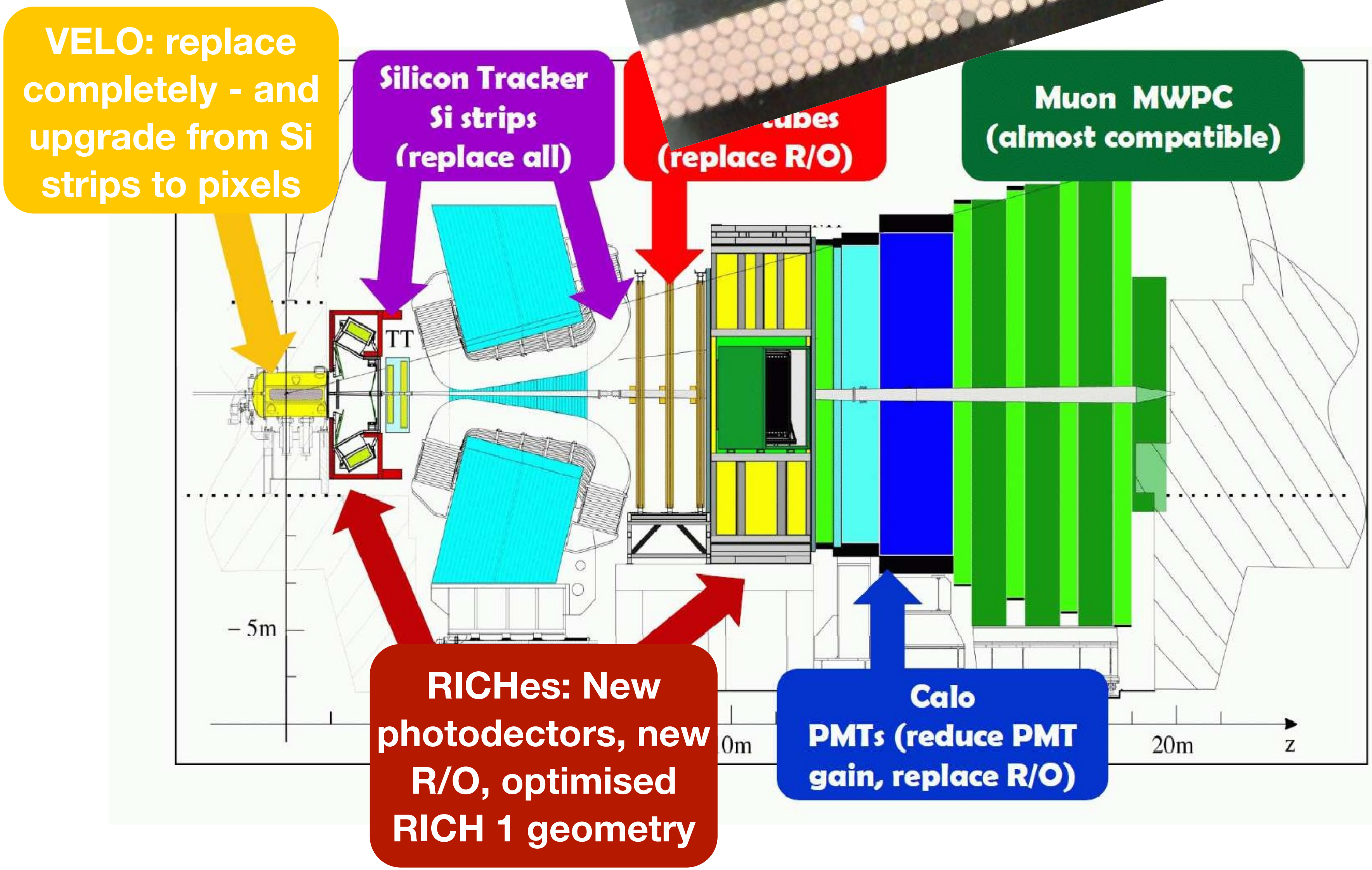


15

BELLE II plans ICHEP 2020 vs now



Changing the trigger is not all.



CP violation and New Physics

- While there is O(10%) agreement between the SM description of CP violation, and recent measurements, there are several orders of magnitude disagreement between CPV in the SM and CPV in the universe.

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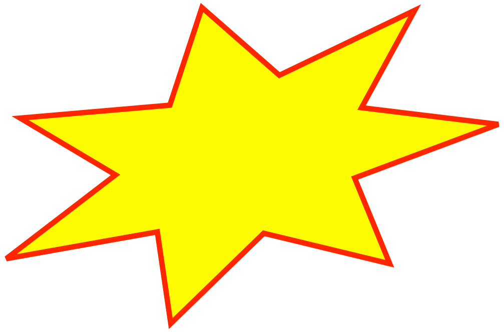

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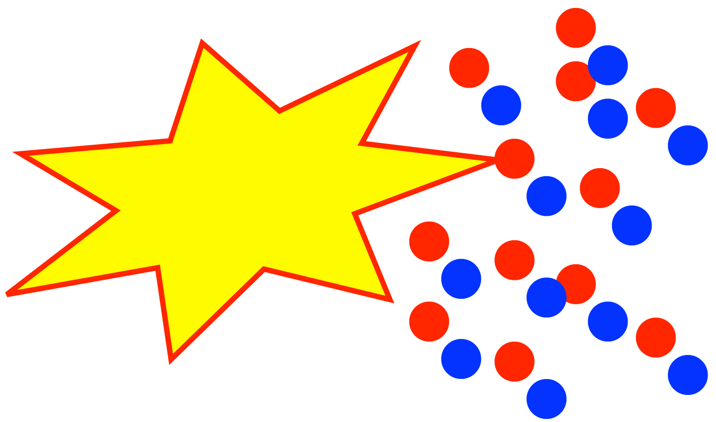

equal amounts of
matter and
antimatter

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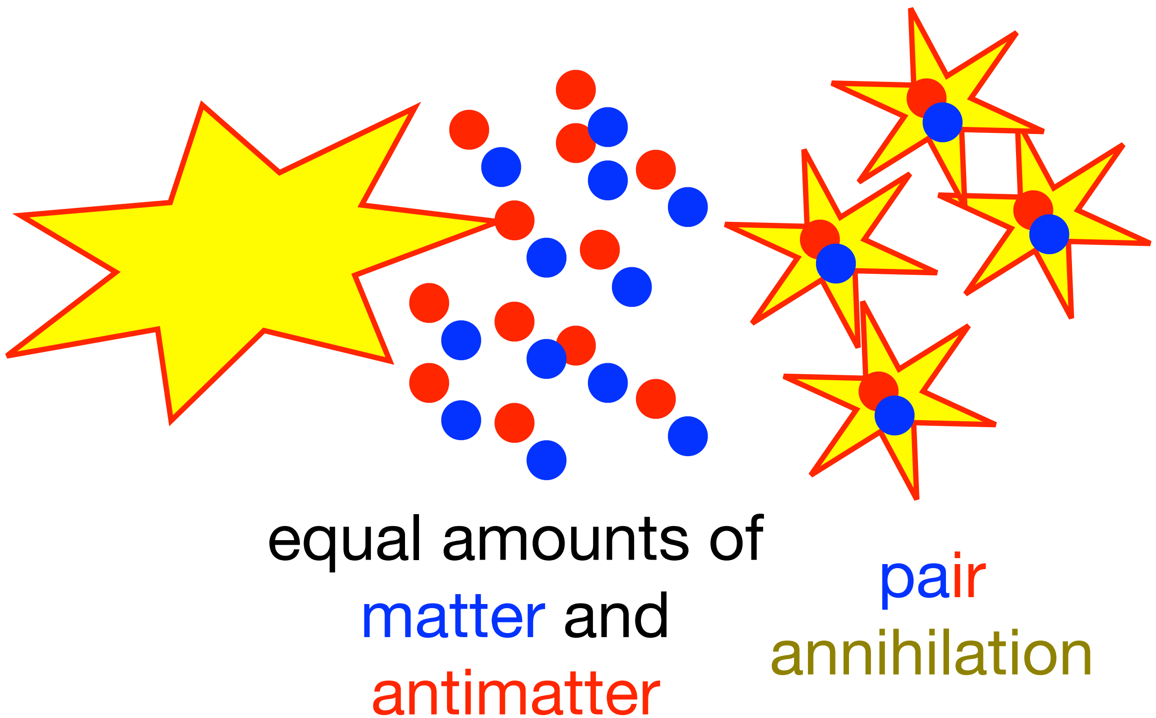

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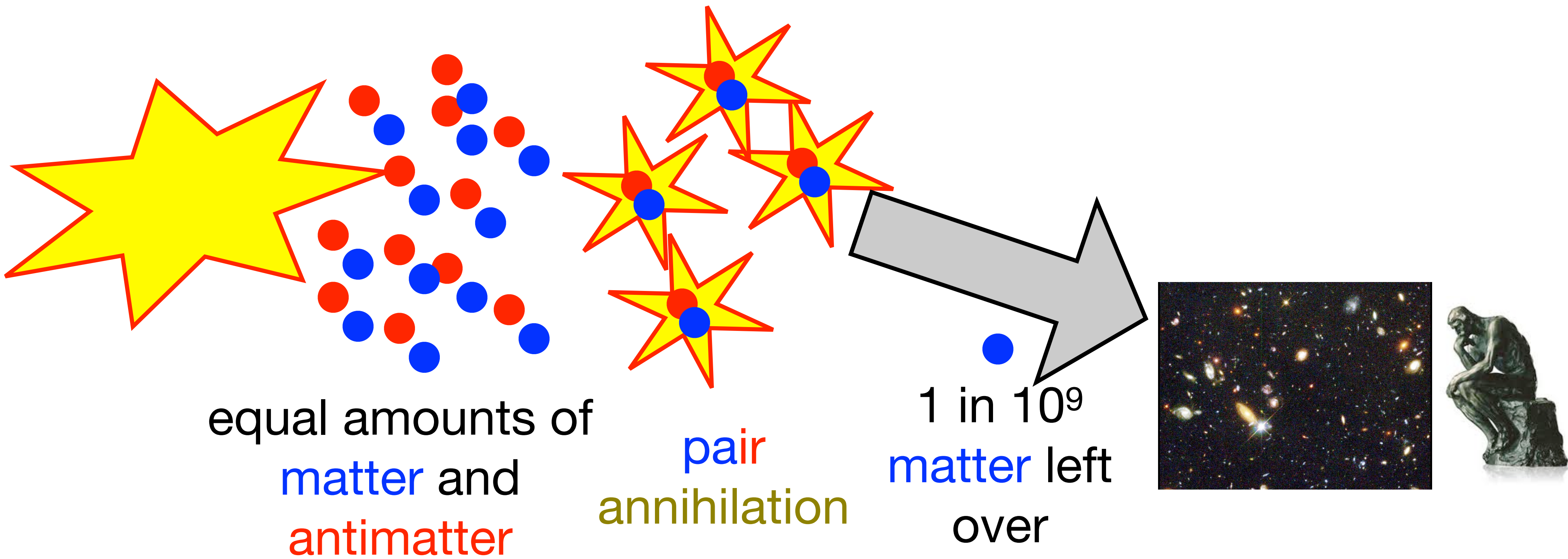

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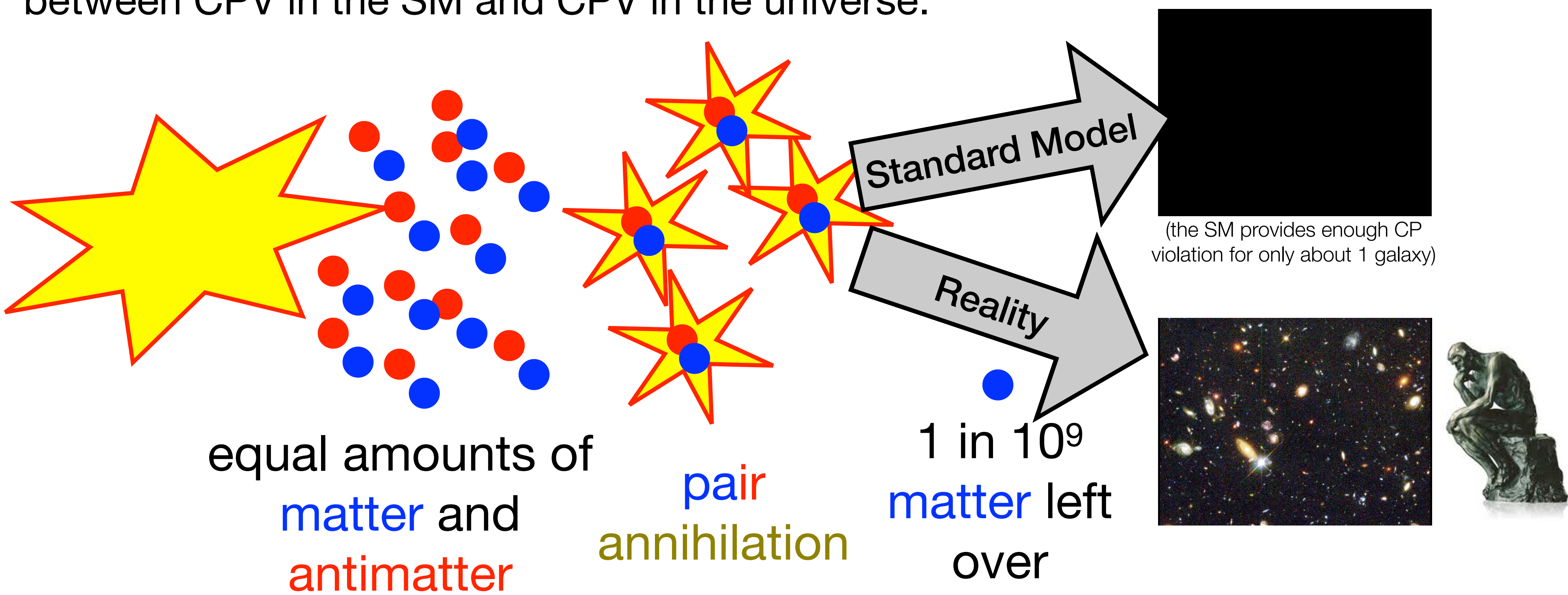

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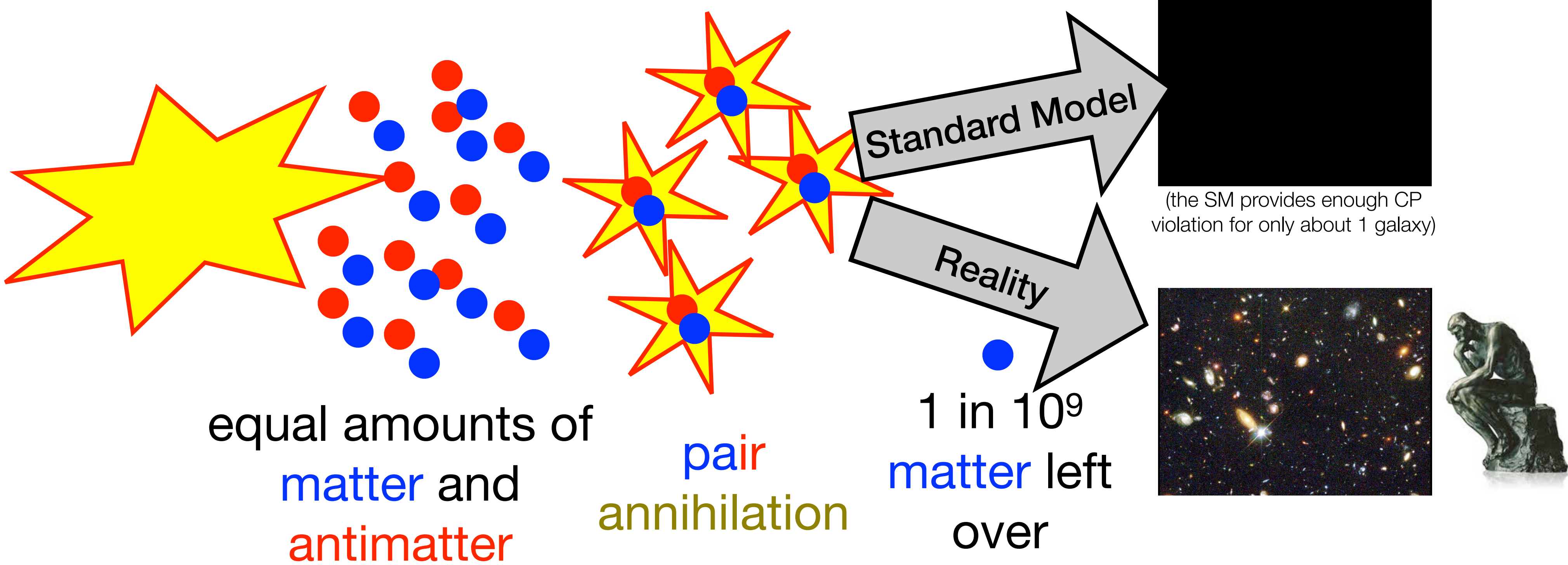

- There must be new sources of CP violation.

How Precise is Precise enough?

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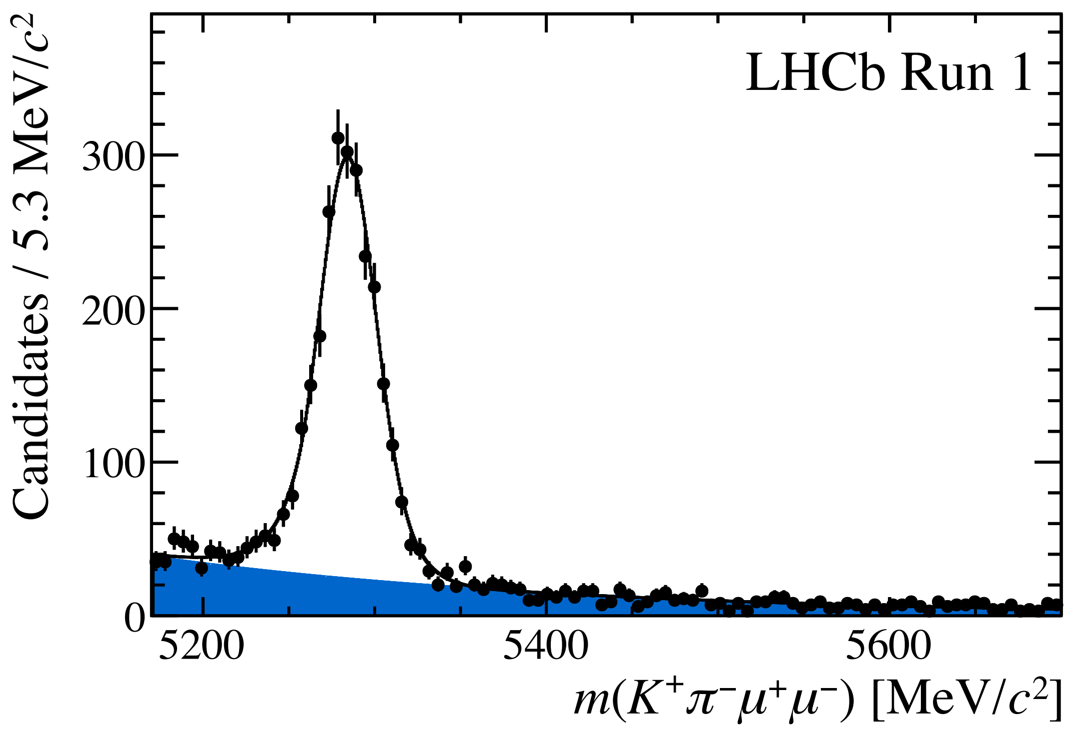
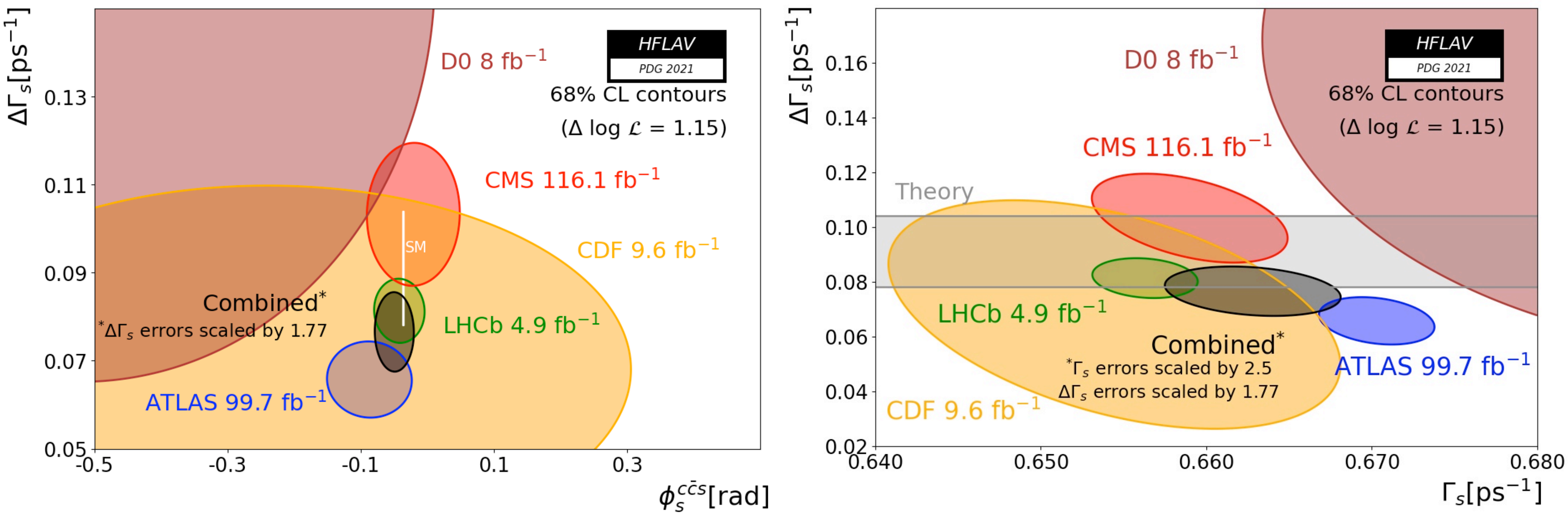
- We need to identify theoretically clean measurements with high sensitivity and discriminating power for New Physics models.

Flavour anomalies

$$B^0 \to K^* \mu^+ \mu^-,$$

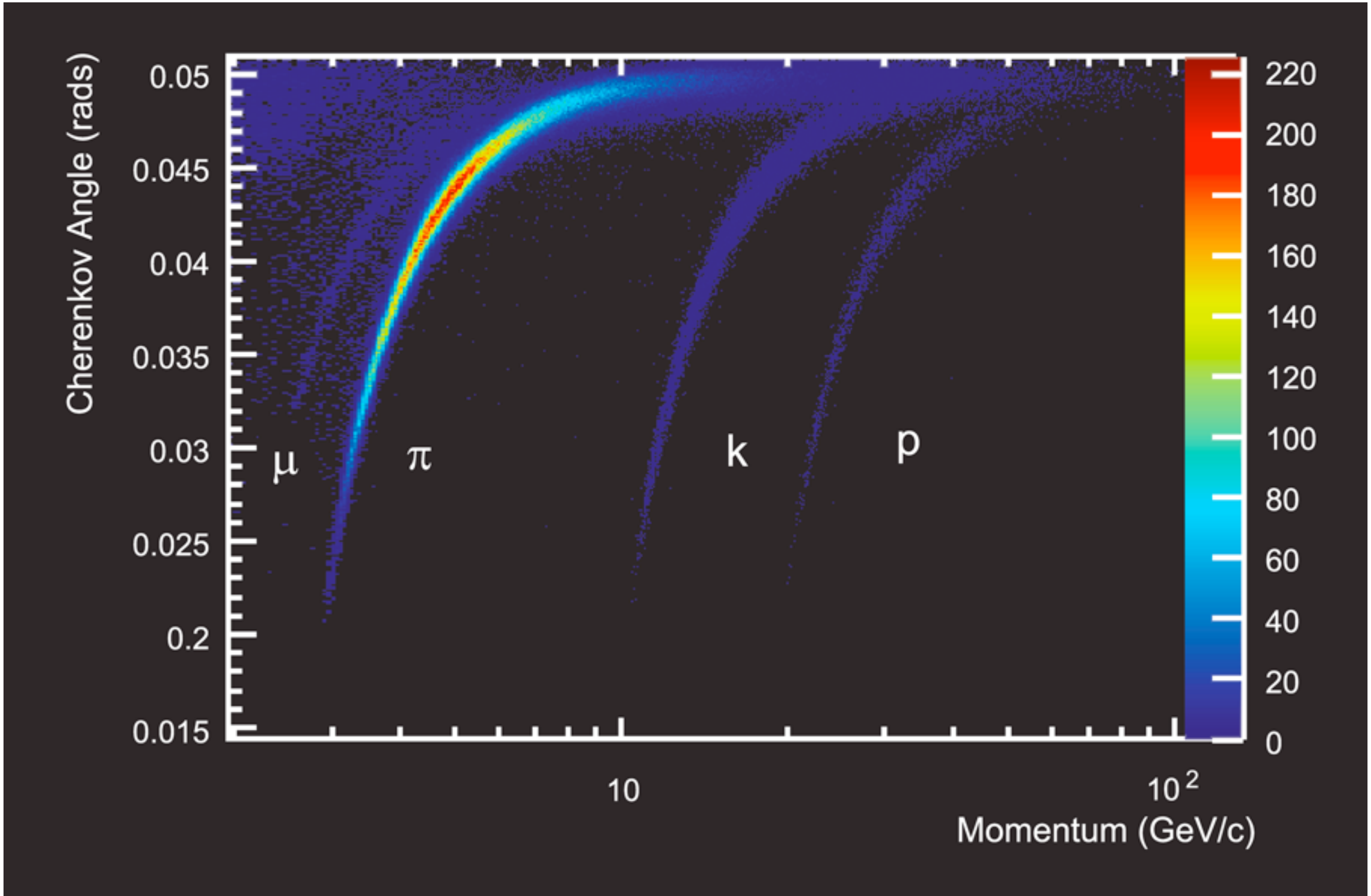




ATLAS result at: https://arxiv.org/abs/2001.07115

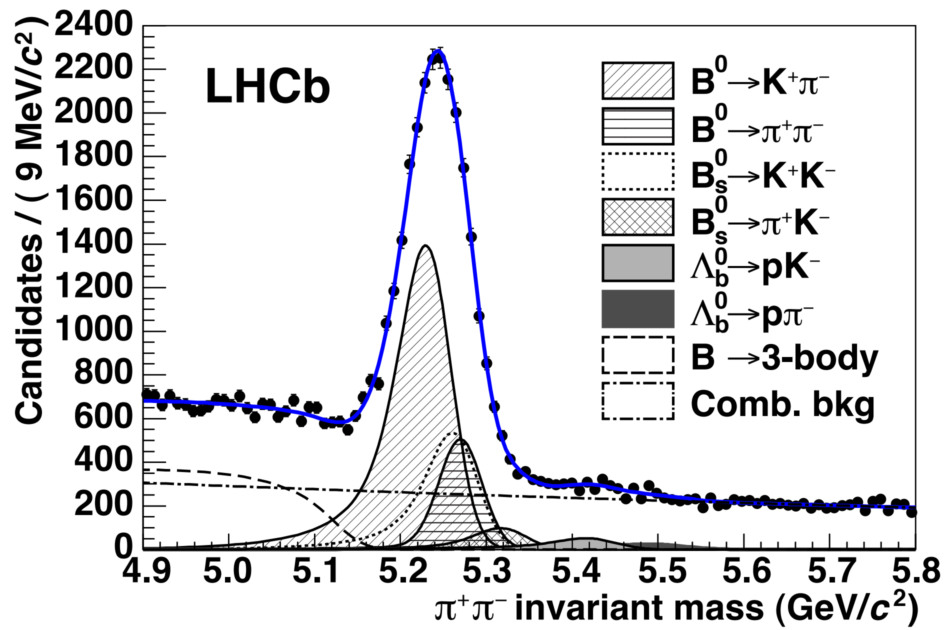
Particle ID with the LHCb RICH

LHCb: EPJ C 73:2431 (2013)



LHCb RICH particle ID in action

LHCb: JHEP 1210 (2012) 037



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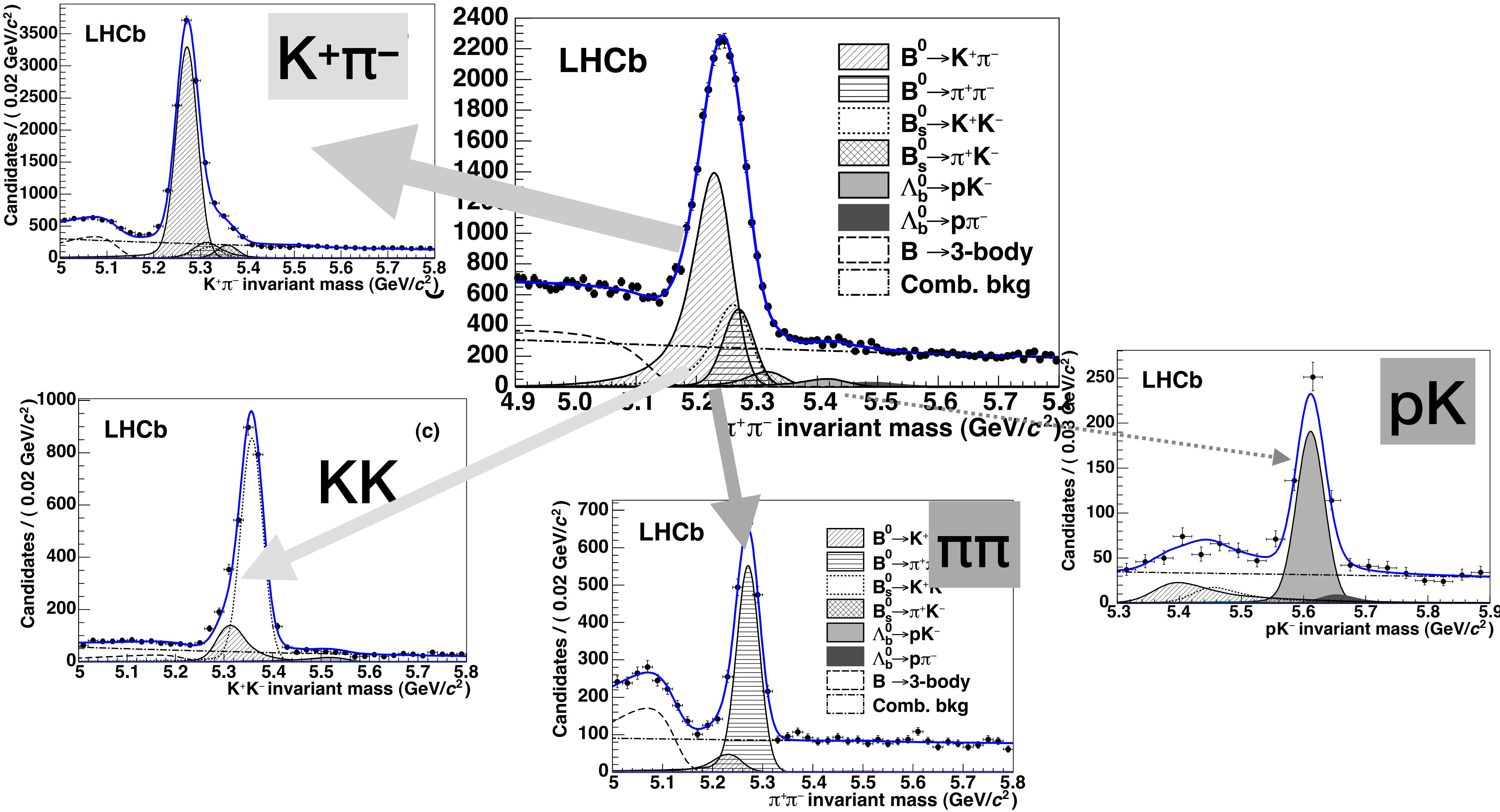

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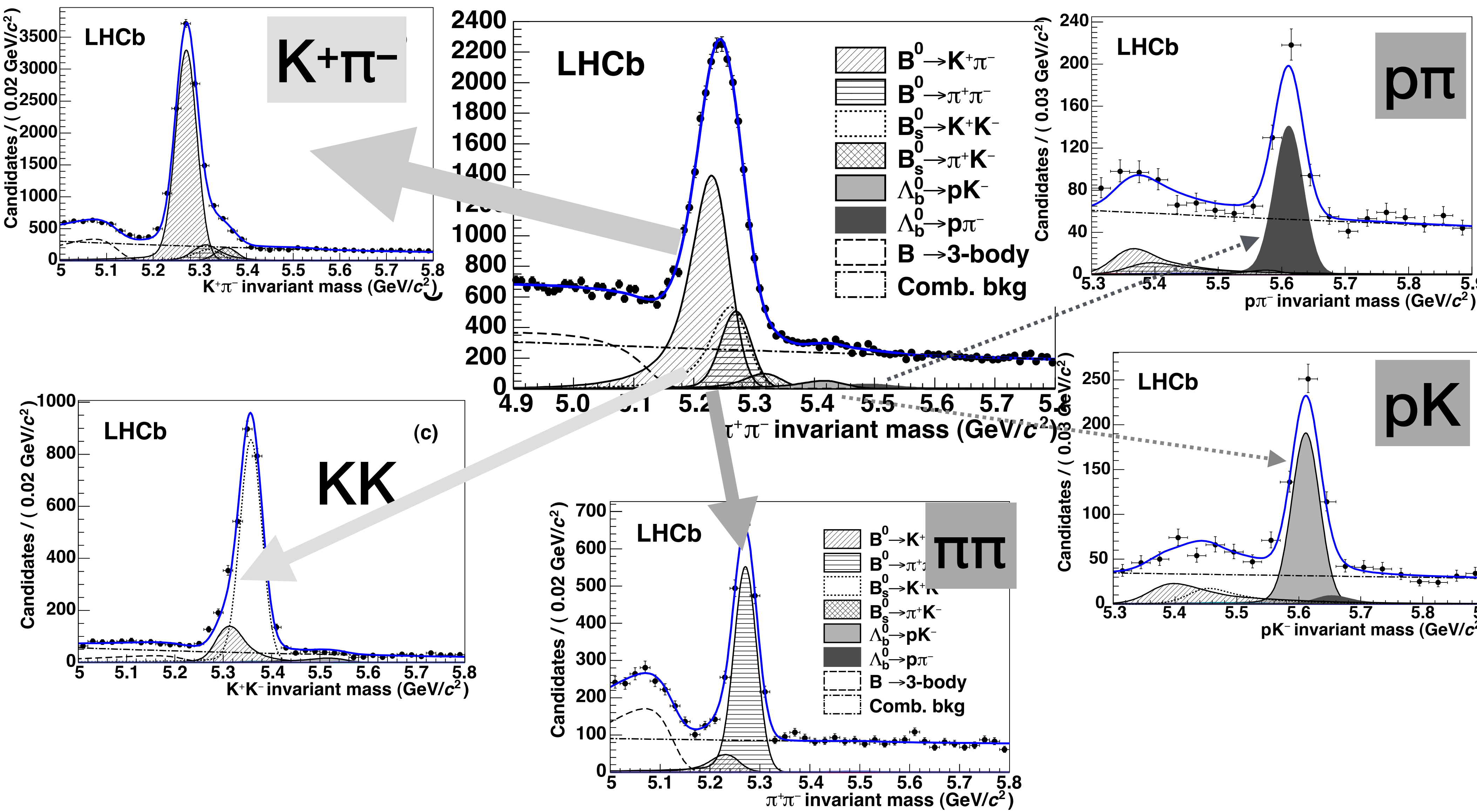


Pentaquarks 2006

PENTAQUARK UPDATE

Written February 2006 by G. Trilling (LBNL).

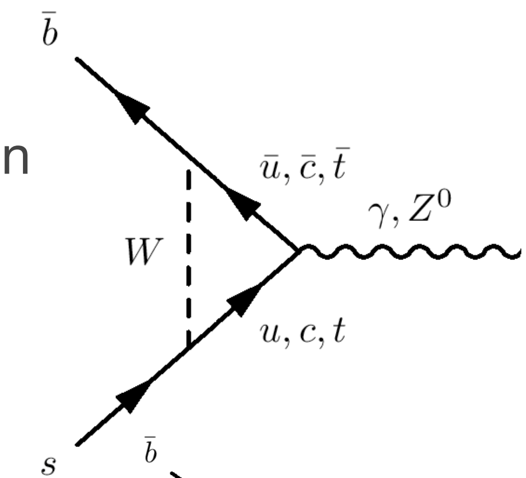
To summarize, with the exception described in the previous paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^+; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling.

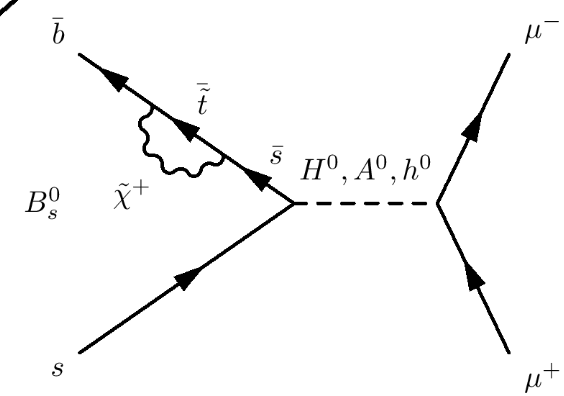
FCNC and New Physics

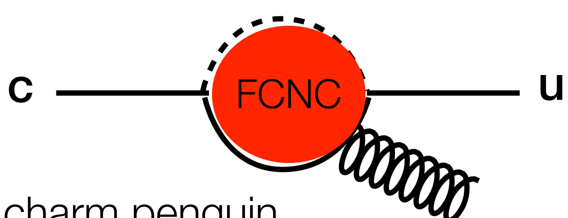
- The suppression of FCNC is an “accidental” symmetry of the SM. There is no fundamental reason why it should persist in models beyond the SM.

- $\Longrightarrow$ High sensitivity to New Physics
  Low “Standard Model background”.

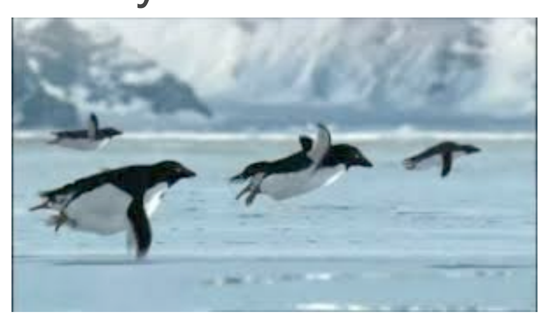
- Note that NP can affect FCNC in up and down-type quarks differently. Study both, beauty & charm!







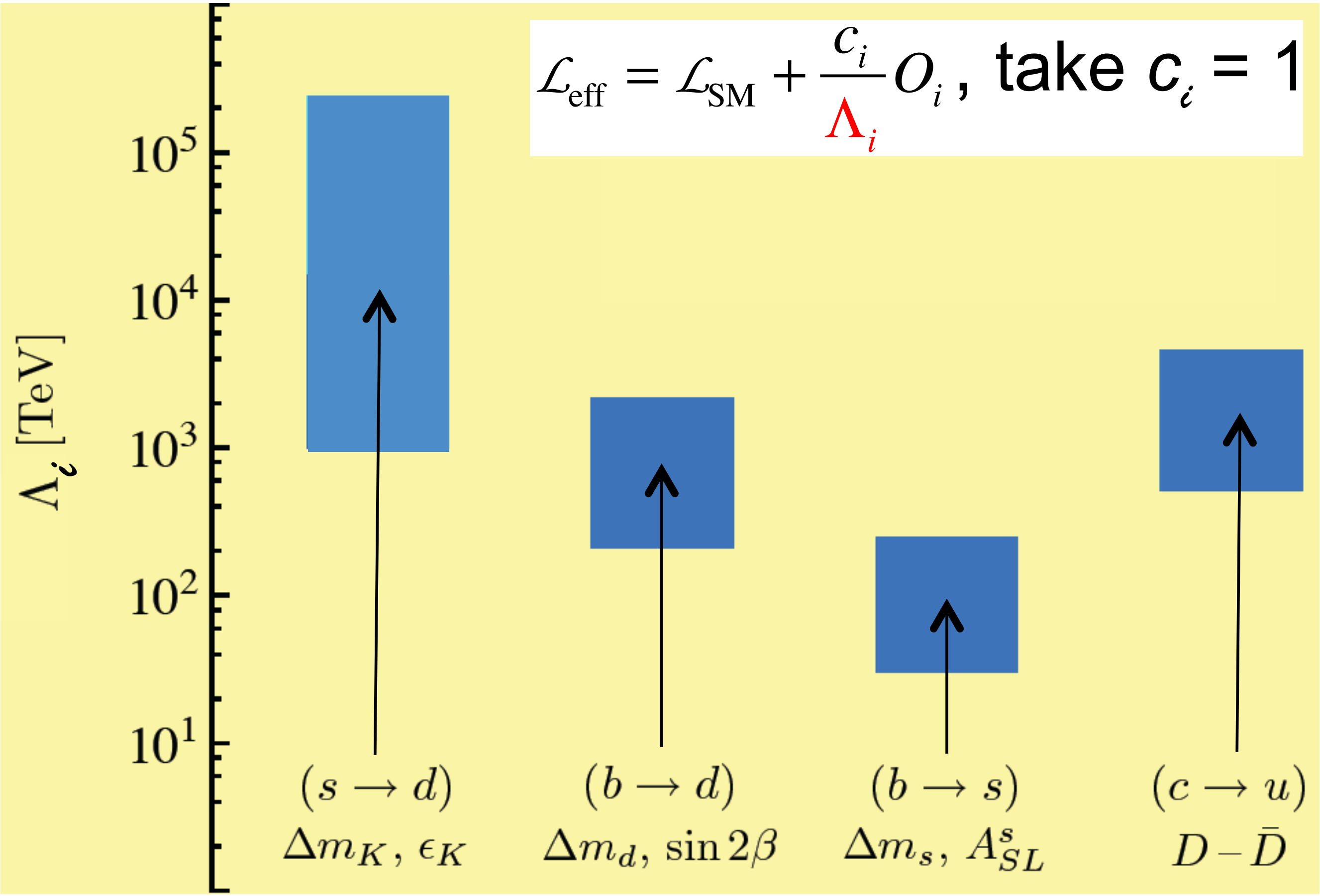
charm penguin



Sensitivity of FCNC to NP mass scales

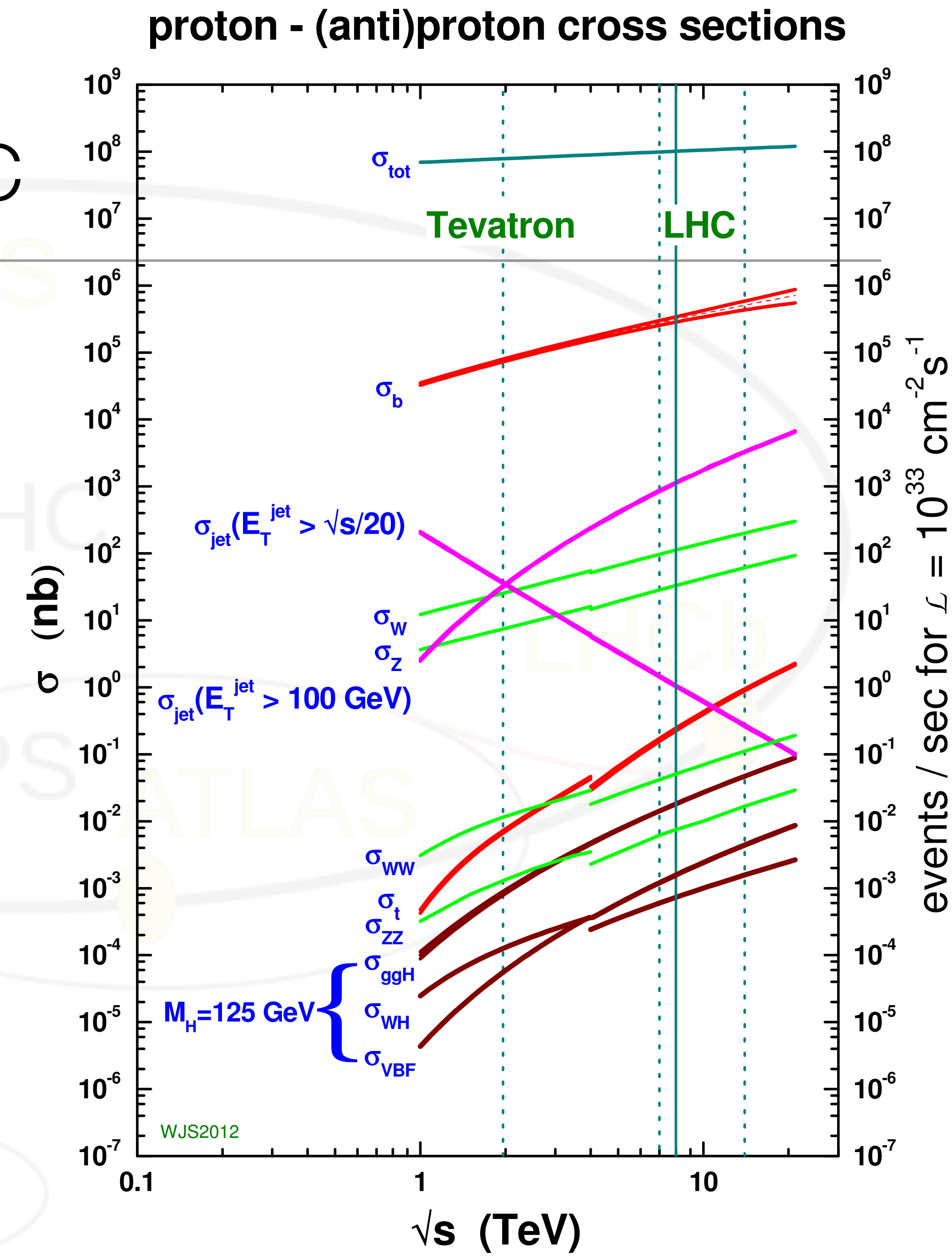
- "Simple" NP models ruled out up to PeV-scale, by Flavour Physics.
- Flavour physics imposes severe constraints on the structure and mass scale of NP

Ann.Rev.Nucl.Part.Sci.60:355,2010
plot from M. Neubert at EPS-HEP 2011



Flavour physics at the LHC

- Huge b cross section, even huger (20×) charm cross section.
- All types of b and c hadrons (like B^0, B_s, B_c, Λ_b, …).
- The world's largest heavy flavour samples, and a dedicated flavour physics detector (LHCb).
- Best place to do heavy flavour physics, today.

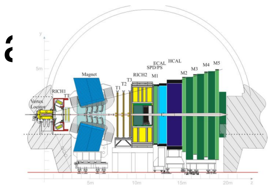


Eur.Phys.J. C63 (2009) 189-285

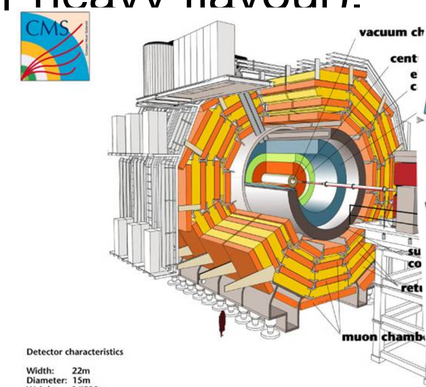
http://www.hep.ph.ic.ac.uk/~wstirlin/plots/plots.html

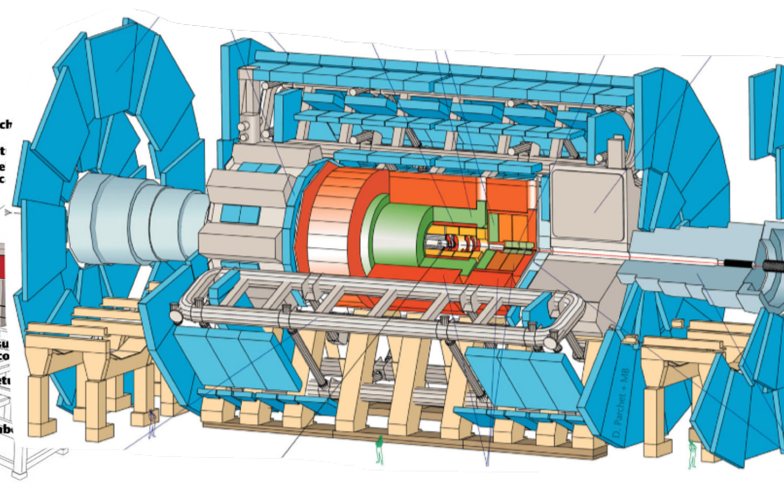
Heavy flavour physics at the LHC

- LHCb: Dedicated flavour physics experiment a
  - Optimised geometry
  - RICH particle ID (K/π separation)
  - Most precise vertexing at LHC
  - Dedicated heavy flavour trigger (incl B→hadrons)
  - Best mass resolution at LHC (for heavy flavour).



small & mighty





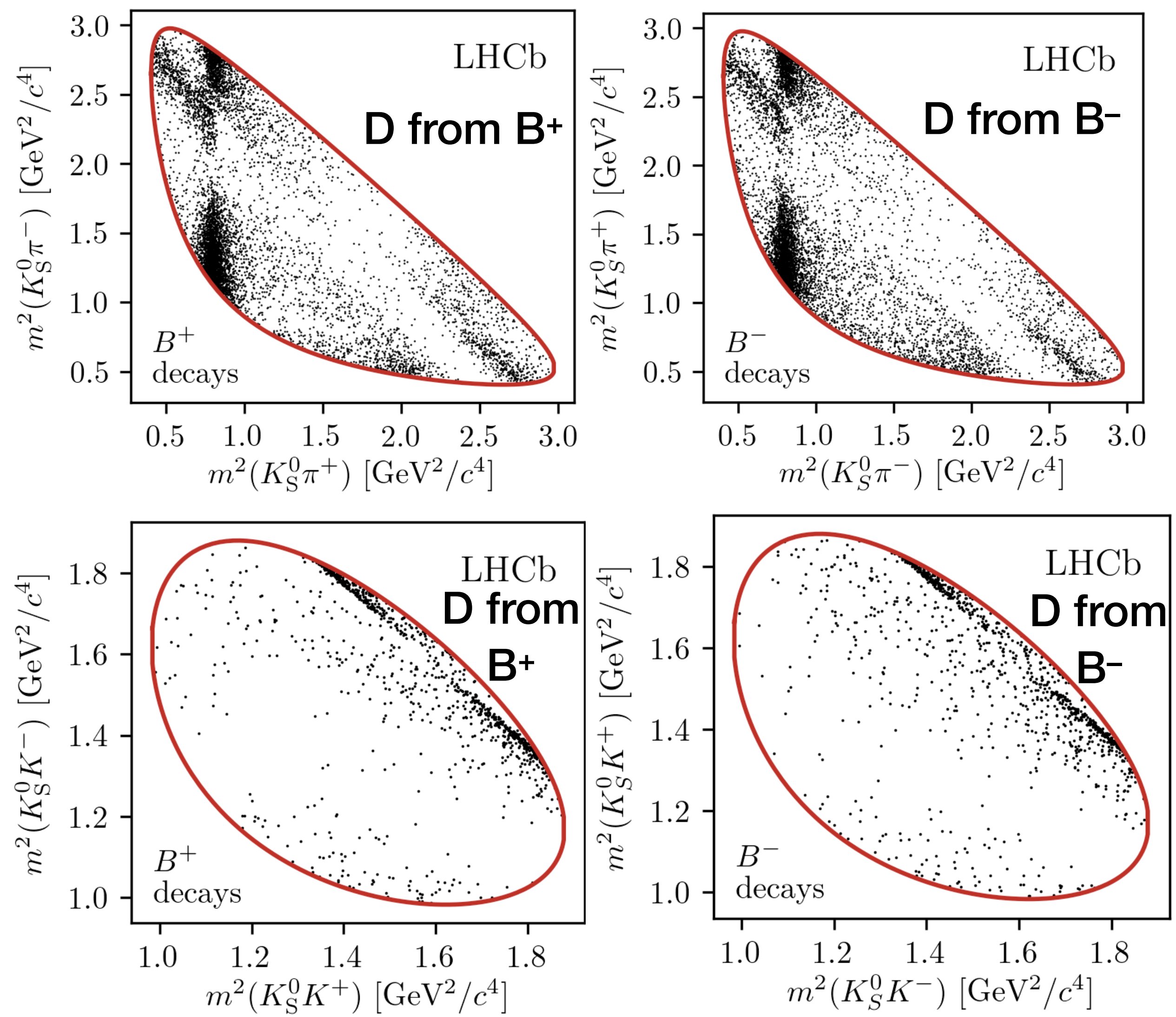
- ATLAS, CMS' heavy flavour skills:
  - good μ coverage,
  - efficient di-muon trigger,
  - maximal luminosity.
  - Good at rare dimuon decays such as $B_{(s)} \to \mu\mu$.

- ALICE: Cleanly reconstructs heavy flavour decays, focussed on y quark-gluon plasma.

LHCb model-independent γ from $B^{\pm} \to (K_S\pi\pi)_D K$ and $B^{\pm} \to (K_S KK)_D K$

- Binned, model-independent analysis using CLEO-c and BES III input.
- Plots show LHCb run I+II data
- Result of combined analysis

$$\gamma = \left(68.7^{+5.2}_{-5.1}\right)^{\circ}$$

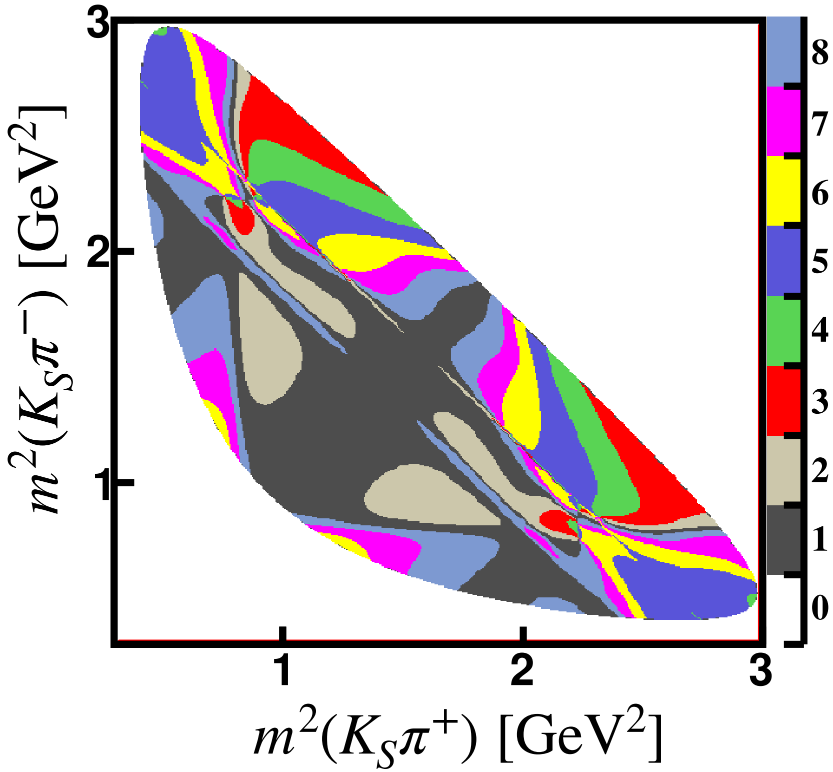


CLEO-c input:: Phys. Rev. D 82 112006. BESIII input:
Model-independent method: Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003). Optimal binning: Bondar, Poluektov hep-ph/0703267v1 (2007)

Biggest change for charm inputs to CPV in B since 2018: BES III

$$D^0 \to K_S\pi^+\pi^-$$

binning



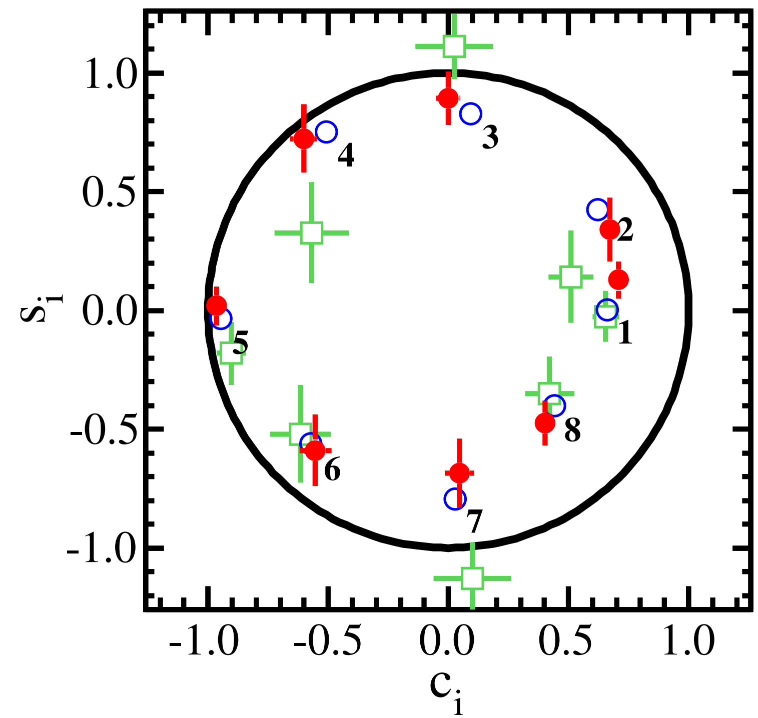
$$Z_i = c_i + is_i$$

CLEO-c

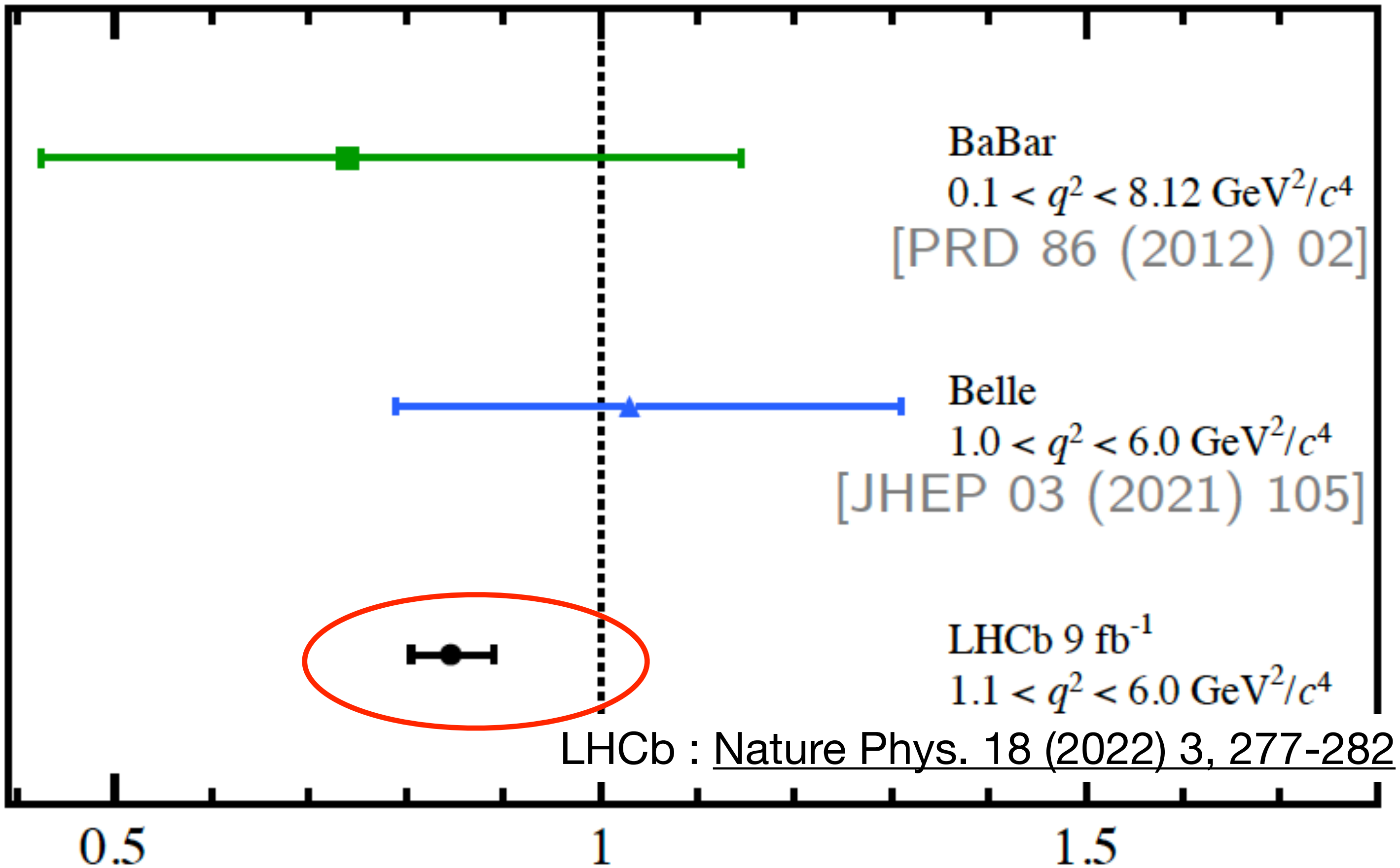
BES III

Model

results



R(K): $B^+ \to K^+\mu^+\mu^-$ / $B^+ \to K^+e^+e^-$



LHCb : Nature Phys. 18 (2022) 3, 277-282

3.1σ deviation from SM

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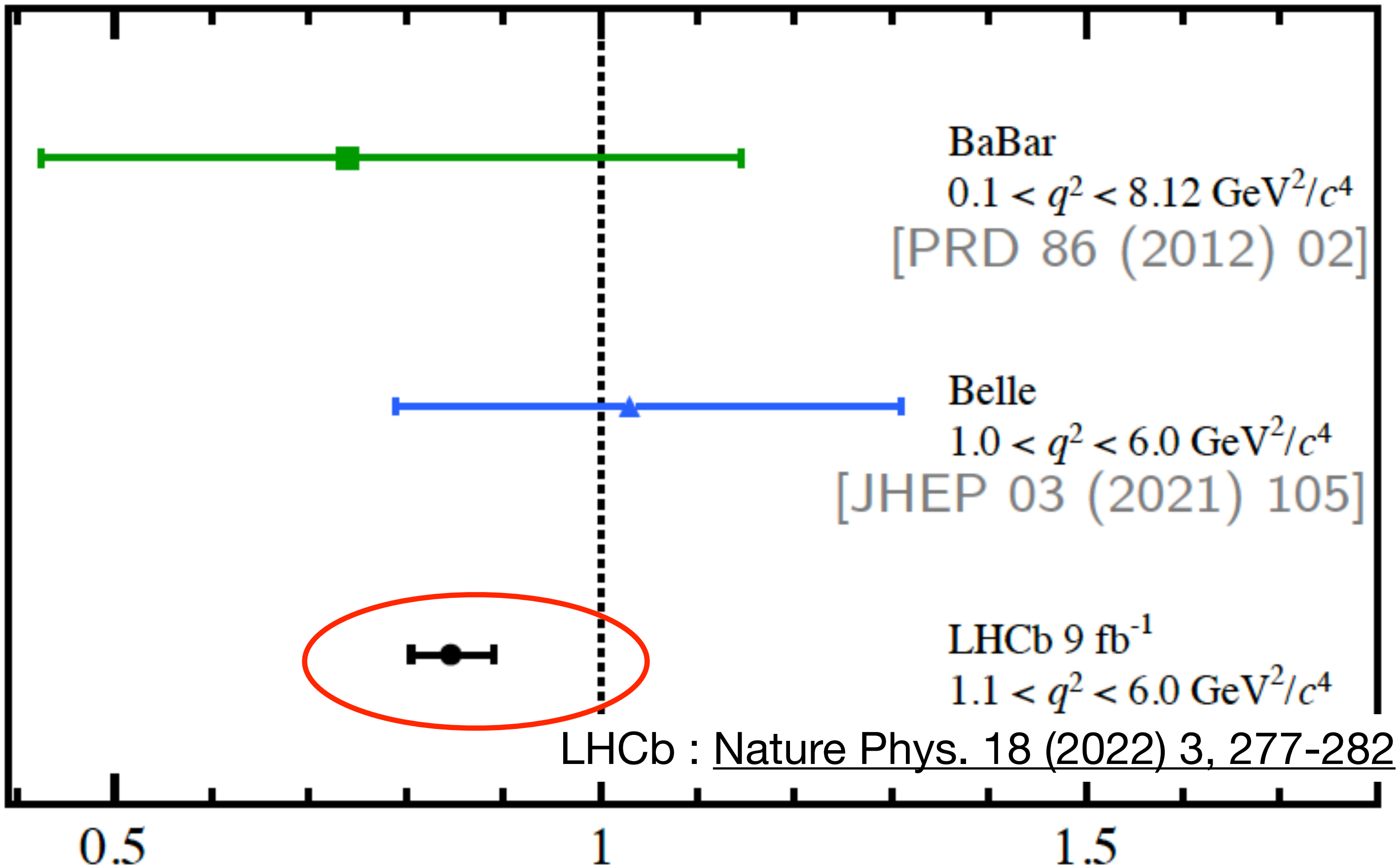
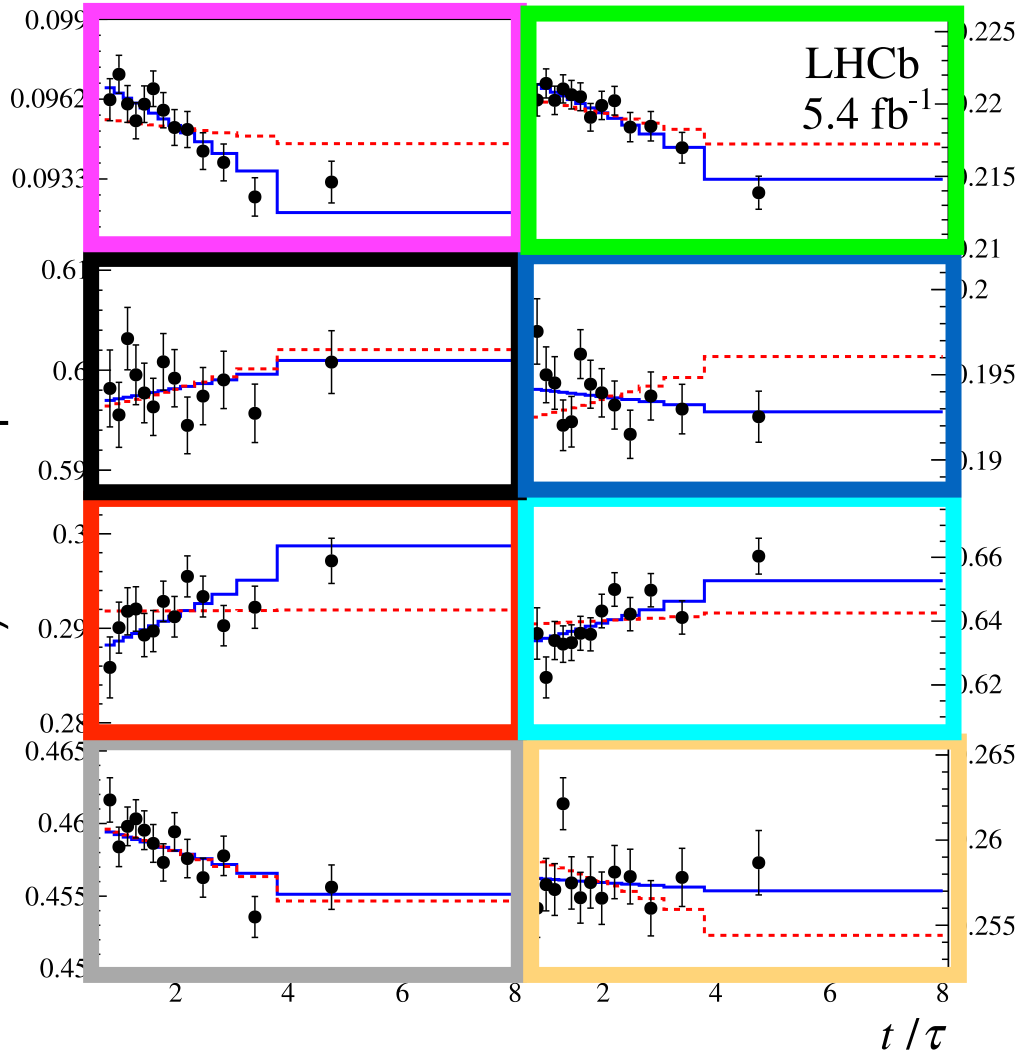


LHCb : Nature Phys. 18 (2022) 3, 277-282

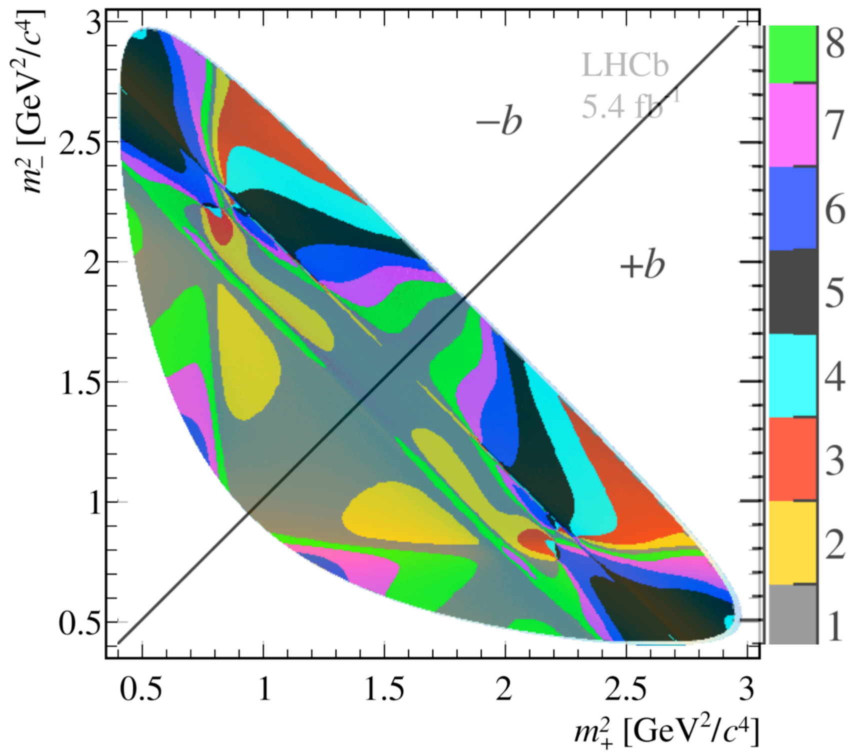
3.1σ deviation from SM

LHCb: PRL 127 (2021) 11, 111801

ratio of $D^0/\overline{D}^0$ rate in (colour-coded) Dalitz plot bin→

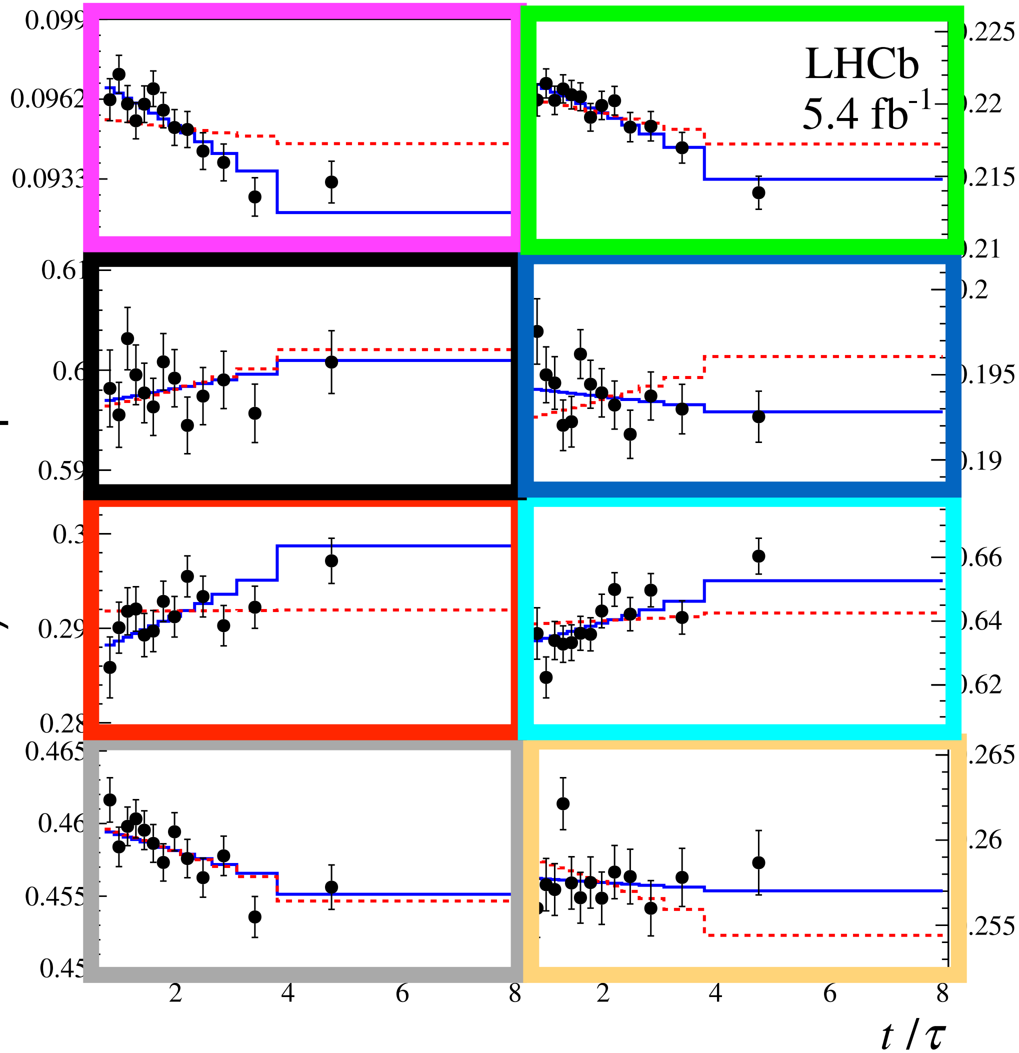


time→

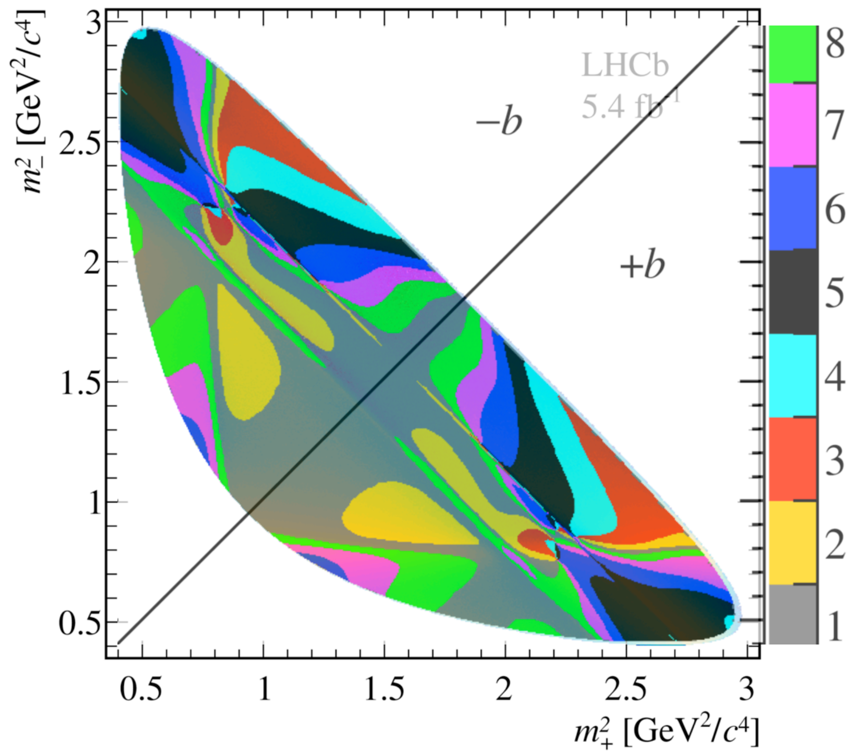


Parameter	Value	95.5% CL interval
$x\ [10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$	$[2.9, 5.0]$
$y\ [10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$	$[2.0, 7.5]$
$\lvert q/p\rvert$	0.996 ± 0.052	$[\ \ 0.890, 1.110]$
ϕ	$-0.056\,^{+0.047}_{-0.051}$	$[-0.172, 0.040]$

ratio of $D^0/\overline{D}^0$ rate in (colour-coded) Dalitz plot bin→



time→



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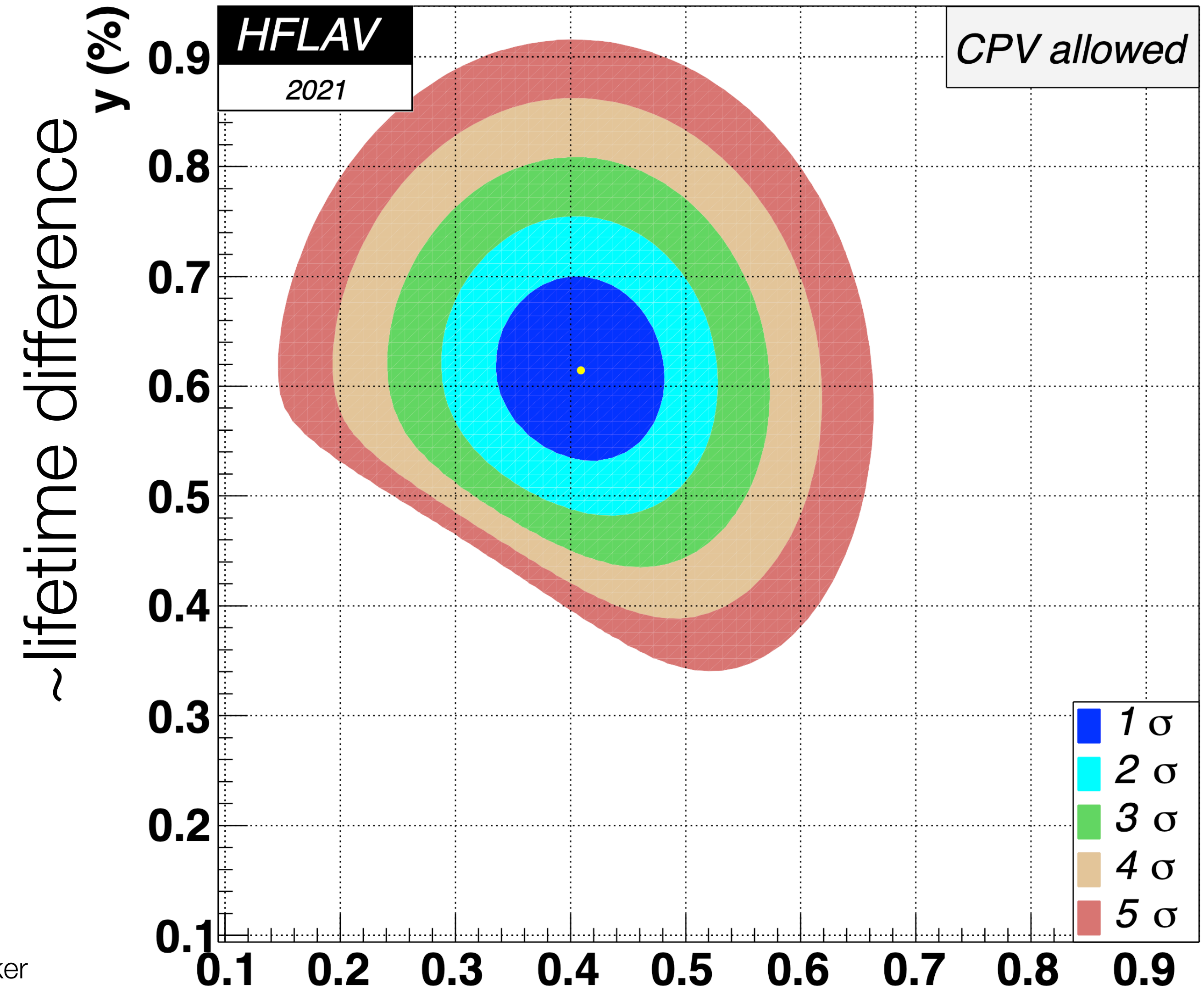
Mixing results

LHCb: PRL 127 (2021) 11, 111801

$x = 3.98^{+0.56}_{-0.54}$, $x \neq 0$ at 5σ CL - first observation!



Mixing results

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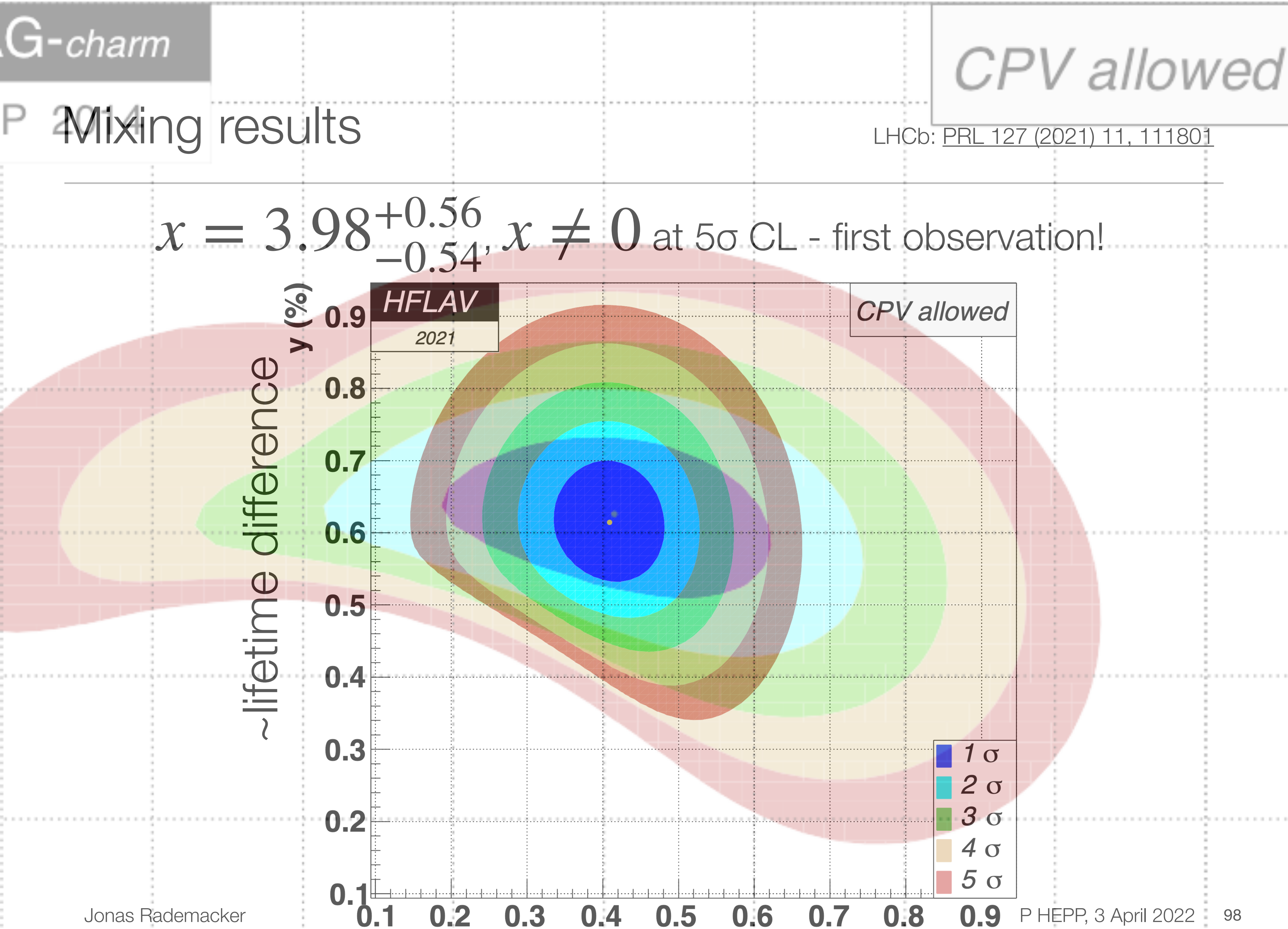
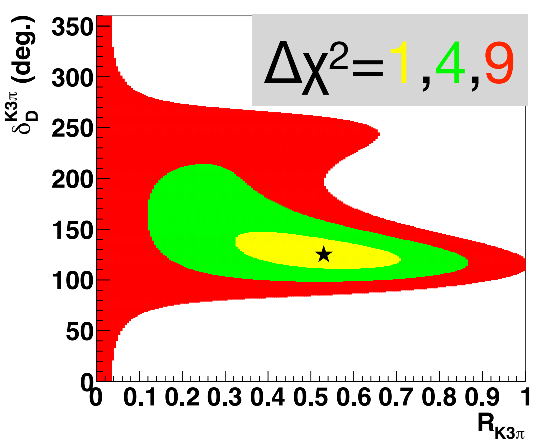


Charm input to γ from CLEO-c and LHCb mixing measurements

Use interference effects in charm as input to γ

$$\Gamma\left(B^- \to \left(K^+ 3\pi\right)_D K^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2 R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

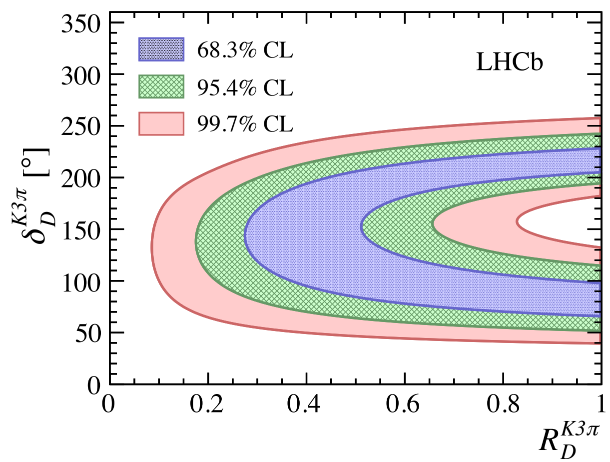
from D-$\bar{D}$ superpositions at CLEO-c



Phys.Lett. B757 (2016) 520-527

+

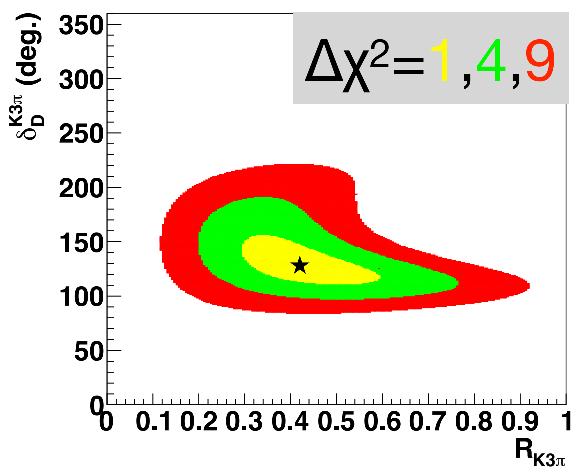
Input from charm mixing (LHCb)



PRL 116 (2016) no.24, 241801

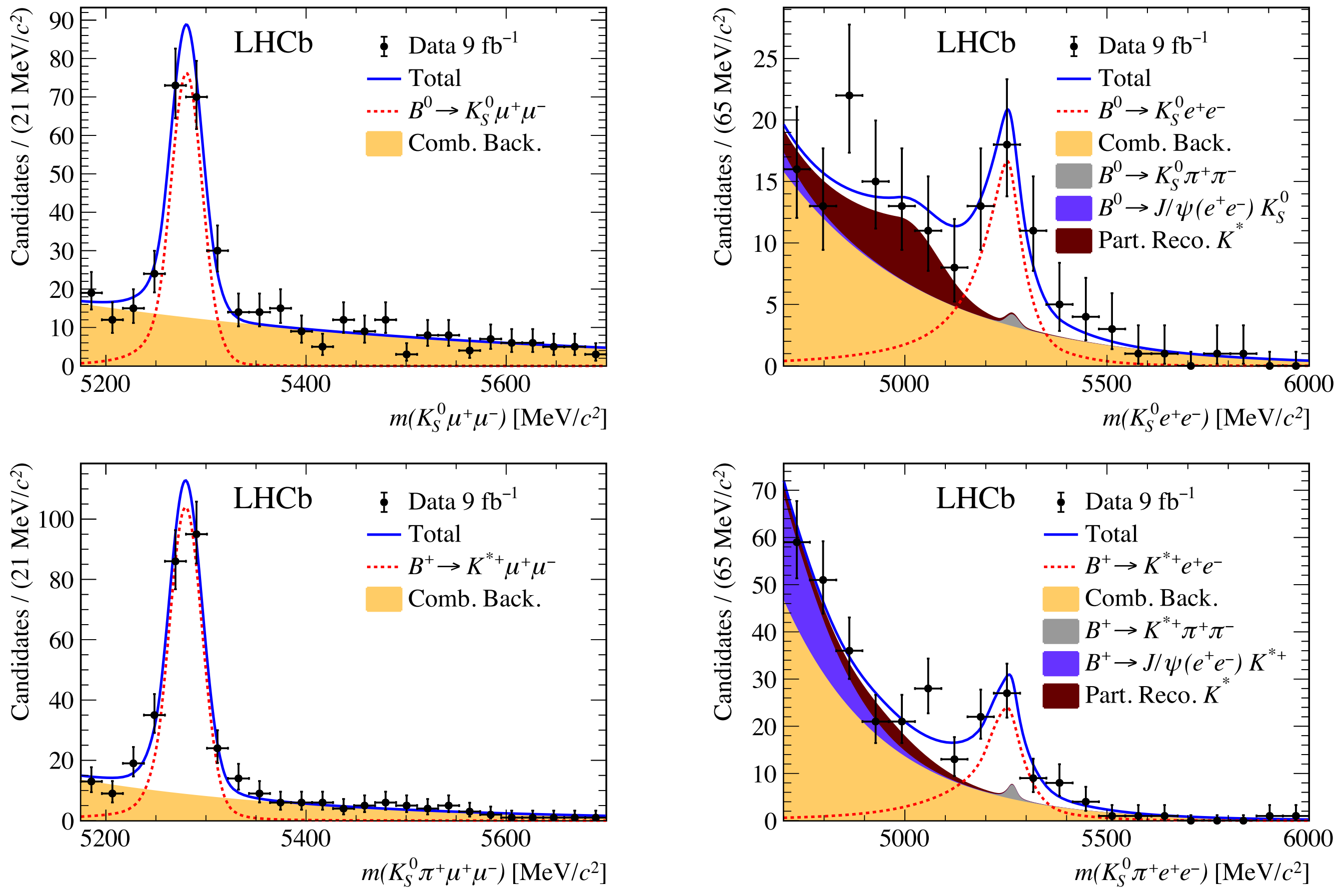
=

Combination:CLEO-c and mixing



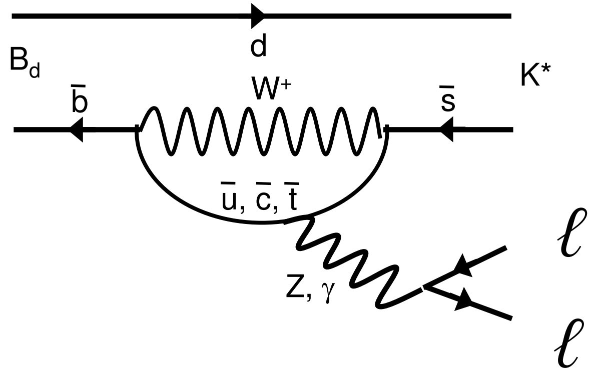
Phys.Lett. B757 (2016) 520-527

CLEO-c input theory: Atwood, Soni: Phys.Rev. D68 (2003) 033003
CLEO-c input: Phys.Rev.D80:031105,2009, update
mixing/gamma theory: JHEP 1503 (2015) 169 Phys.Lett. B728 (2014) 296-302

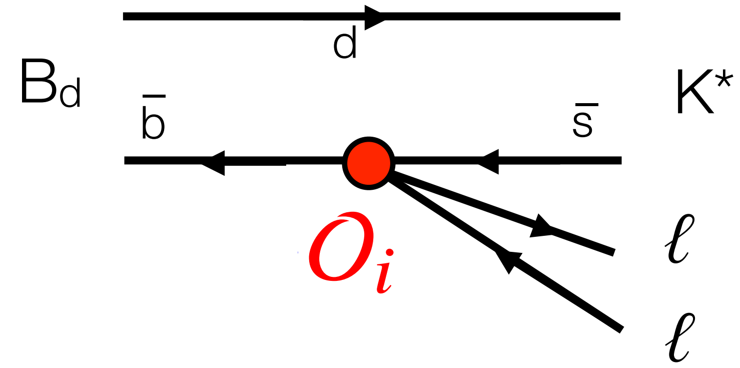

LHCb
Data 9 fb^{-1}
Total
$B^0 \to K_S^0 \mu^+\mu^-$
Comb. Back.
Candidates / (21 MeV/c^2)
$m(K_S^0\mu^+\mu^-)$ [MeV/c^2]
LHCb
Data 9 fb^{-1}
Total
$B^0 \to K_S^0 e^+e^-$
Comb. Back.
$B^0 \to K_S^0 \pi^+\pi^-$
$B^0 \to J/\psi(e^+e^-)\, K_S^0$
Part. Reco. K^*
Candidates / (65 MeV/c^2)
$m(K_S^0 e^+e^-)$ [MeV/c^2]
LHCb
Data 9 fb^{-1}
Total
$B^+ \to K^{*+}\mu^+\mu^-$
Comb. Back.
Candidates / (21 MeV/c^2)
$m(K_S^0\pi^+\mu^+\mu^-)$ [MeV/c^2]
LHCb
Data 9 fb^{-1}
Total
$B^+ \to K^{*+} e^+e^-$
Comb. Back.
$B^+ \to K^{*+}\pi^+\pi^-$
$B^+ \to J/\psi(e^+e^-)\, K^{*+}$
Part. Reco. K^*
Candidates / (65 MeV/c^2)
$m(K_S^0\pi^+ e^+e^-)$ [MeV/c^2]

Putting it all together

$$\mathcal{H}_{\text{eff}} \approx -\frac{4G_F}{\sqrt{2}} \sum_i V_{tb} V_{ts}^* C_i O_i$$

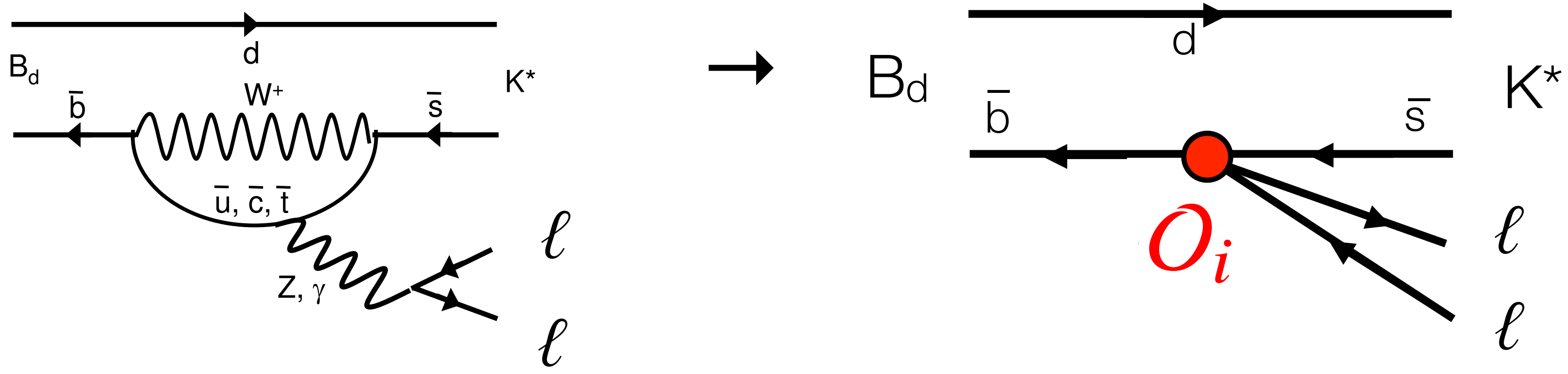


→



Putting it all together

$$\mathcal{H}_{\text{eff}} \approx -\frac{4G_F}{\sqrt{2}} \sum_i V_{tb}V_{ts}^* C_i O_i$$



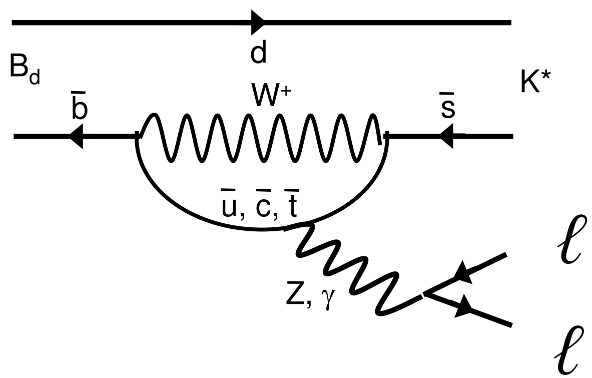
$$\mathcal{O}_7 = \frac{e}{g^2} m_b\, \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$$

$$\mathcal{O}_{9\ell} = \frac{e^2}{g^2}\bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma^\mu \ell$$

$$\mathcal{O}_{10\ell} = \frac{e^2}{g^2}\bar{s}\gamma_\mu(1-\gamma_5)b\, \bar{\ell}\gamma^\mu\gamma_5 \ell$$

Putting it all together

$$\mathcal{H}_{\text{eff}} \approx -\frac{4G_F}{\sqrt{2}} \sum_i V_{tb} V_{ts}^* C_i O_i$$



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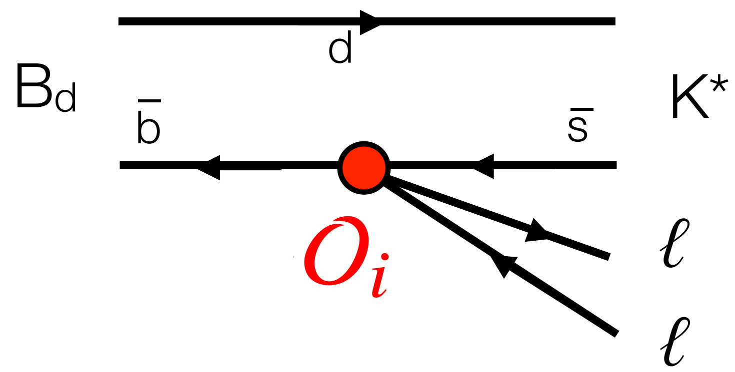

$$\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$$ soft/real photon

$$\mathcal{O}_{9\ell} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu \ell$$ Z/hard photon

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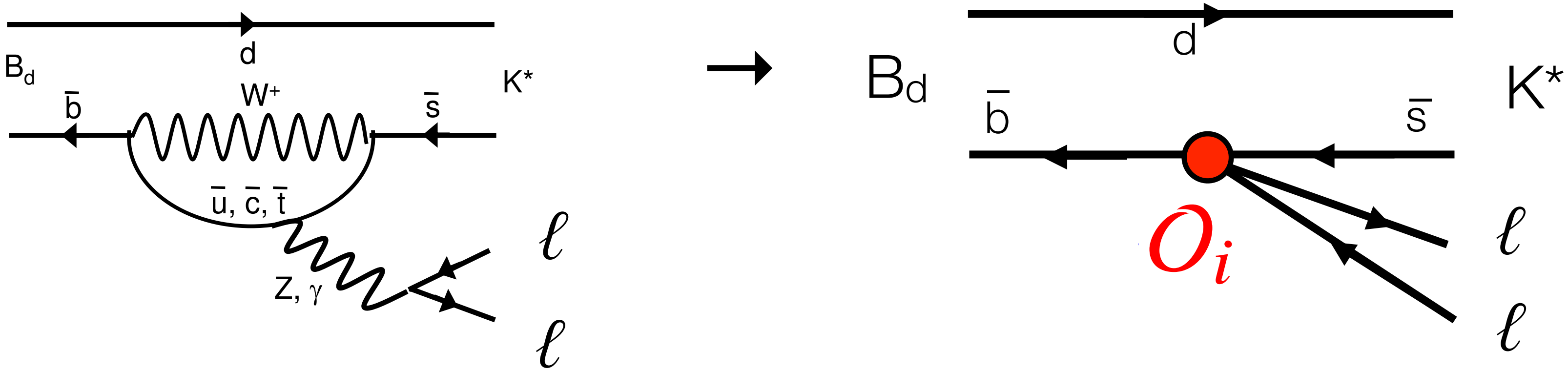
Putting it all together

$$\mathcal{H}_{\text{eff}} \approx -\frac{4G_F}{\sqrt{2}} \sum_i V_{tb} V_{ts}^* C_i O_i$$



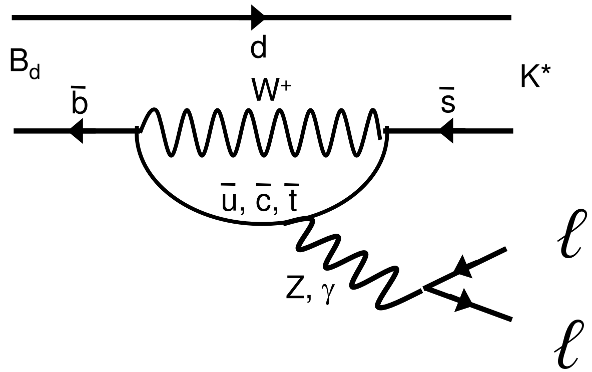
$\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s}\sigma^{\mu\nu}(1+\gamma_5)F_{\mu\nu}\, b$ soft/real photon $C_7^{SM} = -0.29$

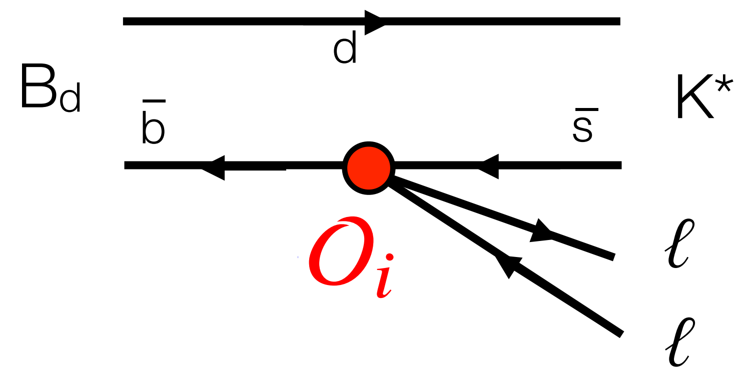
$\mathcal{O}_{9\ell} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu \ell$ Z/hard photon $C_9^{SM} = 4.1$

$\mathcal{O}_{10\ell} = \frac{e^2}{g^2} \bar{s}\gamma_\mu(1-\gamma_5)b\; \bar{\ell}\gamma^\mu\gamma_5 \ell$ Z $C_{10}^{SM} = -4.3$

Putting it all together

$$\mathcal{H}_{\text{eff}} \approx -\frac{4G_F}{\sqrt{2}} \sum_i V_{tb} V_{ts}^* C_i O_i$$



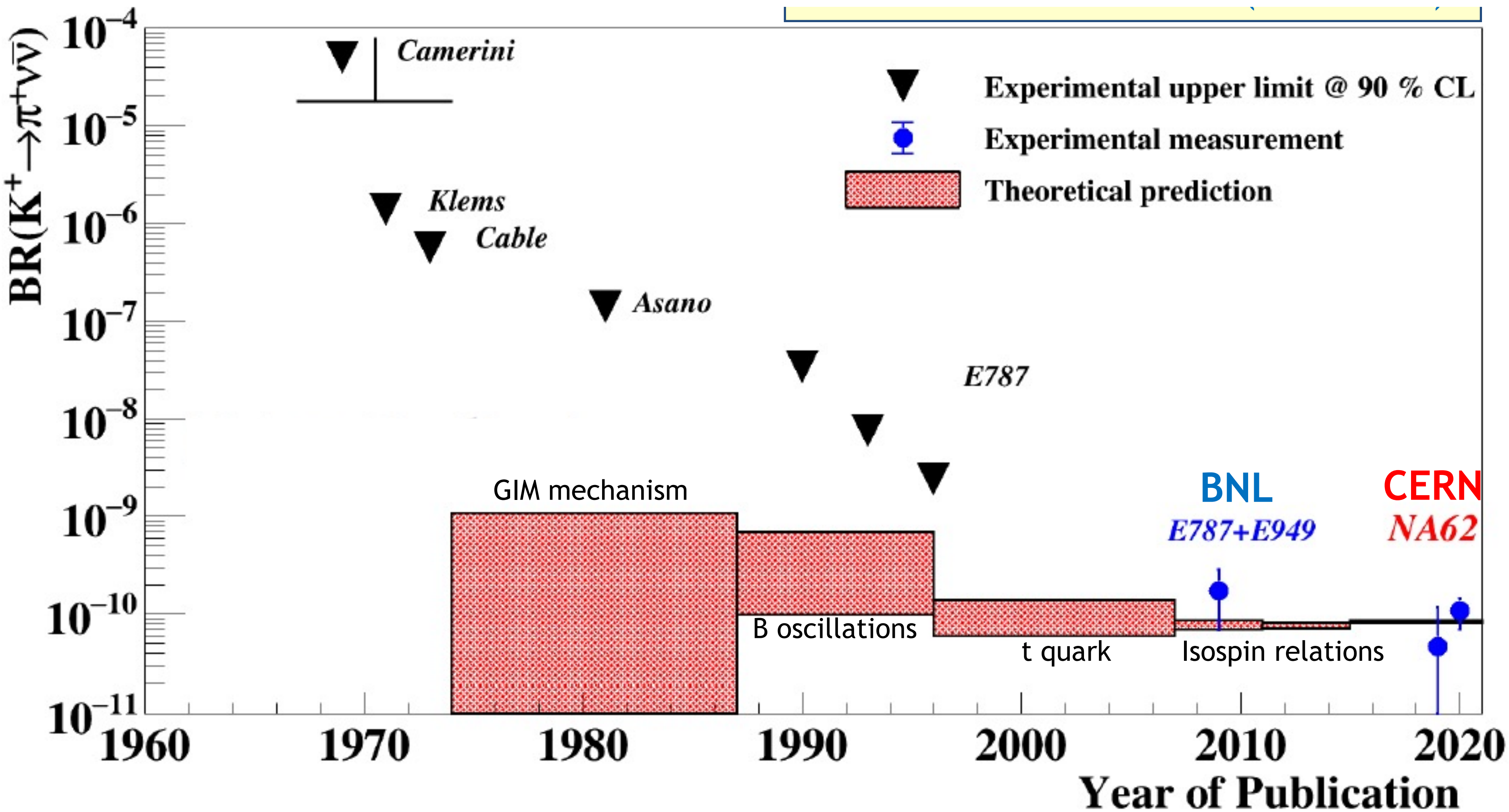


$\mathcal{O}_7 = \frac{e}{g^2} m_b \bar{s} \sigma^{\mu\nu} (1+\gamma_5) F_{\mu\nu} b$ soft/real photon $C_7^{SM} = -0.29$

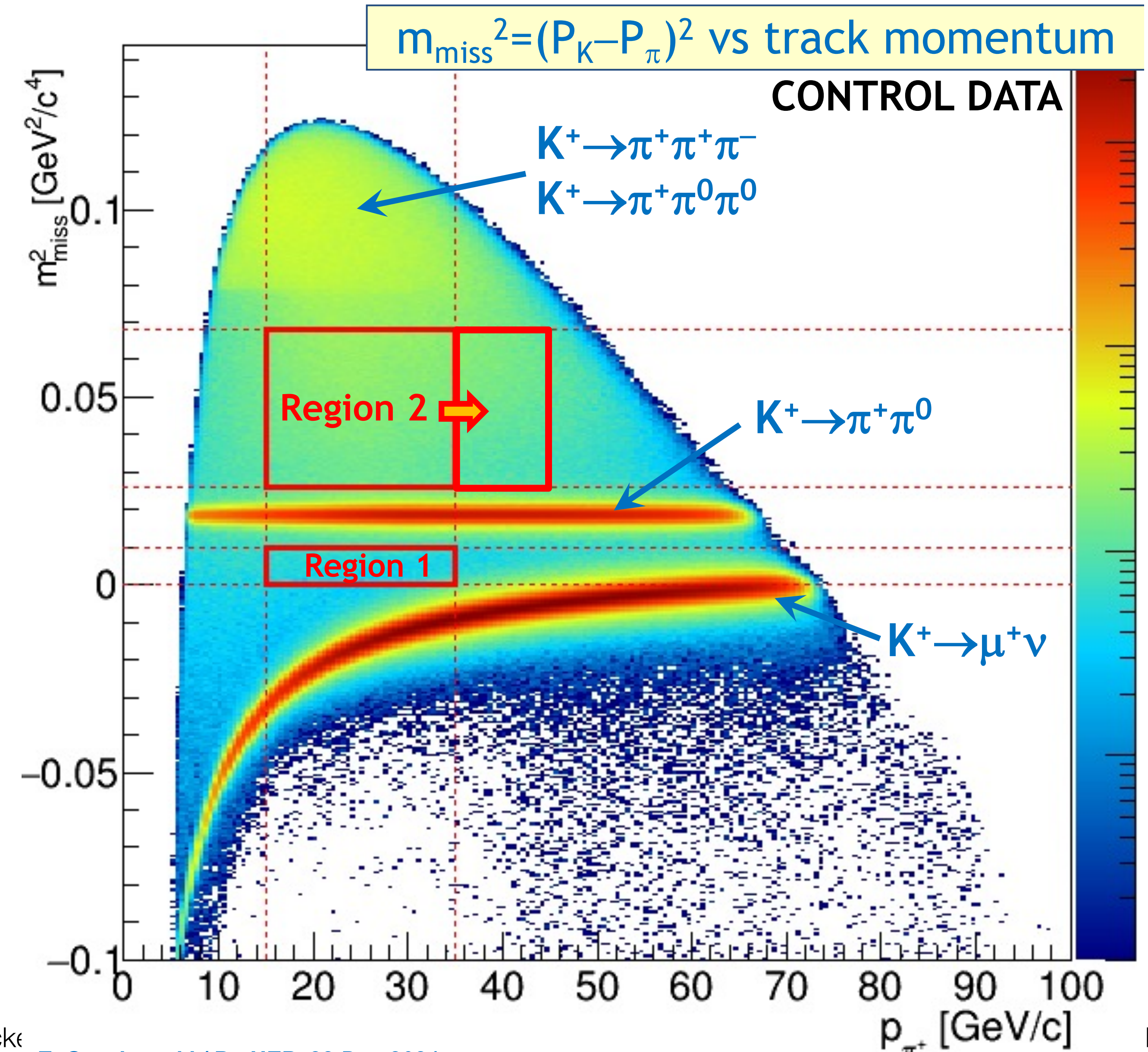
$\mathcal{O}_{9\ell} = \frac{e^2}{g^2} \bar{s} \gamma_\mu (1-\gamma_5) b \, \bar{\ell} \gamma^\mu \ell$ Z/hard photon $C_9^{SM} = 4.1$

$\mathcal{O}_{10\ell} = \frac{e^2}{g^2} \bar{s} \gamma_\mu (1-\gamma_5) b \, \bar{\ell} \gamma^\mu \gamma_5 \ell$ Z $C_{10}^{SM} = -4.3$

NP can modify C_i and add new operators

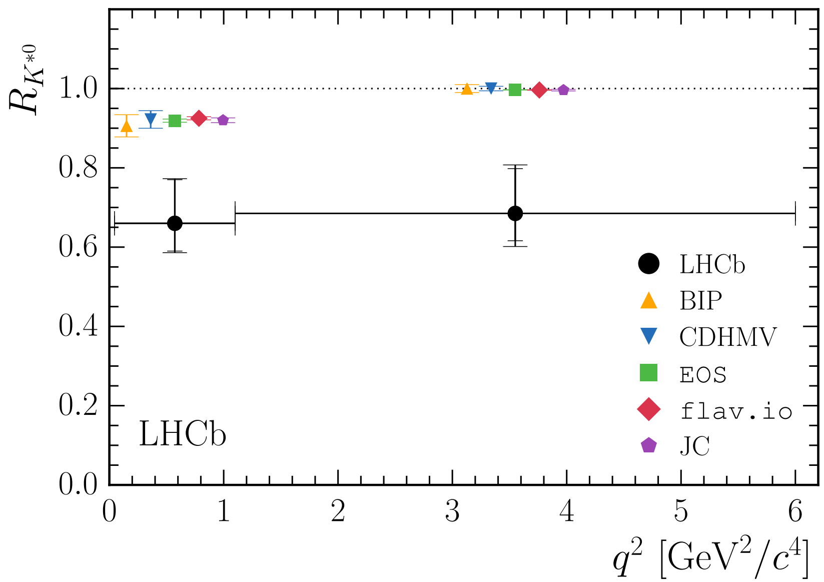


BR(K⁺→π⁺νν̄)
Camerini
Klems
Cable
Asano
E787
Experimental upper limit @ 90 % CL
Experimental measurement
Theoretical prediction
GIM mechanism
B oscillations
t quark
Isospin relations
BNL
E787+E949
CERN
NA62
1960
1970
1980
1990
2000
2010
2020
Year of Publication



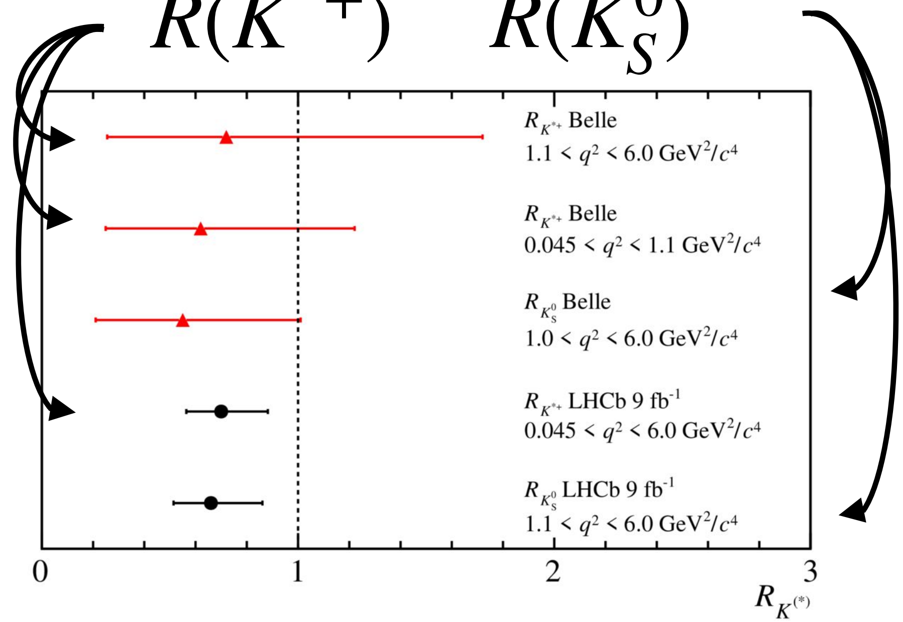
E. Goudzovski / Be.HEP, 22 Dec 2021

$R(K^{*0})$



$R_{K^{*0}}$
1.0
0.8
0.6
0.4
0.2
0.0
LHCb
LHCb
BIP
CDHMV
EOS
flav.io
JC
0
1
2
3
4
5
6
q^2 [GeV$^2/c^4$]

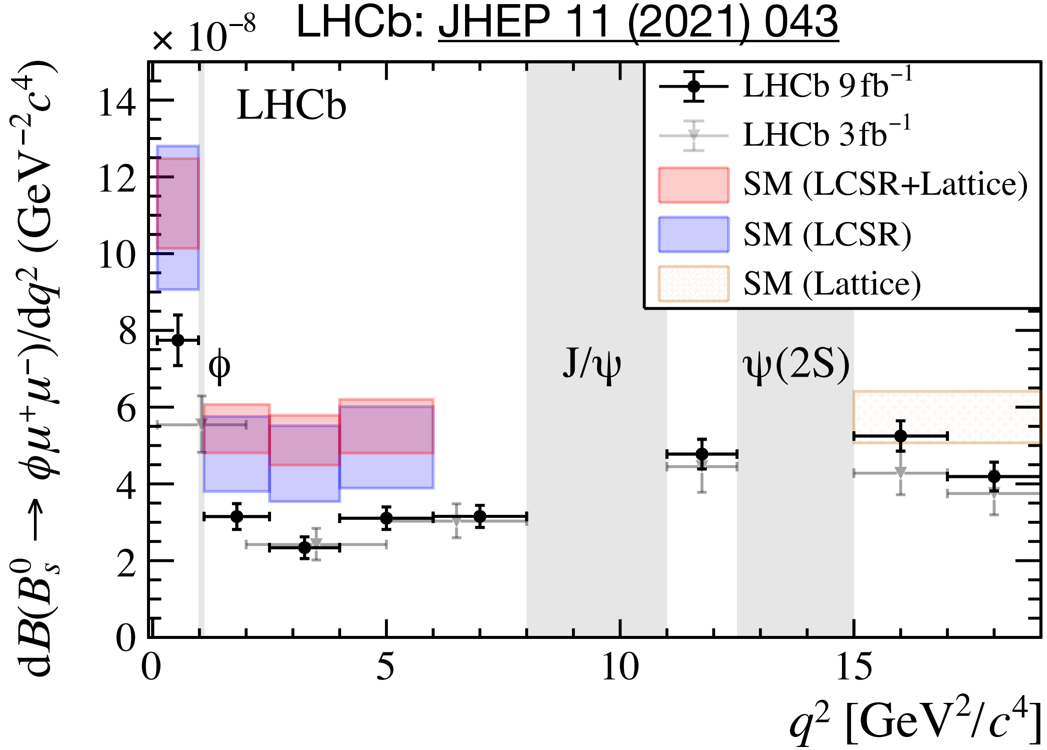
$R(K^{*+})$ $R(K^0_S)$



$R_{K^{*+}}$ Belle
$1.1 < q^2 < 6.0$ GeV$^2/c^4$
$R_{K^{*+}}$ Belle
$0.045 < q^2 < 1.1$ GeV$^2/c^4$
$R_{K^0_S}$ Belle
$1.0 < q^2 < 6.0$ GeV$^2/c^4$
$R_{K^{*+}}$ LHCb 9 fb^{-1}
$0.045 < q^2 < 6.0$ GeV$^2/c^4$
$R_{K^0_S}$ LHCb 9 fb^{-1}
$1.1 < q^2 < 6.0$ GeV$^2/c^4$
0
1
2
3
$R_{K^{(*)}}$

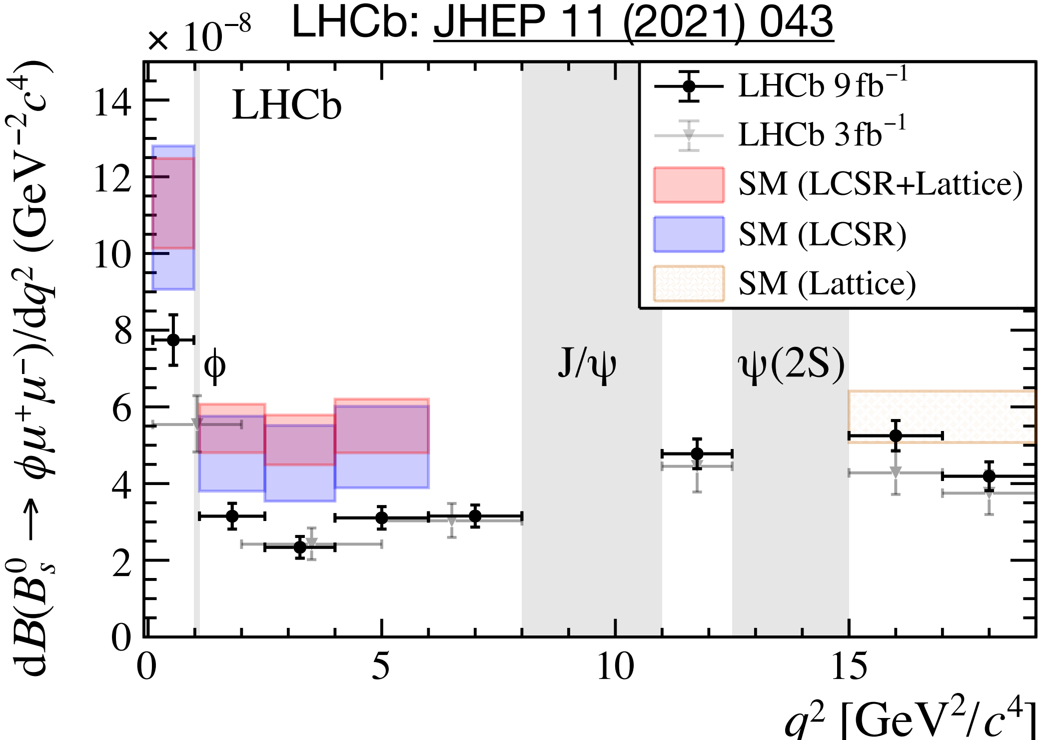
$\frac{d\Gamma}{dq^2}$ in $B_s \to \phi\mu^+\mu^-$ and others

LHCb: JHEP 11 (2021) 043

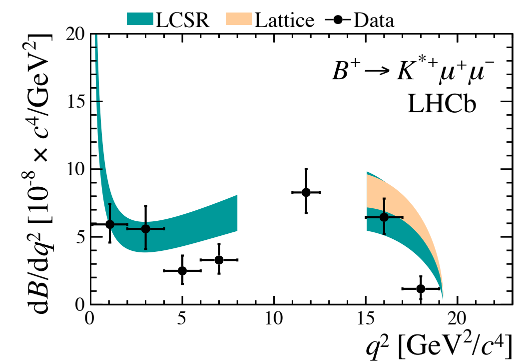


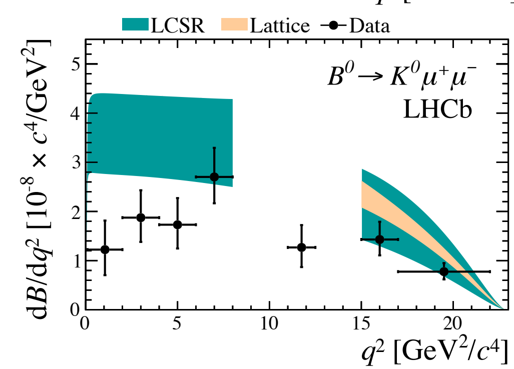
$\frac{d\Gamma}{dq^2}$ in $B_s \to \phi\mu^+\mu^-$ and others

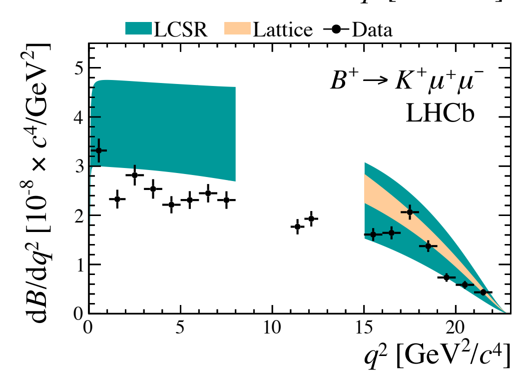
LHCb: JHEP 11 (2021) 043

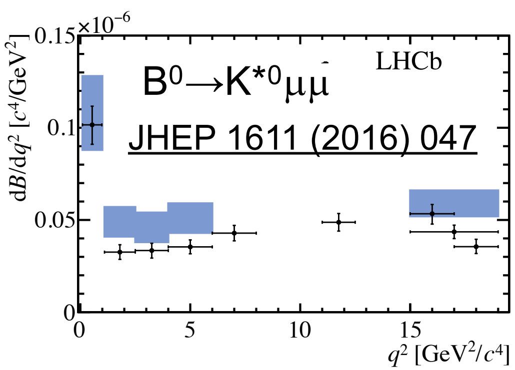


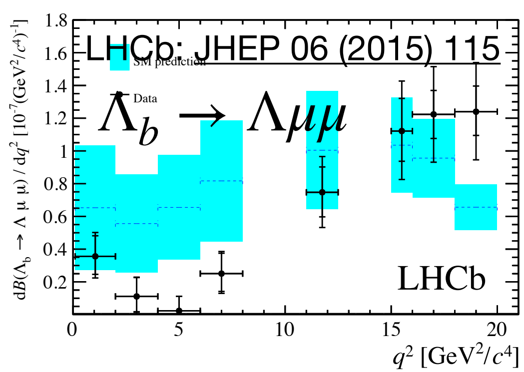
LHCb: JHEP 06 (2014) 133







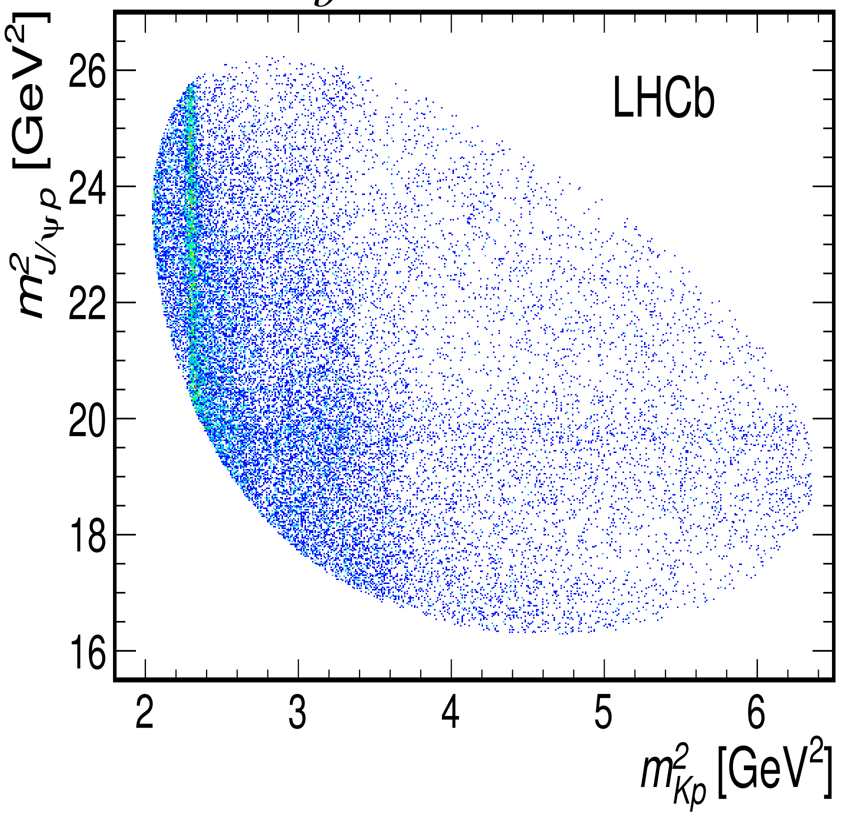


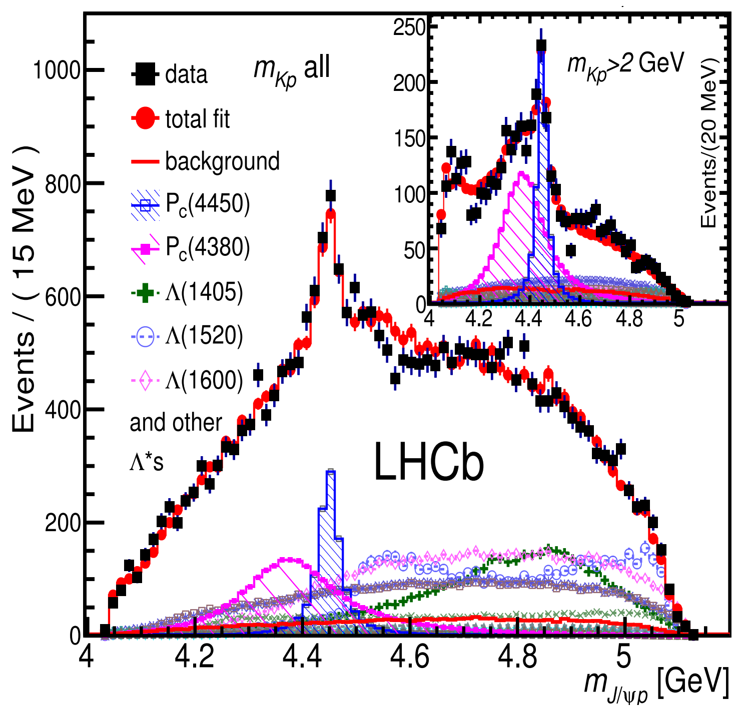


Pentaquarks 2018

$\Lambda_b^0 \to J/\psi K^- p$

LHCb: PRL 115 (2015) 072001

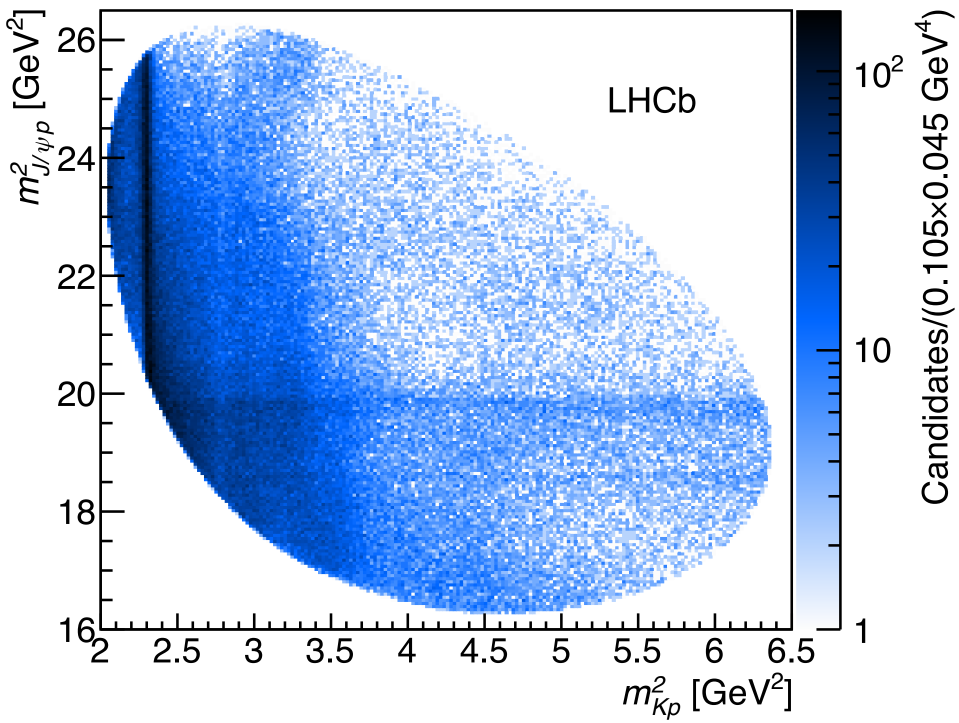


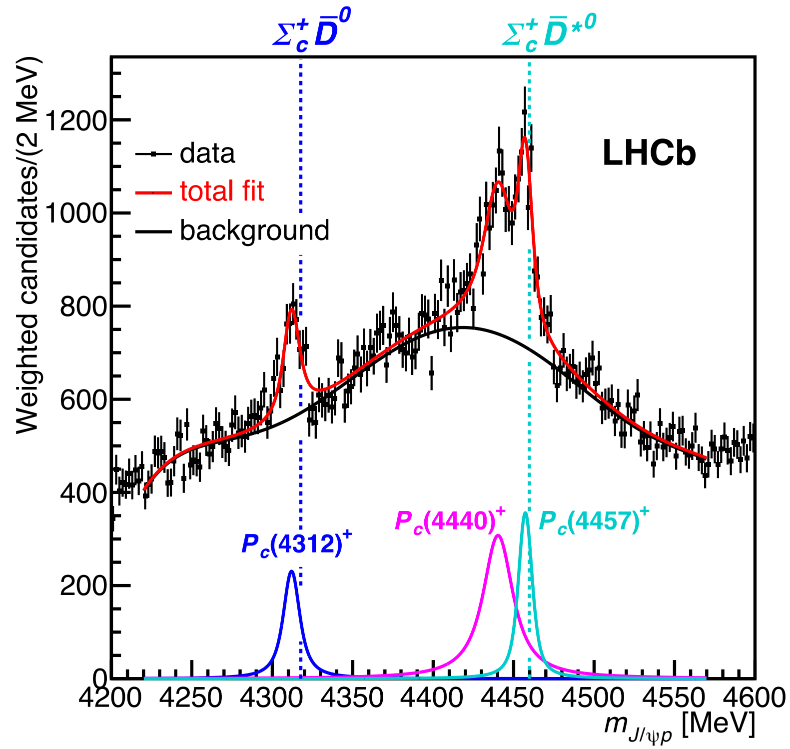


Pentaquarks 2020

$$\Lambda_b^0 \to J/\psi K^- p$$

LHCb: PRL 122 (2019) 22, 222001



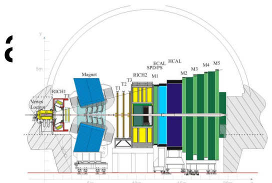


9×stats

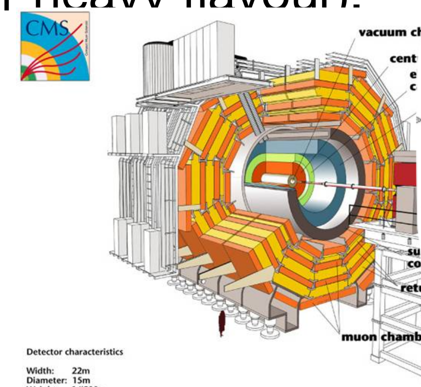
State	M [MeV]	Γ [MeV] (95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$ (< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$ (< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$ (< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

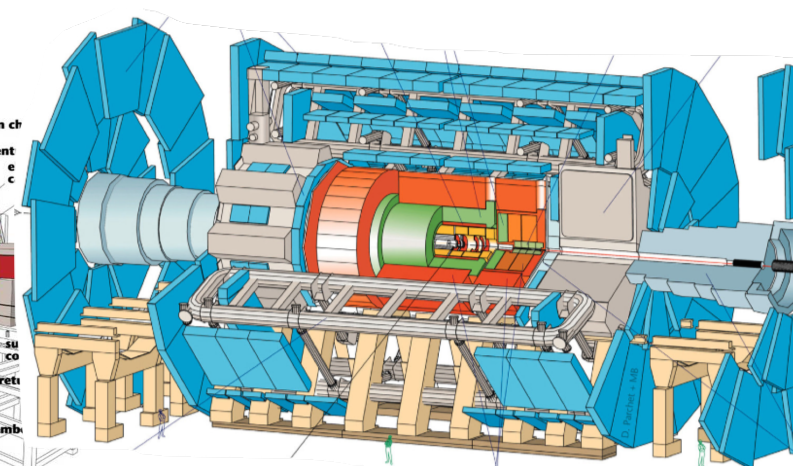
Heavy flavour physics at the LHC

- LHCb: Dedicated flavour physics experiment a
  - Optimised geometry
  - RICH particle ID (K/π separation)
  - Most precise vertexing at LHC
  - Dedicated heavy flavour trigger (incl B→hadrons)
  - Best mass resolution at LHC (for heavy flavour).



small & mighty





- ATLAS, CMS' heavy flavour skills:
  - good μ coverage,
  - efficient di-muon trigger,
  - maximal luminosity.
  - Good at rare dimuon decays such as $B_{(s)} \to \mu\mu$.

- ALICE: Cleanly reconstructs heavy flavour decays, focussed on y quark-gluon plasma.

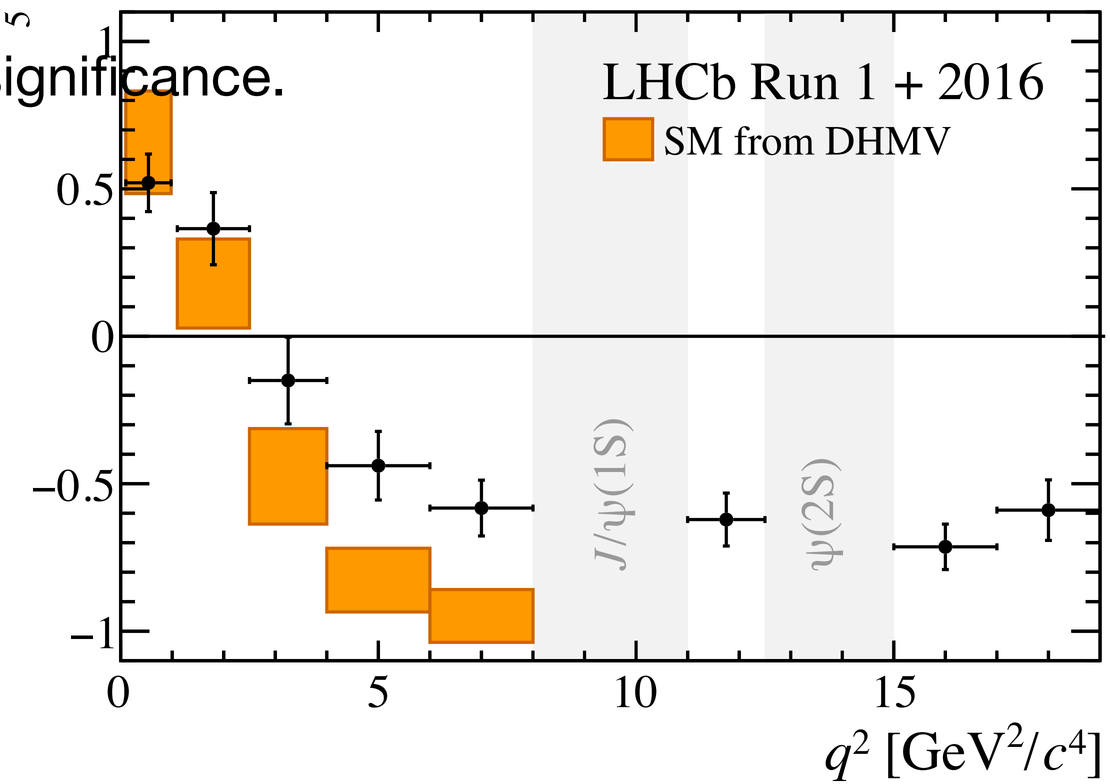
$B \to K^{*} \mu^{+} \mu^{-}$: P'5

LHCb: Phys.Rev.Lett. 125 (2020)

- Describes interference between polar and axial vector currents.

Theory: JHEP 05 (2013) 137

- Deviation from SM: 3.3 σ global significance.



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LHCb: Phys.Rev.Lett. 125 (2020)

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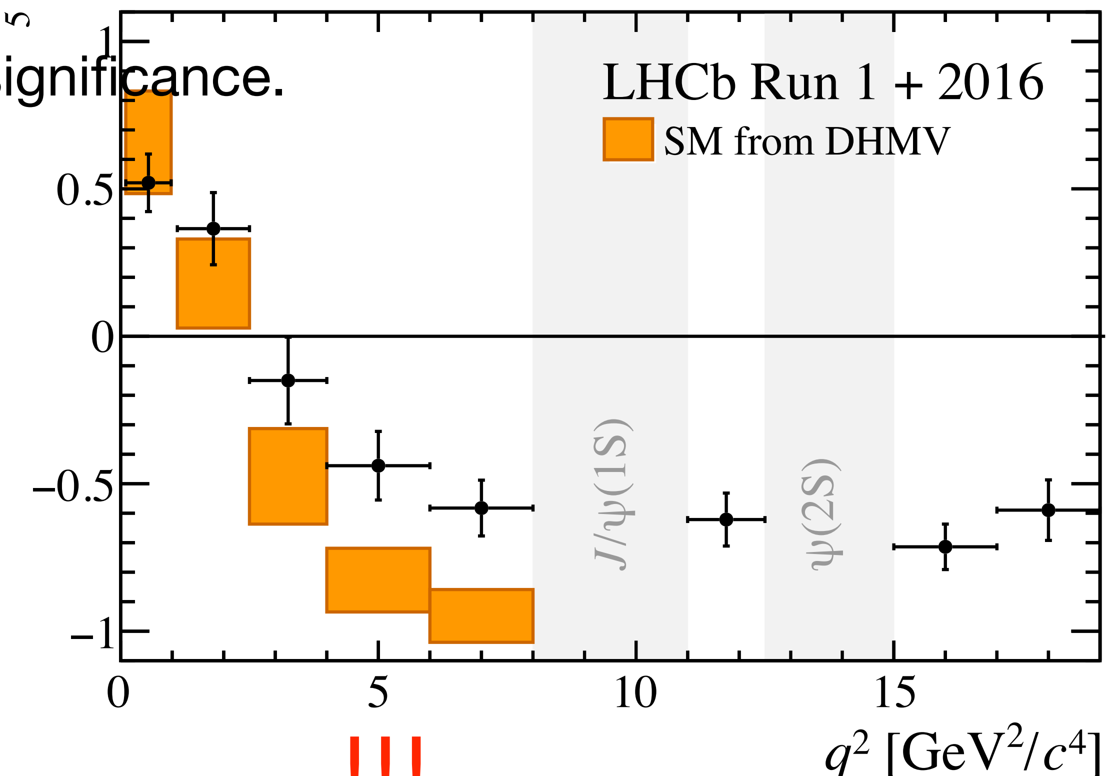
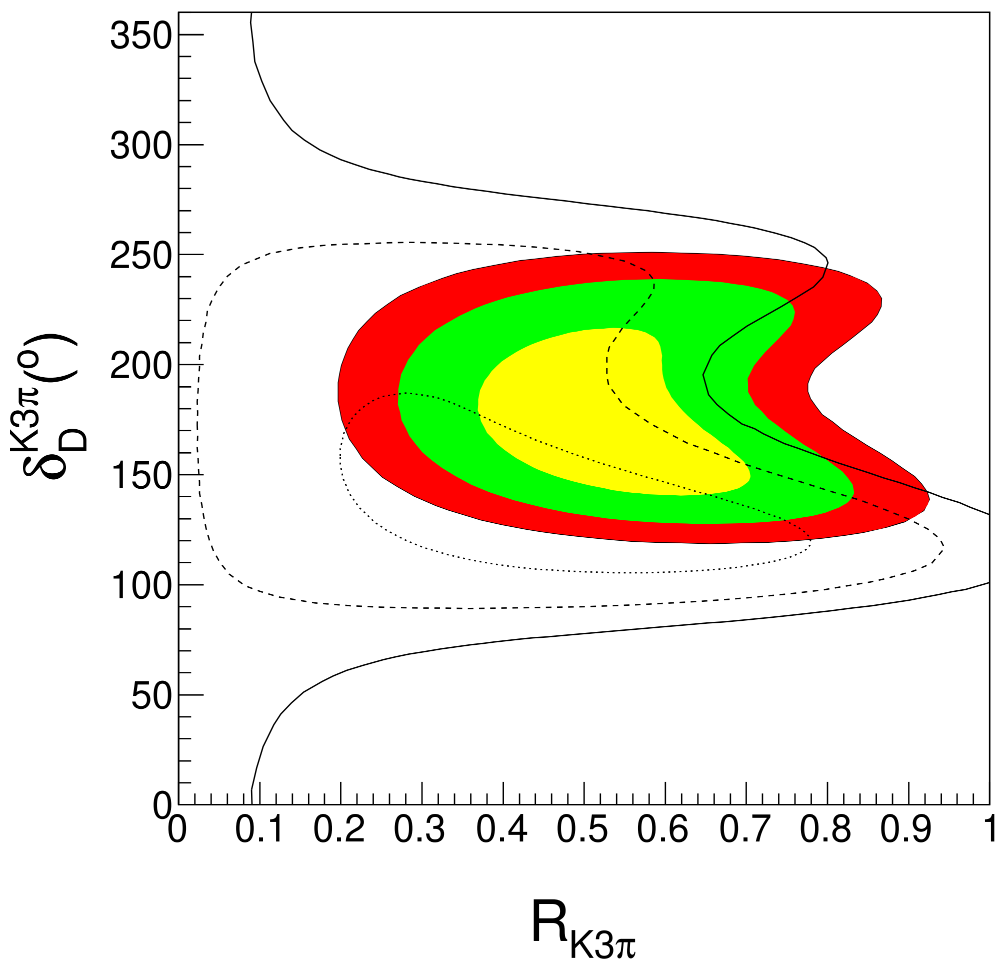
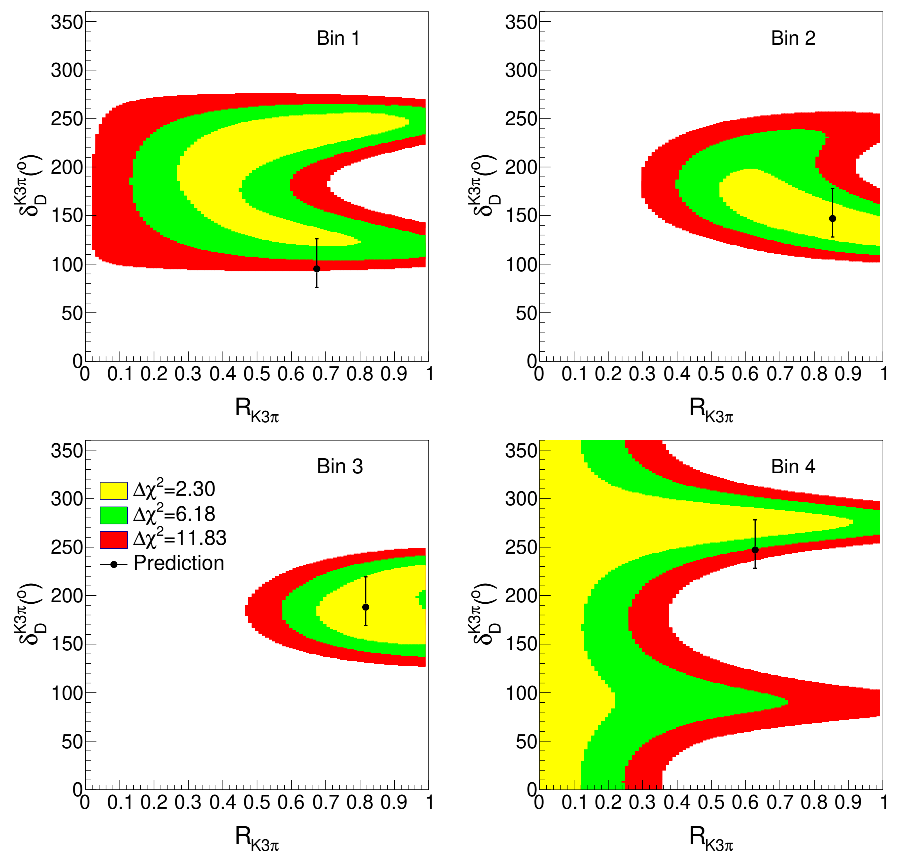


!!!

Slide on B->DK, D->K3pi, with new BES III result

BESIII: JHEP 05 (2021) 164

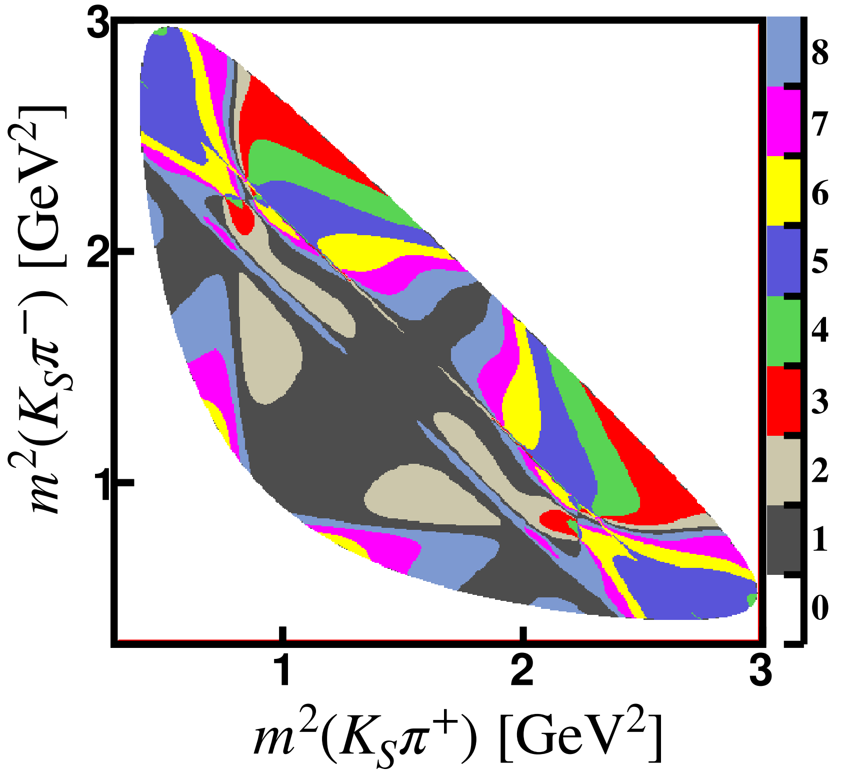




Biggest change for charm inputs to CPV in B since 2018: BES III

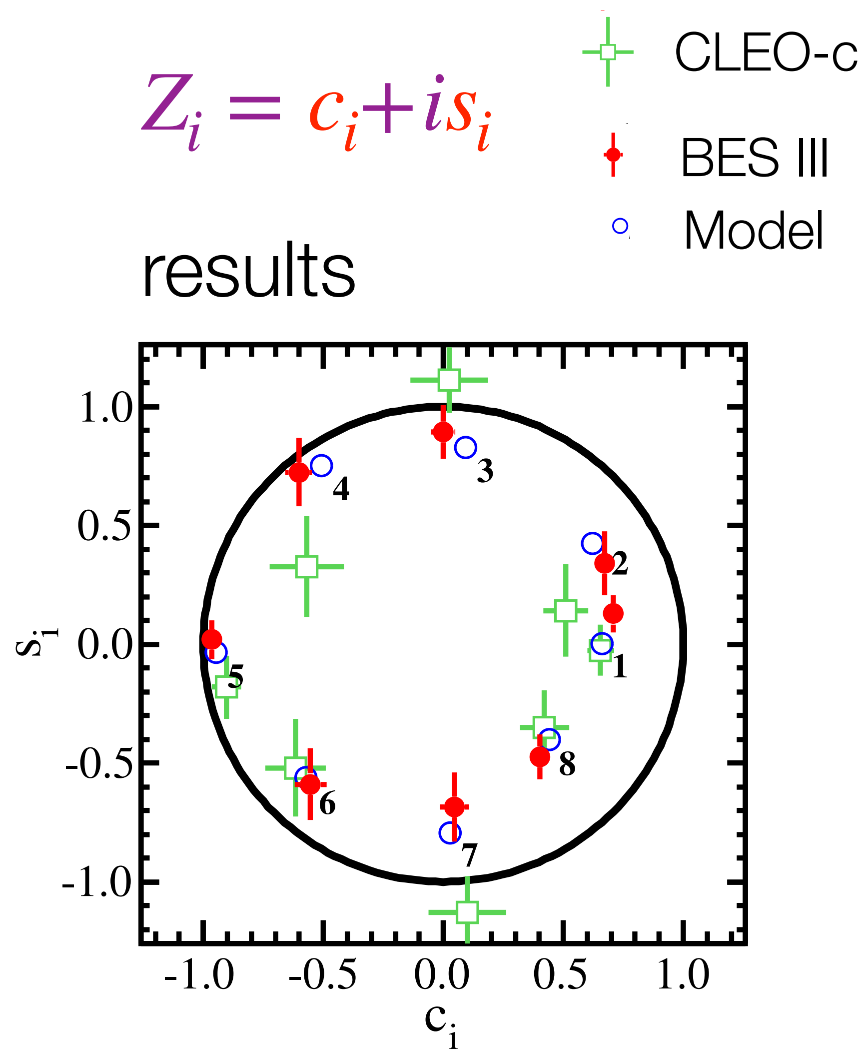
$$D^0 \to K_S\pi^+\pi^-$$

binning

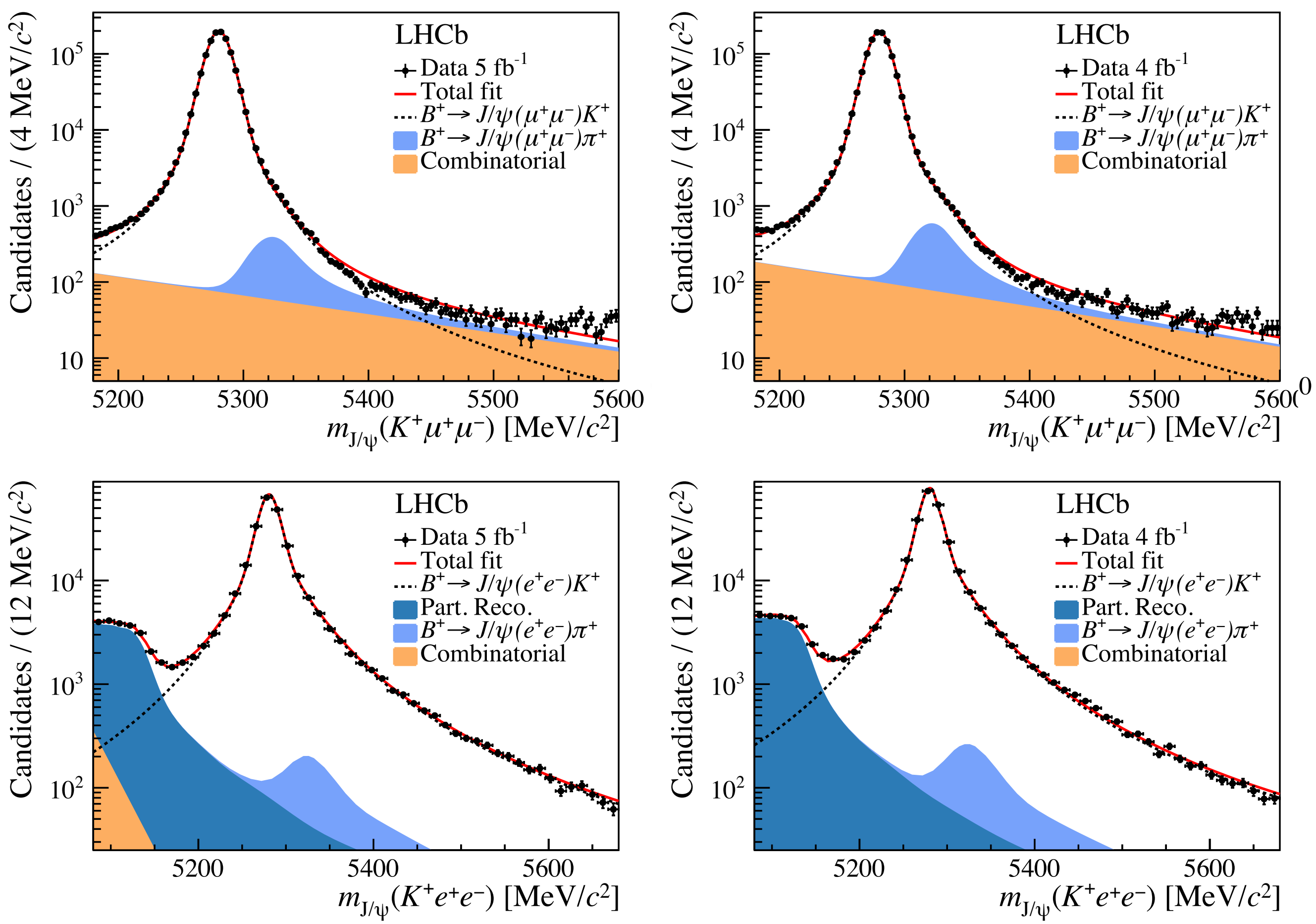


$$Z_i = c_i + i s_i$$

results



Normalisation channel: $B^+ \rightarrow K^+ J/\psi$



$B^+ \rightarrow K^+ J/\psi(\mu^+\mu^-)$

$B^+ \rightarrow K^+ J/\psi(e^+e^-)$

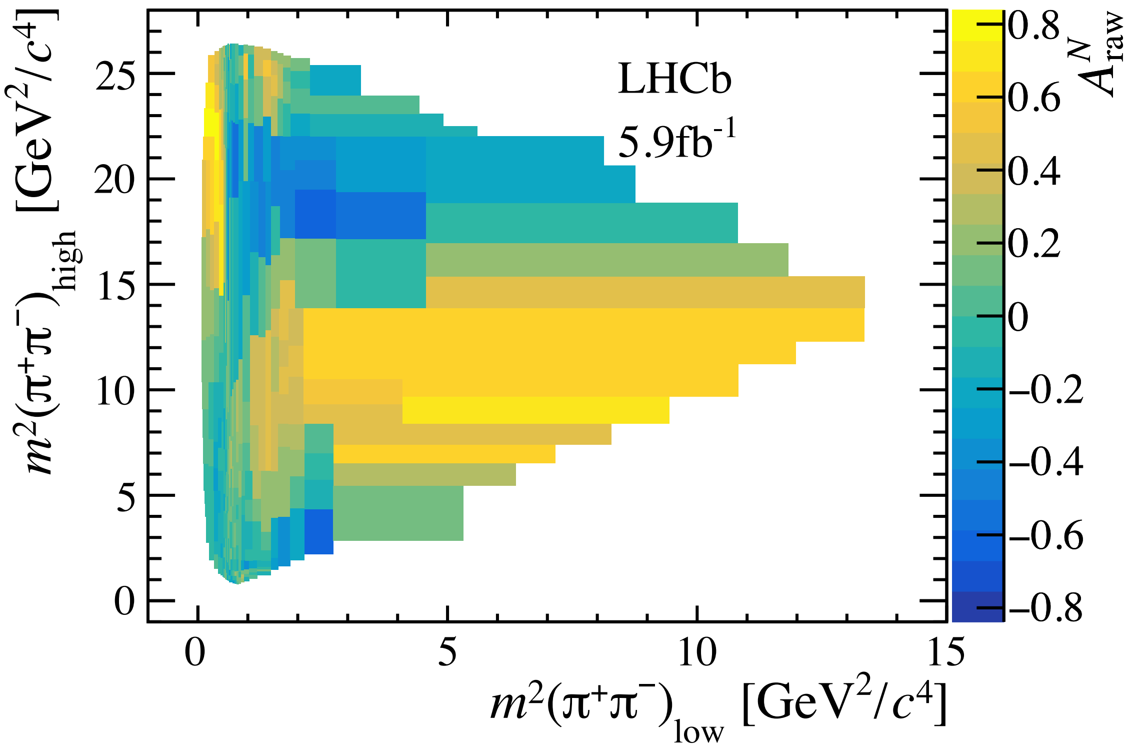
+ further $B^+ \rightarrow K^+ J/\psi(e^+e^-)$ samples (different trigger lines)

LHCb: PRL 112 (2014) 1, 011801
LHCb: PRD 90 (2014) 11, 112004

LHCb: PRL 124 (2020) no.3, 031801
LHCb: PRD101 (2020) no.1, 012006

LHCb-PAPER-2021-049
LHCb-PAPER-2021-050

$B^\pm \to \pi^\pm\pi^+\pi^-$



Color scale:

$$\frac{\Gamma(B^+ \to \pi^+\pi^-\pi^+) - \Gamma(B^- \to \pi^-\pi^+\pi^-)}{\Gamma(B^+ \to \pi^+\pi^-\pi^+) + \Gamma(B^- \to \pi^-\pi^+\pi^-)}$$

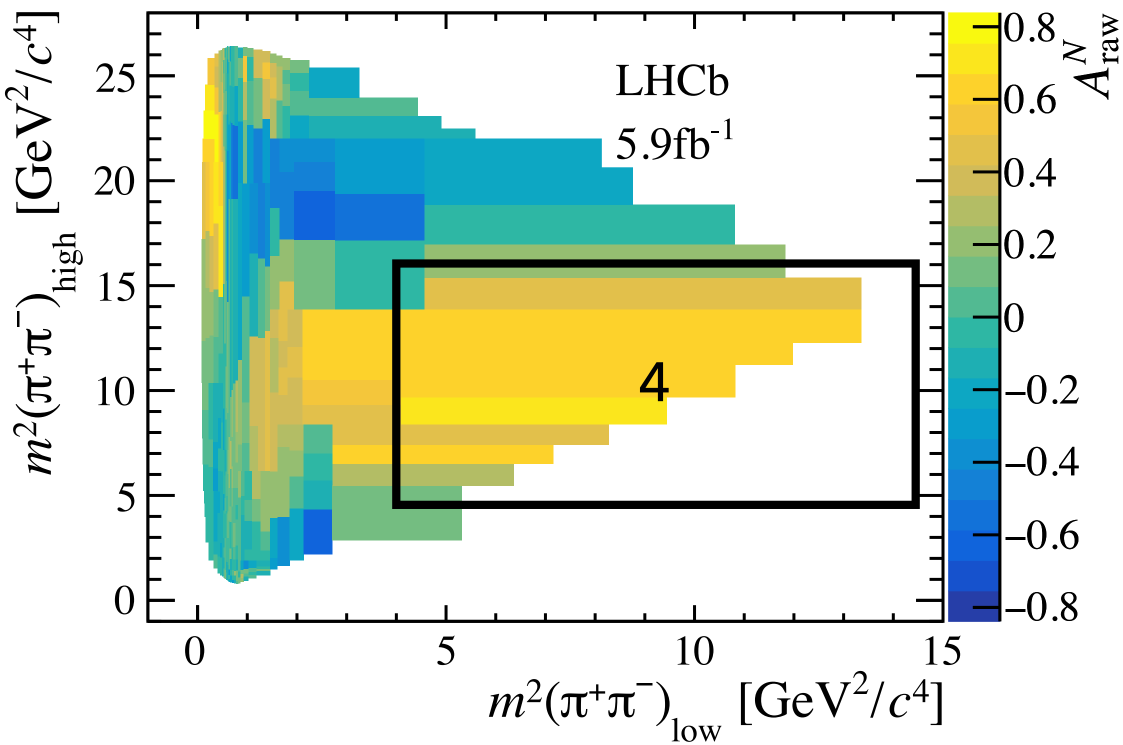
Magalhães et al - PLB 806 (2020) 135490

LHCb: PRL 112 (2014) 1, 011801
LHCb: PRD 90 (2014) 11, 112004

LHCb: PRL 124 (2020) no.3, 031801
LHCb: PRD101 (2020) no.1, 012006

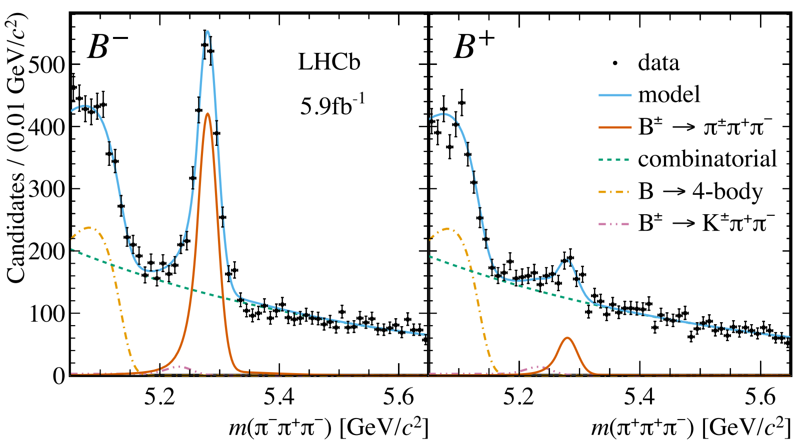
LHCb-PAPER-2021-049
LHCb-PAPER-2021-050

$B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$



Color scale:

$$\frac{\Gamma(B^+ \to \pi^+\pi^-\pi^+) - \Gamma(B^- \to \pi^-\pi^+\pi^-)}{\Gamma(B^+ \to \pi^+\pi^-\pi^+) + \Gamma(B^- \to \pi^-\pi^+\pi^-)}$$



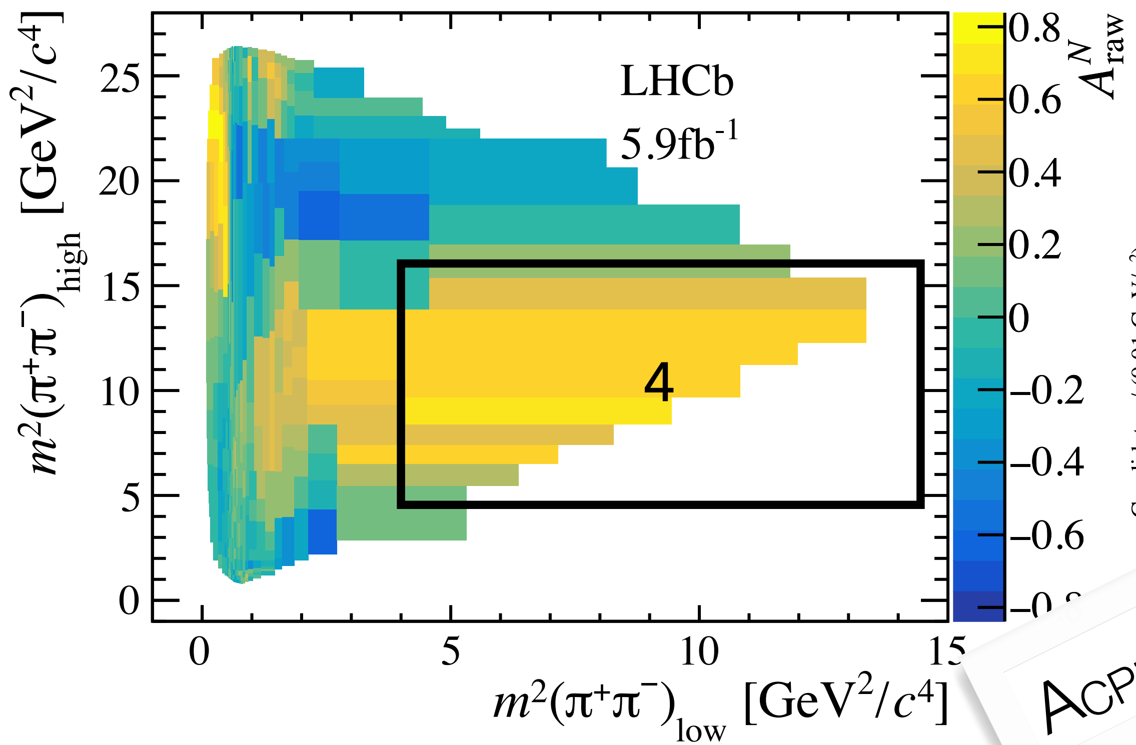
Magalhães et al - PLB 806 (2020) 135490

LHCb: PRL 112 (2014) 1, 011801
LHCb: PRD 90 (2014) 11, 112004

LHCb: PRL 124 (2020) no.3, 031801
LHCb: PRD101 (2020) no.1, 012006

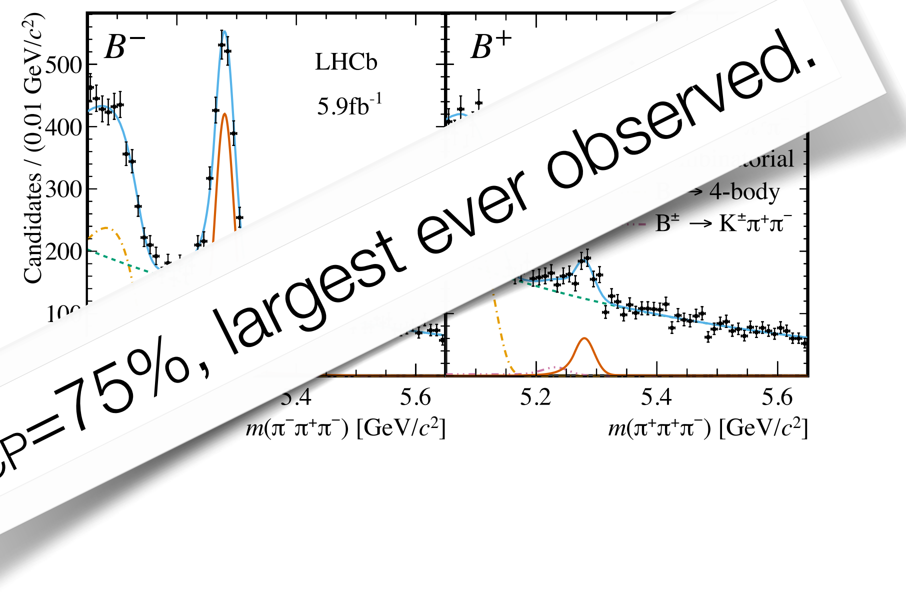
LHCb-PAPER-2021-049
LHCb-PAPER-2021-050

$B^\pm \to \pi^\pm\pi^+\pi^-$



Color scale:

$$\frac{\Gamma(B^+ \to \pi^+\pi^-\pi^+) - \Gamma(B^- \to \pi^-\pi^+\pi^-)}{\Gamma(B^+ \to \pi^+\pi^-\pi^+) + \Gamma(B^- \to \pi^-\pi^+\pi^-)}$$



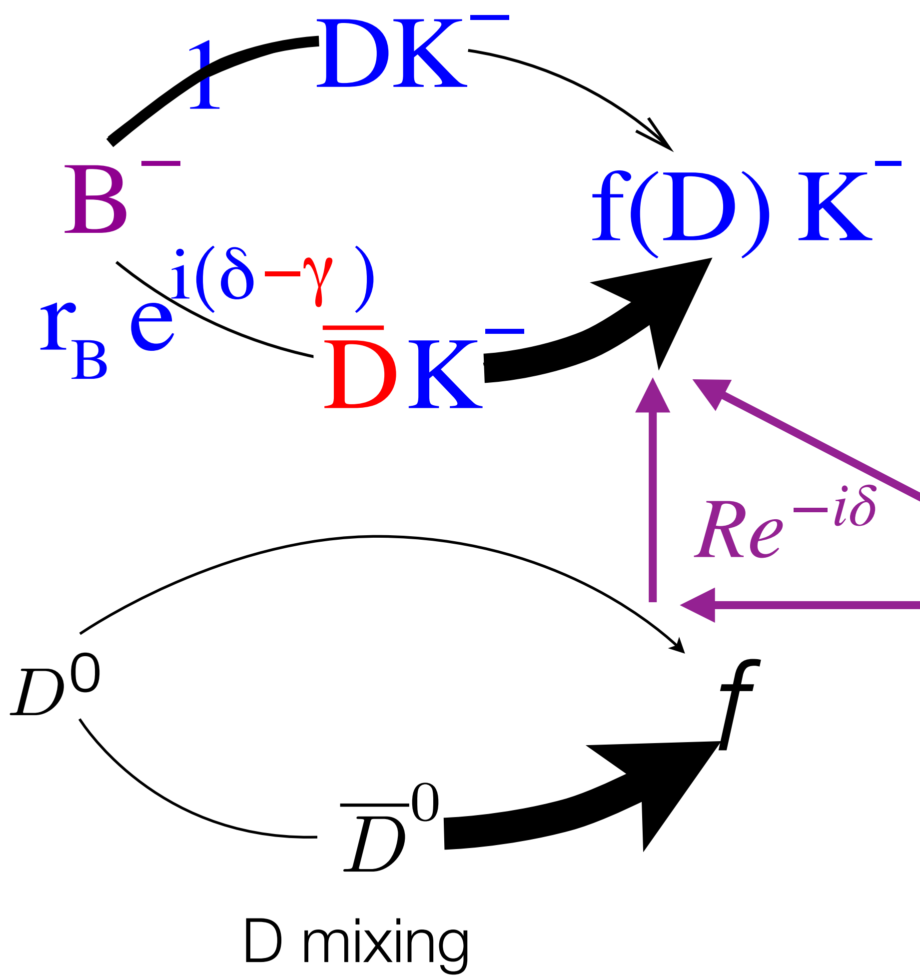
ACP=75%, largest ever observed.

Magalhães et al - PLB 806 (2020) 135490

Heavy flavour physics

- LHCb: Dedicated flavour physics experiment at the LHC. Huge $b\overline{b}$ and $c\overline{c}$ cross section, optimised detector and trigger.
- ATLAS, CMS Main flavour skill: B decays with two muons, such as $B_{(s)} \to \mu\mu$.
- BaBar, BELLE, BELLE II: Know initial state in $e^{+}e^{-}$ collisions, good at reconstructing missing momentum, decays with neutral particles.
- BES III: Its quantum-correlated D-D pairs have unique properties.
- NA62: Dedicated Kaon experiment.

Charm input to CPV in B



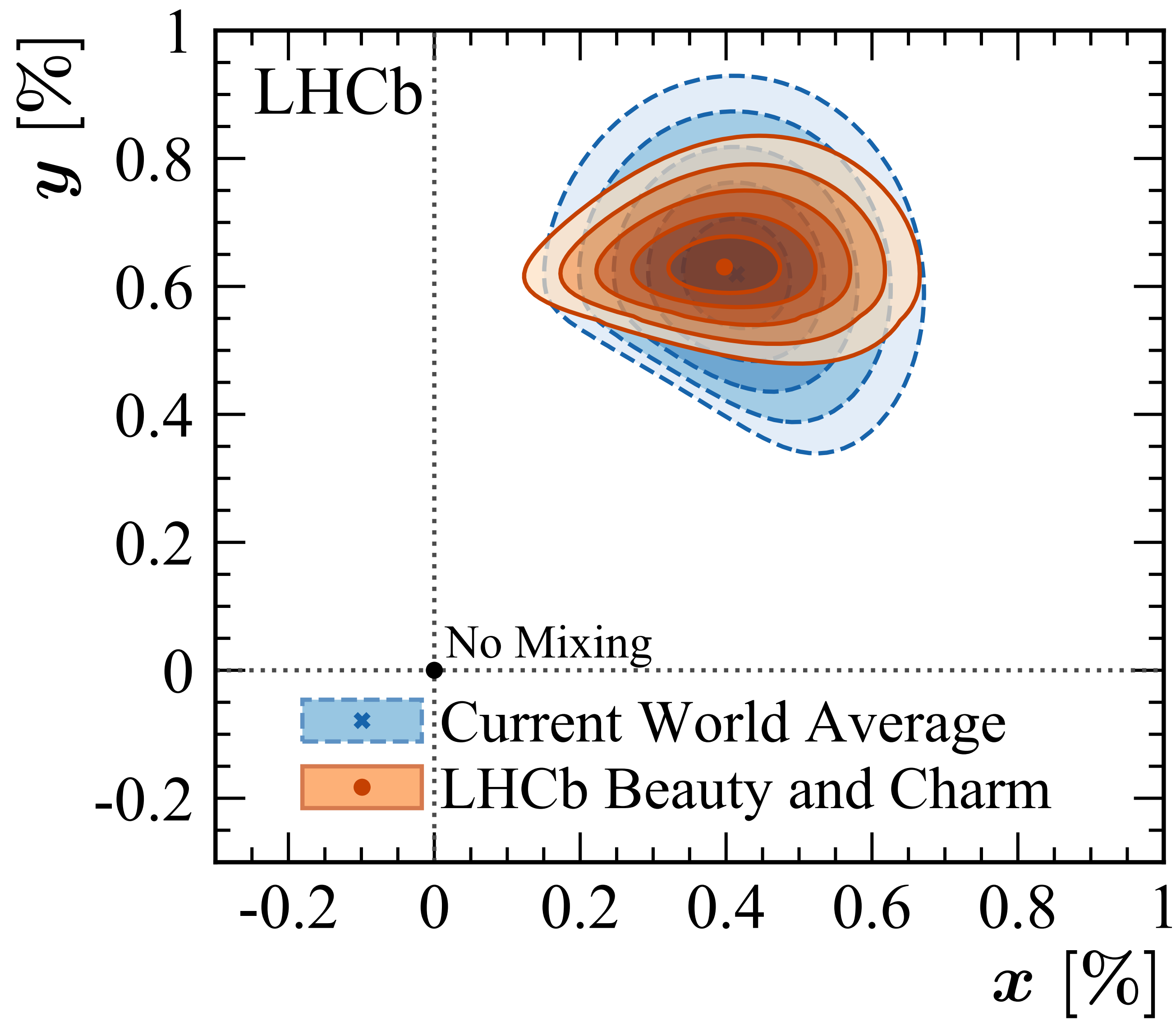
All three processes sensitive to the same charm parameters

(one complex number $Re^{-i\delta}$ per phase-space region)

CLEO-c
BESIII
$\frac{1}{\sqrt{2}}\left(|D^0\rangle + |\overline{D}^0\rangle\right) \rightarrow |f\rangle$

Charm is not just input to $B \to DK$ (and related) for γ. $B \to DK$ is also input to charm.

LHCb: JHEP 12 (2021) 141

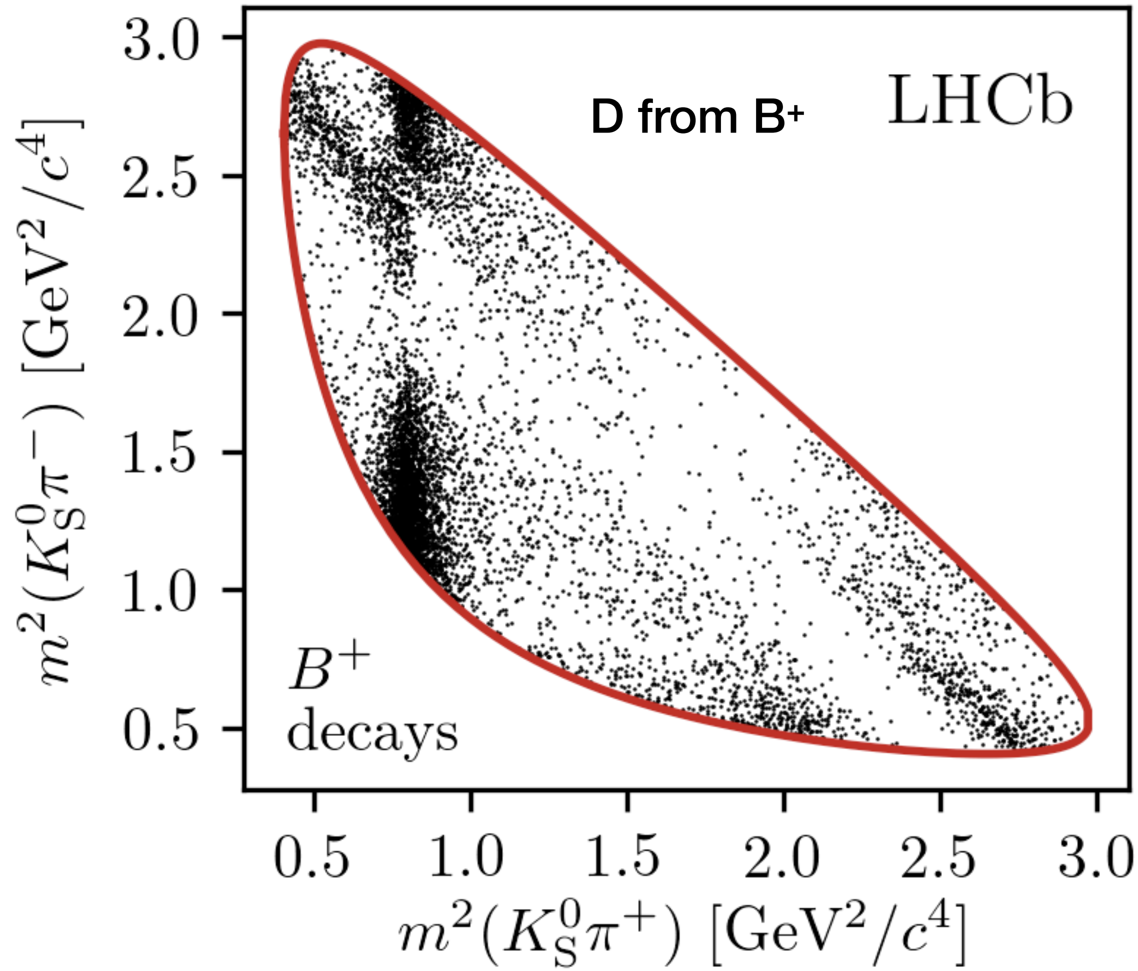


LHCb model-independent γ from $B^{\pm} \to (K_S\pi\pi)_D K$ and $B^{\pm} \to (K_S KK)_D K$

LHCb: JHEP 02 (2021) 169

- Model-independent analysis using CLEO-c and BES III input.
- Plots show LHCb run I+II data
- Result of combined analysis

$$\gamma = \left(68.7^{+5.2}_{-5.1}\right)^{\circ}$$



CLEO-c input:: Phys. Rev. D 82 112006. BESIII input:
Model-independent method: Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003). Optimal binning: Bondar, Poluektov hep-ph/0703267v1 (2007)

LHCb model-independent γ from $B^\pm \to (K_S\pi\pi)_D K$ and $B^\pm \to (K_SKK)_D K$

LHCb: JHEP 02 (2021) 169

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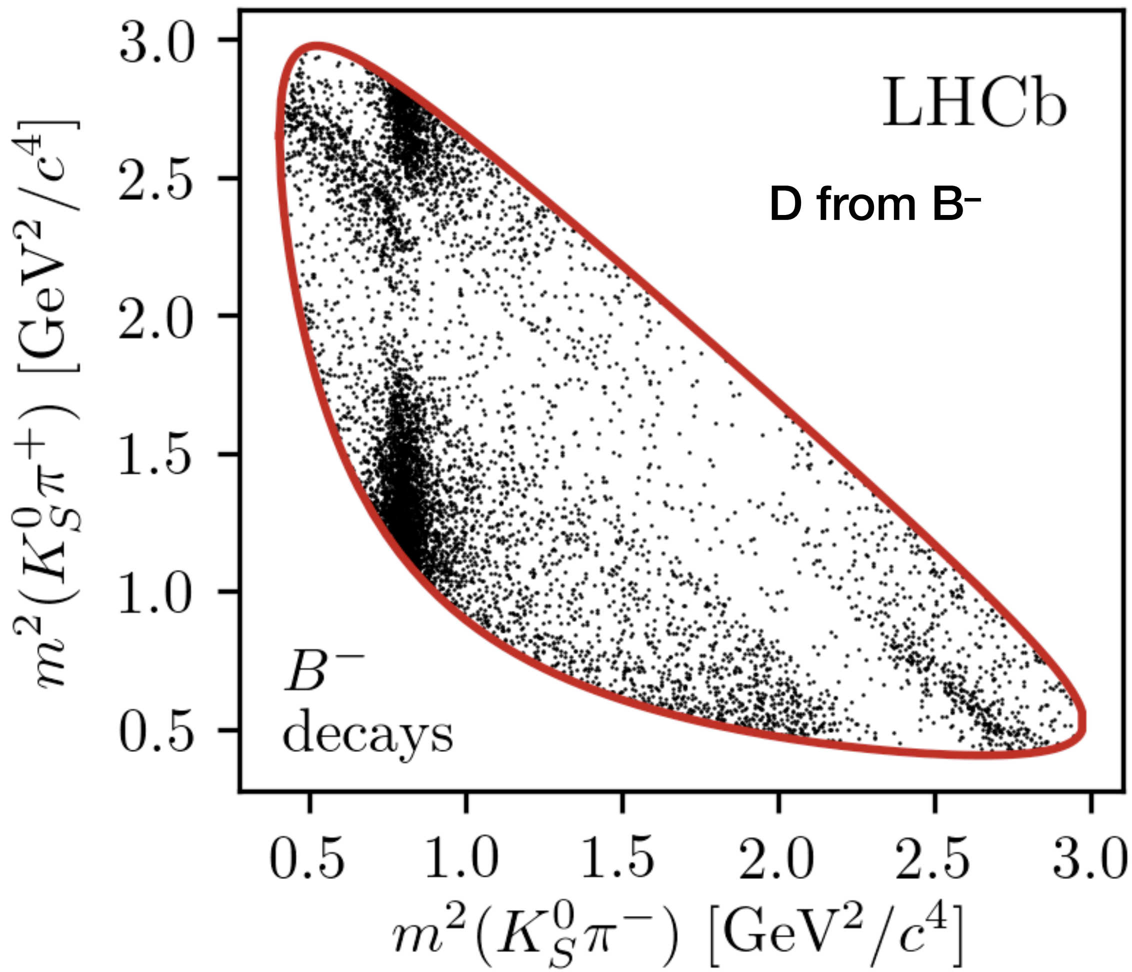

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Model-independent method: Giri, Grossmann, Soffer, Zupan, Phys Rev D 68, 054018 (2003). Optimal binning: Bondar, Poluektov hep-ph/0703267v1 (2007)

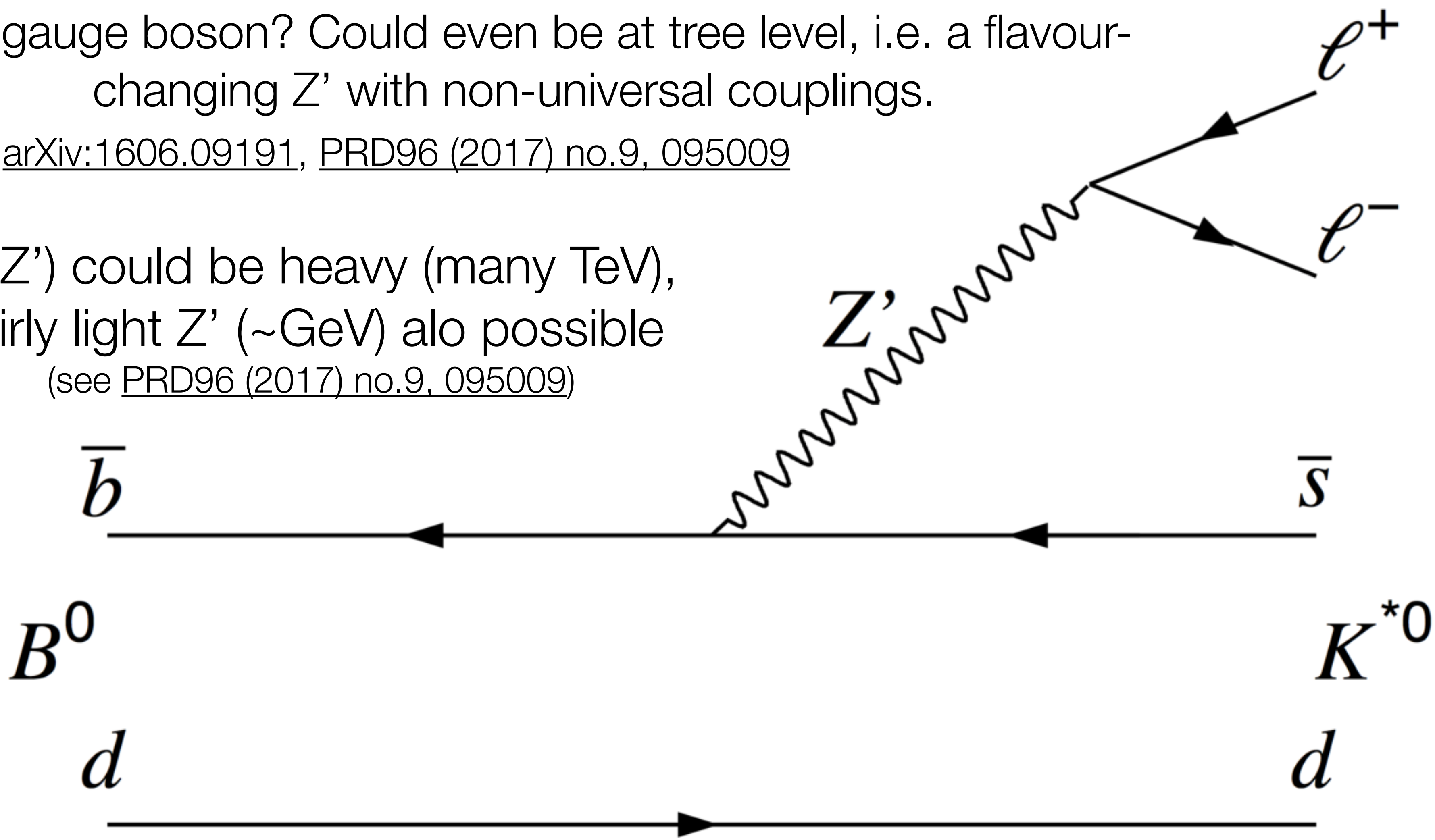
Interpretation

New gauge boson? Could even be at tree level, i.e. a flavour-changing Z' with non-universal couplings.

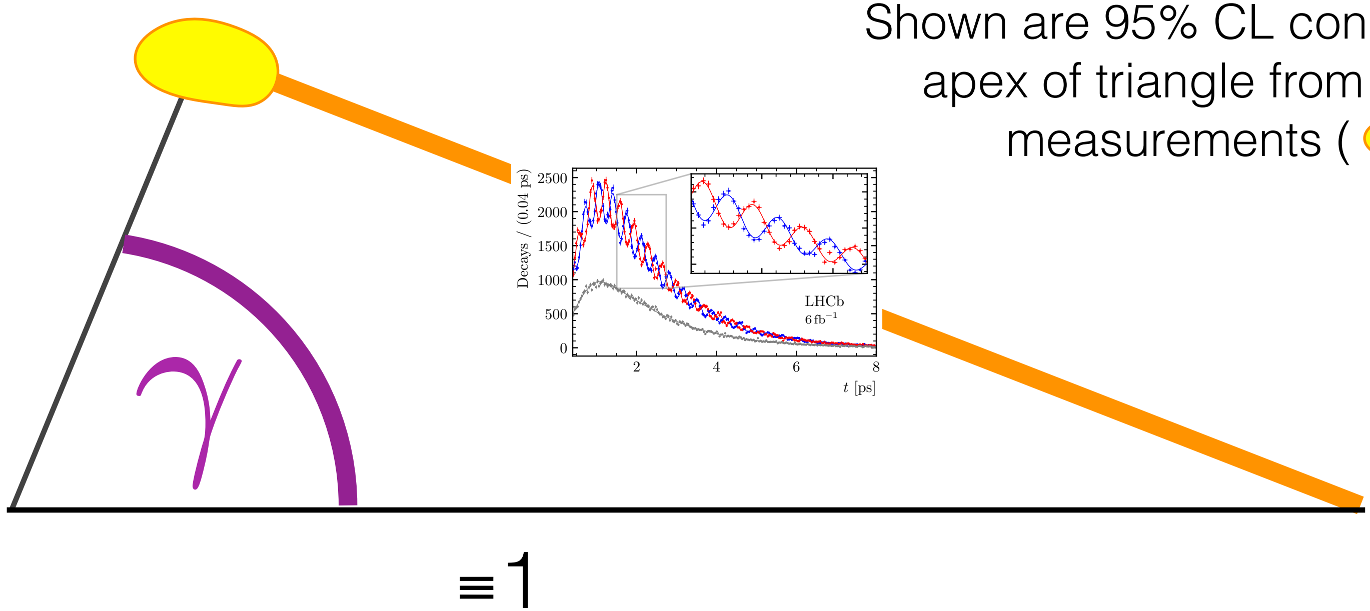
e.g. arXiv:1606.09191, PRD96 (2017) no.9, 095009

m(Z') could be heavy (many TeV), fairly light Z' (~GeV) alo possible

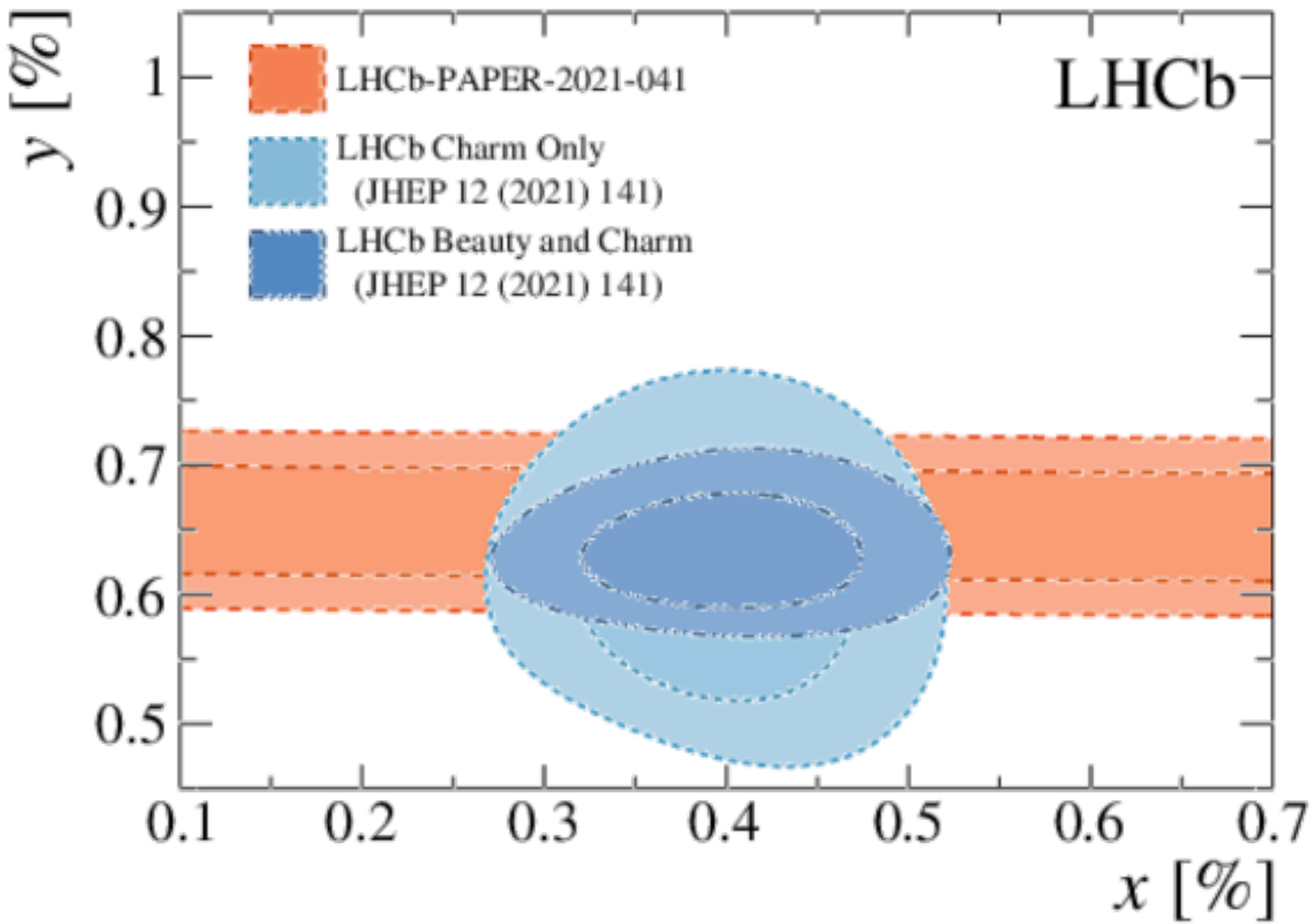
(see PRD96 (2017) no.9, 095009)

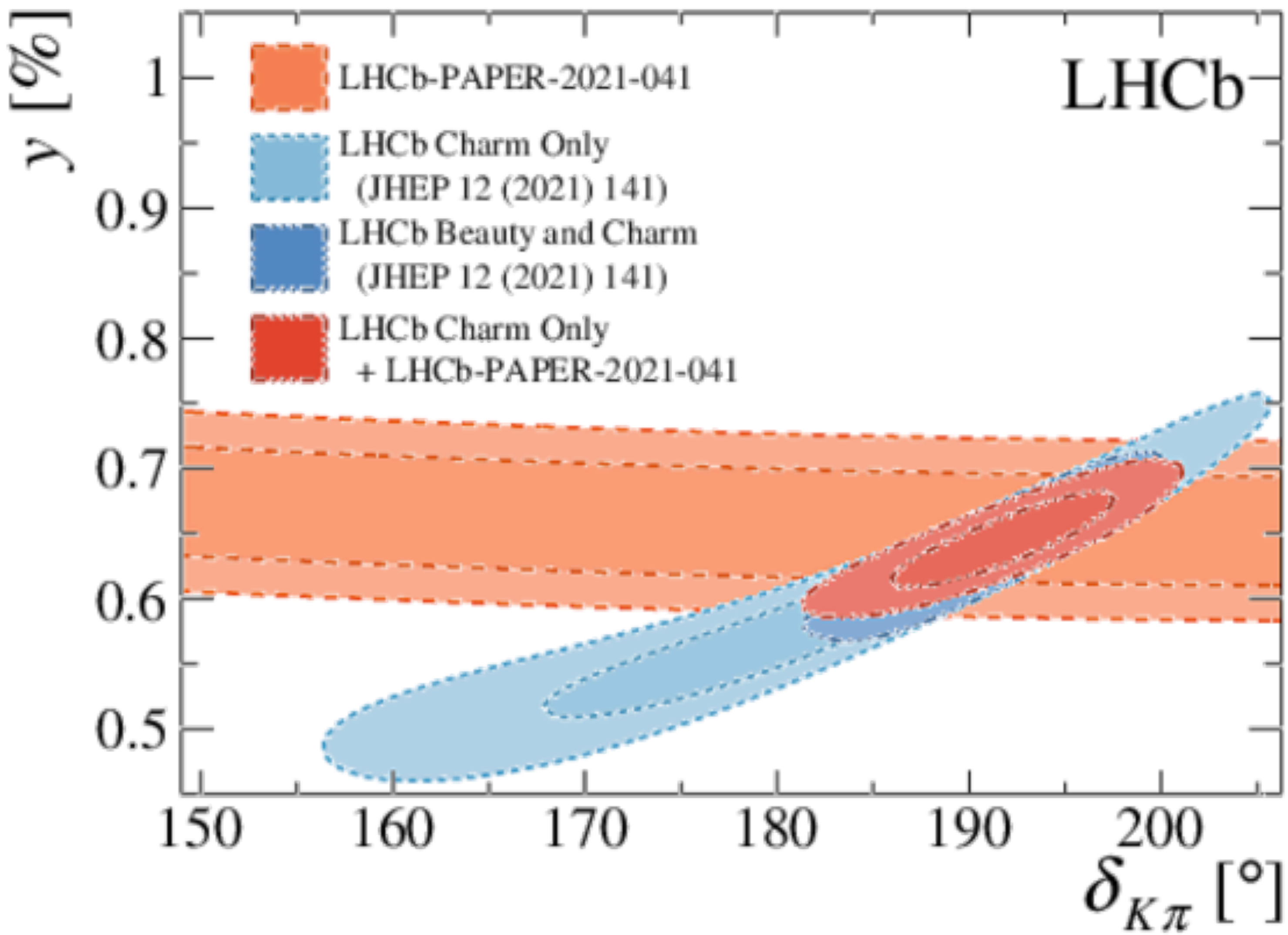


Unitarity triangle



Shown are 95% CL constraints on apex of triangle from various measurements ( )


LHCb-PAPER-2021-041
LHCb Charm Only
(JHEP 12 (2021) 141)
LHCb Beauty and Charm
(JHEP 12 (2021) 141)
LHCb
y [%]
x [%]
1
0.9
0.8
0.7
0.6
0.5
0.1
0.2
0.3
0.4
0.5
0.6
0.7



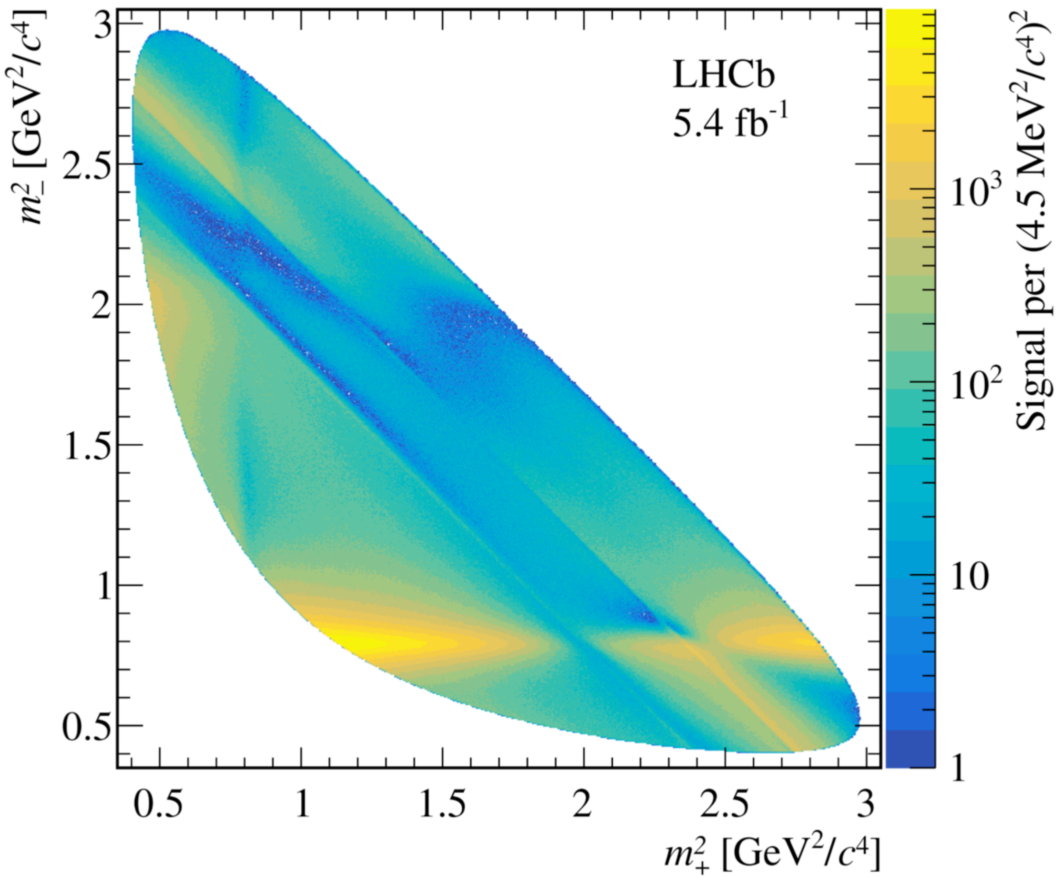
LHCb-PAPER-2021-041
LHCb Charm Only
(JHEP 12 (2021) 141)
LHCb Beauty and Charm
(JHEP 12 (2021) 141)
LHCb Charm Only
+ LHCb-PAPER-2021-041
LHCb
y [%]
1
0.9
0.8
0.7
0.6
0.5
150
160
170
180
190
200
δ_Kπ [°]

Model-independent analysis of charm mixing in $D^0 \to K_S \pi^+ \pi^-$

LHCb: PRL 127 (2021) 11, 111801

Uses input from CLEO-c and BES III to remove amplitude model dependence

Parameter	Value
$x\ [10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$
$y\ [10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$
$\lvert q/p \rvert$	0.996 ± 0.052
ϕ	$-0.056\,^{+0.047}_{-0.051}$

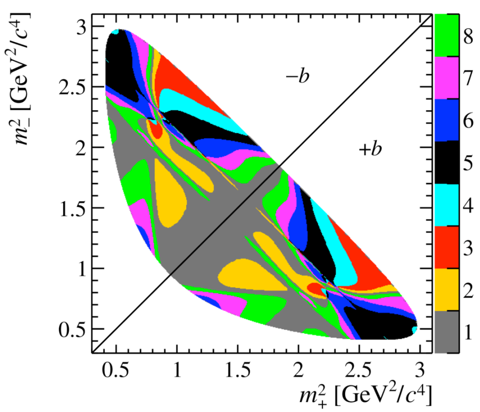


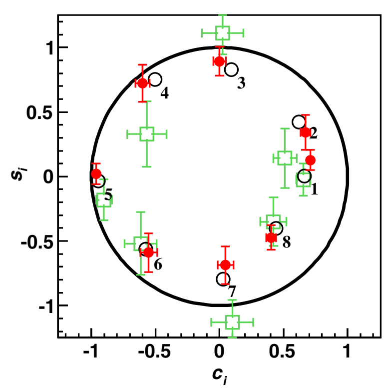
This is real data, not simulation. 30.6M signal events

Model-independent analysis of charm mixing in $D^0 \to K_S \pi^+ \pi^-$

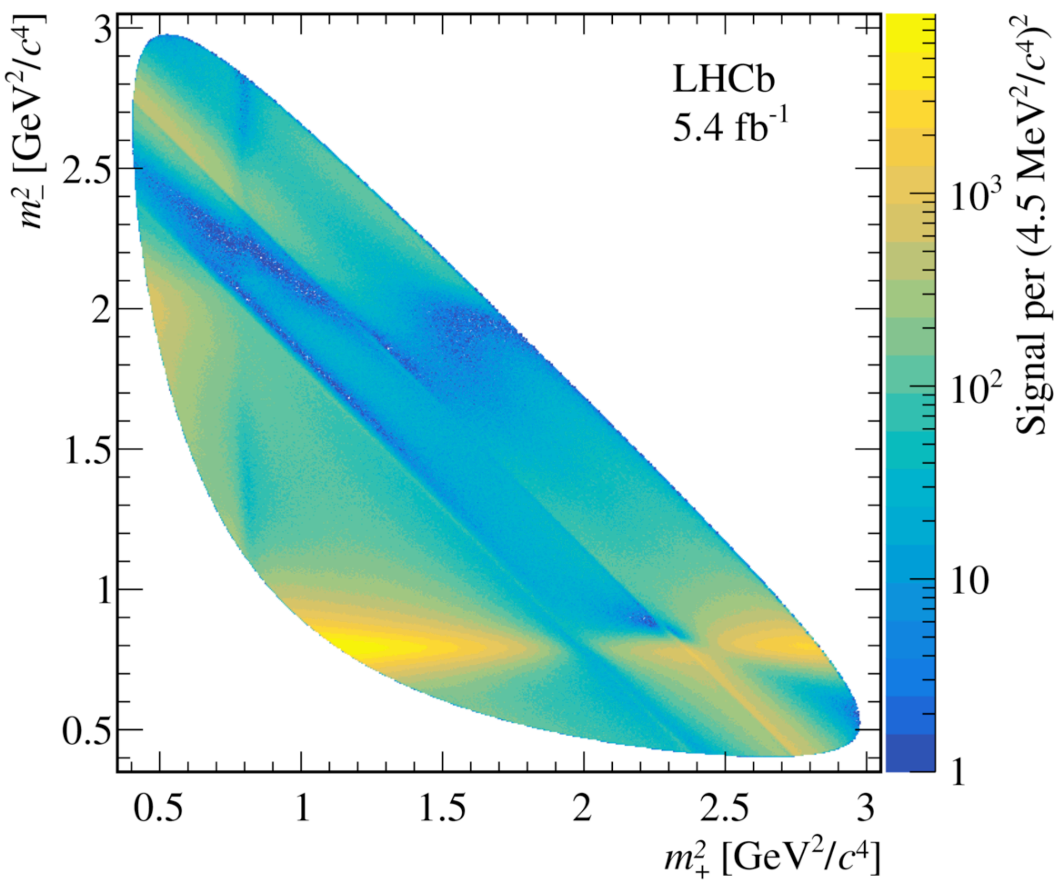
LHCb: PRL 127 (2021) 11, 111801

Uses input from CLEO-c and BES III to remove amplitude model dependence





Time-dependent analysis in each bin



This is real data, not simulation. 30.6M signal events