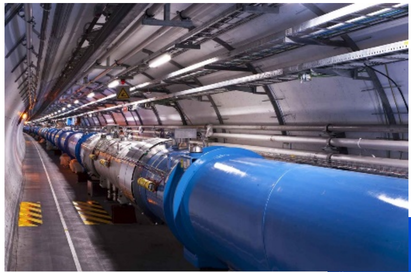
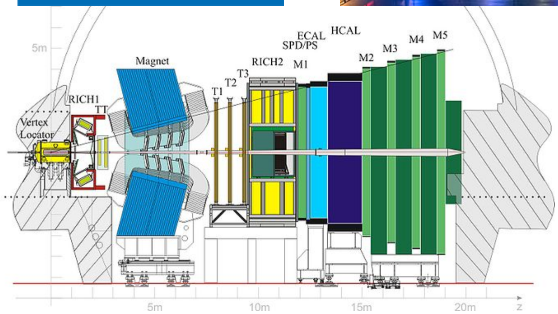
A precise measurement of γ

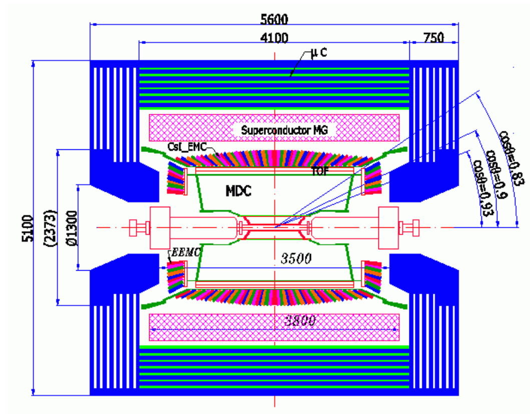
Sneha Malde
University of Oxford

Introduction



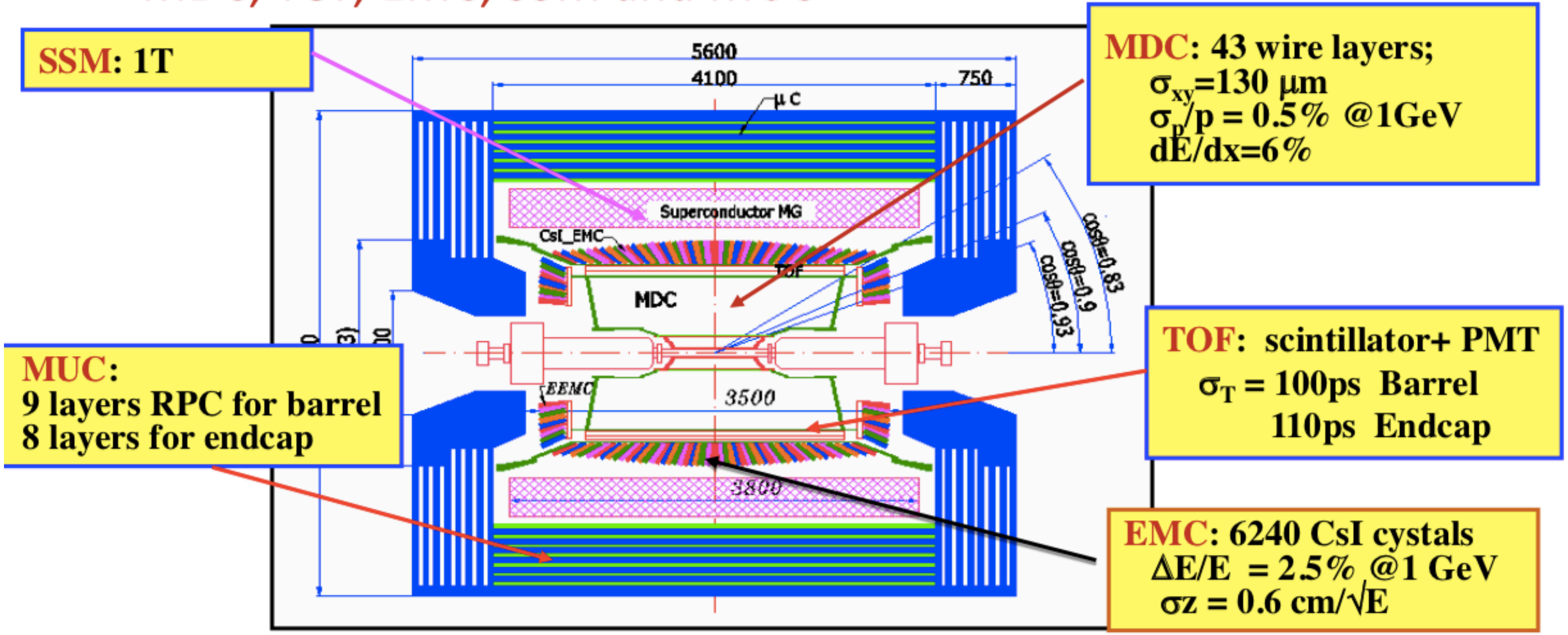


Oct 2020 arXiv:2010.08483



March 2020 PRD 101 112002

BESIII detector

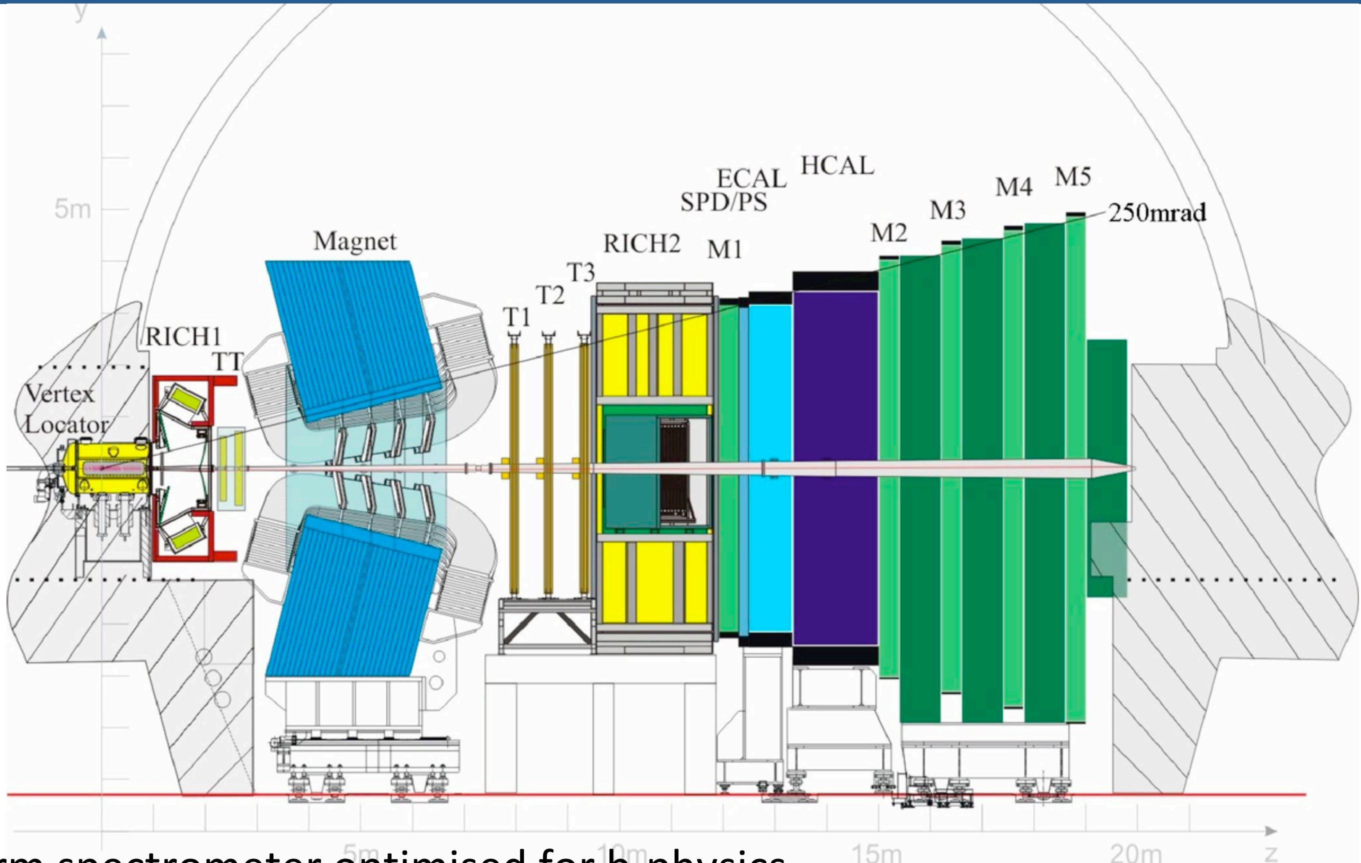


BESIII, Beijing @ BEPCII e^+e^- collider, Hermetic 4π detector – full event coverage.

Does a variety of charm & light hadron physics √s = 2-4.6 GeV- Known energy of collision

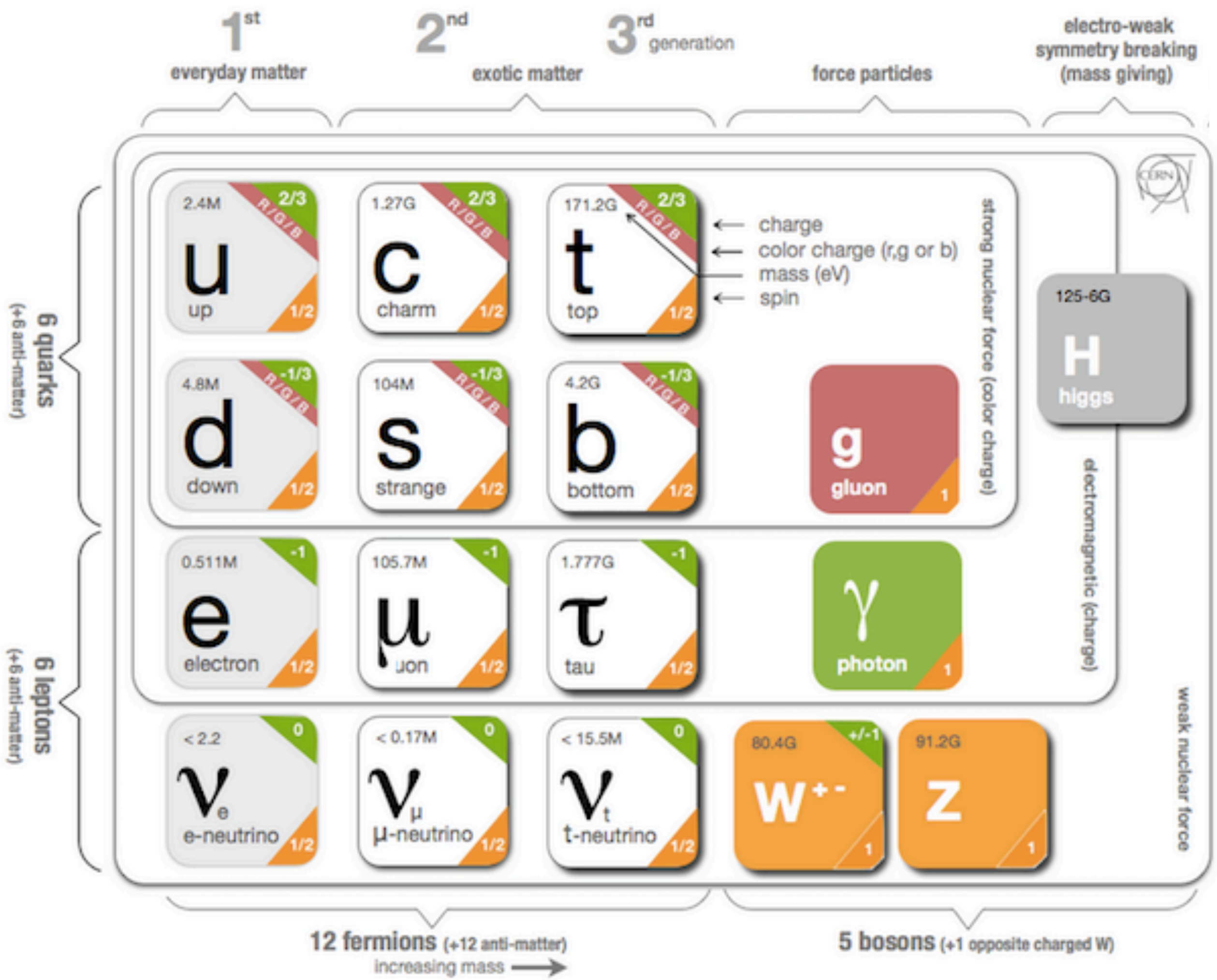
√s = 3.776 GeV – largest sample in the world

LHCb detector

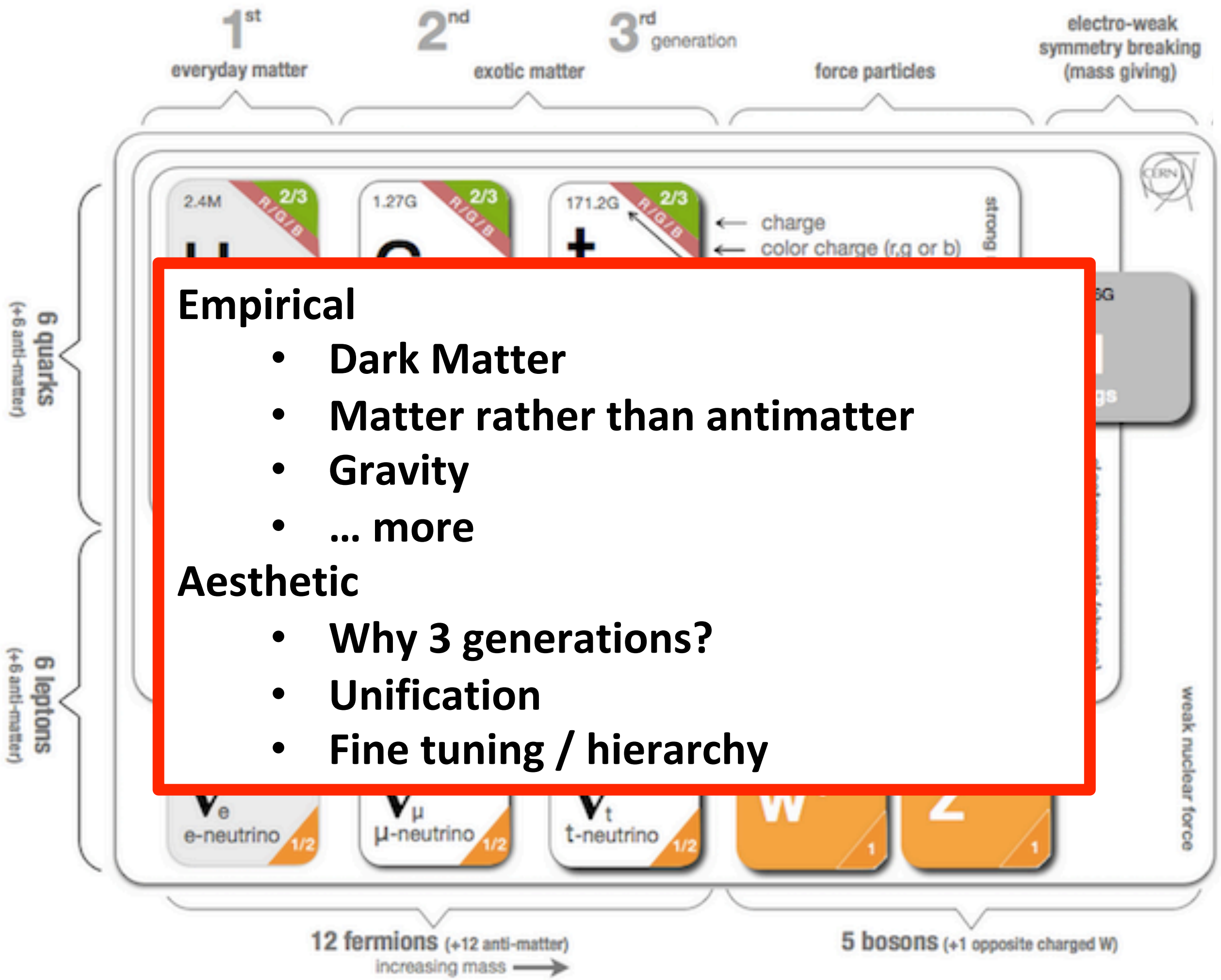


A forward-arm spectrometer optimised for b-physics
Excellent vertexing, PID, tracking
Ability to trigger on fully hadronic decays
Narrow acceptance, unknown quark collision energy

The Standard Model



The Standard Model – not full story



Empirical

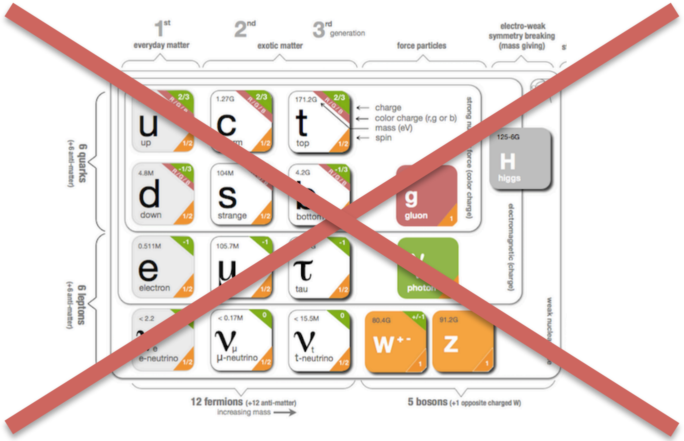
- **Dark Matter**
- **Matter rather than antimatter**
- **Gravity**
- **… more**

Aesthetic

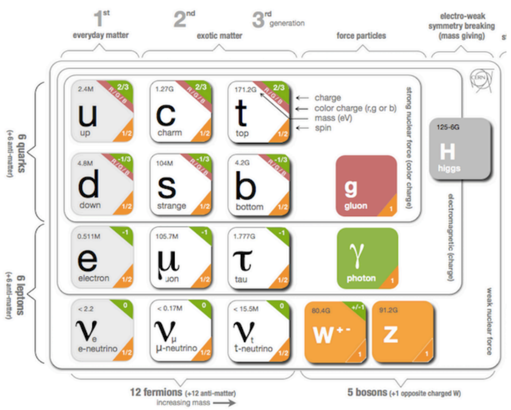
- **Why 3 generations?**
- **Unification**
- **Fine tuning / hierarchy**

Where is New Physics

It is not a case that



But rather



Fully theory

??????

New Physics (NP)

Goal

CP Violation (CPV)

Matter dominance of the universe can be investigated by studying CP violation

CP is a type of "symmetry"

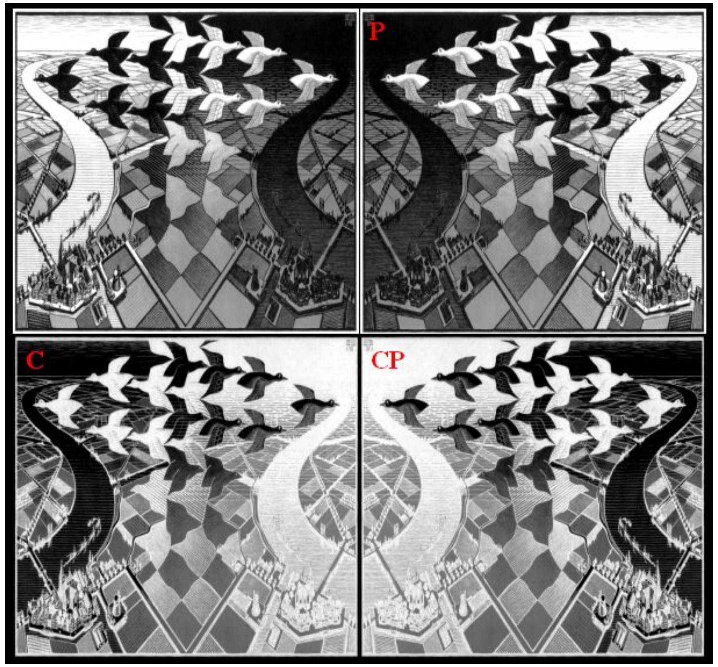
Relates to the laws of physics of particles and their corresponding anti-particles.

Initial expectations (in the 1950s) assumed CP was conserved.

CPV first observed in 1964 , at a very small level

Incorporated into the SM

P = mirror reflection



C = black➔white

There exists (at least) one source of CPV that is yet to be discovered.

A promising area - CP violation

- Probing CPV further may uncover the effects of NP
- CKM matrix describes the coupling of the weak and mass eigenstates of quarks.
- Single free phase in the CKM matrix gives rise to Standard Model CPV

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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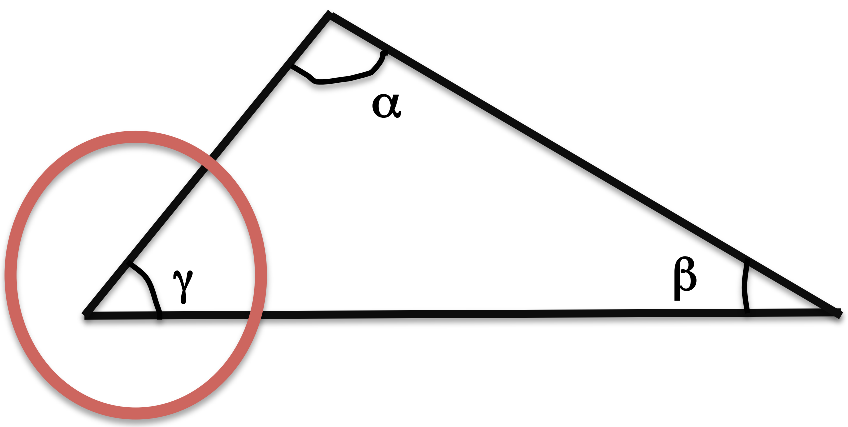


Using the properties of unitary matrices

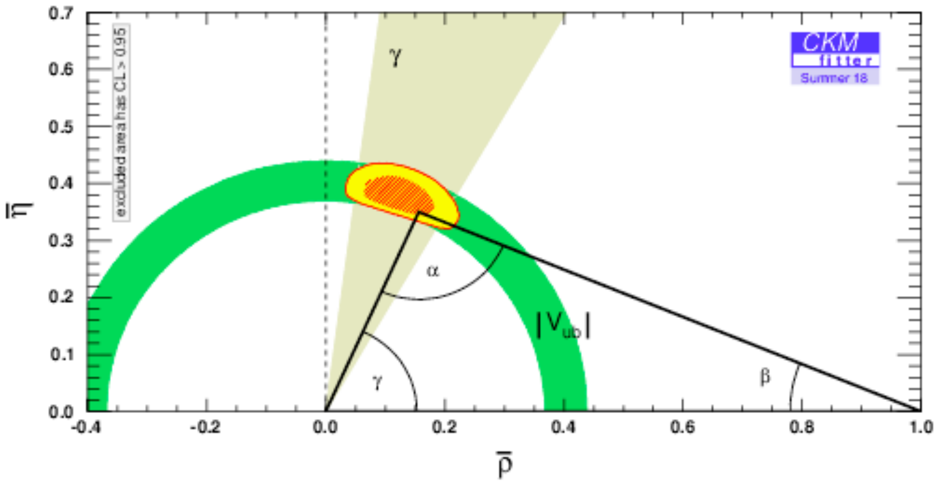
$$0 = 1 + \frac{V_{tb}^{*} V_{td}}{V_{cb}^{*} V_{cd}} + \frac{V_{ub}^{*} V_{ud}}{V_{cb}^{*} V_{cd}}$$

$$\gamma = -\arg\left(\frac{V_{ud} V_{ub}^{*}}{V_{cd} V_{cb}^{*}}\right)$$

CKM angle γ

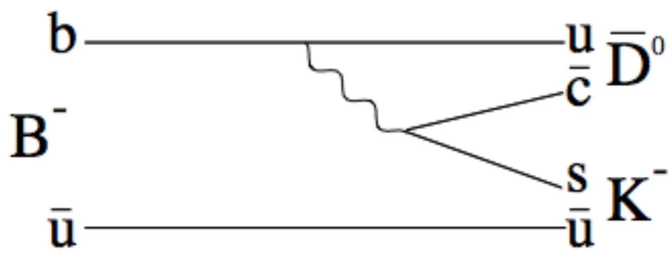
Direct measurement

- γ only angle easily accessible at tree level.
- Tree level measurements are "SM" benchmark values - no interference from New Physics
- Effectively no theory uncertainties.

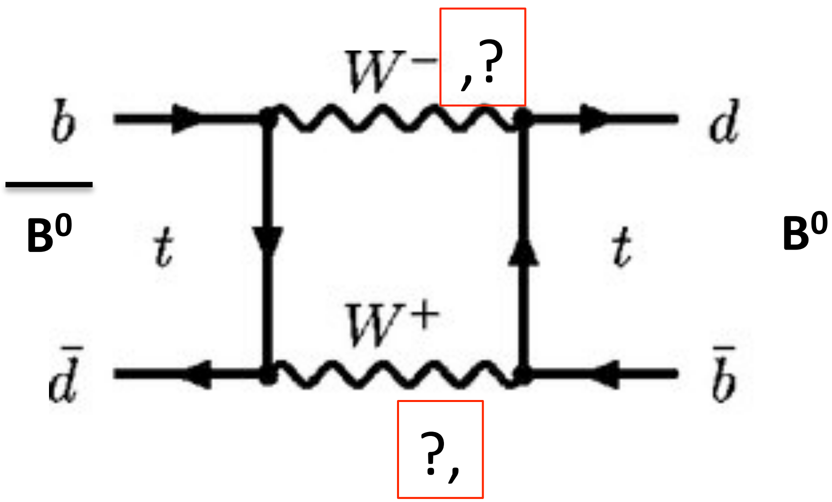


Standard model benchmark

Tree level



Loop level



Plots and results from CKMFitter

CKM angle γ

Direct measurement vs Indirect determination

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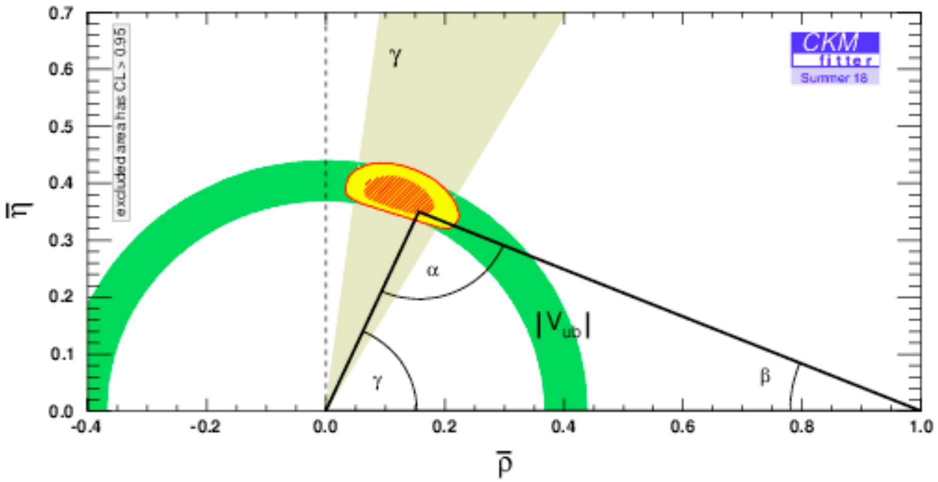
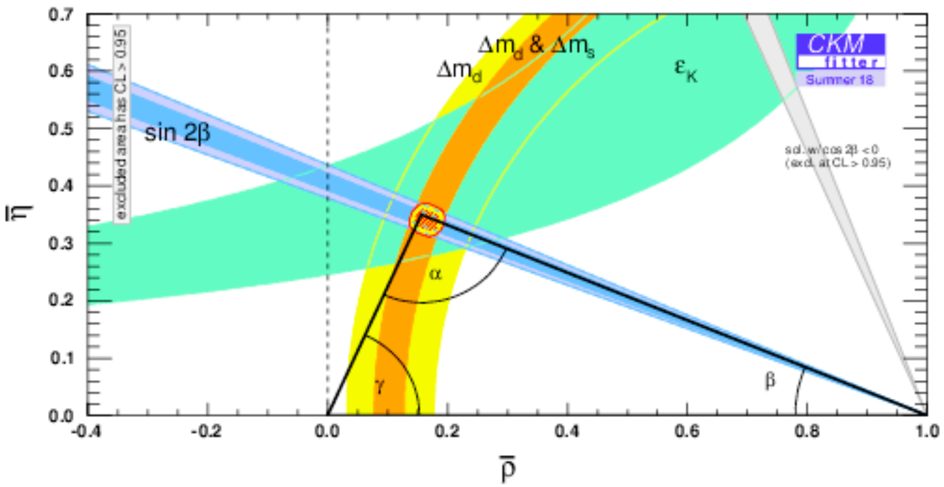
- Assume the triangle is closed. Measurements of the other sides and angles are used to infer the value of γ.
- New Physics can contribute – potential for different central value.





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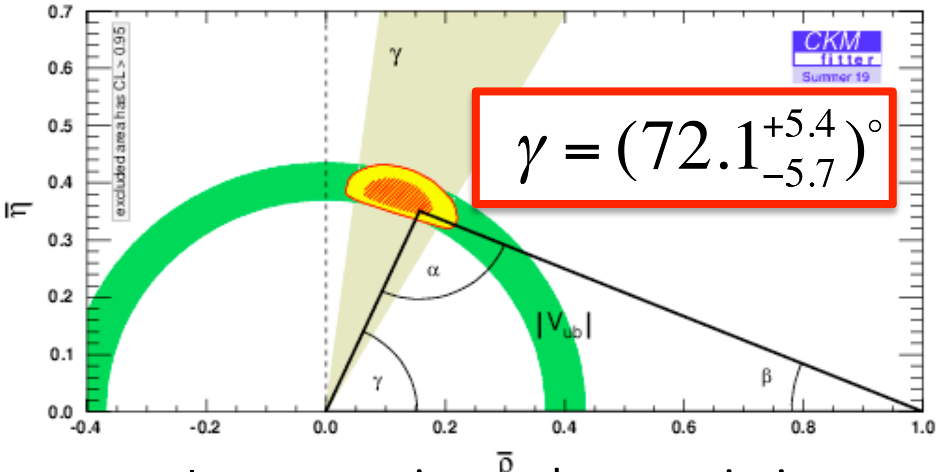
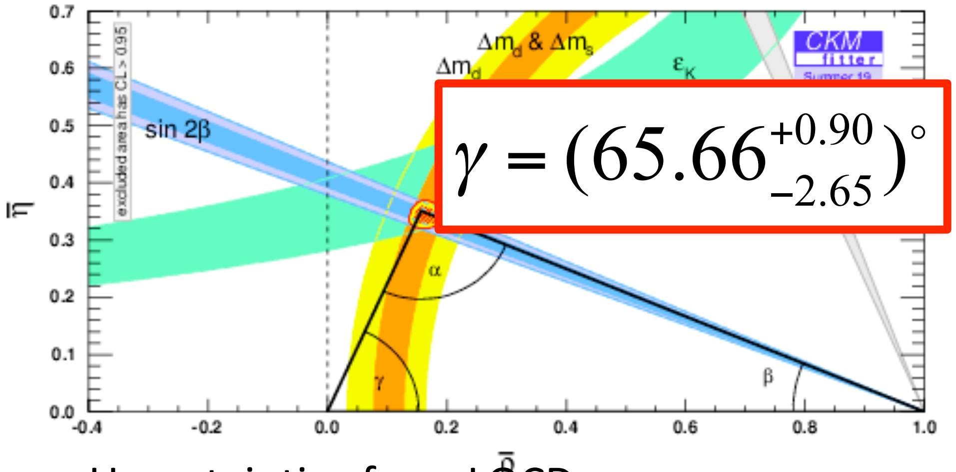


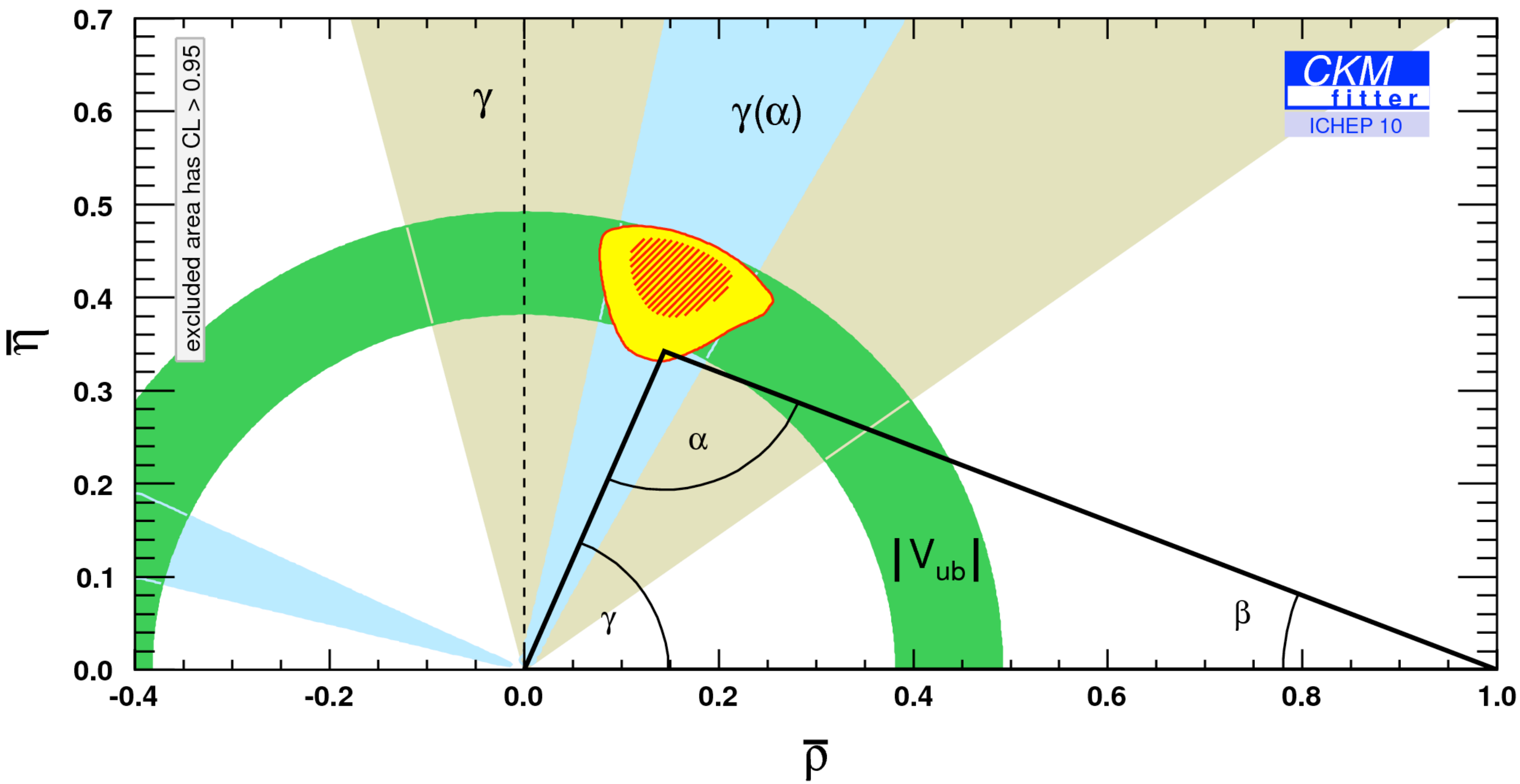
- Large experimental uncertainties.
- **Significant progress possible in next few years**

- Assume the triangle is closed. Measurements of the other sides and angles are used to infer the value of γ.
- New Physics can contribute – potential for different central value.



- Uncertainties from LQCD
- Can expect reduction in time

When data collection began: 2010

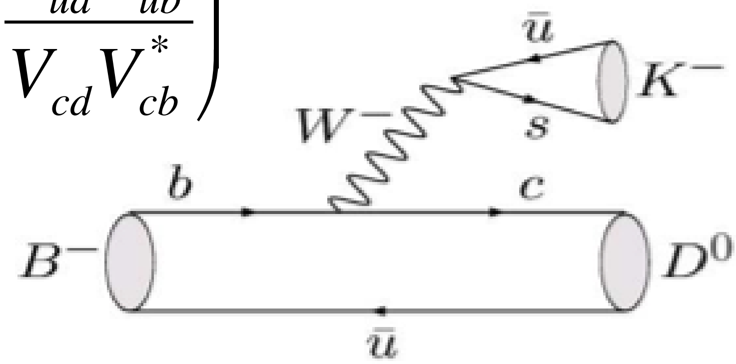


LHCb data 2011-2018

BESIII data 2010+2011

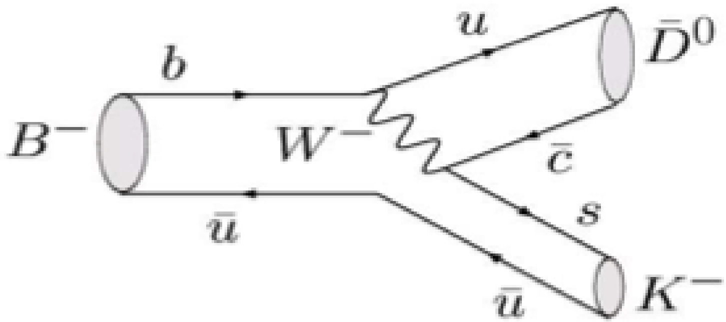
Measurements of γ using B→DK

$$\gamma = -\arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



b → c (favoured)

b → u (suppressed)



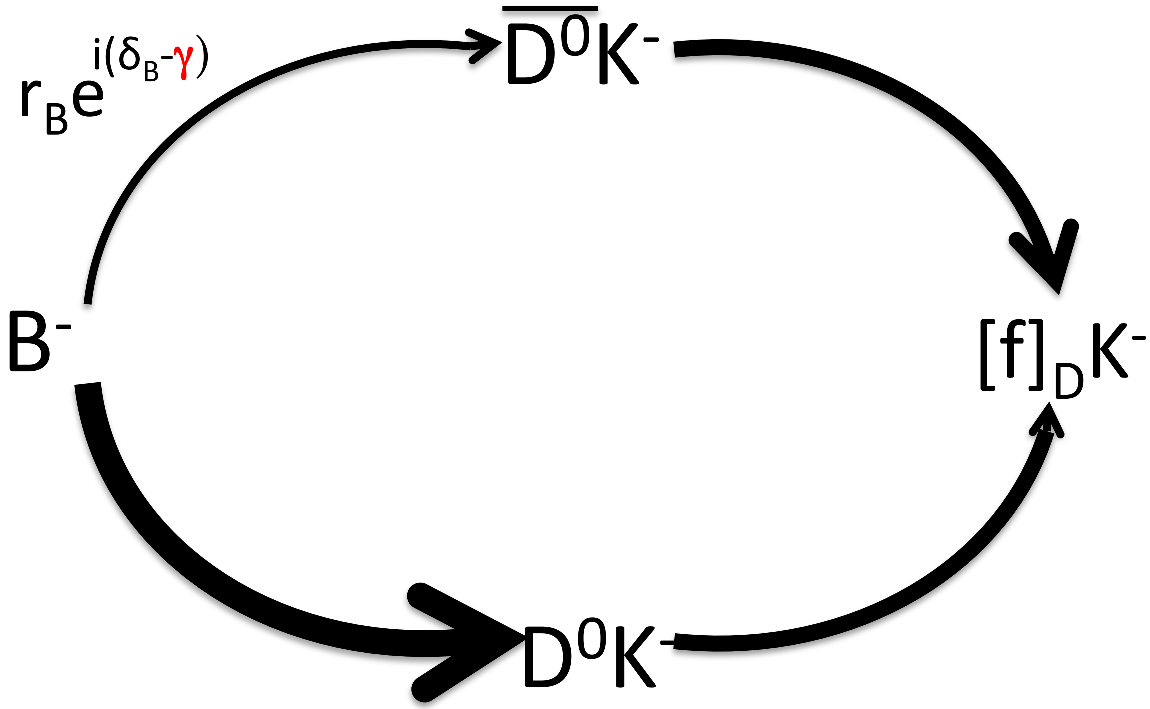
Amplitude ratio between two decays is $r_B e^{i(\delta_B - \gamma)}$

r_B and δ_B "nuisance parameters" to be measured alongside γ

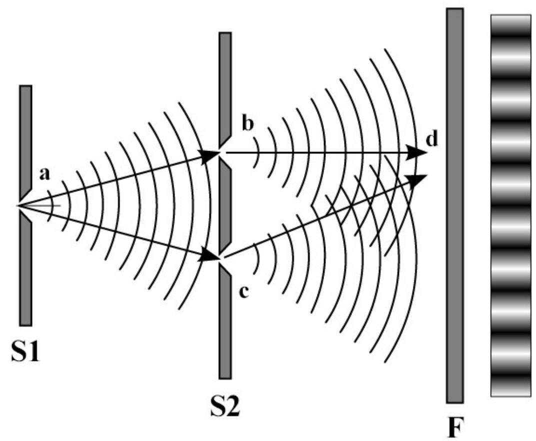
r_B – amplitude ratio, δ_B - strong phase difference

Interference possible if D^0 and $\bar{D}^0$ decay to same final state

Using a common D decay final state

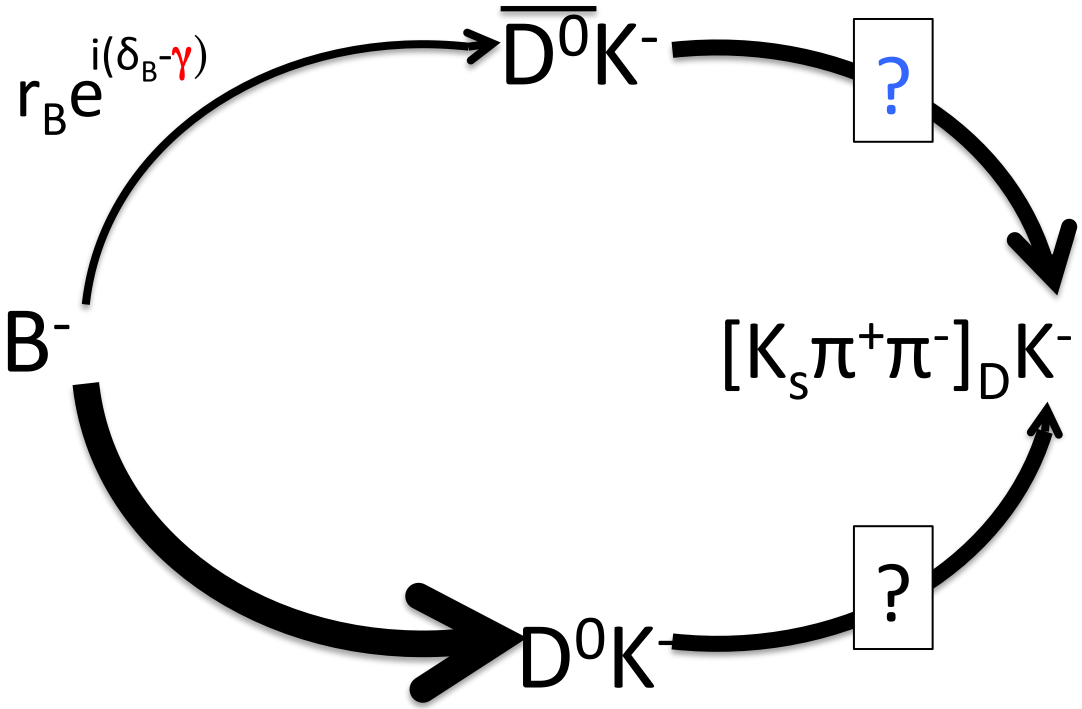


- Common final state allows interference between the two paths
- Interference gives access to the phase



The level of interference, and its exact manifestation is dependent on the physics of the B decay AND D decay

Self-conjugate D decays using Dalitz plot



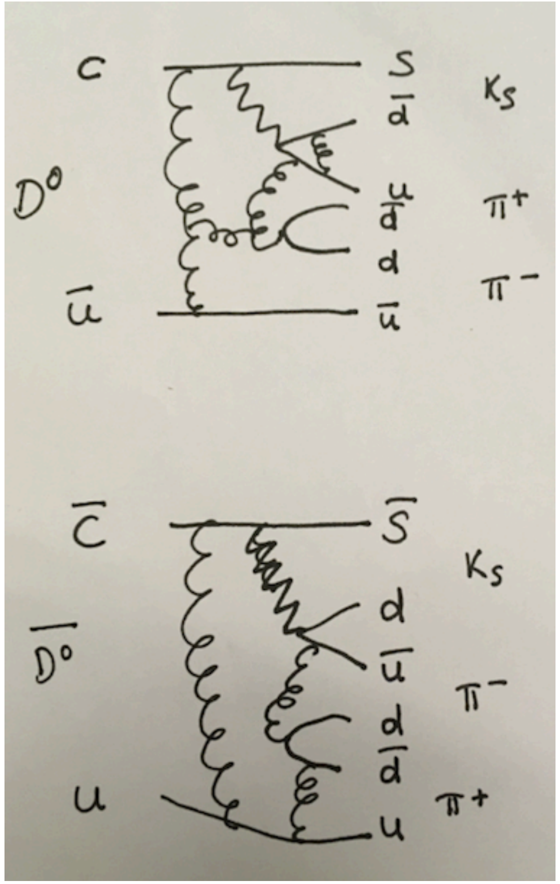
3-body D meson decay.

The level of interference, and its exact manifestation is dependent on the physics of the B decay AND D decay

Giri, Gronau, Soffer & Zupan, (GGSZ) PRD 68 (2003) 054018

Charm Strong Phases differences: What?

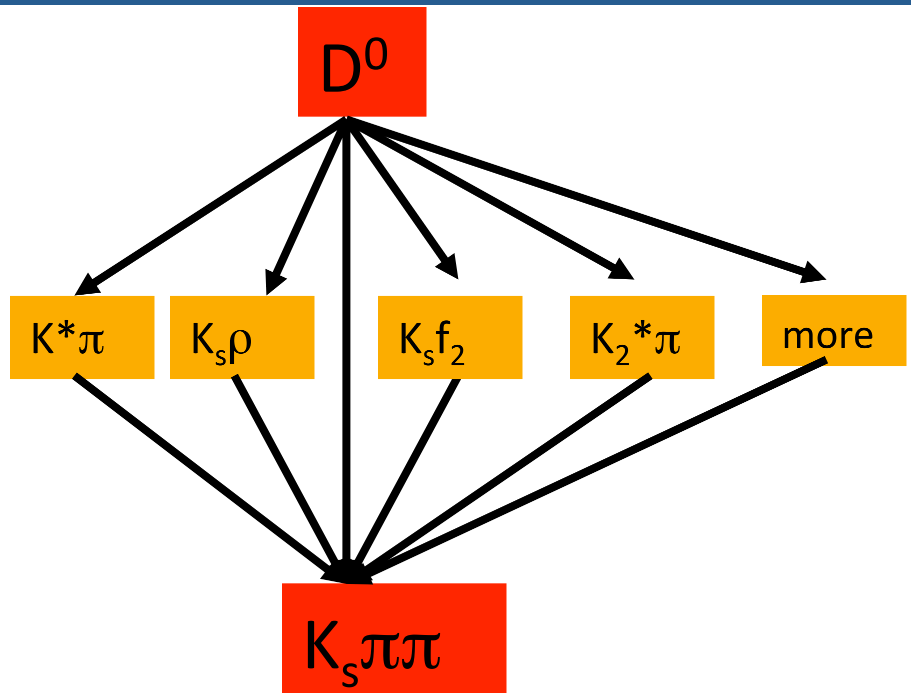
$\delta_1 - \delta_2 = ?$

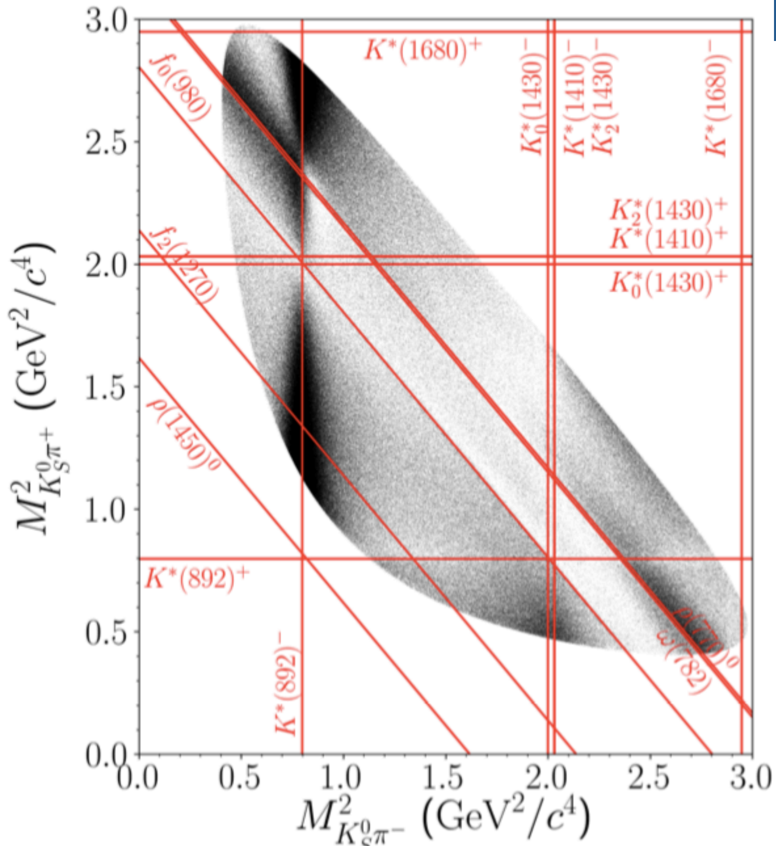


δ_1

δ_2

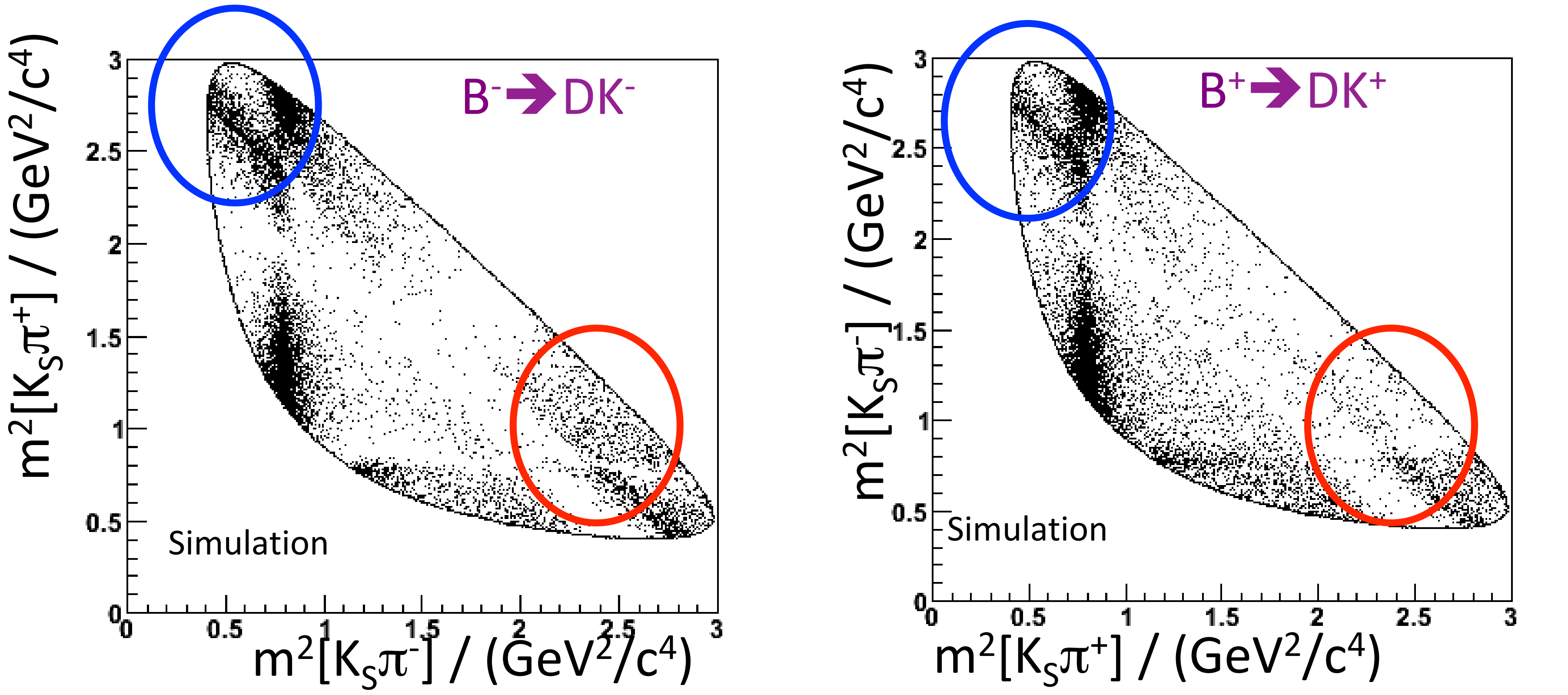
D→$K_s\pi\pi$: Decay proceeds via intermediate states





- After conservation (e.g E, momentum) considerations taken into account the phasespace can be described by just 2 variables. (Dalitz plot)
- Understanding the physics contained in this plot is necessary – 3-body decay does add complexity
- Worth it in overall measurement of γ

How will CP violation be observable?



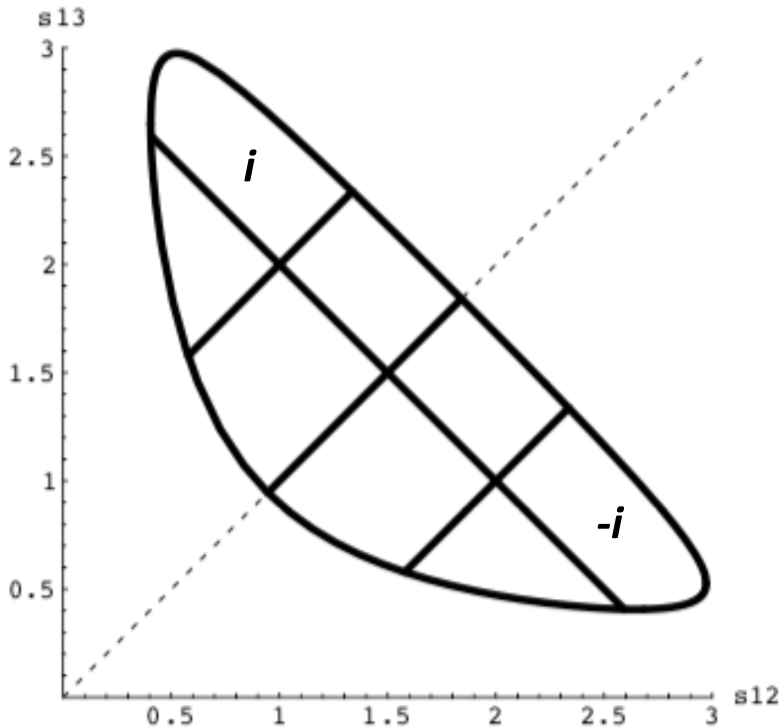
- Simulated CP violation exaggerated for illustrative purposes.

- How much difference and where the differences arise is driven by the values of r_B, γ, and δ_B and the physics of the D decay

B meson yield dependence

$$N_i\left(B^-\right) = h\left(K_i + r_B^2 K_{-i} + 2r_B^2\sqrt{K_i K_{-i}}\left[c_i\cos\left(\delta_B - \gamma\right) + s_i\sin\left(\delta_B - \gamma\right)\right]\right)$$

r_B , δ_B , γ → B decay



Charm decay:

$$K_i = \int_i A(p)^2\, dp$$

$$c_i = \int_i A(p)\overline{A(p)}\cos\left(\delta(p) - \overline{\delta(p)}\right) dp$$

$$A(p) = A(D^0 \rightarrow K_S^0\pi^+\pi^- \mid p)$$

$$\overline{A(p)} = A(\overline{D^0} \rightarrow K_S^0\pi^+\pi^- \mid p)$$

What do we need

Really high yields of $B^+ \rightarrow DK^+$

LHCb ?
Belle II ?

This is much trickier to measure.
Realistically : CLEO
BESIII

Ki could come from Babar or Belle
Or LHCb

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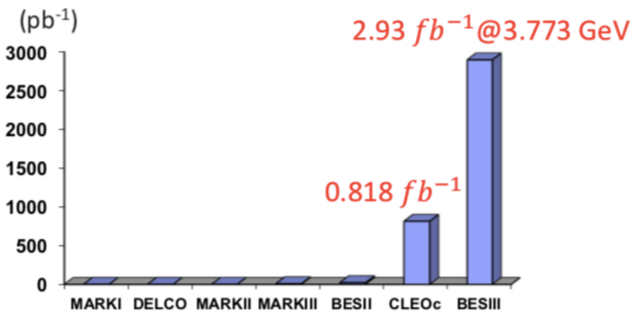
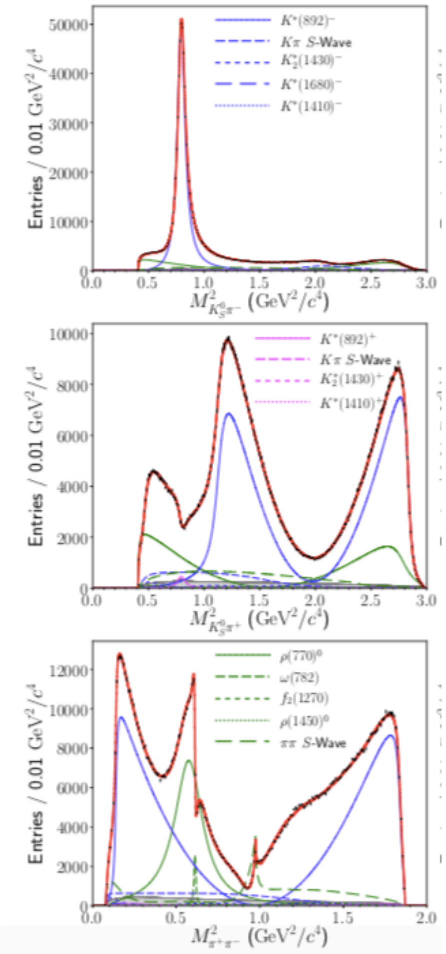


Amplitude model

Babar, Belle, LHCb have huge samples of D decays



- Can fit an amplitude model - Gives a model of the amplitude and strong phase of the decay at each phase point
- Projections show $|A|^2$ - Really good agreement
- Data doesn't allow a plot of strong-phase in order to compare the model.
- It is very hard to quantify the uncertainty in the knowledge in the strong-phase from the model
- Unsatisfactory in the precision-era
- This data can measure K_i but only predict c_i and s_i

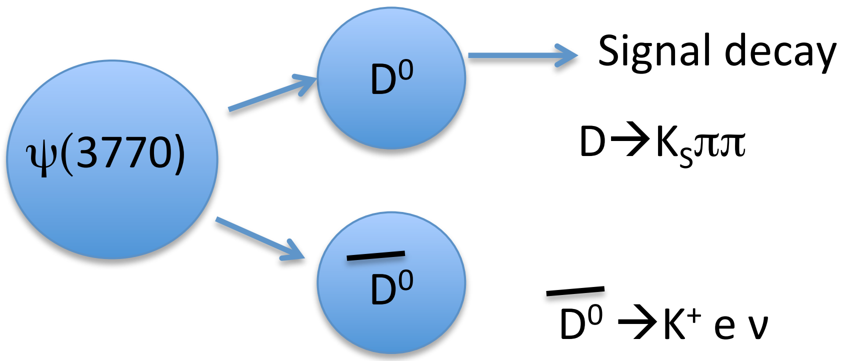
How can strong phases be accessed ?

Require : Phase information of the D decay, requires a system with interference

Production mechanism of interest at BESIII : $e^+ e^- \rightarrow \psi(3770)$ (cc-bar resonance)

It is just above the mass of two D mesons

$\psi(3770) \rightarrow DD$



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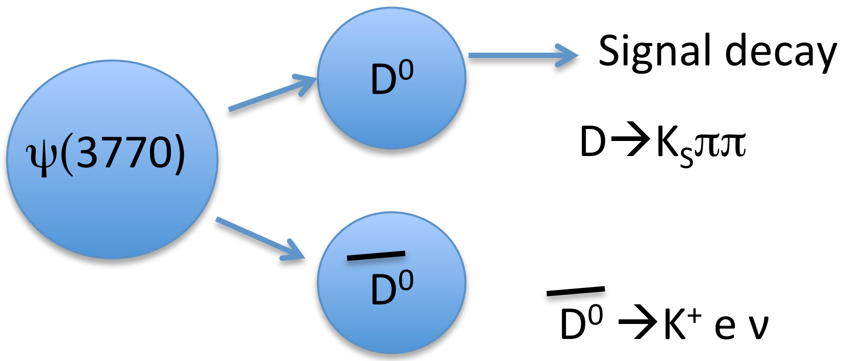

So far no different to the B factories?

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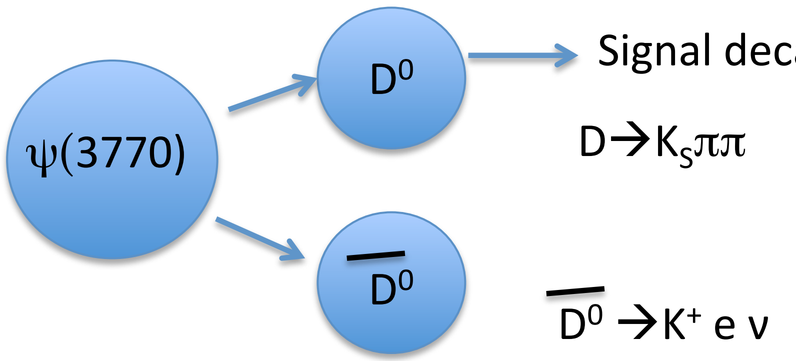
Strong decay

Quantum numbers are conserved

Final state must have C=-1

Two D mesons are quantum entangled

They do not decay independently of one another



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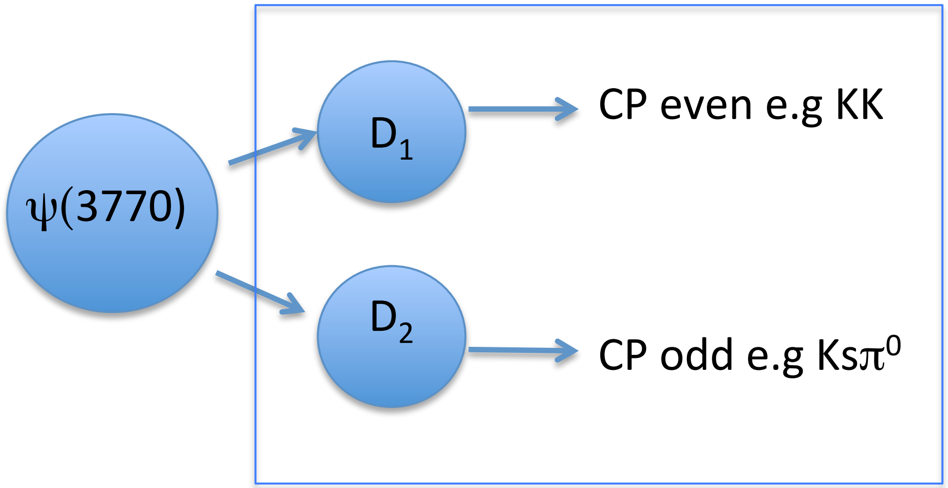

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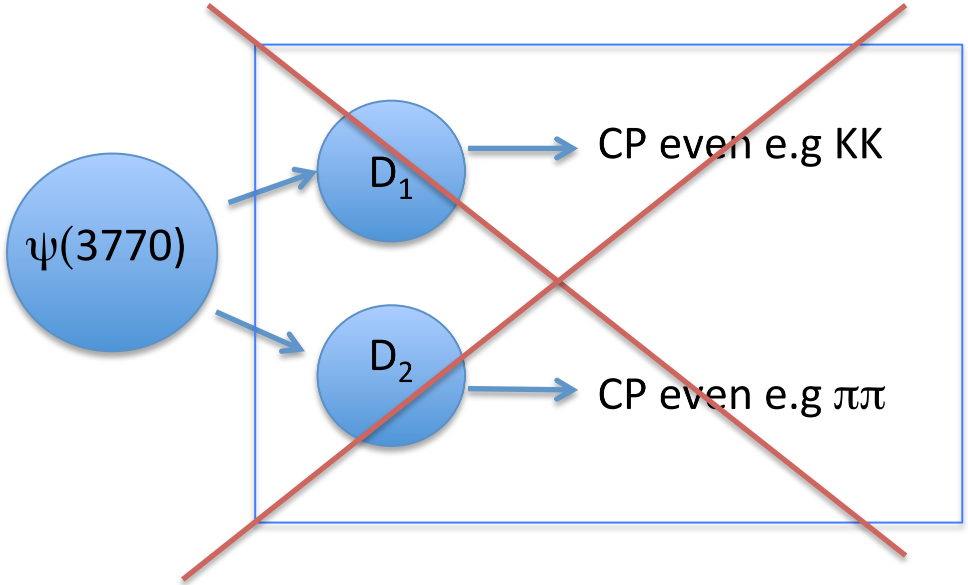

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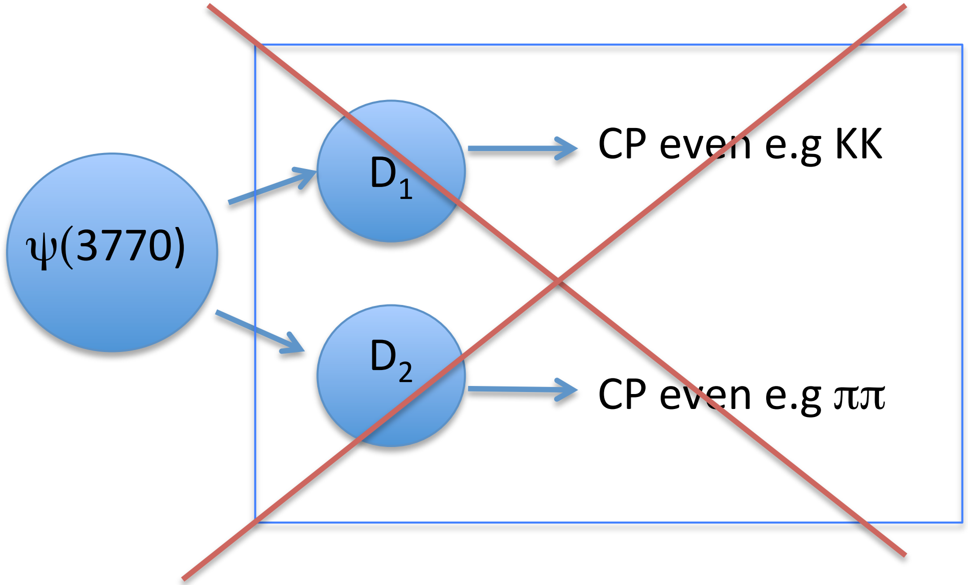
D_1 and D_2 are superpositions of D^0 and $\overline{D^0}$

If D_1 is CP even then you **know** that D_2 is CP odd regardless of its final state



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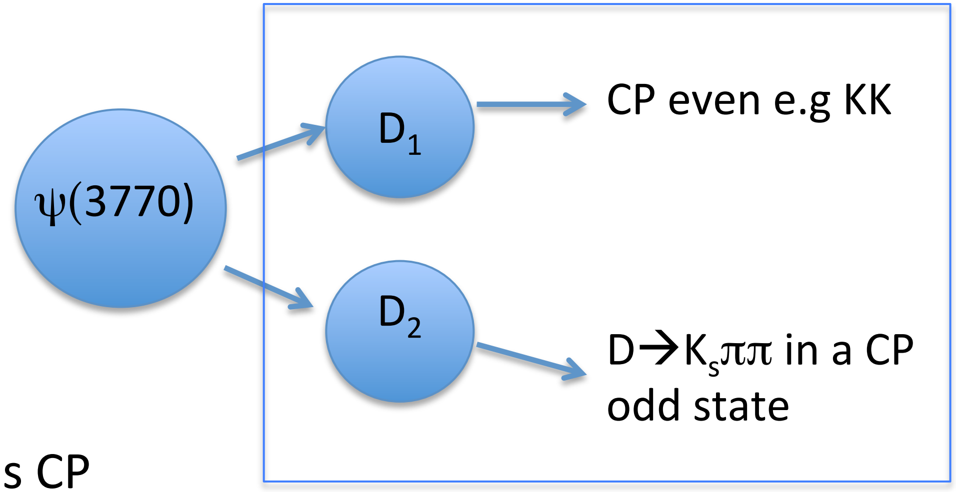
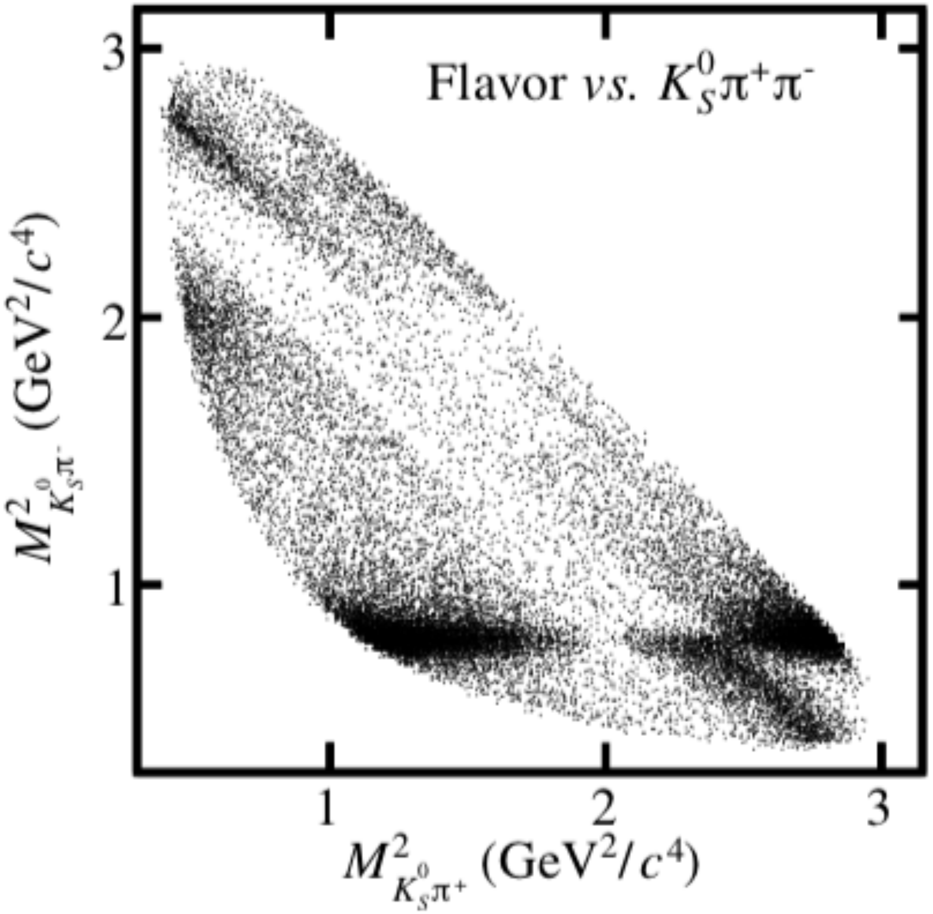


Take a closer look – flavor tagged decays

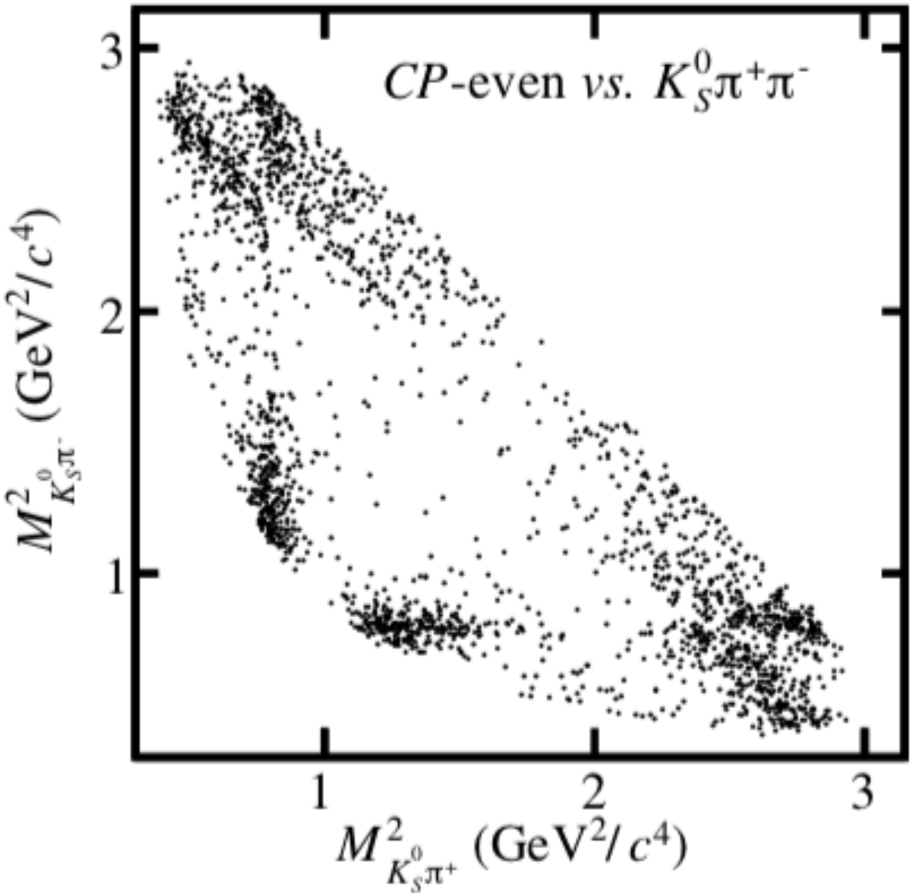
Flavour-tagged D→$K_s\pi\pi$

Same as the B factories

$$I(p) \propto |A(p)|^2$$

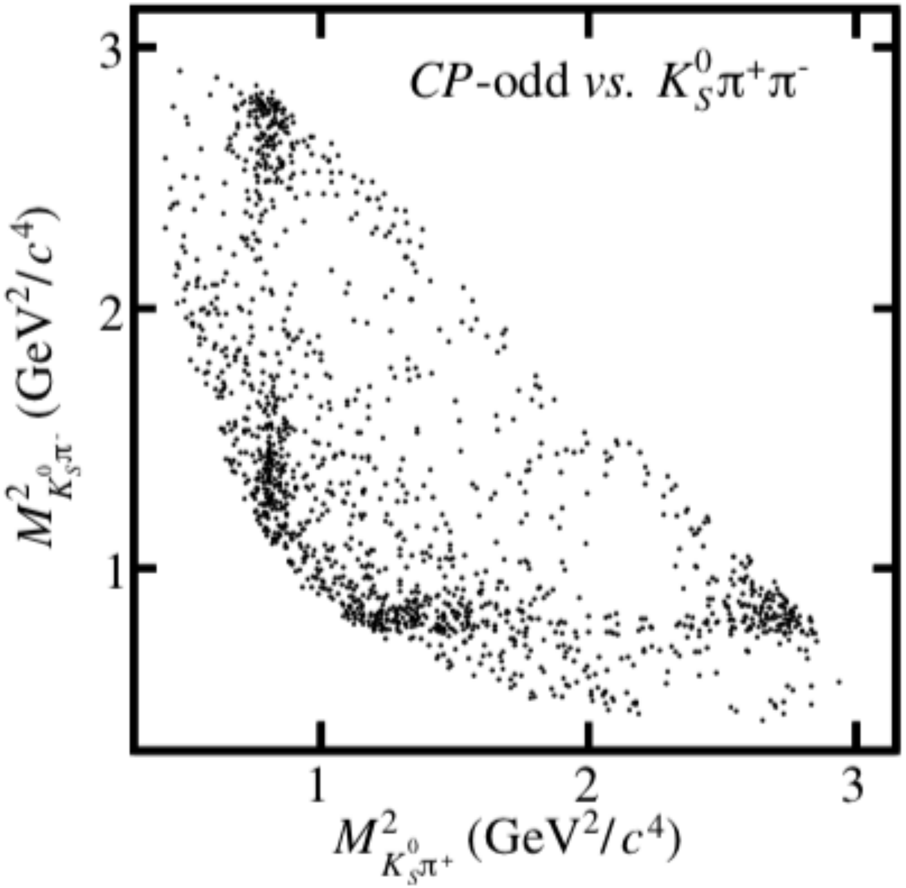


Take a closer look – CP even tagged



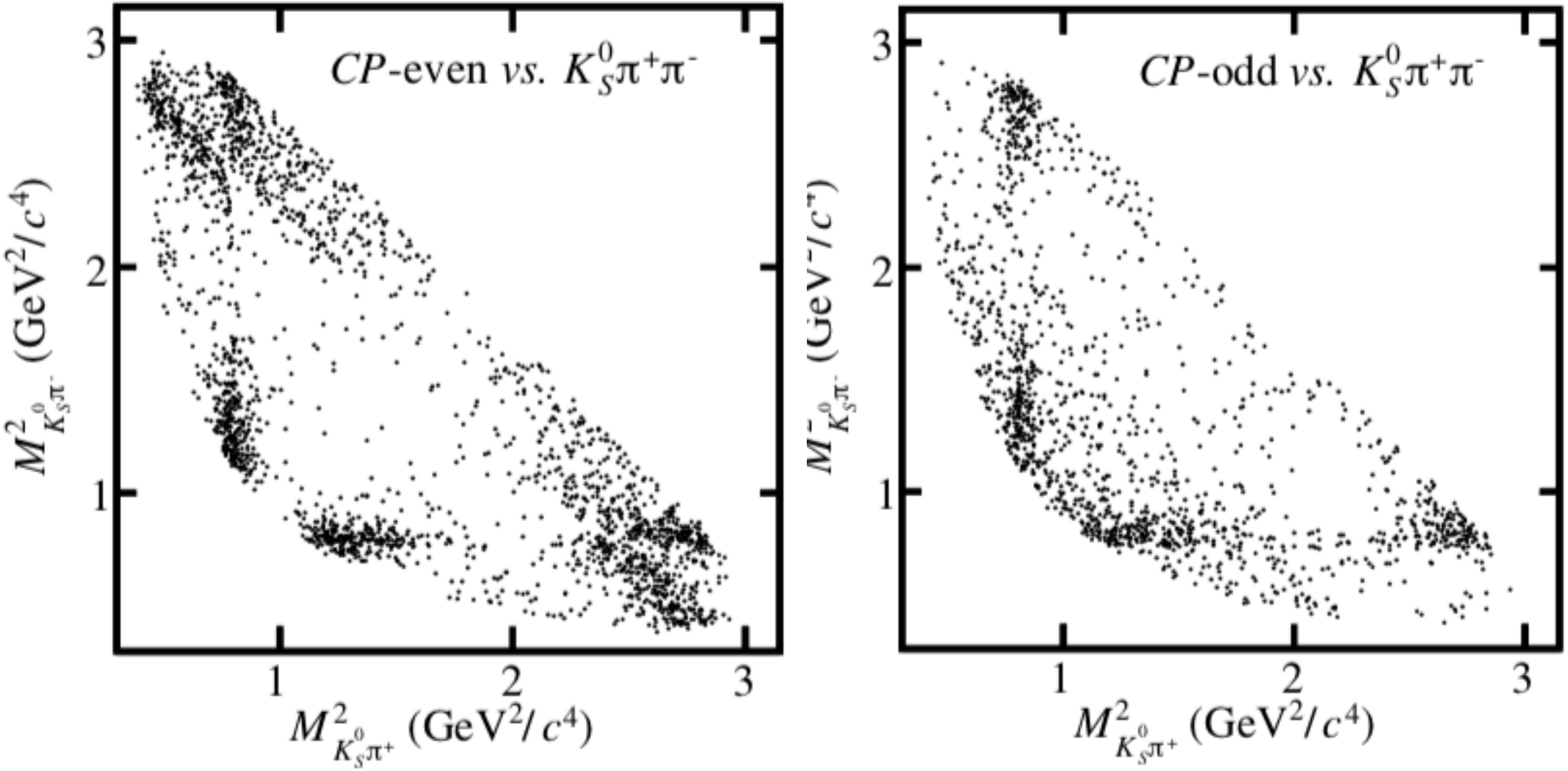
$$I(p) \propto |A(p)|^2 + |\overline{A(p)}|^2 + 2|A(p)||\overline{A(p)}|\cos(\delta(p))$$

Take a closer look – CP odd tagged



$$I(p) \propto |A(p)|^2 + |\overline{A(p)}|^2 - 2|A(p)||\overline{A(p)}|\cos(\delta(p))$$

Quantum entanglement



CP tagged yield distributions

$$M_i = h_{CP}(K_i - (2F_{CP} - 1)2c_i\sqrt{K_iK_{-i}} + K_{-i})$$

The *observed* yield where one D decays to a CP eigenstate, and the other to D→$K_S\pi\pi$

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= 1 for CP even, -1 for CP odd, can take advantage of states where the CP even fraction is known from CLEO measurements

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− Can be obtained by reconstructing D→$K_S\pi\pi$ vs D→Definite flavour

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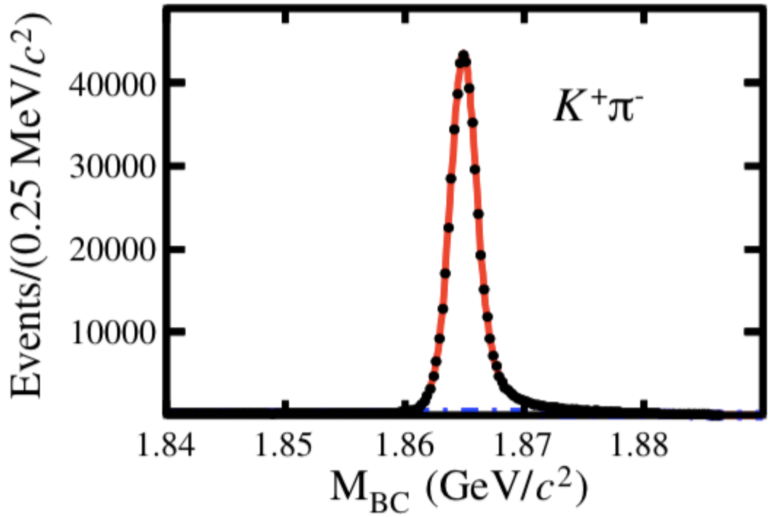
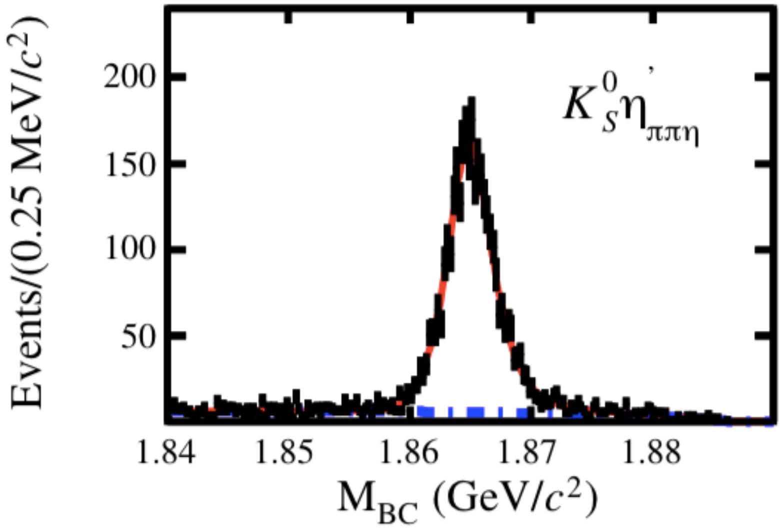
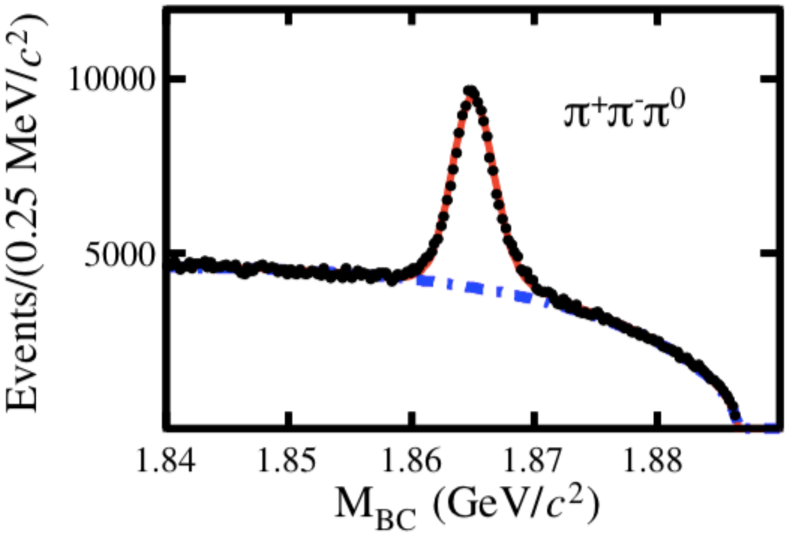
Normalization constant. Dependent on number of DD events, Branching fractions of signal and tag decay, reconstruction efficiencies.
Data driven way of is used to determine the normalisation constant where possible to improve accuracy

Single Tags





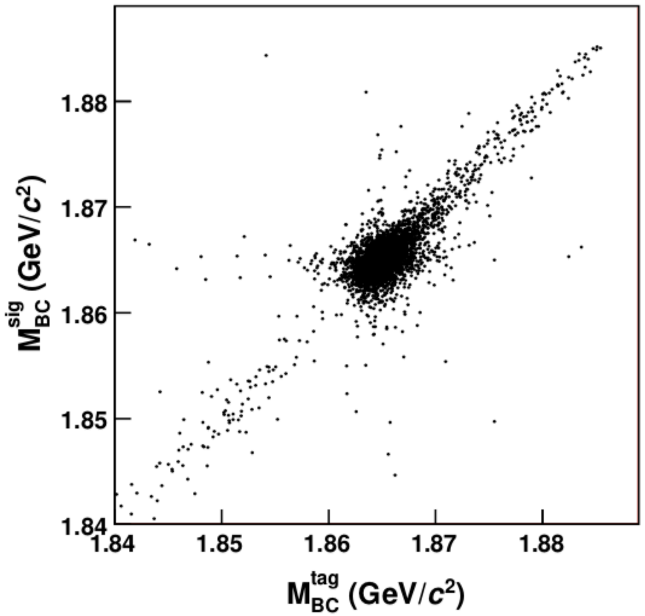


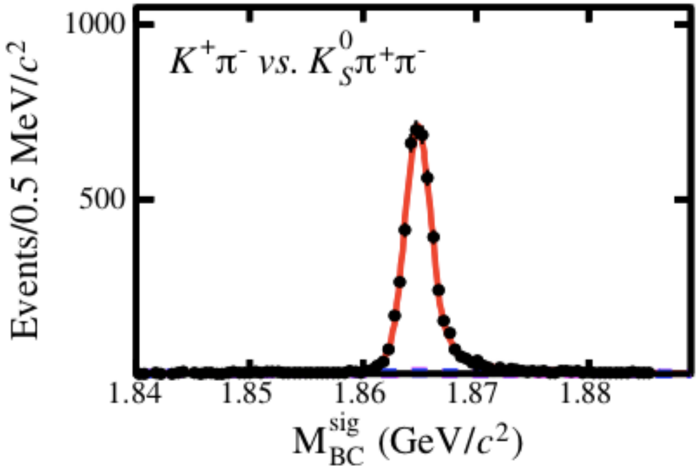
- Only the tag decay is searched for
- Single Tag yield encapsulates the normalisation quantities.

- $N_{ST} = 2 * N_{DD} * BF * \varepsilon(D \rightarrow tag)$
- $h_{CP} \propto S_{CP} / S_{FT}$

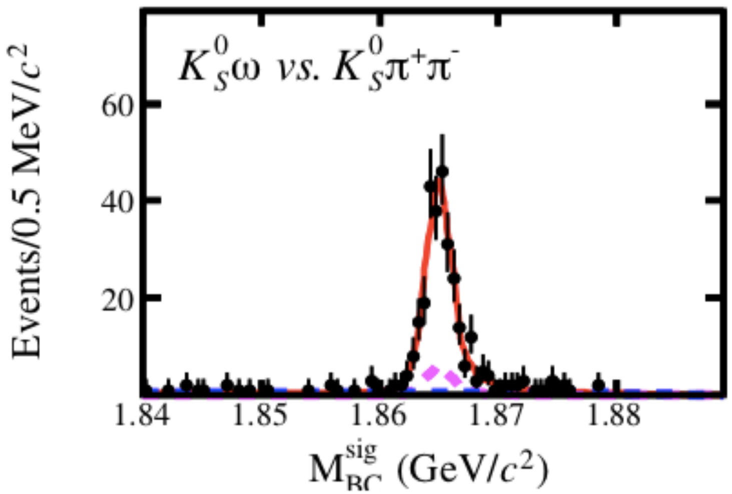
- Range of yields and purities shown (14 channels in total)

Double tags





2 example double tags



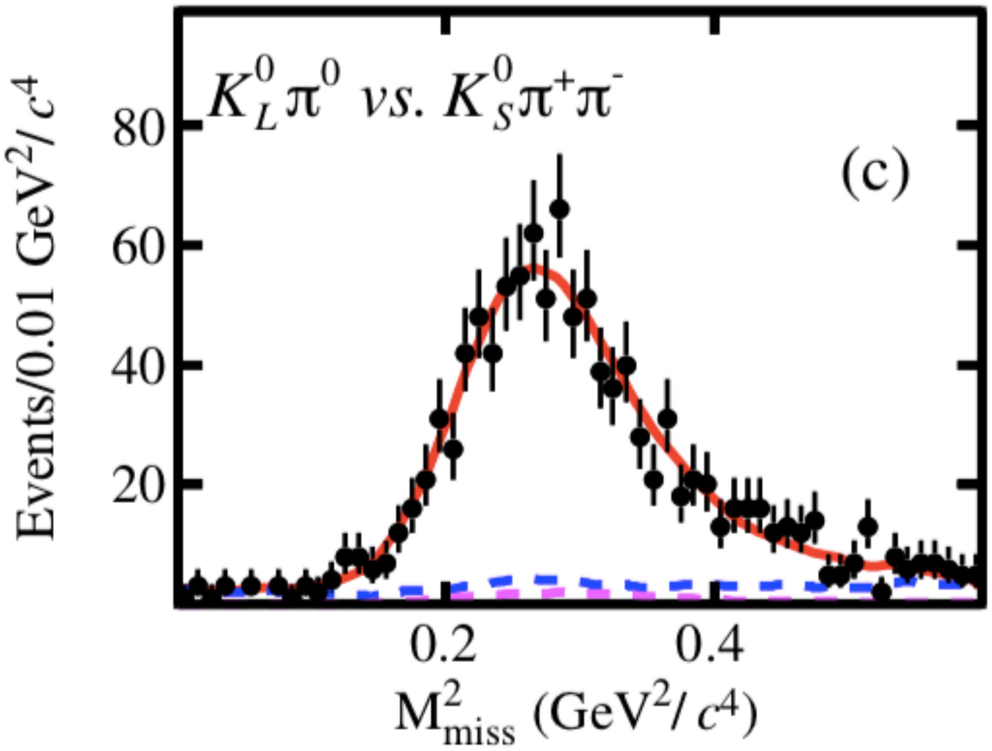
Backgrounds can be reliably determined from MC/data with some corrections

Partial reconstruction

Hermitic detector:

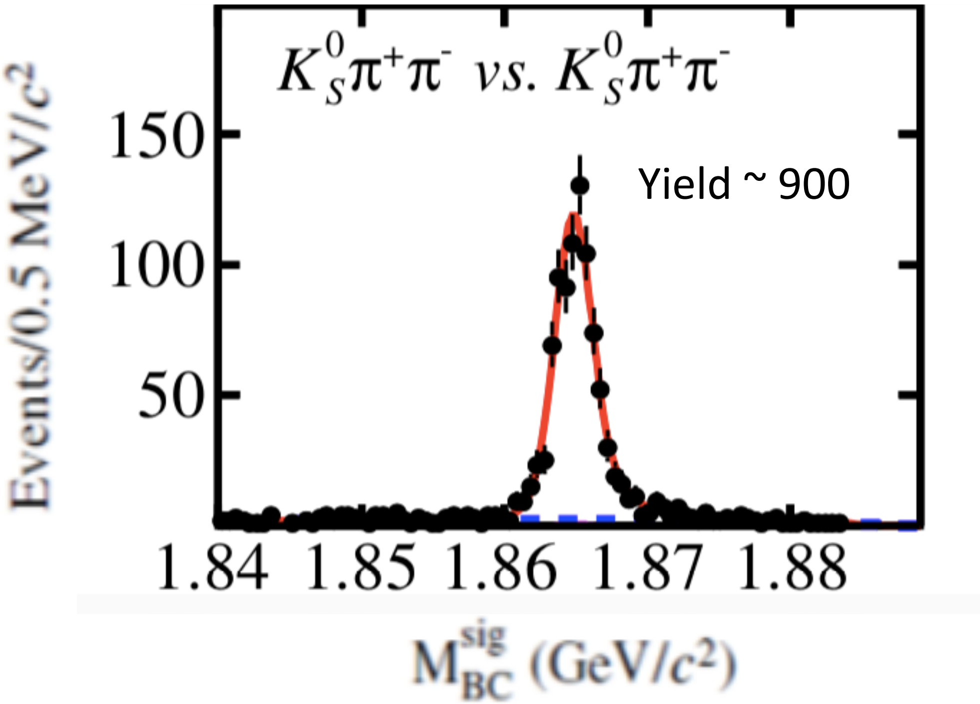
Energy and momentum of a single missing particle can be inferred by Energy and Momentum conservation

Parameterised as “missing mass”
Allows to infer the presence of K_L



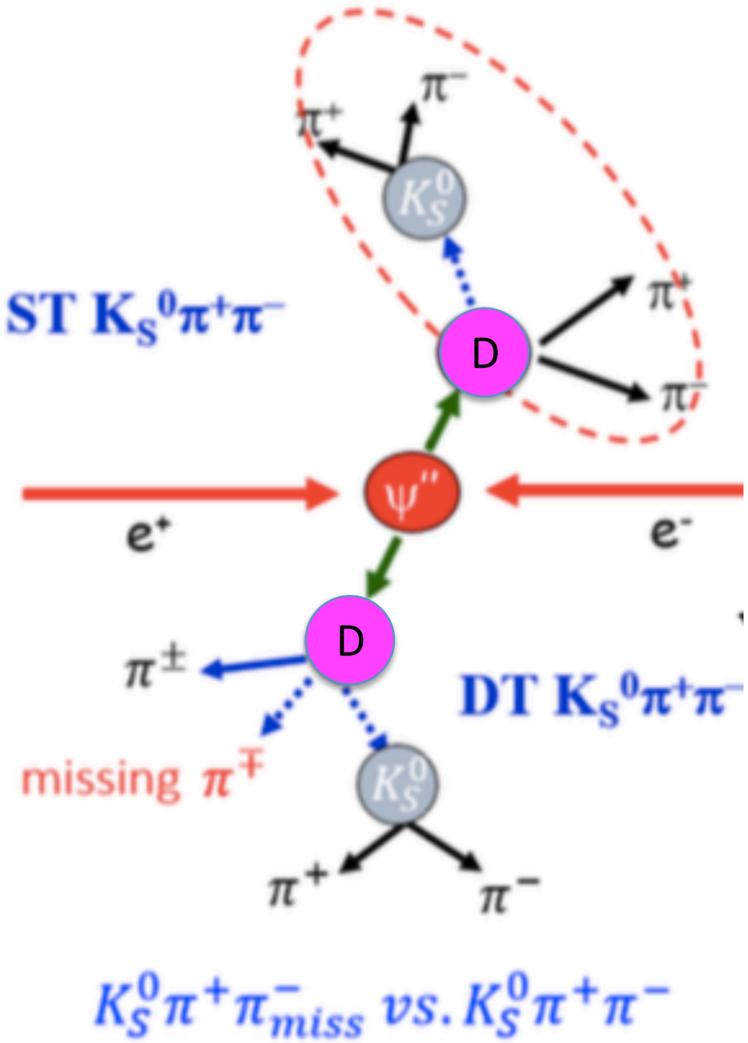
CP tags are only sensitive to the cosine

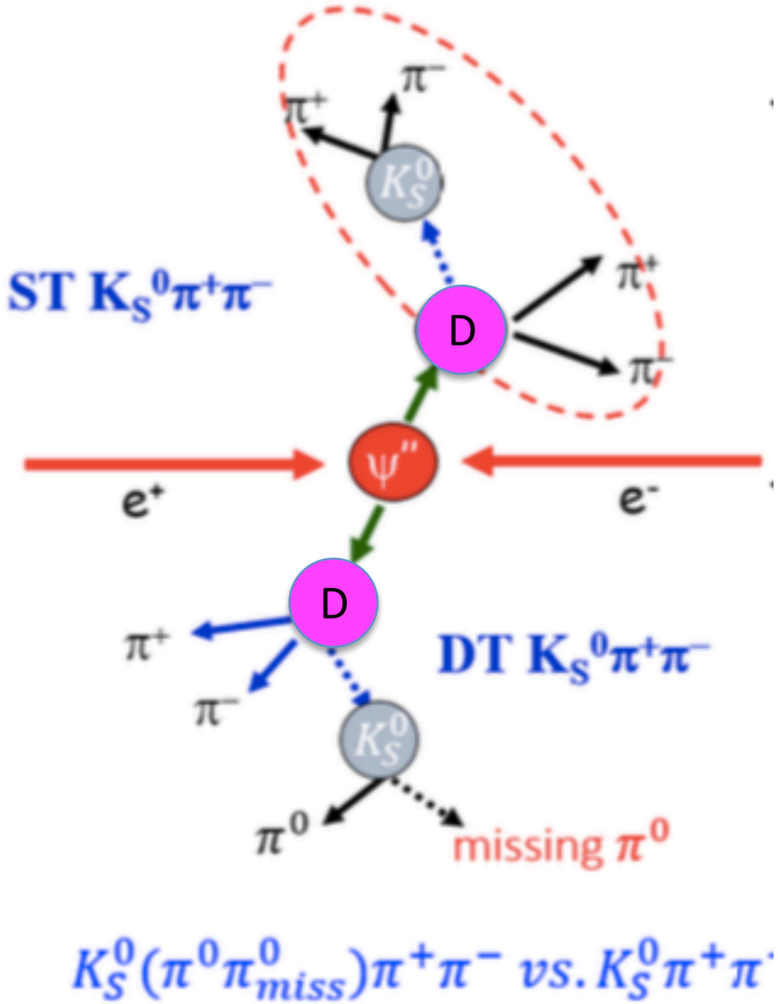
$$M_{ij} = h_{\text{corr}}[K_i K_{-j} + K_{-i} K_j - 2\sqrt{K_i K_{-j} K_{-i} K_j}(c_i c_j + s_i s_j)$$



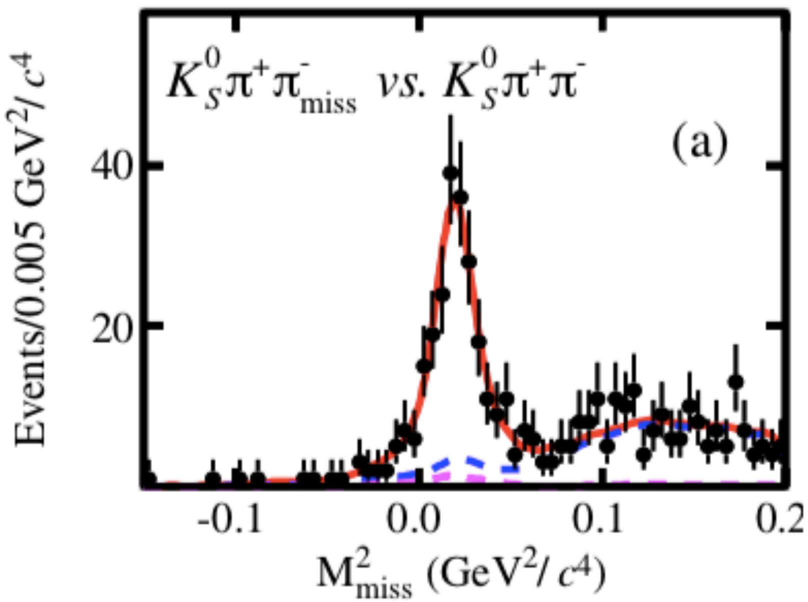
The yield where one $D \rightarrow K_S\pi\pi$ is reconstructed in bin i and the other $D \rightarrow K_S\pi\pi$ is reconstructed in bin j

Make use of partial reconstruction

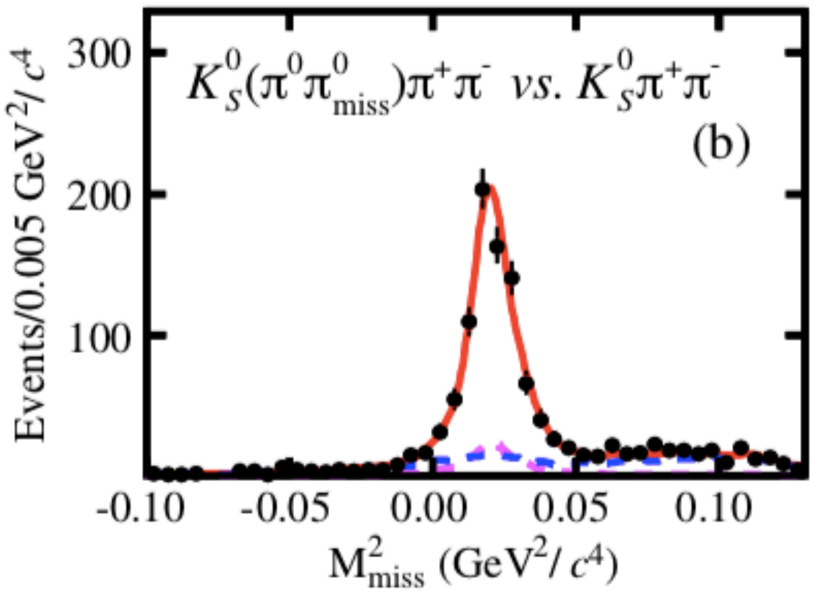




Make use of partial reconstruction



224±17



710±34

Partial reconstruction ~ doubles the D→$K_S\pi\pi$ vs D→$K_S\pi\pi$ yield

$K_S\pi\pi$ vs $K_L\pi\pi$

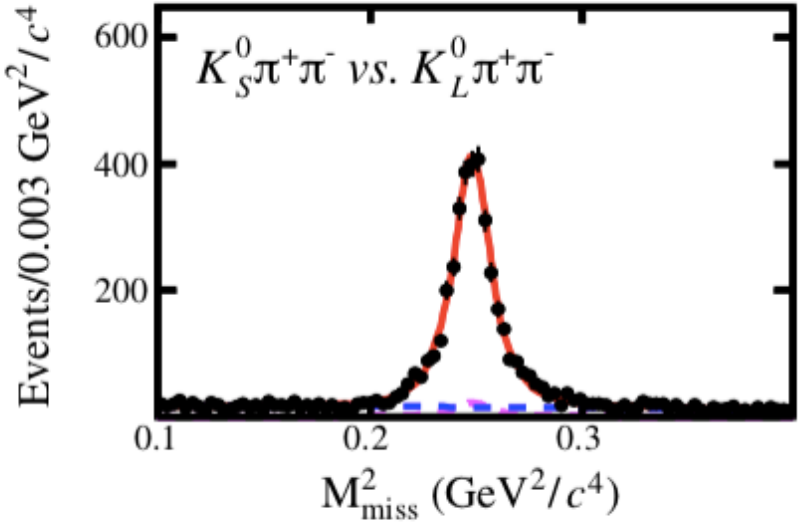
$$M'_{ij} = h'_{corr}[K_i K'_{-j} + K_{-i} K'_j + 2\sqrt{K_i K'_{-j} K_{-i} K'_j}(c_i c'_j + s_i s'_j)]$$

Observed yield where $D\rightarrow K_S\pi\pi$ is reconstructed in bin i and $D\rightarrow K_L\pi\pi$ is reconstructed in bin j

Yield is 3434 ± 72

~3.5 times $D\rightarrow K_S\pi\pi$ vs $D\rightarrow K_S\pi\pi$ yield but doubled the fit parameters.

Ki' -These can be determined from $D\rightarrow K_L\pi\pi$ vs FT
ci' – From $D\rightarrow K_L\pi\pi$ vs CP
Constraints between c_i and s_i and c_i' and s_i' imposed from theory.



Data Yields

Signal vs Tag	Factor Increase wrt to CLEO
$D \to K_S\pi\pi$ vs CP	5.3
$D \to K_S\pi\pi$ vs $D \to K_S\pi\pi$	3.9
$D \to K_S\pi\pi$ vs $D \to K_L\pi\pi$	2.9
$D \to K_L\pi\pi$ vs CP	9.2

Data size is only 3.5 larger

Systematic increase in CP tags

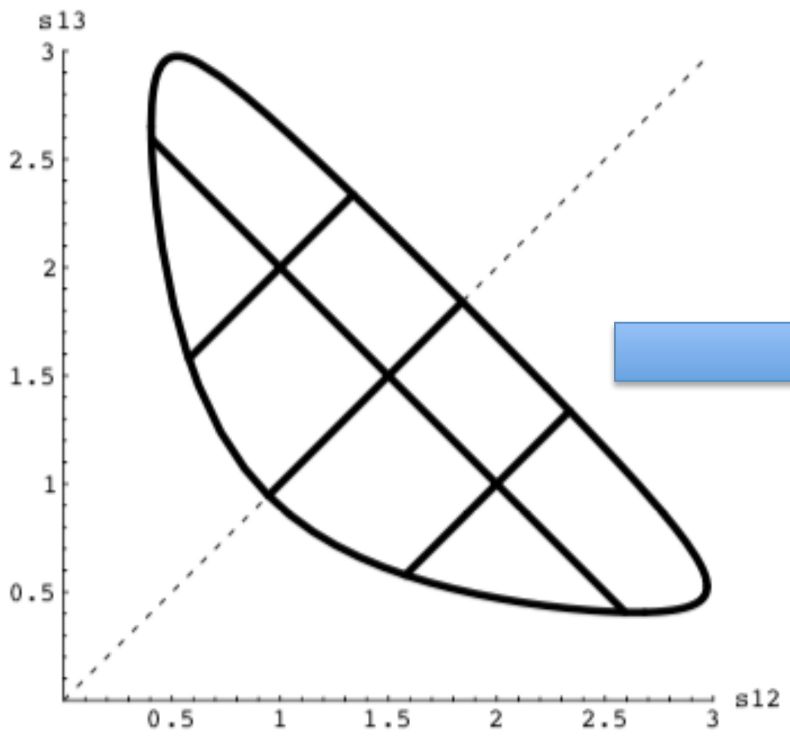
Extensive use of partial reconstruction

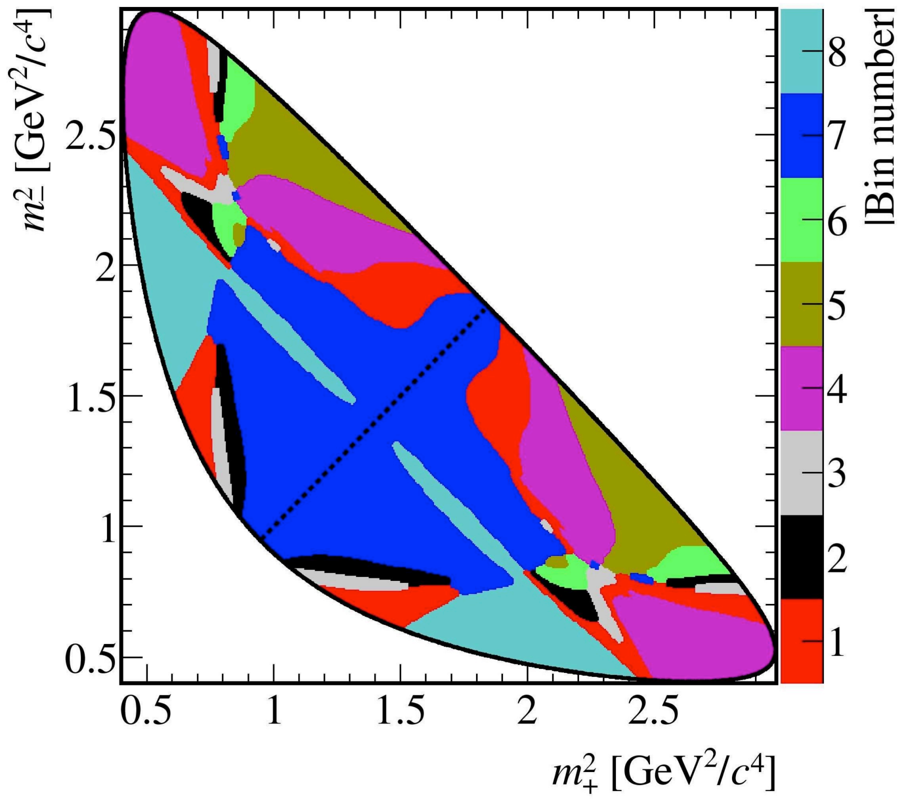
High purity, background well understood

Efficiency and migration effects can be taken from simulation with a high degree of accuracy.

PRD 101 112002, PRD 82 112006

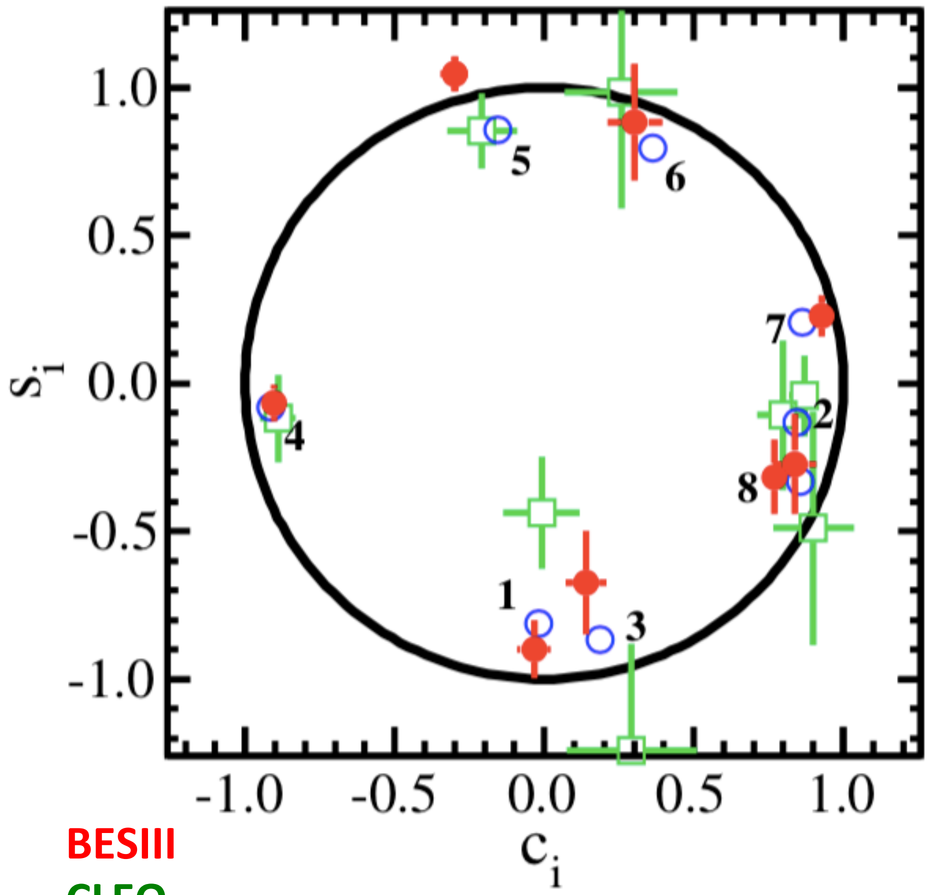
Preferred Bin Choice





An optimal binning scheme for sensitivity to γ was determined by CLEO
In order to allow combination of the two results the same is used for BESIII

Results

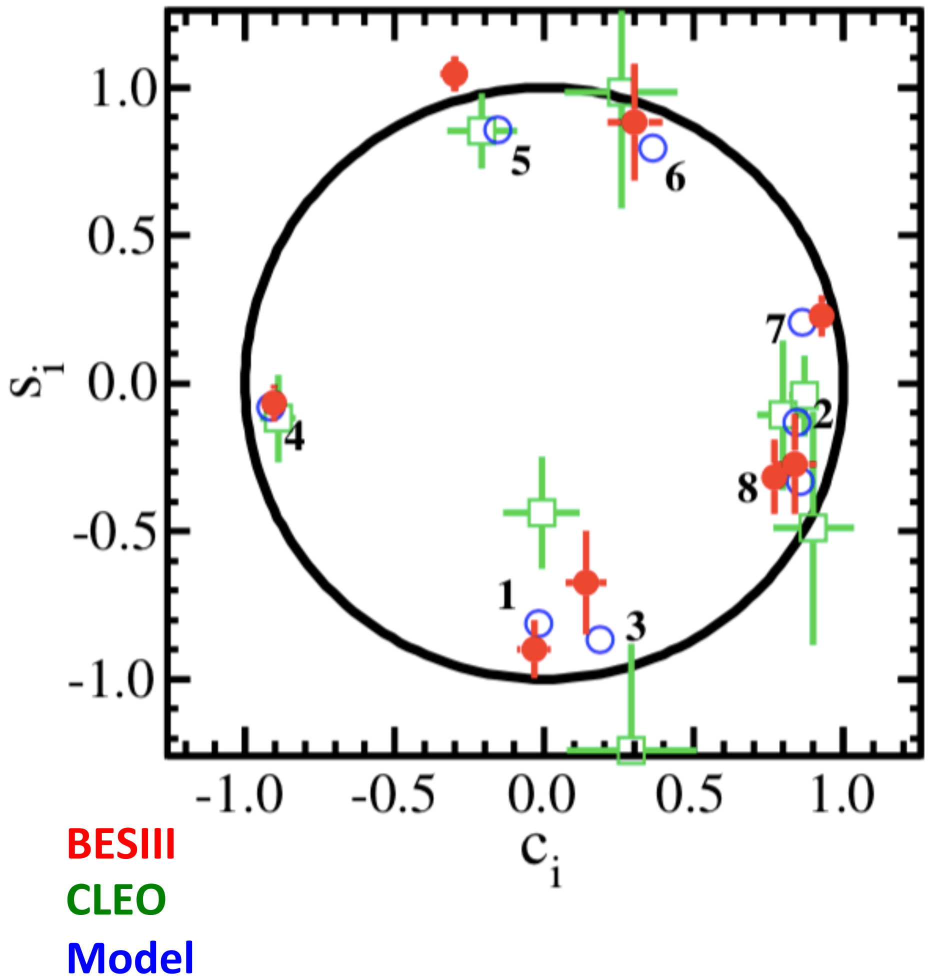


BESIII
CLEO
Model

- Statistical uncertainties are dominant
- Systematic uncertainties come from a variety of sources:
  - Fit parameterisations
  - MC
  - Corrections to FT yields
  - Background distributions
  - External inputs
- No source of systematic uncertainty is leading.
- Model agrees well with the data

PRD 101 112002, PRD 82 112006

Results



- Compared to CLEO
  - Precision on ci is improved x2.5
  - Precision on si is improved x2
- Expectation for propagated uncertainty to a measurement of γ is ~1° : CLEO ~4°
- Results also combined with CLEO given in the publication.

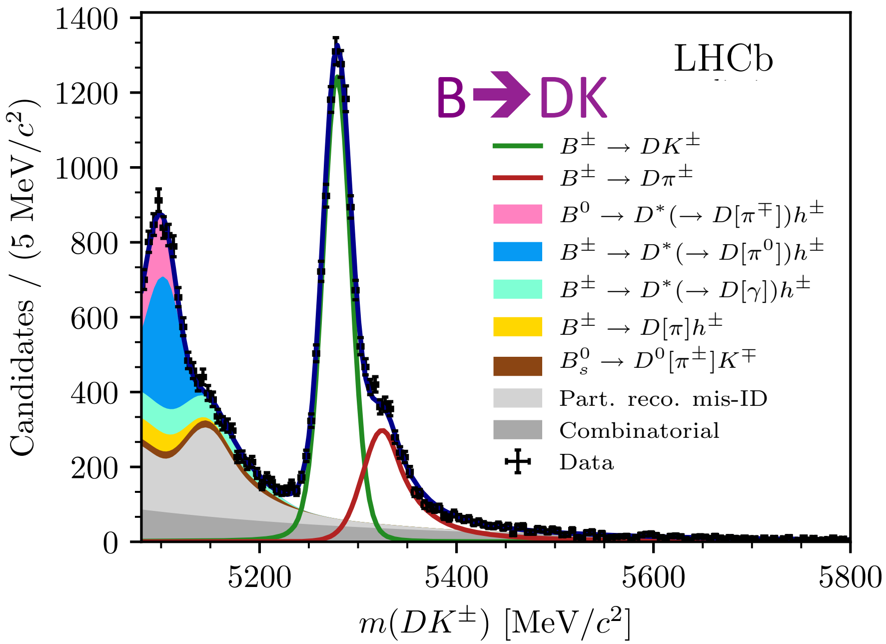
Now we have the charm strong phases …

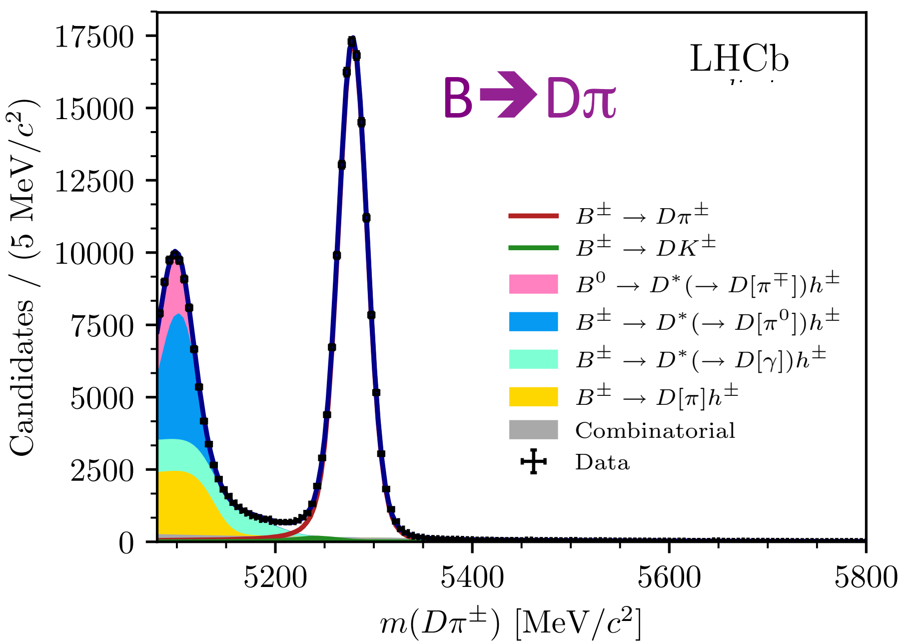
Return to LHCb

LHCb data selection

Excellent detector performance:

- Trigger efficiency, IP resolution, momentum resolution and hadron PID lead to large yields with high purity

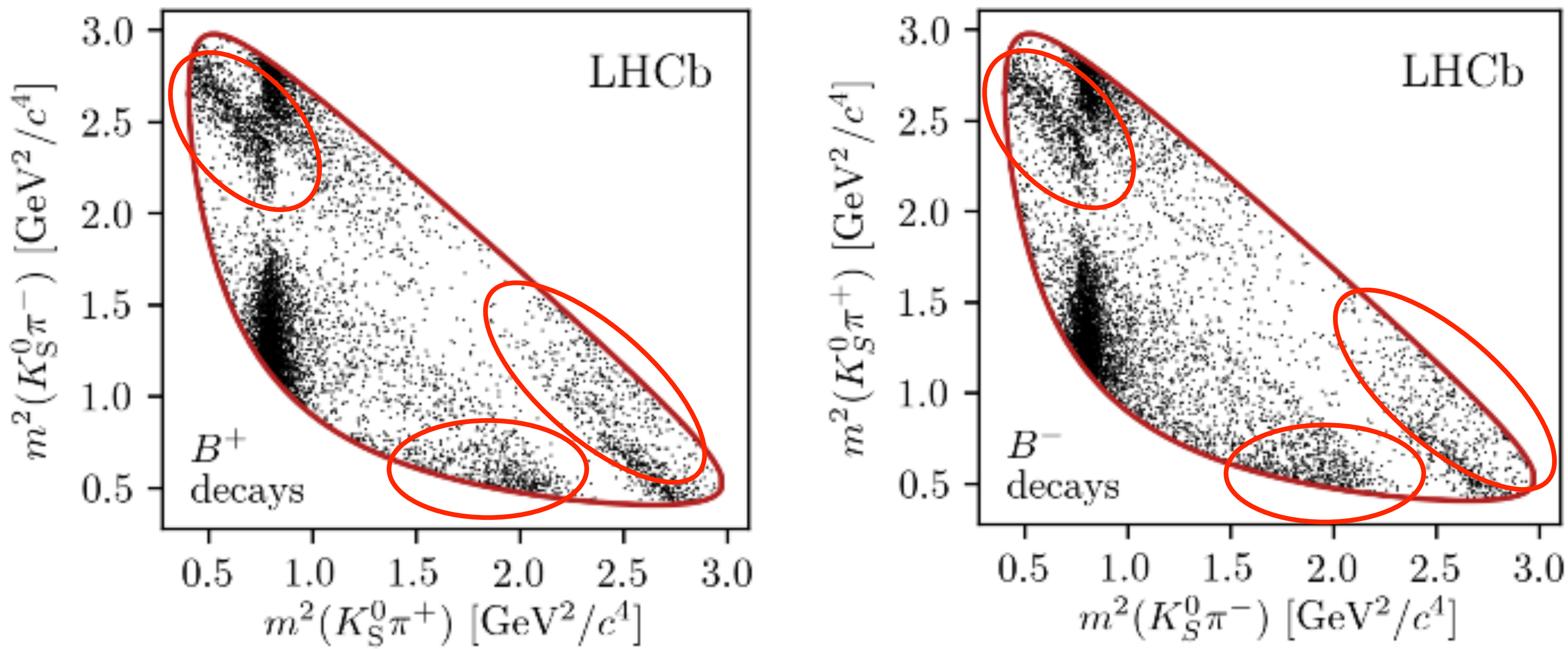




In total ~ 13K B→DK
180K B→Dπ

Full dataset from 2011 - 2018

Spot the difference



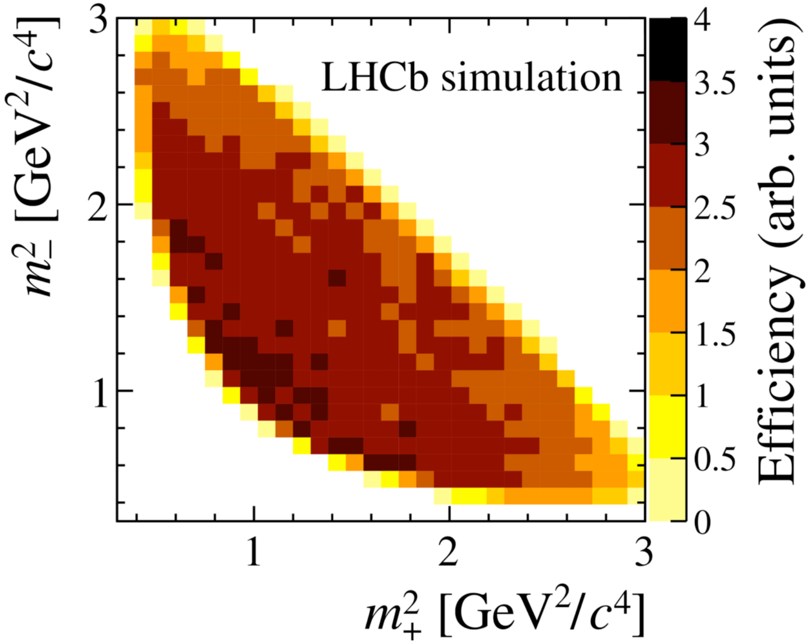
Idealised → real life

$$N_i\left(B^-\right) = h\left(K_i + r_B^2 K_{-i} + 2r_B^2\sqrt{K_i K_{-i}}\left[c_i\cos\left(\delta_B - \gamma\right) + s_i\sin\left(\delta_B - \gamma\right)\right]\right)$$

This equation doesn’t take into account any efficiency effects or any other minor ongoing physics effects

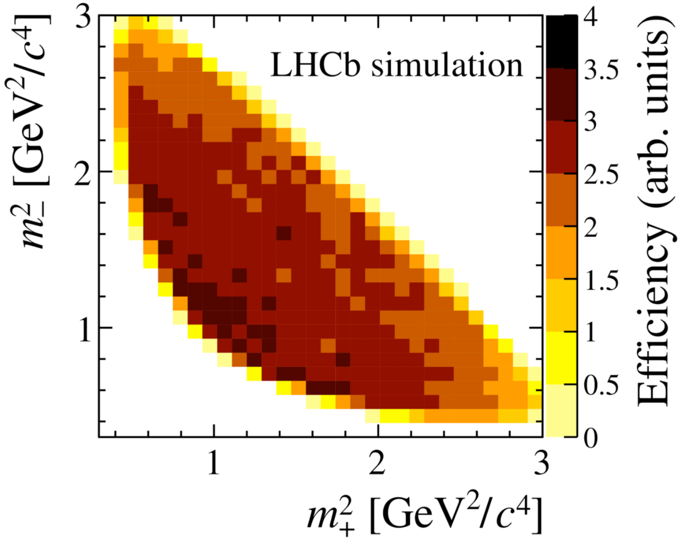
Efficiency and B→Dπ

Efficiency profile is not uniform



- Efficiency and migration effects cannot be determined purely from simulation at LHCb for these decay modes → leading uncertainties
- B→D*μν and simulation to determine the efficiency – but the trigger and selection can't be the same → large leading systematic uncertainty
- Efficiency profile in B→Dπ would be the same – topology same
- Branching fraction ~ x12 larger - obvious control mode BUT CPV and other physics effects in this channel must be understood/taken into account.

Efficiency and B→Dπ



- For the first time, use this as the control mode to determine the efficiency and simultaneously determine the CPV parameters in B→Dπ
- F_i are the "efficiency" modulated K_i – the observed fractional yields of a D^0 meson in each bin.
- Determined directly from data, inherently includes all first order efficiency, migration, charm mixing, KS CPV and KS-KL matter regeneration effects. Without the need to model any of it
- i.e the parameters mix physics and detector effects – buts that fine no interest in the parameter itself

Reduce systematic uncertainties, reduce reliance on simulation

Yield equations

- Observed yields in each bin can be related to physics parameters of interest and D^0 decay information

$$N^+_{+i} = h_{B^+}\left[F_{-i} + \left(\left(x_+^{DK}\right)^2 + \left(y_+^{DK}\right)^2\right)F_{+i} + 2\sqrt{F_i F_{-i}}\left(x_+^{DK}c_{+i} - y_+^{DK}s_{+i}\right)\right]$$

$$N^-_{+i} = h_{B^-}\left[F_{+i} + \left(\left(x_-^{DK}\right)^2 + \left(y_-^{DK}\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_-^{DK}c_{+i} + y_-^{DK}s_{+i}\right)\right]$$

Yield equations

- Observed yields in each bin can be related to physics parameters of interest and D^0 decay information

$$N^{+}_{+i} = h_{B^+}\left[F_{-i} + \left(\left(x^{DK}_{+}\right)^2 + \left(y^{DK}_{+}\right)^2\right)F_{+i} + 2\sqrt{F_i F_{-i}}\left(x^{DK}_{+} c_{+i} - y^{DK}_{+} s_{+i}\right)\right]$$

$$N^{-}_{+i} = h_{B^-}\left[F_{+i} + \left(\left(x^{DK}_{-}\right)^2 + \left(y^{DK}_{-}\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x^{DK}_{-} c_{+i} + y^{DK}_{-} s_{+i}\right)\right]$$

- Physics parameters of interest $x_{\pm} = r_B\cos(\delta_B \pm \gamma)$; $y_{\pm} = r_B\sin(\delta_B \pm \gamma)$

Yield equations

- Observed yields in each bin can be related to physics parameters of interest and D^0 decay information

$$N^{+}_{+i} = h_{B^+}\left[F_{-i} + \left(\left(x_{+}^{DK}\right)^2 + \left(y_{+}^{DK}\right)^2\right)F_{+i} + 2\sqrt{F_i F_{-i}}\left(x_{+}^{DK}c_{+i} - y_{+}^{DK}s_{+i}\right)\right]$$

$$N^{-}_{+i} = h_{B^-}\left[F_{+i} + \left(\left(x_{-}^{DK}\right)^2 + \left(y_{-}^{DK}\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_{-}^{DK}c_{+i} + y_{-}^{DK}s_{+i}\right)\right]$$

- Physics parameters of interest $x_{\pm} = r_B\cos(\delta_B \pm \gamma)$; $y_{\pm} = r_B\sin(\delta_B \pm \gamma)$
- Strong phase parameters of the D decay from BESIII+CLEO

Yield equations

- Observed yields in each bin can be related to physics parameters of interest and D^0 decay information

$$N_{+i}^{+} = h_{B^+}\left[F_{-i} + \left(\left(x_+^{DK}\right)^2 + \left(y_+^{DK}\right)^2\right)F_{+i} + 2\sqrt{F_i F_{-i}}\left(x_+^{DK}c_{+i} - y_+^{DK}s_{+i}\right)\right]$$

$$N_{+i}^{-} = h_{B^-}\left[F_{+i} + \left(\left(x_-^{DK}\right)^2 + \left(y_-^{DK}\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_-^{DK}c_{+i} + y_-^{DK}s_{+i}\right)\right]$$

  - Physics parameters of interest $x_\pm = r_B\cos(\delta_B \pm \gamma)$; $y_\pm = r_B\sin(\delta_B \pm \gamma)$
  - Strong phase parameters of the D decay from BESIII+CLEO
  - Fraction of pure D^0 decay to bin *i* taking into account the reconstruction and selection efficiency, from the $B \rightarrow D\pi$ data

Yield equations

- Observed yields in each bin can be related to physics parameters of interest and D^0 decay information

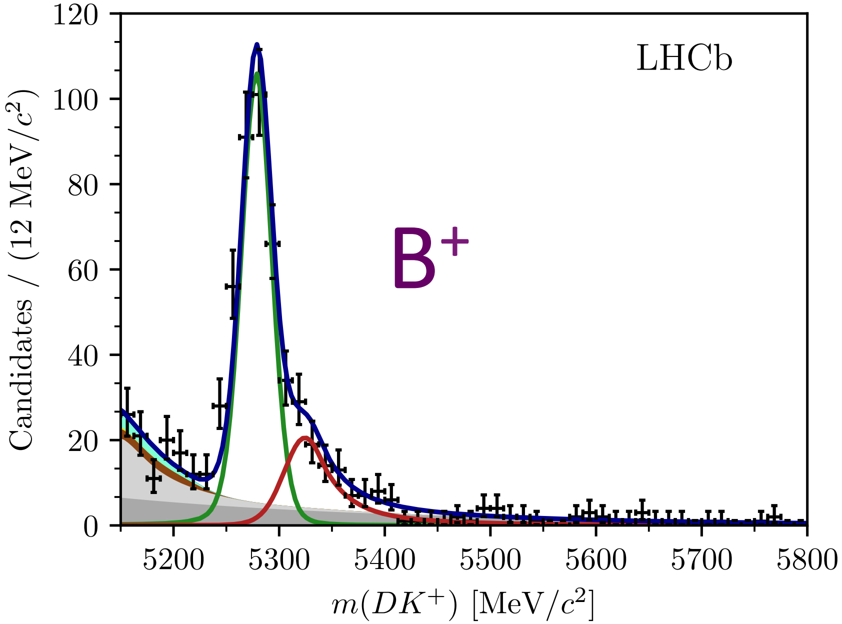
$$N^+_{+i} = h_{B^+}\left[F_{-i} + \left(\left(x_+^{DK}\right)^2 + \left(y_+^{DK}\right)^2\right)F_{+i} + 2\sqrt{F_i F_{-i}}\left(x_+^{DK}c_{+i} - y_+^{DK}s_{+i}\right)\right]$$

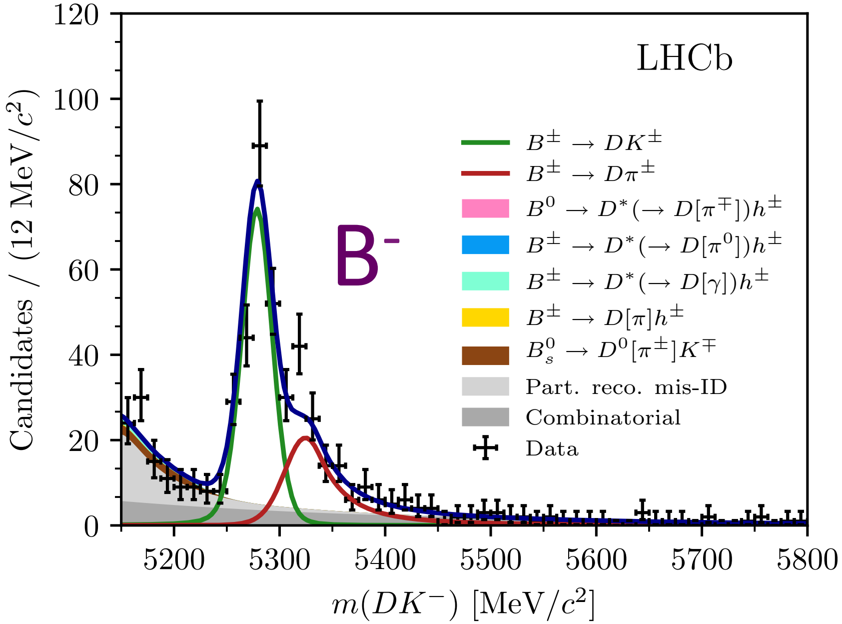
$$N^-_{+i} = h_{B^-}\left[F_{+i} + \left(\left(x_-^{DK}\right)^2 + \left(y_-^{DK}\right)^2\right)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_-^{DK}c_{+i} + y_-^{DK}s_{+i}\right)\right]$$

- Physics parameters of interest $x_\pm = r_B\cos(\delta_B \pm \gamma)$; $y_\pm = r_B\sin(\delta_B \pm \gamma)$
- Strong phase parameters of the D decay from BESIII+CLEO
- Fraction of pure D^0 decay to bin *i* taking into account the reconstruction and selection efficiency, from the $B \rightarrow D\pi$ data
- Split normalisation by charge, result becomes insensitive to production asymmetry and most detection asymmetries

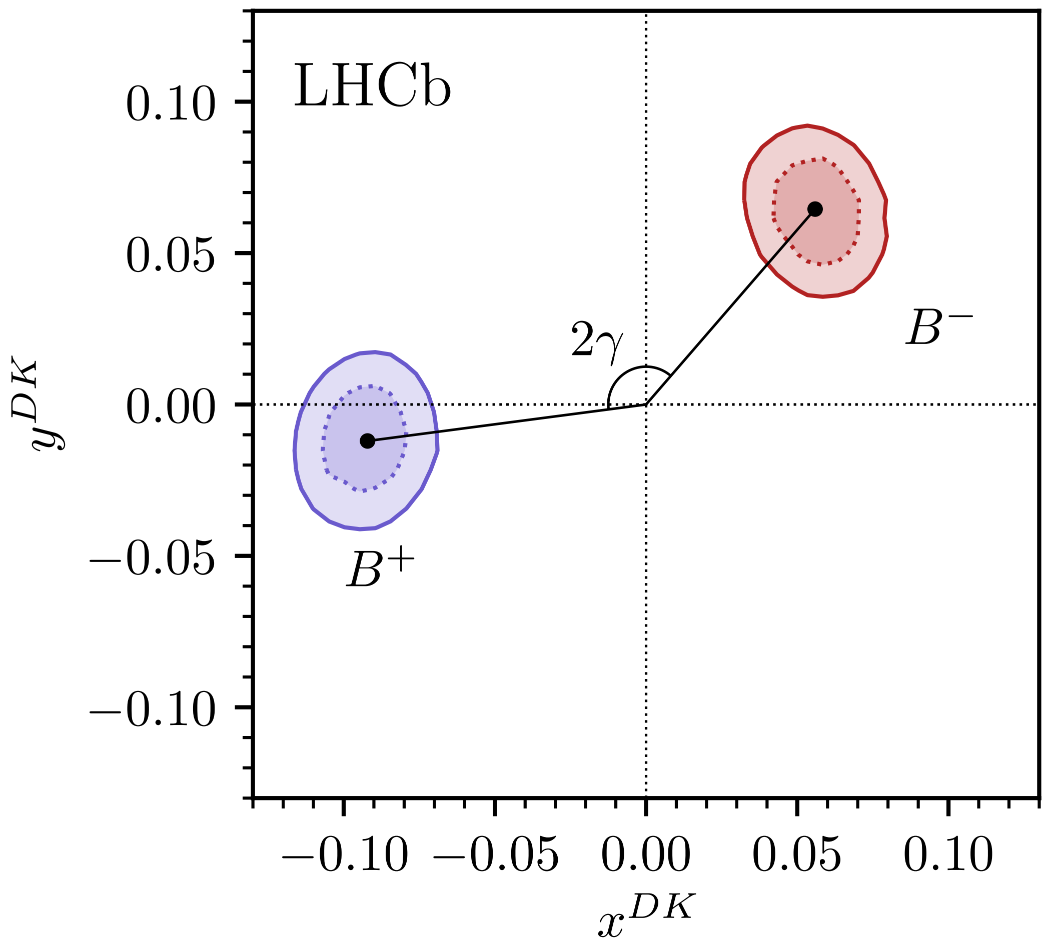
Fit

- Mass fit performed in each Dalitz plot bin to determine x, y CP observables
- Example bin 4 shown below and demonstrates a region of large asymmetry





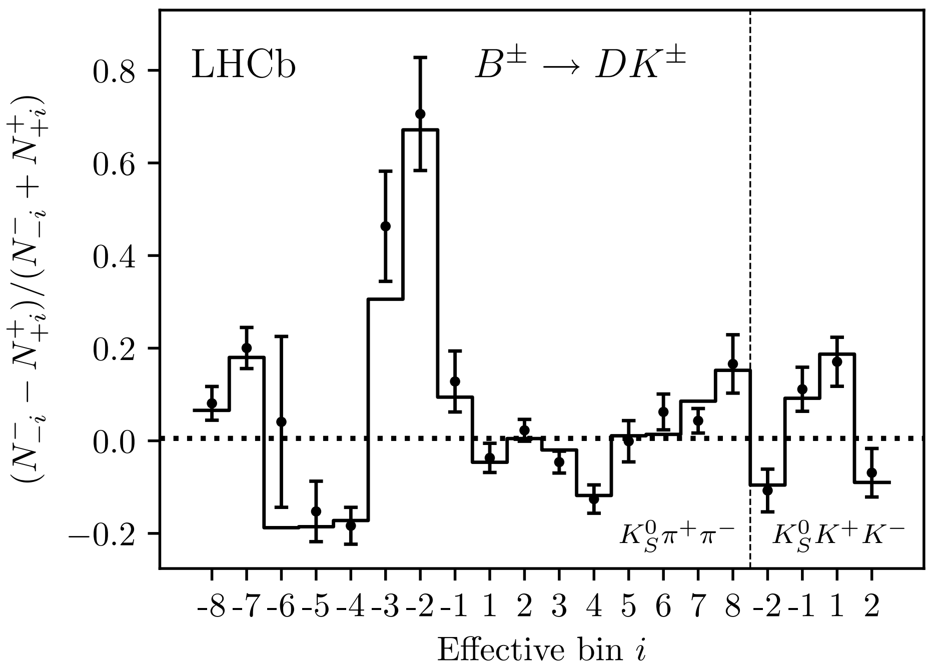
Results

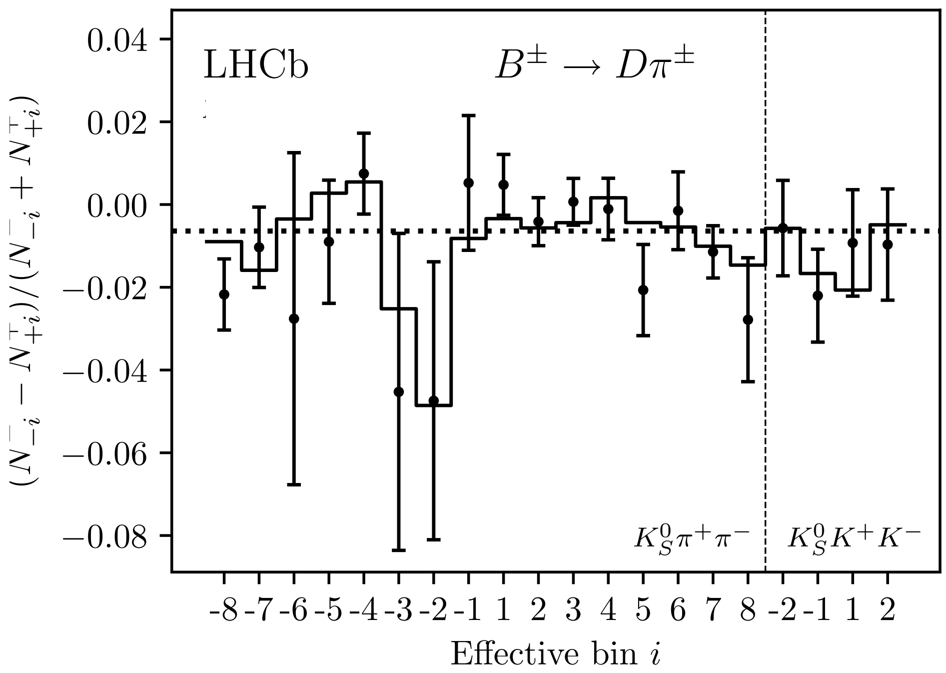


Separation is >10 σ

CP violation clearly observed

Results





- CP violation is clearly observed in B→DK.
- Data insufficient to see CPV in B→Dπ
- Everything also holds for D→KsKK, charm strong phases also measured at BESIII

Interpretation + Comparison

2011 -2018:

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

σ(stat) ~ 5° σ(BESIII+CLEO) ~ 1°, σ(syst) ~1°

Interpretation + Comparison

2011 -2018:

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

σ(stat) ~ 5°   σ(BESIII+CLEO) ~ 1°, σ(syst) ~1°

2011 -2016:

$$\gamma = (80^{+10}_{-9})^{\circ}$$

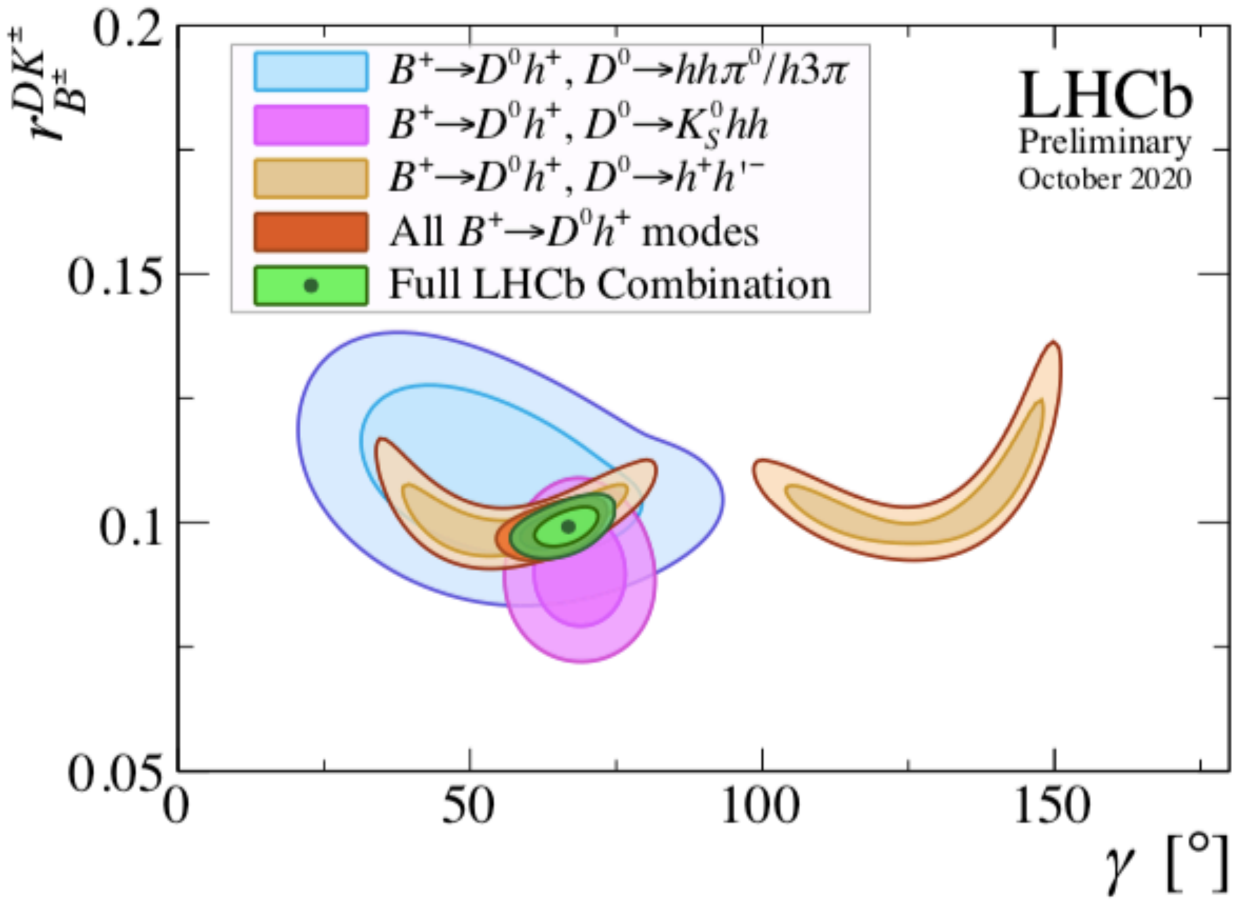
σ(stat) ~ 9°   σ(CLEO) ~ 4°, σ(syst) ~3°

New inputs from BESIII on strong phases in D→Ksππ make a large difference

Use of the B→Dπ decay mode to incorporate the efficiency effects reduces the experimental systematic uncertainties.

Reaches similar precision as all other measurements of γ combined

Gamma combination



Many B and D decay modes can be used in similar ways

Other strong-phase measurements from CLEO are used in some contributions

$$\gamma = (67 \pm 4)^{\circ}$$

Results consistent with indirect measurement

How to get from 4° to < 1° (BESIII)

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

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

$D \to K^+ K^- \pi^+ \pi^-$

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

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

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

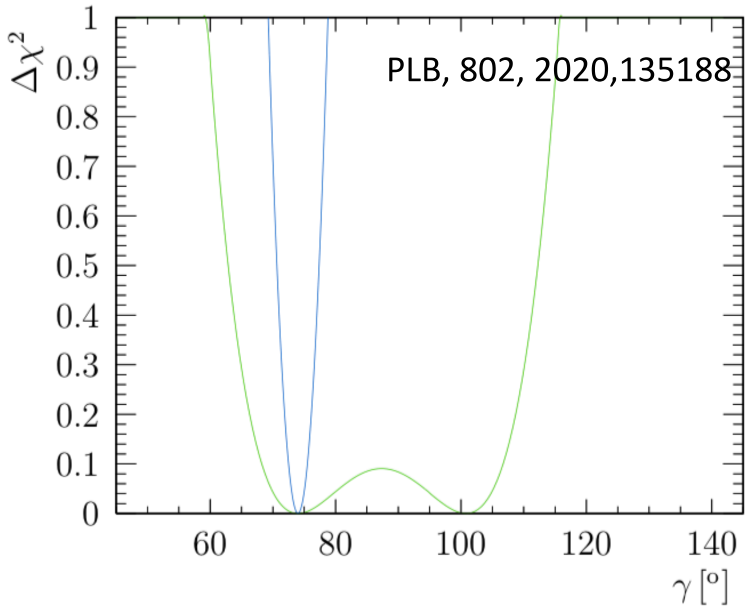
$D \to \pi^0 K^+ K^-$

$D \to \pi^- K^+ \pi^+ \pi^-$

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

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

$D \to \pi^- K^+$



In 2021 and 2022 BESIII will increase their ψ'' dataset to 20 fb^{-1}

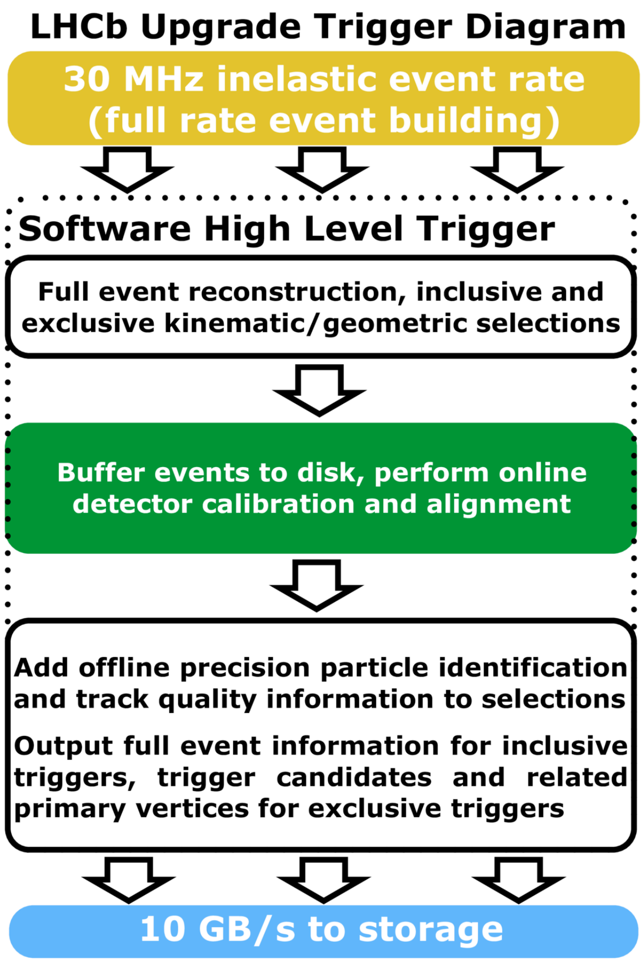
Approx x6 increase

Systematic measurement of strong phases in a large range of D decay modes underway

What we measure at BESIII also important – new binning methods will have high impact e.g PLB, 802, 2020,135188,

Allow LHCb to get the most out of its data

How to get from 4° to < 1° (LHCb)



New detector able to perform in an higher intensity scenario

Removal of hardware trigger

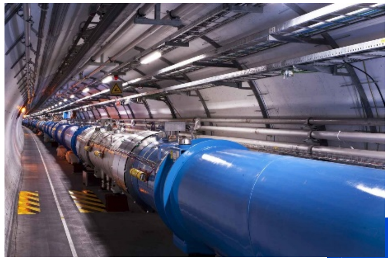
Removal of the efficiency bottleneck

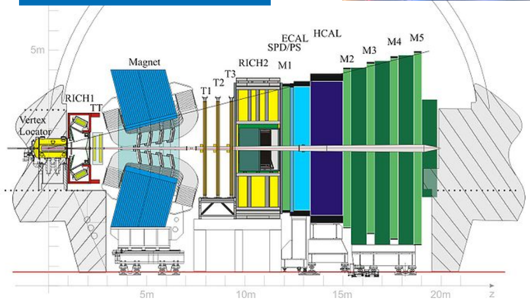
Rate at which yield of decays useful for γ are collected will be astonishing

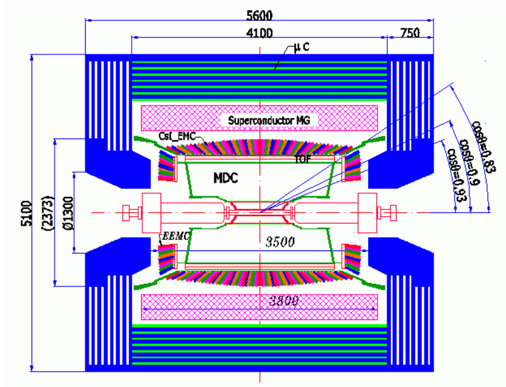
It has taken a decade to reduce the uncertainty on γ by a factor 5

The next factor 5 reduction should come much faster.

Summary and outlook







Complex analyses from both experiments were brought together to show that precision measurements of γ are possible. A 5° degree measurement has been the culmination of an intensive 2-yr period, but in practice many more years. Look forward to many further results with existing data, but much larger datasets are just around the corner.

END