

Charmless $B \rightarrow VV$ decays $B_{(s)}^0 \rightarrow \phi\phi$ at LHCb

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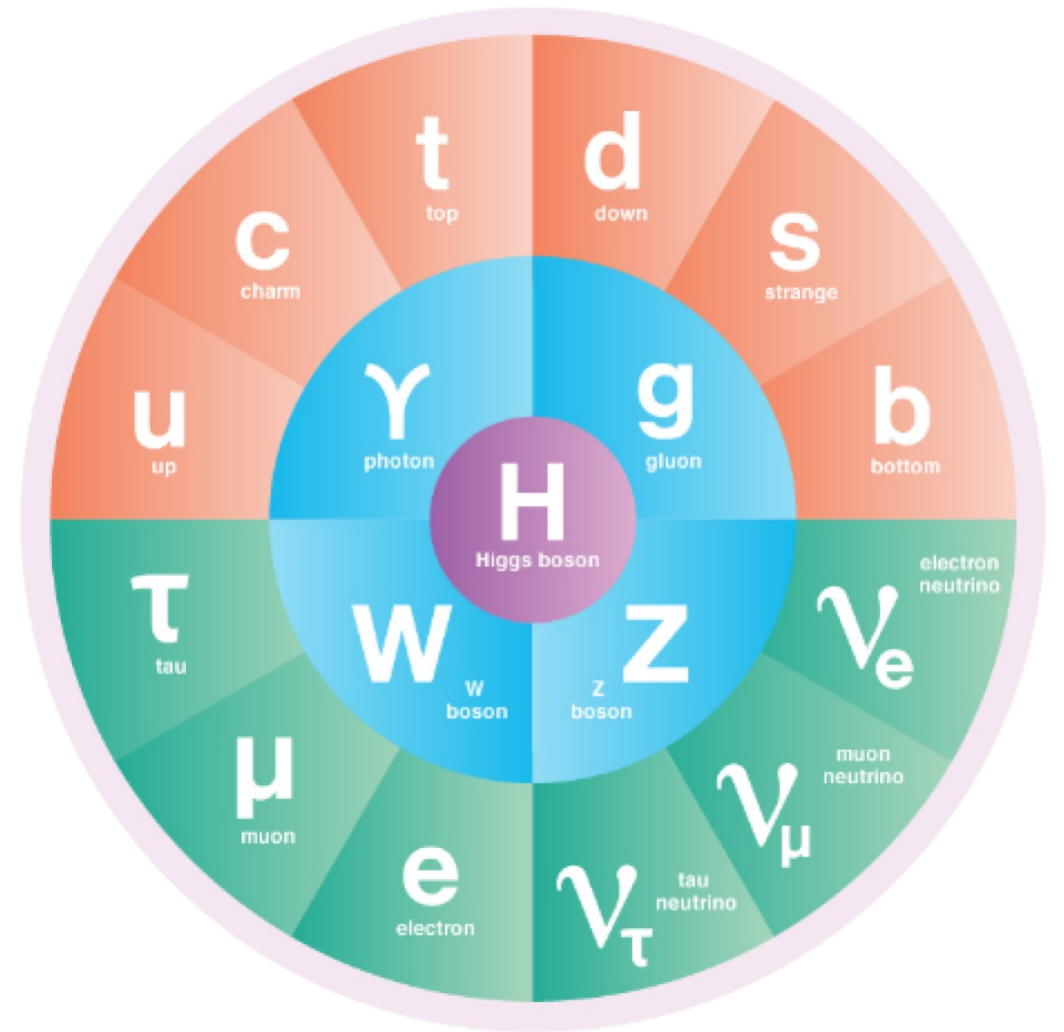
Contents

- What are charmless $B \rightarrow VV$ decays, and why do we care?
 - The Standard Model + its shortcomings
 - CP violation in the Standard Model
 - The polarisation puzzle
- The LHCb experiment
- Analysis of $B_{(s)}^0 \rightarrow \phi\phi$
 - Measuring CP violation in $B_S^0 \rightarrow \phi\phi$
 - The search for $B^0 \rightarrow \phi\phi$ recent!
- Status and roadmap



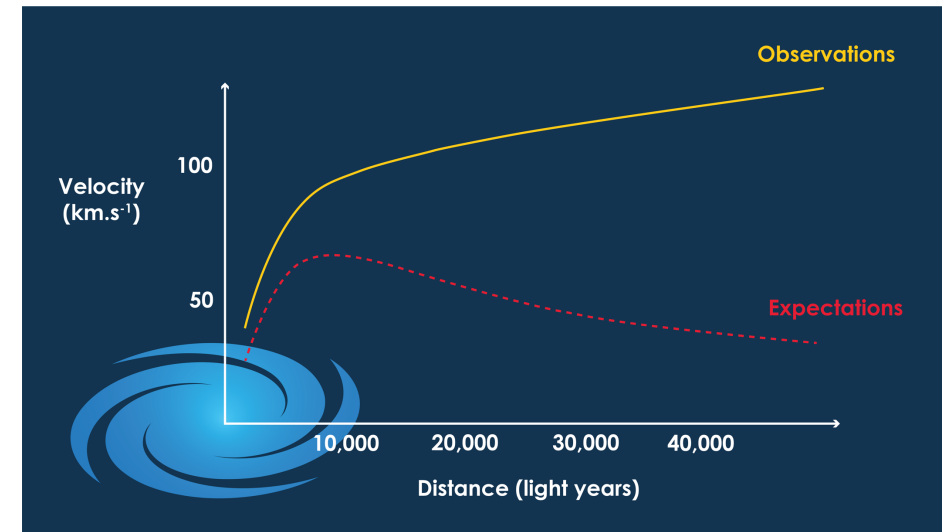
The Standard Model of particle physics

- Describes the fundamental particles and how they interact
- Works incredibly well to explain natural phenomena – has been probed in exquisite detail by some of the biggest experiments for many decades
- Still, there are several things it cannot explain...



Some things are not understood

- The Universe is made entirely of matter, but we believe it they were produced in equal amounts
 - Where did the antimatter go?
- What is dark matter?
 - Know it must be there from e.g. galactic rotation curves, not enough observable matter to account for rotational velocities at large radius
- Neutrino mass, are neutrinos majorana?



Matter-antimatter asymmetry

- How can we generate an asymmetry in the matter and antimatter?
- Three conditions from Sakharov:
 - Baryon number violation
 - Violation of C and CP symmetries
 - Universe moves away from thermal equilibrium
- Next up – **how do we get CP violation in the Standard Model?**

CP violation in the SM: the CKM matrix

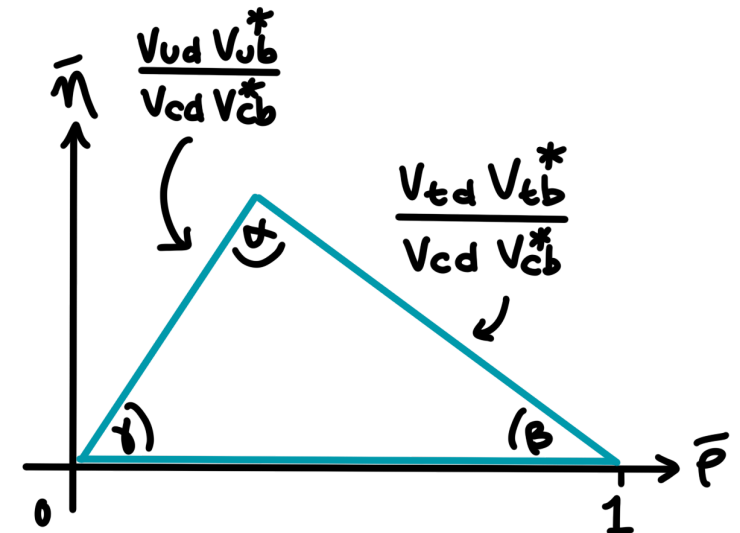
- Quark flavour mixing determined by **CKM matrix** – connects mass and flavour eigenstates

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & \lambda^2 \\ \lambda^3 A(1 - \rho - i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

- CP -violation in SM – complex phase in CKM
- Unitarity of CKM matrix $\Rightarrow$ unitarity relations

$$\sum_k V_{ik} V_{jk}^* = 0$$

- Form **triangles** in the complex plane

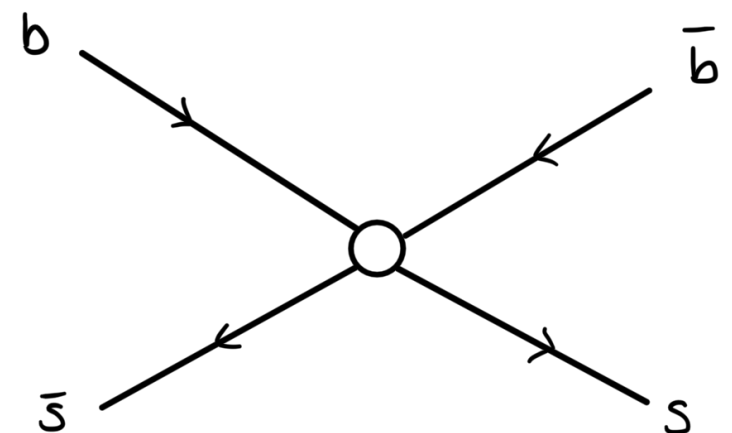


CP violation in the SM is not enough to explain the observed asymmetry...

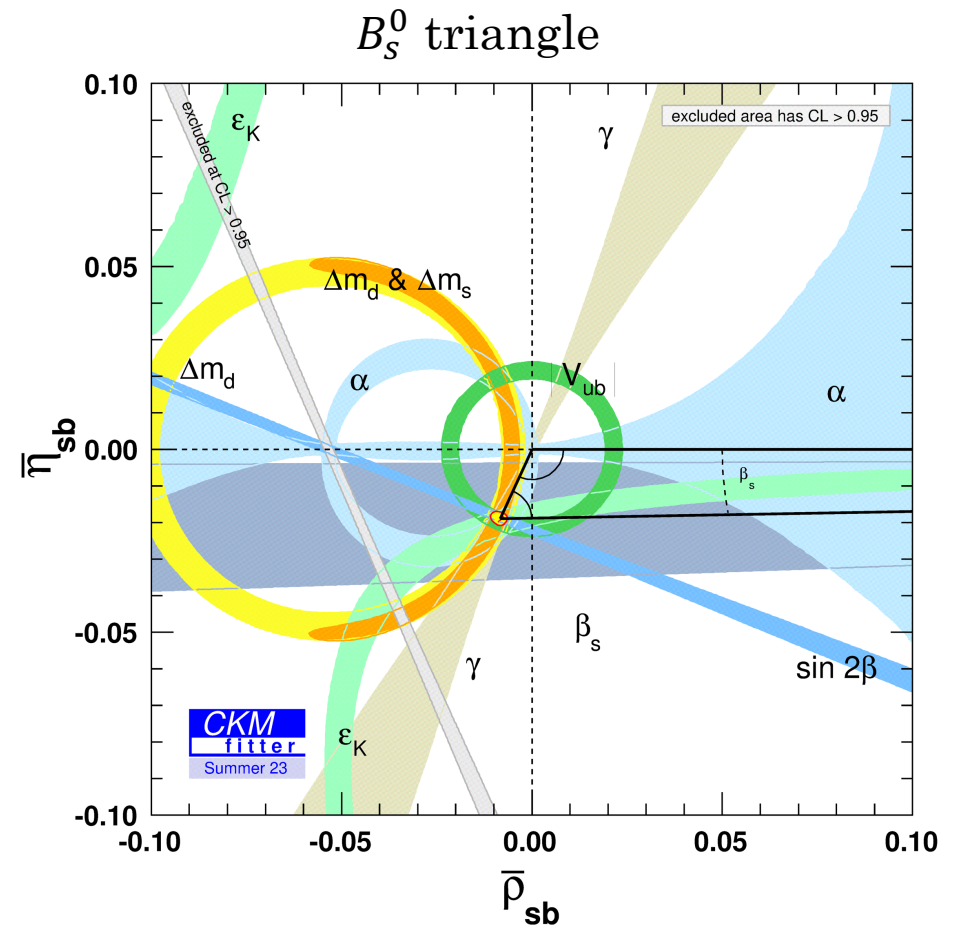
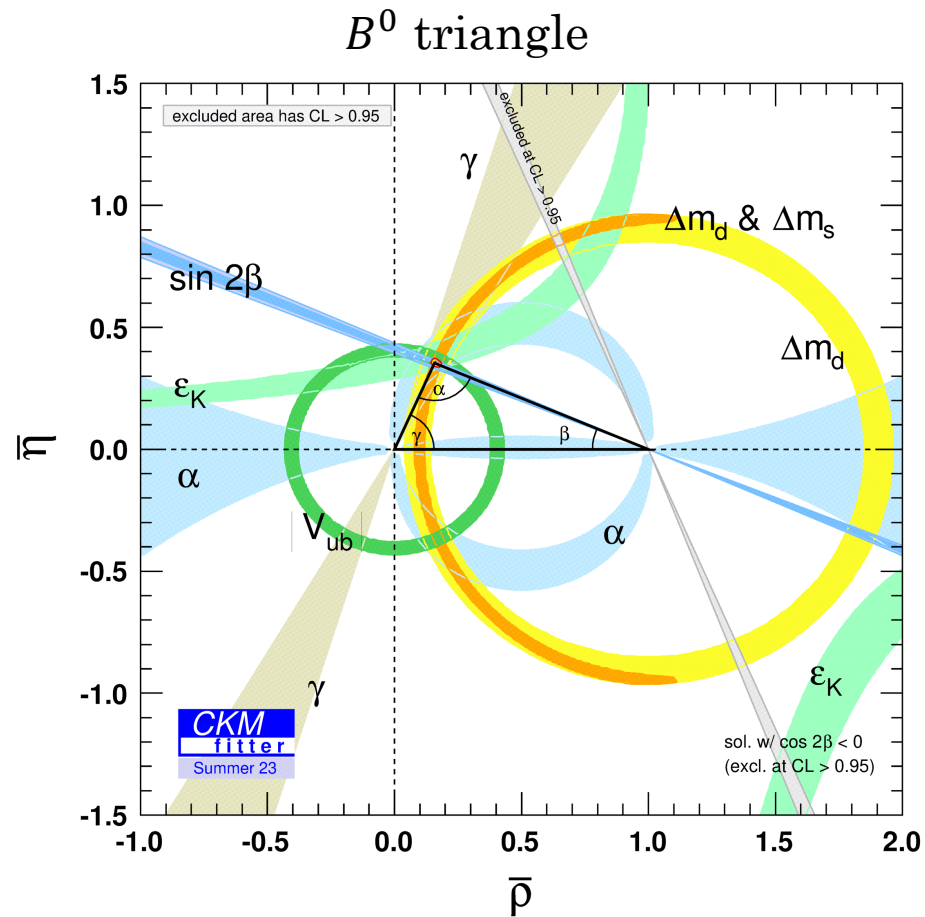
- **Observed asymmetry not explained by SM CP violation**
- Want to search for additional sources of CP violation

GOAL: measure the triangles!

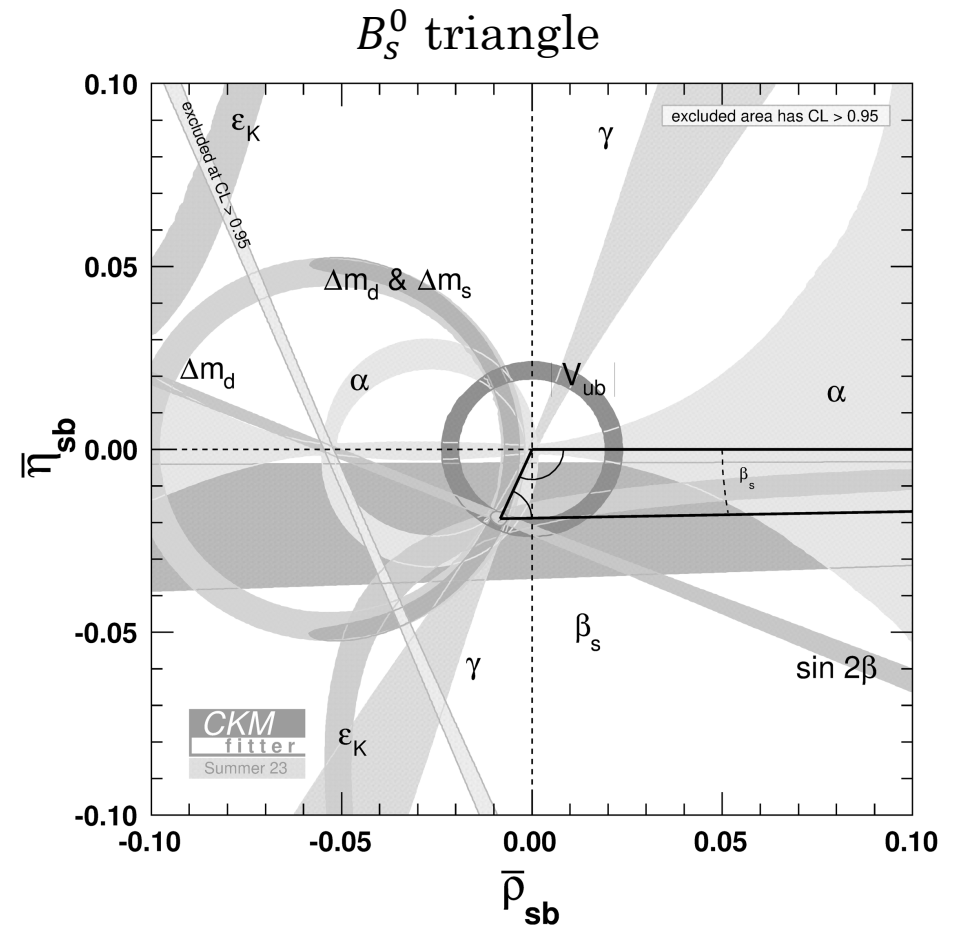
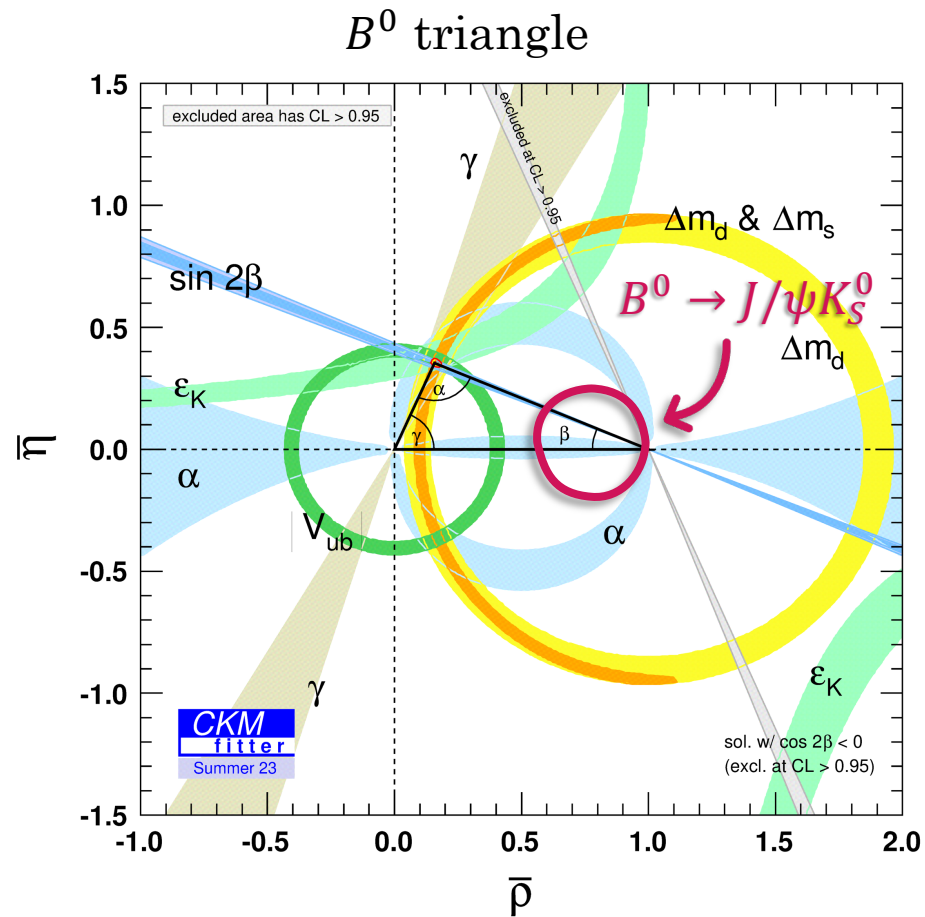
- **Overconstrain** the SM parameters to look for an **inconsistency coming from high-scale new physics** that can affect one mode but not another
- E.g. New physics that looks like this...



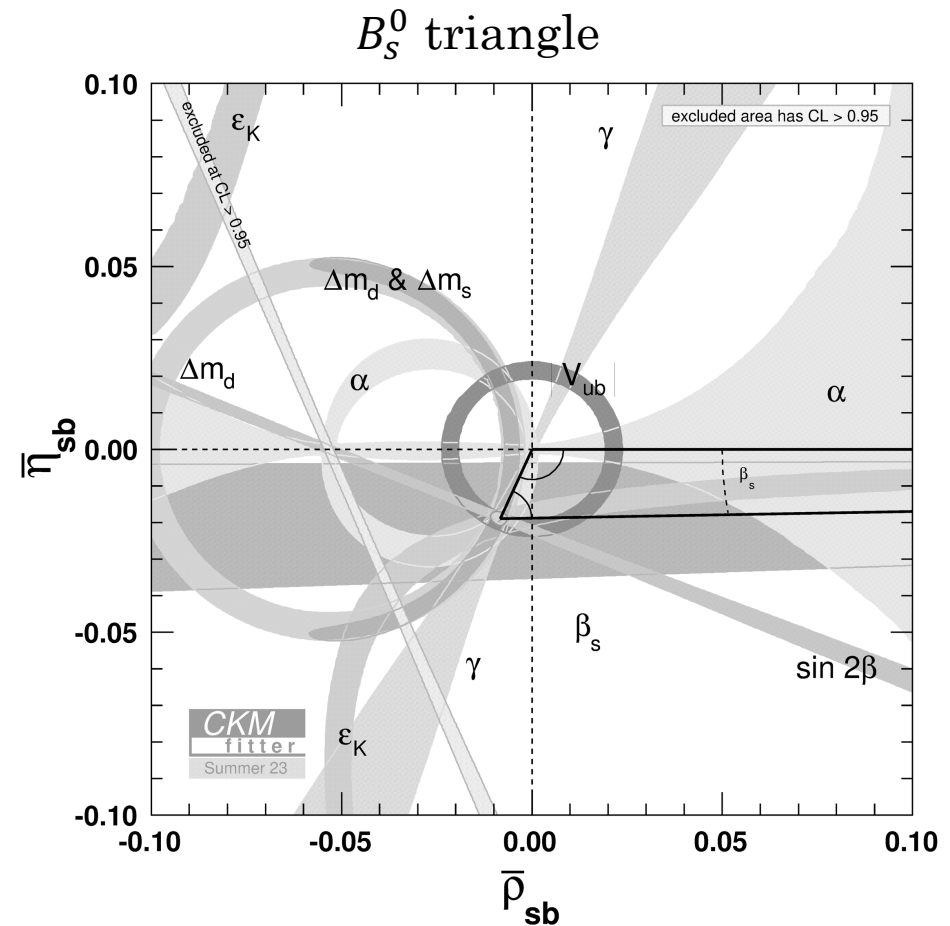
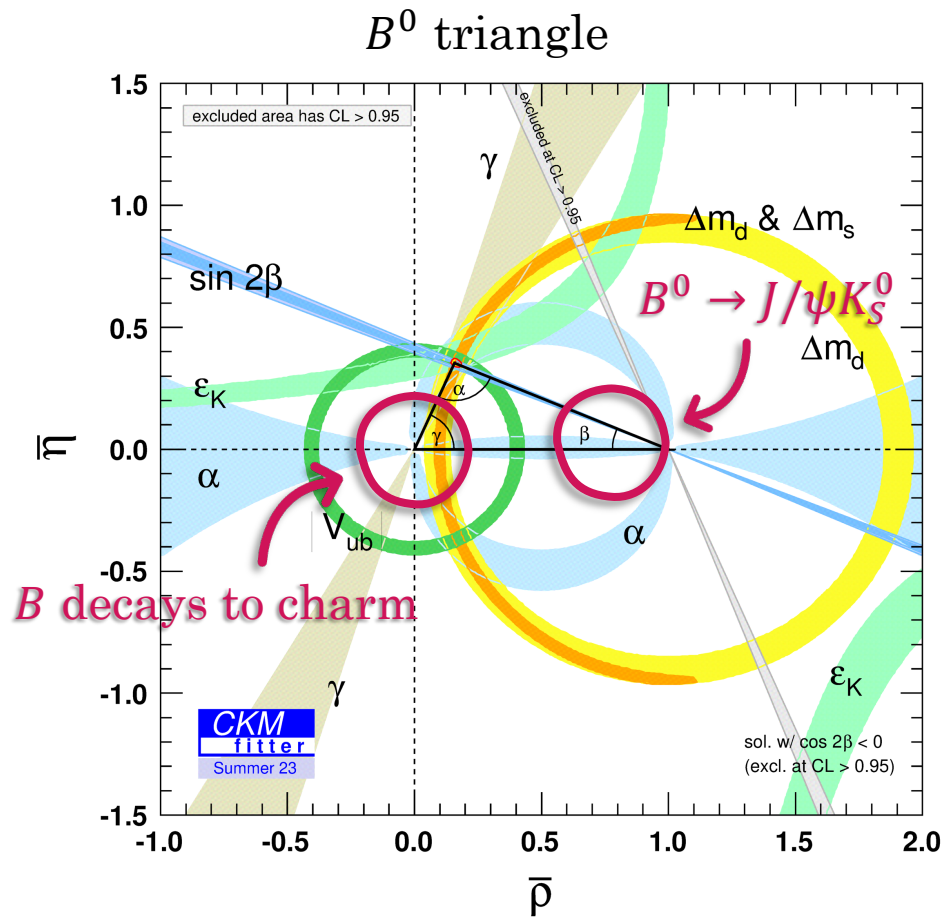
How do we measure triangles?



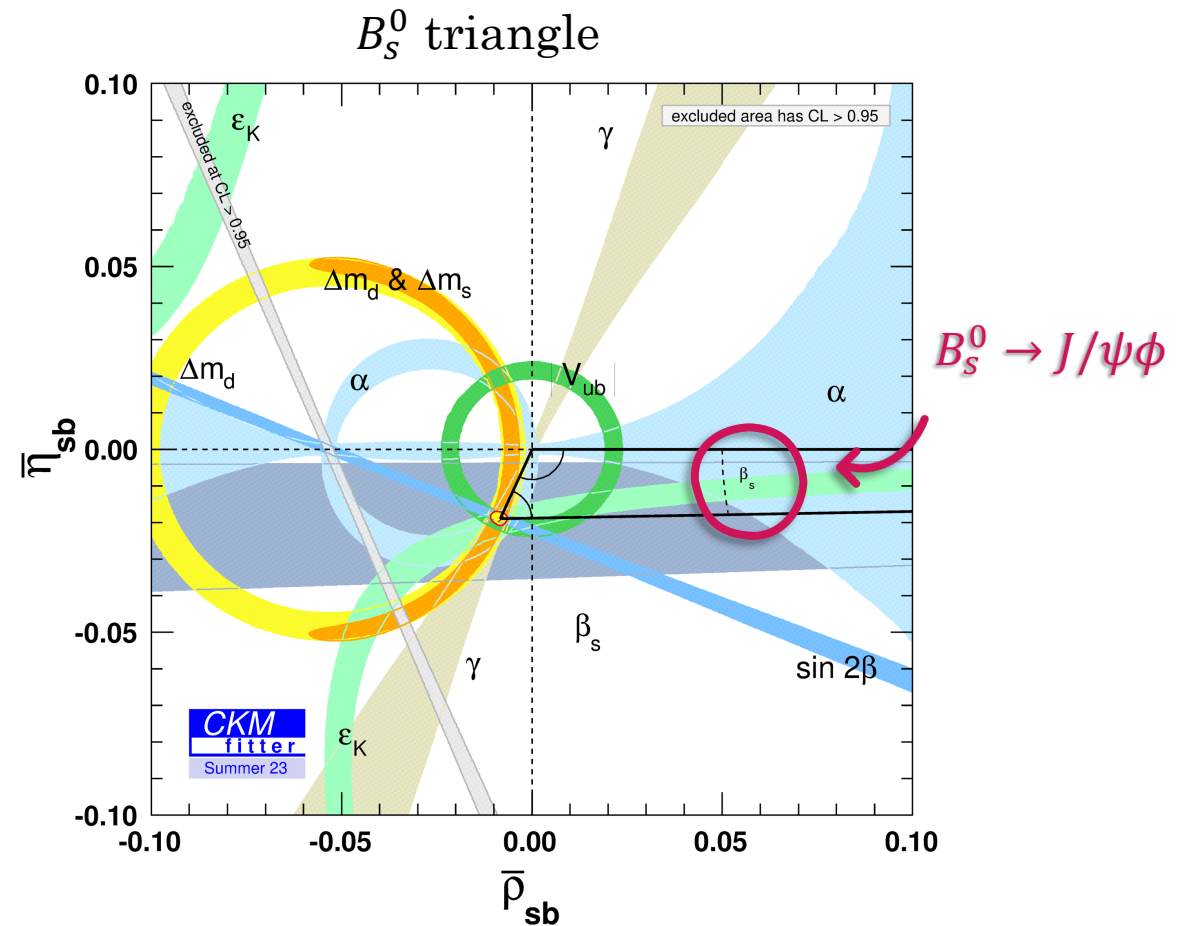
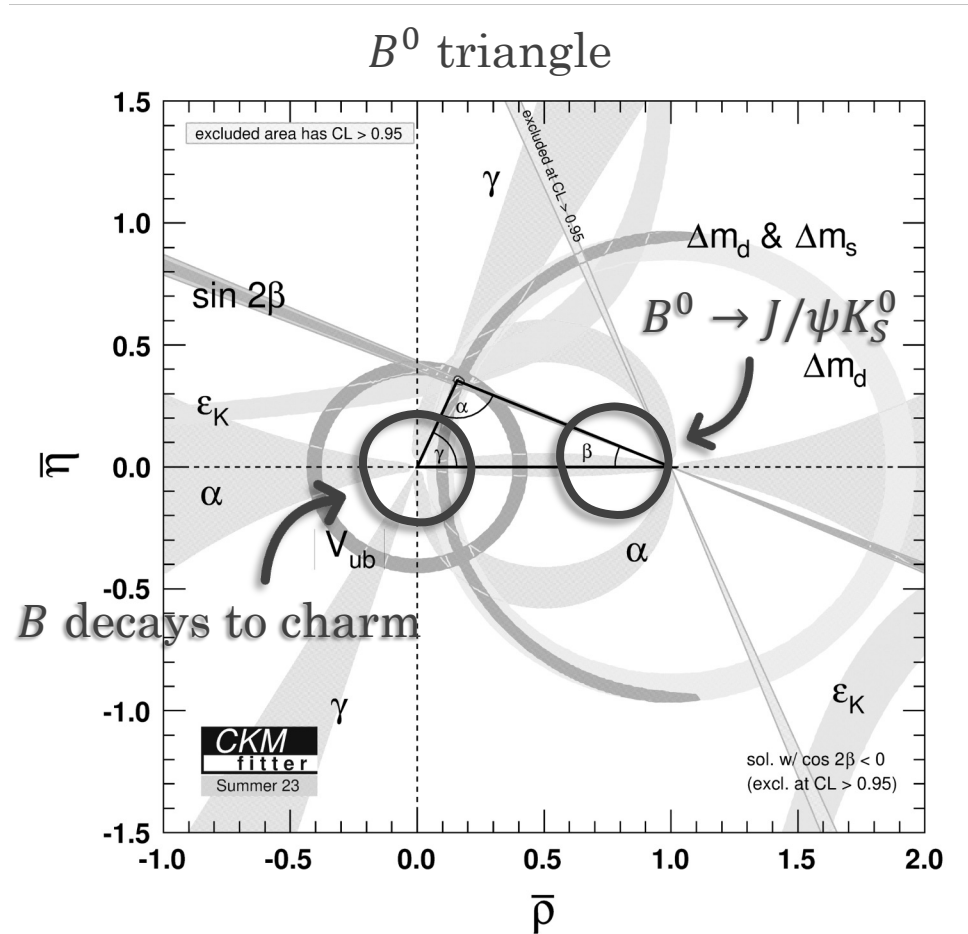
How do we measure triangles?



How do we measure triangles?



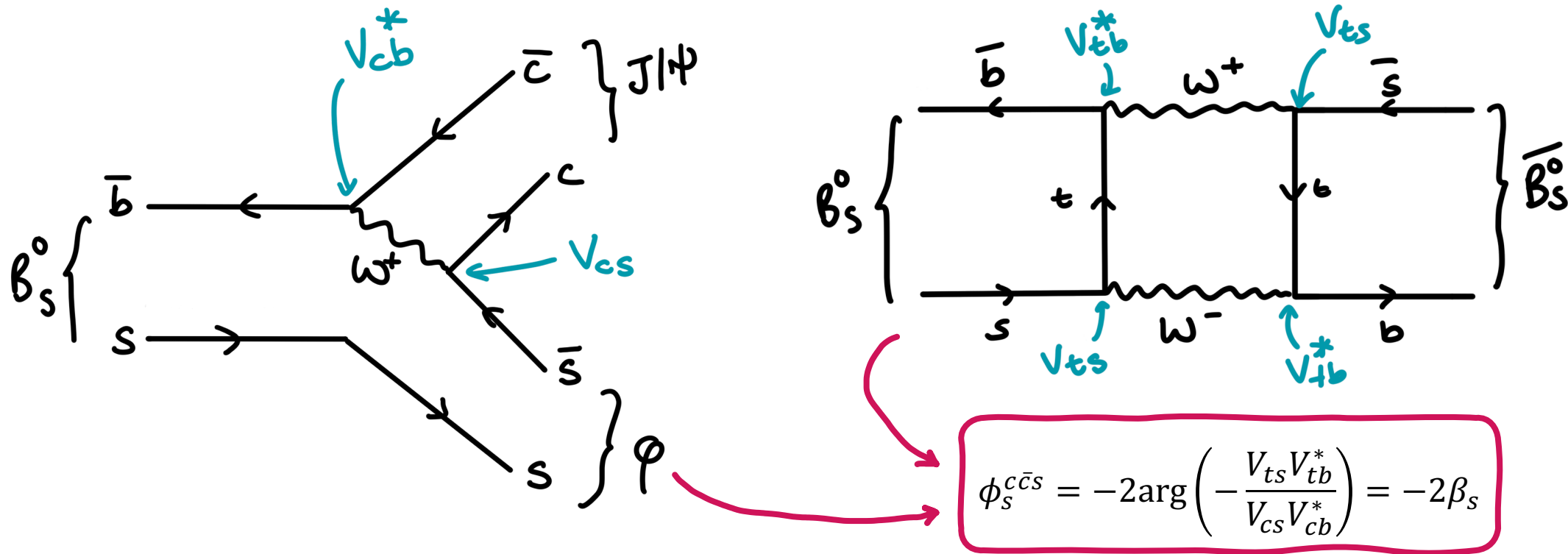
How do we measure triangles?



$B_s^0 \rightarrow J/\psi \phi$: charming golden mode



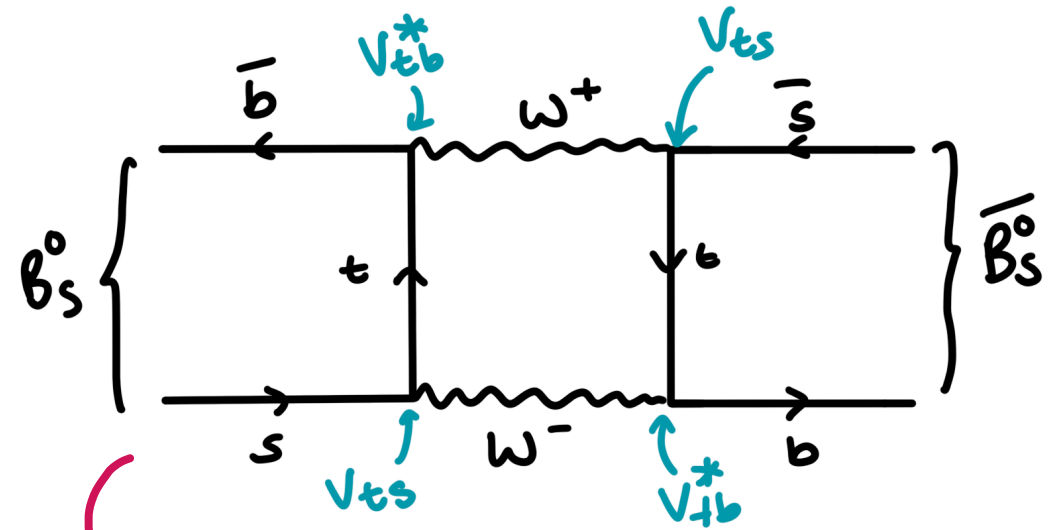
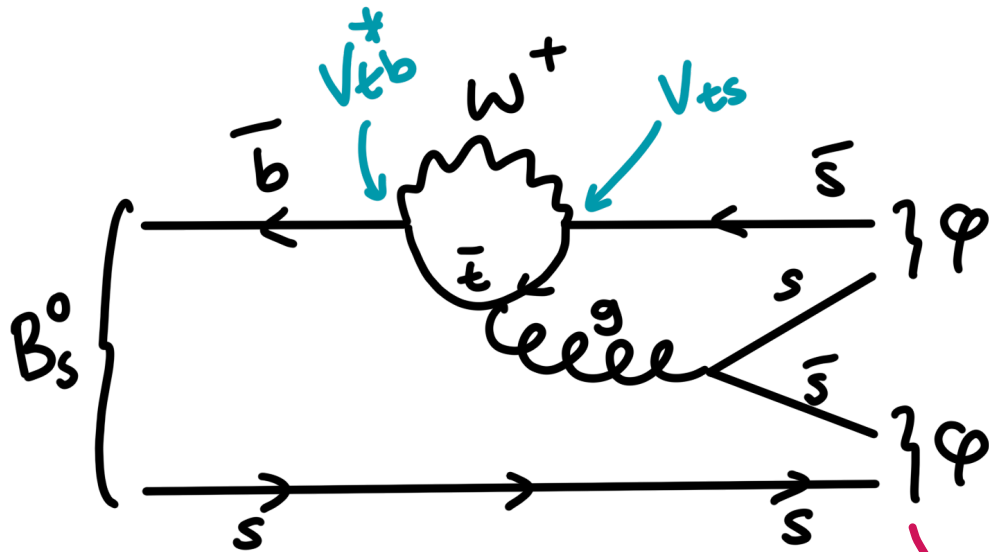
- $B_s^0 \rightarrow J/\psi \phi$ decays can measure CP violating phase $\phi_s^{c\bar{c}s}$
- Relates to the B_s^0 triangle angle β_s as $\phi_s^{c\bar{c}s} = -2\beta_s$



Get rid of the charm – $B_s^0 \rightarrow \phi\phi$



- Decay only at **penguin** level, but same mixing diagram



$$\phi_S^{s\bar{s}s} \approx 0$$

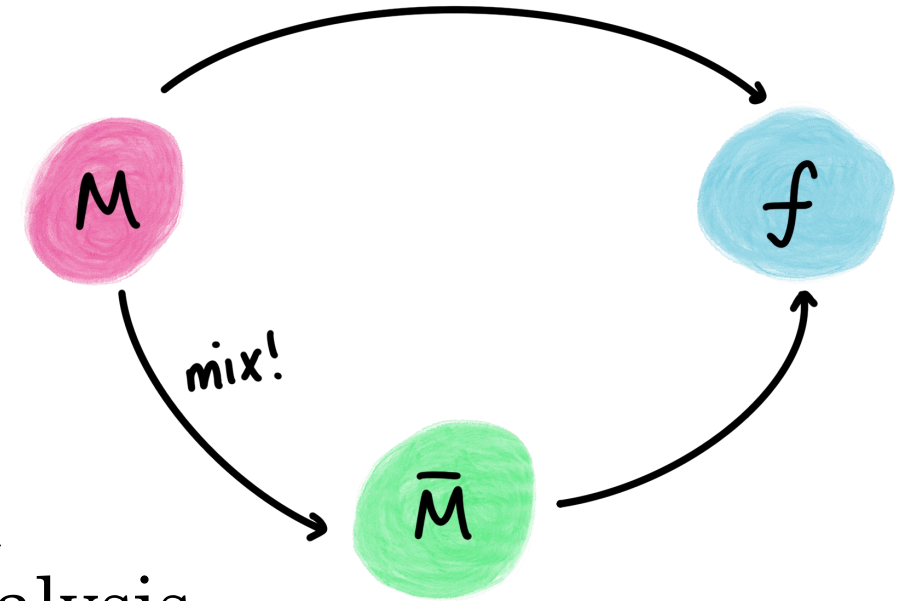
Cancellation since same CKM elements appear in mixing and decay

Both are examples of mixing-induced CP violation

- Also known as “indirect” CP -violation
- Start with a neutral meson, M
 - Could decay to final state f
 - Could mix to $\bar{M}$ and then decay to f
- For these types of decays, need to do a **flavour-tagged time-dependent** analysis

Was it a B_s^0 or $\bar{B}_s^0$
to begin with?

Mixing encoded in tagged
decay-time distributions



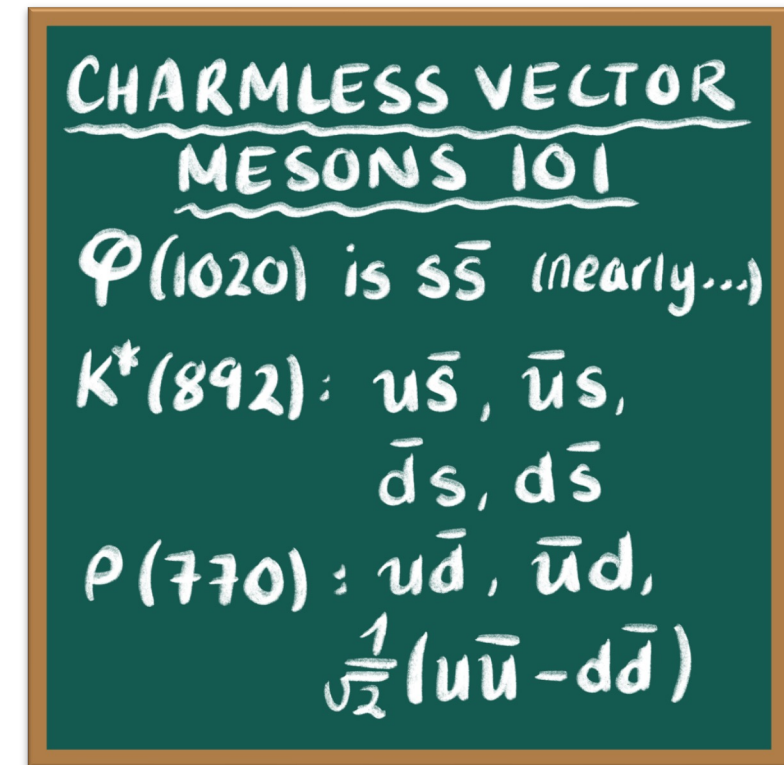
Requires M and $\bar{M}$ to be
accessible to
same final state

$B_s^0 \rightarrow \phi\phi$ is a charmless $B \rightarrow VV$ decay

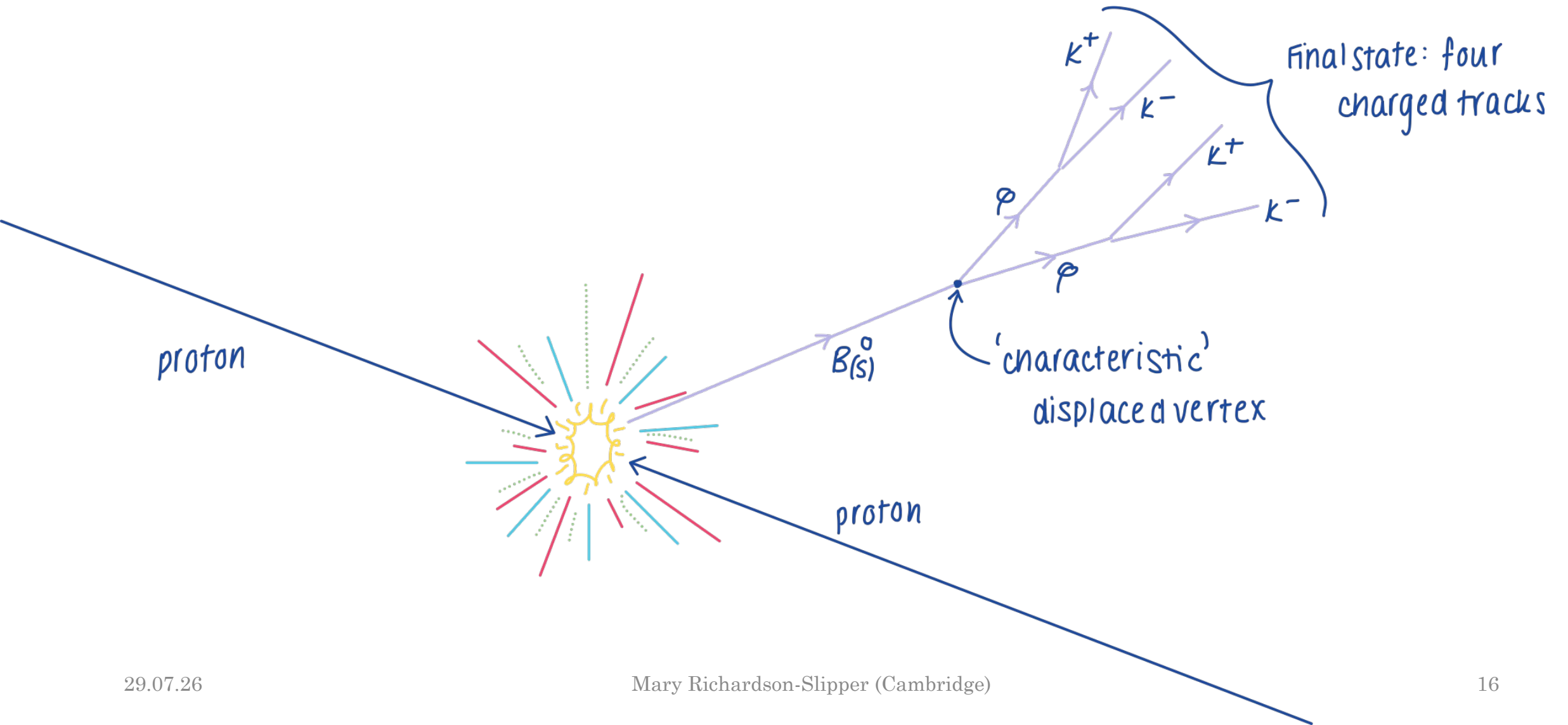
- Decay of a B meson (B^0, B^+, B_s^0) to a (charm-free!) vector meson (ϕ, K^*, ρ)
- Many of these, I'm going to focus on my favourites...

$$B_s^0 \rightarrow \phi\phi \text{ and } B^0 \rightarrow \phi\phi$$

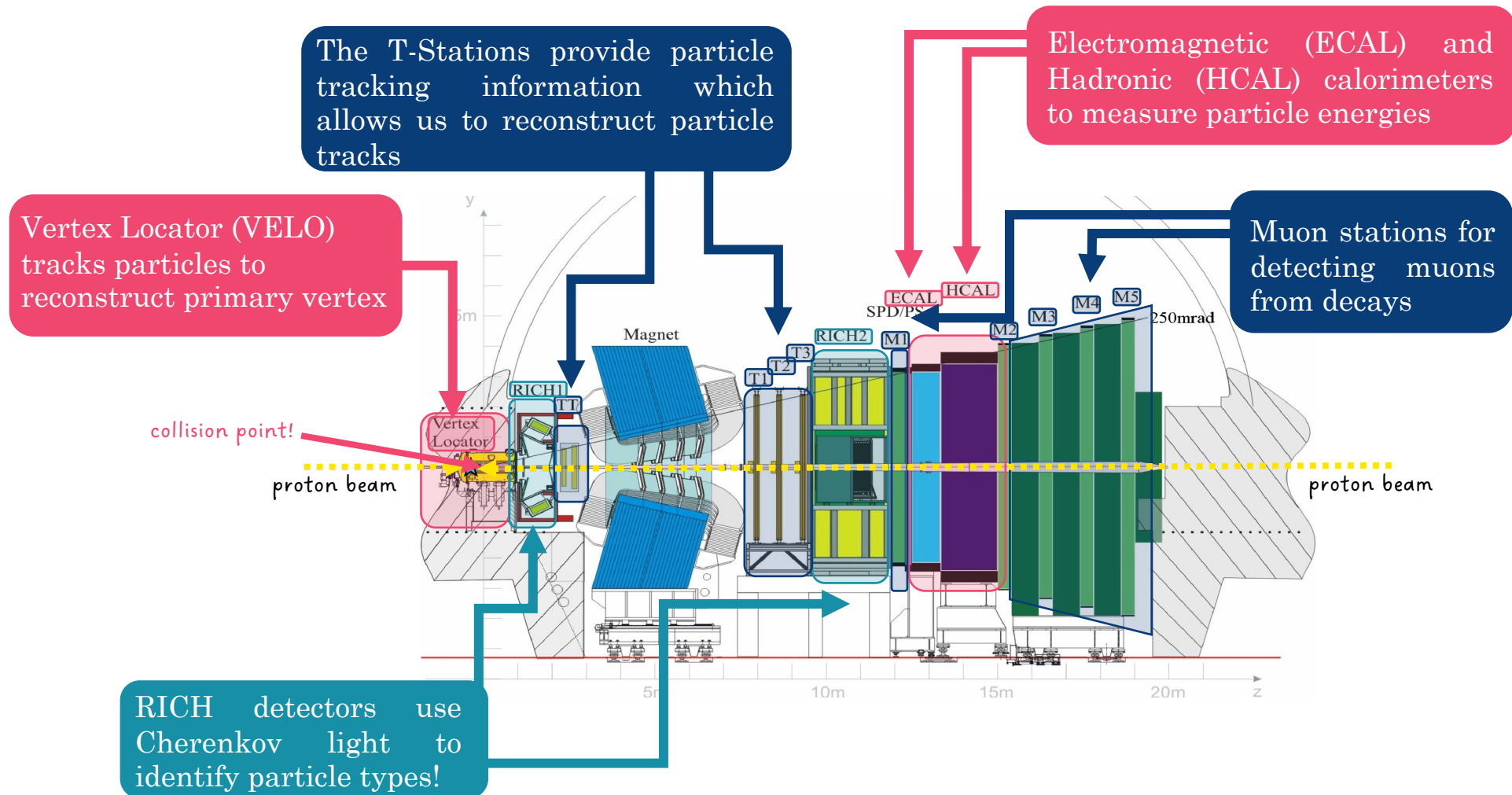
- Measuring CP violation
- Measuring the polarization puzzle
- Branching fraction sensitive to new physics
- Constrains $B_s^0 \rightarrow \phi\phi$



Anatomy of a $B_{(s)}^0 \rightarrow \phi\phi$ decay



Measuring $B_{(s)}^0 \rightarrow \phi\phi$ with LHCb



Measuring $B_{(s)}^0 \rightarrow \phi\phi$ with LHCb

Measurements of track momentum and energy (HCAL also used for triggering)

Identify B mesons using displaced vertices

The T-Stations provide particle tracking information which allows us to reconstruct particle tracks

Vertex Locator (VELO) tracks particles to reconstruct primary vertex

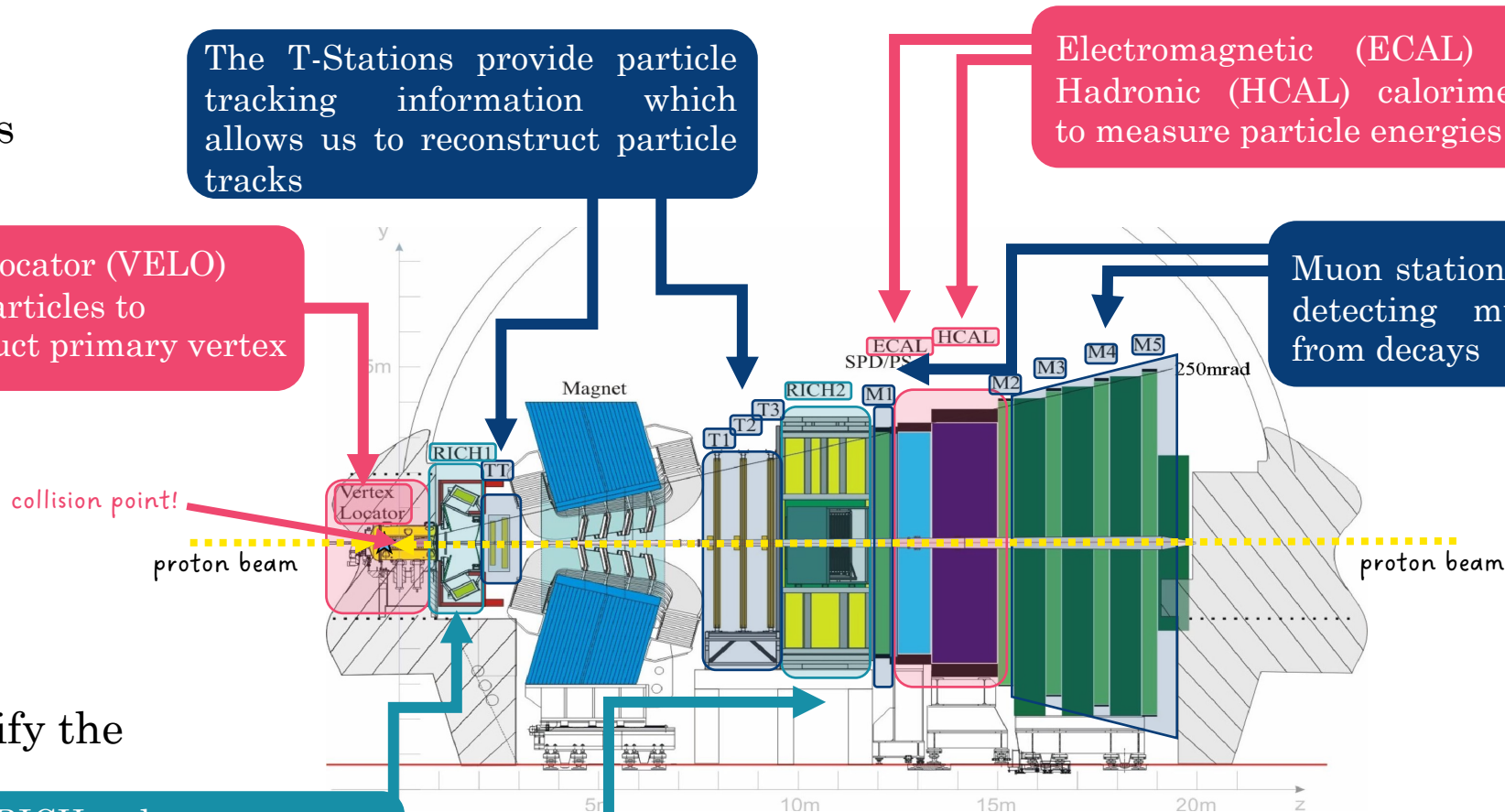
Electromagnetic (ECAL) and Hadronic (HCAL) calorimeters to measure particle energies

Muon stations for detecting muons from decays

Needed to reject background with muons

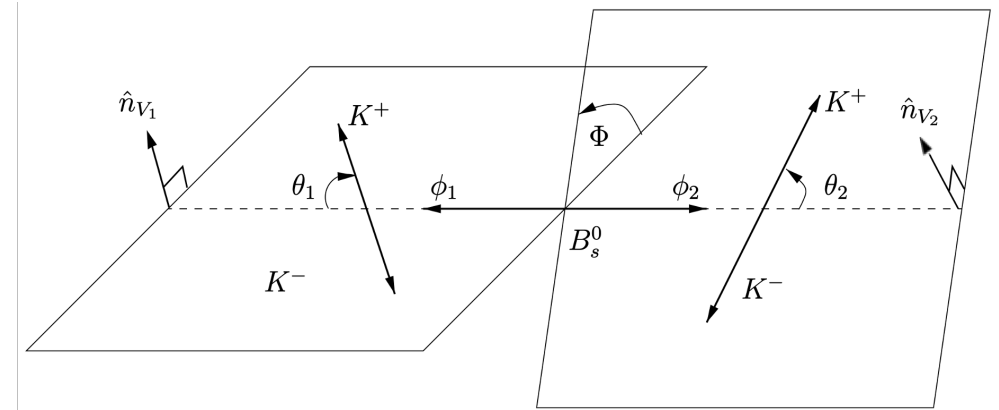
Needed to identify the kaons as kaons

RICH detectors use Cherenkov light to identify particle types!



Getting physics out of $B_s^0 \rightarrow \phi\phi$ decay

- B_s^0 ($\bar{b}s$) mesons are **pseudoscalar** mesons with total spin 0 and odd parity
- ϕ ($\bar{s}s$) mesons are **vector** mesons with total spin 1 and odd parity
- Three contributing amplitudes from different helicity combinations – these are each **CP-even** or **CP-odd**:
 $A_{\parallel}$, A_0 , $A_{\perp}$
- Define the decay in the helicity basis



Angle Φ : the angle between ϕ meson decay planes in the rest frame of the B_s^0 meson

Angles θ_1 and θ_2 : angle between K^+ momentum in ϕ rest frame and ϕ momentum in B_s^0 rest frame

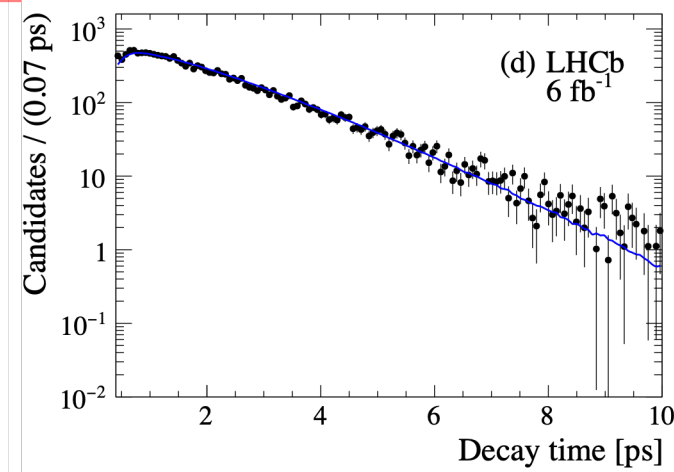
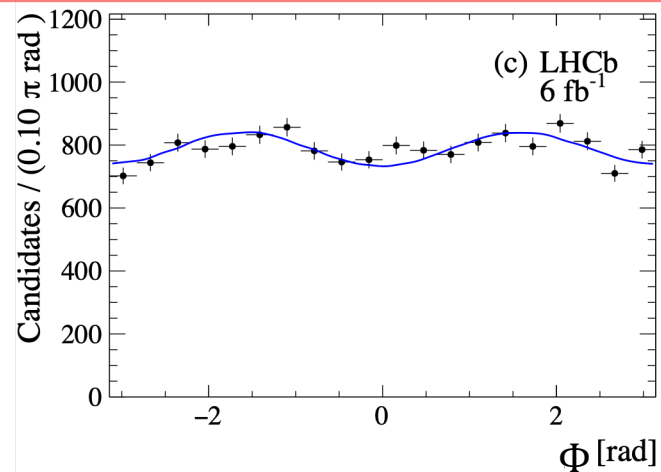
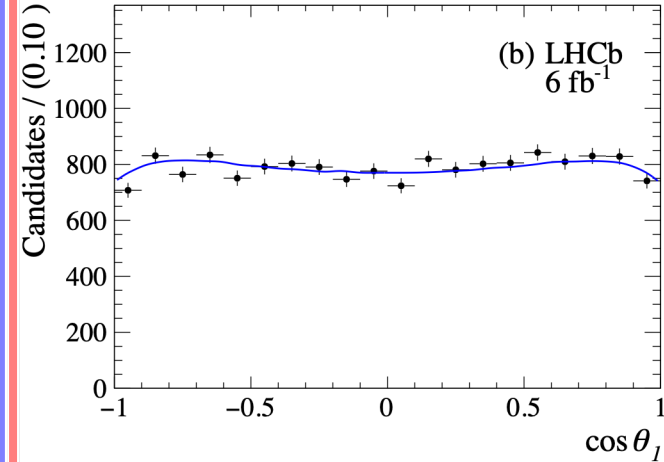
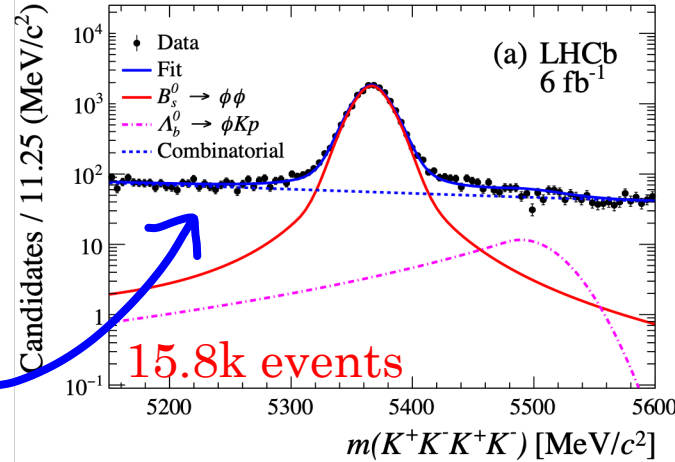
Differential decay rate a function of helicity angles

- Differential decay rate a function of the helicity angles Φ , θ_1 and θ_2 and decay time
- A time-dependent, flavour-tagged 4D fit to these helicity angles and the decay time allows us to extract
 - the magnitude of the amplitudes $|A_0|^2$ and $|A_\perp|^2$
 - Knowing $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$
 - the strong phase differences between the amplitudes: $\delta_\perp - \delta_0$ and $\delta_\parallel - \delta_0$
 - the ***CP*** violating phase, $\phi_S^{s\bar{s}s}$

The latest measurement of $\phi_s^{s\bar{s}s}$

LHCb
Run 2

Fit to the $K^+K^-K^+K^-$ invariant mass – used to statistically subtract the background



4D fit to the **signal-weighted** decay time and helicity angles to extract $\phi_s^{s\bar{s}s}$

Another way to probe CP violation in the SM: Triple Product Asymmetries (TPAs)

- Time-integrated triple product asymmetries a complementary probe for CP violation
- T -odd scalar triple products defined in terms of helicity angle Φ

$$U \equiv \sin \Phi \cos \Phi$$

$$V \equiv \sin(\pm\Phi) \text{ with positive taken} \\ \text{if } \cos \theta_1 \cos \theta_2 \geq 0$$

- Asymmetries given by

$$A_U = \frac{\Gamma(U>0) - \Gamma(U<0)}{\Gamma(U>0) + \Gamma(U<0)}$$

$$A_V = \frac{\Gamma(V>0) - \Gamma(V<0)}{\Gamma(V>0) + \Gamma(V<0)}$$



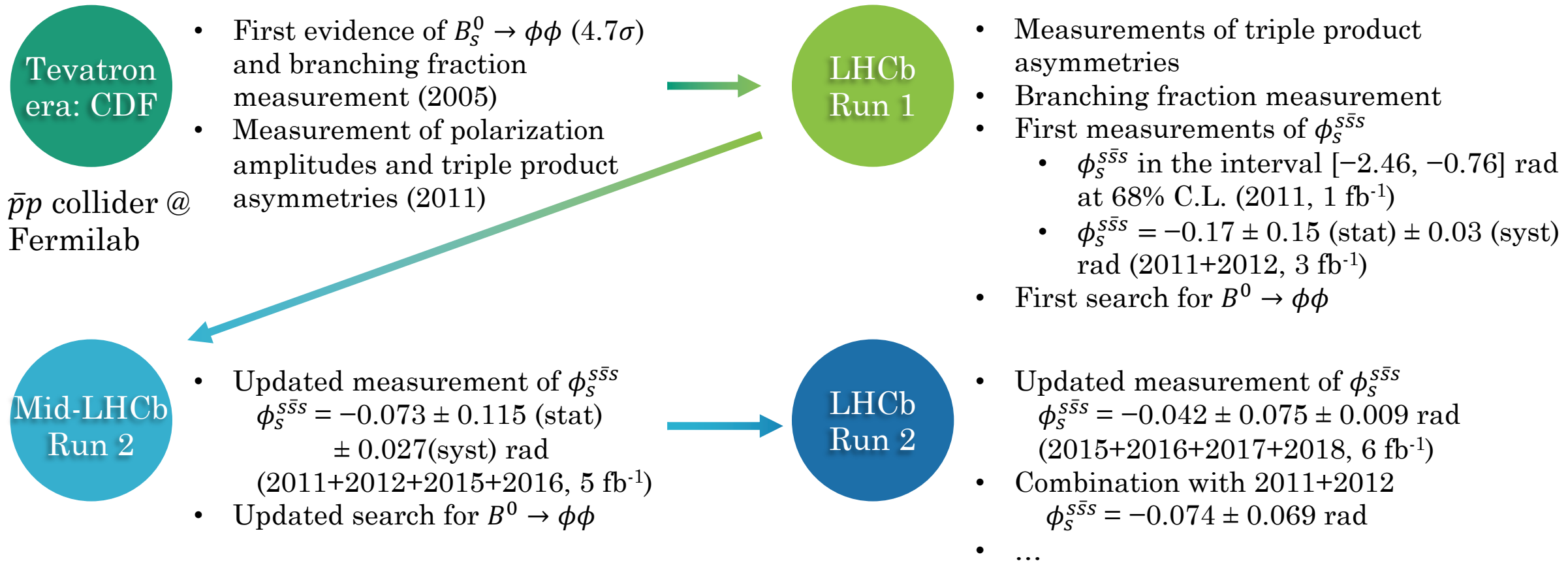
Asymmetry in T -odd scalar triple product $\Rightarrow$ BSM CPV

The polarisation puzzle

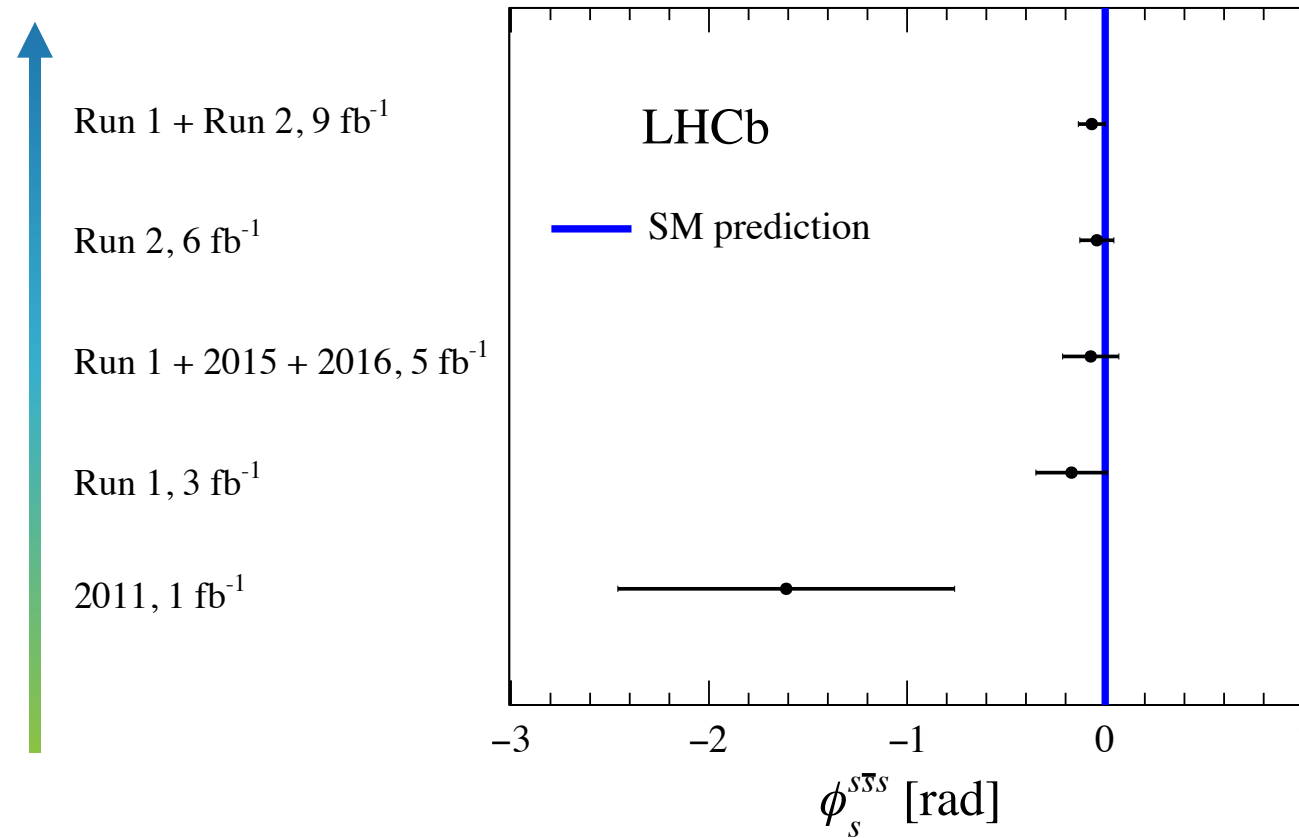
- For $B \rightarrow VV$ decays, there are the three polarisation amplitudes
- The longitudinal polarisation should dominate since helicity suppression affects the transverse polarisations
- True for tree-level $B \rightarrow VV$ but not the case for penguins where sizeable transverse polarisations are observed



History of $B_{(s)}^0 \rightarrow \phi\phi$ measurements



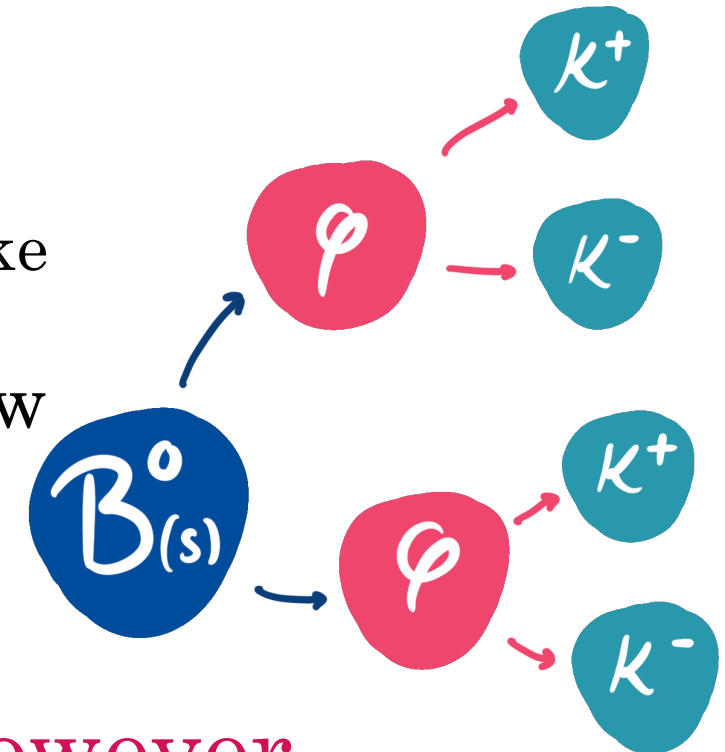
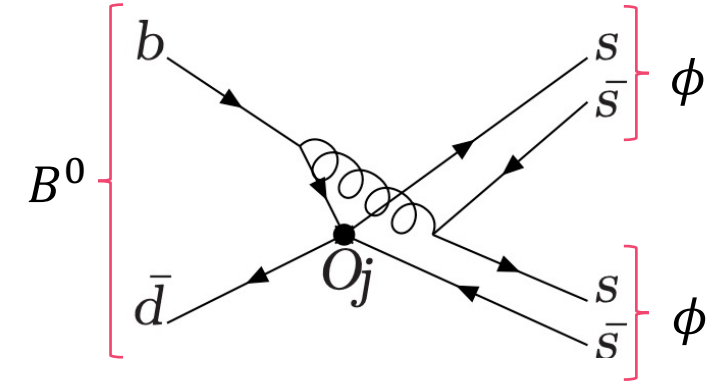
Measurements of $\phi_s^{s\bar{s}s}$



- Slowly but surely improving the value of $\phi_s^{s\bar{s}s}$ with more data
- Consistent with the SM **so far**
- What else can we probe with $\phi\phi$?

Searching for $B^0 \rightarrow \phi\phi$

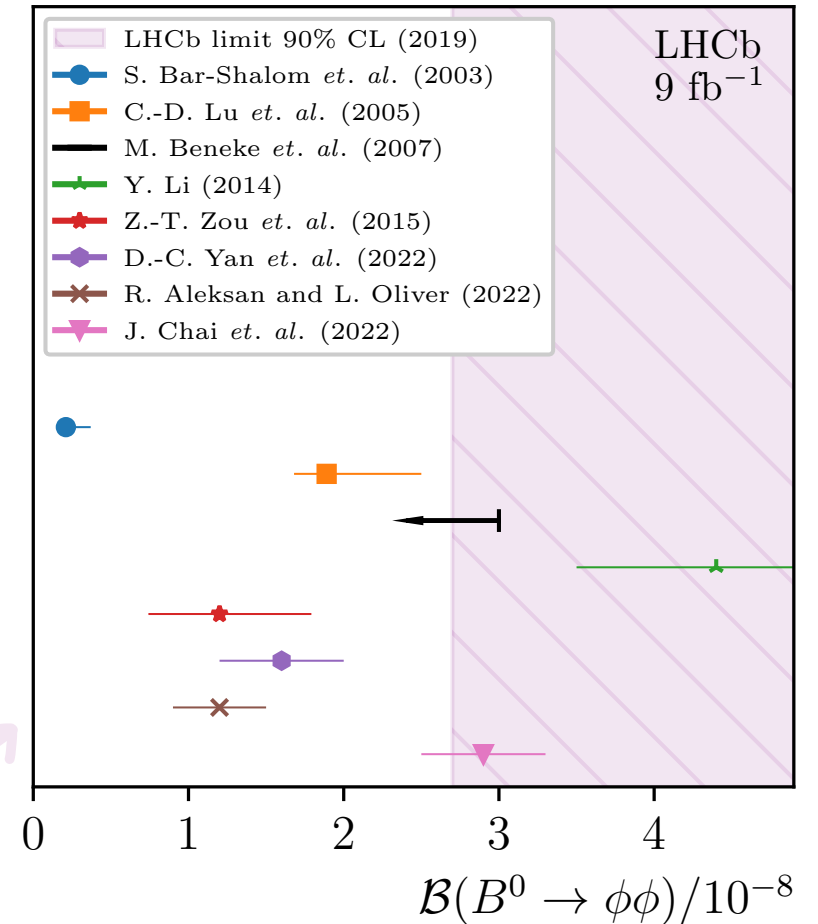
- This is an example of a $\bar{b}d \rightarrow s\bar{s}$ annihilation and it is **very** suppressed in the SM
 - Cabibbo suppression – quarks from different families
 - Suppression from loops in Feynman diagram
 - OZI suppression – can you cut gluon lines to make two disconnected diagrams?
- Branching fraction can be **enhanced** in a few scenarios
 - R -parity-violating SUSY
 - Models of $\omega - \phi$ mixing
 - Rescattering



However...

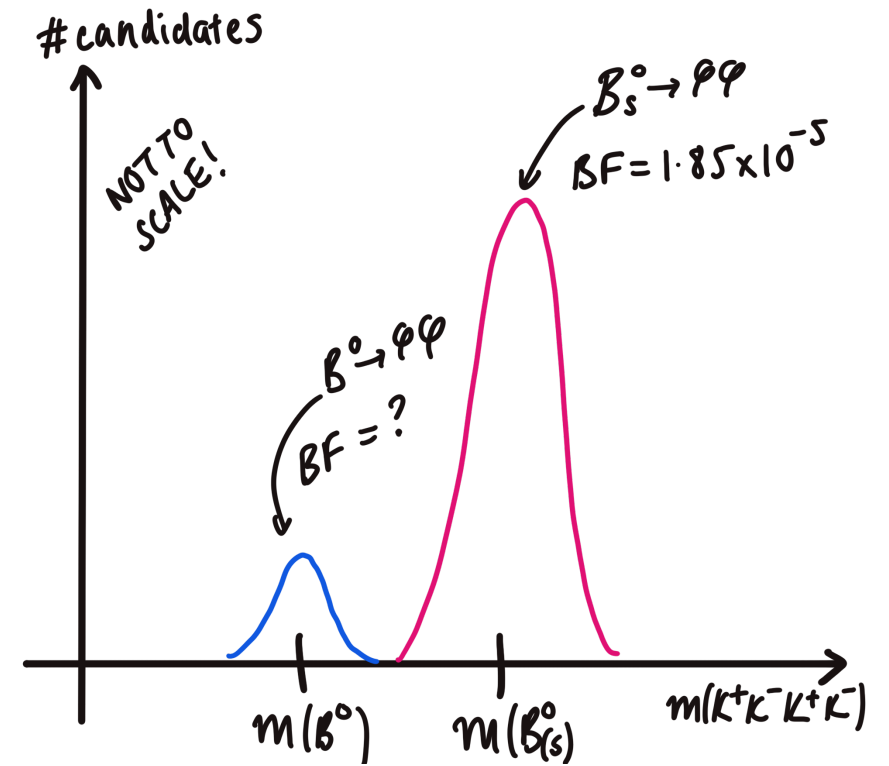
Theory predictions for the branching fraction are very different...

- Vary by up to an order of magnitude
- Vary depending on how they are calculated (perturbative QCD vs. QCD factorization)
- Let's see if LHCb can find it
 - Previous best limit from LHCb using 2011, 2012, 2015 and 2016 data
 - $\mathcal{B}(B^0 \rightarrow \phi\phi) < 2.7 \times 10^{-8}$ (90% C.L.)



The search for $B^0 \rightarrow \phi\phi$ at LHCb

- Reconstruct ϕ s from $\phi \rightarrow K^+ K^-$
 - Nice final state to reconstruct
- Require that the ϕ mesons are consistent with coming from a B
- Find $B^0 \rightarrow \phi\phi$ by looking for a significant peak at the B^0 mass in the four-kaon invariant mass spectrum
- Compare to the $B_s^0 \rightarrow \phi\phi$ signal – **normalisation** mode
- In a perfect world, would have a peak at the B_s^0 mass and at the B^0 mass...



Not so simple in reality

Backgrounds limit sensitivity

- **We cannot do everything perfectly**
- Events coming from things that are not signal can pollute the dataset
 - **Mis-identified backgrounds** – if a particle is given the wrong label it looks like $B_{(s)}^0 \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$ but it **isn't**
 - **Combinatorial background** – adding random pieces together looks like it could be $B_{(s)}^0 \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$
 - **Partially reconstructed backgrounds** – some tracks are missed and others misidentified, could look like $B_{(s)}^0 \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$

Another ‘background’ – $B_s^0 \rightarrow \phi\phi$

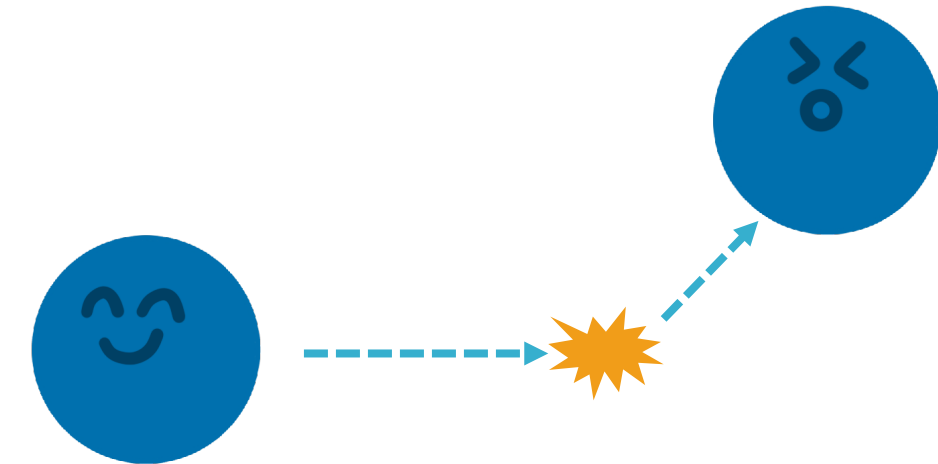
- $B_s^0 \rightarrow \phi\phi$ is the **normalisation mode** – we know what its branching fraction is (with some uncertainty)
 - **benchmark for checking the $B^0 \rightarrow \phi\phi$**
- Due to limited precision on the momentum, the $B_s^0 \rightarrow \phi\phi$ distribution and $B^0 \rightarrow \phi\phi$ distributions **overlap**
- Want to limit this as much as possible to improve sensitivity to $B^0 \rightarrow \phi\phi$
- Main culprit – **kaons that decay in flight or interact hadronically within the detector**

Kaons interactions*

kaon



Hasn't interacted, nice track

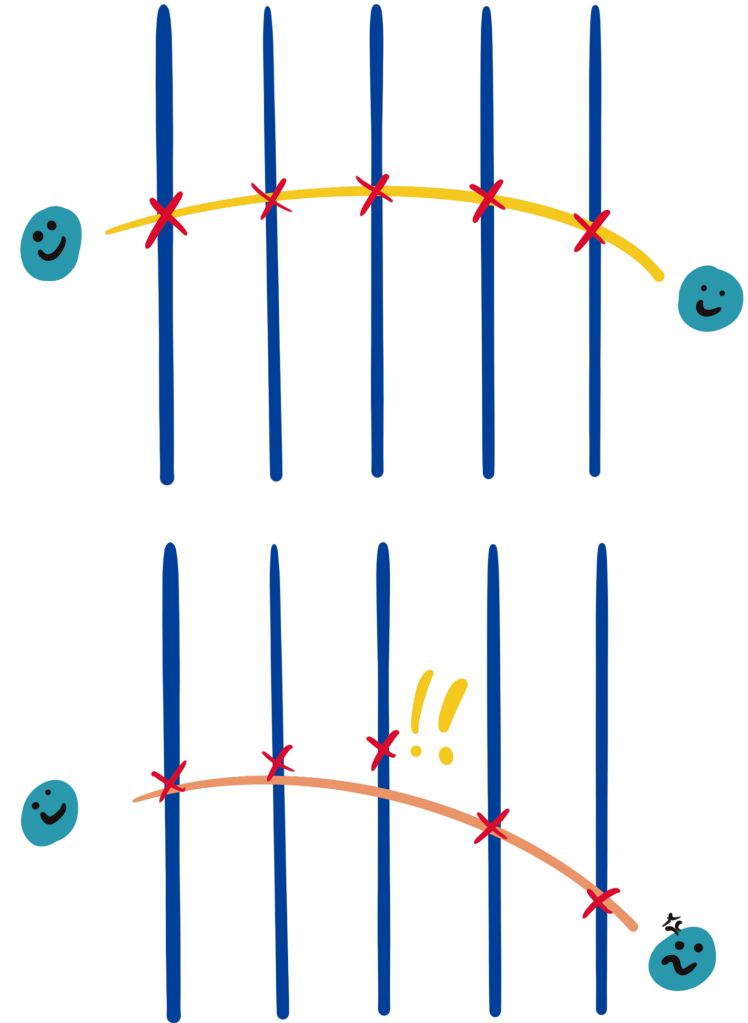


Something happened – kinked track

If this happens before the tracking stations, **poorer track reconstruction** and **worse determination** of B mass as a result

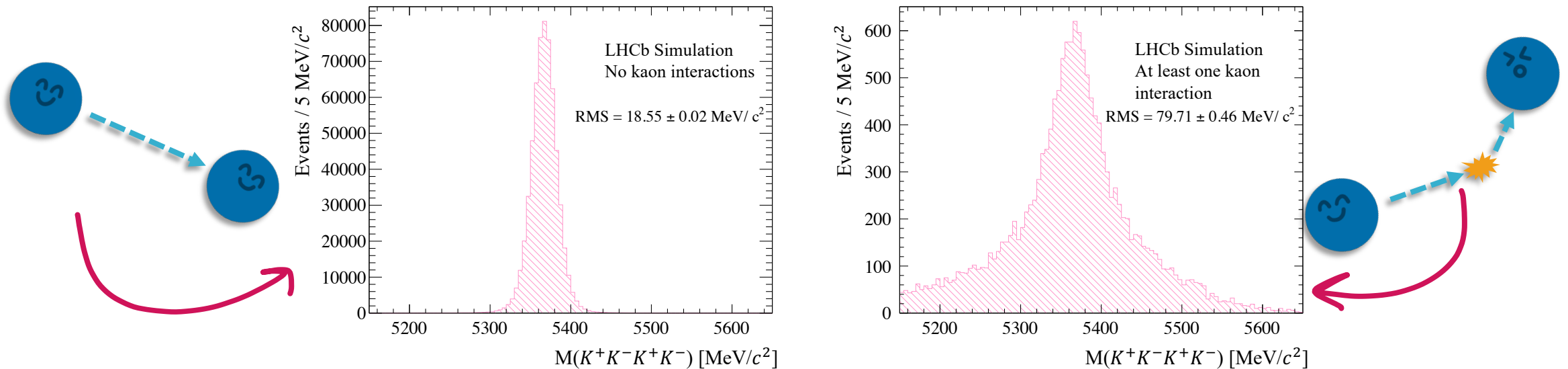
Why are kaon interactions a problem?

- We see a series of hits in the detector
- Track reconstruction – do a fit to these hits
- Reconstructed track provides measurement of momentum
- **Track fitter does not know that the track is kinked**



Why are kaon interactions a problem?

- If the momentum is poorly reconstructed the value of the B meson mass will be worse
- Can see this in simulated events

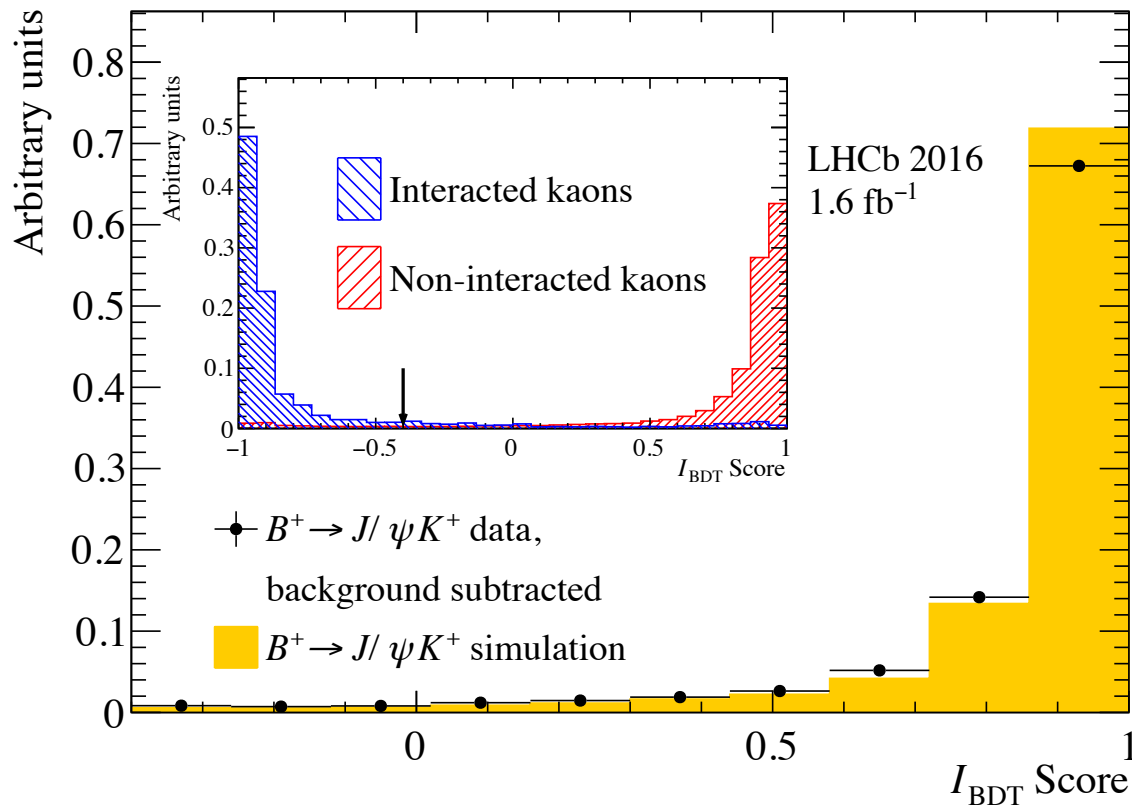


How do we deal with this?

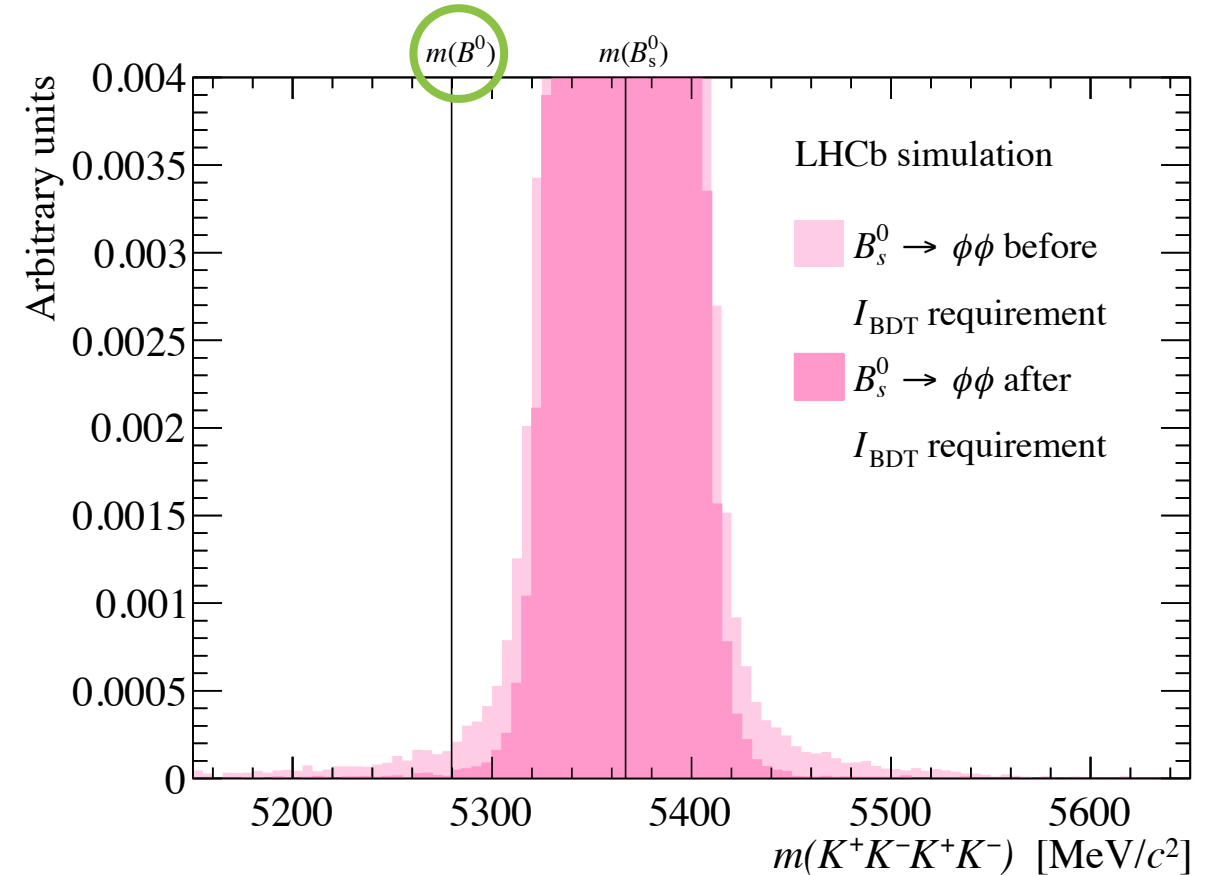
- Only option is to **remove them**
- Can train a **boosted decision tree** (BDT) classifier to be able to distinguish interacted kaons from the good ones
- BDT is trained on **discriminating variables** that relate to
 - The quality of the track fit
 - How likely it is that the track is a ghost (random hits joined to form a track)
 - Number of hits the track leaves in the tracker
 - Track kinematics: momentum and pseudorapidity

Performance of the classifier

Rejects 89% of interacted kaons for a 95% per-track efficiency



Excellent separation between interacted and non-interacted kaons



$B_s^0 \rightarrow \phi\phi$ events in region of B^0 mass much reduced

Thinking carefully about combinatorial background

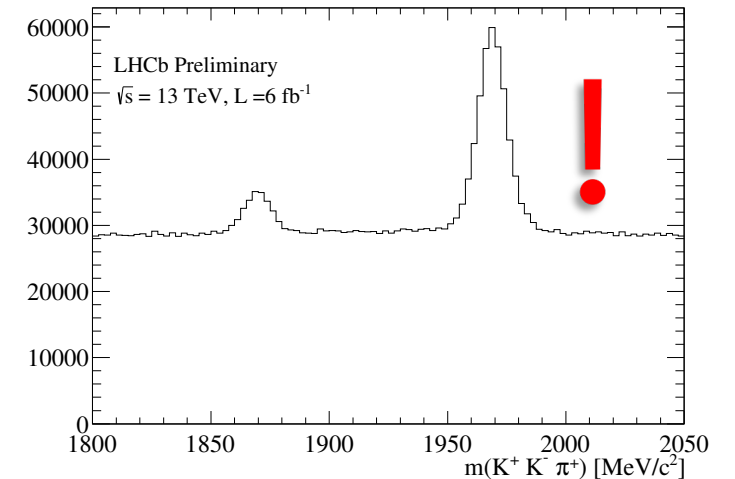
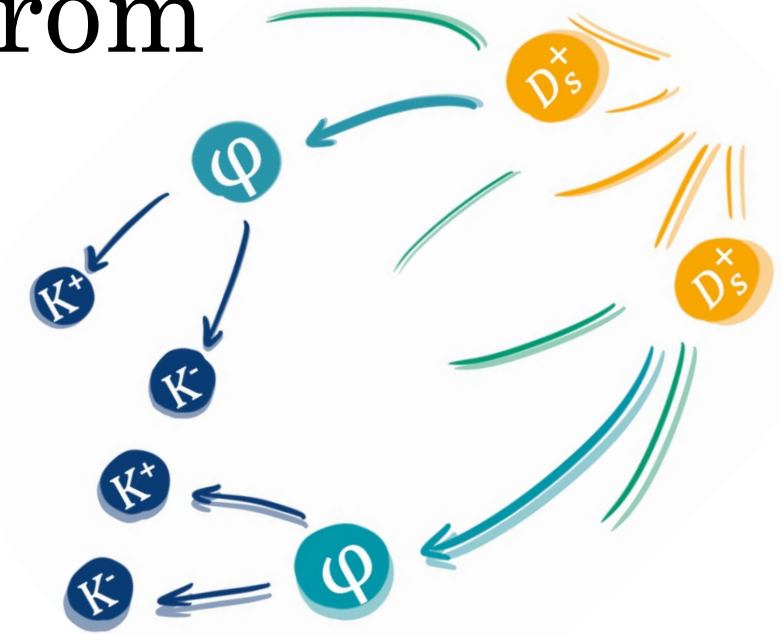
- Comes from randomly combined tracks that could look like the signal
- **Some combinatorial is less random than others**
- We get a lot of D_s^+ mesons produced in pp collisions, both prompt and from B_s
- Decays of $D_s^+ \rightarrow \phi X$ make up around 15% of the branching fractions of decays of D_s^+
- Are we combining ϕ mesons coming from decays of D_s^+ ?

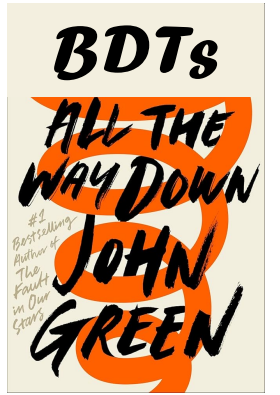
Combinatorial background from $D_s^+ \rightarrow \phi X$

We can check for these events in a data-driven way – checking $D_s^+ \rightarrow \phi\pi^+$

1. Take the sidebands of the $B_{(s)}^0 \rightarrow \phi\phi$ data and take one of the ϕ mesons
2. Look in the rest of the event and vertex the ϕ with a displaced pion track
3. Look for a D_s^+ peak in the $K^+K^-\pi^+$ invariant mass
4. Find **clear peak** – $D_s^+ \rightarrow \phi\pi^+$ is in our data sideband

This is just the $\phi\pi^+$, there are many other modes that will contribute but have neutrals/neutrinos that we do not reconstruct





How can we use this information?

Can now tag background as D_s^+ or non- D_s^+

D_s^+ -tagged

- Can veto these events – throw them away
- Can **USE them** to train a classifier to catch those we didn't tag
 - Will have similar properties to the modes we **cannot tag but are still there**

Non- D_s^+ -tagged

- Train an MVA to target combinatorial more generally

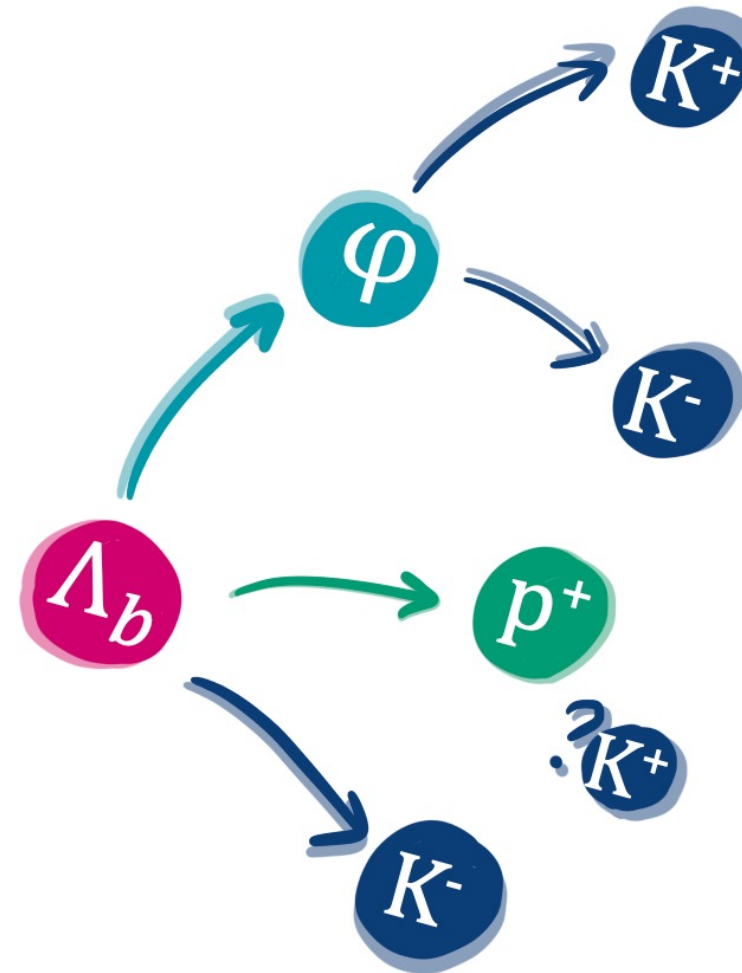
Get better reduction of background by targeting these categories separately

Selection requirements on these classifiers optimized together

How do we veto mis-ID background?

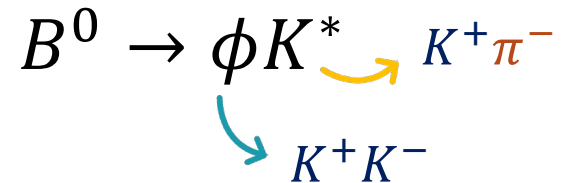
$$\Lambda_b^0 \rightarrow p K^- \phi$$

- Can reject this background by tightening the requirement on the proton and kaon PID
- Apply a window around the ϕ mass – $m(K^+ K^-)$ must be within 15 MeV of known ϕ mass

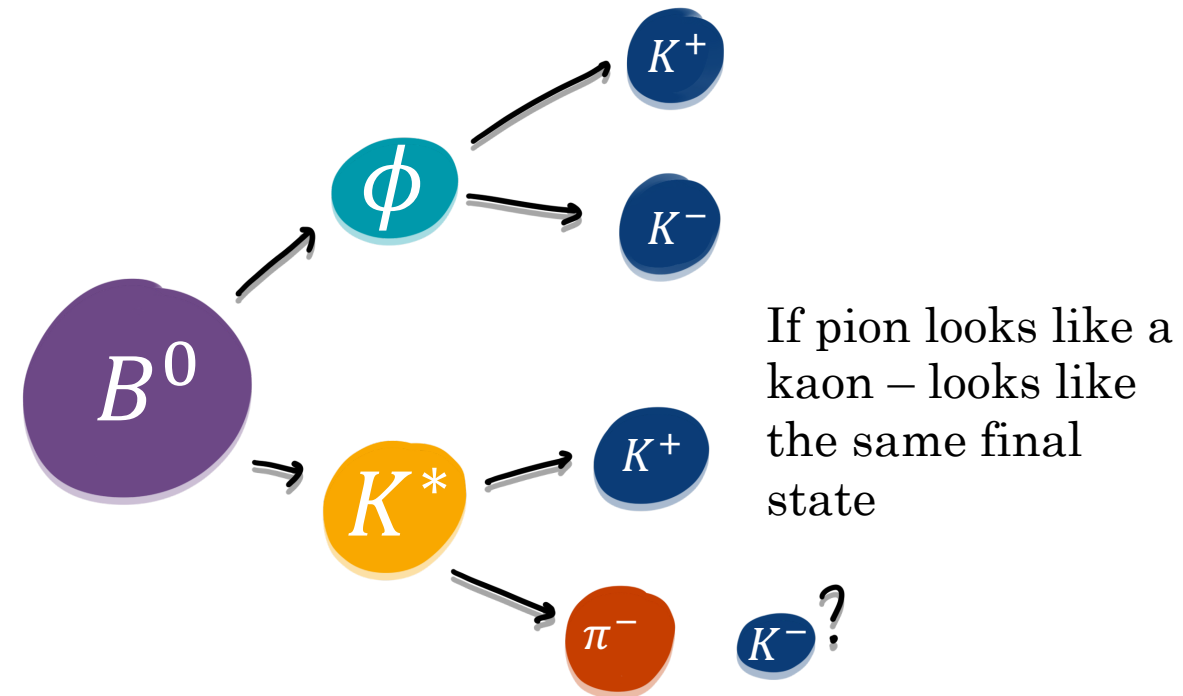


If proton looks like a kaon – looks like the same final state

How do we veto mis-ID background?



- Find which of the four tracks is most pion-like
- If $m(K\pi)$ close to K^* mass or $m(K\pi KK)$ is close to the B^0 mass then these events have more strict requirements on the PID applied



Putting it all together



Develop selections to clean the data as much as possible while retaining as much signal as possible

- Classifiers for background rejection
 - Combinatorial
 - Decays in flight
- Vetoes for peaking backgrounds
- PID and combinatorial classifier selection **optimized** using Punzi figure of merit

Model the contributions that exist in the data

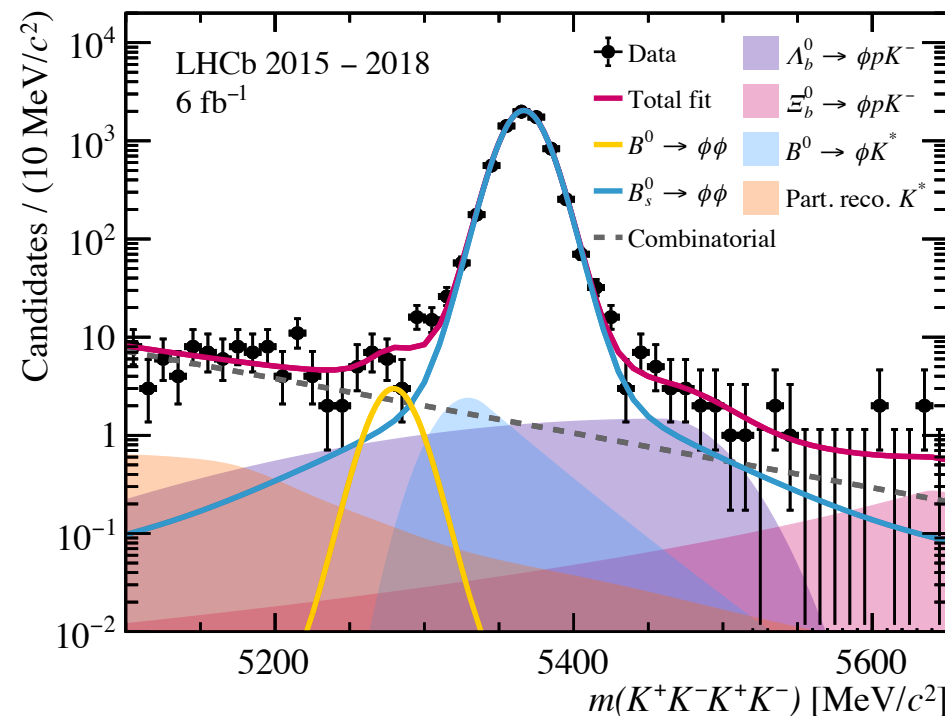
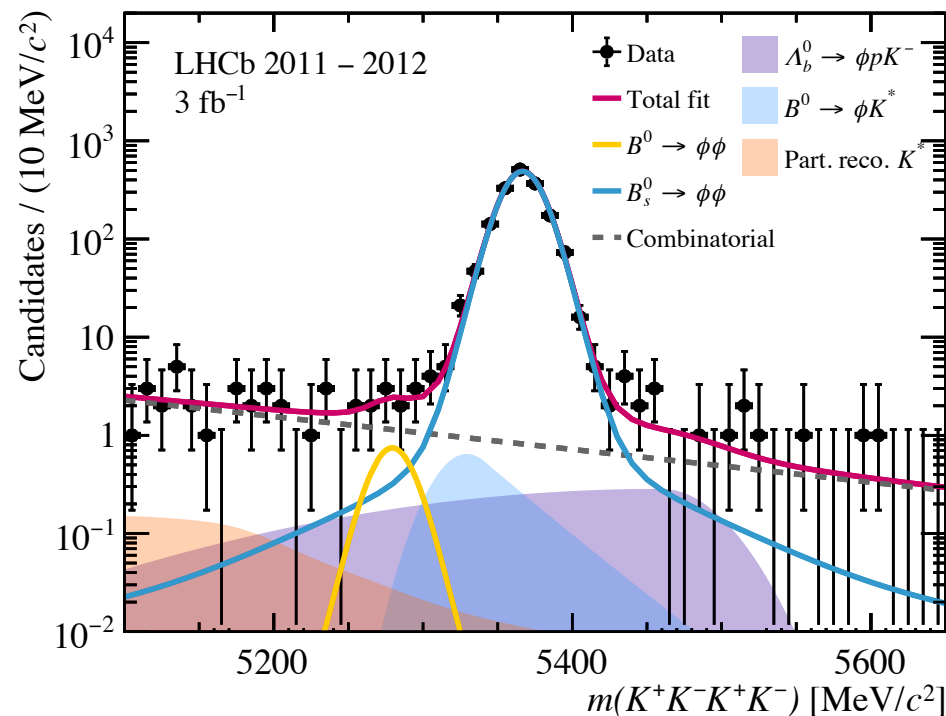
- Shapes modelled with simulated events
- Yields of backgrounds estimated using both data-driven methods and using simulation efficiencies and known branching fractions

Fit the data – fit to the four-kaon invariant mass distribution to look for a peak at the B^0 mass

- Due to differences in data-taking conditions, split data into Run 1 and Run 2 and fit simultaneously

Fits to the invariant mass

Simultaneous fit to Run 1 and Run 2



$$N_{B^0 \rightarrow \phi\phi}^{\text{Run 1}} = 2.6 \pm 1.5 \text{ and } N_{B^0 \rightarrow \phi\phi}^{\text{Run 2}} = 10.5 \pm 6.3$$

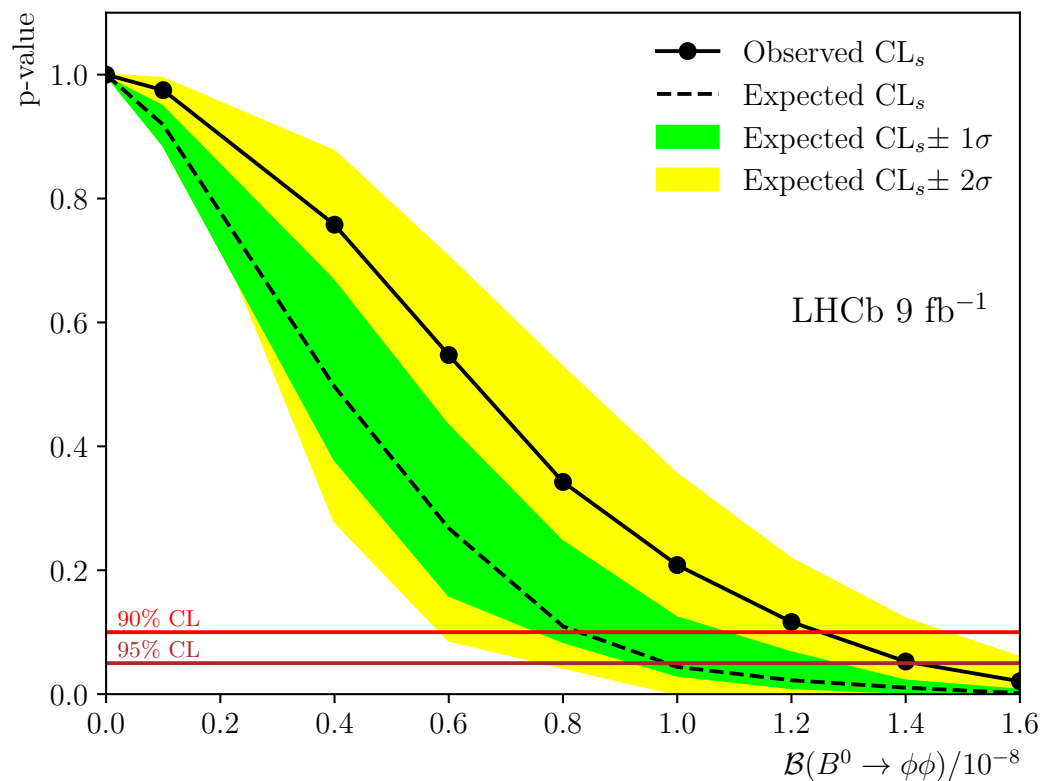
Significance: 1.9σ



We didn't find it... but...



New best upper limit!

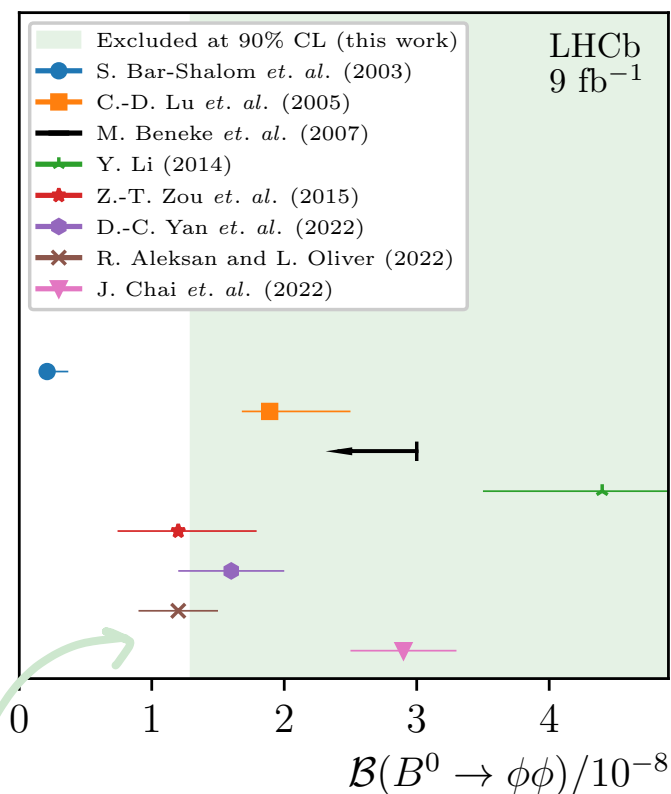


Set the limit on the branching fraction using the CL_s method

$$B(B^0 \rightarrow \phi\phi) < 1.3 \times 10^{-8} \text{ (90\% C.L.)}$$

Improved by factor of 2 on previous LHCb limit!

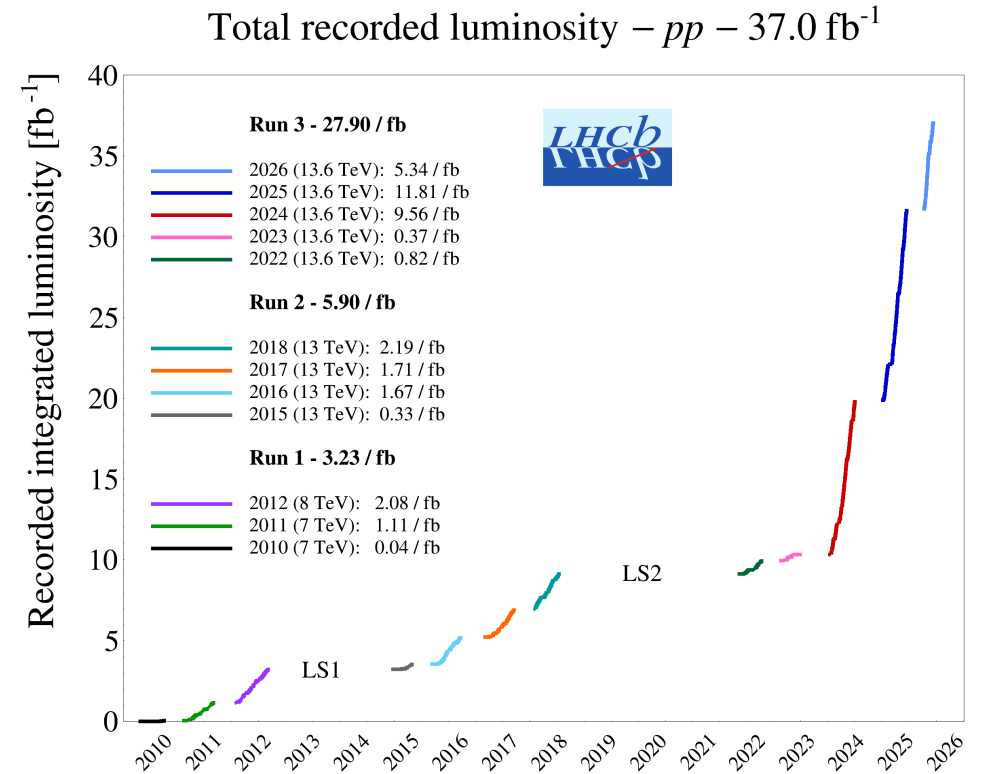
Expected limit improved by factor 2.5 – factor of 1.4 from increased statistics and 1.8 from novel methods



Compare to theory predictions – many ruled out 90% C.L.

So what's next for $\phi\phi$?

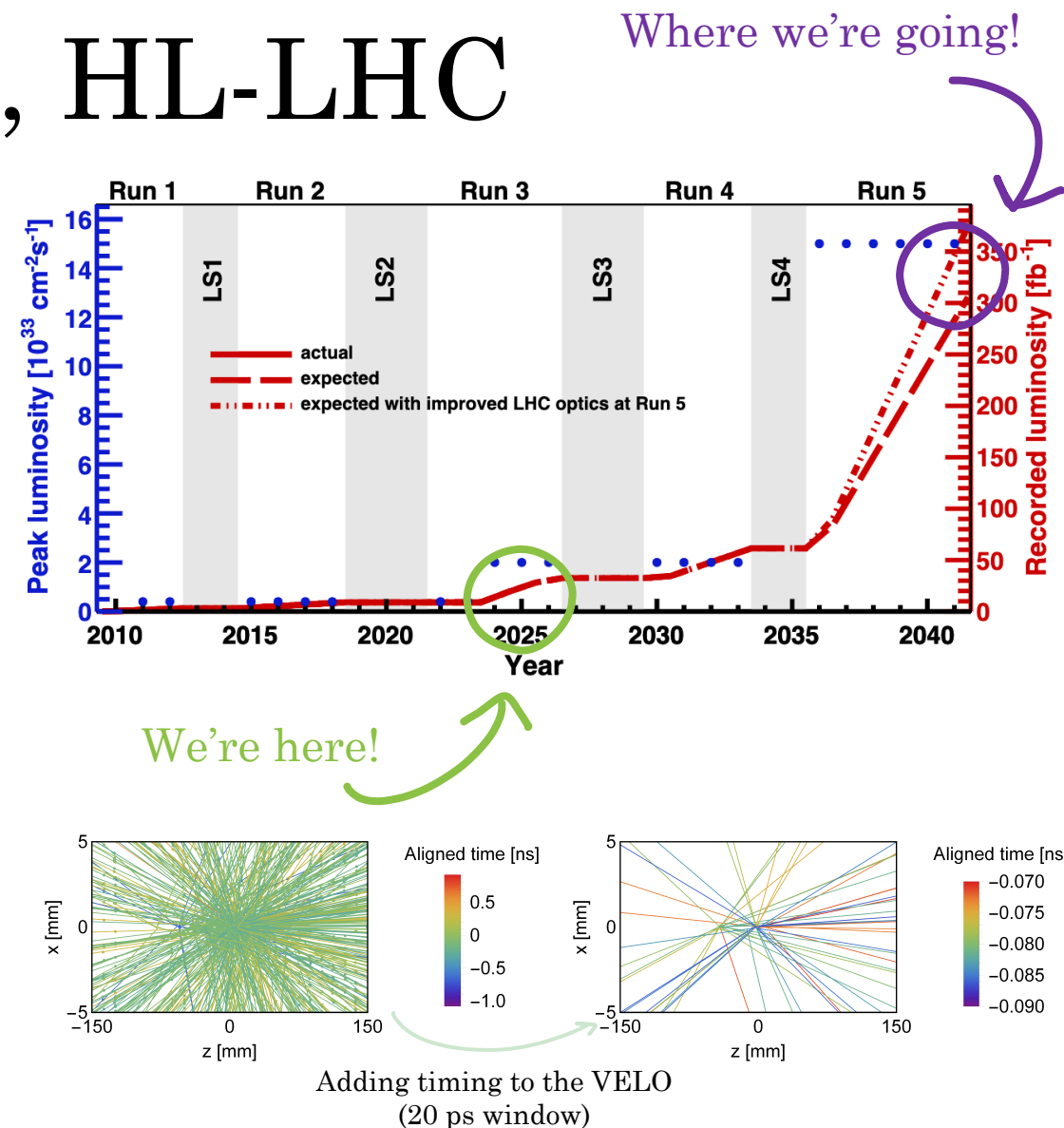
- Squeezed everything we can out of LHCb Run 1 and Run 2
- Luckily for us, LHCb Run 3 collected a record amount of data
- $B_{(s)}^0 \rightarrow \phi\phi$ benefit from fully software trigger
 - Harsh momentum cuts from hardware trigger gone – efficiency improved up to a **factor 2**
- Collecting more data – LHCb now operates at LHC bunch crossing rate



More fb^{-1} **and** more $B_{(s)}^0 \rightarrow \phi\phi$ **per** fb^{-1} !
Assuming similar performance as Run 1 and 2, can get sensitivity of **23 mrad** on $\phi_s^{s\bar{s}}$ (69 mrad in Run 1 and 2)

Looking even further, HL-LHC

- LHCb to be upgraded again before the high-luminosity LHC project – LHCb Upgrade II
- LHCb needs to be able to cope with the large number of interactions happening per bunch crossing
- Introduce **timing** to the detectors for **4D** reconstruction



Summary and conclusions

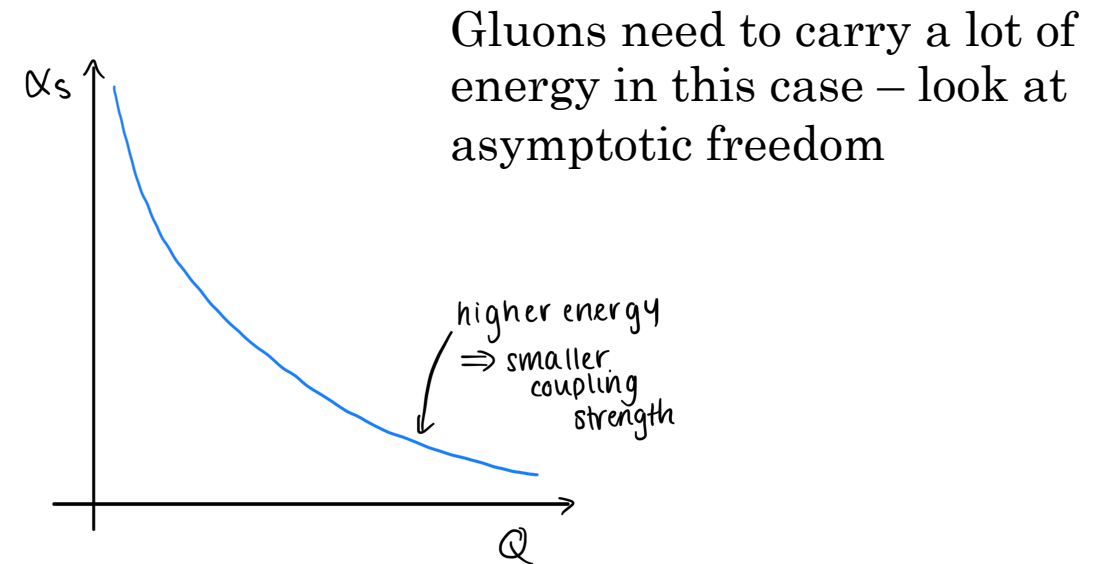
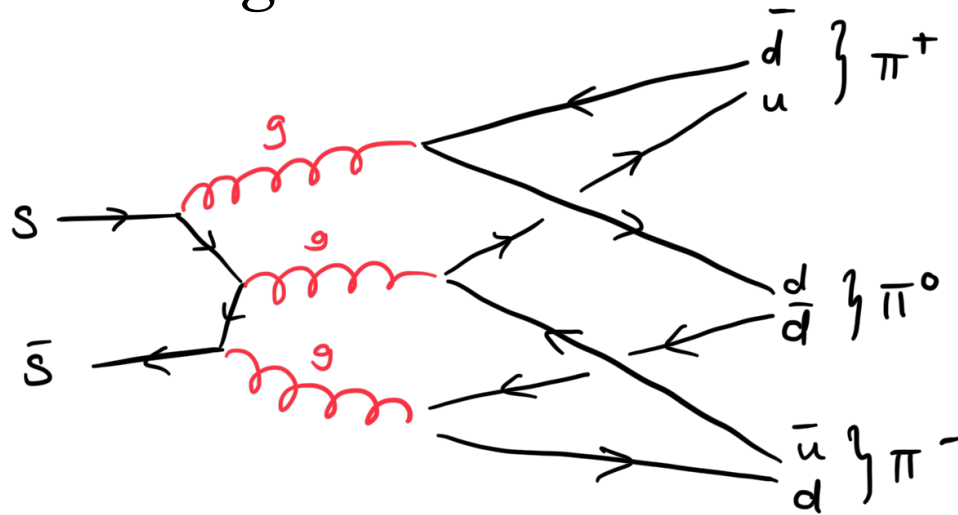
- There are lots of interesting things to study with charmless $B \rightarrow VV$ decays
 - One to watch!
- The $B_{(s)}^0 \rightarrow \phi\phi$ decays provide excellent tests of the standard model
 - Non-zero $\phi_s^{s\bar{s}s}$ or TPAs would be a smoking gun for BSM physics
 - The branching fraction $\mathcal{B}(B^0 \rightarrow \phi\phi)$ is enhanced in many scenarios and its complexity puts theory calculations to the test
- Measurements all limited by low statistics
 - These modes are a target for upcoming LHCb upgrades
 - If $\mathcal{B}(B^0 \rightarrow \phi\phi)$ at the lower end of theory predictions, could see in Run 3... stay tuned!



Back-up material

OZI suppression

- Demonstrated by ϕ meson decay
- Two modes: $\phi \rightarrow K^+ K^-$ or $\phi \rightarrow \pi^+ \pi^- \pi^0$
- The 3π mode has more phase space, should be more likely, but diagram like this:



R -parity

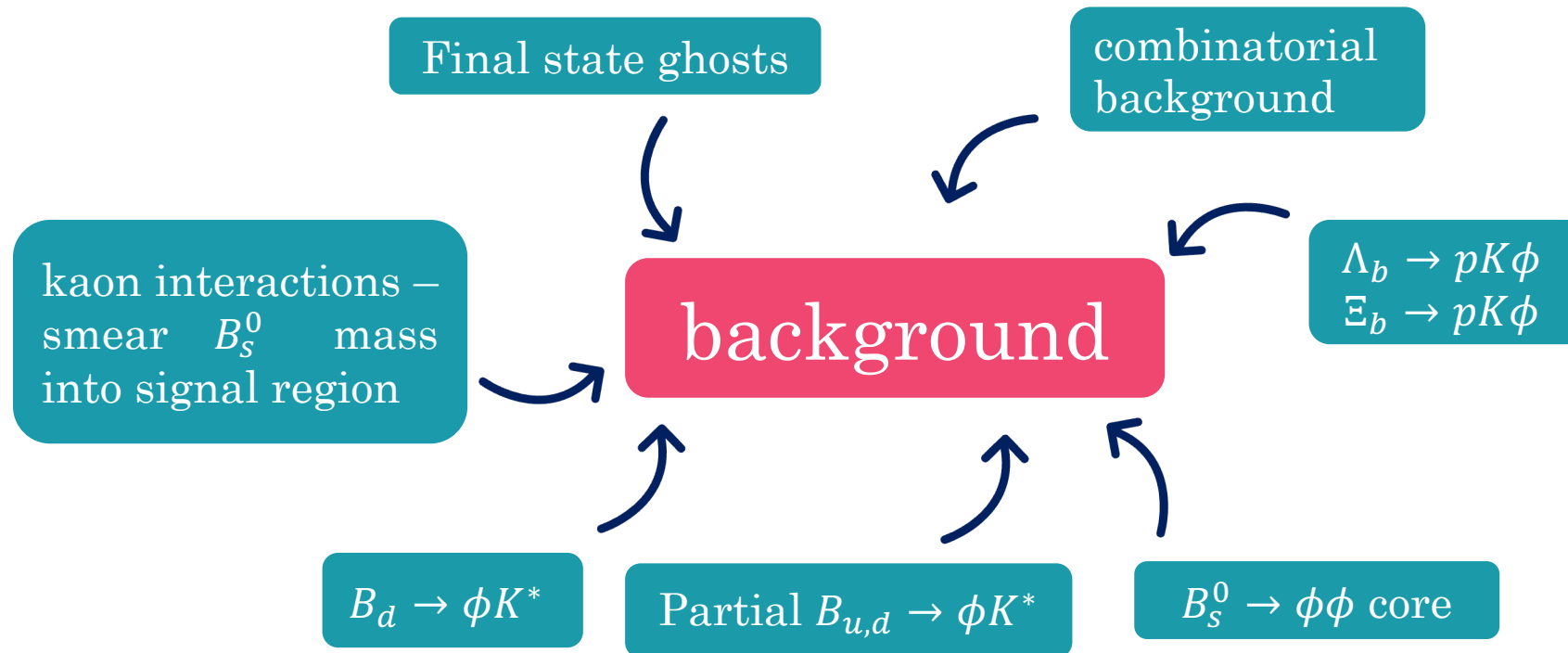
- Defined as
$$P_R = (-1)^{3(B-L)+2s}$$
- Has value of +1 for SM particles and -1 for SUSY particles

B = baryon number
 L = lepton number
 s = spin

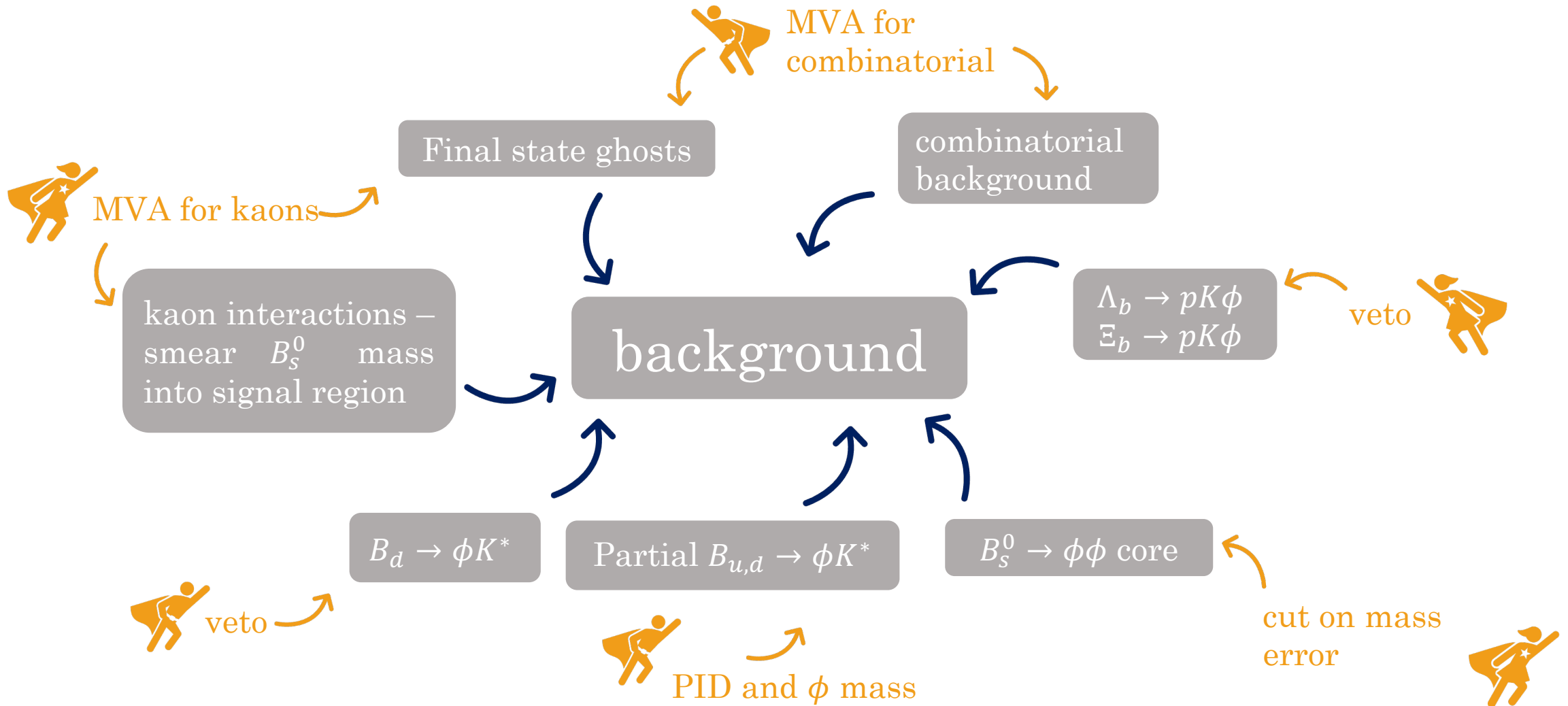
Rescattering

- B^0 decays to some favoured intermediate state – particles then “rescatter” to produce the two ϕ mesons

How to tackle these backgrounds



How to tackle these backgrounds



Selection optimisation

- Selection now consists of several things
 - Kaon interaction MVA – fixed to per-track efficiency of 95%
 - Vetos for misidentified backgrounds – fixed from studies of MC
 - Kaon particle identification requirements
 - MVA for D_s^+ -tagged background
 - MVA for generic combinatorial background
 - Trained separately for different trigger categories – different requirements leads to different distribution of kinematic variables
- Optimise selection using the Punzi multiclass figure-of-merit

Punzi figure of merit

multichannel Punzi figure of merit^[1]

$$\text{F.O.M.} = \frac{A^2/B}{a/2 + A^{3/2}/B},$$

$a = 3$ for 3σ

$$A = \sum_i \frac{\epsilon_i^2}{b_i}, \quad B = \sum_i \frac{\epsilon_i^3}{b_i^2}$$

ϵ_i - selection efficiency on
signal in category i

b_i - estimated background
level in blind region in
category i
category i = TIS or TOS

The CL_s method

Probability that t is as large or larger than t_{exp} under $s + b$ hypothesis

$$CL_{s+b} = \int_{t_{\text{exp}}}^{\infty} g(t; s + b) dt$$

$$1 - CL_b = \int_{-\infty}^{t_{\text{exp}}} g(t; b) dt$$

Probability that t is as low or lower than t_{exp} under b -only hypothesis

$$CL_s \equiv \frac{CL_{s+b}}{CL_b}$$

$t = -2 \log Q$ test statistic
 $Q = \mathcal{L}(f_{s+b}) / \mathcal{L}(f_b)$ likelihood ratio

