Flavour Physics and CP violation

Lecture 3 of 3

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Contents

- Part 1
  - Why is flavour physics & CP violation interesting?
- Part 2
  - What do we know from the previous generation of experiments?
- Part 3
  - What do we hope to learn from current and future heavy flavour experiments?

The ingredients for precision flavour

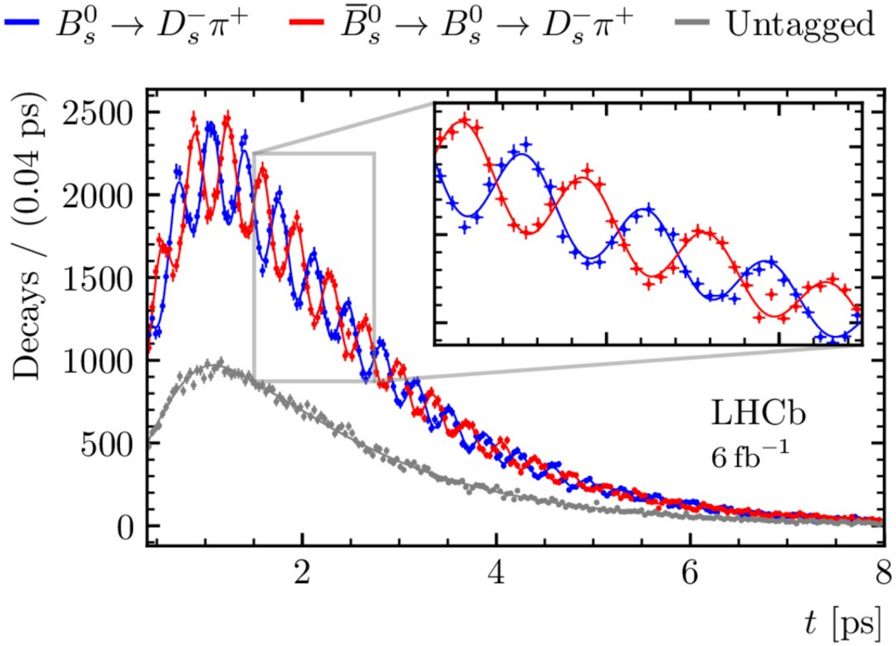
Enormous production cross-section of beauty and charm

Large boost

Ability to identify displaced vertices …
 with capability to exploit this online

Detection and separation of different final state particles

- charged: e, π, μ, K, p
- neutral: γ, π^0 [challenging]
- missing: ν, K_L, n [challenging^2]



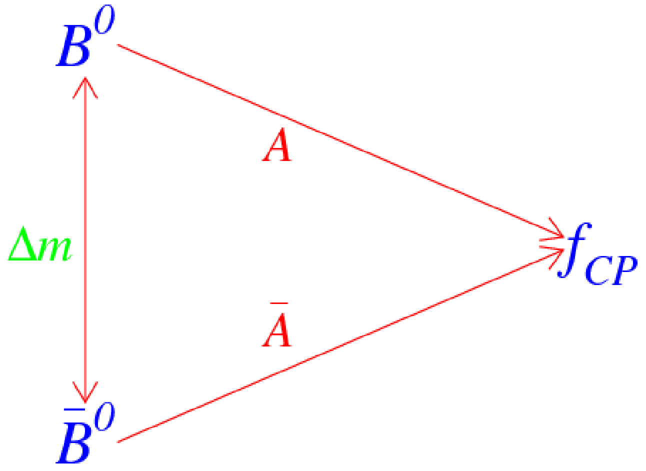
$\Delta m_s = (17.7683 \pm 0.0051 \pm 0.0032)\ \mathrm{ps}^{-1}$

Nature Physics 18 (2022) 1

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate

$$\lambda_{CP} = \frac{q}{p}\frac{\bar{A}}{A}$$



$$\left|\frac{q}{p}\right| \neq 1$$

CP violation in mixing

$$\left|\frac{\bar{A}}{A}\right| \neq 1$$

CP violation in decay

$$\Im\left(\frac{q}{p}\frac{\bar{A}}{A}\right) \neq 0$$

CP violation in interference between mixing and decay

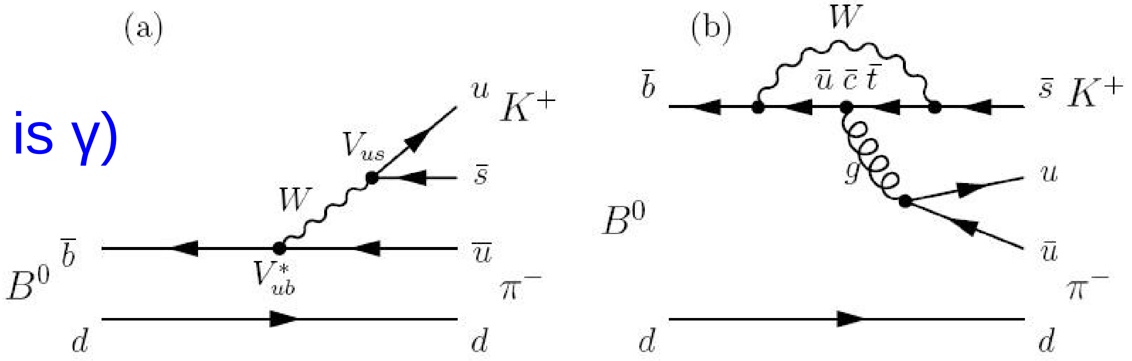
CP violation in decay

- Condition for CPV in decay: $|\bar{A}/A| \neq 1$
- Need $\bar{A}$ and A to consist of (at least) two parts
  - with different weak (φ) and strong (δ) phases
- Often realised by “tree” and “penguin” diagrams

$$A = |T| e^{i(\delta_T - \phi_T)} + |P| e^{i(\delta_P - \phi_P)} \qquad \bar{A} = |T| e^{i(\delta_T + \phi_T)} + |P| e^{i(\delta_P + \phi_P)}$$

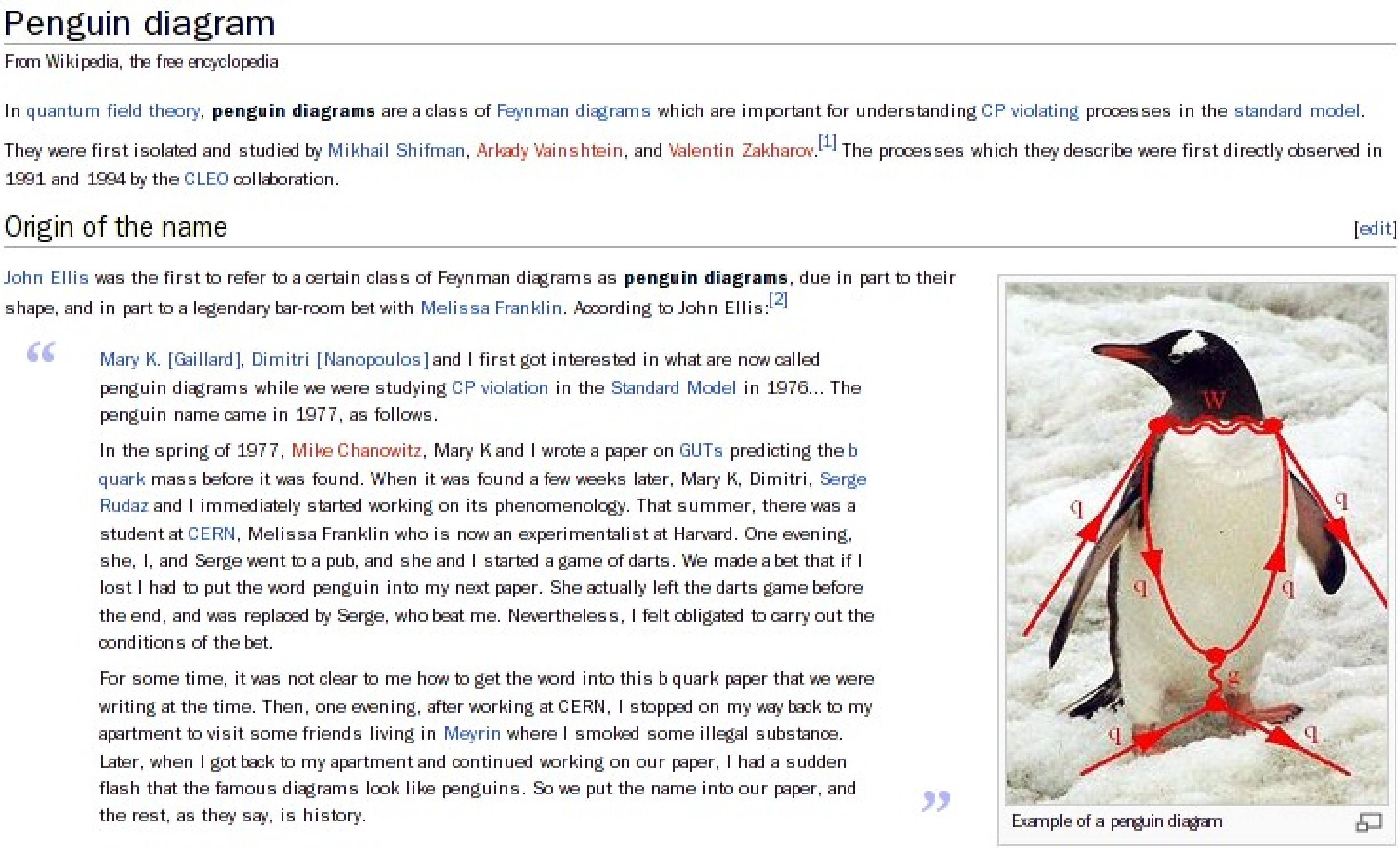
$$A_{CP} = \frac{|\bar{A}|^2 - |A|^2}{|\bar{A}|^2 + |A|^2} = \frac{2\,|T||P| \sin(\delta_T - \delta_P) \sin(\phi_T - \phi_P)}{|T|^2 + |P|^2 + 2\,|T||P| \cos(\delta_T - \delta_P) \cos(\phi_T - \phi_P)}$$

Example: B→Kπ
(weak phase difference is γ)



Feynman tree (a) and penguin (b) diagrams for the $B_d^0 \to K^+\pi^-$ decay

The famous penguin story



Penguin diagram

From Wikipedia, the free encyclopedia

In quantum field theory, **penguin diagrams** are a class of Feynman diagrams which are important for understanding CP violating processes in the standard model. They were first isolated and studied by Mikhail Shifman, Arkady Vainshtein, and Valentin Zakharov.[1] The processes which they describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name

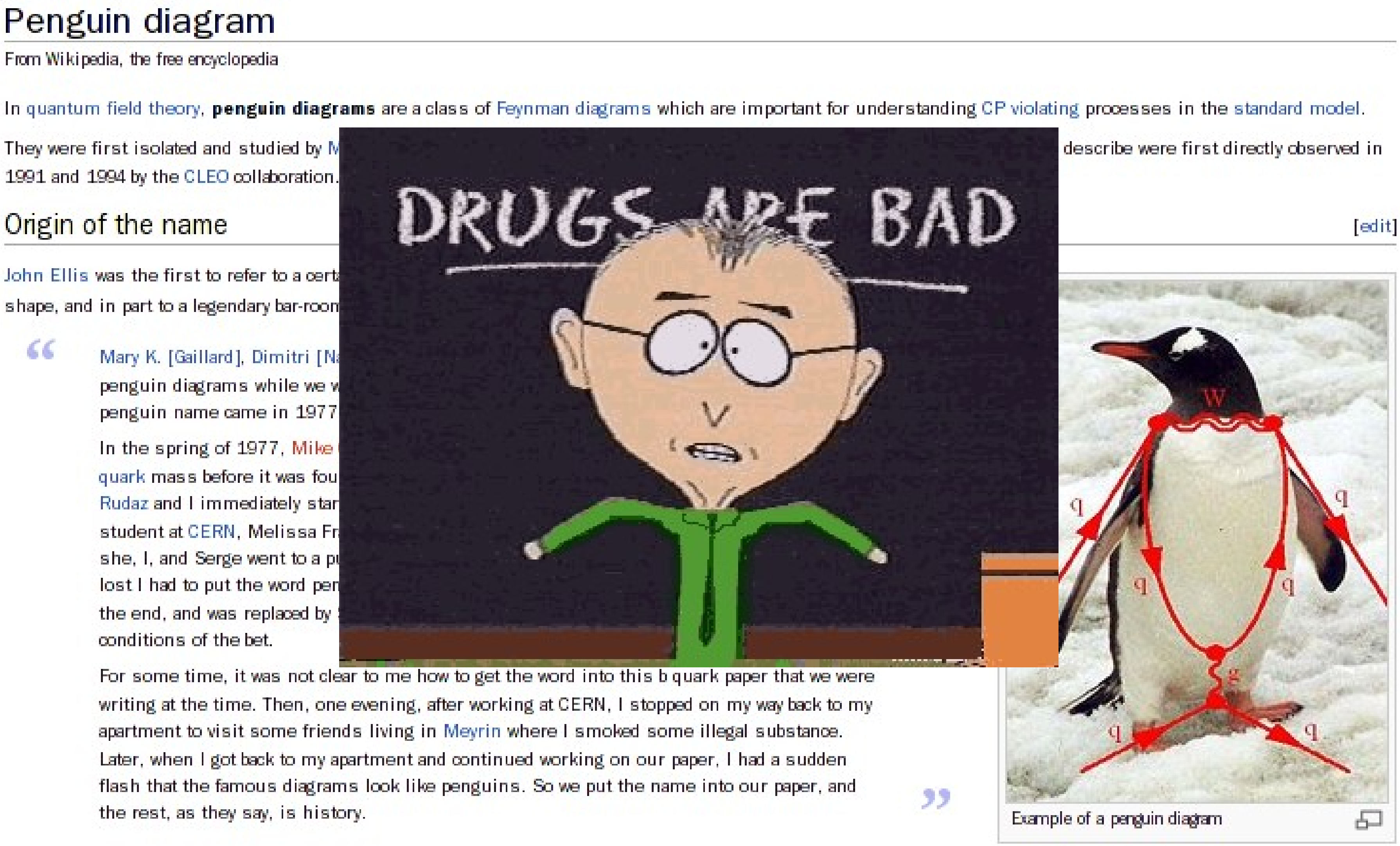
[edit]

John Ellis was the first to refer to a certain class of Feynman diagrams as **penguin diagrams**, due in part to their shape, and in part to a legendary bar-room bet with Melissa Franklin. According to John Ellis:[2]

> “ Mary K. [Gaillard], Dimitri [Nanopoulos] and I first got interested in what are now called penguin diagrams while we were studying CP violation in the Standard Model in 1976... The penguin name came in 1977, as follows.
>
> In the spring of 1977, Mike Chanowitz, Mary K and I wrote a paper on GUTs predicting the b quark mass before it was found. When it was found a few weeks later, Mary K, Dimitri, Serge Rudaz and I immediately started working on its phenomenology. That summer, there was a student at CERN, Melissa Franklin who is now an experimentalist at Harvard. One evening, she, I, and Serge went to a pub, and she and I started a game of darts. We made a bet that if I lost I had to put the word penguin into my next paper. She actually left the darts game before the end, and was replaced by Serge, who beat me. Nevertheless, I felt obligated to carry out the conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history. ”

Example of a penguin diagram

The famous penguin story



Penguin diagram

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They were first isolated and studied by M … describe were first directly observed in 1991 and 1994 by the CLEO collaboration.

Origin of the name

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John Ellis was the first to refer to a cert… shape, and in part to a legendary bar-room…

> Mary K. [Gaillard], Dimitri [N… penguin diagrams while we w… penguin name came in 1977…
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> In the spring of 1977, Mike … quark mass before it was fou… Rudaz and I immediately star… student at CERN, Melissa Fr… she, I, and Serge went to a p… lost I had to put the word pe… the end, and was replaced by … conditions of the bet.
>
> For some time, it was not clear to me how to get the word into this b quark paper that we were writing at the time. Then, one evening, after working at CERN, I stopped on my way back to my apartment to visit some friends living in Meyrin where I smoked some illegal substance. Later, when I got back to my apartment and continued working on our paper, I had a sudden flash that the famous diagrams look like penguins. So we put the name into our paper, and the rest, as they say, is history.

Example of a penguin diagram

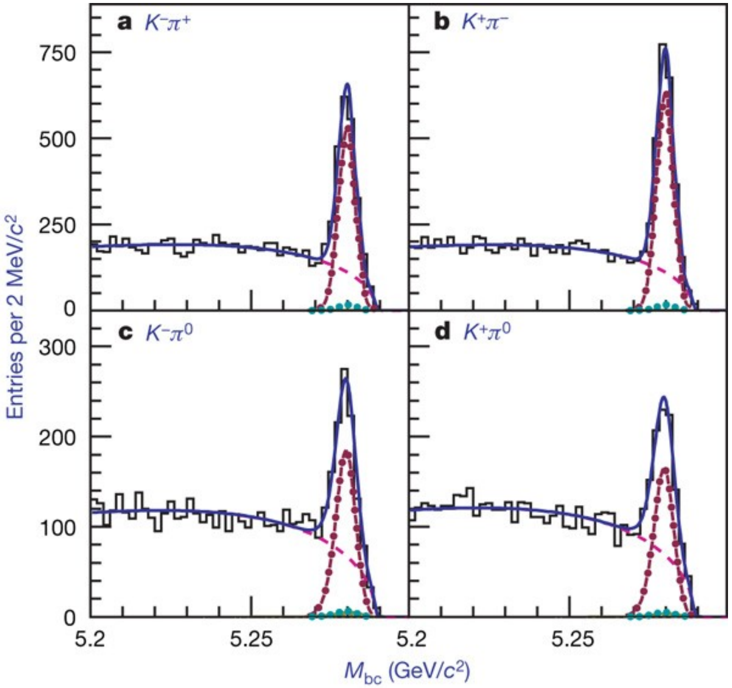
Direct CP violation in B → Kπ

- Direct CP violation in B → Kπ sensitive to γ

too many hadronic parameters ⇒ need theory input

NB. interesting deviation from naïve expectation

Belle Nature 452 (2008) 332



"Kπ puzzle"

$A_{CP}(K^-\pi^+) = -0.0831 \pm 0.0031$

$A_{CP}(K^-\pi^0) = +0.027 \pm 0.012$

HFLAV averages
(dominated by LHCb results)

Could be a sign of new physics …
… first need to rule out possibility of
larger than expected QCD corrections

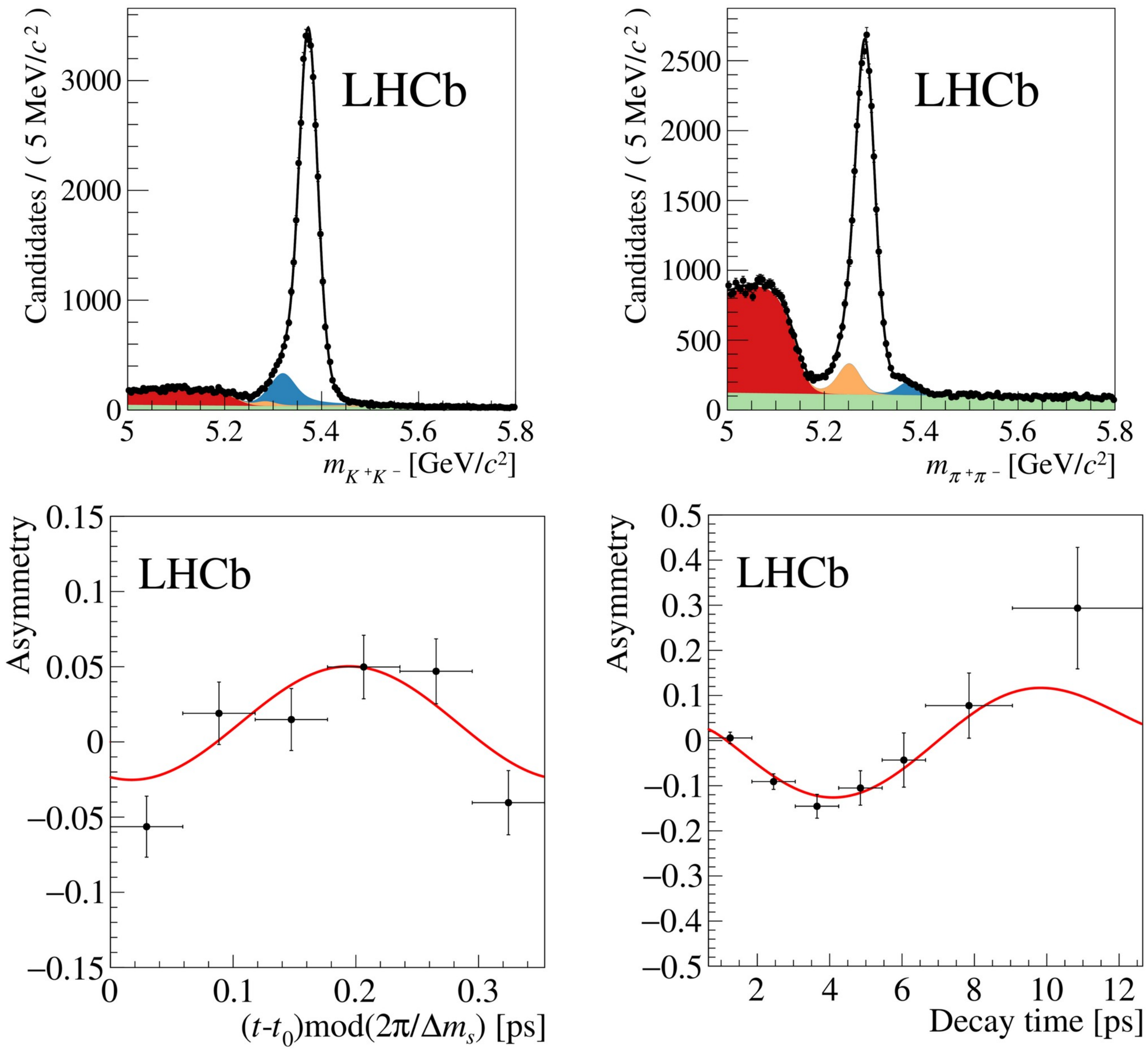
Clean observables in $B \to K\pi$ (etc.)

- Measure more $B_{u,d} \to K\pi$ decays & relate by isospin
- Perform similar analysis on $B \to K^*\pi$ &/or $B \to K\rho$
  - Dalitz plot analyses of $K\pi\pi$ final states extract both amplitudes and relative phases → more observables
- Measure $B_s \to KK$ decays & relate by U-spin
  - U-spin: like isospin but relating d↔s instead of d↔u
  - e.g. relation between time-dependent CP violation observables in $B_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$
- Dalitz plot analyses of $B_{(s)} \to hhh$

Note: flavour symmetries very useful
But, still get theory error from symmetry breaking (difficult to evaluate)
… data driven methods will win in the end (unless miracle breakthrough)

$B^0 \to \pi^+\pi^-$ & $B_s^0 \to K^+K^-$

PR D98 (2018) 032004

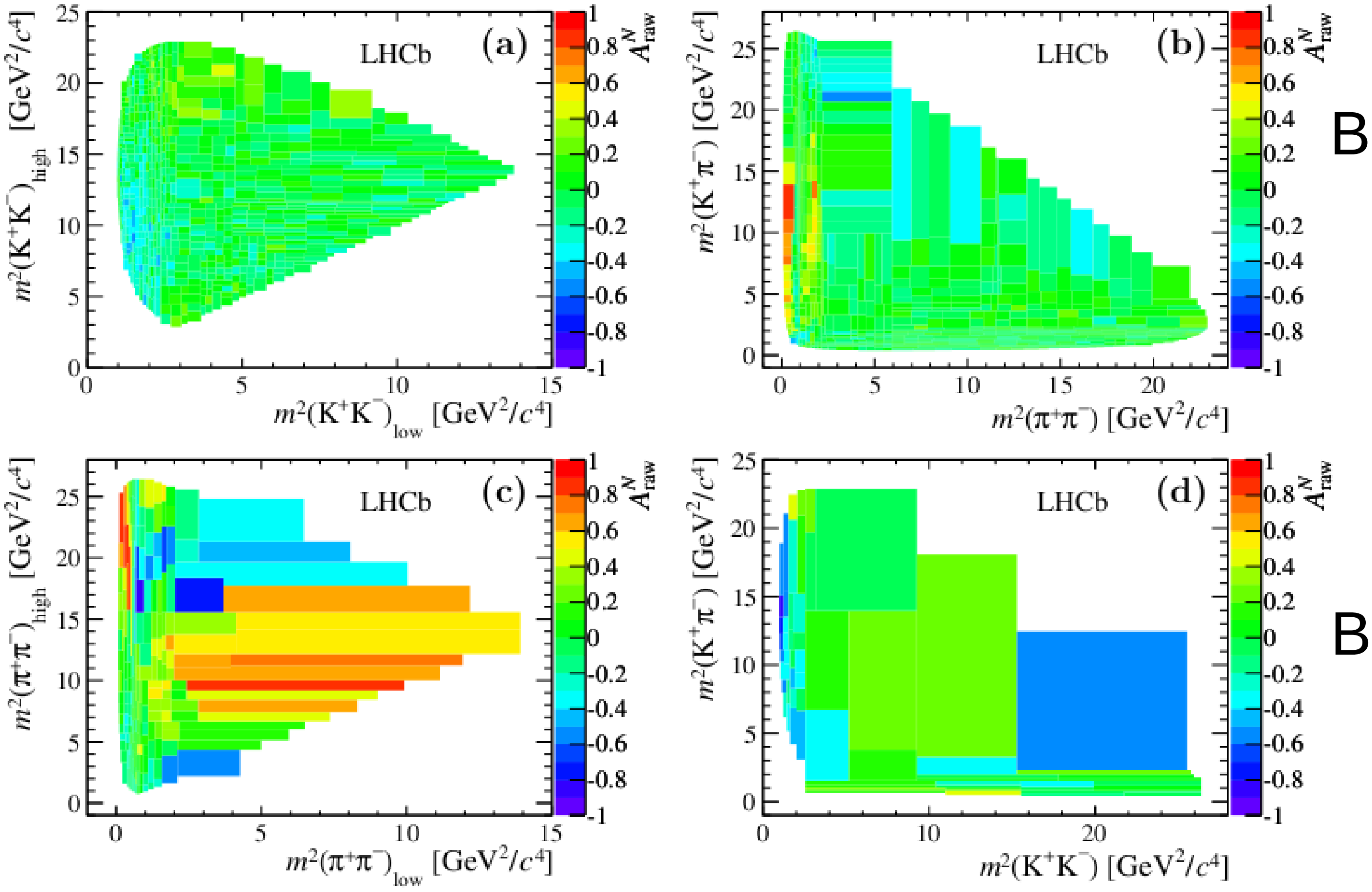


CP violation in multibody charmless B decays

PRD 90 (2014) 112004

B → KKK

B → Kππ



B → πππ

B → KKπ

Large CP violation effects with strong variation across the Dalitz plot

Detailed studies necessary to understand origin of these effects

Importance of γ from B → DK

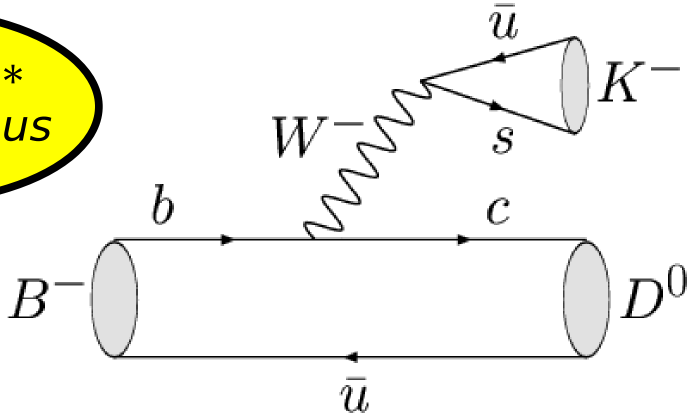
- γ plays a unique role in flavour physics

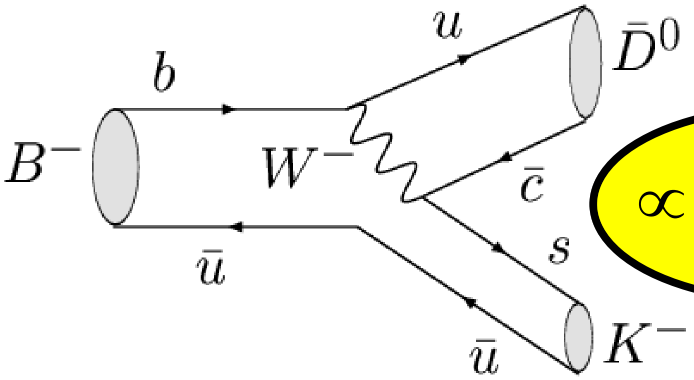
the only CP violating parameter that can be measured through tree decays (*)

(*) more-or-less

- A benchmark Standard Model reference point
  - doubly important after New Physics is observed

$\propto V_{cb} V_{us}^{*}$



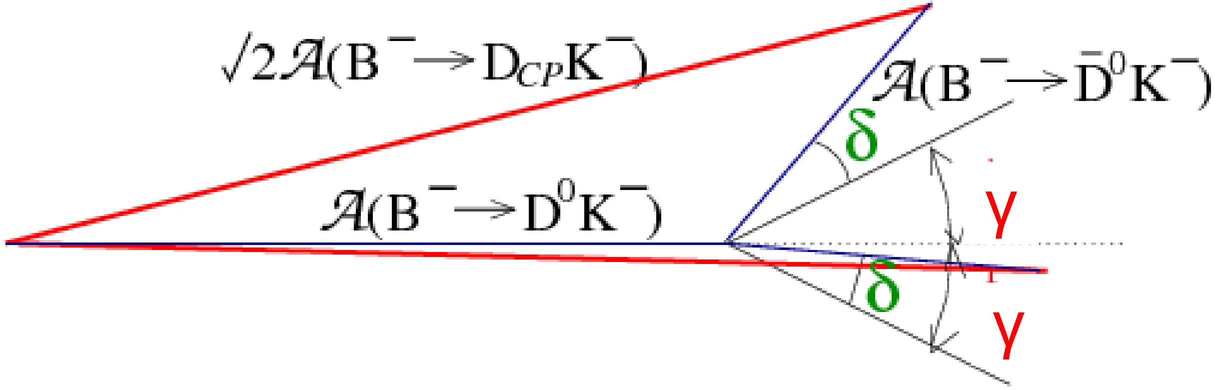


$\propto V_{ub} V_{cs}^{*}$

Variants use different B or D decays
require a final state common to both D^0 and $\bar{D}^0$

Why is B → DK so nice?

- For theorists:
  - theoretically clean: no penguins; factorisation works
  - all parameters can be determined from data
- For experimentalists:
  - many different observables (different final states)
  - all parameters can be determined from data
  - γ & δ_B (weak & strong phase differences), r_B (ratio of amplitudes)



$B \to DK$ methods

- Different D decay final states
  - CP eigenstates, e.g. K^+K^- (GLW)
  - doubly-Cabibbo-suppressed decays, e.g. $K^+\pi^-$ (ADS)
  - self-conjugate multibody decays, e.g., $K_S\pi^+\pi^-$ (GGSZ)
- Different B decays
  - $B^- \to DK^-$, D^*K^- , DK^{*-}
  - $B^0 \to DK^{*0}$ (or $B \to DK\pi$ Dalitz plot analysis)
  - $B^0 \to DK_S$, $B_s^0 \to D\phi$ (with or without time-dependence)
  - $B_s^0 \to D_sK$, $B^0 \to D^{(*)}\pi$ (time-dependent)

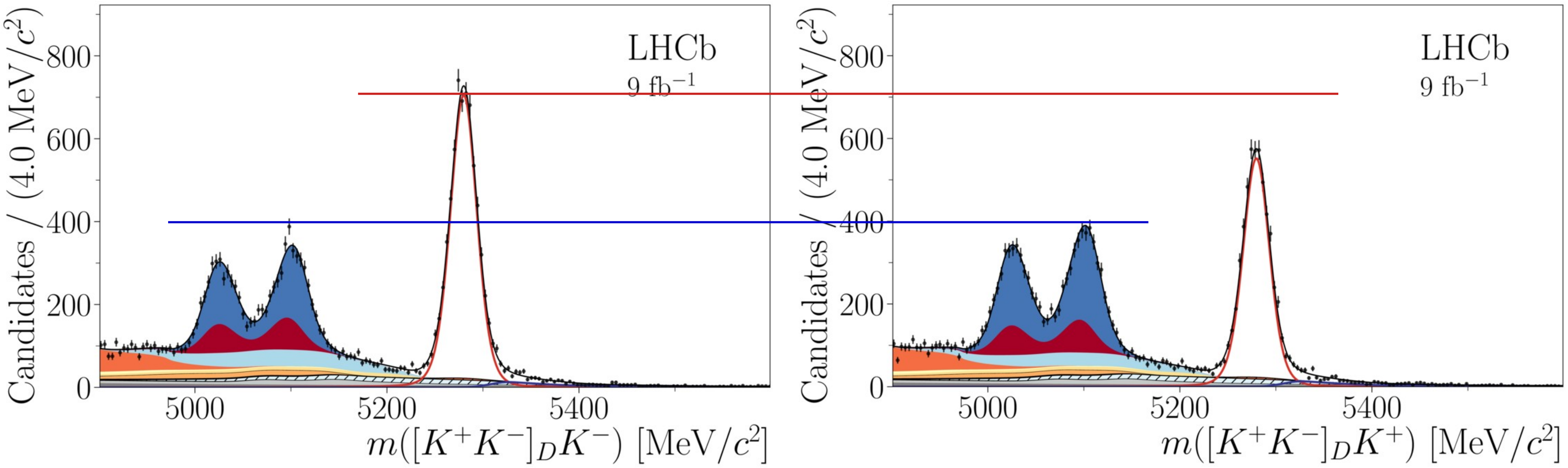
All parameters from data – no theory input needed!

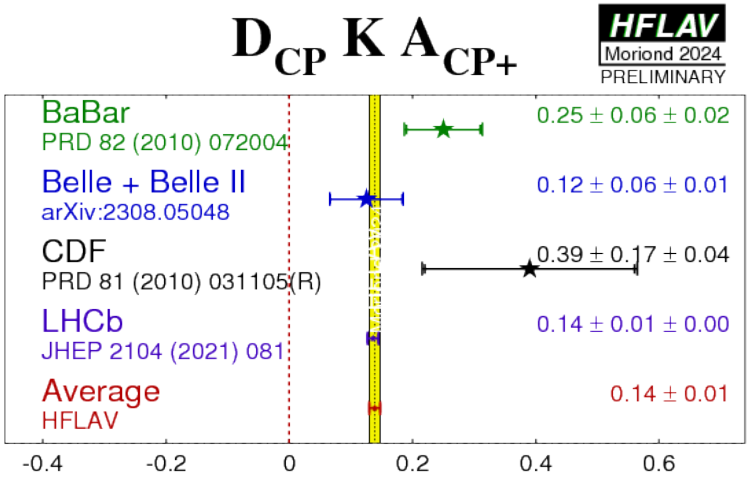
Hadronic parameters related to D decays can be taken from external measurements, e.g. BESIII data on quantum correlated $\psi(3770) \to D\overline{D}$ decays

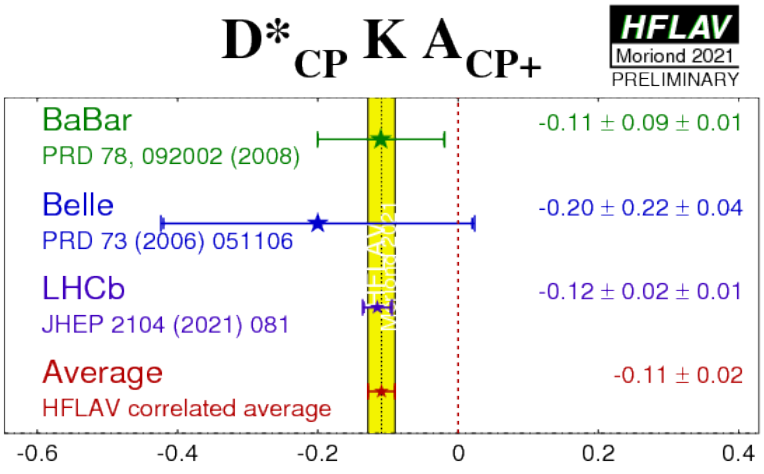
Latest results on B → DK : GLW

Clear CP violation effect (γ≠0) in both $B^- \to DK^-$ and $B^- \to D^*K^-$

JHEP 04 (2021) 081







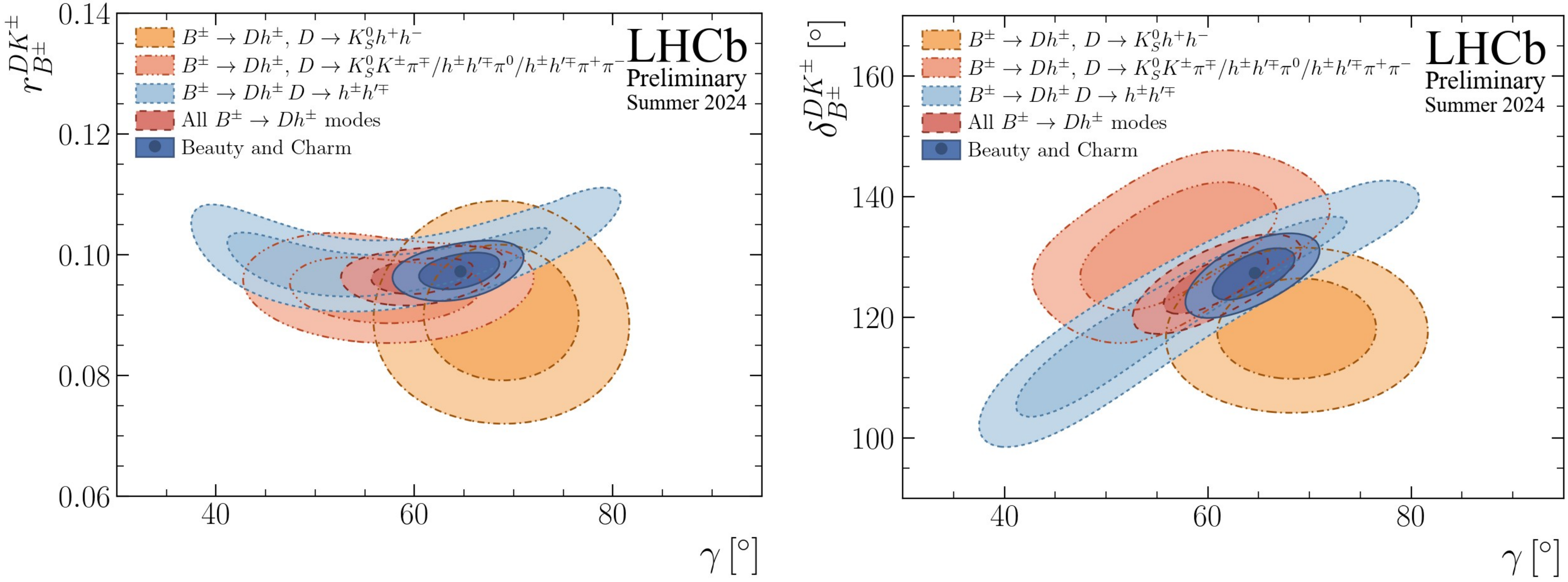
γ combination

JHEP 12 (2021) 141
LHCb-CONF-2024-004

Best sensitivity by combining most information

Include all B → DK type measurements, plus results on charm mixing and data from ψ(3770) → $D\overline{D}$ decays

Great care needed over potential correlations and statistical procedures



γ = (64.6 ± 2.8)°

World average in principle more precise (though LHCb dominates), but not yet done simultaneously with charm mixing observables

The other Unitarity Triangles

- High statistics becoming available in experiments gives sensitivity to smaller CP violating effects
  - CP violating phase in B_s oscillations ($O(\lambda^4)$)
    - B_s oscillations (Δm_s) measured 2006 (CDF)
  - CP violating phase in D^0 oscillations ($O(\lambda^5)$)
    - D^0 oscillations ($x_D = \Delta m_D/\Gamma_D$ & $y_D = \Delta\Gamma_D/2\Gamma_D$) measured 2007 (BaBar, Belle, later CDF and LHCb)

- Observations of CP violation in both K^0 and B^0 systems won Nobel prizes!

Time-dependent CP Violation Formalism

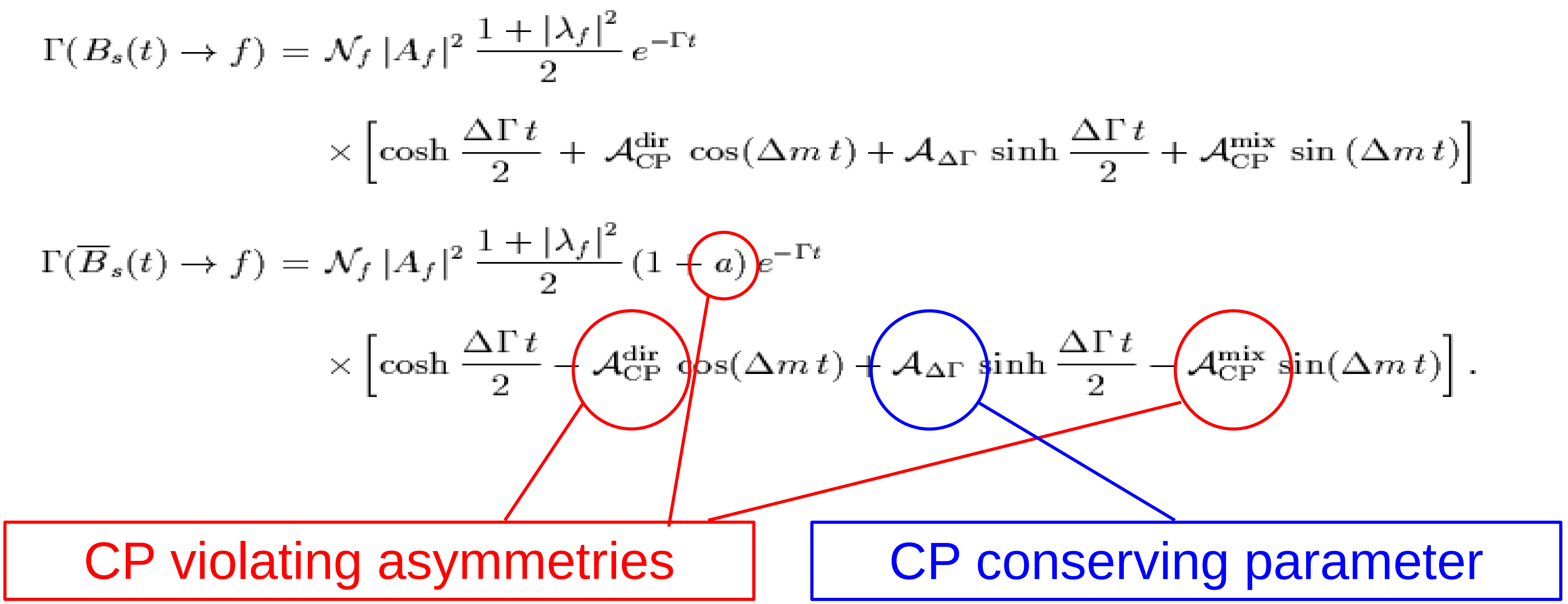
- Generic (but shown for B_s) decays to CP eigenstates

$$
\begin{aligned}
\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \\
\times \left[\cosh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right]
\end{aligned}
$$

$$
\begin{aligned}
\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t} \\
\times \left[\cosh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \, \cos(\Delta m \, t) + \mathcal{A}_{\Delta\Gamma} \, \sinh \frac{\Delta\Gamma \, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \, \sin(\Delta m \, t) \right] .
\end{aligned}
$$

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates



$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t} \times \left[\cosh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t} \times \left[\cosh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m\, t) + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m\, t) \right] .$$

CP violating asymmetries

CP conserving parameter

$$A_{CP}^{dir} = C_{CP} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2} \qquad A_{\Delta\Gamma} = \frac{2\,\Re(\lambda_{CP})}{1+|\lambda_{CP}|^2} \qquad A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

$$(A_{CP}^{dir})^2 + (A_{\Delta\Gamma})^2 + (A_{CP}^{mix})^2 = 1$$

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad) + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \qquad \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma \, t}{2} \qquad + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma \, t}{2} \qquad \right] .$$

- Untagged analyses still sensitive to some interesting physics

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma\, t}{2} + \boxed{0} + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma\, t}{2} + \mathcal{A}_{\rm CP}^{\rm mix} \sin\left(\Delta m \, t\right) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1 + \boxed{0} \; e^{-\Gamma t}$$

$$\times \left[\cosh \frac{\Delta\Gamma\, t}{2} - \boxed{0} + \mathcal{A}_{\Delta\Gamma} \sinh \frac{\Delta\Gamma\, t}{2} - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right] .$$

- In some channels, expect no CP violation in decay
- and/or no CP violation in mixing

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$

$$\times \left[1 + \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) + 0 + \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right]$$

$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$

$$\times \left[1 - \mathcal{A}_{\rm CP}^{\rm dir} \cos(\Delta m \, t) + 0 - \mathcal{A}_{\rm CP}^{\rm mix} \sin(\Delta m \, t) \right].$$

- In some channels, expect no CP violation in decay
- B_d case: ΔΓ negligible

Time-dependent CP Violation Formalism

- Generic (but shown for B_s) decays to CP eigenstates

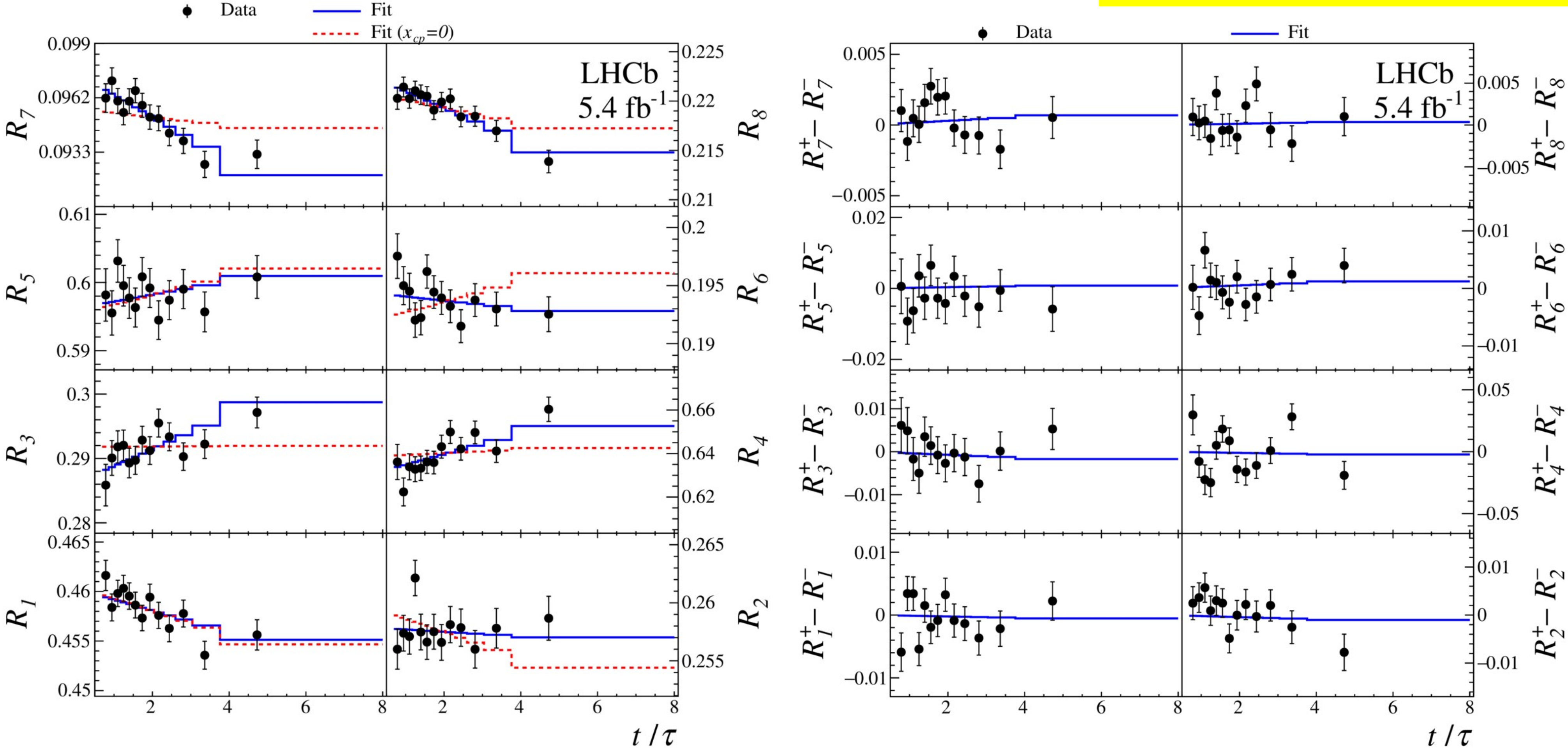
$$\Gamma(B_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, e^{-\Gamma t}$$
$$\times \left[1 + \mathcal{A}_{\rm CP}^{\rm dir} \; 1 + \mathcal{A}_{\Delta\Gamma} \; y\Gamma t + \mathcal{A}_{\rm CP}^{\rm mix} \; x\Gamma t \right]$$
$$\Gamma(\overline{B}_s(t) \to f) = \mathcal{N}_f \, |A_f|^2 \, \frac{1+|\lambda_f|^2}{2} \, (1+a) \, e^{-\Gamma t}$$
$$\times \left[1 - \mathcal{A}_{\rm CP}^{\rm dir} \; 1 + \mathcal{A}_{\Delta\Gamma} \; y\Gamma t - \mathcal{A}_{\rm CP}^{\rm mix} \; x\Gamma t \right] .$$

- In some channels, expect no CP violation in decay
- B_d case: $\Delta\Gamma$ negligible
- D^0 case: both $x = \Delta m/\Gamma$ and $y=\Delta\Gamma/2\Gamma$ small

Charm mixing and CP violation

$D^0 \rightarrow K_S \pi^+ \pi^-$ (“bin-flip Dalitz plot method”)

PRL 127 (2021) 111801



Ratios of yields in symmetric Dalitz-plot bins evolves with time due to D mixing
Any difference in time evolution for initial D^0 or $\overline{D}^0$ due to CP violation
Requires knowledge of same hadronic parameters as γ measurement

Charm mixing and CP violation

From same LHCb γ+charm combination shown previously

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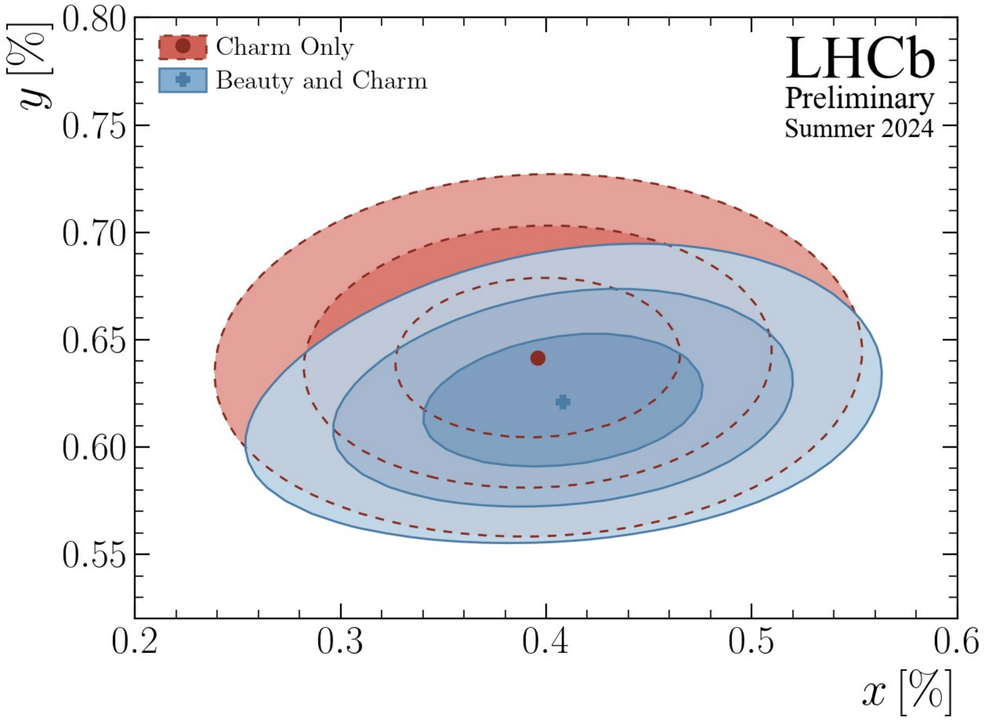
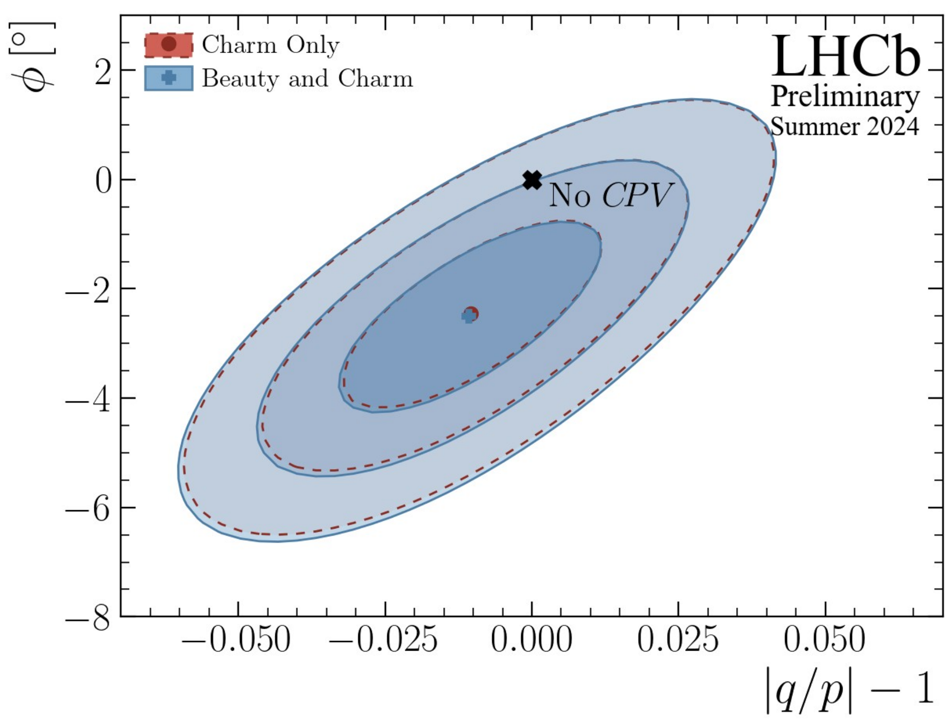


Inconsistent with no mixing point (0,0)



Consistent with no CP violation point (1,0)

World average in principle more precise (though LHCb dominates),
but not yet done simultaneously with B→DK and B→Dπ observables

CP violation in D decay

PRL 122 (2019) 211803

Measurement of CP asymmetry at pp collider requires knowledge of production and detection asymmetries; e.g. for $D^0 \to f$, where D meson flavour is tagged by $D^{*+} \to D^0\pi^+$ decay

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + A_{\mathrm{D}}(f) + A_{\mathrm{D}}(\pi_s^+) + A_{\mathrm{P}}(D^{*+}).$$

final state detection asymmetry vanishes for CP eigenstate

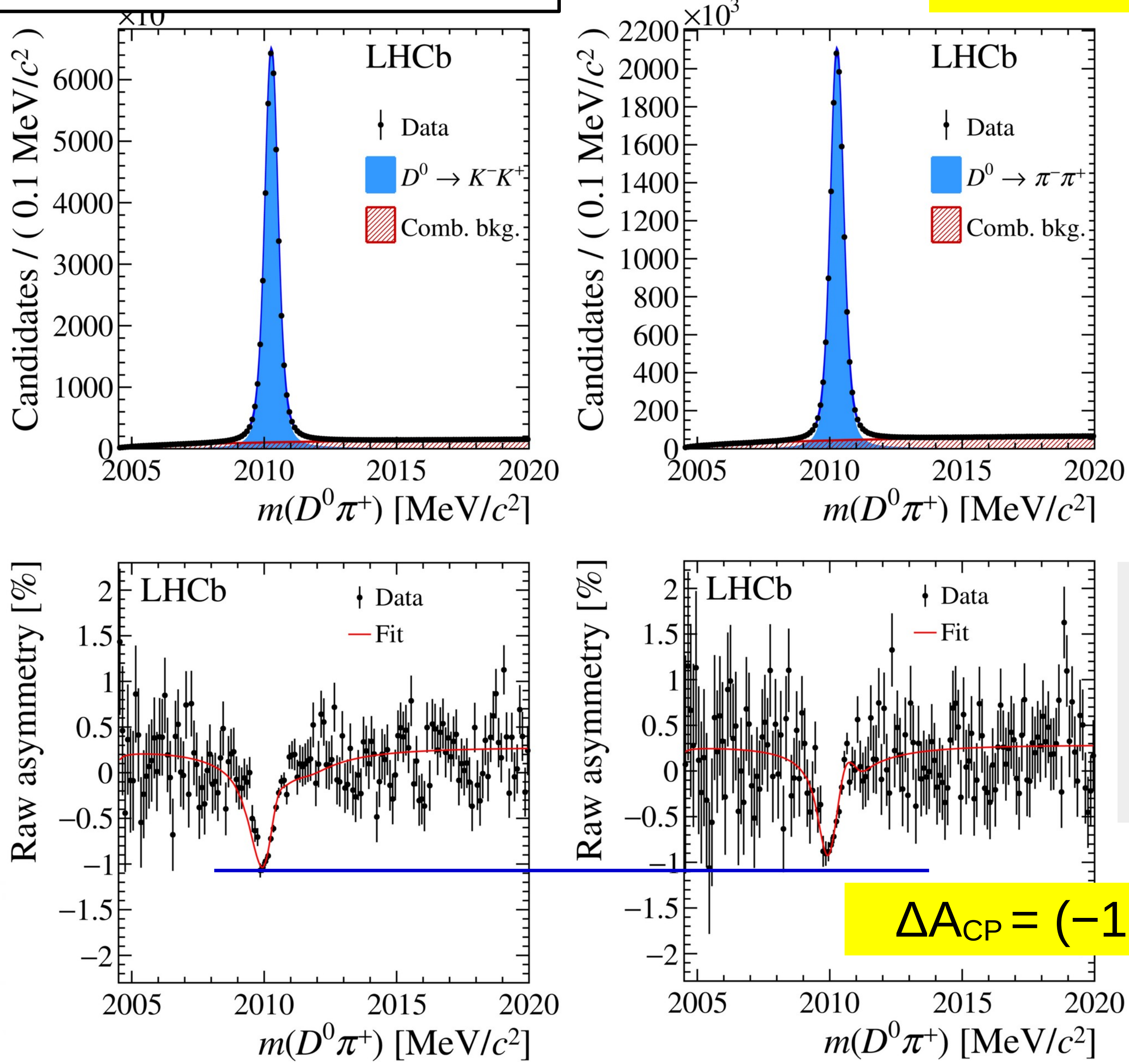
Cancel asymmetries by taking difference of raw asymmetries in two different final states (Since A_D and A_P depend on kinematics, must bin or reweight to ensure cancellation)

$$\Delta A_{CP} = A_{\mathrm{raw}}(K^-K^+) - A_{\mathrm{raw}}(\pi^-\pi^+).$$

CP violation in D decay

$$\Delta A_{CP} = A_{\text{raw}}(K^- K^+) - A_{\text{raw}}(\pi^- \pi^+).$$

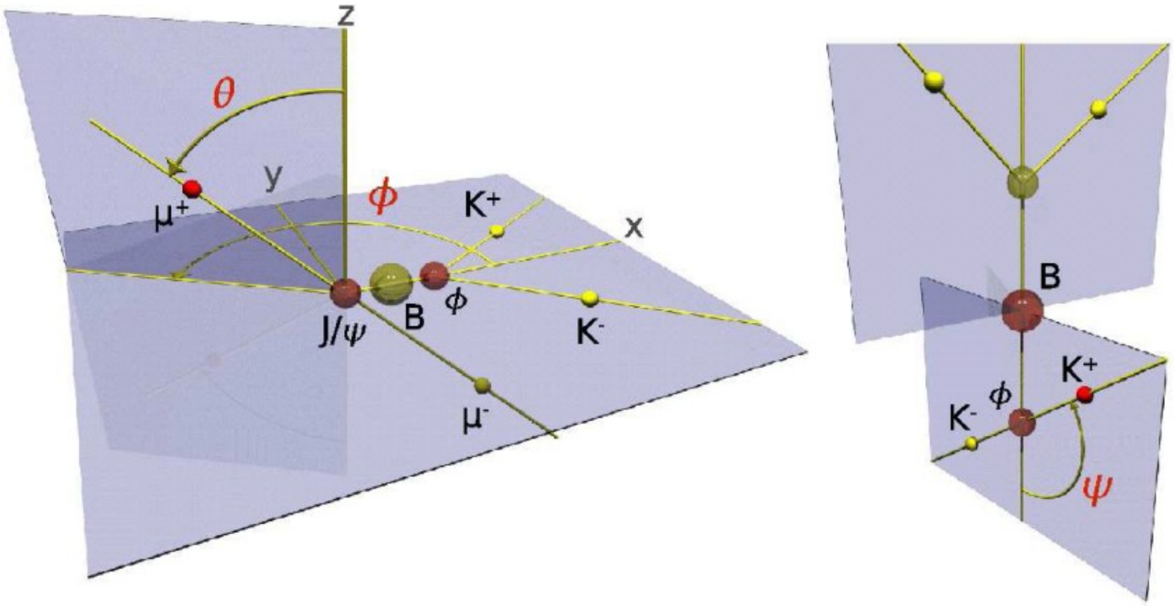
PRL 122 (2019) 211803



Small, but still larger than expected in the SM. Need more inputs to constrain possible NP contributions.

$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

$\Phi_s = -2\beta_s$ ($B_s \to J/\psi\varphi$)



- VV final state

  three helicity amplitudes

  → mixture of CP-even and CP-odd

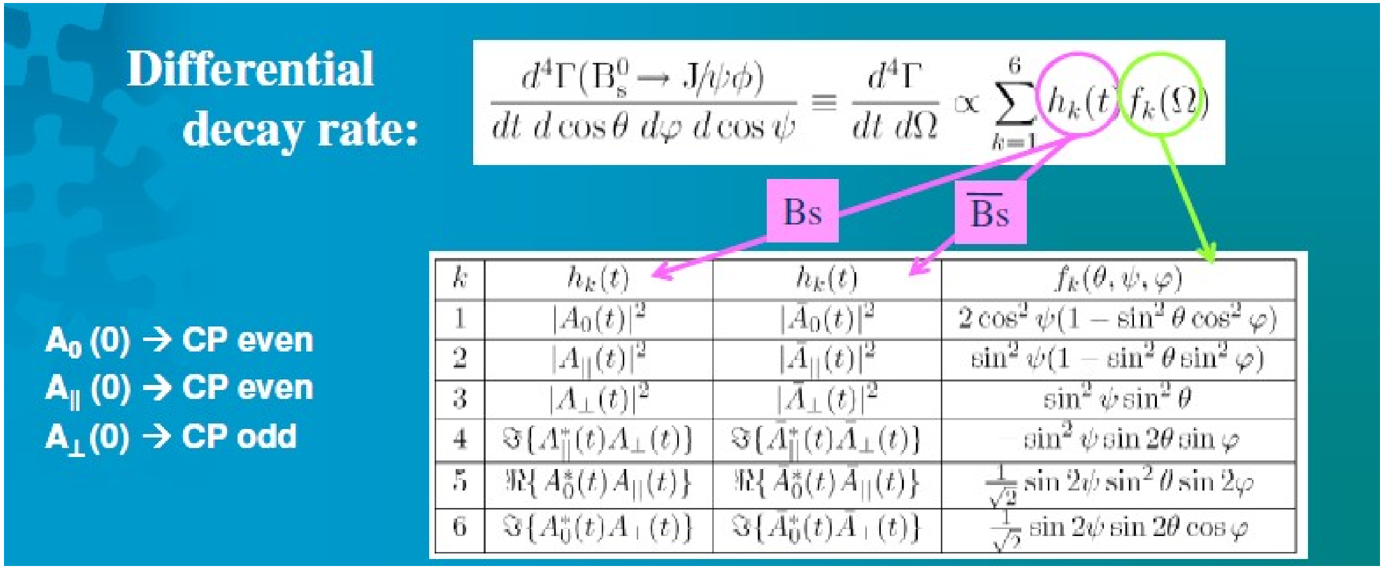
  disentangled using angular & time-dependent distributions

  → additional sensitivity

  many correlated variables

  → complicated analysis

$B_s \to J/\psi\phi$ formalism



Differential decay rate:

$$\frac{d^4\Gamma(B^0_s \to J/\psi\phi)}{dt\; d\cos\theta\; d\varphi\; d\cos\psi} \equiv \frac{d^4\Gamma}{dt\; d\Omega} \propto \sum_{k=1}^{6} h_k(t)\, f_k(\Omega)$$

Bs

$\overline{\text{Bs}}$

$A_0(0) \to$ CP even

$A_\parallel(0) \to$ CP even

$A_\perp(0) \to$ CP odd

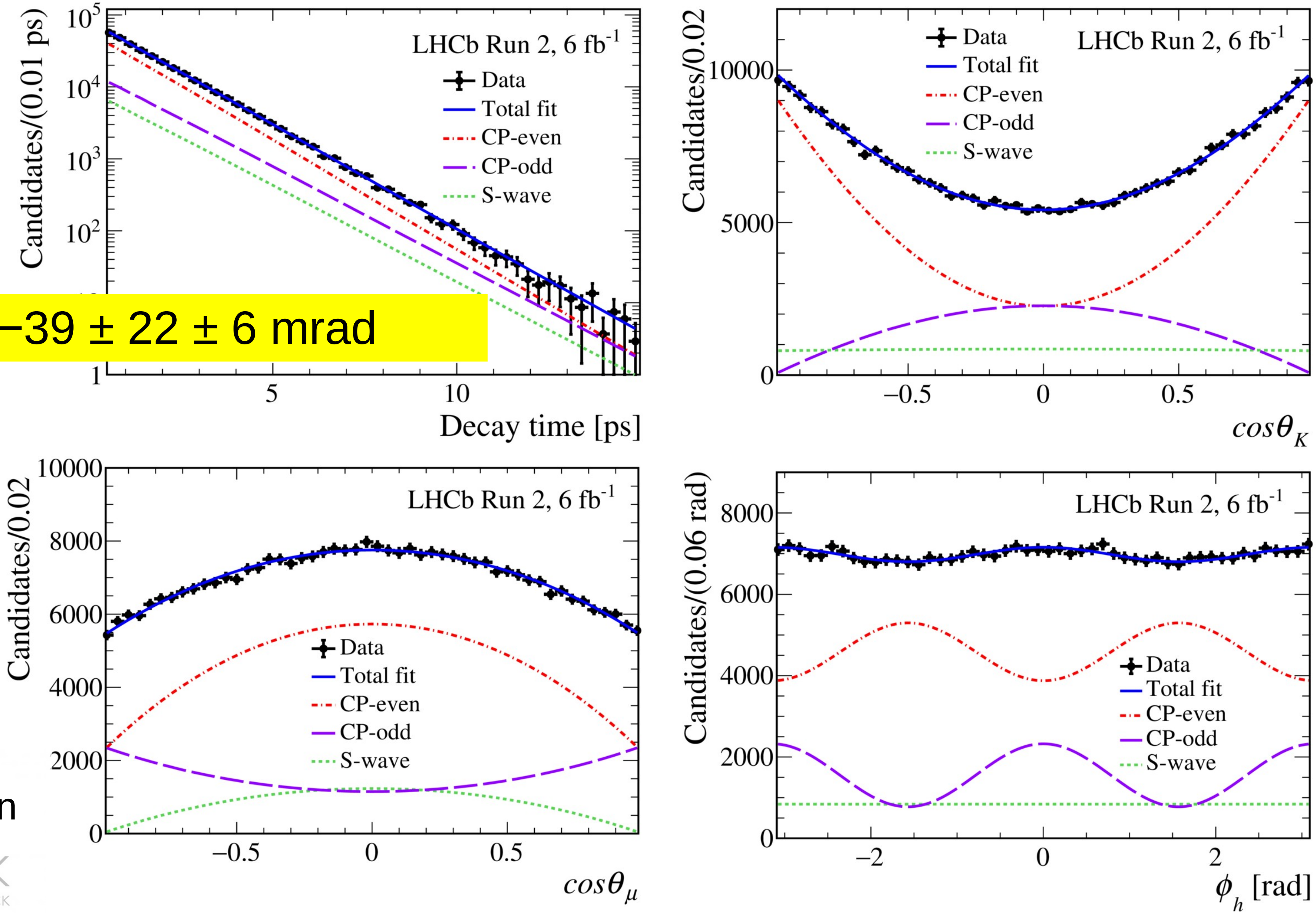
k	$h_k(t)$	$h_k(t)$	$f_k(\theta,\psi,\varphi)$
1	$\lvert A_0(t)\rvert^2$	$\lvert \bar{A}_0(t)\rvert^2$	$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)$
2	$\lvert A_\parallel(t)\rvert^2$	$\lvert \bar{A}_\parallel(t)\rvert^2$	$\sin^2\psi(1-\sin^2\theta\sin^2\varphi)$
3	$\lvert A_\perp(t)\rvert^2$	$\lvert \bar{A}_\perp(t)\rvert^2$	$\sin^2\psi\sin^2\theta$
4	$\Im\{A^*_\parallel(t)A_\perp(t)\}$	$\Im\{\bar{A}^*_\parallel(t)\bar{A}_\perp(t)\}$	$-\sin^2\psi\sin 2\theta\sin\varphi$
5	$\Re\{A^*_0(t)A_\parallel(t)\}$	$\Re\{\bar{A}^*_0(t)\bar{A}_\parallel(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi$
6	$\Im\{A^*_0(t)A_\perp(t)\}$	$\Im\{\bar{A}^*_0(t)\bar{A}_\perp(t)\}$	$\frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi$

± signs differ for B_s and $\overline{B}_s$

$$\begin{aligned}
|\bar{A}_0(t)|^2 &= |\bar{A}_0(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],\\
|\bar{A}_\parallel(t)|^2 &= |\bar{A}_\parallel(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - \sin\Phi\sin(\Delta m_s t)\right],\\
|\bar{A}_\perp(t)|^2 &= |\bar{A}_\perp(0)|^2 e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) + \sin\Phi\sin(\Delta m_s t)\right],\\
\Im\{\bar{A}^*_\parallel(t)\bar{A}_\perp(t)\} &= |\bar{A}_\parallel(0)||\bar{A}_\perp(0)| e^{-\Gamma_s t}\Big[-\cos(\delta_\perp-\delta_\parallel)\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\\
&\quad - \sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) + \cos(\delta_\perp-\delta_\parallel)\cos\Phi\sin(\Delta m_s t)\Big],\\
\Re\{\bar{A}^*_0(t)\bar{A}_\parallel(t)\} &= |\bar{A}_0(0)||\bar{A}_\parallel(0)| e^{-\Gamma_s t}\cos\delta_\parallel\Big[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\\
&\quad - \sin\Phi\sin(\Delta m_s t)\Big] \text{ and}\\
\Im\{\bar{A}^*_0(t)\bar{A}_\perp(t)\} &= |\bar{A}_0(0)||\bar{A}_\perp(0)| e^{-\Gamma_s t}\Big[-\cos\delta_\perp\sin\Phi\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\\
&\quad - \sin\delta_\perp\cos(\Delta m_s t) + \cos\delta_\perp\cos\Phi\sin(\Delta m_s t)\Big].
\end{aligned}$$

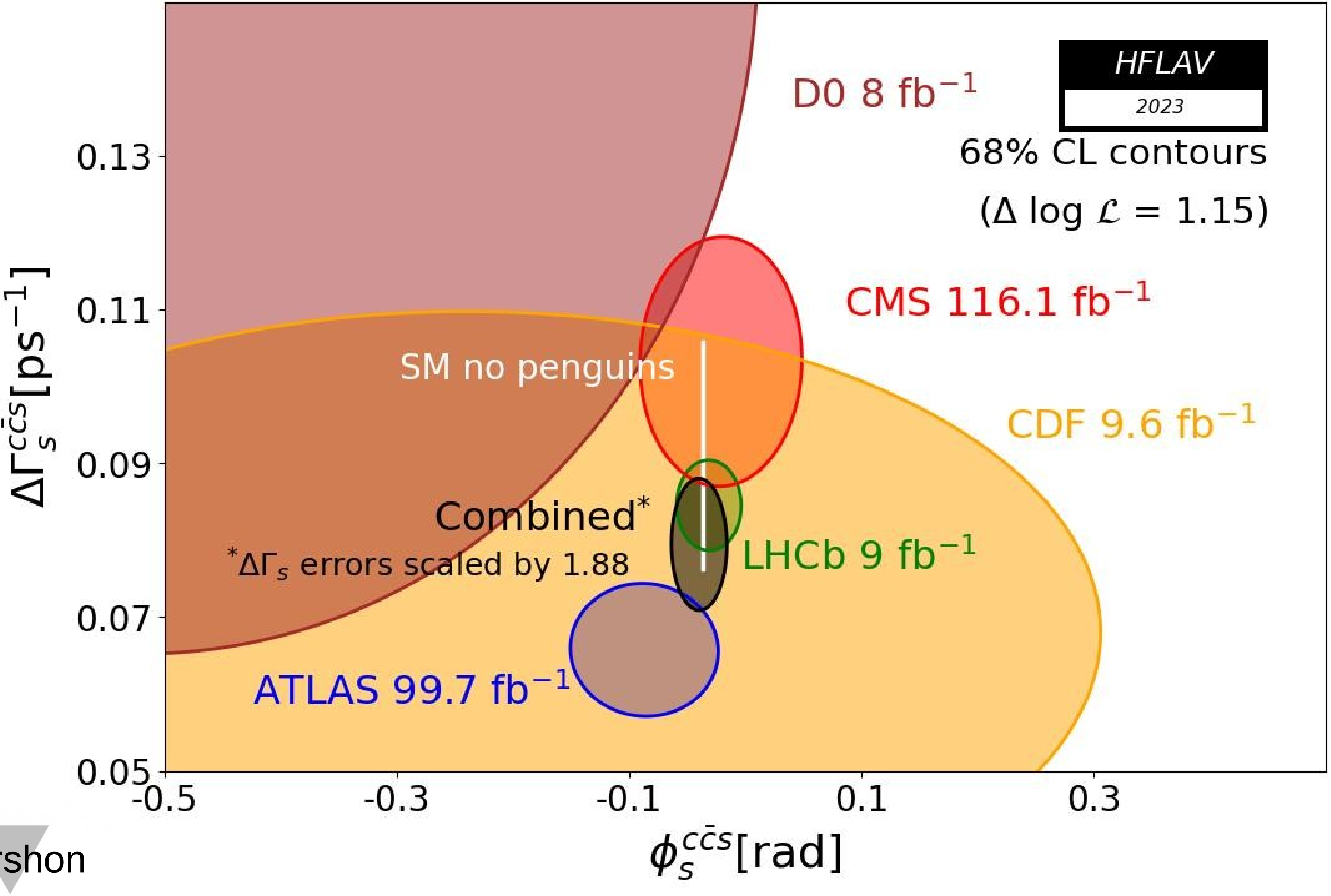
CP violation in $B_s \to J/\psi\phi$ & $J/\psi\pi\pi$

PRL 132 (2024) 051802



$\phi_s = -39 \pm 22 \pm 6$ mrad

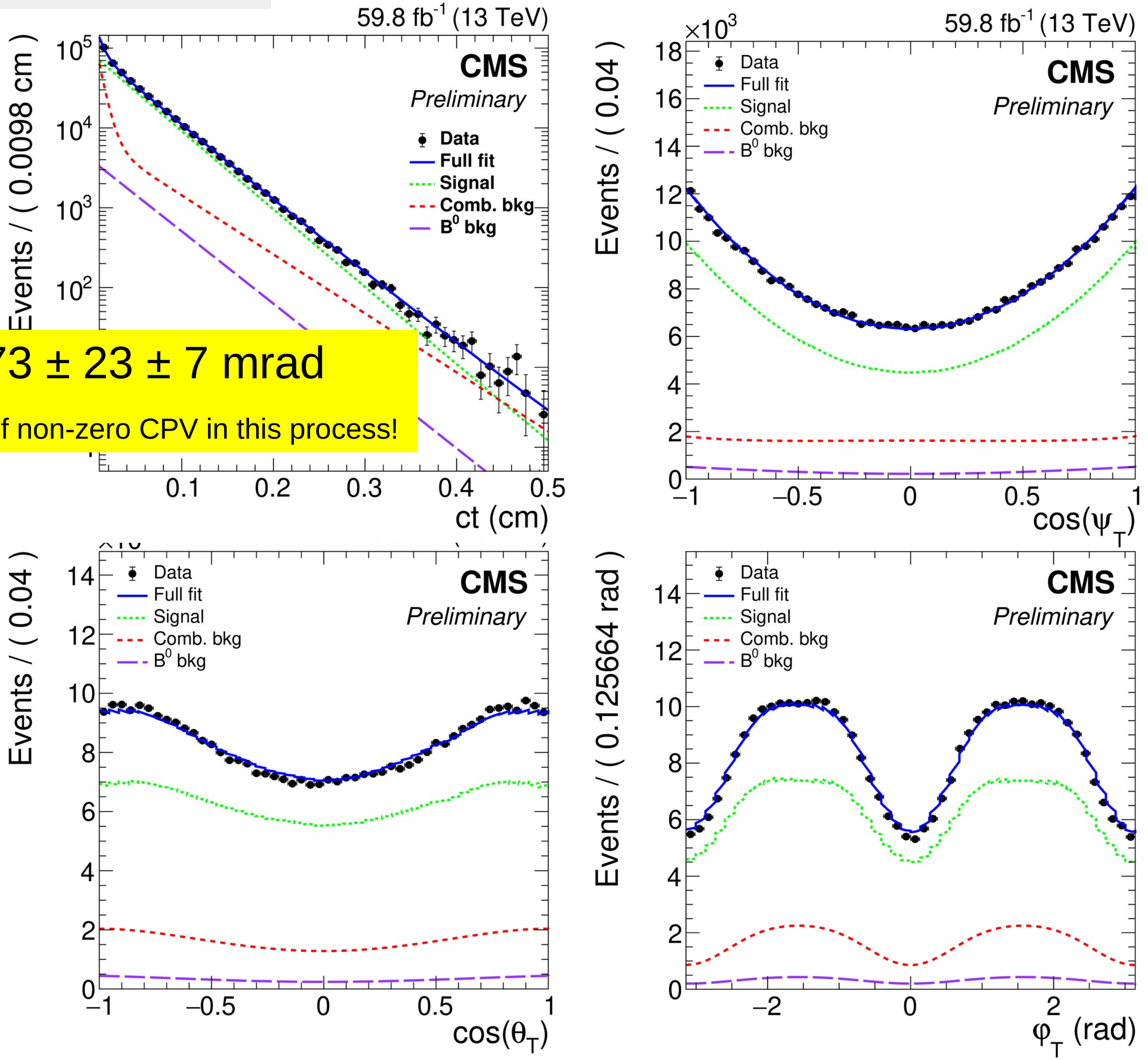
CP violation in interference between B_s mixing and $b \rightarrow c\bar{c}s$ decay (φ_s)



We are lacking good plots that demonstrate the observed CP violation effect … but working on it (EPJ C84 (2024) 327)

Enter CMS!

CMS-PAS-BPH-23-004



$\phi_s = -73 \pm 23 \pm 7$ mrad

First evidence of non-zero CPV in this process!

Tim Gershon

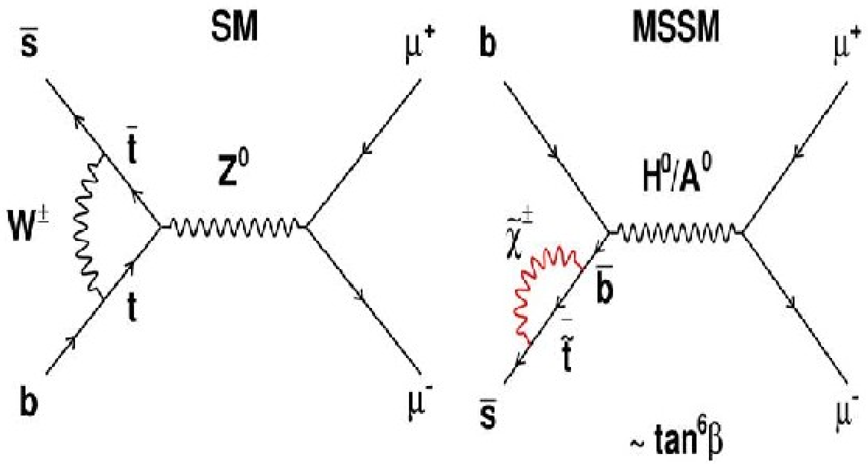
Flavour physics & CP violation

Rare Decays

$B_{(s)}^0 \rightarrow \mu^+\mu^-$

Killer app. for new physics discovery

- Very small in the SM
  - no tree-level FCNC
  - CKM suppression
  - helicity suppression

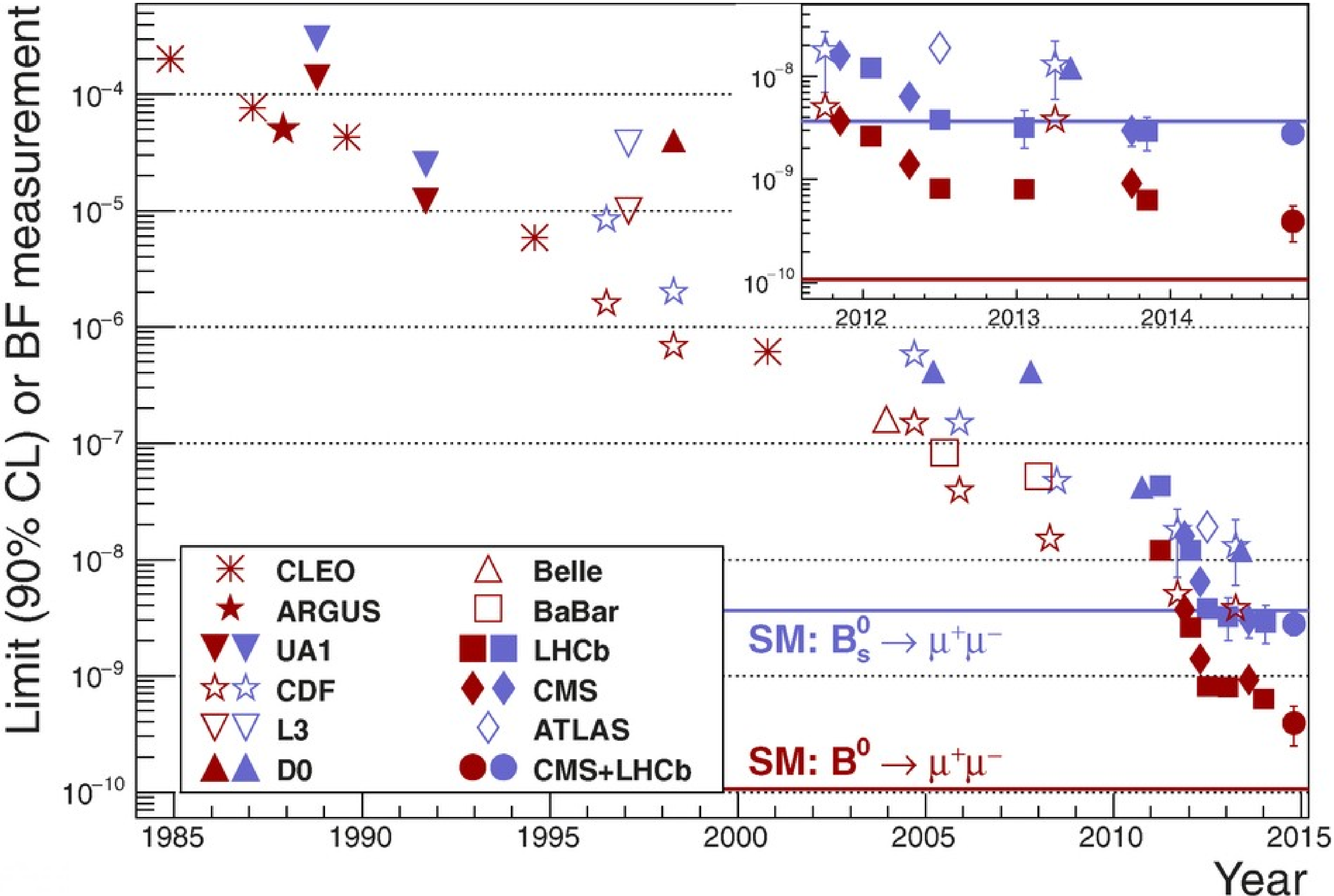


- Huge NP enhancement possible (tan β = ratio of Higgs vevs)

$$BR(B_s \rightarrow \mu^+\mu^-)^{SM} = (3.3 \pm 0.3) \times 10^{-9} \qquad BR(B_s \rightarrow \mu^+\mu^-)^{MSSM} \propto \tan^6\beta / M_{A0}^4$$

- Clean experimental signature

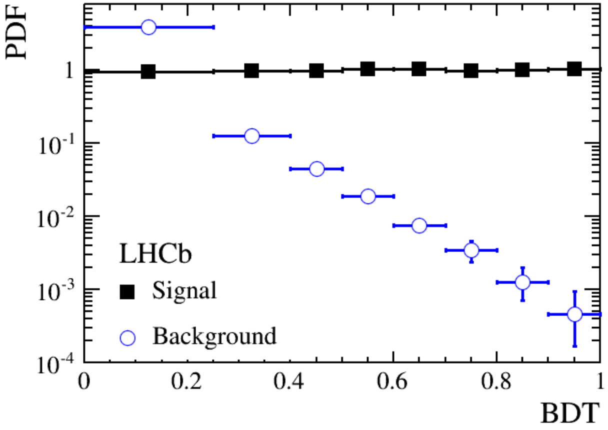
$B_{(s)}^0 \rightarrow \mu^+\mu^-$



Searches over 30 years

$B_{(s)}^0 \to \mu^+\mu^-$ – analysis ingredients

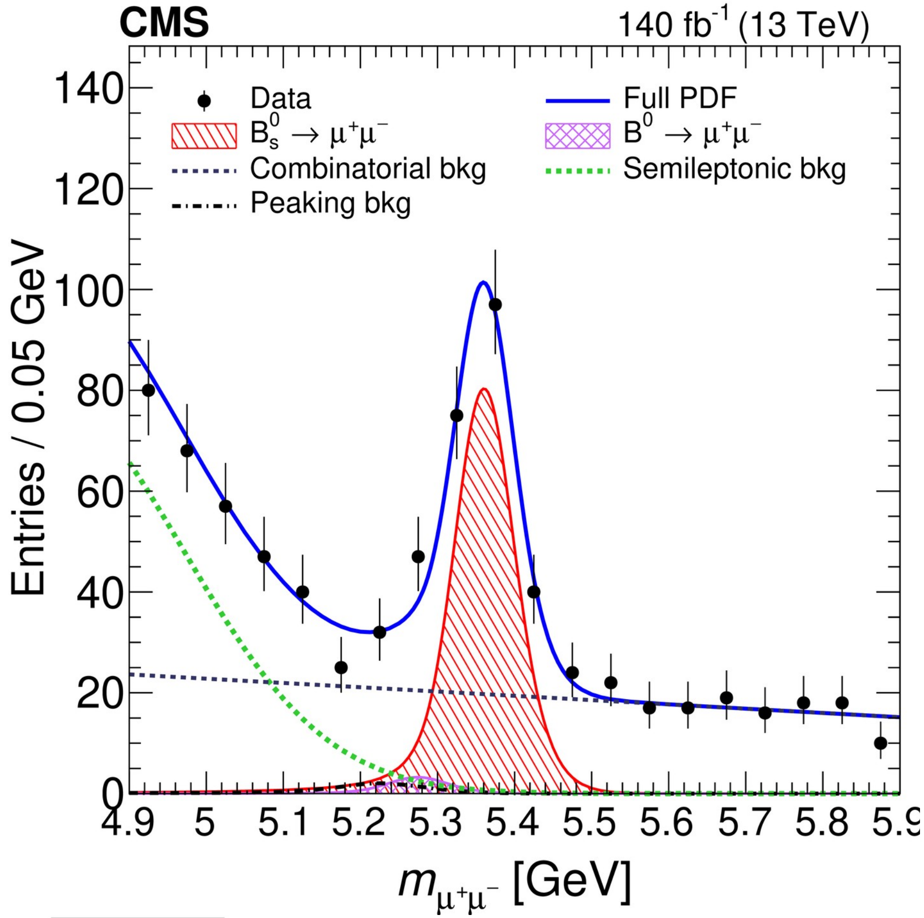
- Produce a very large sample of B mesons
- Trigger efficiently on dimuon signatures
- Reject background
  - excellent vertex resolution (identify displaced vertex)
  - excellent mass resolution (identify B peak)
    - also essential to resolve B^0 from B_s^0 decays
  - powerful muon identification (reject background from B decays with misidentified pions)
  - typical to combine various discriminating variables into a multivariate classifier
    - e.g. Boosted Decision Trees algorithm



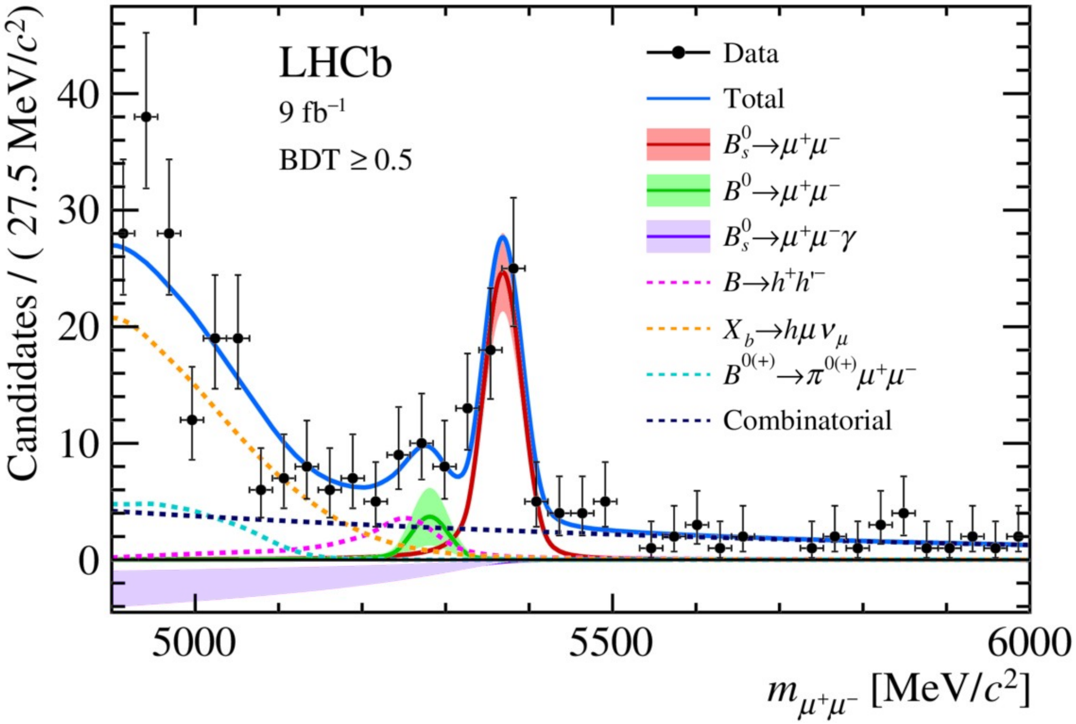
$B_{(s)}^0 \to \mu^+\mu^-$

Run 1+2 results from CMS & LHCb

PL B842 (2023) 137955



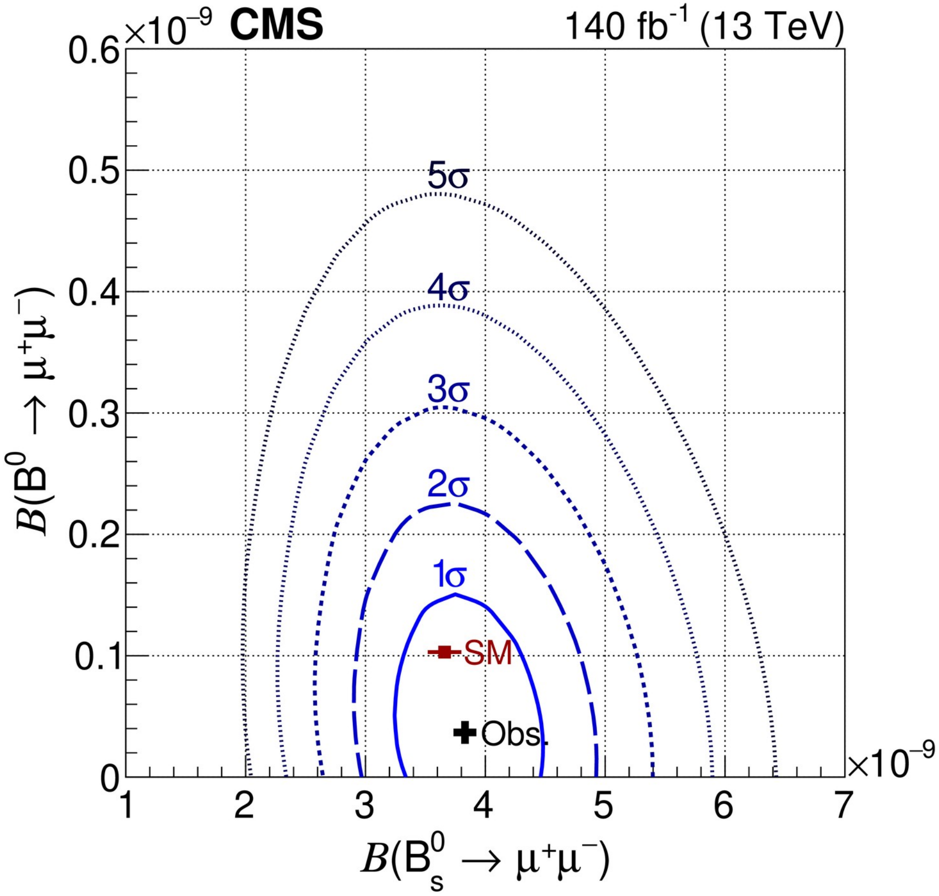
PRL 128 (2022) 041801



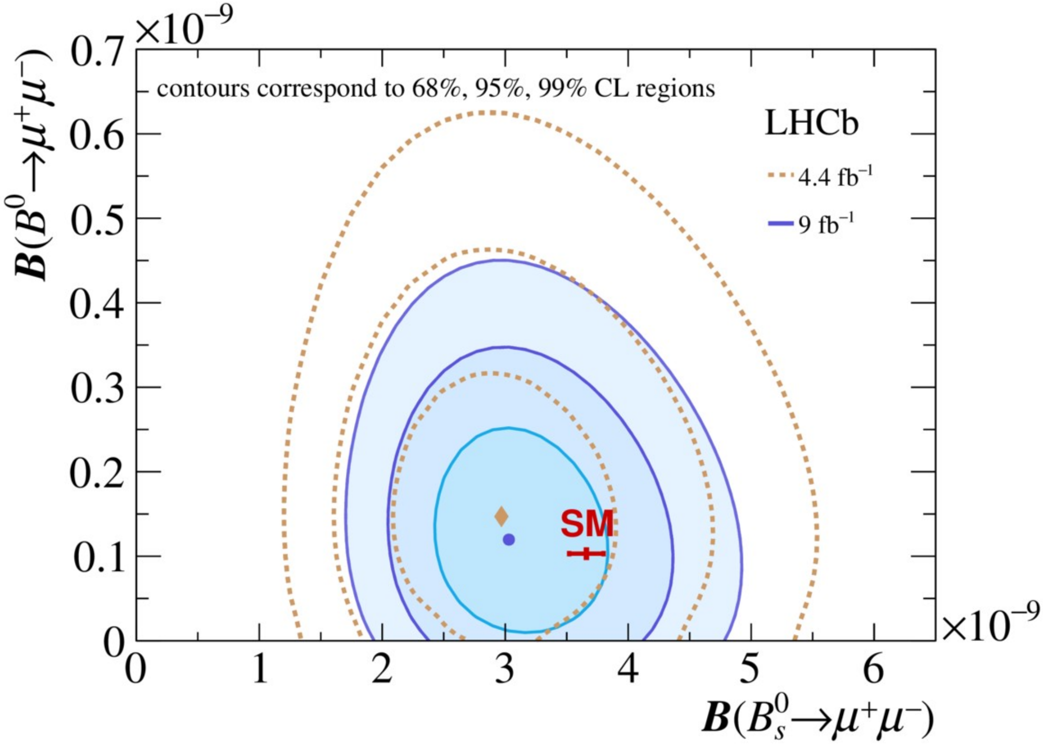
$B_{(s)}{}^0 \to \mu^+\mu^-$

Run 1+2 results from CMS & LHCb

PL B842 (2023) 137955



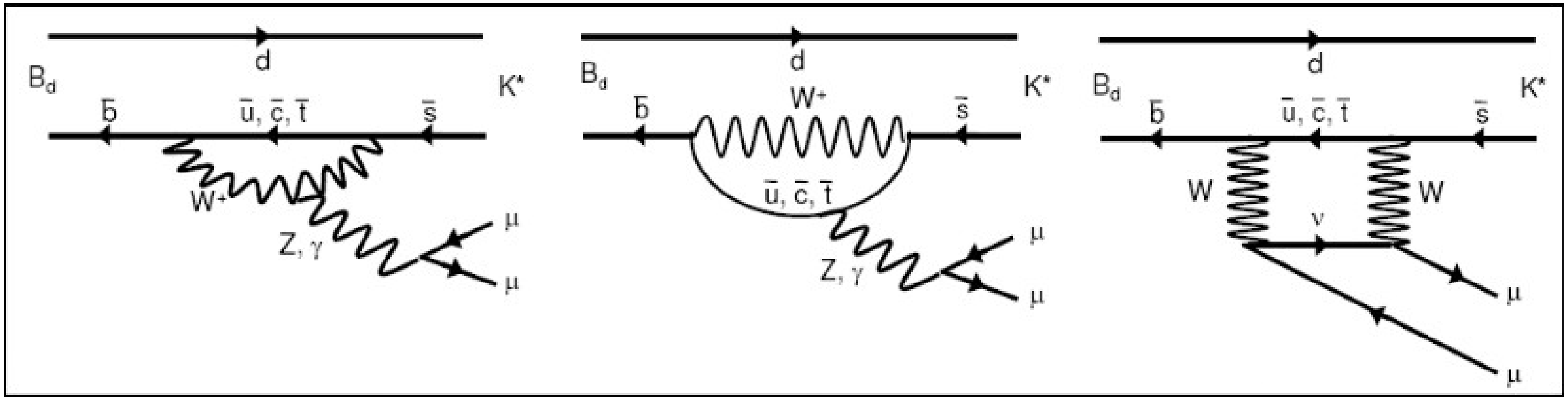
PRL 128 (2022) 041801



Future results (including from ATLAS) will reduce uncertainties
Can also probe new observables, including CP violation

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

- $b \rightarrow s l^+ l^-$ processes also governed by FCNCs
  - rates and asymmetries of many exclusive processes sensitive to NP
- Queen among them is $B_d \rightarrow K^{*0}\mu^+\mu^-$
  - superb laboratory for NP tests
  - experimentally clean signature
  - many kinematic variables …
  - … with clean theoretical predictions (at least at low q^2)



Operator Product Expansion

Build an effective theory for b physics

- take the weak part of the SM
- integrate out the heavy fields (W,Z,t)
- (like a modern version of Fermi theory for weak interactions)

$$\mathcal{L}_{\text{(full EW}\times\text{QCD)}} \longrightarrow \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED}\times\text{QCD}}\left(\begin{smallmatrix}\text{quarks} \neq t\\ \text{\& leptons}\end{smallmatrix}\right) + \sum_n C_n(\mu)\, Q_n$$

Q_n – local interaction terms (operators), C_n – coupling constants (Wilson coefficients)

Wilson coefficients

- encode information on the weak scale
- are calculable and known in the SM (at least to leading order)
- are affected by new physics

r K*$\mu\mu$ we care about C_7 (also affects b → sγ), C_9 and C_{10}

Effective operators

$$\mathcal{H}_W^{\Delta B=1,\Delta C=0,\Delta S=-1} = 4\frac{G_F}{\sqrt{2}}\Big(\lambda_c^s\big(C_1(\mu)Q_1^c(\mu) + C_2(\mu)Q_2^c(\mu)\big)$$
$$+\lambda_u^s\big(C_1(\mu)Q_1^u(\mu) + C_2(\mu)Q_2^u(\mu)\big) - \lambda_t^s\sum_{i=3}^{10} C_i(\mu)Q_i(\mu)\Big)$$

where the $\lambda_q^s = V_{qb}^* V_{qs}$ and the operator basis is given by

$$\begin{aligned}
Q_1^q &= \bar{b}_L^\alpha\gamma^\mu q_L^\alpha\,\bar{q}_L^\beta\gamma_\mu s_L^\beta & Q_2^q &= \bar{b}_L^\alpha\gamma^\mu q_L^\beta\,\bar{q}_L^\beta\gamma_\mu s_L^\alpha \\
Q_3 &= \bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q \bar{q}_L^\beta\gamma_\mu q_L^\beta & Q_4 &= \bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q \bar{q}_L^\beta\gamma_\mu q_L^\alpha \\
Q_5 &= \bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q \bar{q}_R^\beta\gamma_\mu q_R^\beta & Q_6 &= \bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q \bar{q}_R^\beta\gamma_\mu q_R^\alpha \\
Q_7 &= \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q e_q\bar{q}_R^\beta\gamma_\mu q_R^\beta & Q_8 &= \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q e_q\bar{q}_R^\beta\gamma_\mu q_R^\alpha \\
Q_9 &= \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\sum_q e_q\bar{q}_L^\beta\gamma_\mu q_L^\beta & Q_{10} &= \frac{3}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\beta\sum_q e_q\bar{q}_L^\beta\gamma_\mu q_L^\alpha
\end{aligned}$$

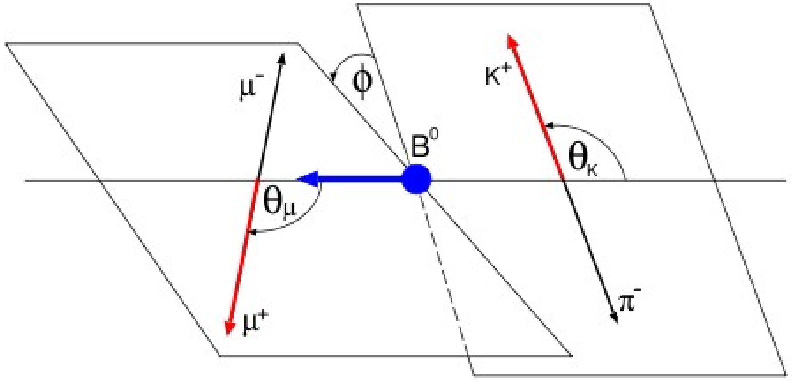
$$\begin{aligned}
Q_{7\gamma} &= \frac{e}{16\pi^2}m_b\bar{b}_L^\alpha\sigma^{\mu\nu}F_{\mu\nu}s_L^\alpha \\
Q_{8g} &= \frac{g_s}{16\pi^2}m_b\bar{b}_L^\alpha\sigma^{\mu\nu}G_{\mu\nu}^A T^A s_L^\alpha \\
Q_{9V} &= \frac{1}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\,\bar{l}\gamma_\mu l \\
Q_{10A} &= \frac{1}{2}\bar{b}_L^\alpha\gamma^\mu s_L^\alpha\,\bar{l}\gamma_\mu\gamma_5 l
\end{aligned}$$

Four-fermion operators (except $Q_{7\gamma}$ & Q_{8g}) – dimension 6

Angular analysis of $B \to K^{*}\mu^{+}\mu^{-}$

- Differential decay distribution

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big].$$

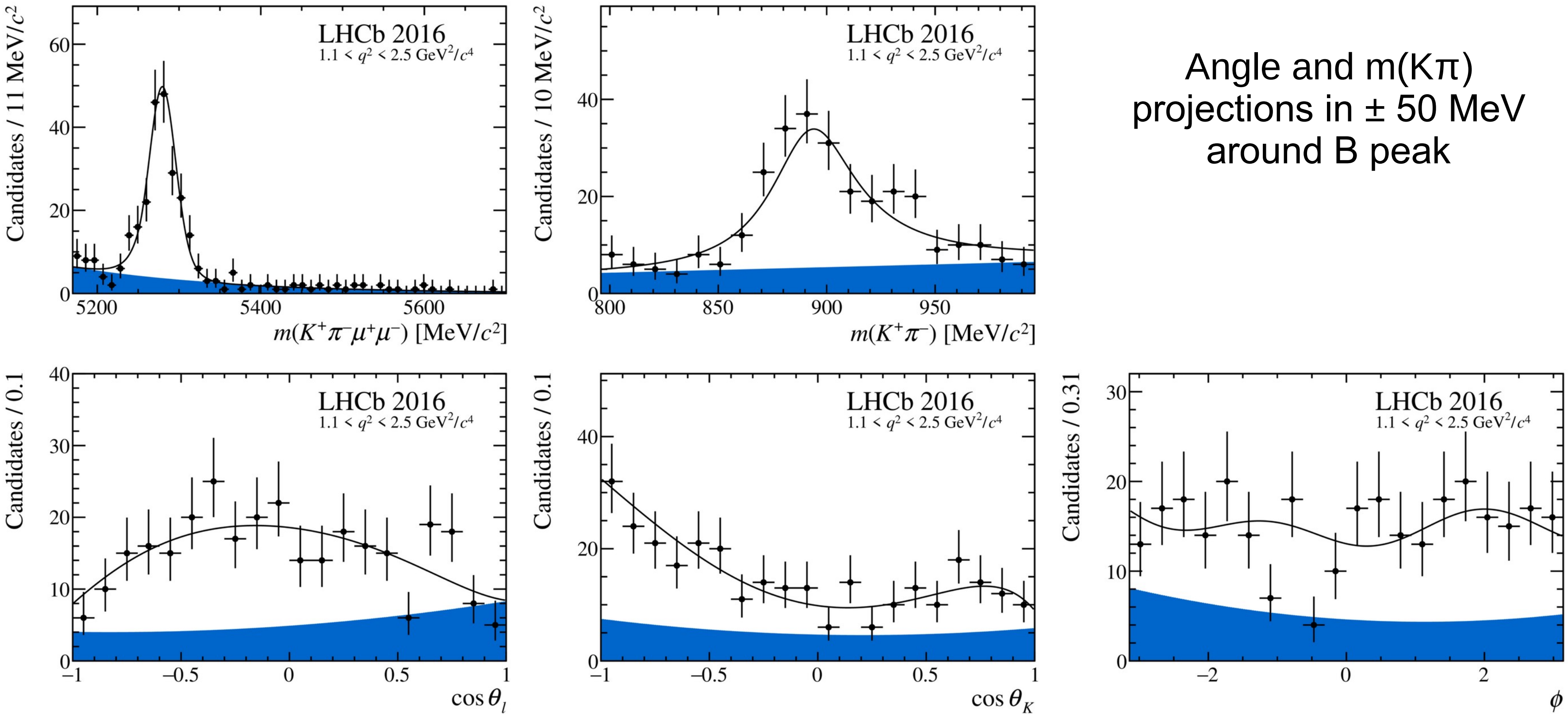


S_i terms related to Wilson coefficients and form factors

Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

PRL 125 (2020) 011802

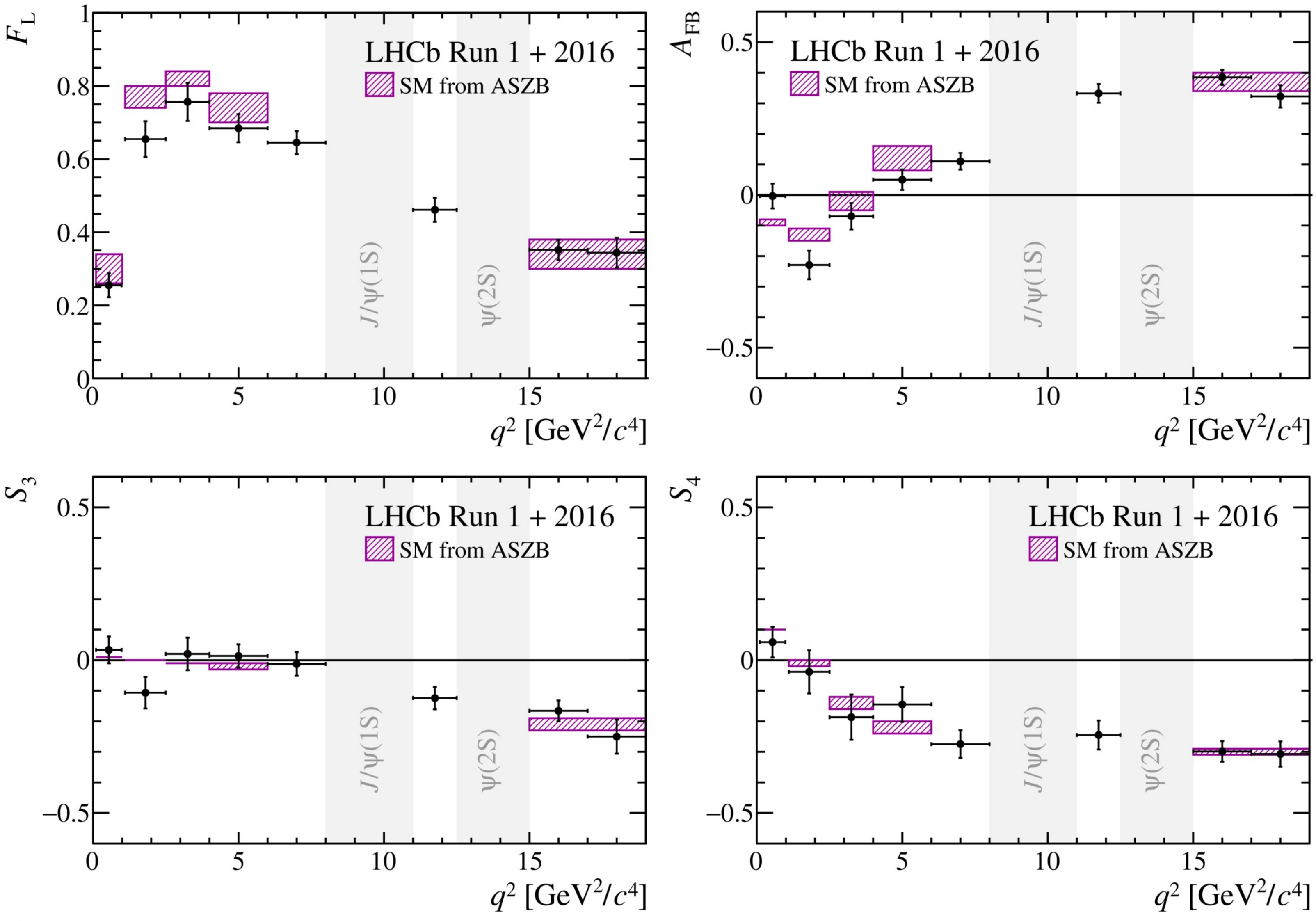
- Example of fits, in $1.1 < q^2 < 2.5$ GeV^2 bin



Angle and m(Kπ) projections in ± 50 MeV around B peak

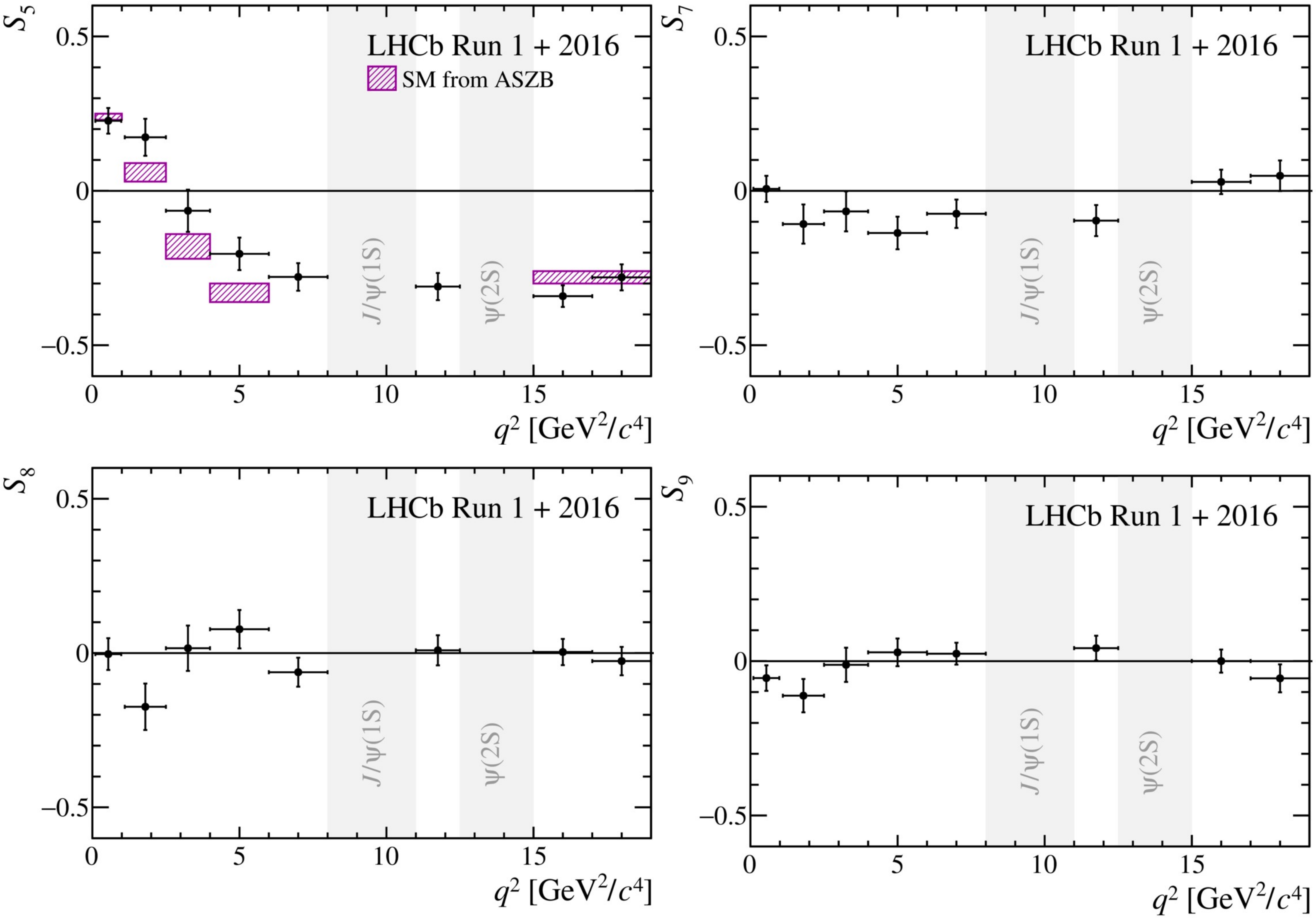
Full angular analysis of $B^0 \to K^{*0}\mu^+\mu^-$

PRL 125 (2020) 011802



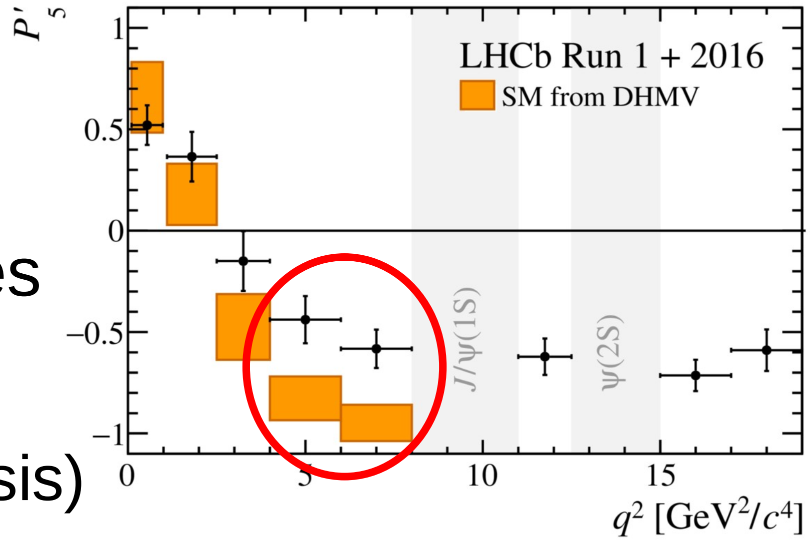
Full angular analysis of $B^0 \rightarrow K^{*0}\mu^+\mu^-$

PRL 125 (2020) 011802



Tension in P_5'

PRL 125 (2020) 011802

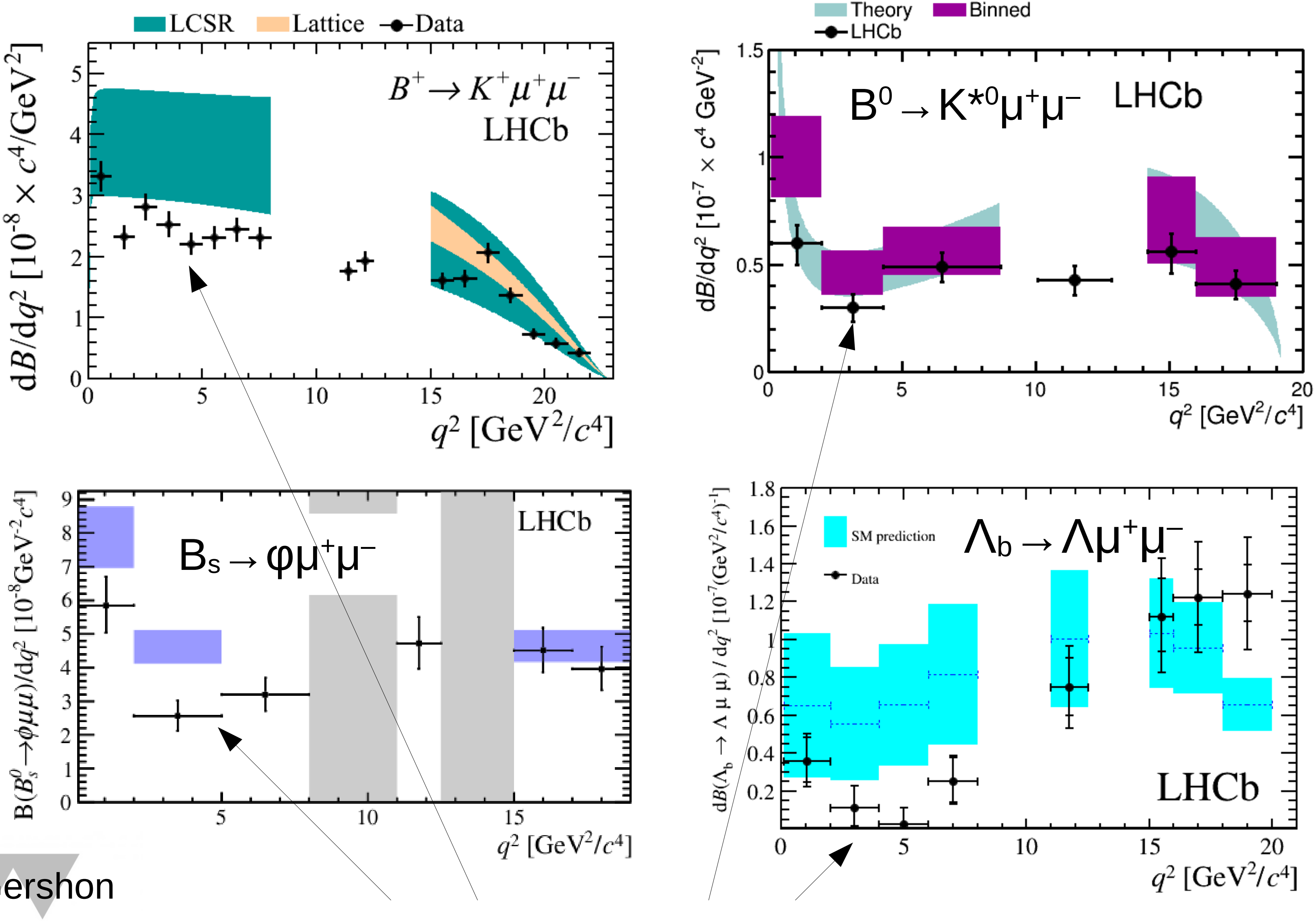


- Dimuon pair is predominantly spin-1
  - either vector (V) or axial-vector (A)
- There are 6 non-negligible amplitudes
  - 3 for VV and 3 for VA
  - expressed as $A^{L,R}_{0,\perp,\parallel}$ (transversity basis)
- P_5' related to difference between relative phase of longitudinal (0) and perpendicularly ($\perp$) polarised amplitudes for VV and VA
  - constructed so as to minimise form-factor uncertainties

$$P_5' = \sqrt{2}\frac{\mathrm{Re}\left(A_0^{\mathrm{L}}A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}}A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

Sensitive to NP in V or A couplings (Wilson coefficients $C_9^{(\prime)}$ & $C_{10}^{(\prime)}$)

b → sμ⁺μ⁻ branching fractions



Trend to be below SM prediction at low q^2?

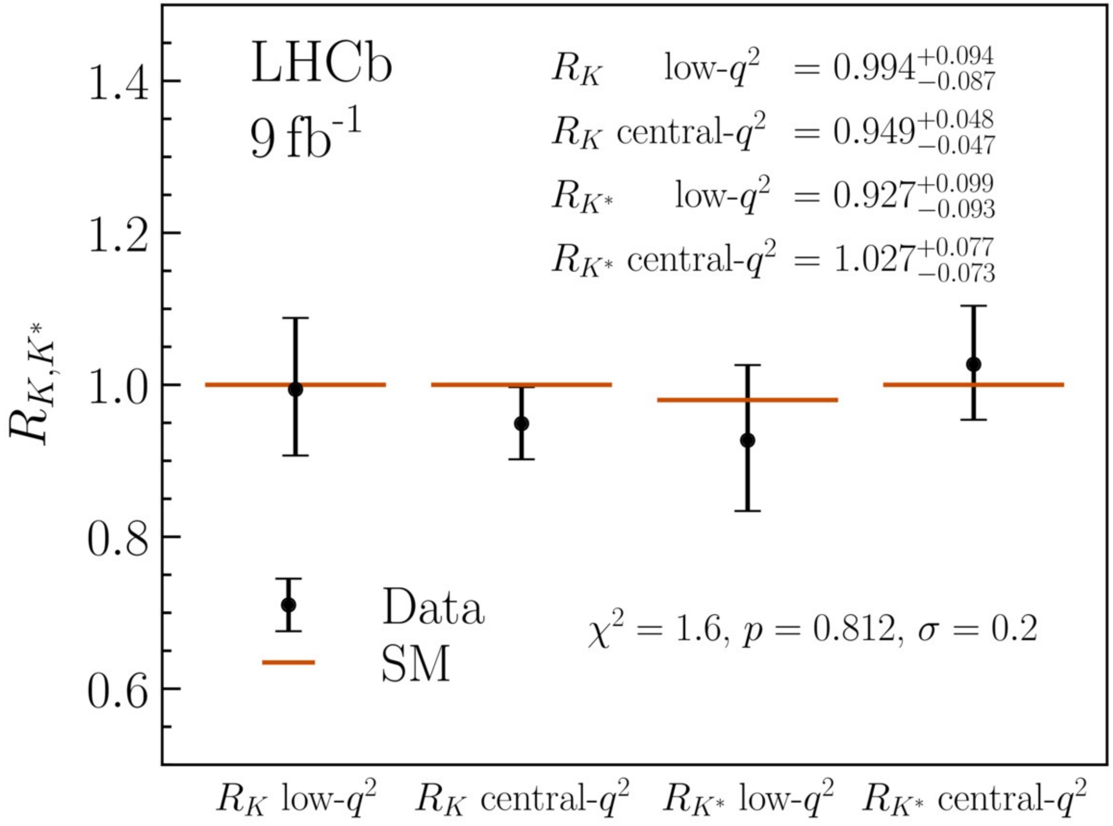
Lepton universality – R_K and R_{K^*}

PRL 131 (2023) 051803
PR D 108 (2023) 032002

Deficit of *B*(B → $K^{(*)}\mu^+\mu^-$) compared to expectation

Does *B*(B → $K^{(*)}e^+e^-$) have same trend?

- Lepton universality ratios (R_X) have negligible theoretical uncertainty
- Several measurements appeared to show accumulating evidence, until ...

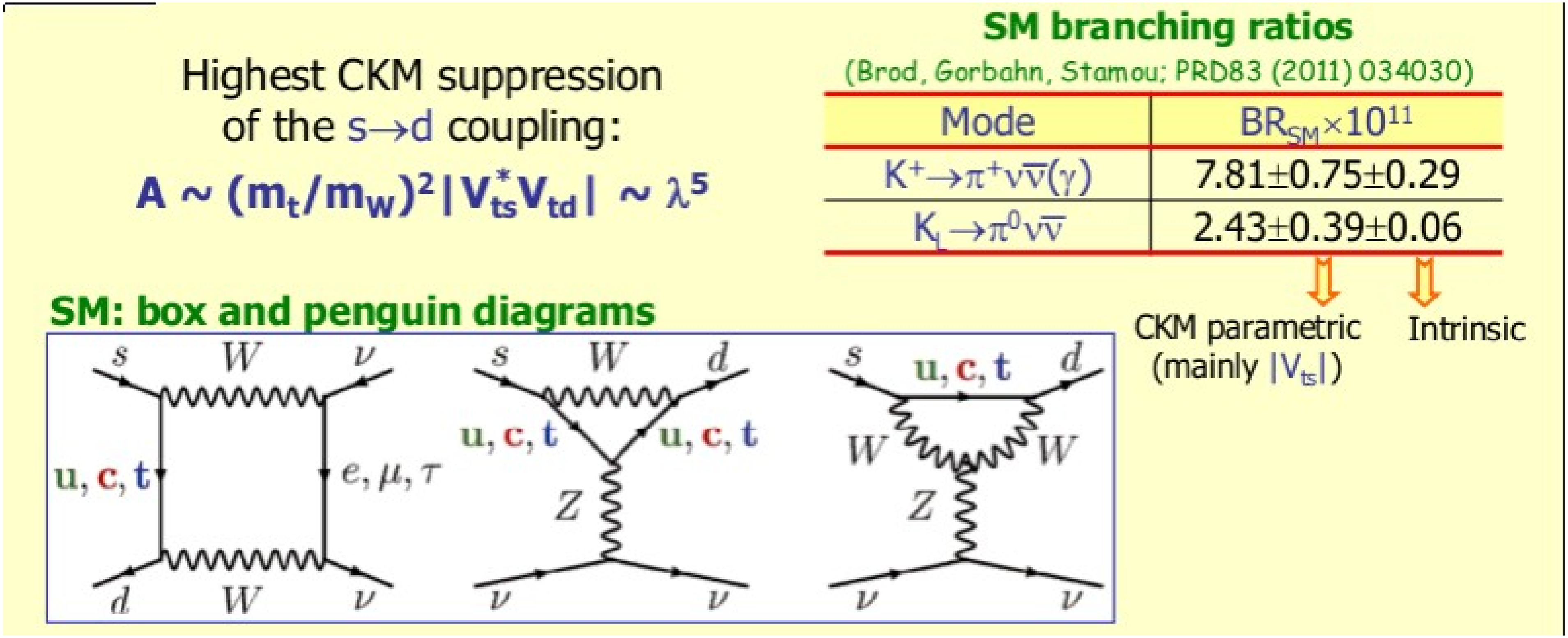


Latest and most precise results well consistent with SM

More precise measurements remain well motivated

Future prospects

The holy grail of kaon physics: $K \to \pi\nu\bar{\nu}$



Highest CKM suppression of the $s \to d$ coupling:

$$A \sim (m_t/m_W)^2 |V_{ts}^* V_{td}| \sim \lambda^5$$

SM branching ratios

(Brod, Gorbahn, Stamou; PRD83 (2011) 034030)

Mode	$BR_{SM} \times 10^{11}$
$K^+ \to \pi^+ \nu\bar{\nu}(\gamma)$	$7.81 \pm 0.75 \pm 0.29$
$K_L \to \pi^0 \nu\bar{\nu}$	$2.43 \pm 0.39 \pm 0.06$

CKM parametric (mainly $|V_{ts}|$)

Intrinsic

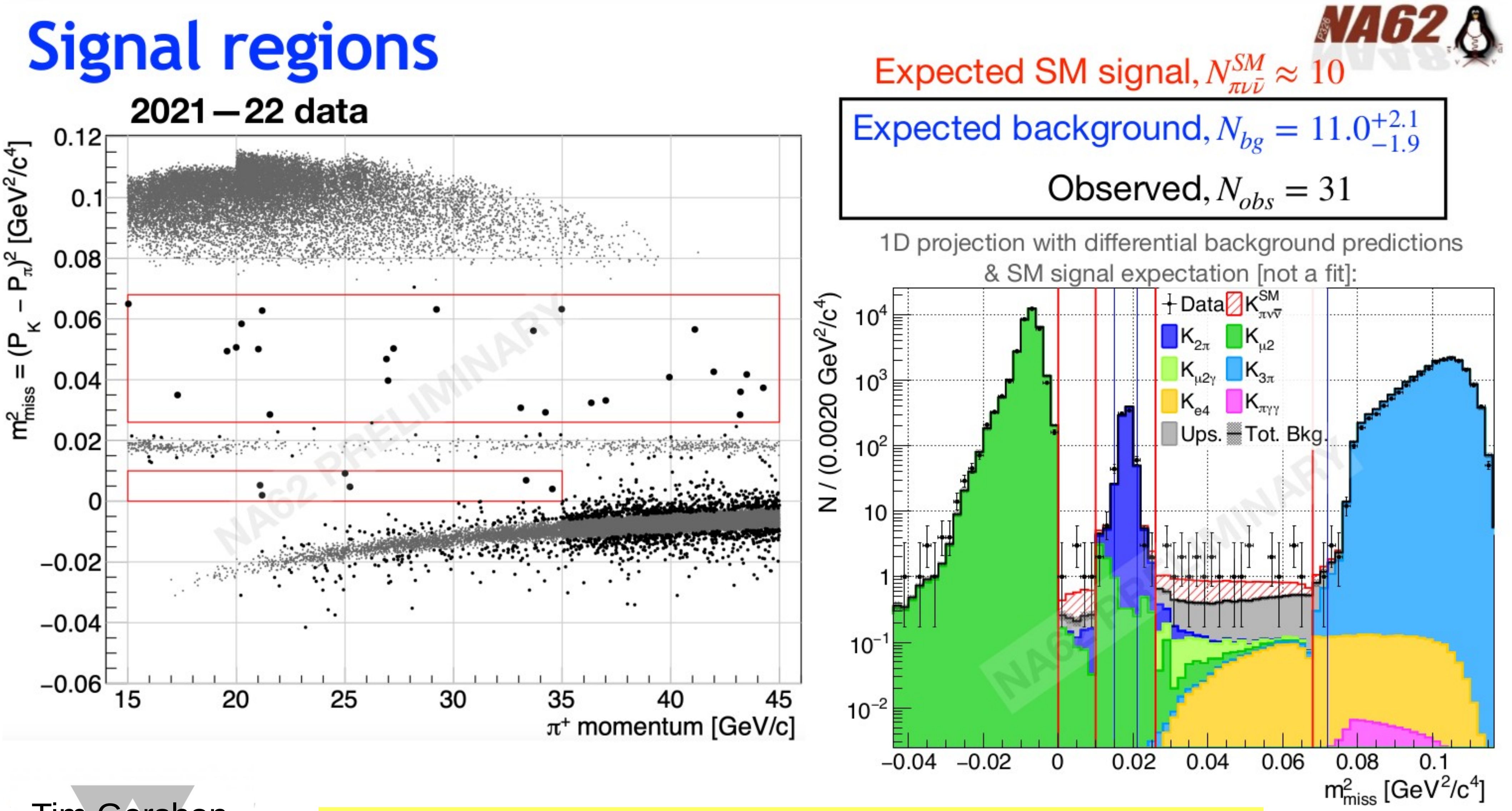
SM: box and penguin diagrams

Next generation experiments should measure these decays for the 1st time

- $K^+ \to \pi^+ \nu\bar{\nu}$ (NA62, CERN)
- $K^0 \to \pi^0 \nu\bar{\nu}$ (K0T0, J-PARC)

https://indico.cern.ch/event/1447422/

Hot off the press from NA62



Signal regions

Expected SM signal, $N^{SM}_{\pi\nu\bar{\nu}} \approx 10$

Expected background, $N_{bg} = 11.0^{+2.1}_{-1.9}$

Observed, $N_{obs} = 31$

1D projection with differential background predictions & SM signal expectation [not a fit]:

First observation of the K+ → $\pi^+\nu\bar{\nu}$ decay!

Hot off the press from NA62

BNL E787/E949 experiment
[Phys.Rev.D 79 (2009) 092004]

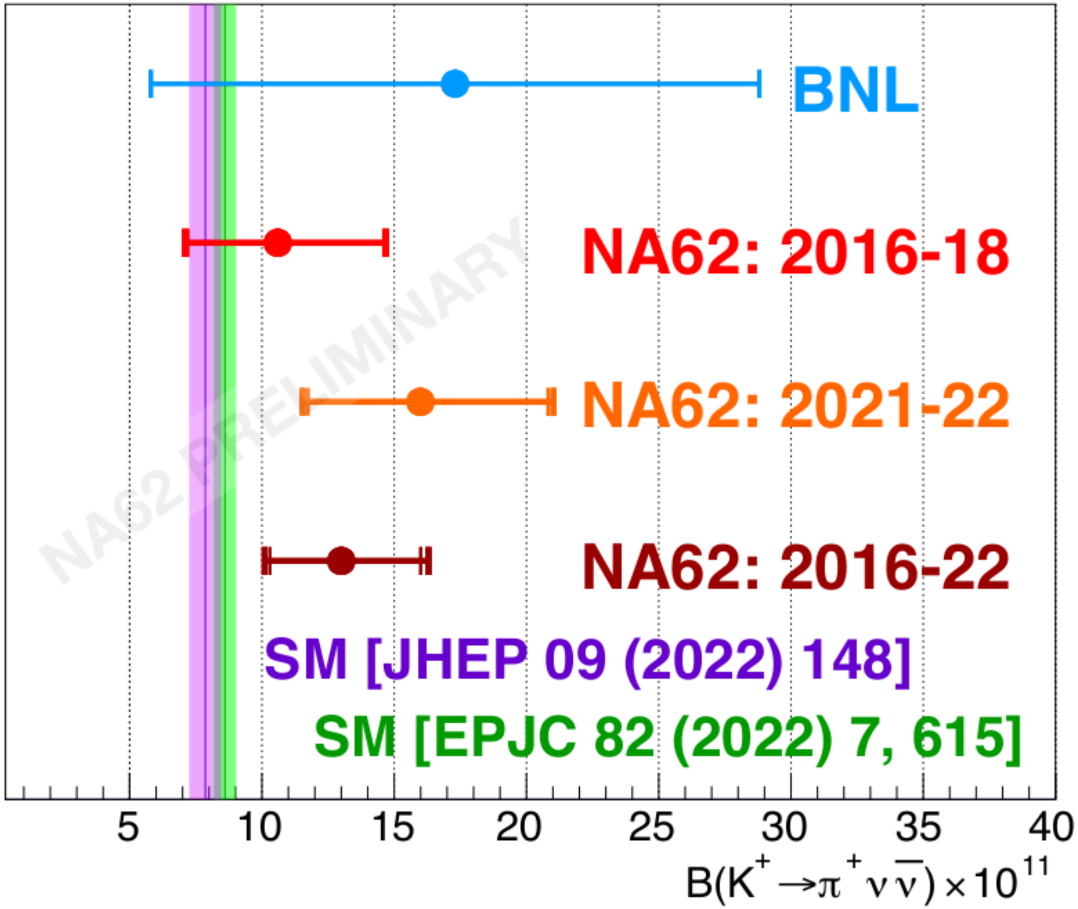
$$\mathcal{B}^{16-18}_{\pi\nu\bar{\nu}} = \left(10.6^{+4.1}_{-3.5}\right) \times 10^{-11}$$

[JHEP 06 (2021) 093]

$$\mathcal{B}^{21-22}_{\pi\nu\bar{\nu}} = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11}$$

$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = \left(13.0^{+3.3}_{-2.9}\right) \times 10^{-11}$$

- NA62 results are consistent
- Central value moved up (now 1.5–1.7σ above SM)
- Fractional uncertainty decreased: 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5



More precise measurements well motivated.
However, CERN dedicated to end kaon programme after NA62

Tim Gershon
Flavour physics
& CP violation

SuperKEKB/Belle II

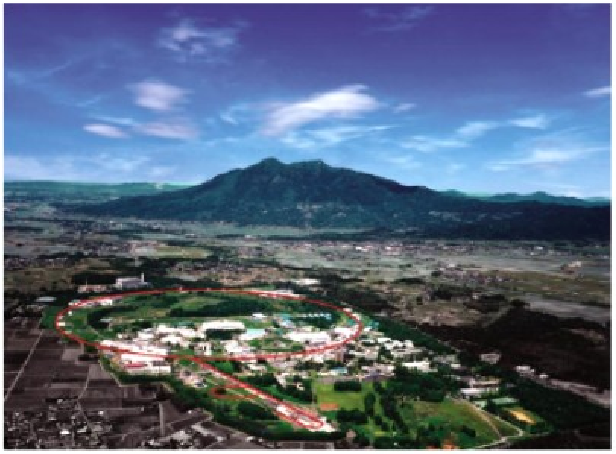
New intensity frontier facility at KEK

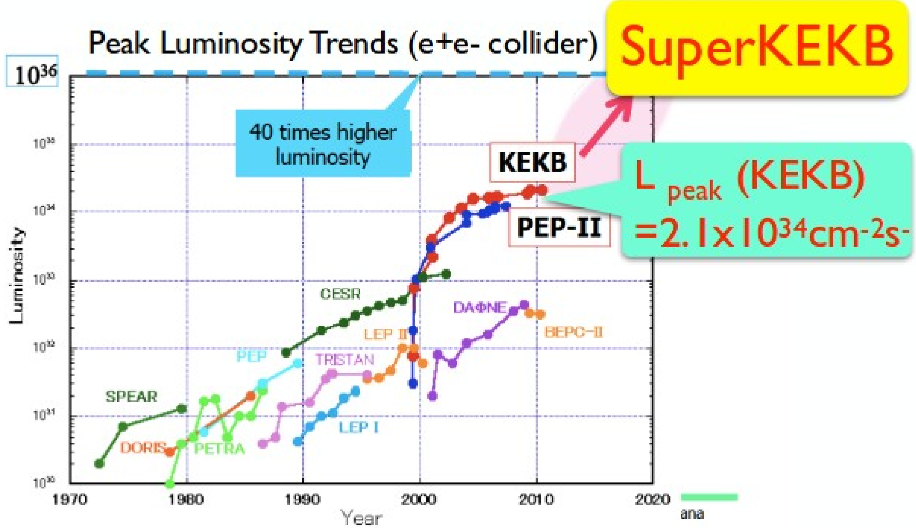
- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}\ B\bar{B}, \tau^+\tau^-$ and charms per year !

  $L_{int} > 50\ ab^{-1}$

- Rich physics program
  - Search for New Physics through processes sensitive to virtual heavy particles.
  - New QCD phenomena (XYZ, new states including heavy flavors) + more





The first particle collider after the LHC !

SuperKEKB Accelerator

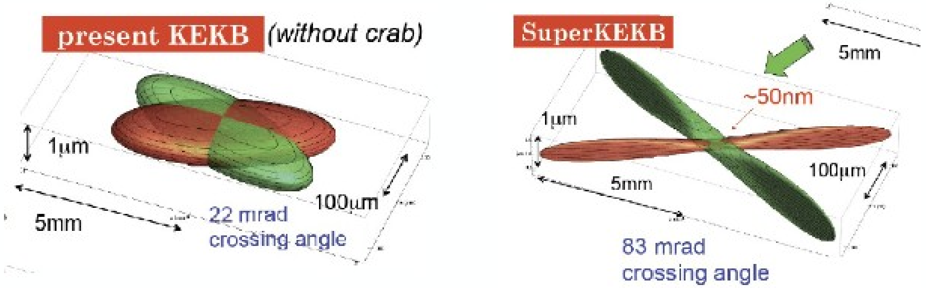
- Low emittance ("nano-beam") scheme employed (originally proposed by P. Raimondi)

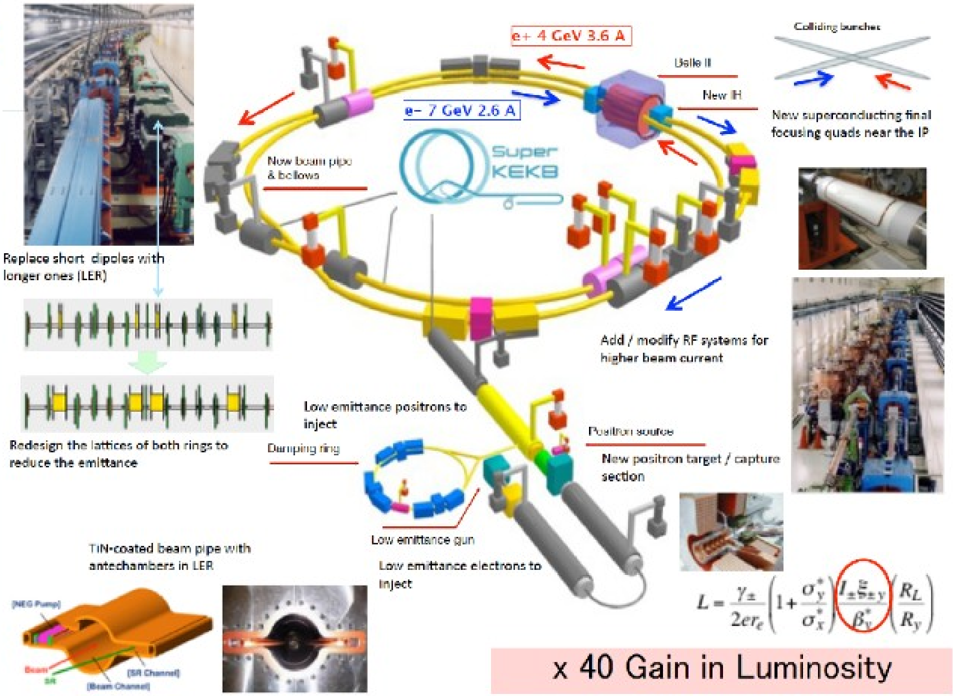
Machine parameters

	SuperKEKB LER/HER	KEKB LER/HER
E(GeV)	4.0/7.0	3.5/8.0
ε_x (nm)	3.2/4.6	18/24
β_y at IP(mm)	0.27/0.30	5.9/5.9
β_x at IP(mm)	32/25	120/120
Half crossing angle(mrad)	41.5	11
I(A)	3.6/2.6	1.6/1.2
Lifetime	~10min	130min/200min
L(cm^{-2}s^{-1})	80×10^{34}	2.1×10^{34}

x20

x2



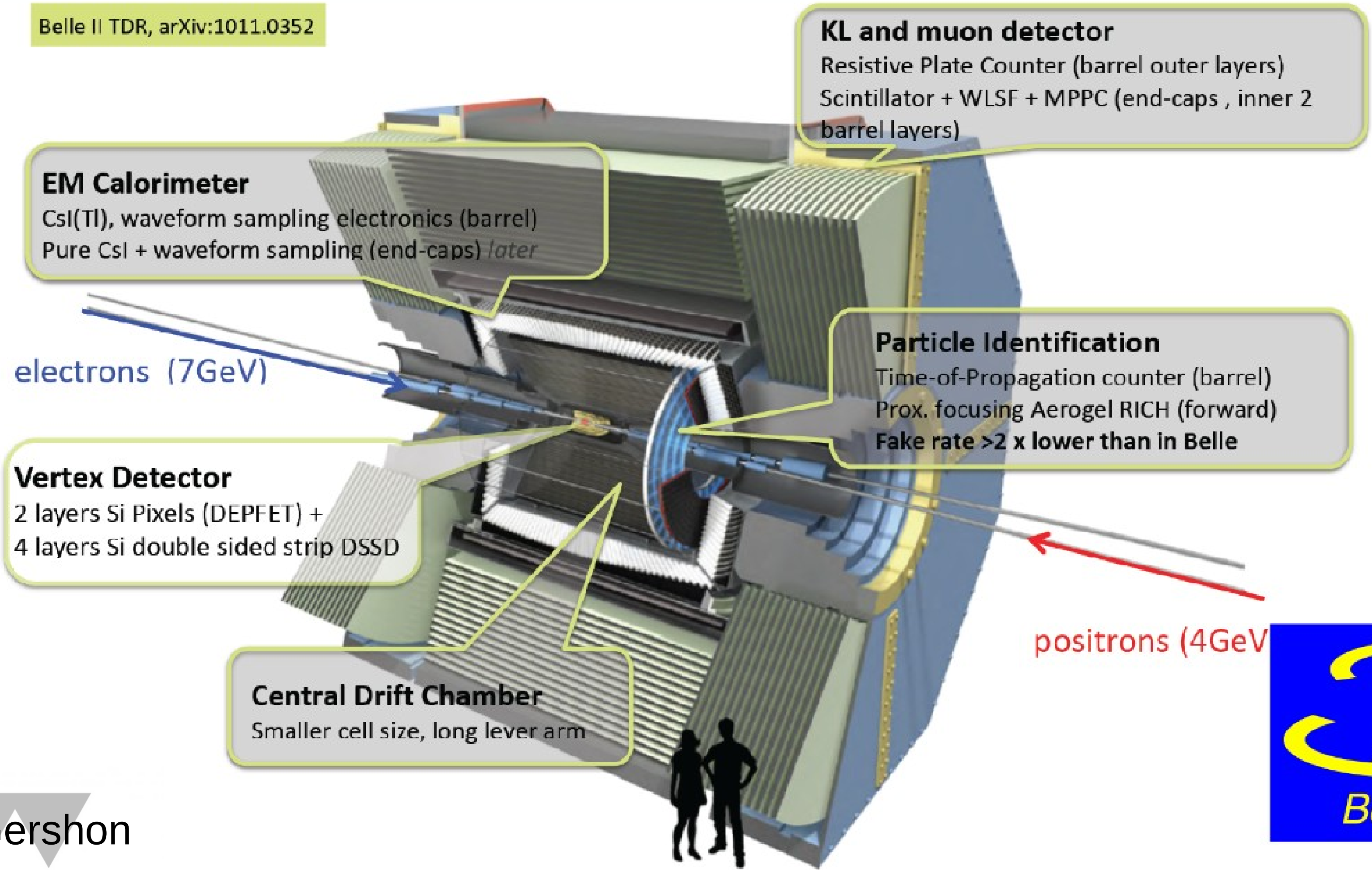


$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

x 40 Gain in Luminosity

Belle II Detector

- Deal with higher background (10-20×), radiation damage, higher occupancy, higher event rates (L1 trigg. 0.5→30 kHz)
- Improved performance and hermeticity



Belle II TDR, arXiv:1011.0352

KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps , inner 2 barrel layers)

EM Calorimeter
CsI(Tl), waveform sampling electronics (barrel)
Pure CsI + waveform sampling (end-caps) *later*

electrons (7GeV)

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)
Fake rate >2 x lower than in Belle

Vertex Detector
2 layers Si Pixels (DEPFET) +
4 layers Si double sided strip DSSD

positrons (4GeV

Central Drift Chamber
Smaller cell size, long lever arm

Belle2 physics

arXiv:1808.10567

Physics programme includes a broad range of CP violation measurements and rare decay studies

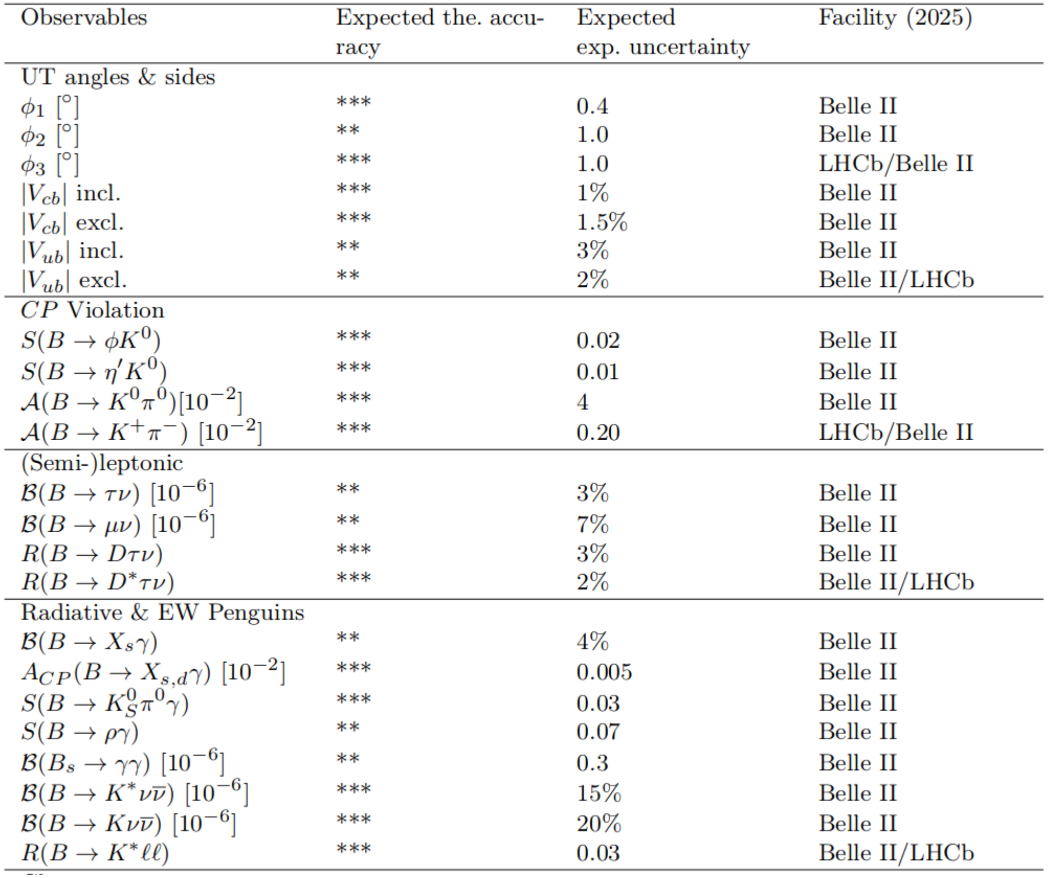
Both competition and complementarity with LHCb

Examples of unique potential:

- $B \to l\nu$
- $B \to K^{(*)}\nu\bar{\nu}$
- Inclusive $B \to X_s\gamma$, $X_s l^+ l^-$

Also much non-B physics

- including charm & tau



Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\bar{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb

Belle2 physics

arXiv:1808.10567

Physics programme includes a broad range of CP violation measuremen
studies

Both compet
complement

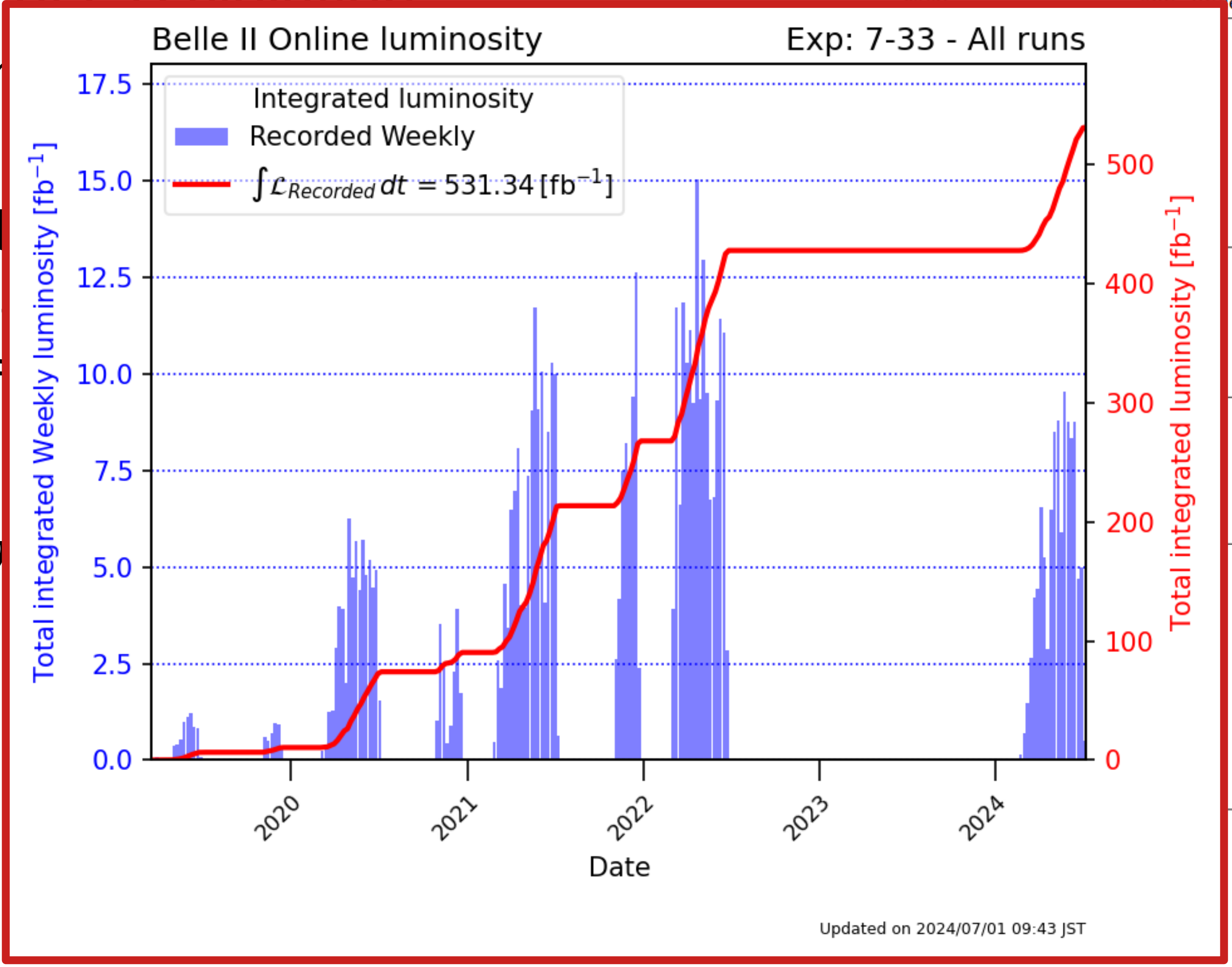
Examples of

- $B \rightarrow l\nu$
- $B \rightarrow K^{(*)}\nu$
- Inclusive

Also much n

- including

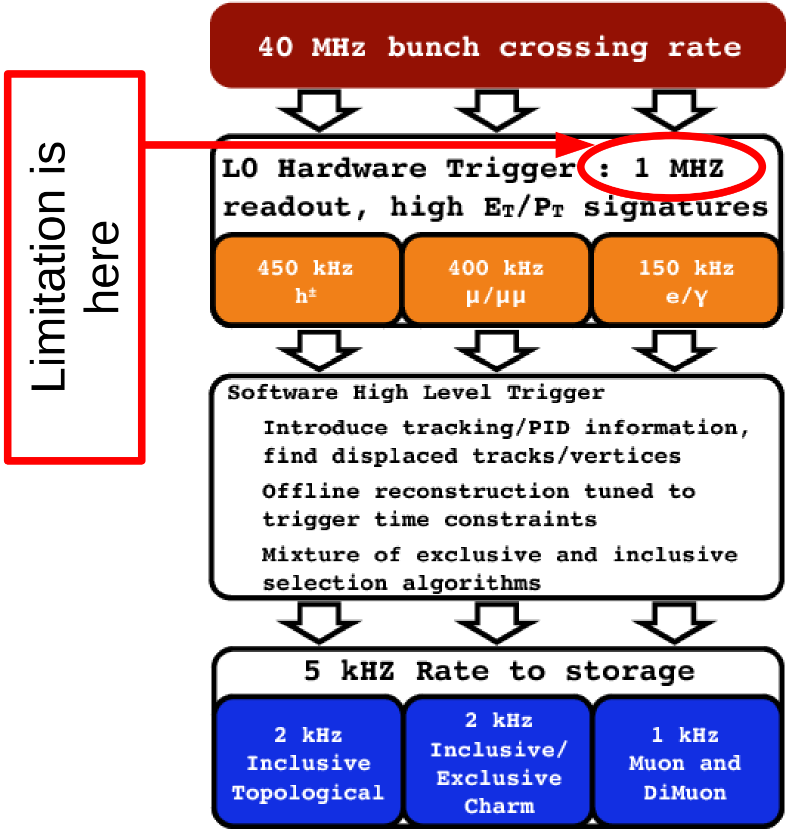
Observables	Expected the. accu-	Expected ertainty	Facility (2025)
			Belle II
			Belle II
			LHCb/Belle II
			Belle II
			Belle II
			Belle II
			Belle II/LHCb
			Belle II
			Belle II
			Belle II
			LHCb/Belle II
			Belle II
			Belle II
			Belle II
			Belle II/LHCb
			Belle II
			Belle II
			Belle II
			Belle II
			Belle II
			Belle II
			Belle II
			Belle II/LHCb



Unfortunately, data taking so far not at the expected performance, hope for improvement in forthcoming runs

LHCb upgrade and the all important trigger

Why couldn't LHCb run at higher luminosity in Run 1 & 2?



Limitation is here

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$	400 kHz $\mu/\mu\mu$	150 kHz e/γ

Software High Level Trigger

Introduce tracking/PID information, find displaced tracks/vertices

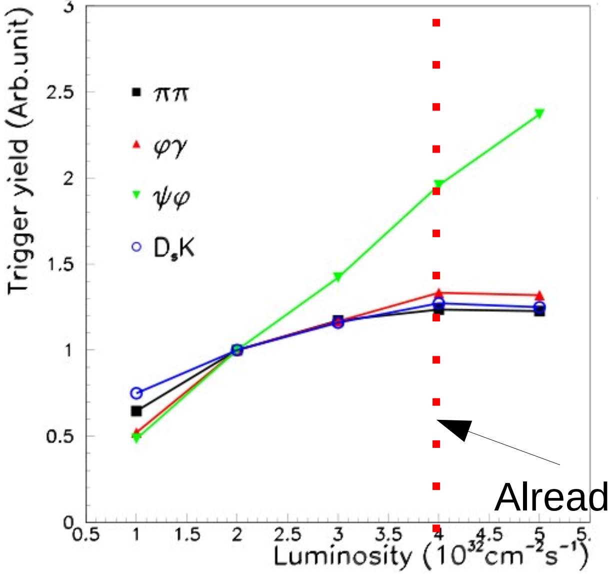
Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHZ Rate to storage

2 kHz Inclusive Topological	2 kHz Inclusive/ Exclusive Charm	1 kHz Muon and DiMuon

higher luminosity
→ need to cut harder at L0 to keep rate at 1 MHz
→ lower efficiency

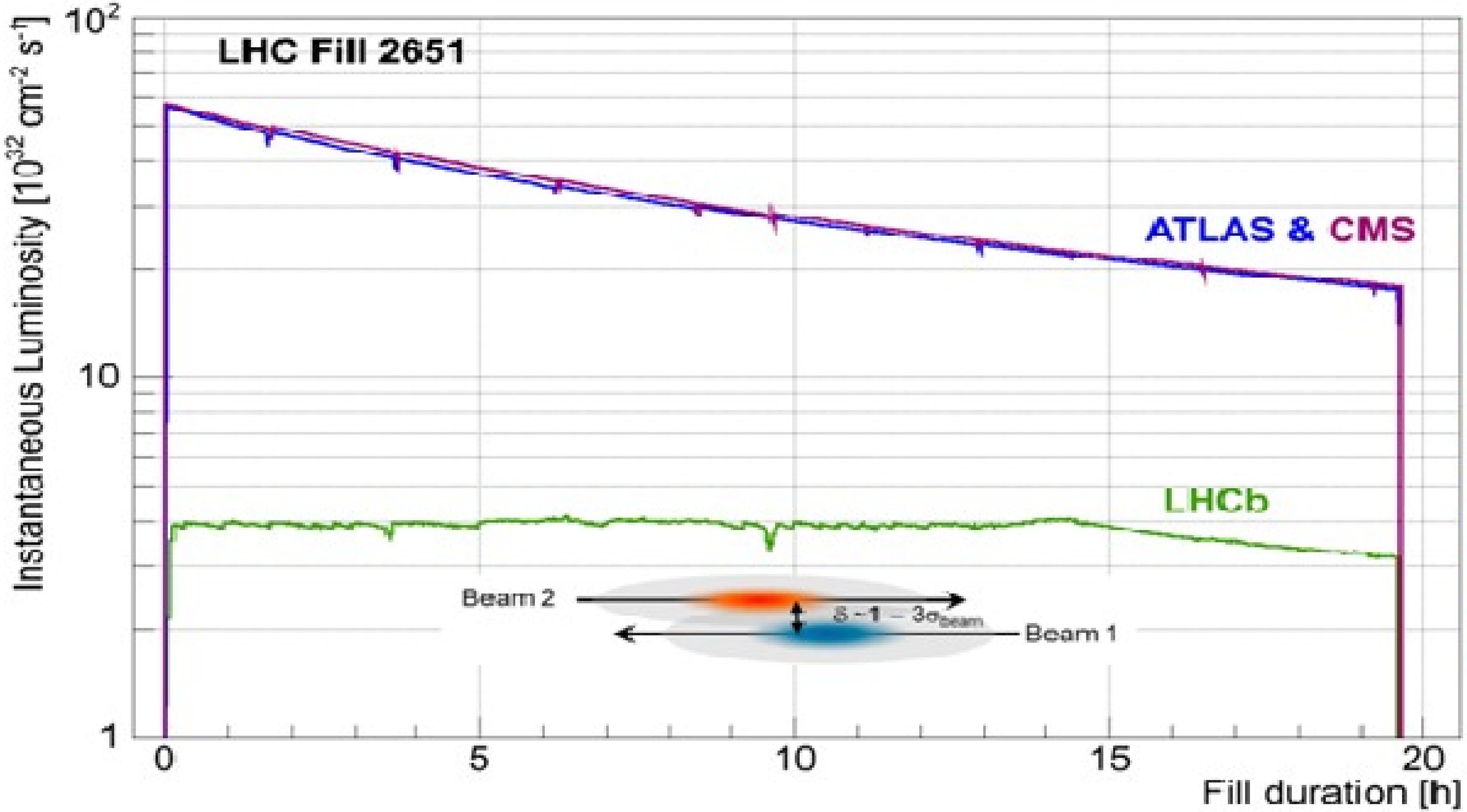


Already running here

- readout detector at 40 MHz
- trigger fully in software → efficiency gains
- run at L_{inst} up to 2 10^{33}/cm^2/s

Luminosity levelling in LHCb

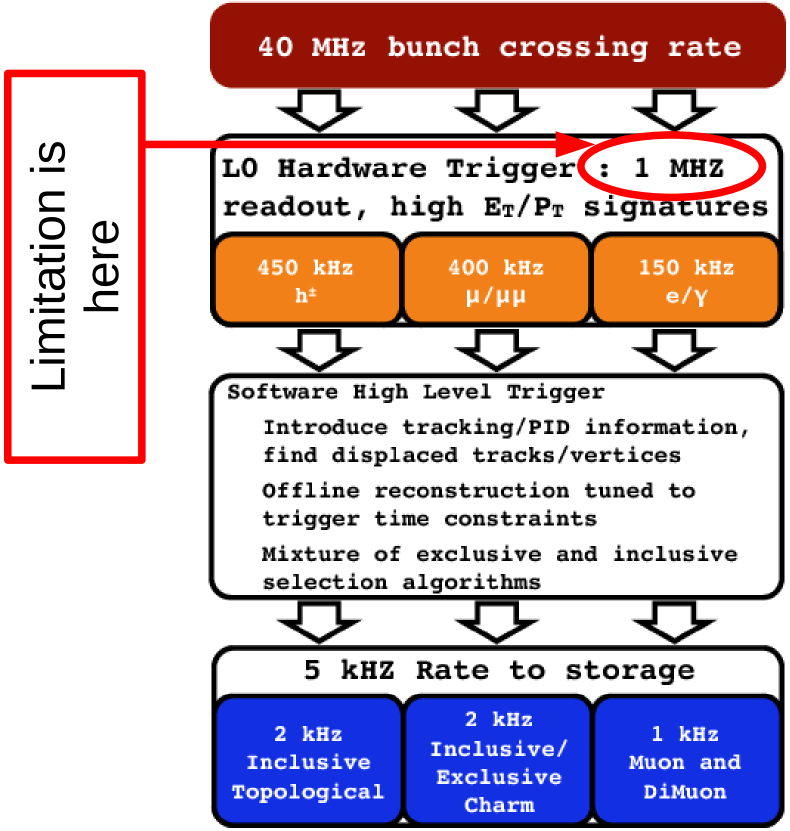
Why couldn't LHCb run at higher luminosity in Run 1 & 2?
More is available if the detector is able to take it



luminosity levelling at around 4×10^{32} cm^{-2}s^{-1} via transverse separation
(with tilted crossing angle)

from C. Gaspar, via. F. Zimmerman

LHCb upgrade and the all important trigger



Limitation is here

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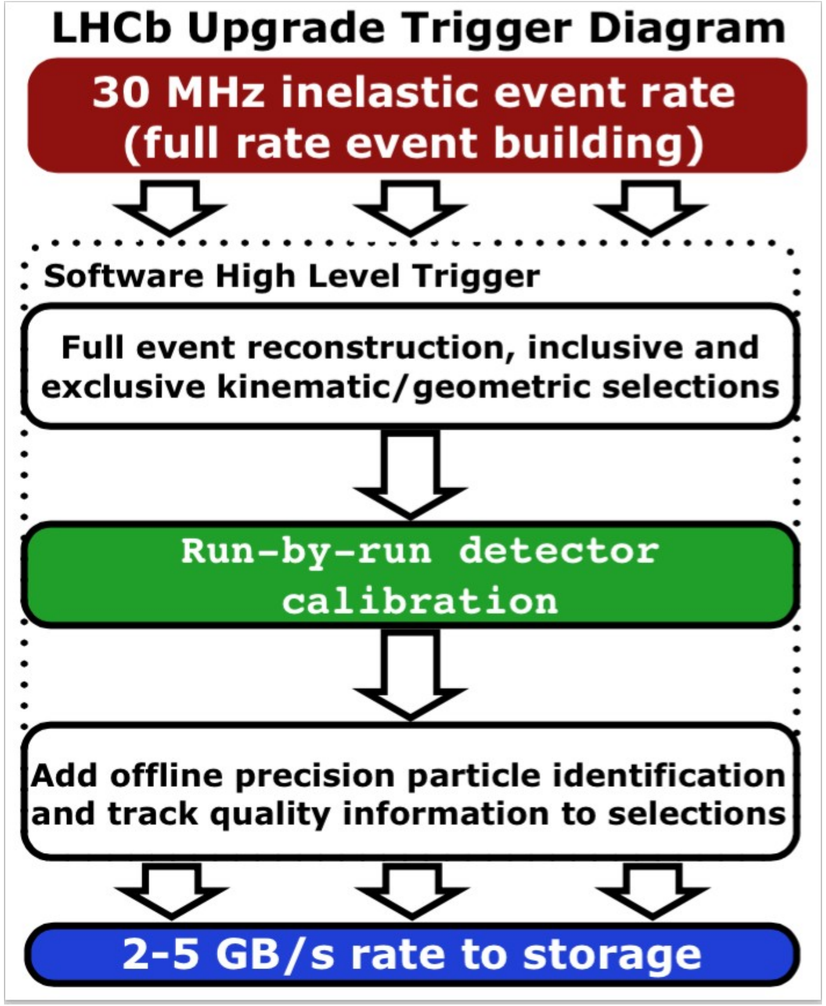


LHCb Upgrade Trigger Diagram

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

Run-by-run detector calibration

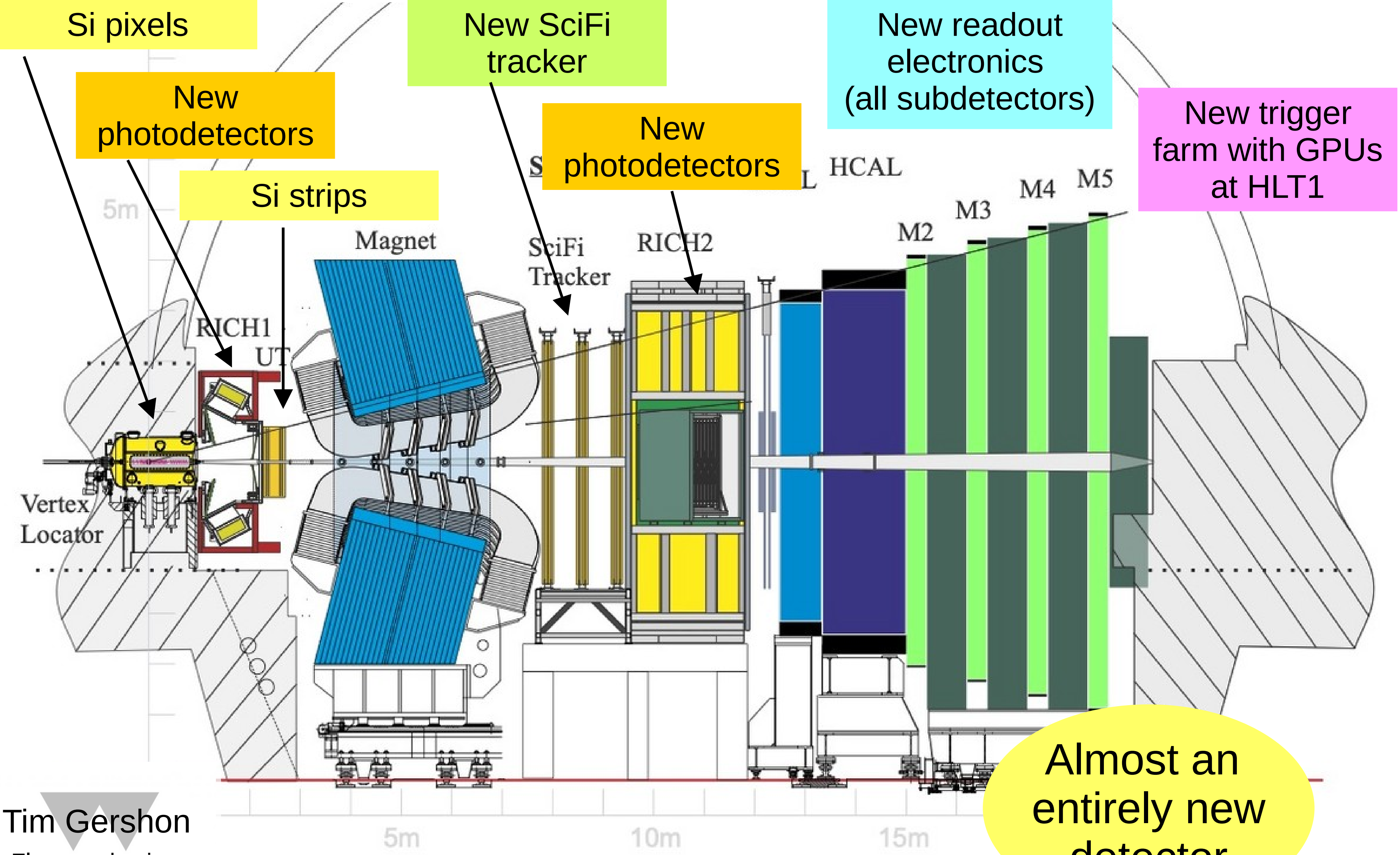
Add offline precision particle identification and track quality information to selections

2-5 GB/s rate to storage

Real-time analysis

JINST 19 (2024) P05065

LHCb detector upgrade



Si pixels

New photodetectors

Si strips

New SciFi tracker

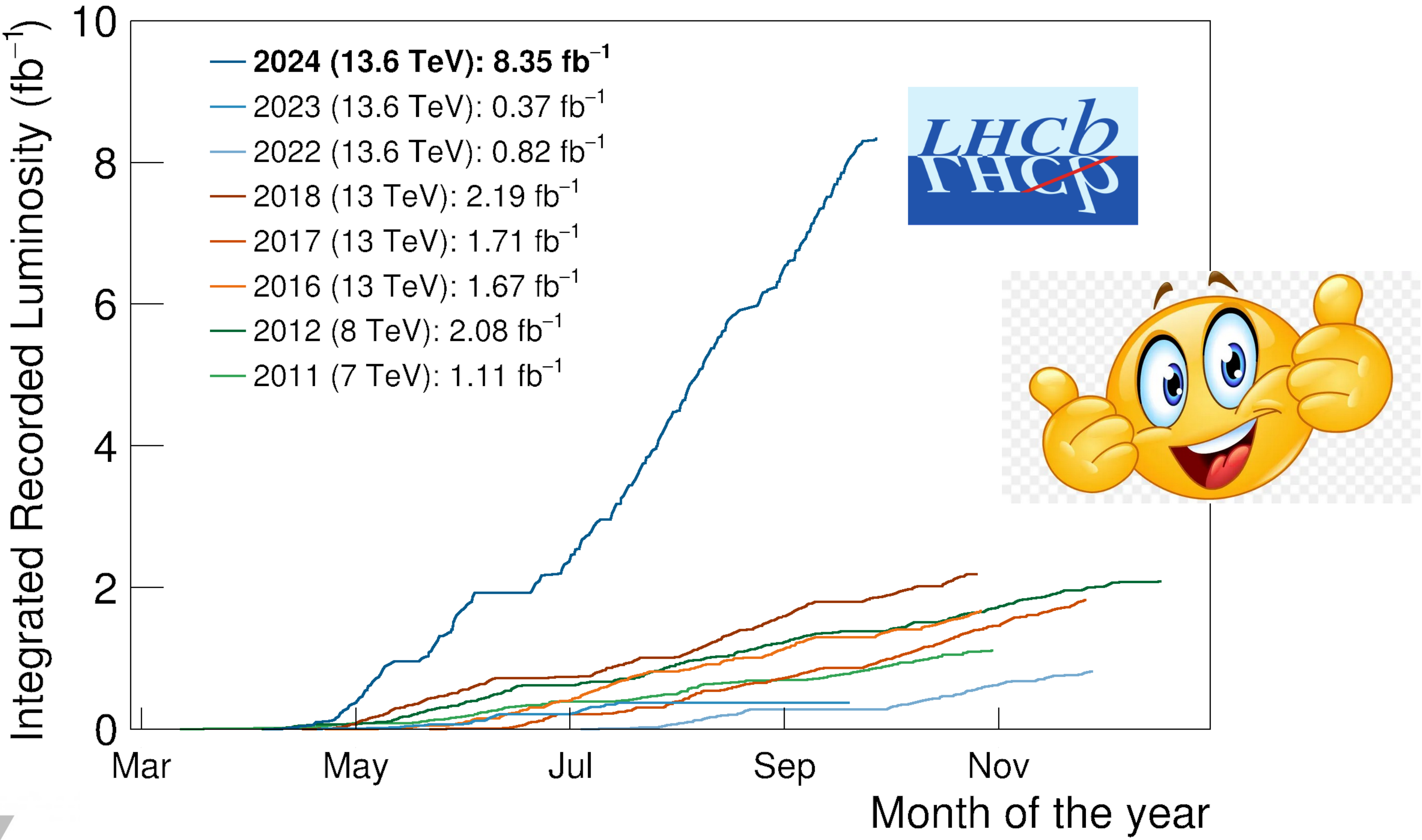
New photodetectors

New readout electronics (all subdetectors)

New trigger farm with GPUs at HLT1

Almost an entirely new detector

Data taking with upgraded LHCb detector

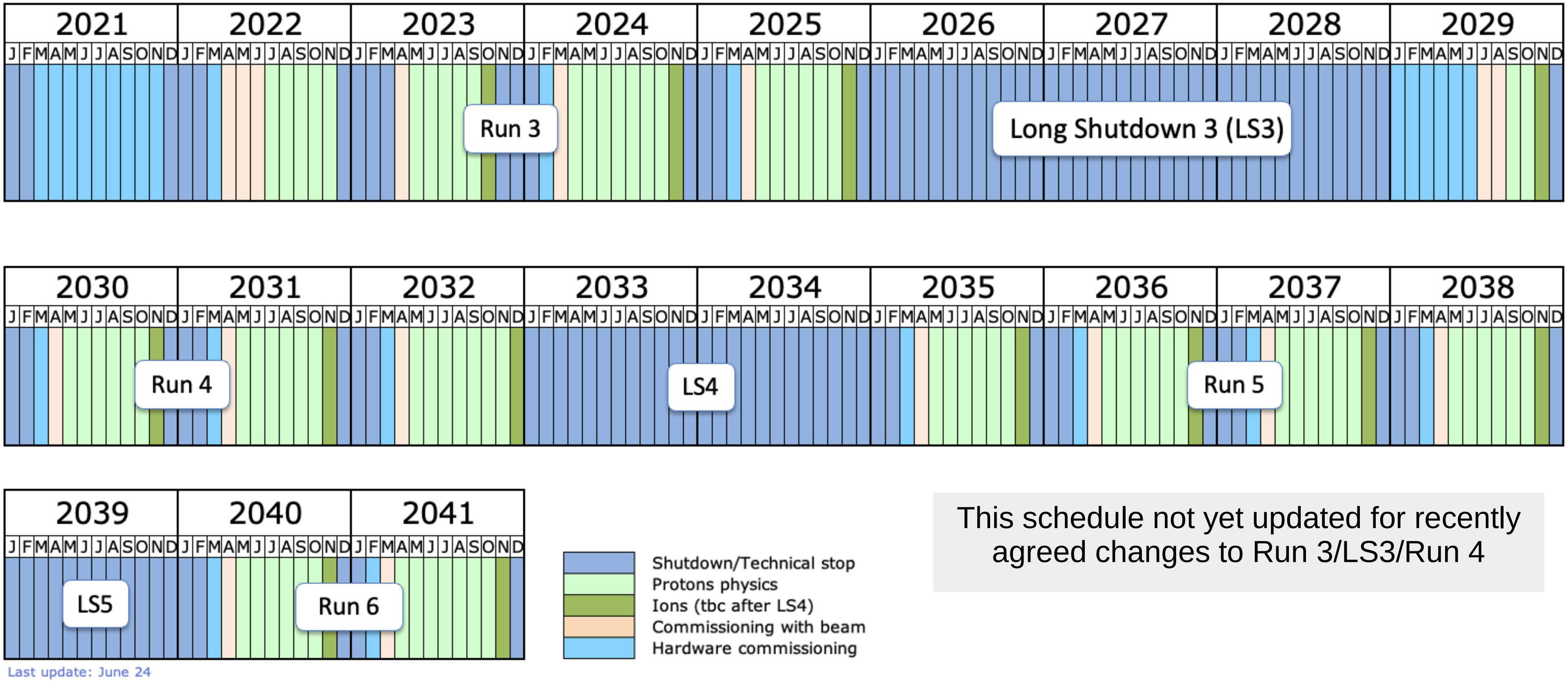


Summary (1)

- In the 40+ years since the b quark discovery, data samples have increased (on average) by an order of magnitude every ~5 years
- Improvements in accelerator and detector technologies have led to remarkable discoveries
  - Both e^+e^- & hadron collider experiments important
  - Good overall consistency with the SM, but ...
  - … exciting anomalies in the current data (not for the first time, however)
- Can expect dramatic further progress in coming years
  - but why stop there?

LHCb Upgrade 2

Current LHCb detector designed to accumulate 50 fb^{-1}, will be achieved by end of Run 4



Last update: June 24

This schedule not yet updated for recently agreed changes to Run 3/LS3/Run 4

Opportunity for further upgrade to run at highest possible luminosity until end of HL-LHC

The need for more precision

- “Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

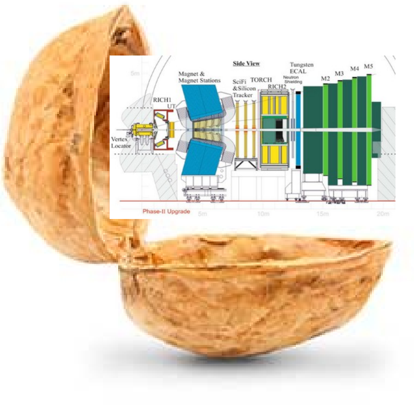
– A.Soni

- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

– L.Okun

(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

LHCb Upgrade 2 in a nutshell



- Unique science programme with BSM discovery potential
  - Unprecedented sensitivity for B & D physics
  - Broad (general purpose) programme
    - Unique forward acceptance
    - spectroscopy, EW precision measurements, top quark and Higgs physics, dark sector, heavy ions and fixed target physics ...
  - Beyond √N scaling with new subdetectors and reconstruction techniques
- Exciting technology roadmap (“technology frontier”)
  - high granularity, fast timing, extreme radiation hardness
  - developments with impact both inside and outside of HEP

Summary (2)

- We still don't know:
  - why there are so many fermions in the SM
  - what causes the baryon asymmetry of the Universe
  - where exactly the new physics is …
  - … and what it's flavour structure is
- Prospects are good for progress in the next few years
- Will have continuing programme of flavour physics until the end of the HL-LHC, and perhaps beyond
  - complementary to the high-p_T programme of the LHC
  - interesting prospects for flavour with FCC-ee at Z pole