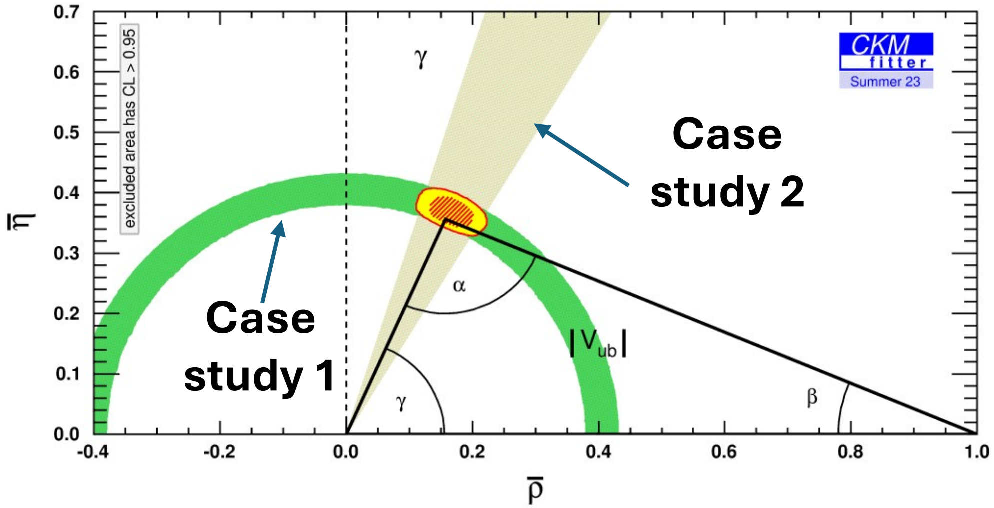
Lecture 2

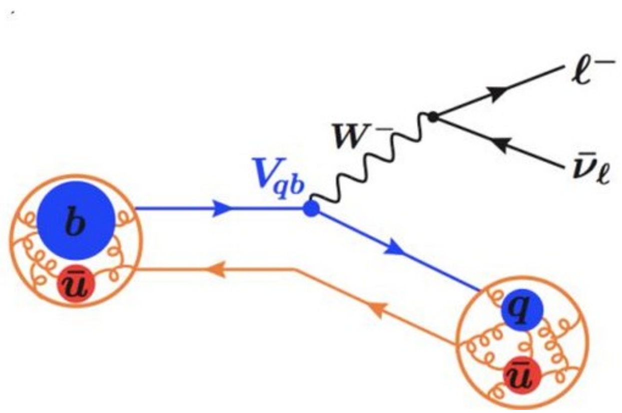
Lecture plan

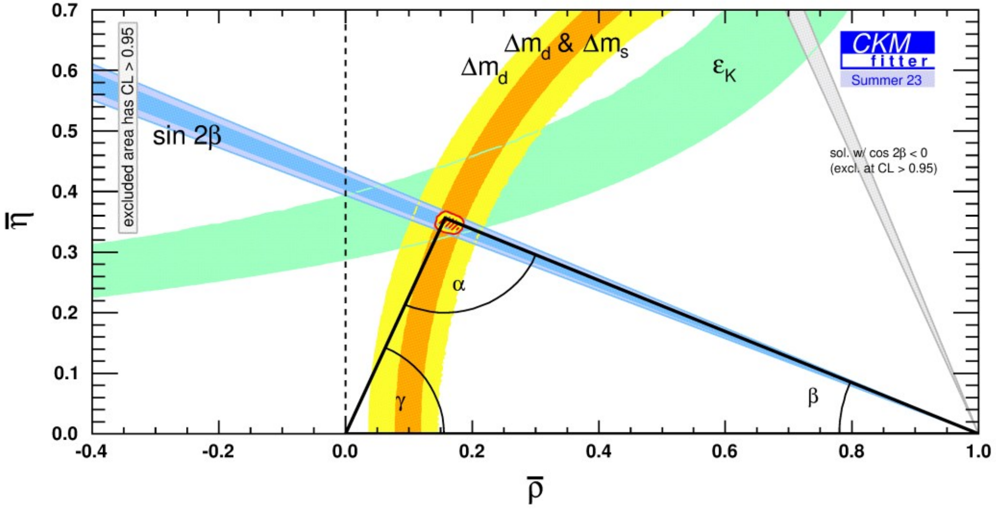
- A brief introduction to flavour
- Cabibbo-Kobayashi-Maskawa quark-mixing matrix
- Main experimental players: Belle II and LHCb
- **Case study 1:** V_{cb}
- **Case study 2:** γ – *CP* violating phase ← **HALFTIME somewhere here**
- Beyond the *b* quark: charm physics
- **Case study 3:** *CP* violation in *D* mesons
- Beyond the quarks: tau physics
- **Case study 4:** lepton-flavour universality and tau mass
- Outlook

Today the goal is over constraint – loop sensitivity

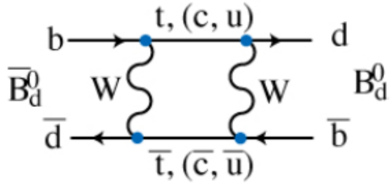


Tree level only

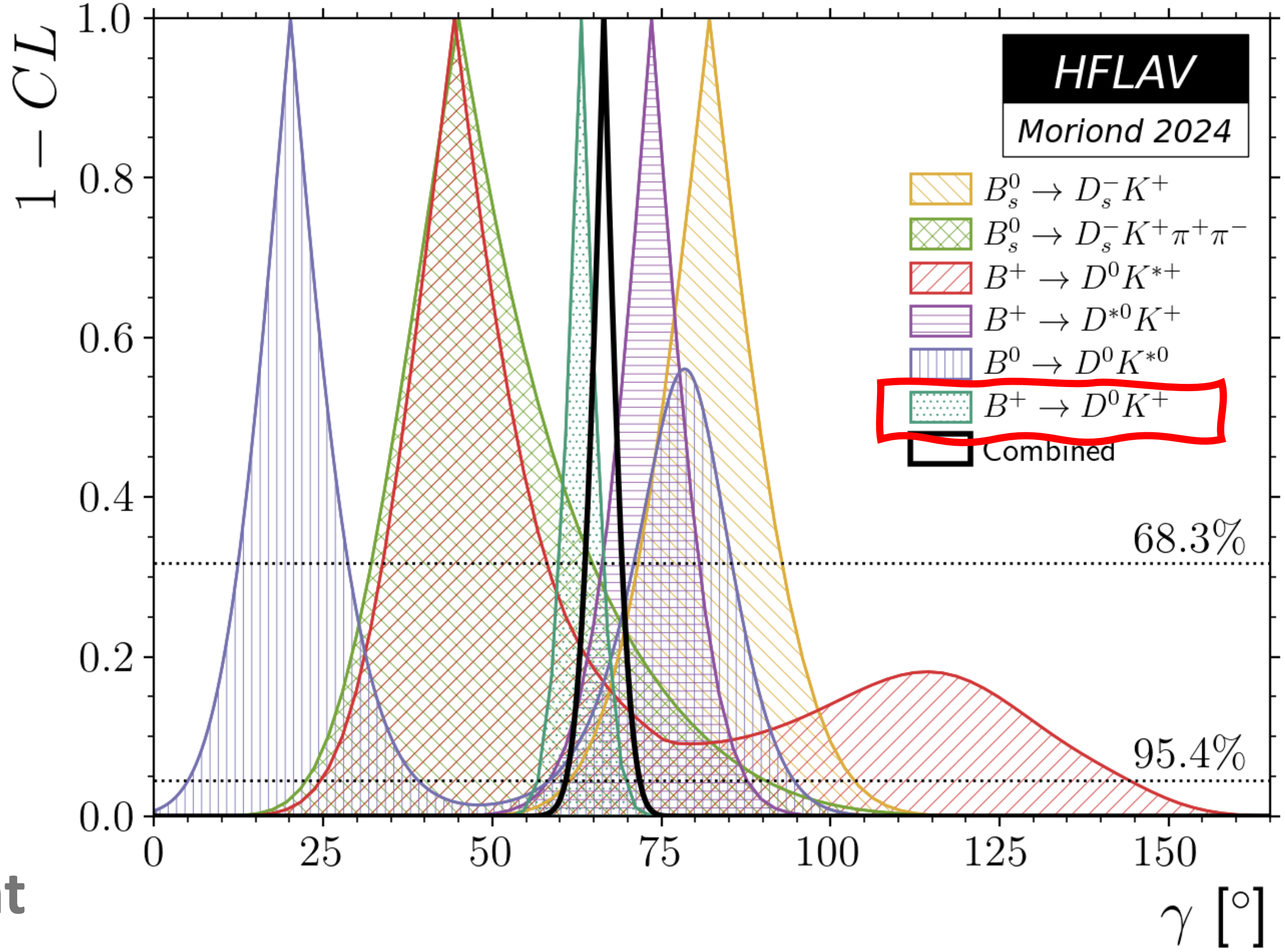




Loop-level only



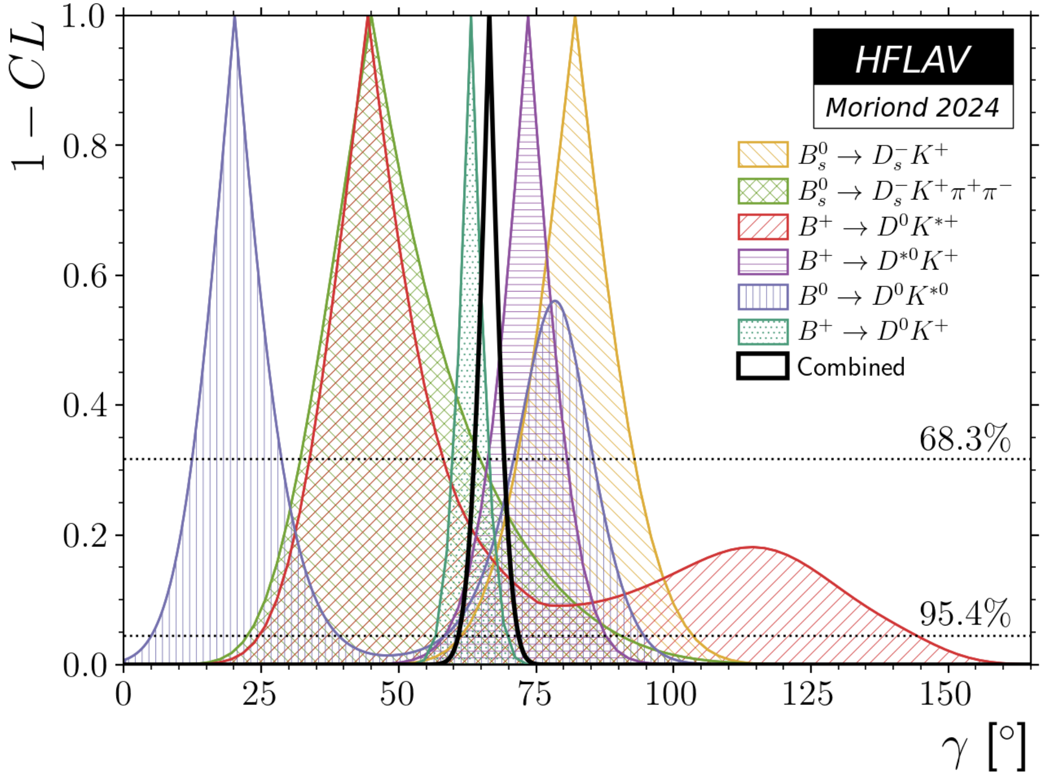
NP at O(>TeV)?



Case study 2: γ

A theory free measurement

Why γ ?



$\gamma_{\text{measured}} = (66 \pm 3\ )^\circ$ HFLAV

$\gamma_{\text{predicted}} = (66\ \pm 1.3)^\circ$ CKMfitter

$\beta_{\text{measured}} = (22.6 \pm 0.5)^\circ$ HFLAV

Principal experimental goal in CKM physics in the next decade is to reduce uncertainty to 1°

What is γ?

DECAY OF KAONS AND CP VIOLATION

- If it is CP violation only in mixing (the short-lived state is not only K_1), the phenomenology is simple. Define ϵ_K so that

$$|K_S\rangle = |K_1\rangle - \epsilon_K|K_2\rangle \qquad |K_L\rangle = |K_2\rangle + \epsilon_K|K_1\rangle$$

where K_S is the short-lived state and K_L is the long-lived state.

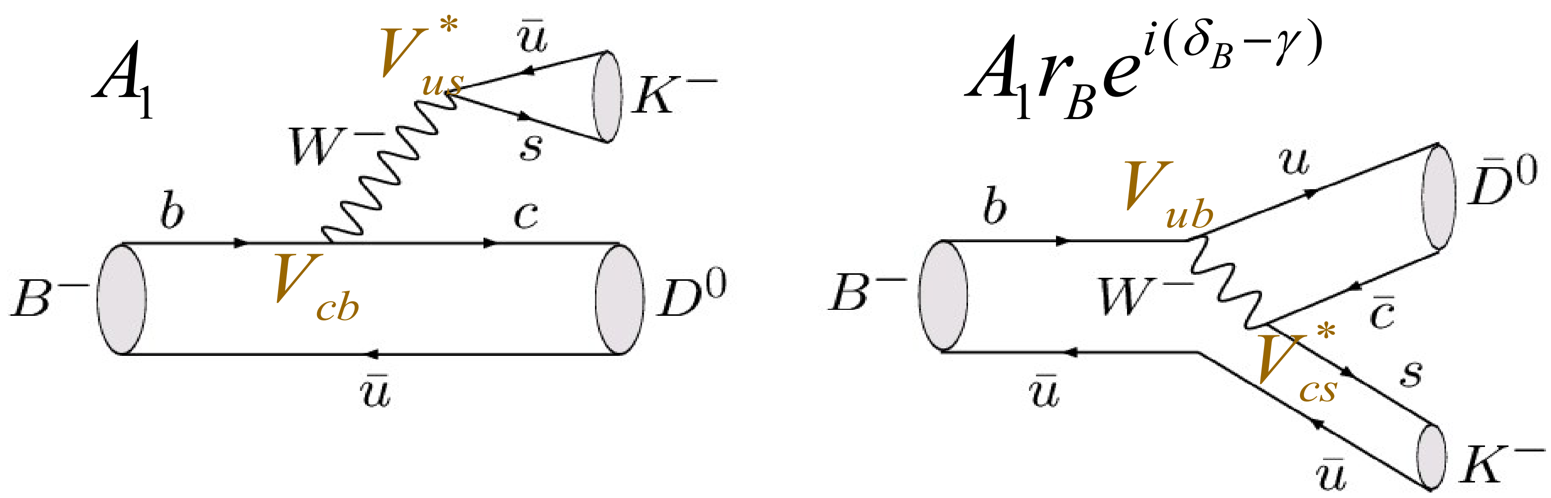
K. McFarland Day 1

- It is basically the irreducible weak phase of V_{ub}, i.e., the phase of the CKM matrix – origin of CP violation
  - $V_{ub} \neq (V_{ub})^*$
- How to observe as all rates proportional to $|V_{qq'}|^2$?
- Interference between two different amplitudes
  1. In mixing – neutral kaon decay (see Day 1)
  2. Interference between mixing and decay
     - two paths mixed or unmixed to the same final state
     - The triumph of Babar and Belle: sin2β in from time-dependent CP violation in $B^0 \to K^0_S J/\psi$
  3. **In decay (direct)**

$$\mathcal{A}_{f^\pm} \equiv \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)} \neq 0$$

M^+ = charged meson, e.g., B^+
f^+ and f^- CP conjugate of the final state

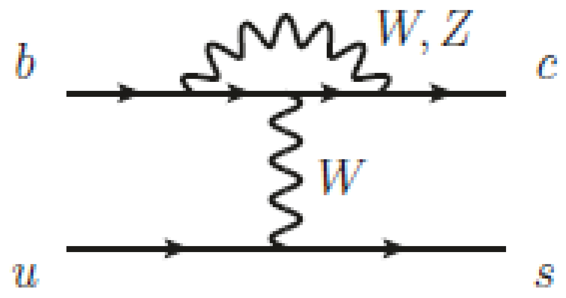
Measuring γ: $B \rightarrow DK$

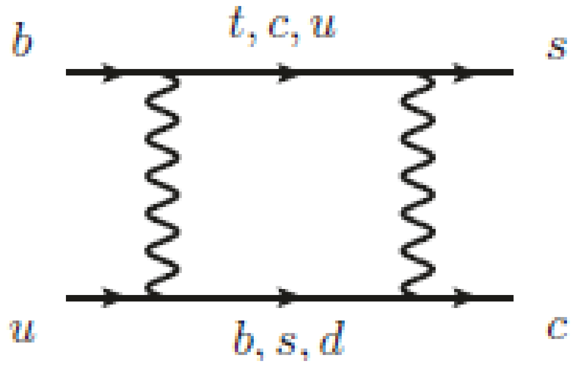


- Same final state for D and $\overline{D} \Rightarrow$ interference $\Rightarrow$ **the possibility of DCPV**
- Different types of D final states generally used
  1. **Self-conjugate multibody states: $K_S h^+ h^-$ [Dalitz/BPGGSZ]**
     Giri, Grossman, Soffer and Zupan, PRD **68**, 054018 (2003); Bondar (unpublished)
  2. **CP-eigenstates [GLW]**
     Gronau & London, PLB **253**, 483 (1991), Gronau, & Wyler, PLB **265**, 172 (1991)
  3. **K^+X^- ($X^-=\pi^-$, $\pi^- \pi^0$, $\pi^-\pi^- \pi^+$) - CF and DCS [ADS]**
     Atwood, Dunietz & Soni, PRD **63**, 036005 (2001)

Theory plays no role

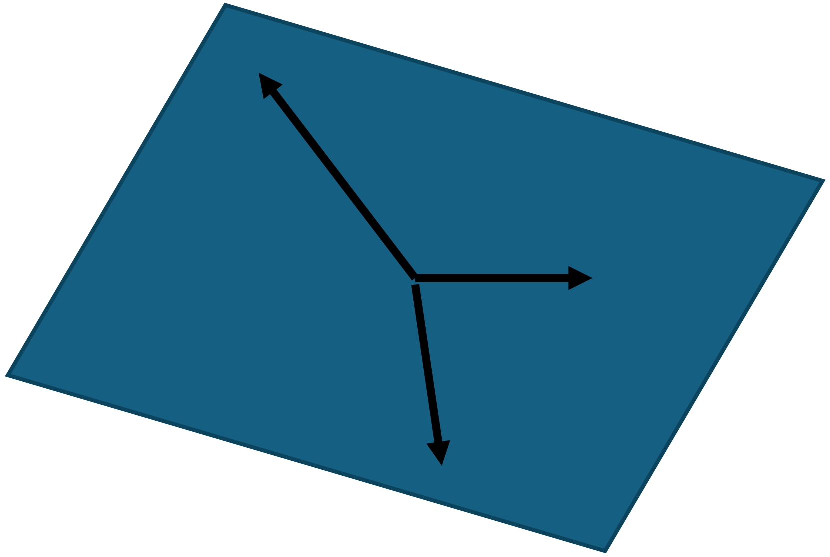
- At least three parameters common to all *B*→*DK*
  - Amplitude ratio $r_{B,}$ strong phase difference δ_B and γ
  - First two in principle calculable from QCD but very hard c.f. hadronic states to measure V_{cb}
  - However, if you have enough measurements of different D final states or in bins of the D phase space you determine these from data along with γ
- First amplitude that could disrupt this introduces a relative correction of order 10^{-7} on γ – JHEP **1401** (2014) 051
- Will focus on the most measurement
  - ***$B^{-}\to D(K_S h^{+} h^{-})h^{-}$***
  - ***CP* violation measured across the three-body phase space (Dalitz plot) of the *D* decay**





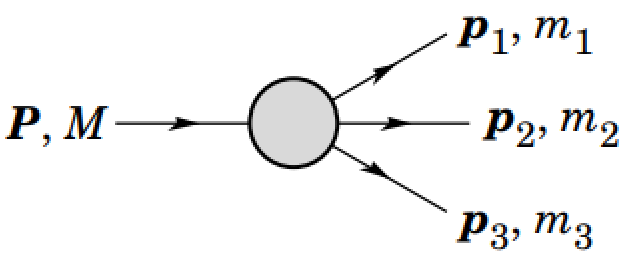
Dalitz plot

- Considering a scalar or pseudoscalar decaying into a three-body final state how many variables are required to describe it?
  - 3 four-momenta = 12 variables
  - Constraints:
    - Energy-momentum conservation = 4
    - Particle masses = 3
    - Orientation of decay plane choice = 3



- 12-10 = two-independent variables

Dalitz plot: math



- Following (and figures) from PDG kinematics review general form with just the kinematic constraints - energies in rest frame of M and α, β and γ are Euler angles to define the orientation

$$d\Gamma = \frac{1}{(2\pi)^5}\frac{1}{16M}|\mathscr{M}|^2\, dE_1\, dE_3\, d\alpha\, d(\cos\beta)\, d\gamma$$

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{8M}\overline{|\mathscr{M}|^2}\, dE_1\, dE_3$$

$$= \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\, dm_{12}^2\, dm_{23}^2$$

$$(p_i + p_j)^2 = m_{ij}^2$$

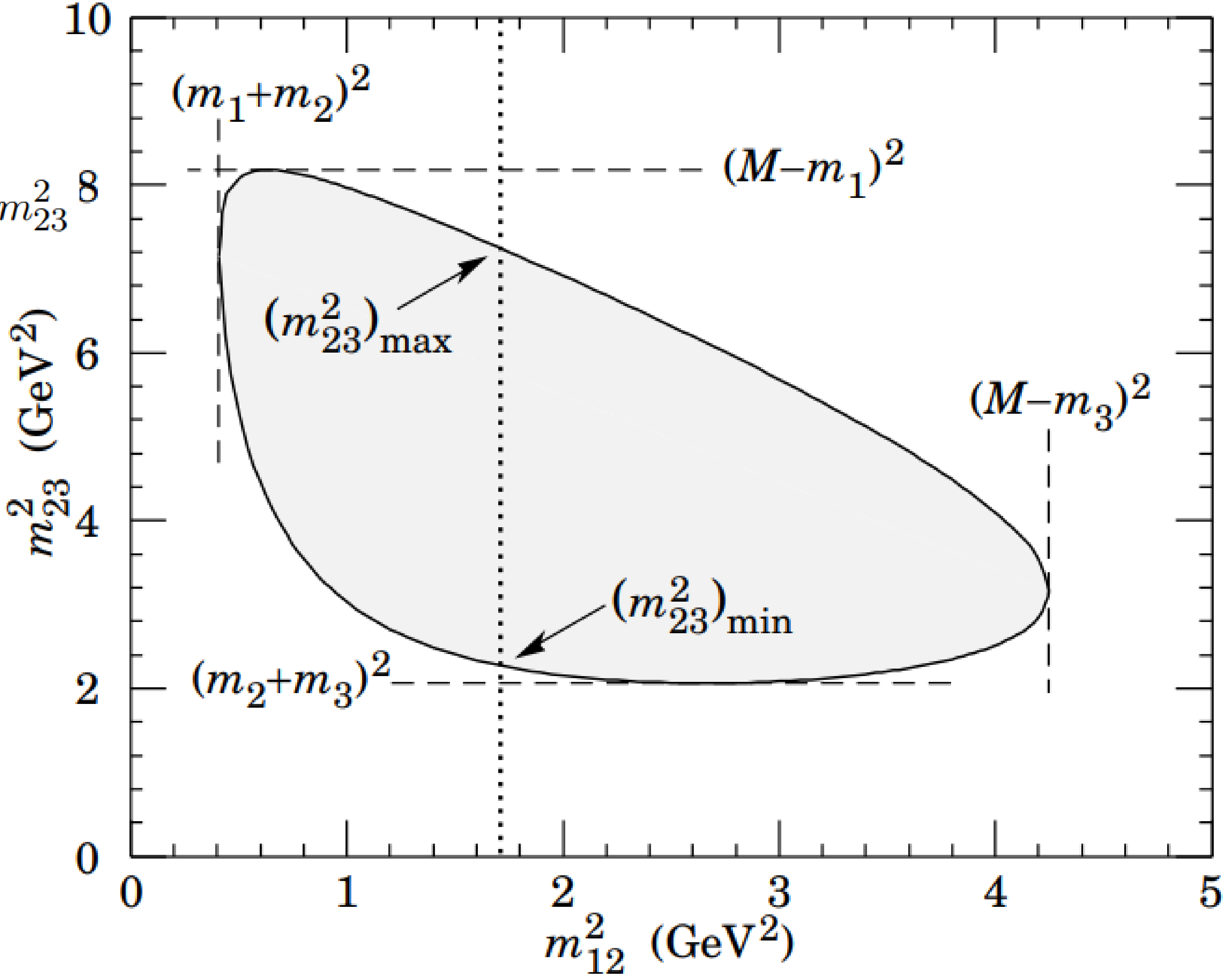
$$P = p_1 + p_2 + p_3$$

$$\Rightarrow (p_i + p_j)^2 = (P - p_k)^2 = M^2 + m_k^2 - 2P \cdot p_k$$

$$\therefore m_{ij}^2 = M^2 + m_k^2 - 2ME_k$$

Dalitz plot

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\, dm_{12}^2\, dm_{23}^2$$

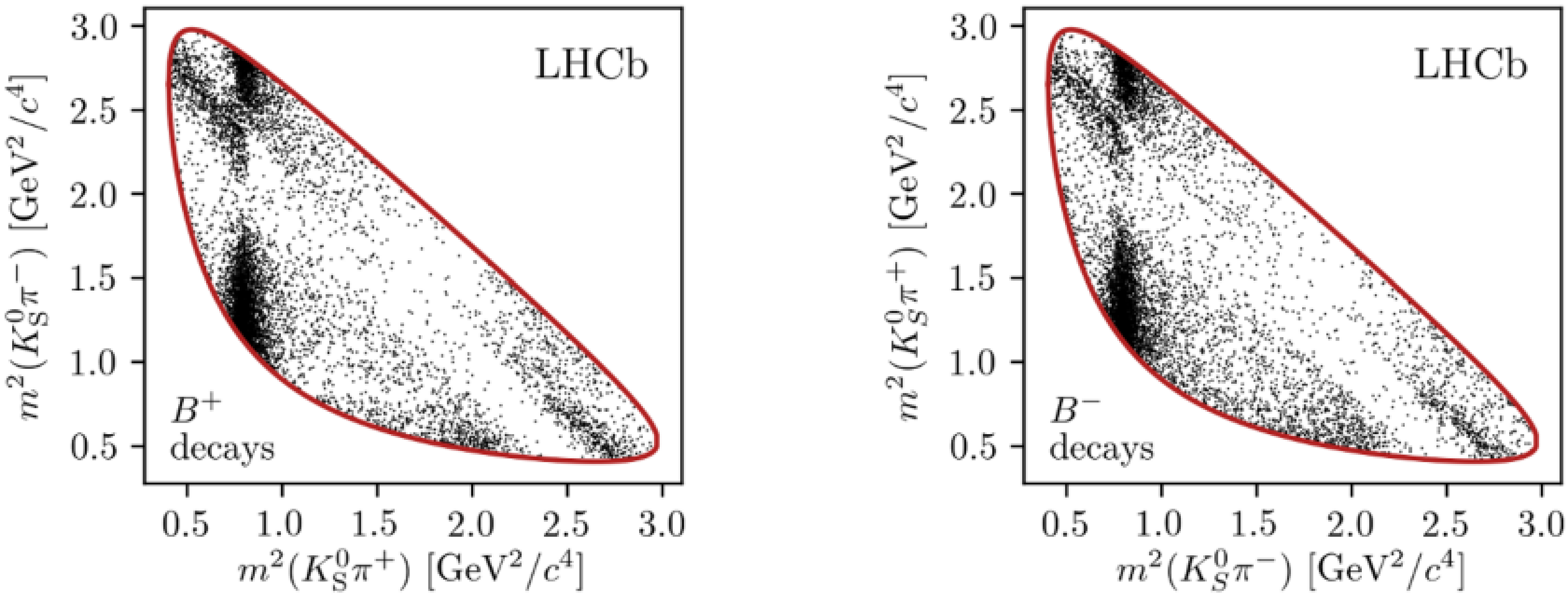


Note if matrix element Independent of kinematics Dalitz distribution is uniform

Therefore, resonance structures In the (12), (13) and (23) systems show up as bands

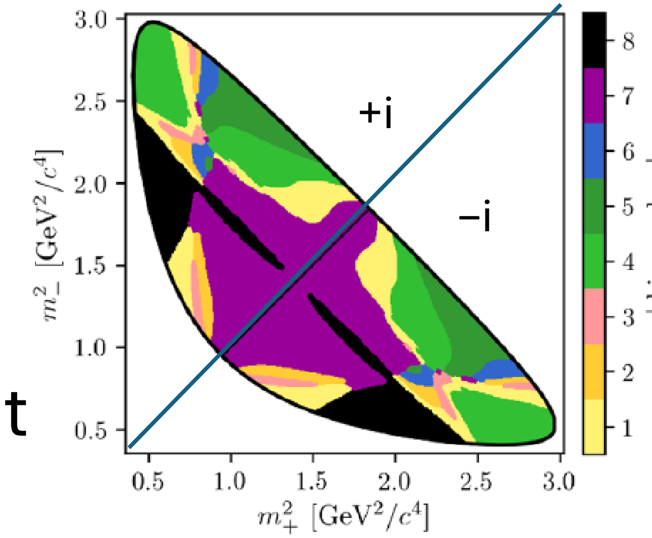
$B^- \to D(K_S h^+ h^-)h^-$ Dalitz plots

JHEP 02 (2021) 169



- First measurements from BaBar and Belle fit the whole Dalitz plot to an amplitude model of resonances $K^*\pi$, $K\rho$ etc. but the answer depends on the number of amplitudes included and the parameters of the model
  - Uncertainties up to 10 degrees on γ

What if you bin the Dalitz?



- The $B^- \rightarrow DK^-$ amplitude at each point in the Dalitz plot

$$A_B(m_-^2, m_+^2) \propto A_D(m_-^2, m_+^2) + r_B^{DK} e^{i(\delta_B^{DK} - \gamma)} A_{\overline{D}}(m_-^2, m_+^2)$$

- Find $|A_B|^2$ integrated over each bin to get expression like

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

h is norm factor

where this are the number of B^- events in the +i bin with

$$F_i = \frac{\int_i dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \eta(m_-^2, m_+^2)}{\sum_j \int_j dm_-^2 dm_+^2 |A_D(m_-^2, m_+^2)|^2 \eta(m_-^2, m_+^2)}$$

[Fraction of D decays in each bin inc. acceptance η]

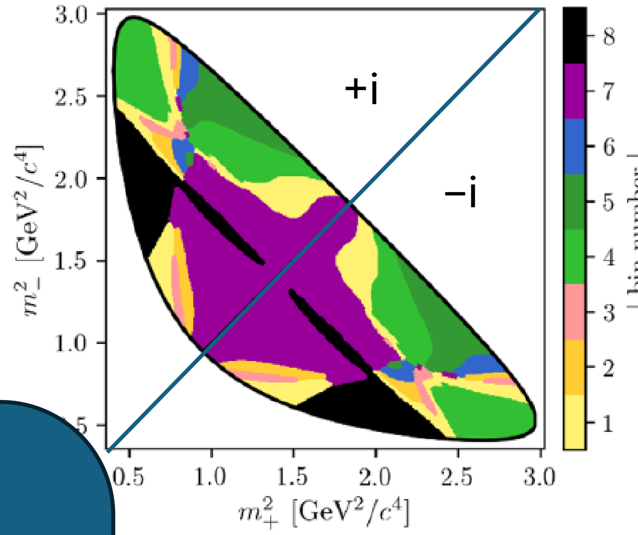
$$x_\pm^{DK} \equiv r_B^{DK} \cos(\delta_B^{DK} \pm \gamma) \text{ and } y_\pm^{DK} \equiv r_B^{DK} \sin(\delta_B^{DK} \pm \gamma).$$

[What we want to know?]

$$c_i \equiv \frac{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)||A_D(m_+^2, m_-^2)| \cos\left[\delta_D(m_-^2, m_+^2) - \delta_D(m_+^2, m_-^2)\right]}{\sqrt{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)|^2 \int_i dm_-^2\, dm_+^2\, |A_D(m_+^2, m_-^2)|^2}}$$

[Amplitude weighted average of the strong phase difference between D^0 and D^0 bar]

What if you bin the Dalitz?



- The amplitude at each point in the Dalitz plot is

$A_B(m_-^2$ ...

- Find $|A_B|$ ...

$N_{+i}^+ = h_{B^+}$ ...

where this ...

$F_i = \frac{\int_i dm \ldots}{\sum_j \int_j d \ldots}$ ... inc. acceptance η]

Important assumption

$A_D(m_-^2, m_+^2) = A_{\bar{D}}(m_+^2, m_-^2)$,

i.e., no CP violation in D decay

Looks intimidating but derivation is simple: do it over lunch?

$x_\pm^{DK} \equiv r_B^{DK}\cos(\delta_B^{DK} \pm \gamma)$ and $y_\pm^{DK} \equiv r_B^{DK}\sin(\delta_B^{DK} \pm \gamma)$. [What we want to know]

$$c_i \equiv \frac{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)||A_D(m_+^2, m_-^2)| \cos\left[\delta_D(m_-^2, m_+^2) - \delta_D(m_+^2, m_-^2)\right]}{\sqrt{\int_i dm_-^2\, dm_+^2\, |A_D(m_-^2, m_+^2)|^2 \int_i dm_-^2\, dm_+^2\, |A_D(m_+^2, m_-^2)|^2}}$$

[Amplitude weighted average of the strong phase difference between D^0 and D^0 bar]

Dalitz model-independent method

Binned fit proposed by Giri *et al.* [PRD 68 (2003) 054018] and developed by Bondar & Poluektov [EPJ C 55 (2008) 51; EPJ C47 (2006) 347] removes model dependence by relating events in bin i of Dalitz plot to *experimental observables*.

$B^{\pm}$ events in bin i of Dalitz plot

Determined from a sample of more abundant $B \to D\pi$ with little CPV

$x_{\pm} = r_B \cos(\delta_B \pm \gamma)$

$y_{\pm} = r_B \sin(\delta_B \pm \gamma)$

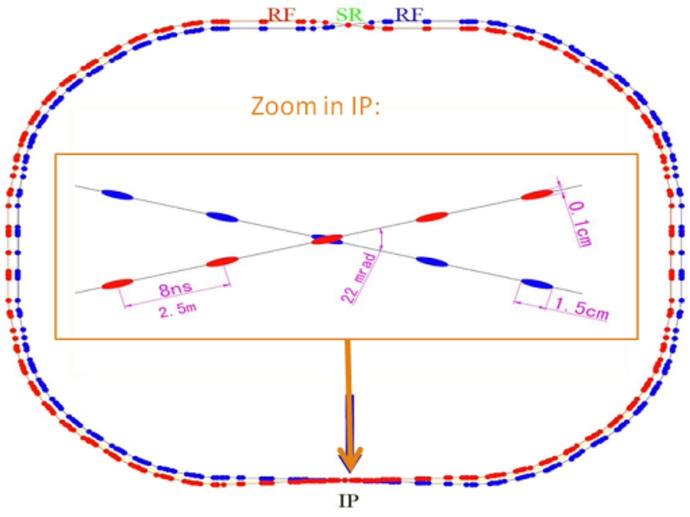
$$N^{+}_{+i} = h_{B^+}\left[F_{-i} + \left(\left(x_{+}^{DK}\right)^2 + \left(y_{+}^{DK}\right)^2\right)F_{+i} + 2\sqrt{F_iF_{-i}}\left(x_{+}^{DK}c_{+i} - y_{+}^{DK}s_{+i}\right)\right]$$

c_i, s_i : average in bin of cosine, sine of strong phase difference

Choosing bins of *expected* similar strong phase difference maximises statistical precision – currently 16 bins – **if you know ci and si** loss in statistical sensitivity w.r.t. unbinned result is ~20% **but no model error!**

BEPCII and BESIII

- e^+e^- collisions to directly produce charmonium
- $\sqrt{s} = 2.0 - 4.9$ GeV
- Achieved design instantaneous luminosity of 10^{33} cm^{-2}s^{-1}



Circumference 240 m

BESIII

93% of 4π

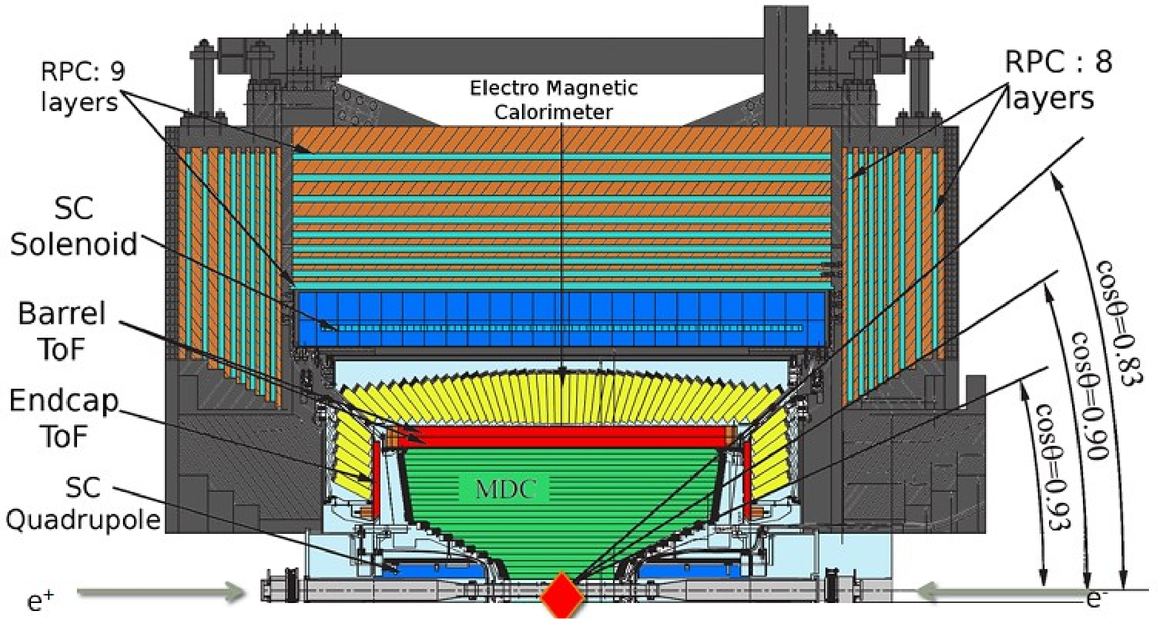
Main drift chamber + 1 T superconducting solenoid

$\rightarrow \sigma_p/p$ = 0.5% @ 1 GeV + dE/dx for PID

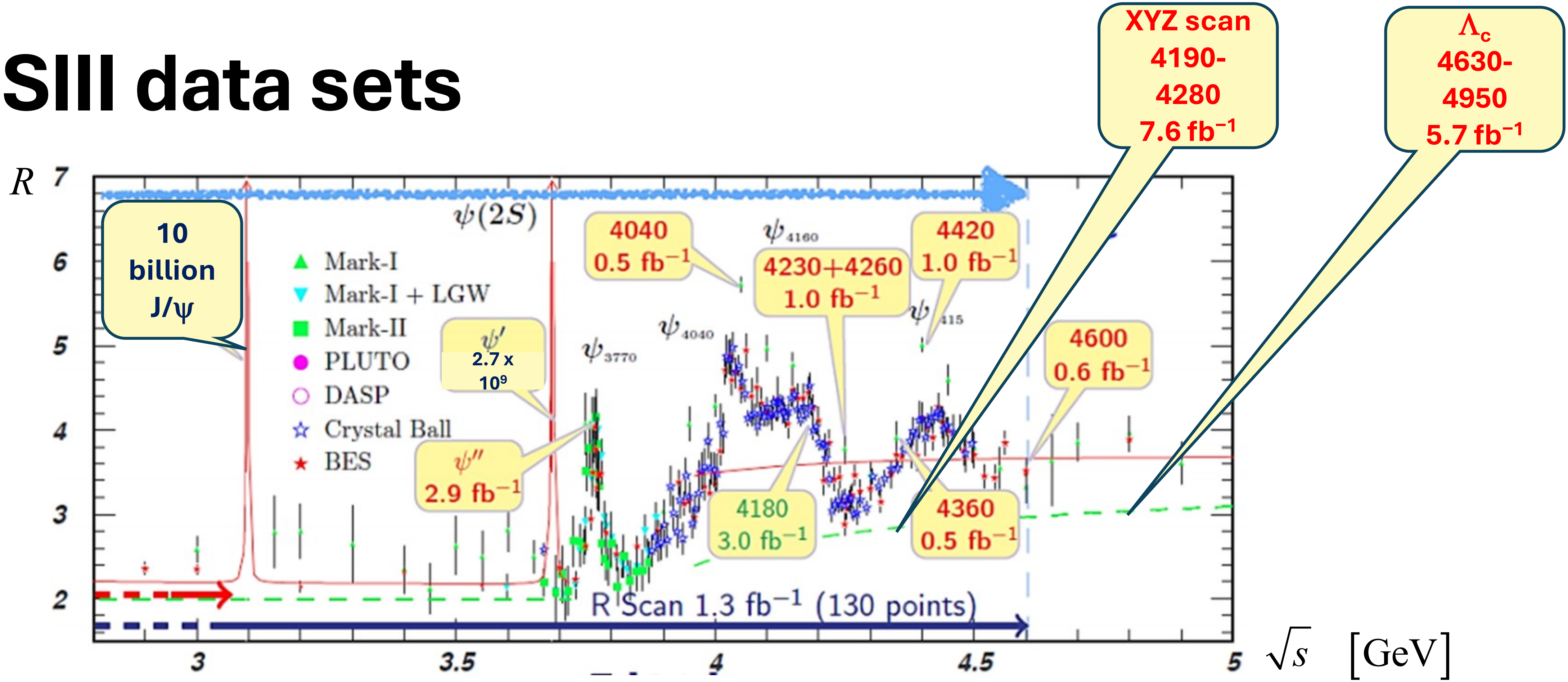
TOF system with σ = 100 ps (110 ps) in barrel (endcap)

Electromagnetic calorimeter with σ_E/E = 2.5% @ 1 GeV

RPC muon system embedded in flux return



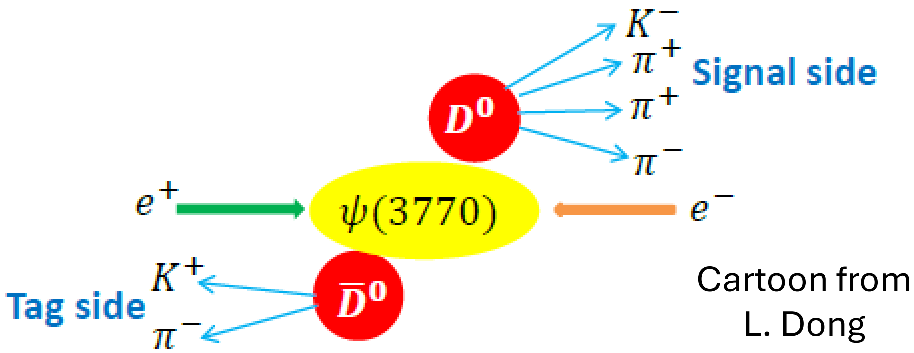
BESIII data sets



$\sqrt{s}$ (GeV)	Dominant processes of interest	Integrated luminosity (fb^{-1})	× CLEO-c
3.773	$e^+e^- \to \psi(3770) \to D^0\overline{D}^0/D^+D^-$	2.93 + (17 this year)	3.6

The "single vs. double-tag" techniques

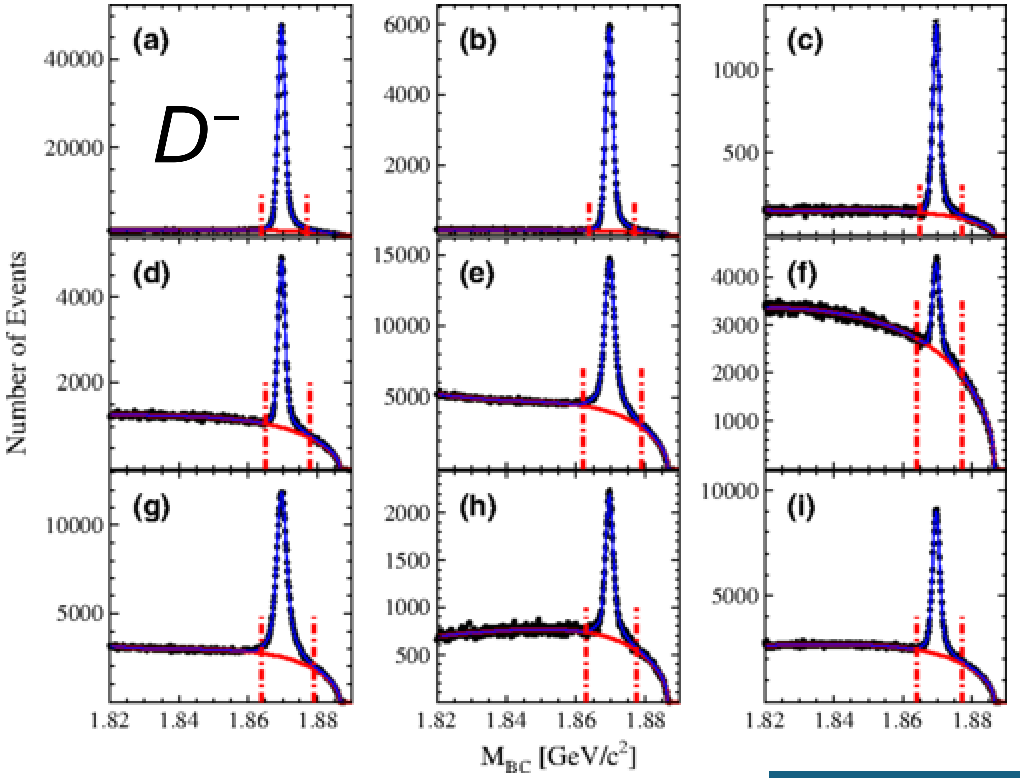
- Threshold production means that **no other** particles are produced along with the *DD* or *DD** pair
- Full event reconstruction "double tag" possible
  - Advantages
    1. absolute branching fractions
    2. full kinematic constraint to reconstruct ν or long-lived neutral hadron (neutron or K_L^0), and
    3. low backgrounds (i.e. amplitude analyses)
    4. Access to quantum correlation
  - Disadvantage
    1. reduced reconstruction efficiency



Cartoon from L. Dong

Single tag samples

$$M_{\rm BC} = \sqrt{E_{\rm beam}^2 - |\vec{\mathbf{p}}_D|^2}$$



$(a)\ K^+\pi^-\pi^-$

$(b)\ K^0_S\pi^-$

$(c)\ K^0_S K^-$

$(d)\ K^+K^-\pi^-$

$(e)\ K^+\pi^-\pi^-\pi^0$

$(f)\ \pi^+\pi^-\pi^-$

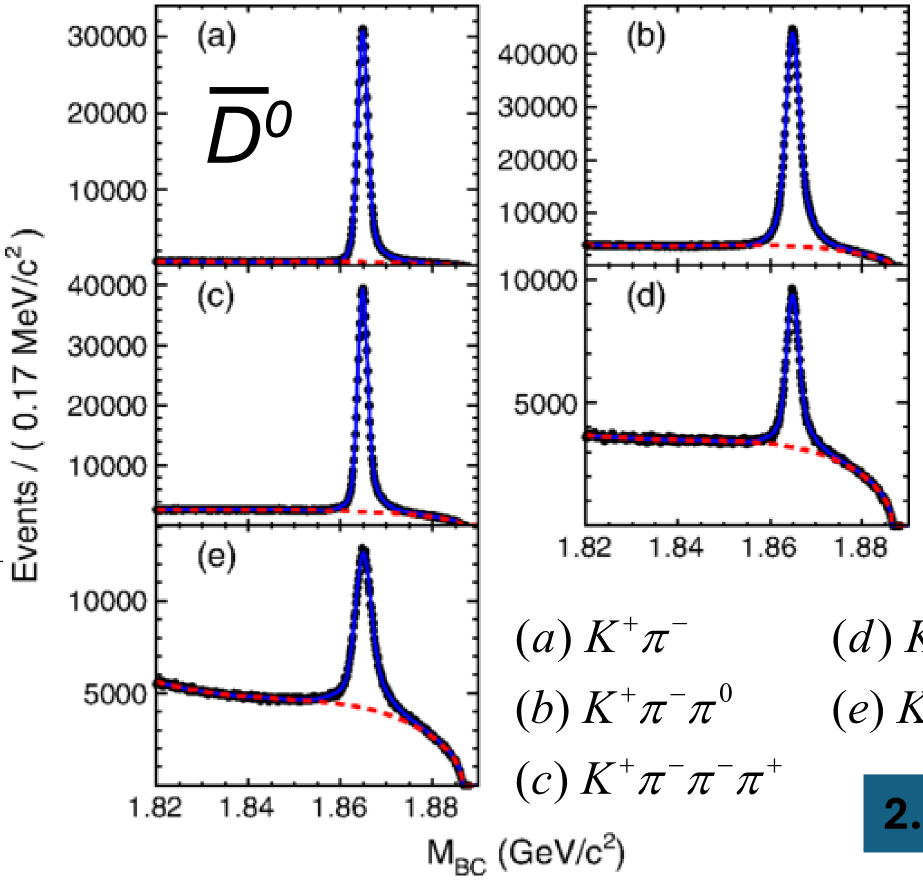
$(g)\ K^0_S\pi^-\pi^0$

$(h)\ K^+\pi^-\pi^-\pi^+$

$(i)\ K^0_S\pi^-\pi^+\pi^-$

1.7 million

Phys. Rev. D **89**, 051104(R) (2014)



$(a)\ K^+\pi^-$

$(b)\ K^+\pi^-\pi^0$

$(c)\ K^+\pi^-\pi^-\pi^+$

$(d)\ K^+\pi^-\pi^-\pi^+\pi^0$

$(e)\ K^+\pi^-\pi^0\pi^0$

2.8 million

Phys. Rev. D **92**, 072012 (2015)

Quantum correlated measurements

At the ψ (3770) neutral *D* pairs produced in quantum-entangled state:

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D^0\bar{D}^0 - \bar{D}^0 D^0\right]$$

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D_{CP-}D_{CP+} - D_{CP+}D_{CP-}\right]$$

$$\text{where } D_{CP\pm} = \tfrac{1}{\sqrt{2}}\left[D^0 \pm \bar{D}^0\right]$$

Reconstruct one $D \to K_s\pi\pi$ and the other in a *CP* eigenstate such as *KK*, $K_s\pi^0$ then *CP* of the other is fixed

$$CP \pm \text{ tagged yield in bin } i \propto F_i + F_{-i} \pm 2c_i\sqrt{F_iF_{-i}}$$

fractional D^0 yield in each bin

Also tag with $K_S\pi\pi$ tag

$$\text{Yield in bin } i \text{ tagged by bin } j \propto F_iF_{-j} + F_{-i}F_j - 2\sqrt{F_iF_{-j}F_{-i}F_j}\left(c_ic_j + s_is_j\right)$$

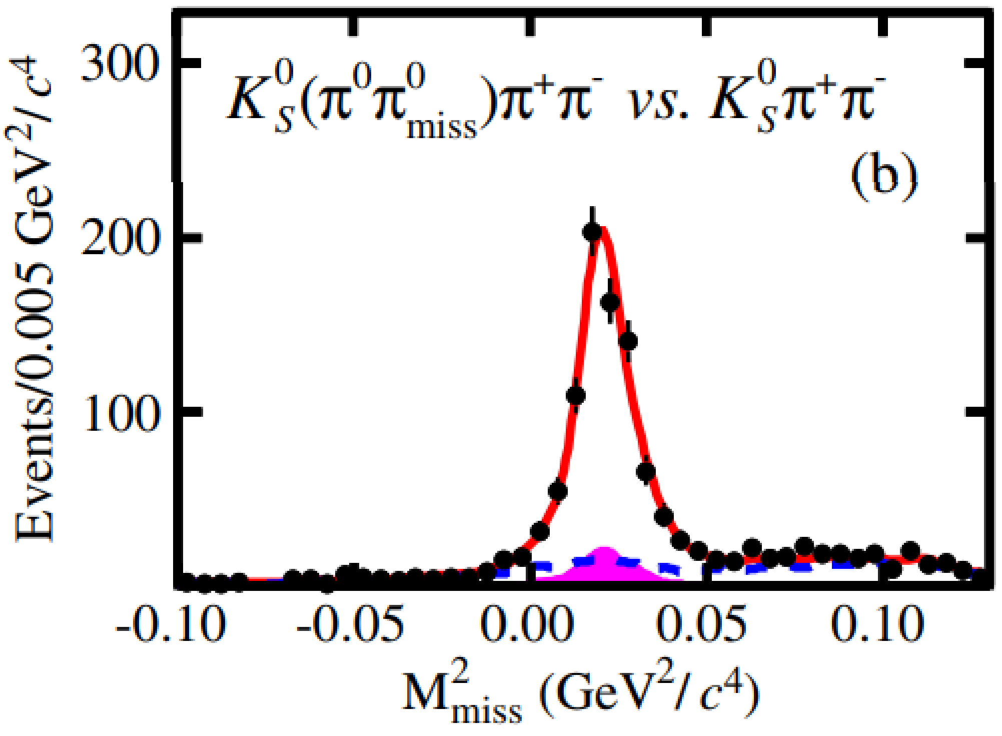
Yields

PRL **124** (2020) 241802
PRD **101** (2020) 112002

2.93 fb^{-1} of data compared with 0.82 fb^{-1} for CLEO – PRD **82** (2010) 112006

0

0 is



Mode	$N_{DT}^{K^0_S\pi^+\pi^-}$	$N_{DT}^{K^0_L\pi^+\pi^-}$
$K^+\pi^-$	4740 ± 71	9511 ± 115
$K^+\pi^-\pi^0$	5695 ± 78	11906 ± 132
$K^+\pi^-\pi^-\pi^+$	8899 ± 95	19225 ± 176
$K^+e^-\nu_e$	4123 ± 75	
CP-even tags		
K^+K^-	443 ± 22	1289 ± 41
$\pi^+\pi^-$	184 ± 14	531 ± 28
$K^0_S\pi^0\pi^0$	198 ± 16	612 ± 35
$\pi^+\pi^-\pi^0$	790 ± 31	2571 ± 74
$K^0_L\pi^0$	913 ± 41	
CP-odd tags		
$K^0_S\pi^0$	643 ± 26	861 ± 46
$K^0_S\eta_{\gamma\gamma}$	89 ± 10	105 ± 15
$K^0_S\eta_{\pi^+\pi^-\pi^0}$	23 ± 5	40 ± 9
$K^0_S\omega$	245 ± 17	321 ± 25
$K^0_S\eta'_{\pi^+\pi^-\eta}$	24 ± 6	38 ± 8
$K^0_S\eta'_{\gamma\pi^+\pi^-}$	81 ± 10	120 ± 14
$K^0_L\pi^0\pi^0$	620 ± 32	
Mixed-*CP* tags		
$K^0_S\pi^+\pi^-$	899 ± 31	3438 ± 72
$K^0_S\pi^+\pi^-_{miss}$	224 ± 17	
$K^0_S(\pi^0\pi^0_{miss})\pi^+\pi^-$	710 ± 34	

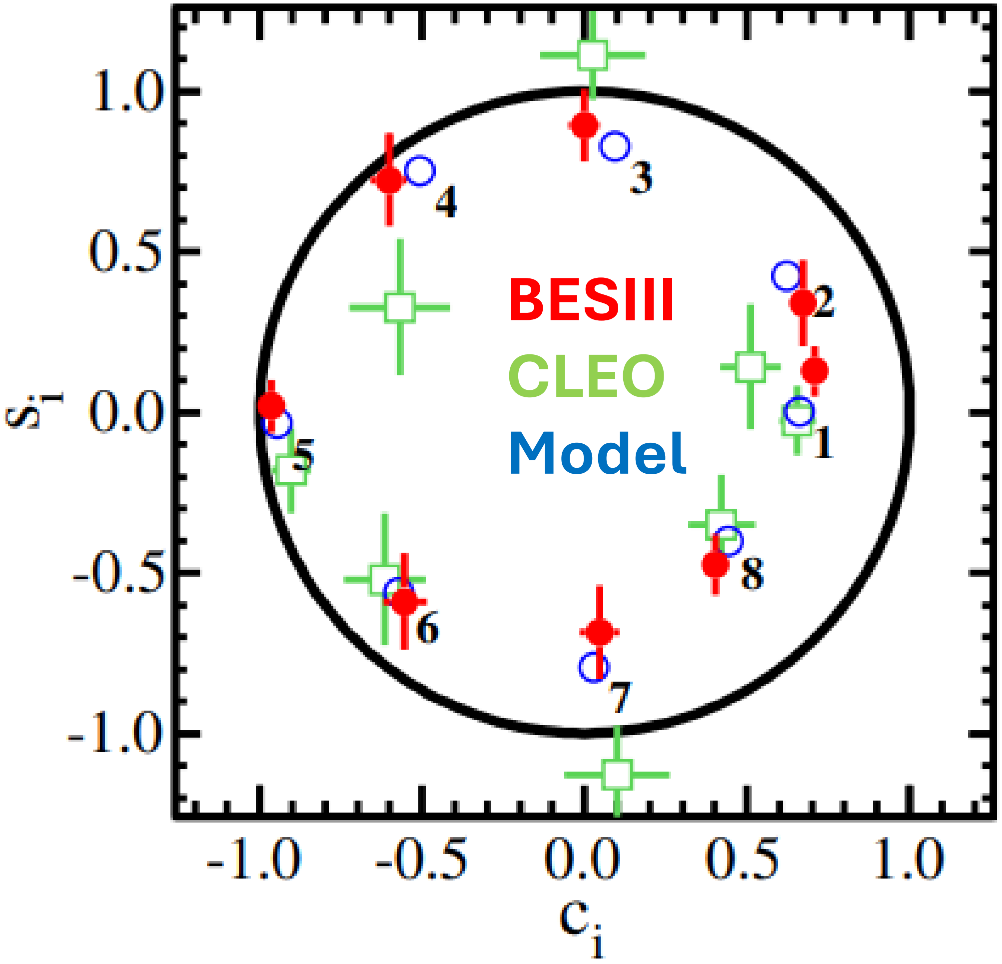
Results

PRL **124** (2020) 241802
PRD **101** (2020) 112002

- Three different binning schemes – some for γ measurements
- Use equal strong-phase binning - $\pi/4$ intervals
- Fit binned quantum-correlated yields to extract

	c_i	s_i
1	$0.708 \pm 0.020 \pm 0.009$	$0.128 \pm 0.076 \pm 0.017$
2	$0.671 \pm 0.035 \pm 0.016$	$0.341 \pm 0.134 \pm 0.015$
3	$0.001 \pm 0.047 \pm 0.019$	$0.893 \pm 0.112 \pm 0.020$
4	$-0.602 \pm 0.053 \pm 0.017$	$0.723 \pm 0.143 \pm 0.022$
5	$-0.965 \pm 0.019 \pm 0.013$	$0.020 \pm 0.081 \pm 0.009$
6	$-0.554 \pm 0.062 \pm 0.024$	$-0.589 \pm 0.147 \pm 0.031$
7	$0.046 \pm 0.057 \pm 0.023$	$-0.686 \pm 0.143 \pm 0.028$
8	$0.403 \pm 0.036 \pm 0.017$	$-0.474 \pm 0.091 \pm 0.027$

Statistically dominated



Systematic uncertainties - eye to the future

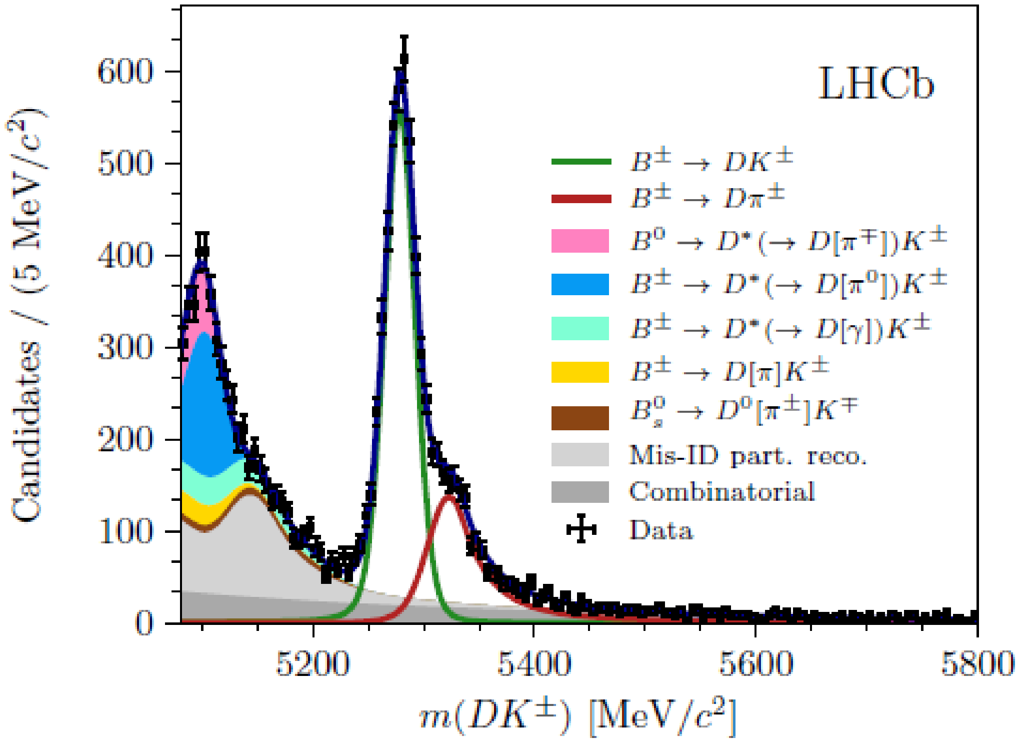
PRD **101** (2020) 112002
ST (DT) = single (double) tag

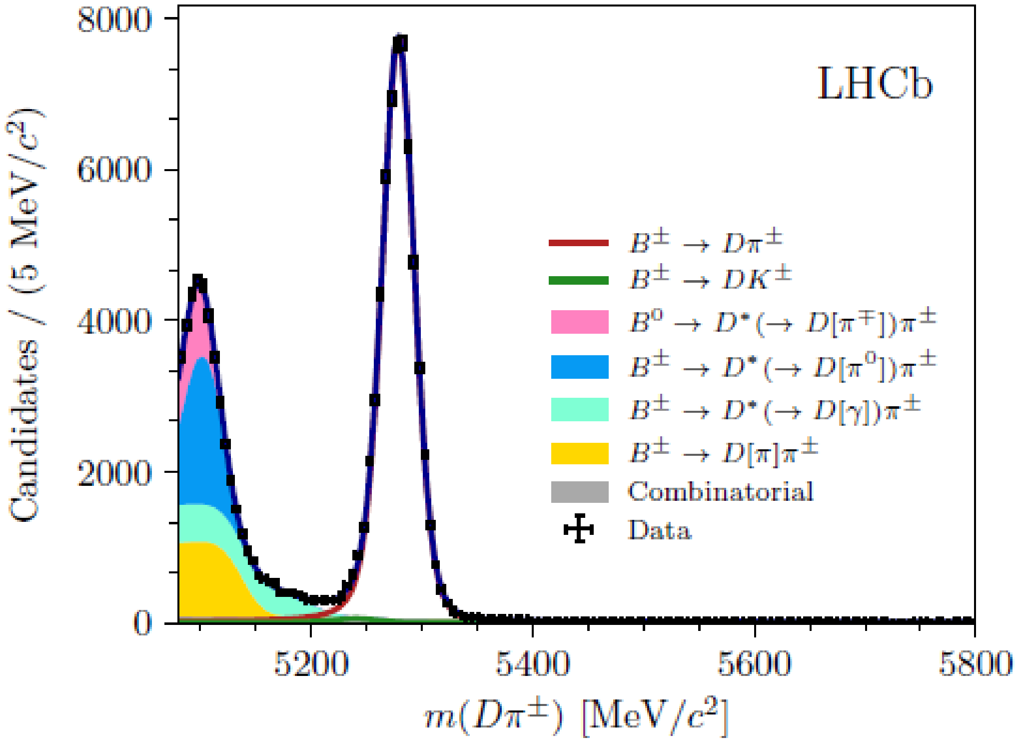
Uncertainty	c_5
K_i and K'_i	0.005
ST yields	0.004
MC statistics	0.001
DT peaking-background subtraction	0.005
DT yields	0.001
Momentum resolution	0.010
$D^0\bar{D}^0$ mixing	0.000
Total systematic	0.013
Statistical plus $K^0_L\pi^+\pi^-$ model	0.019
$K^0_L\pi^+\pi^-$ model alone	0.007
Total	0.023

1. Ignoring asymmetric bin-to-bin migration
   - can be mitigated by unfolding in the future
2. To leverage $D\to K_L\pi\pi$ we have to make assumptions related to the model and the size CF to DCS interference induced difference between $D\to K_L\pi\pi$ and $D\to K_S\pi\pi$
   - implemented a constraint hence appears in statistical uncertainty
   - potentially learn more from studying the $D\to K_L\pi\pi$ amplitude model
   - more weight to $D\to K_S\pi\pi$
3. Better understanding with more data

LHCb data

- Displaced vertex reduces background to very low level
  - Its modelling is the dominant experimental systematic though





Getting to γ

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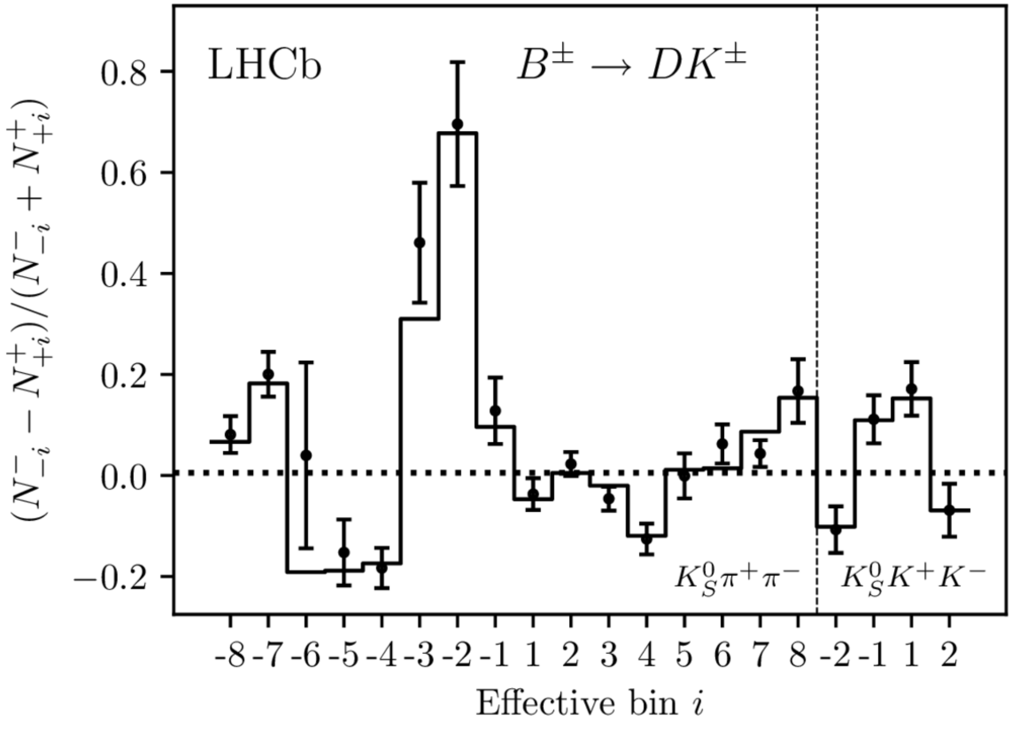
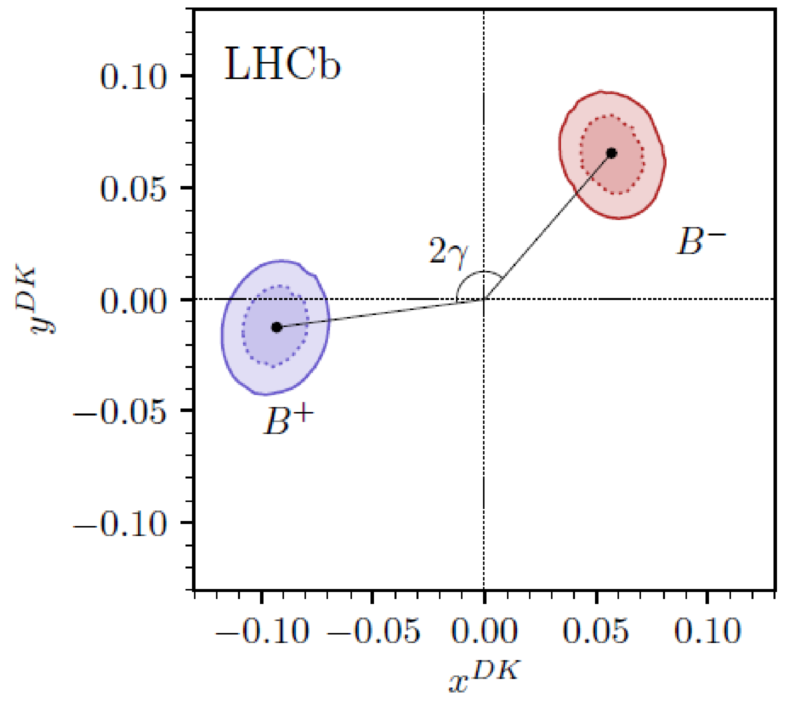




$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$

Statistics dominated only 1 degree error from strong phases

- Also uses $D^0 \to K^0_S K^+ K^-$
- 12% more data in the γ measurement
- Strong phases:
  - arXiv:2007.07959 [hep-ex]

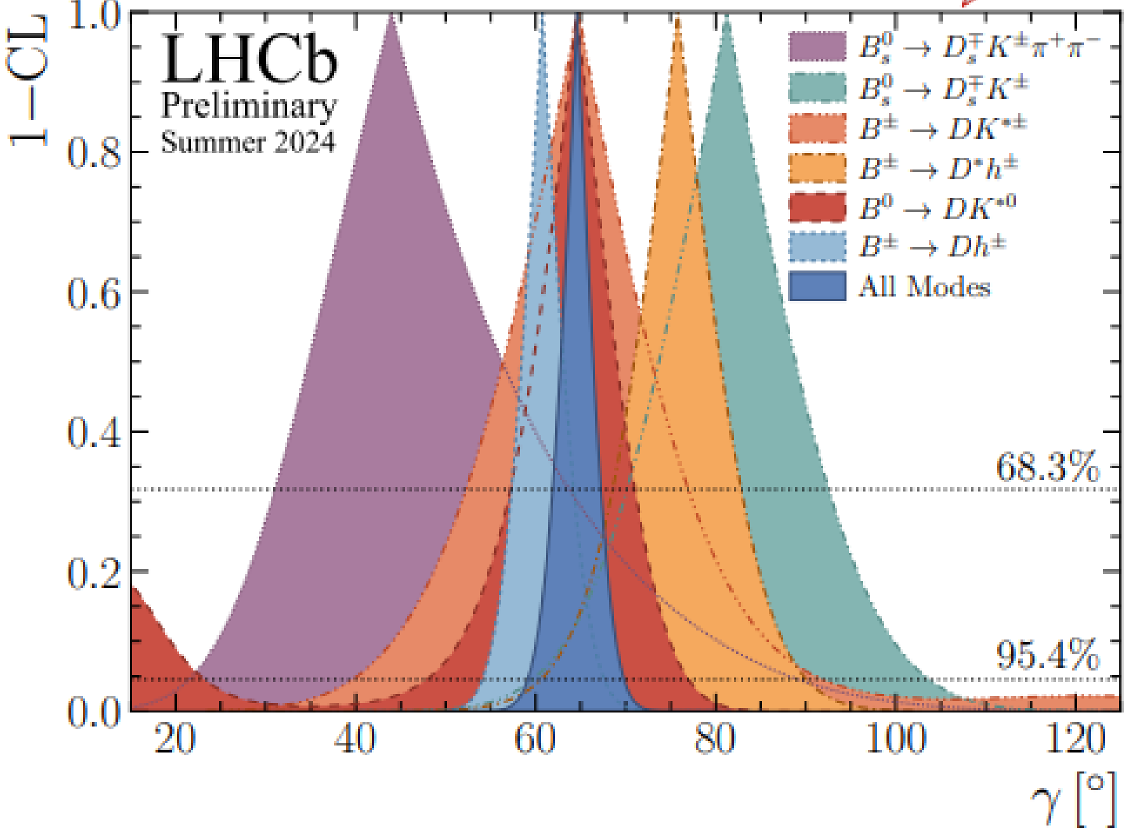
2024 LHCb γ

[In preparation, LHCb-CONF-2024-004]

NEW

$$\gamma = (64.6 \pm 2.8)^{\circ}$$

- Decreased uncertainty by $\sim 0.7^{\circ}$ since 2022
- Reduced tension between the B_s^0 decays
- B^0 now sits amongst the B^+ measurements

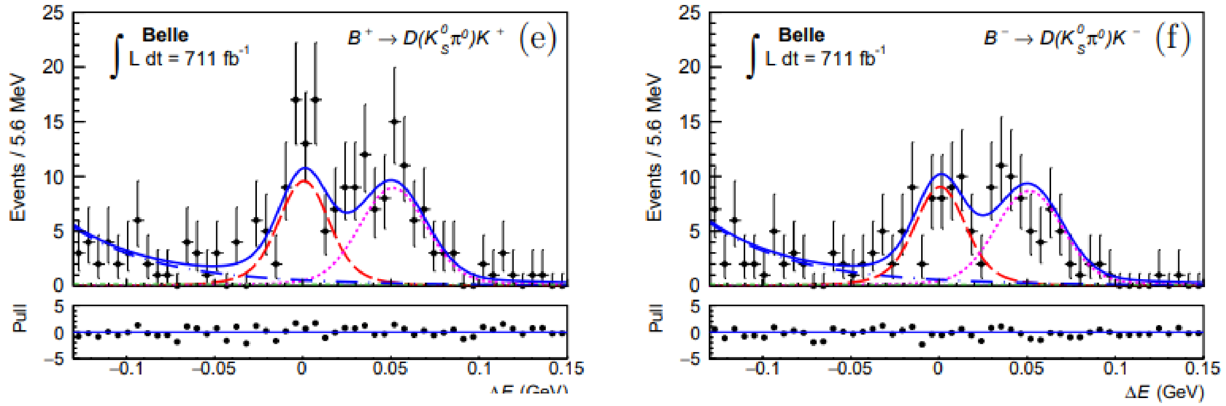


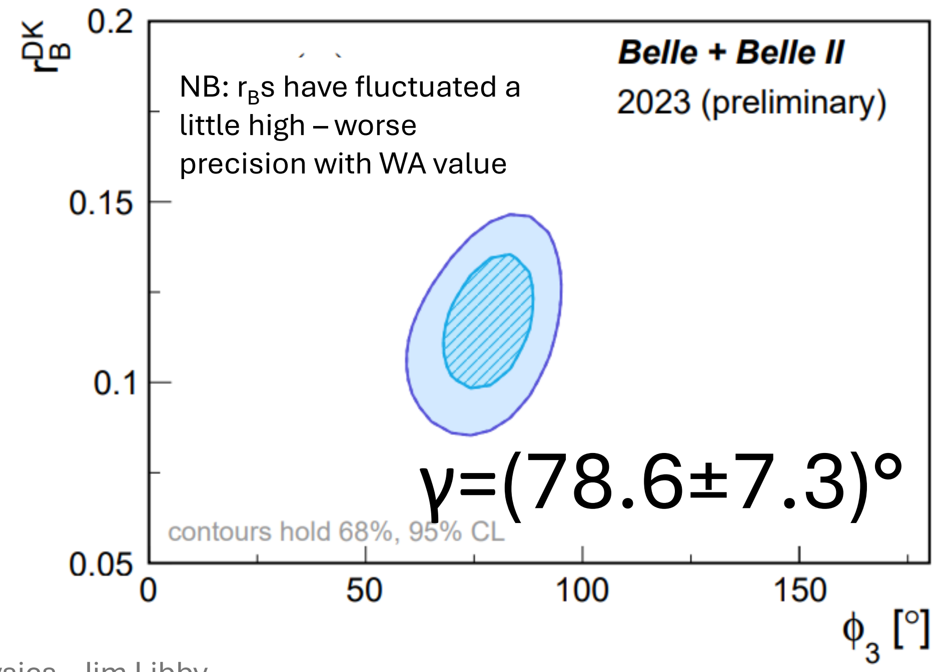
2024 LHCb γ combination per B decay

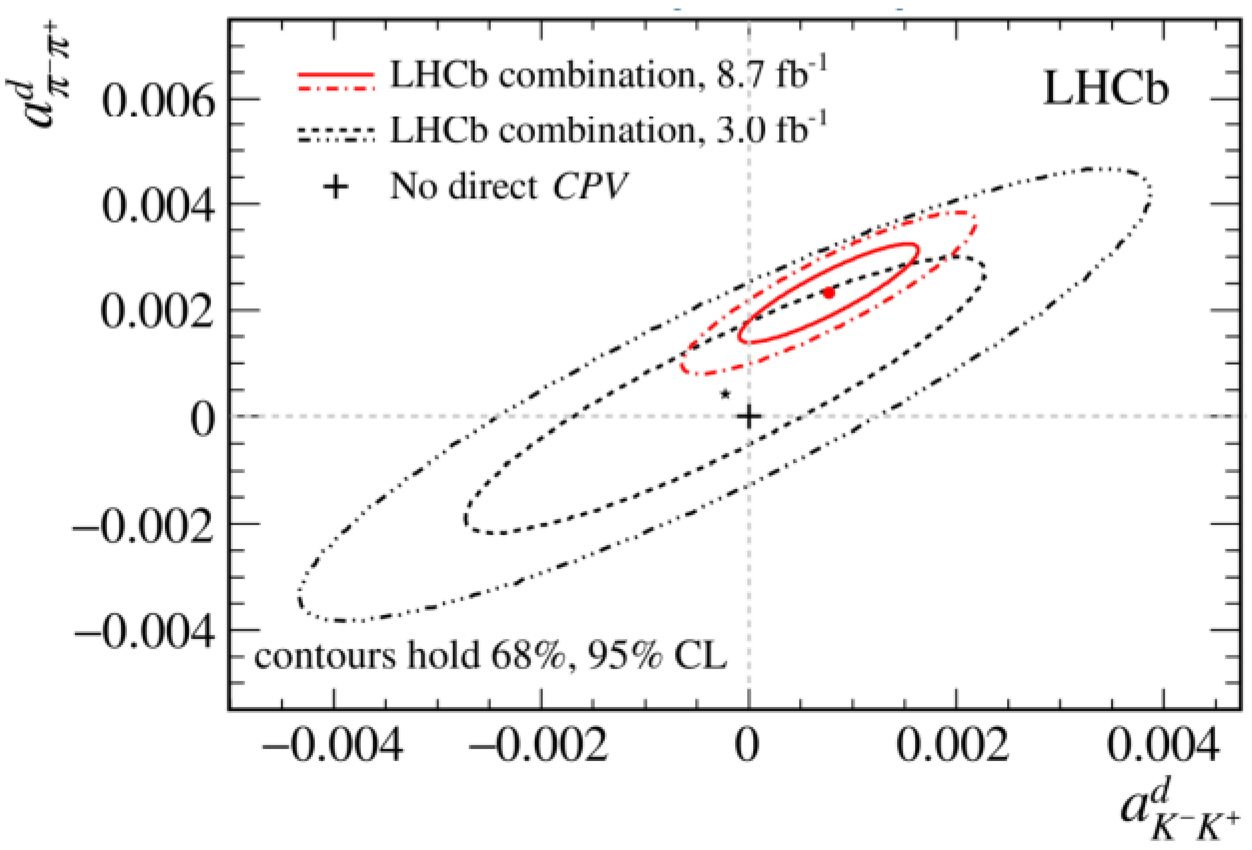
Aidan Wiederhold 14 University of Manchester arXiv:2404.12817

γ/ϕ_3: power of Belle + Belle II

- To be compared to LHCb lead the way: $\gamma=(64.6\pm2.8)^\circ$
- Several Belle (711 fb^{-1}) + Belle II measurements (varying sample size) – total O(1 ab^{-1})
  - $D\to K^0_S hh$ - JHEP 02 (2022) 063
  - $D\to K^0_S K\pi$ - JHEP 09 (2023) 146
  - $D\to K^0_S \pi^0$, KK - accepted JHEP
  - + Belle-only $D\to K\pi$ and others
- A few ab^{-1} will give a good cross check of this important SM parameter







Case study 3: CP violation in charm

Better than parts per mille

Why is it small?

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3[1-(\rho-i\eta)] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

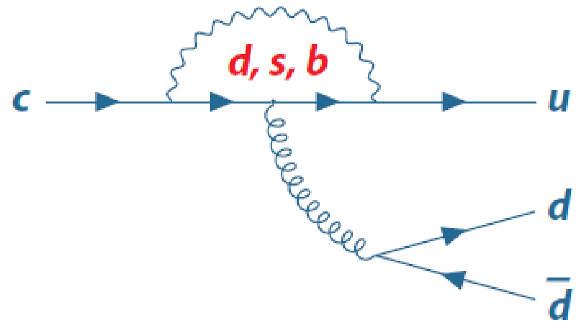
- In Wolfenstein parameterization we see the 2nd row/column is real to order λ^4

$$V_{cd} = -0.2245 - 2.6 \times 10^{-5} i, \quad V_{cs} = 0.97359 - 5.9 \times 10^{-6} i, \quad V_{cb} = 0.0416.$$

- For physical manifestation we can look at combinations that can arise in **singly-Cabibbo suppressed decay** and mixing

$$\lambda_d = -0.21874 - 2.51 \times 10^{-5}\, i, \qquad \lambda_q = V_{cq} V_{uq}^*$$

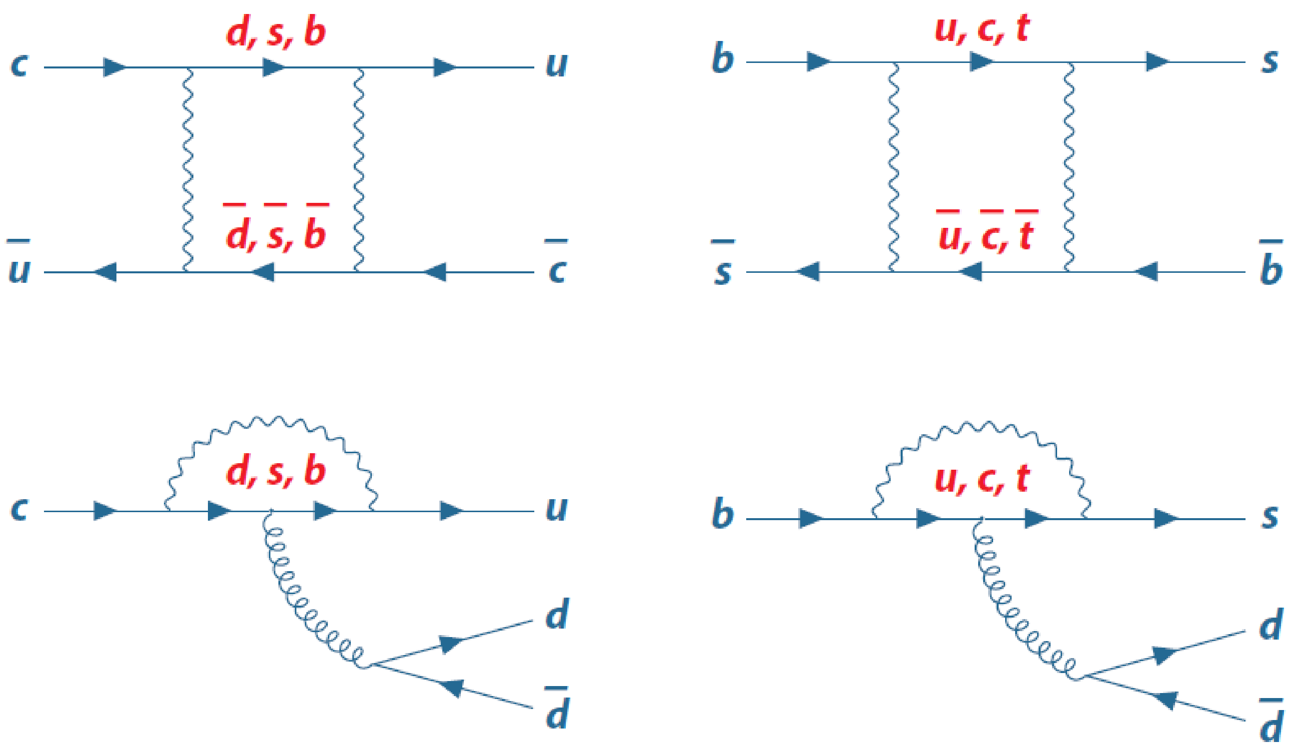
$$\lambda_s = +0.21890 - 0.13 \times 10^{-5}\, i, \qquad \lambda_b = -1.5 \times 10^{-4} + 2.64 \times 10^{-5}\, i.$$



- GIM suppression almost complete with first two generations only real and imaginary terms similar in third – **most promising place for CPV in charm**

Ann. Rev. Nucl. Part. Sci. **71** (2021) 59

Further suppression



Loop suppression

Charm	**Beauty**
$\left(\frac{m_d}{M_W}\right)^2 \approx 0,$	$\left(\frac{m_u}{M_W}\right)^2 \approx 0,$
$\left(\frac{m_s}{M_W}\right)^2 \approx 1.3 \times 10^{-6},$	$\left(\frac{m_c}{M_W}\right)^2 \approx 2.5 \times 10^{-4},$
$\left(\frac{m_b}{M_W}\right)^2 \approx 2.8 \times 10^{-3},$	$\left(\frac{m_t}{M_W}\right)^2 \approx 4.5.$

The good news is that large CP is a “clear” signature of new physics in the loops – naïvely expect $O(10^{-4})$

Charm at LHCb I

- Not originally part of the programme but large samples of
  - $D^{*+} \to D^0 \pi^+$ through high-pT hardware trigger then detached vertex + two-body D decay software trigger and
  - $B \to D^0 \mu^- \nu X$ where the high-pT muon hardware trigger and then the $D^0 \mu^-$ vertex

were reconstructed – accompanying particle allows **"raw"** asymmetries to be determined

$$A_{\mathrm{raw}}^{\pi-\mathrm{tagged}}(f) \equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \bar{D}^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \bar{D}^0(f)\pi^-)},$$

$$A_{\mathrm{raw}}^{\mu-\mathrm{tagged}}(f) \equiv \frac{N(\bar{B} \to D^0(f)\mu^-\bar{\nu}_\mu X) - N(B \to \bar{D}^0(f)\mu^+\nu_\mu X)}{N(\bar{B} \to D^0(f)\mu^-\bar{\nu}_\mu X) + N(B \to \bar{D}^0(f)\mu^+\nu_\mu X)},$$

PRL **122**, 211803 (2019)

Charm at LHCb II

- They reconstruct in the SCS decays
  - $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
- But what is this “raw”

$$A_{\rm raw}^{\pi-\rm tagged}(f) \approx A_{CP}(f) + A_{\rm D}(\pi) + A_{\rm P}(D^*),$$
$$A_{\rm raw}^{\mu-\rm tagged}(f) \approx A_{CP}(f) + A_{\rm D}(\mu) + A_{\rm P}(B),$$

- Experimental: charged-particle detection asymmetry
  - e.g., eff(μ+)≠ eff(μ−)
- Production: it is a pp collider (not a CP symmetric),
  - e.g., $N(D^{*+}) \neq N(D^{*-})$

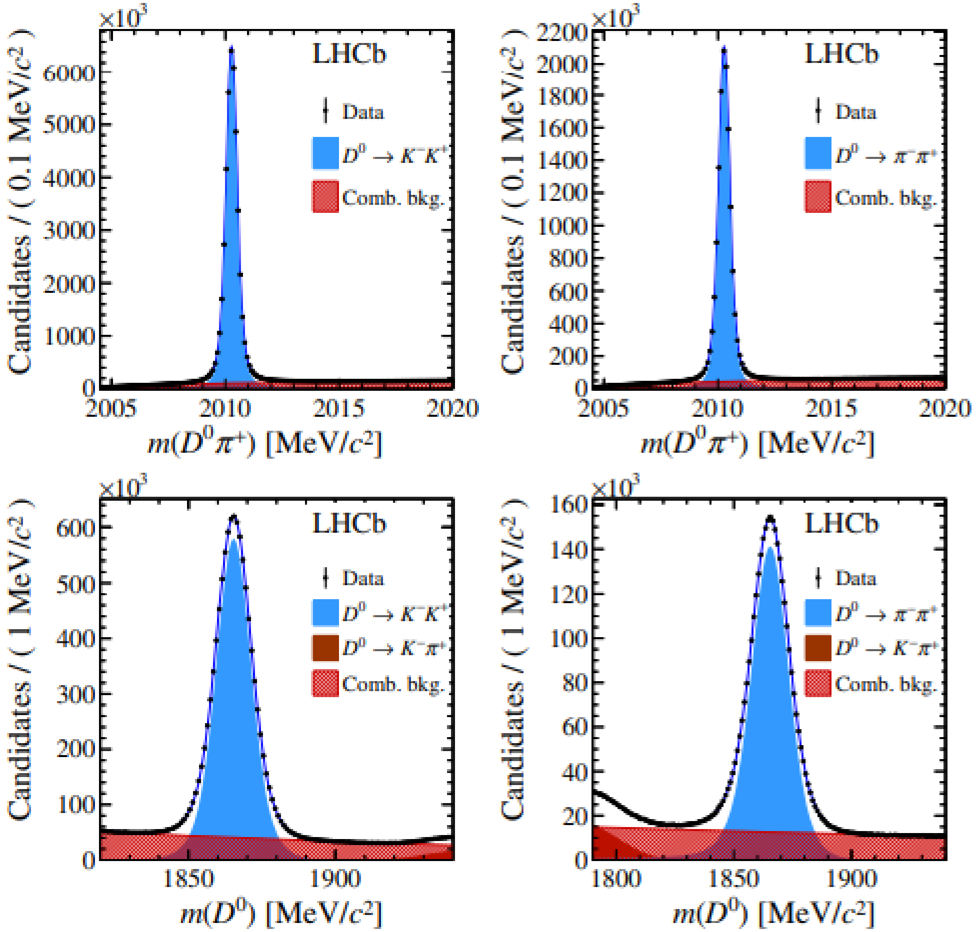


FIG. 1. Mass distributions of selected (top) $\pi^\pm$-tagged and (bottom) $\mu^\pm$-tagged candidates for (left) K^-K^+ and (right) $\pi^-\pi^+$ final states of the D^0-meson decays, with fit projections overlaid.

Observation of CP violation in charm

- Take difference of A_{CP} raw in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ so that production and detection asymmetries cancel out
  - If non-zero one or both asymmetries for the individual modes are too

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-4},$$

[Dominant systematic PDF modelling]

$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8(\text{stat}) \pm 5(\text{syst})] \times 10^{-4}.$$

[Dominant systematic muon identification]

$$\Delta a_{CP}^{\text{dir}} = (-15.7 \pm 2.9) \times 10^{-4},$$

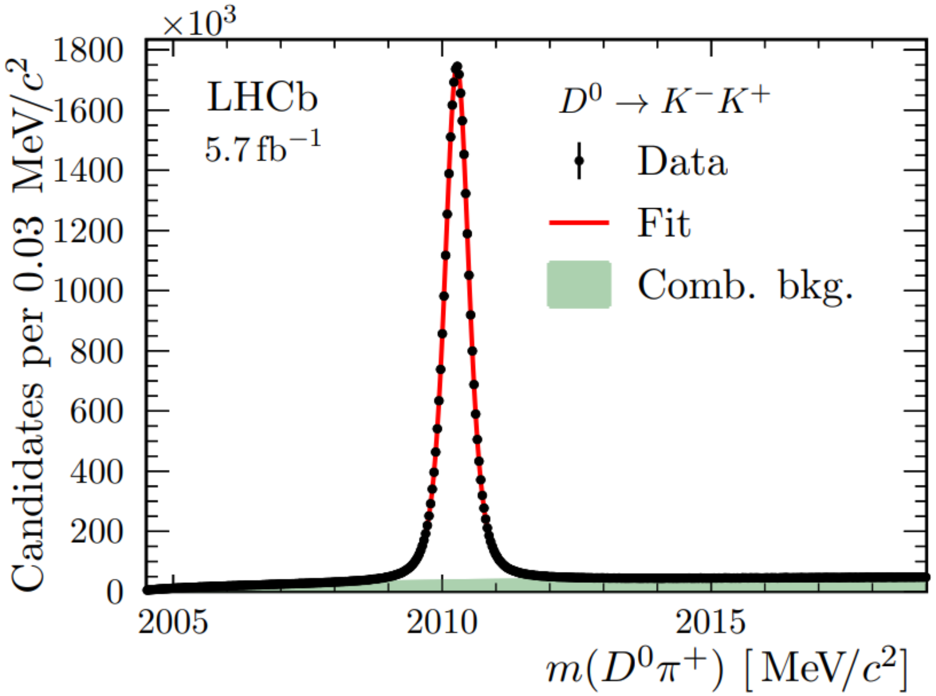
5.3 sigma (<u>not an anomaly</u>)

- Includes +0.3 correction due to any indirect *CP* violation

PRL 131 (2023) 091802

Measuring the absolute asymmetry

- Followed up with a measurement of the asymmetry in $D^0 \rightarrow K^+K^-$
  - Used five Cabbibo-favoured control modes to cancel production and detection asymmetries from all the measurements in two different ways
  - $D^0 \rightarrow \pi^+K^-$, $D^+ \rightarrow \pi^+\pi^+K^-$, $D^+ \rightarrow \pi^+K^0$, $D_s^+ \rightarrow \pi^+K^+K^-$ and $D_s^+ \rightarrow K^+K^0$
  - Also reweighted the kinematics to match the signal modes

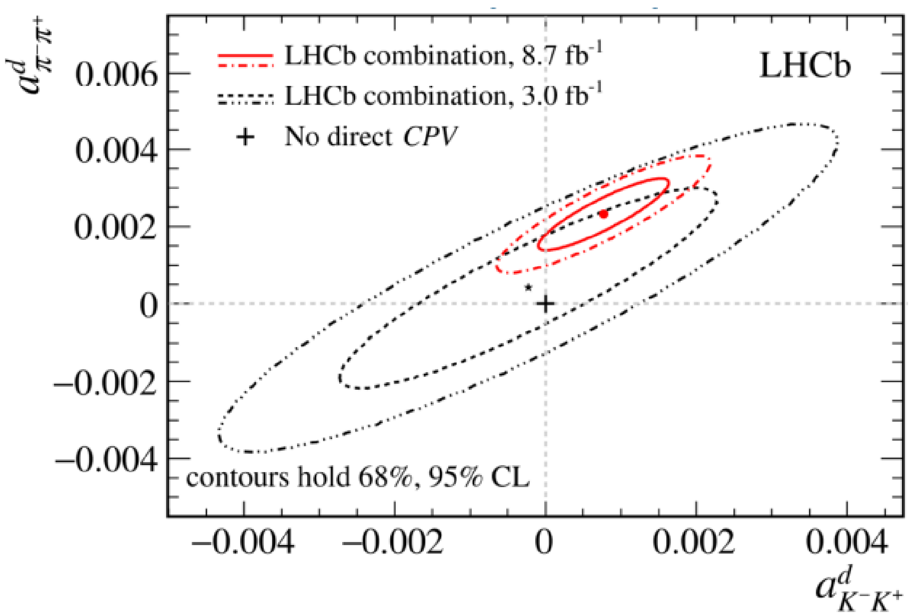


$$\mathcal{A}^{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$

[PRL 131 (2023) 091802]

Measuring the absolute asymmetry

- Followed up with a measurement of the asymmetry in $D^0 \to K^+K^-$
  - Used five Cabbibo-favoured control modes to cancel production and detection asymmetries from all the measurements in two different ways
  - $D^0 \to \pi^+K^-$, $D^+ \to \pi^+\pi^+K^-$, $D^+ \to \pi^+K^0$, $D_s^+ \to \pi^+K^+K^-$ and $D_s^+ \to K^+K^0$
  - Also reweighted the kinematics to match the signal modes

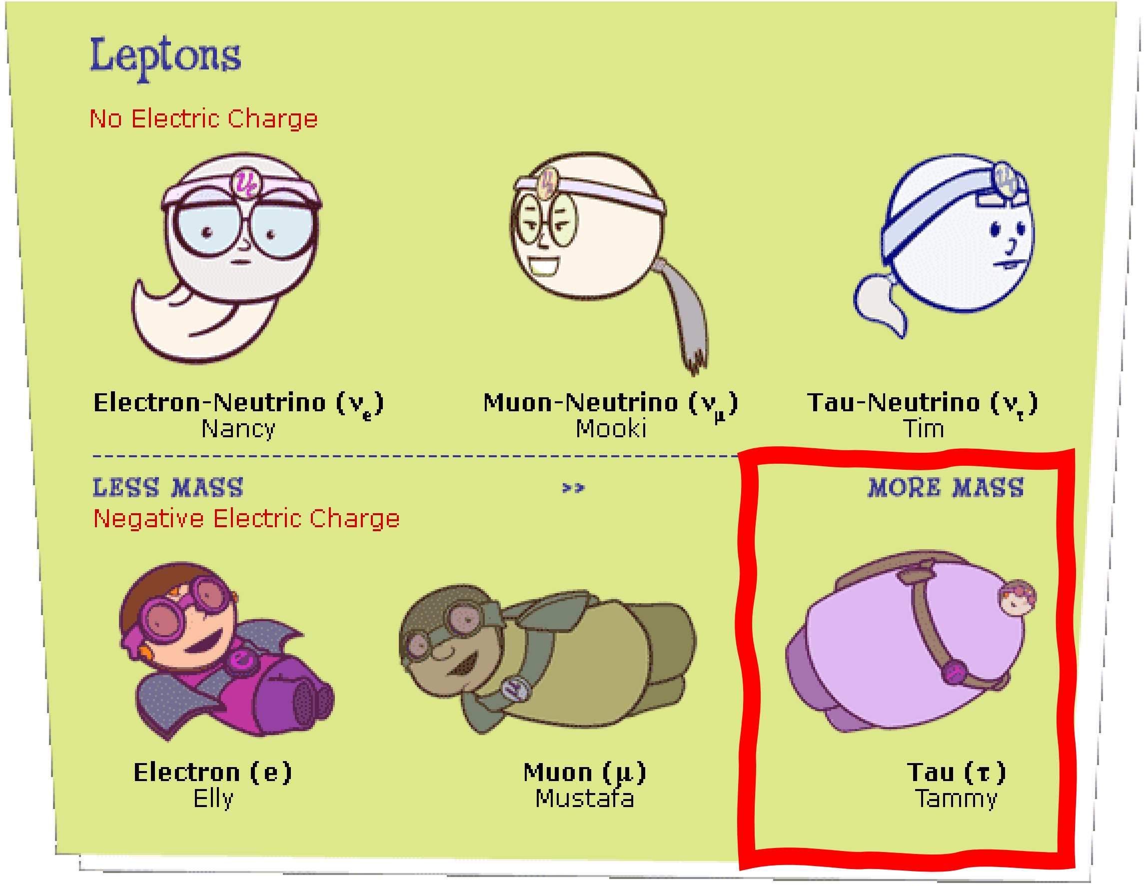


$$\mathcal{A}^{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4}$$

What next?

- We have seen CP violation in $D^0 \to \pi^+\pi^-$ but is it SM or not?
- The observed size 10^{-3} is larger than the naïve expectation from the size of the λ_q parameters and the relative size of the penguin to tree diagram
  - However, breaking of SU(3) flavour assumptions can enhance penguin + possible long-distance rescattering (non-perturbative) effects can play a role
    - We know SU(3) flavour broken in D→PP decays, e.g., $\Gamma(D \to K^+K^-) \approx 3\ \Gamma(D \to \pi^+\pi^-)$
- So more measurements required to disentangle what is going on
  - e.g. $D \to \pi^0\pi^0$ or $D \to \pi^0\pi^+$
  - An opportunity for Belle II? Unfortunately, our sample size is much smaller so it will take time or innovation at LHCb

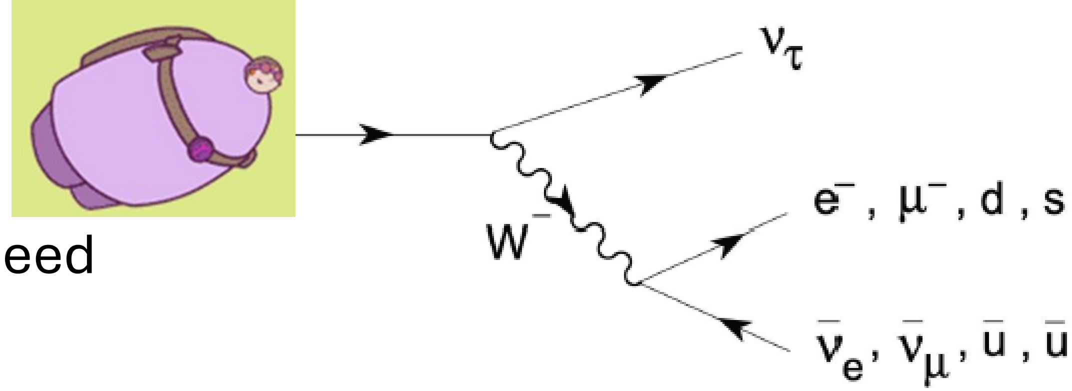
https://www.quarked.org/



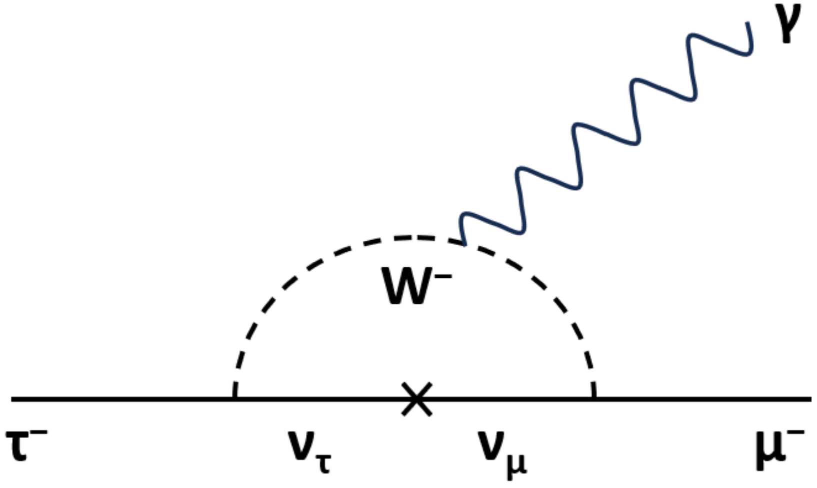
Case study 4: tau lepton at Belle II

Flavour beyond quarks

Tau physics motivation I



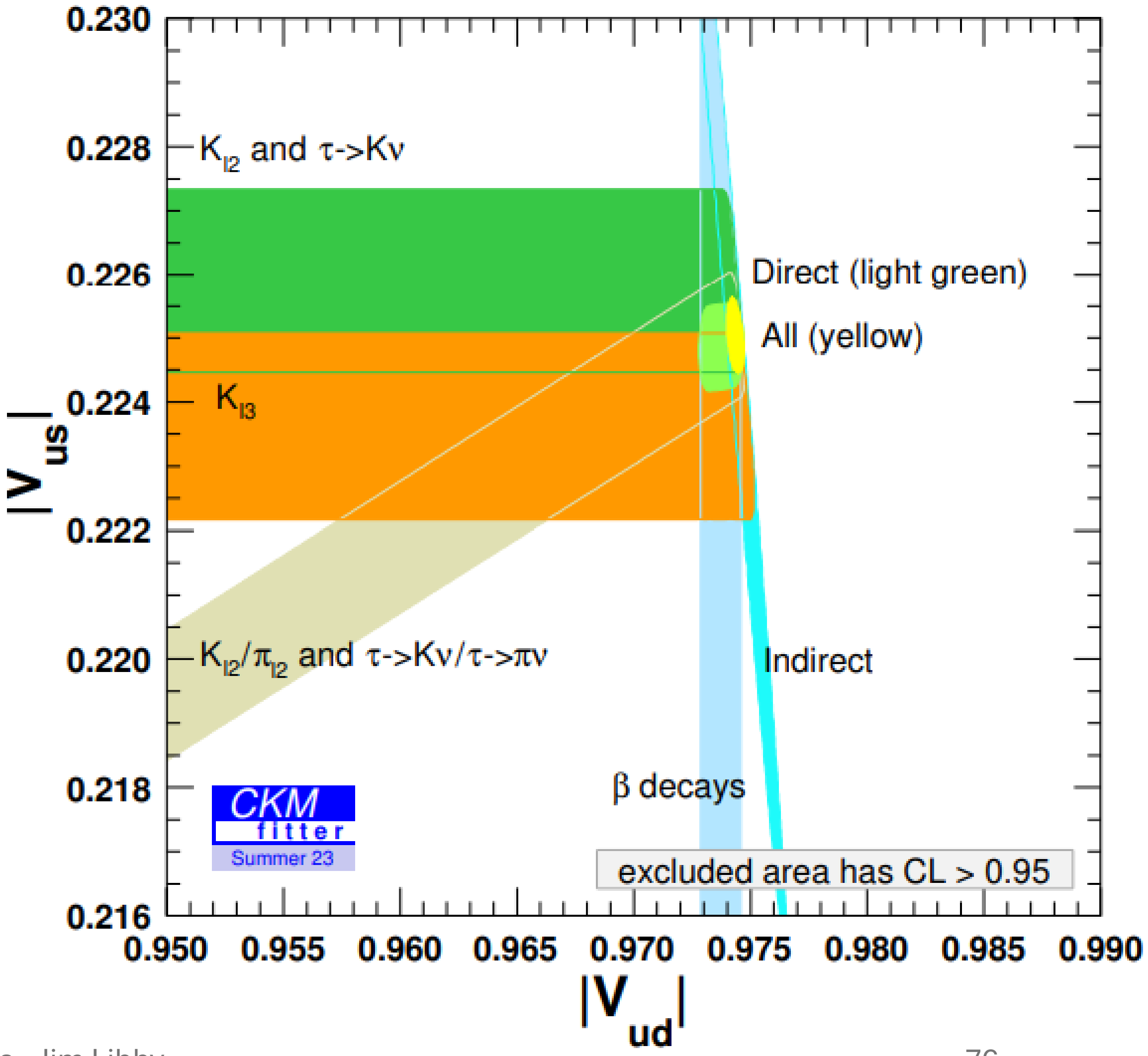
- Because neutrinos are massless there is no need for a CKM like matrix in the charged current interactions
    - Therefore, lepton flavour violation a clear signature of BSM physics
- tau has 185 standard model decay modes studied
    - **principally hadronic final states**
- Unique laboratory to study weak interaction
- Third-generation therefore beyond-SM-sensitivity anticipated
    - Any observation of lepton-flavour violation in $\tau \to 3\mu$, $\tau \to \mu\gamma$, $\tau \to l\phi$ etc **new physics**
    - SM highly suppressed
- Connections to g-2 and lepton universality violation in b decay



Tau physics motivation II

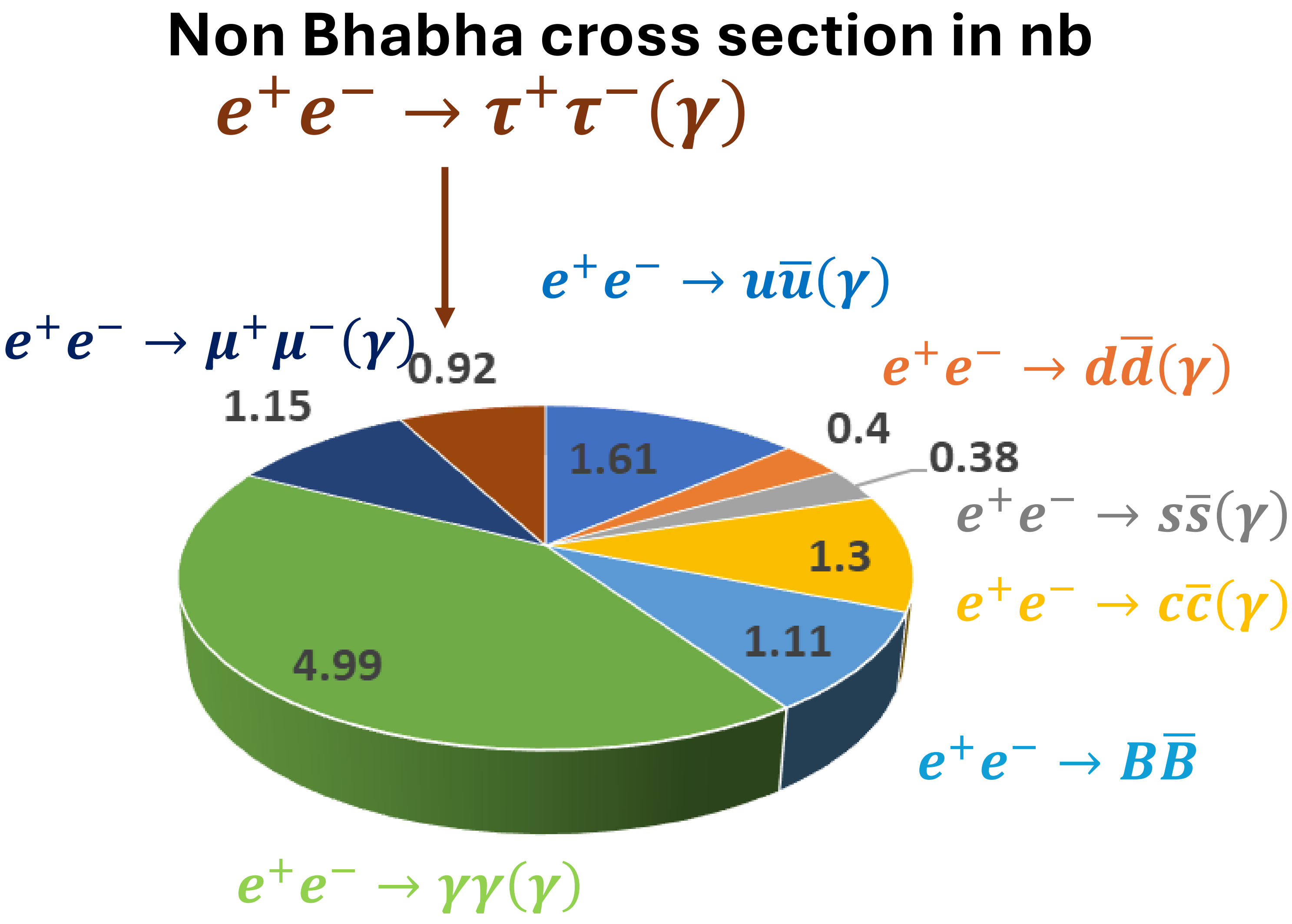
- **Precision measurements** of the τ lepton can have significant impact
- Example:
  - first row unitarity of CKM matrix – ‘Cabibbo angle anomaly’
  - $B(\tau \to K\nu)/B(\tau \to \pi\nu)$ proportional to $|V_{us}/V_{ud}|^2$
  - Combine with lattice QCD information to provide additional constraint
- Additionally, lepton-flavour universality and dipole moments
- **Mass** and lifetime important inputs to these calculations

Luiz Vale Silva (CKM 2023)



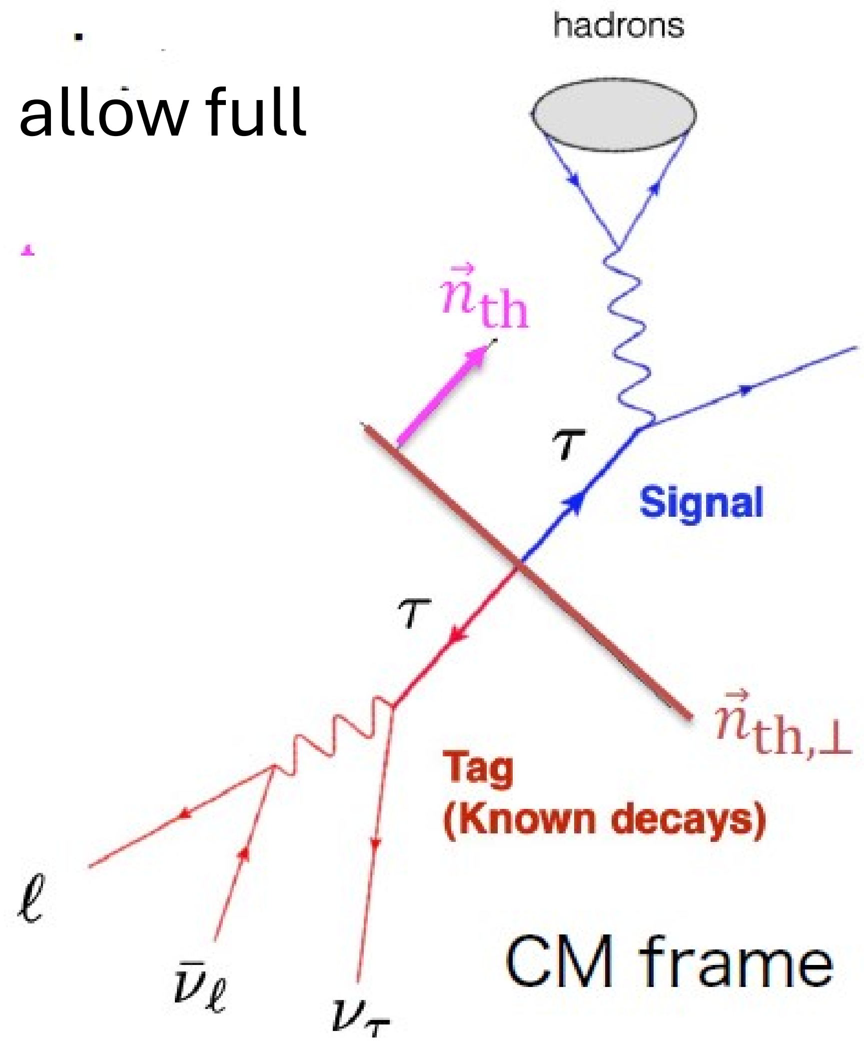
Why τ physics at the Υ(4S)?

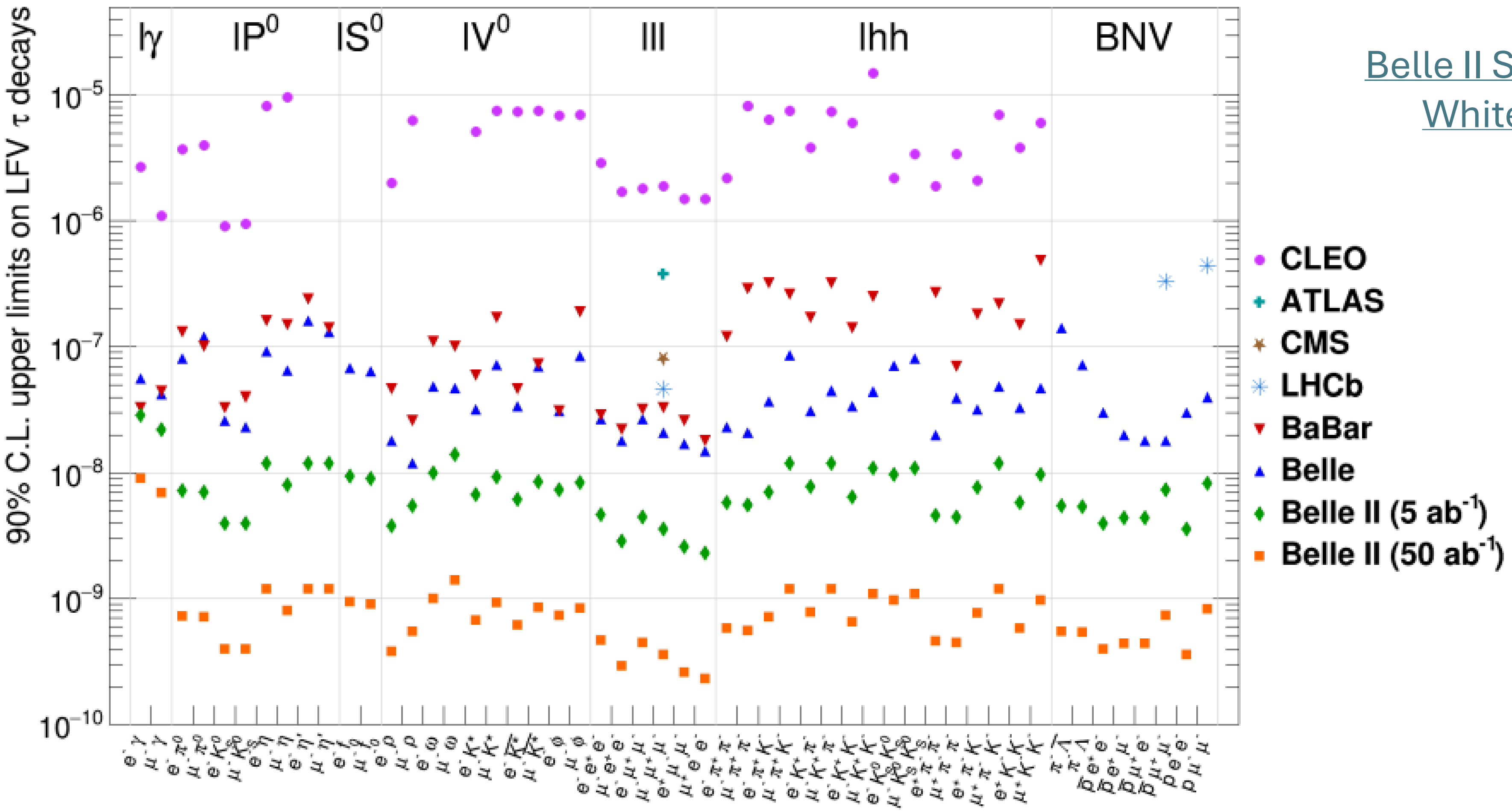
- The centre-of-mass energy of the B factories process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$
- Similar cross section for $e^+e^- \to \tau^+\tau^-$
- 920 million tau pairs per ab^{-1} of integrated luminosity
- **A tau factory too**



How to reconstruct a τ lepton at Belle (II)

- Missing energy from neutrinos does not allow full reconstruction
  - Identify using the thrust axis $\vec{n}_{\mathrm{th}}$
    - maximizes the momentum projection
  - Divide event into two hemispheres
- Signal side
  - e.g. $\tau \to \nu$ + hadrons
- Tag side: a standard model decay
  - single prong: $\tau \to l\nu\nu$ or $\tau \to \pi\nu + n\pi^0$
  - three prong decay: $\tau \to 3\pi\nu + n\pi^0$





[Belle II Snowmass White Paper]

Lepton-flavour violating searches

LFV: $\tau \to l V^0$ ($V^0 = \rho, \omega, \phi, K^*$)

- Forbidden in SM but enhanced many leptoquark models, c.f., R(D(*))

- $V^0 = \rho, \omega, \phi, K$
- Full data set of 980 fb^{-1}
- 3 and 1 prong tag: $3\pi\nu$, $l\nu\nu$, $\pi\nu$+up to $2\pi^0$
- Background suppression with BDT
- JHEP **06** (2023) 118

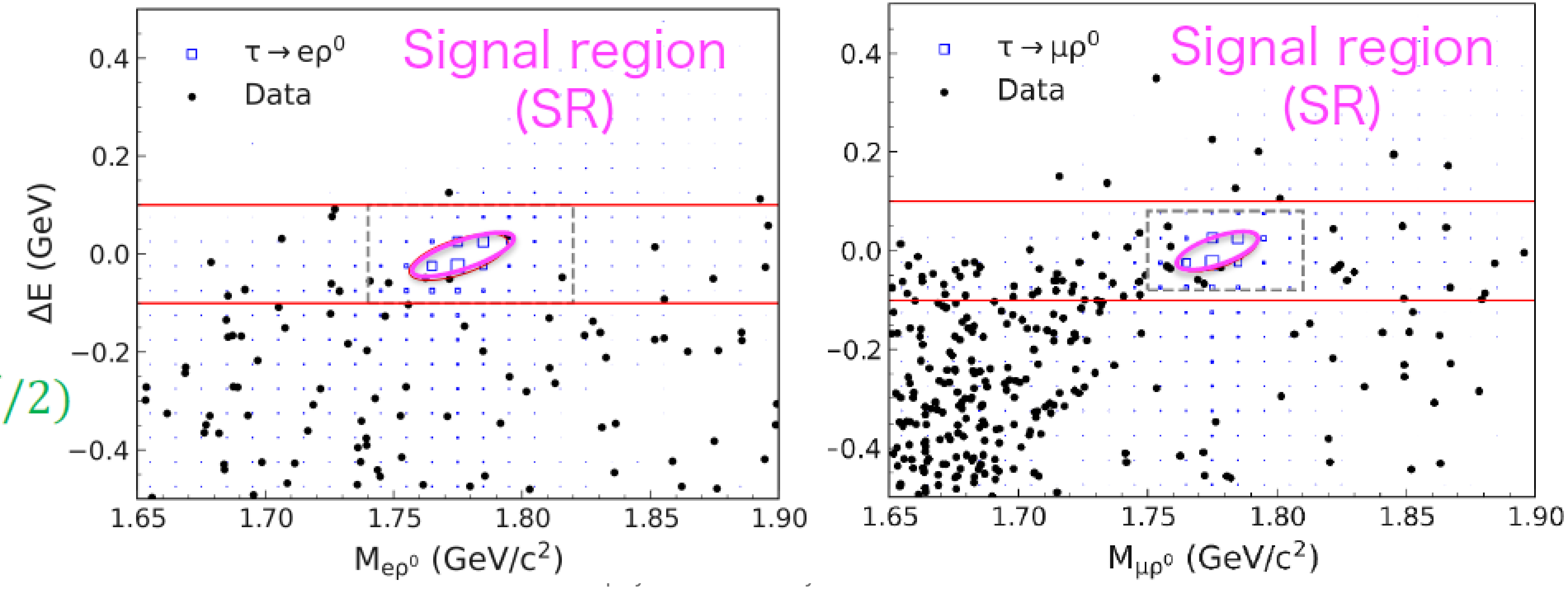
- $V^0 = \phi$
- Data set of 190 fb^{-1}
- **Inclusive tag**
- Background suppression with BDT
- arXiv:2305.04759

High efficiency key for best sensitivity: multivariate selection and inclusive tagging

LFV: Belle $\tau \rightarrow lV^0$ ($V^0 = \rho, \omega, \phi, K^*$) approach

- Tagged with 1-prong or 3-prong decay
- Background from $\tau \to 3\pi\nu$ and $ee \to qq$ suppressed with a boosted decision tree (BDT)
- Prepared separate BDT classifier for each lV^0 mode

$$\Delta E = (E^{\mathrm{CM}}_{\ell V^0} - \sqrt{s}/2)$$



LFV: Belle $\tau \to lV^0$ ($V^0 = \rho, \omega, \phi, K^*$) results

No significant excess in all ℓV^0 modes

World leading results

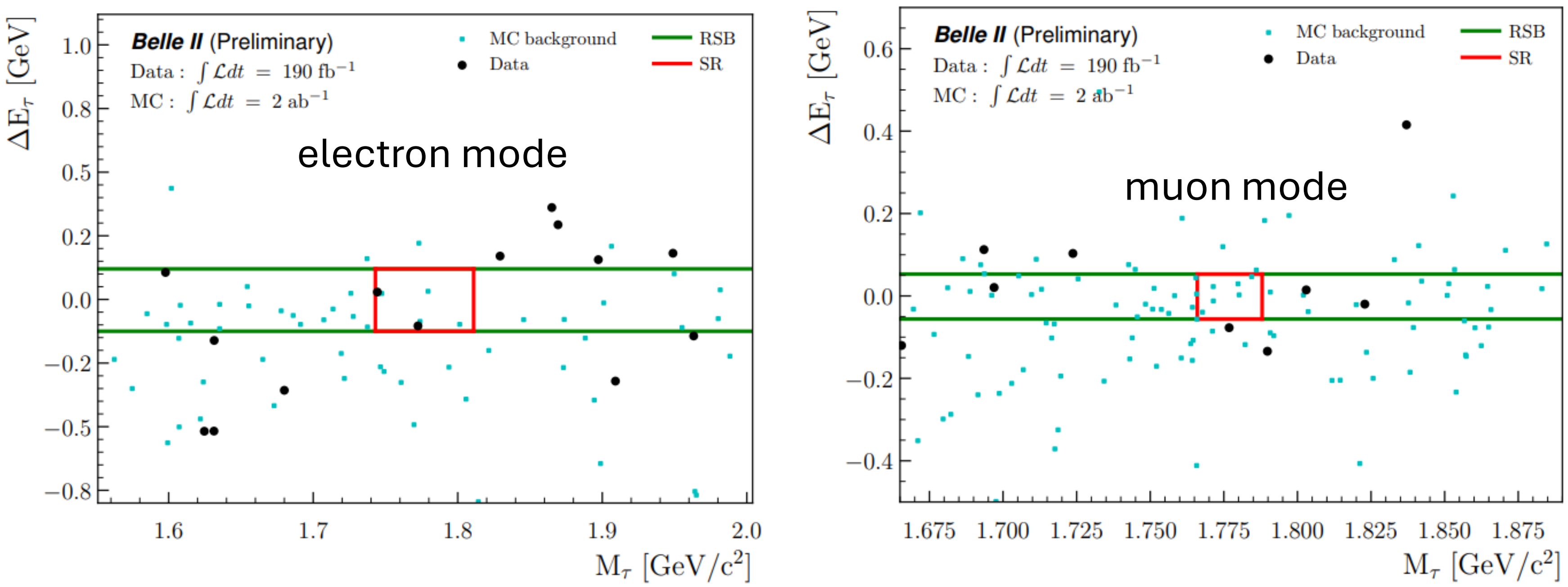
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3 *
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0 *
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9 *
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4 *
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9 *
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9 *
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3 *
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7 *

Counting method 90% confidence levels

30% improvement over previous measurements

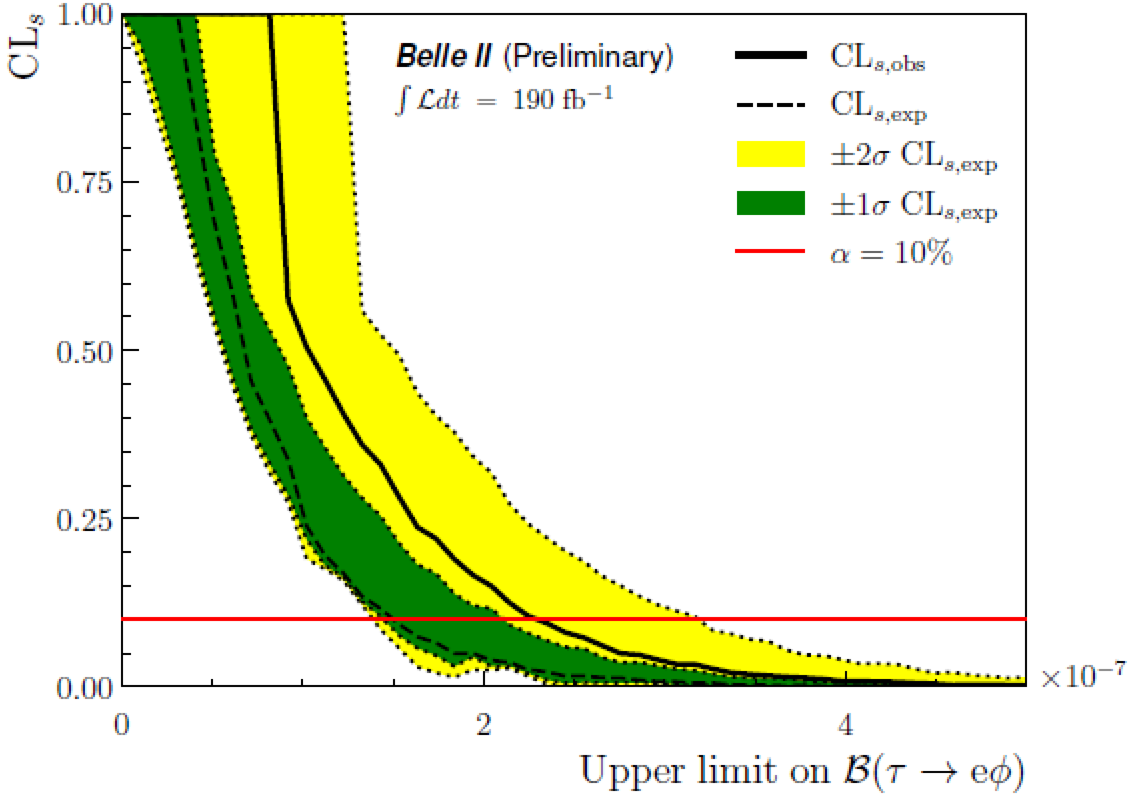
LFV: Belle II τ→lϕ approach

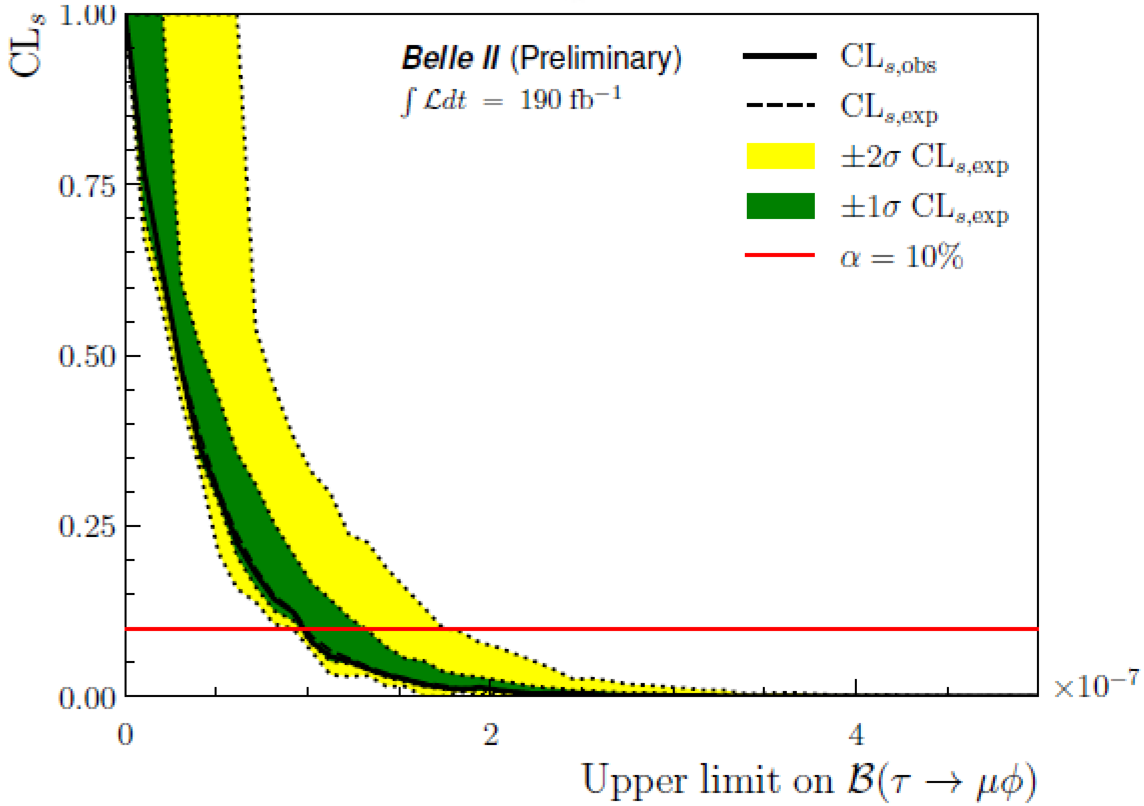
- Untagged: train BDT inclusively to discriminate from background
  - event shape variables, signal kinematics, ϕ mass and rest-of-the-event, i.e., tracks and clusters not used to reconstruct signal
  - 6% efficiency – twice Belle



LFV: Belle II τ→lϕ results

Not competitive with the Belle results
But first application of the inclusive tag



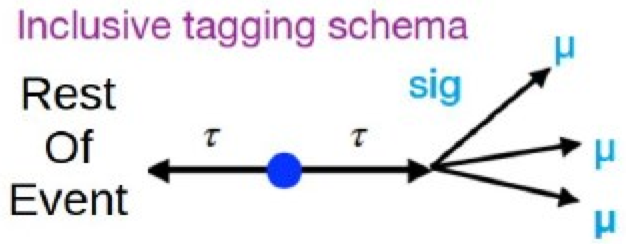


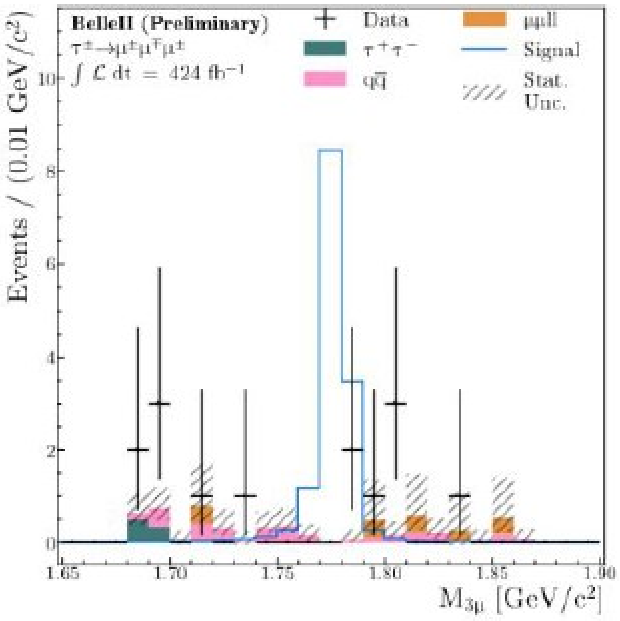
Obs. $B_{\text{UL}}(\tau \to e\phi) = 23\times10^{-8}$
Exp. $B_{\text{UL}}(\tau \to e\phi) = 15\times10^{-8}$

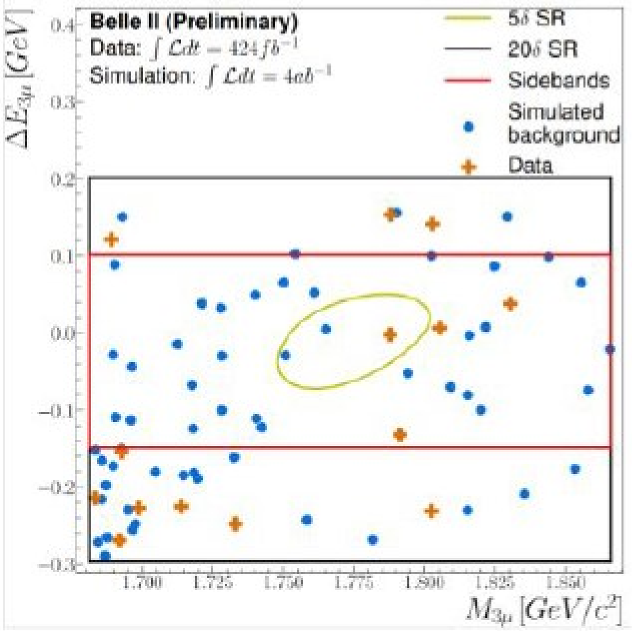
Obs. $B_{\text{UL}}(\tau \to \mu\phi) = 9.7\times10^{-8}$
Exp. $B_{\text{UL}}(\tau \to \mu\phi) = 9.9\times10^{-8}$

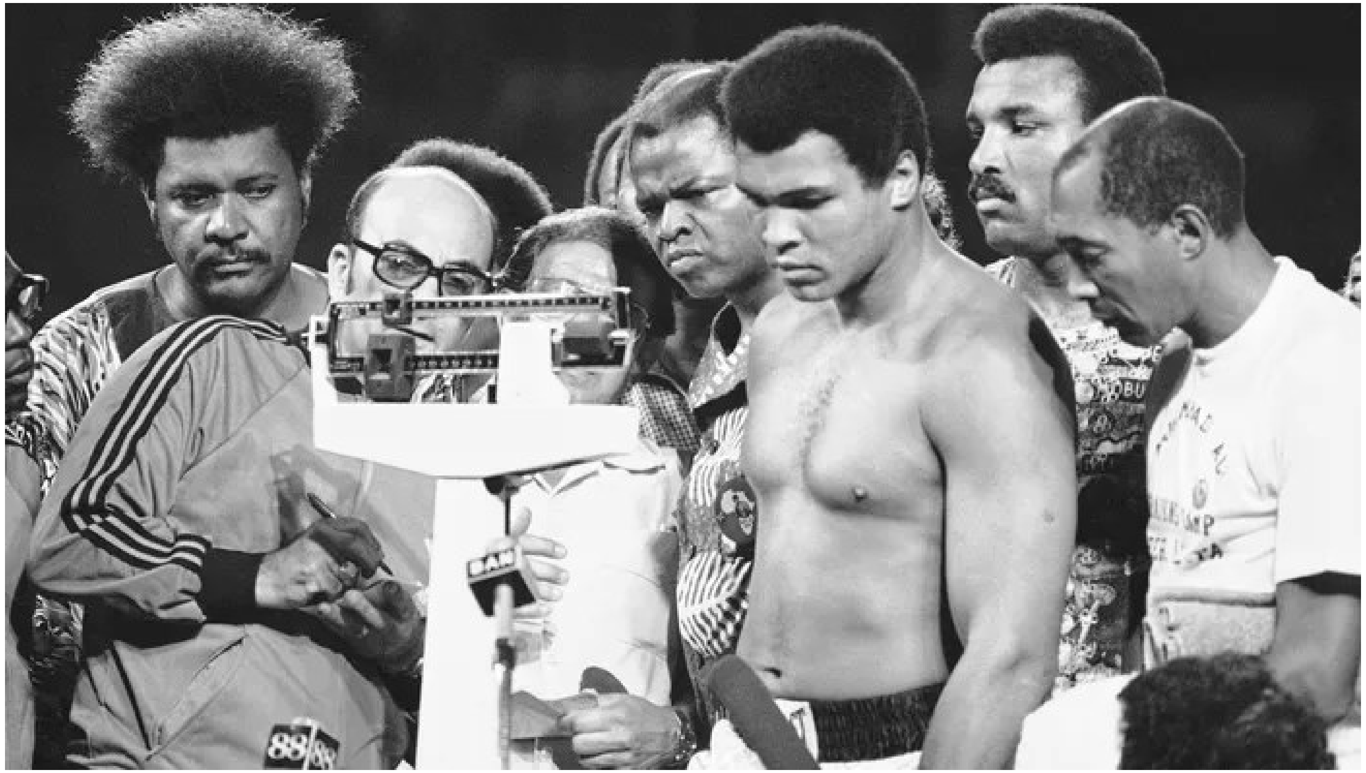
τ→3μ– lepton flavour violation search

- Inclusive tag of the non-signal τ to increase efficiency – multivariate
- Cut ‘n’ count in 2D plane of
  - $M_{3\mu}$ and $\Delta E = E_{3\mu} - E_{beam}$ (in c.m.)
  - Sideband derived background estimate $0.5^{+1.4}_{-0.5}$ events
- One event observed
- World best limit
  - **BF < 1.9×10^{-8} (90% c.l.)**
- Area of competition
  - LHCb BF < 4.1×10^{-8} (Run 1 only)
  - CMS BF < 2.9×10^{-8} (Run 1+2)









“Ali’s weight was announced as 206 pounds. He had not been so low in years: 216 pounds came through as the correction. A miscalculation of the kilos. A whistle from the press. He was four to eight pounds heavier than he said he would be, a poor prospect for his ability to dance and run”, *The Fight*, Norman Mailer

Heavyweight weigh-in: τ mass measurement:

Phys. Rev. D **108**, 032006 (2023)

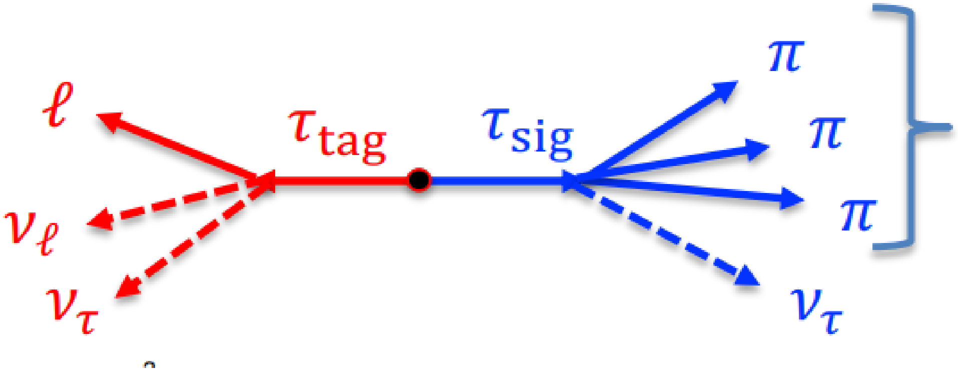
τ mass measurement

- Fundamental parameter of the standard model
  - Important input to lepton-flavour-universality tests

$$R_e = \frac{\mathcal{B}[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}{\mathcal{B}[\mu^- \to e^- \bar{\nu}_e \nu_\mu]} \qquad \left(\frac{g_\tau}{g_\mu}\right)_e = \sqrt{R_e \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^3}{m_\tau^3} (1+\delta_W)(1+\delta_\gamma)}$$

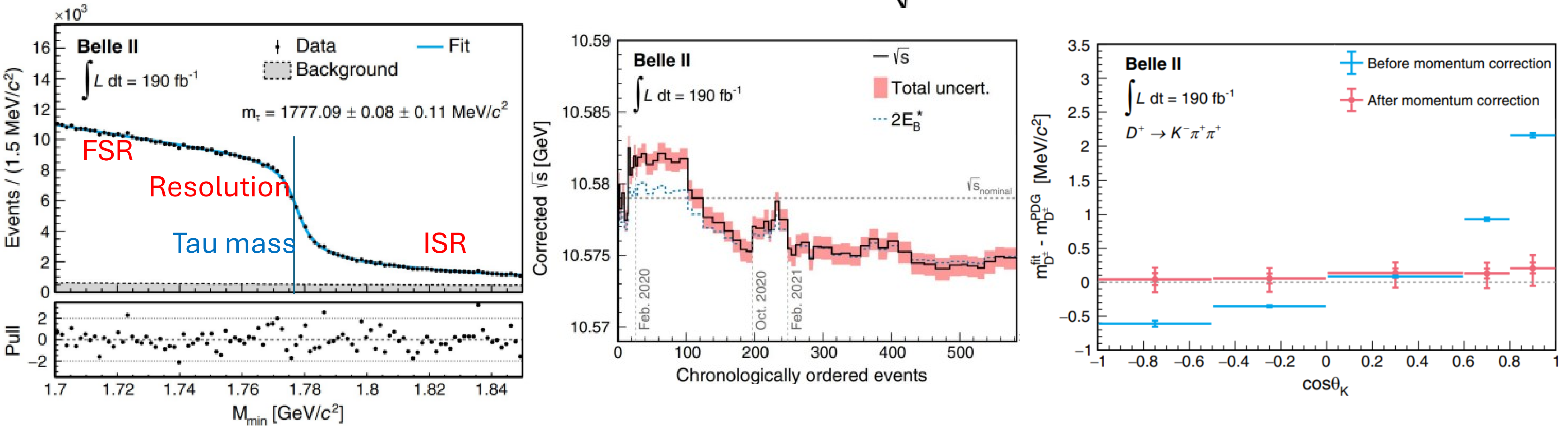
(δs are radiative corrections)

- We use the pseudomass variable to determine mass



$$M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau$$

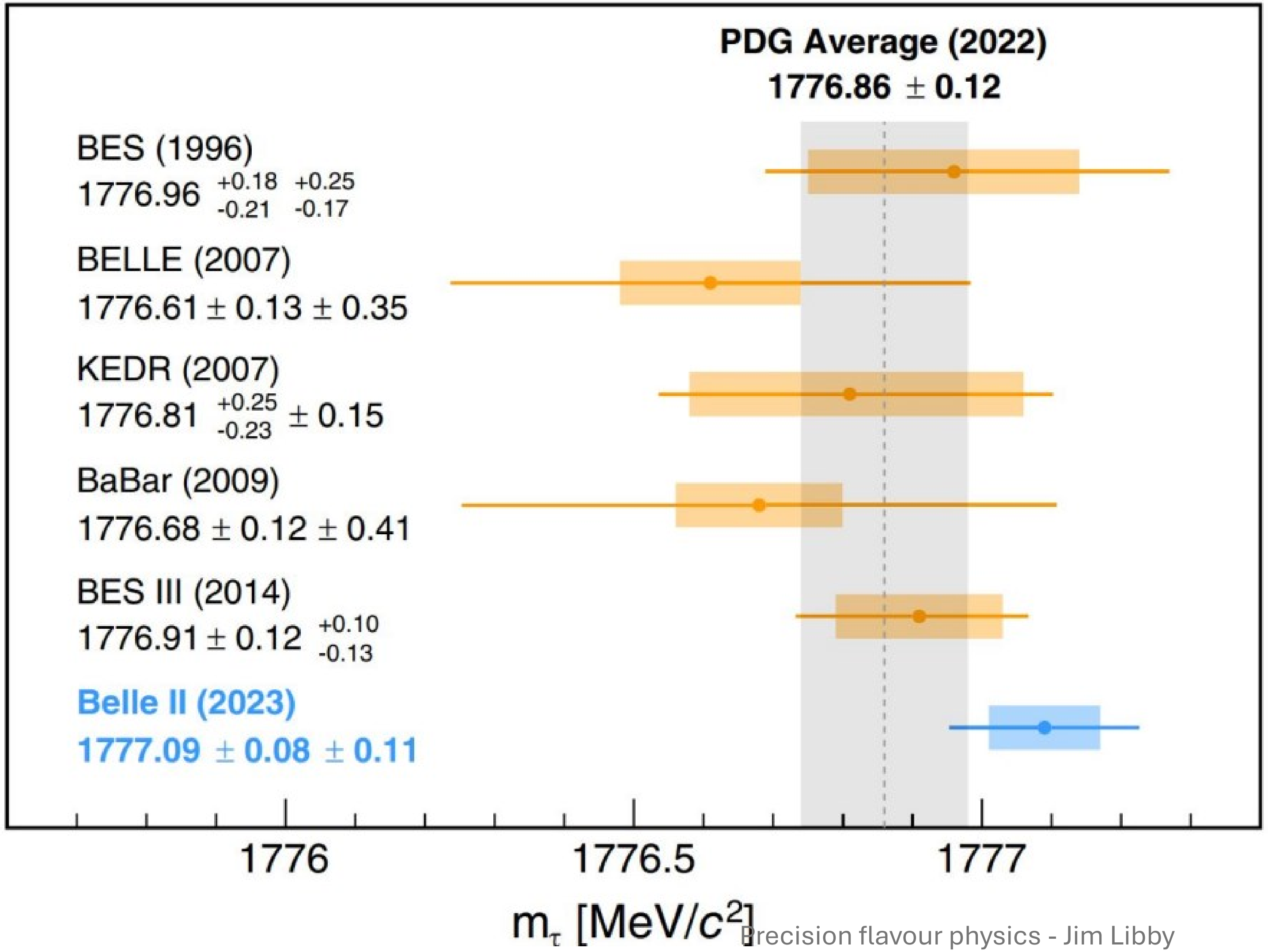
τ mass measurement $M_{\min} = \sqrt{m_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})(E_{3\pi} - |\vec{p}_{3\pi}|)} \leq m_\tau$



- Fit to distribution with analytic form that accounts for ISR/FSR and resolution
- Knowing the scale key:
  - beam energy (from E_B*) and
  - momentum (from D mass)

Phys. Rev. D **108**, 032006 (2023)

τ mass measurement

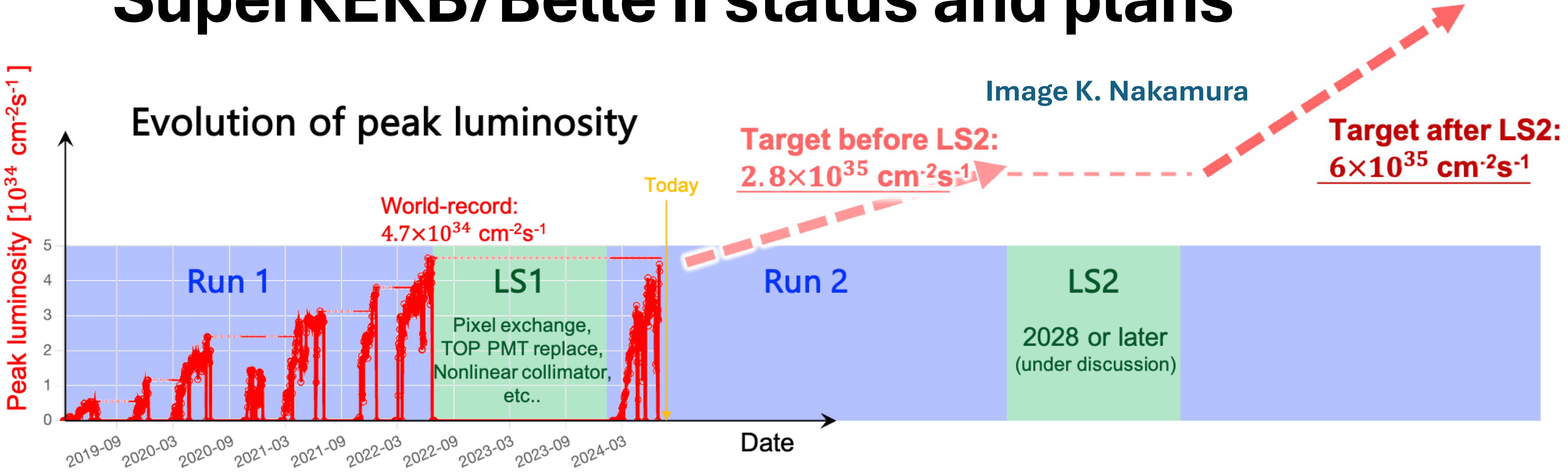


World's most precise measurement to date
- dominant systematics from beam energy and momentum scale

Outlook

JL ICHEP

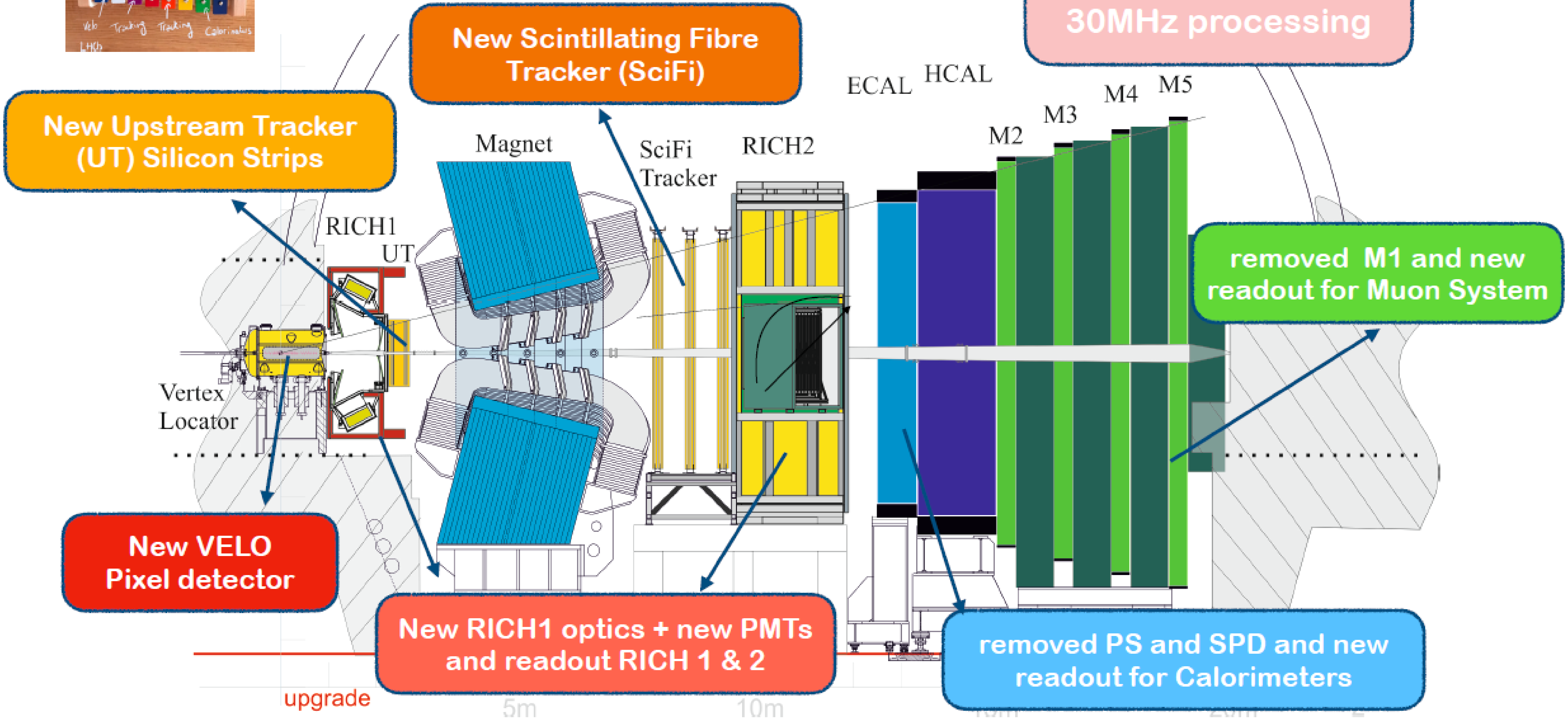
SuperKEKB/Belle II status and plans



- Run 2 is long – end 2028 or later
  - Steady accumulation at ~2 x 10^{35} $cm^{-2}s^{-1}$ for several ab $^{-1}$ – 2nd generation
  - After Run 2 – upgrade proposal for reach design luminosity and tens of ab $^{-1}$
    - Talks by K. Nakamura and M. Roney (polarized beams) – Framework CDR arXiv:2406.19421

Y. Amhis ICHEP 2024

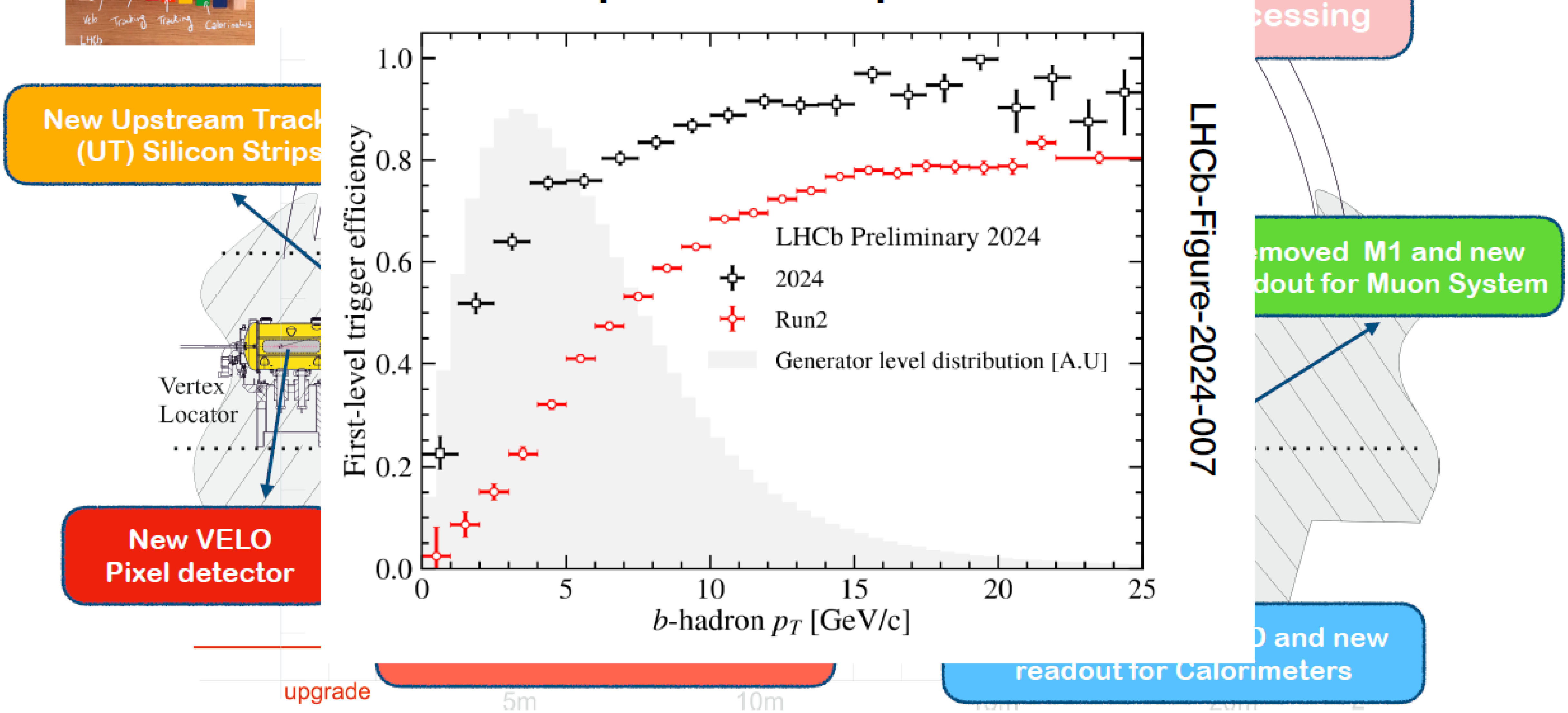
FULL SOFTWARE TRIGGER
30MHz processing



Major upgrade of all sub-detectors and readout

The LHCb Upgrade I arXiv:2305.10515

[Y. Amhis ICHEP 2024]



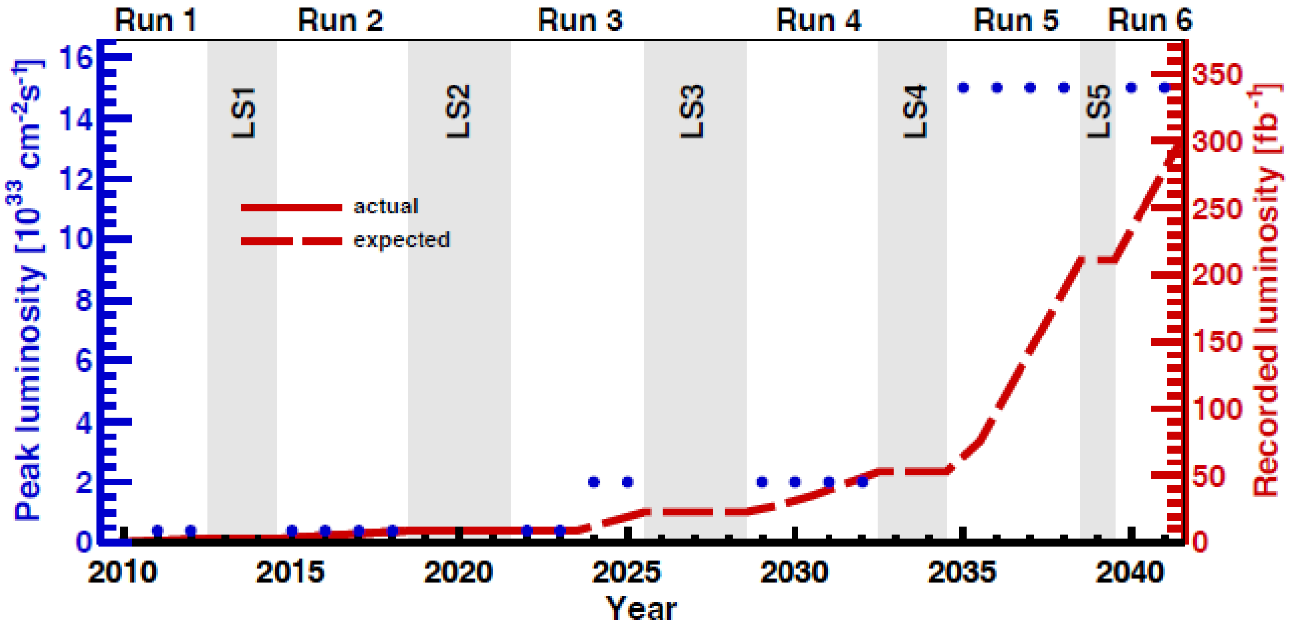
Major upgrade of all sub-detectors and readout

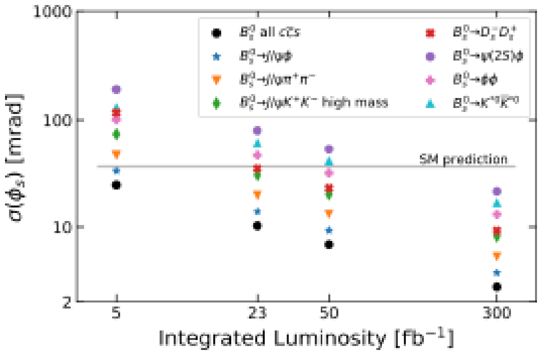
[The LHCb Upgrade I arXiv:2305.10515]

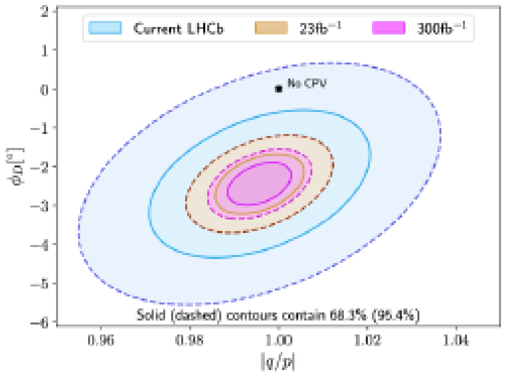
Upgrade II

Y. Amhis ICHEP 2024

Physics programme limited by detector,
so there's a clear case for
an ambitious plan of upgrades
covering the full HL-LHC phase

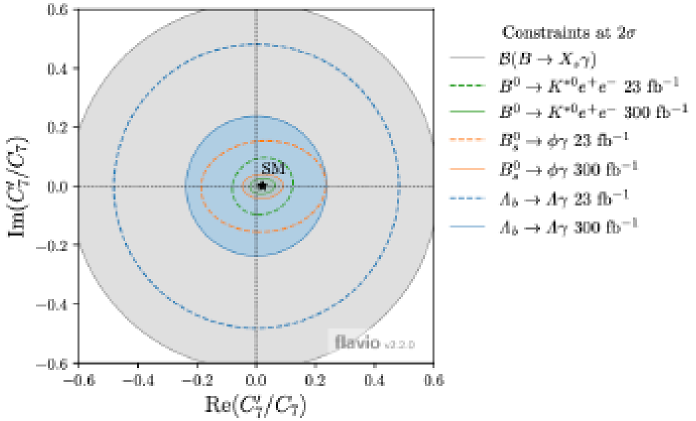






LHCB-TDR-023

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



Far future: FCC-ee

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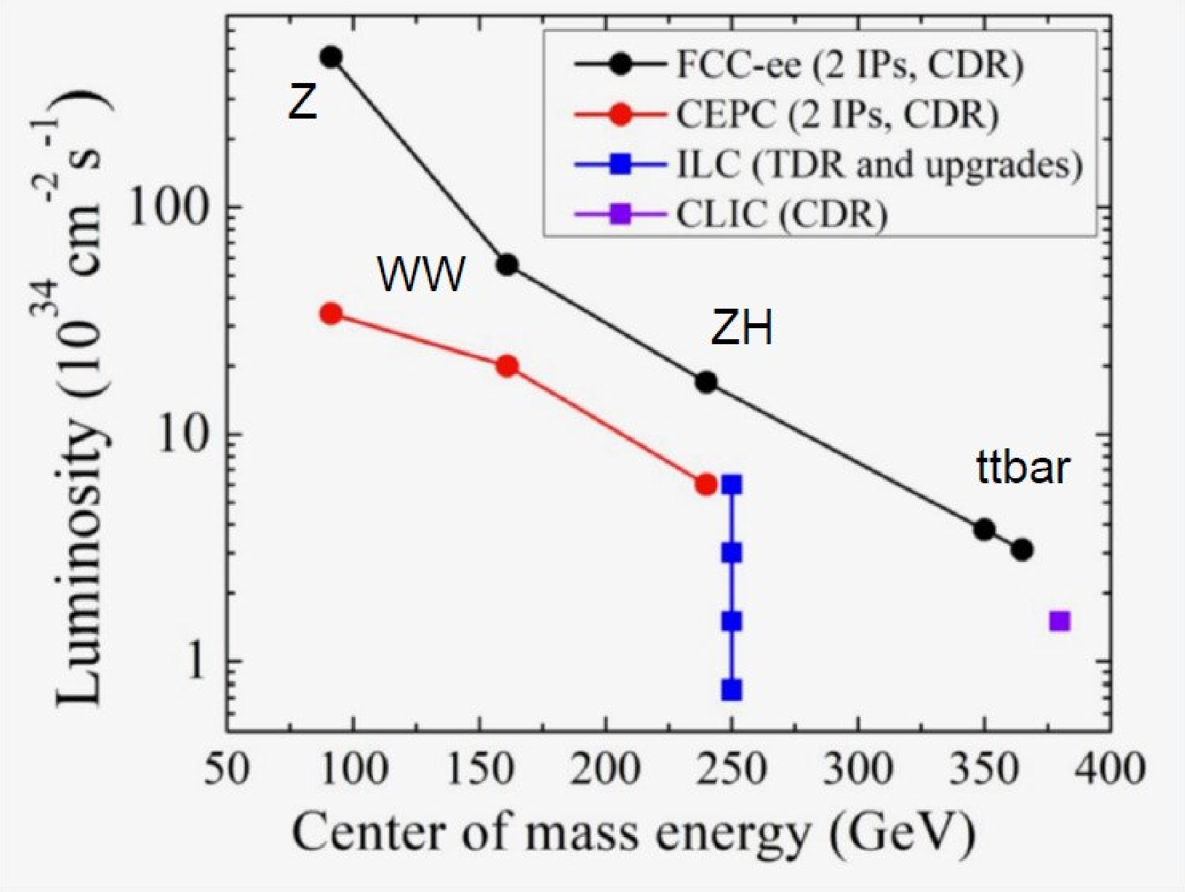

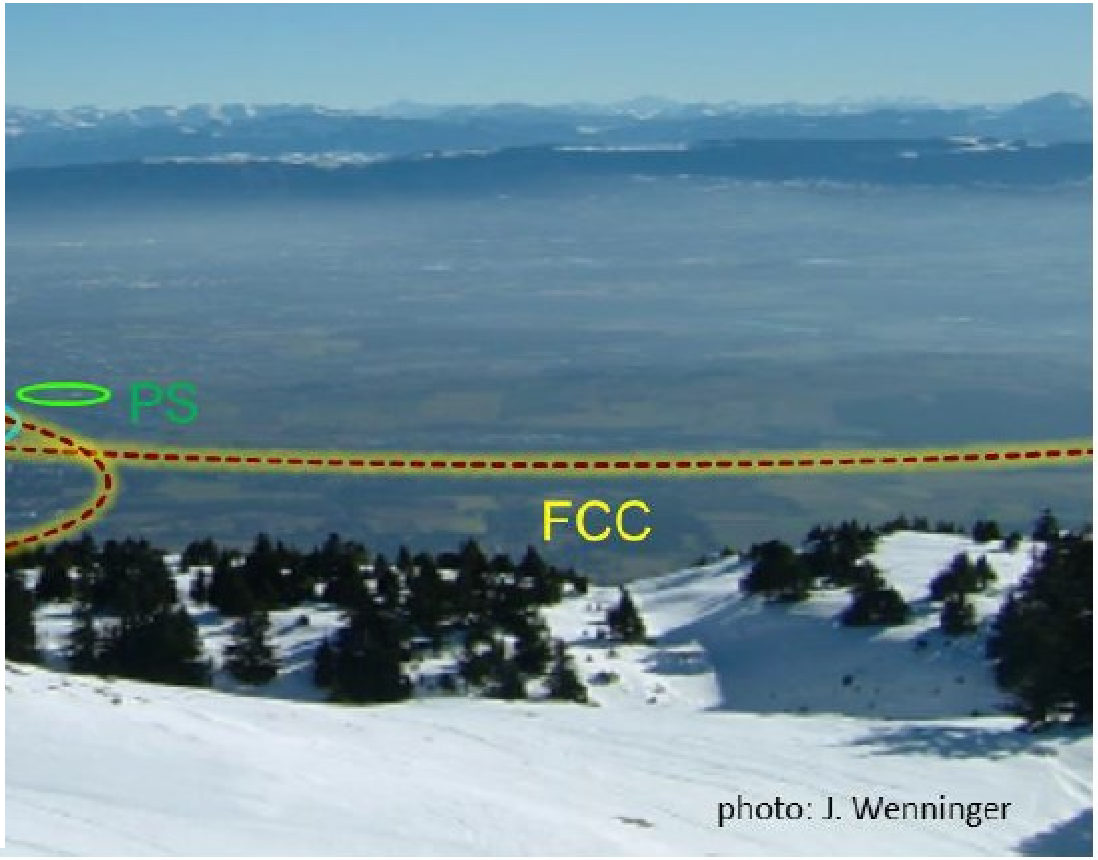

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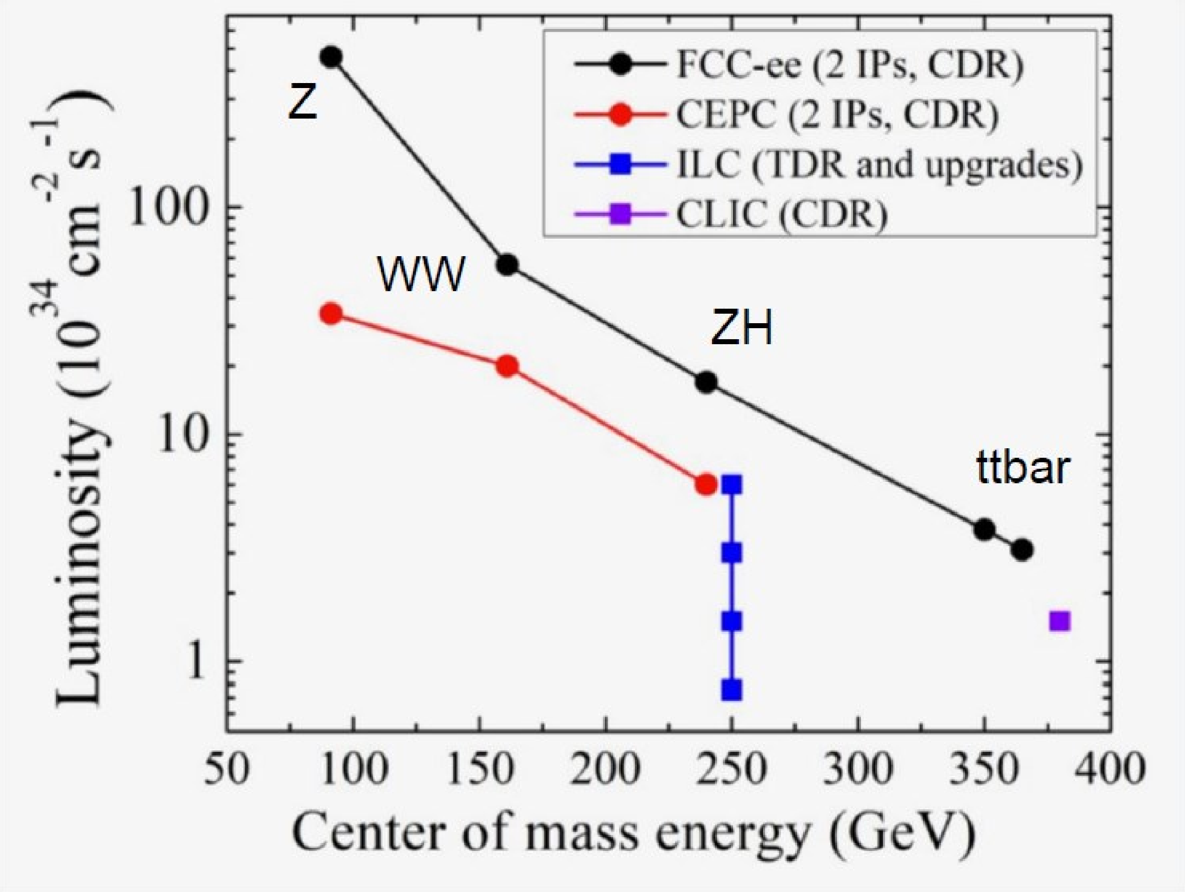
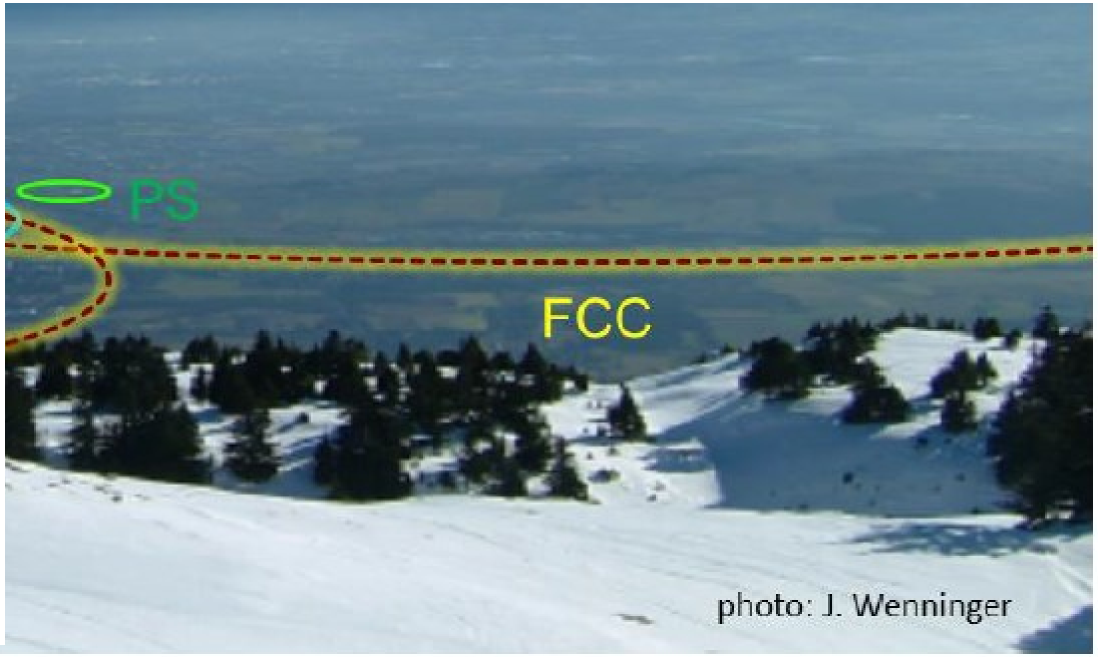


	Y(4S)	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production x-sec		✓	
Negligible trigger losses	✓		✓
Low background environment	✓		✓
Initial energy constraint	✓		(✓)



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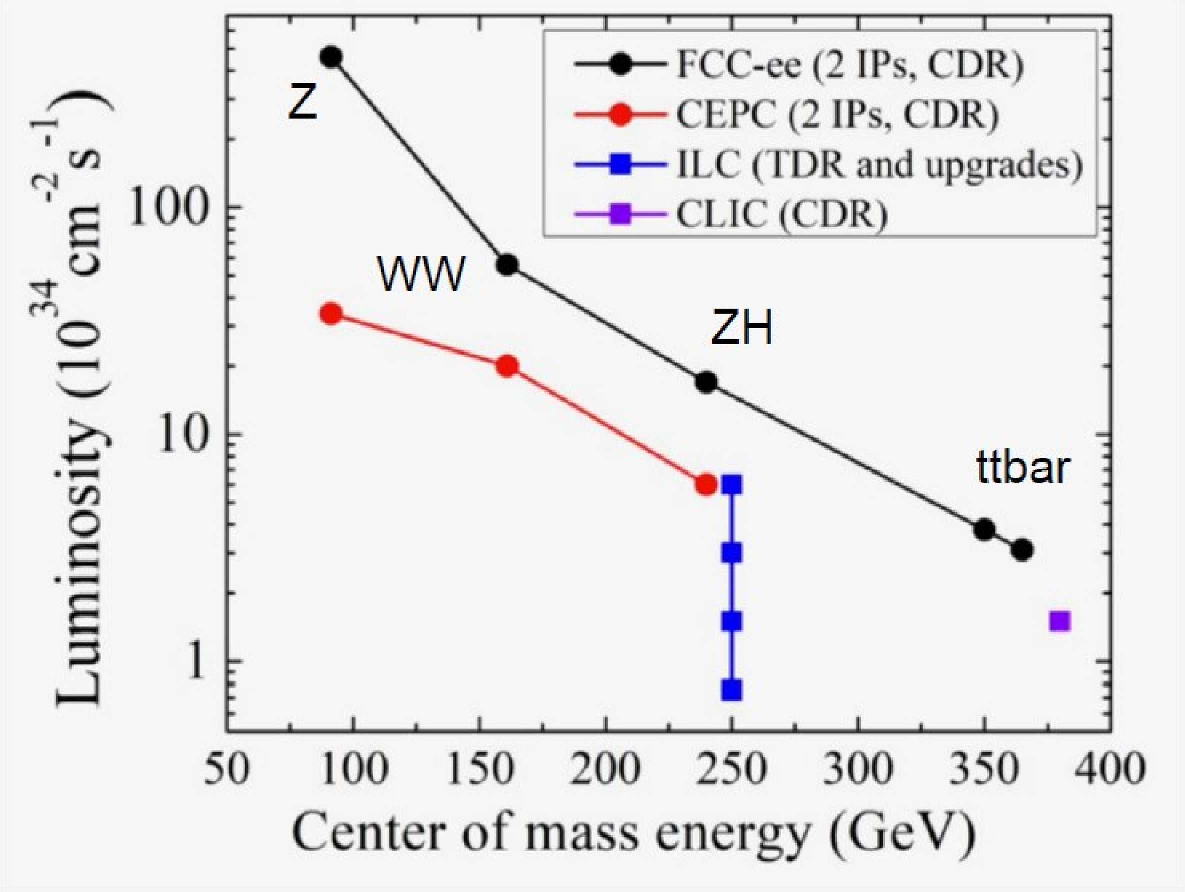

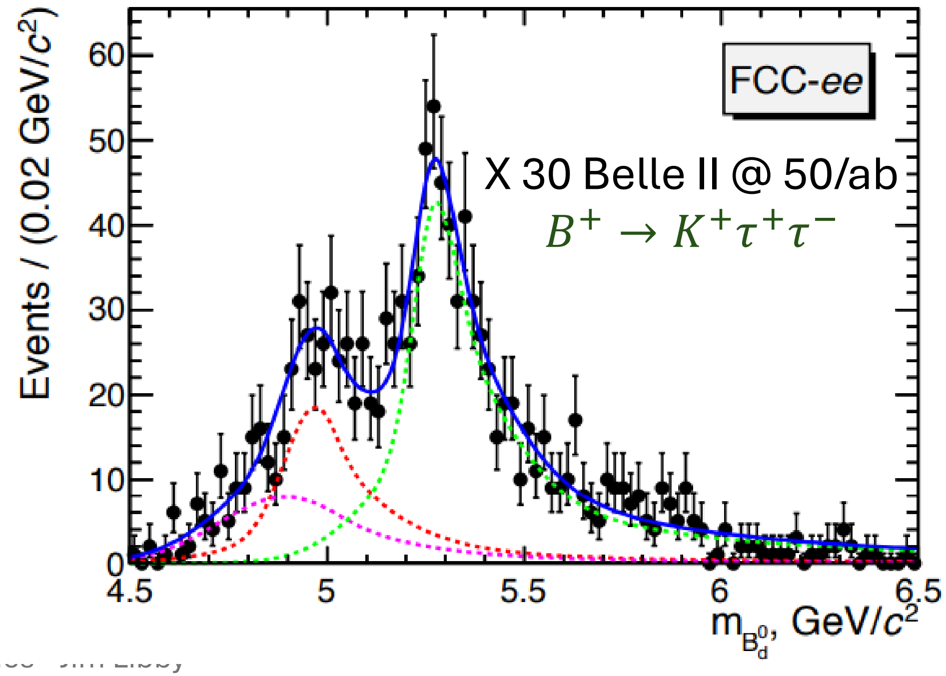

SSI 2024

SSI 2045-if I'm lucky

Another use of ML in HEP

Conclusion

- Flavour measurements at LHCb and Belle II are very much in the precision era
  - CKM physics
  - Searches for rare decays
  - Charm and tau physics
- Both experiments plan for another decade or more so precision will be ever more important
  - Also LHC general purpose experiments more and more interested in flavour for the HL-HLC era – see M. Pierini at ICHEP
  - Already lead the way for some states with muons
- For you (if not for me) – a Higgs factory Tera-Z programme would have a substantial flavour component