Flavour Physics: current experimental status and prospects

Monica Pepe Altarelli (LNF/INFN)

Corfu Workshop on Future Accelerators – Corfu, 19-26 May 2024

Many mysteries related to flavour..

- Why three generations? What determines the observed pattern of masses and mixing angles of quarks and leptons? …
- Sizeable CP violation expected in many b decays and CP violation is connected to origin of matter-antimatter asymmetry in Universe
- Where did the antimatter go? Why is the universe globally asymmetric?
- The observed baryon asymmetry of the Universe requires CPV beyond the SM (CKM matrix)
  - Not necessarily in flavour changing processes, nor necessarily in the quark sector, it could originate from the lepton sector

Flavour physics as a tool of discovery

- Test, how precisely the SM description of flavour and CP violation holds through :
  - consistency checks of the CKM paradigm
  - the study of rare decays (eg, $b \to s\ell^+\ell^-$)
- Indirect approach to New Physics searches, limited by sample size, plus theoretical precision and intrinsic sensitivity (*intensity frontier*)
- Complementary to direct collider production of new particles, limited by available centre of mass energy (*energy frontier*)
- Indirect approach probes scales much higher than those accessible to direct searches.

A large experimental effort…

- Constraints coming from K mesons from. e.g., NA48 at CERN, KLOE at LNF, KTeV at FNAL
- Measurements of CKM parameters from D and B mesons pioneered by ARGUS at DESY, CLEO, and CLEO-c at CESR, Cornell, followed by the so-called B-factory experiments BaBar at SLAC and Belle at KEK
- Significant contributions from CDF and D0 at FNAL, especially on B_s^0 mesons
- All the above experiments have been terminated while Belle has been upgraded (Belle II)
- LHCb at the LHC is now dominating physics with b and c hadrons while the general purpose detectors ATLAS and CMS contribute in several key areas and Belle II has resumed data taking after a long shut-down
- BESIII in China provides many results on c hadrons, NA62 at CERN and KOTO at J-Parc measure very rare Kaon decays

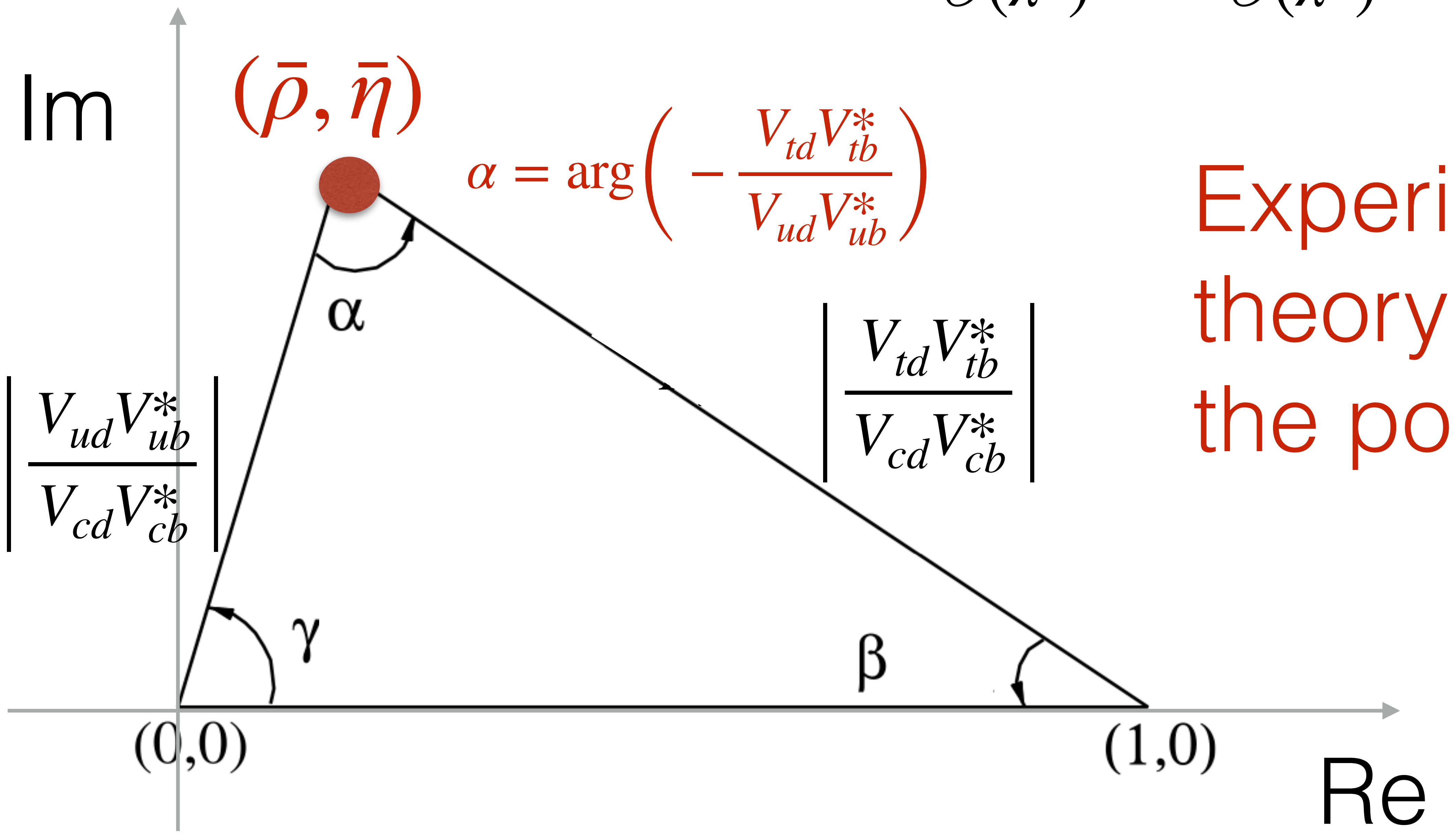
Unitarity conditions

- Unitarity of CKM matrix implies relations of the form $\sum_i V_{ij}V^*_{ik} = \delta_{j,k}$, with $j \neq k$
- Each of these 6 unitarity constraints can be seen as the sum of 3 complex numbers closing a triangle in the complex plane

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$

$\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^3)$ $\lambda = \sin\theta_c \approx 0.22$

CP violation in the quark sector ($\bar{\eta} \neq 0$) is translated into a non flat UT



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

$\beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$

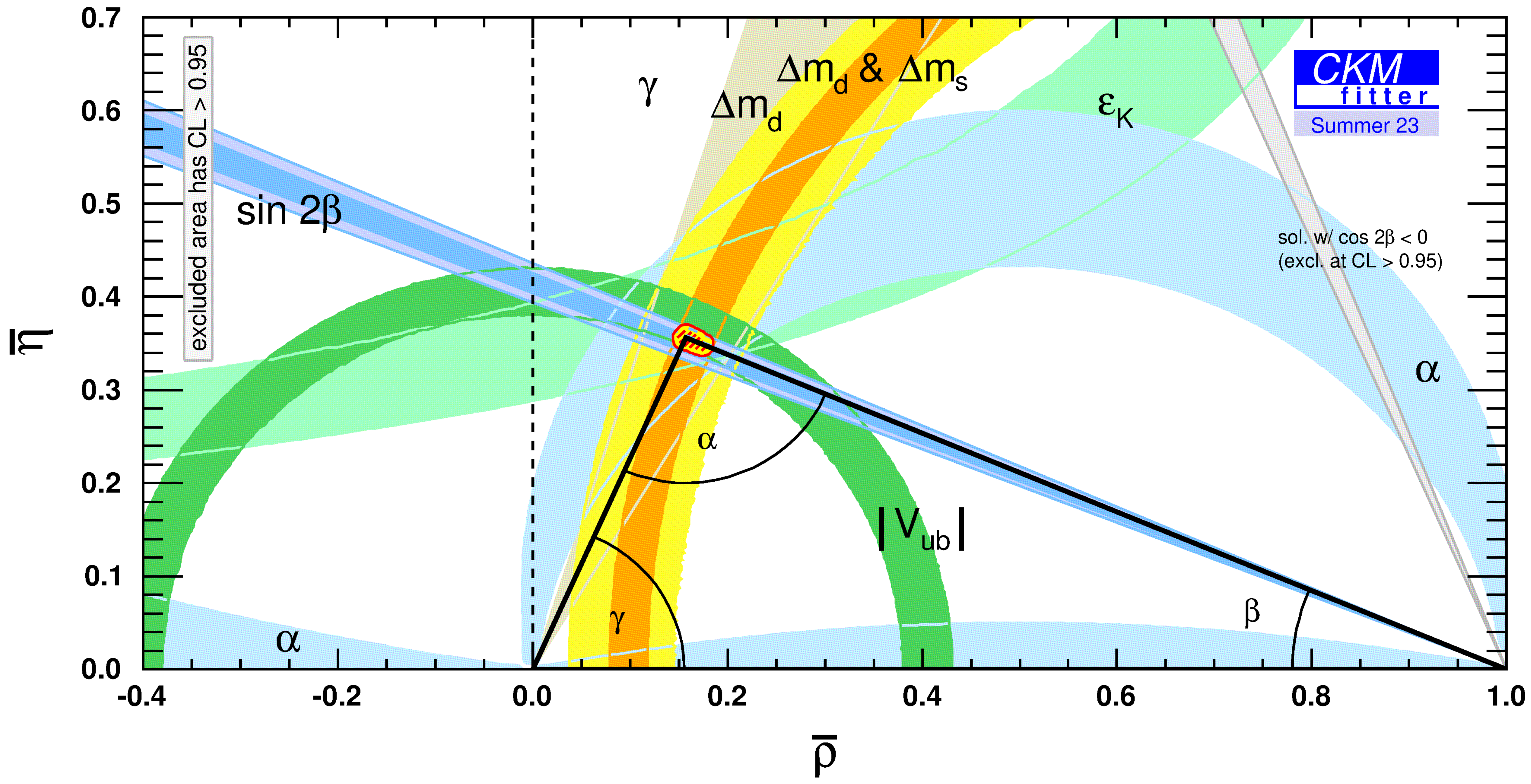
Experiments test the theory by constraining the position of the apex

Consistency tests of the CKM paradigm

- The physics impact of the measurements of the CKM elements is not so much in their absolute values (matrix is not predicted) but rather in testing the (in)consistency of the “ensemble” of measurements and how precisely the SM description of flavour and CP violation holds.

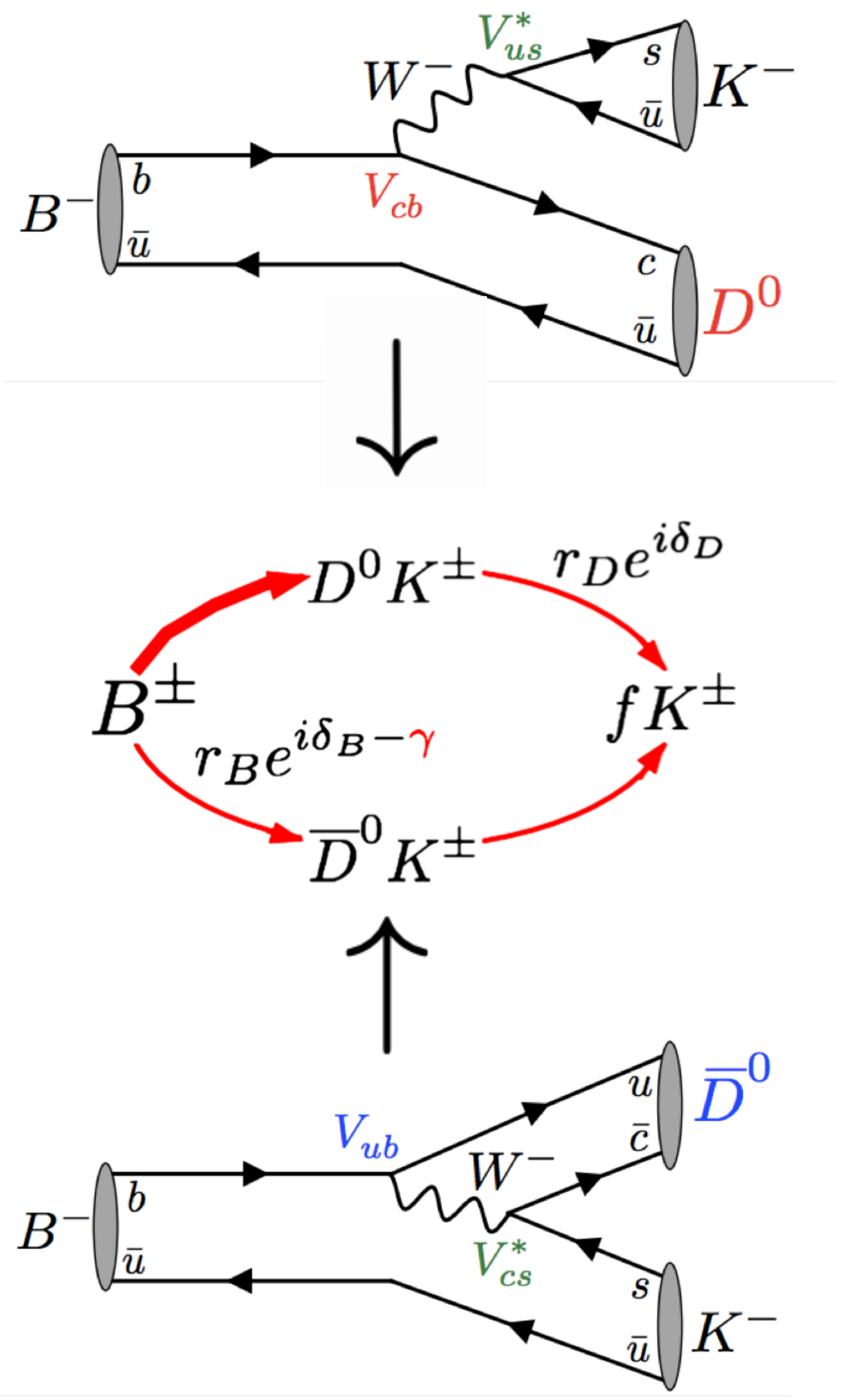
- “Redundant" measurements are performed, which test different combinations of flavour parameters

CKMfitter, similar plots from UTfit



Measuring the CKM angle γ

- The only angle that can be measured purely from tree-level decays
- Sensitivity through interference between $b \to c$ and $b \to u$ amplitudes in decays of the type $B \to DX$, with D an admixture of D^0 and $\overline{D}^0$ ($\to f$)
- Theoretically very clean (irreducible theory error $\lesssim O(10^{-7})$)
- Direct measurement from B decays: $\gamma = \left(66.5^{+2.8}_{-2.9}\right)^\circ$ (HFLAV), uncertainty below 3°, dominated by LHCb
- Check for deviations between direct measurement and indirect determinations from global CKM fits which assume validity of the SM : $\gamma = \left(66.3^{+0.7}_{-1.9}\right)^\circ$ (CKMfitter), and $\gamma = \left(65.2 \pm 1.5\right)^\circ$ (UTfit)



r_B: ratio of $b \to u$ and $b \to c$ amplitudes
r_D: ratio of $D^0 \to f$ and $\overline{D}^0 \to f$ amplitudes
δ_B, δ_D : strong phase differences

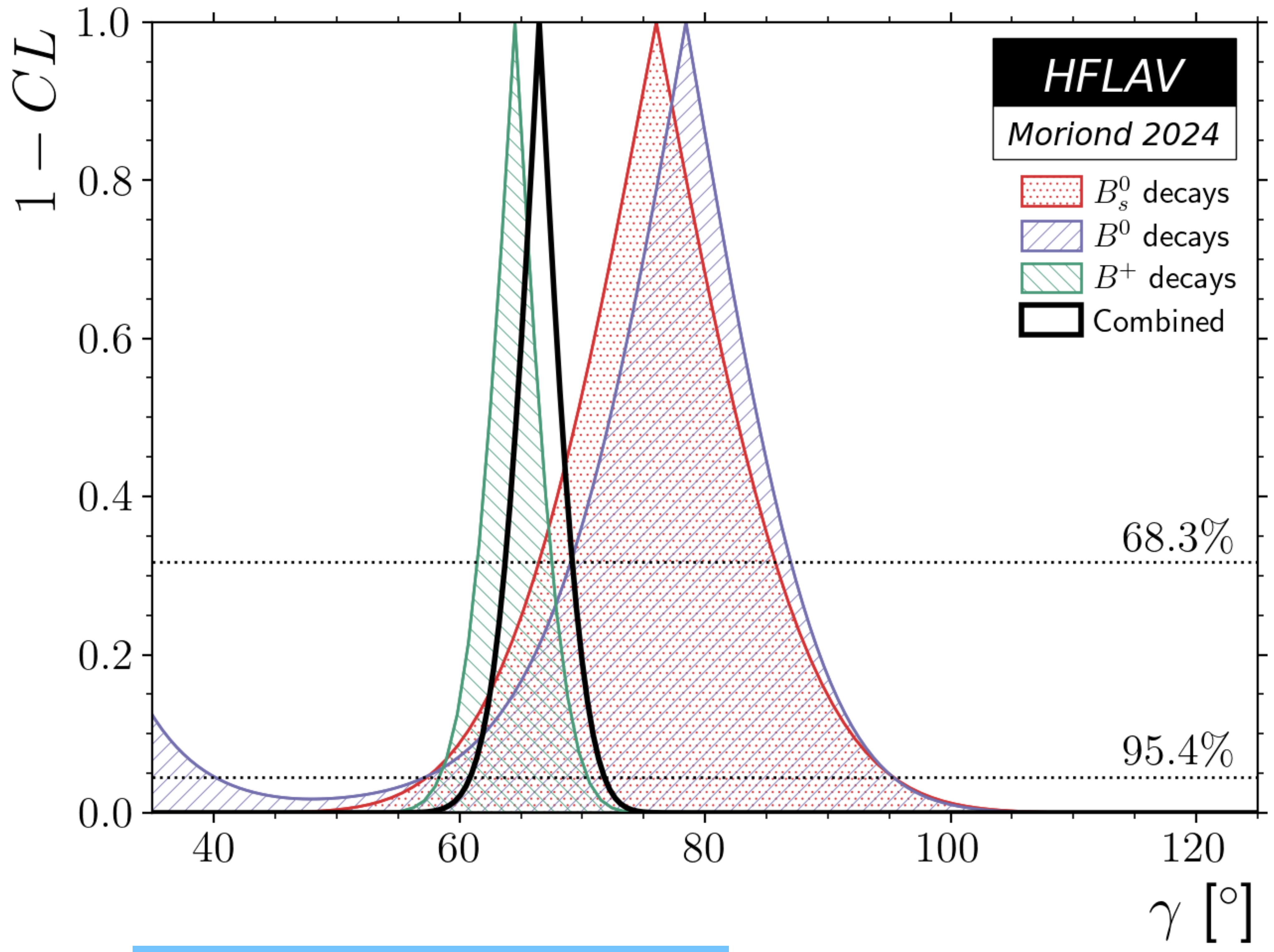
Measuring the CKM angle γ (LHCb)

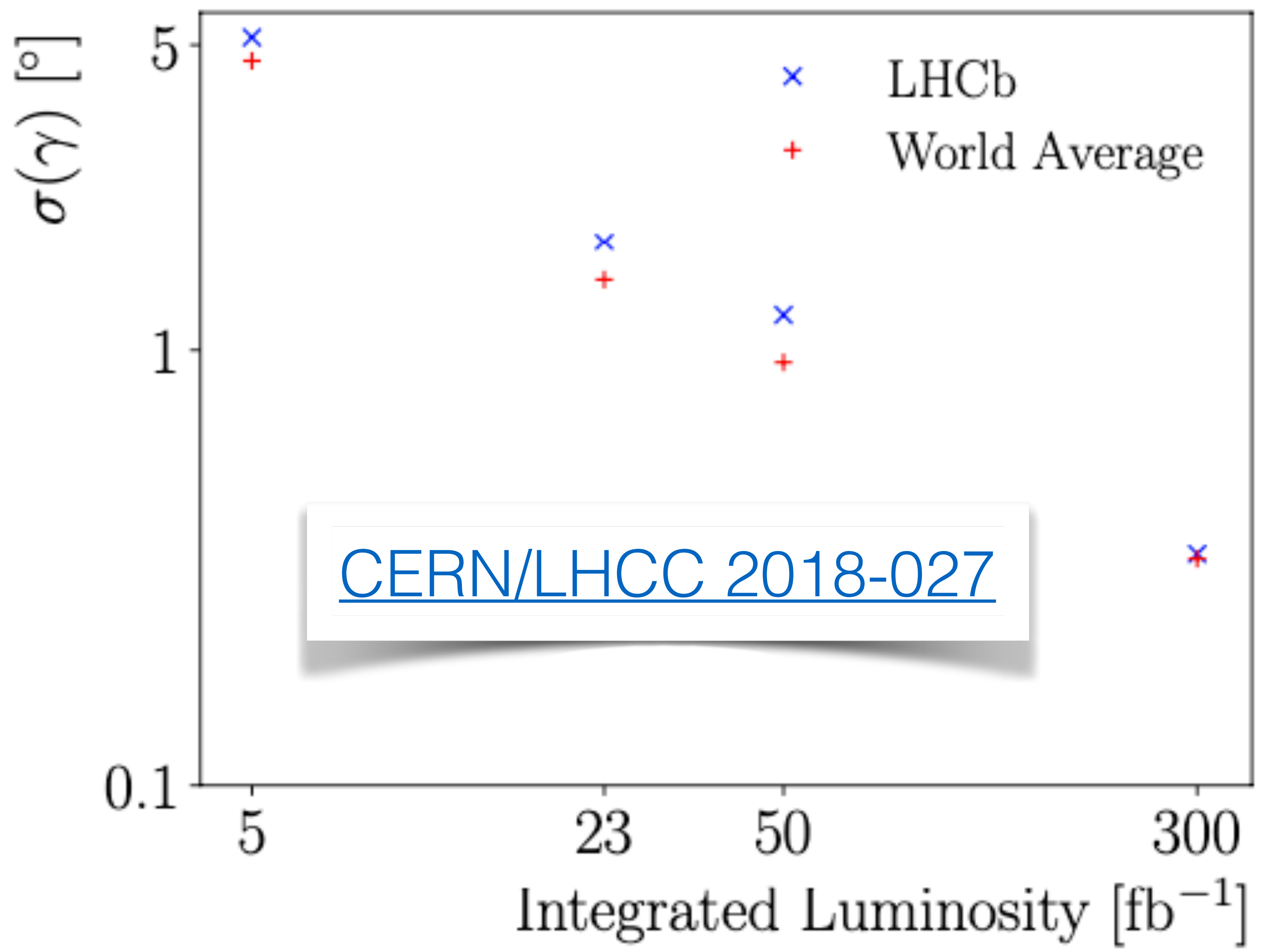
- Combination of many B decay modes
  - Time -integrated asymmetries in $B \to DK$, $B \to DK^*$ with $D \to hh$, $hh\pi^0$, $hhhh$
  - Dalitz plot analyses of $D^0 \to K^0_S h^+ h^-$ from $B \to Dh, B \to DK^*$
  - Time dependent analyses, e.g. $B^0_s \to D_S K, B^0 \to D\pi$
- Measurements sensitive to charm mixing also included in the combination

B decay	D decay	Dataset
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	Run 1&2
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	Run 1&2
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	Run 1&2(*)
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2(*)
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	Run 1&2(*)
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	Run 1&2

LHCB-CONF-2022-003

Measuring the CKM angle γ





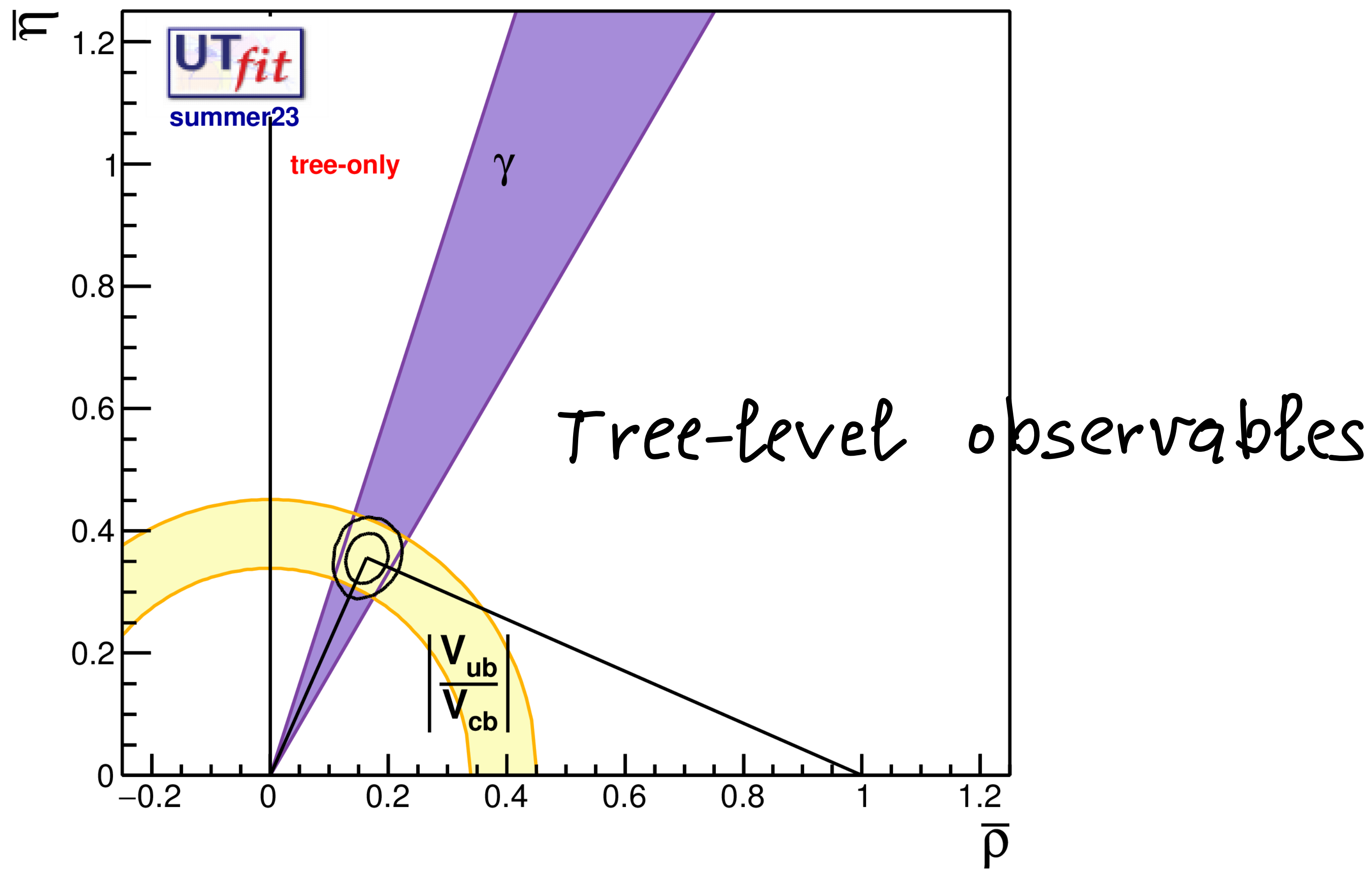
$\gamma = \left(66.5^{+2.8}_{-2.9}\right)^\circ$ ~4% uncertainty   Uncertainty on α is ~4°

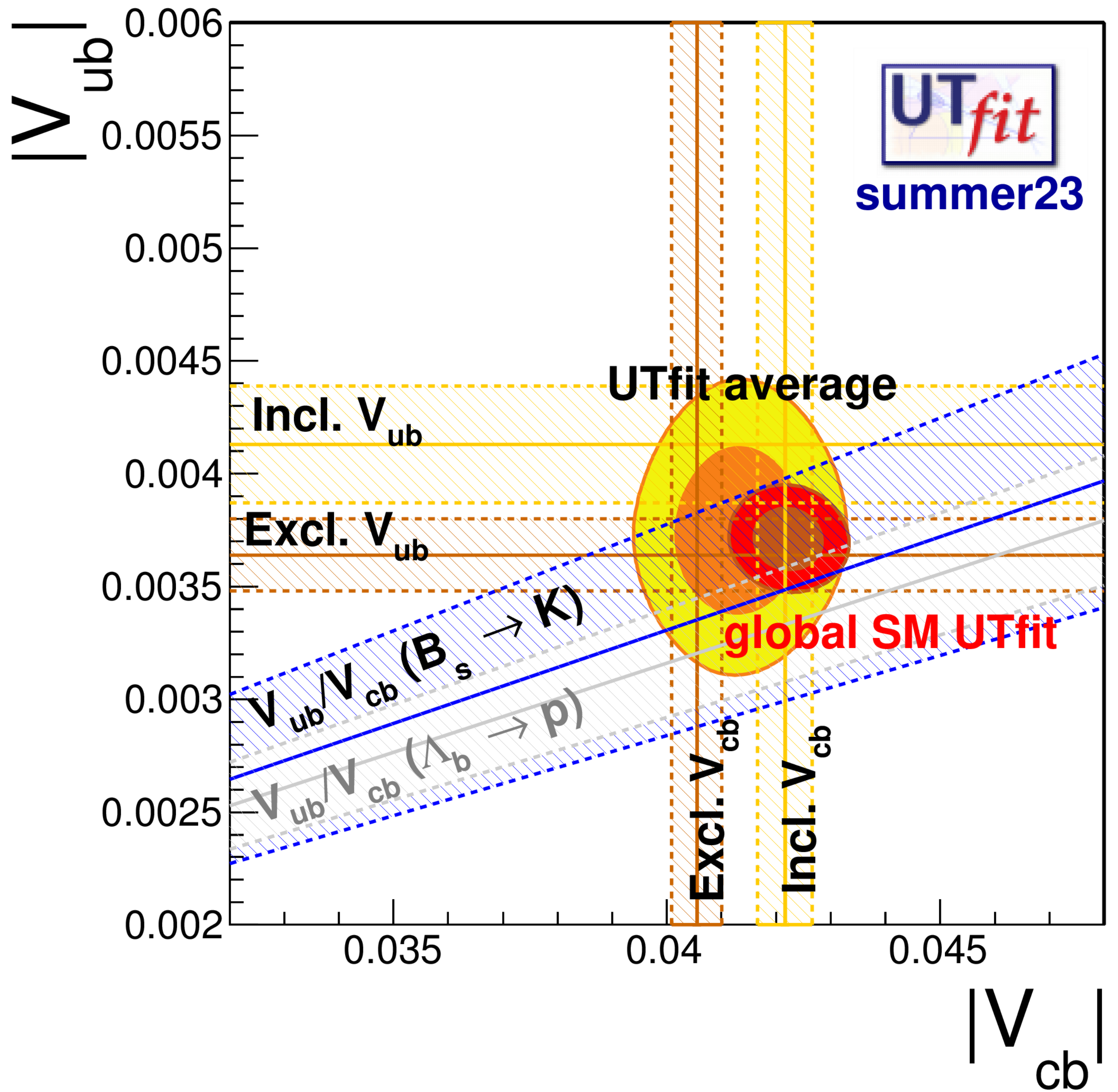
- In excellent agreement with CKM fit predictions $\gamma = \left(65.2 \pm 1.5\right)^\circ$ (UTfit), $\gamma = \left(66.3^{+0.7}_{-1.9}\right)^\circ$ (CKMfitter)
- Uncertainty still statistically dominated (LHCb: contribution of syst. uncertainties $\sim 1.4^\circ$)
- To reach ultimate sensitivity one will need input on hadronic D parameters from the analysis of future larger datasets at BESIII (quantum-correlated $D\overline{D}$ pairs from $\psi(3770) \rightarrow D\overline{D}$)

$|V_{ub}|$ and $|V_{cb}|$

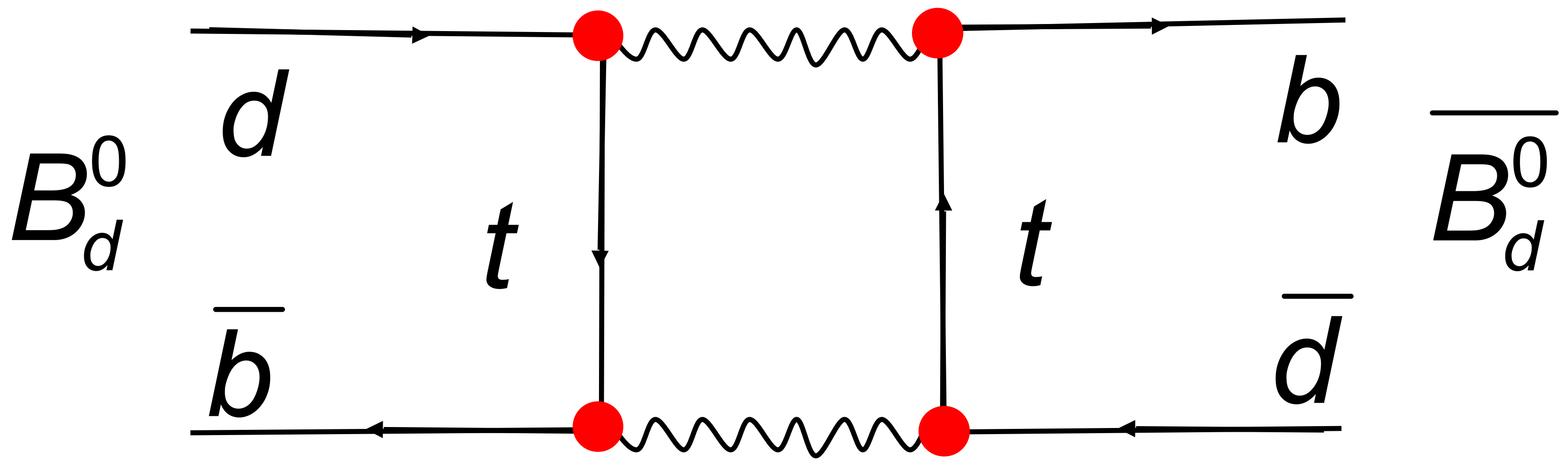
UTfit, similar plots from CKMfitter

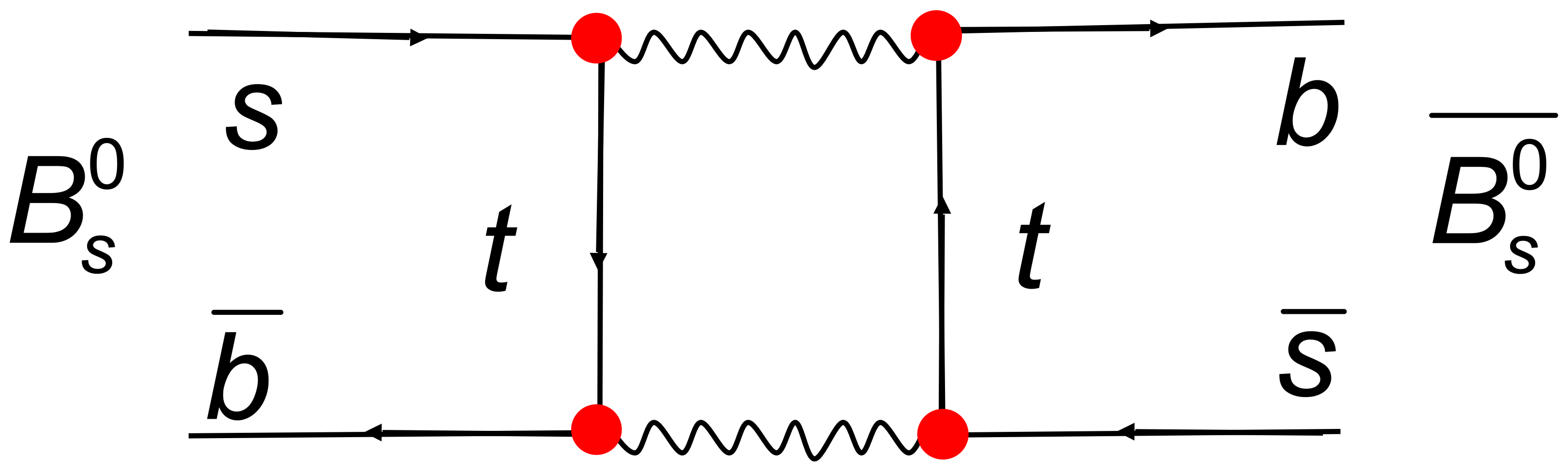
- $|V_{ub}|/|V_{cb}|$ important tree-level constraint of the UT apex
- $|V_{ub}|, |V_{cb}|$ measured in semileptonic B decays (plus input from theory calculations of form factors)
- Persistent tensions between exclusive and inclusive determinations of $|V_{cb}|$ weakens the power of theoretically clean observables (eg, $B_{(s)} \to \mu\mu$)
- Belle II will lead the way: hermetic detector and energy constraints
- LHCb also in the game with B_s and Λ_b modes



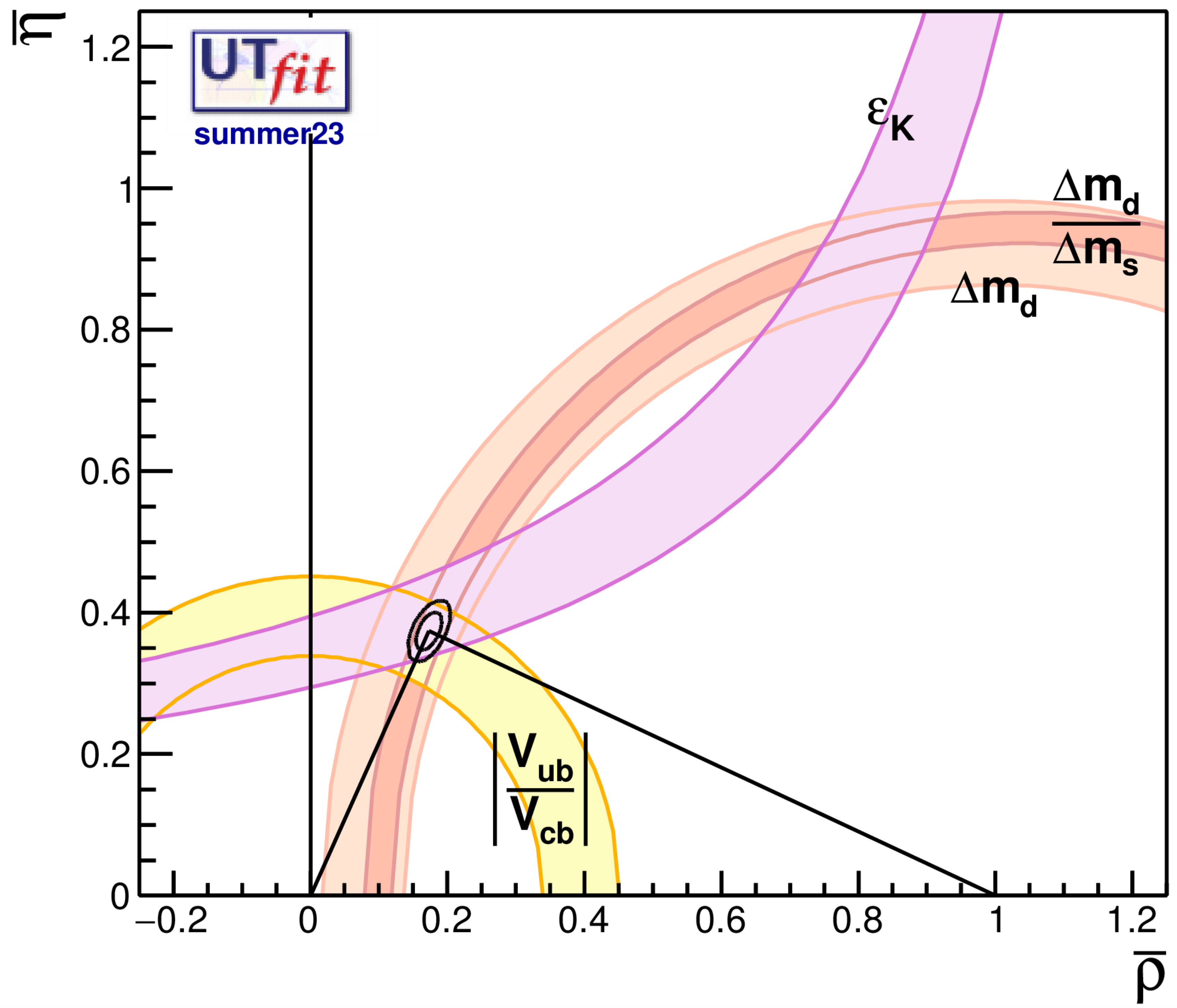


$B^0 \leftrightarrow \overline{B}^0$ mixing

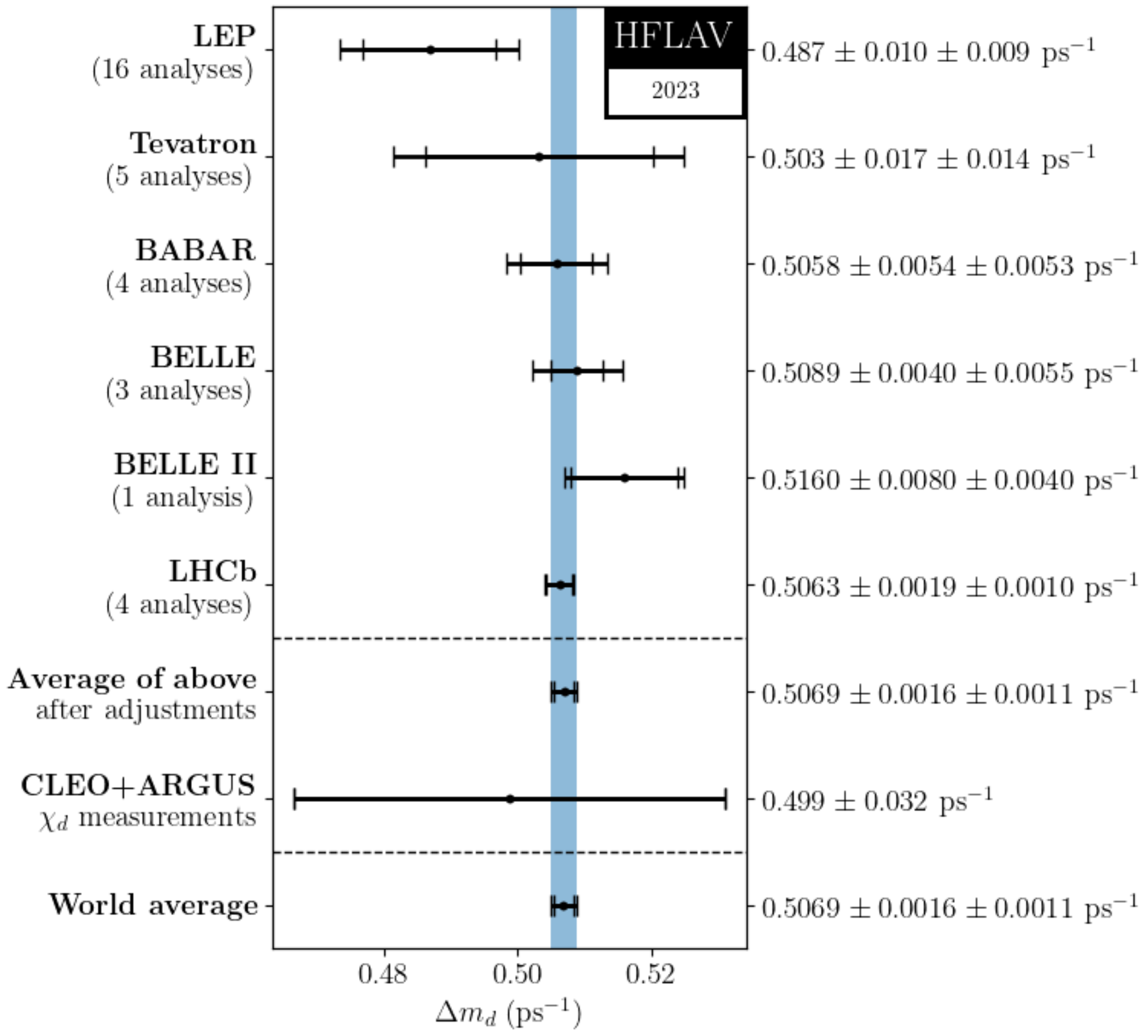




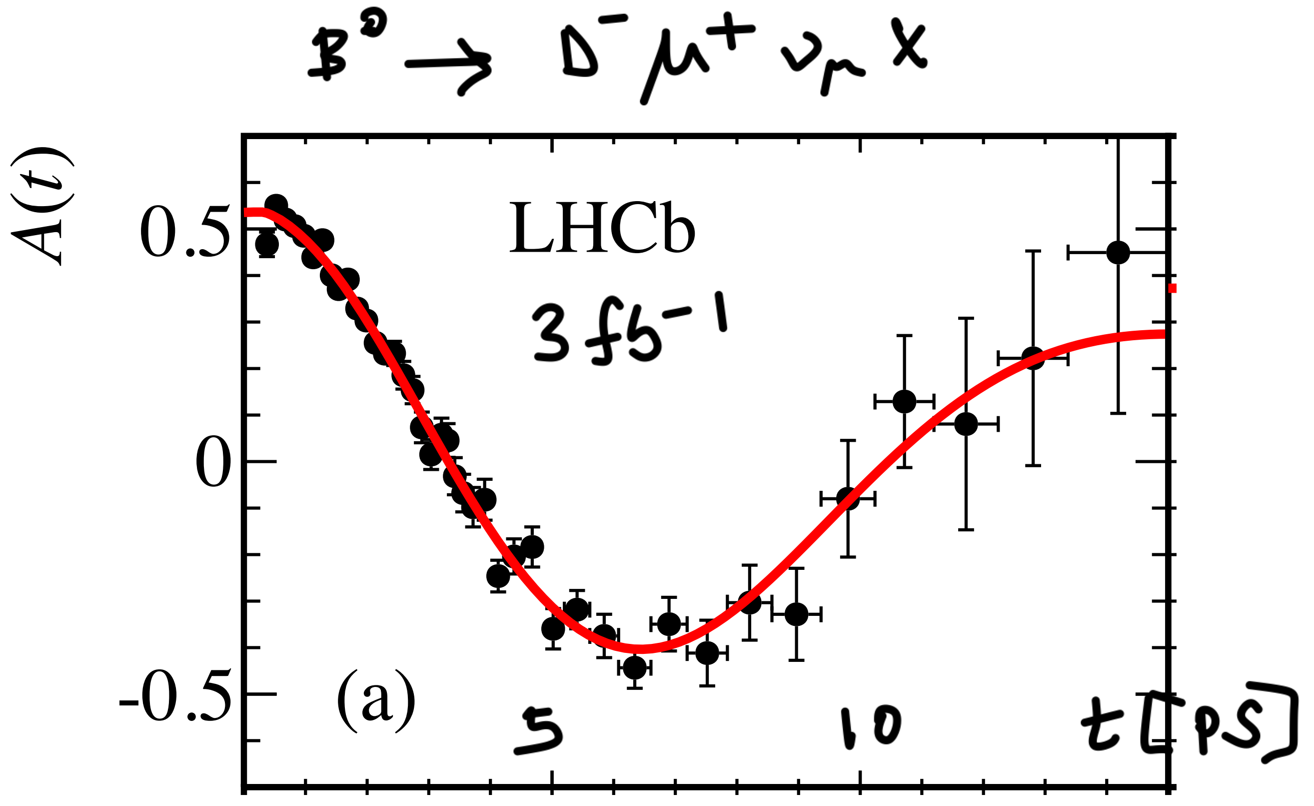
- Mixing gives mass eigenstates that are different from flavour eigenstates $|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$, with $|B^0\rangle, |\overline{B}^0\rangle$ flavour eigenstates,
- $\Delta m = m_H - m_L$, $\Delta\Gamma = \Gamma_L - \Gamma_H$ $\Delta m_s \sim (1/\lambda^2)\,\Delta m_d$
- $\Delta m_d \sim m_t^2 |V_{tb}V_{td}|^2 \sim m_t^2 \cdot \lambda^6$
  $\Delta m_s \sim m_t^2 |V_{tb}V_{ts}|^2 \sim m_t^2 \cdot \lambda^4$
- World-leading measurements of oscillation frequencies Δm_d and Δm_s from LHCb



Δm_d and Δm_s

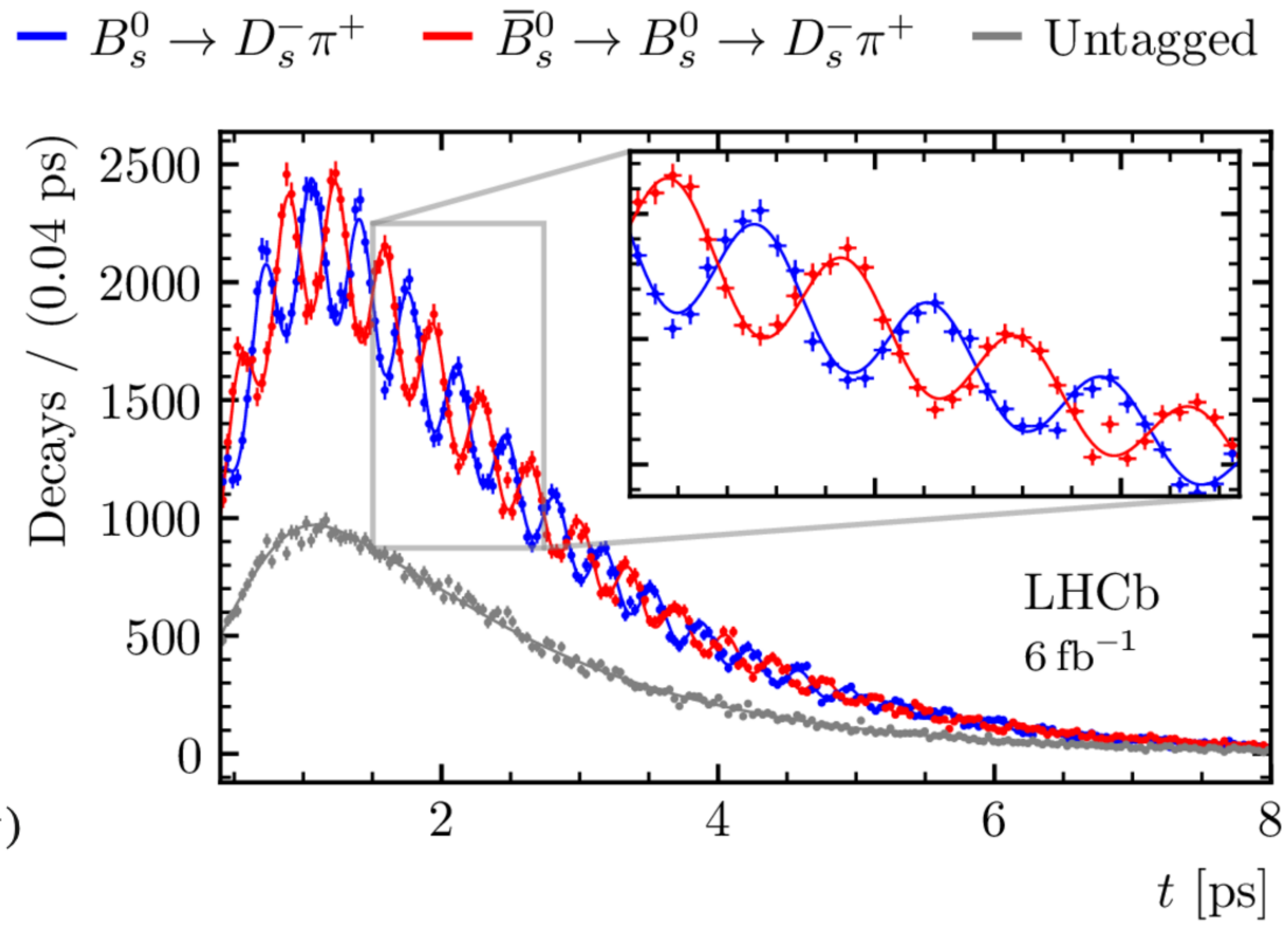


WA: $\Delta m_d = 0.5069 \pm 0.0019$ ps^{-1}



$$A(t) = \frac{N^{\text{unmix}}(t) - N^{\text{mix}}(t)}{N^{\text{unmix}}(t) + N^{\text{mix}}(t)} = \cos(\Delta m_d t)$$

Eur. Phys. J. C76 (2016) 412



- Different flavour at decay and production
- Same flavour at decay and production

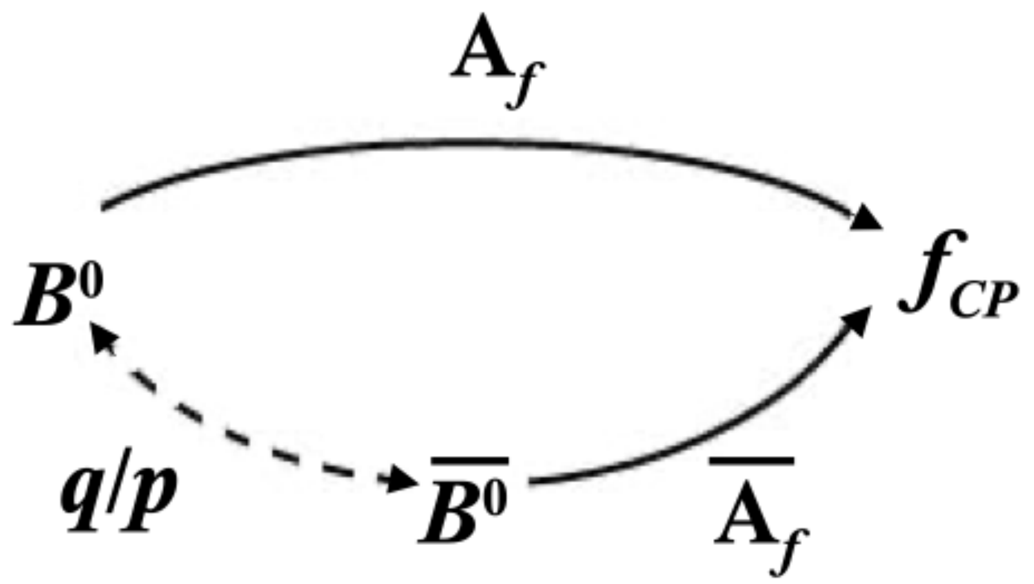
LHCb: $\Delta m_s = 17.741 \pm 0.0057\, \text{ps}^{-1}$ 0.03% accuracy

Nature Physics 18 (2022) 1-5

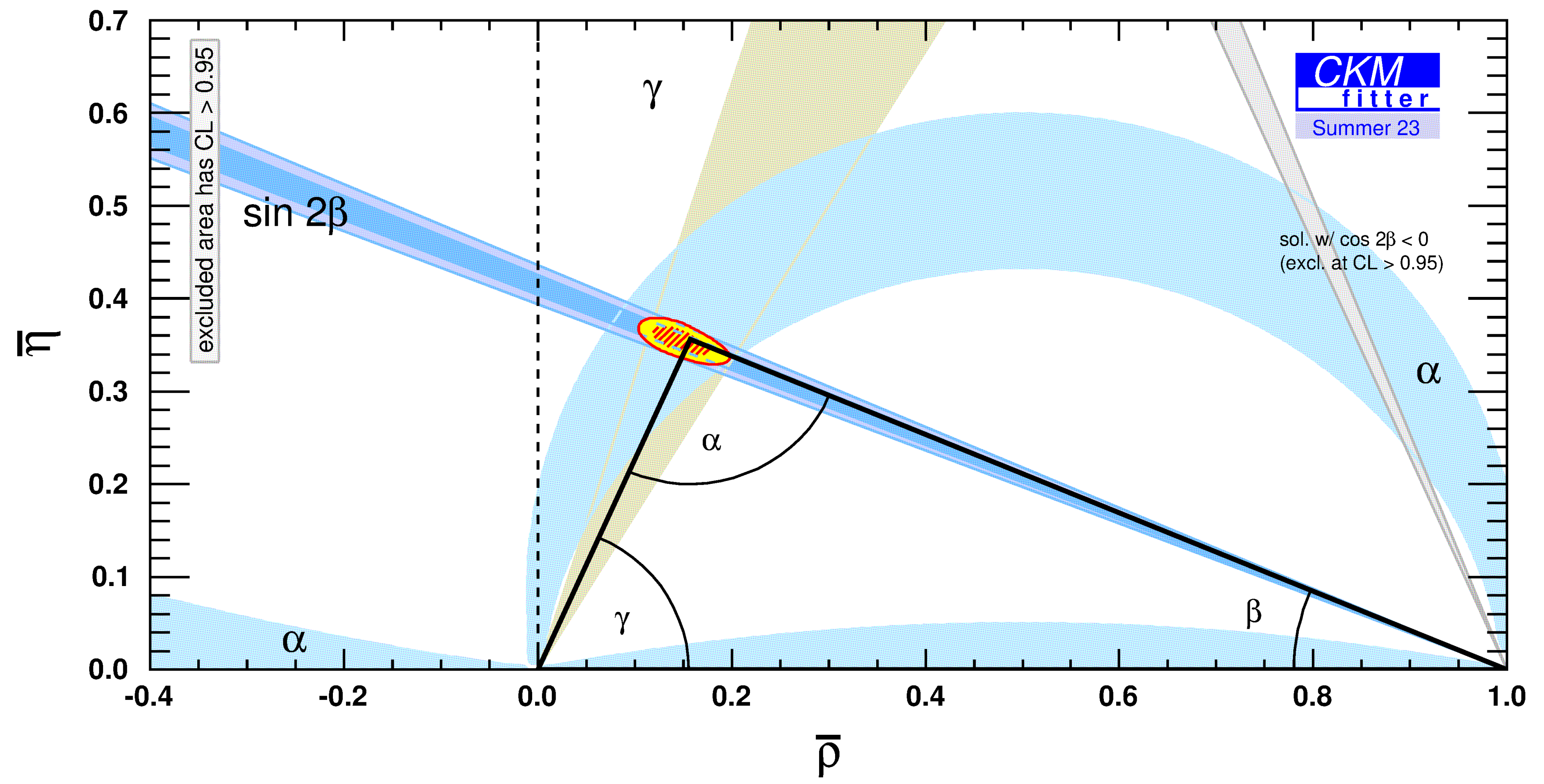
CP violation in interference between decay and mixing

- Interference between mixing and decay amplitudes in $B^0_{(s)}$ decays used to constrain $\sin 2\beta$ from B^0 and β_s from B^0_s

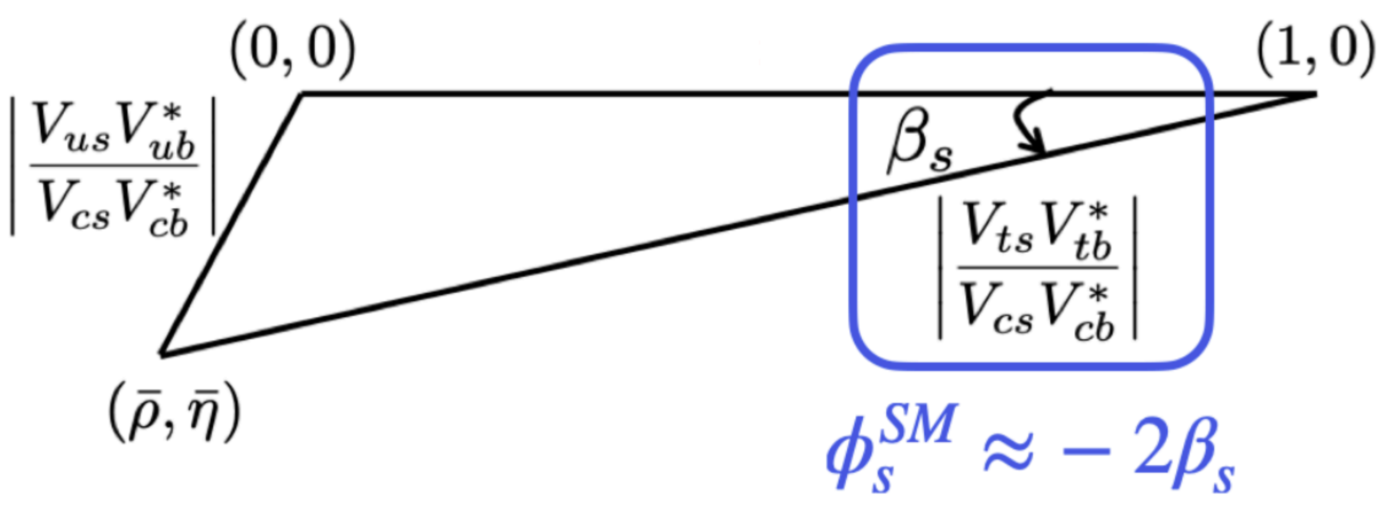
- $$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to f) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to f) + \Gamma(B^0 \to f)}$$

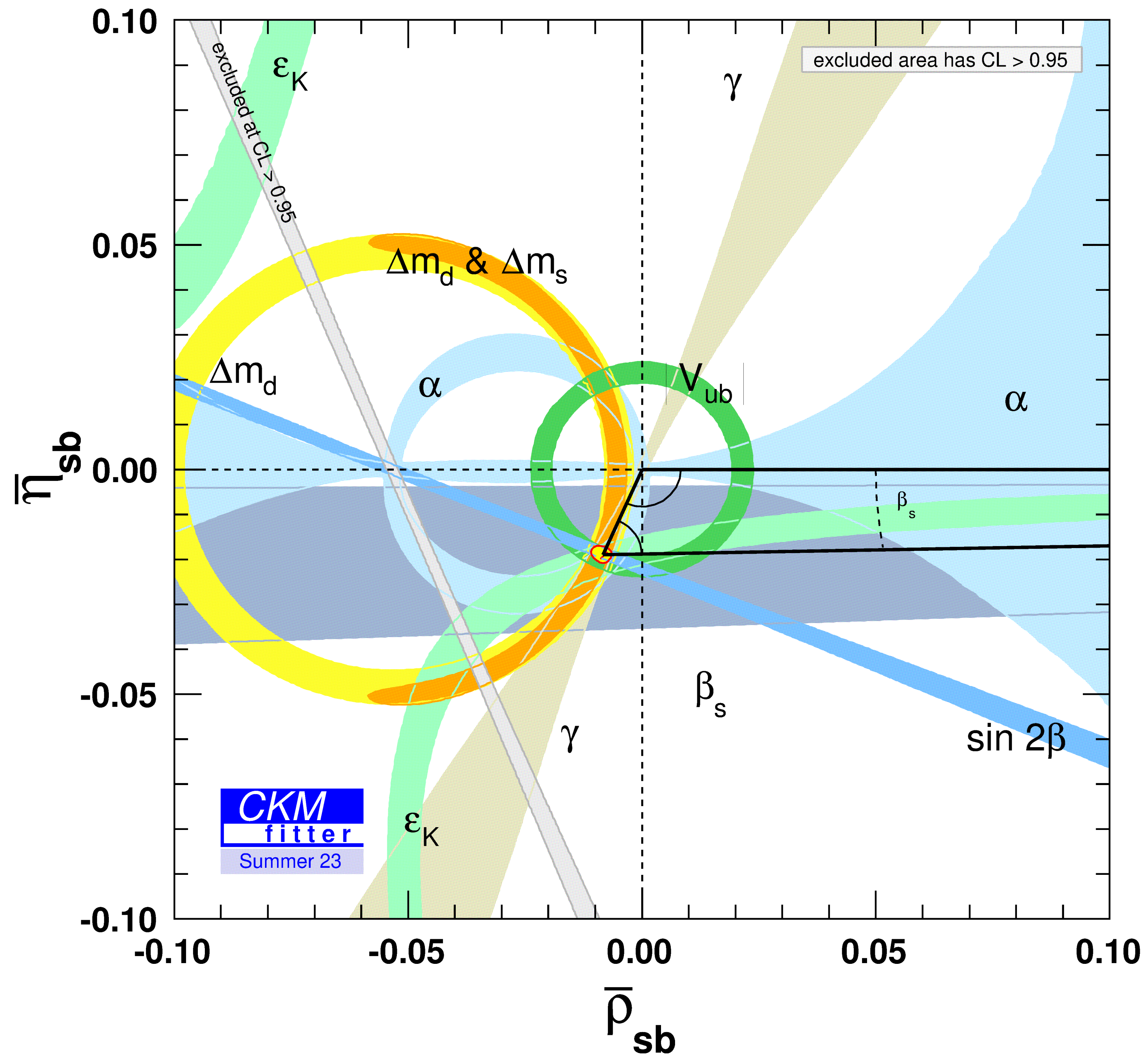


- Golden modes are $B^0_s \to J/\psi K^+K^-$ and $B^0 \to J/\psi K^0_s$ dominated by tree-level $b \to c\bar{c}s$ transitions



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$





$\phi_s \approx -2\beta_s = -37 \pm 1$ mrad (CKMFitter, UTFit, assuming no BSM),
$\beta_s \approx 1°$ while $\beta \approx 22° \sim 0.38$ rad

Measurement of sin2β

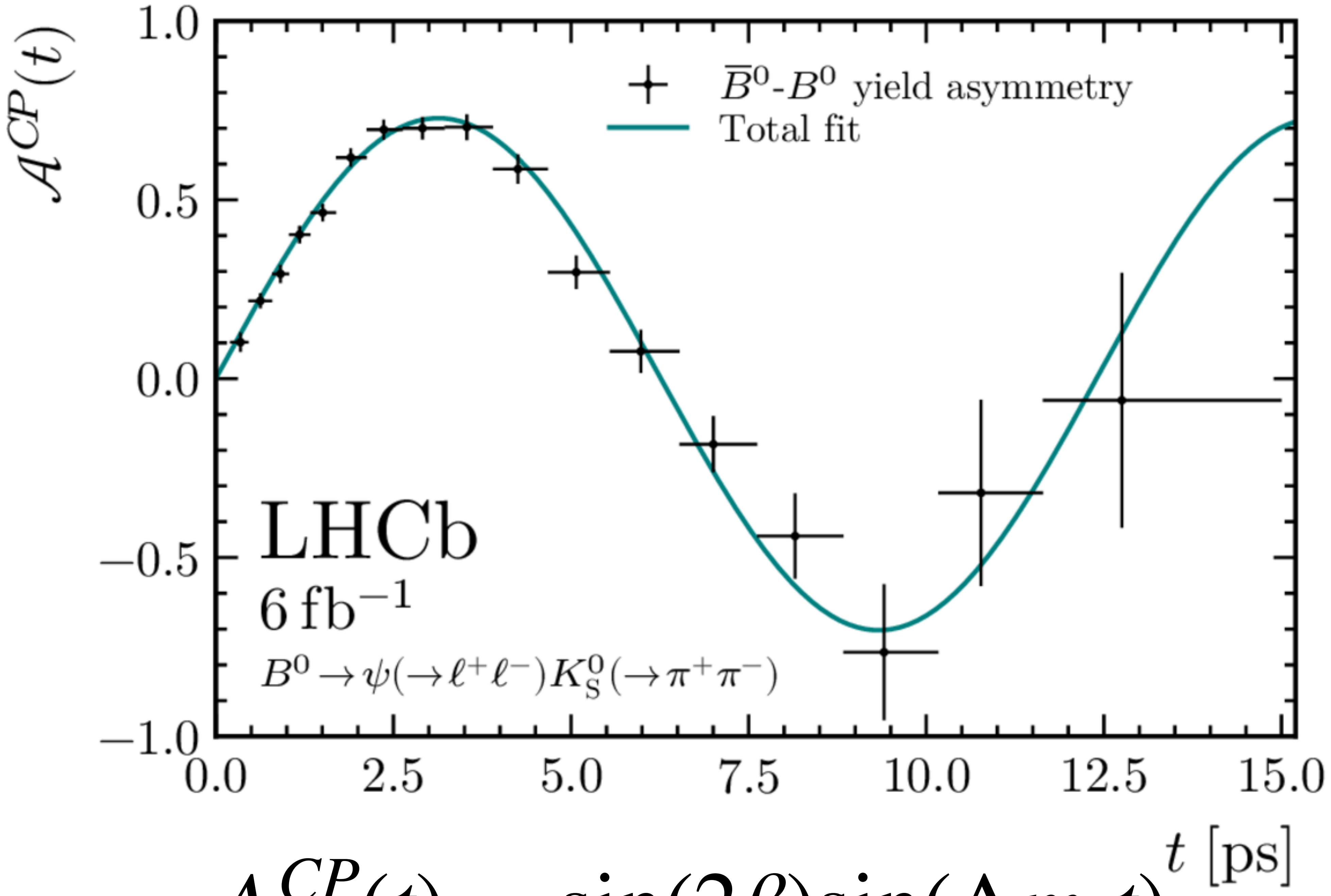
LHCb result with Run2 data

$B^0 \to J/\psi(\to \mu^+\mu^-)K_s^0$ ~306K

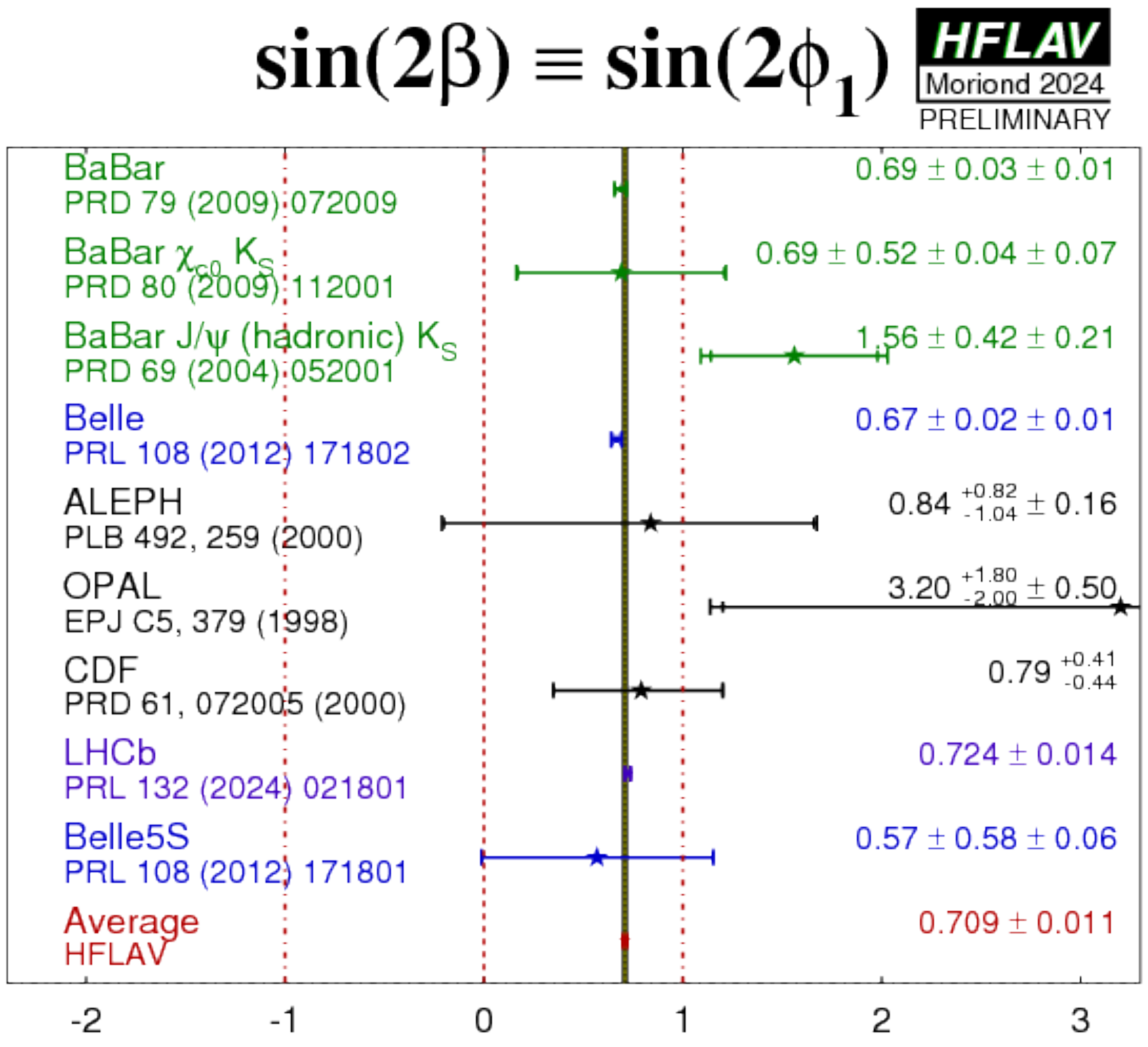
$B^0 \to \psi(2S)(\to \mu^+\mu^-)K_s^0$ ~24K

$B^0 \to J/\psi(\to e^+e^-)K_s^0$ ~43K

PRL 132, 021801



$$A^{CP}(t) = \sin(2\beta)\sin(\Delta m_d t)$$

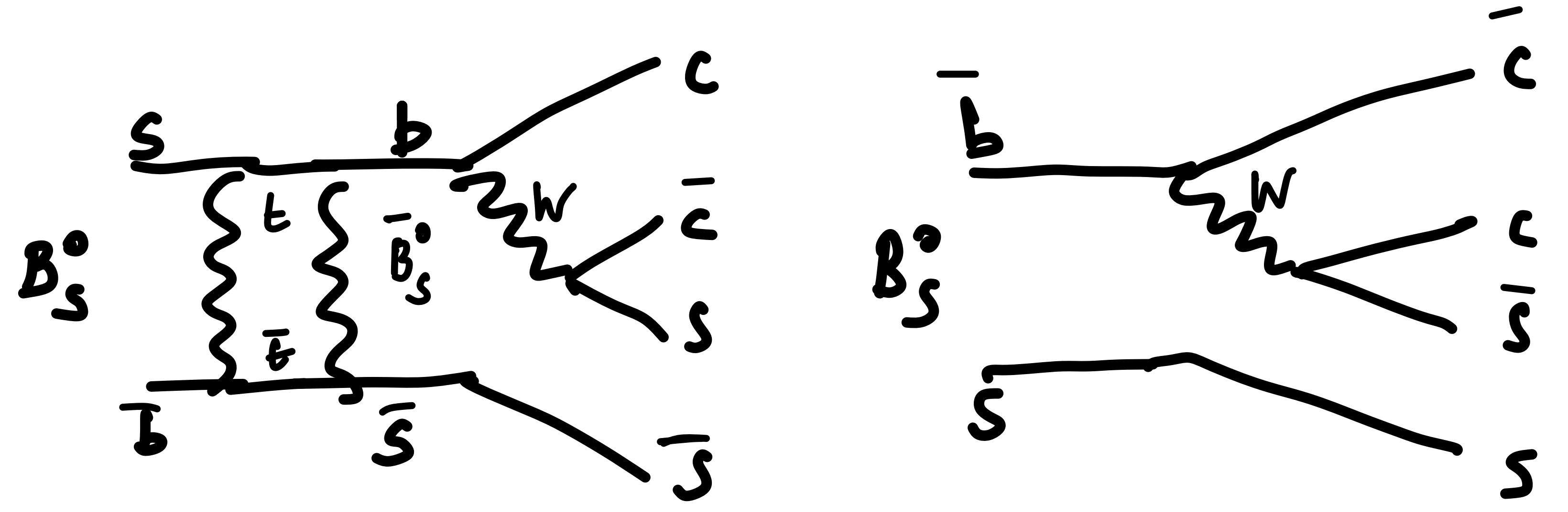


LHCb Run2 : $\sin 2\beta = 0.717 \pm 0.013_{stat} \pm 0.08_{syst}$

More precise than previous world average!

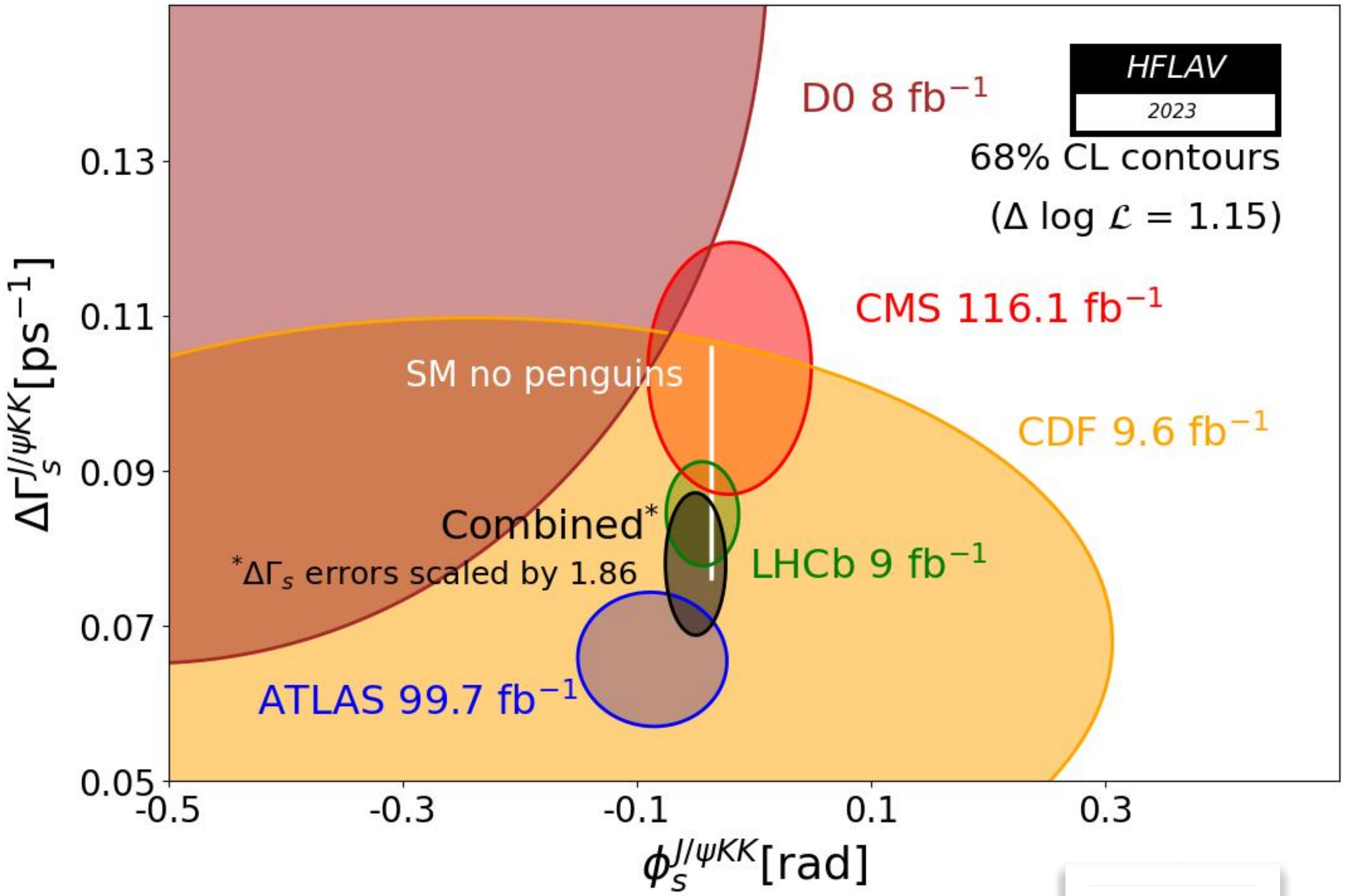
B_s^0 mixing phase ϕ_s

- Tiny CP-violating phase ϕ_s arising from interference between mixing and decay amplitudes in B_s^0 decays; precisely predicted from UT constraints: $\phi_s = -37 \pm 1$ mrad (CKMFitter, UTFit)



- First measured by CDF&D0, then by ATLAS, CMS &LHCb
  - Golden channel $B_s^0 \to J/\psi\phi(1020) \to \mu^+\mu^-K^+K^-$
  - For LHCb, several other channels: $B_s^0 \to J/\psi \to \mu^+\mu^-K^+K^-$, $B_s^0 \to J/\psi(\to e^+e^-)K^+K^-$, $B_s^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to D_s^+D_s^-$, $B_s^0 \to \psi(2S)K^+K^-$
- Core ingredients :
  - time-dependent angular analysis to separate the CP eigenstates
  - time dependent flavour analysis to resolve the B_s^0 oscillations ($T \sim 350$ fs)
    - LHCb: excellent decay time resolution ~42 fs
    - LHCb: Tagging power $P_{\text{tag}} = \epsilon_{\text{tag}}(1-w)^2 \sim 4.4\,\%$
    - LHCb: 349 000 $B_s^0 \to J/\psi K^+K^-$ signal events (6 fb^{-1} from Run2)
    - $\phi_s = -0.039 \pm 0.022_{\text{stat}} \pm 0.006_{\text{syst}}$ rad (6 fb^{-1} from Run2)

PRL 132 (2024) 051802



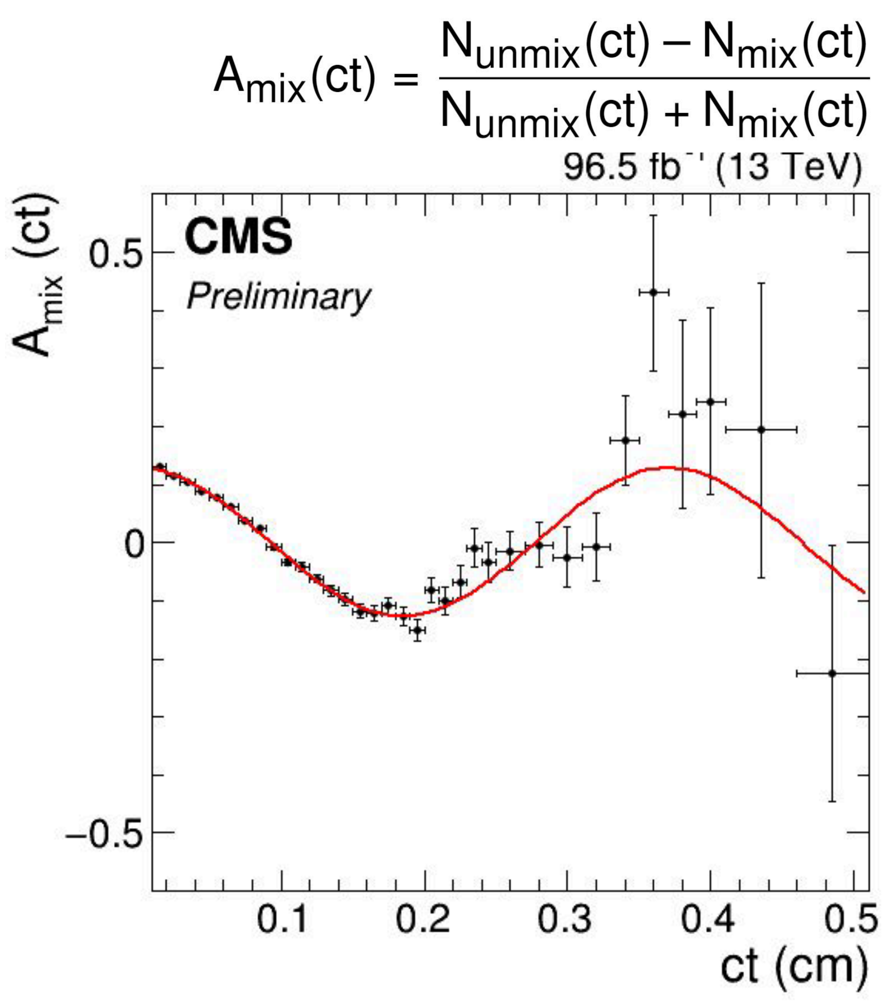
HFLAV

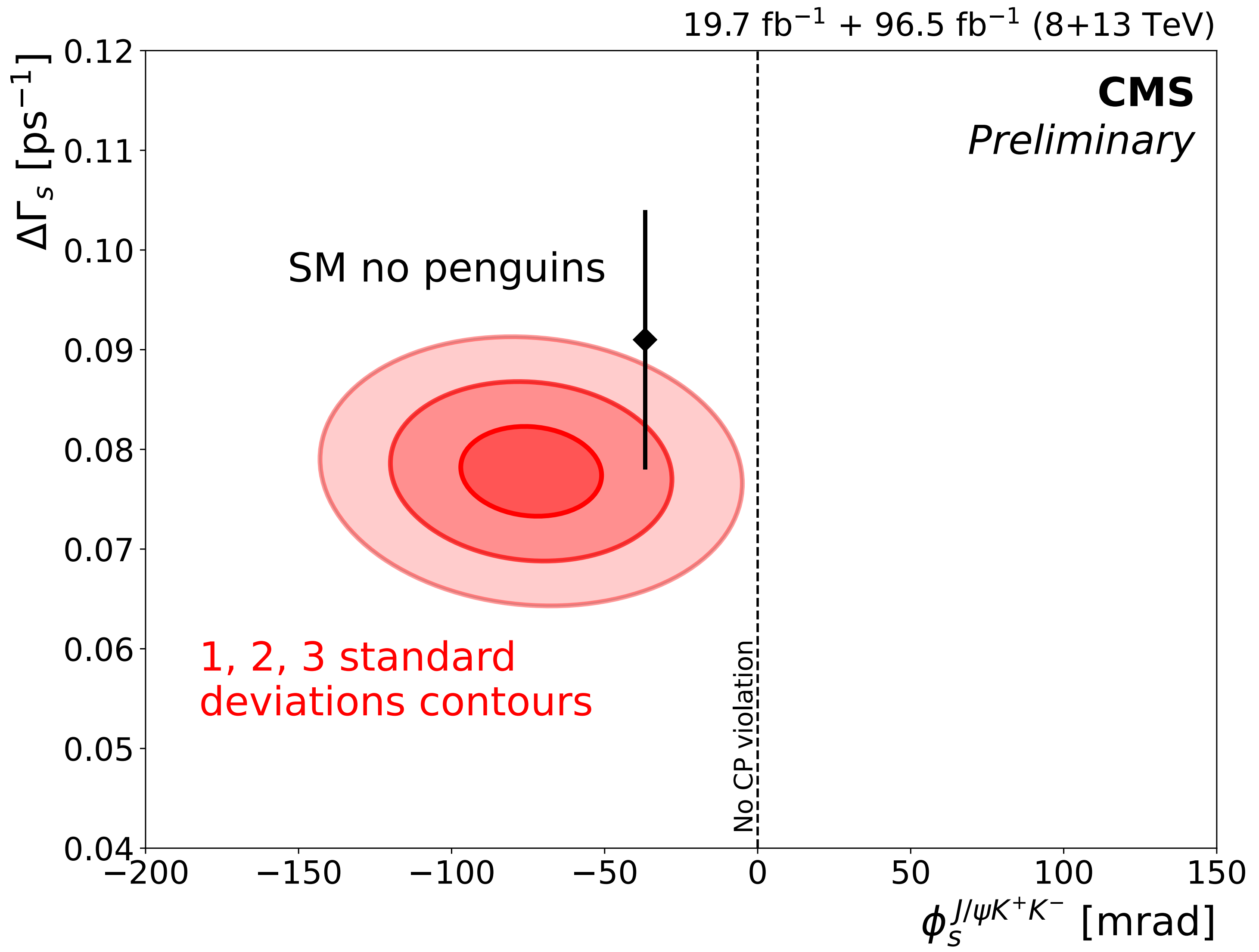
June '23 WA:

$$\phi_s^{J/\psi KK} = -0.039 \pm 0.016 \text{ rad}$$

CMS: CPV with $B_s^0 \to J/\psi\phi$

- New impressive CMS measurement (Moriond '24)
  - $N_{B_S^0} \sim 490000$ [96.5 fb^{-1}]
  - time resolution ~67 fs
  - major improvements to flavour tagging (~x3-4) with $P_{\text{tag}} = 5.6\,\%$ based on state-of-the-art machine learning (4 DNN based algorithms)
  - largest ever effective statistics for single ϕ_s measurement ($N_{B_S^0} \cdot P_{\text{tag}} \sim 490\text{k} \cdot 5.6\,\% \sim 27.5\text{k}$)
  - tagging framework validated in $B^0 \to J/\psi K^{*0}$ control channel (~2M events) with measurement of Δm_d at $\sim 1\,\%$ (comparable with Belle &BaBar)

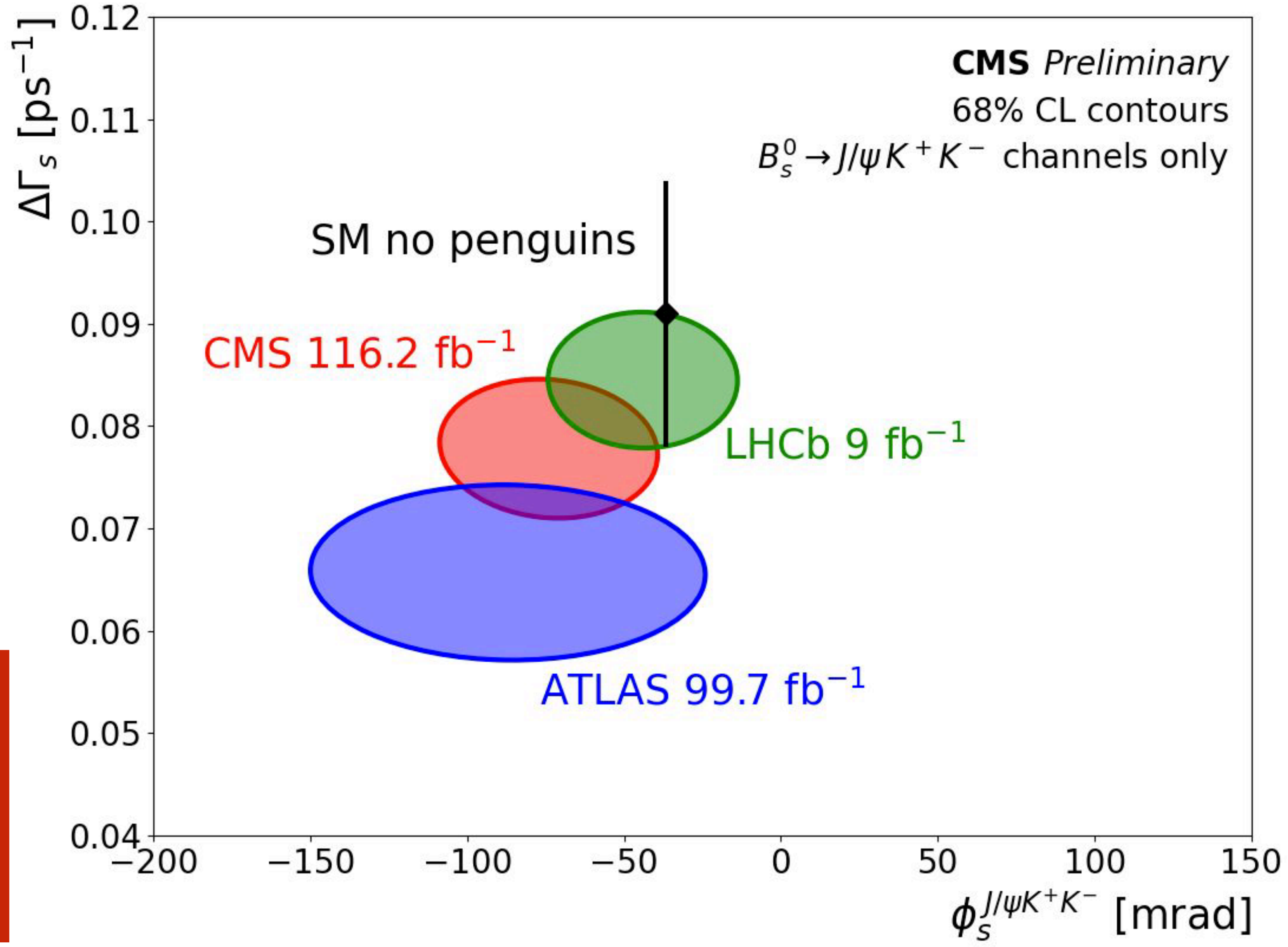




$$\phi_s[\text{mrad}] = -73 \pm 23_{\text{stat}} \pm 7_{\text{syst}}$$

$$\Delta\Gamma_s[\text{ps}^{-1}] = 0.0761 \pm 0.0043_{\text{stat}} \pm 0.0019_{\text{syst}}$$

CMS PAS BPH-23-004



- Combination with previous results gives

$$\phi_s[\text{mrad}] = -74 \pm 23$$

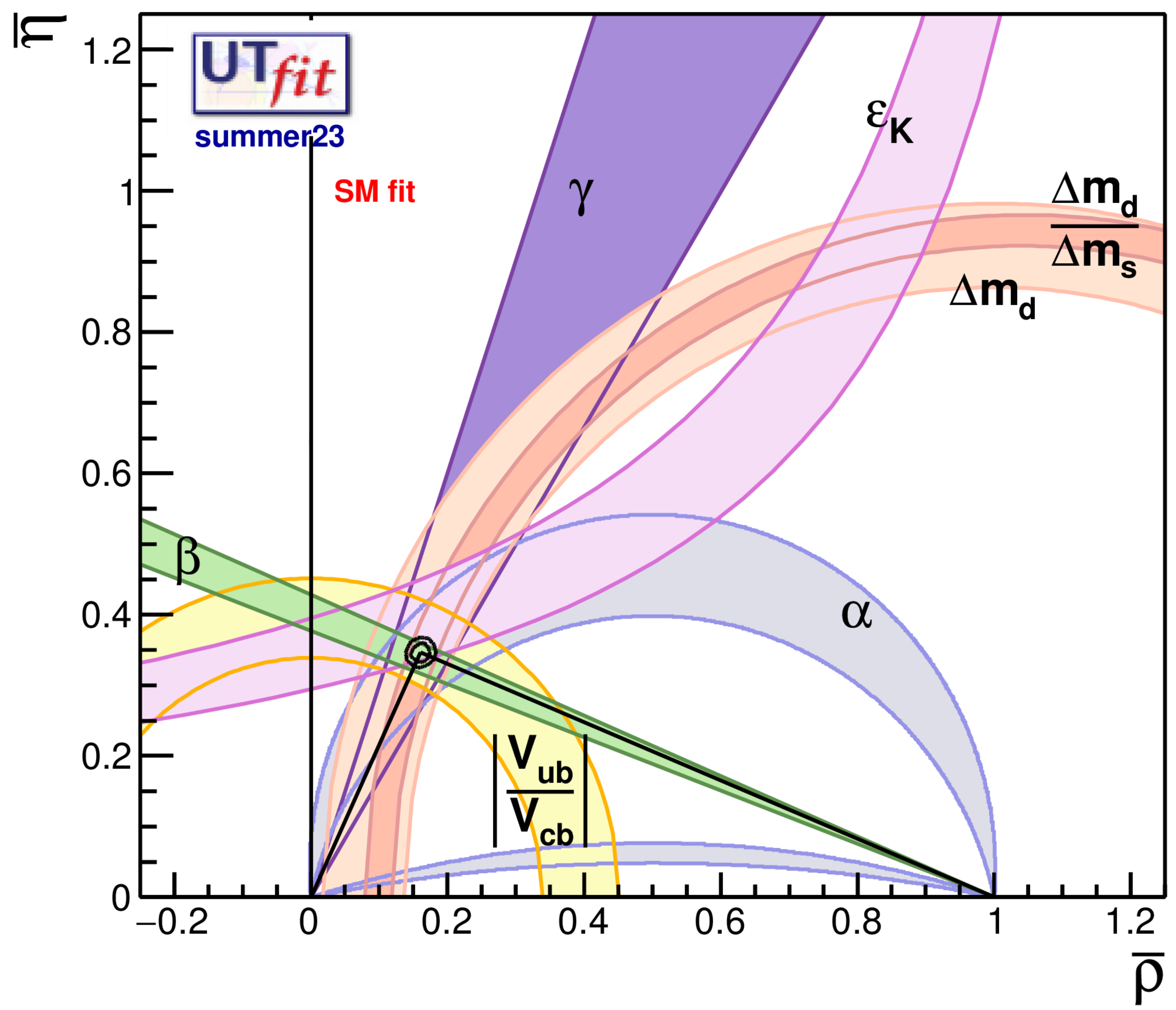
$$\Delta\Gamma_s[\text{ps}^{-1}] = 0.0780 \pm 0.0045$$

In agreement with SM predictions
ϕ_s different from zero by 3.2σ
First evidence of CPV in $B_s^0 \to J/\psi\phi$

Consistency tests of the CKM matrix

- At the current level of precision (~%), all measurements are consistent and intersect in the apex of the UT
- What is particularly noteworthy is the consistency of the tree-level determinations of CKM elements, with those obtained from meson-anti meson mixing

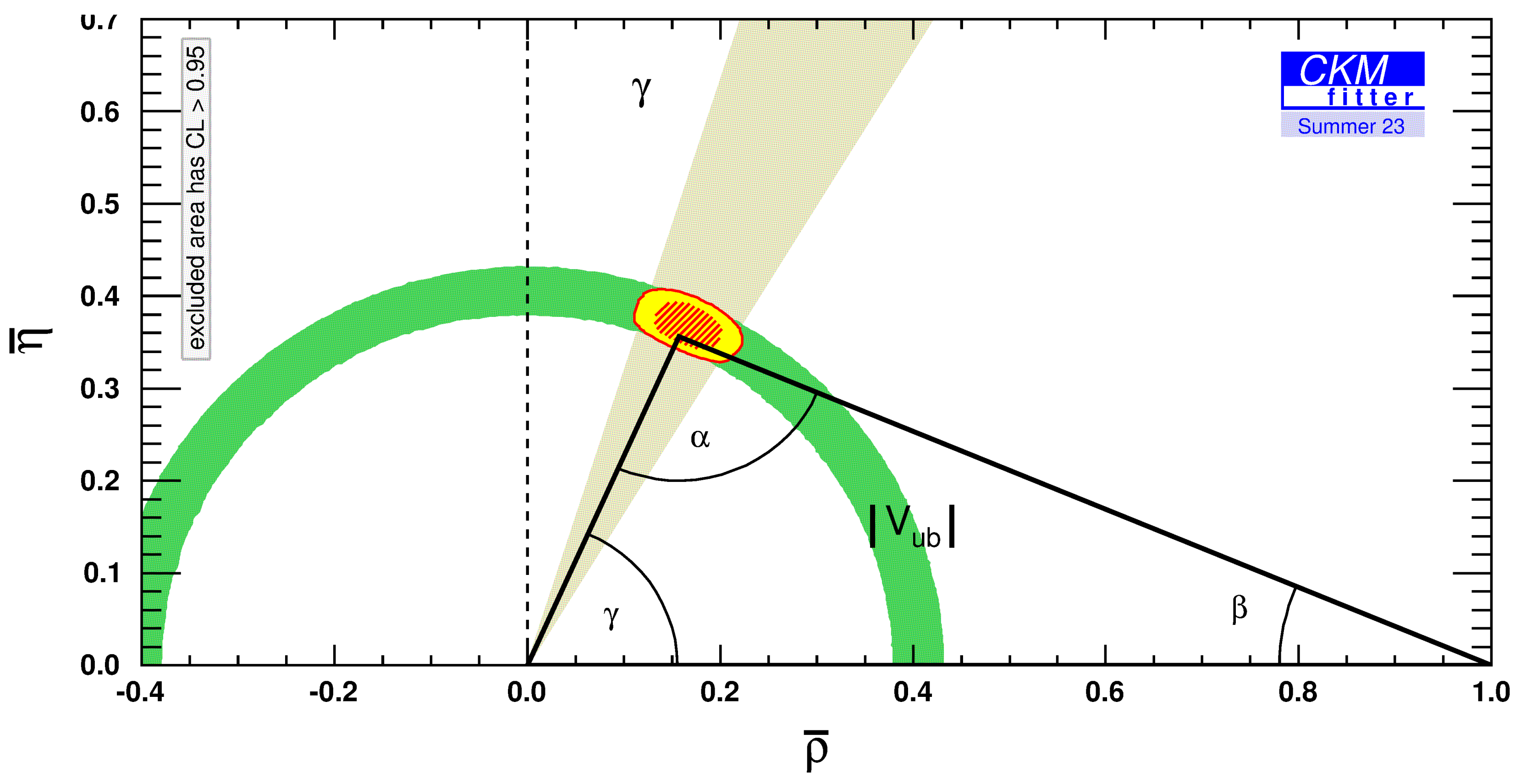
arXiv:2212.03894 UTfit, & CKMfitter



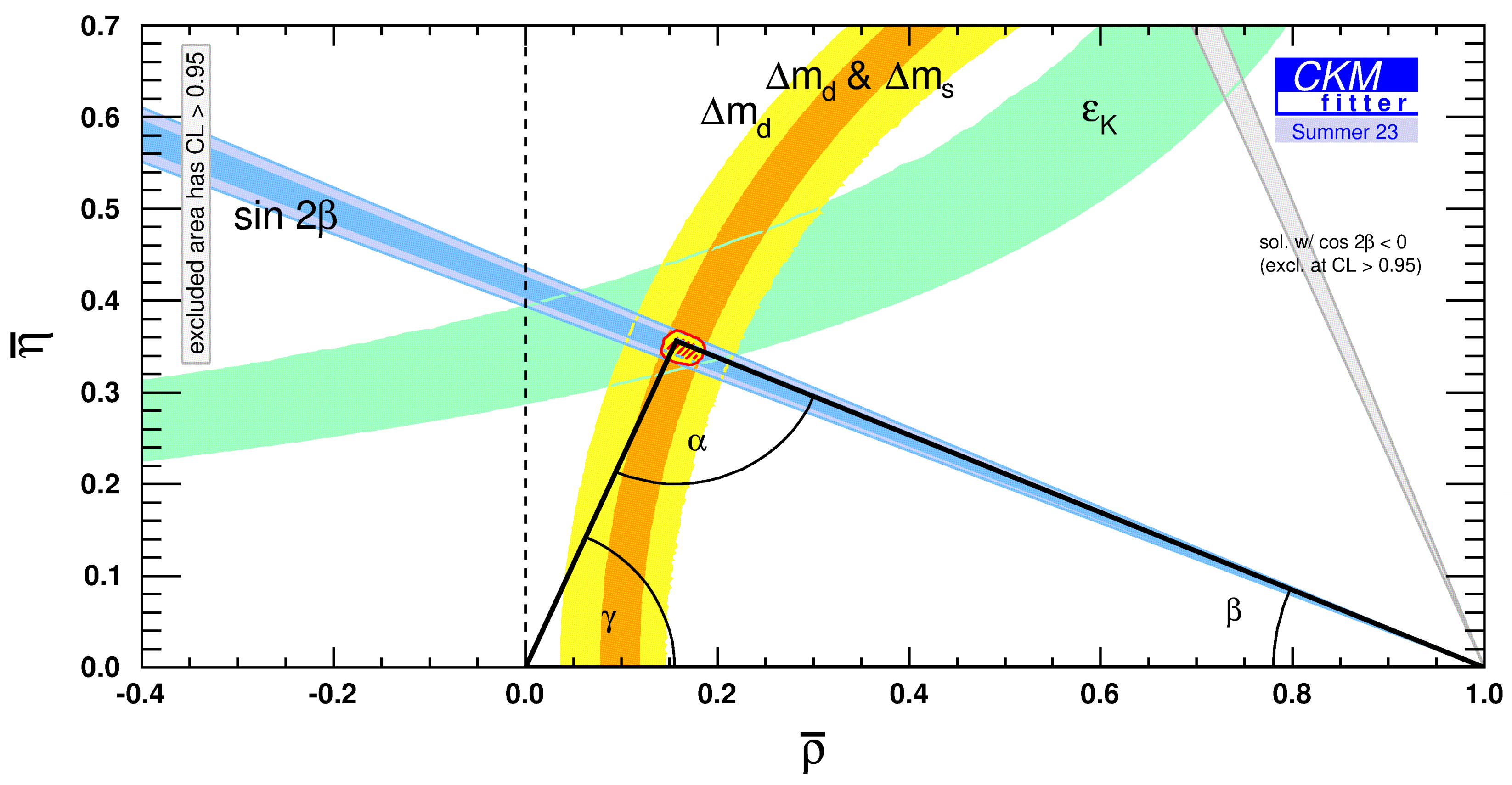
$\bar{\rho} = 0.160 \pm 0.009$ ~6%

$\bar{\eta} = 0.346 \pm 0.009$ ~3%

Tree-level observables



Loop observables



- New Physics effects (if there) are small!
- But… past examples show that it is unwise to think that few % is good enough and further efforts in theoretical and experimental accuracy are required

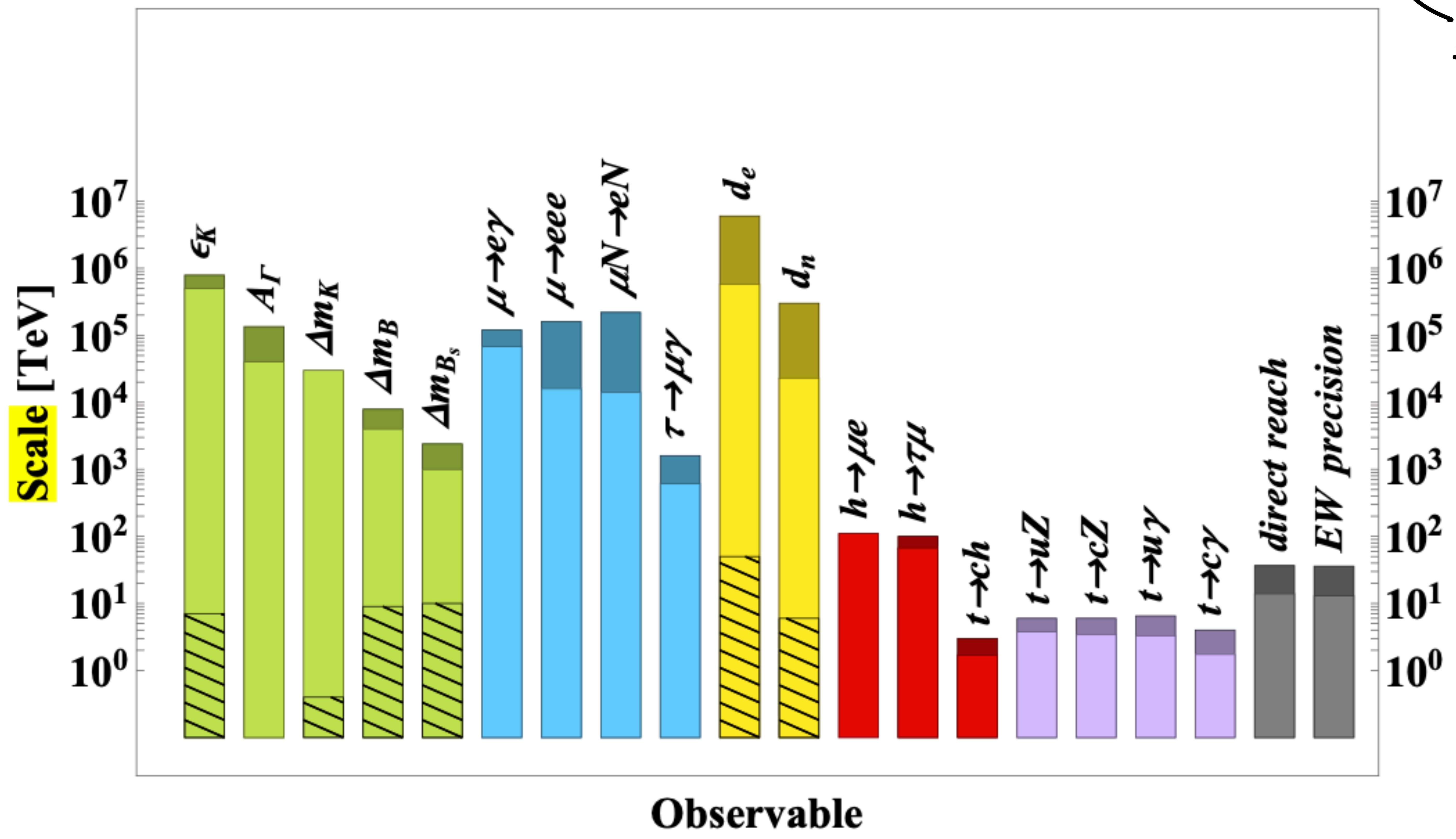
Impact of B-meson mixing measurements

- Stringent bounds on the scale of NP from meson-anti meson mixing (assuming generic NP effects in loop-mediated amplitudes).
- Can we make sense of the tight NP bounds from flavour-violating processes and still see NP at low scale to solve the fine tuning problem?

The NP Flavour Puzzle

$\mathcal{H}_{NP} \propto \frac{C_{NP}}{\Lambda^2_{NP}}$ (NP couplings; NP scale)

Energy reach of various indirect precision tests of BSM compared to direct searches



Physics Briefing Book, Input for European Strategy, B.Gavela et al

CPV in charm

- in the SM expected to be extremely small level with $A_{CP} \sim 10^{-4}$-10^{-3} → very sensitive null tests of the CKM picture
- Opportunity to measure CPV with particles containing only up-type quarks even if theoretical predictions are difficult to compute reliably due to low-energy strong-interaction effects
- LHCb'19: First observation of CPV in charm from time-integrated CP asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$ decays

$$A_{CP}(f;t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)} \quad \to \Delta A_{CP} = A^{CP}(K^+K^-) - A^{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$$

PRL 122, 211803

5.3 σ

PRL 131 (2023) 091802

- LHCb'22: Direct measurement of

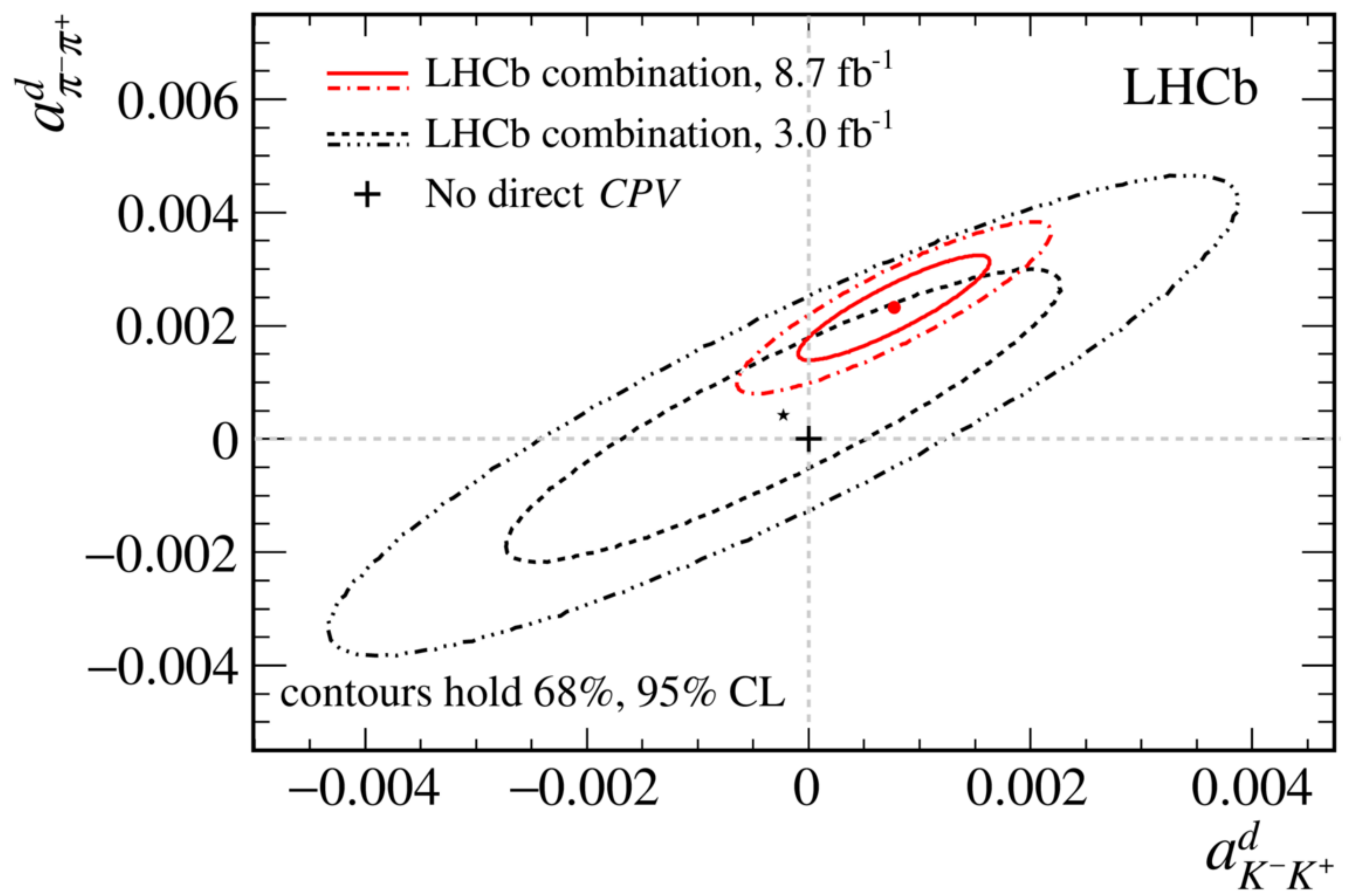
$$A_{CP}(K^+K^-) = [6.8 \pm 5.4_{\rm stat} \pm 1.6_{\rm sys}] \times 10^{-4}$$

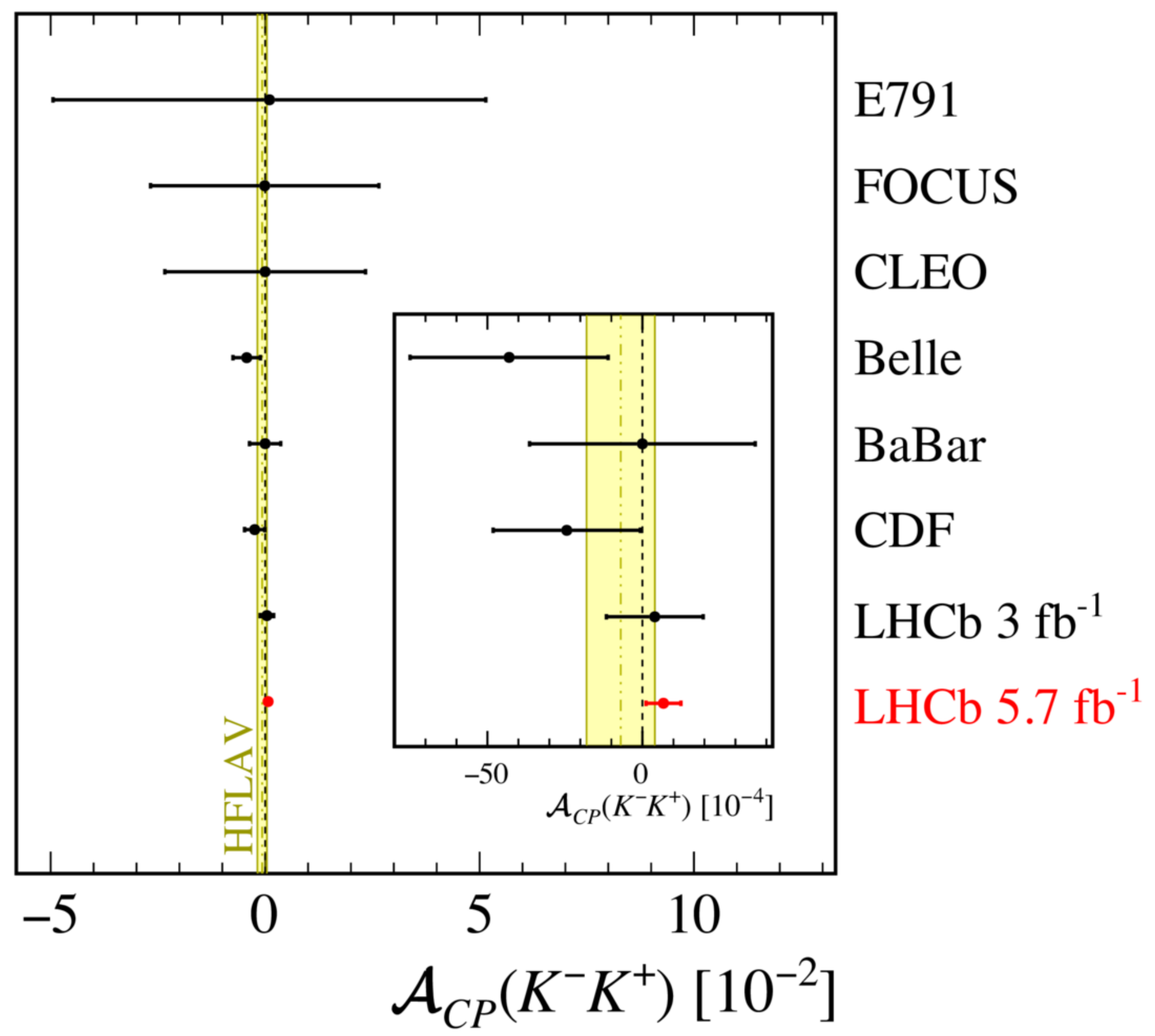
$$a^{\rm dir}_{K^+K^-} = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^{\rm dir}_{\pi^+\pi^-} = (23.2 \pm 6.1) \times 10^{-4}$$

$$\rho = 0.88$$

- First evidence of direct CPV in a specific decay ($D^0 \to \pi^+\pi^-$ at 3.8 σ)
- U-spin limit sum rule $(d \leftrightarrow s)(a^{\rm dir}_{K^+K^-} + a^{\rm dir}_{\pi^+\pi^-} = 0)$ violated at 2.7σ

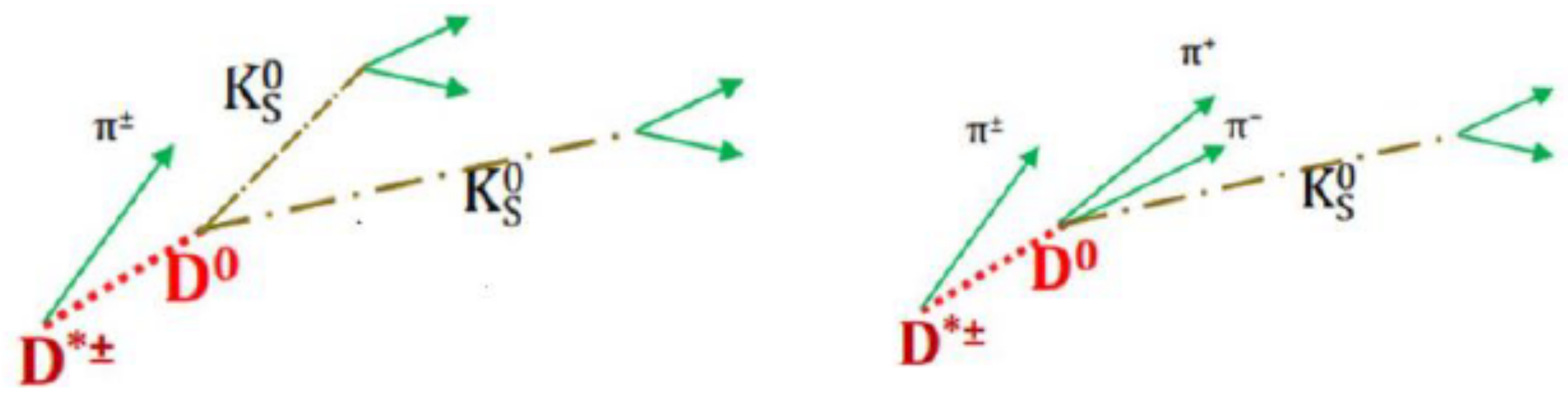




Search for CPV in $D^0 \to K_s^0 K_s^0$

- First measurement of CPV in charm by CMS experiment and first $A_{CP}(K_s^0 K_s^0)$ measurement in fully hadronic final state at the nominal LHC luminosity using the new data parking technique

- $$A_{CP} = \frac{\Gamma(D^0 \to K_s^0 K_s^0) - \Gamma(\overline{D}^0 \to K_s^0 K_s^0)}{\Gamma(D^0 \to K_s^0 K_s^0) + \Gamma(\overline{D}^0 \to K_s^0 K_s^0)}$$



- Strategy: measure $\Delta A_{CP} = A_{CP}(D^0 \to K_s^0 K_s^0) - A_{CP}(D^0 \to K_s^0 \pi^+ \pi^-)$

- $A_{CP}(D^0 \to K_s^0 K_s^0) = \left(6.2 \pm 3.0_{\text{stat}} \pm 0.2_{\text{sys}} \pm 0.8\, A_{CP}(K_s^0 \pi^+ \pi^-)\right)$ % , consistent with no CPV at ~2σ, and consistent with LHCb and Belle (at ~2σ)

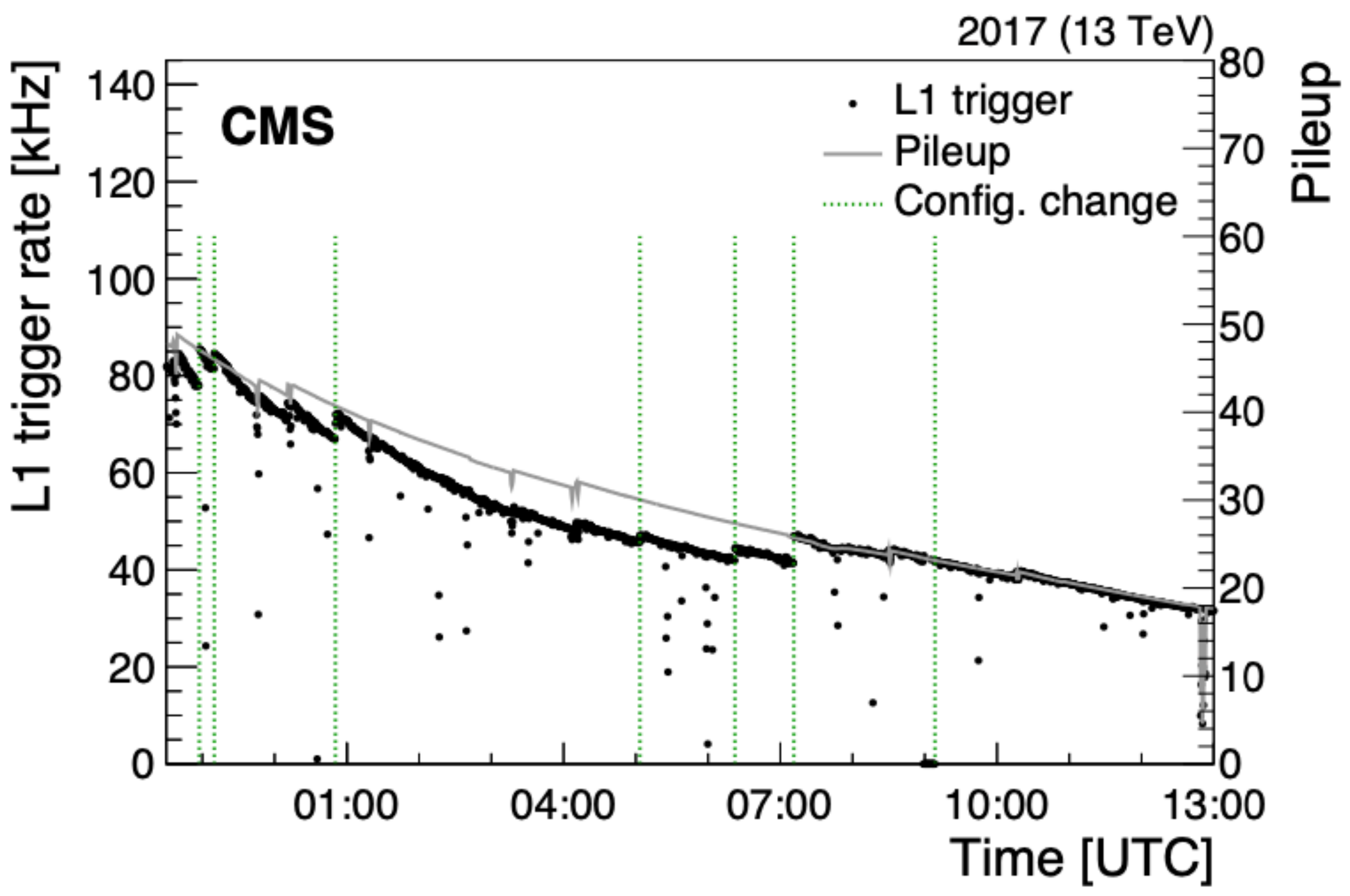
- Measurement paves the way for other future measurements

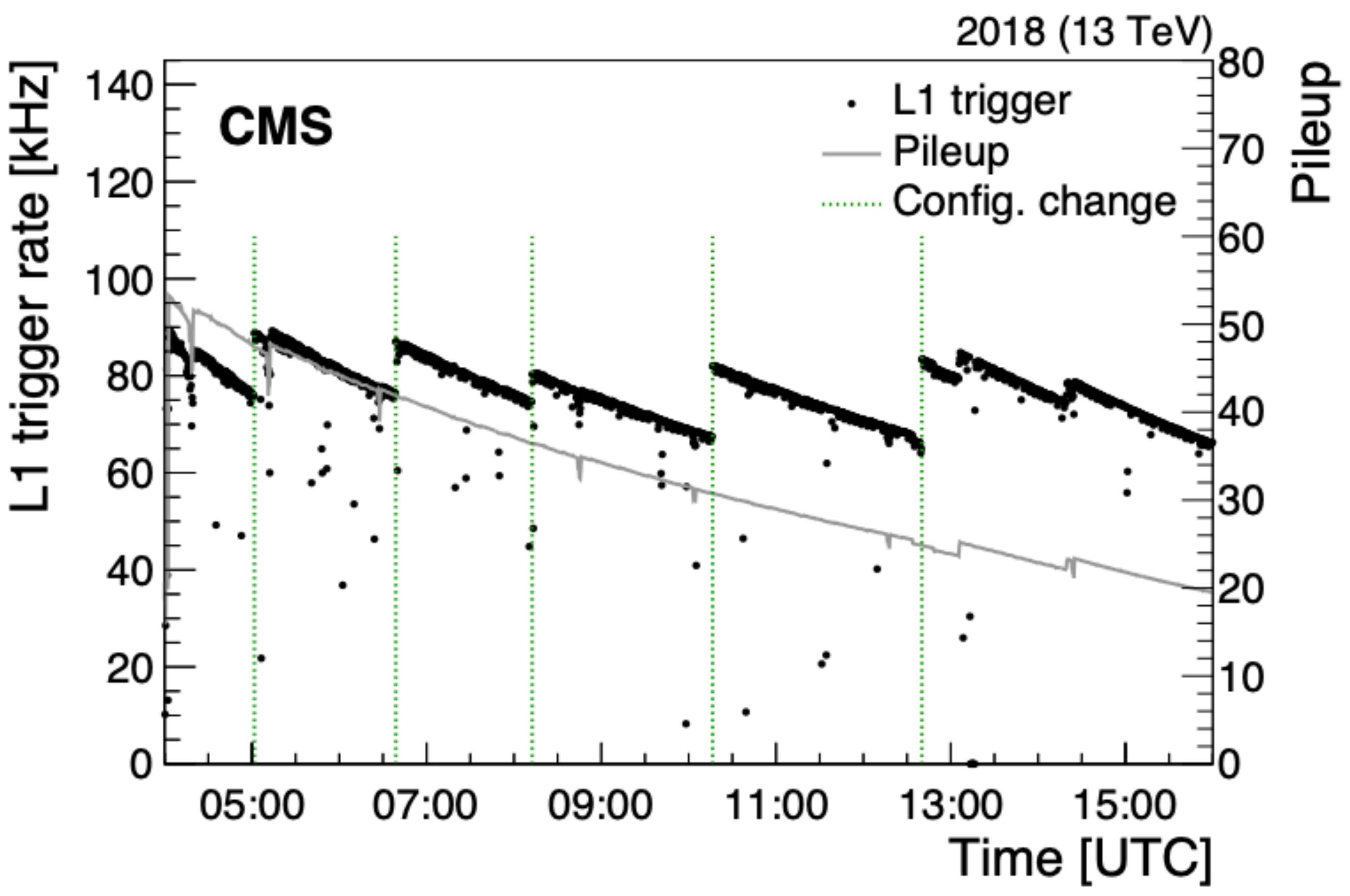
CMS PAS BPH-23-005

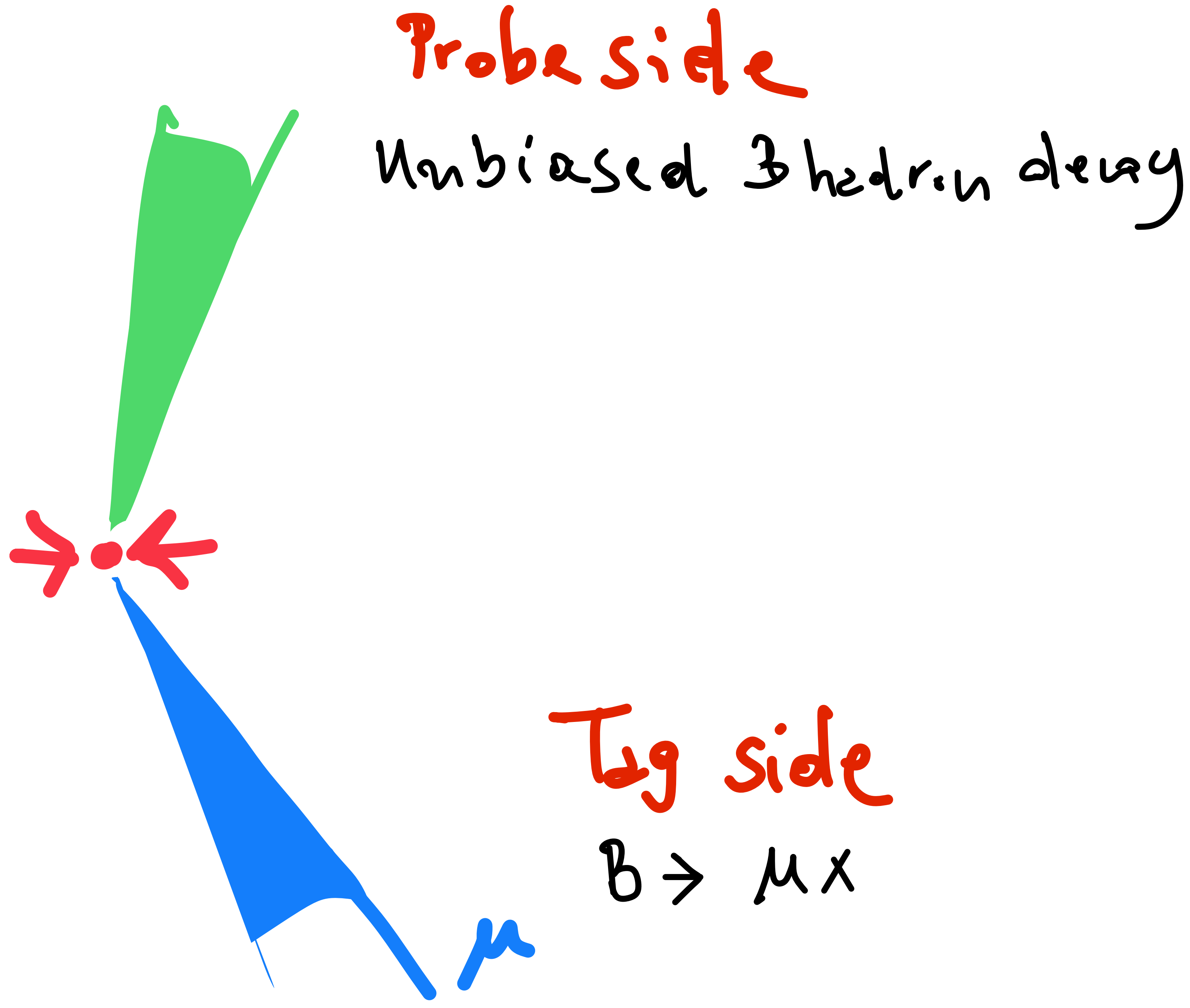
Enhancement of CMS B physics capabilities through data parking

- Expanded physics program by storing a large amount of data with low trigger thresholds to be processed when sufficient computational power is available, with no impact on “standard” physics program
- Perform B physics measurements on any final state, including fully hadronic → 10 billion unbiased B decays collected in 2018
- Tag side with set of single μ triggers with varying p_{T} & impact parameter triggers
- During fill, $\mathscr{L}_{\mathrm{inst}}$ decreases with time → less restrictive triggers allowed
- Maximizes available trigger bandwidth
  - Events parked for later reconstruction
  - Average purity $\approx 80\,\%$

CMS-EXO-23-007

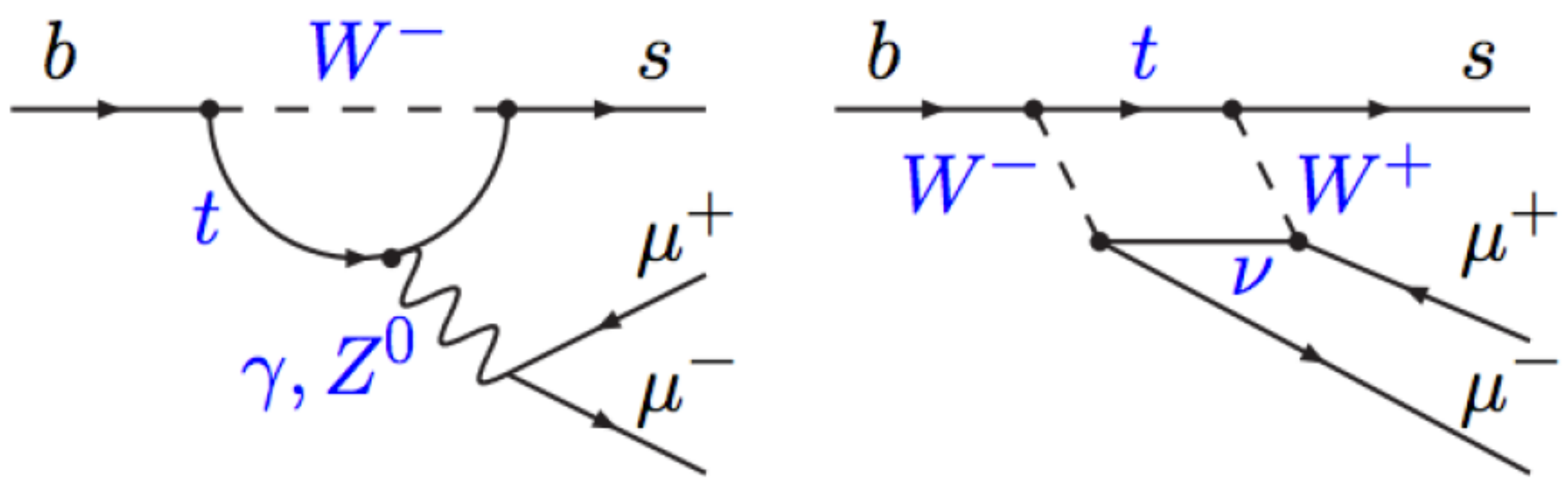


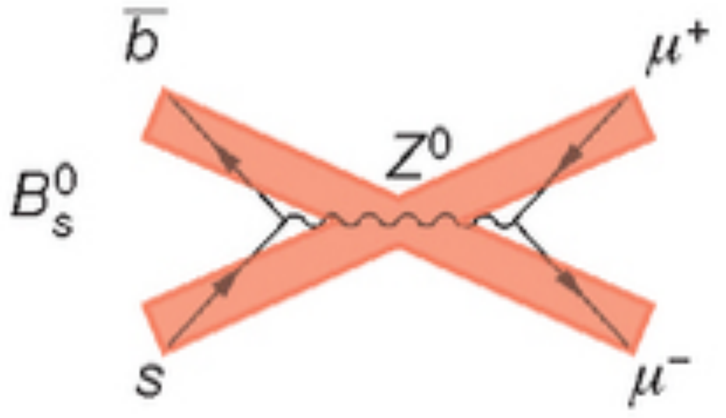




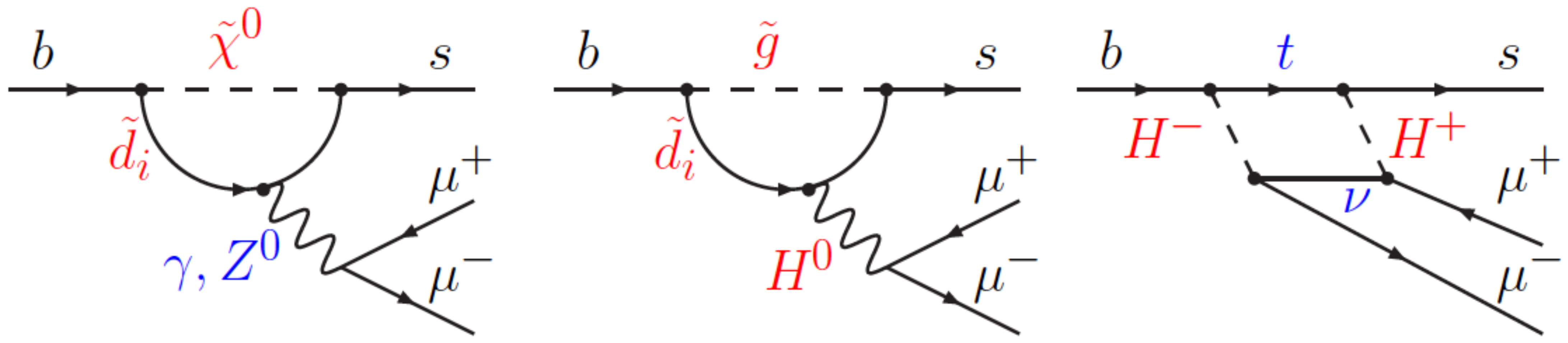
Search for NP through rare decays

- In the SM, some rare decays are forbidden at tree level and can only occur at loop level (penguin and box), e.g. $B_s \to \mu^+\mu^-$





- A new particle, too heavy to be produced at the LHC, can still give sizeable effects when exchanged in a loop (e.g. modify BFs, angular distributions,…)



→ Strategy: use well-predicted observables to look for deviations

$B_{(s)} \to \mu^+\mu^-$: a milestone of the flavour programme

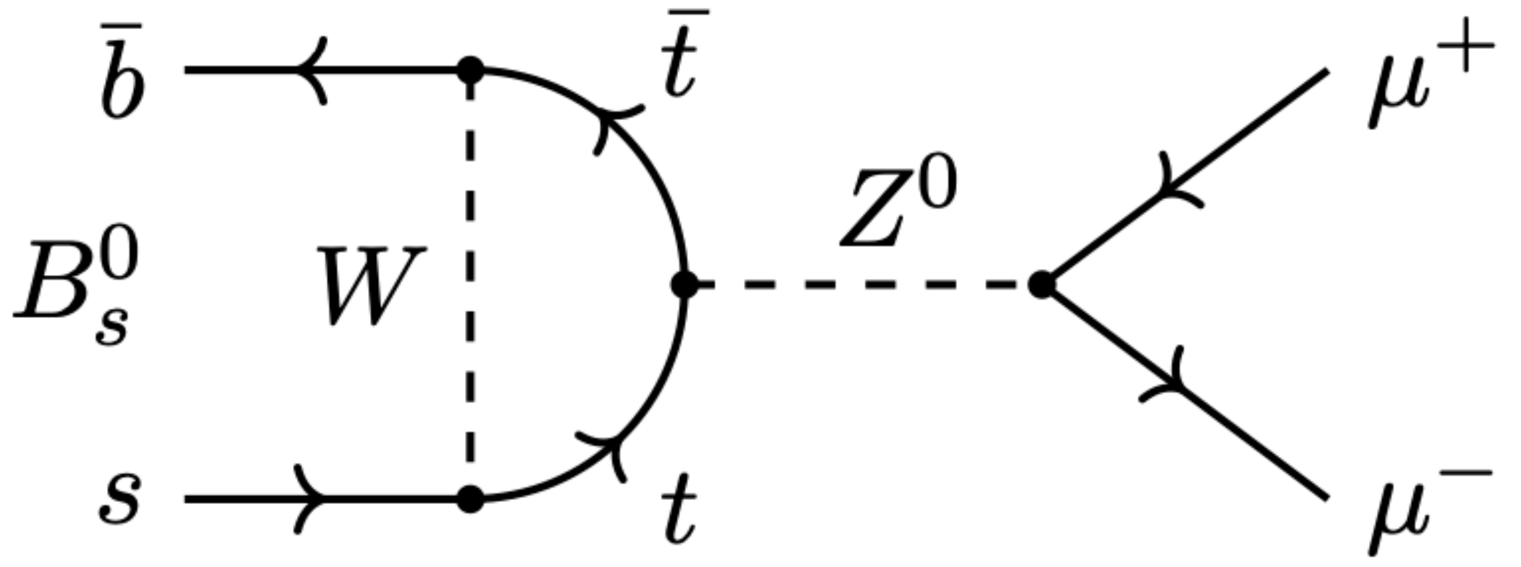
- Very suppressed in the SM
  - Loop, CKM ($|V_{ts}|^2$ for B_s) and helicity ~ $\left(\frac{m_\mu}{M_B}\right)^2$
  - Theoretically "clean" → precisely predicted (~5%)

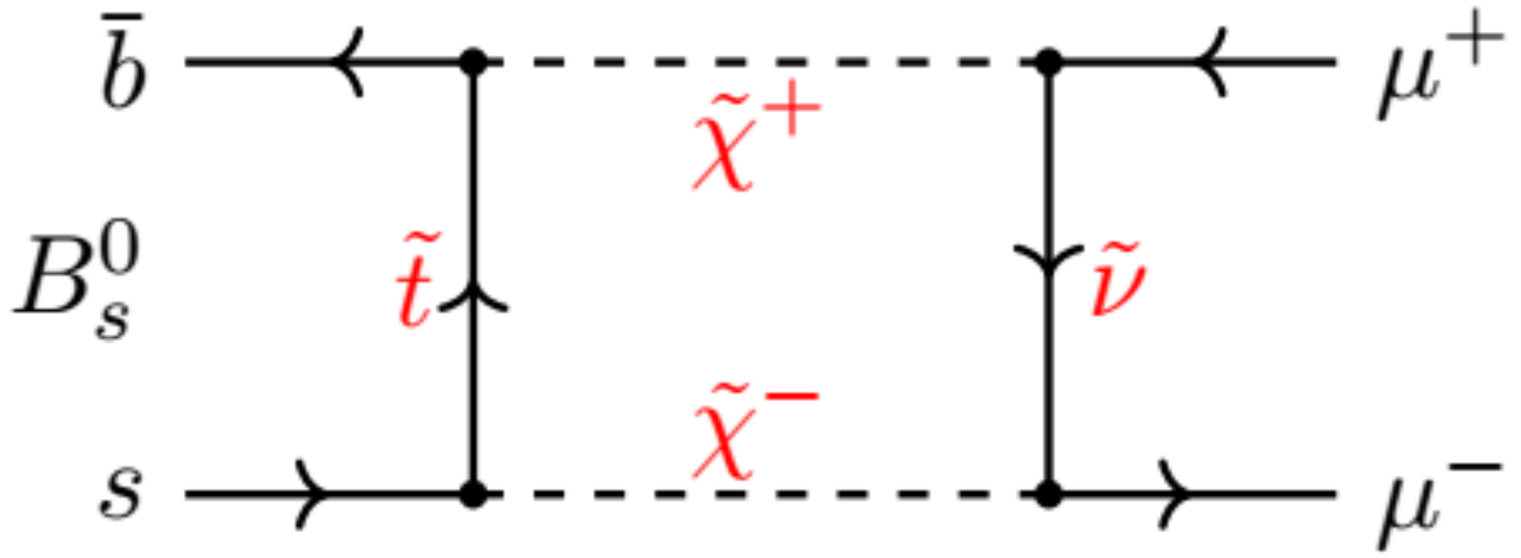
$$\mathscr{B}(B_s \to \mu^+\mu^-) = (3.62^{+0.15}_{-0.10}) \times 10^{-9}$$

$$\mathscr{B}(B_d \to \mu^+\mu^-) = (0.99^{+0.05}_{-0.03}) \times 10^{-10}$$

Bobeth et al. PRL 112 (2014) 101801, Beneke et al. JHEP 10 (2019) 232

Buras & Venturini arXiv:2109.11032, independent of $|V_{cb}|$





- Sensitive to New Physics
  - A large class of NP theories, such as SUSY, predict significantly higher values for the $B_{(s)}$ decay probability

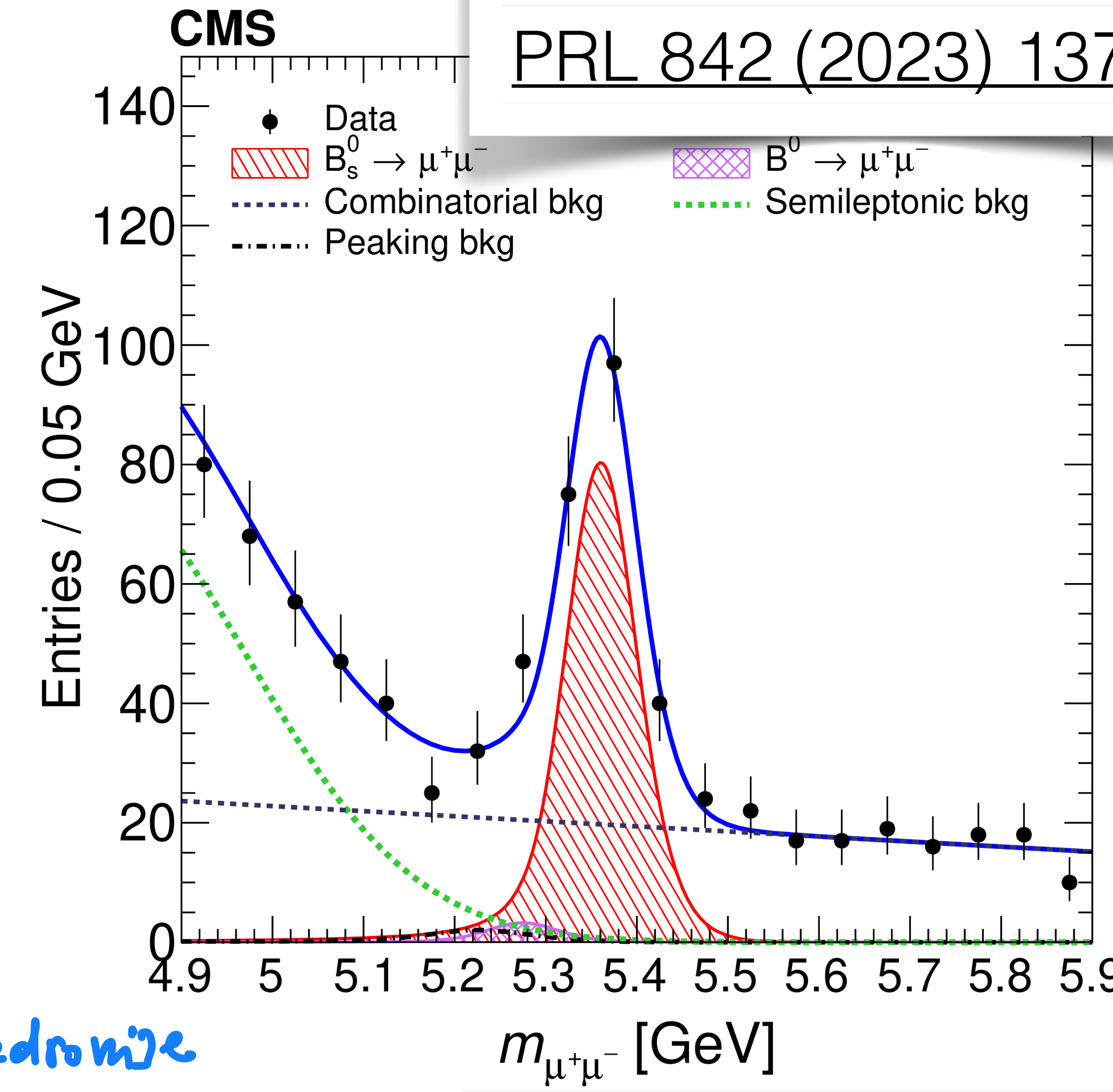
- Very clean experimental signature
  - Studied by all high-energy hadron collider experiments

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

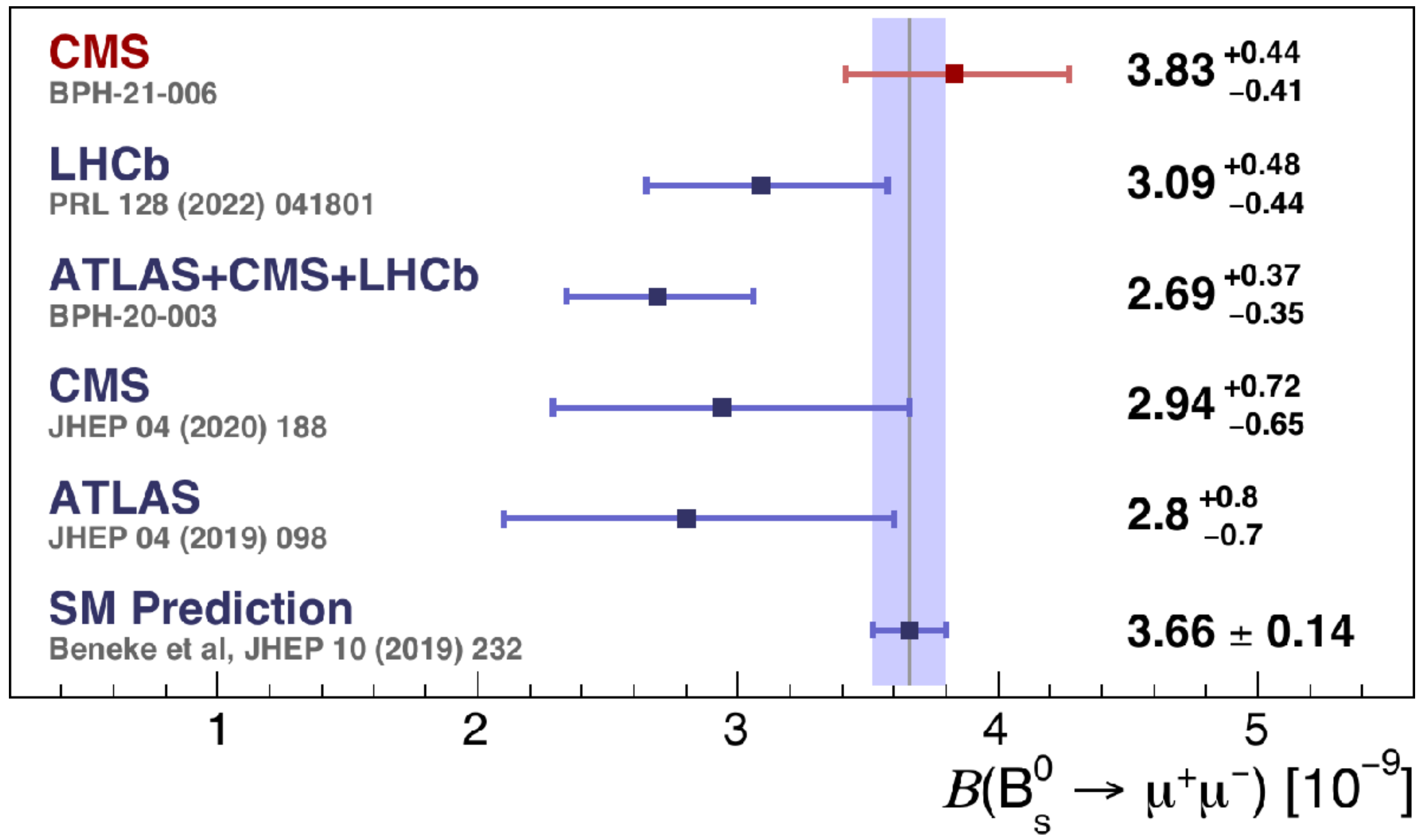
- Latest CMS measurement (140 fb^{-1}), most precise to date :

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = \left[3.83^{+0.38}_{-0.36}\ (\text{stat})\ ^{+0.19}_{-0.16}\ (\text{syst})\ ^{+0.14}_{-0.13}\ (f_s/f_u)\right] \times 10^{-9},$$

  - CMS measurement moves average towards SM



PRL 842 (2023) 137955



- Measurement statistically limited. Systematic uncertainty for $B_s \to \mu^+\mu^-$ dominated by uncertainty associated with b-quark fragmentation probability ratio f_s/f_d (~3%)

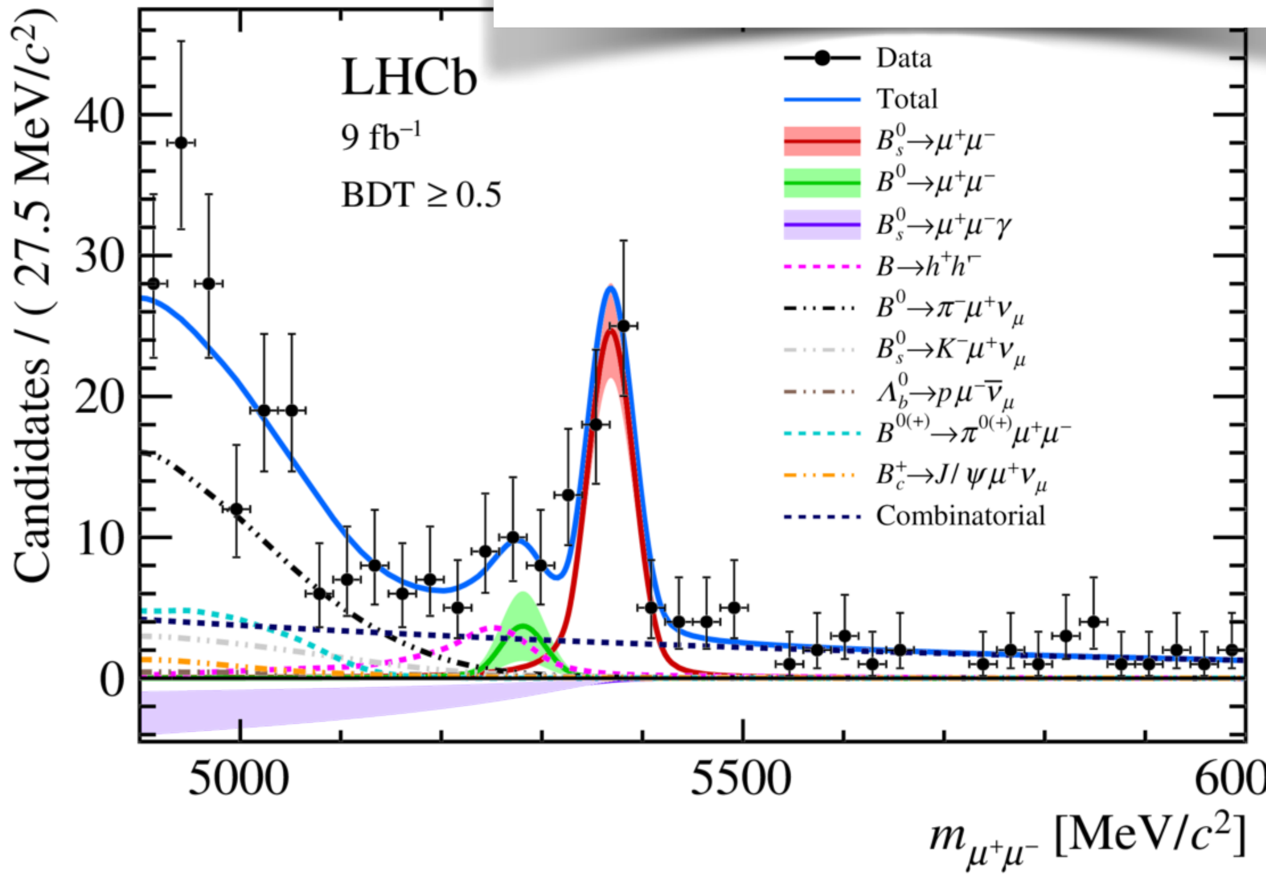
f_s/f_d : probability for a b-quark to hadronize into a $B^{+,0}$, B^0_s

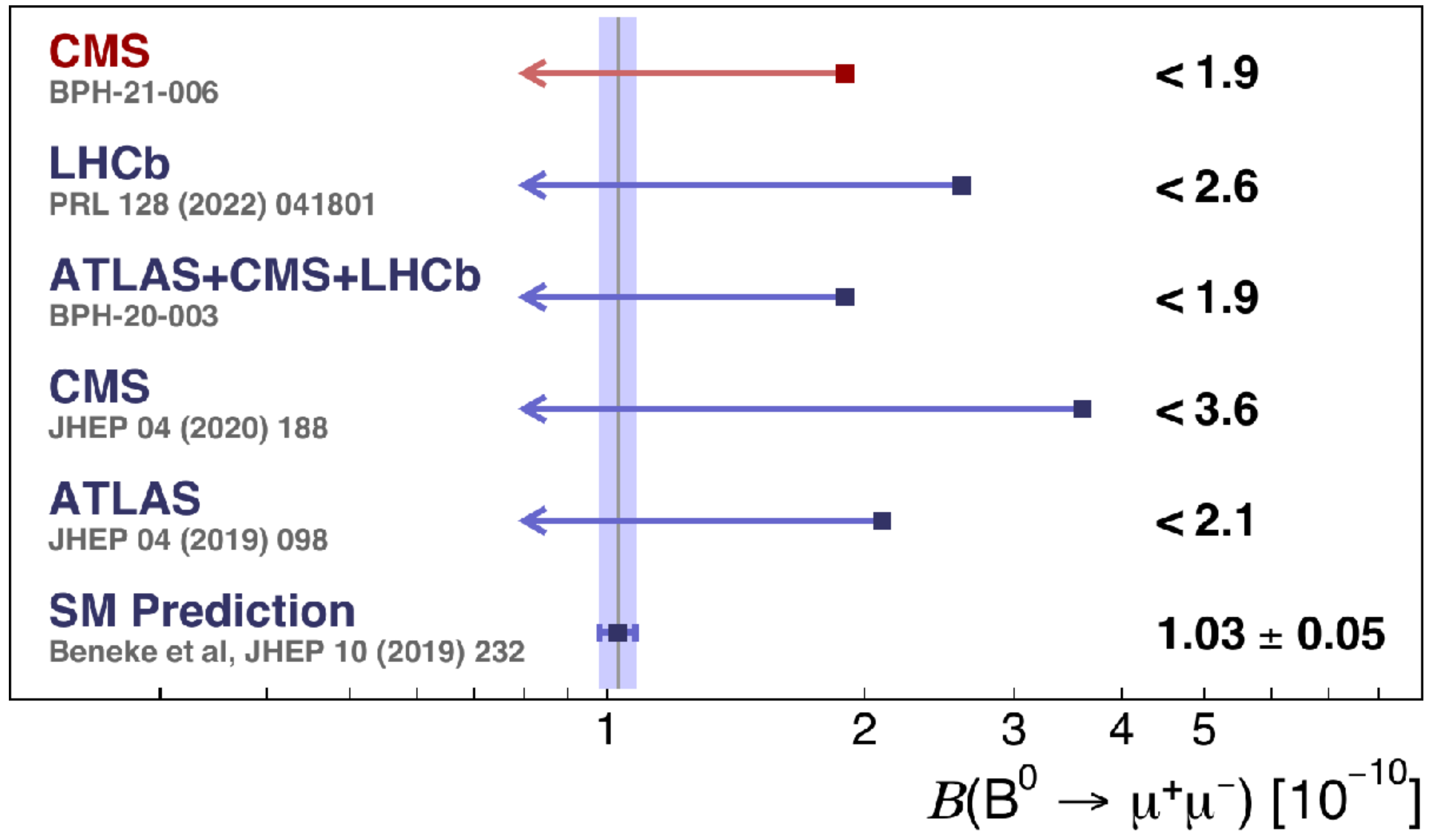
PRL 128 (2022) 041801
PRD 105 (2022) 012010

- The rarer $B^0 \to \mu^+\mu^-$ is still unobserved, but its expected ~10^{-10} rate is within reach

- The ratio of BF $\dfrac{\mathcal{B}(B_d \to \mu^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)}$ will remain stat. limited

- $B_{(s)} \to \mu^+\mu^-$ results alone have had a major impact on constraining the parameter space of several BSM theories, in particular SUSY

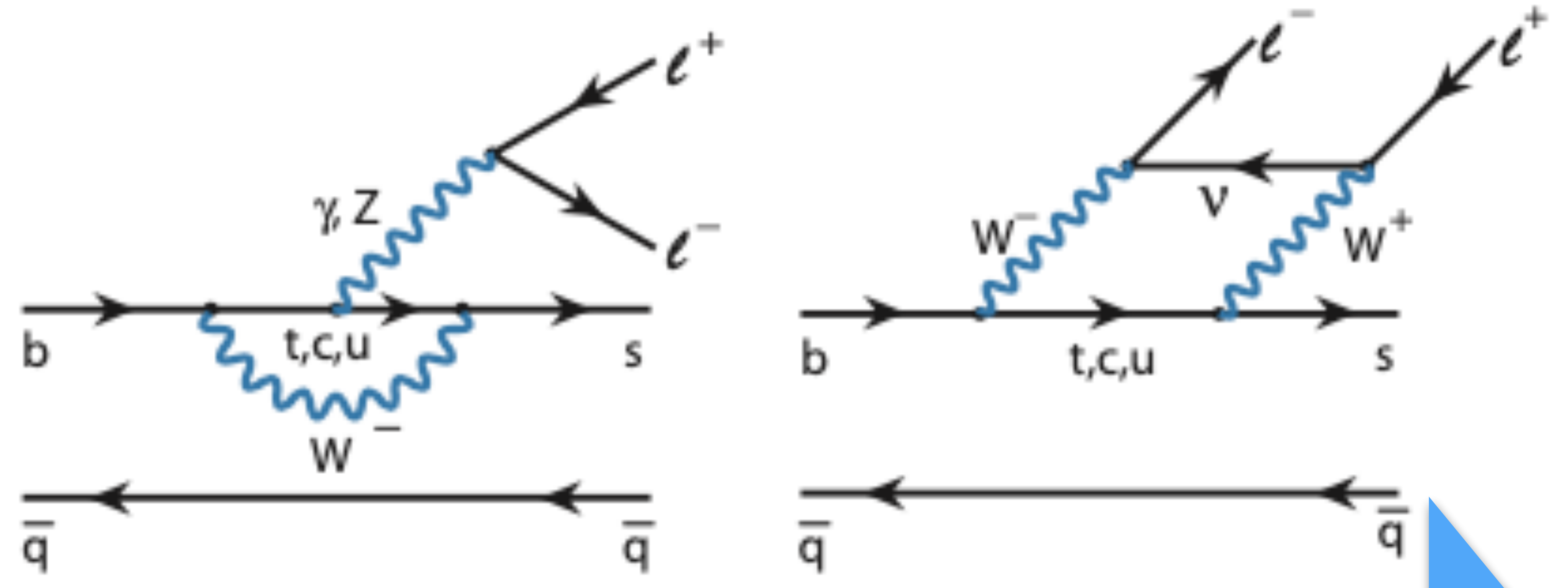




$b \to s\ell^+\ell^-$ decays

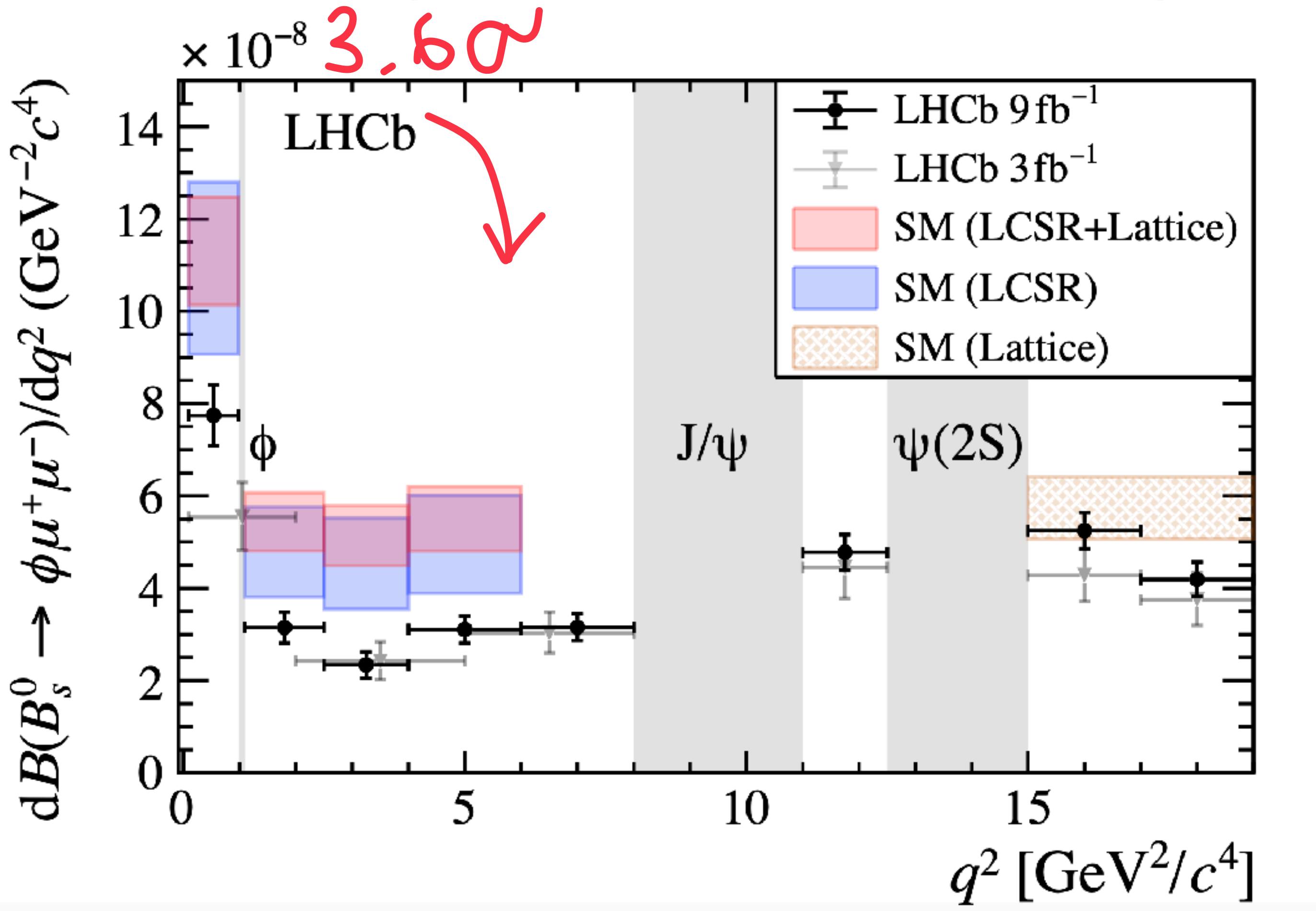
BF$\sim\mathcal{O}(10^{-7})$

- Rich set of observables with different degree of theoretical "cleanliness"
- Long-standing set of deviations from SM expectations, but latest measurements of LFU fractions R_K, R_{K^*} in agreement with SM



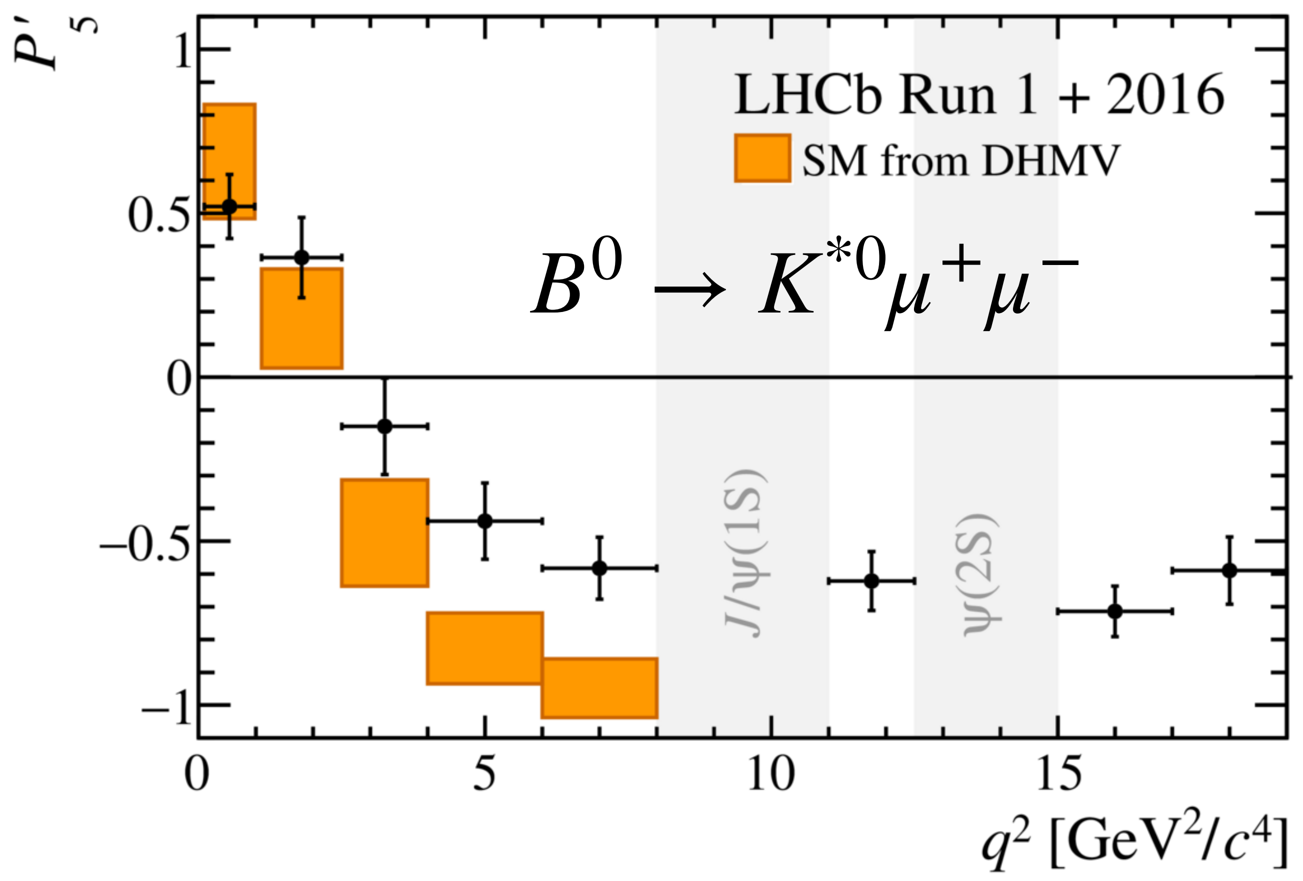
Increasing precision of SM predictions

PRL 127 (2021) 151801



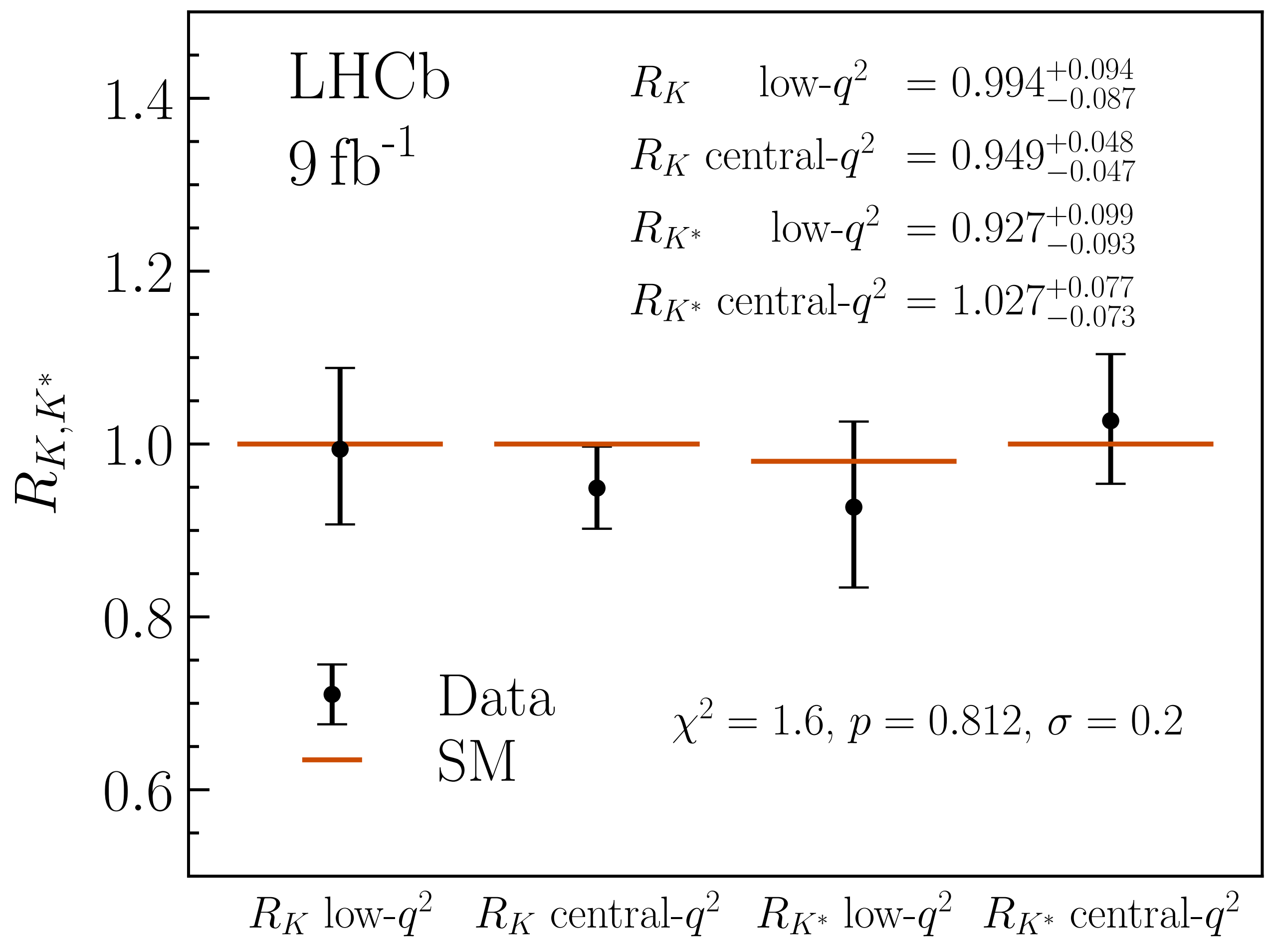
Differential BFs $\frac{d\Gamma(B \to H\ell\ell)}{dq^2}$, affected by form factors and charm loops

PRL 125 (2020) 011802



Angular observables ($P'_5, A_{FB}, ..$) affected by form factors

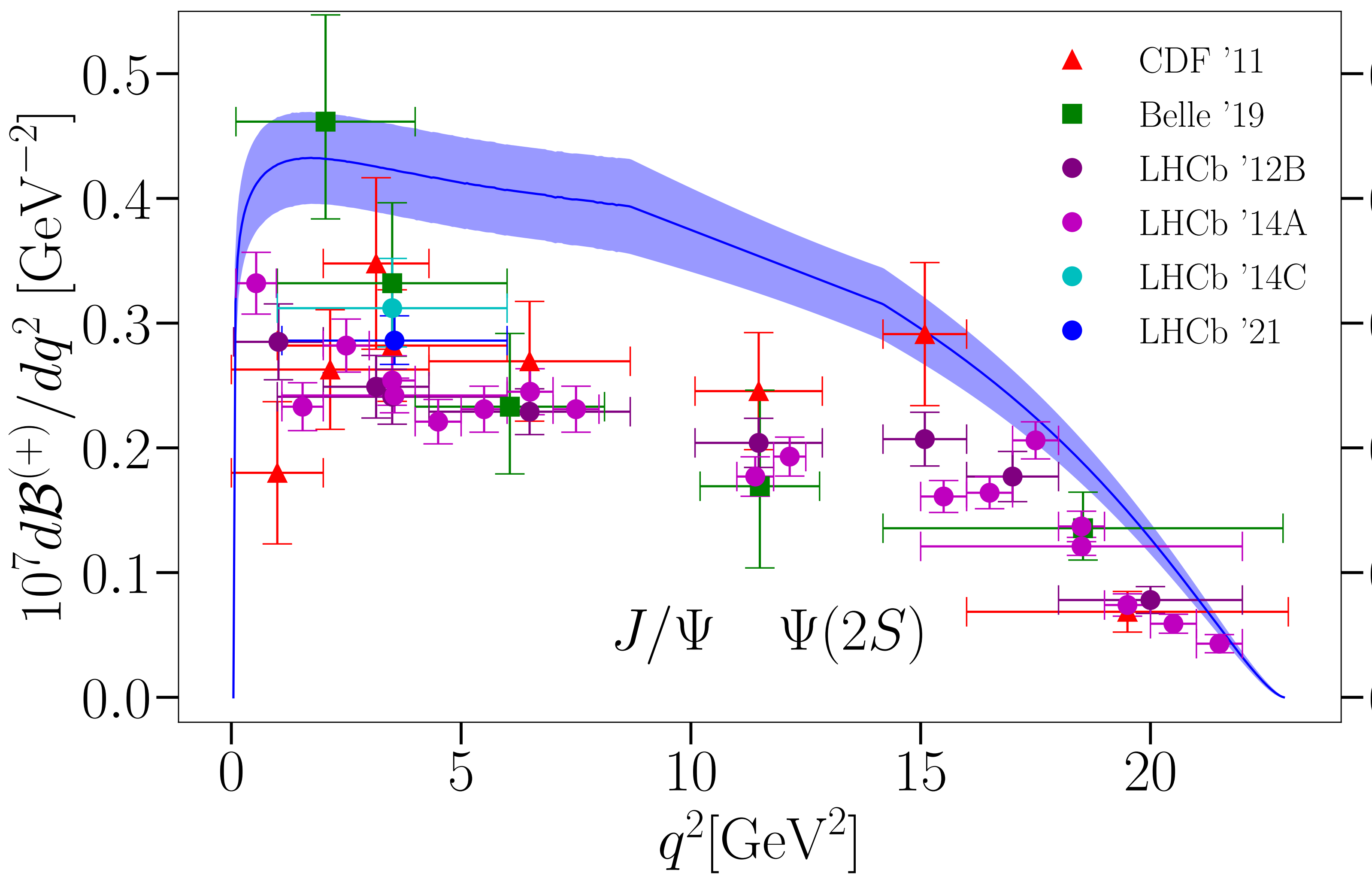
PRL 131 (2023) 051803



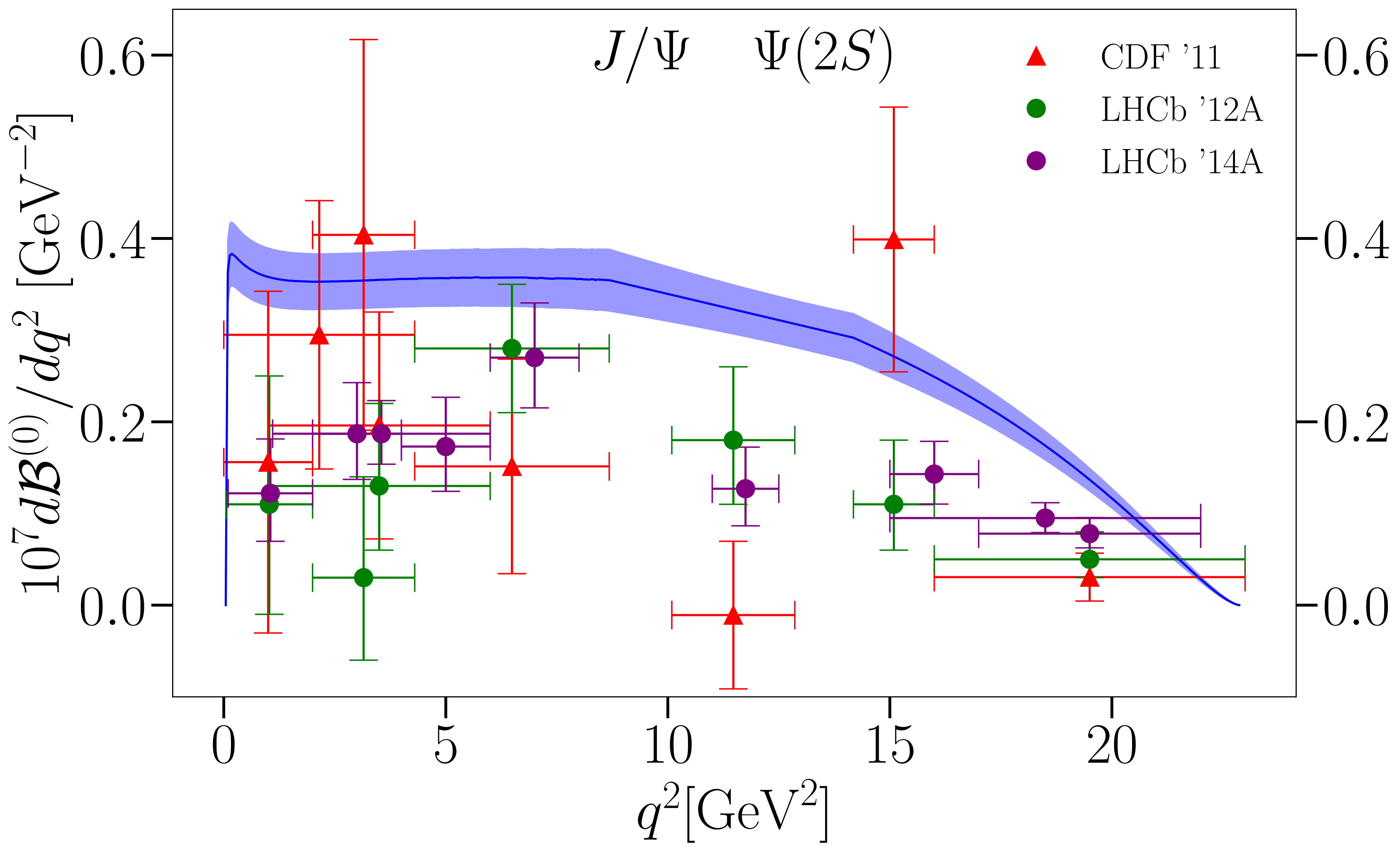
Lepton Universality Tests (R_K, R_{K^*},..)"clean"

BF of semileptonic $b \to s\mu^+\mu^-$

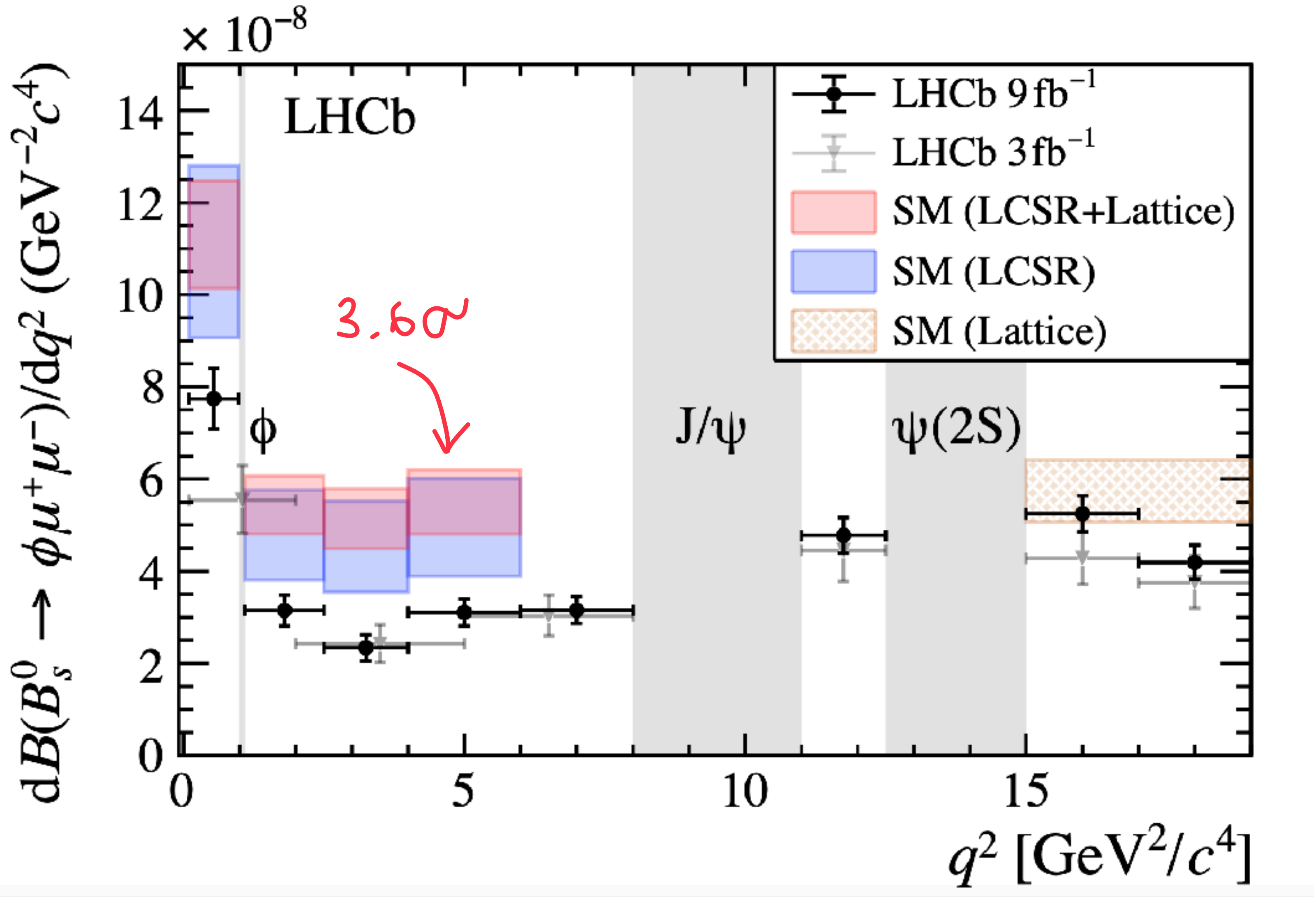
HPQCD $B^+ \to K^+\mu^+\mu^-$ [PRD 107 (2023)119903]



HPQCD $B^0 \to K^{*0}\mu^+\mu^-$ [PRD 107 (2023)119903]



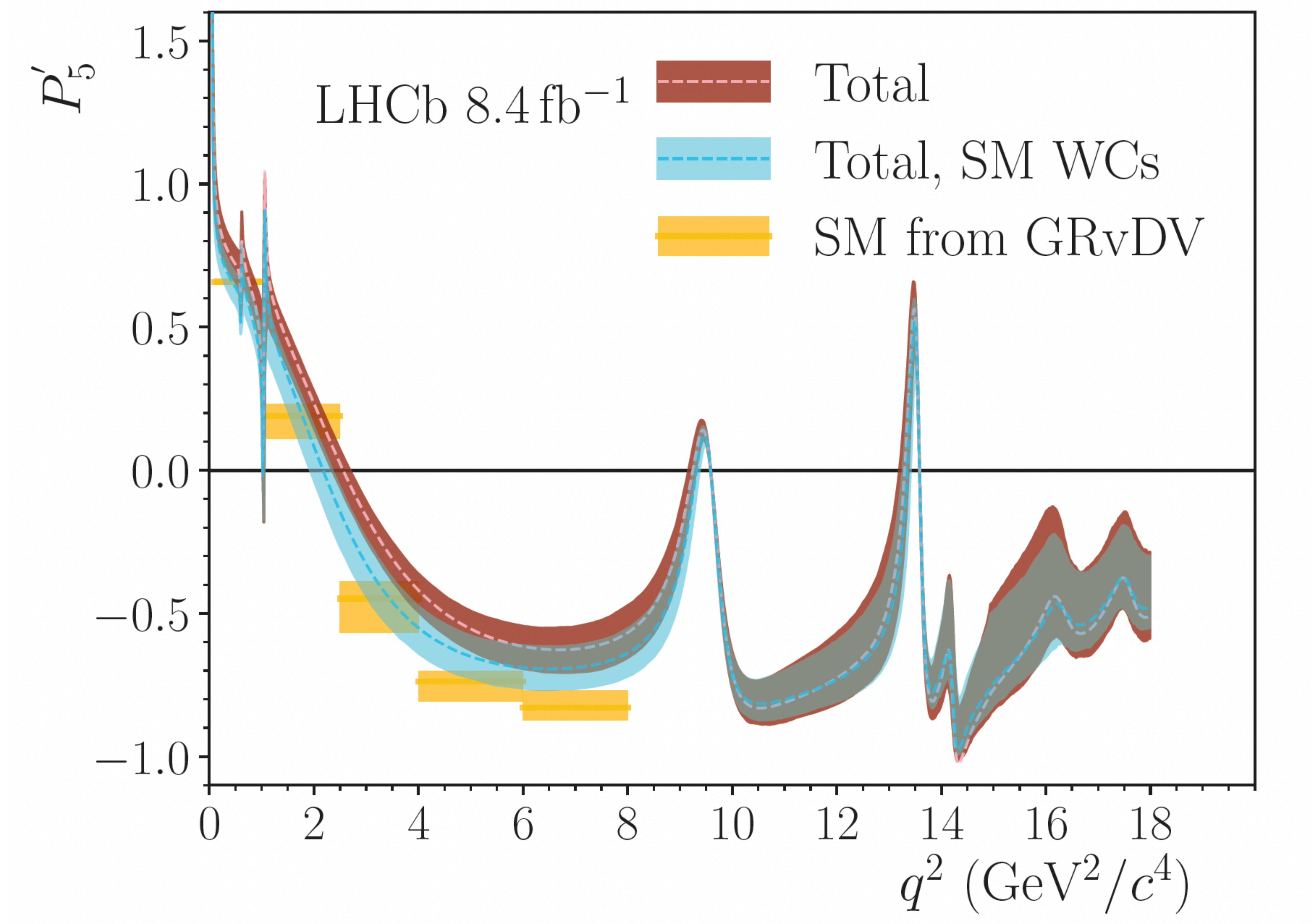
$B_s \to \phi\mu^+\mu^-$ PRL 127 (2021) 151801



- Data consistently lower than predictions, particularly below the charmonium thresholds

Angular analysis of $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$

- LHCb observed a tension in the "optimised variable" P_5' , not exactly intuitive, but constructed from ratios of angular observables to be robust from 'form-factor uncertainties'
- New result on measurement of local and non-local amplitudes in $B^0 \to K^{*0}\mu^+\mu^-$ decays based on Run1 and Run2
- Unbinned amplitude analysis using the whole $q^2 = m^2(\mu^+\mu^-)^2$



$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$, with F_L and S_5 combinations of K^* spin amplitudes dependent on Wilson coefficients and form factors

Tom Hadavizadeh, Moriond QCD 2024

LHCb-Paper-2024-011, in preparation

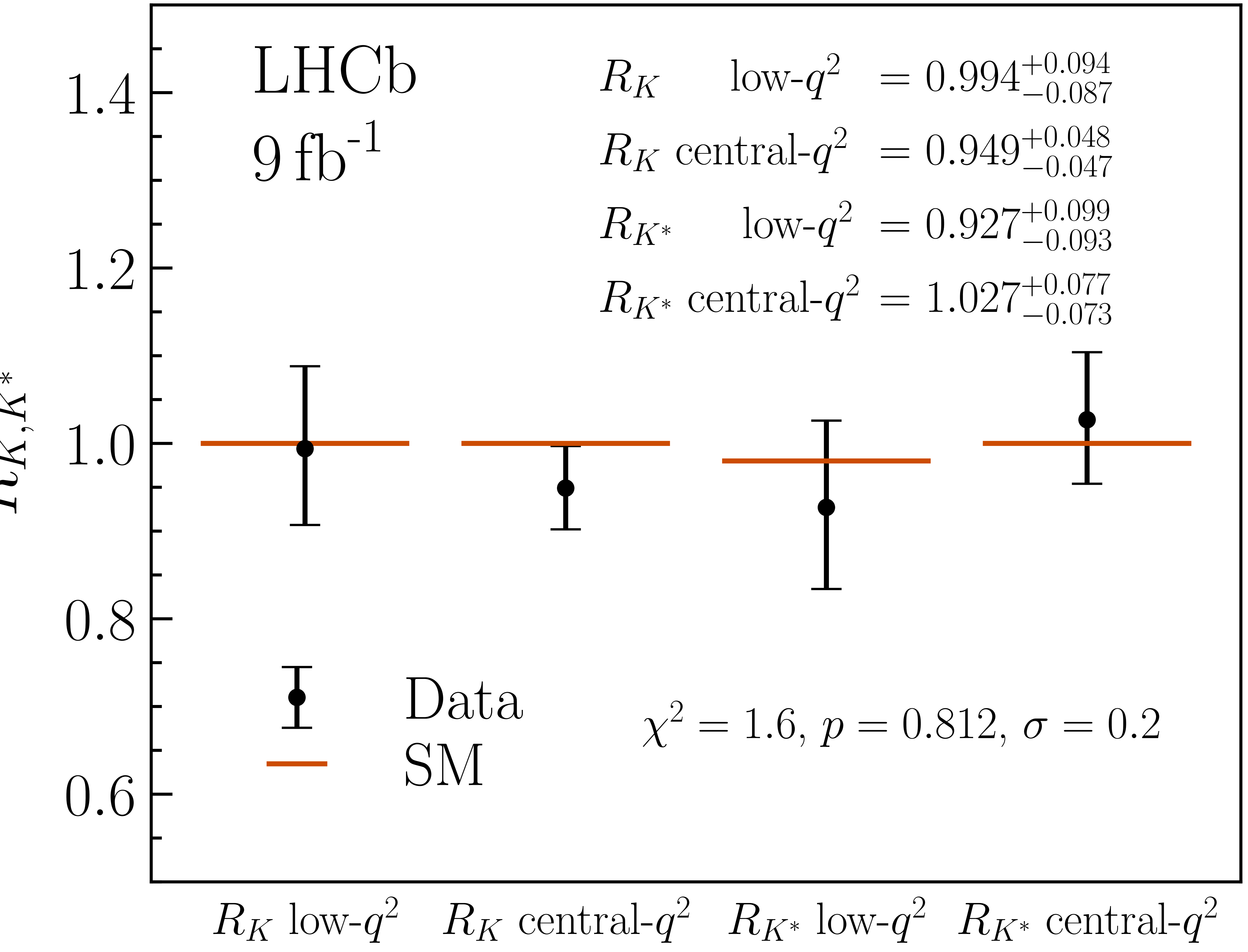
Red vs Cyan: Impact of allowing NP
Cyan vs Yellow: Impact of nonlocal modelling

- Non-local contributions play a clear role in the $B^0 \to K^{*0}\mu^+\mu^-$ angular distribution (even if they do not explain the full deviation)
- Wilson coefficients derived directly from the fit
- Agreement with SM at 1.5 σ (2.1 σ tension in C_9)

Tests of Lepton Flavour Universality
(electrons are complicated…)

$$R_X = \frac{BR(X_b \to X_s\mu^+\mu^-)}{BR(X_b \to X_s e^+e^-)}$$

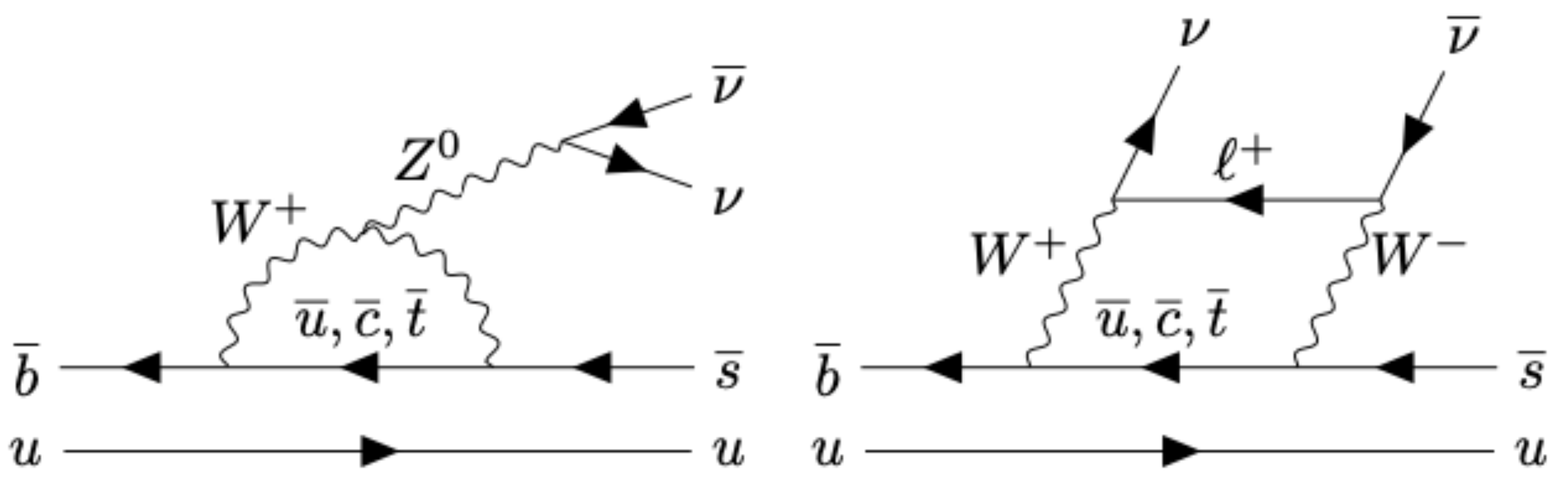
PRD 108 (2023) 032002
PRL 131 (2023) 051803

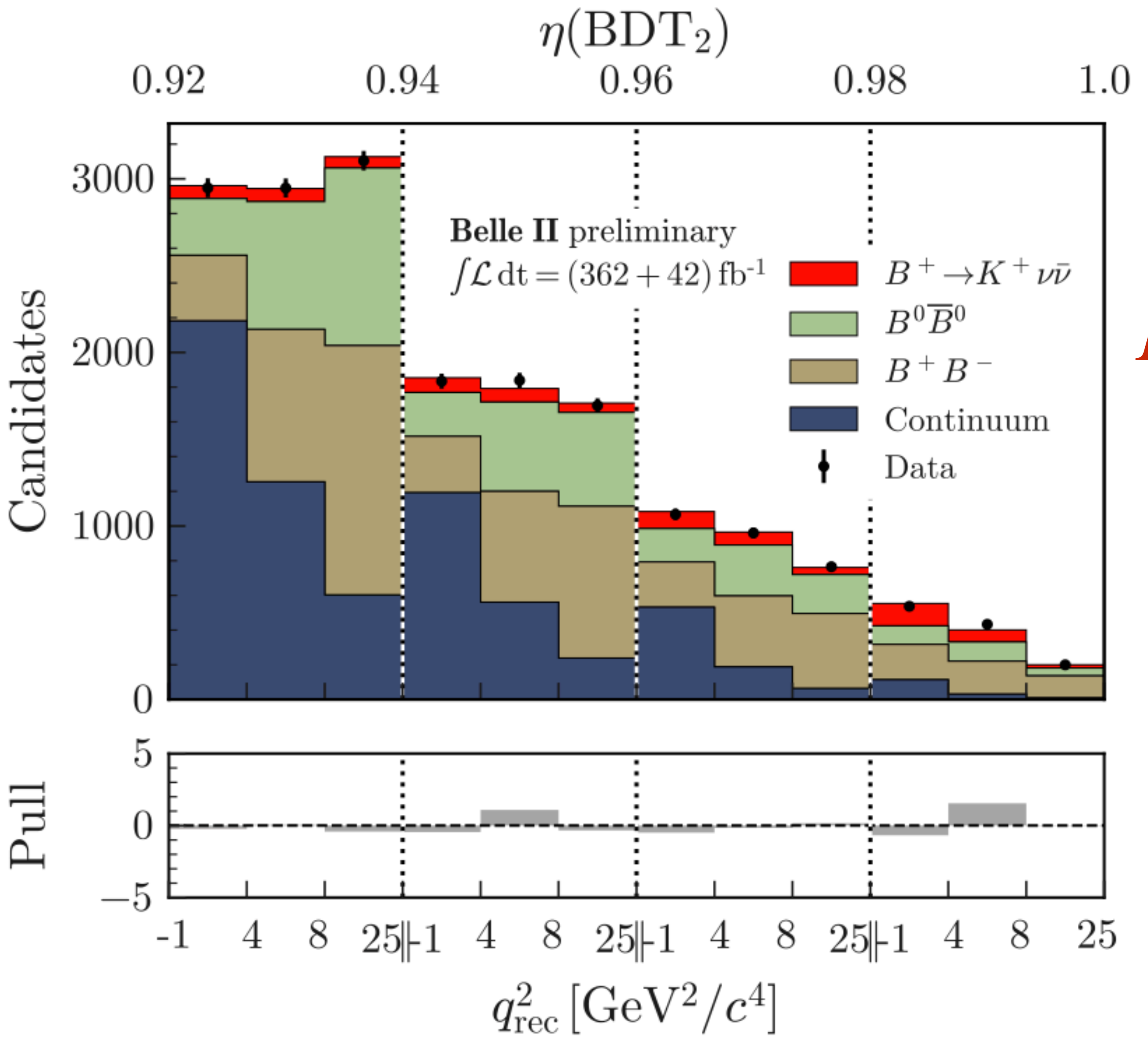


- Electrons: higher trigger thresholds & bremsstrahlung losses
- Latest measurements benefit from more stringent electron PID and data-driven background estimates
- R_K, R_{K^*} in agreement with SM at ~5% level

A new mode from Belle II: $B^+ \to K^+ \nu \bar{\nu}$

- $b \to s \nu \bar{\nu}$ transition
- Precisely predicted:
  - $B(B \to K \nu \bar{\nu})_{SM} = (5.6 \pm 0.4) \times 10^{-6}$ PRD 107, 014511 (2023)
- Experimentally challenging (unique to e^+e^- colliders)
- Measurement based on new inclusive and more efficient tagging technique, validated using hadronic B tagging (low eff. and low background)





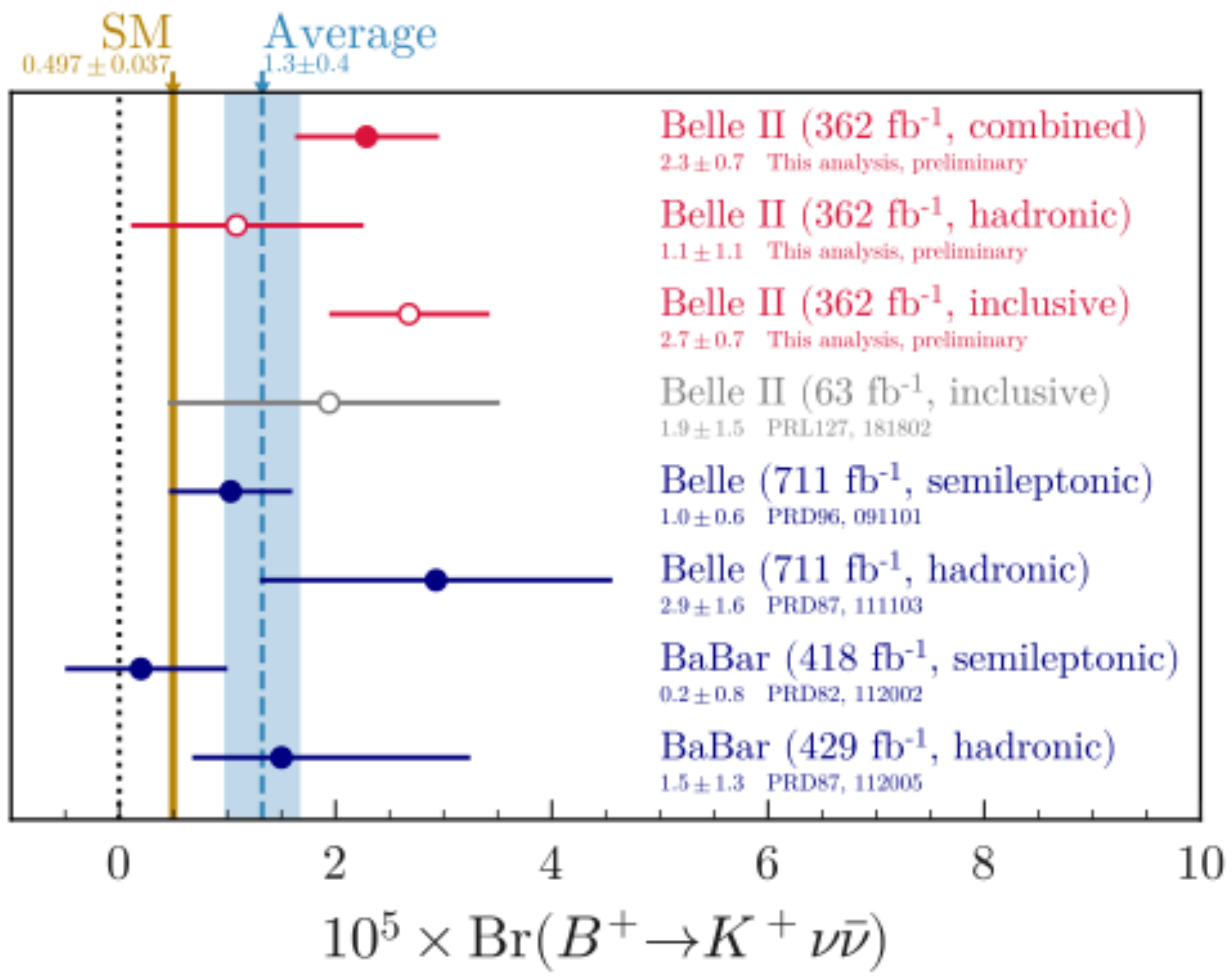
arXiv:2311.14647

$$B(B \to K \nu \bar{\nu}) = \left(2.3 \pm 0.5^{+0.5}_{-0.4}\right) \times 10^{-5}$$

First evidence of $B^+ \to K^+ \nu \bar{\nu}$

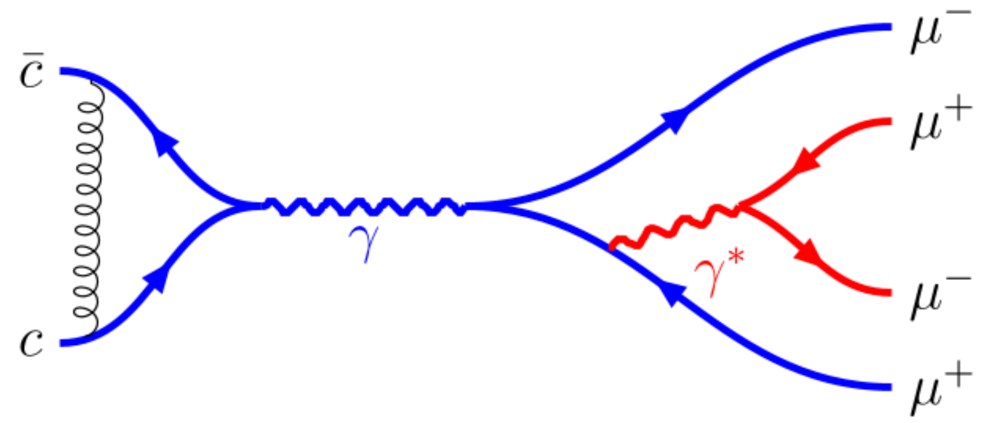
3.5σ significance wrt null hypothesis

2.7σ above SM prediction



Observation of $J/\psi \to \mu^+\mu^-\mu^+\mu^-$

- Rare electromagnetic decay that proceeds through final-state radiation of virtual photon
- Precise SM prediction PRD 104 (2021) 094023
  $B(J/\psi \to 4\mu) = (9.74 \pm 0.05) \times 10^{-7}$

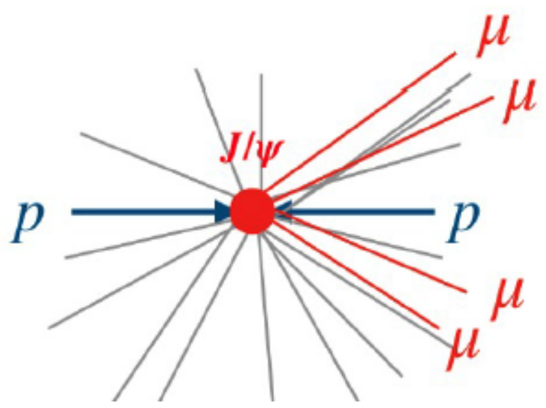


PRD 109 (2024) 052006

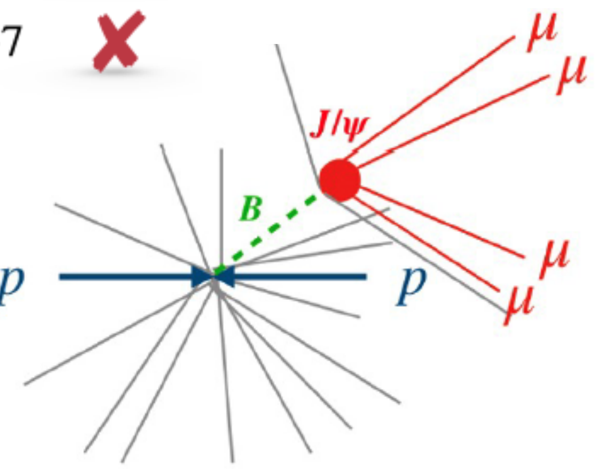
$J/\psi \to e^+e^-e^+e^-$ ✓

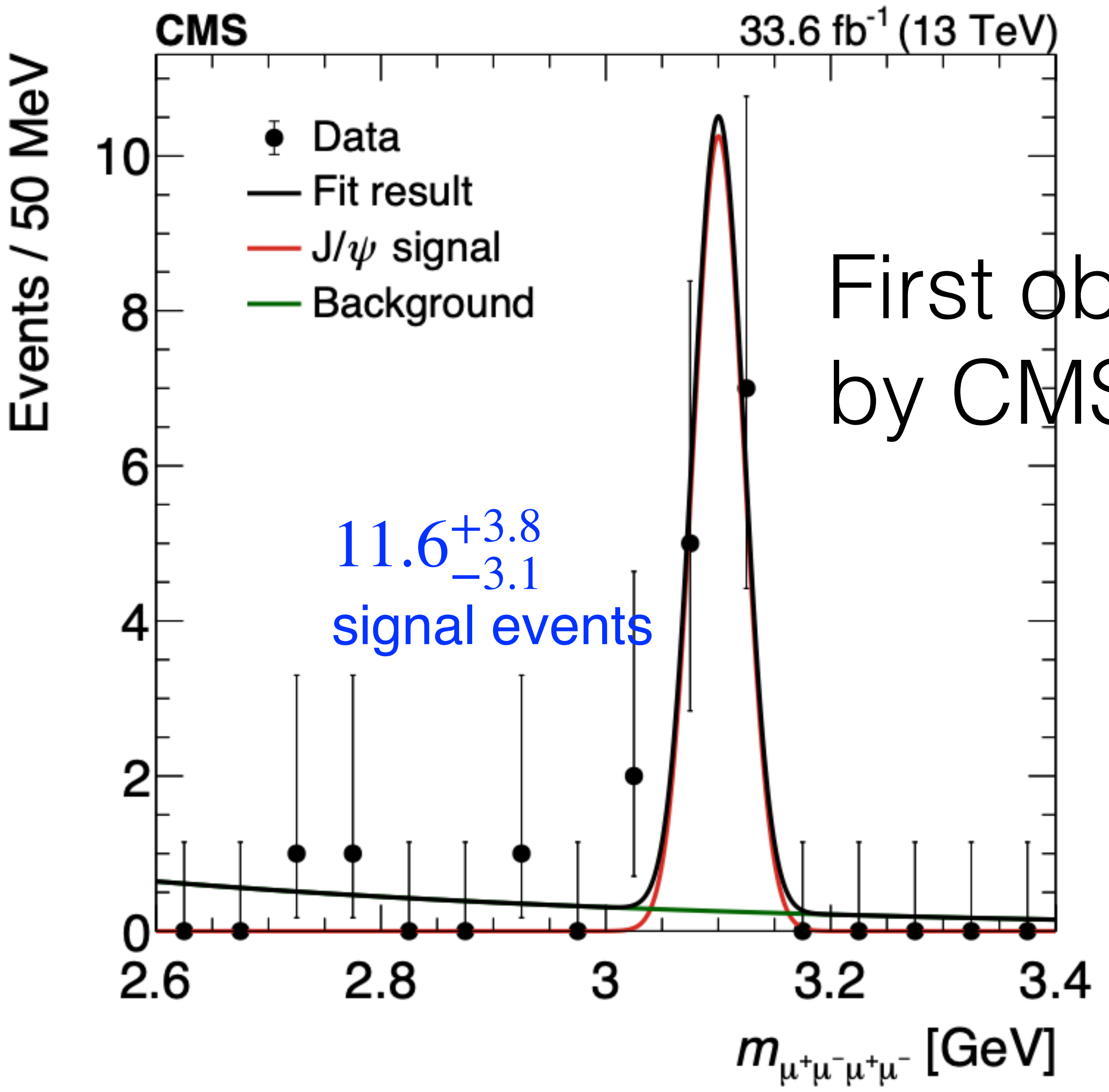
$J/\psi \to e^+e^-\mu^+\mu^-$ ✓

$\mathscr{B}(J/\psi \to \mu^+\mu^-\mu^+\mu^-) < 16 \times 10^{-7}$ (90%CL) ✗



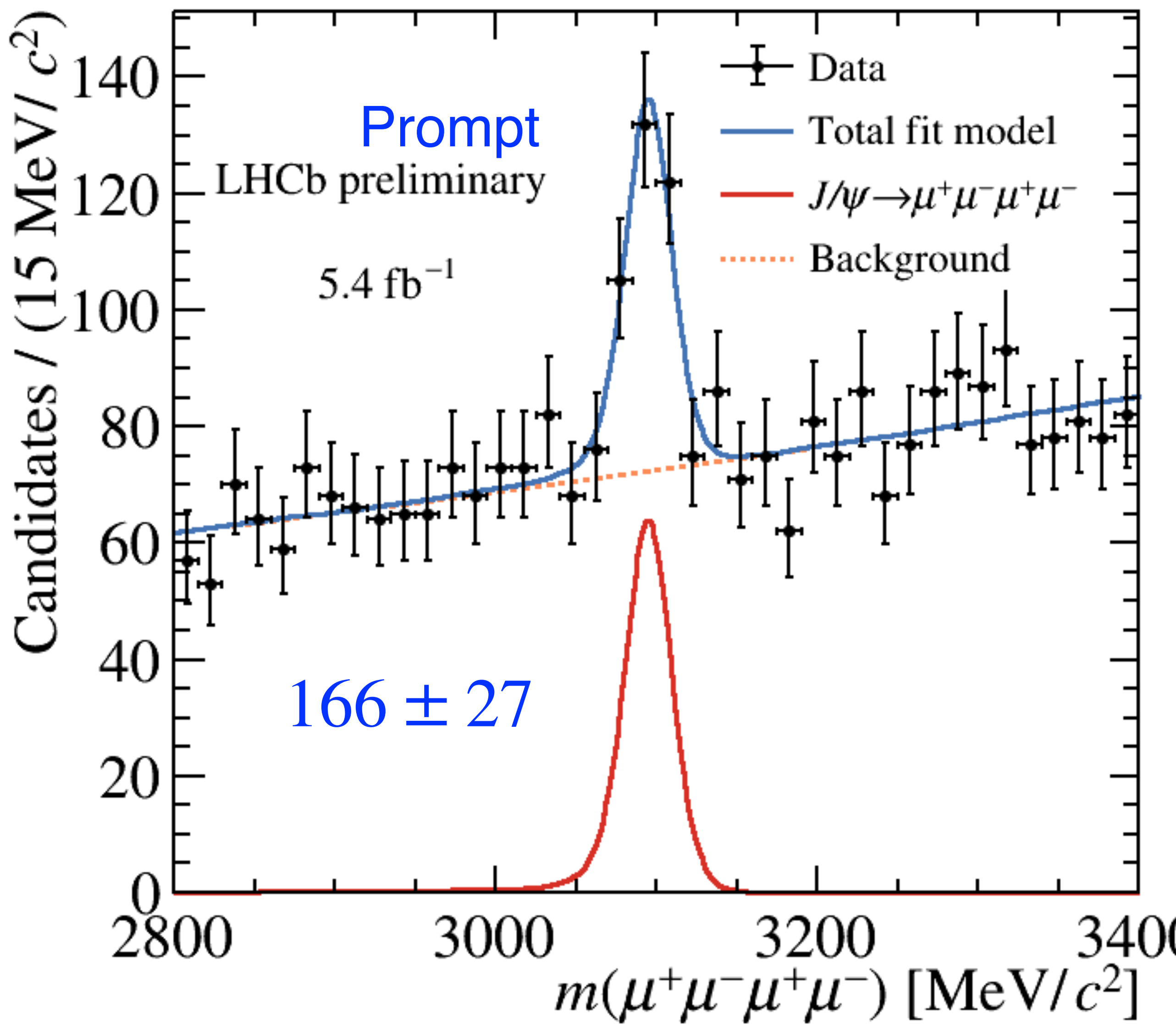
LHCb-CONF-2024-001

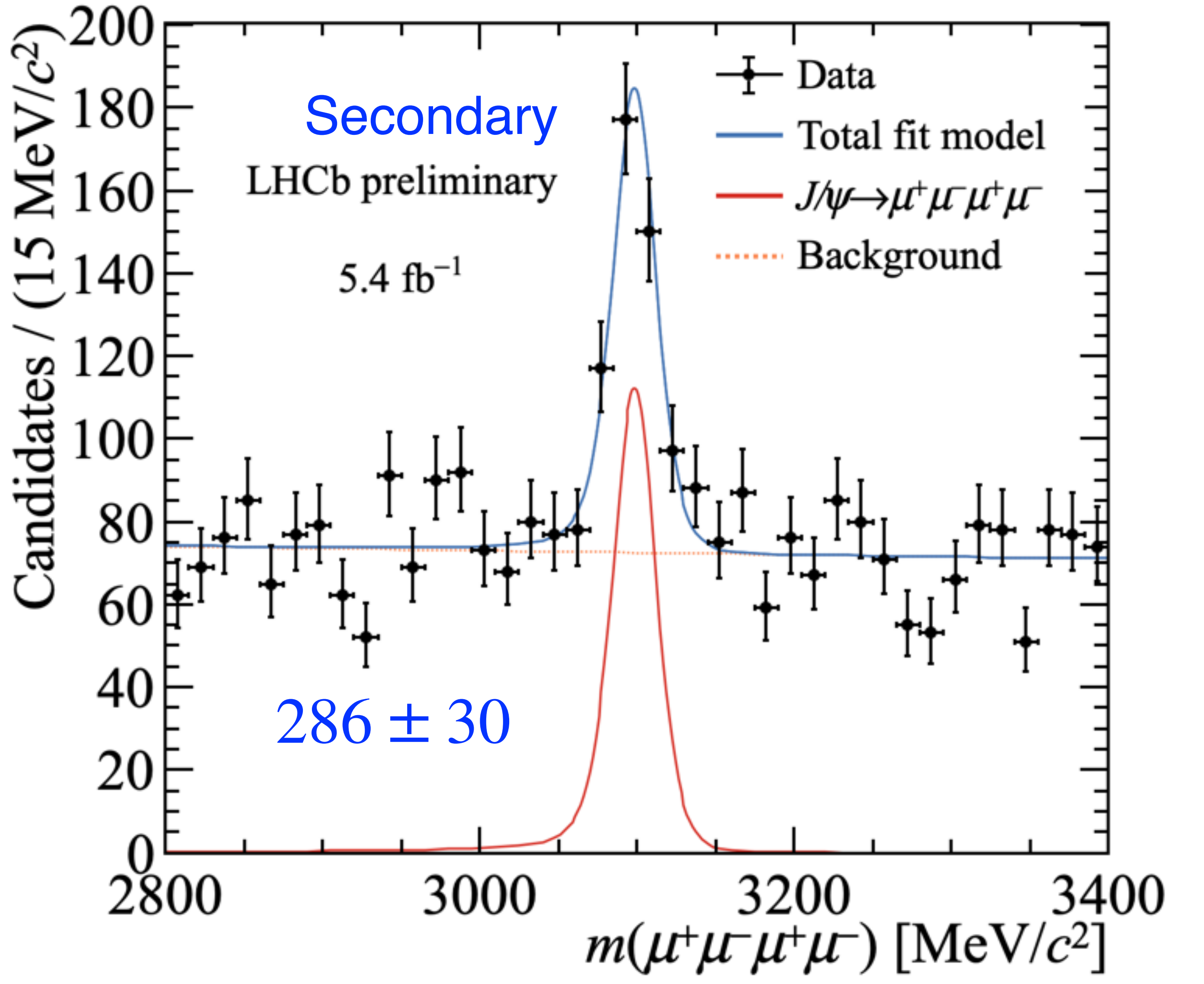




First observation by CMS

arXiv:2403.11352

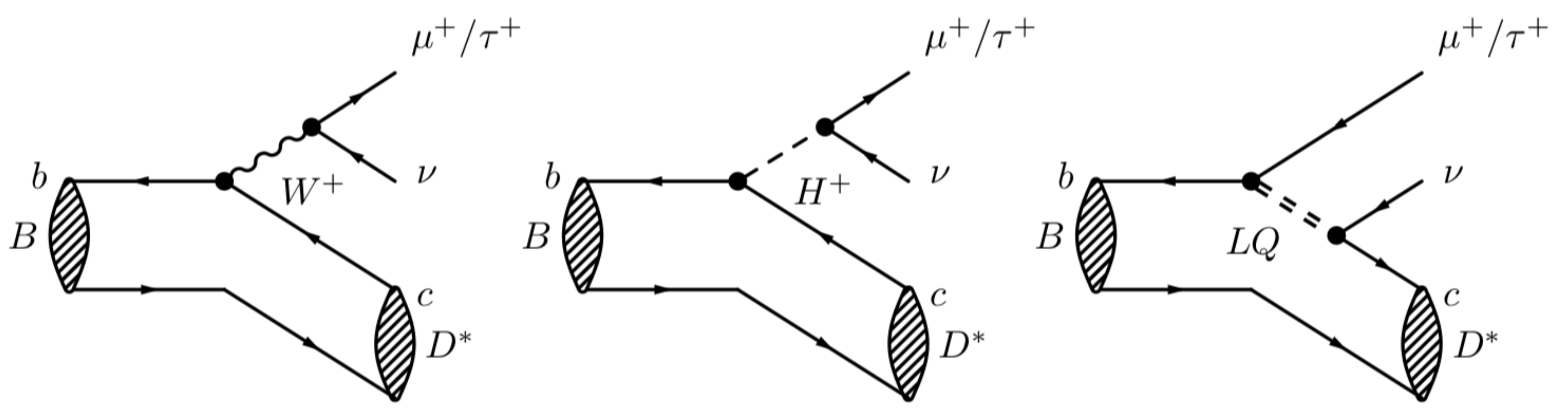




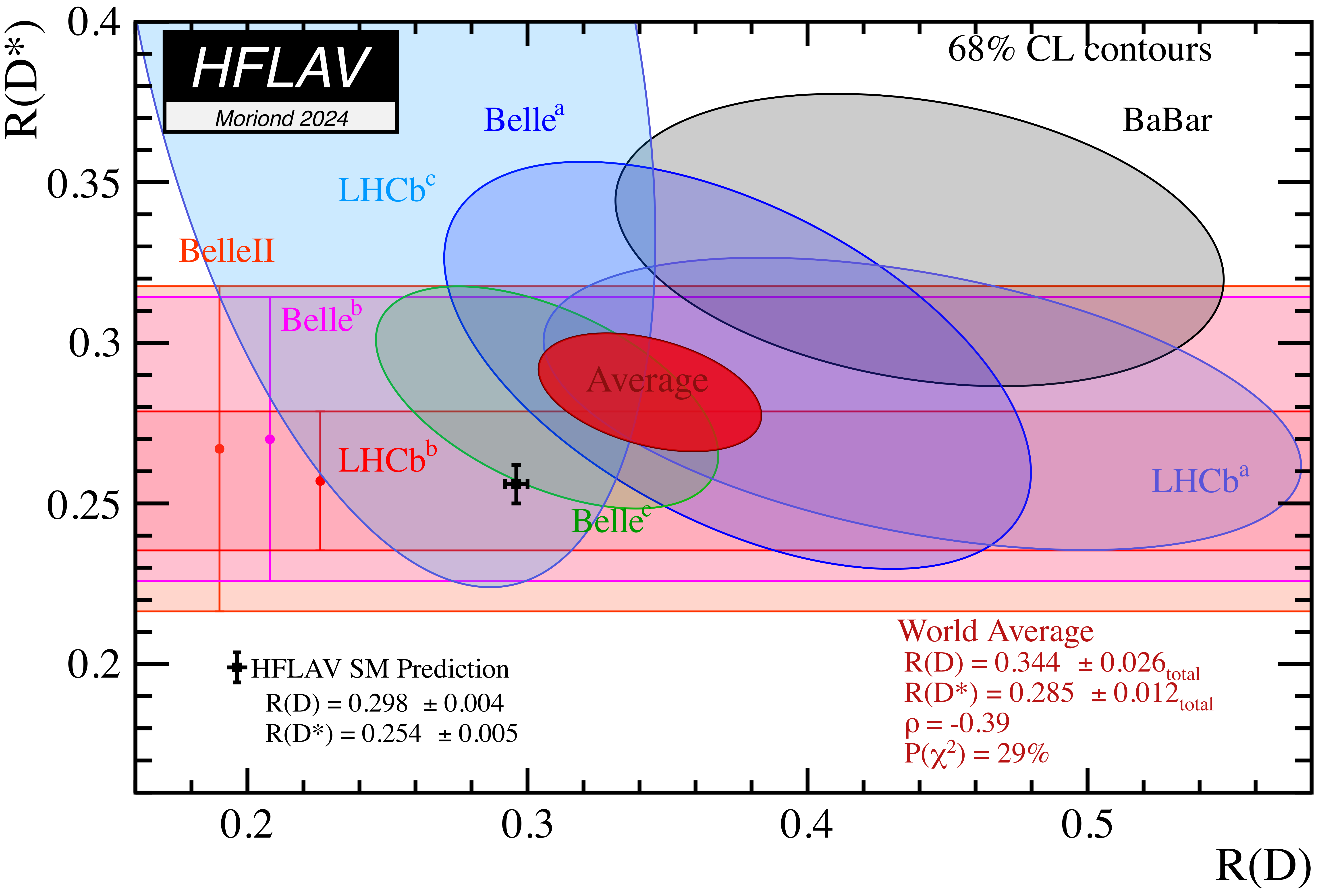
$B(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = (1.01^{+0.33}_{-0.27} \pm 0.04) \times 10^{-6}$

$B(J/\psi \to \mu^+\mu^-\mu^+\mu^-) = (1.13 \pm 0.10 \pm 0.05 \pm 0.01) \times 10^{-6}$

LFU studies in $B \to D^{(*)}\tau\nu$ decays



- Different class of decays (tree-level charged current)
- Not at all rare: $B(B^0 \to D^{*-}\tau^+\nu_\tau) \sim 1\ \%$, problem is the background
- LFU ratio: $R(D^{(*)}) = \dfrac{\mathscr{B}(B \to D^{(*)}\tau^+\nu_\tau)}{\mathscr{B}(B \to D^{(*)}\mu^+\nu_\mu)}$ sensitive to NP involving third generation



$$R(D)_{SM} = 0.298 \pm 0.004$$
$$R(D^*)_{SM} = 0.254 \pm 0.005$$

HFLAV 2023 average

3.2 σ tension

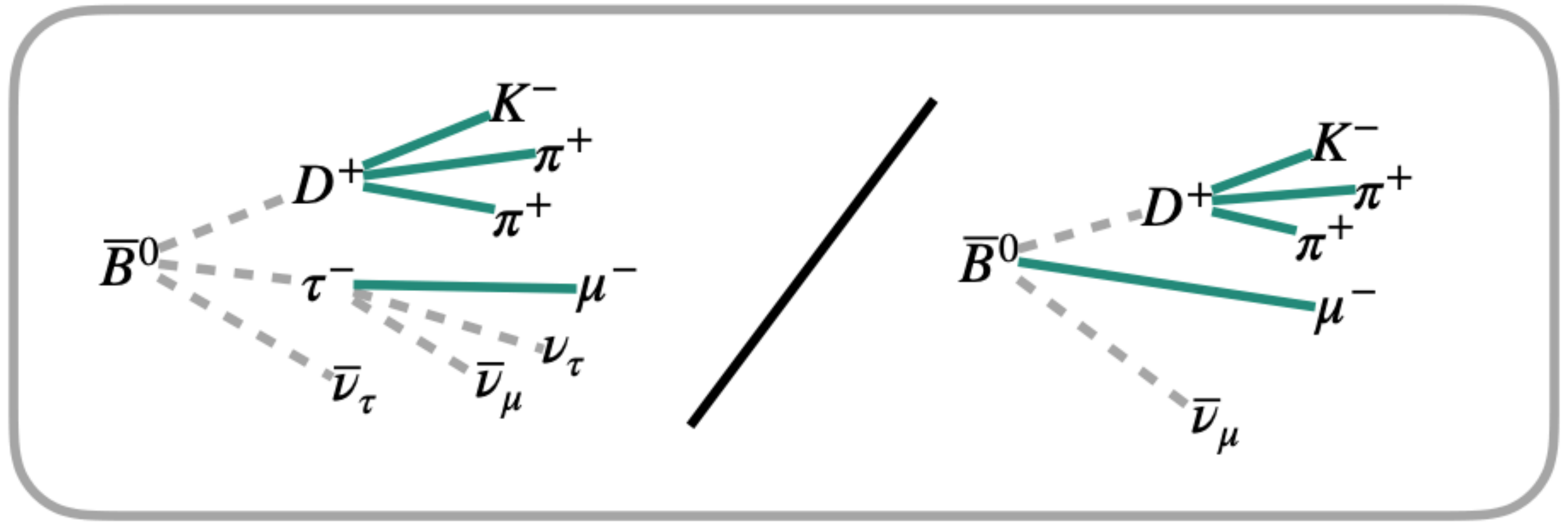
HFLAV

New LHCb measurement of $R(D^{(*)+})$

J. García Pardiñas, Moriond 2024
LHCb-PAPER-2024-007

- First LHCb measurement using $D^+ \to K^-\pi^+\pi^-$ and $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ decays

R(D⁺) =



- Feed down from $D^{*+} \to D^+\pi^0/\gamma$ gives access to $R(D^{*+})$

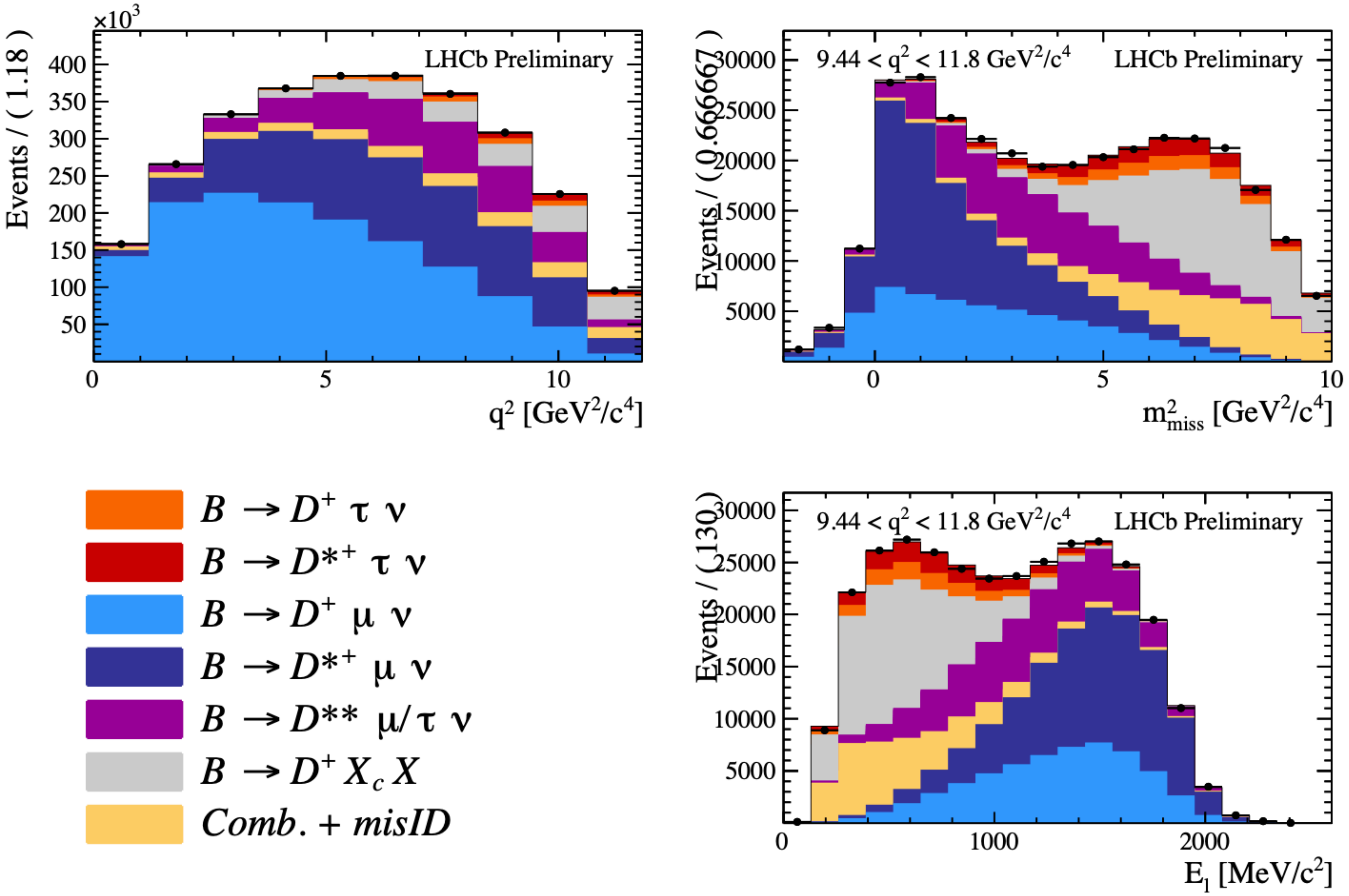
- 3D binned template fit to $q^2 = (p_B - p_{D^{(*)}})^2$, $m^2_{\text{miss}} = (p_B - p_{D^{(*)}} - p_\mu)^2$, E^*_μ (muon energy in B rest frame)

LHCb preliminary

$$R(D^+) = 0.249 \pm 0.043_{\text{stat}} \pm 0.047_{\text{syst}}$$

$$R(D^{*+}) = 0.402 \pm 0.081_{\text{stat}} \pm 0.085_{\text{syst}}$$

$$\rho = -0.39$$



- Main systematic uncertainties from form-factor parametrisatior &background modelling

LHCb measurement of $R(D^{(*)+})$

J. García Pardiñas, Moriond 2024
LHCb-PAPER-2024-007

- First LHCb measurement using $D^+ \to K^-\pi^+\pi^-$ and $\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$ decays
- Feed down from $D^{*+} \to D^+\pi^0/\gamma$
- 3D binned template fit to $q^2 = (p_B -$ $m^2_{\text{miss}} = (p_B - p_{D^{(*)}} - p_\mu)^2$, E^*_μ (muon ener

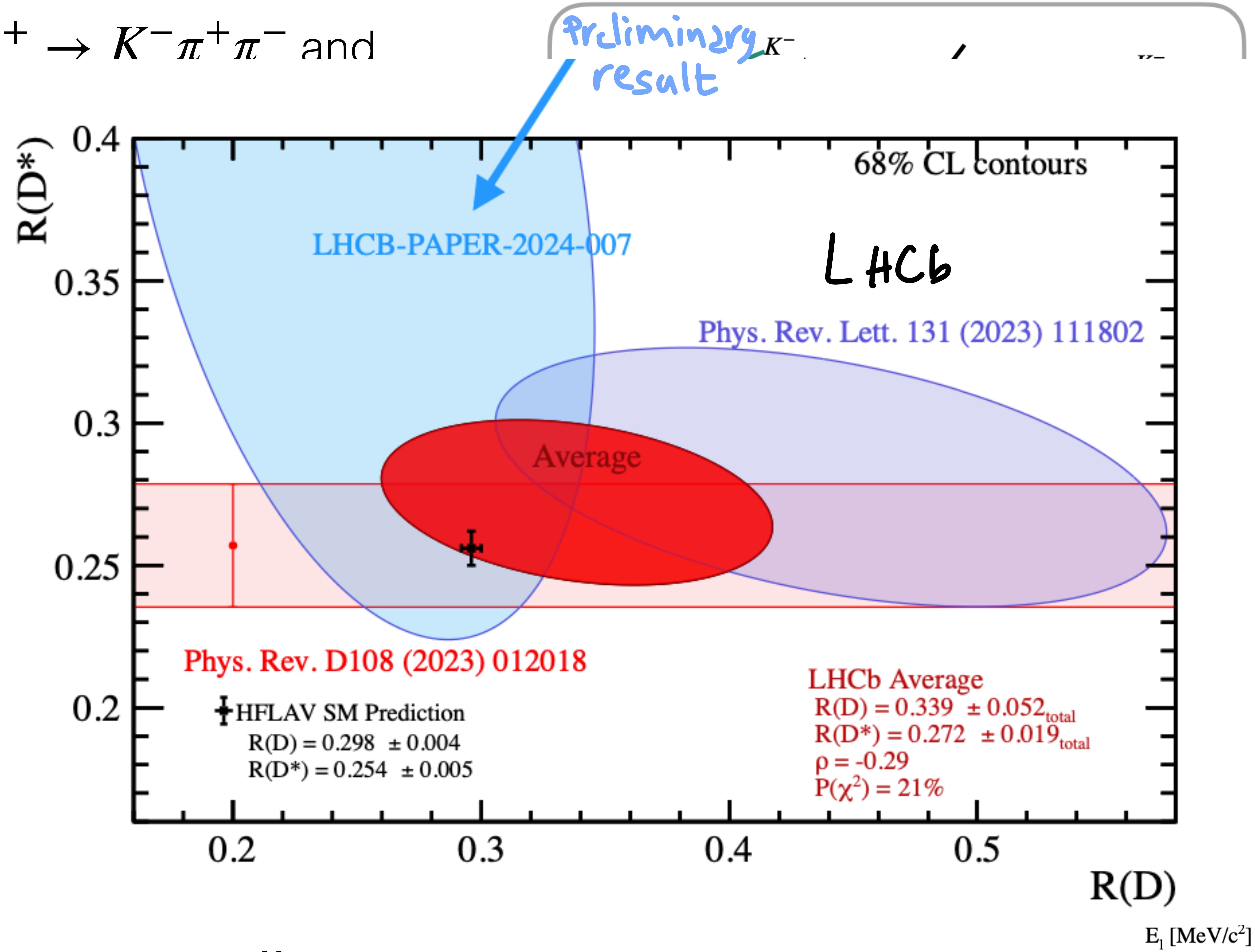
LHCb preliminary

$R(D^+) = 0.249 \pm 0.043_{\text{stat}} \pm 0.047_{\text{syst}}$

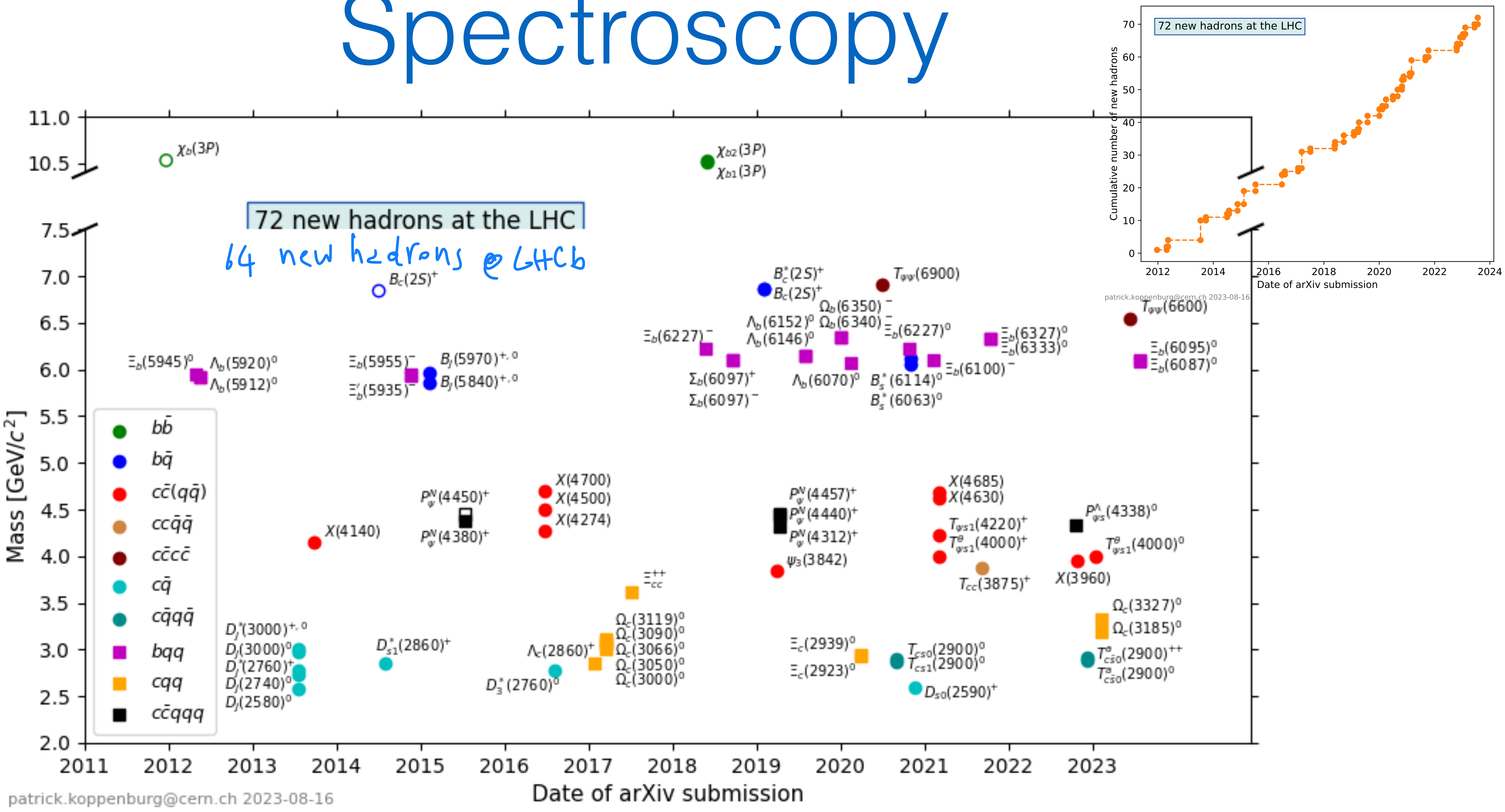
$R(D^{*+}) = 0.402 \pm 0.081_{\text{stat}} \pm 0.085_{\text{syst}}$

$\rho = -0.39$

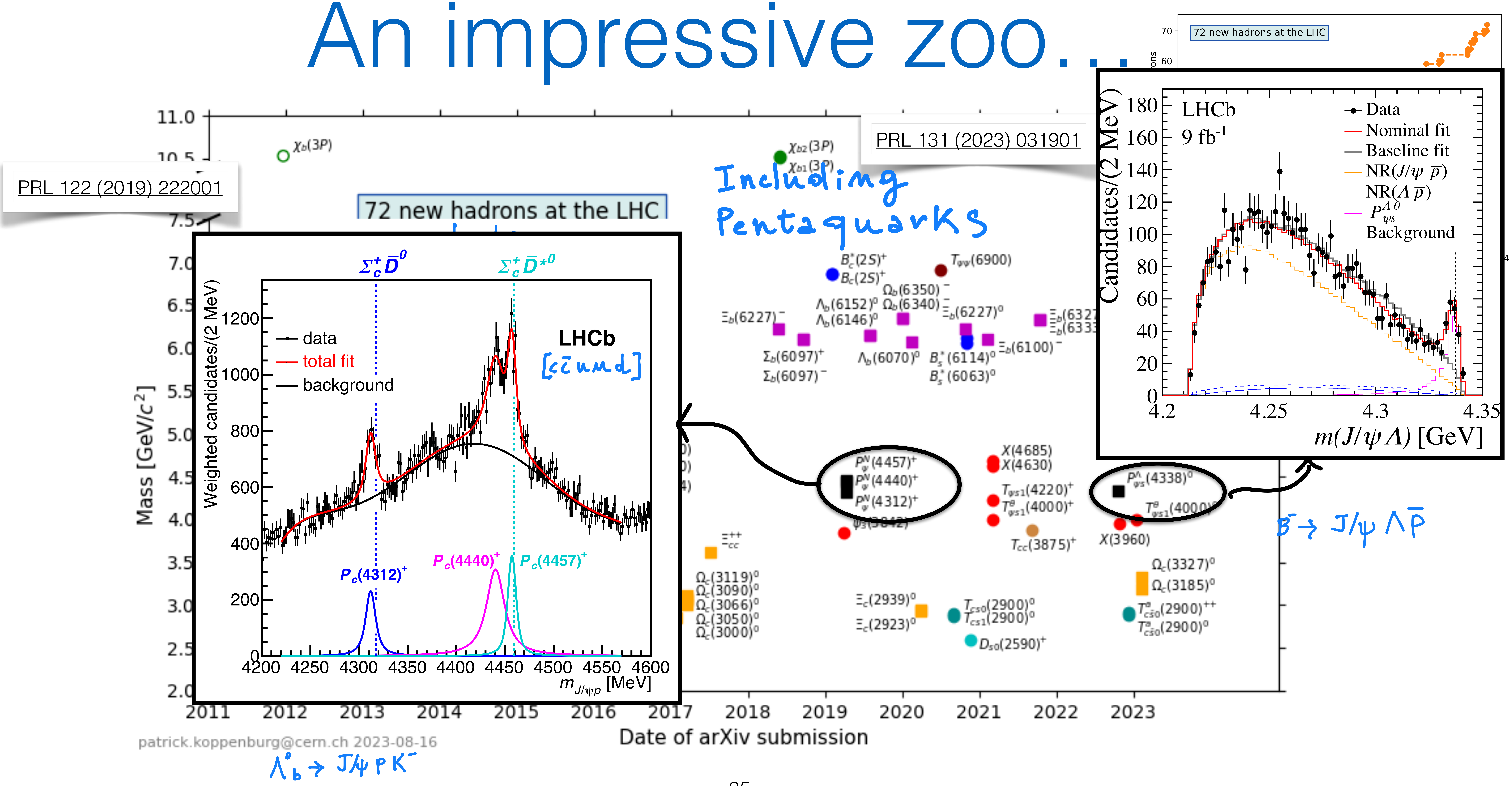
- Main systematic uncertainties from form-fac &background modelling



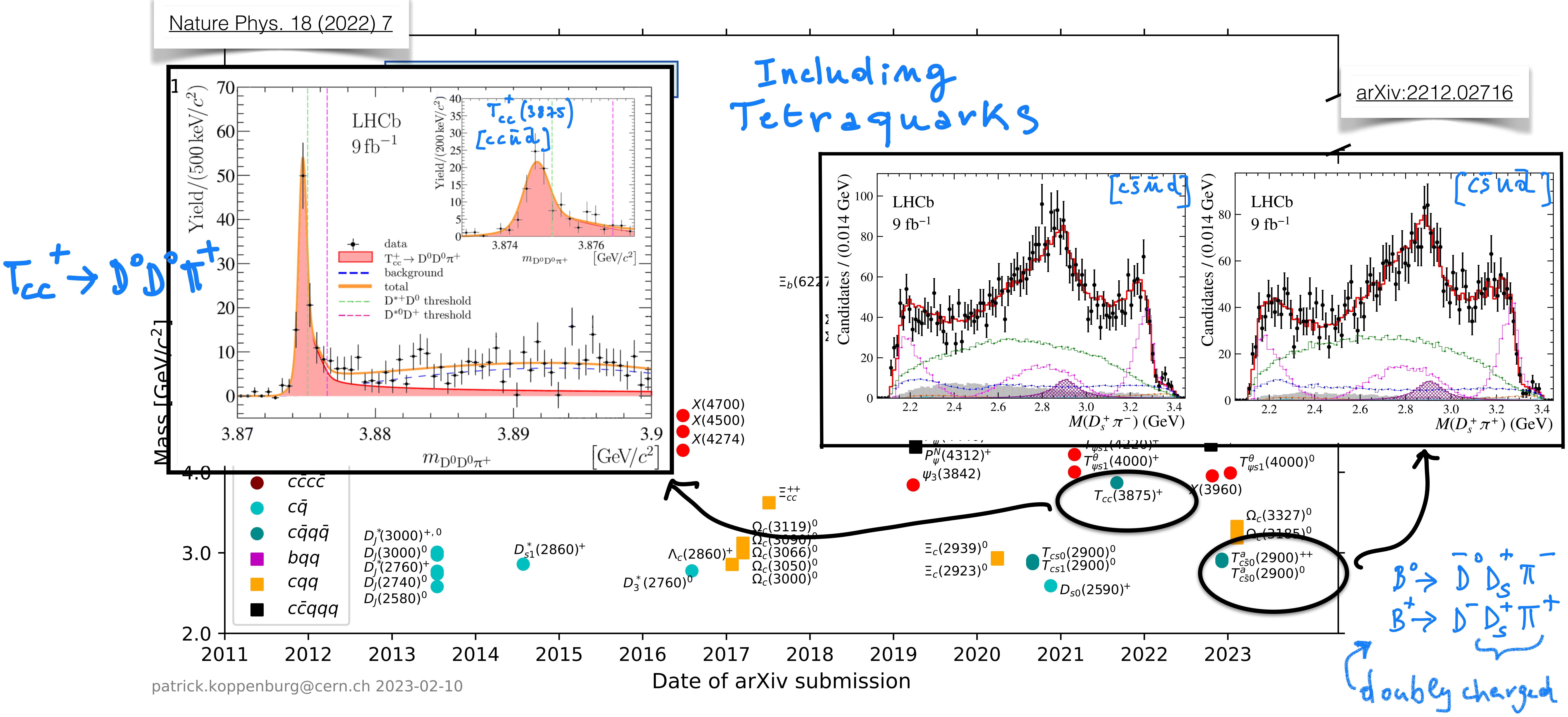
Spectroscopy



An impressive zoo…

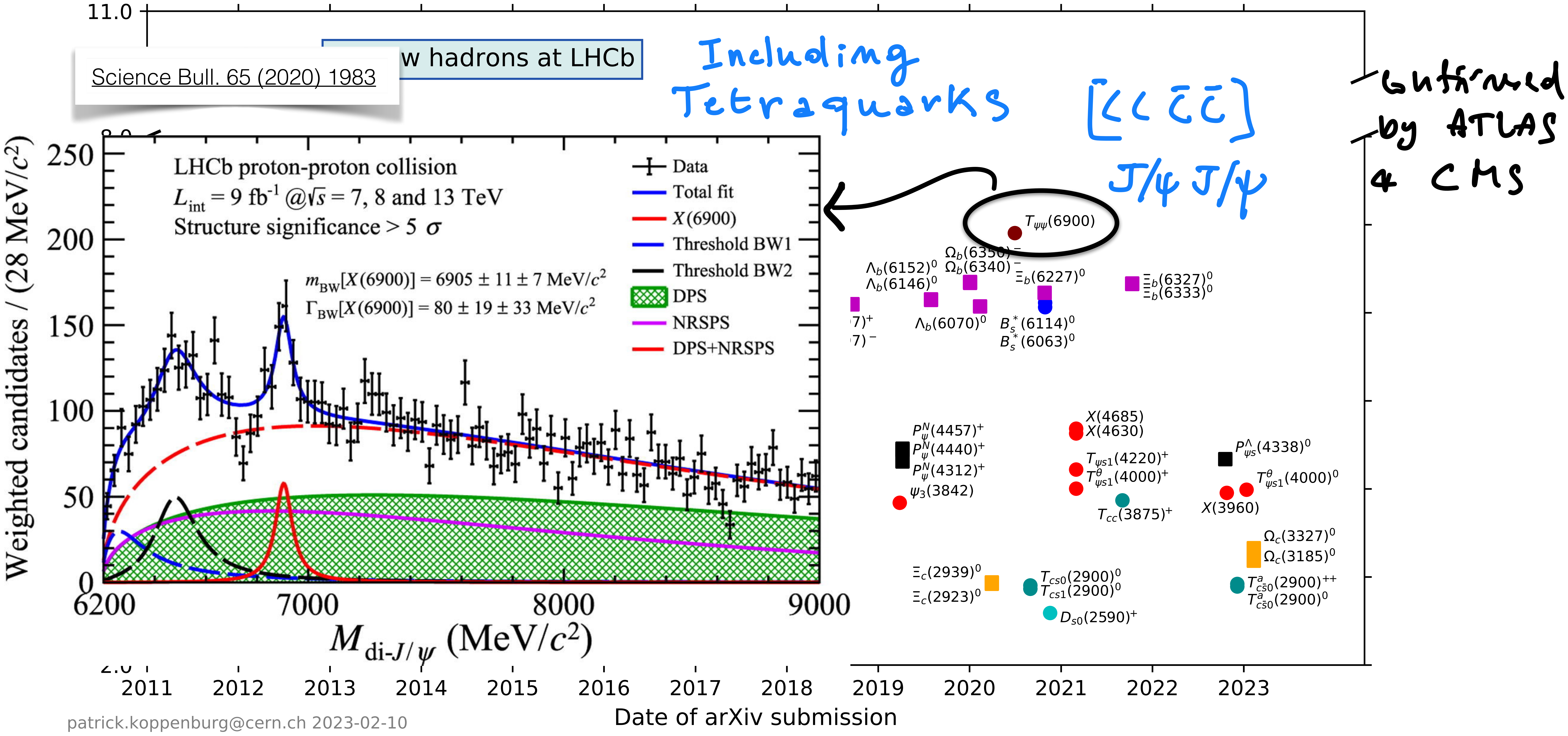


An impressive zoo…



patrick.koppenburg@cern.ch 2023-02-10

An impressive zoo…



patrick.koppenburg@cern.ch 2023-02-10

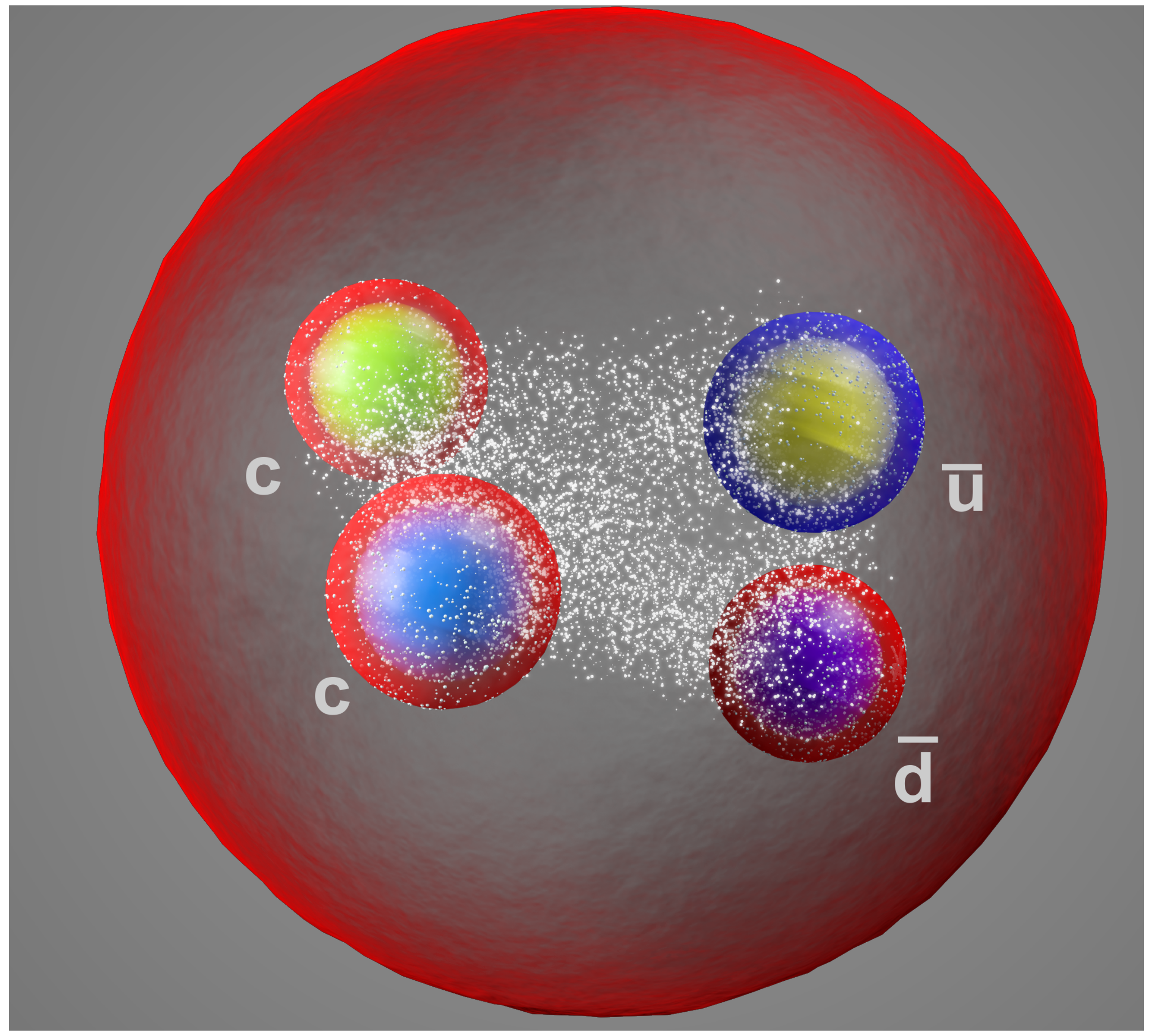
Lively debate on nature of such exotic states

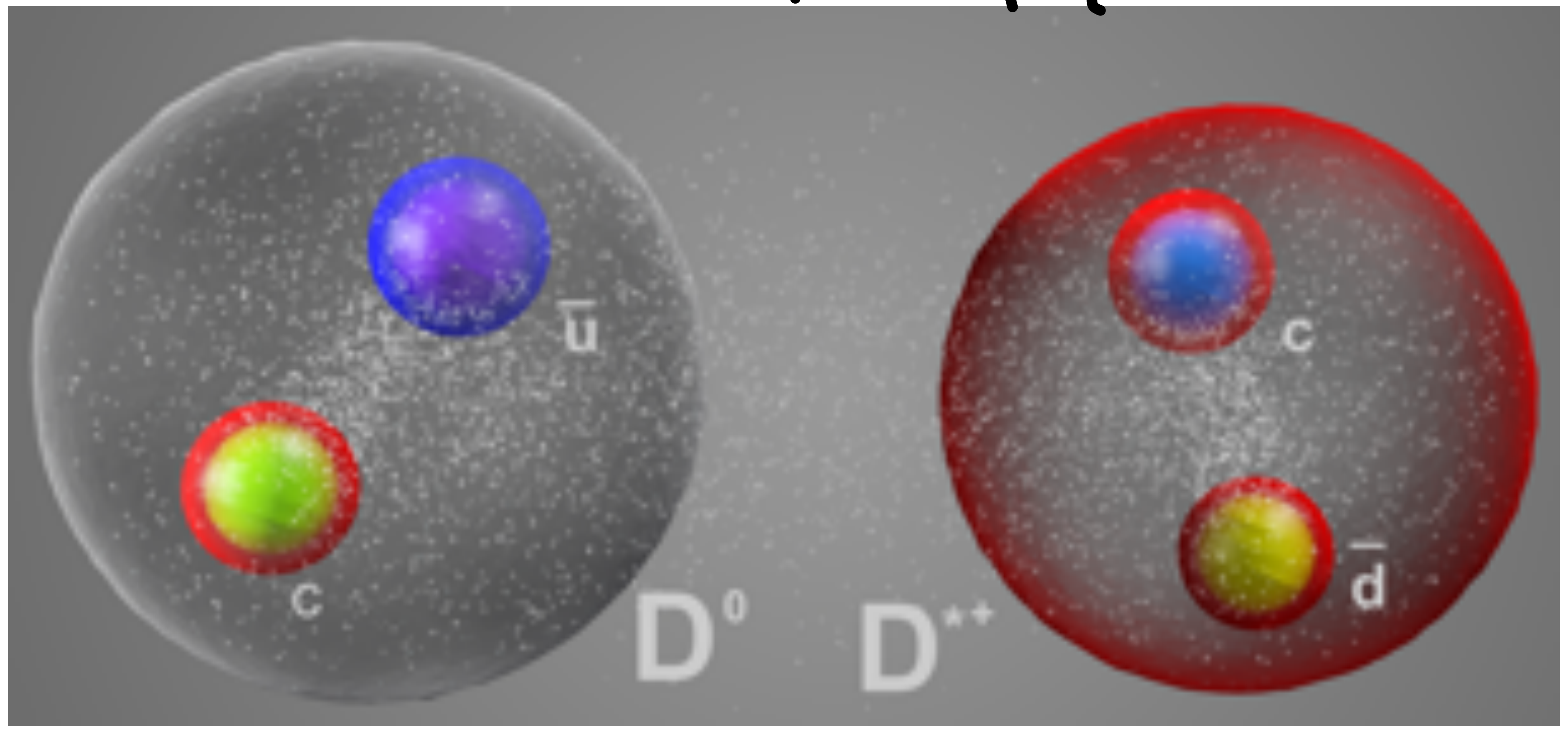
- Compact tetraquarks (pentaquarks) vs meson-meson (meson-baryon) molecules

$[(q\bar{q})(qq)]$

$(Q\bar{q}) - (q\bar{q})$

π, ρ, ω, η

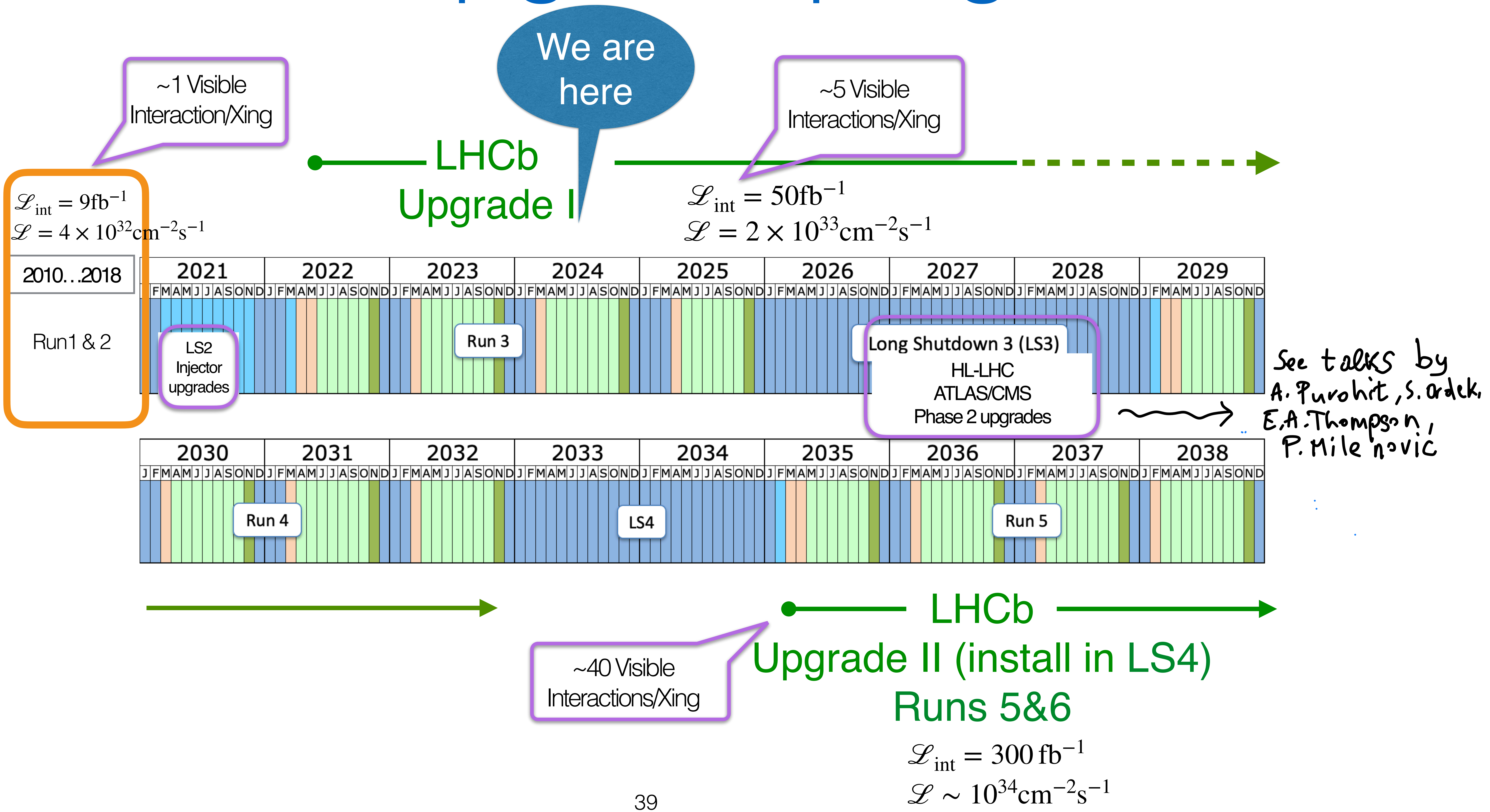




- It will be difficult to explain these multi-quark states unambiguously

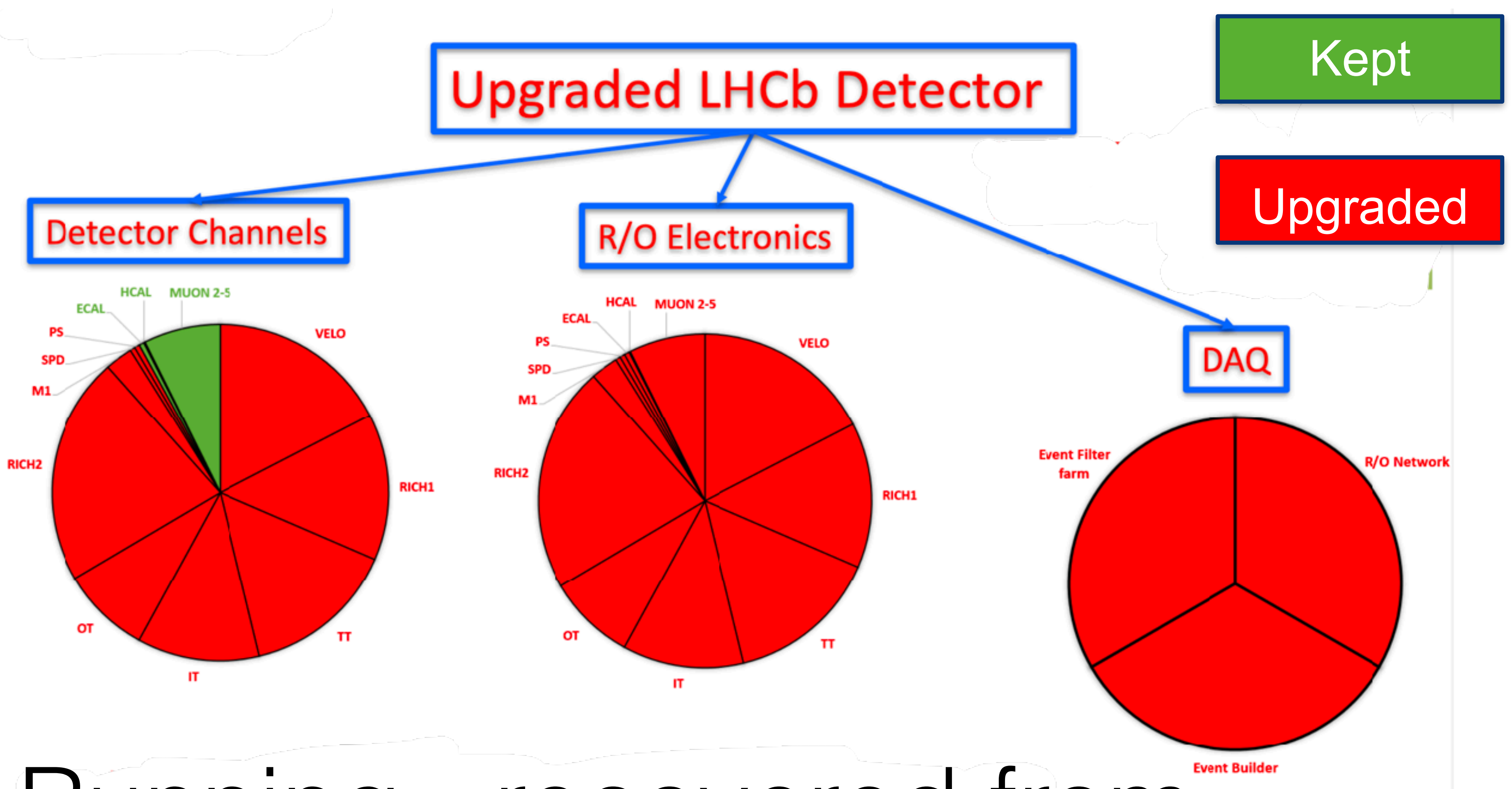
- The best we can probably hope for is to demonstrate the presence of different dominant binding mechanisms in different systems

LHCb upgrade program

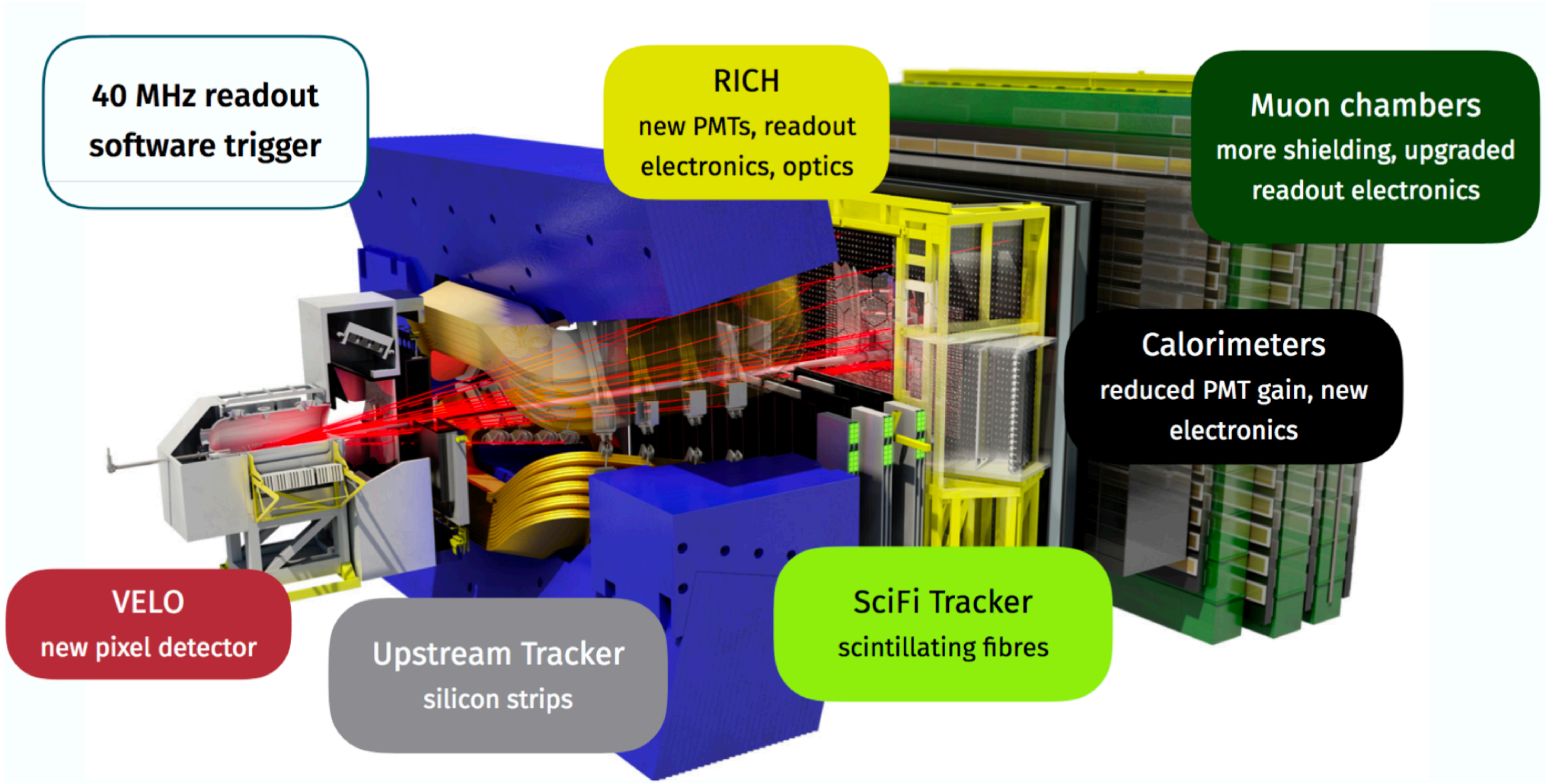


The upgraded LHCb

- Full software trigger
- Raise $\mathscr{L}$ to 2x10^{33}cm^{-2}s^{-1}(5x Run2) but maintain current reconstruction performance
- Major redesign of all sub-detectors and ambitious readout upgrade



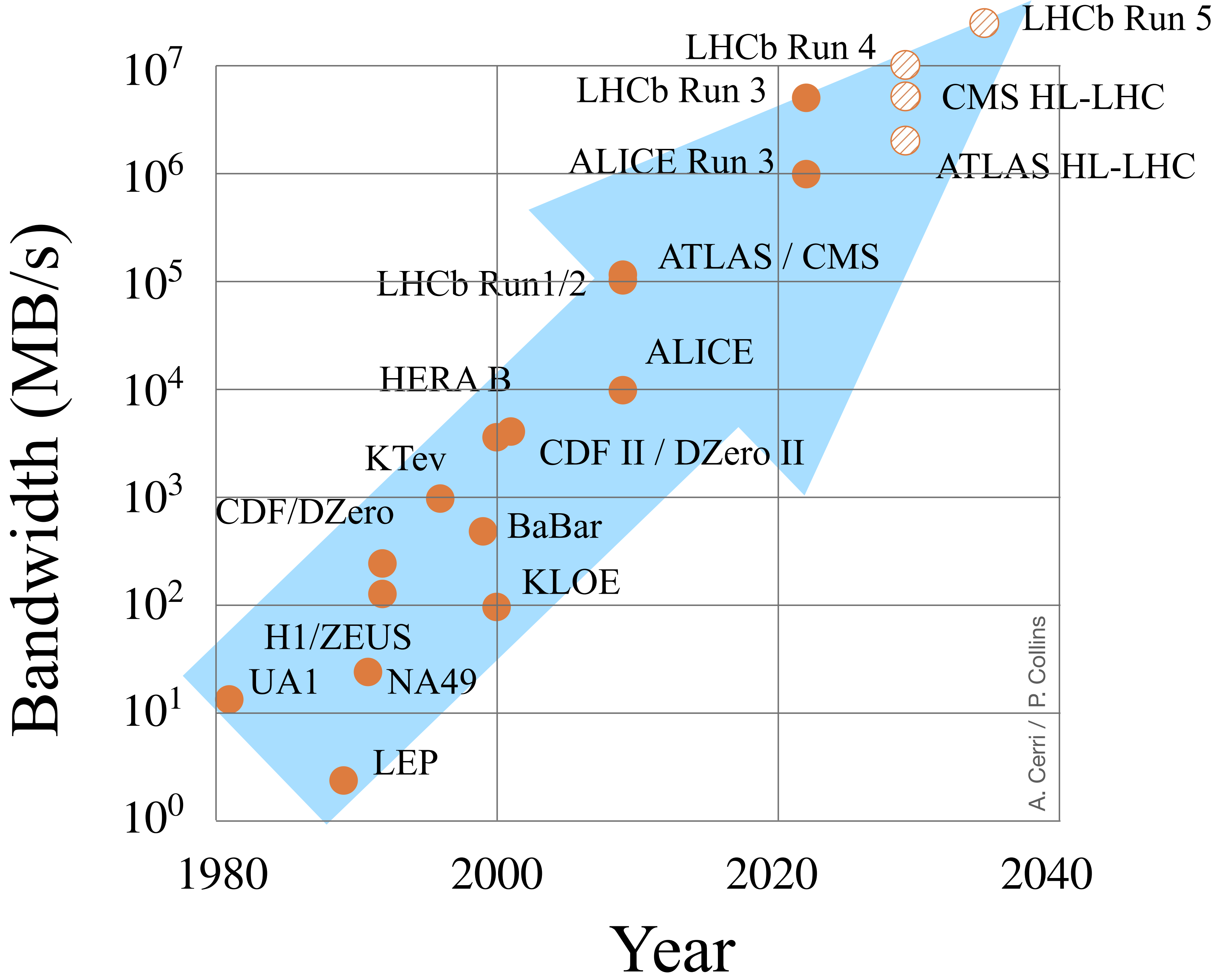
Running - recovered from vacuum incident in LHCb Velo



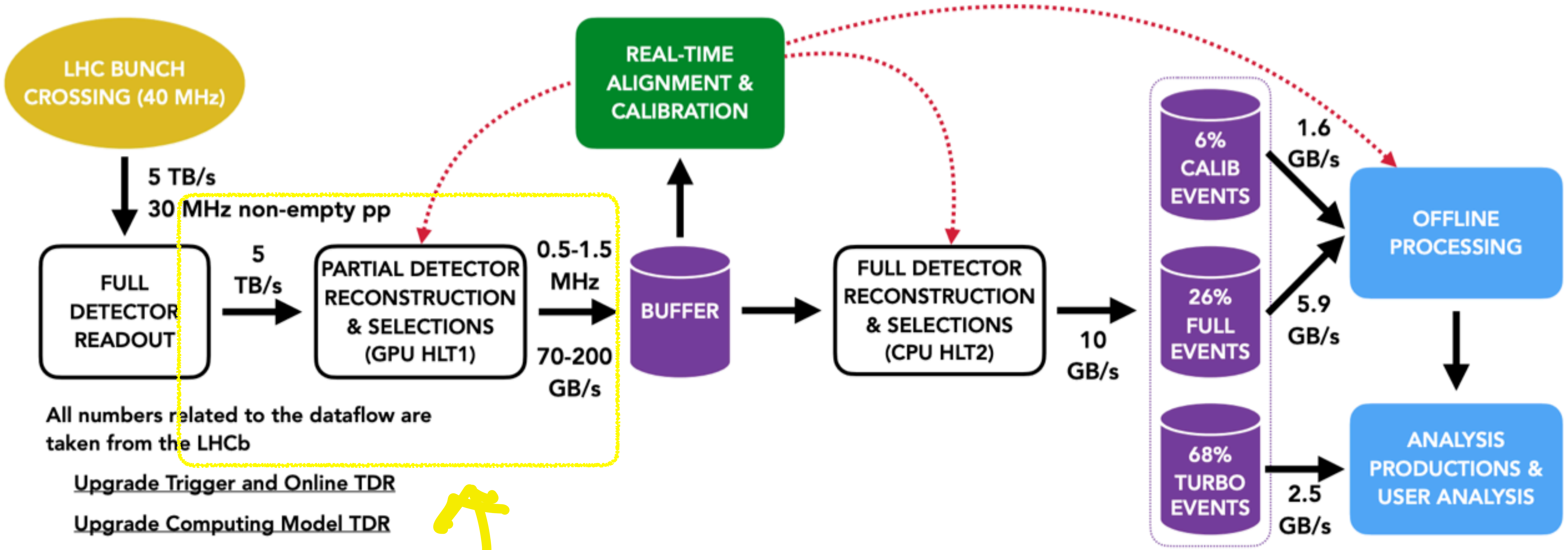
New pixel-based **VELO** closer to the beam (8.2 mm → 5.1 mm)
New **RICH** mechanics, optics, photodetectors
New Silicon strip upstream tracker **UT**
New **SciFi** tracker
New electronics for **MUON** and **CALO**
New luminometer **PLUME**
New **SMOG2** system for fixed target physics

A lot of signal → a lot of data to process

- Full software trigger will process 30 MHz of inelastic collisions → factor ~10 increase in hadronic yield in Run 3

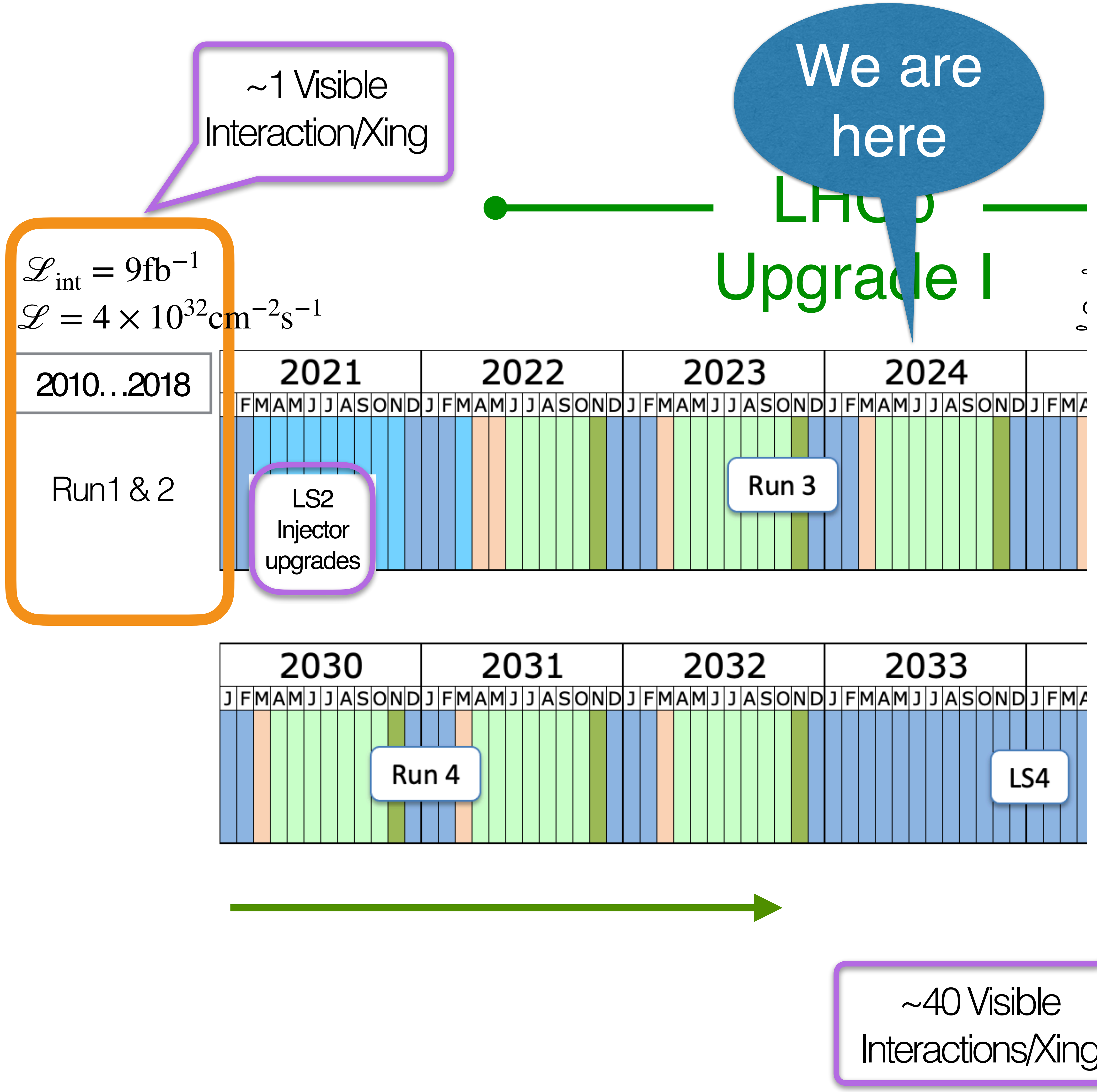


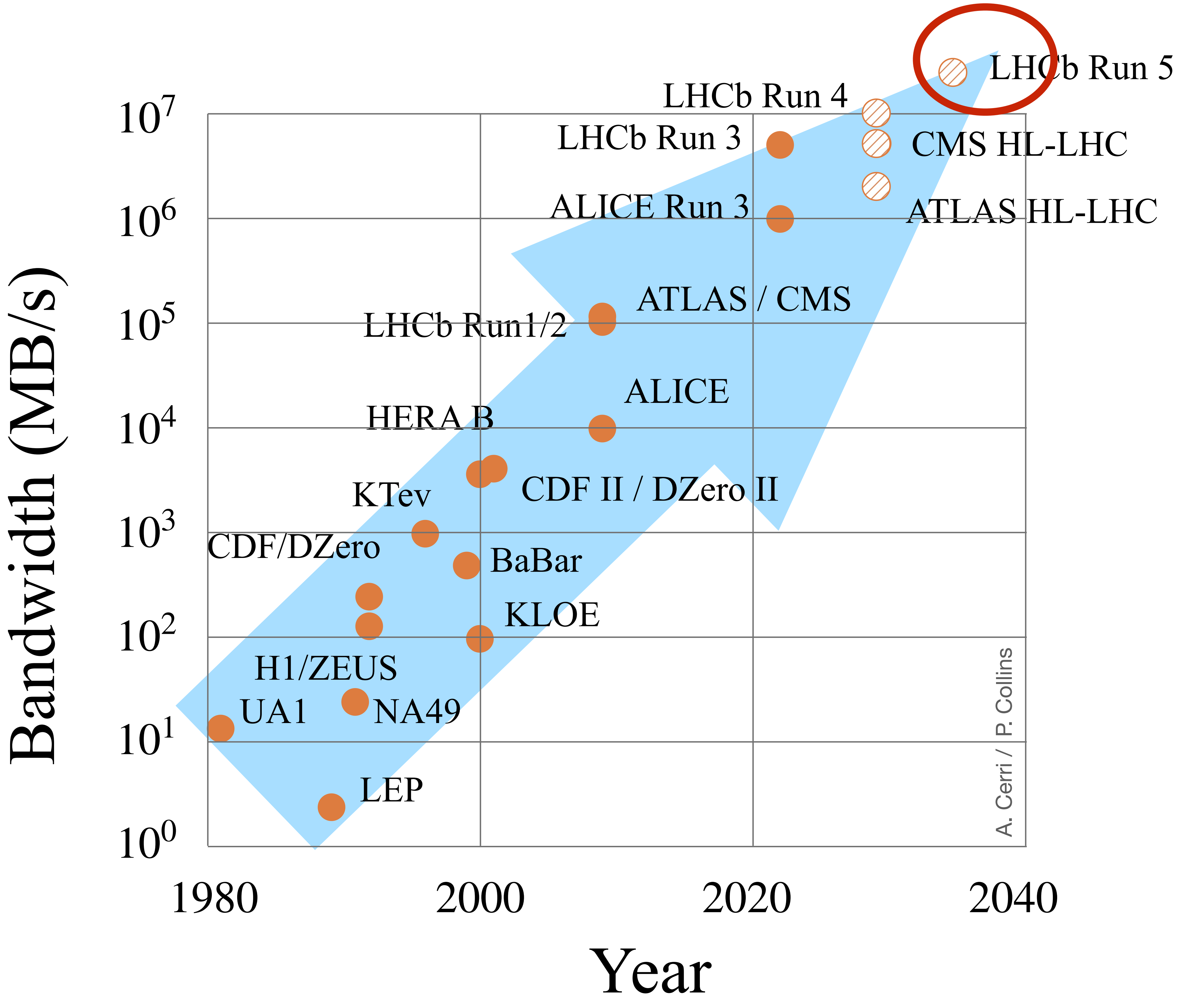
[P.Collins]



First stage of all-software trigger implemented on GPU farm

LHCb upgrade program





Upgrade II (instal in LS4)
Runs 5&6

$\mathscr{L}_{int} = 300 \, fb^{-1}$

$\mathscr{L} = 1.5 \times 10^{34} cm^{-2}s^{-1}$

LHCb upgrade program

Goal is to run at ~10^{34} cm^{-2} s^{-1} , and integrate ~300 fb^{-1}, which poses enormous detector challenges.

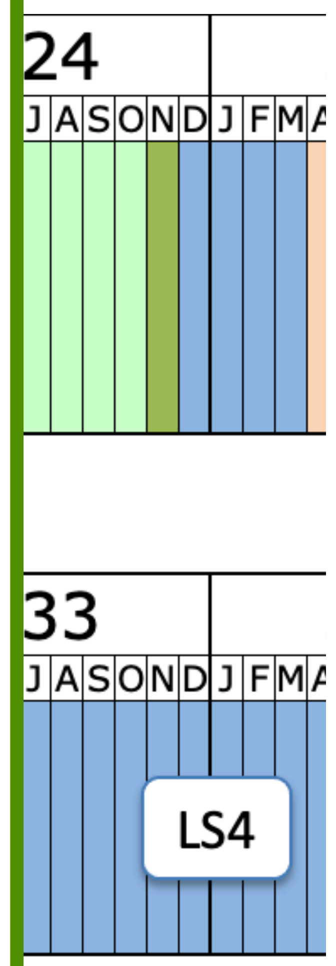
Pileup of 40 and 200 Tb/s of produced data !

Installation in LS4, with smaller detector enhancements in LS3.

Potentially the only general purpose flavour facility in the world on this timescale.

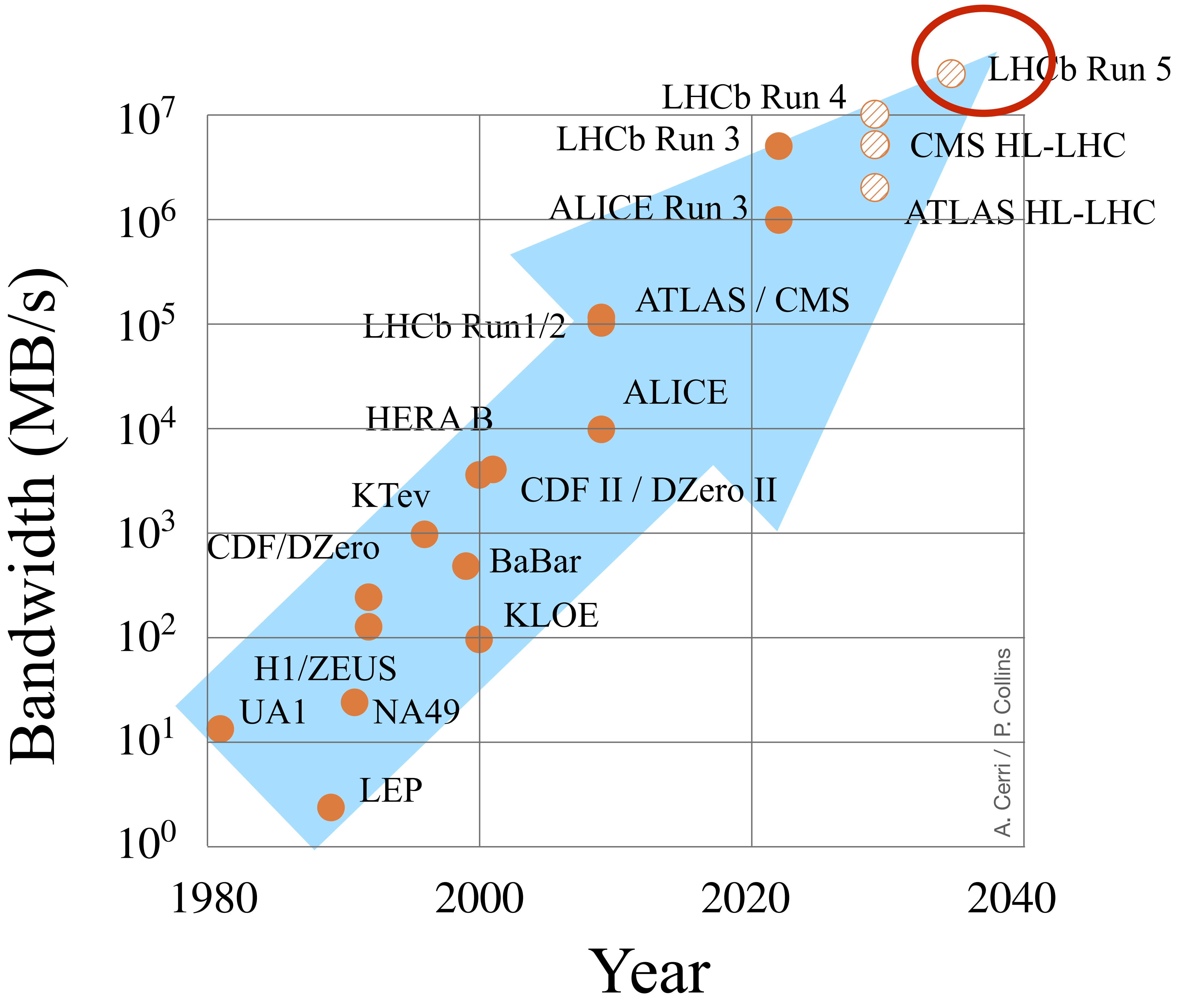
Require excellent radiation tolerance, higher granularity and **inclusion of precise timing information** (a few 10 ps) to be able to mitigate pileup

More groups are welcome to join the effort!



e I

40 Visible
actions/Xing



Upgrade II (instal in LS4)
Runs 5&6

$\mathcal{L}_{int} = 300\,\text{fb}^{-1}$

$\mathcal{L} = 1.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$

Concluding remarks

- Precision measurements of flavour observables provide a powerful way to search for NP effects beyond the SM, complementing direct searches for NP. This is particularly important as direct evidence for new physics remains elusive .

- In general, the SM still (depressingly) in good health. We'll keep looking!

- A lot has been done, with many world record and sometimes unexpected results (CPV in charm, exotic spectroscopy…). Much more to come from LHCb, Belle II, and from the ATLAS and CMS B-physics programs.

- The precision program in flavour physics over the next 10 ÷ 15 years is, in my view, the most promising direction to make discoveries before the next accelerator (assuming NP is on the horizon).

Some extra slides

Projected uncertainties for some key observables

CERN-LHCC-2021-012

- EoI, Physics case document and FTDR, all very favourably reviewed by LHCC.
- Strong support received in European strategy: "The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited”

.

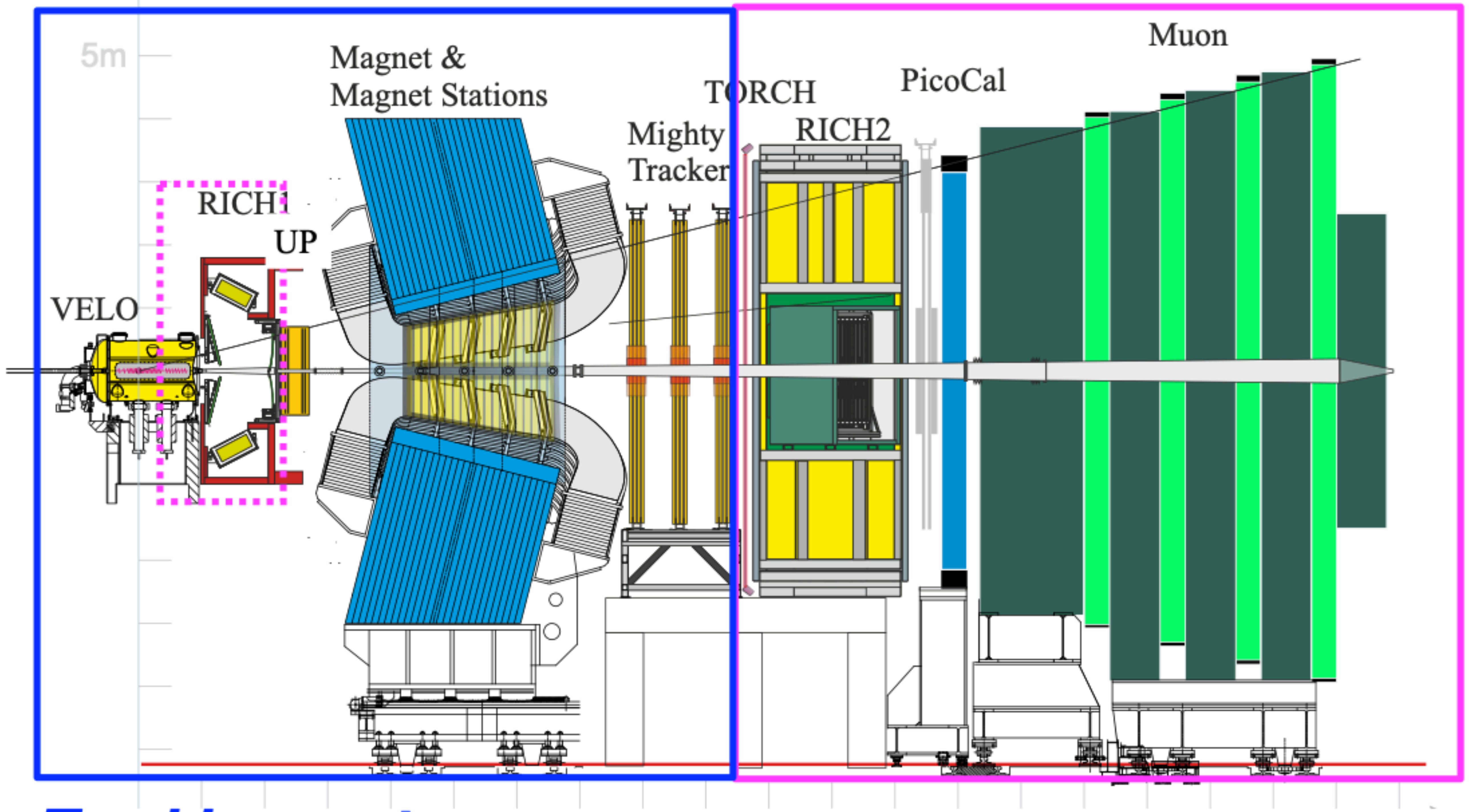
Run 3 — Run 4 — Run 6

Observable	Current LHCb (up to $9\,\text{fb}^{-1}$)		Upgrade I ($23\,\text{fb}^{-1}$)	($50\,\text{fb}^{-1}$)	Upgrade II ($300\,\text{fb}^{-1}$)
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
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a_{sl}^d ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a_{sl}^s ($B_s^0 \to D_s^-\mu^+\nu_\mu$)	33×10^{-4}	[35]	10×10^{-4}	7×10^{-4}	3×10^{-4}
Charm					
ΔA_{CP} ($D^0 \to K^+K^-, \pi^+\pi^-$)	29×10^{-5}	[5]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \to K^+K^-, \pi^+\pi^-$)	11×10^{-5}	[38]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \to K_S^0\pi^+\pi^-$)	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
$A_{\text{T}}^{(2)}$ ($B^0 \to K^{*0}e^+e^-$)	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
$\alpha_\gamma(\Lambda_b^0 \to \Lambda\gamma)$	$^{+0.17}_{-0.29}$	[53]	0.148	0.097	0.038
Lepton Universality Tests					
R_K ($B^+ \to K^+\ell^+\ell^-$)	0.044	[12]	0.025	0.017	0.007
R_{K^*} ($B^0 \to K^{*0}\ell^+\ell^-$)	0.12	[61]	0.034	0.022	0.009
$R(D^*)$ ($B^0 \to D^{*-}\ell^+\nu_\ell$)	0.026	[62, 64]	0.007	0.005	0.002

The detector challenge

M.Palutan
RRB 24/04/24

Baseline design: *targeting same (or better in certain domains) performance as in Run 3, but running at 1.5x10^{34}cm^{-2}s^{-1} with pile-up ×7 wrt Run 3!*



PID system

RICH: *reduced pixel with SiPM/MCP, timing info added*

TORCH: *new time-of-flight for low momentum, quartz and SiPM/MCP* ***NEW SYSTEM***

PicoCal: *timing and longitudinal segmentation, SPACAL with radiation hard crystals inner region, old Shashlik outer region*

Muon: *muRWELL technology inner region, keep old MWPCs outer region*

Tracking system

VELO: *pixel 3D silicon, hit time resolution 50ps, ASIC 28nm*

UP (upstream tracker) and Mighty Tracker (downstream): *MAPS pixel for UP and inner region of Mighty Tracker, scintillating fibres for outer region of Mighty Tracker*

Magnet Stations: *scintillating slabs covering side walls of magnet, for low momentum* ***NEW SYSTEM***

Exciting technology roadmap: the developments needed to face the harsh experimental conditions of HL-LHC in the forward direction will represent a bridge towards projects based at future accelerators