Flavor Physics status report

Xabier Cid Vidal (IGFAE)

L International Meeting on Fundamental Physics and XV CPAN days

Santander (October 6th 2023)

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

IGFAE Instituto Galego de Física de Altas Enerxías

Introduction

CKM metrology

Rare and SL decays

Spectroscopy

Future

Conclusions

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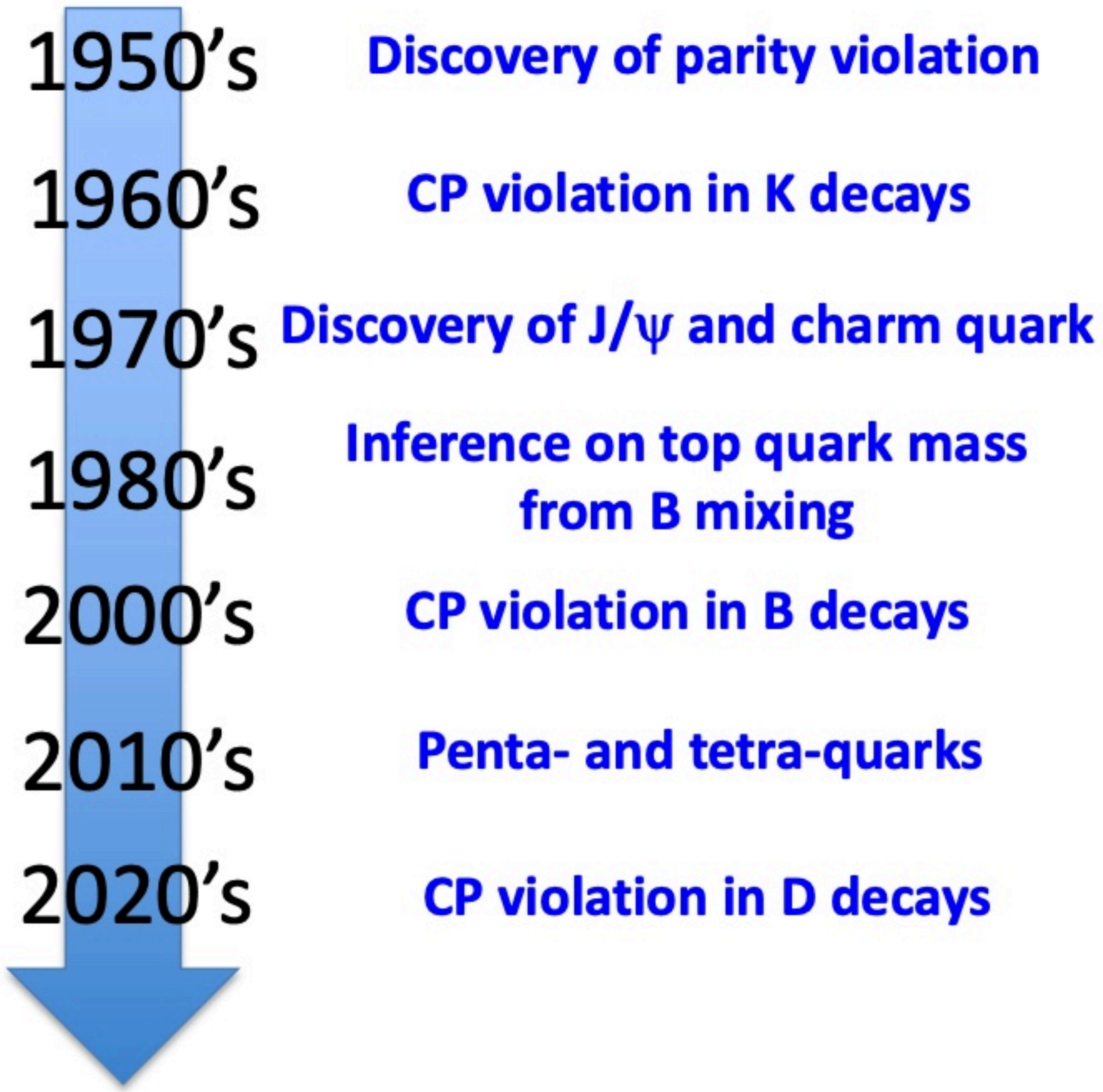
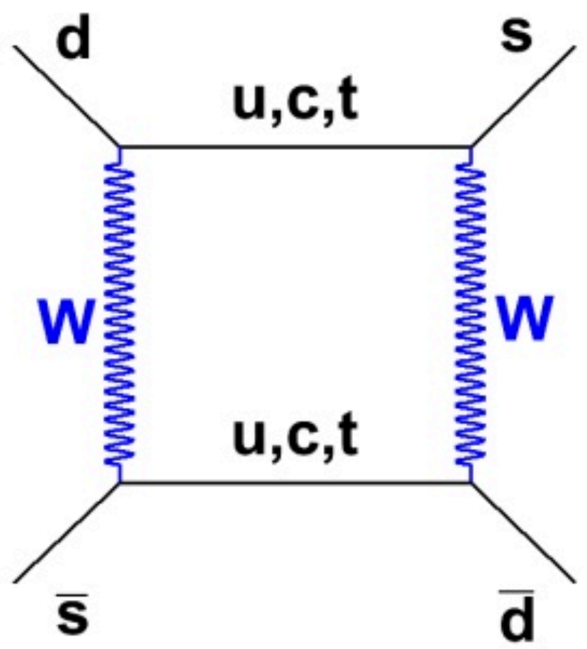
Introduction

- **Flavor physics**: study of hadrons, their characteristics, and their particle-decay processes: a story of success!
  - ➡ Great to check the consistency and completeness of SM. Critically assessing its coherence!
- Such "**indirect**" searches for particles outside SM powerful because they cover the energy scale where such particles are expected to exist.
  - ➡ Possible to explore masses that are much beyond the capability of direct synthesis at current particle accelerators!
  - ➡ Quark flavor research imposed extremely strict restrictions on several types of beyond-SM physics, ruling out new particles below 10^4–10^5 TeV that pair to SM hadrons generically

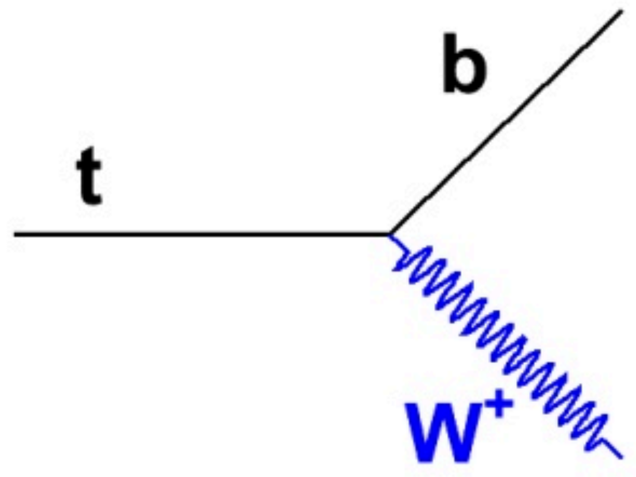


Power of indirect searches

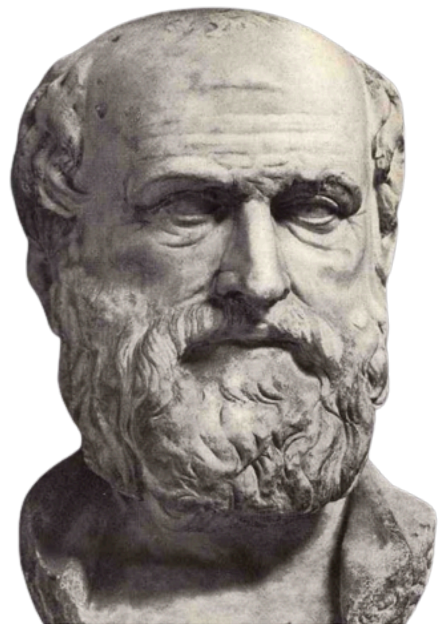
- 3rd quark family proposed by Kobayashi and Maskawa (1973) to explain CPV in K mixing (1964). **Directly** observed in 1977 (b) and 1995 (t)



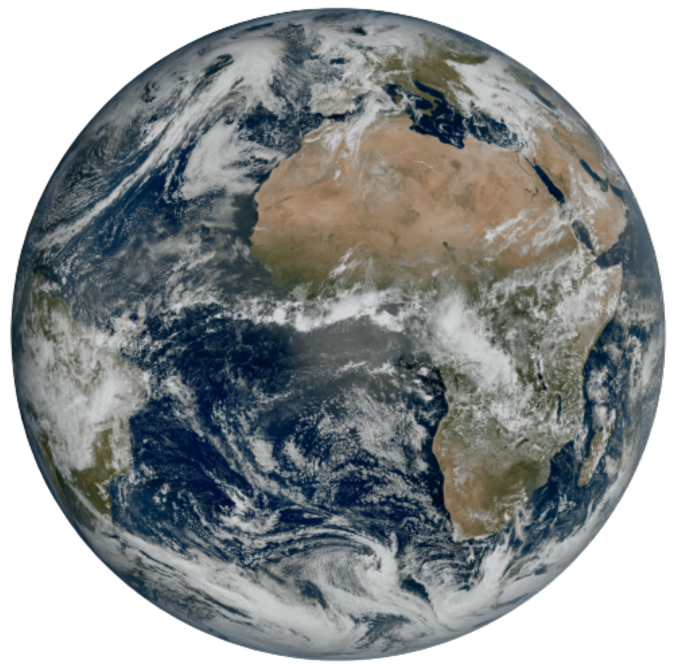
30 years



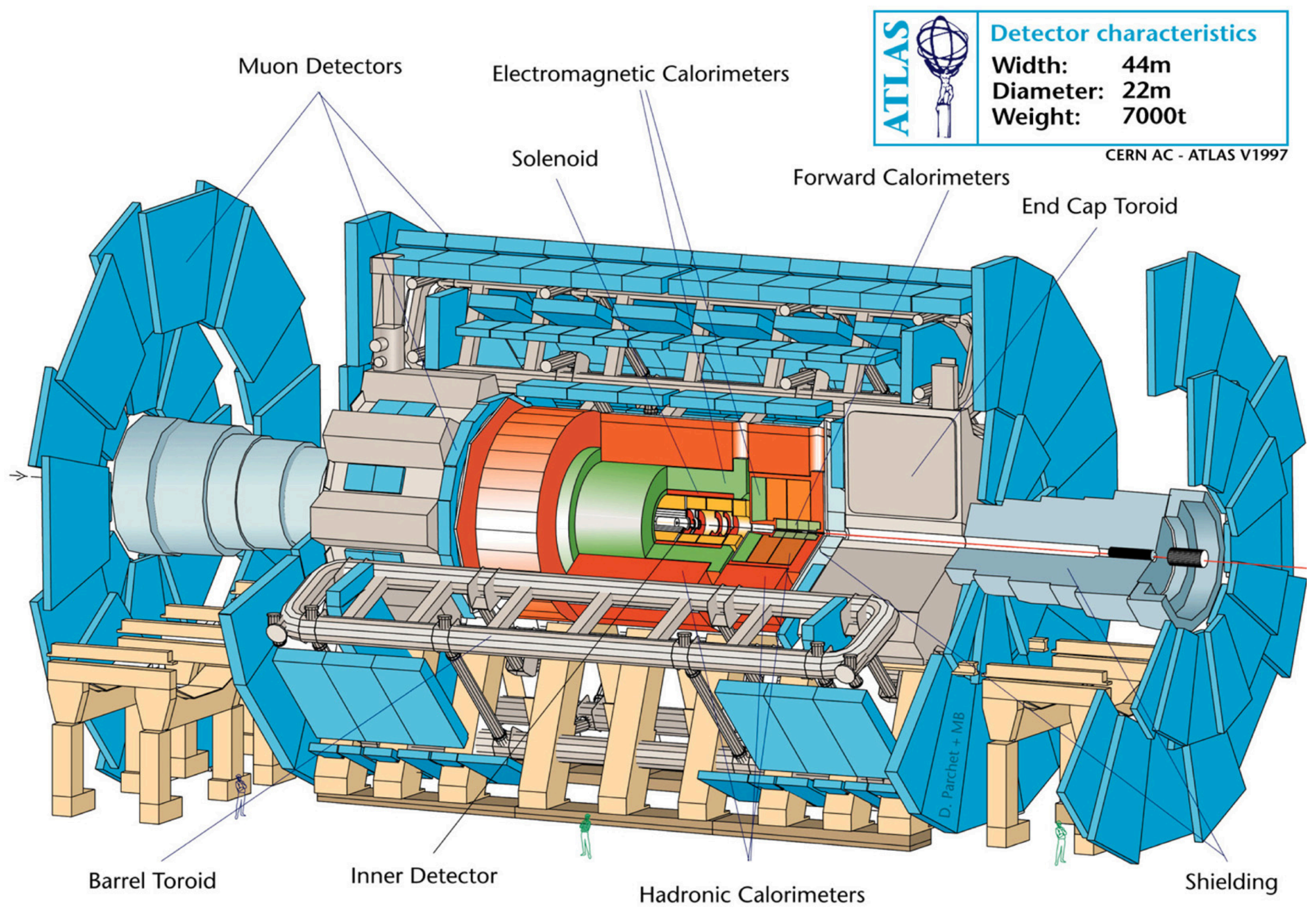
- Eratosthenes' measurement of the Earth's radius in the 3rd century BC (using variations in shadow lengths at various towns): Earth must be some sort of sphere. Direct observation wouldn't arrive till 20th century.

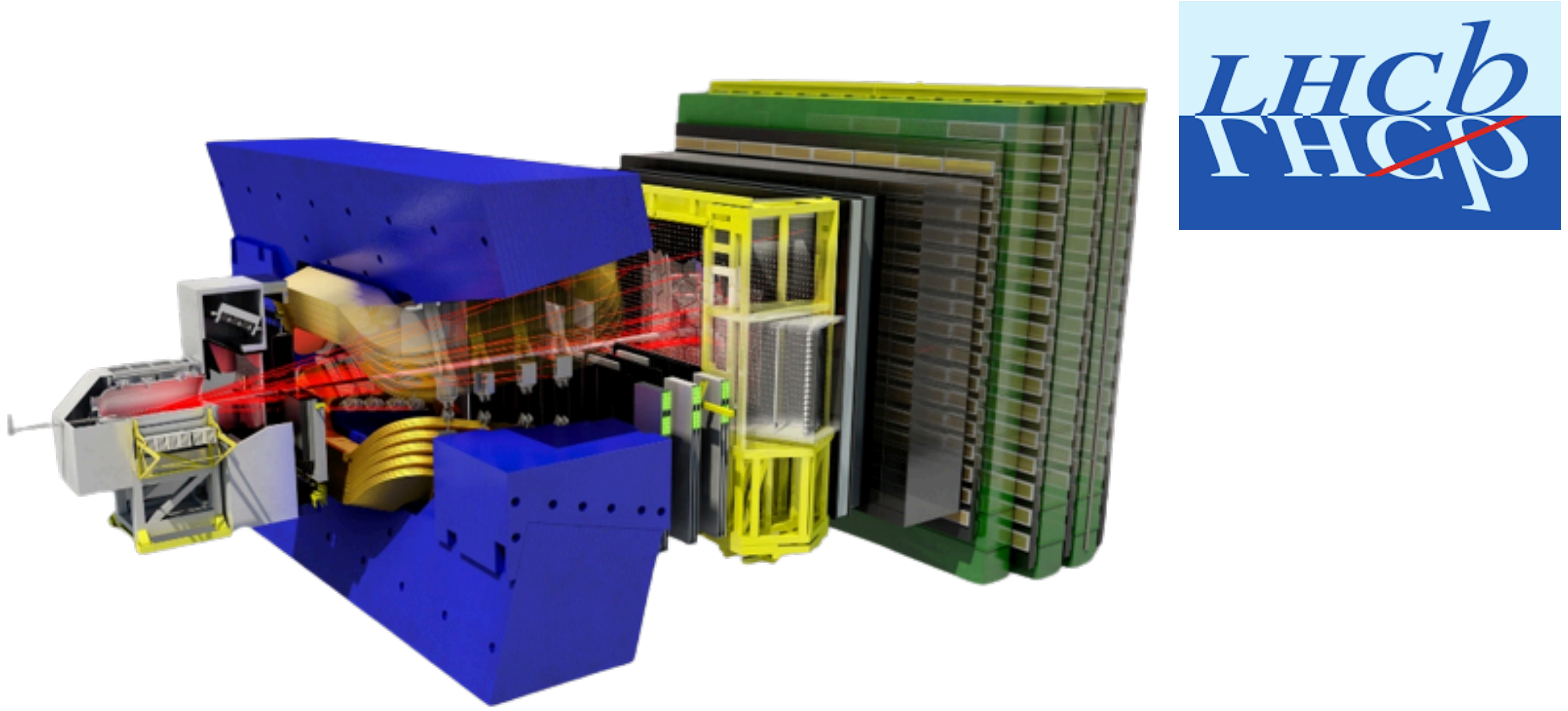


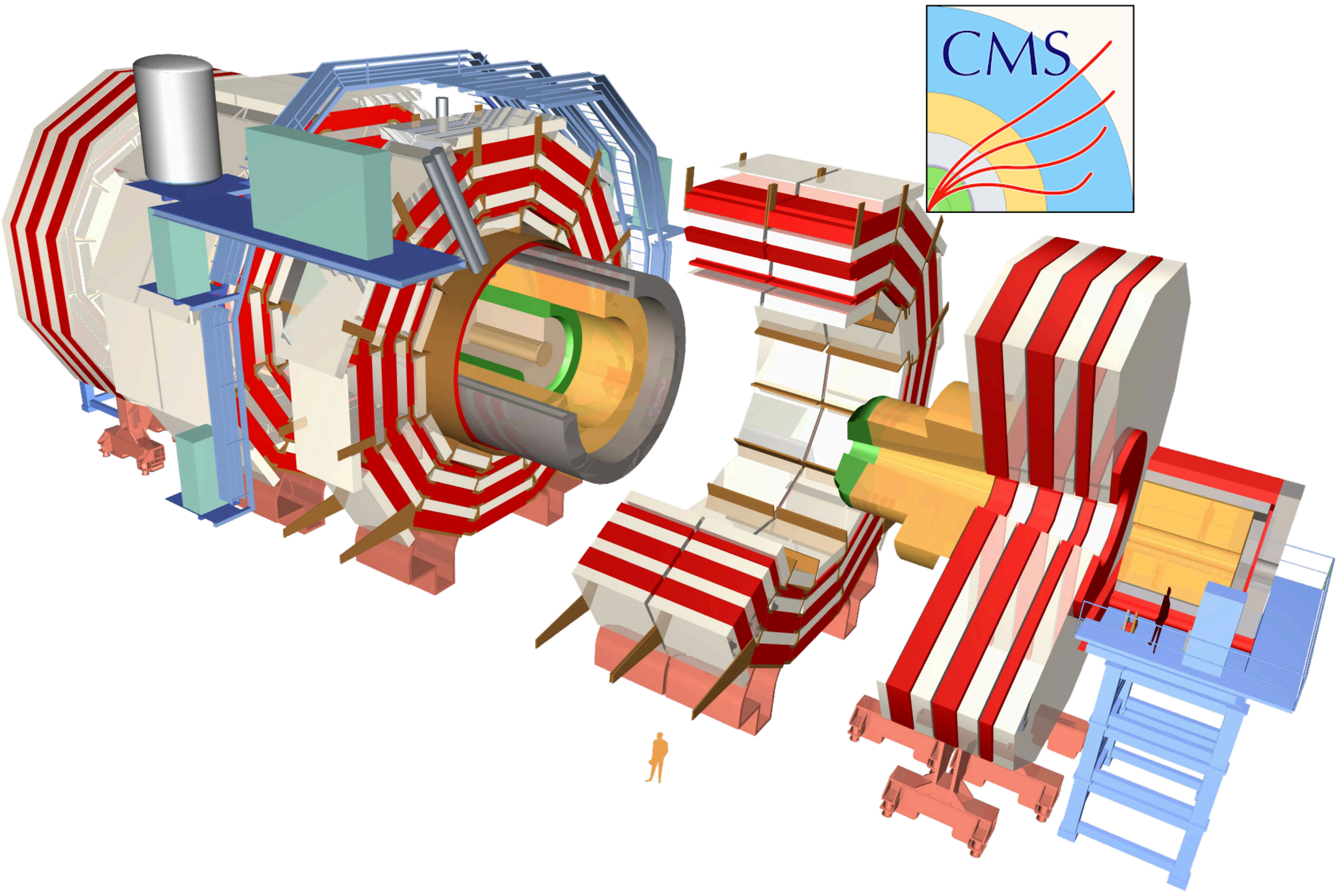
2300 years

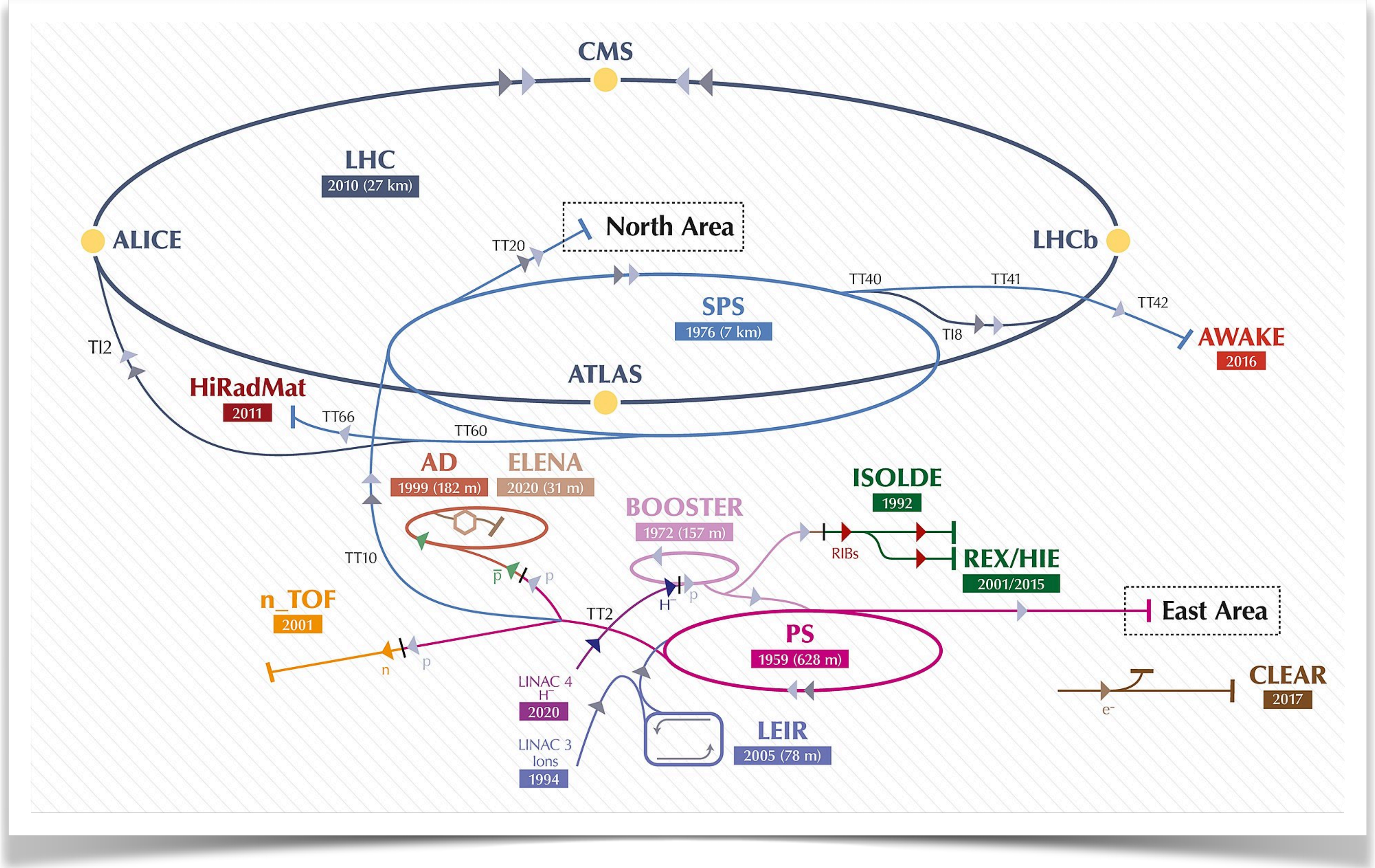


Main players (I)

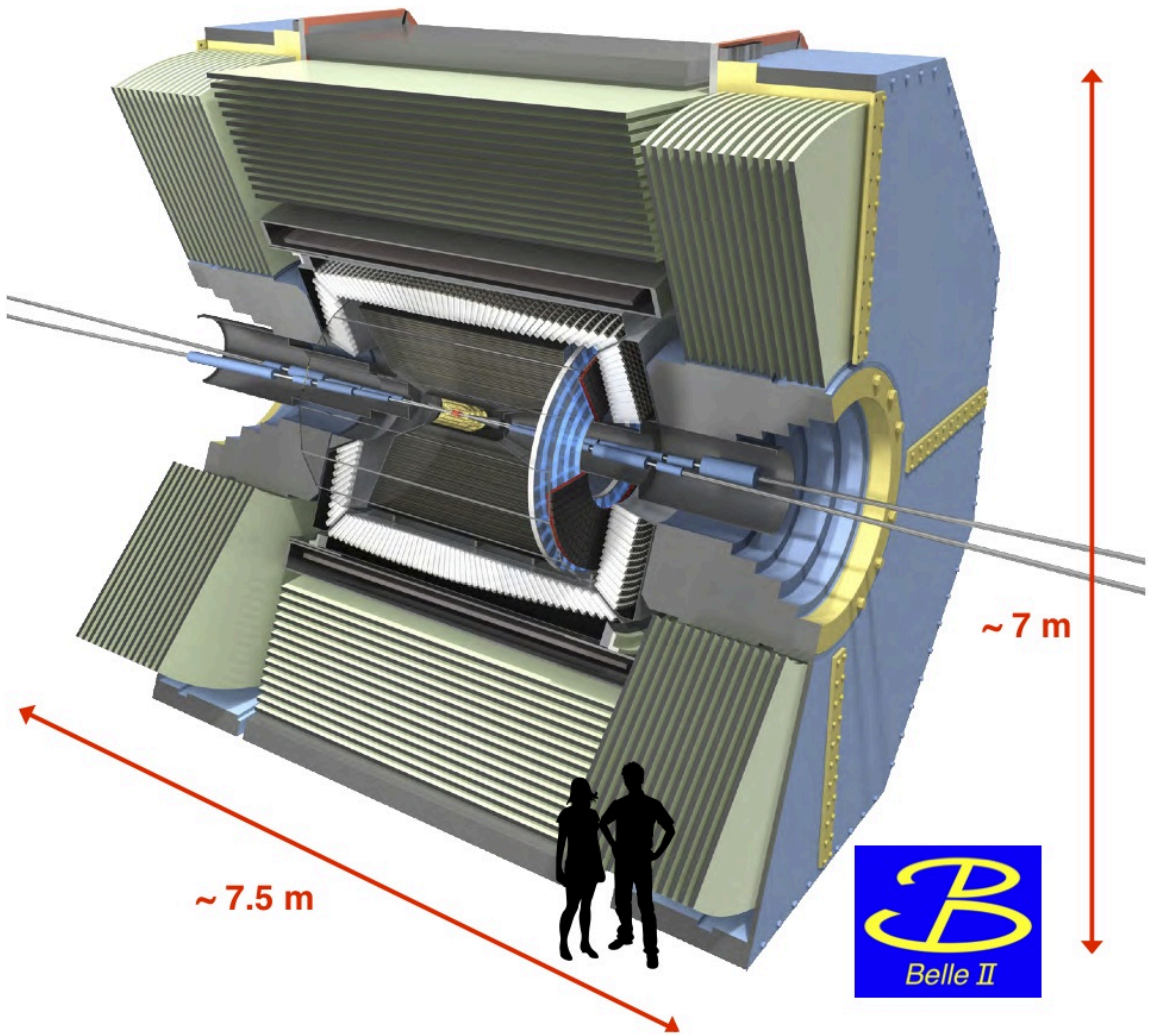


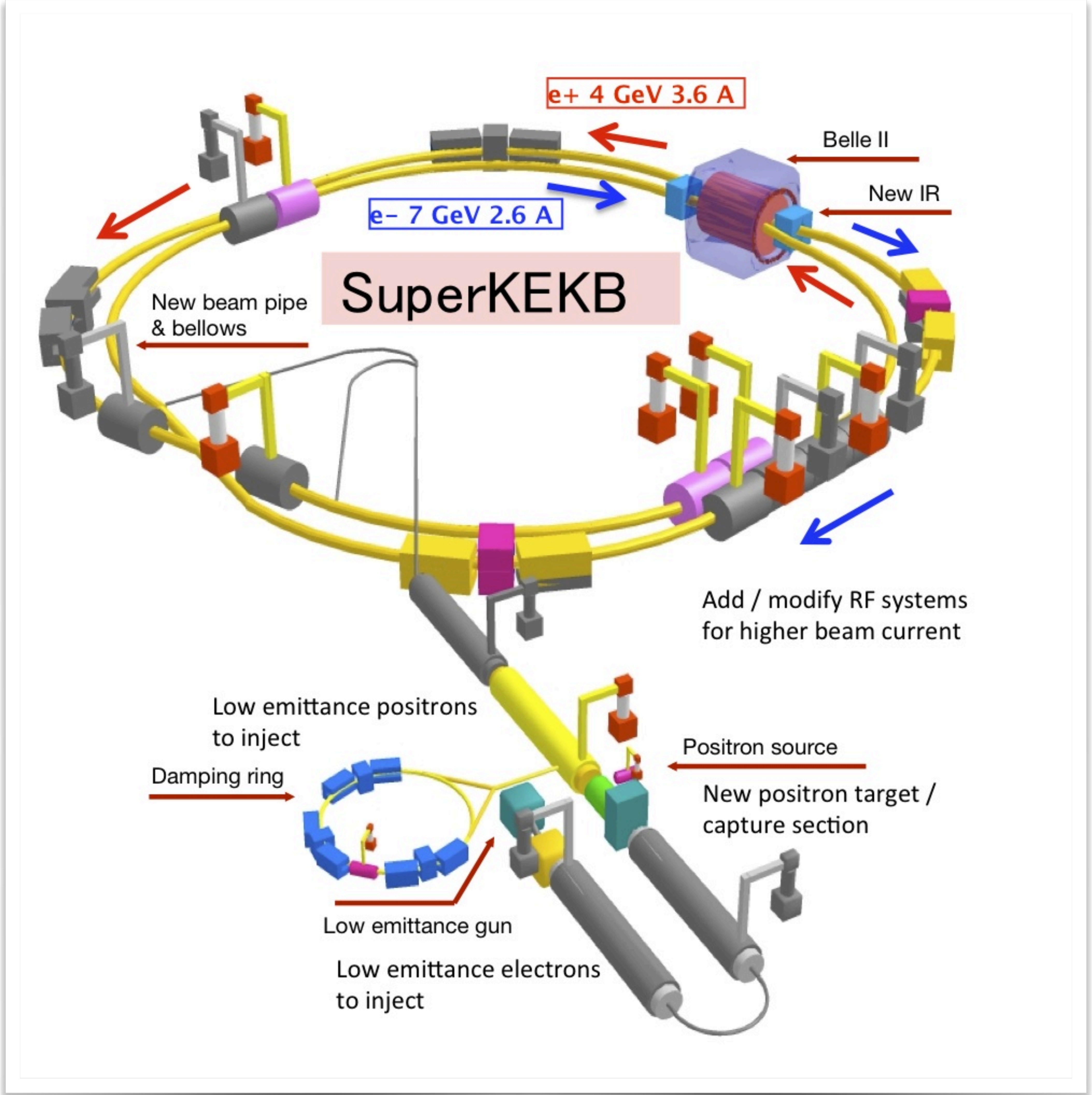




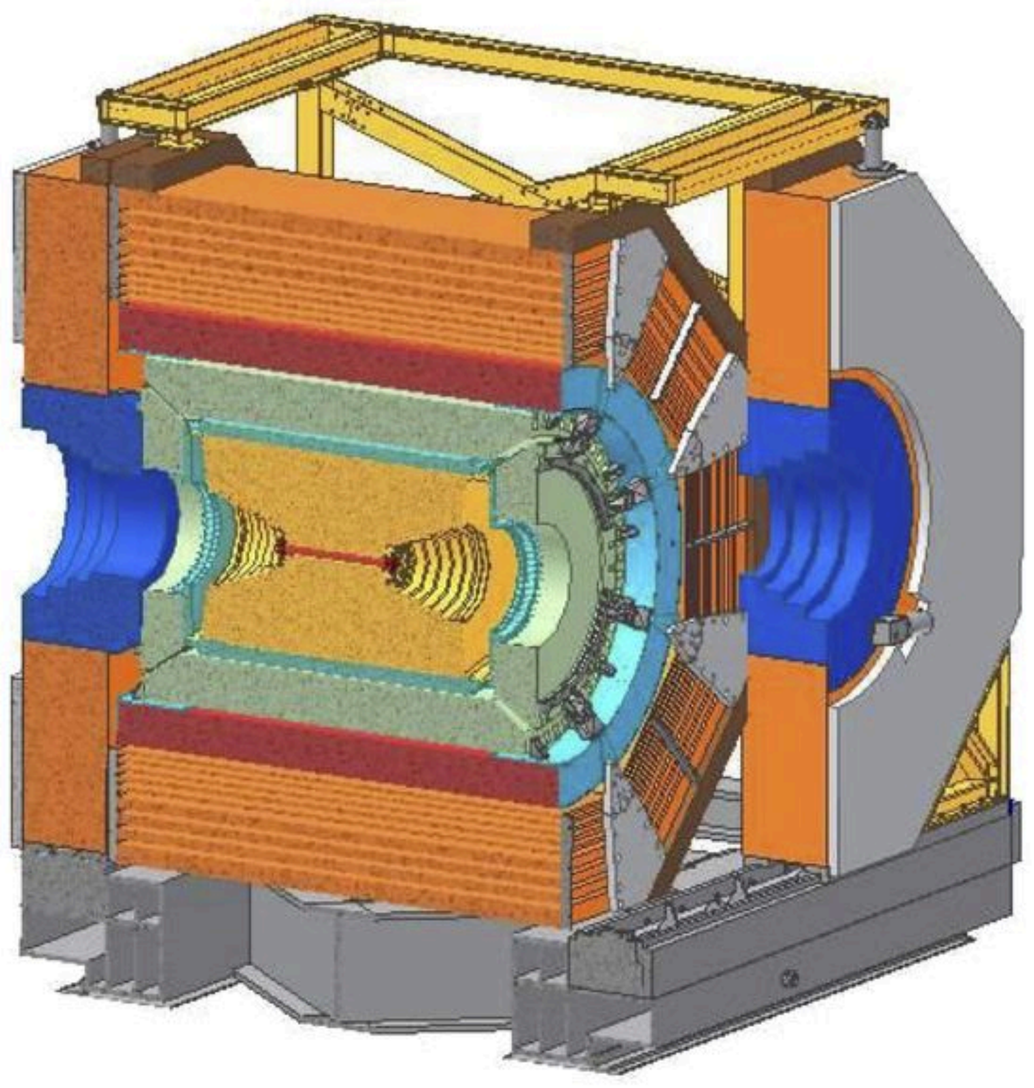


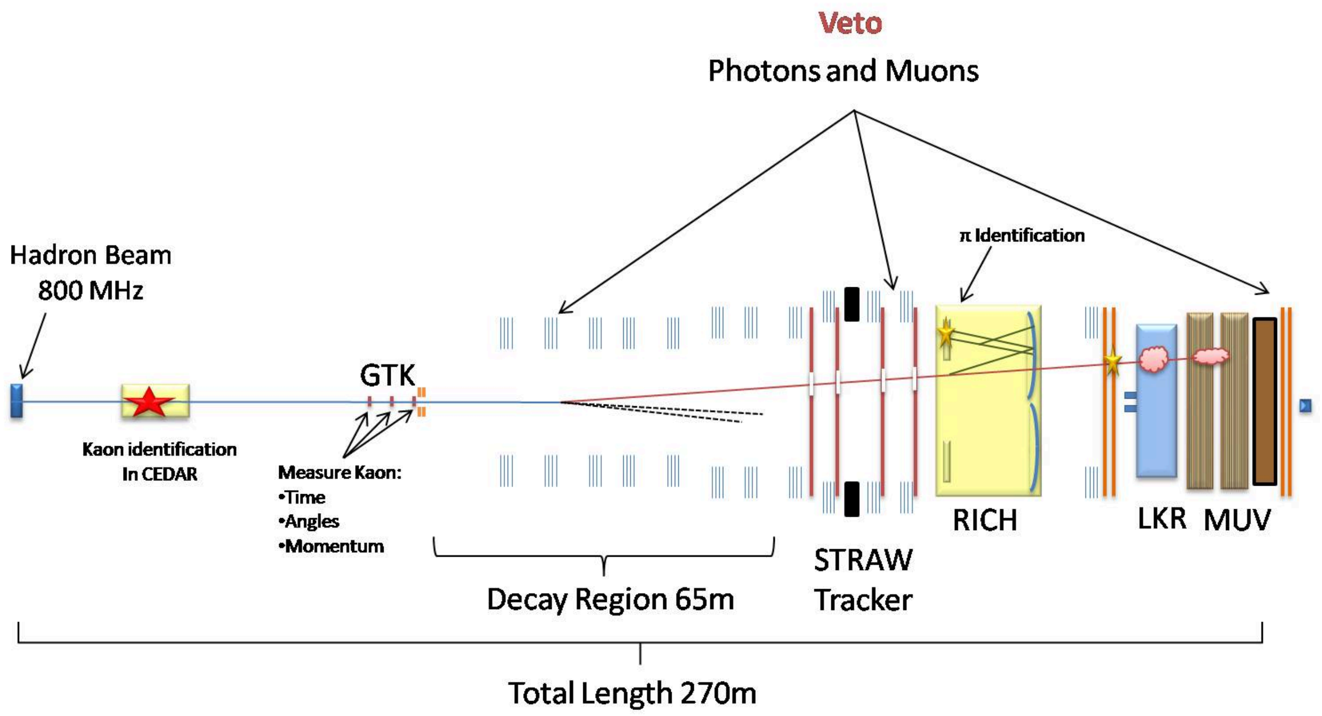
Main players (II)

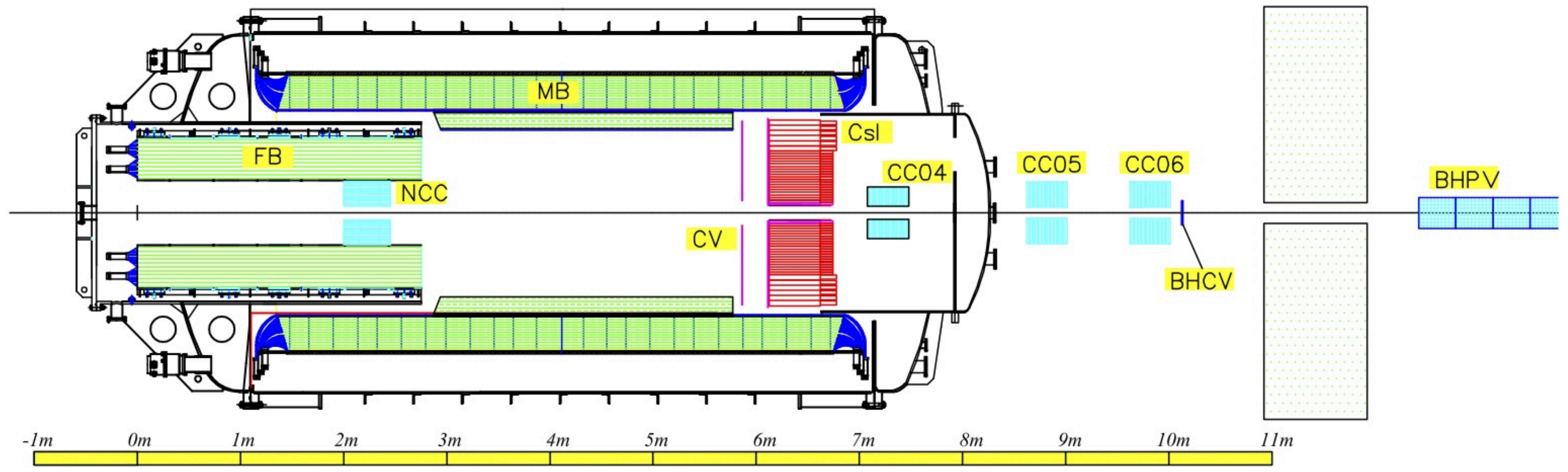




Main players (III)







Main players (III)

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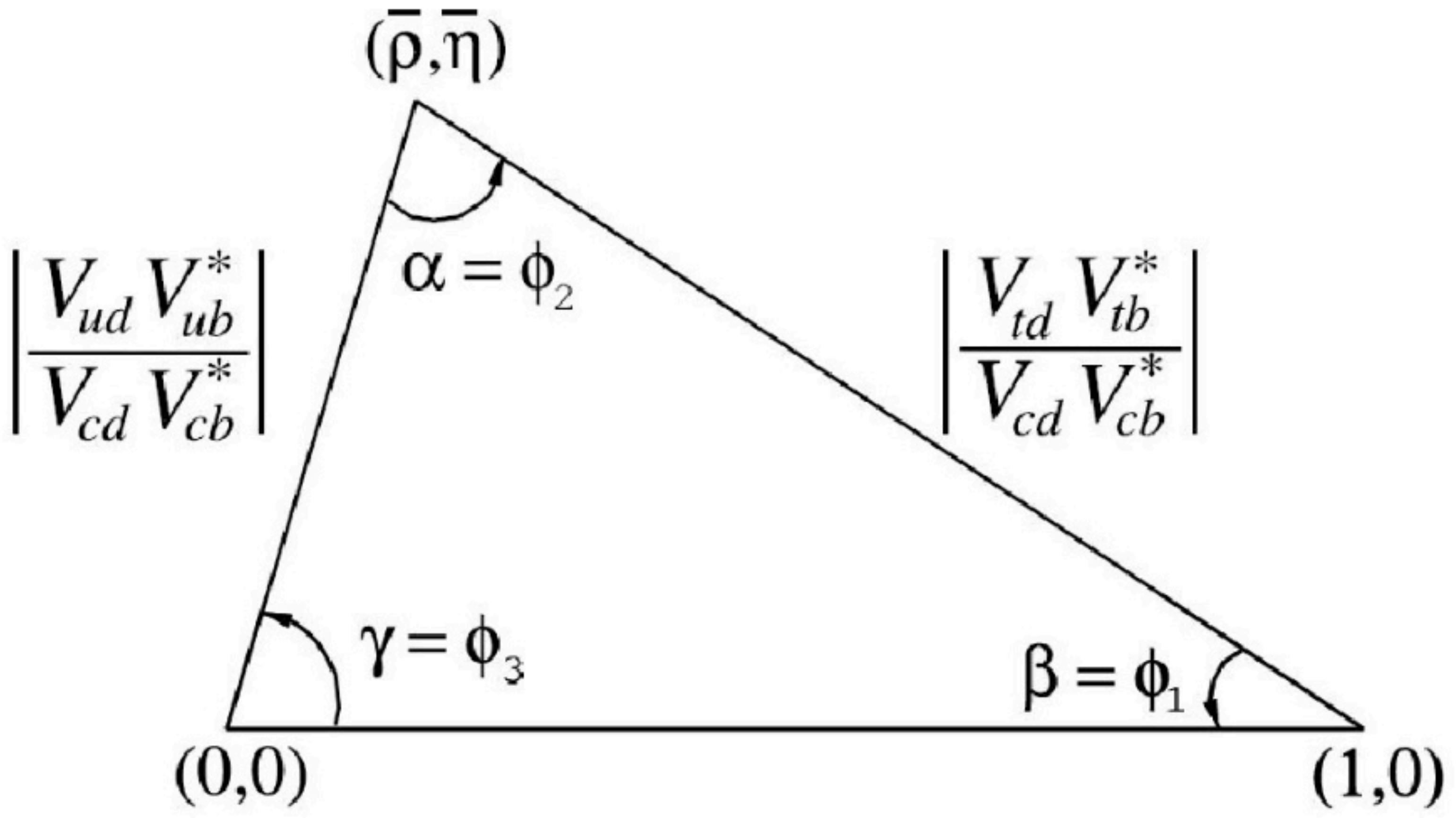
Overview (I)

- Mixing of quarks' mass and flavor eigenstates resulting from the breakdown of electroweak symmetry, accommodated by CKM matrix
  - ➡ Quantifies strength of quark flavor transitions
  - ➡ Complex phase in the CKM mixing matrix → source of CP violation in the quark sector of SM

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

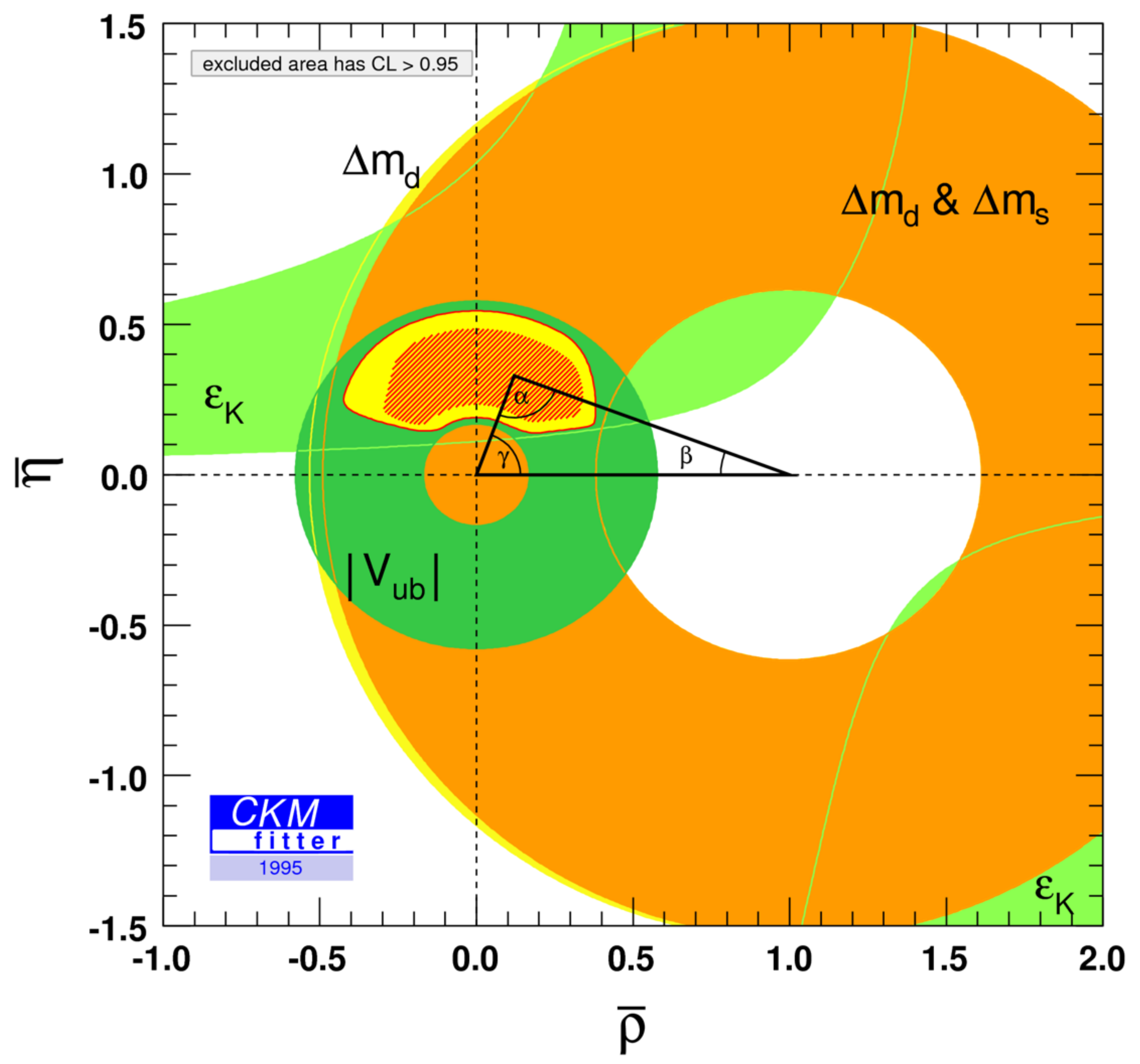
3x3 complex unitary



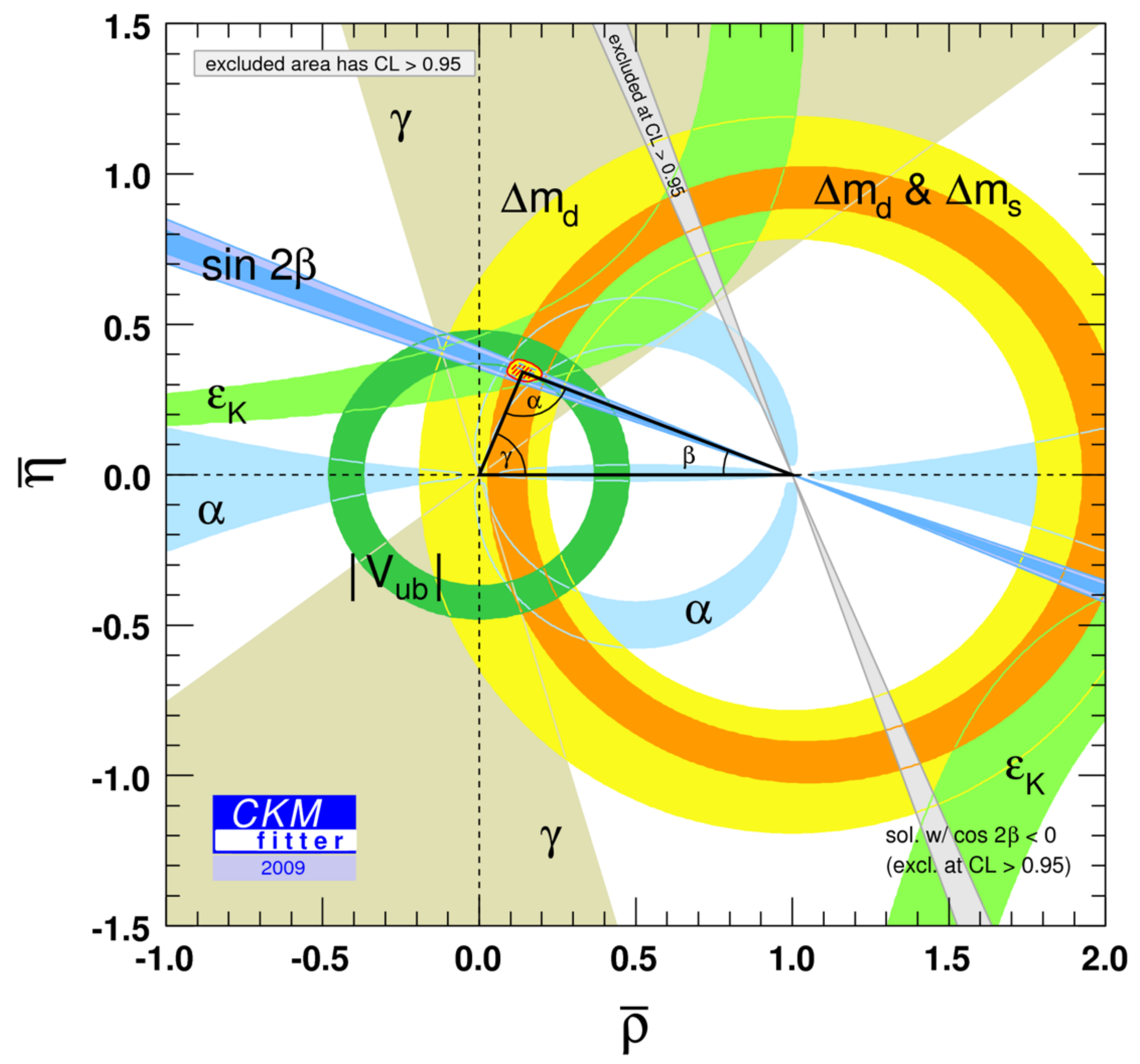
Unitary conditions

Overview (II)

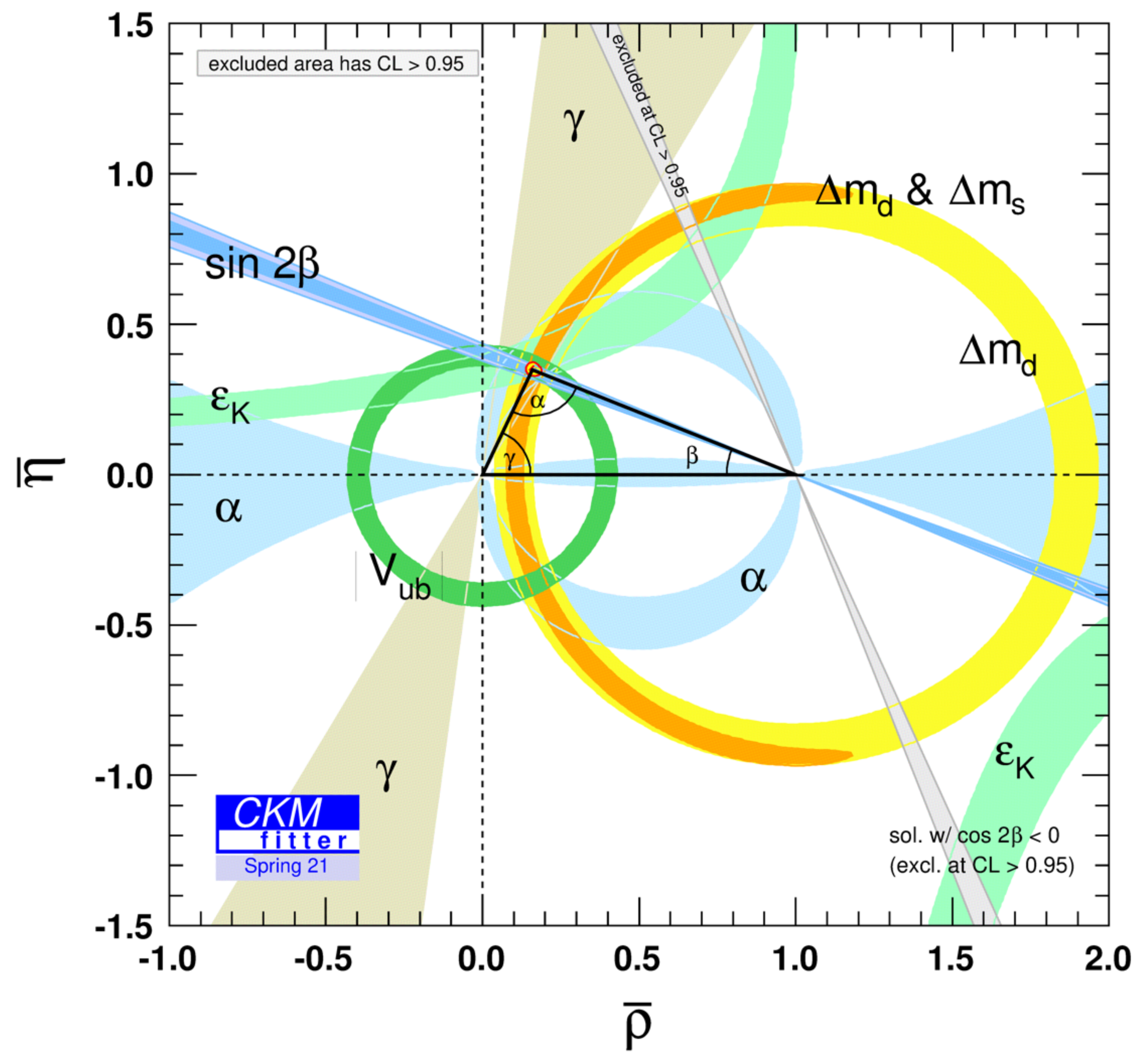
- Just 4 parameters in the CKM matrix: Several measurements severely overconstrain the Unitary Triangle (UT). Example of SM consistency check!



1995



2009



2021

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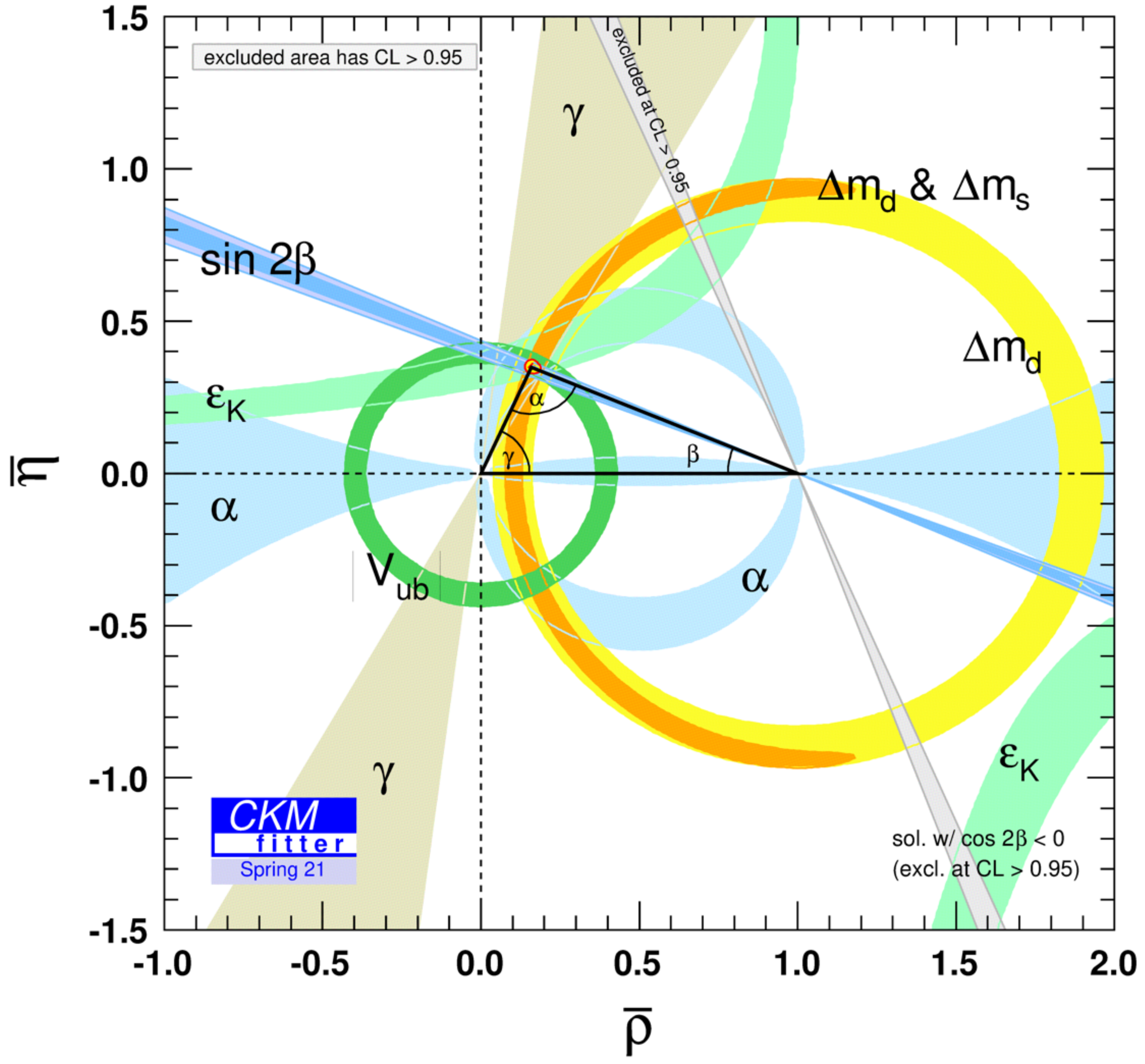
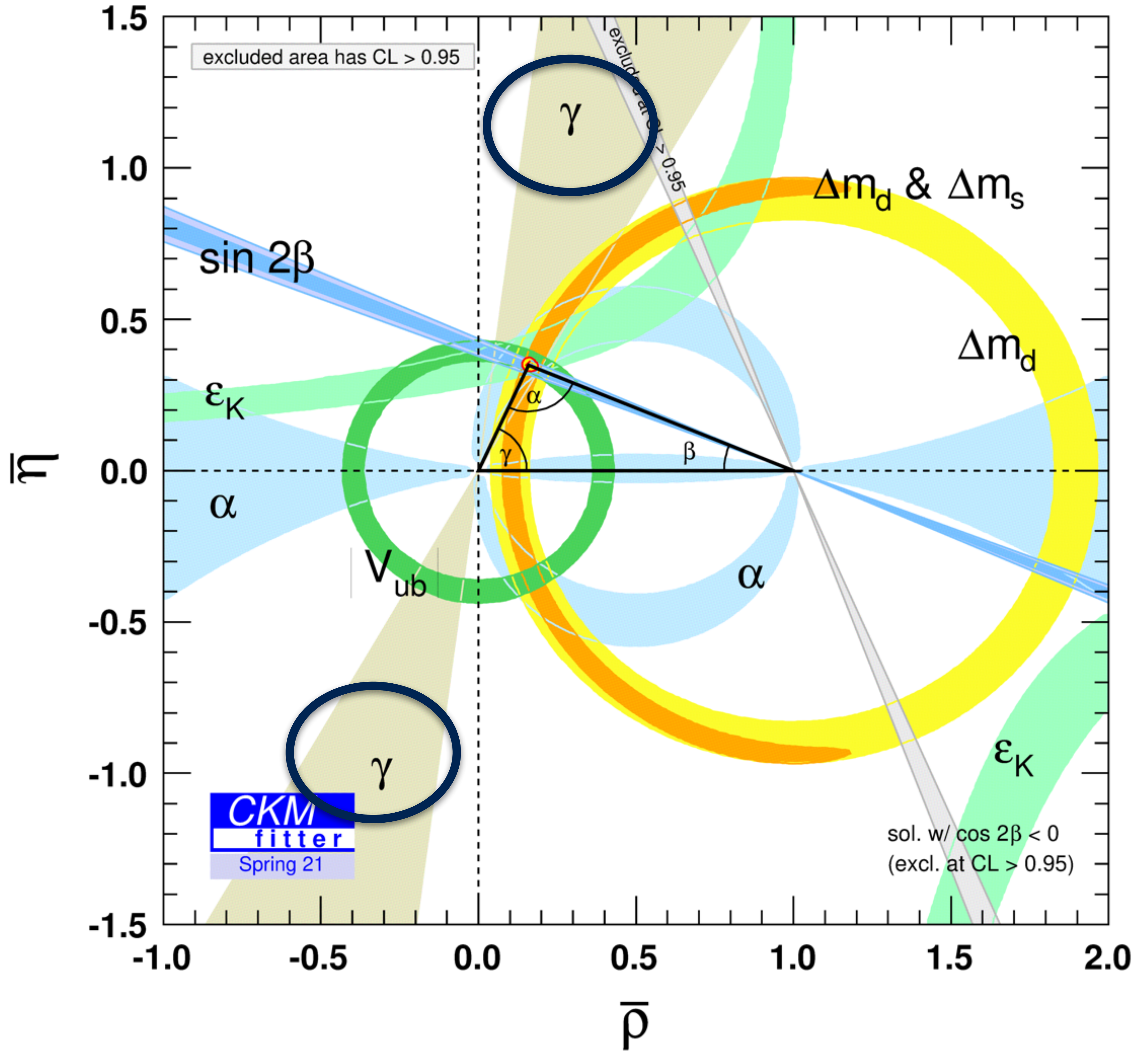
Global CKM picture

- Just 4 parameters in the CKM matrix: Several measurements severely overconstrain the Unitary Triangle (UT). Example of SM consistency check!



γ

- Just 4 parameters in the CKM matrix: Several measurements severely overconstrain the Unitary Triangle (UT). Example of SM consistency check!



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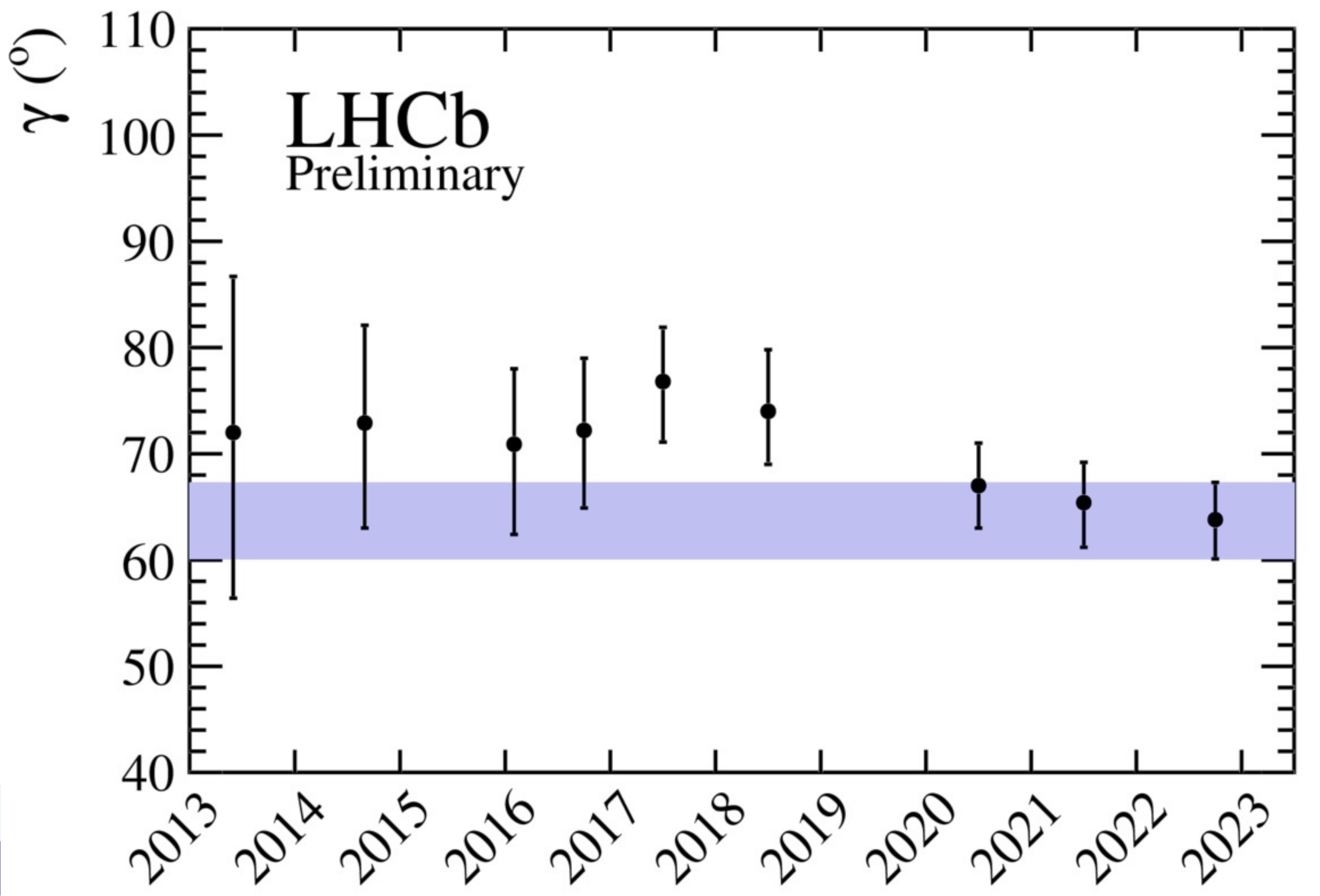
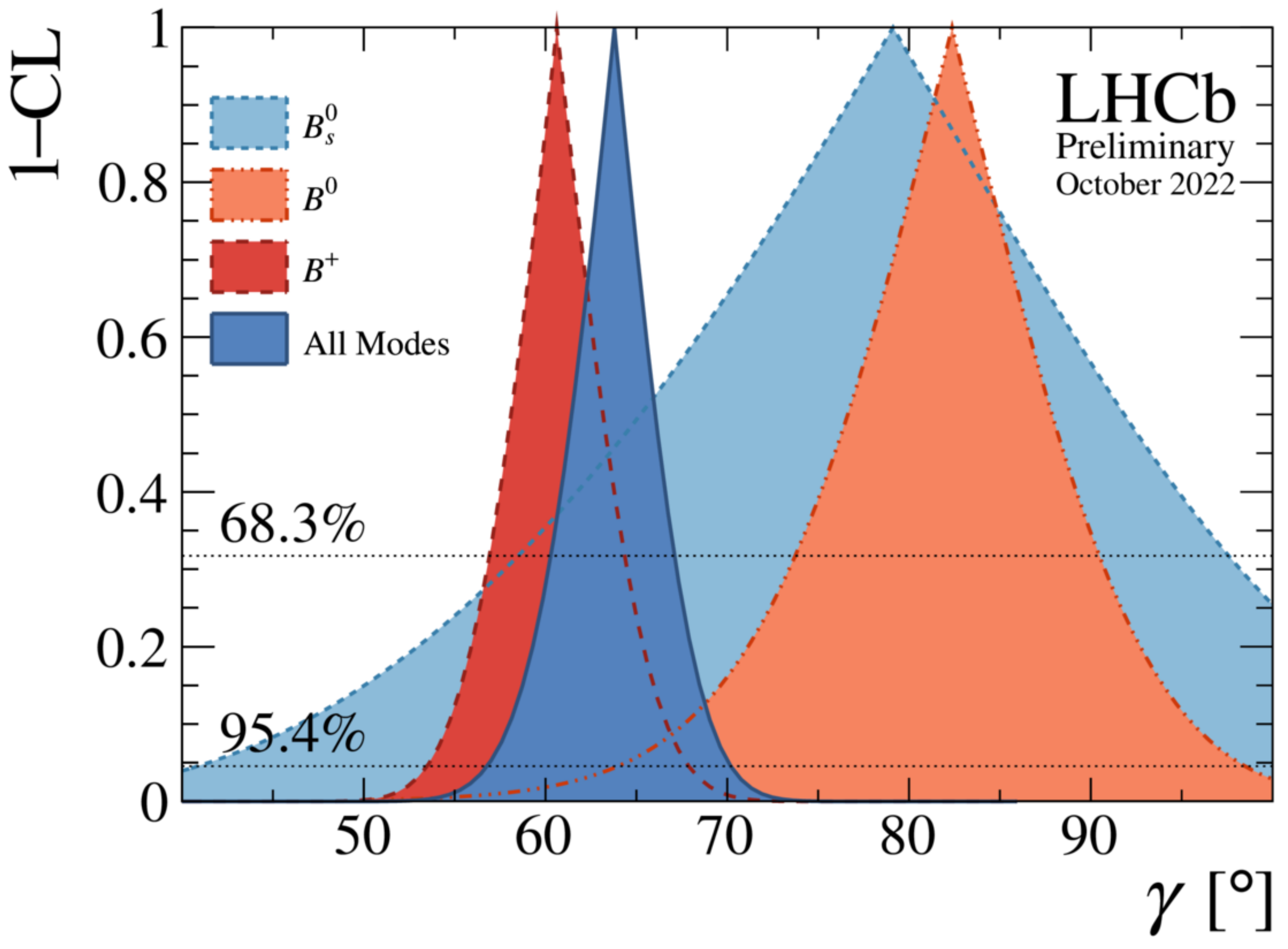
γ (I)

- Very clean test of SM
  - Theoretical error in the interpretation of γ measurements is 10^{-7} [arXiv:1308.5663]
  - Given the great accuracy, also necessary to consider the mixing and CPV effects in charm decays, as well as to have an understanding of the hadronic D decay parameters to increase sensitivity.
- Latest **LHCb** combination includes
  - $B^{\pm} \to Dh^{\pm}$ analyses [arXiv:2112.10617, arXiv:2209.03692]
  - Direct and indirect CPV in charm [PRD105(2022)092013, arXiv:2208.06512, arXiv:2209.03179]
  - Agrees with indirect result (from rest of CKM angles)
    - $\gamma = (65.7^{+0.9}_{-2.7})^{\circ}$ CKMFitter
    - $\gamma = (65.8 \pm 2.2)^{\circ}$ UTFit
  - LHCb dominates world average

$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^{\circ}$$

[LHCb-CONF-2022-003]

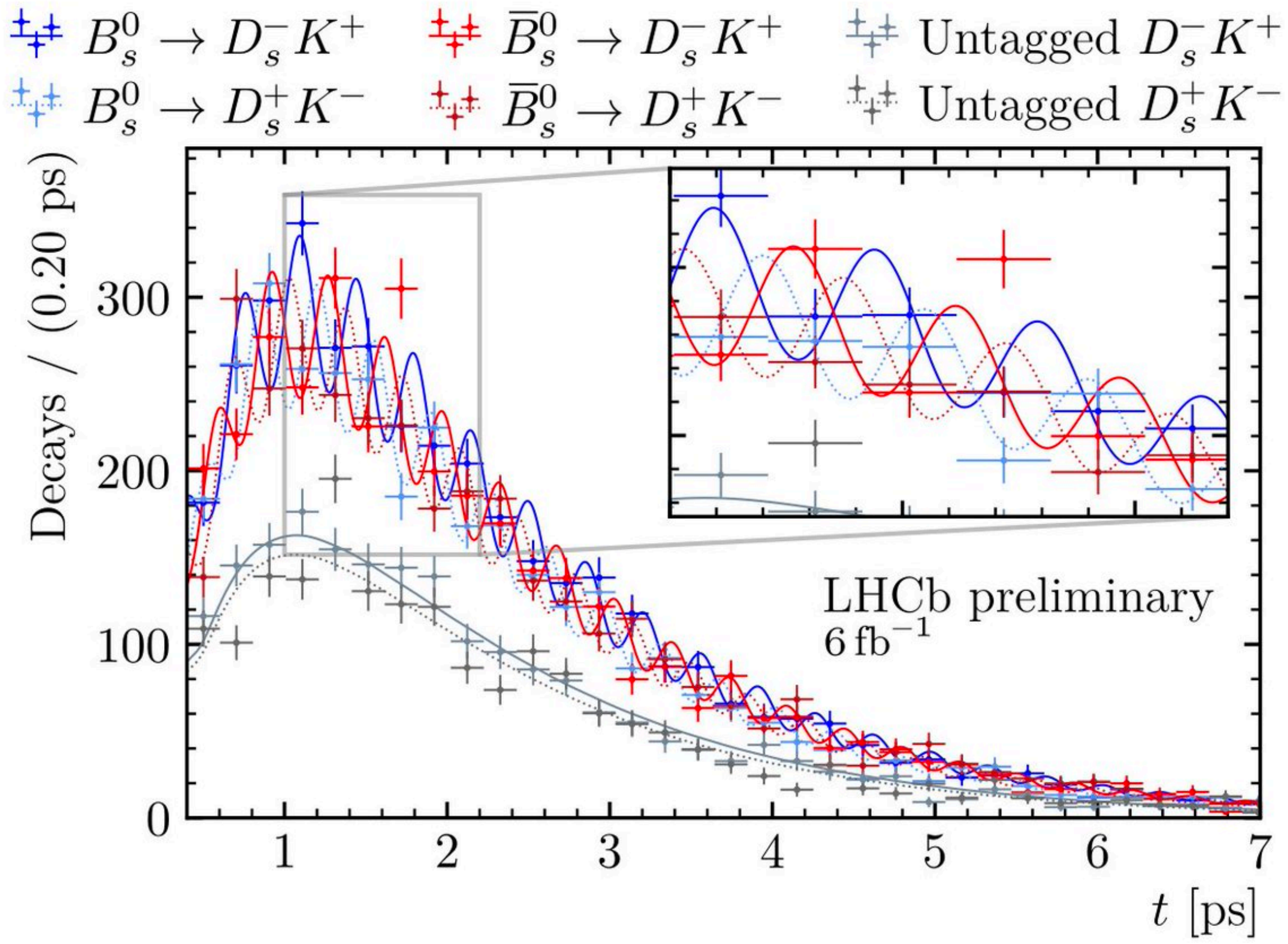


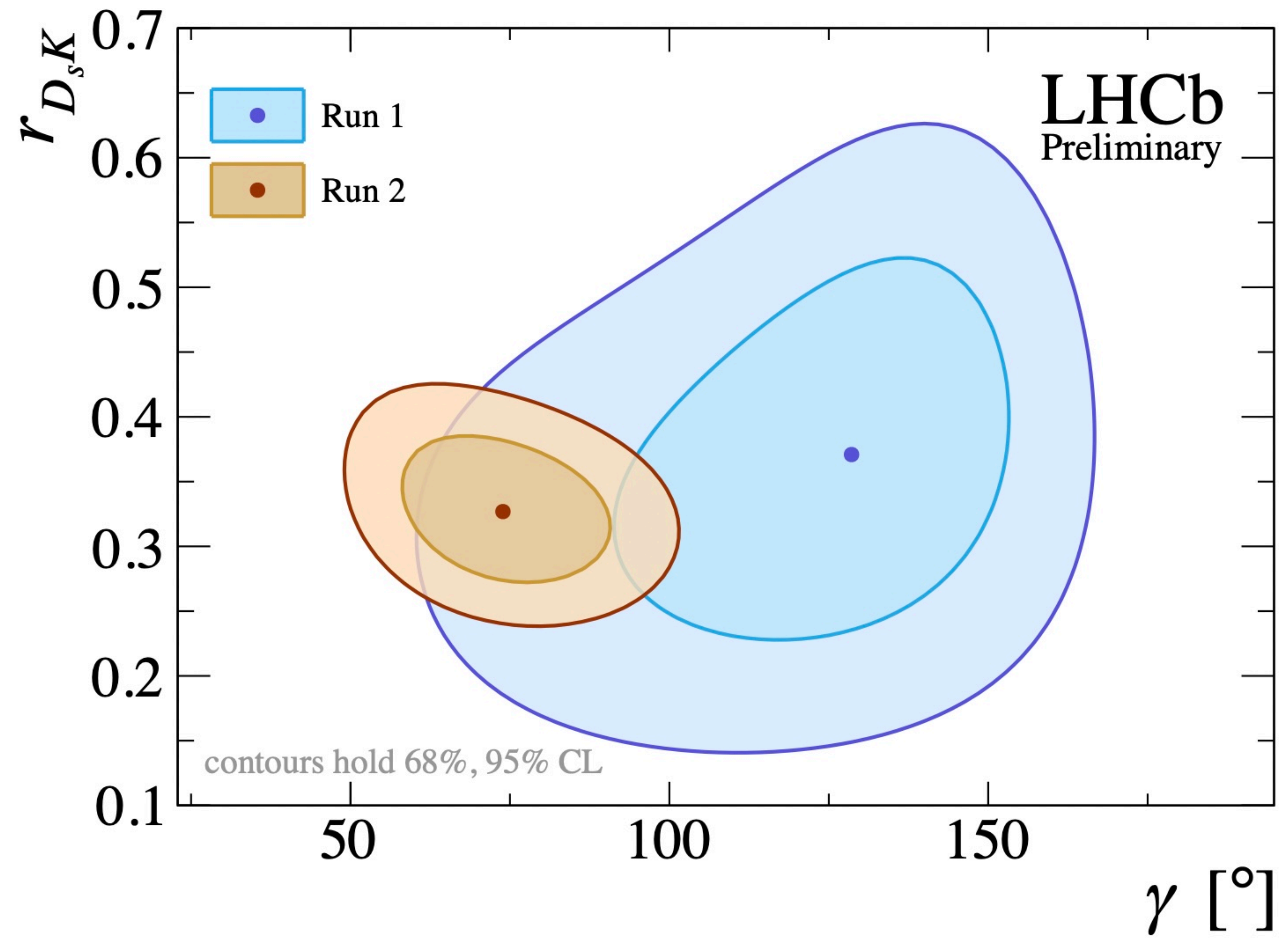


γ (II)

- Very active area, new results across different experiments
  - Complementarity in decay channels and methods (e.g. most recent results)
  - Most recent, LHCb measurement of γ with $B_s^0 \to D_s^{\mp}K^{\pm}$, relies on inputs from $B_s^0 \to D_s^-\pi^+$ and $B_s^0 \to J/\Psi\phi$

[LHCb-CONF-2023-004]





$r^{D_s^K}$: ratio of amplitudes D_s^+/D_s^-

$$\gamma = (74 \pm 11)^\circ$$

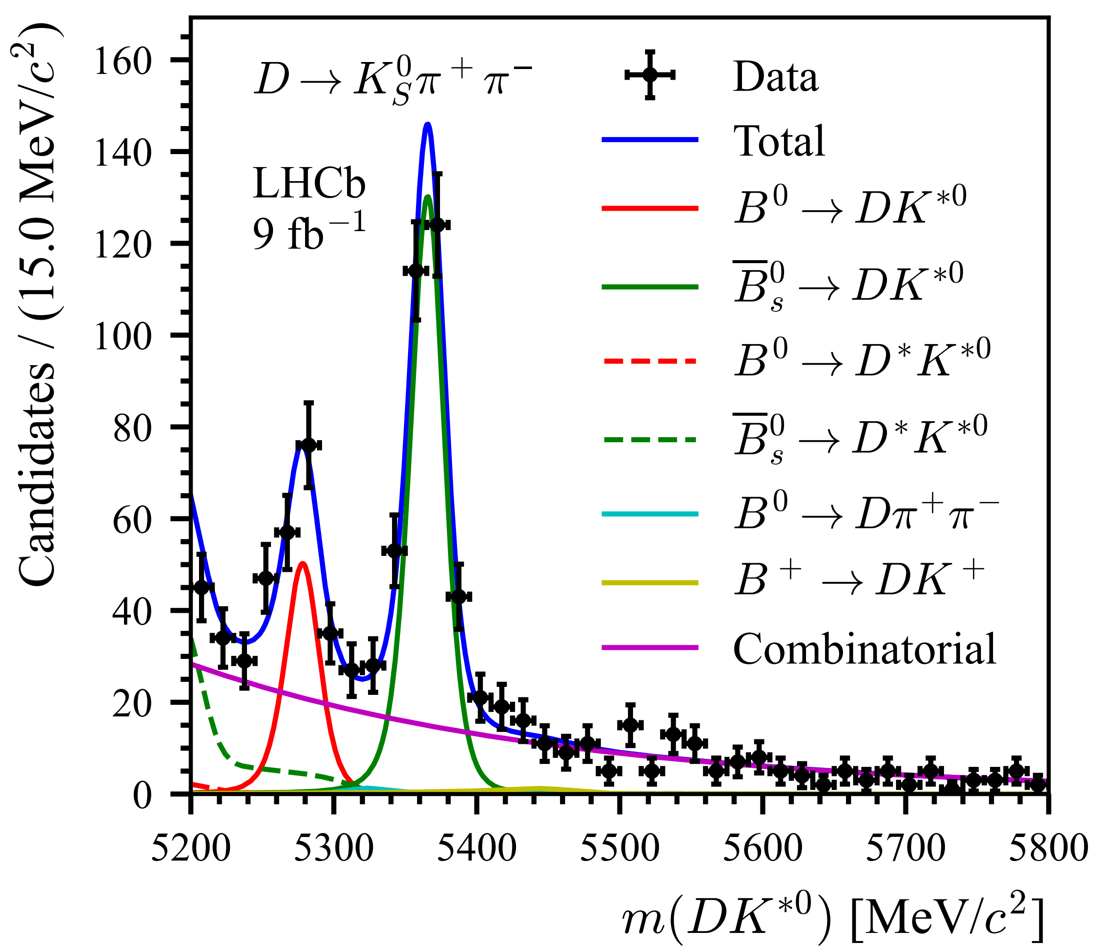
γ (III)

- Very active area, new results across different experiments
  - Complementarity in decay channels and methods (e.g. most recent results)

Analysis of $B^0 \to D^0 K^*$, with $D^0 \to K^0_S h^+ h^-$ @LHCb

$\gamma = (49^{+23}_{-18})^\circ$

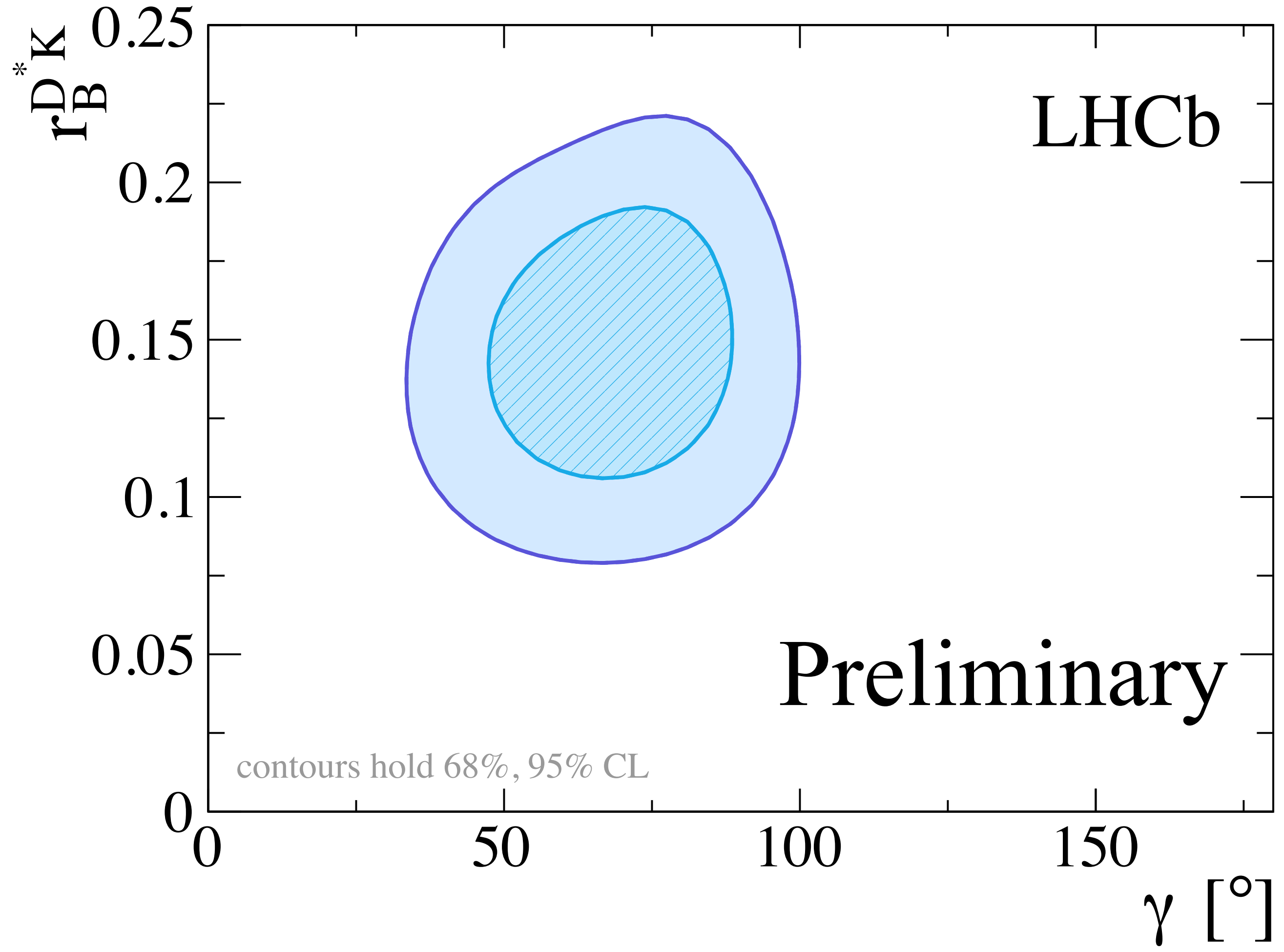
[arXiv:2309.05514]



Analysis of $B^+ \to D^* h^+$, with $D^* \to D\pi^0/\gamma$ and $D^0 \to K^0_S h^+ h^-$ @LHCb $\gamma = (69 \pm 14)^\circ$

[LHCb-PAPER-2023-012]

[EPS talk]

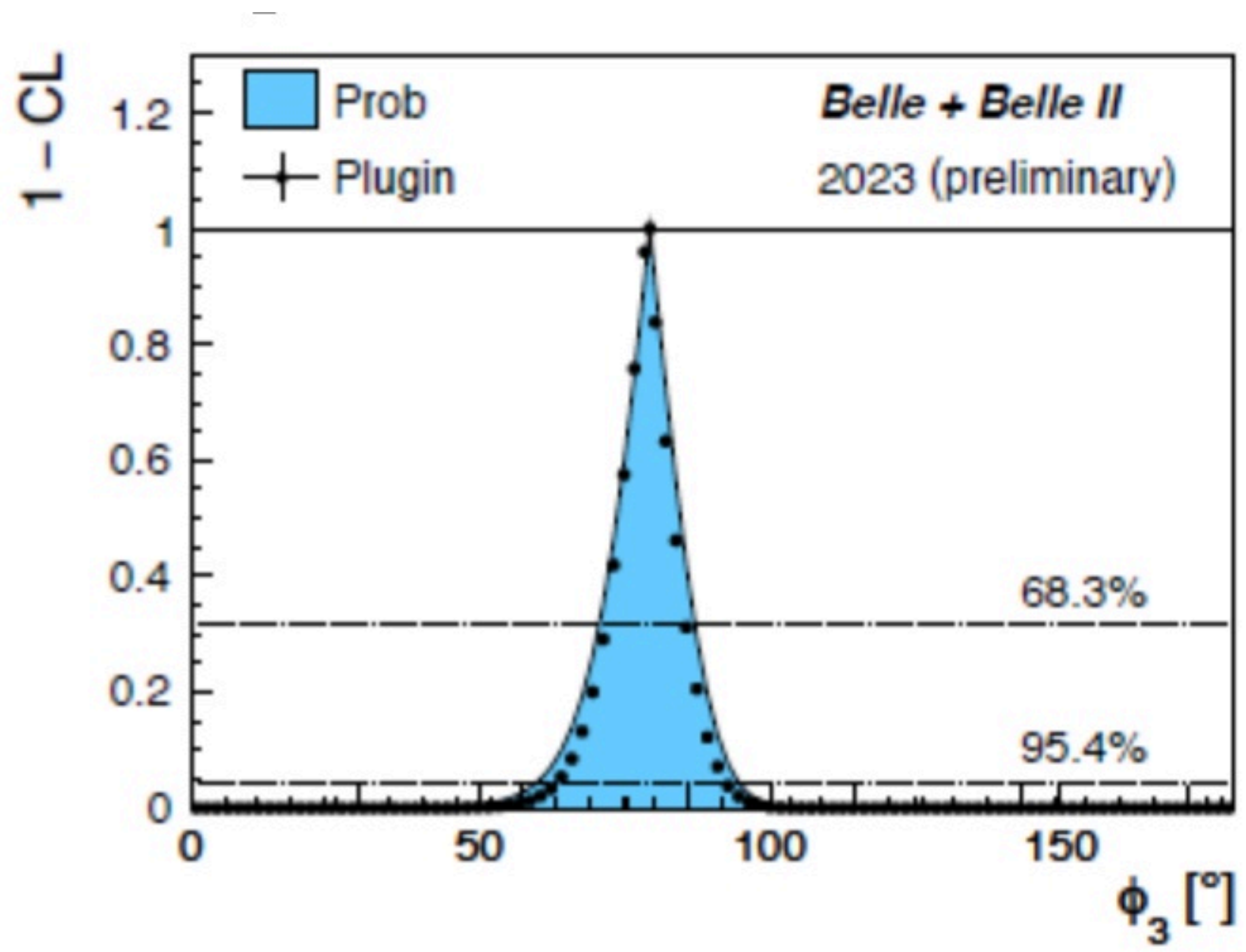


$r_B^{D^*K}$: ratio of amplitudes $D^*/\bar{D}^*$

Preliminary combined analysis of γ at @Belle II + Belle

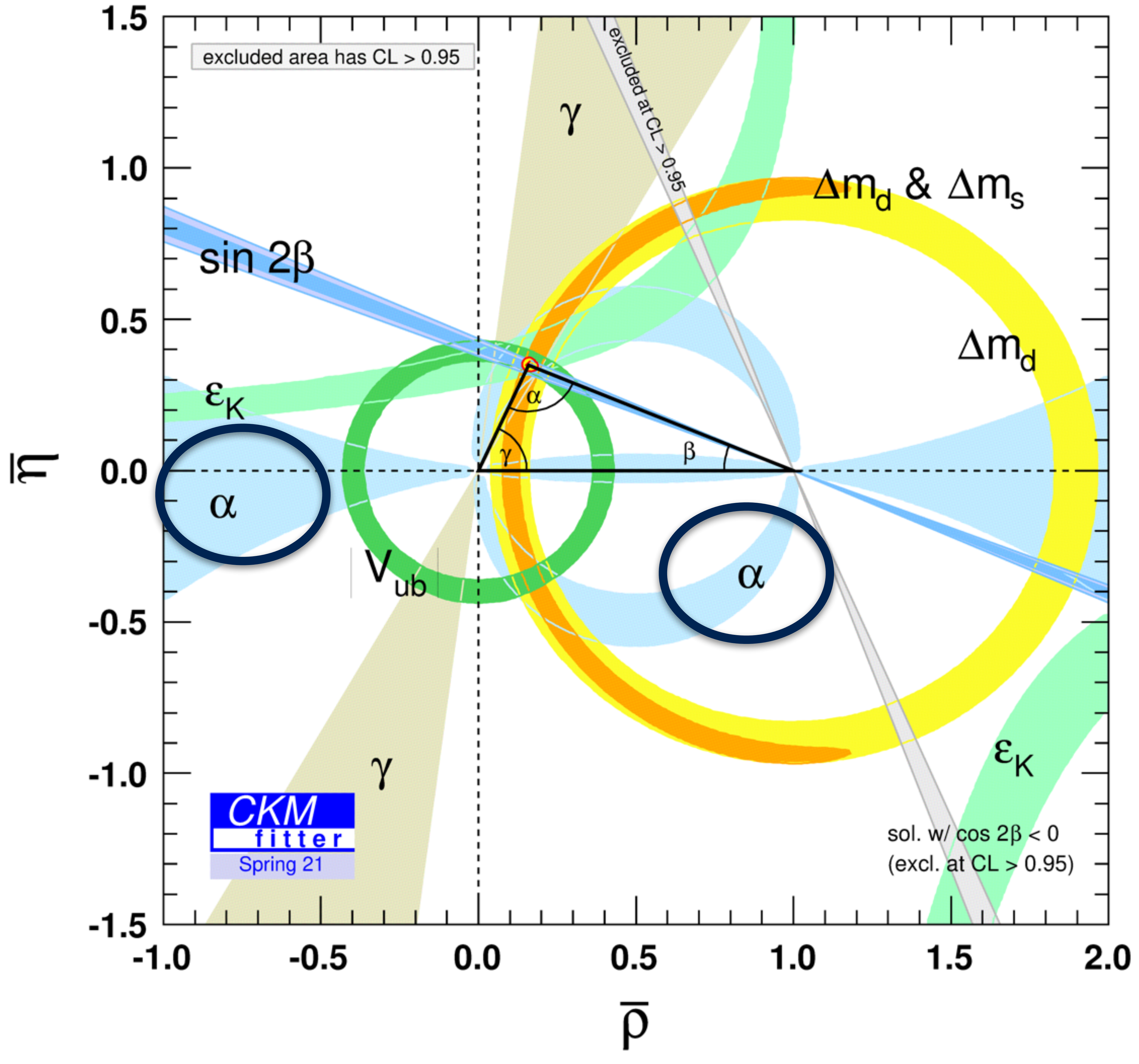
$\phi_3 = \gamma = (78.6 \pm 7.3)^\circ$

[CKM slides]



α

- Just 4 parameters in the CKM matrix: Several measurements severely overconstrain the Unitary Triangle (UT). Example of SM consistency check!



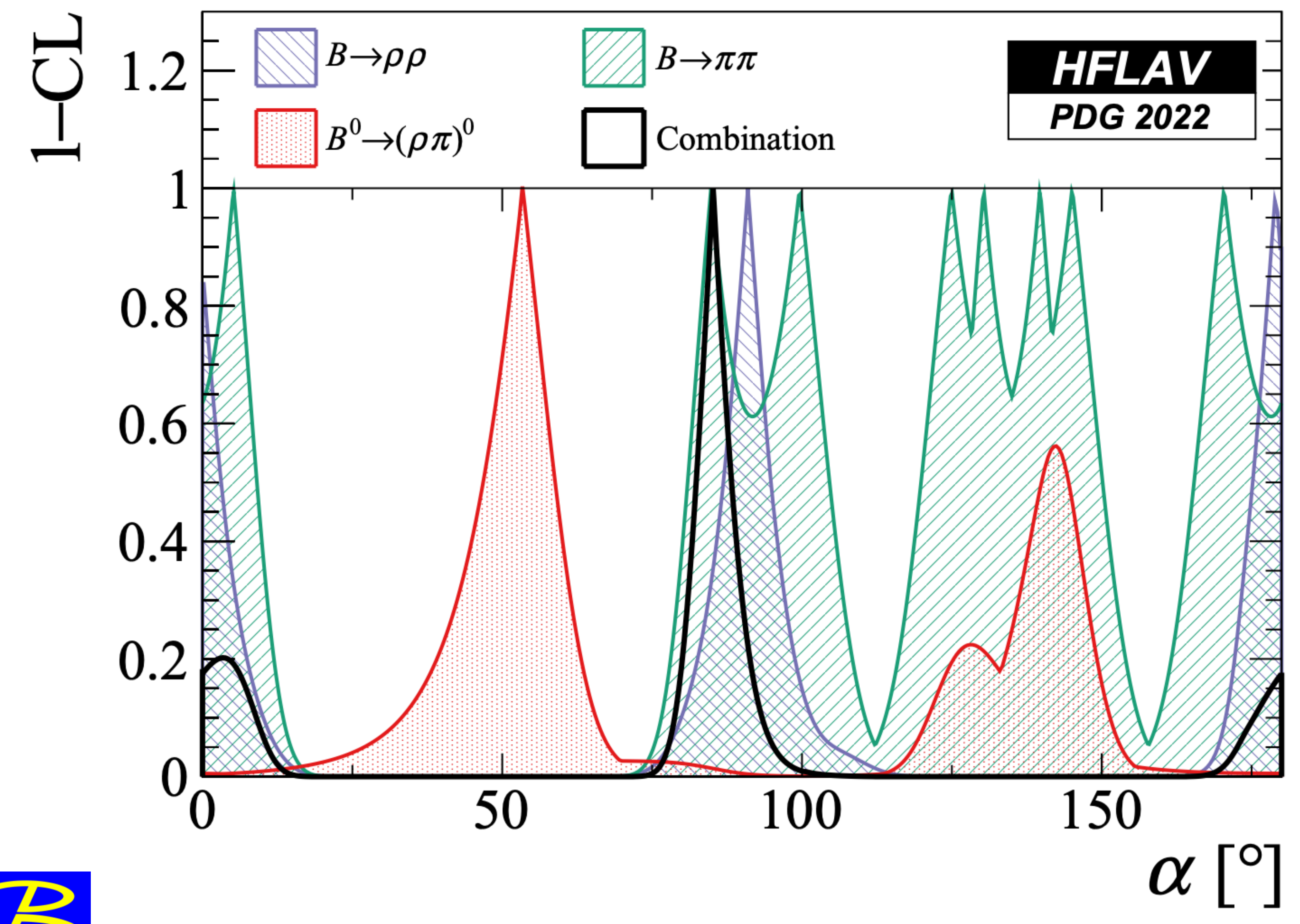
α

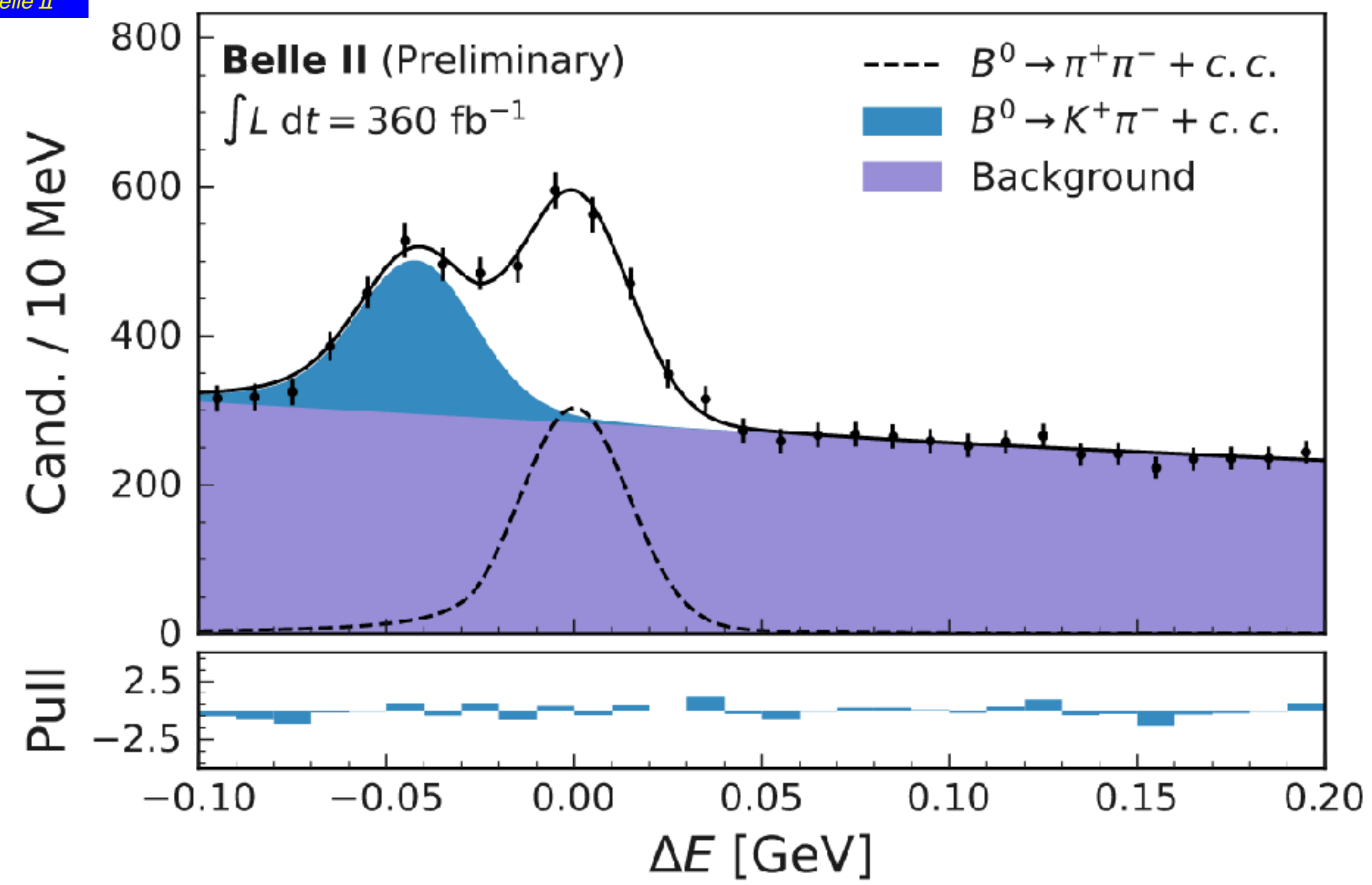
- Least well-known angle of UT (uncertainty ~4°)
  - Obtained through isospin analysis of $B \to \pi\pi, \rho\rho, \rho\pi$ decays. Theoretical uncertainty of ~1°: isospin breaking and EW penguin
  - Better accuracy from $B \to \rho\rho$ @B-factories (access to all final states, including neutrals). Dominates world average! LHCb can contribute in final states
  - Very recent (preliminary) from Belle II

Proceedings @[arXiv:2305.12193]

$$BR(B \to \pi^+\pi^0) = (5.02 \pm 0.28 \pm 0.32) \times 10^{-6}$$

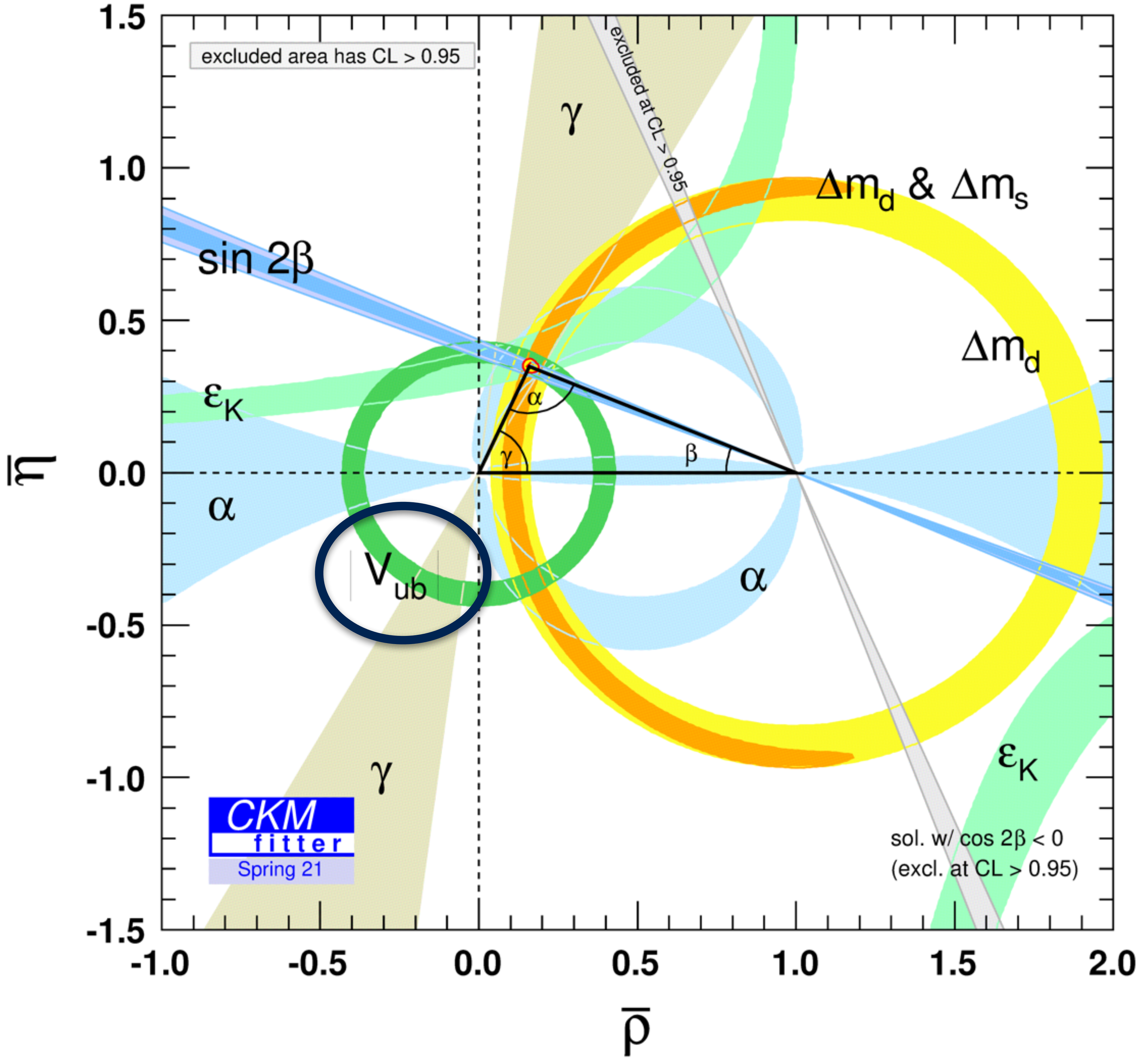
$$A_{CP}(B \to \pi^+\pi^0) = (-0.08 \pm 0.05 \pm 0.01)$$

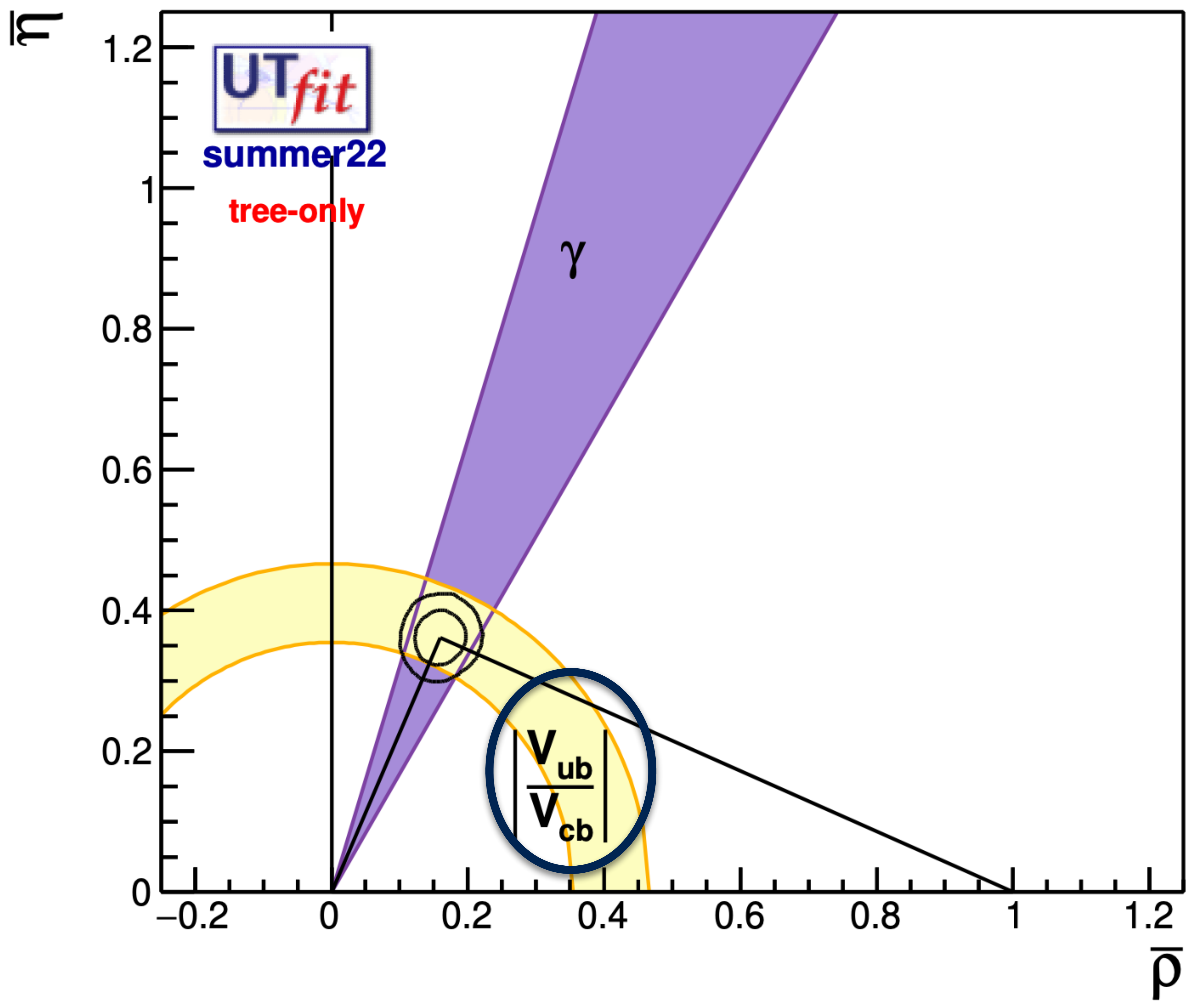




$|V_{ub}|$ and $|V_{cb}|$

- Just 4 parameters in the CKM matrix: Several measurements severely overconstrain the Unitary Triangle (UT). Example of SM consistency check!





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

- Tree-level constraint on the UT apex, currently limiting factor in global picture
  - ➡ Determined by semileptonic decay rates + lattice QCD
  - ➡ Long-standing disagreement between exclusive and inclusive measurements

$$|V_{cb}|_{\mathrm{excl}} = (39.10 \pm 0.50) \times 10^{-3}$$
$$|V_{ub}|_{\mathrm{excl}} = (4.19 \pm 0.17) \times 10^{-3}$$

⟵ HFLAV world average (2021)

- ➡ Summary of results from Belle II:

	$\lvert V_{cb}\rvert \times 10^3$	Reference
Belle II $B^0 \to D^{*-} l^+ \nu_l$ untagged	40.9 ± 1.2 (BGL)	To be submitted to PRD
Belle II $B^0 \to D^{*-} l^+ \nu_l$ tagged	37.9 ± 2.7 (CLN)	[arXiv.2301.04716]
Belle II $B^0 \to D l \nu_l$ untagged	38.28 ± 1.16 (BGL)	[arXiv:2210.13143]
Belle II B → D*ℓ+ν full angular	40.9 ± 0.7 (CLN)	[CKM slides]

	$\lvert V_{ub}\rvert \times 10^3$	Reference
Belle II $B^0 \to \pi e \nu_e$ tagged	3.88 ± 0.45	[arXiv:2206.08102]
Belle II $B^0 \to \pi e \nu_e$ untagged	3.55 ± 0.25	[arXiv.2210.04224]

+ brand new ratio $|V_{ub}^{\mathrm{excl.}}|/|V_{ub}^{\mathrm{incl.}}| = 0.97 \pm 0.12$

[arXiv:2303.17309]

* BGL and CLN are different parameterizations of the form factors of the B decays

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

- ✦ Tree-level constraint on the UT apex, currently limiting factor in global picture
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$$|V_{cb}|_{excl} = (39.10 \pm 0.50) \times 10^{-3}$$
$$|V_{ub}|_{excl} = (4.19 \pm 0.17) \times 10^{-3}$$

← HFLAV world average (2021)

- ➡ Summary of results from LHCb:

	$\|V_{cb}\|$ x 10^3	Reference
LHCb $B_s^0 \to D_s^{(*)} \mu \nu_\mu$	$41.4 \pm 0.6 \pm 0.9 \pm 1.2$ (BGL)	PRD101(2020)072004
LHCb $B_s^0 \to D_s^{(*)} \mu \nu_\mu$	$42.3 \pm 0.8 \pm 0.9 \pm 1.2$ (CLN)	PRD101(2020)072004

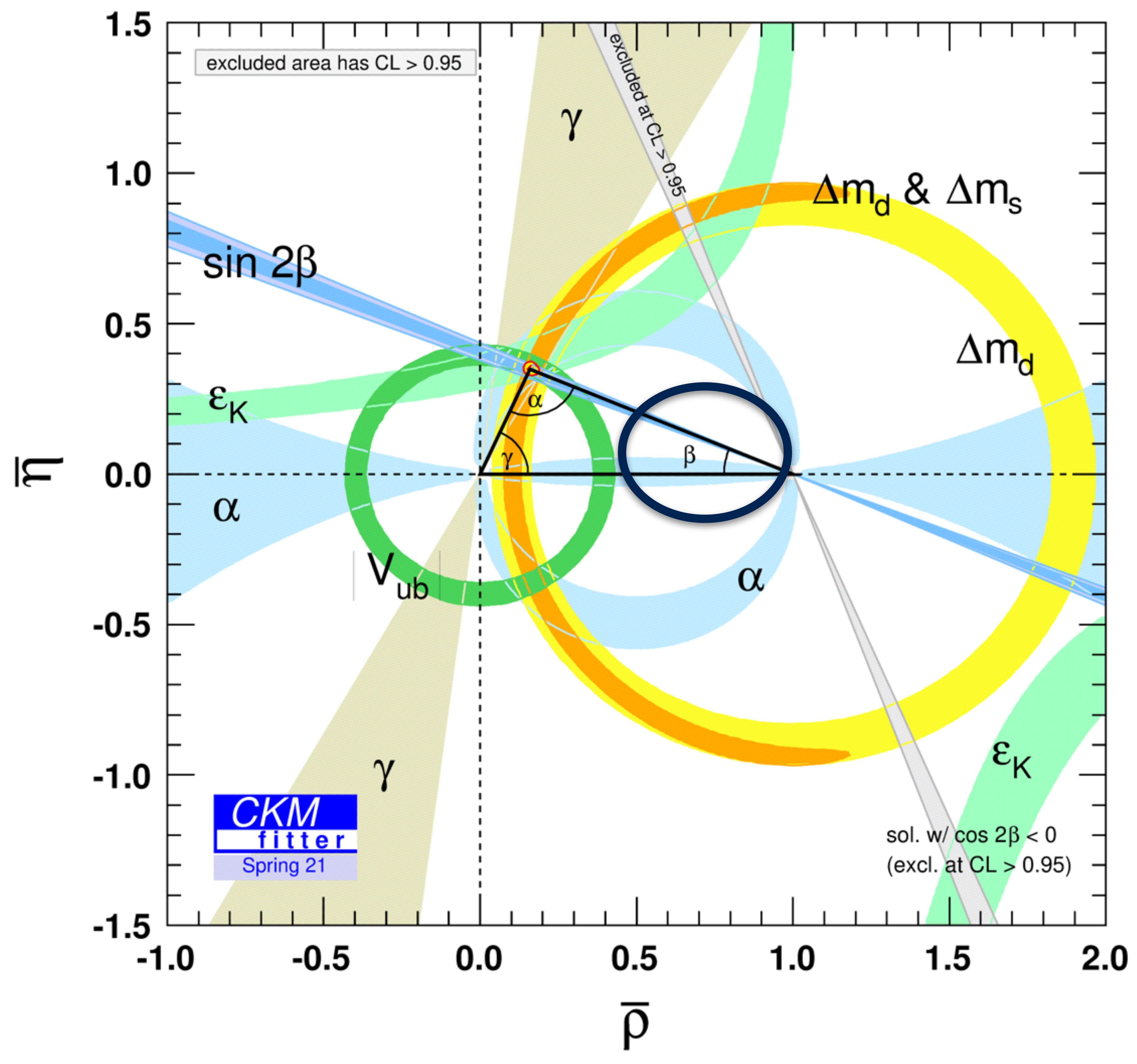
Results on $|V_{ub}|$ from LHCb measurement of $|V_{ub}|/|V_{cb}|$ and using world average of exclusive $|V_{cb}|$

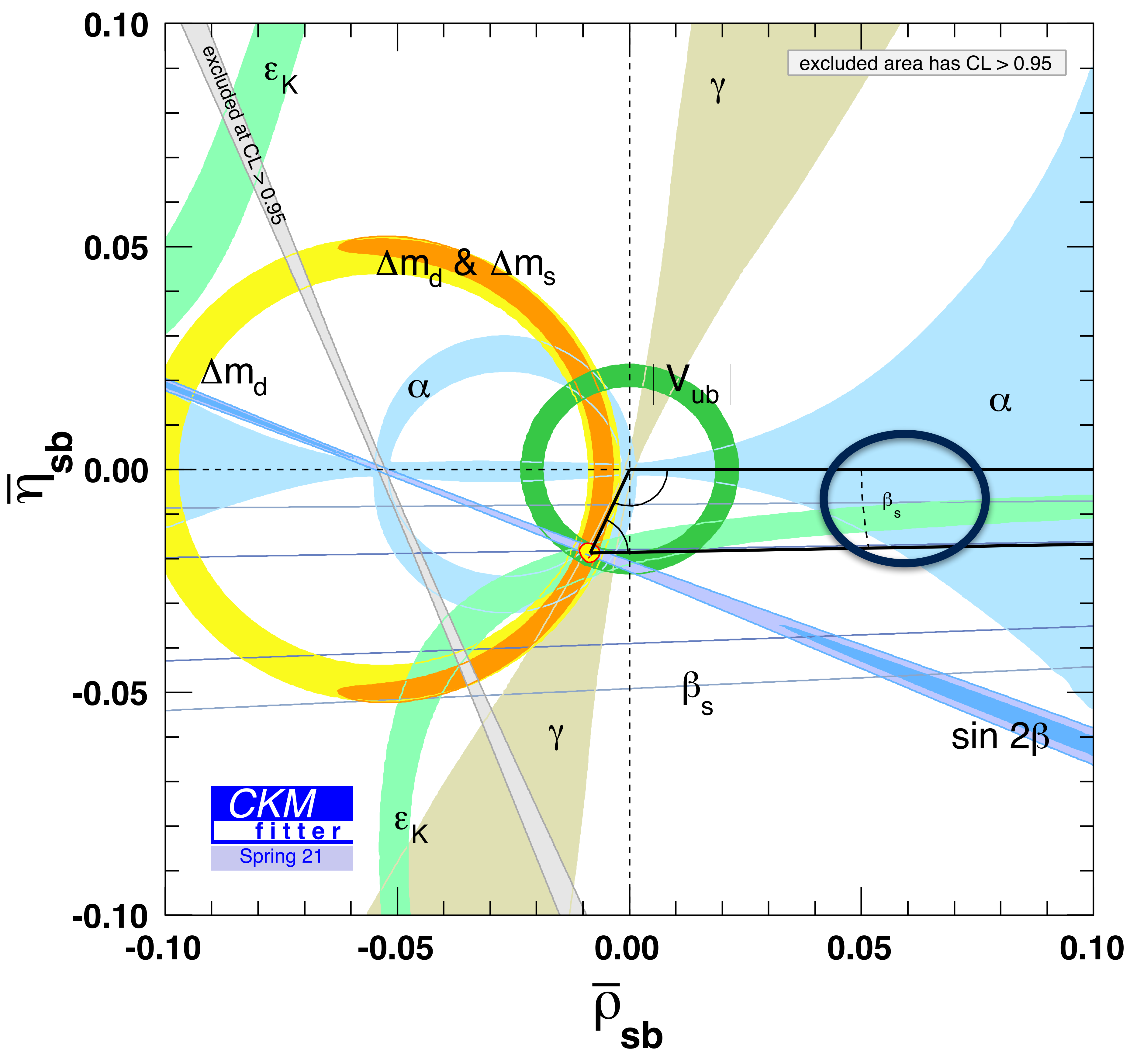
	$\|V_{ub}\|$ x 10^3	Reference
LHCb $B_s^0 \to K^- \mu^+ \nu_\mu$	2.40 ± 0.16 ($q^2 < 7$ GeV^2/c^4)	PRL126(2021)081804
LHCb $B_s^0 \to K^- \mu^+ \nu_\mu$	3.74 ± 0.32 ($q^2 > 7$ GeV^2/c^4)	PRL126(2021)081804
LHCb $\Lambda_b^0 \to p \mu^+ \nu_\mu$	3.27 ± 0.23	NaturePhysics11(2015)743

* BGL and CLN are different parameterizations of the form factors of the B decays

$B^0_{(s)}$ mixing phases

- Just 4 parameters in the CKM matrix: Several measurements severely overconstrain the Unitary Triangle (UT). Example of SM consistency check!



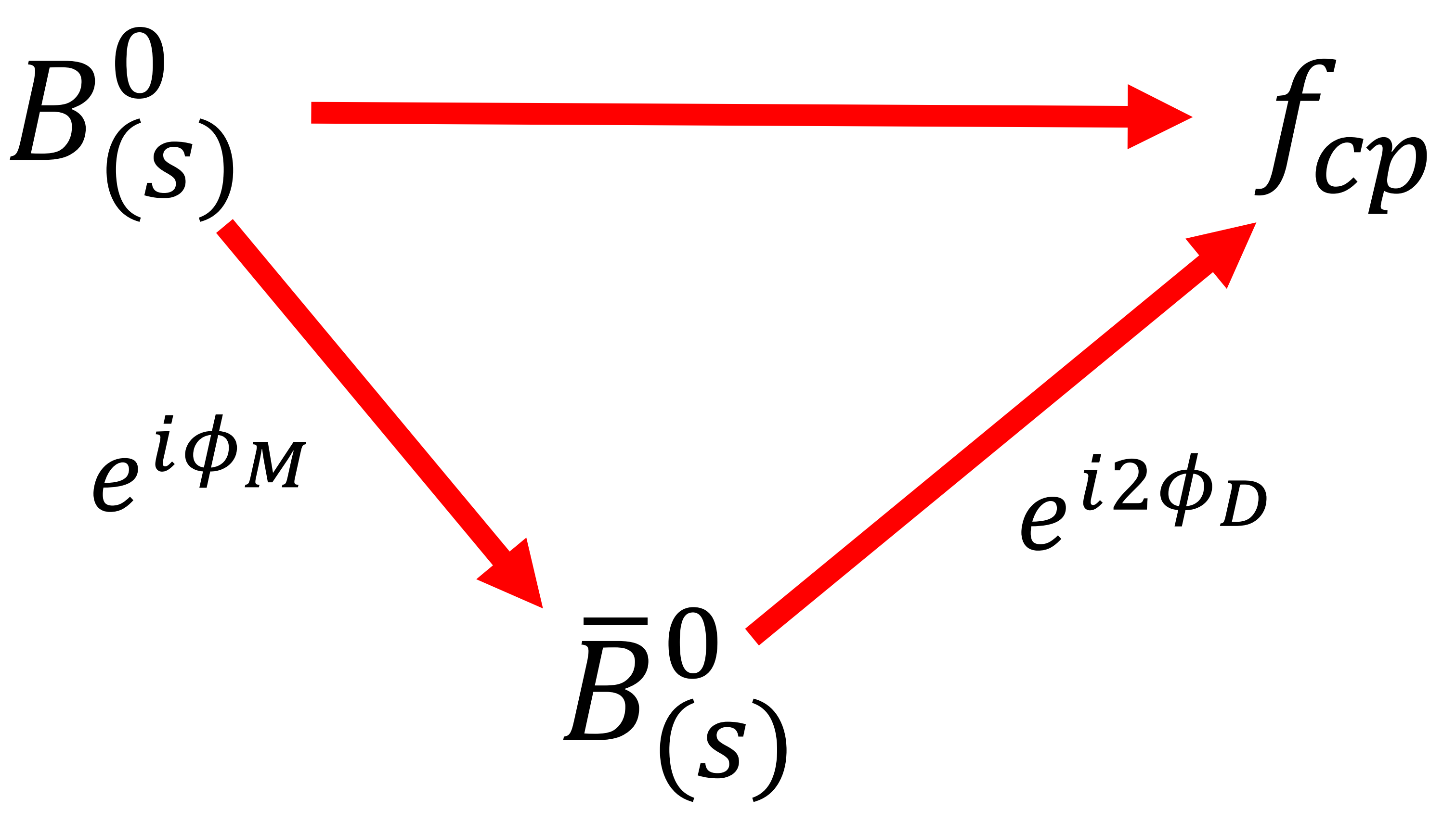


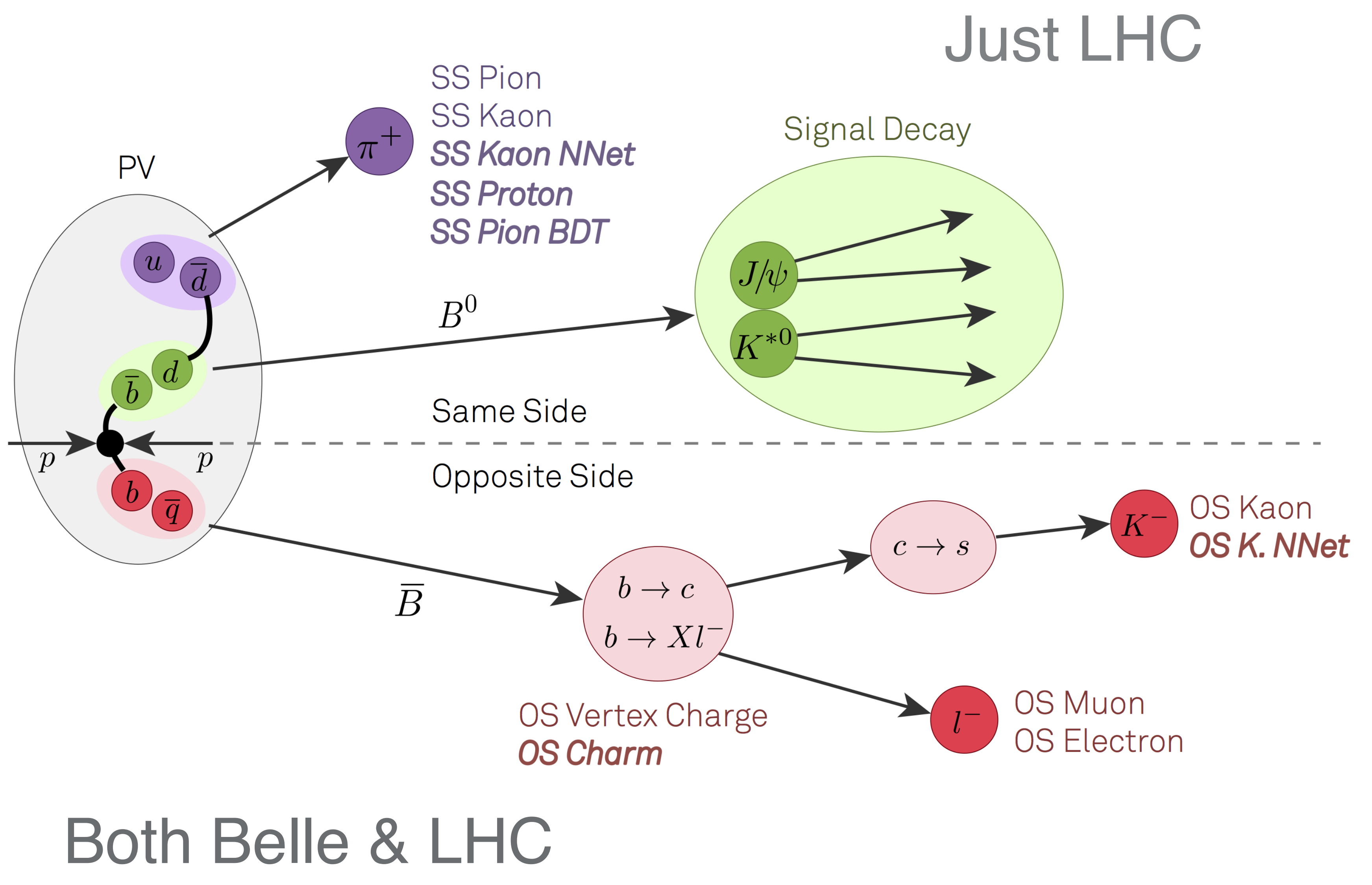
$B^0_{(s)}$ mixing phases

- Constraints to the UT apex may be obtained from the mixing phases of B^0 (sin2β) and B^0_s (ϕ_s) thanks to time-dependent CPV.
  - Measure CP phase through interference between B-mixing and decay
  - Golden modes: $B^0_s \to J/\Psi h^+ h^-$ and $B^0 \to J/\Psi K^0_s$ → decay dominated by tree-level $b \to c\bar{c}q$ transitions (No CPV in decay)
- Essential for determining the B's flavor at production: flavor tagging
  - Effective flavor tagging:

$$\varepsilon_{eff}^{LHC} \approx 5-8\%,\ \varepsilon_{eff}^{BelleII} \approx 30\%$$

Belle profits from cleaner environment!



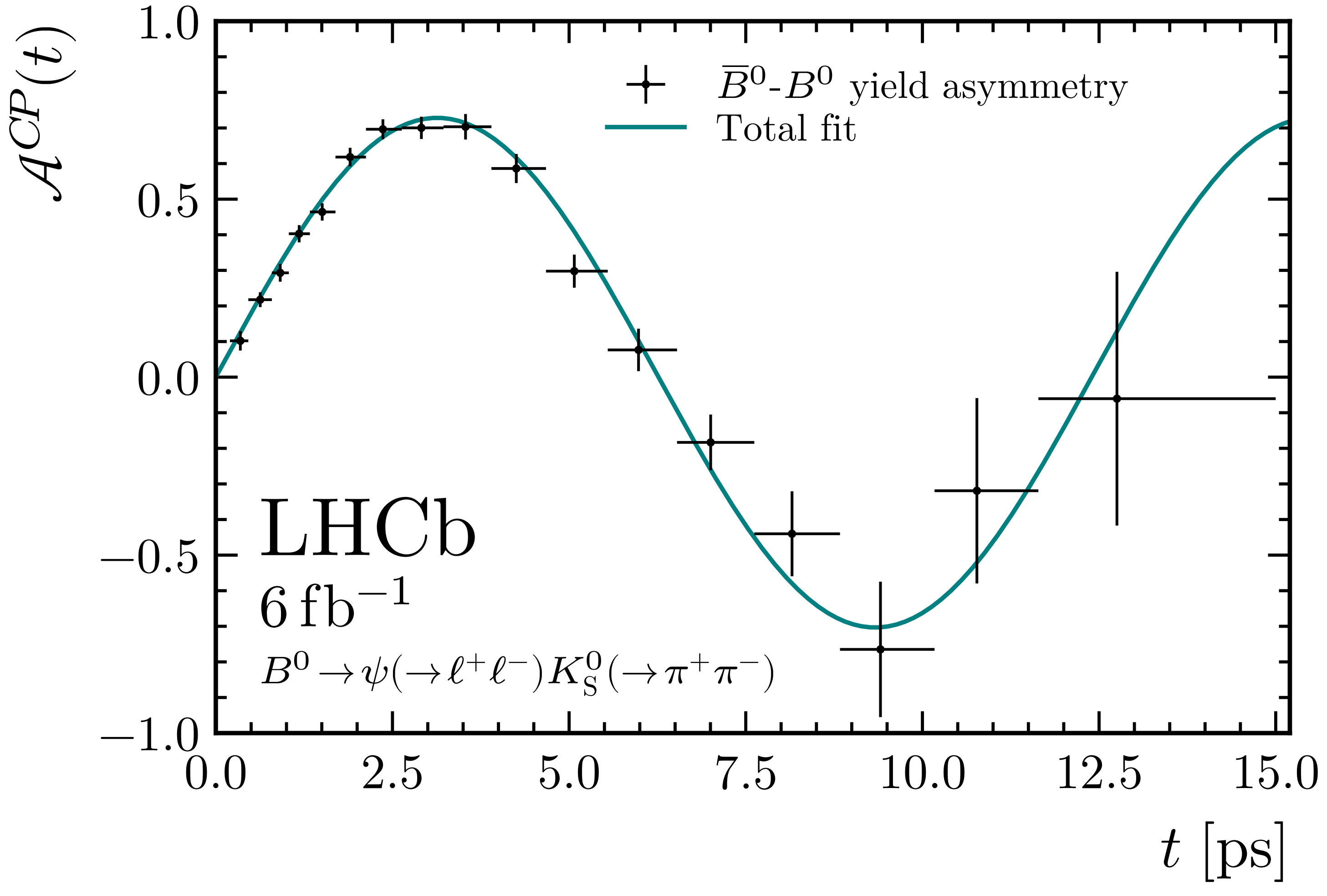


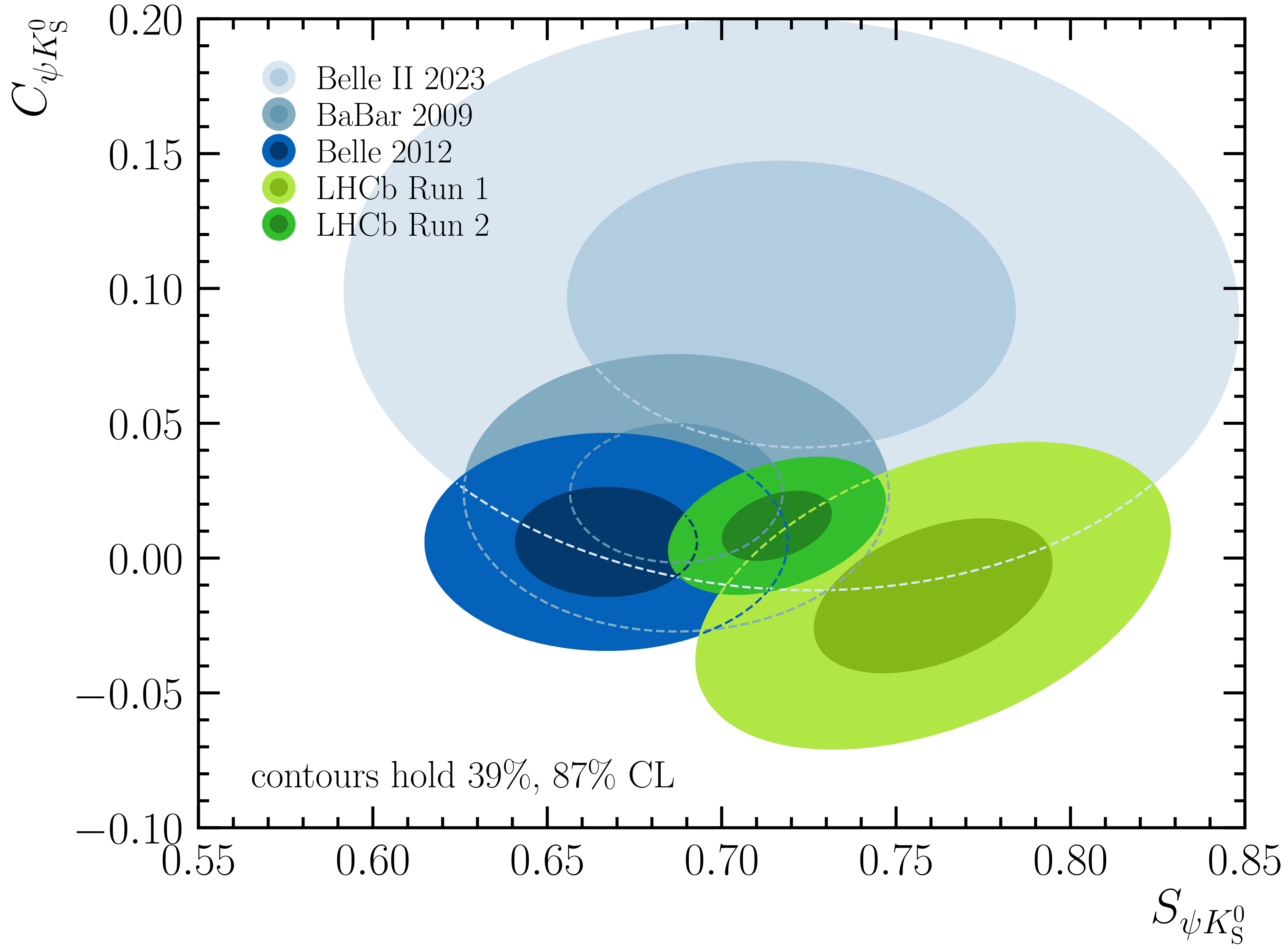
sin(2β)

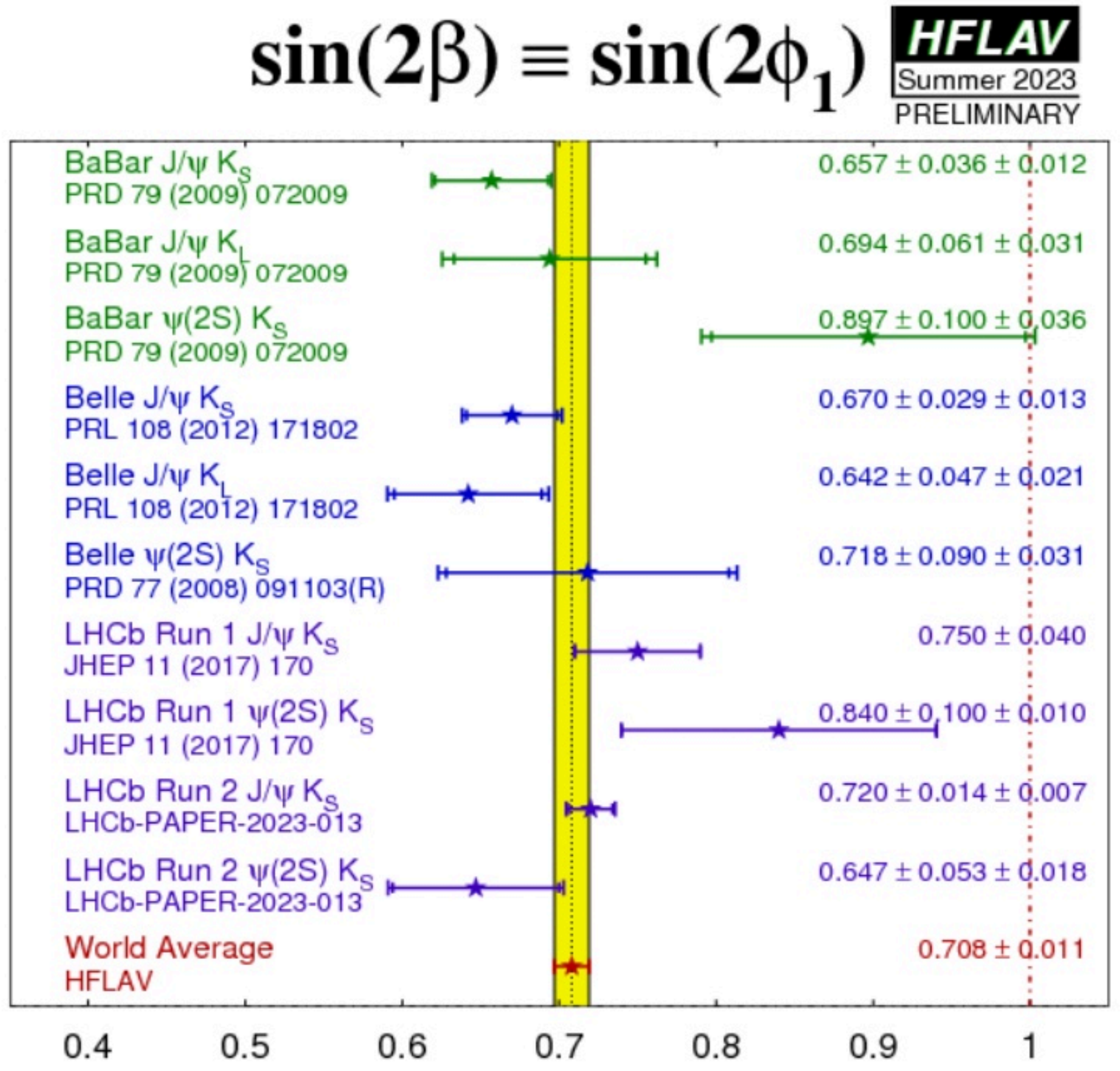
- New **LHCb** Run 2 legacy result, using J/Ψ decays both to muons and electrons: [arXiv:2309.09728]

$$S_{\psi K^0_S}^{\text{Run 1+2}} = 0.723 \pm 0.014\,(\text{stat+syst})$$
$$C_{\psi K^0_S}^{\text{Run 1+2}} = 0.007 \pm 0.012\,(\text{stat+syst})$$

  - ➡ Most precise to date, still dominated by statistics





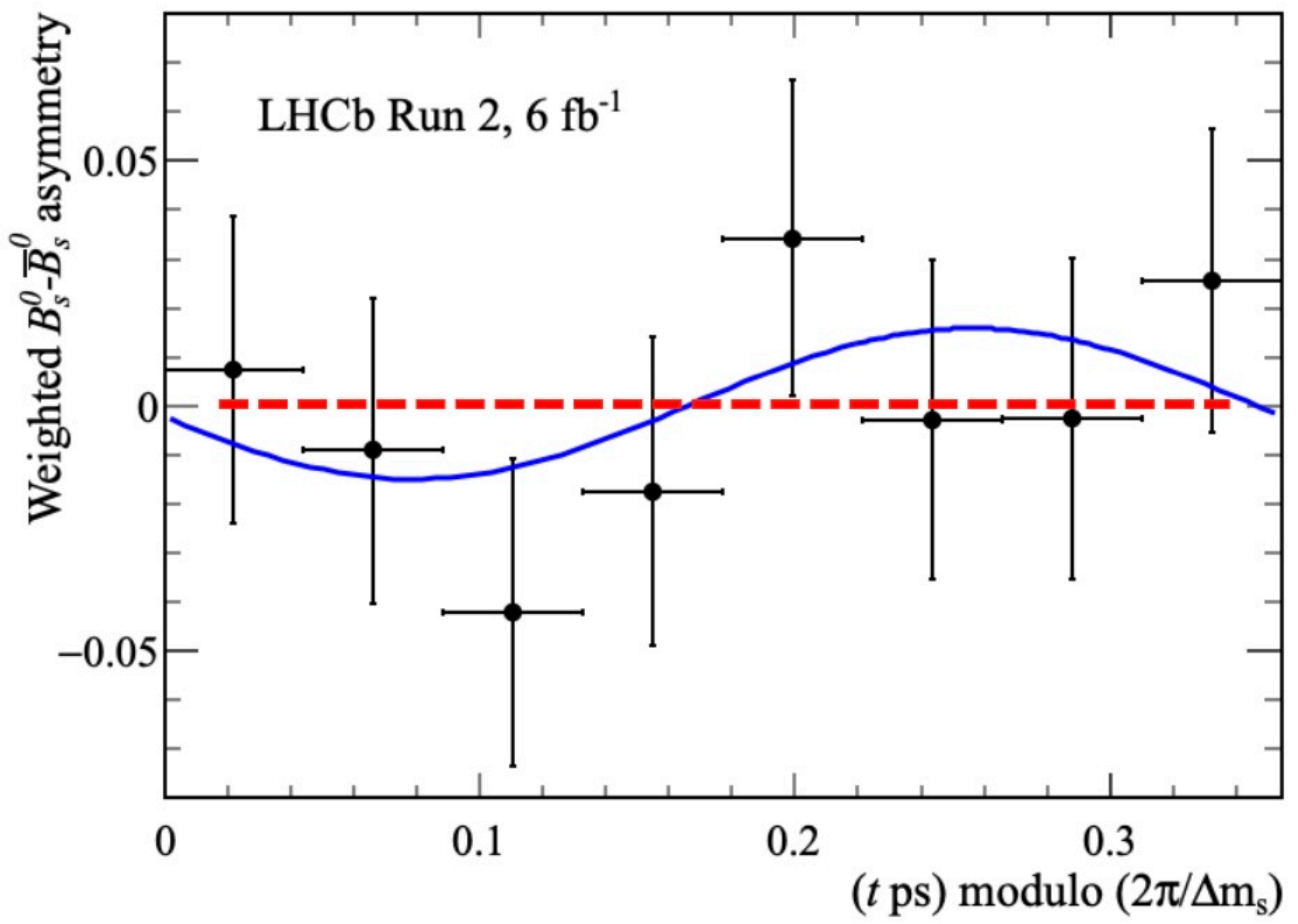


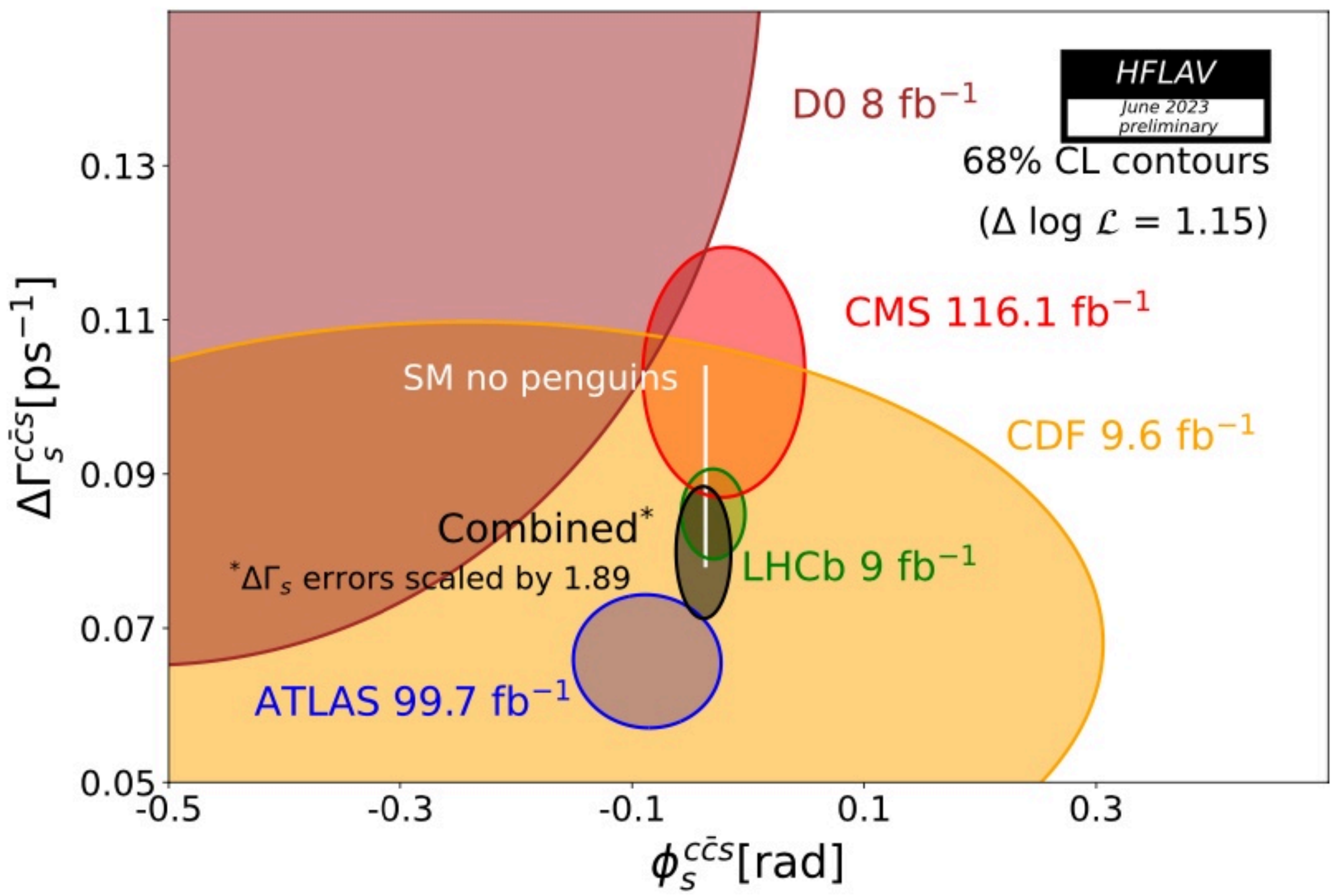
ϕ_s

- The B_s^0 mixing phase is very small in the SM and determined with extreme precision by UT restrictions.
  - ➡ Newest result from LHCb, Run 2 legacy. Uses $B_s^0 \to J/\Psi\phi$, to provide results:
    - Compatible with SM, ϕ_s 1.7σ away from 0 (→ no CPV in interference)
    - |λ| consistent with 1 (→ no direct CPV)

[arXiv:2308.01468]

$$\phi_s = (-0.039 \pm 0.022 \pm 0.006)\ \text{rad}$$
$$\lambda = 1.001 \pm 0.011 \pm 0.005$$
$$\Gamma_s - \Gamma_d = 0.0056^{+0.0013}_{-0.0015}\ \text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024\ \text{ps}^{-1}$$





new preliminary HFLAV combination:

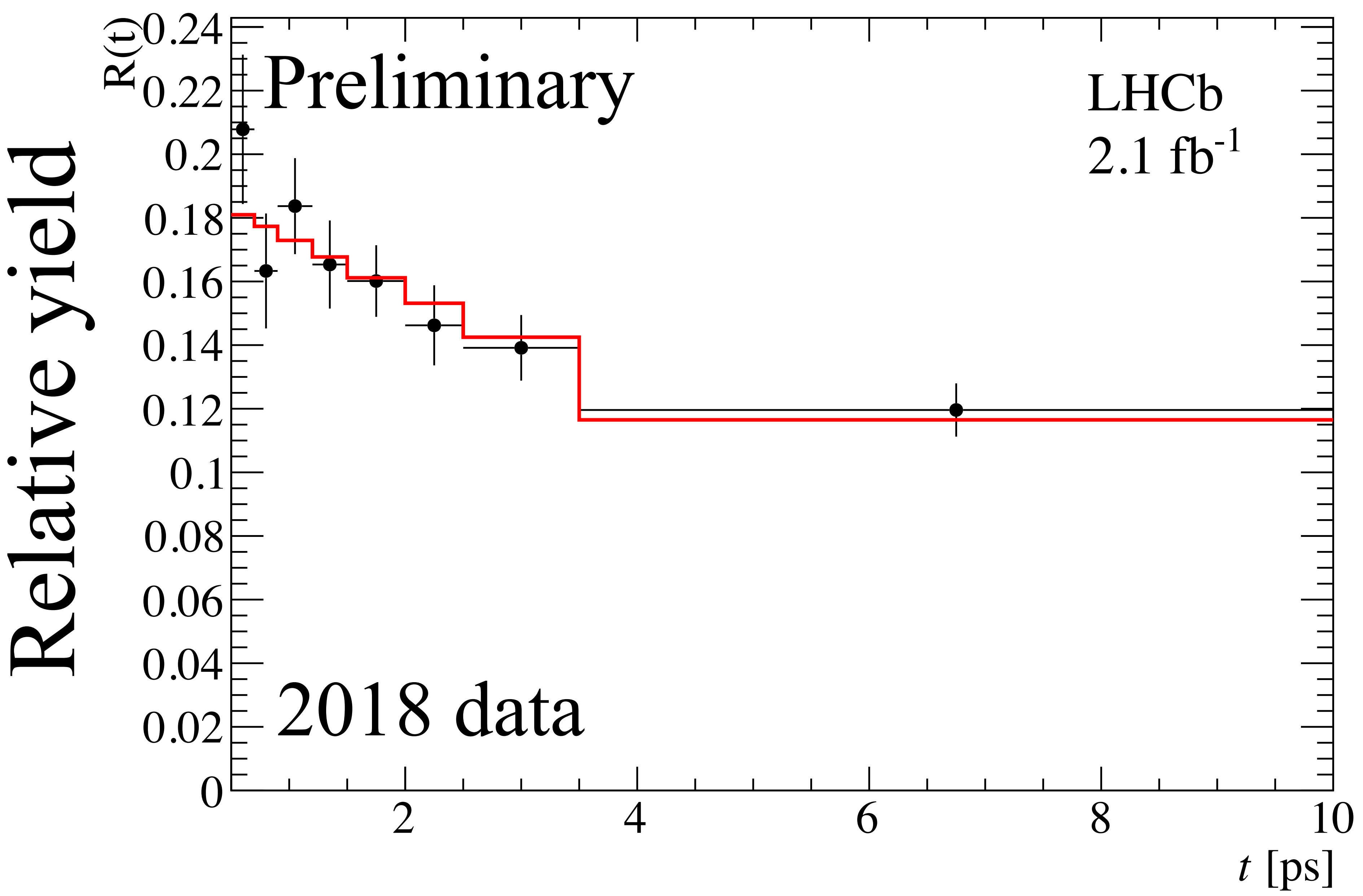
$$\phi_s(2021) = (-0.049 \pm 0.019)\ \text{rad}$$
$$\phi_s(2023) = (-0.050 \pm 0.016)\ \text{rad}$$

CMS [arXiv:2007.02434] CDF [arXiv:1208.2967]
ATLAS [arXiv:2001.07115] D0 [arXiv:1109.3166]

Yet another $\Delta\Gamma_s$ measurement

- Effective lifetime measurements good to probe $\Delta\Gamma_s, \Gamma_s$, but with less precision than $B_s^0 \to J/\Psi\phi$.
  - New LHCb analysis through $B_s^0 \to J/\Psi\eta'$ (CP even) and $B_s^0 \to J/\Psi\pi\pi$ (CP odd) in the $f_0(980)$ region [LHCb-PAPER-2023-025]
  - Relative yield as a function of decay time gives access to $\Delta\Gamma_s$

$$\Delta\Gamma_s = (0.087 \pm 0.012 \pm 0.009)\ \mathrm{ps}^{-1}$$

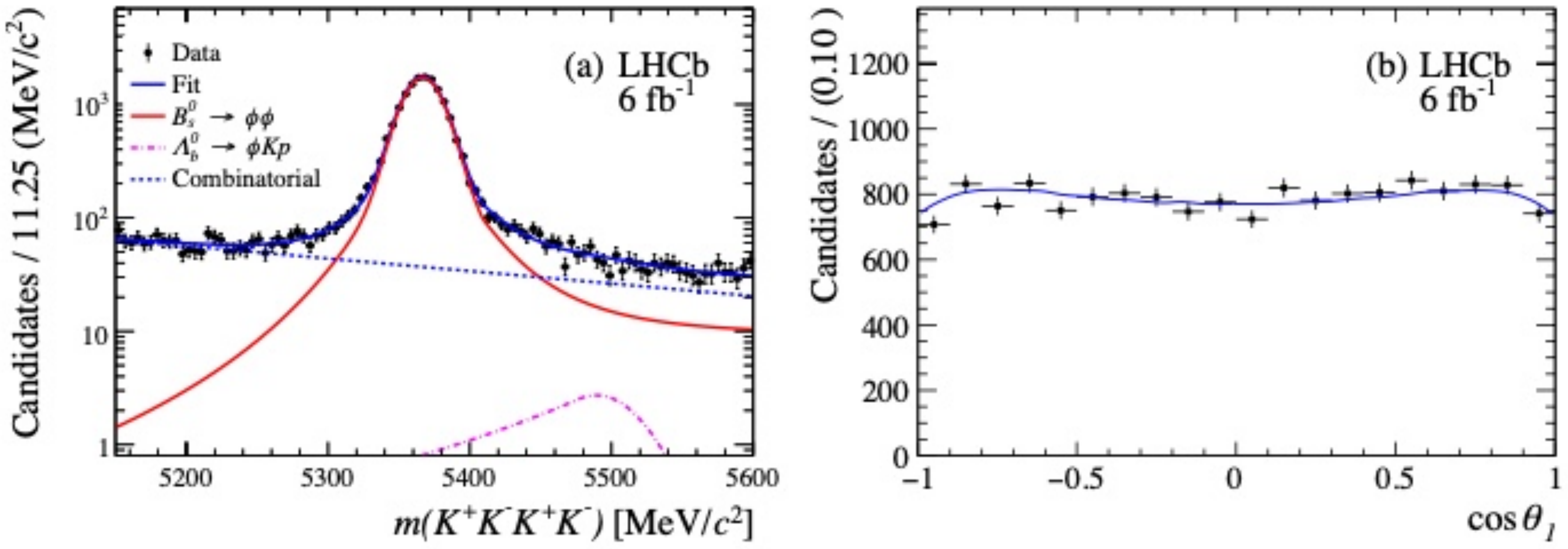


  - Good agreement with LHCb determination from ϕ_s measurements and HFlav averages!

Charmless decays (I)

- b→s(d) penguin transitions provide significant contributions to charmless B-hadron decays
  - Measure observables where BSM effects may affect known SM processes. Interpretation in terms of CKM parameters not trivial!
- Excellent example provided by $B_s^0 \to \phi\phi$, with tiny CPV in SM ($\phi_s^{s\bar{s}s} \sim 0$)
  - Tagged time dependent angular analysis with LHCb Run 2 dataset

[arXiv:2304.06198]



LHCb full dataset combination

$$\phi_s^{s\bar{s}s} = 0.074 \pm 0.069$$

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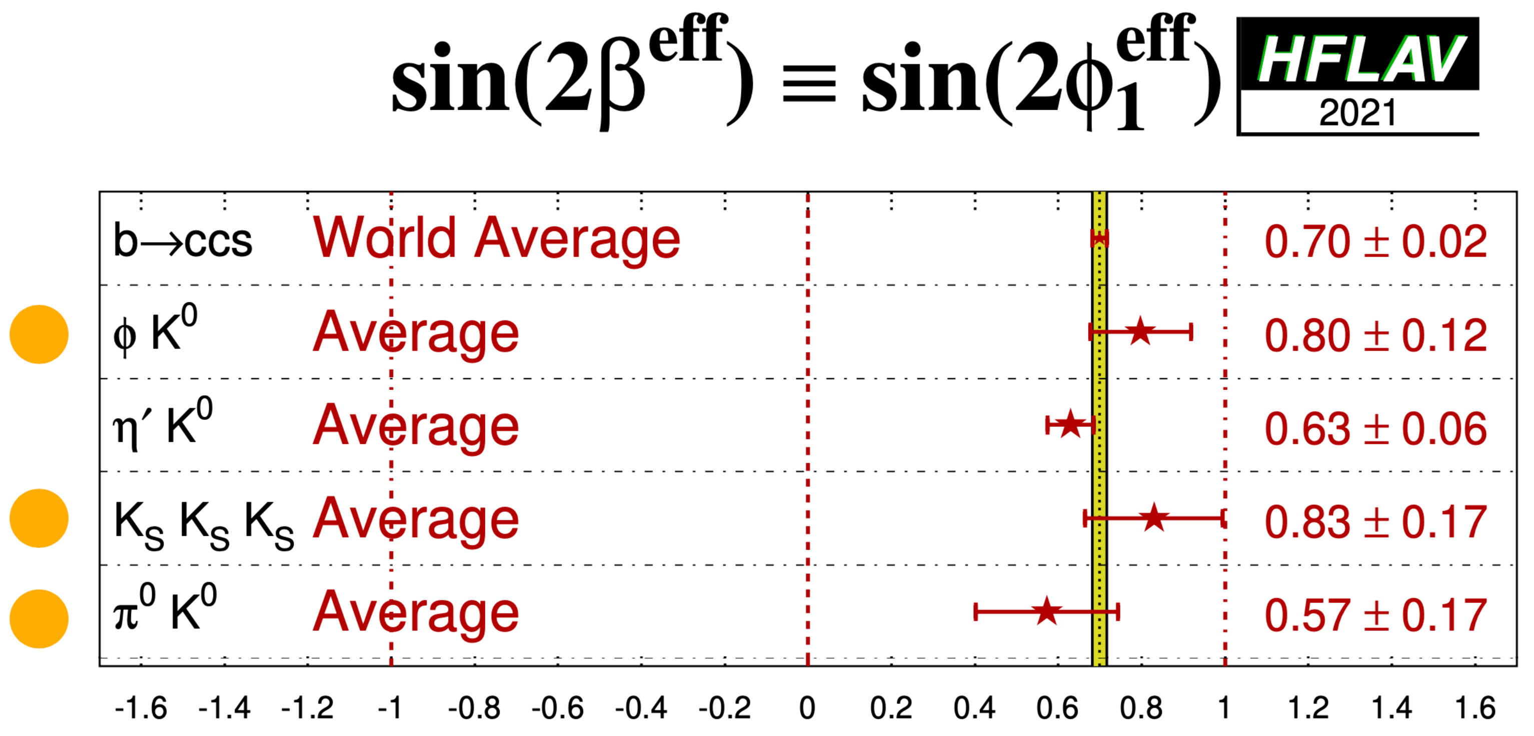
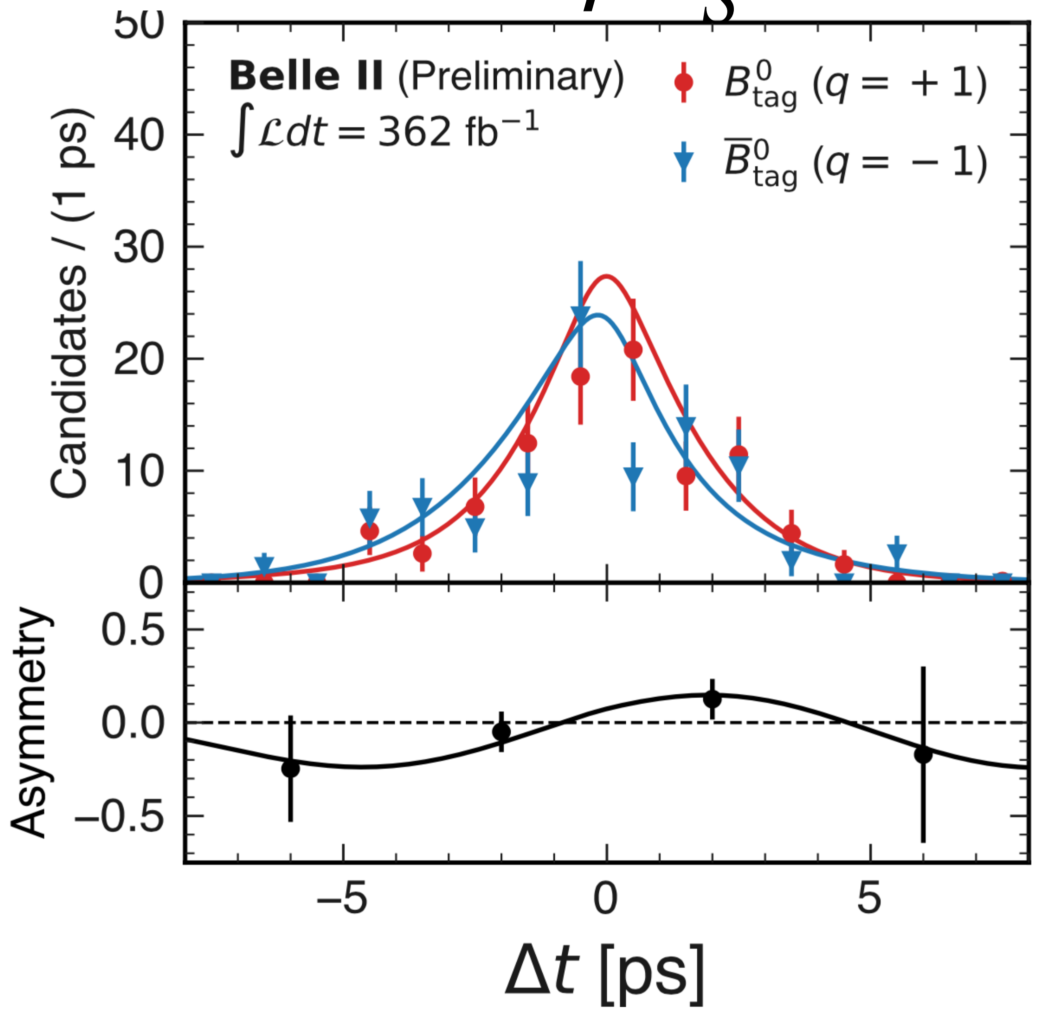
Charmless decays (II)

- Recent Belle II measurements of $\sin(2\beta_{eff})$
  - Already competitive with world best average in some cases!



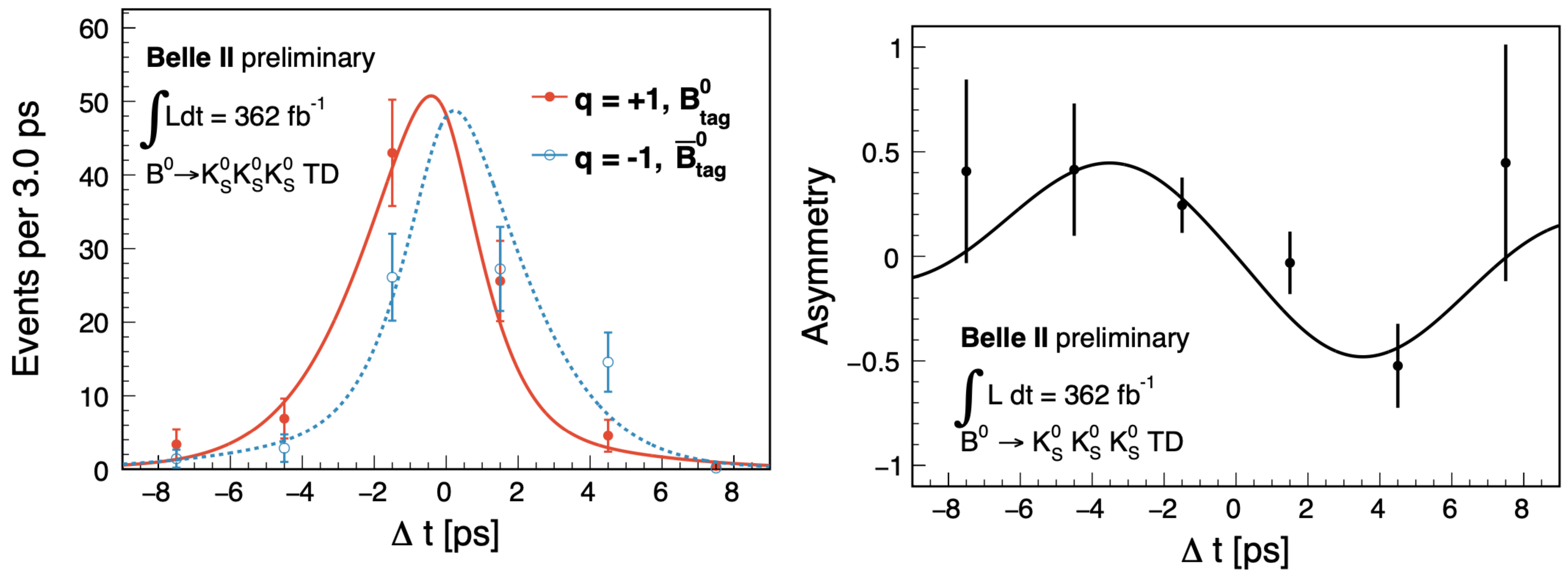
$B^0 \to \phi K_S^0$



$$A_{CP} = 0.31 \pm 0.20^{+0.05}_{-0.06}$$
$$S_{CP} = 0.54 \pm 0.26^{+0.06}_{-0.08}$$

[arXiv:2307.02802]

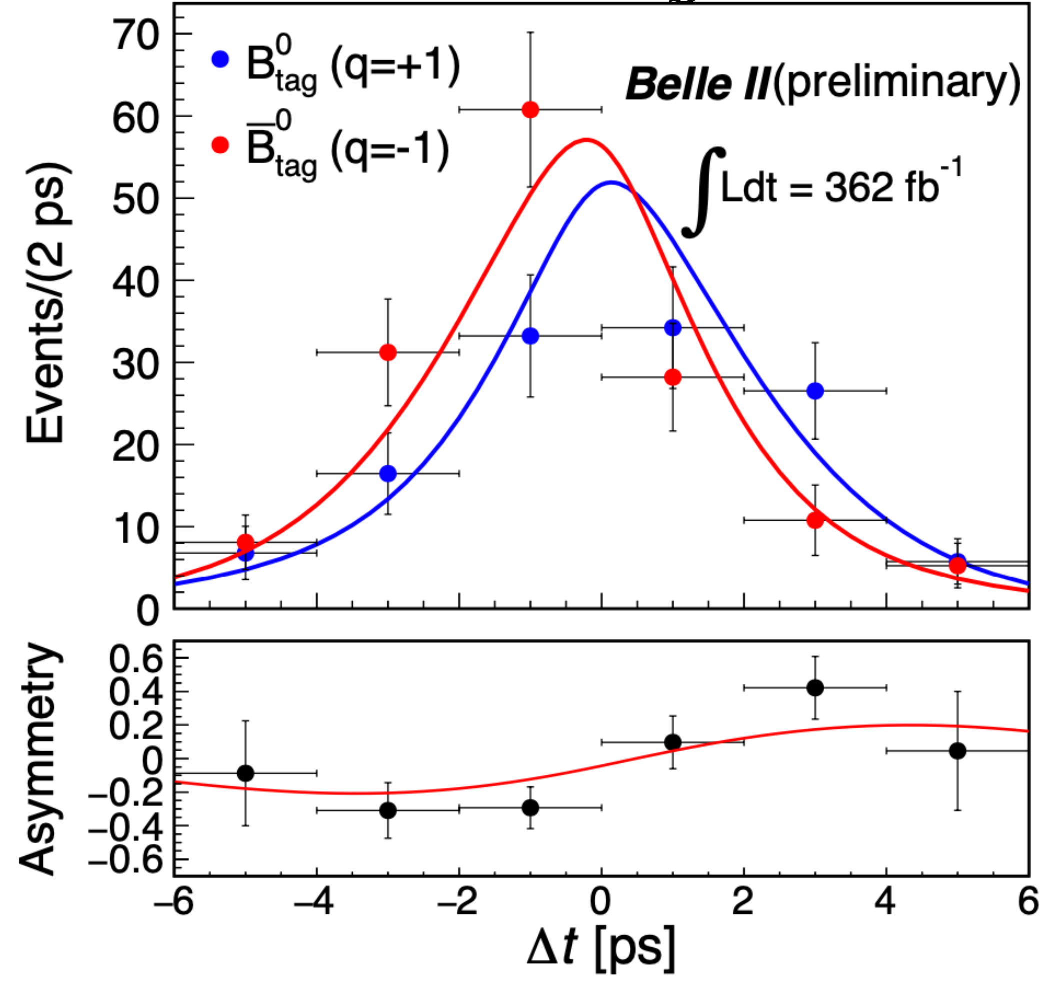
$B^0 \to K_S^0 K_S^0 K_S^0$



$$A_{CP} = 0.07^{+0.15}_{-0.20} \pm 0.02$$
$$S_{CP} = -1.37^{+0.35}_{-0.45} \pm 0.03$$

Proceedings @[arXiv:2305.09153]

$B^0 \to K_S^0 \pi^0$



$$A_{CP} = 0.04 \pm 0.15 \pm 0.05$$
$$S_{CP} = 0.75^{+0.20}_{-0.23} \pm 0.04$$

[arXiv:2305.07555]

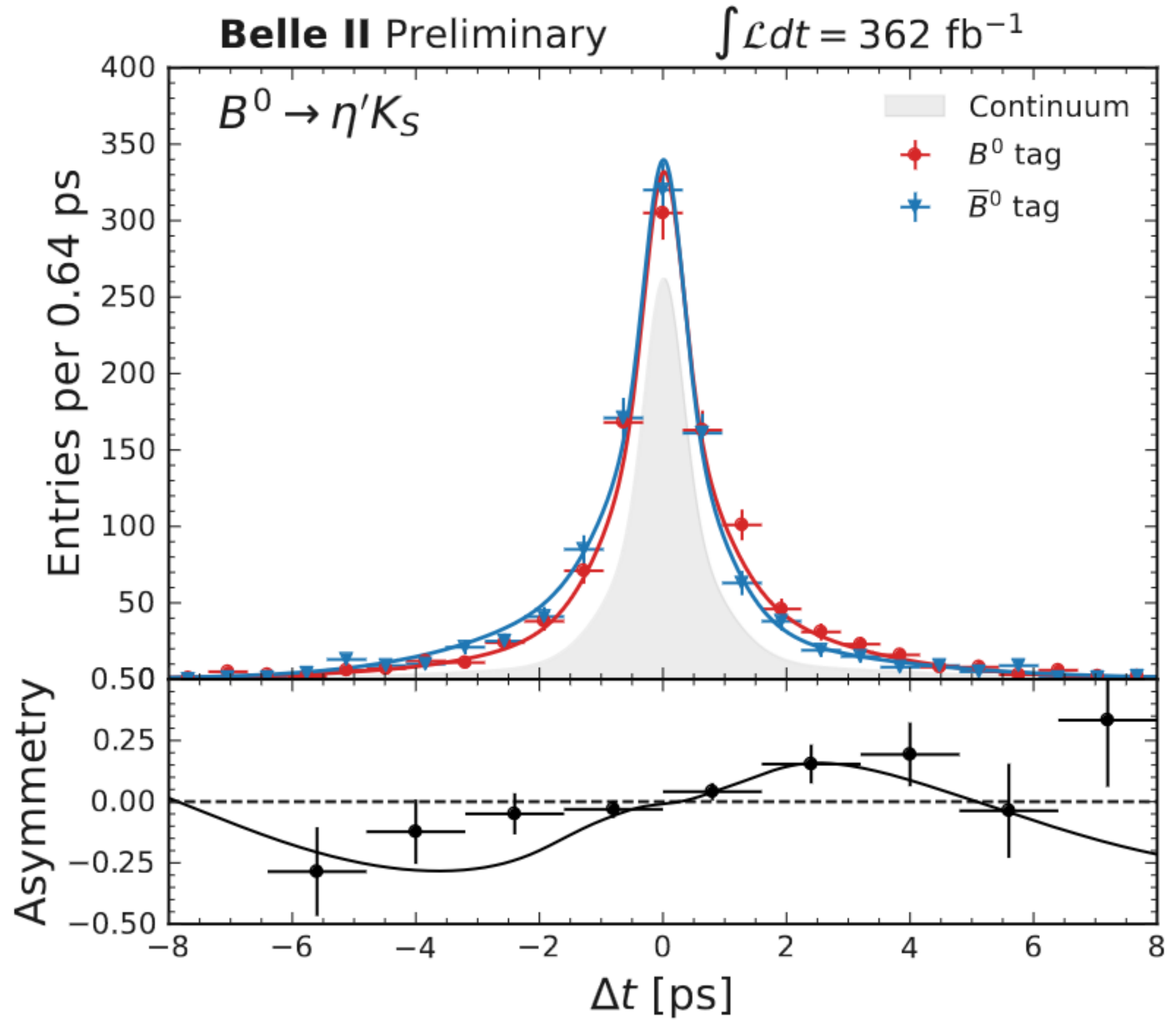
Charmless decays (III)

✦ Other relevant examples from Belle II [EPS talk]

$B^0 \to \eta' K_S^0$

➡ Loop suppressed $b \to \bar{s}qq$ transition, provides access to S_{CP} [very close to sin(2β)]

$$S_{CP} = 0.67 \pm 0.10 \pm 0.04$$

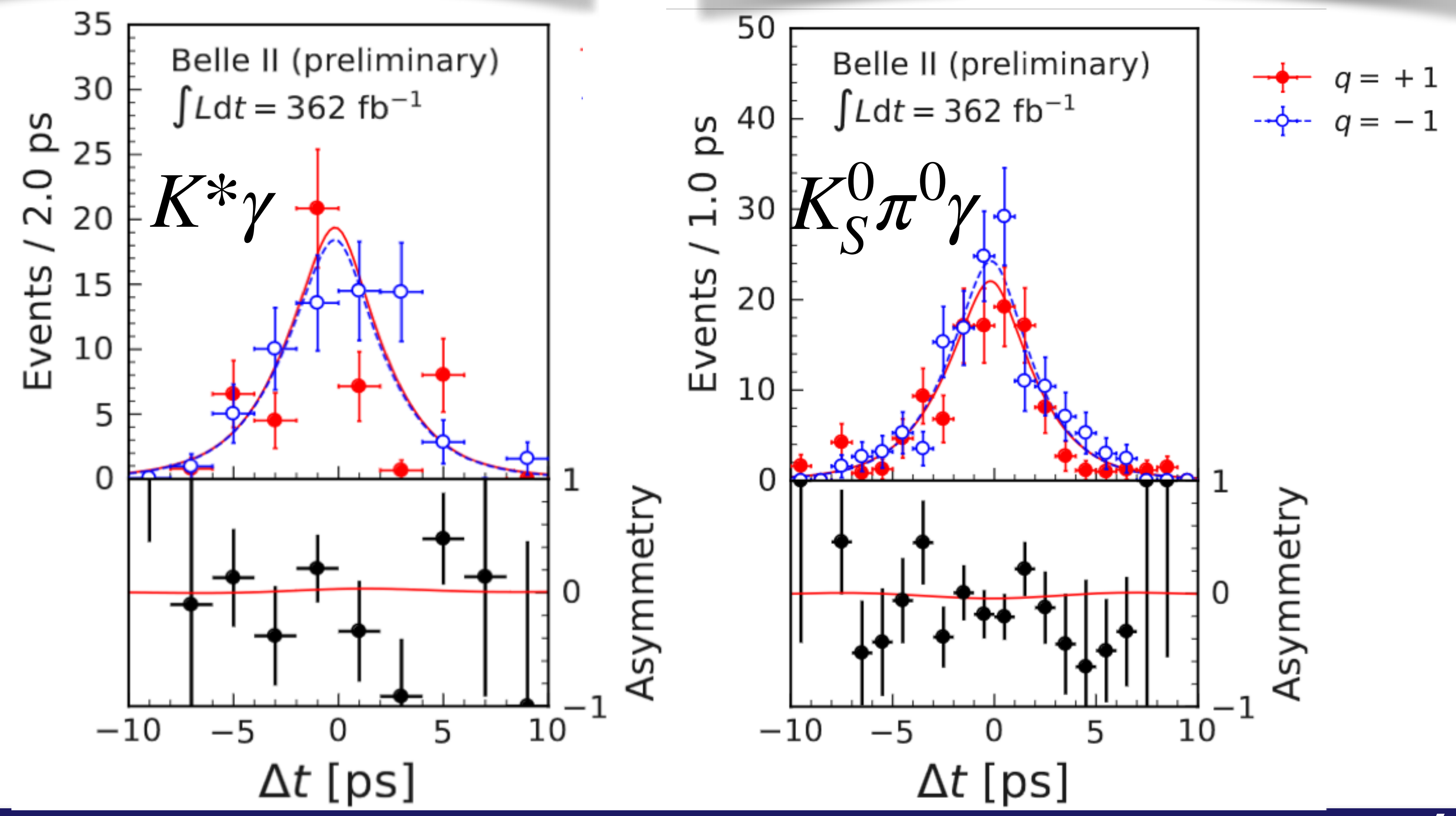


$B^0 \to K^*\gamma$ and $B^0 \to K_S^0\pi^0\gamma$

➡ Challenge → no access to secondary vertex! World best results achieved.

$$S_{CP}(K^*\gamma) = 0.00^{+0.27+0.03}_{-0.26-0.04}$$

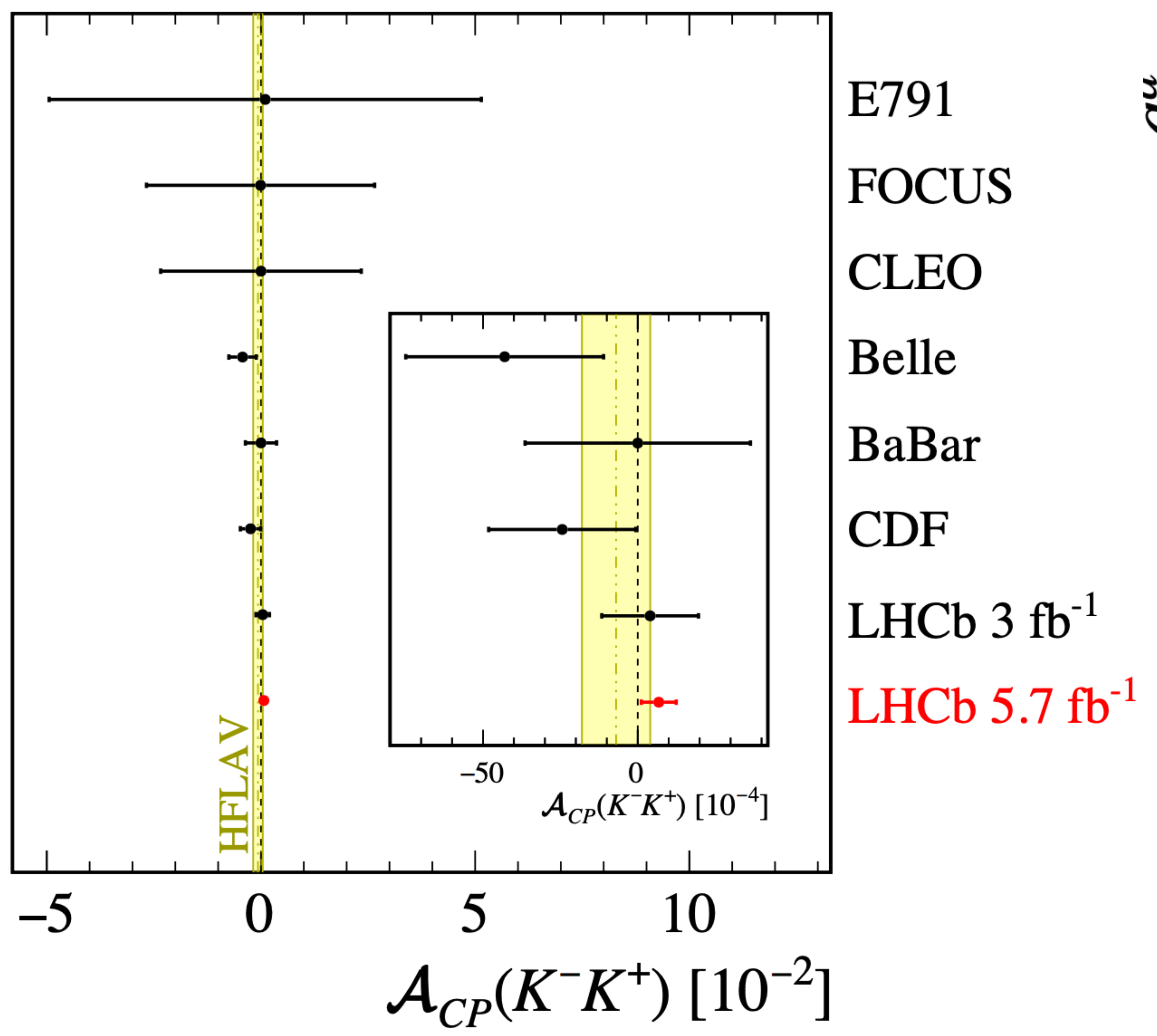
$$S_{CP}(K_S^0\pi^0\gamma) = 0.04^{+0.45}_{-0.44} \pm 0.10$$

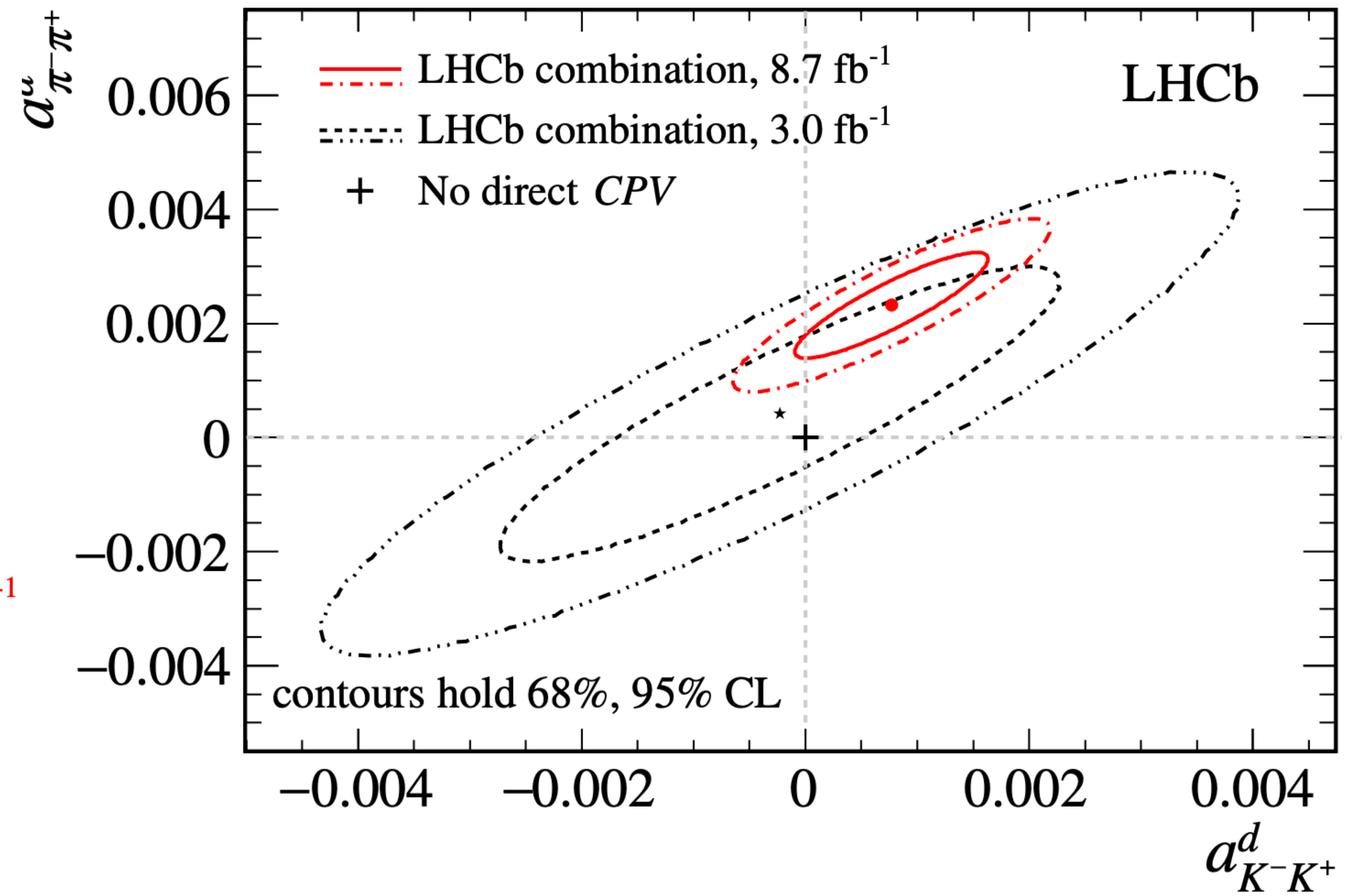


CP violation in charm

- Charm: excellent to study CPV in up-type quark decays
  - Expected small CPV effects: $A_{CP} \sim 10^{-4} - 10^{-3}$, although long distance contributions hard for theory predictions
  - Very large sample of charm data from **LHCb** led to the first discovery of CPV, more measurements are required for full picture: e.g., is CPV in charm QCD effects or New Physics?

[arXiv:2209.03179]





$$a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4}$$
$$a^d_{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$$

Evidence of direct CPV in $D^0 \to \pi\pi$ at 3.8σ!

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Introduction

CKM metrology

Rare and SL decays

Spectroscopy

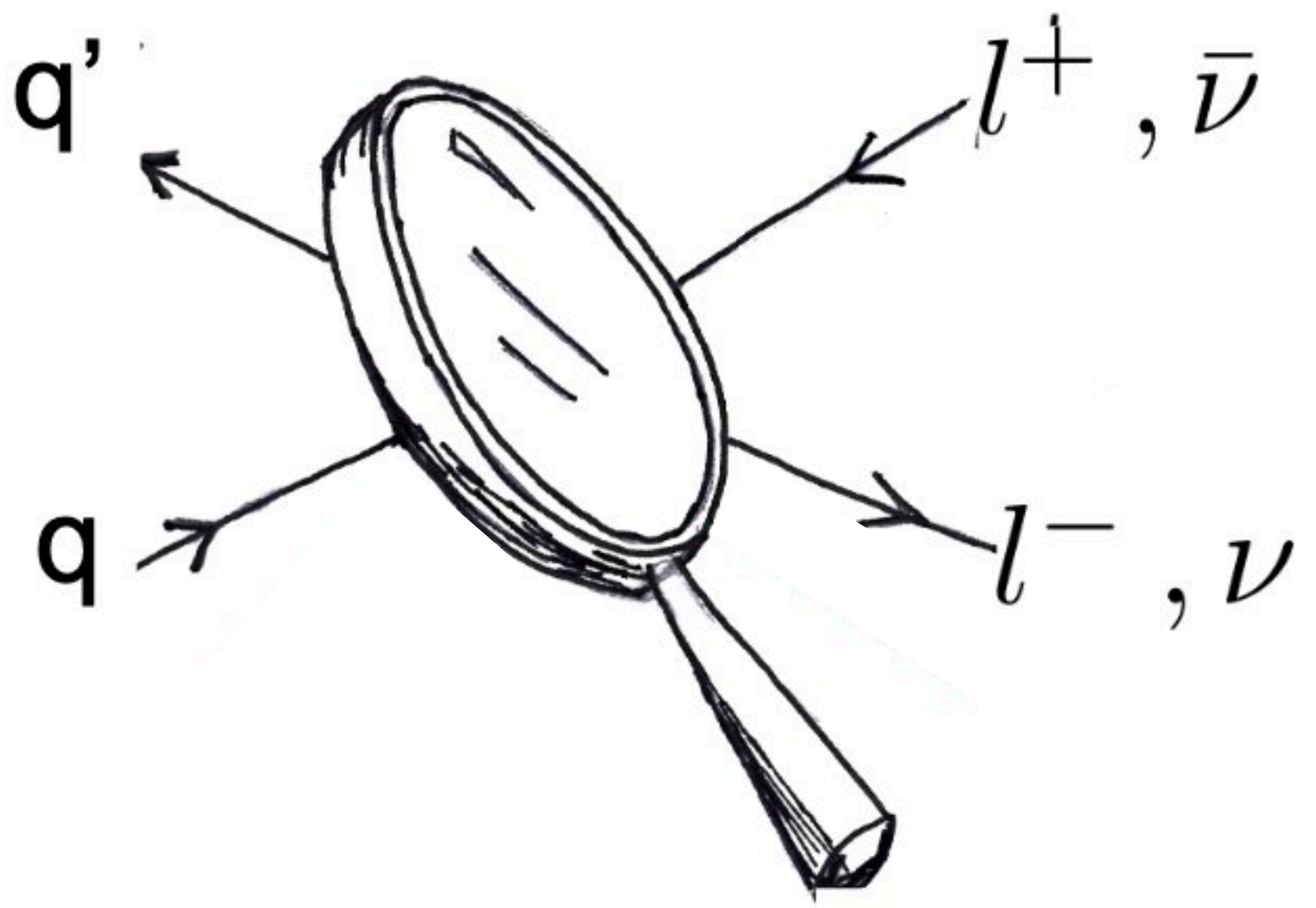
Future

Conclusions

Overview

- As we have seen, loops can provide unique insights to find new physics. Different avenues are possible to exploit this property (beyond CKM metrology):
  - Define accessible observables with high BSM sensitivity, and not too sensitive to QCD effects. In particular ***FCNC*** processes!
  - Search for processes that the SM's (accidental) symmetries prevent. Examples of very clean new physics probes are Lepton Universality Violation (***LUV***) or Lepton Flavor Violation (***LFV***).

$$\mathcal{O}_{exp} = \mathcal{O}_{SM}(1+\delta_{NP})$$



In both cases, experimental precision is key!

$B^0_{(s)} \to \mu\mu$

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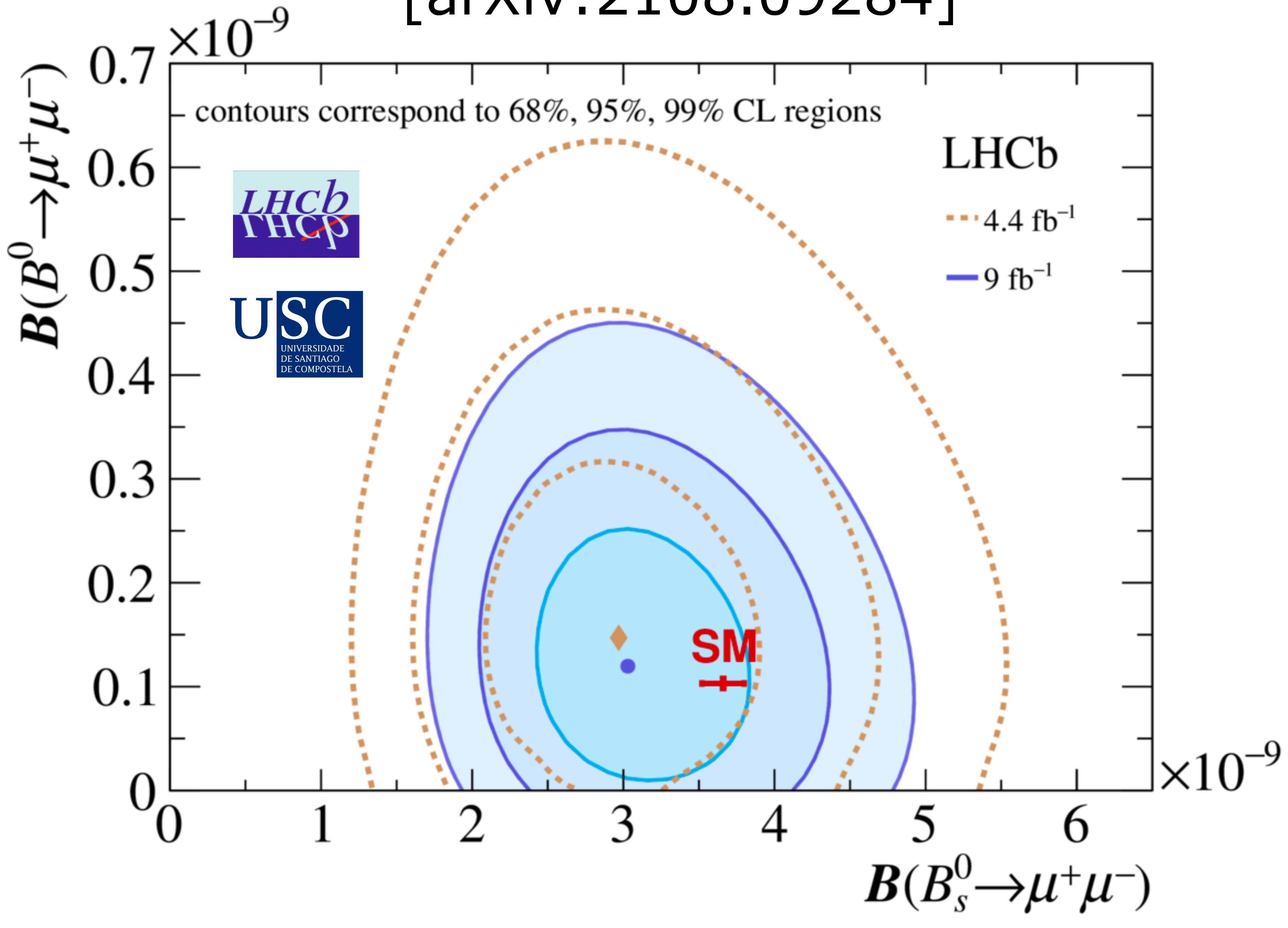
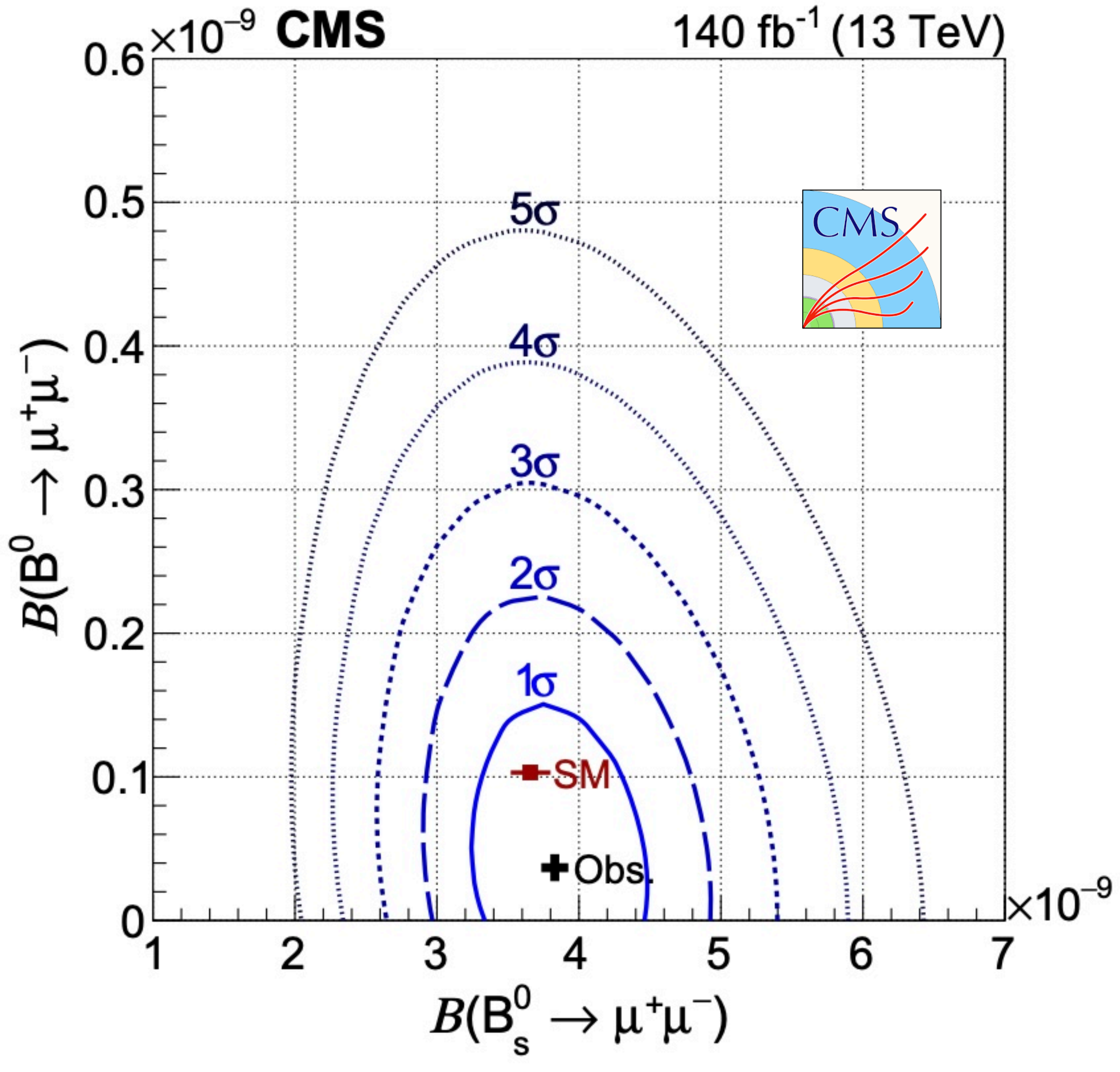
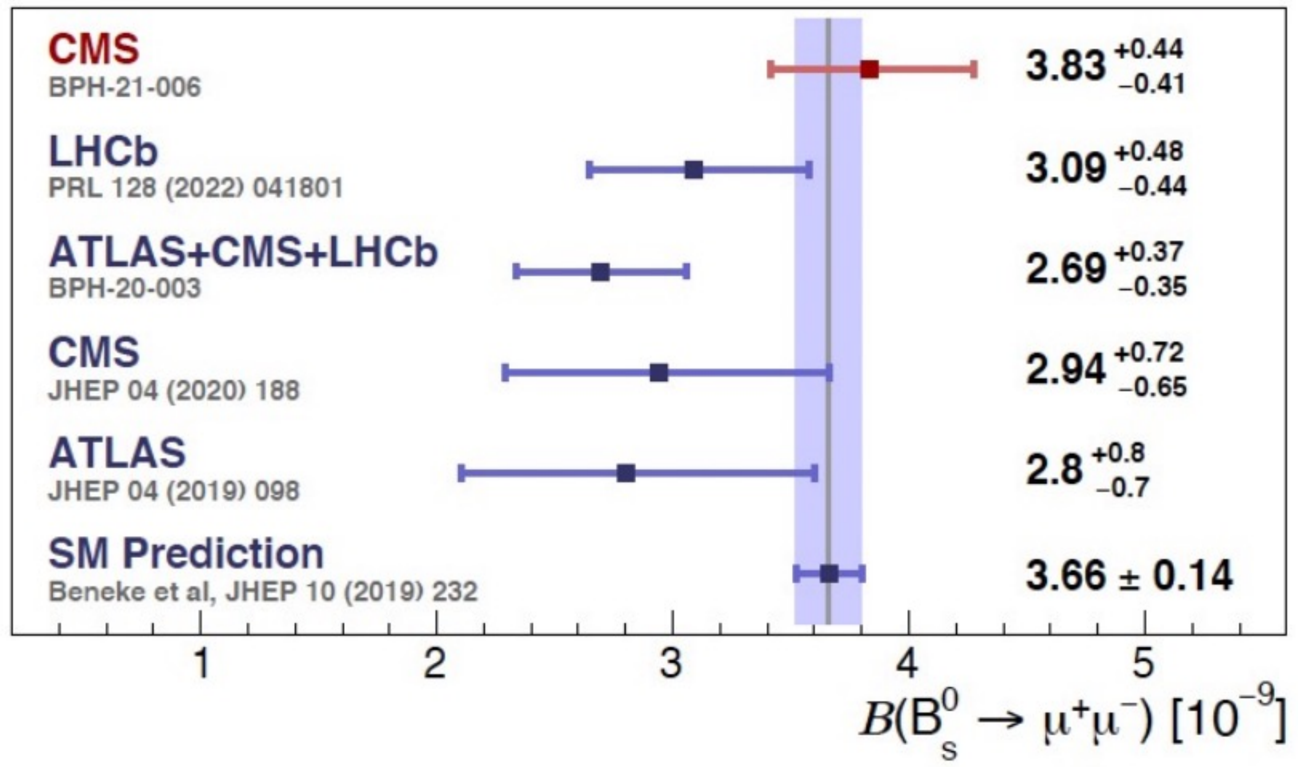
- Very rare FCNC decays, helicity suppressed.
  - Accurate predictions in SM, very sensitive to BSM effects. Interesting to measure both BR and effective lifetime!
  - B_s discovered, close to evidence for B^0. BR measurements dominated by LHCb and CMS

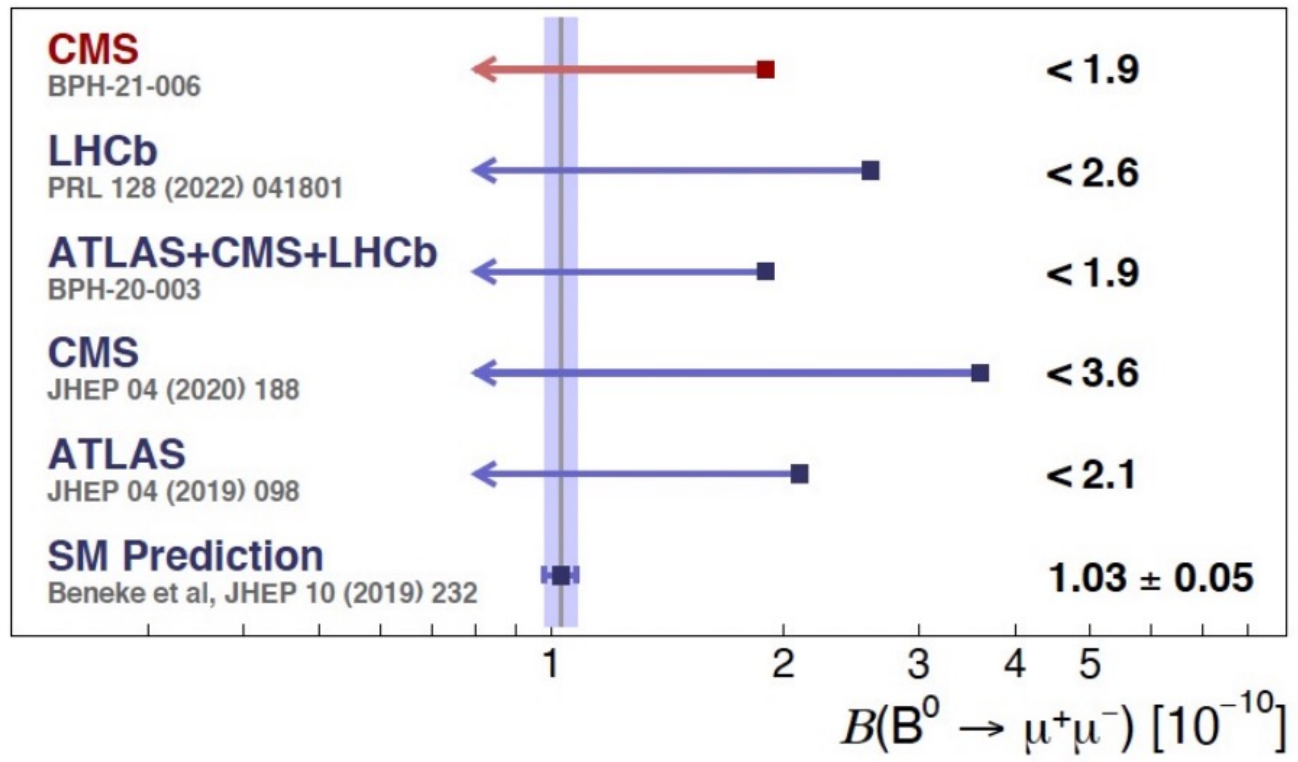
[arXiv:2108.09284]



[arXiv:2212.10311]







$B^0_{(s)} \to \mu\mu$ effective lifetime

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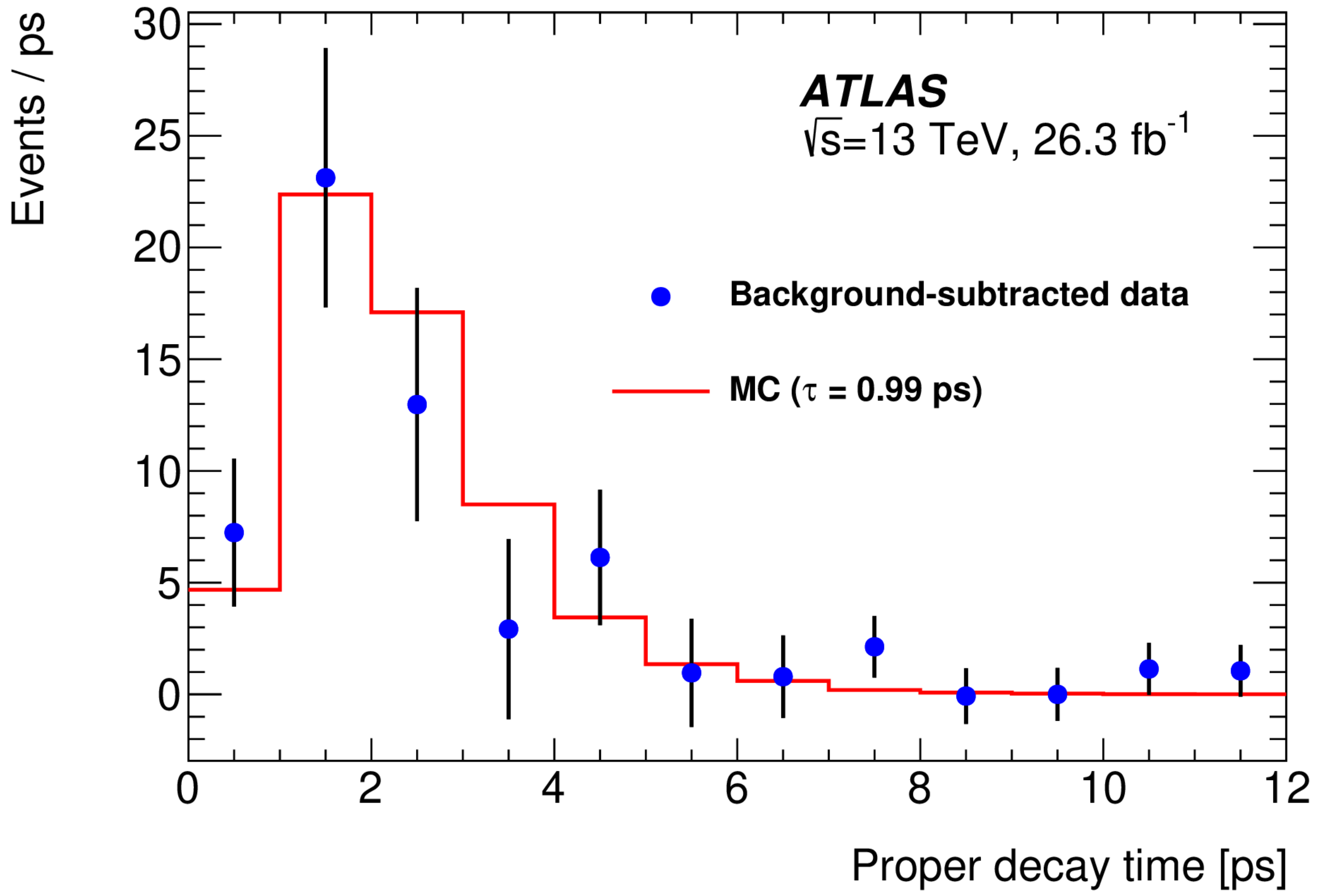
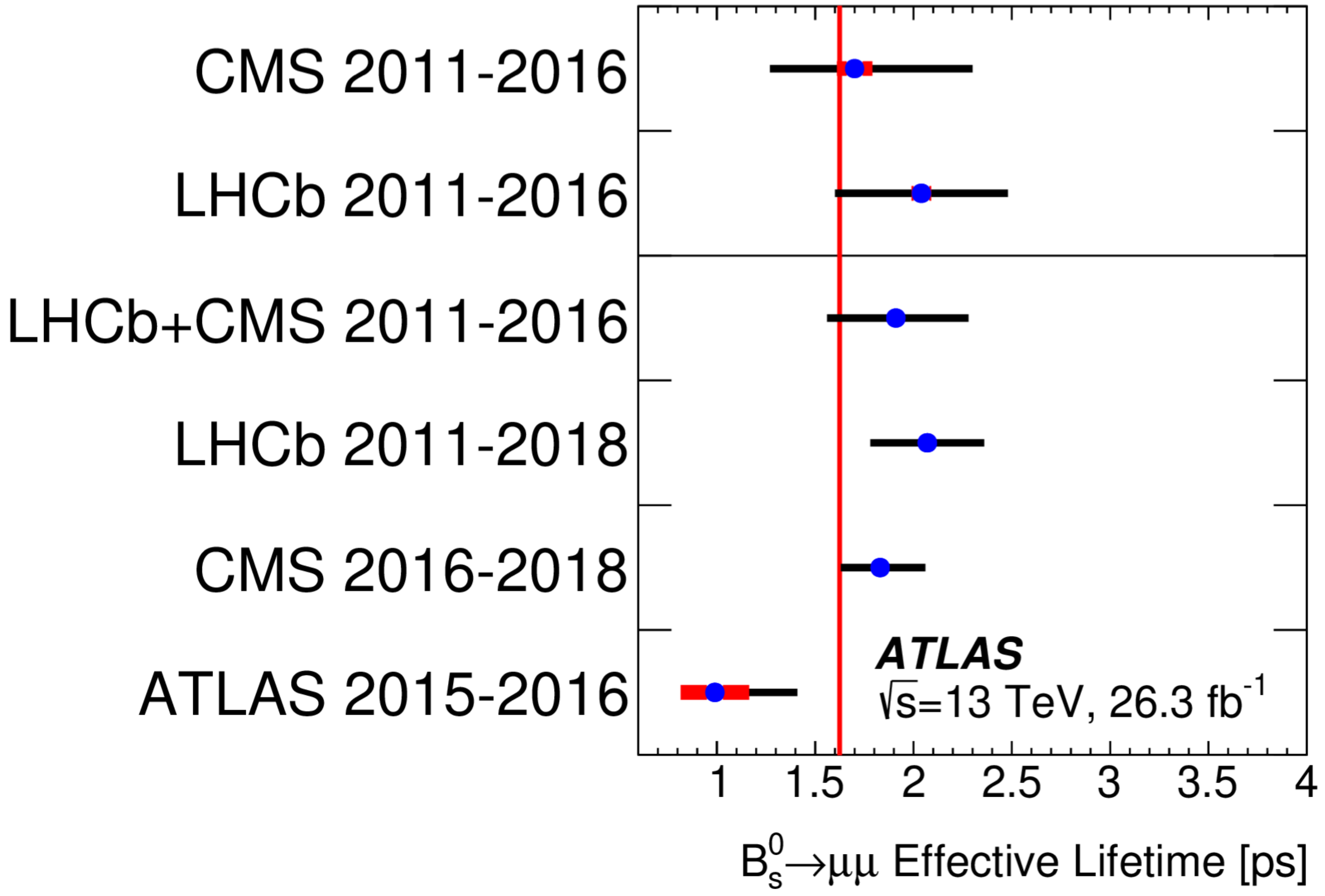
- Measurement of effective lifetime, sensitive to BSM effects, potentially orthogonal to BR
  - ➡ Relevant contributions from three LHC experiments!
  - ➡ Measurement, typically from the study of proper decay-time distribution of background subtracted candidates. Newest result, from ATLAS





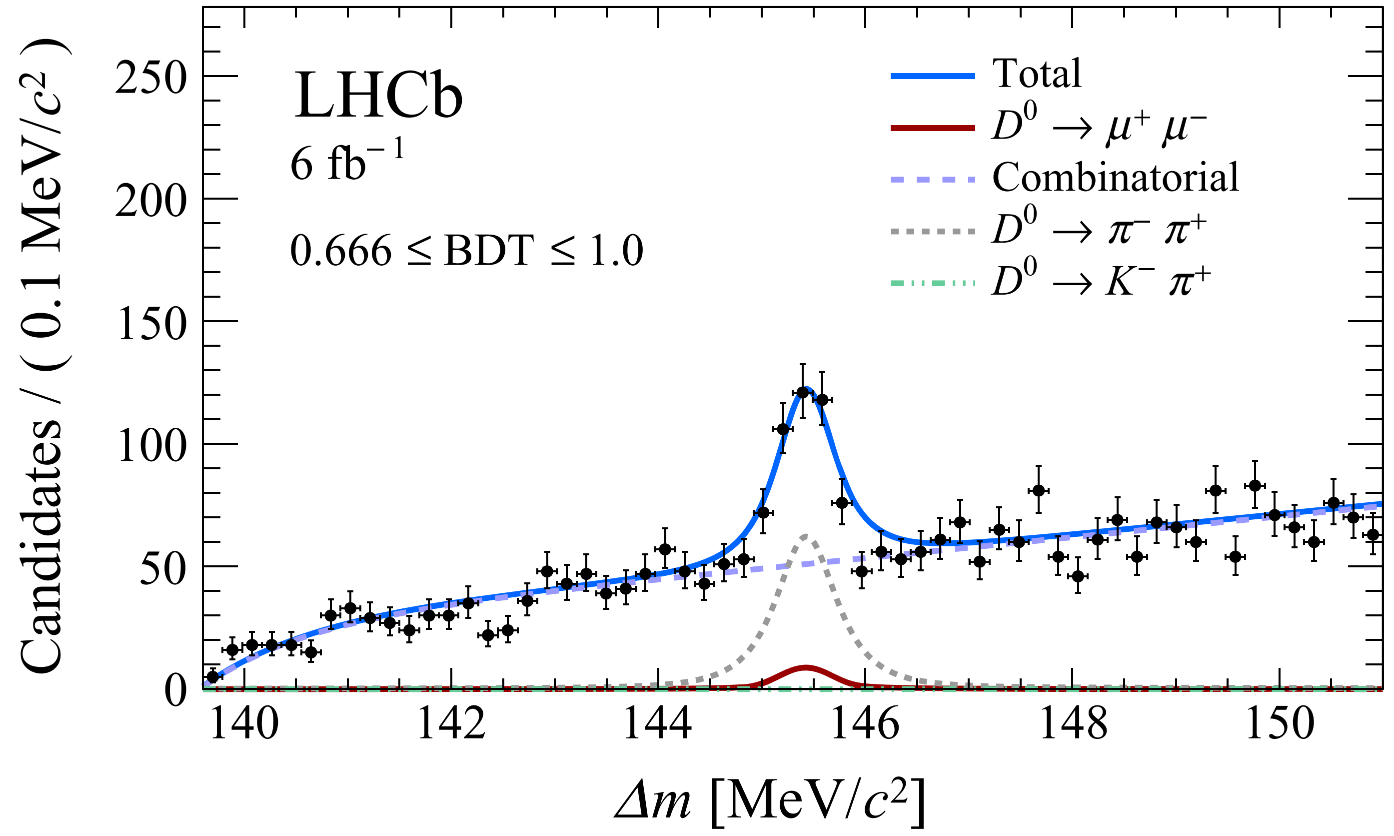
ATLAS EXPERIMENT [arXiv:2308.01171]

CMS [arXiv:2212.10311]

LHCb [arXiv:2108.09284]

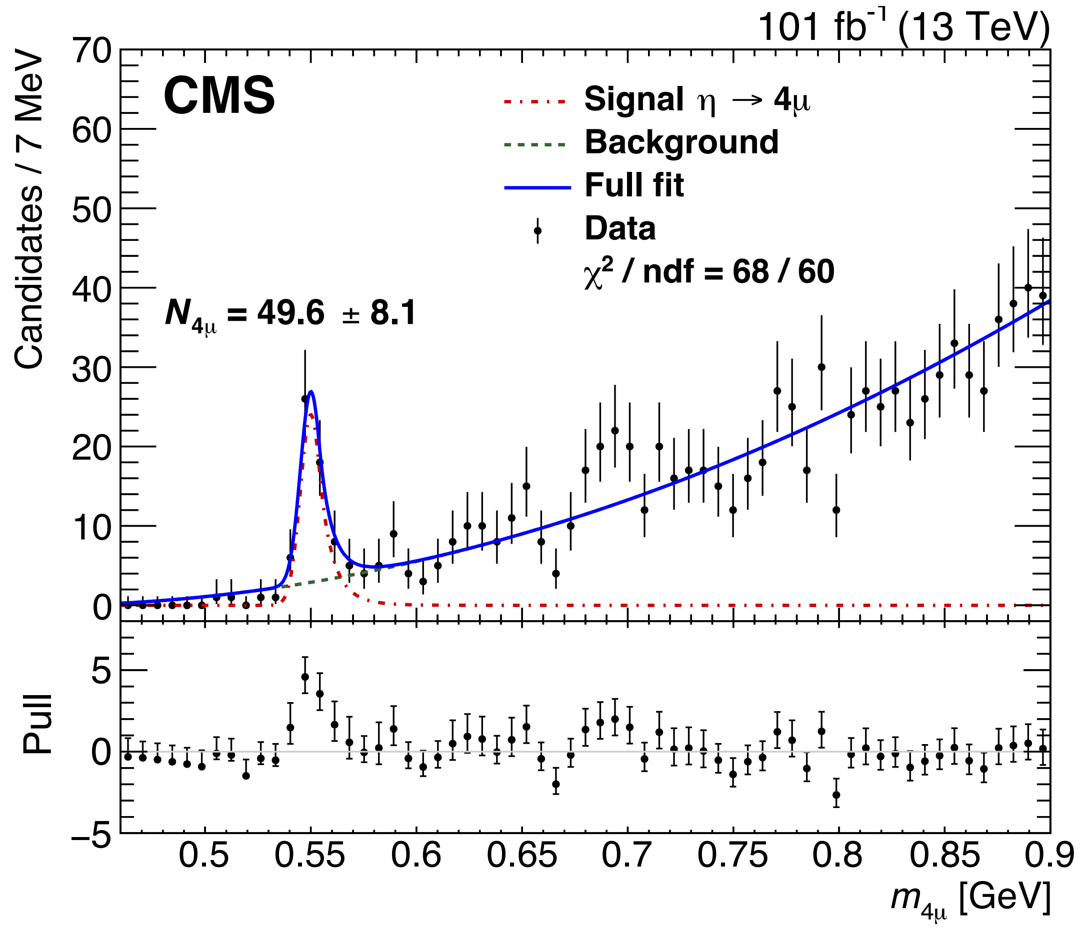
USC

More recent examples with muons…



[arXiv:2212.11203]

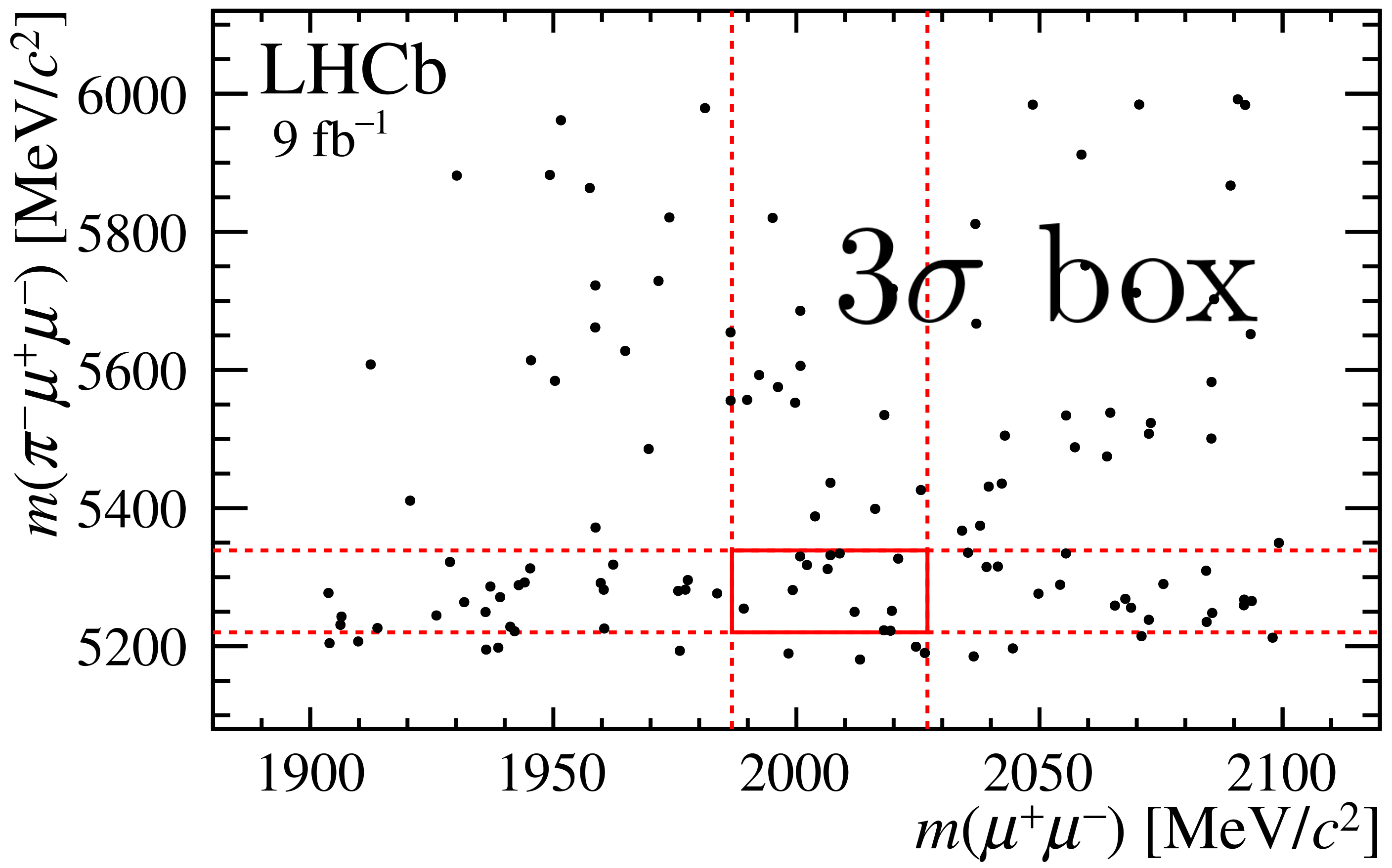
$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1(3.5) \times 10^{-9} \text{ at } 90(95)\%\text{C.L.}$$



[arXiv:2305.04904]

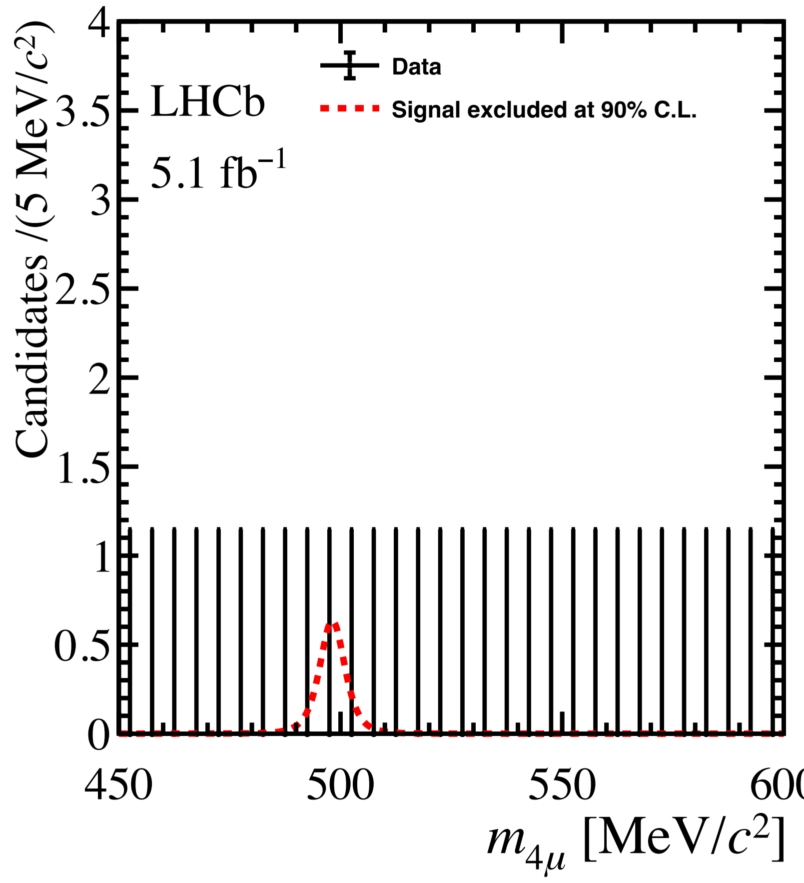
First observation! BR in agreement with SM

$$\mathcal{B}(\eta \to 4\mu) = (5.0 \pm 0.8\,(\text{stat}) \pm 0.7\,(\text{syst}) \pm 0.7\,(\mathcal{B}_{2\mu})) \times 10^{-9}$$



[arXiv:2304.01981]

$$\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6\,(3.4) \times 10^{-8} \text{ at } 90\ (95)\%\ \text{CL}$$



[arXiv:2212.04977]

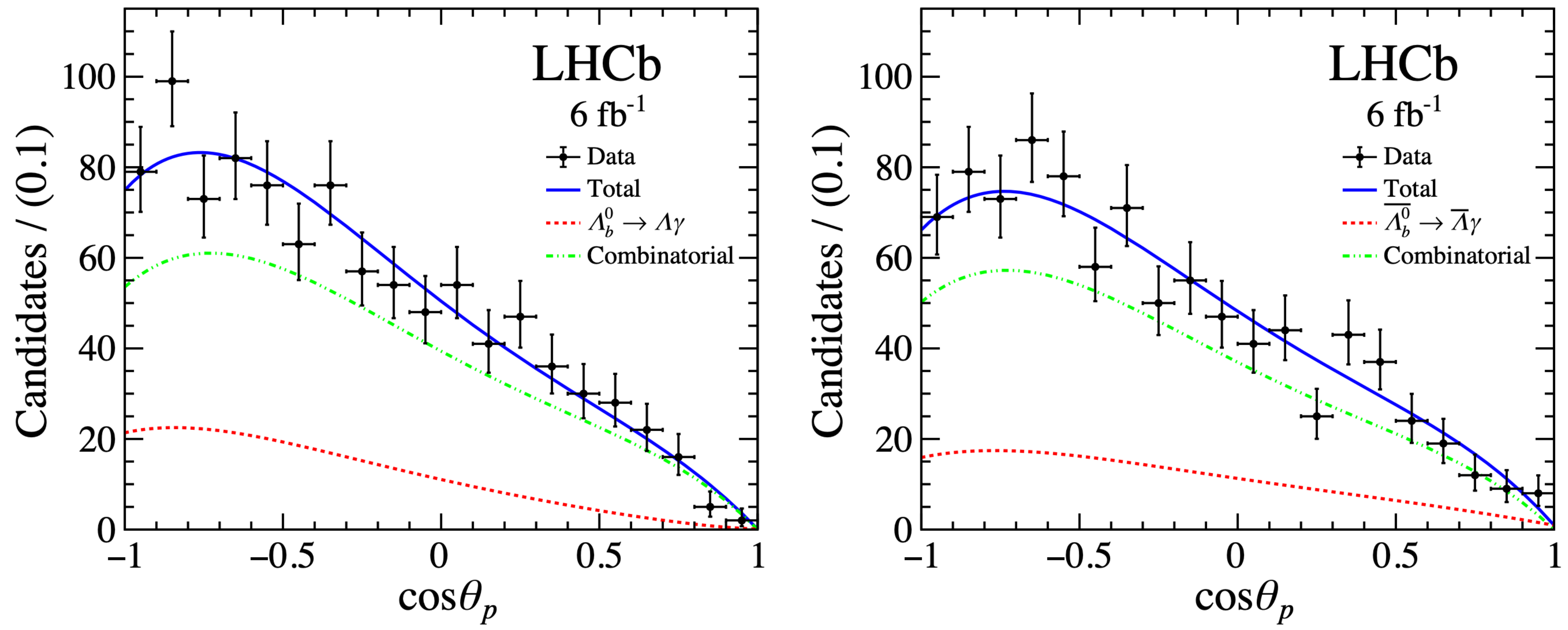
First LHC BR limit in the 10^{-12} region, also in same paper, first K^0_L search at the LHC

$$\mathcal{B}(K^0_S \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$$

Radiative decays

- b→sγ transition-governed decays allow for the investigation of a separate group of operators compared to leptonic decays
  - ➡ Synergy between Belle II (cleaner environment, inclusive measurements) and LHCb (huge statistics, access to b baryons). Most recent examples:

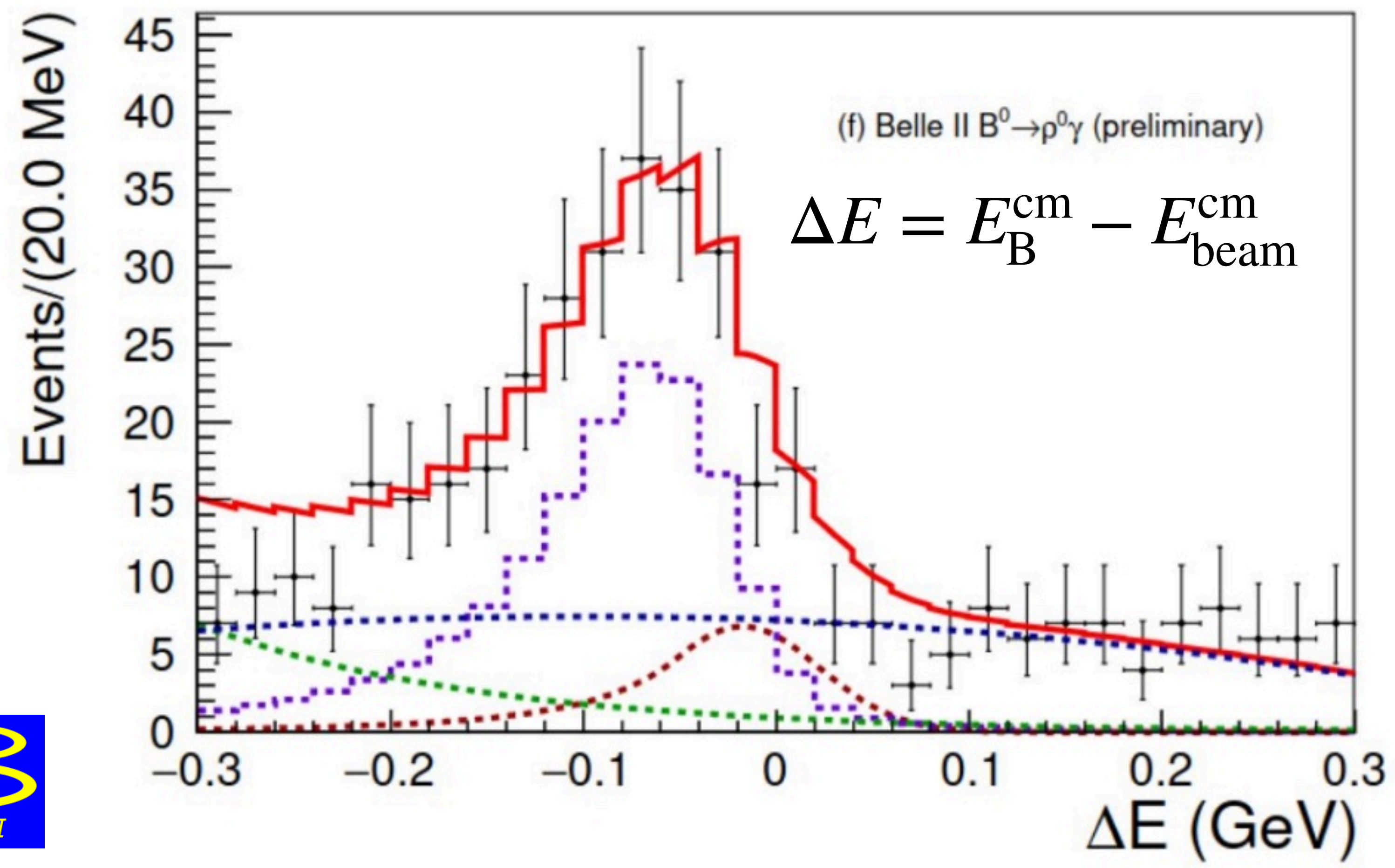
Photon polarisation in $\Lambda_b \to \Lambda\gamma$



[arXiv:2111.10194]

$$\alpha_\gamma = 0.82^{+0.17}_{-0.26}\ (\text{stat.})^{+0.04}_{-0.13}\ (\text{syst.})$$

World best measurement of B→ργ branching fraction (brand new)



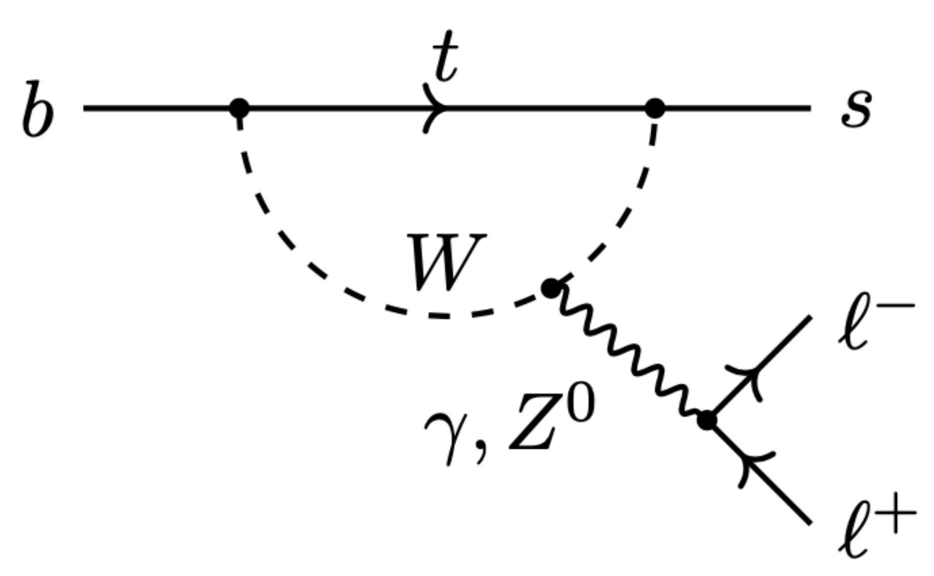
[CKM talk]

$$\mathcal{B}\left(B^+ \to \rho^+\gamma\right) = \left(12.9^{+2.0+1.3}_{-1.9-1.2}\right) \times 10^{-7}$$

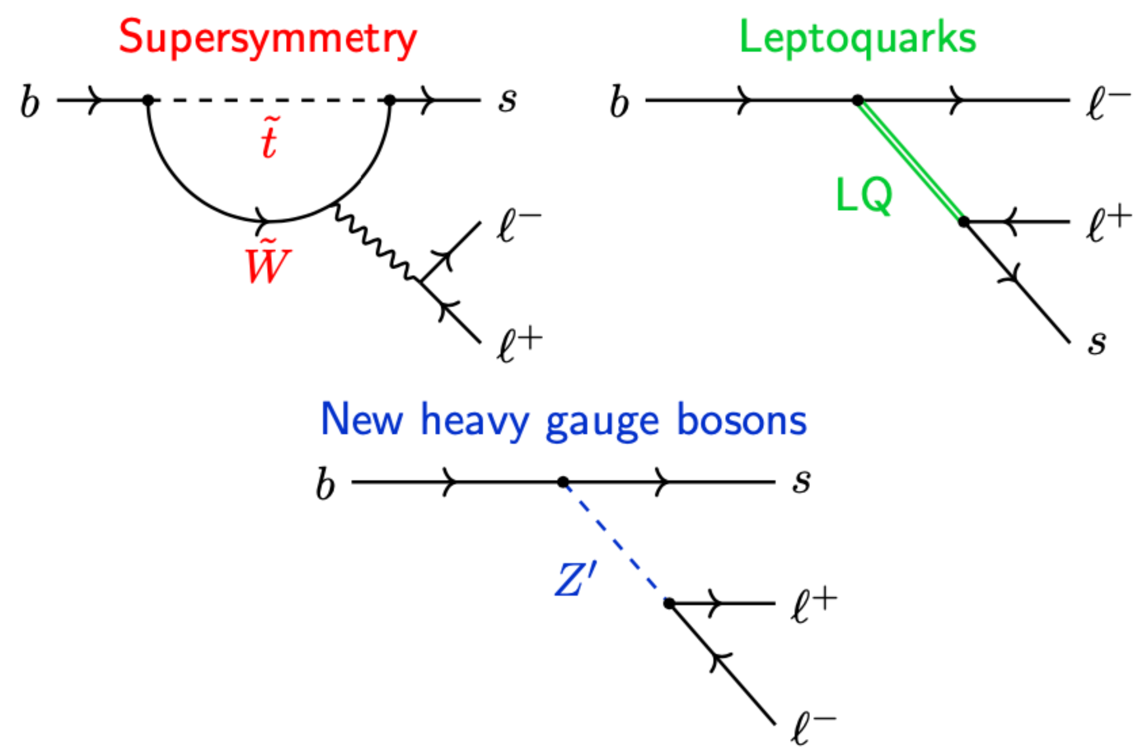
$b \to sl\bar{l}$ penguins

- Different levels of theoretical "cleanliness" across a wide range of observables, but persistent **set of departures** (*anomalies*) from SM expectations (1-3σ level).
  - ➡ Sensitive to several NP scenarios!

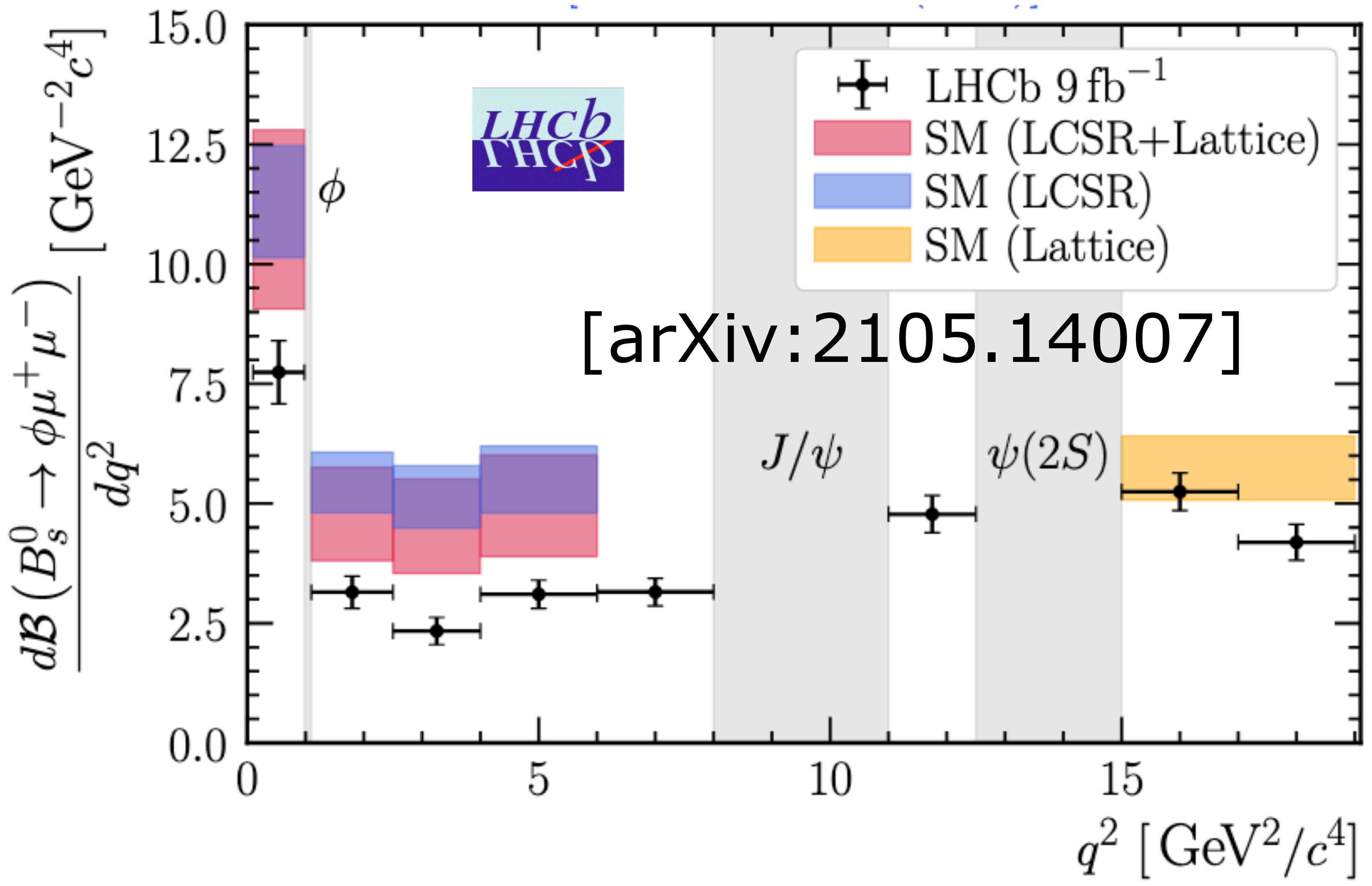
$b \to s\ell\ell$ decays in the SM



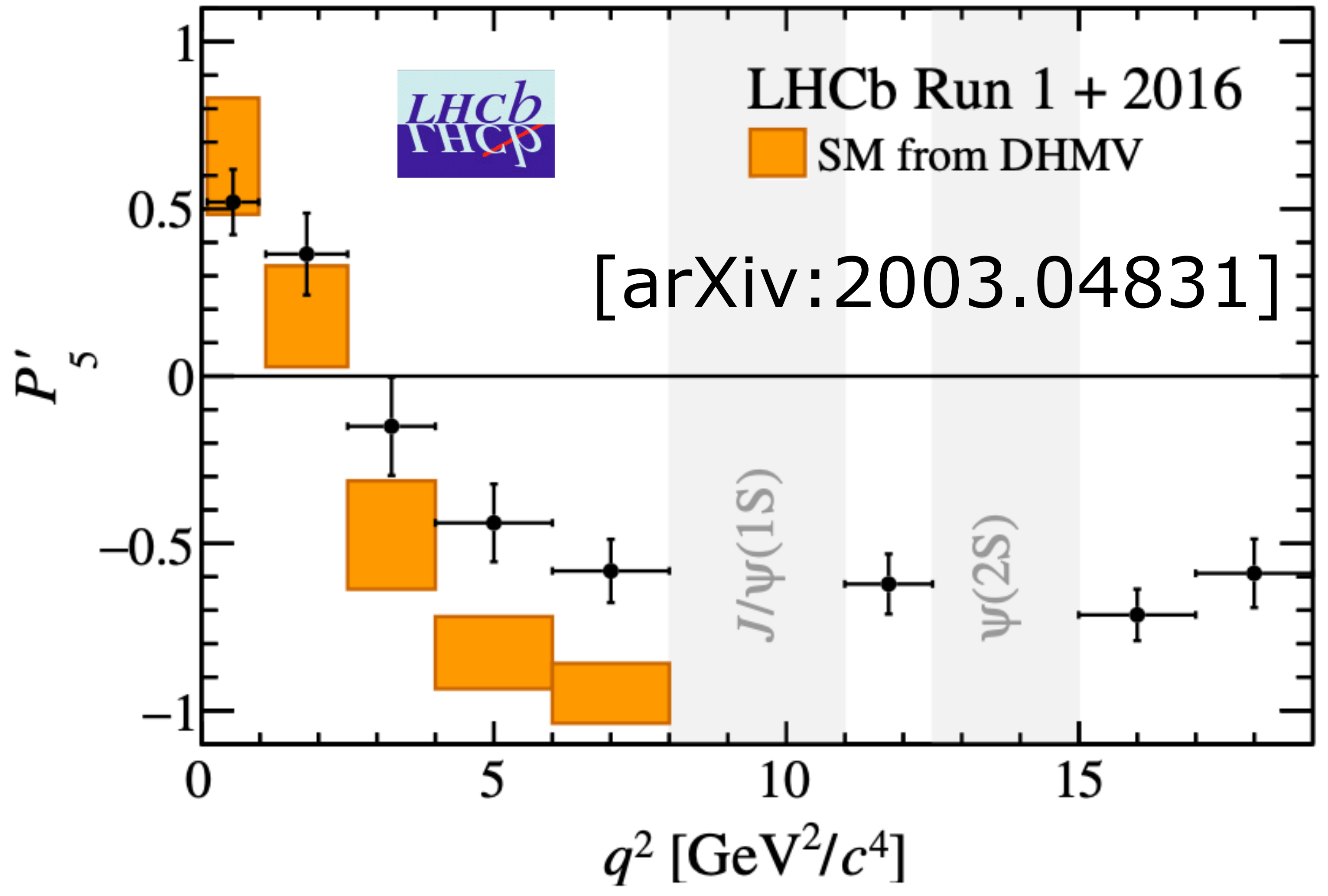
Possible contributions from NP



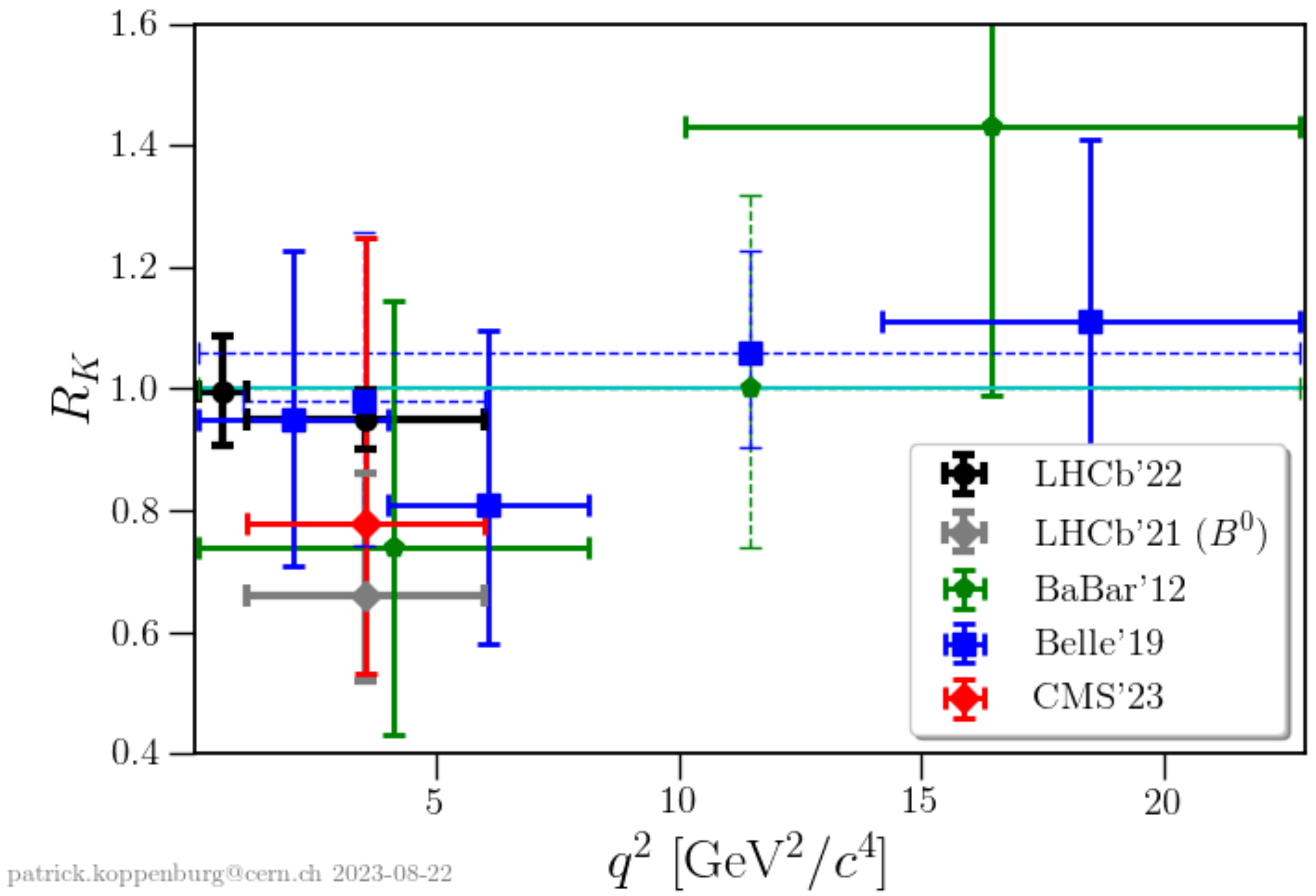
More precise predictions



Branching fractions usually impacted by cc-loops and form factors



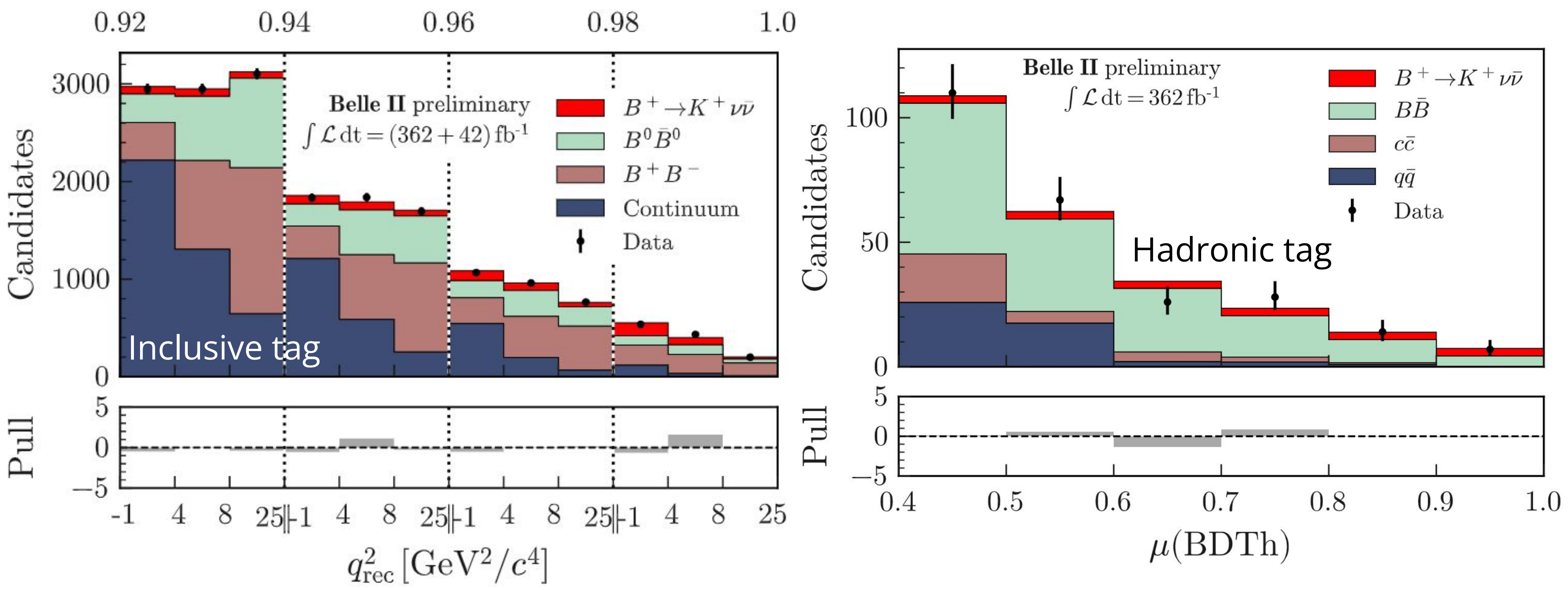
Angular observables affected by cc-loops



Lepton Flavor Universality (LFU) tests: very clean!

$B^+ \to K^+\nu\nu$ (I)

- Golden channel in flavor physics, only accessible at b-factories
  - FCNC, very clean theoretically: $\mathscr{B}(B^+ \to K^+\nu\nu)_{SM} = (5.58 \pm 0.37) \times 10^{-6}$ [arXiv:2207.13371]
  - Several models predict modifications to branching fraction!
  - High background contributions, low branching fraction. No suitable kinematic variable to fit 3-body kinematics. New result from **Belle II** (362 fb^{-1}) [CKM talk]
  - Two analyses: standard hadronic tagging (ε~0.4%) and more sensitive inclusive (ε~8%).
  - Event properties combined in classifier. Use output as (one of) the fit variable(s), then simulate the signal and background.
  - Main backgrounds assessed, $B \to D(\to K^+X)l\nu$, $B \to K^+D(\to K_LX)$ and $B^+ \to K^+K^0K^0$



Final result: simultaneous fit in bins dineutrino mass (q^2_{rec}) and output of the classifiers (classifier just for hadronic tag)

$B^+ \to K^+\nu\nu$ (II)

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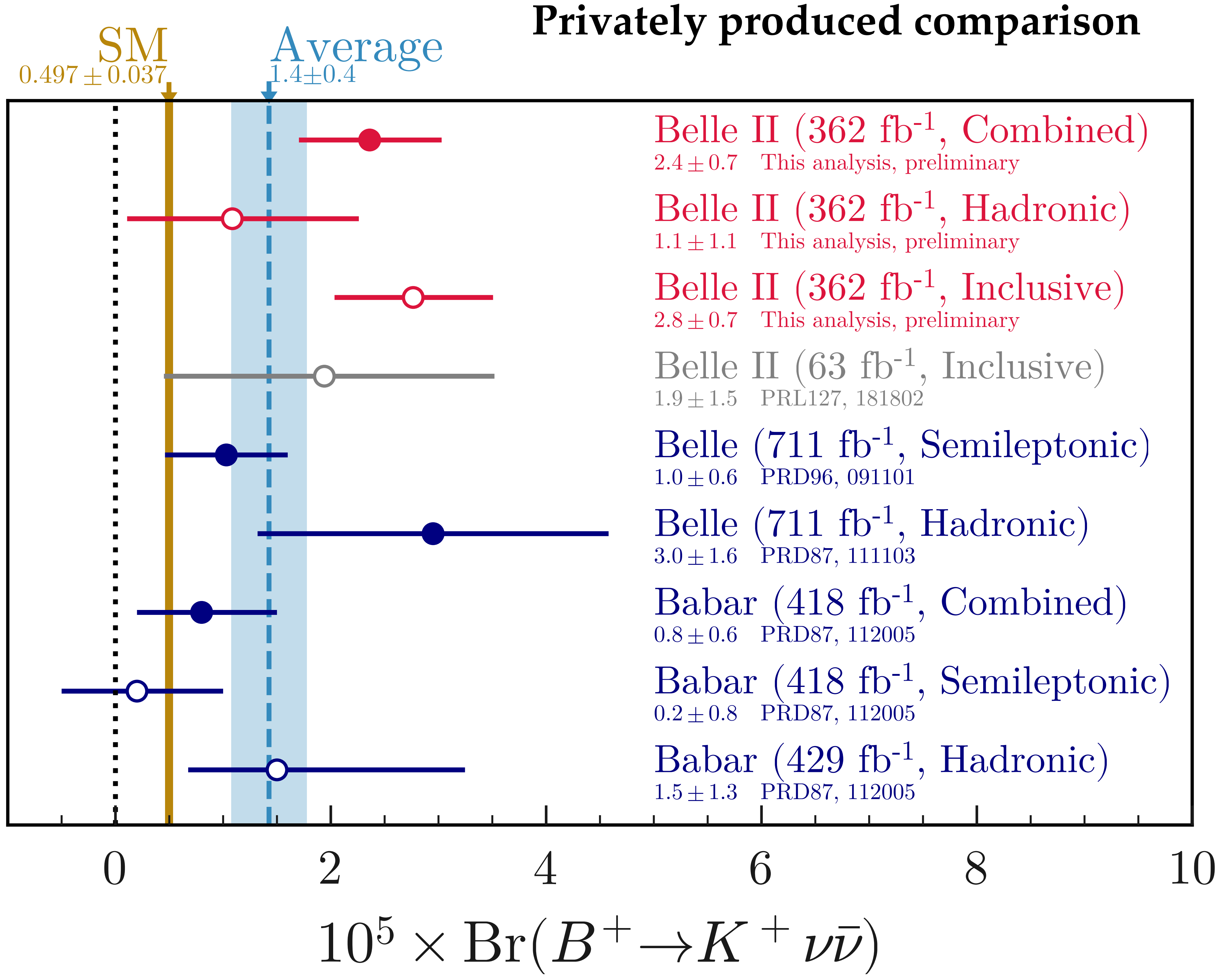
- Impressing first evidence achieved!

$$\mathscr{B}(B^+ \to K^+\nu\nu) = [2.4 \pm 0.5(\text{stat.})^{+0.5}_{-0.4}(\text{syst.})] \times 10^{-5}$$

[CKM talk]

- The **significance is 3.6σ with respect to background-only hypothesis**, 2.8σ away from the SM
- Use of several control channels to verify simulation with actual data, closure test with $B^+ \to \pi^+ K^0$.
- Small tension between the inclusive and semileptonic results for Belle and BaBar, but overall the results are compatible with $\chi^2/\text{ndof} = 4.3/4$.

Privately produced comparison



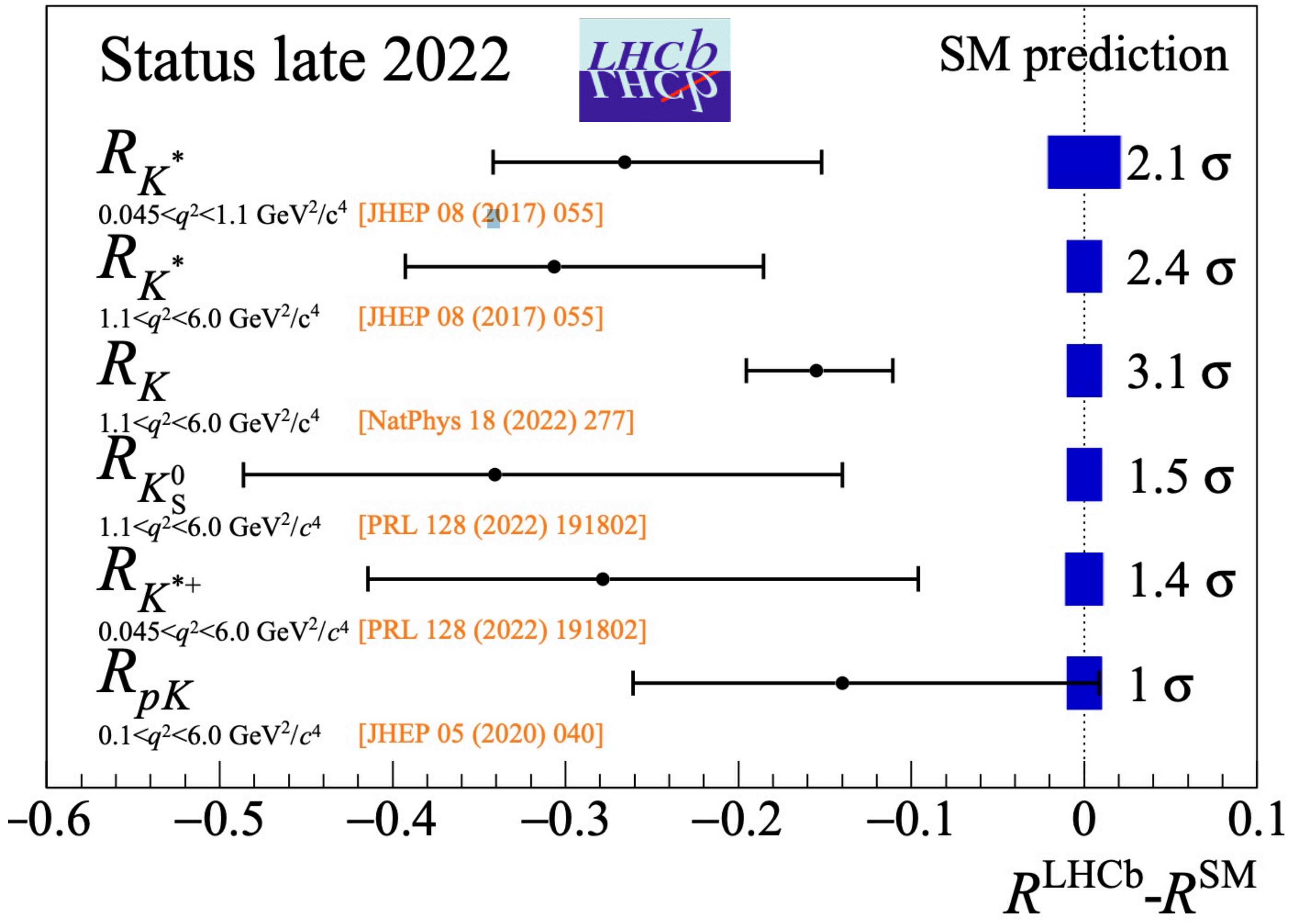
LFU with $b \to s l \bar{l}$

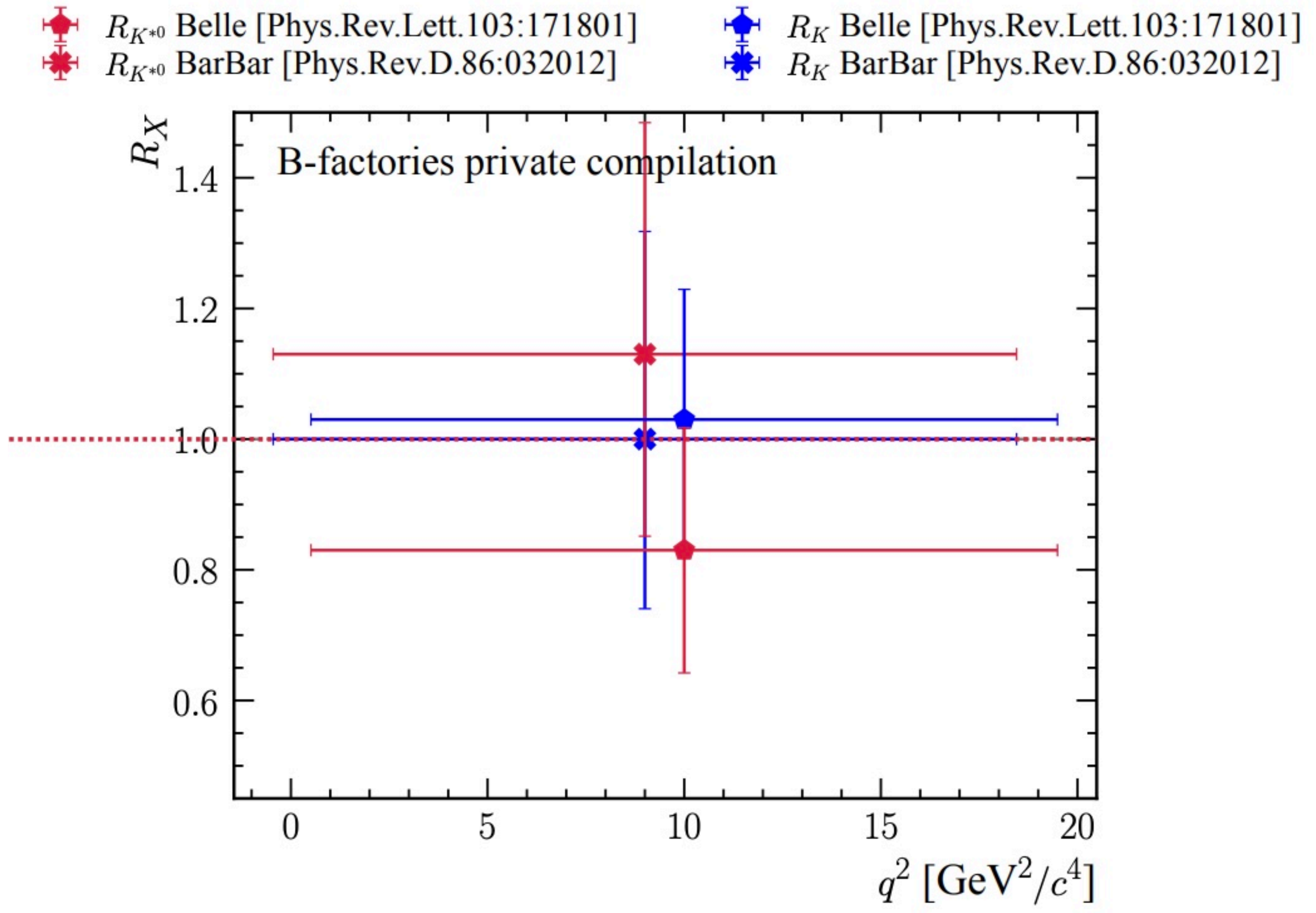
- Challenge, maximize experimental precision:
  - Use double ratio to J/Ψ modes to reduce systematics (the J/Ψ mode has been measured to be 1) [arXiv:1307.1189]

$$R_H = \frac{\mathcal{B}(B \to H_s \mu\mu)}{\mathcal{B}(B \to H_s ee)} \cdot \frac{\mathcal{B}(B \to H_s J/\Psi(ee))}{\mathcal{B}(B \to H_s J/\Psi(\mu\mu))}$$

  where $H_s = K^*, K^+, K_S^0, K^{*+}, \ldots$

  - To remove long distance effects, cc resonances are vetoed and used to validate the analysis
  - Main complexity, different behavior of electrons and muons at the detectors
  - Typically measure as a function of q² (lepton pair invariant mass)

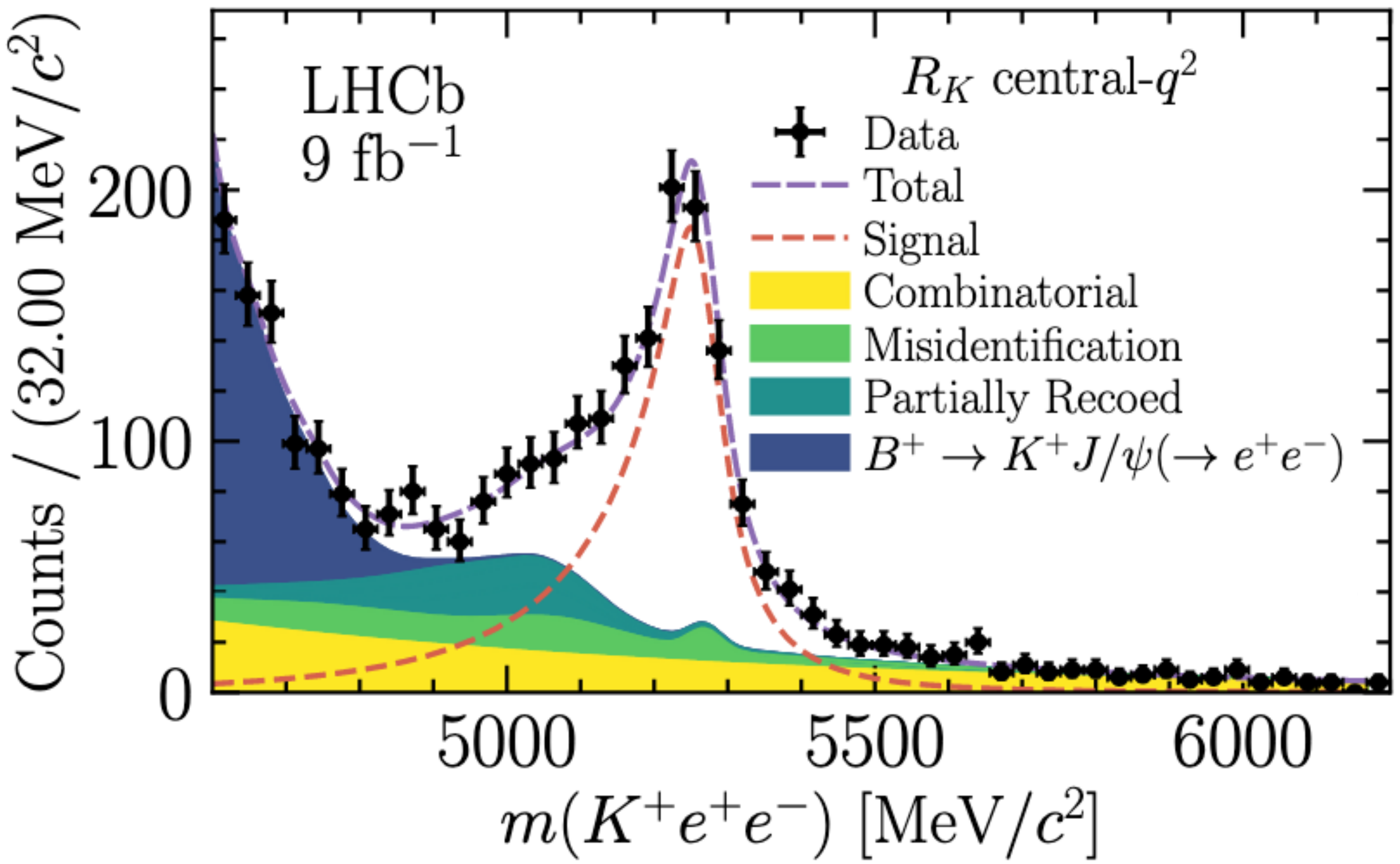


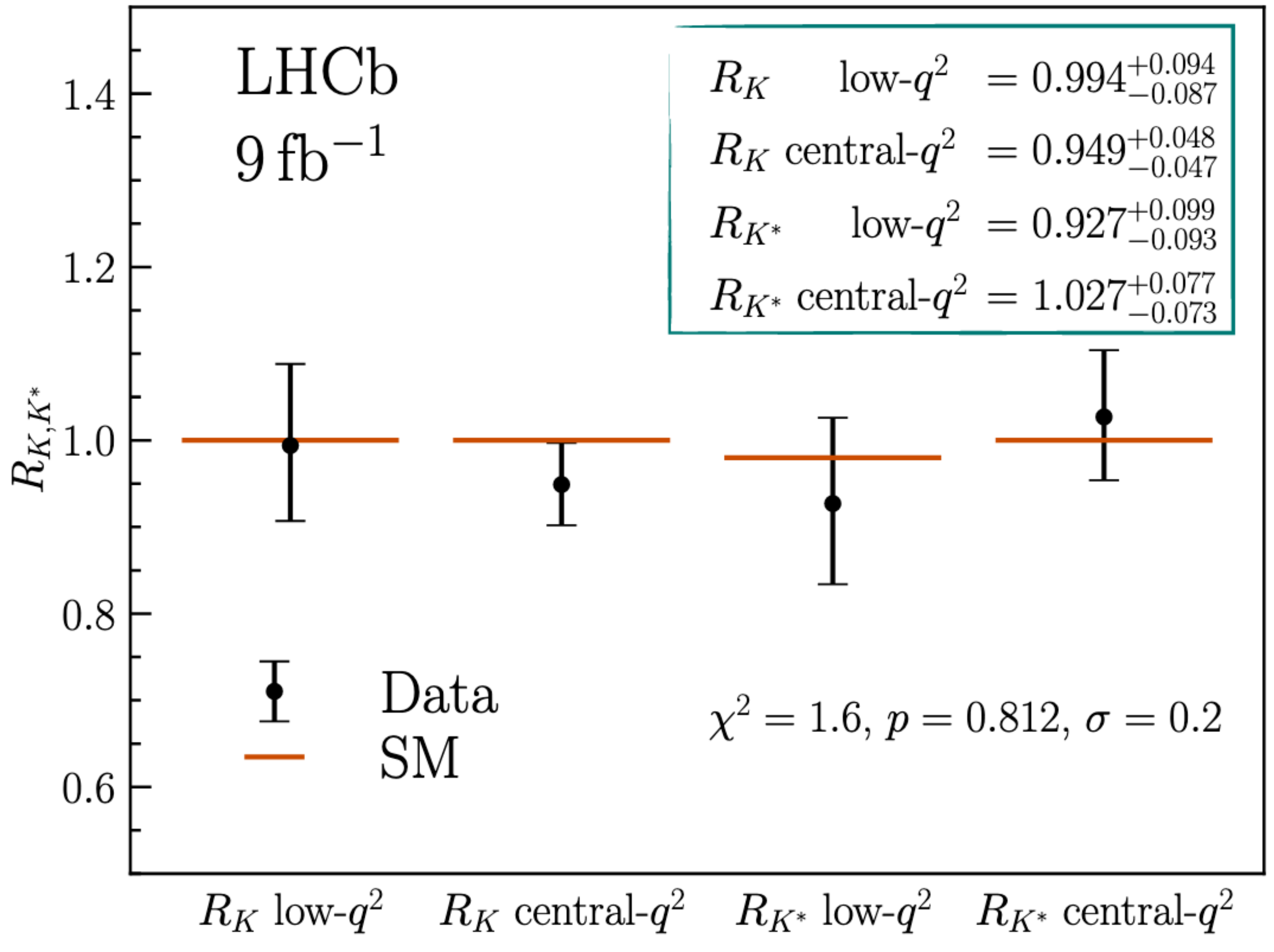


New $R_{K^{(*)}}$ at LHCb

- Combined assessment of R_{K^*} and R_K using the legacy Run 1+2 dataset.
  - Better understanding of systematic uncertainties, in particular PID effects…
  - Previously misidentified backgrounds $B \to D(\to K_{\to e}\pi_{\to e})\pi_{\to K}$ and $B \to K_{\to e}K_{\to e}K_{\to e}$. Now accounted for thanks to control samples.
  - Current results: good agreement with SM. Some tension remains in muon BR

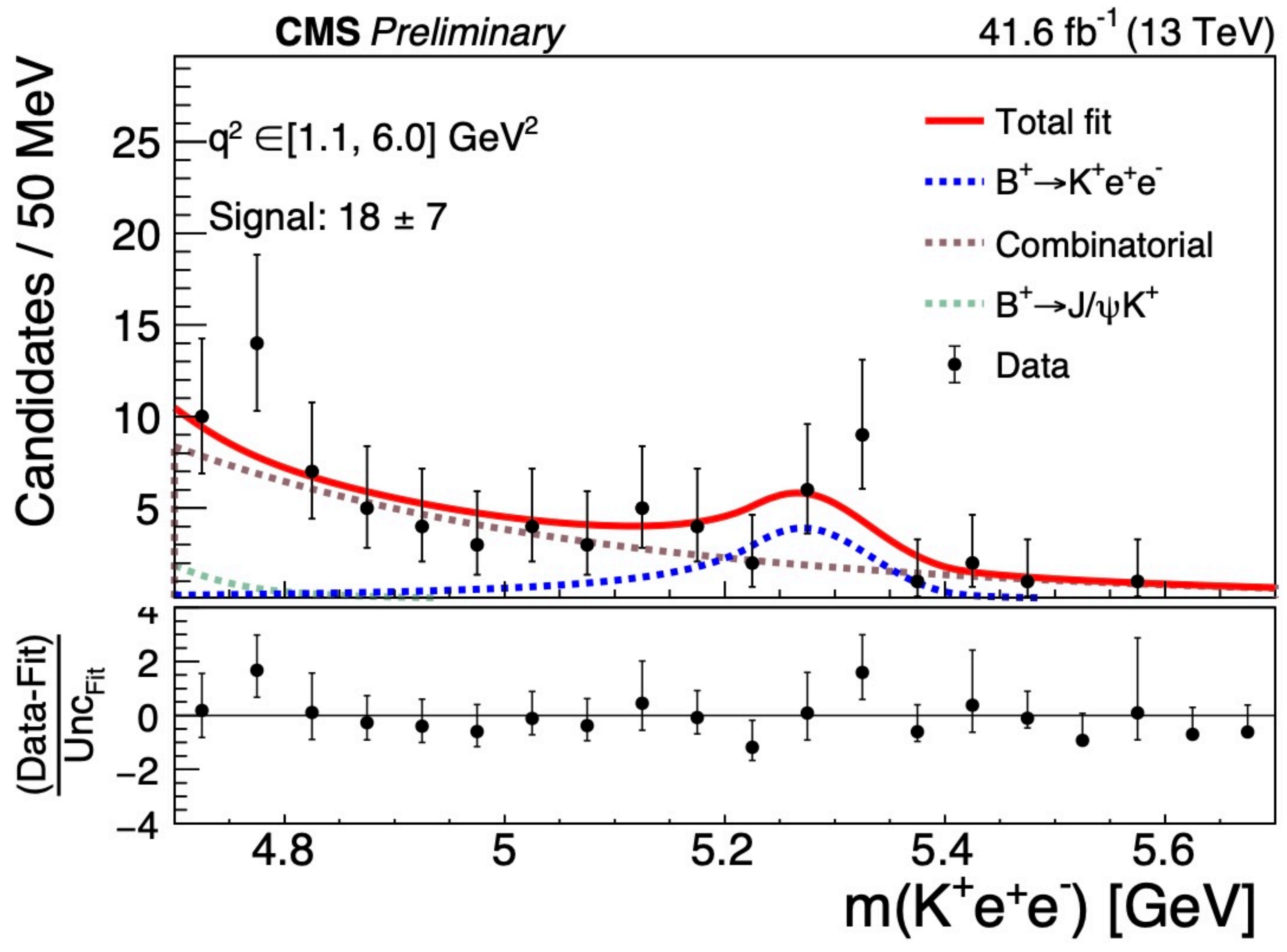
[arXiv:2212.09152]

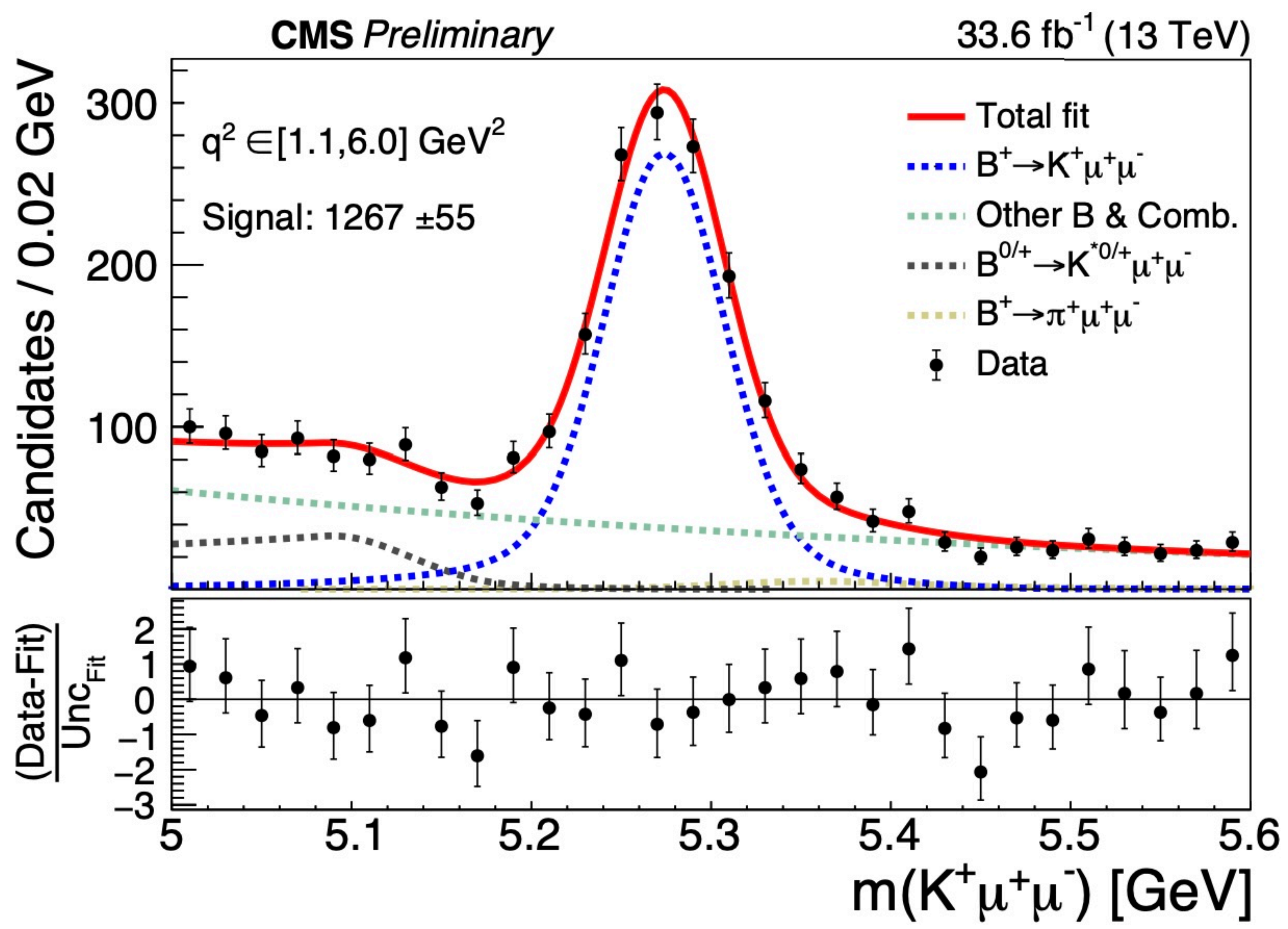




R_K at CMS

- Result based on CMS *Bparked* data → provides access to an $O(10^{10})$ unbiassed sample of b-hadrons
  - Strategy similar to LHCb, measurement done with $1.1 < q^2 < 6.0$ GeV^2
  - First measurement of R_K at CMS, compatible with LHCb and SM
  - Main limitation, statistics in electron sample





[CMS-PAS-BPH-22-005]

$$R(K) = 0.78^{+0.46}_{-0.23}\,(\text{stat.})\,^{+0.09}_{-0.05}\,(\text{syst.})$$

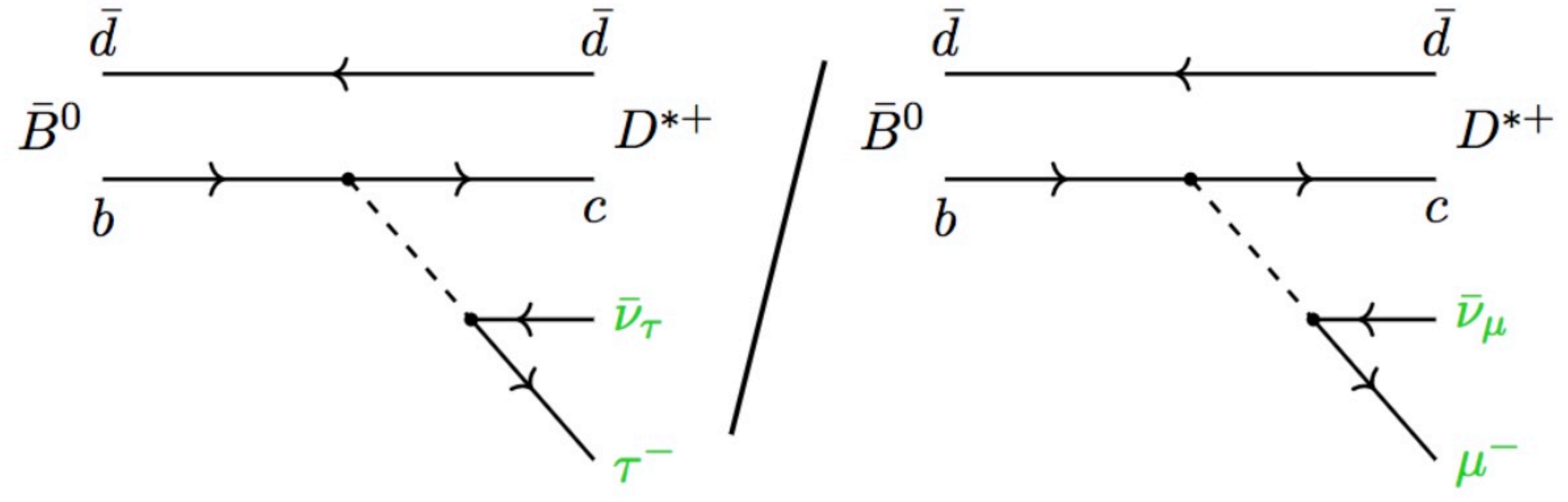
LFU in semileptonic decays

- Use the following ratio to probe LFU

$$R_H = \frac{\mathcal{B}(H_b \to H_c \tau \bar{\nu}_\tau)}{\mathcal{B}(H_b \to H_c l \bar{\nu}_l)}$$

where $H_c = D^{*+}, D^0, D^+, D_s^+, \Lambda_c, J/\Psi$ and $H_b = B^0, B_s^0, B_{(c)}^+, \Lambda_b$ (others possible)

- H_b different to B^0 or B^+ only possible at the LHC. On the other hand, l=μ at the LHC, can also be electrons at b-factories!
- Large MC samples are required for template shapes, approximations are used for signal reconstruction, since neutrinos are not detected.
- Advantages, BRs are large (tree decays) and SM theoretical predictions quite accurate!



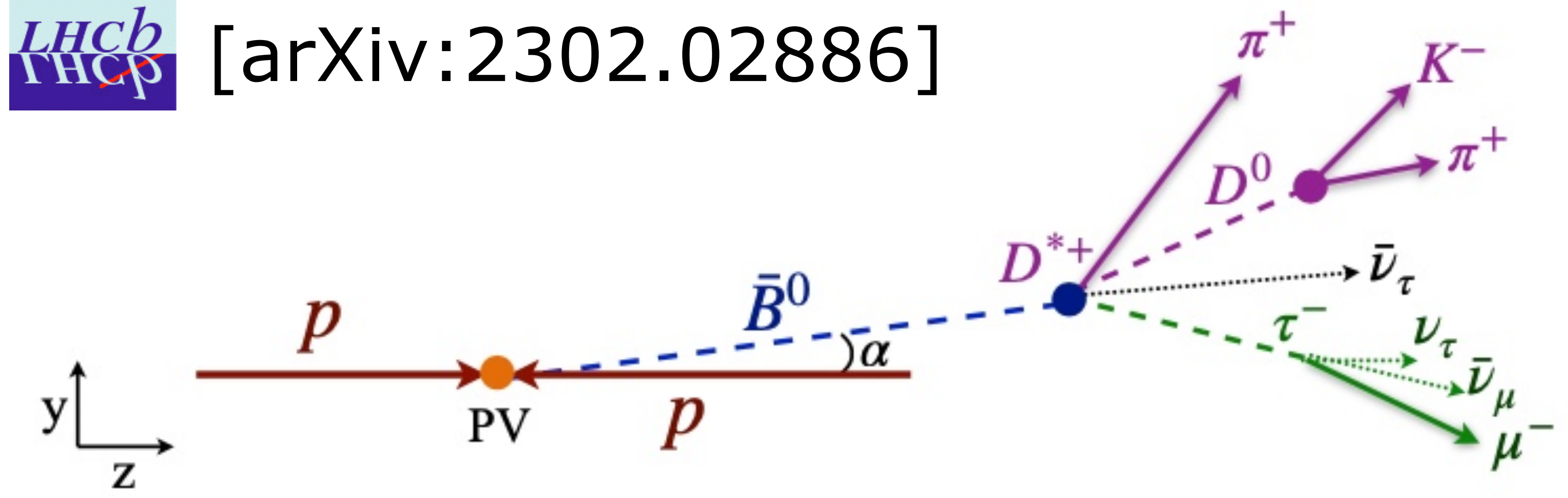
R_{D*} and R_D muonic in LHCb

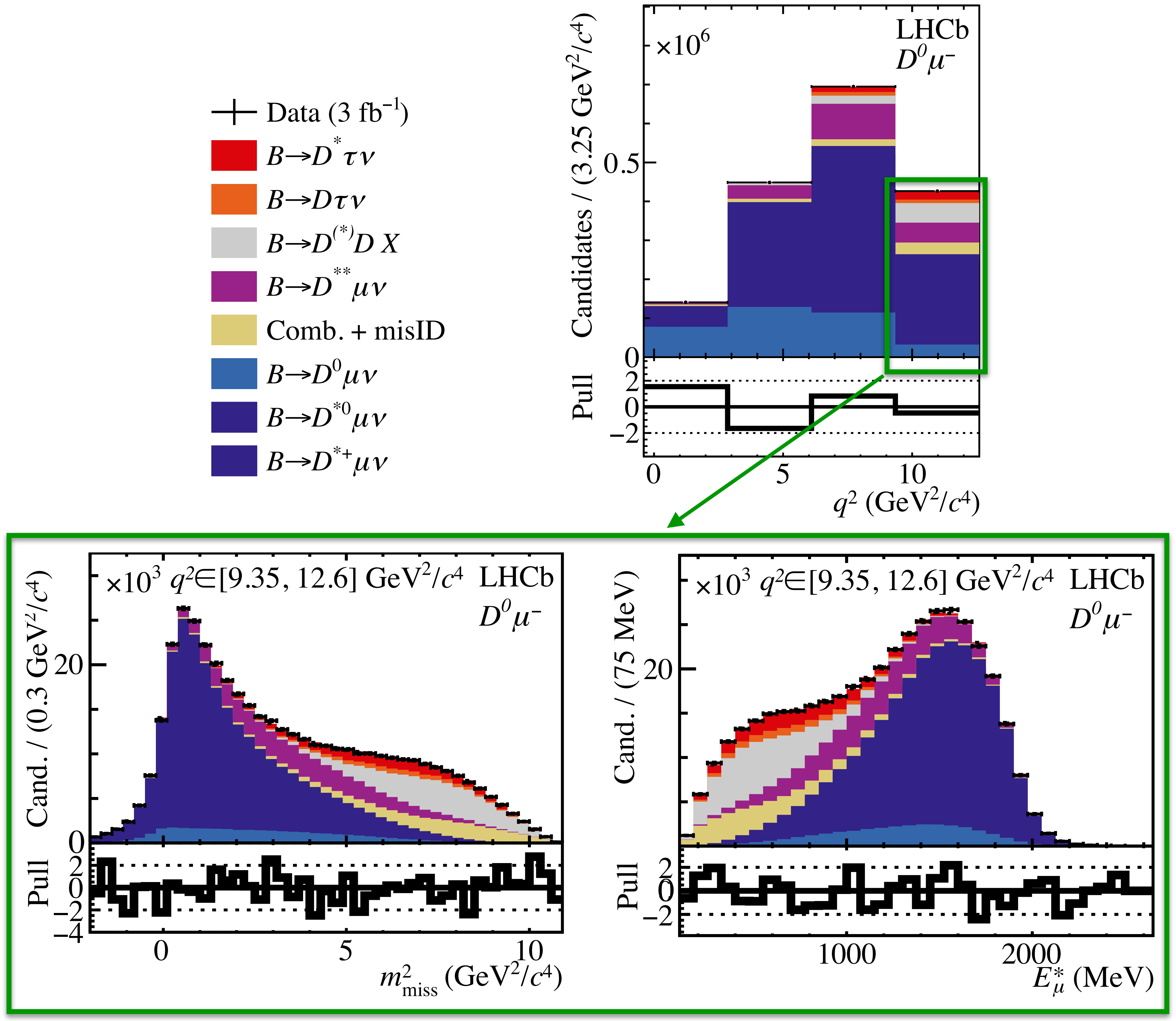
- First measurement of R_D at a hadron collider! Uses LHCb Run 1 dataset
  - Kinematics not so constrained as with hadronic τ decays, but most precise result overall
  - Signal subtracted through 3D fit to $q^2 = (p_B - p_{D^{(*)}})^2, m^2_{miss} = (p_B - p_{D^{(*)}} - p_\mu)^2$, and E^*_μ (muon energy in B rest frame)

$$R_D = 0.441 \pm 0.060(\text{stat.}) \pm 0.066(\text{syst.})$$
$$R_{D*} = 0.281 \pm 0.018(\text{stat.}) \pm 0.024(\text{syst.})$$

  - Result in reasonable agreement with SM. Part of systematics data driven, part MC statistics, possible to reduce!

[arXiv:2302.02886]





R_{D*} hadronic in LHCb

- Challenging analysis at a hadron collider:
  - Use distance of flight to remove prompt backgrounds and measure other b-originated backgrounds with control samples
  - Result compatible with SM

[arXiv:2305.01463]

$$R_{D*} = 0.247 \pm 0.015(\text{stat.}) \pm 0.015(\text{syst.}) \pm 0.012(\text{ext.})$$

†ext. referring to external $\mathscr{B}$

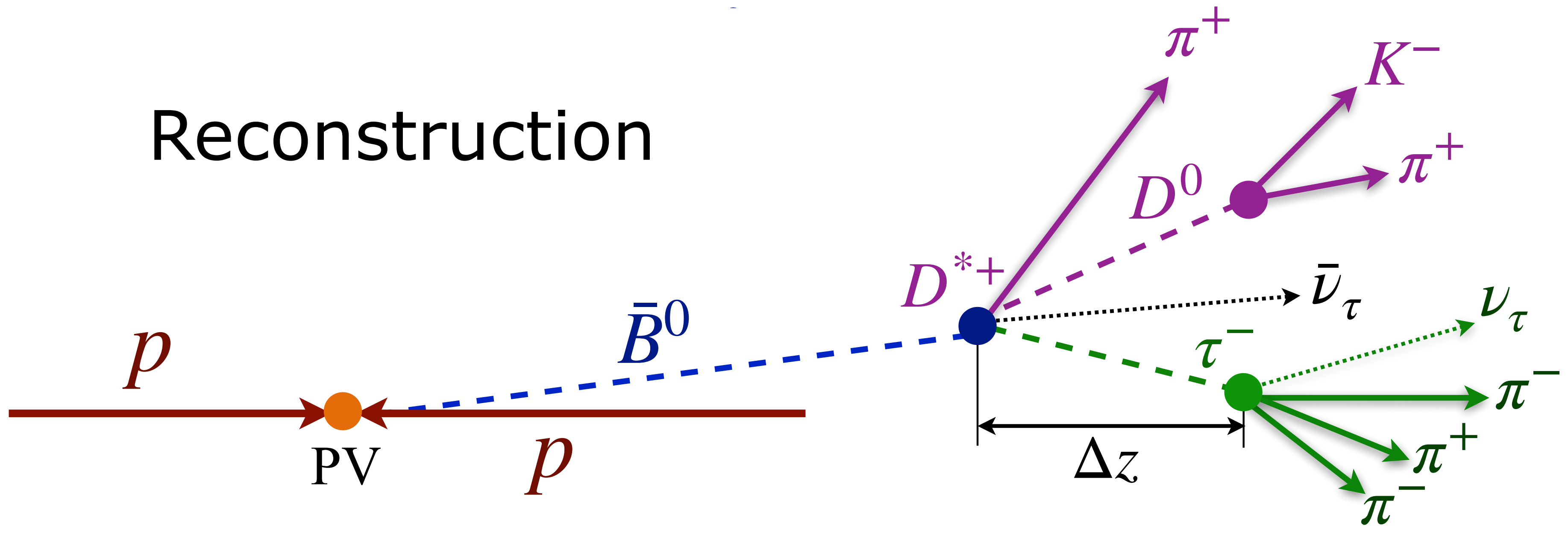
  - Result with fraction of LHCb Run 2 dataset
  - Systematics uncertainties will scale down with more data, but some ~3-4% floor to remain

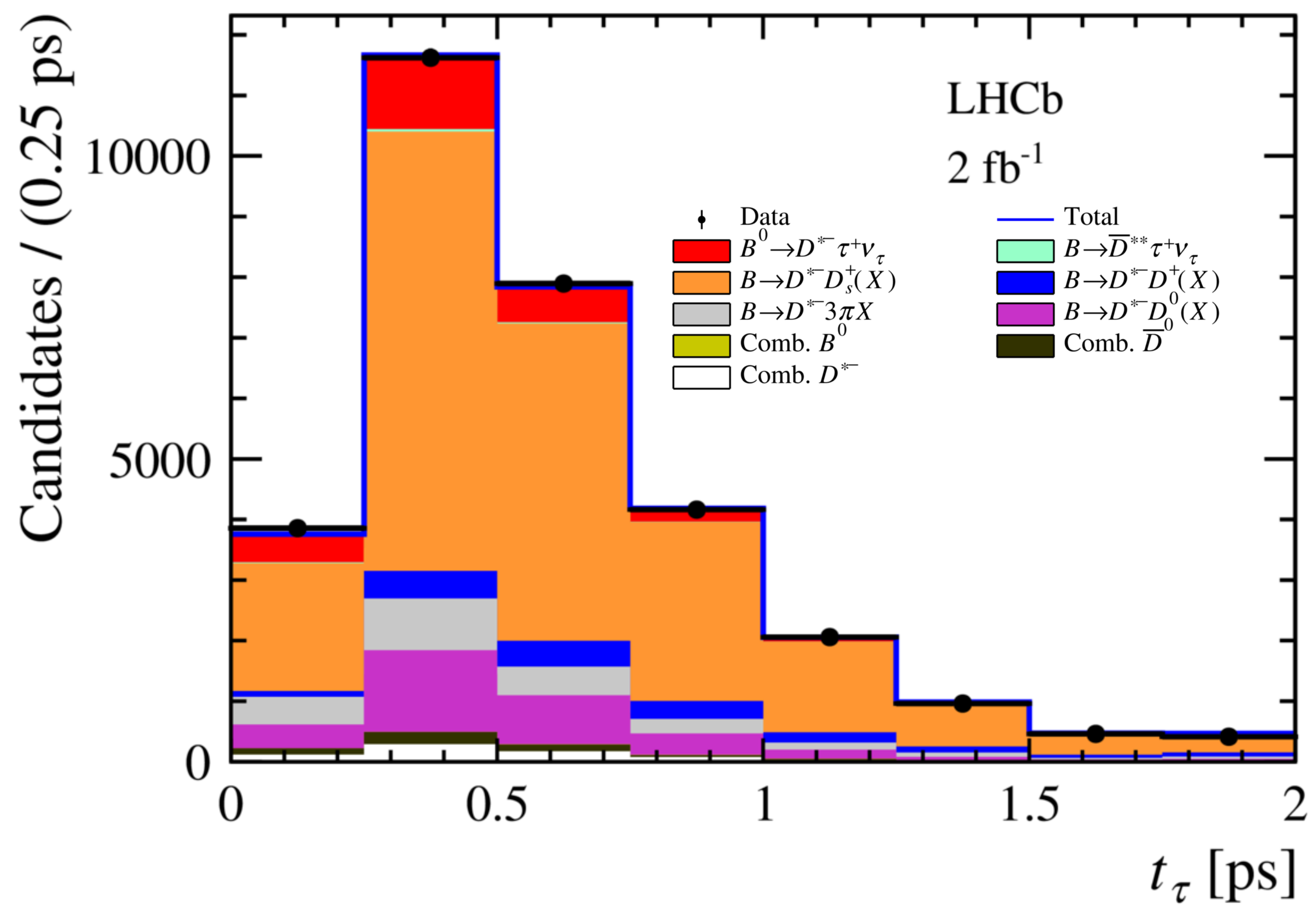
$\mathscr{R}(D^{*+})$ depends on external branching fractions

$$\mathscr{R}(D^*) = \frac{\mathscr{B}(\bar{B} \to D^*\tau\nu_\tau)}{\mathscr{B}(\bar{B} \to D^*\mu\nu_\mu)} = \frac{\mathscr{B}(\bar{B} \to D^*\tau\nu_\tau)}{\mathscr{B}(\bar{B} \to D^*\pi\pi\pi)} \times \frac{\mathscr{B}(\bar{B} \to D^*\pi\pi\pi)}{\mathscr{B}(\bar{B} \to D^*\mu\nu_\mu)}$$

Measure this ratio

Reconstruction





R_{D^*} hadronic in Belle II

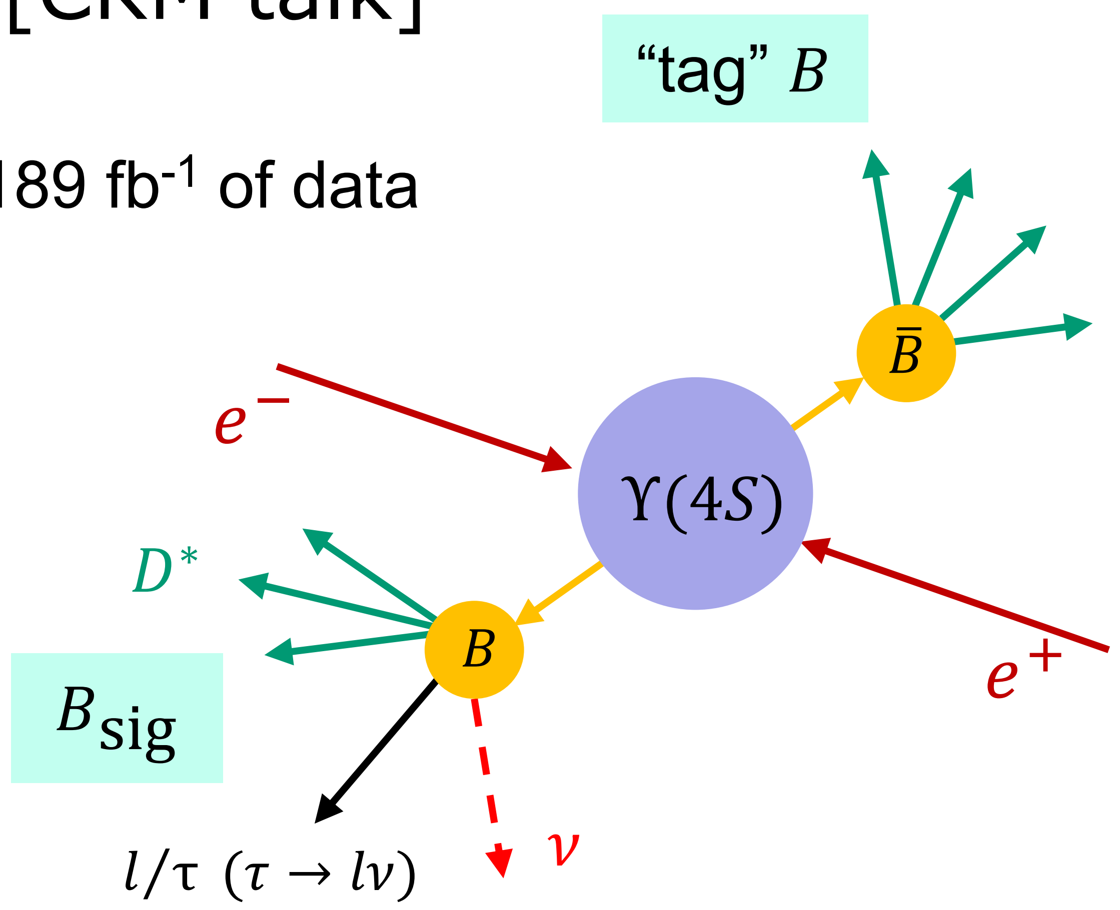
- First R_{D^*} at Belle.
  - Signal extraction, two-dimensional binned likelihood fit to calorimeter energy from rest of event and m^2_{miss}

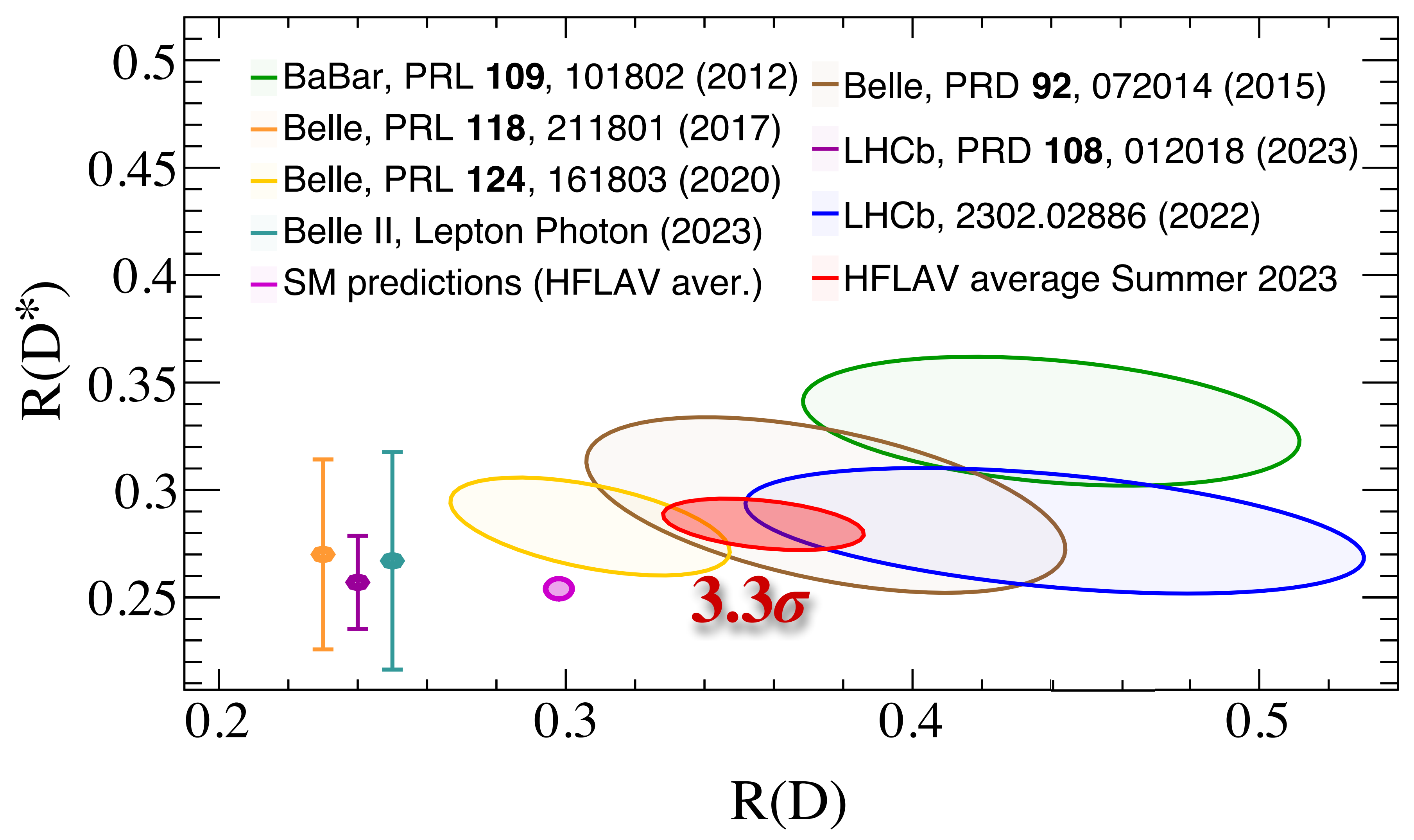
$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$

  - Consistent with SM and previous measurements.
  - Uncertainties comparable to those of Belle. Dominant systematics from MC statistics.
  - Future measurement as a function of angular distribution and q².
  - Overall picture: **tension with SM remains!**

[CKM talk]

189 fb^{-1} of data

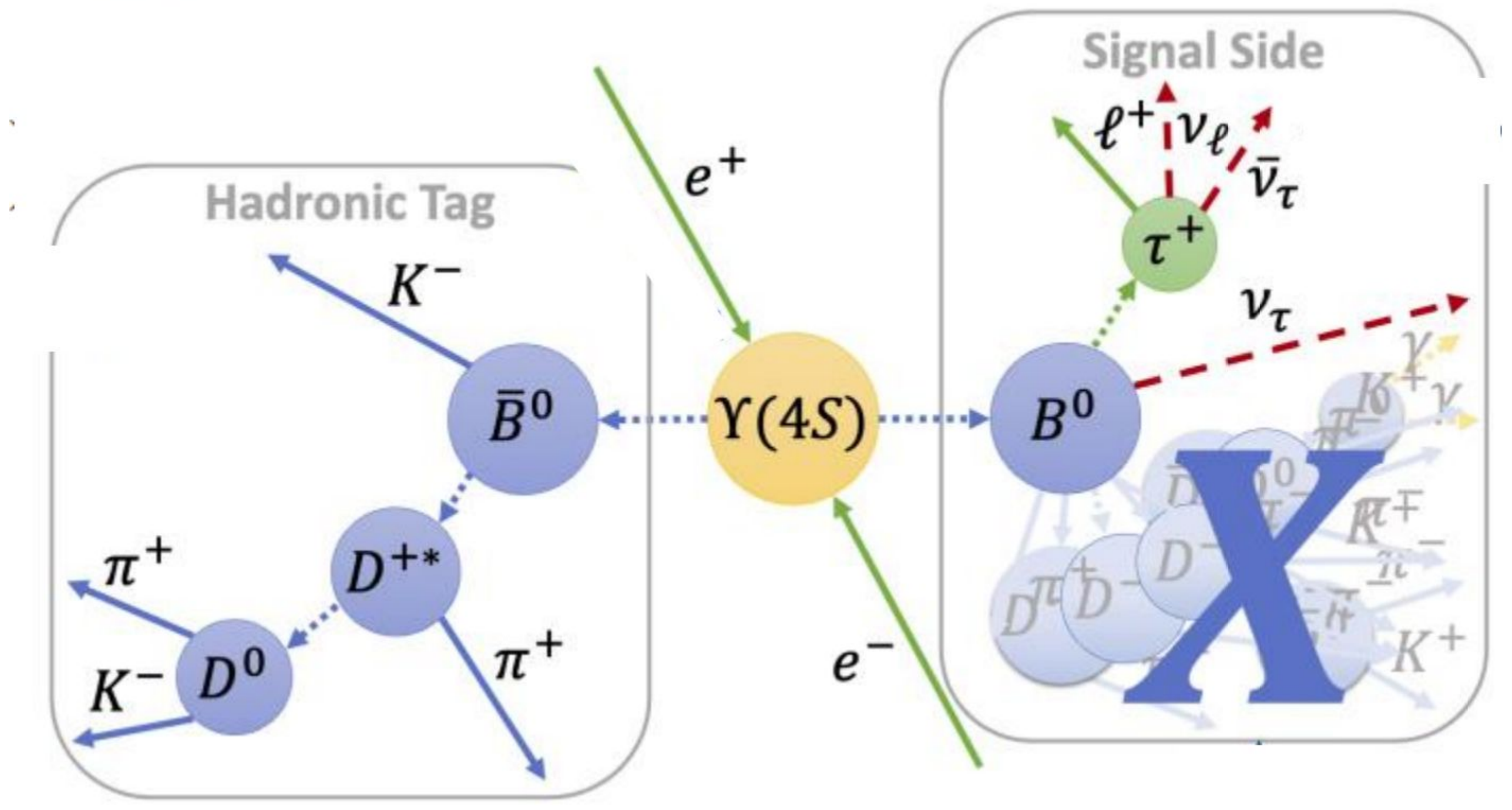




R(X)

- Alternative to $R_{D^{(*)}}$: inclusive ratio

$$R(X_{l_1/l_2}) = \frac{\mathscr{B}(B \to X l_1 \nu_{l_1})}{\mathscr{B}(B \to X l_2 \nu_{l_2})}, \text{ where } l_1, l_2 = \tau, \mu, e$$



  - Novel and theoretically trustworthy alternative. Unique at B-factories! Here: **Belle II** with hadronic tagging.
  - First time using both τ/e and τ/μ channels. Complex analysis, several reweighting/corrections needed for simulated samples. Excellent agreement between measurements of the electron and muon channels:

$$R(X_{\tau/e}) = 0.232 \pm 0.020 \text{ (stat)} \pm 0.037 \text{ (syst)}$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027 \text{ (stat)} \pm 0.050 \text{ (syst)}$$

[CKM talk] Belle II

$$R(X_{\tau/l}) = 0.228 \pm 0.016(\text{stat.}) \pm 0.036(\text{syst.})$$

$$R(X_{\tau/l})^{SM} = 0.223$$
[arXiv:2207.03432]

[arXiv:2301.08266] Belle II

- Also, first measurement of $R(X_{e/\mu})$ at Belle II
- Analysis similar to $R(X_{\tau/l})$

$$R(X_{e/\mu}) = 1.007 \pm 0.009 \pm 0.019$$

- Most accurate to date, agrees with SM

B→D*lν angular asymmetries

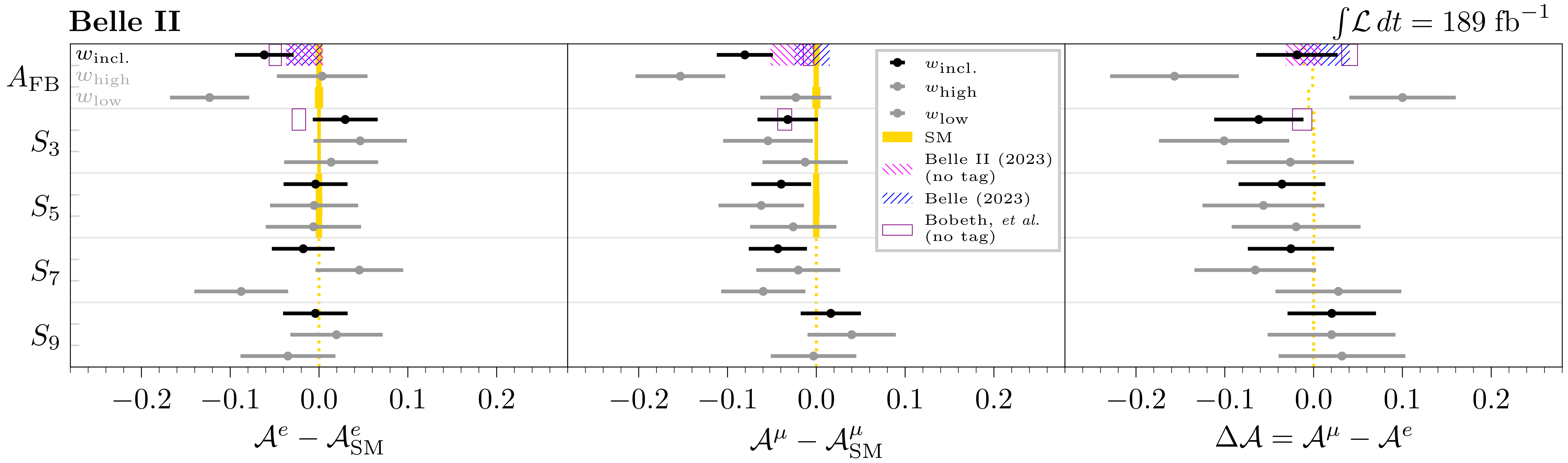
- Measurement of angular asymmetries of B→D*eν and B→D*μν, independent LFU test!
  - Use (again) hadron tag.
  - N_F and N_B taken from missing mass of undetected particles in different angular regions.
  - Results in agreement with SM.

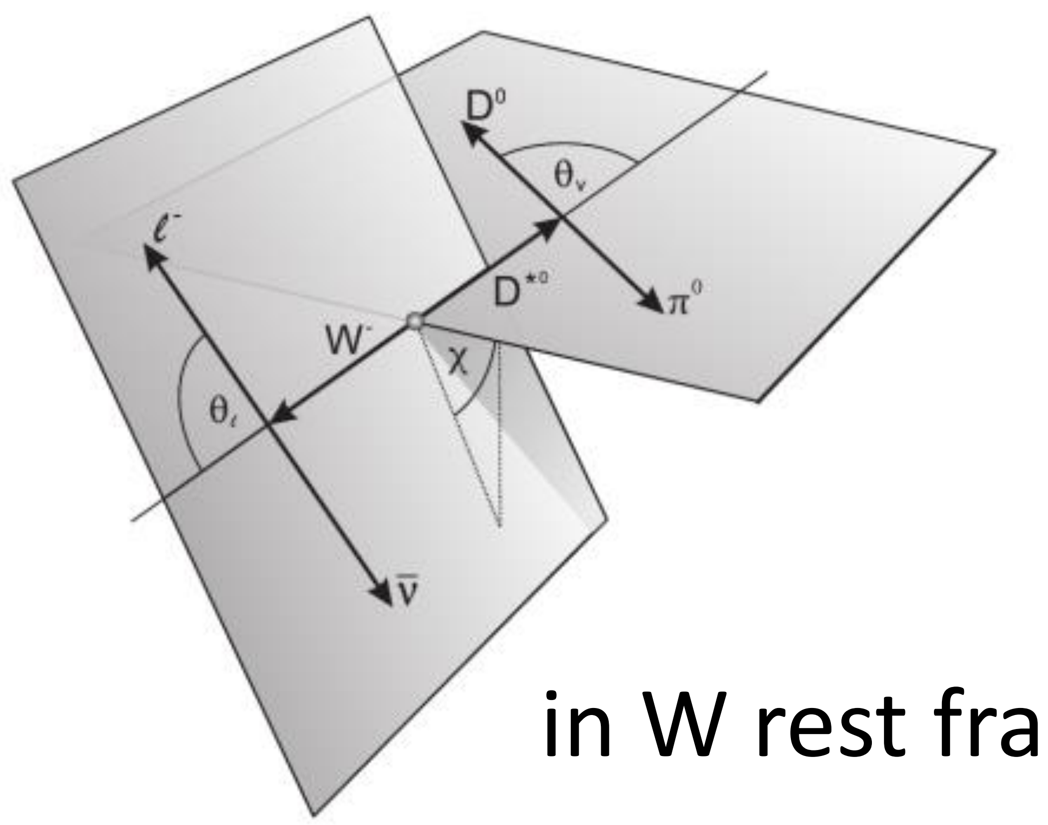
- Example of asymmetry measured, A_{FB}

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

N_F = number of events with cos(θ) > 0
N_B = number of events with cos(θ) < 0

[arXiv:2308.02023]





$R_{J/\Psi}$ in B_c^+ decays

- Ratio of $B_c \to J/\Psi l\nu$, with $l=\mu,\tau$ transitions, clean prediction in SM (0.26)! [arXiv:2007.06956]
  - τ reconstructed through μ decay (3μ in total)
  - Main background J/Ψ+hadron misID ($h \to \mu$)
  - $R_{J/\Psi}$ subtracted by simultaneous fit to different classifier bins

$$R(J/\psi) = 0.17\,^{+0.18}_{-0.17}\,(\text{stat.})\,^{+0.19}_{-0.19}\,(\text{theo.})\,^{+0.21}_{-0.22}\,(\text{syst.})$$

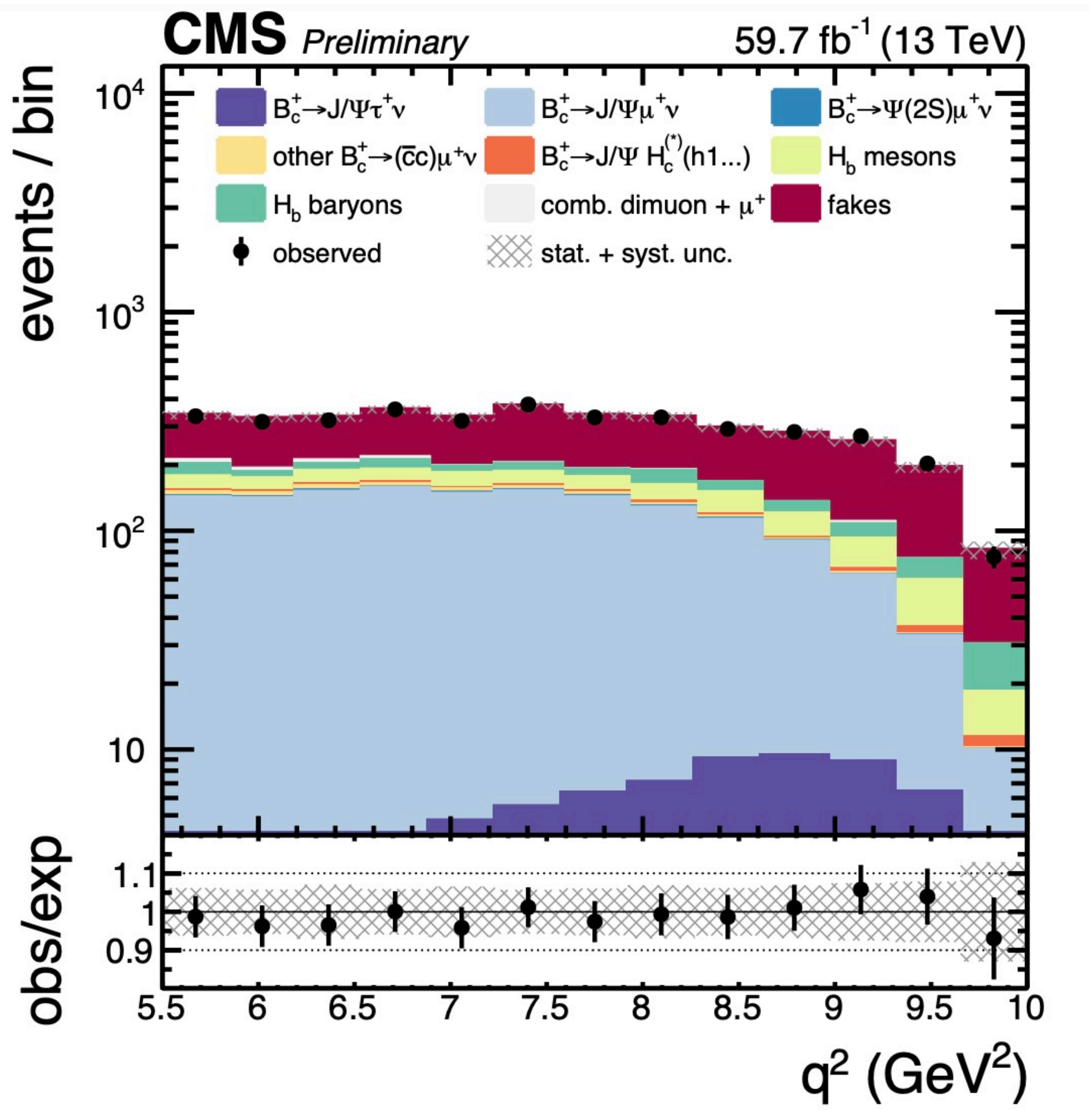
  - First LFU result with $b \to cl\nu$ transition in CMS
  - Compatible with SM and previous LHCb result

[arXiv:1711.05623]

$$q^2 = (p_{B_c} - p_{J/\psi})^2 \text{ where } p_{B_c} = m_{B_c}^{\text{PDG}} / m_{3\mu}^{\text{vis}} \cdot p_{3\mu}^{\text{vis}}$$

$$R(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi\,\tau\,\nu_\tau)}{\mathcal{B}(B_c \to J/\psi\,\mu\,\nu_\mu)}$$

[CMS-PAS-BPH-22-012]



$\tau \to \mu\mu\mu$

- Example of the power of **lepton flavor violating** decays, extremely suppressed in the SM, so clear BSM evidence if observed
  - Latest results, from CMS. Two potential sources of τ leptons: Heavy Flavours (HF) (more stats, less clean), and W boson decays (opposite)
  - Categorisation of candidates based on year, mass resolution, classifier
  - Result achieved:

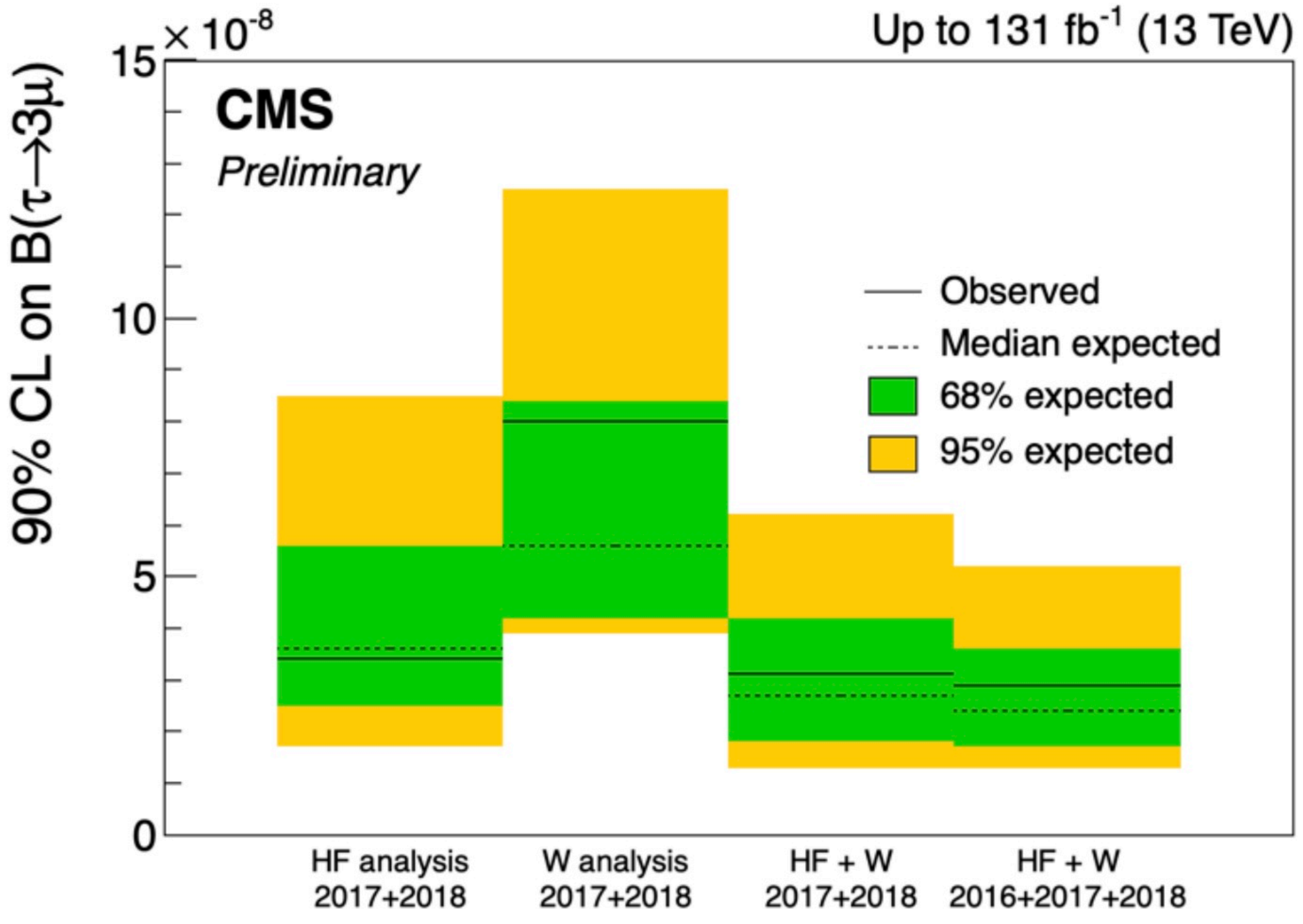
$$\mathscr{B}(\tau \to \mu\mu\mu) < 2.9 \cdot 10^{-8} \text{ at } 90\,\% \text{ CL}$$

  - Compatible with world best from Belle

$$\mathscr{B}(\tau \to \mu\mu\mu) < 2.1 \cdot 10^{-8} \text{ at } 90\,\% \text{ CL}$$

[Phys.Lett.B 687 (2010) 139-143]

[CMS-PAS-BPH-21-005]



- Introduction
- CKM metrology
- Rare and SL decays
- **Spectroscopy**
- Future
- Conclusions

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Overview

Prospect

Politics | World | Ideas | Views | Culture | Latest issue | Podcasts | Newsletters

TECHNOLOGY

Is particle physics at a dead end?

The Large Hadron Collider, which discovered the Higgs boson, has restarted after a three-year upgrade. What if it doesn't find anything else?

By Philip Ball

PHYSICS TODAY

THE MAGAZINE | LATEST | WEBINARS &

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LHC's failure to find new particles casts doubt on supersymmetry FREE

DOI: https://doi.org/10.1063/PT.5.0210086

Science News: Despite exposing the Higgs boson in 2012, the Large Hadron Collider, the world's largest and most powerful particle accelerator, has so far failed to turn up evidence of any of the new particles predicted by the theory of supersymmetry. According to the theory, all the known fundamental particles have more massive counterparts. The failure to turn up evidence of those larger particles does not necessarily disprove supersymmetry, some scientists say. It's possible that the particle predictions may simply need to be modified; the new particles may be much heavier than expected. For other physicists, the lack of data indicates that new theories, such as the relaxation hypothesis or neutral naturalness, should be considered.

Quanta magazine

Physics | Mathematics | Biology | Computer Science | Topics | Archive

PARTICLE PHYSICS

What No New Particles Means for Physics

46

Physicists are confronting their "nightmare scenario." What does the absence of new particles suggest about how nature works?

The New York Times

OPINION

The Uncertain Future of Particle Physics

Ten years in, the Large Hadron Collider has failed to deliver the exciting discoveries that scientists promised.

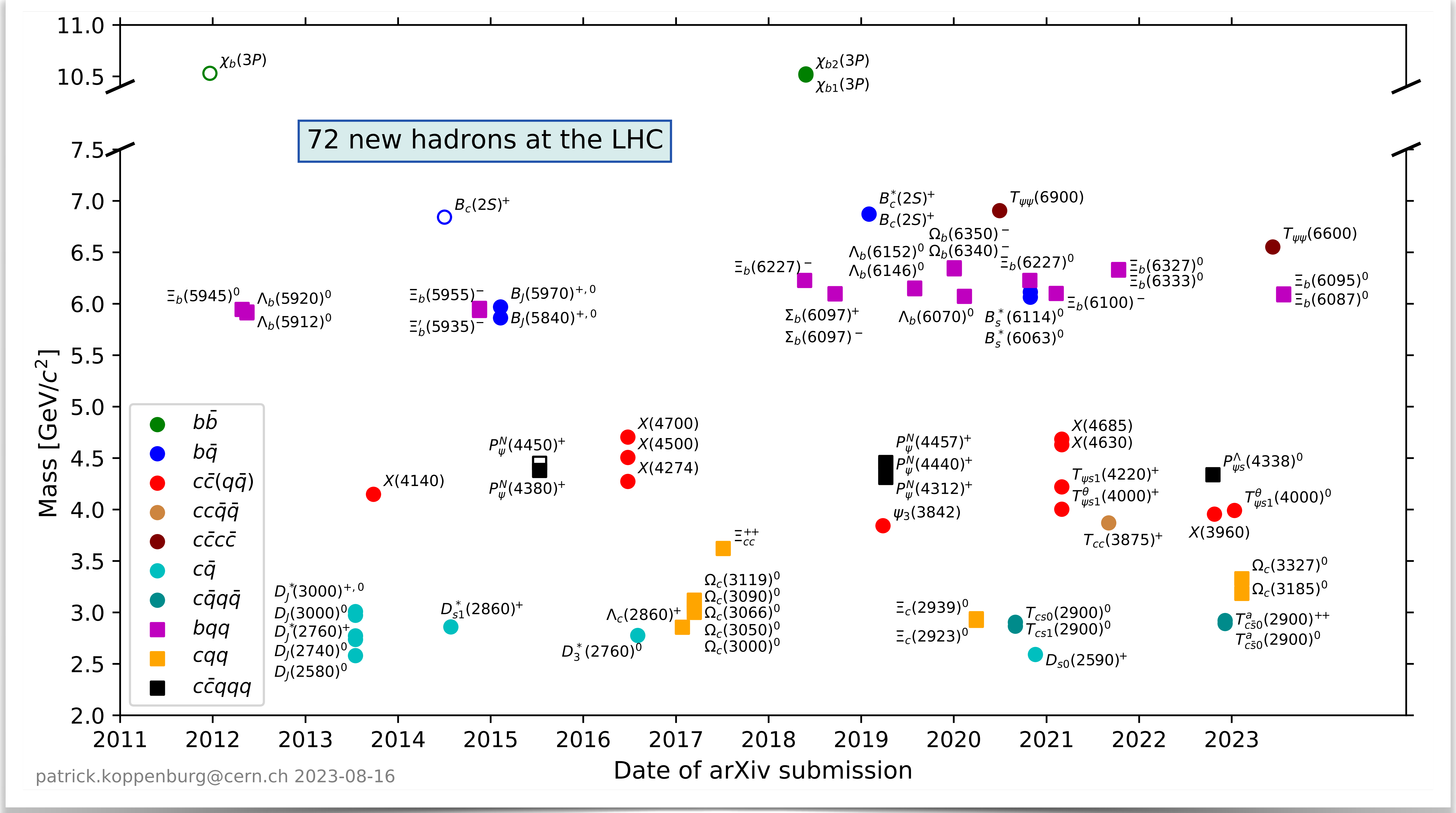
Quora

Search for questions, people, and topics

Was the Large Hadron Collider a complete failure?

Overview

- The LHC has discovered **72 new hadrons**! (+ the Higgs boson)
  - ➡ These go beyond simple quark model, e.g., tetra and penta-quarks!



$\Xi_b^{(*)0/-}(bsq)$ baryons

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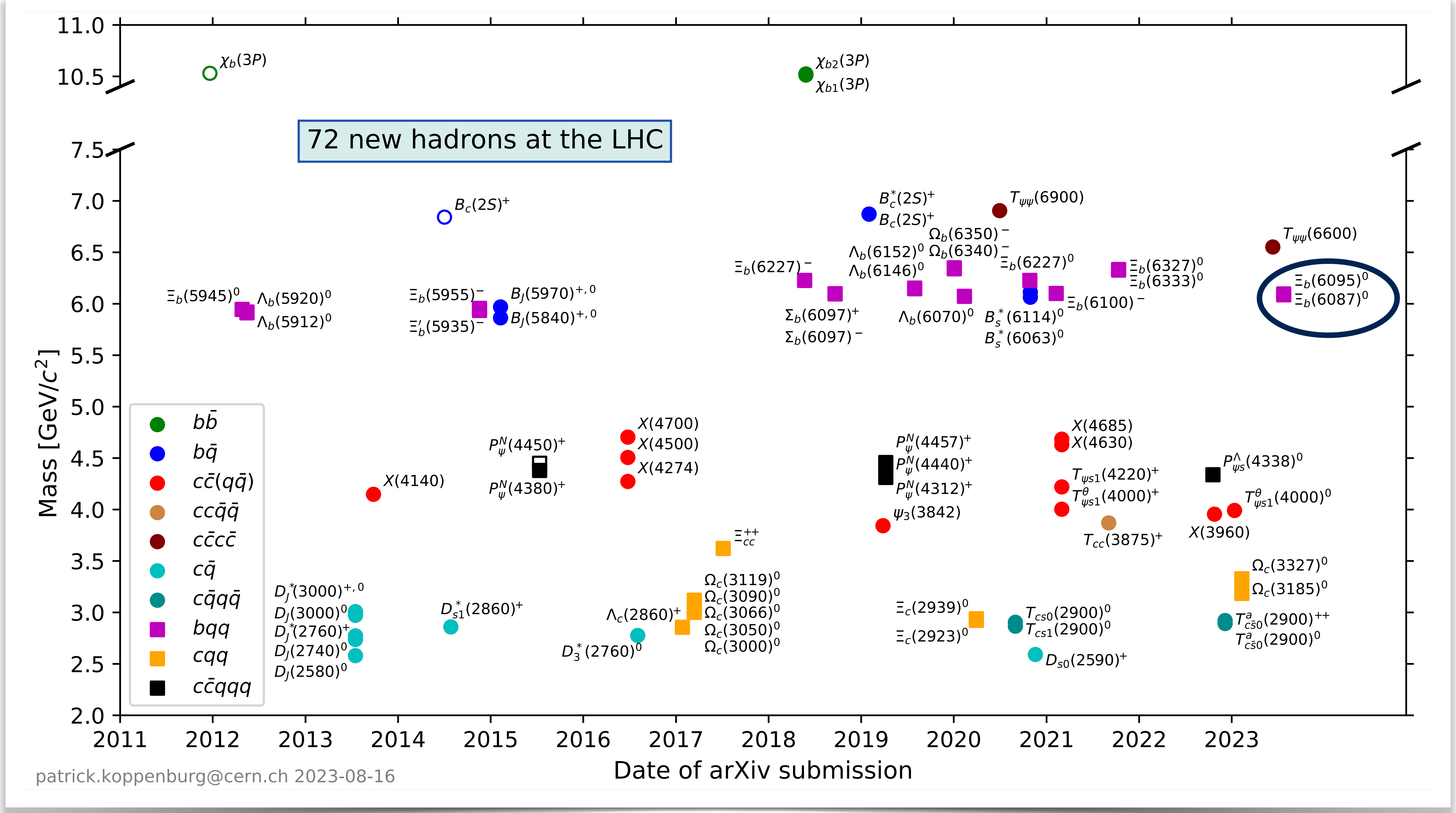
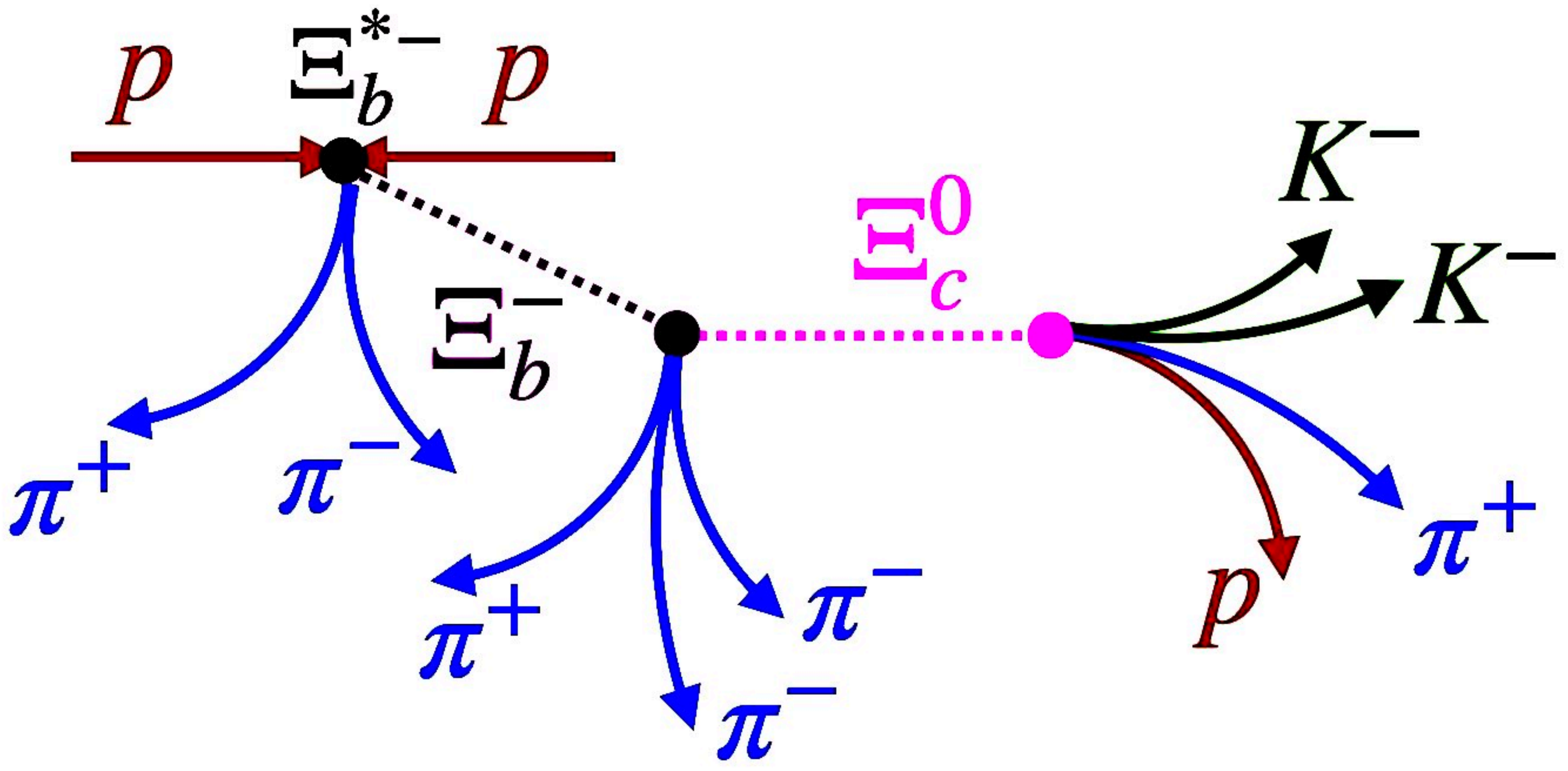
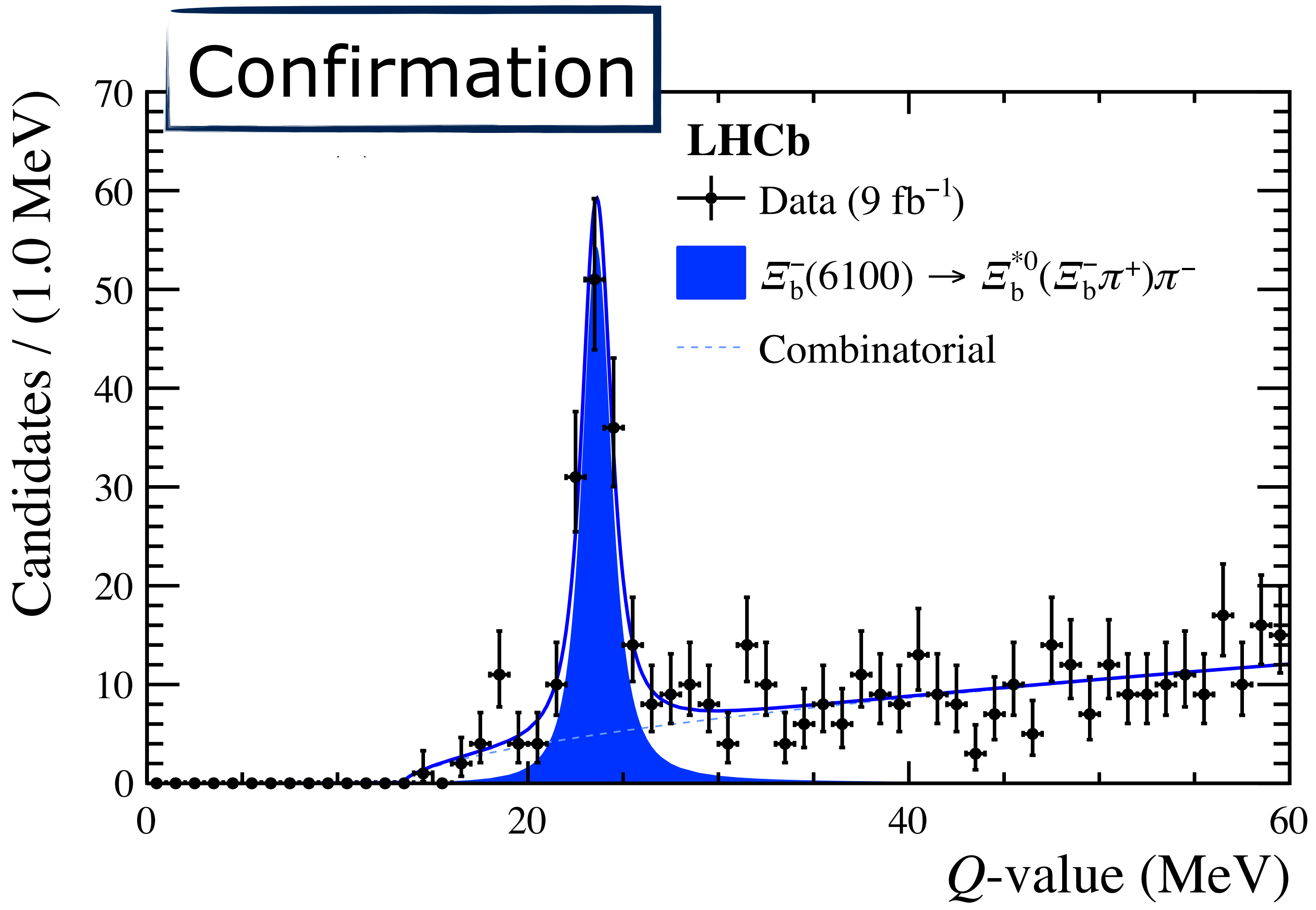


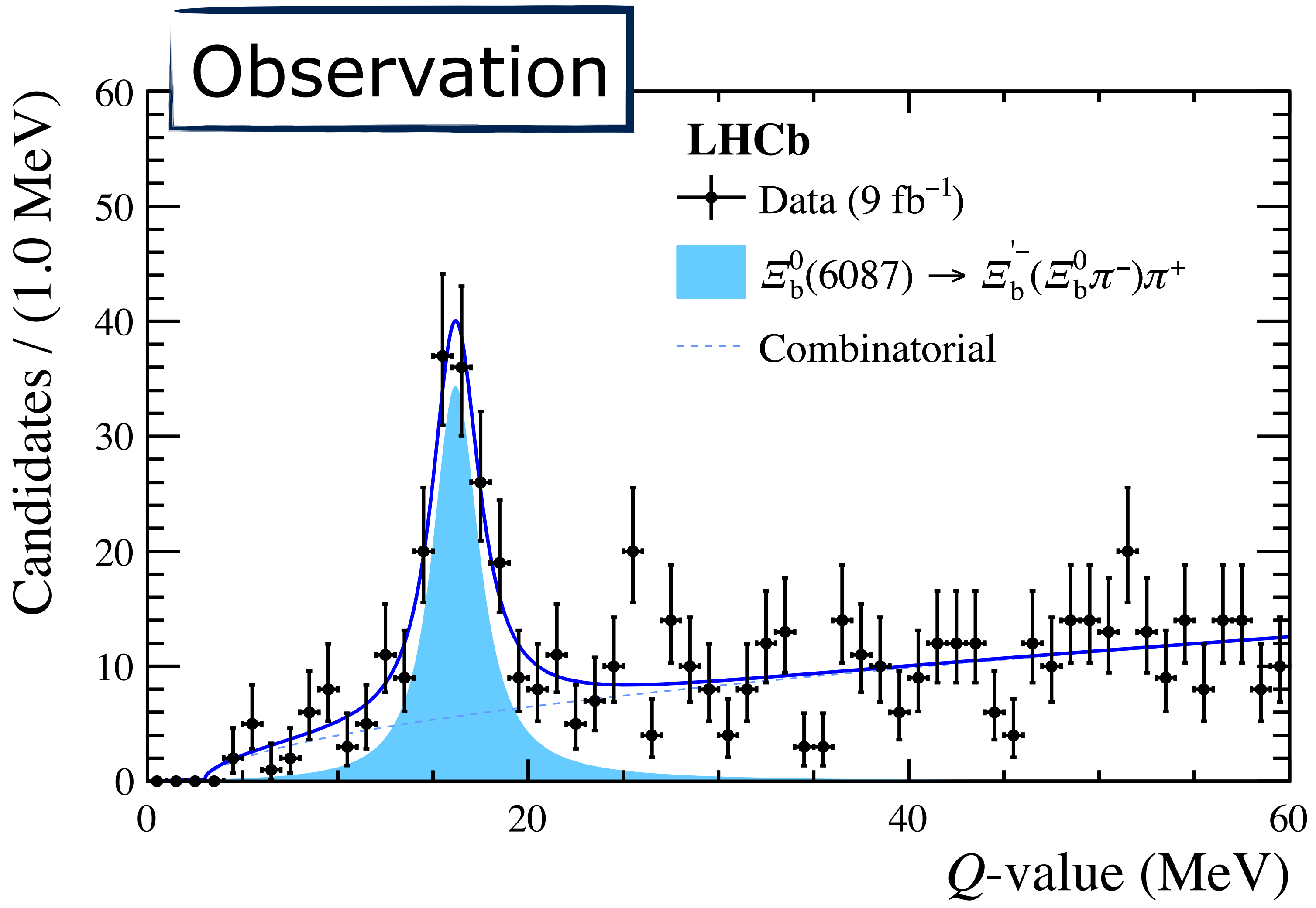
$\Xi_b^{(*)0/-}(bsq)$ baryons

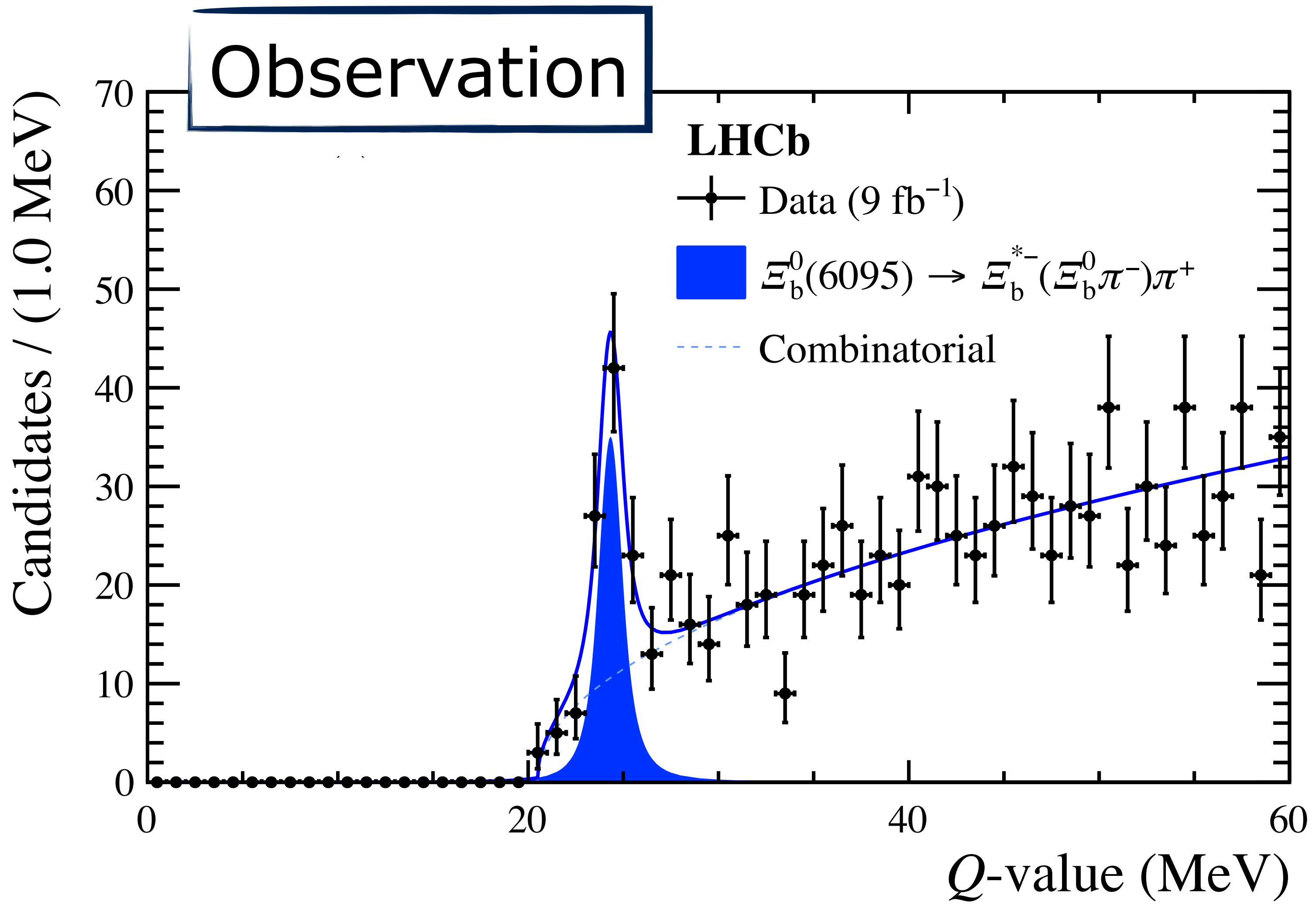
- Study through the $\Xi_b^{0/-}\pi\pi$ decay mode, up to 9 tracks involved!

[arXiv:2307.13399]









Tetraquarks

- The LHC has discovered **72 new hadrons**! (+ the Higgs boson)
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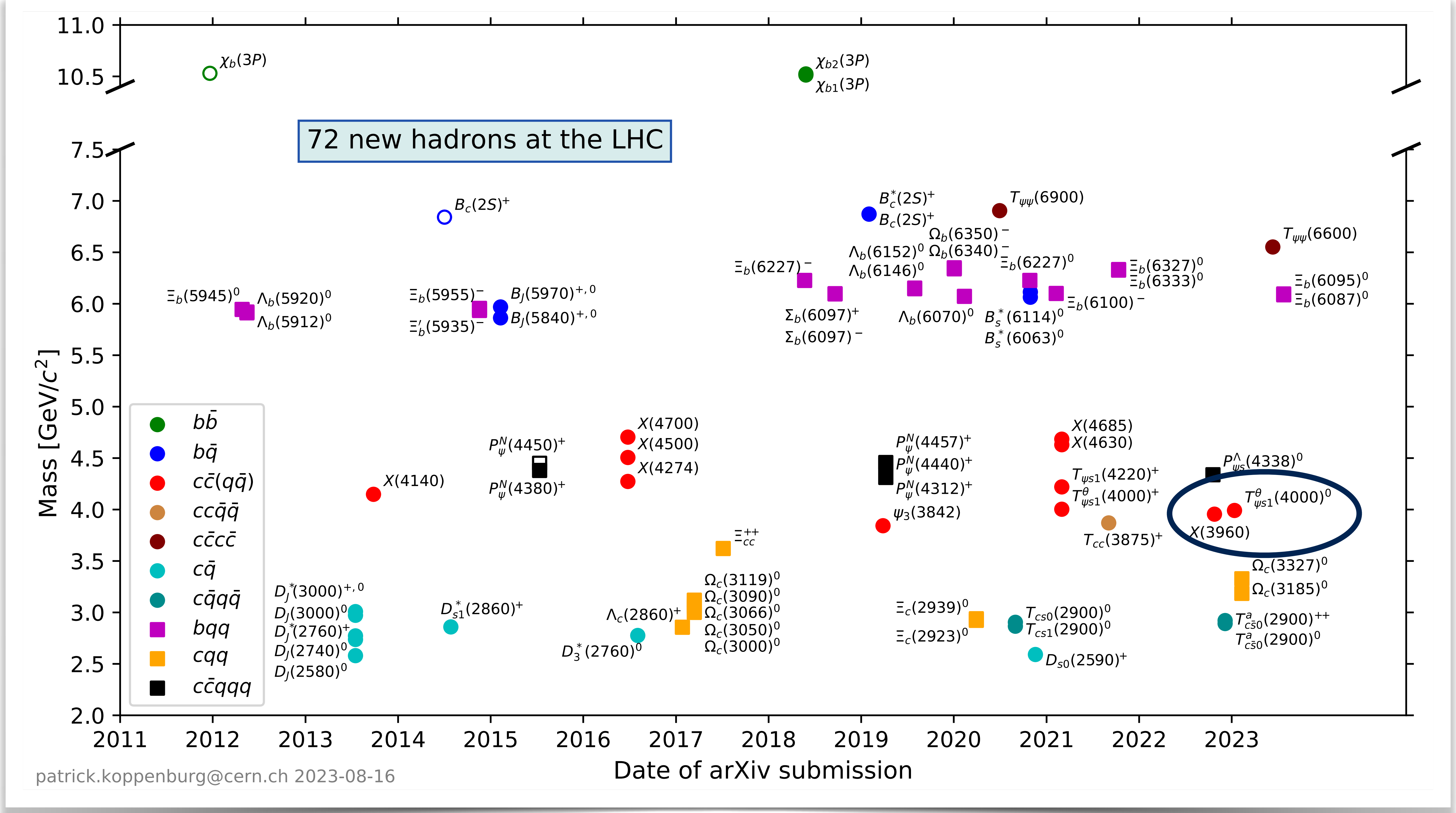
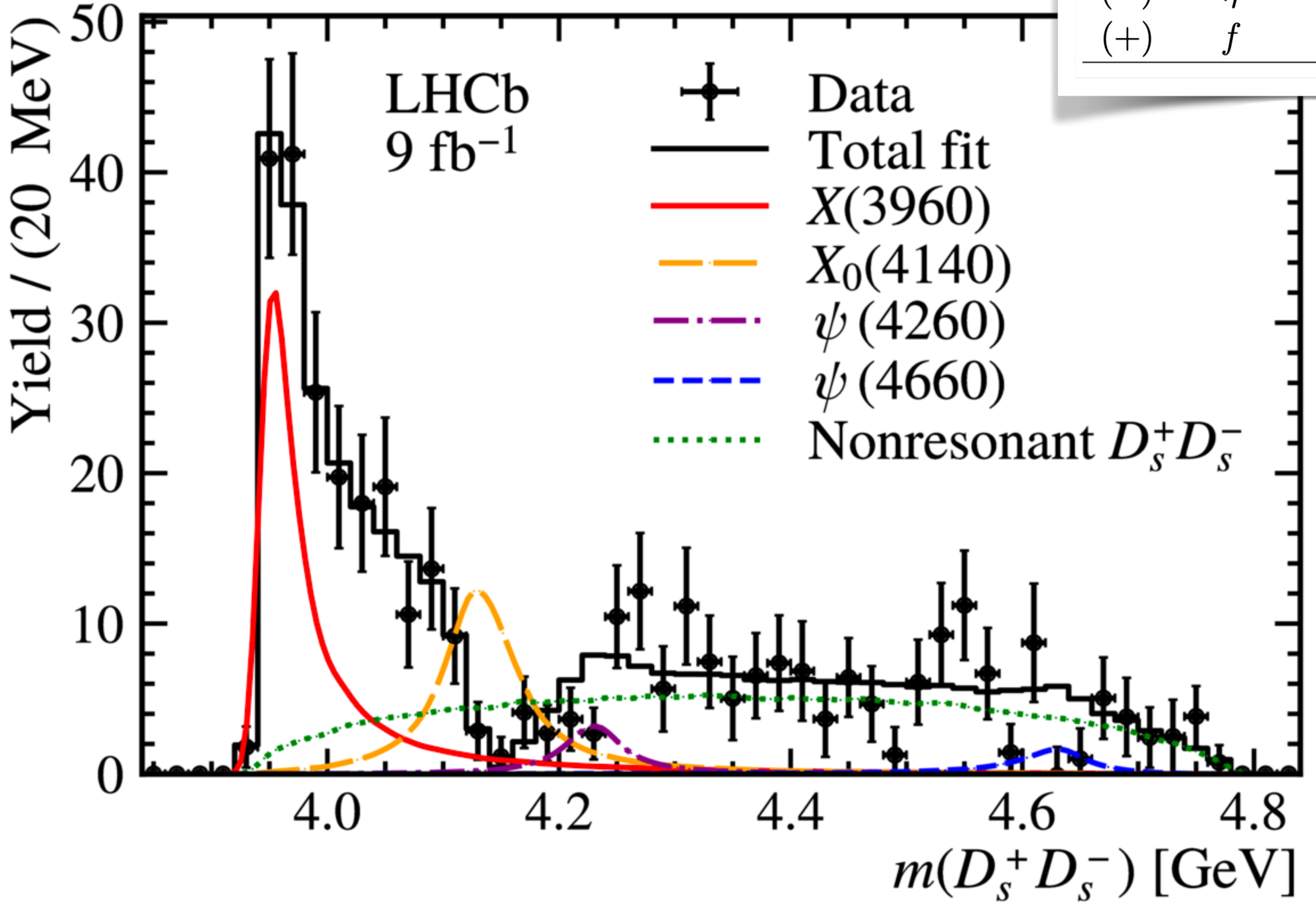


Tetraquarks

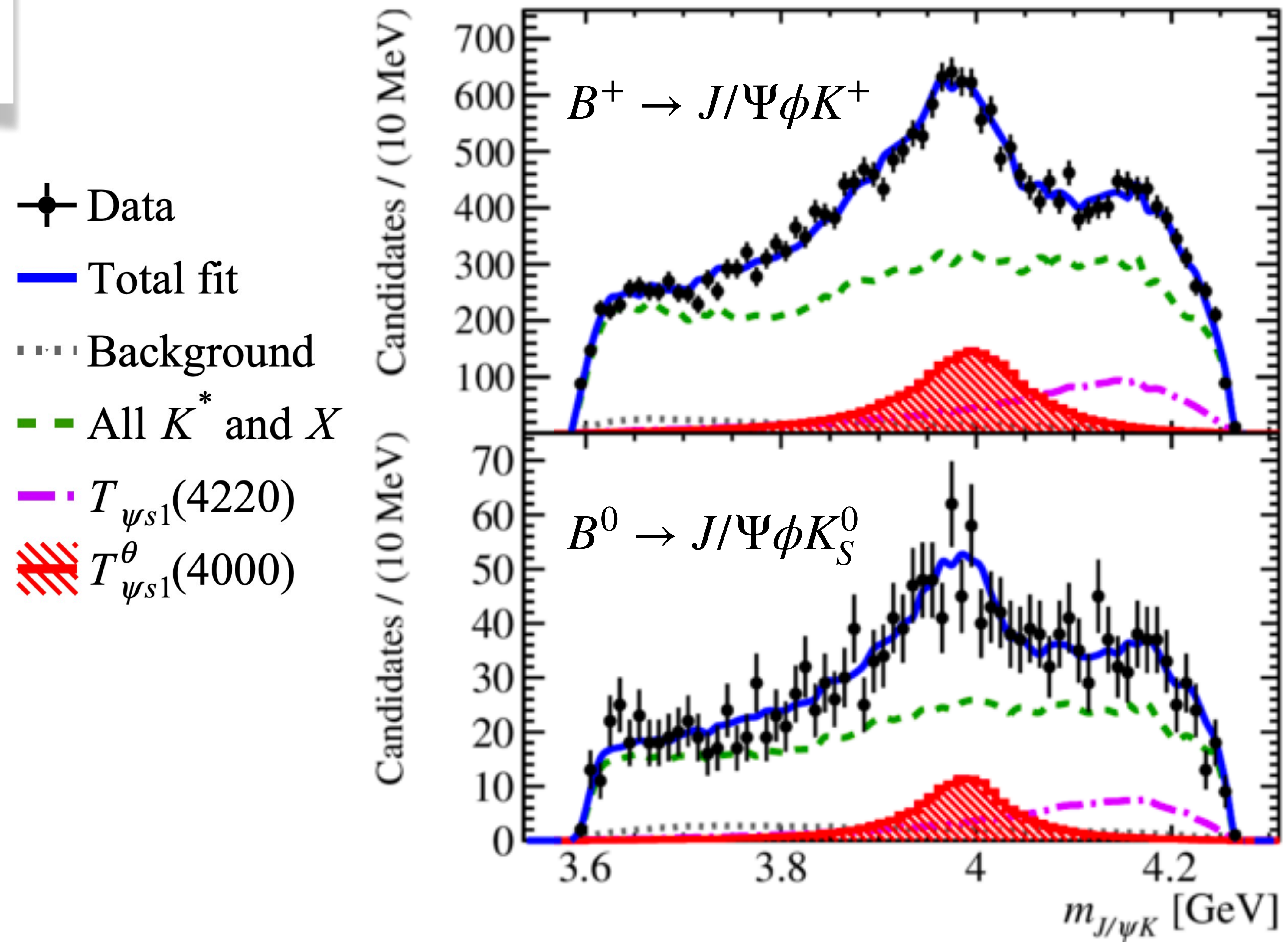
- X(3960) potential new tetraquark, would correspond to $T^{\theta}_{\psi\phi}$ $[c\bar{c}s\bar{s}]$
- New resonant structure, candidate for $T^{\theta}_{\psi s1}(4000)^0$ $[c\bar{c}d\bar{s}]$

[arXiv:2210.15153]

T states			
non-zero net S, C, B			
(P)	$I=0$	$I=\frac{1}{2}$	$I=1$
$(-)$	η	τ	π
$(+)$	f	θ	a



[arXiv:2301.04899]



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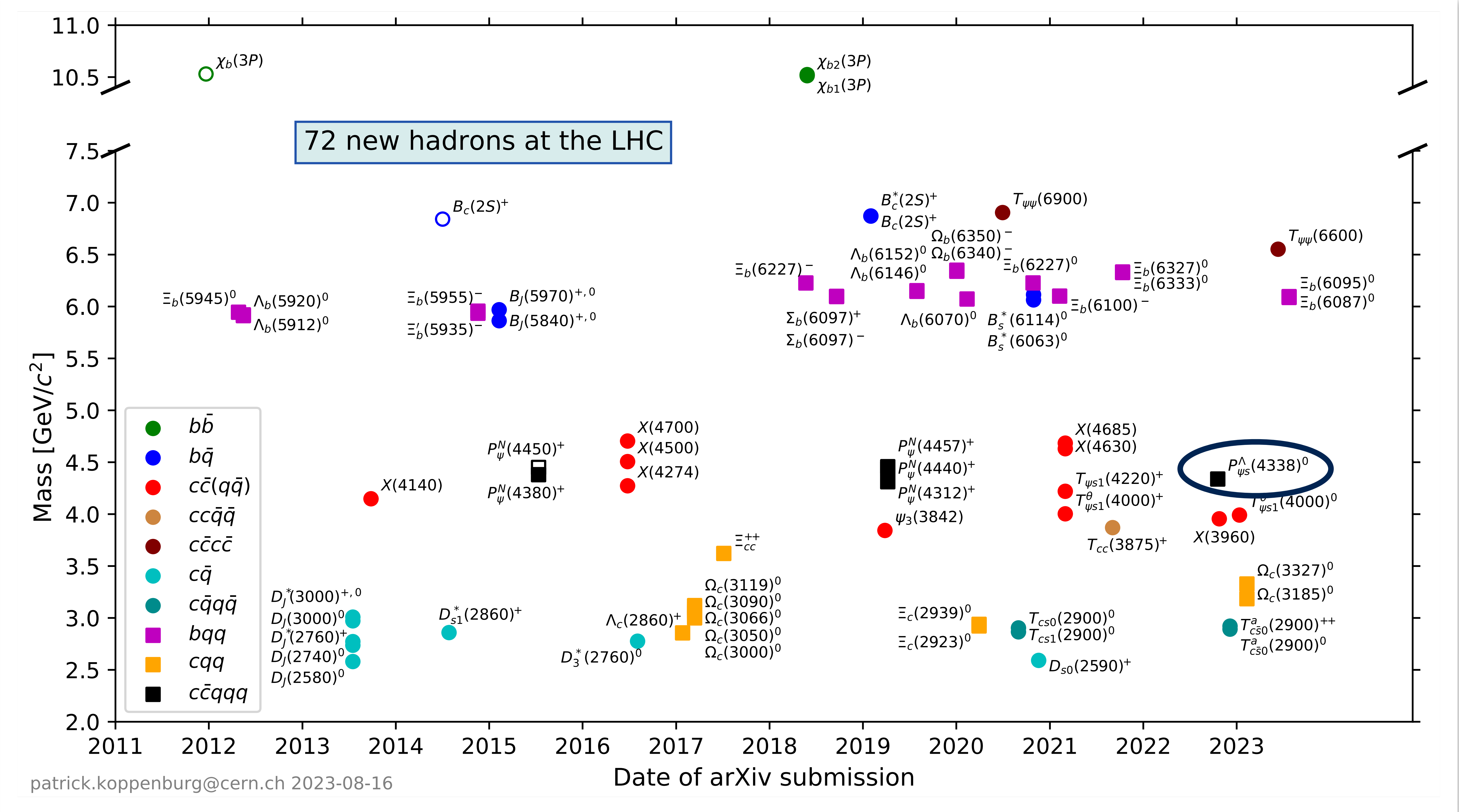
Pentaquarks

- The LHC has discovered **72 new hadrons**! (+ the Higgs boson)
  - ➡ These go beyond simple quark model, e.g., tetra and penta-quarks!

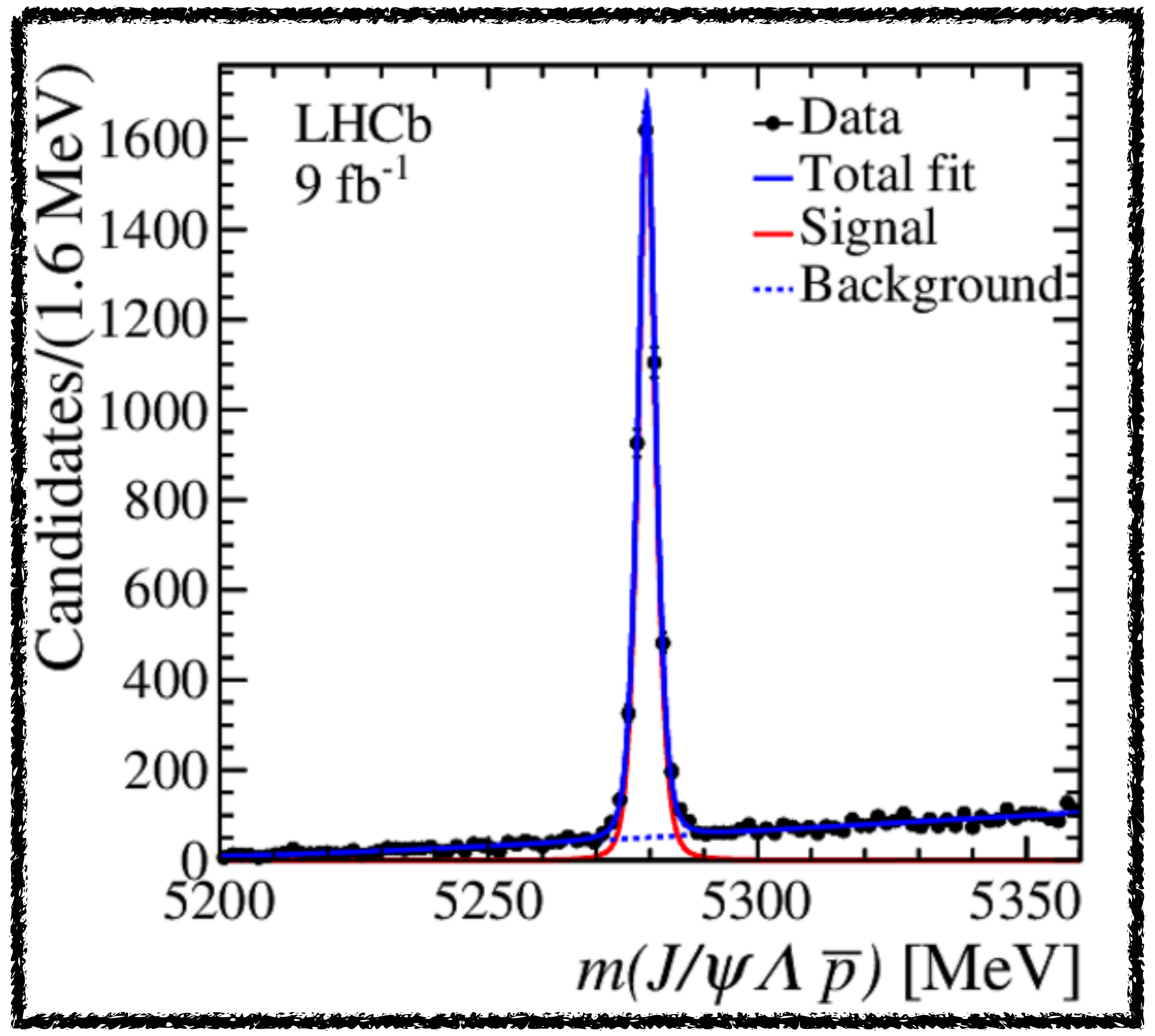


Pentaquarks

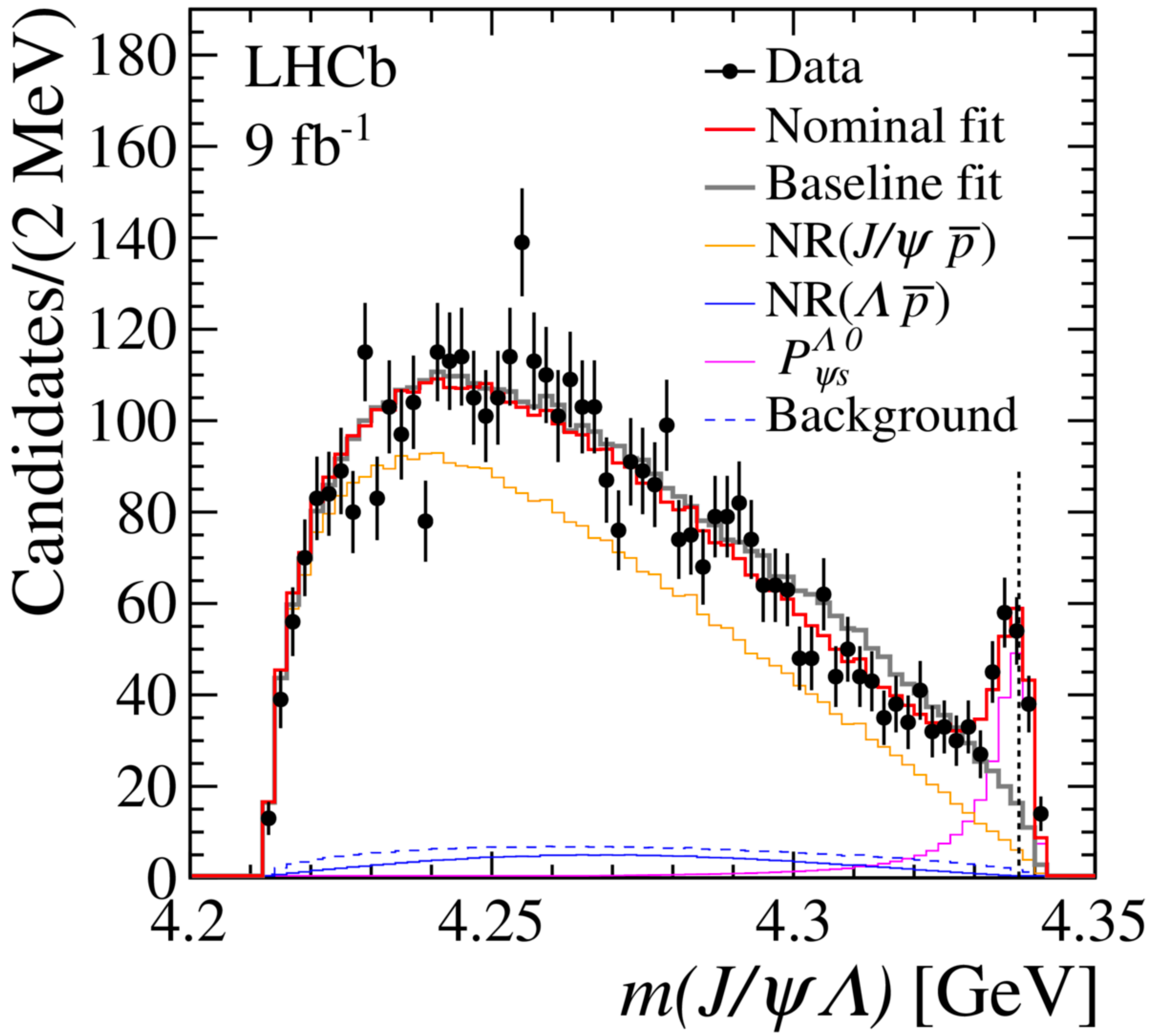
- First pentaquark with strangeness: $P_{\psi s}^{\Lambda}(4338)^0\ [c\bar{c}uds]$
  - Found through amplitude analysis of $B^- \to J/\Psi\Lambda\bar{p}$ decays, with LHCb Run 2 dataset
  - As a bonus, most precise measurement of the B- meson mass achieved (Q of decay very small):

P states			
$I=0$	$I=\frac{1}{2}$	$I=1$	$I=\frac{3}{2}$
Λ	N	Σ	Δ

[arXiv:2210.10346]



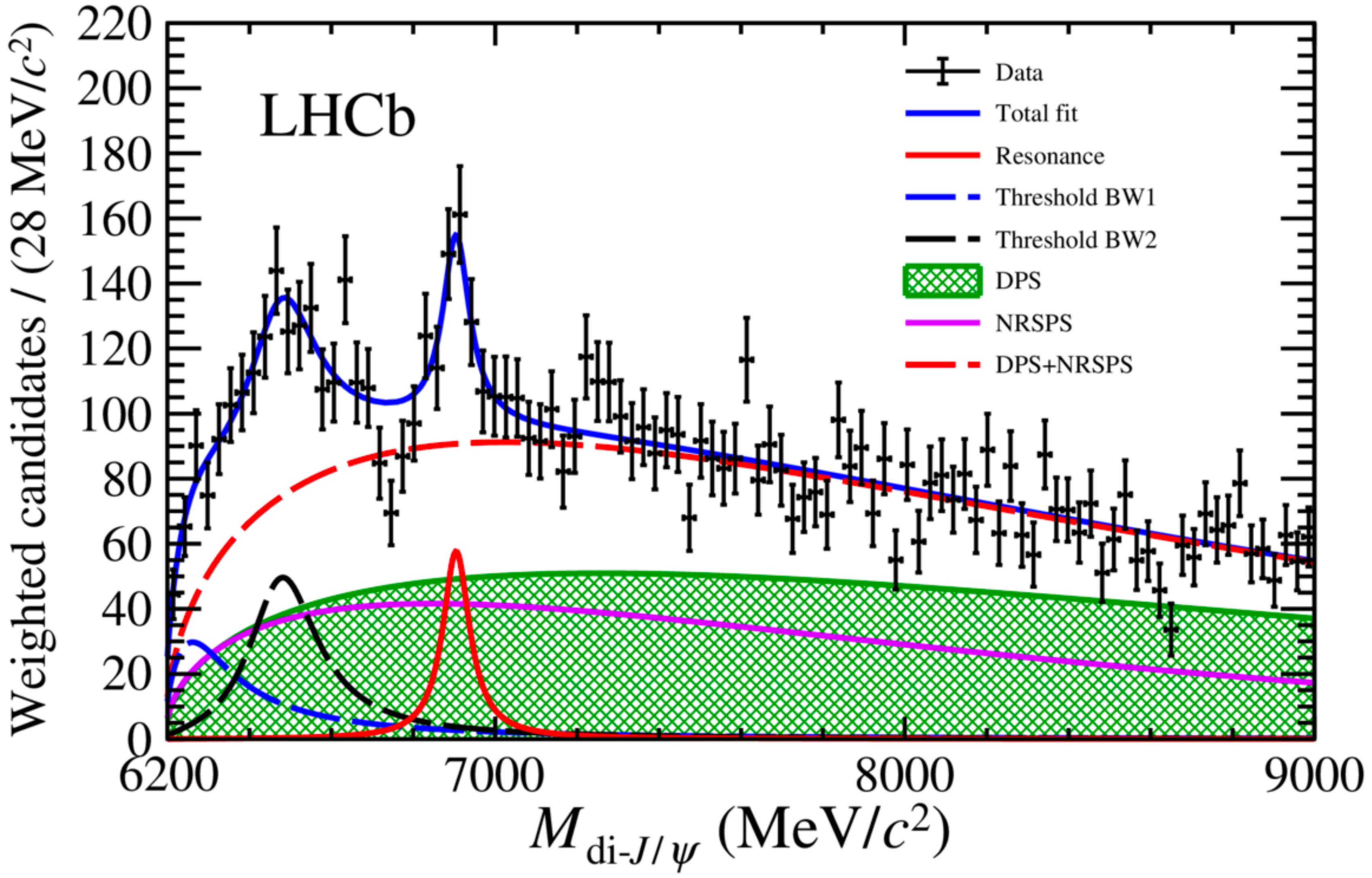
$$m(B^-) = (5279.44 \pm 0.05(\text{stat.}) \pm 0.07(\text{syst.}))\ \text{MeV}$$



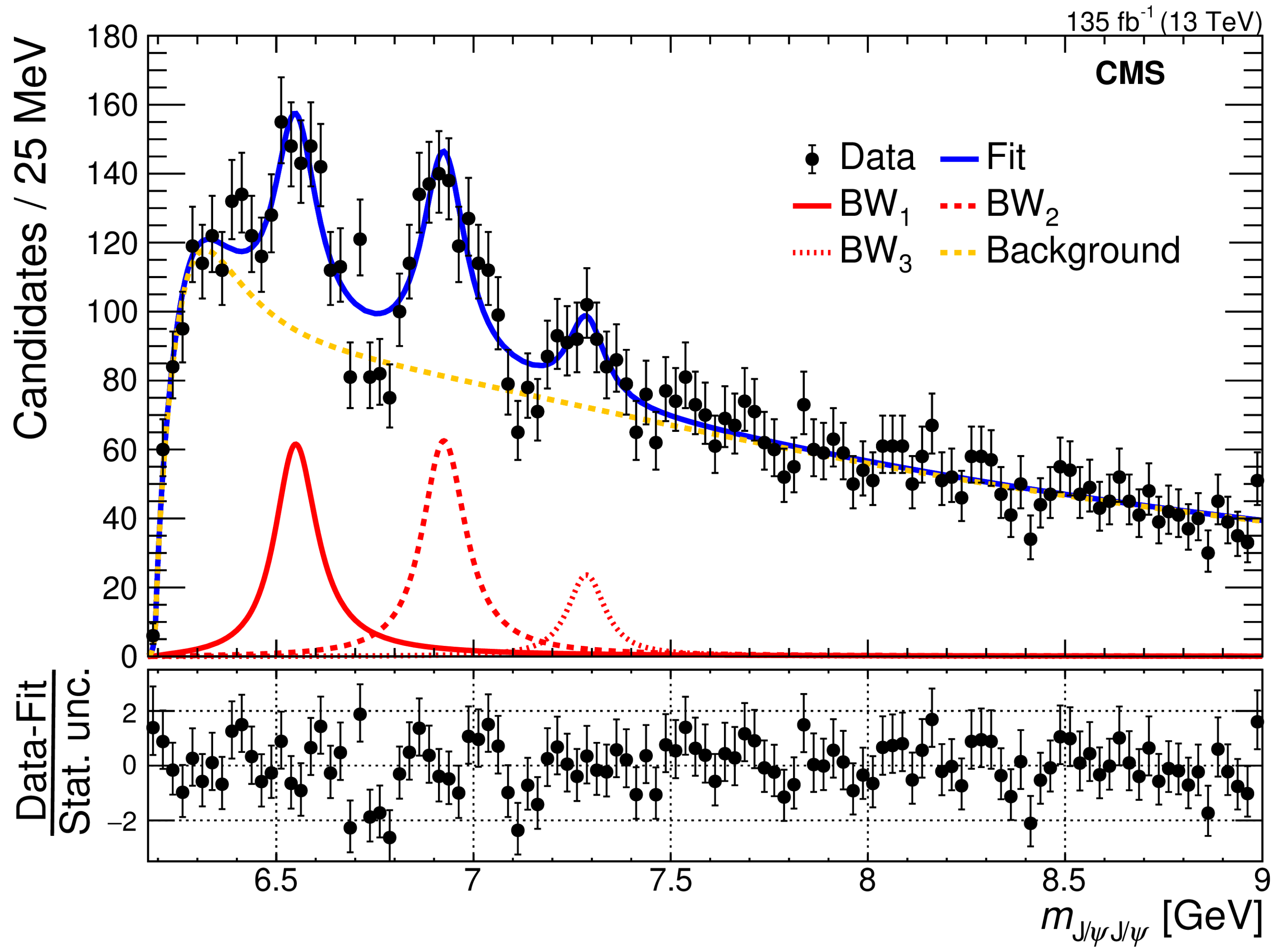
Di-J/Ψ puzzle

- New structures in the di-J/Ψ spectrum observed by LHCb, CMS and ATLAS
  - ➡ More refined analysis required to clearly determine their nature! One or several structures? Widths? Interference?

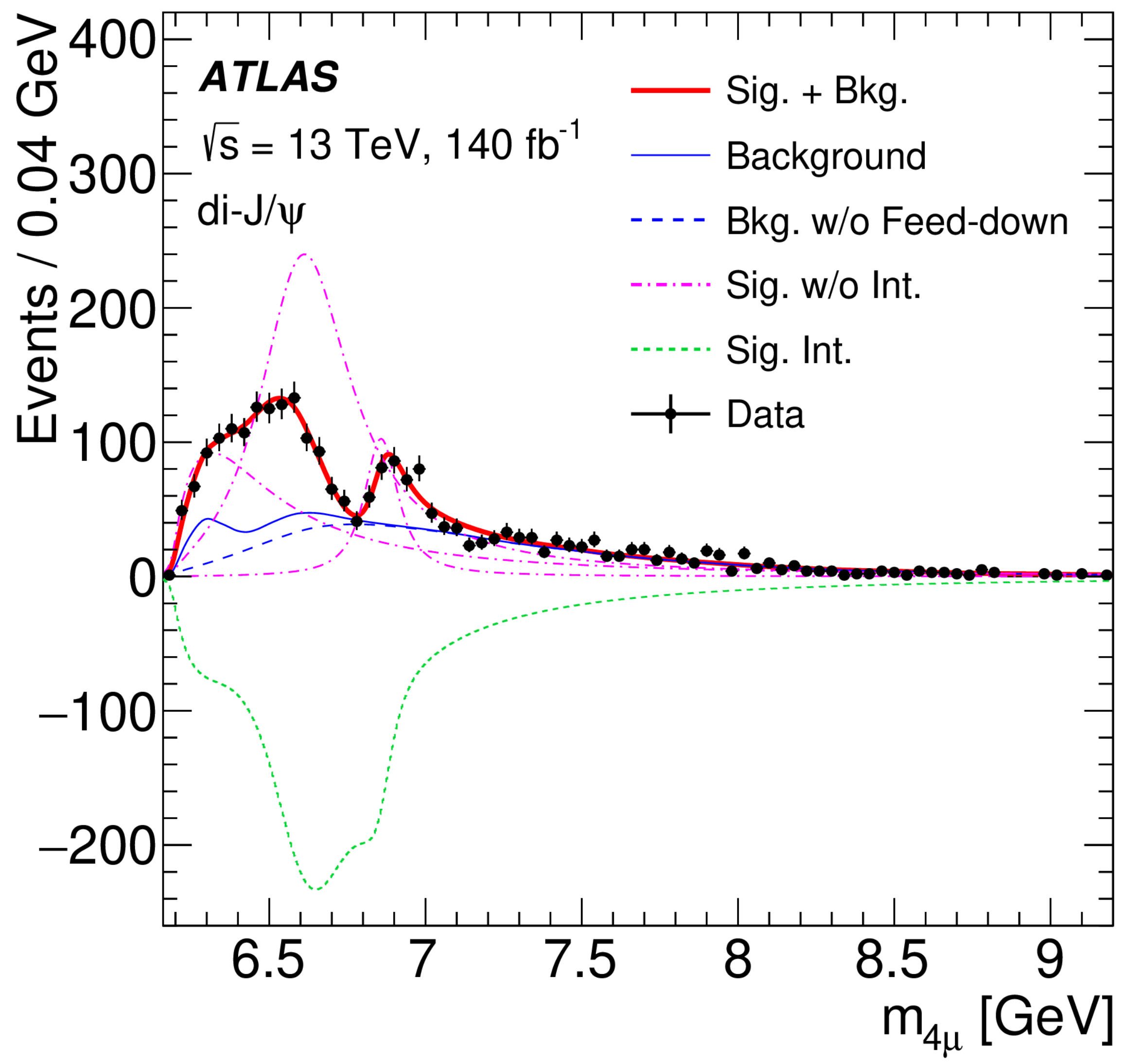
LHCb [arXiv:2006.16957]



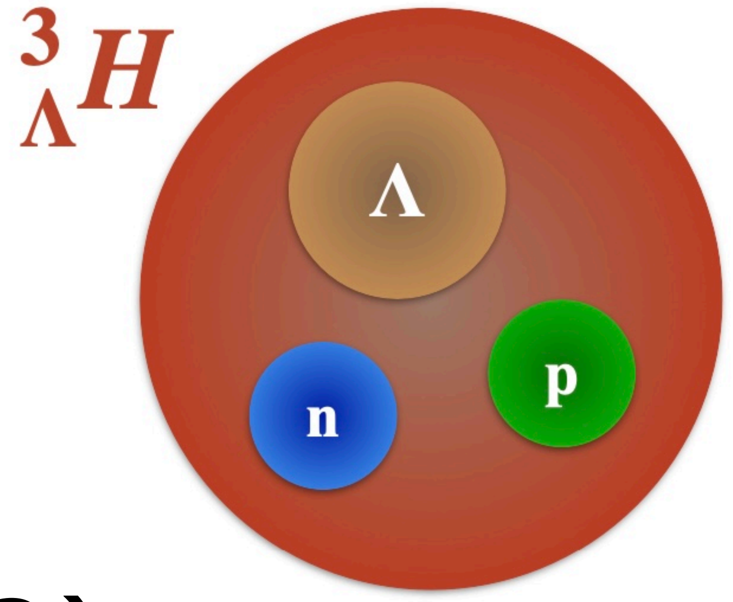
CMS [arXiv:2306.07164]



ATLAS EXPERIMENT [arXiv:2304.08962]

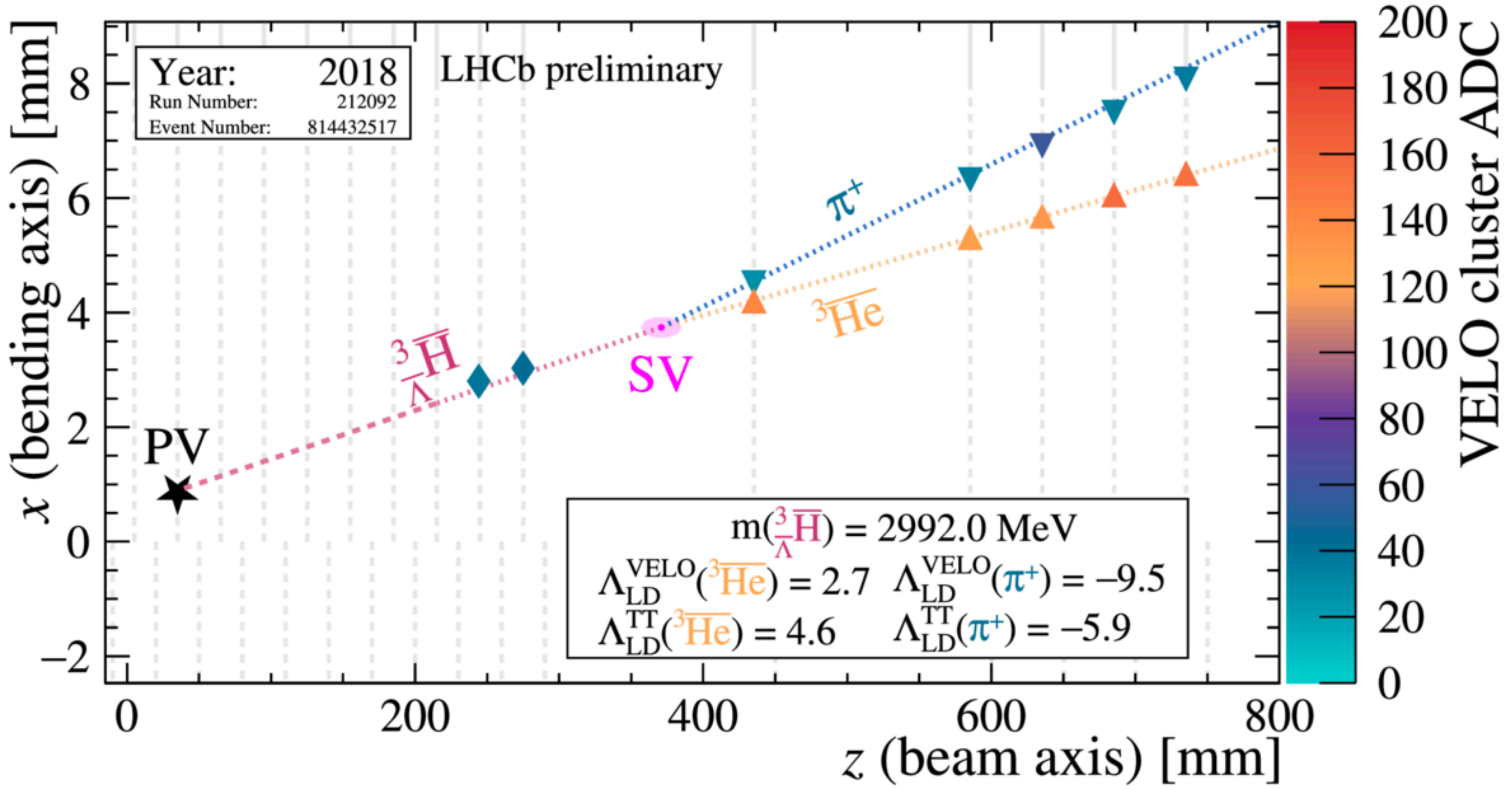


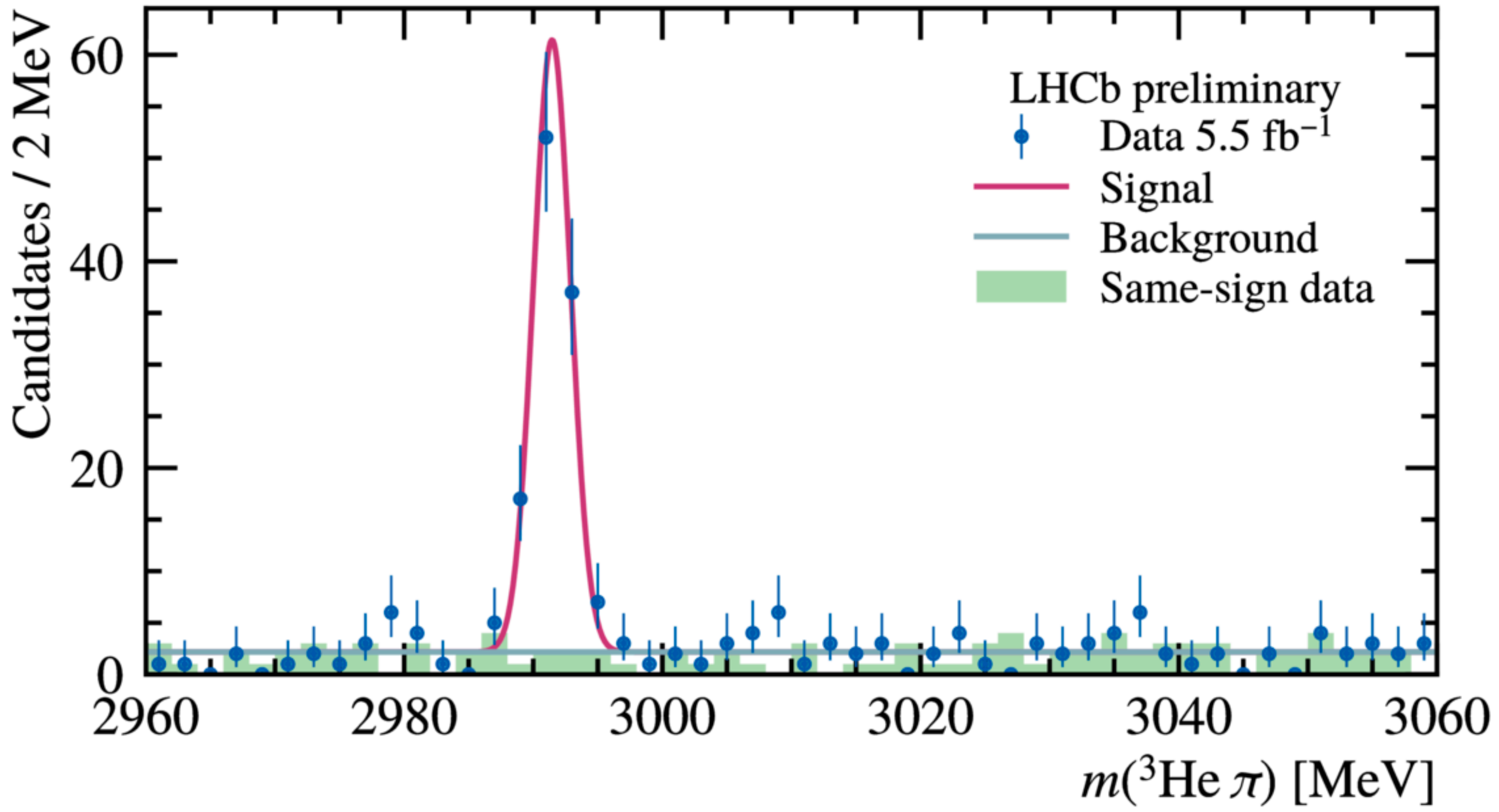
Hypertriton $^{3}_{\Lambda}H$



- A hypertriton is a neutron, proton, and hyperon bound state.
  - Study important for neutron star and QCD.
  - Reconstructed with $^{3}_{\Lambda}H \rightarrow ^{3}He\pi$ decays in pp collisions (Run 2).
  - Uses drift time and ionization energy in silicon trackers. Large signals are left by doubly charged ^{3}He nuclei.

[LHCb-CONF-2023-002]





Introduction

CKM metrology

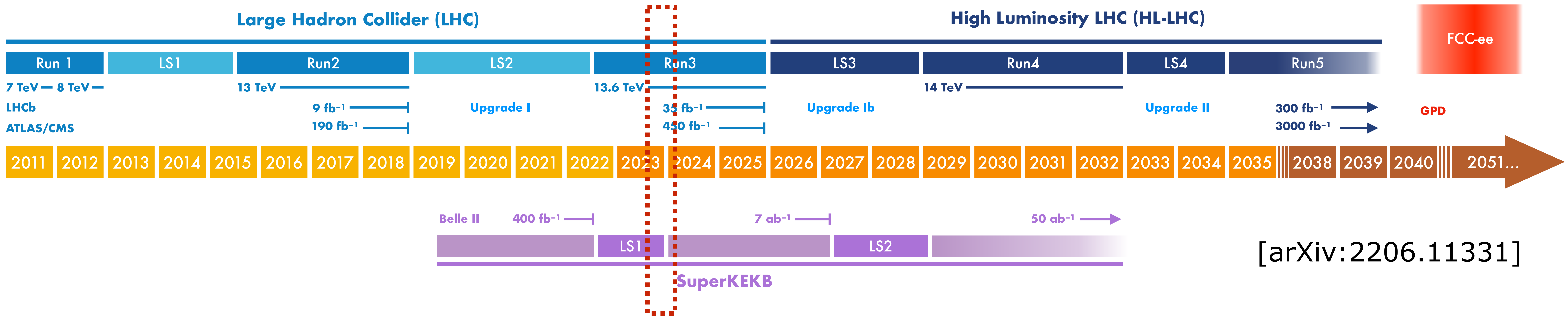
Rare and SL decays

Spectroscopy

Future

Conclusions

Looking at next decades



[arXiv:2206.11331]

- Huge amount of data ahead of us to continue doing good physics
  - Complementarity not only between LHCb and Belle II, but also with ATLAS and CMS. Differences provided by different machines!
  - In any case, existing overlap allows for cross-checks.
  - Also, big challenges to be faced, commissioning a new detector requires patience! (We know at LHCb and Belle II)

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Future sensitivities...

Belle II [arXiv:2203.11349]

Observable	2022 Belle(II), BaBar	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°
α/ϕ_2 (WA)	4°	2°	0.6°
$\|V_{ub}\|$ (Exclusive)	4.5%	2%	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035
$R(B \to K^* \ell^+ \ell^-)^\dagger$	0.26	0.09	0.03
$R(B \to D^* \tau\nu)$	0.018	0.009	0.0045
$R(B \to D \tau\nu)$	0.034	0.016	0.008
$\mathcal{B}(B \to \tau\nu)$	24%	9%	4%
$B(B \to K^* \nu\bar{\nu})$	—	25%	9%
$\mathcal{B}(\tau \to \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}

LHCb [LHCb Upgrade II FTDR (LHCb-TDR-023)]

Observable	Current LHCb (up to 9 fb^{-1})		Upgrade I (23 fb^{-1})	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
CKM tests					
γ ($B \to DK$, *etc.*)	4°	[9, 10]	1.5°	1°	0.35°
ϕ_s ($B^0_s \to J/\psi\phi$)	32 mrad	[8]	14 mrad	10 mrad	4 mrad
$\|V_{ub}\|/\|V_{cb}\|$ ($\Lambda^0_b \to p\mu^-\bar{\nu}_\mu$, *etc.*)	6%	[29, 30]	3%	2%	1%
a^d_{sl} ($B^0 \to D^-\mu^+\nu_\mu$)	36×10^{-4}	[34]	8×10^{-4}	5×10^{-4}	2×10^{-4}
a^s_{sl} ($B^0_s \to D^-_s\mu^+\nu_\mu$)	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 ($D^0 \to K^0_S\pi^+\pi^-$)	18×10^{-5}	[37]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare Decays					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	69%	[40, 41]	41%	27%	11%
$S_{\mu\mu}$ ($B^0_s \to \mu^+\mu^-$)	—		—	—	0.2
$A^{(2)}_{T}$ ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
A^{Im}_{T} ($B^0 \to K^{*0}e^+e^-$)	0.10	[52]	0.060	0.043	0.016
$\mathcal{A}^{\Delta\Gamma}_{\phi\gamma}(B^0_s \to \phi\gamma)$	${}^{+0.41}_{-0.44}$	[51]	0.124	0.083	0.033
$S_{\phi\gamma}(B^0_s \to \phi\gamma)$	0.32	[51]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda^0_b \to \Lambda\gamma)$	${}^{+0.17}_{-0.29}$	[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

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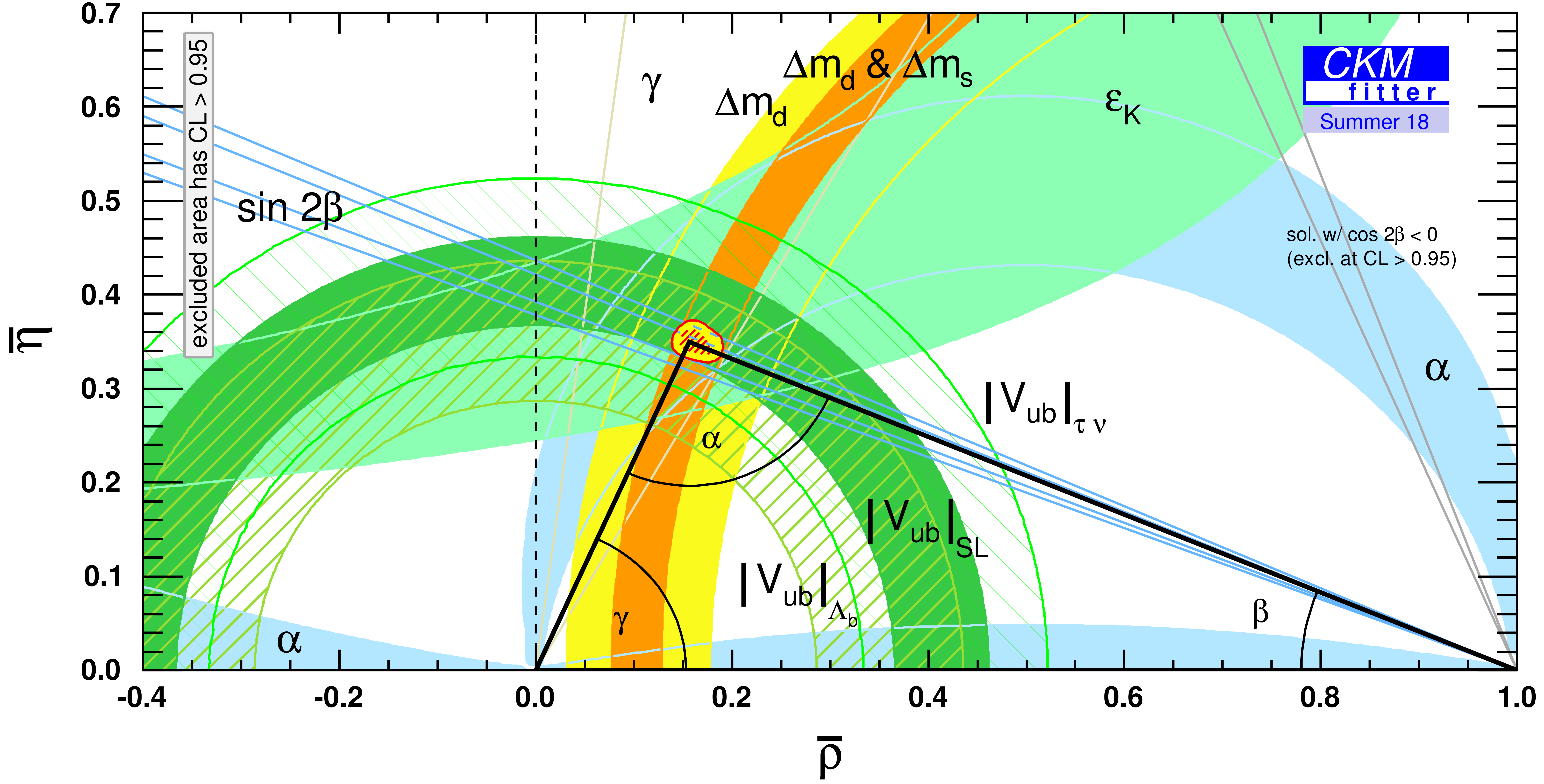
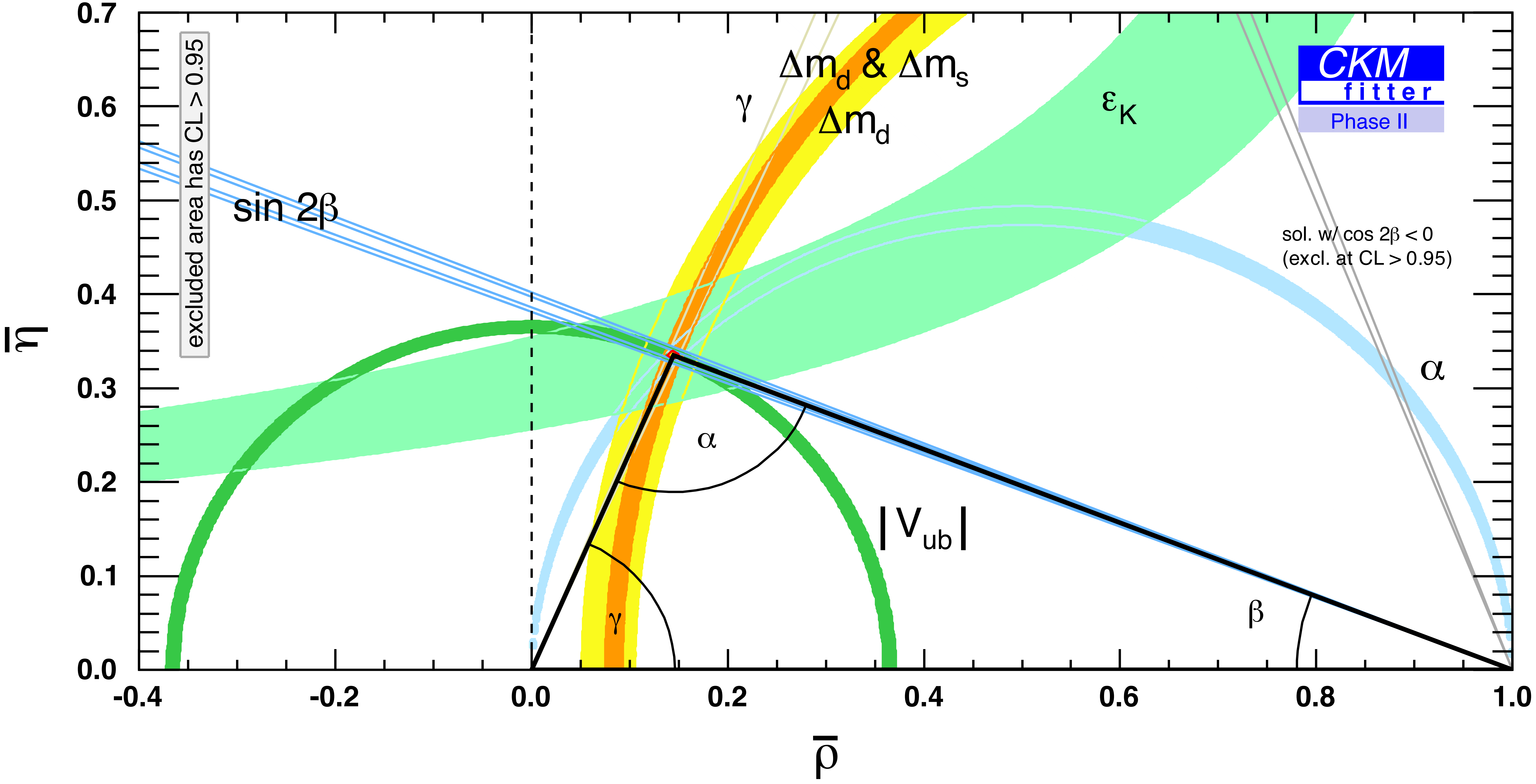
A graphical example

[arXiv:1812.07638]



A graphical example

[arXiv:1812.07638]



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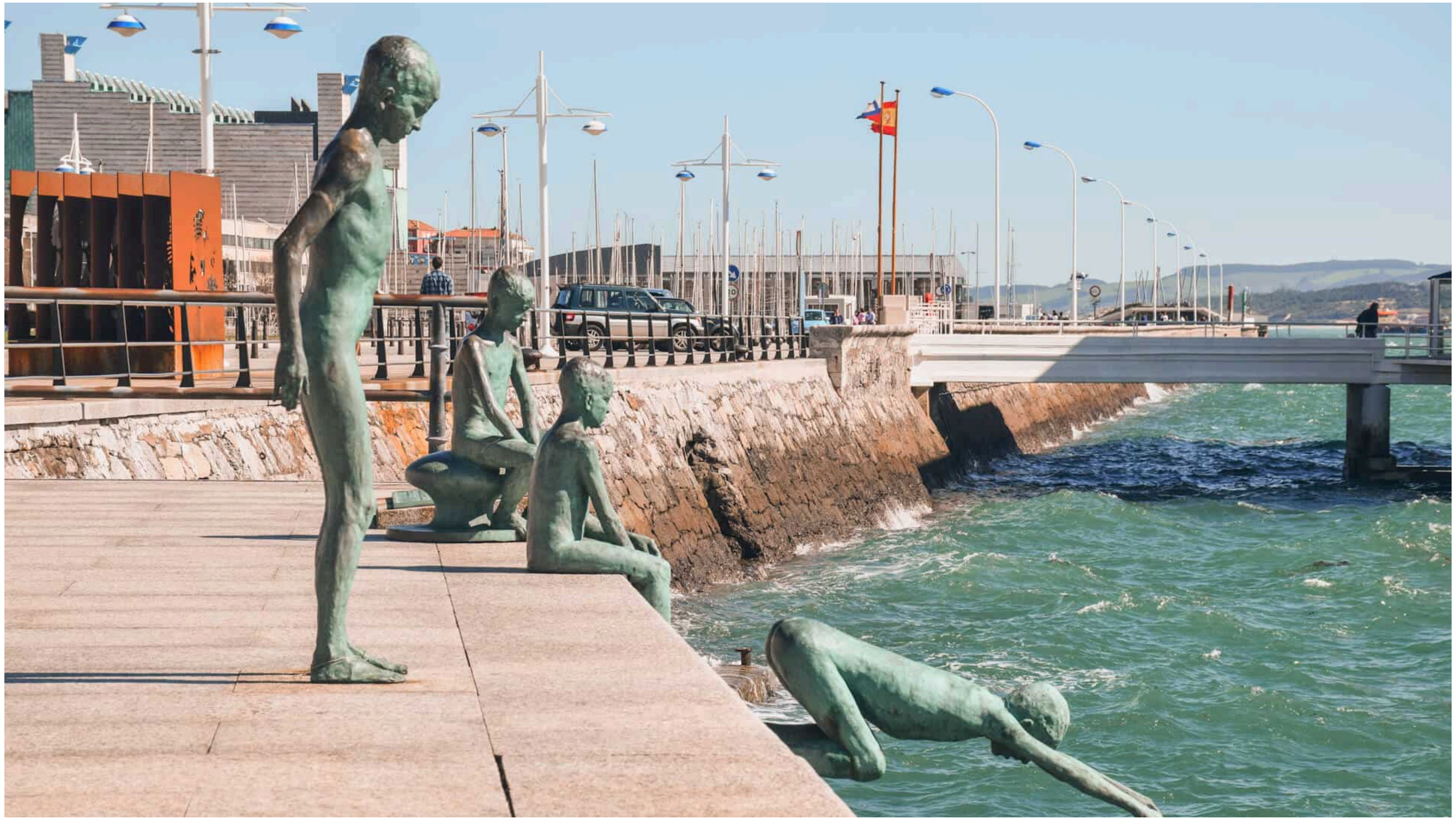


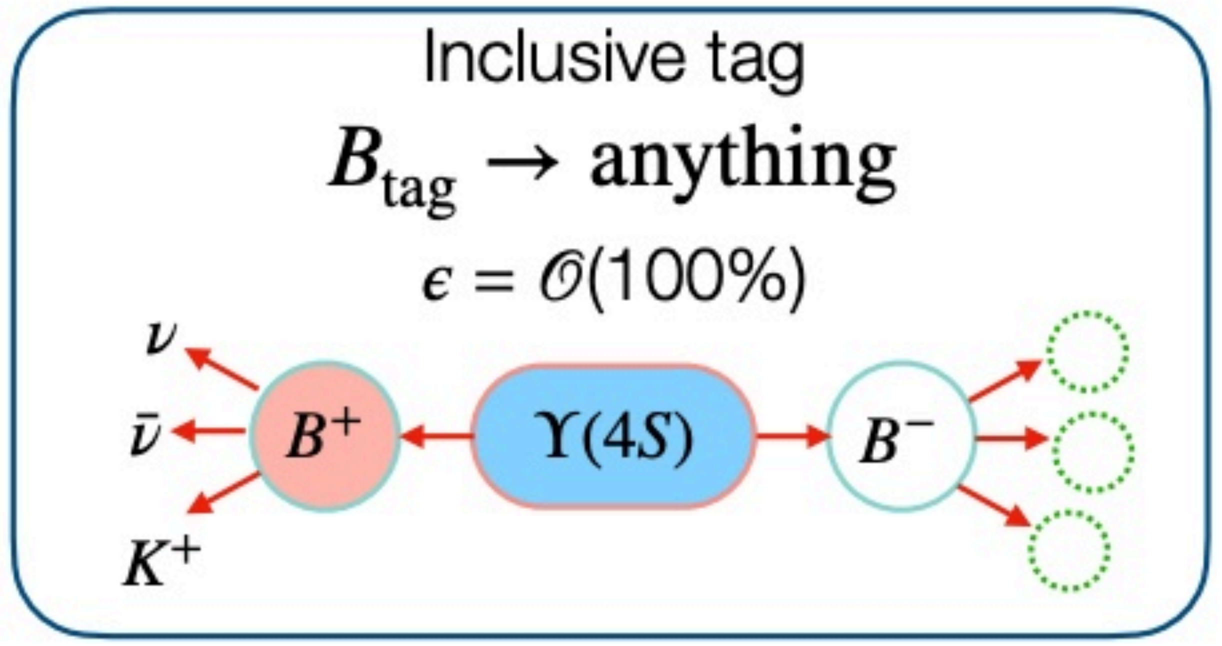
Raqueros de Santander

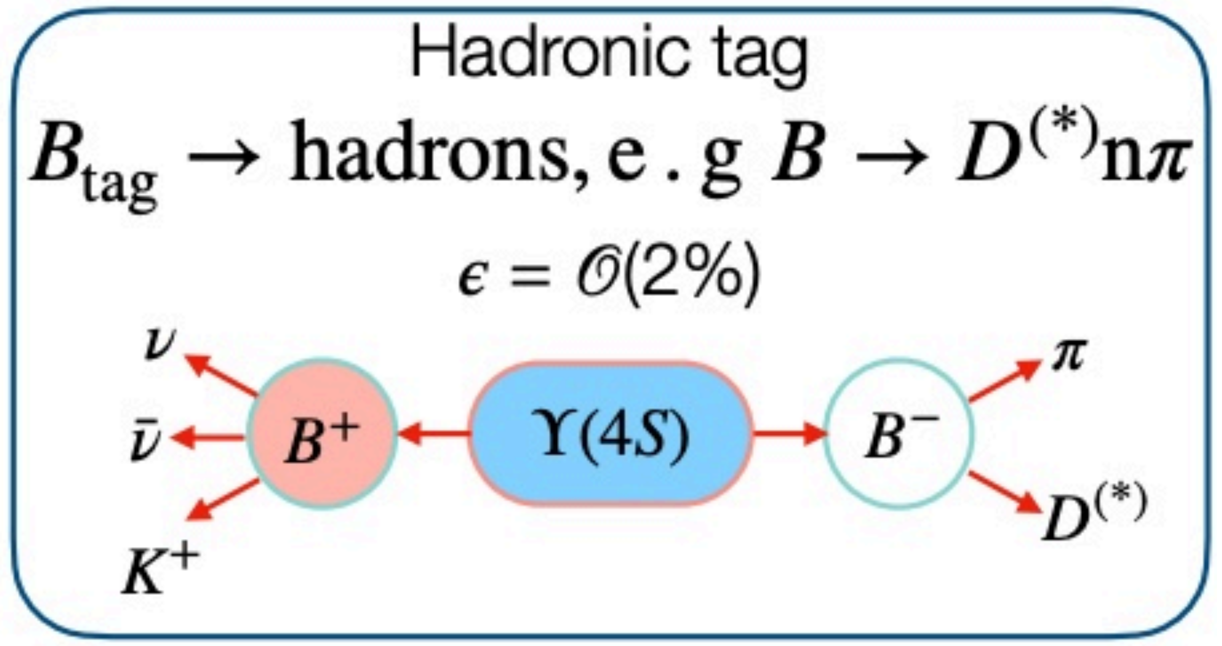
Conclusions

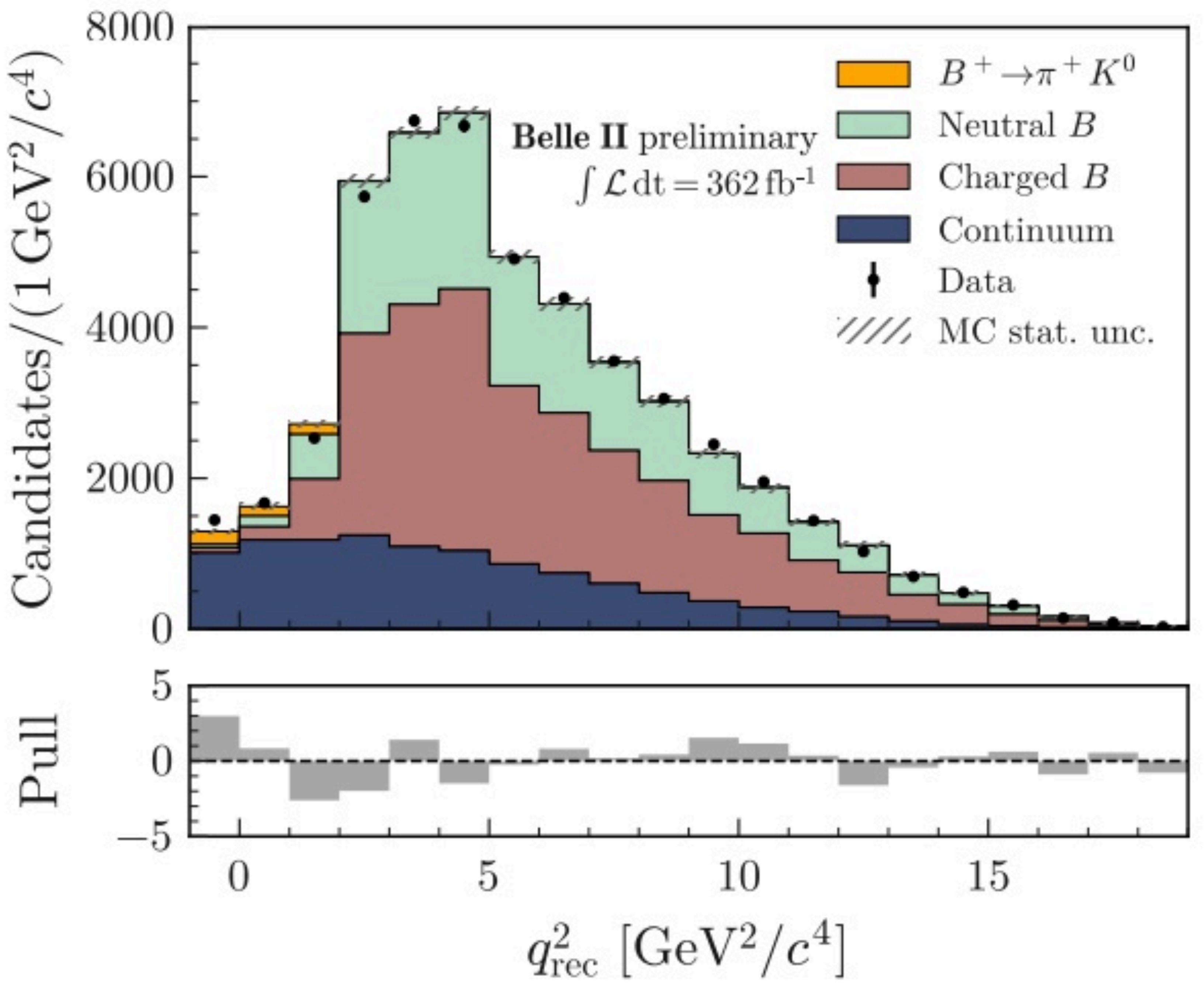
Conclusions

Backup

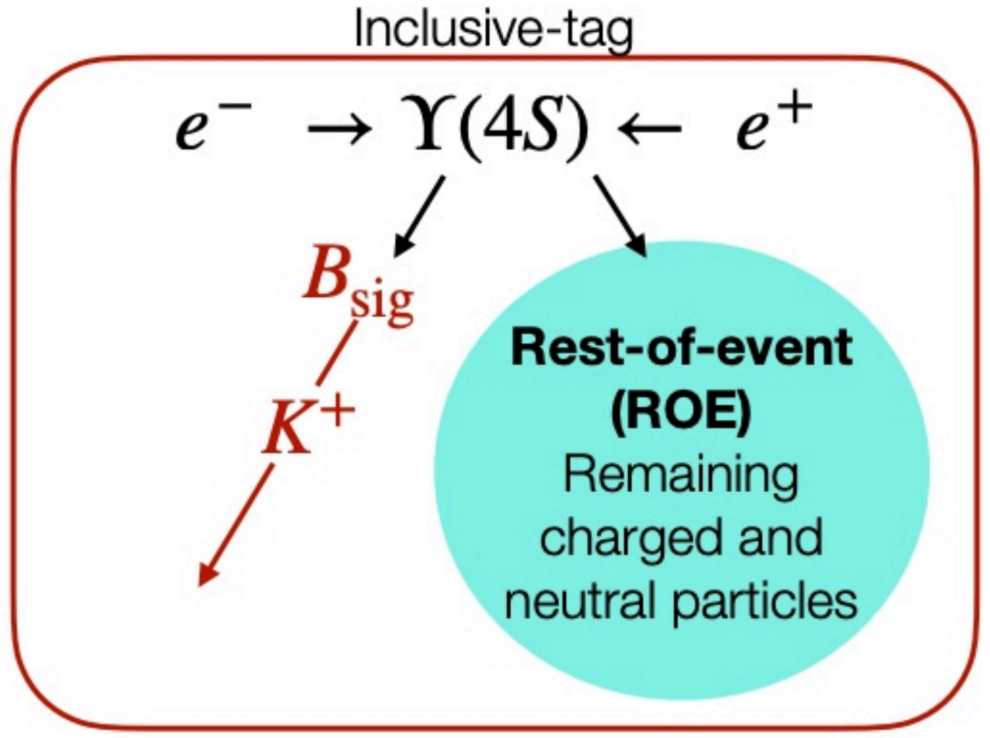
Details on $B^+ \to K^+ \nu\nu$

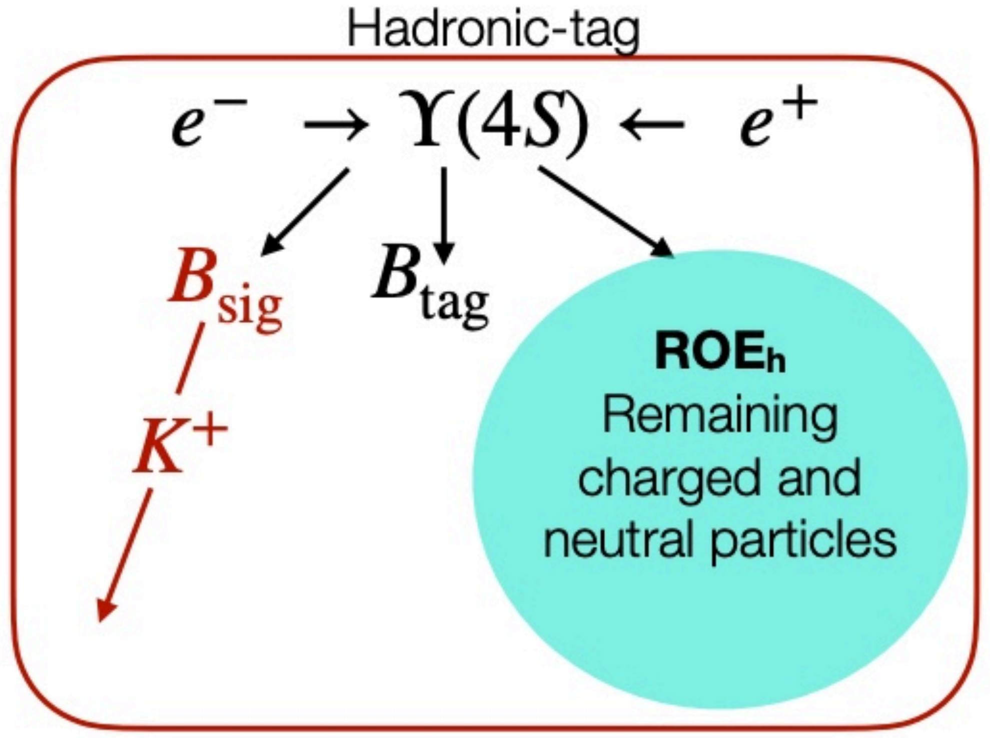






Closure test: recover expected $\mathscr{B}(B^+ \to \pi^+ K^0)$!





BF($B^+ \to \pi^+ K^0$) = (2.5 ± 0.5) x 10^{-5}

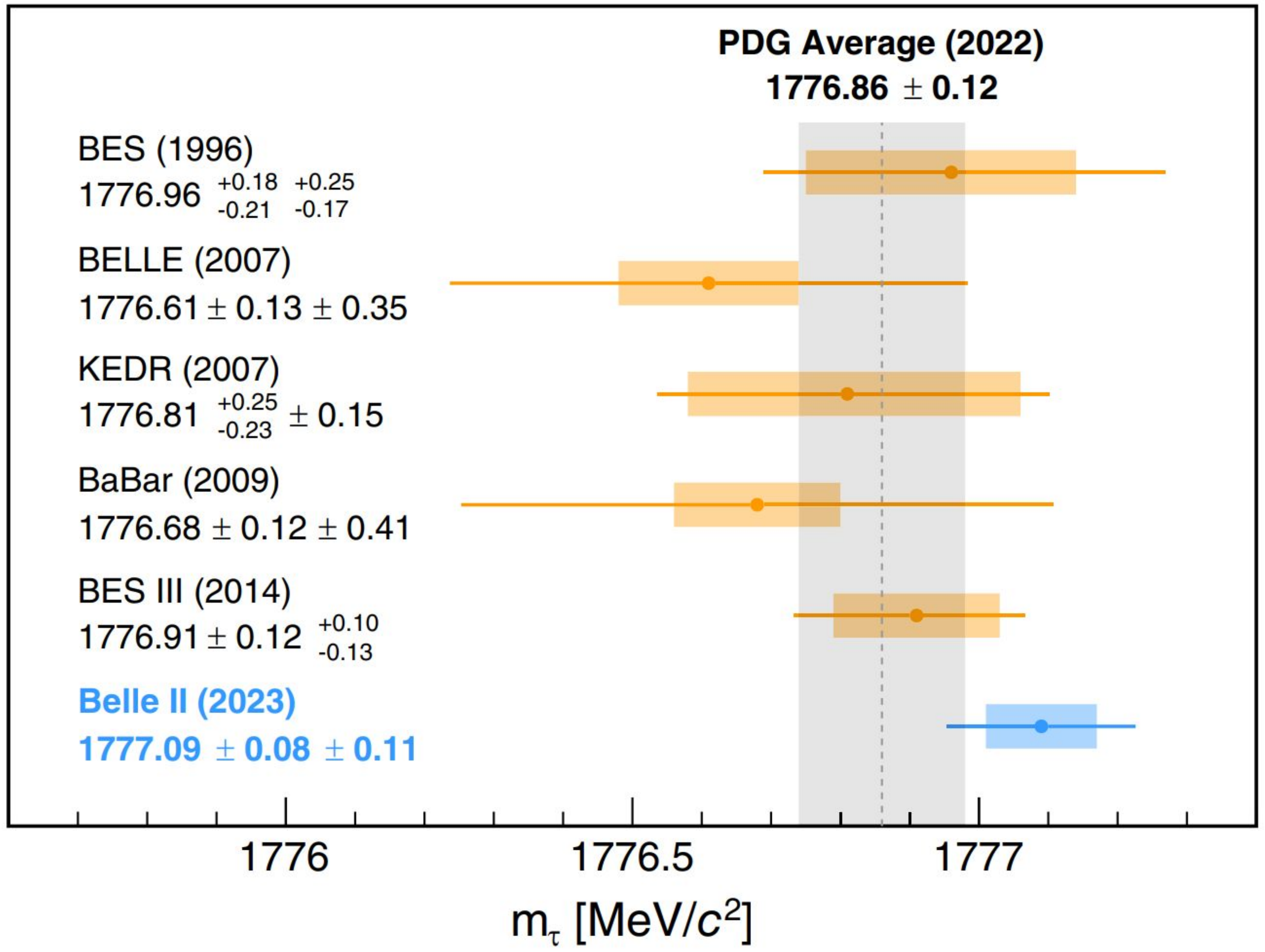
consistent with PDG [(2.38 ± 0.08) x 10^{-5}]

τ mass at Belle II

[arXiv:2305.19116]

- Most precise τ mass measurement!
  - Lots of τ pairs, with almost no background contamination.
  - Measure m_τ using "pseudomass method" with $\tau \to \pi\pi\pi\nu$ decays, beam energy constraints, and the assumption that the neutrino is collinear with the direction of the three pions.
  - Requires a thorough comprehension of both the beam energy and the momentum scale.

$$m_\tau = 1777.09 \pm 0.08\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{MeV}/c^2$$



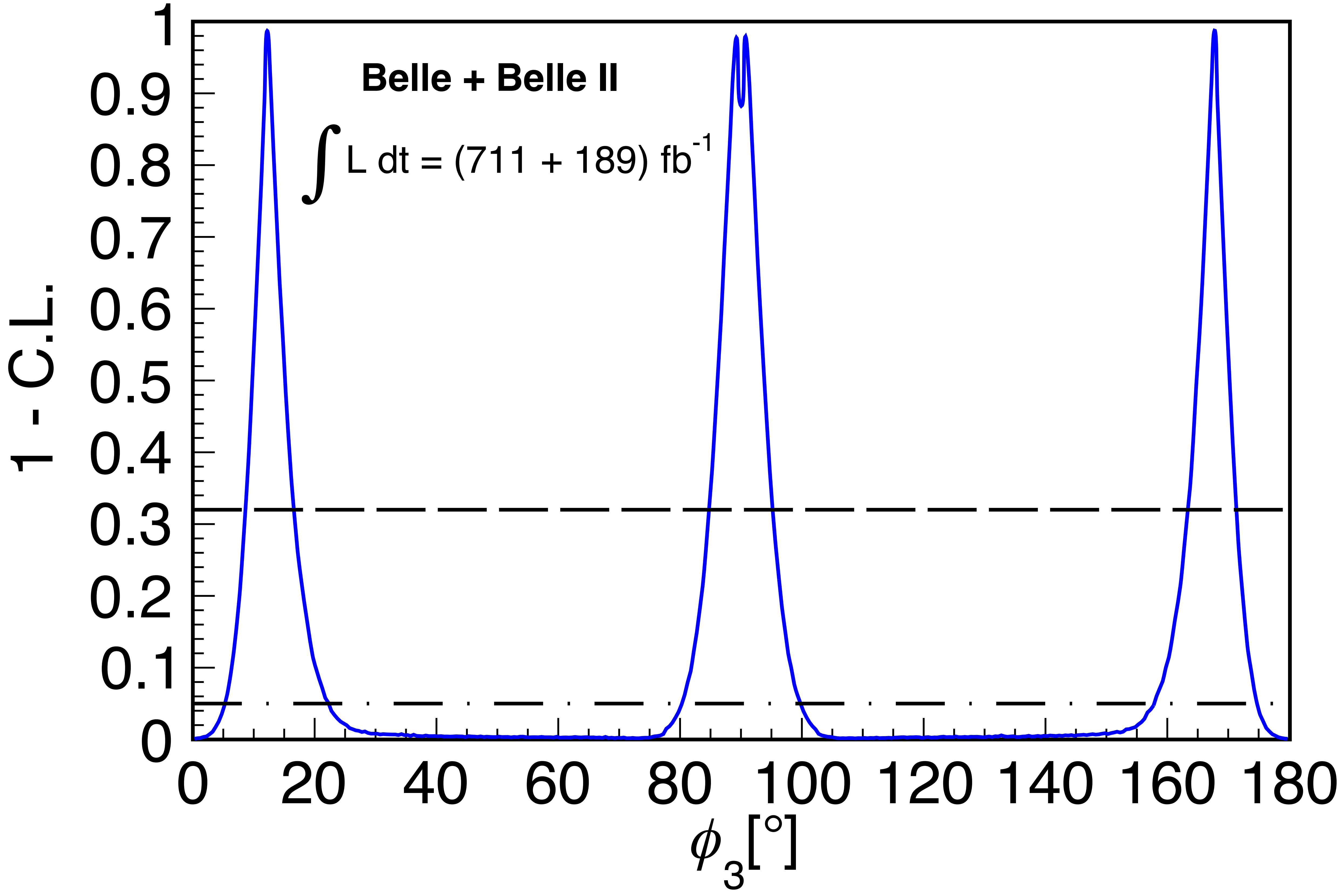
More γ at Belle

- Very active area, new results across different experiments
  - Complementarity in decay channels and methods (e.g. most recent results)

Analysis of $B^+ \to D_{CP} K^+$
@Belle II + Belle

$\gamma \in [84.5, 95.5]^\circ$

[arXiv:2308.05048]



More radiative decays at Belle II

- $b \to s\gamma$ transition-governed decays allow for the investigation of a separate group of operators compared to leptonic decays
  - Synergy between Belle II (cleaner environment, inclusive measurements) and LHCb (huge statistics, access to b baryons). Most recent examples:

Photon-energy spectrum in inclusive $B \to X_s\gamma$ decays

[arXiv:2210.10220]