Heavy flavour: recent results and prospects

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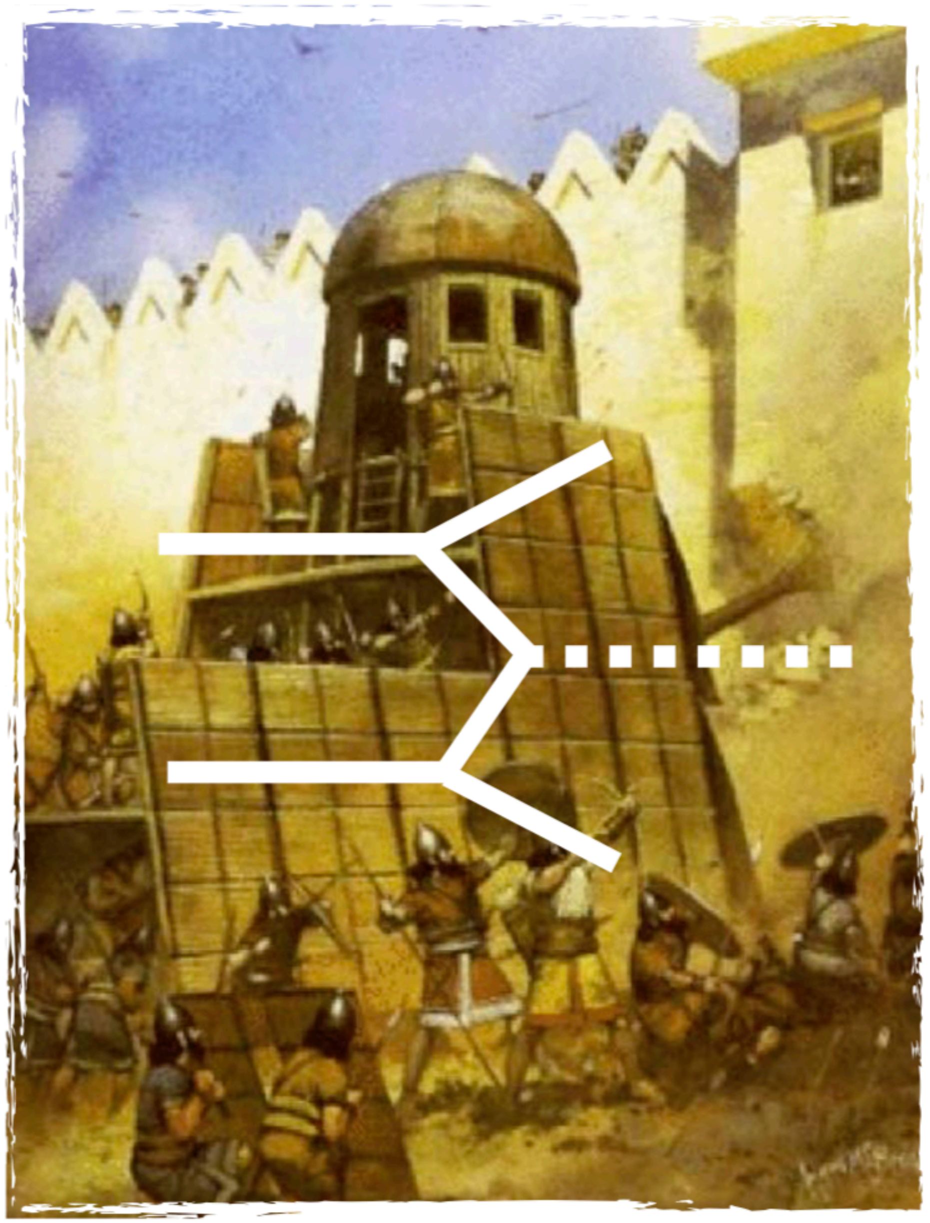
LFC22: Strong interactions from QCD to new strong dynamics at LHC and Future Colliders

Trento, 29 August – 2 September 2022

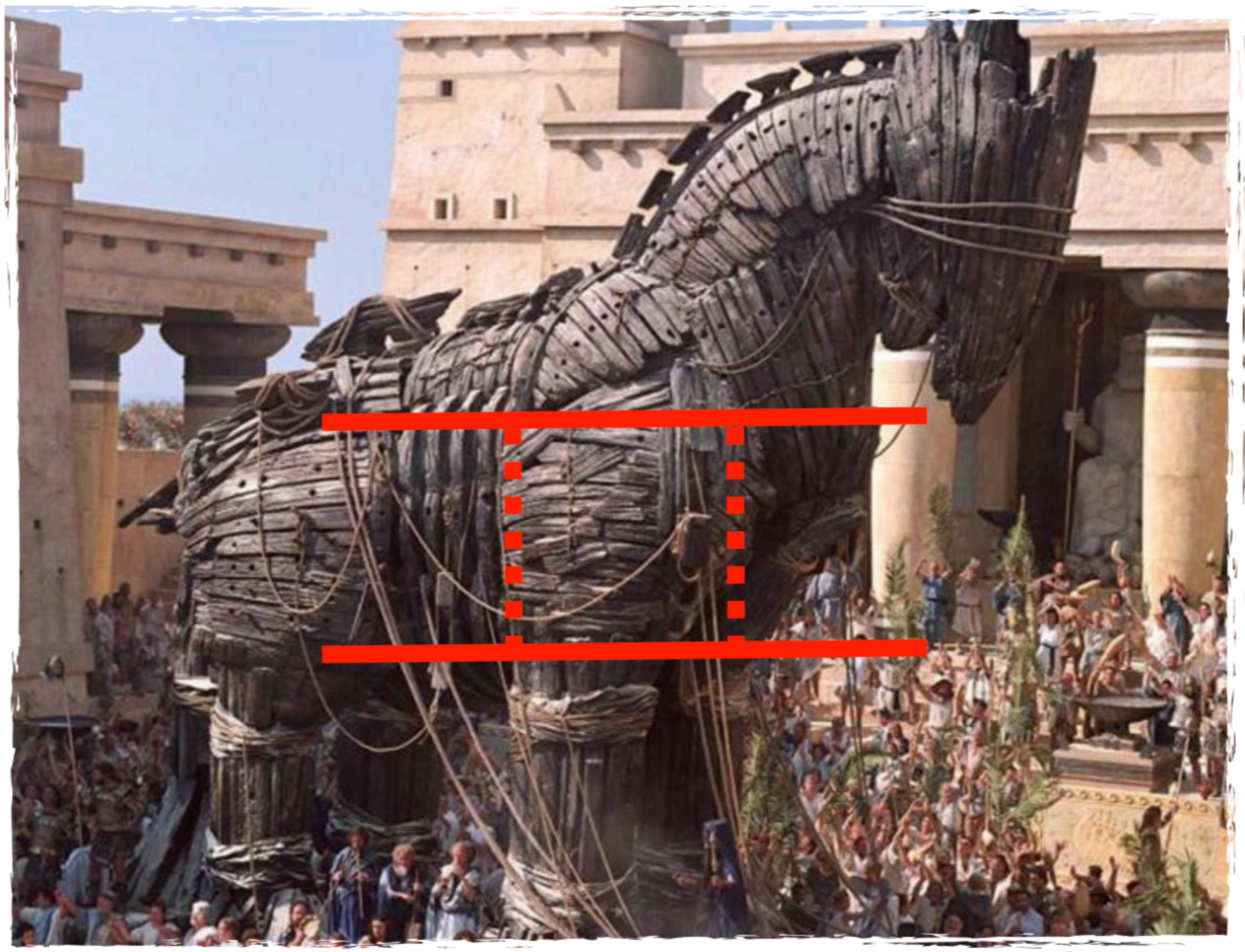
INFN TRIESTE

Probing the next scale

High-energy production of new particles



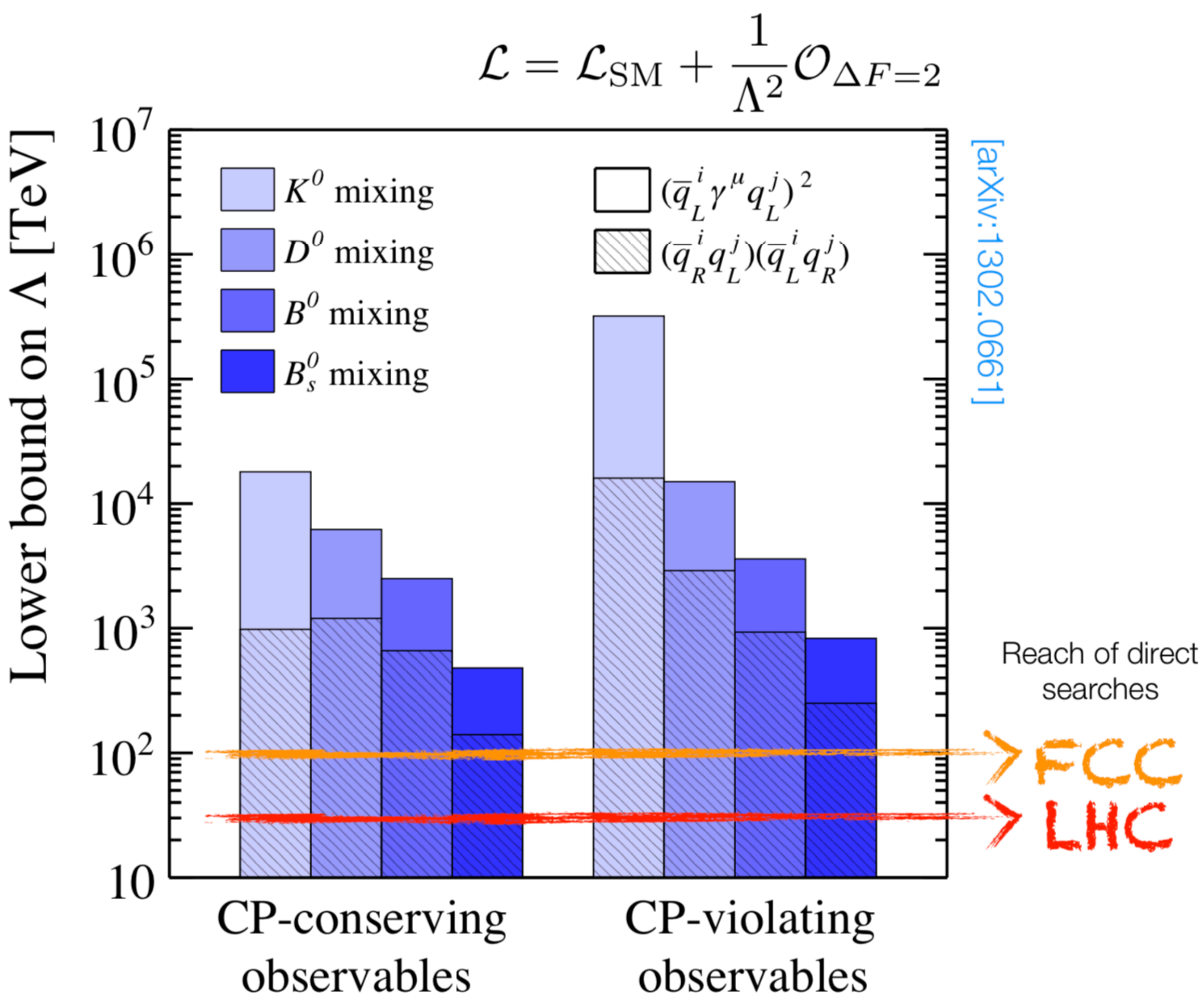
Precision measurements sensitive to quantum interference with new (virtual) particles



Stolen from D. Tonelli

Quark flavour reach

- Challenge is not only in getting precise measurements. Precise predictions are also hard: pervasive strong interaction makes interpretation often challenging.
- Pushing precision on both sides increases the energy well beyond what is directly accessible

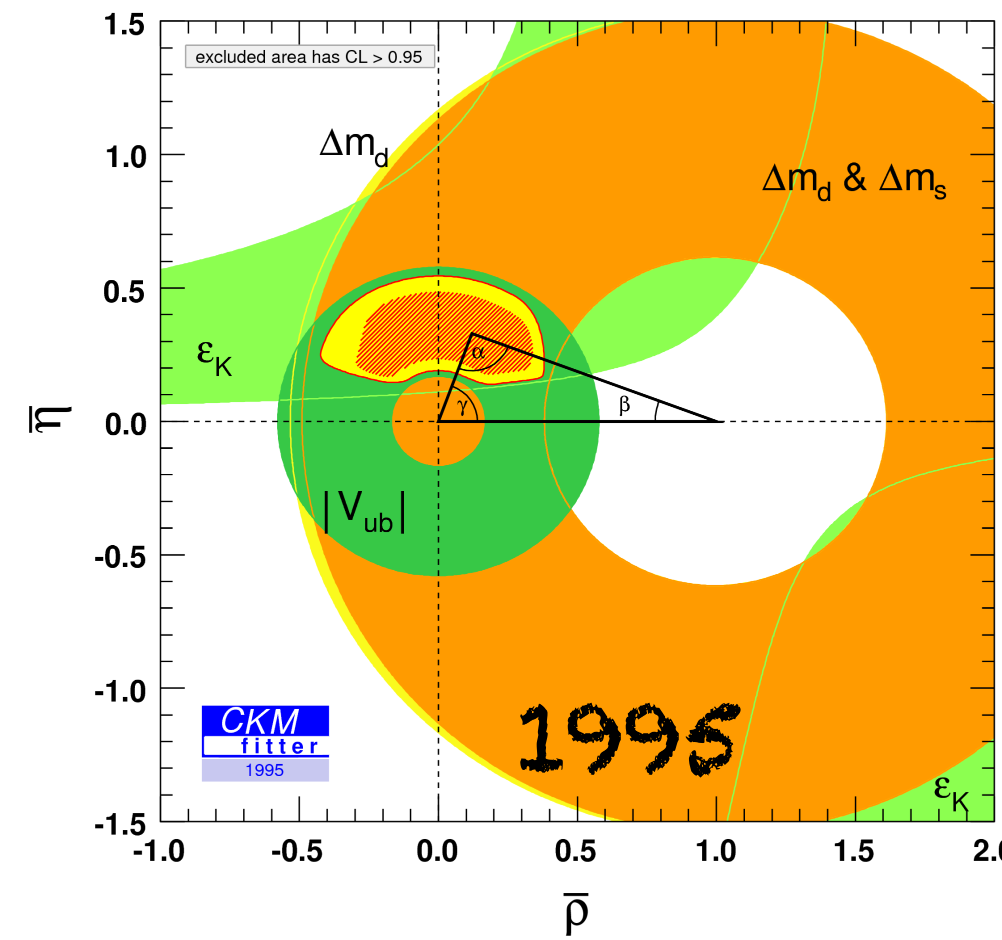


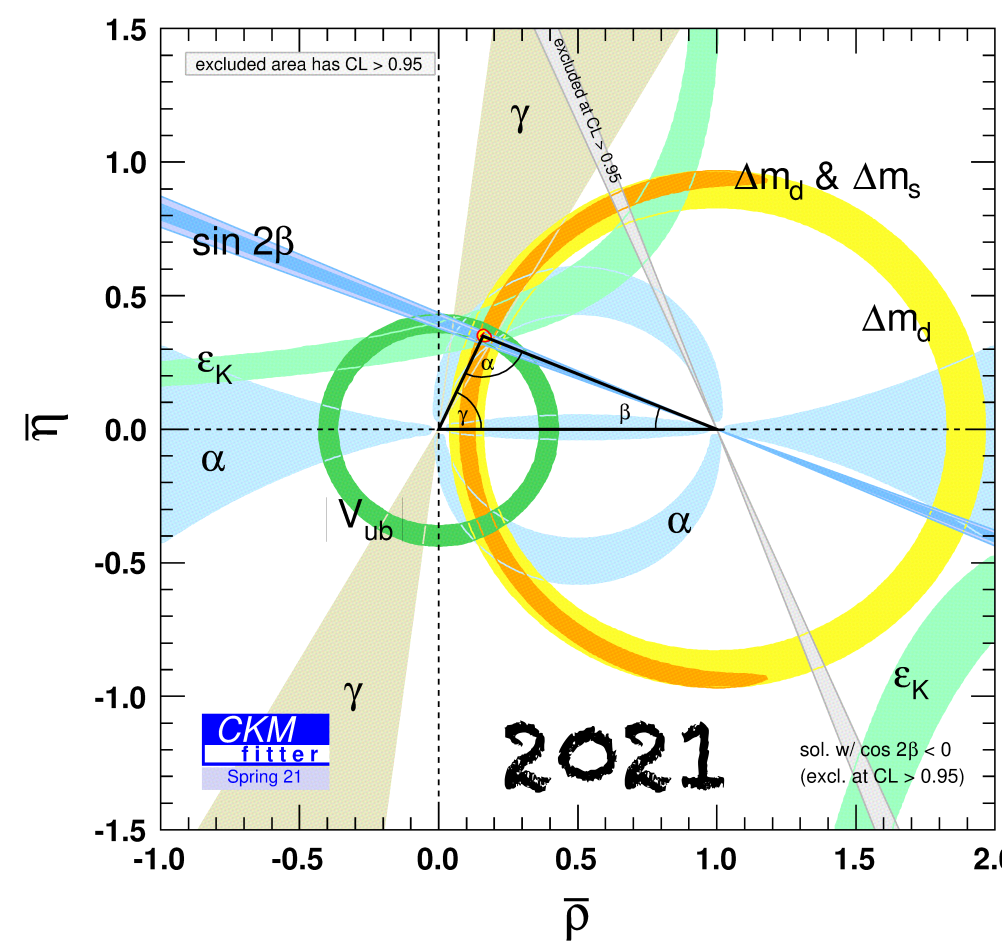
We've come a long way

- Systematic approach to probe many, redundant observables and look for emerging patterns.

- Global campaign of O(1000) measurements conducted in the past 20+ years accompanied by theory/pheno steady advancements.

- Remarkably consistent.
  But deviations still allowed in most of the suppressed processes: need to achieve precision similar to that of favoured ones.





Heavy-flavour tasting

- Overview of recent experimental results and some prospects.
  From SM benchmarks to increasingly sensitive BSM probes:
  from tree to loops, from favoured to suppressed…
  hope to convince you flavour ain't boring at all.
- I'm not talking on behalf of any experiments: topic selection and any mistake are my sole responsibility.
- Biased toward Belle II and LHCb. Recent results from ICHEP22.
  Prospects mainly based on Snowmass.(*)

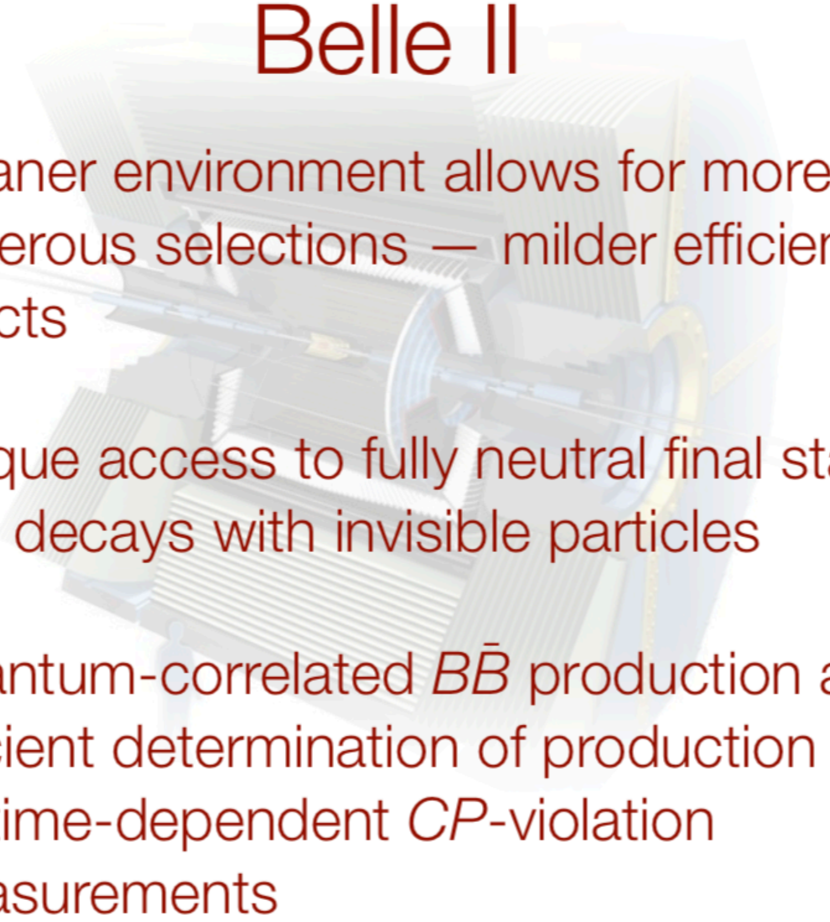
(*) Thanks to many speaker from which I took material, in particular Vava Gligorov, Diego Tonelli, Angelo Di Canto, Rafael Silva Coutinho, …

Players

LHCb

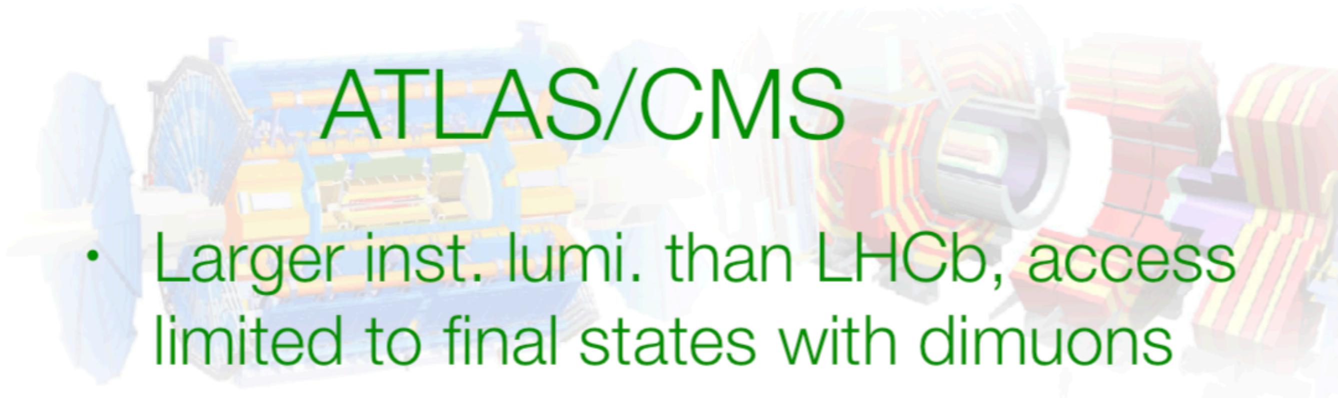
- Huge advantage in production rate, but large backgrounds results in lower efficiencies (advantage remains mostly for charged final states)
- Larger boost and superior decay-time resolution for time-dependent measurements
- Access to all *b*-hadron species

Belle II



- Cleaner environment allows for more generous selections — milder efficiency effects
- Unique access to fully neutral final states and decays with invisible particles
- Quantum-correlated $B\bar{B}$ production allows efficient determination of production flavor for time-dependent *CP*-violation measurements

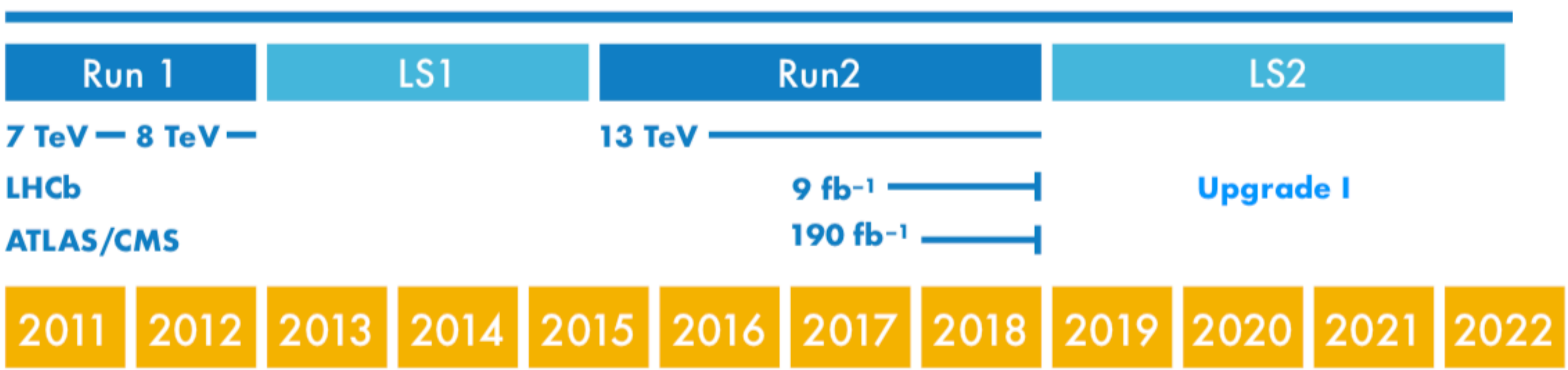
ATLAS/CMS



- Larger inst. lumi. than LHCb, access limited to final states with dimuons

Setting the stage

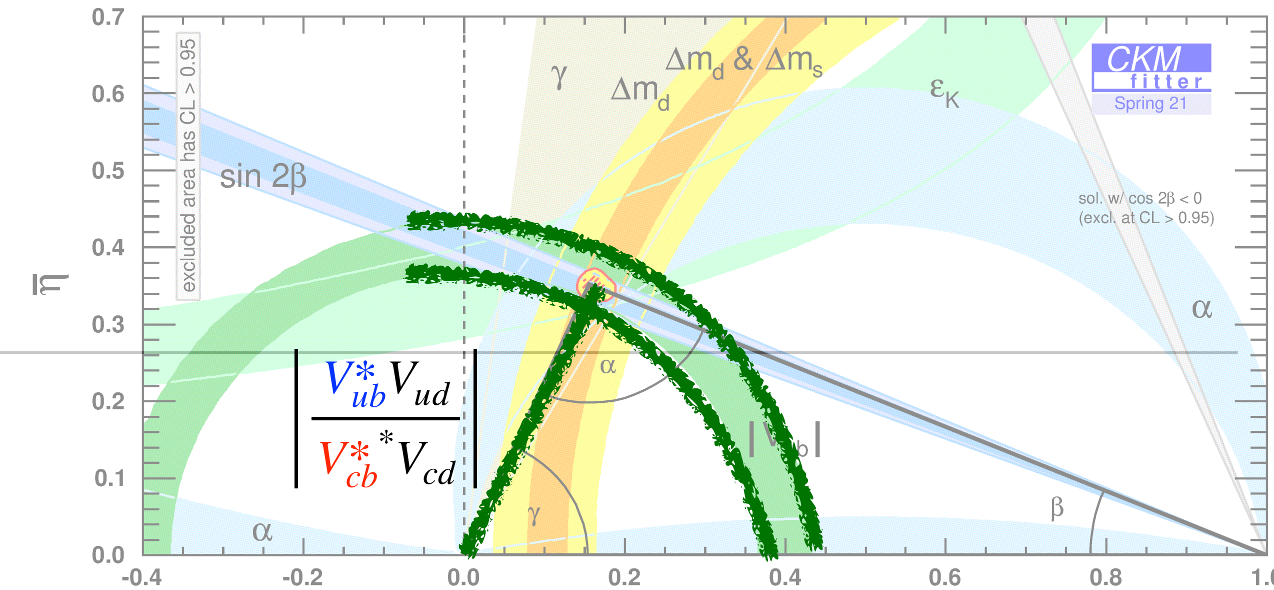
LHC experiments running since 2010. Two major campaigns (Run1 and 2).
Collected unprecedented samples for flavour physics.
Full dataset yet to be exploited in many analyses. And Run3 has just began.



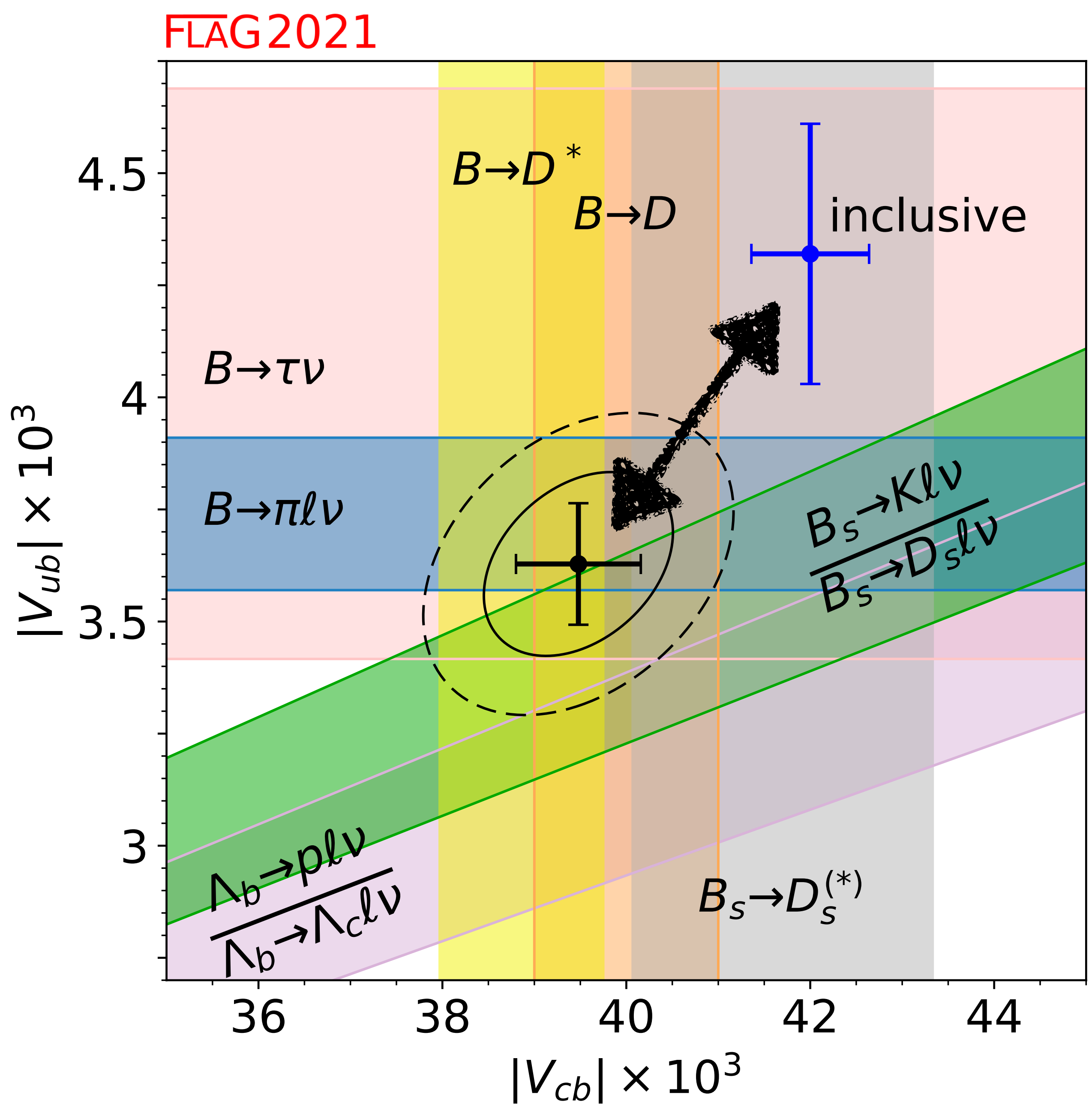
Belle II started data-taking in 2018,
collected dataset ~1xBaBar, ~0.5xBelle.
Now in shutdown for about 1.5 years.

SM benchmarks

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



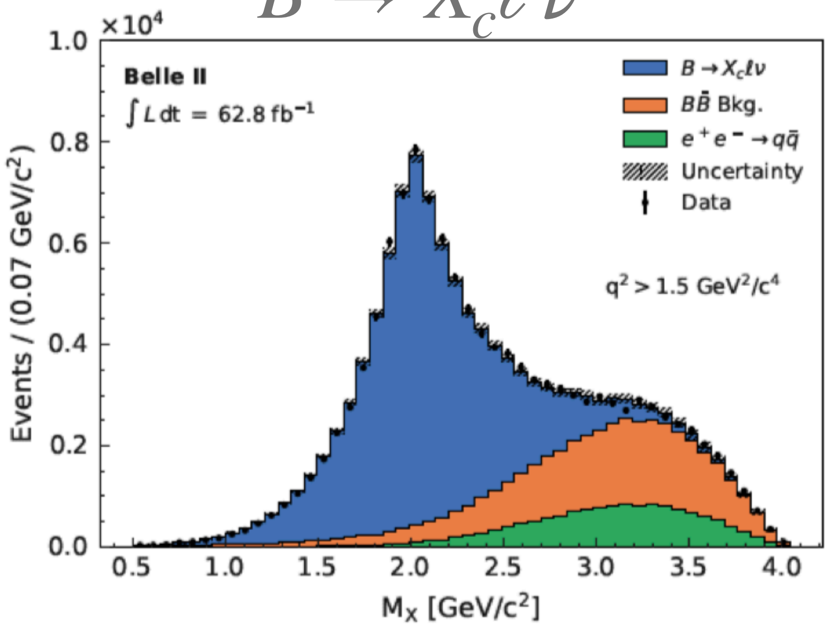
- Measured with $b \to c\ell\nu$ and $b \to u\ell\nu$ decays, where hadronic system reconstructed either exclusively ($D^{(*)}$, π) or inclusively (X_c, X_u).
- Dominated by B-factories, LHCb contributes too. Need inputs from QCD calculations (HQE, lattice, LCSR…)
- Impasse driven by 20-year-long discrepancy between exclusive and inclusive determinations.



Belle II enters the quest

Inclusive $|V_{cb}|$

$$B \to X_c \ell \nu$$

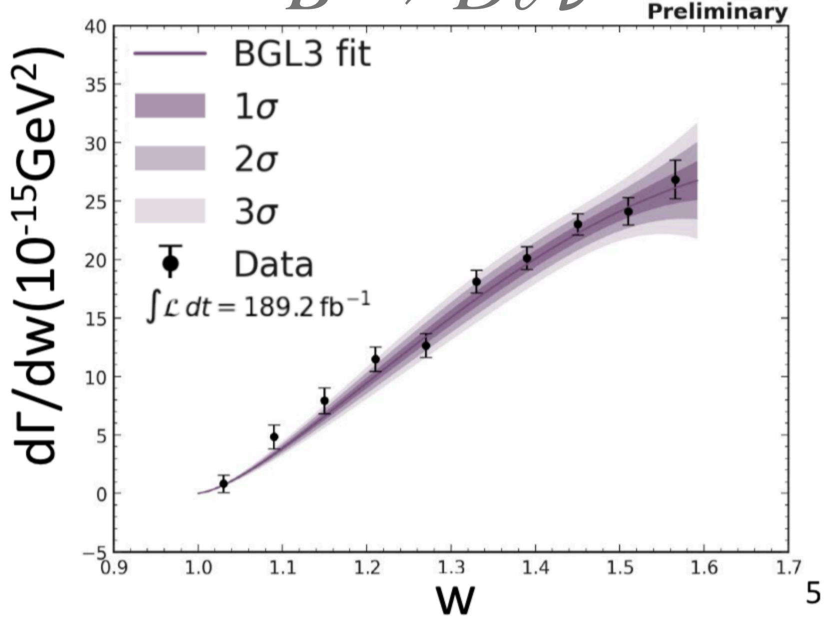


arXiv:2205.06372
arXiv:2205.10274

$$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$$

Exclusive $|V_{cb}|$

$$B \to D \ell \nu$$



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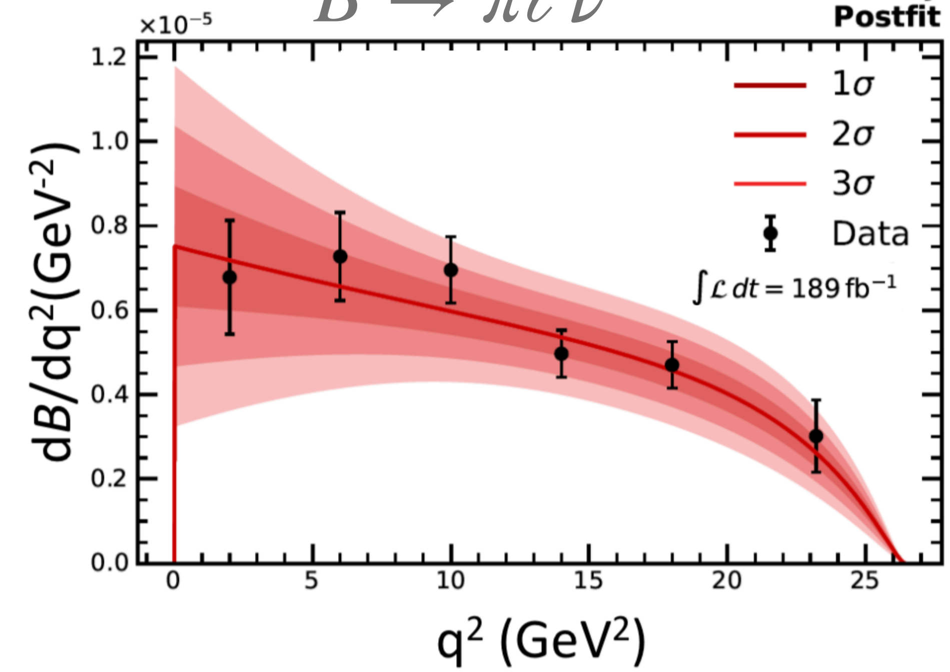
$$|V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}$$

Exclusive $|V_{ub}|$

$$B \to \pi \ell \nu$$



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$$|V_{ub}| = (3.54 \pm 0.25) \times 10^{-3}$$

Belle II will drive the global progress throughout the next decade.
LHCb can contribute on the ratio $|V_{ub}/V_{cb}|$ using Λ_b and B_s.
Further experimental inputs must be matched by theory/lattice progress.

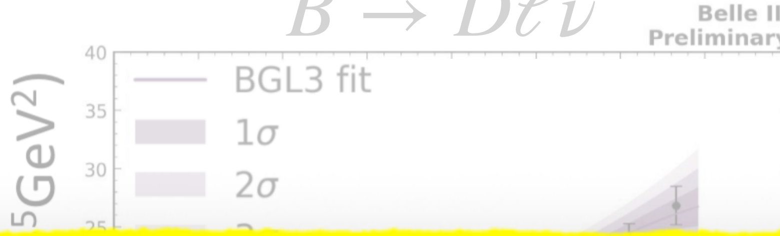
Belle II enters the quest

Inclusive $|V_{cb}|$

$B \to X_c \ell \nu$

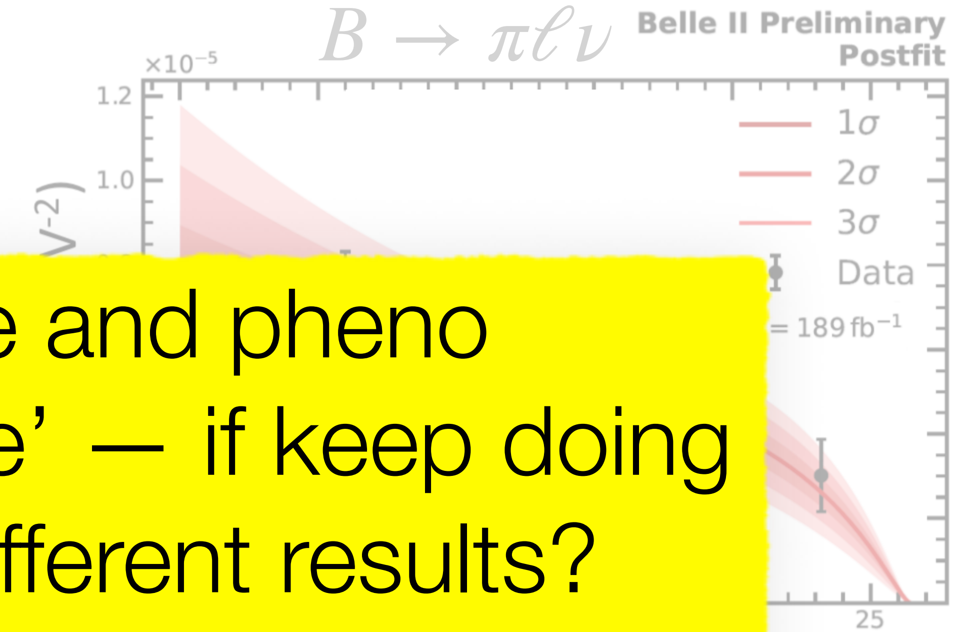
Exclusive $|V_{cb}|$

$B \to D \ell \nu$



Exclusive $|V_{ub}|$

$B \to \pi \ell \nu$



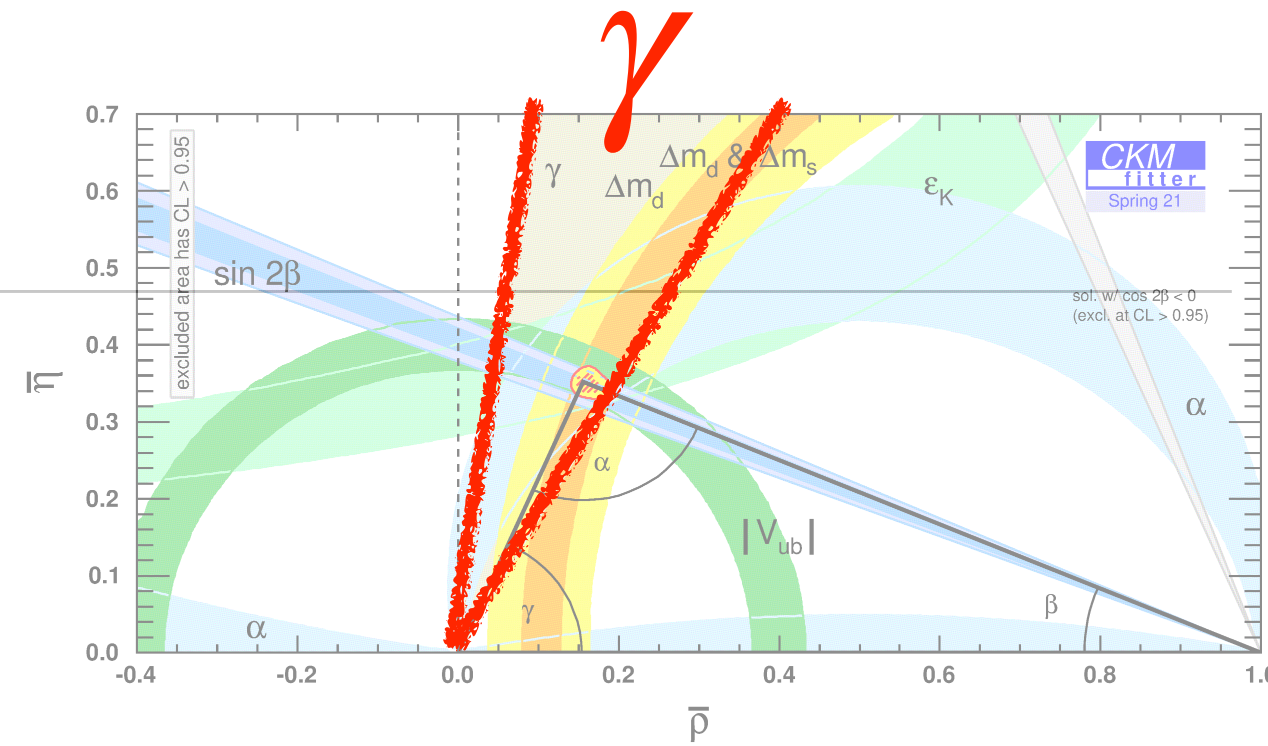
Not obvious that data deluge and pheno improvements will solve the 'puzzle' — if keep doing the same, why would we get different results?
Opportunity (and challenge) is to innovate.

arXiv:2205.10274

Investigate D**, resolve SL gap,
model-independent FF measurements, angular analyses…

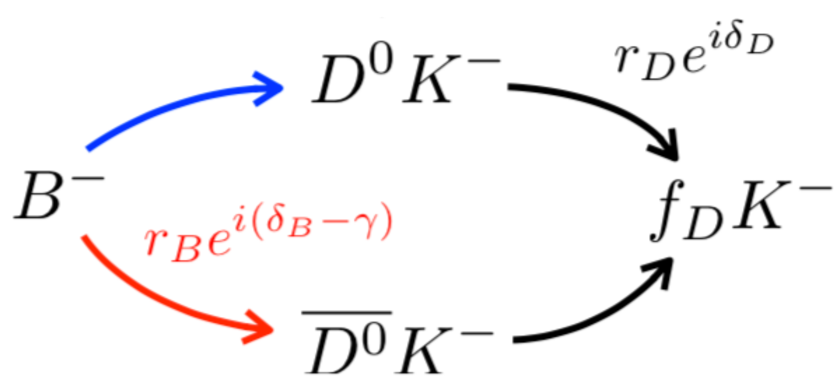
Further experimental inputs must be matched by theory/lattice progress.

CP violation from trees

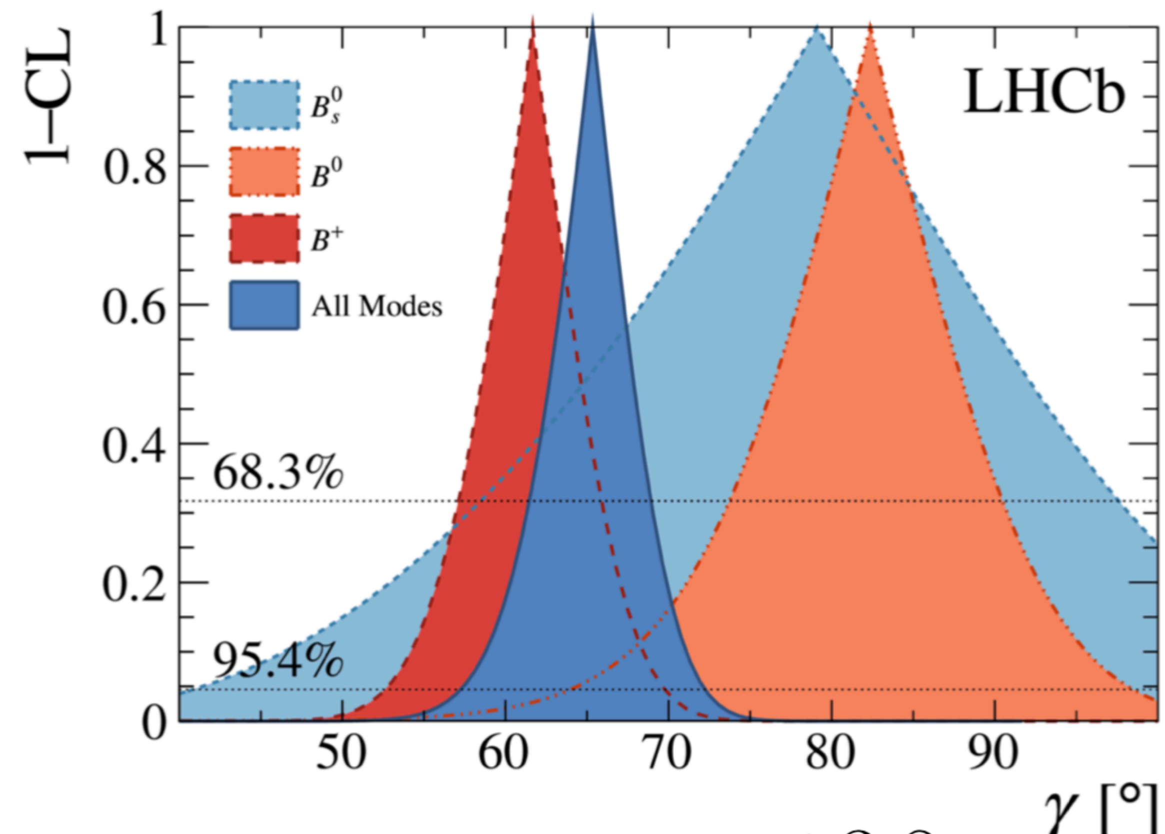


- Principal gauge of SM CP violation: very reliably predicted [arXiv:1308.5663].

- Access through interfering $B^- \to D^0 K^-$ and $B^+ \to \overline{D}^0 K^+$ decays where D^0 and $\overline{D}^0$ are reconstructed in the same final state.



- Can exploit B^0 and B_s too, but less SM clean (involve mixing).



$$\gamma = (65.4\,^{+3.8}_{-4.2})^\circ$$

[JHEP12 (2021) 141]

LHCb lead

Compendium of LHCb Run I+II measurements nearing completion.
First Belle+Belle II joint analysis contribute [JHEP02 (2022) 063], other to come.

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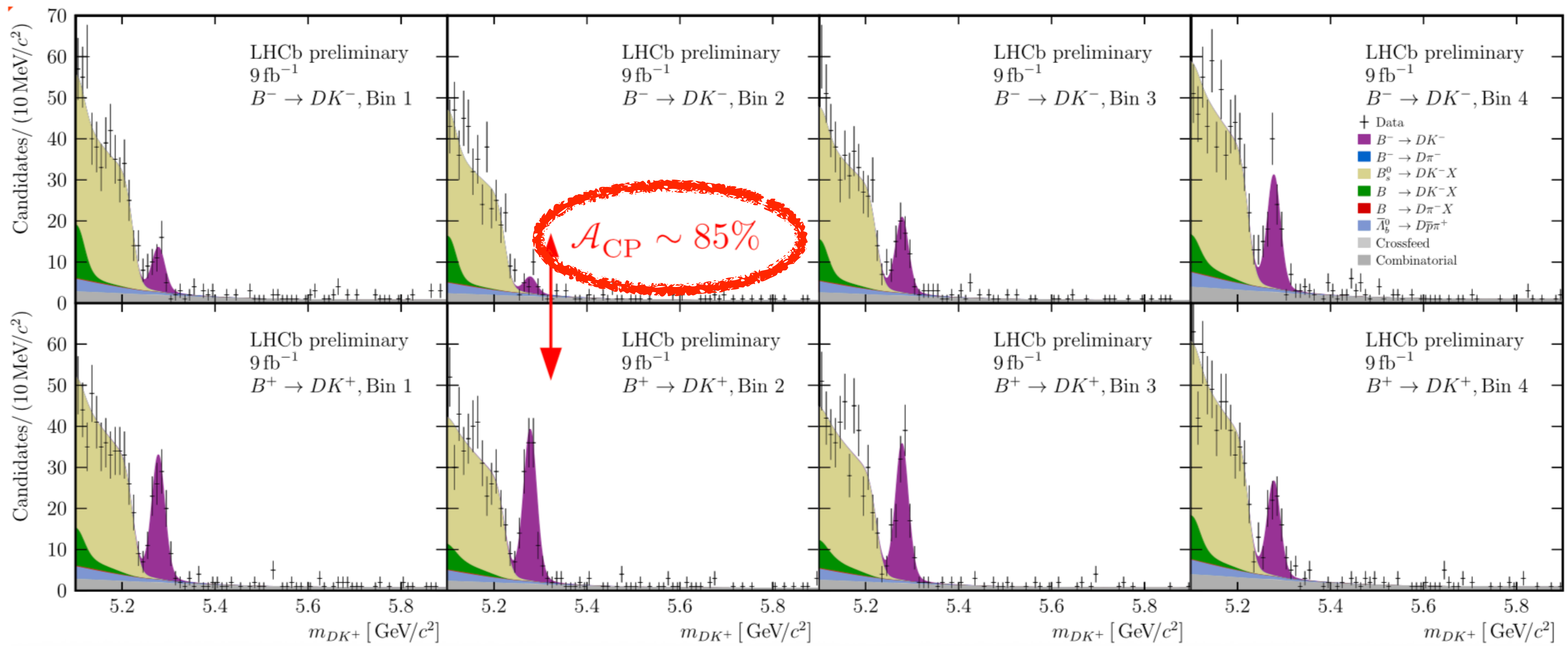
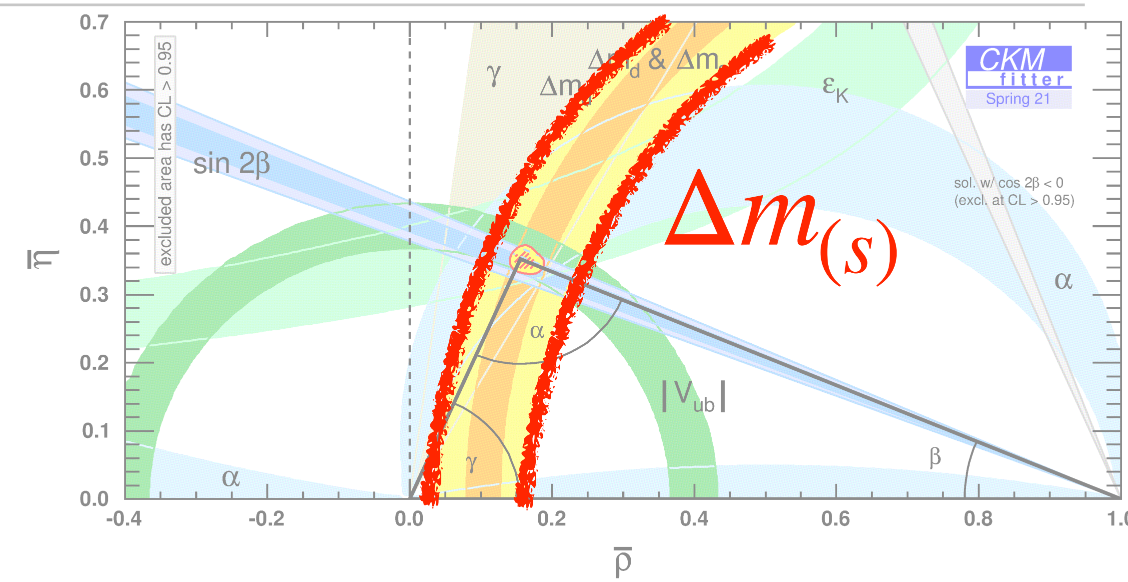


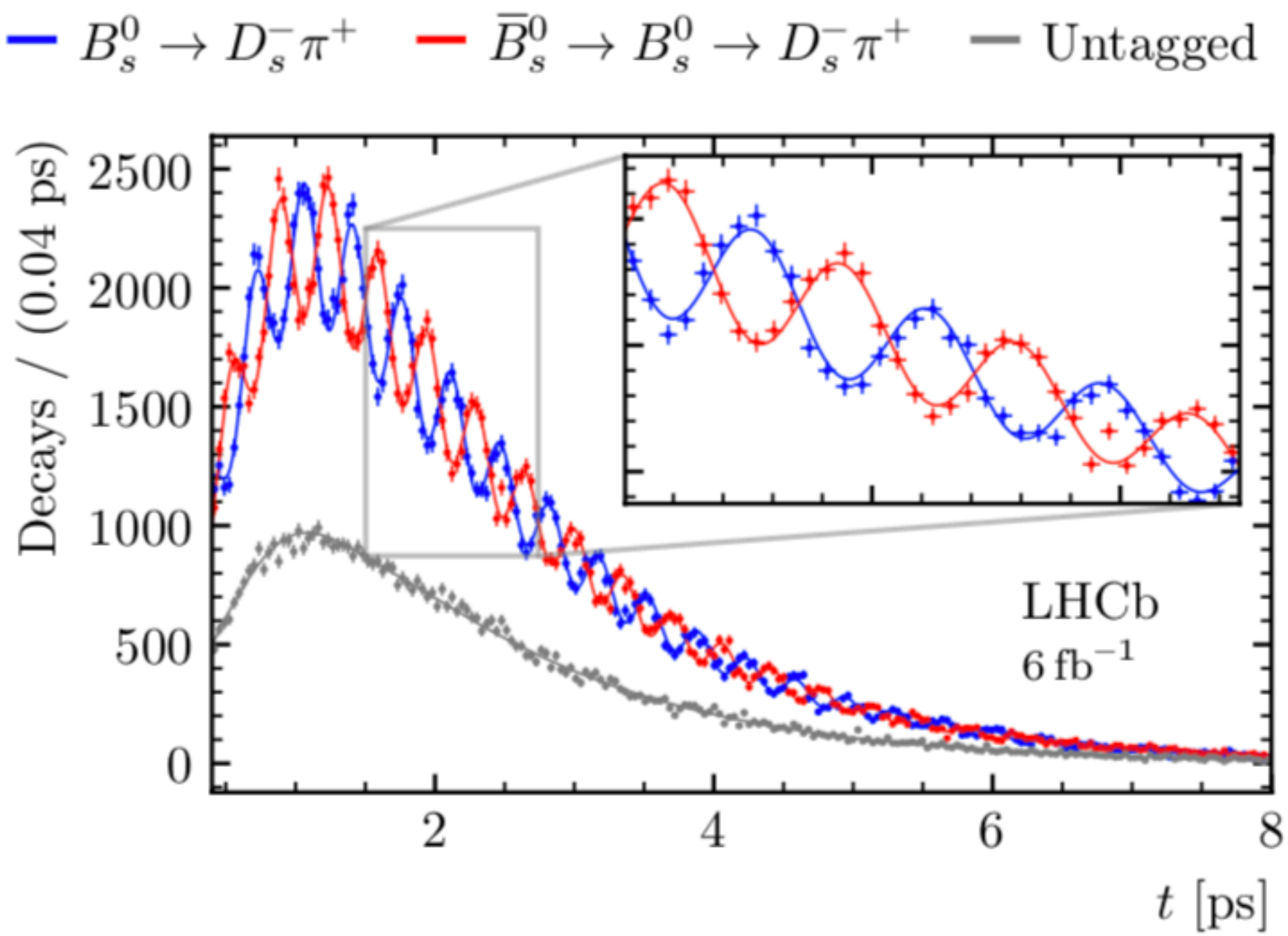
γ currently at 4° global precision (driven by LHCb sample size). Crucially need new input on D strong phases (BESIII, future charm-tau factory) to go below 1°.

Adding loops

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

- Very generic null tests of non-SM physics contributing to $B_{(s)}{}^0$ meson mixing.
- LHCb mpressive time-resolution to resolve fast B_s oscillation (350 fs time-period).





$$\Delta m_s = 17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$$

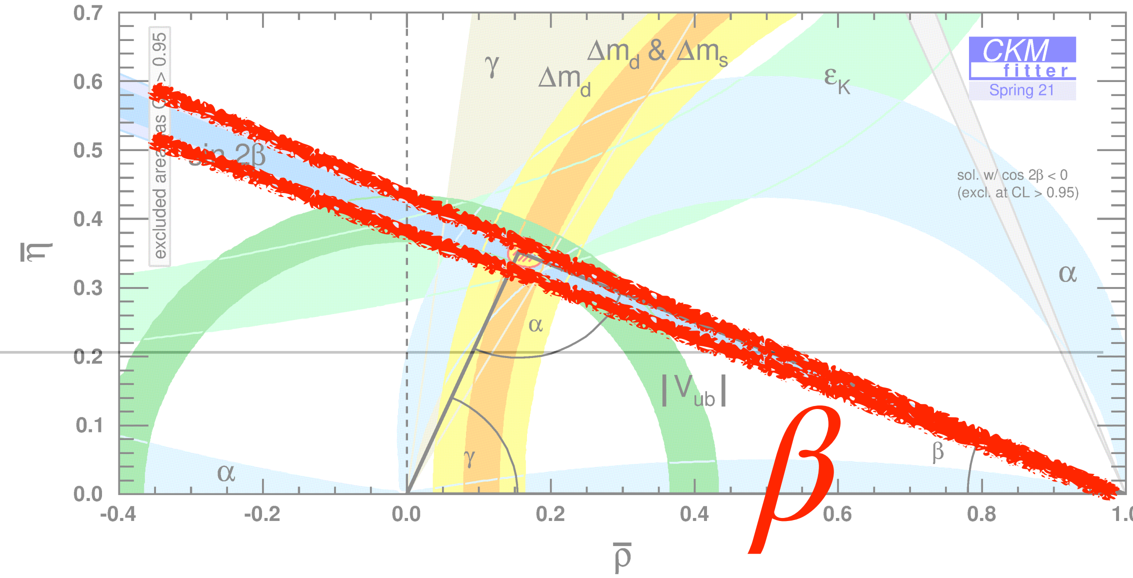
[Nature Physics 18 (2022) 1]

$$\Delta m_d = 0.5065 \pm 0.0019\,\mathrm{ps}^{-1}$$

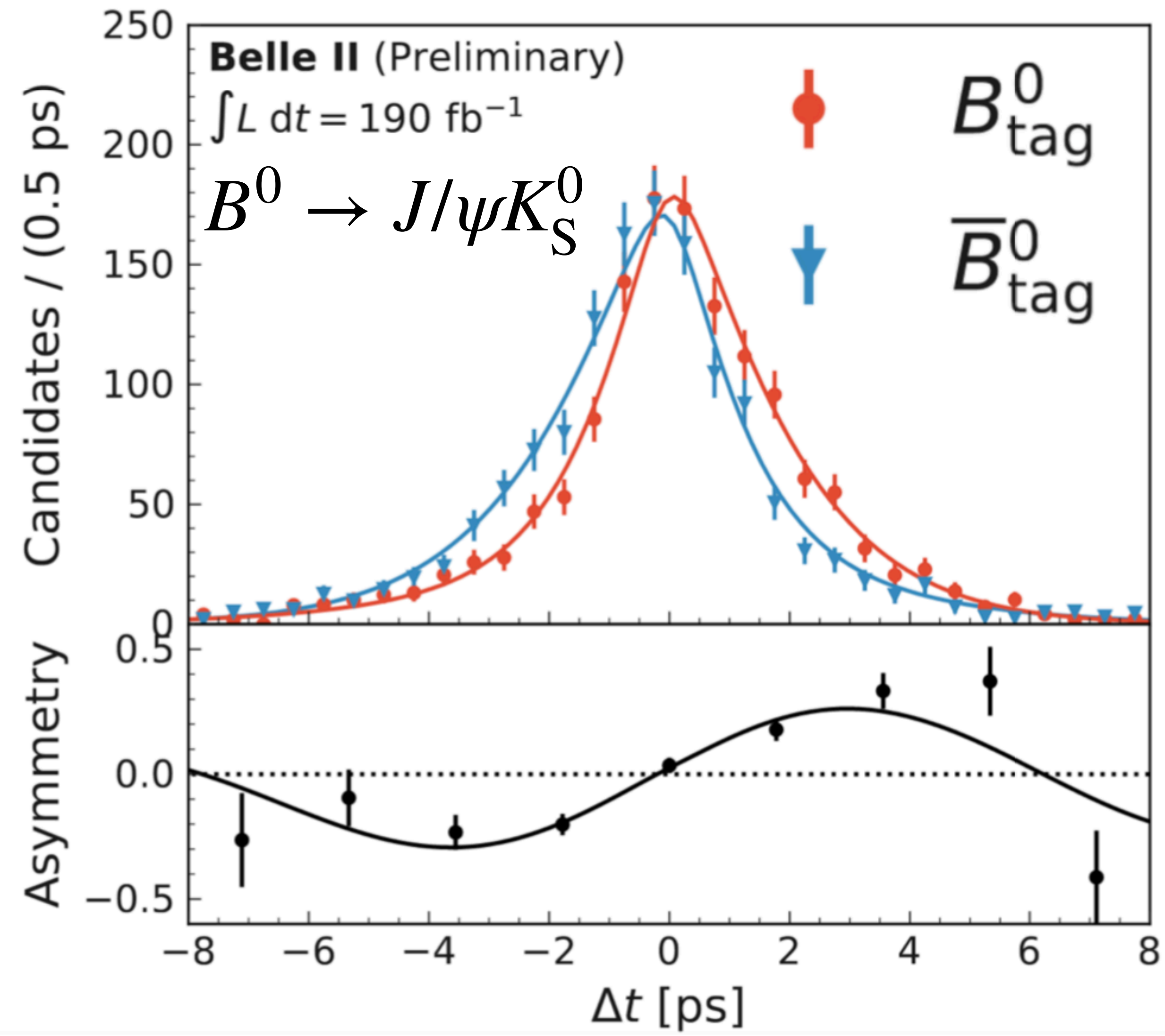
[HFLAV22]

Constraints on BSM limited by QCD uncertainty. Expected to reduce soon.

$B^0_{(s)}$ mixing phase $\beta_{(s)}$



- CP violation in interference between direct decay and mixing+decay. Theoretically clean in tree decays $B^0 \to J/\psi K^0$ and $B^0_s \to J/\psi \phi$.
- Constraints on BSM limited by statistical uncertainties. Large room for improvements.
- Belle II gearing up for the ultimate precision for β. β_s LHC business.



Belle II @ICHEP2022

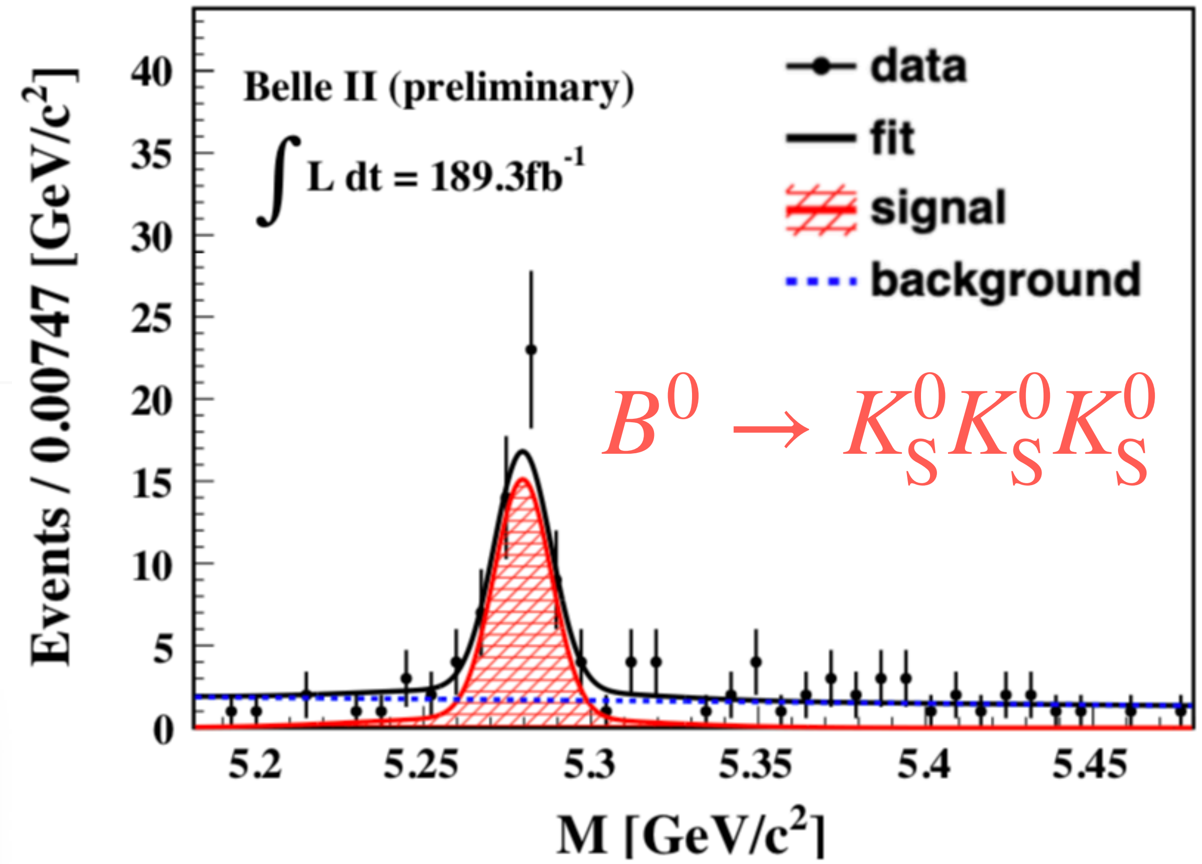
$B^0_{(s)}$ mixing phase $\beta_{(s)}$

- CP violation in interference between direct decay and

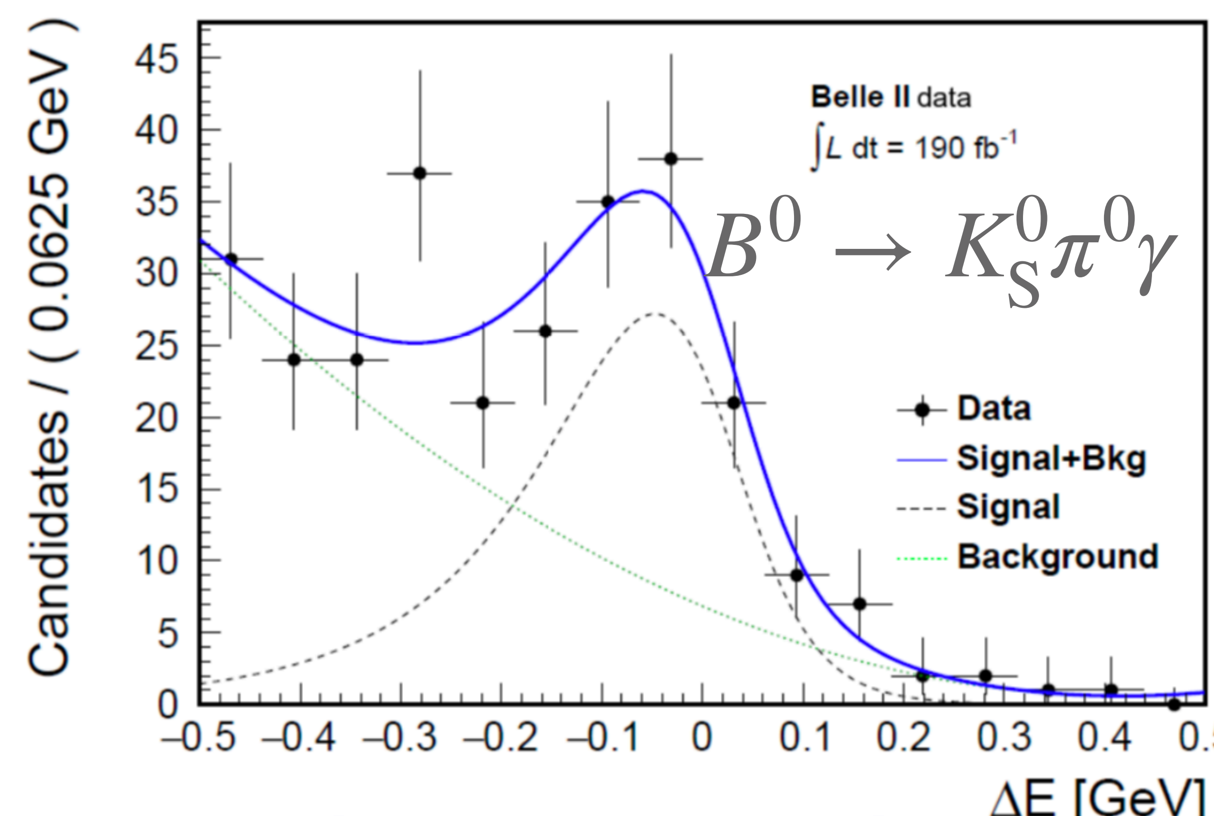
Enhanced BSM sensitivity in suppressed b→s loop transitions.

Search for time-dependent CPV in gluonic-penguin and radiative decays

Large room for improvements. Belle II paving the way towards the ultimate precision for β.
β_s LHC business.



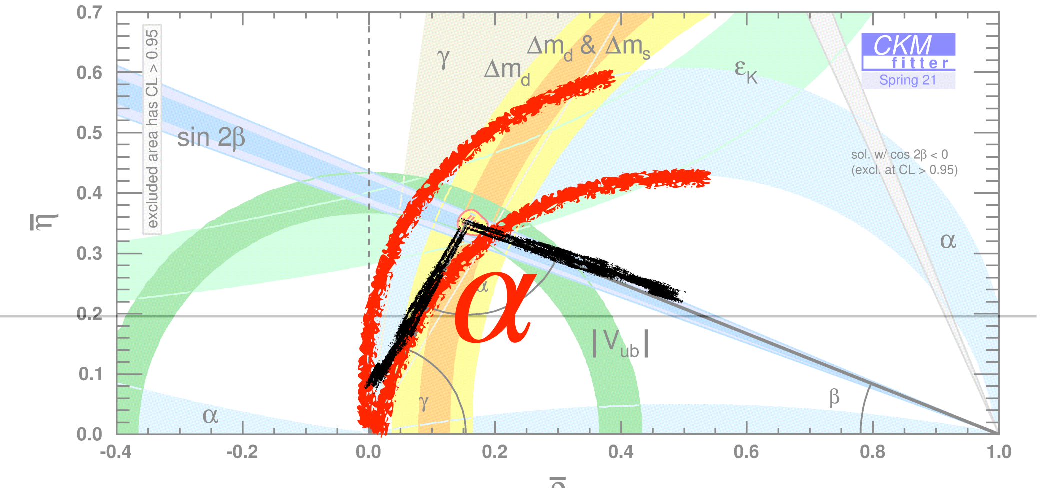
Belle II @ICHEP2022

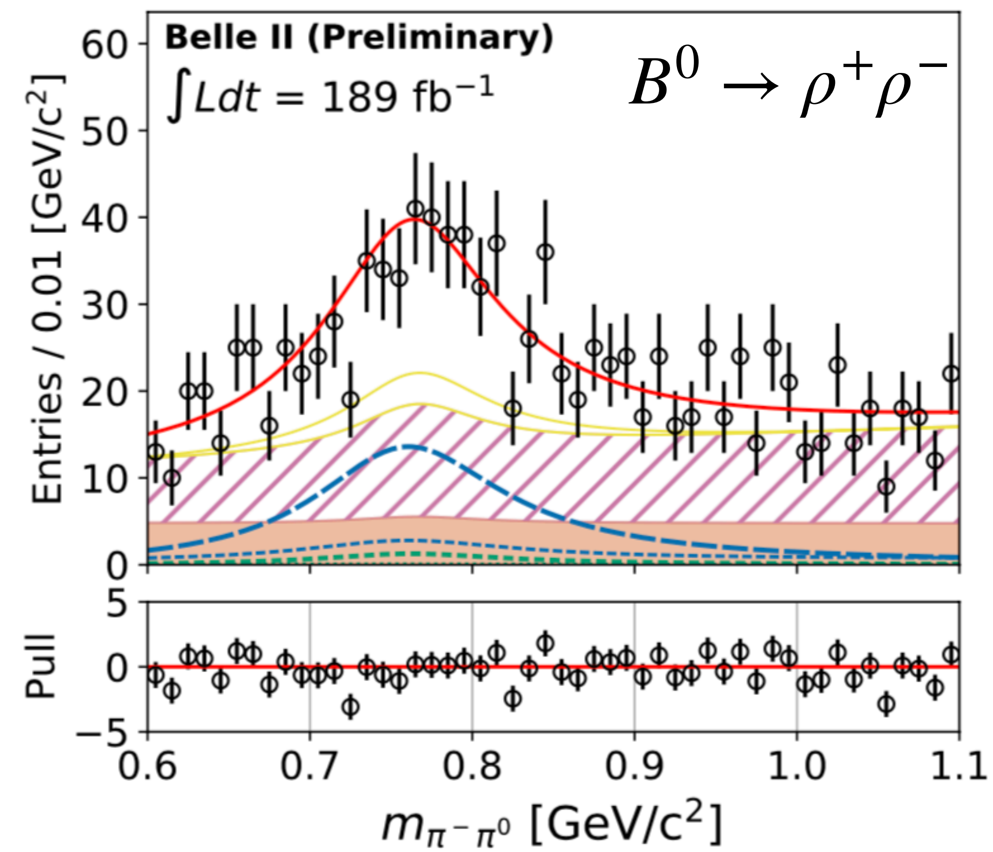


[arXiv:2206.08280]

Fascinating charmless

- α, least known angle of the UT.
- Combine analyses of *BR* and A_{CP} of charmless $B \rightarrow \rho\rho$ and $B \rightarrow \pi\pi$ isospin family to suppress hadronic unknowns.
- Belle II unique access to all inputs, but complex angular analysis to determine decay polarisation.
  On par with Belle/Babar best performance.





$B^+ \rightarrow \rho^+\rho^0$ [arXiv:2206.12362]

$$\mathscr{B} = (23.2^{+2.2}_{-2.1} \pm 2.7) \times 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033} \pm 0.027$$
$$A_{CP} = -0.069 \pm 0.069 \pm 0.060$$

$B^0 \rightarrow \rho^+\rho^-$ [arXiv:2208.03554]

$$\mathscr{B} = (2.67 \pm 0.28 \pm 0.28) \times 10^{-5}$$
$$f_L = 0.956 \pm 0.035 \pm 0.033$$

Neutrals, Belle II strength

$B^0 \to \pi^0\pi^0$, only photons in the final state

$$\mathcal{B} = (1.27 \pm 0.25 \pm 0.17) \times 10^{-6}$$

$$A_{CP} = 0.24 \pm 0.46 \pm 0.07$$

Belle II achieves Belle precision using 1/3 of data

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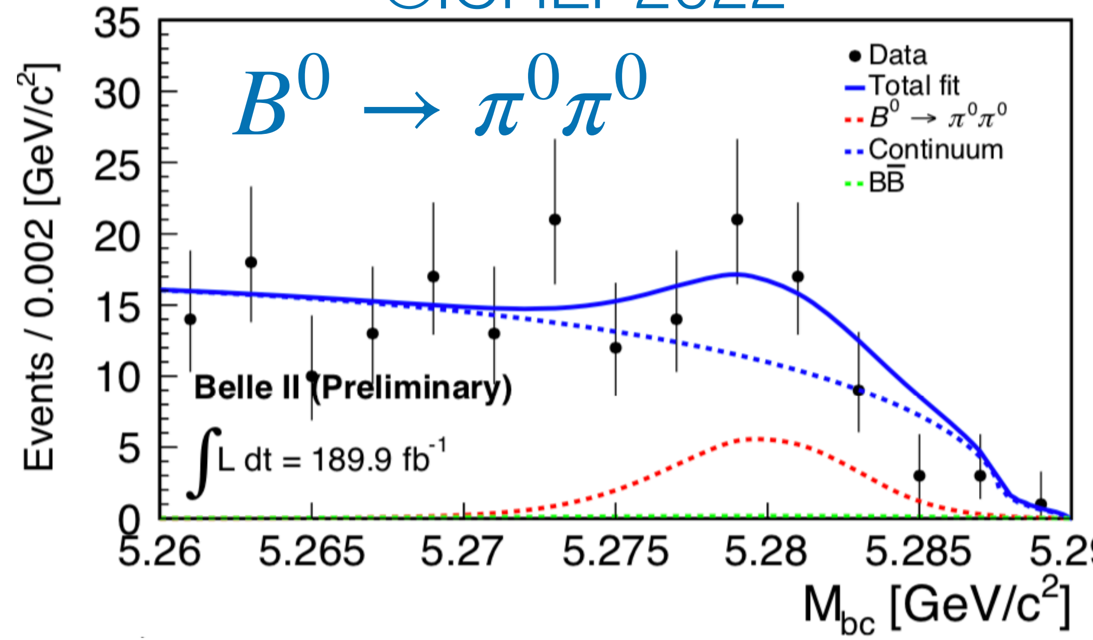
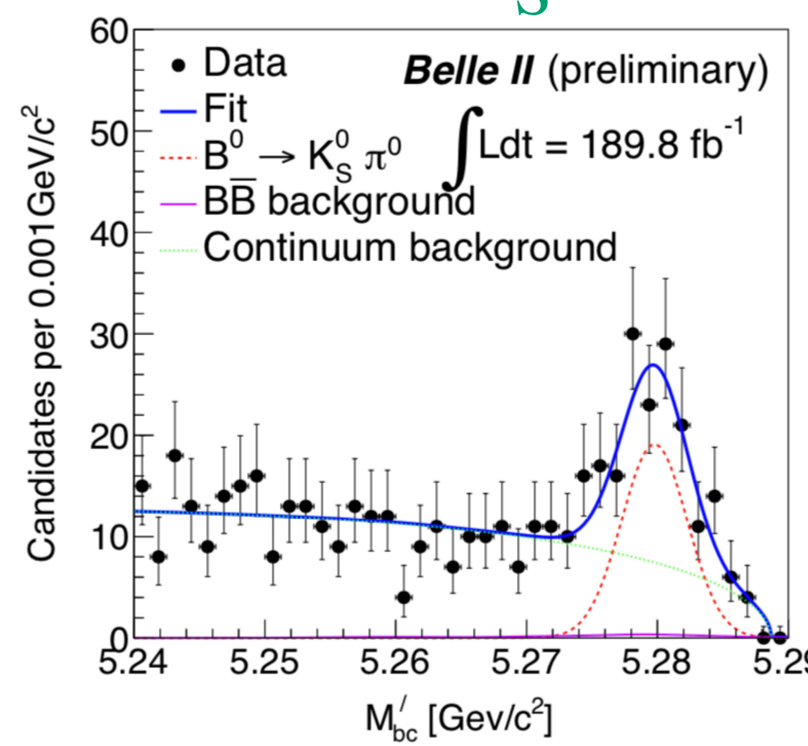


$B^0 \to K_S^0\pi^0$ complex vertexing, yet time-dependent analysis proved feasible. Essential ingredient toward in isospin sum-rule to test SM with suppressed $B \to K\pi$ *decays*



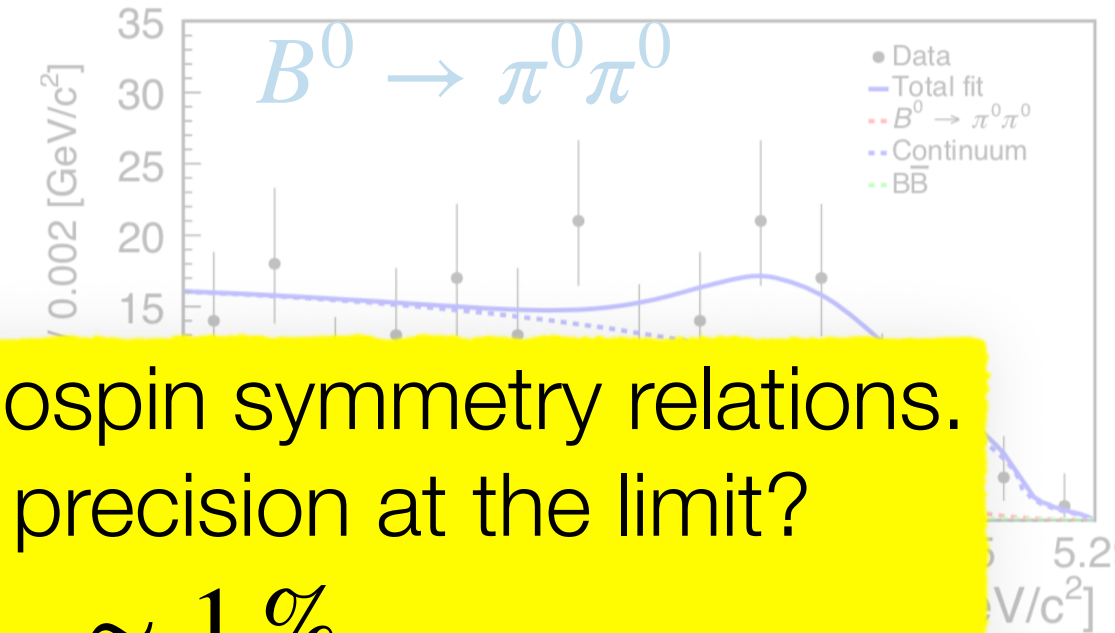
$$\mathcal{B} = (11.0 \pm 1.2 \pm 1.0) \times 10^{-6}$$

$$A_{CP} = -0.41^{+0.30}_{-0.32} \pm 0.09$$

[arXiv:2206.07453]

Neutrals, Belle II strength

- $B^0 \to \pi^0\pi^0$, *only* photons in the finale state. **Belle II achieves Belle precision using 1/3 of data:**



Charmless analyses based on isospin symmetry relations.
Any breaking when pushing precision at the limit?

$\sigma_\alpha < 1^\circ$ and $\sigma_{I_{K\pi}} \sim 1\,\%$

- $B^0 \to K_S{}^0\pi^0$ complex vertexing, yet time-dependent analysis proved feasible. Essential ingredient toward in isospin sum-rule to test SM with suppressed $B \to K\pi$ *decays*

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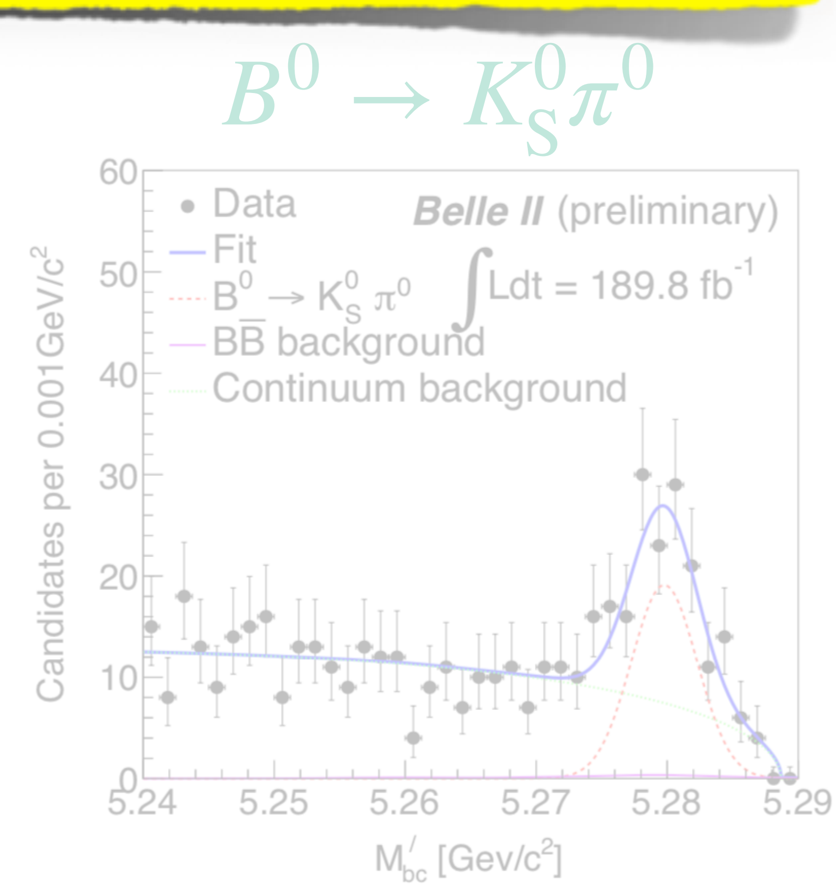
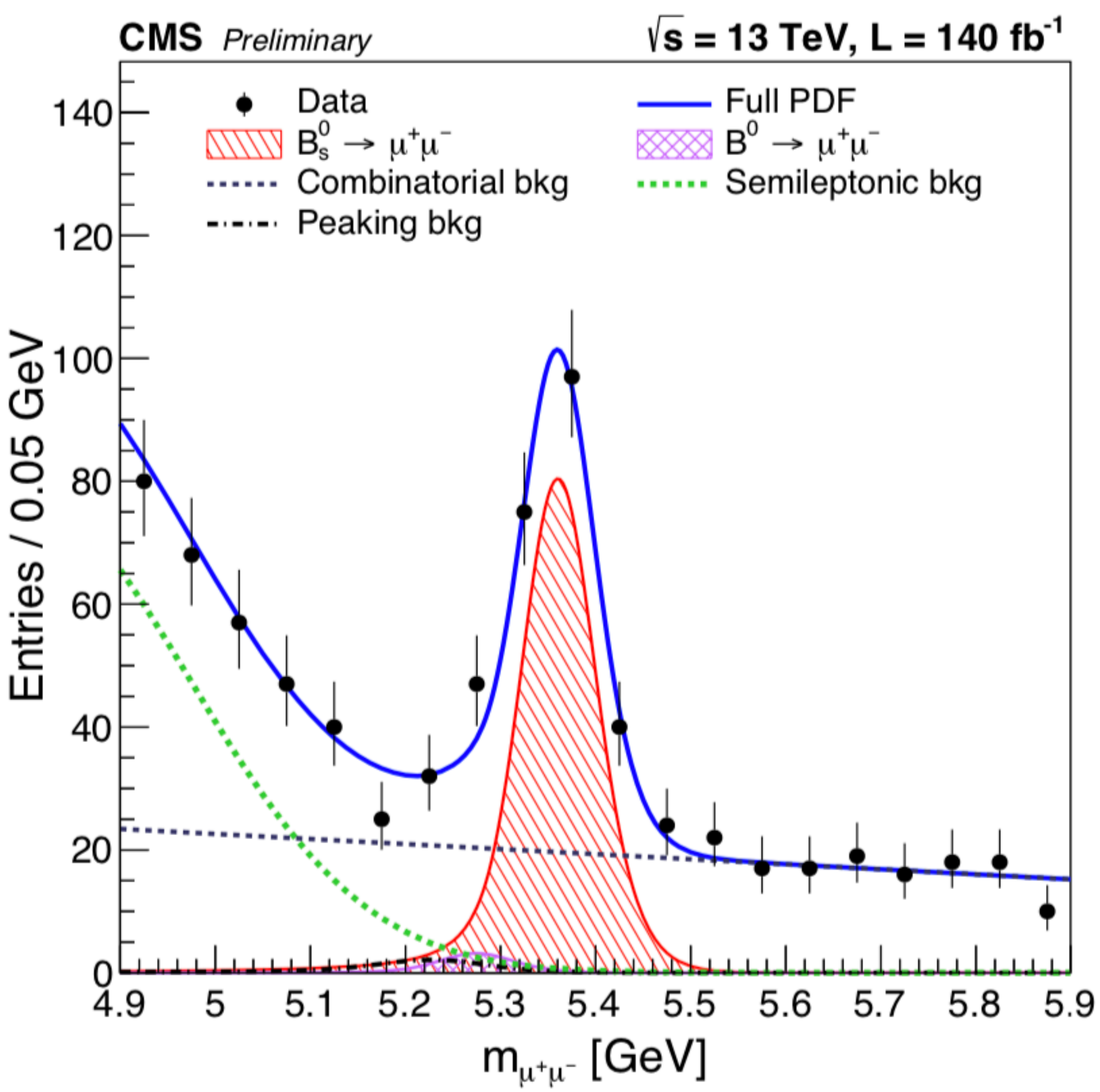
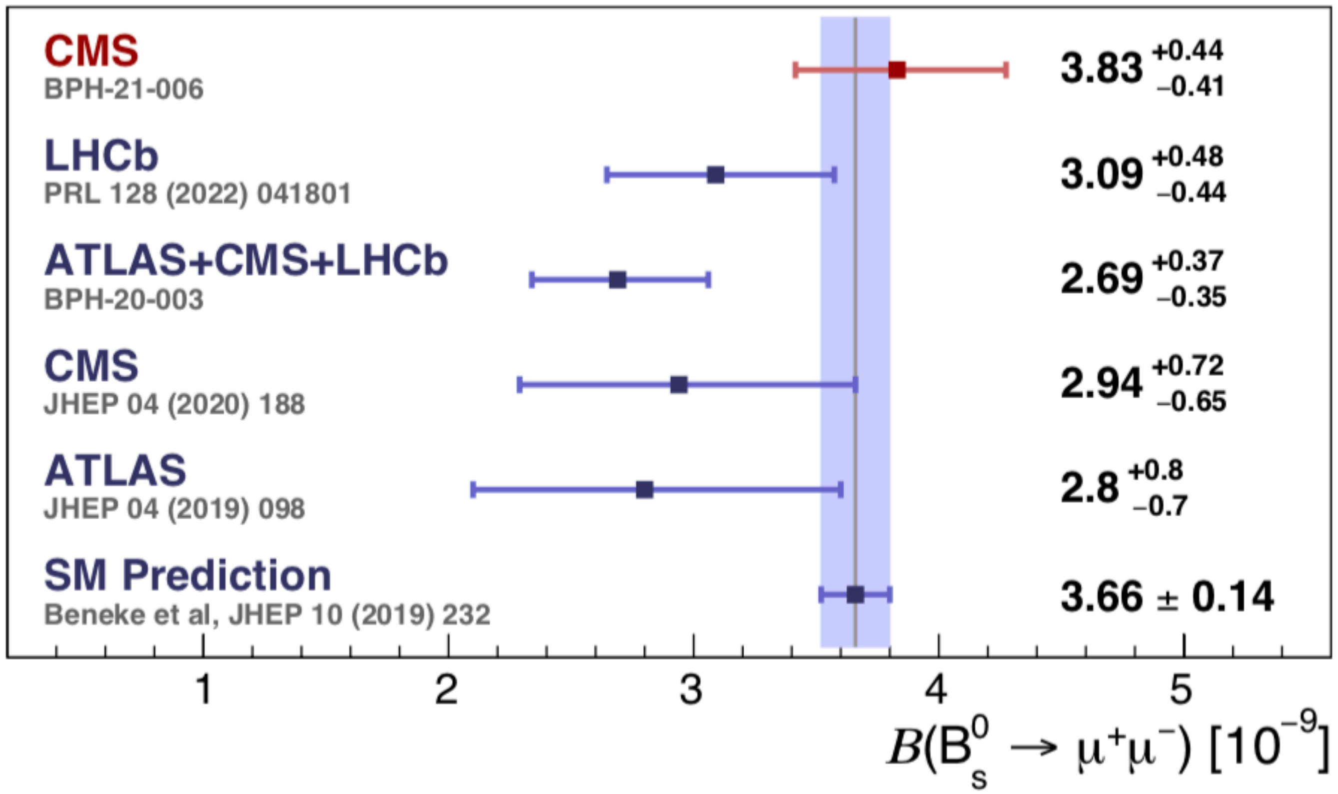


Rare decays

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

Highly suppressed in the SM.
Highly enhanceable elsewhere.
Experimentally accessible.
Theoretically pristine





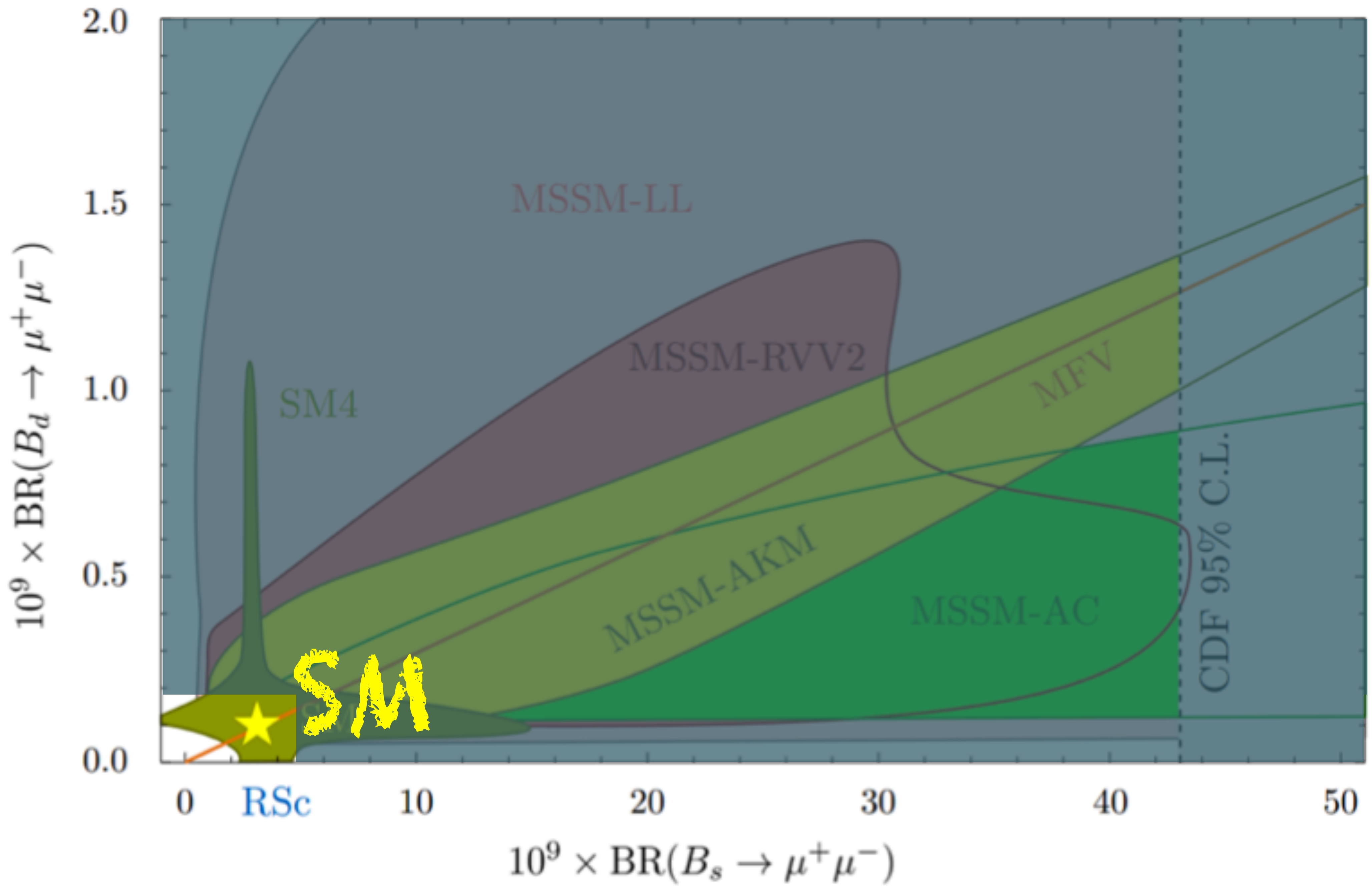
2/3 of LHC Run 1+2 legacy in place. Excellent agreement with SM but a great deal ahead to observe $B^0 \to \mu^+\mu^-$

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 1.9 \times 10^{-10} \text{ at 95\% CL}$$

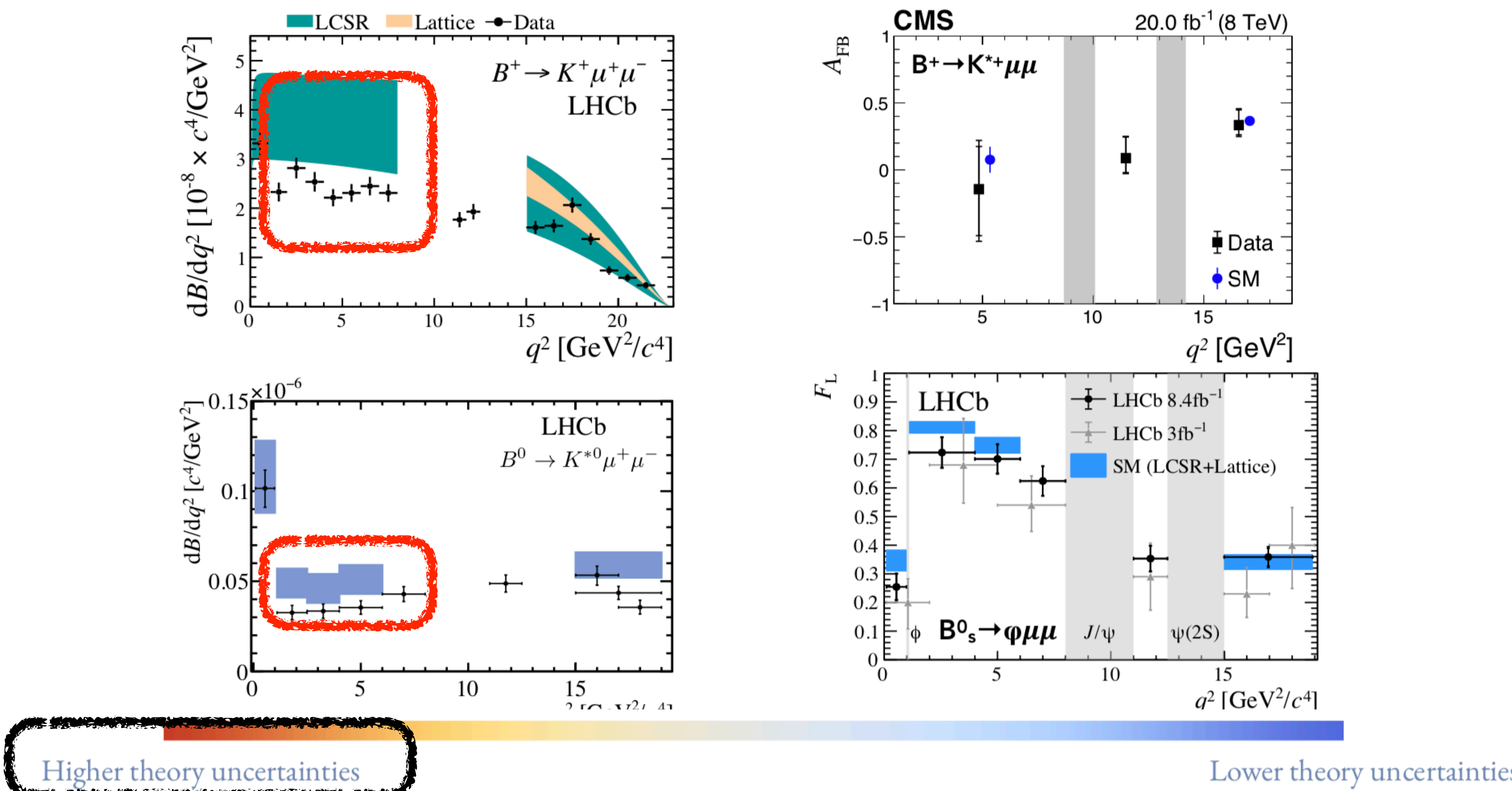
[CMS-PAS-BPH-21-006]

BSM killers

[*Nuovo Cim.C* 035N1 (2012) 249]



Angular tests in $b \to s\ell^+\ell^-$ decays

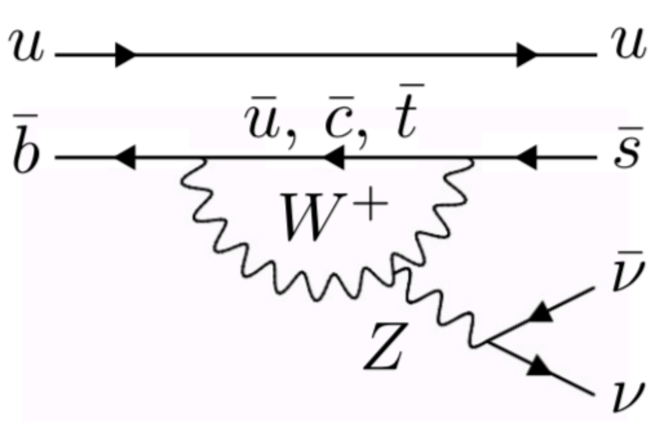


[LHCb, PRL 125 (2020) 011802, 126 (2021) 161802, JHEP 11 (2021) 043, 12 (2016) 065, 09 (2018) 146]
[Belle, PRL 118 (2017) 11, 111801, ATLAS, JHEP 10 (2018) 047, CMS, PLB 781 (2018) 517]
[LHCb, JHEP 06 (2014) 133, 11 (2016) 047, 06 (2015) 115, PRL 127 (2021) 151801]

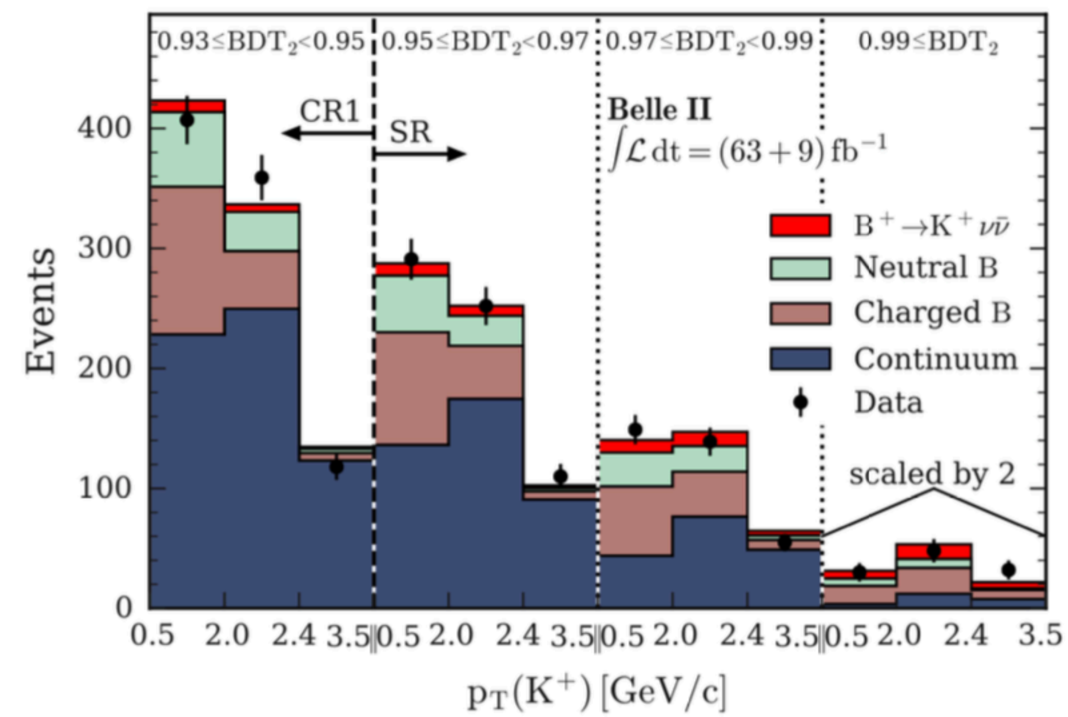
A clear pattern of deviations from expectations in the last years, however there is ongoing debate over its cause (*eg* charm loops)

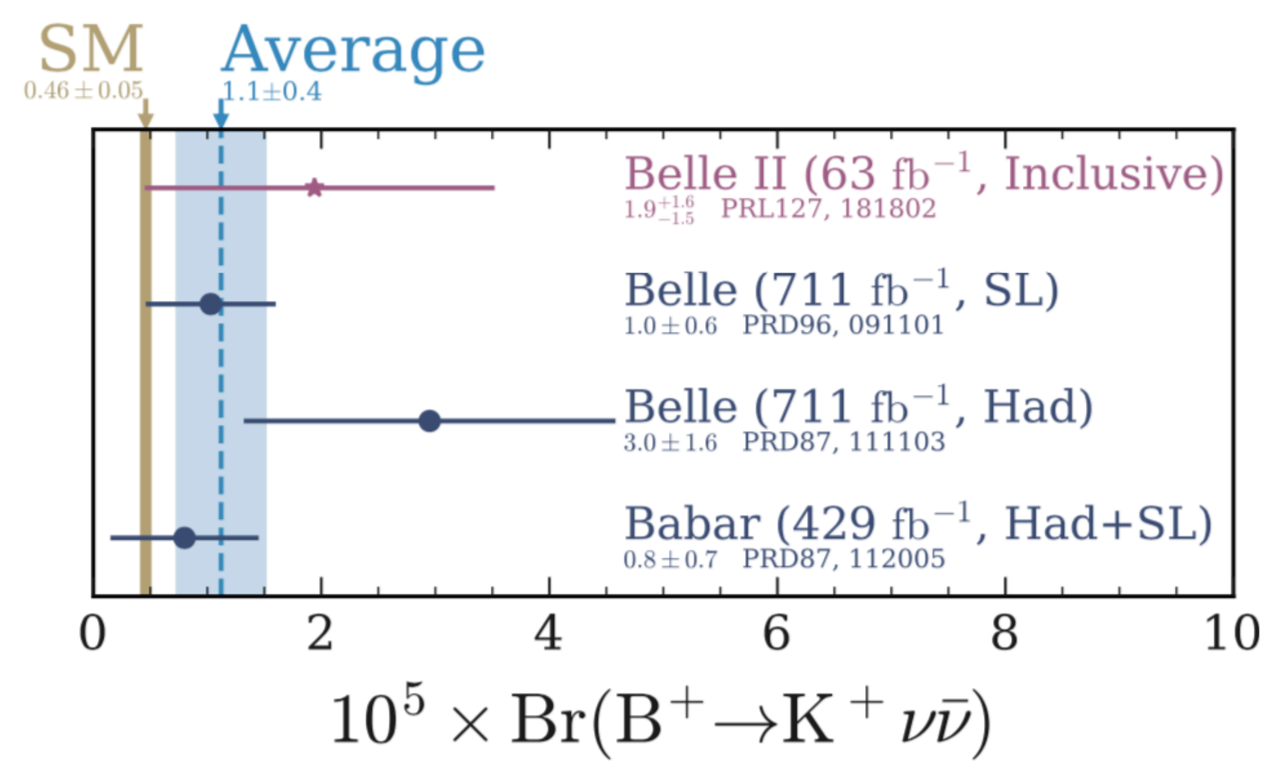
$B \to K\nu\bar{\nu}$, a complementary road

- Complementary to $b \to s\ell^+\ell^-$ transitions, but with no charm-loop contamination (theoretically clean)



- Accessible only at Belle II
  - SM rate of $B^+ \to K^+\nu\bar{\nu}$ can be measured at >3σ with 5/ab





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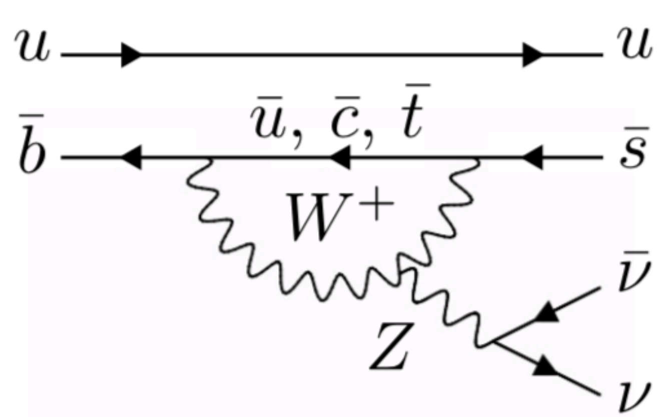

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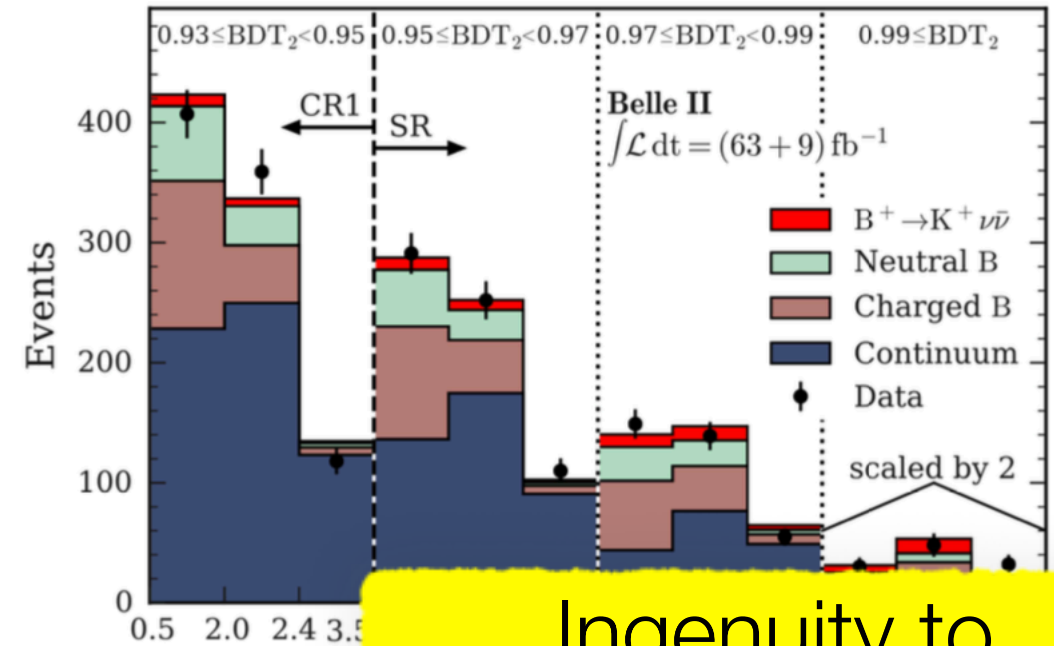
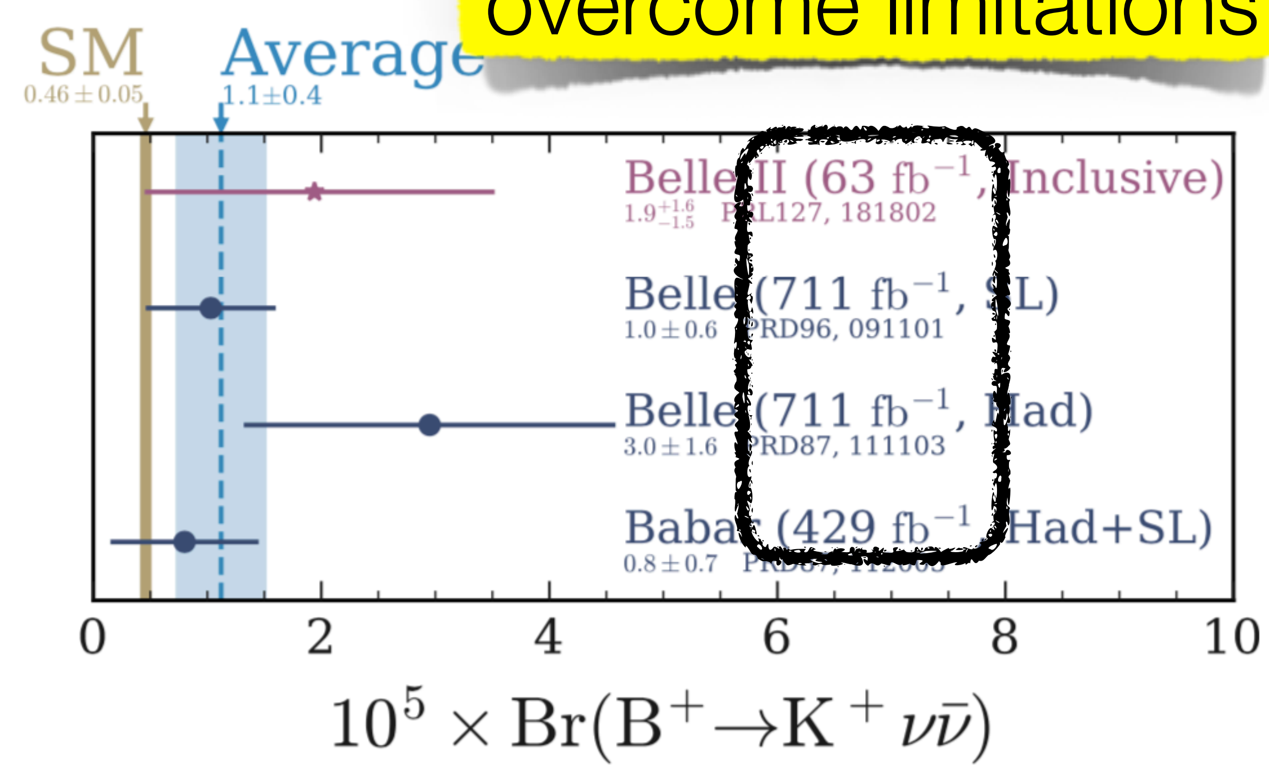


Ingenuity to overcome limitations



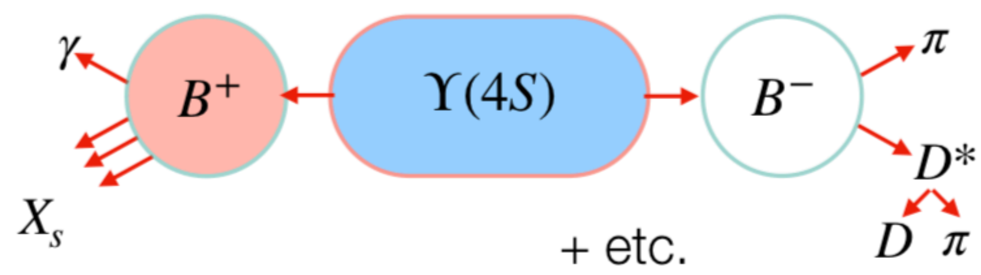
$B \to X_s\gamma$, another complementary road

$b \to s\gamma$ has higher rates and is sensitive differently to NP wrt $b \to sll$

Inclusive **Exclusive**

Experimental challenge

Theory challenge

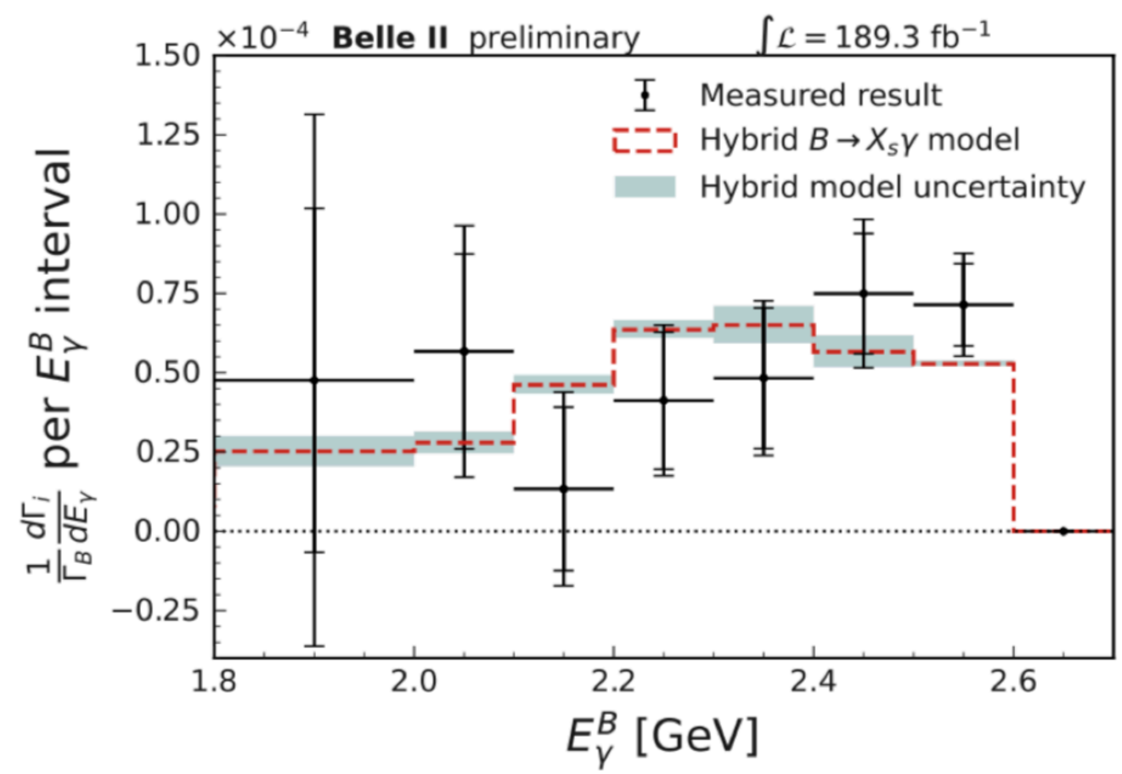


E_γ^B - photon energy in the B_{sig} rest frame

Study of inclusive $B \to X_s\gamma$ decay. In addition to NP searches extract:

- Integrate results for various E_γ^B thresholds

E_γ^B threshold, GeV	$\mathcal{B}(B \to X_s\gamma)(10^{-4})$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)



- Largest systematic effects due to simulation mismodelings and bkg normalization data-simulation discrepancy.
- BaBar hadron tag result for $E_\gamma^B > 1.9$ GeV (210 fb^{-1}): $(3.66 \pm 0.85 \pm 0.60) \times 10^{-4}$ [PRD77,051103]
- SM prediction for $E_\gamma^B > 1.6$ GeV: $(3.40 \pm 0.17) \times 10^{-4}$ [JHEP06(2020)175]

Competitive with the BaBar hadronic tag measurement

Sharpening your tools

Lepton-Flavour Universality tests

Get rid of hadronic uncertainties by comparing rates.

Suppressed loops

$$\frac{\mathcal{B}(b \to s\,\mu^+\mu^-)}{\mathcal{B}(b \to s\,e^+e^-)}$$

1st *vs* 2nd family

Correct for different muon and electron selections.

Favoured trees

$$\frac{\mathcal{B}(b \to c\,\tau\,\nu)}{\mathcal{B}(b \to c\ell\nu)}$$

3rd *vs* 1st/2nd family

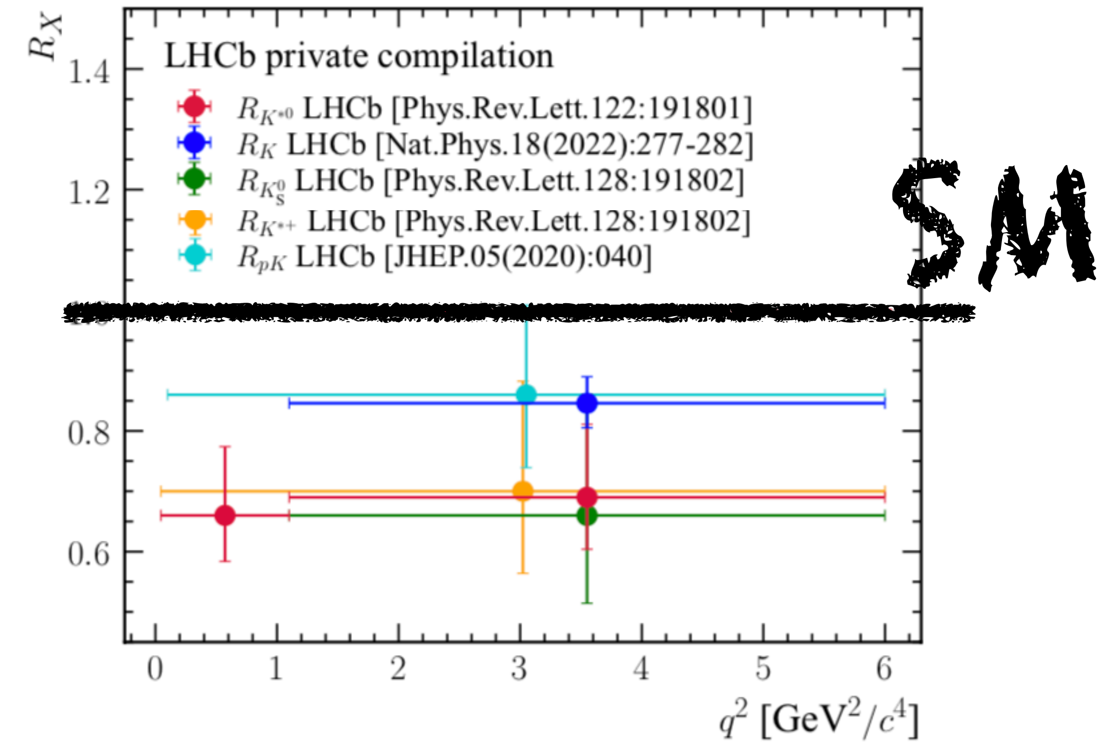
Undetected neutrinos, large backgrounds

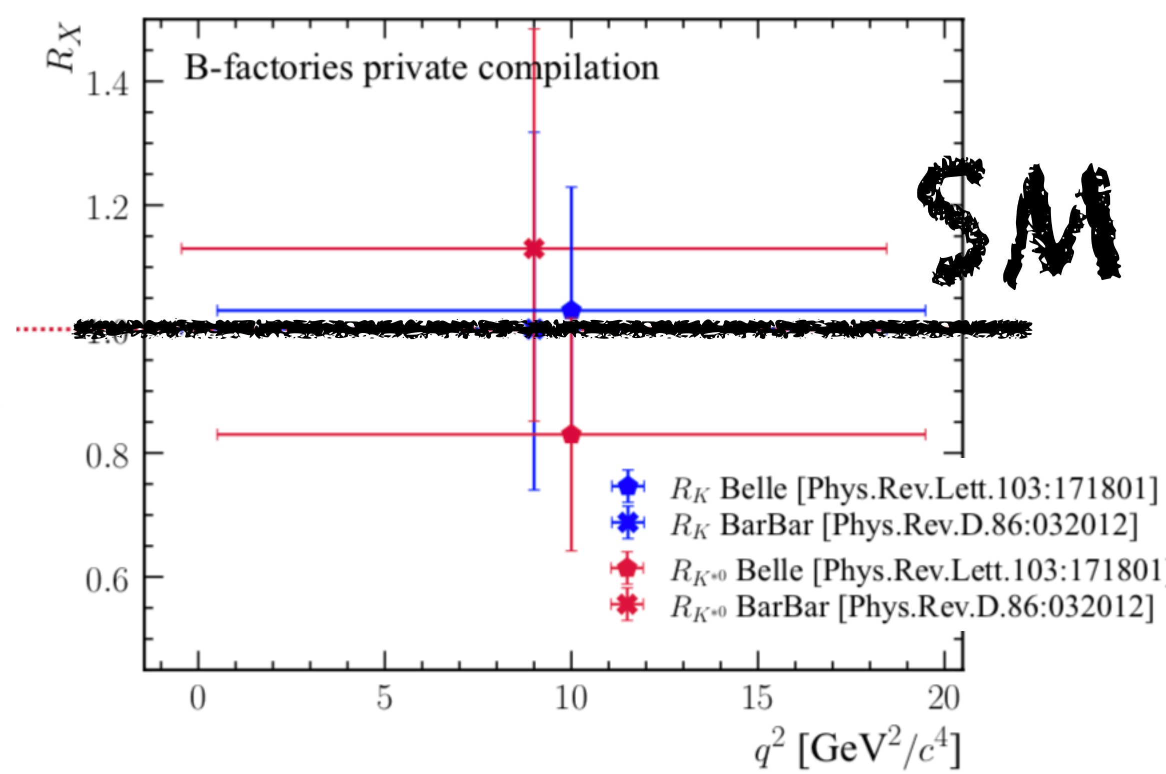
Theoretically pristine observables. Experimentally challenging.

$(b \to s\,\mu^+\mu^-)$ *versus* $(b \to s\,e^+e^-)$

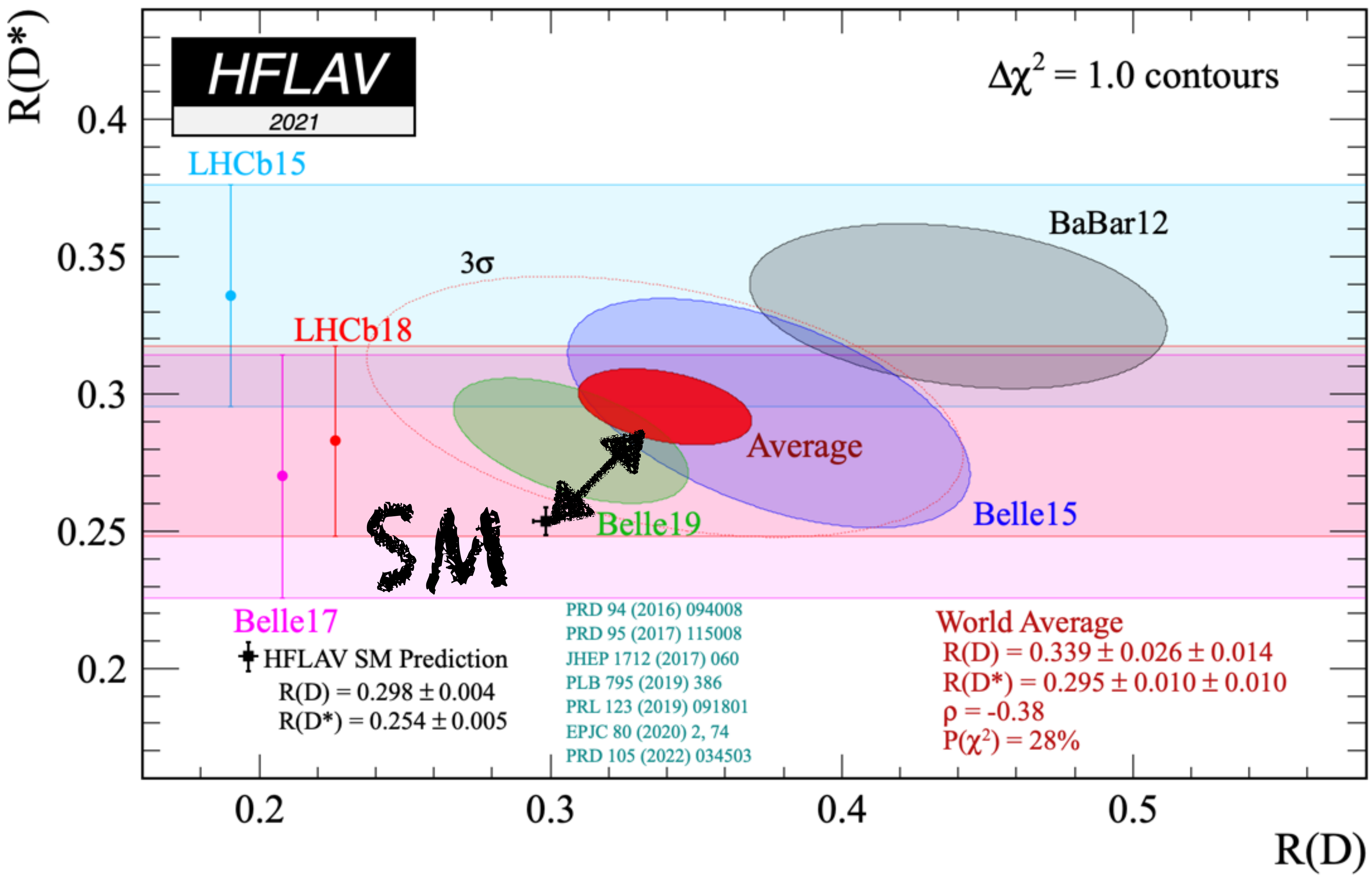
- Precision dominated by LHCb. Now focus on completing a combined analysis of R_K and R_{K^*} with the Run 1+2 legacy dataset.
- Belle II will be able to independently verify with 5/10 ab^{-1}.

Eagerly awaiting updates from LHCb.
Would be interesting to see also CMS impact from *B* parked data





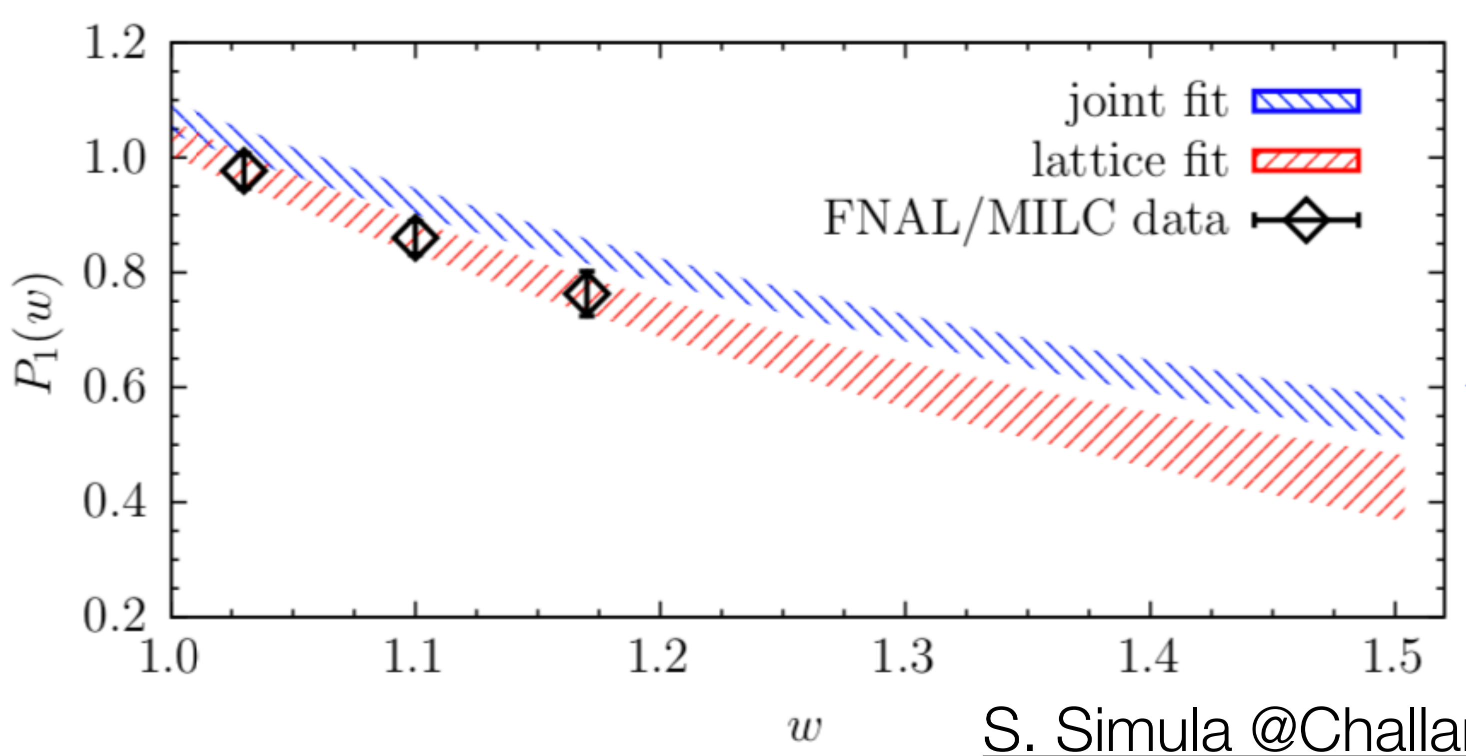
$(b \to c\,\tau\,\nu)$ versus $(b \to c\,\ell\,\nu)$



Eagerly awaiting new results to update this 2D plane.
LHCb adding also Λ_b and B_s in the game.

$(b \to c\,\tau\,\nu)$ *versus* $(b \to c\,\ell\,\nu)$

Do we know (D**) backgrounds enough?
Do we trust our SM reference enough?



$|V_{cb}| > |V_{cb}|^{\text{joint fit}}$

$R(D^*) = 0.2483 \pm 0.0013$

$R(D^*) = 0.265 \pm 0.013$

S. Simula @Challanges in B SL decays

R(D)

Eagerly awaiting new results to update this 2D plane.
LHCb adding also Λ_b and B_s in the game.

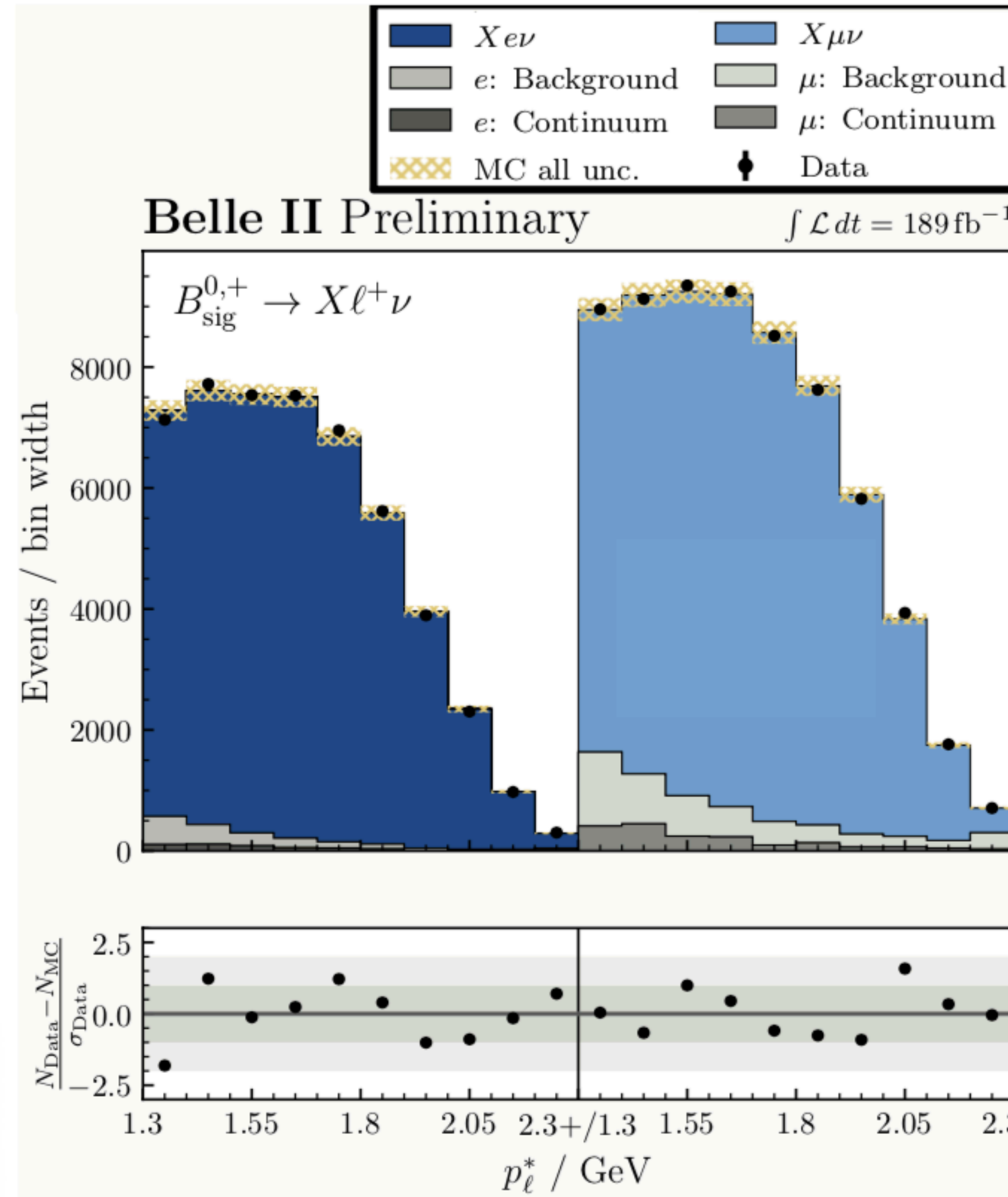
Belle II gearing up: $(B \to X_c\, \mu\, \nu)$ vs $(B \to X_c\, e\, \nu)$

- Preparing novel inclusive approach to test LFU to enhance efficiency.

$$\frac{\mathscr{B}(B \to X_c e\nu)}{\mathscr{B}(B \to X_c \mu\nu)} = 1.033 \pm 0.010 \pm 0.020$$

- Most stringent LFU test to date, exemplifying the specific and complementary capabilities of Belle II.

Expect competitive precision with Belle/LHCb using just <1/3 of Belle sample size.



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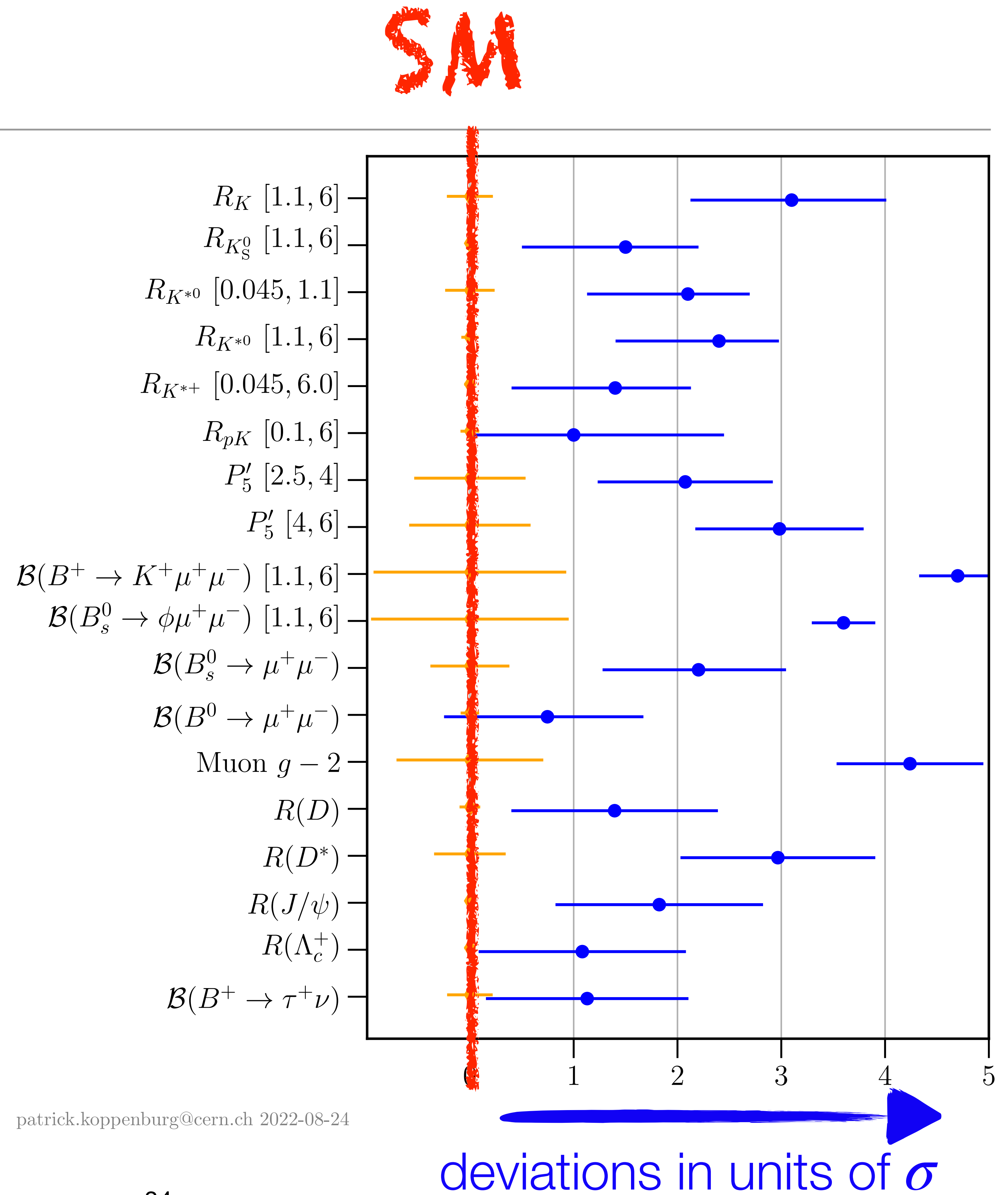
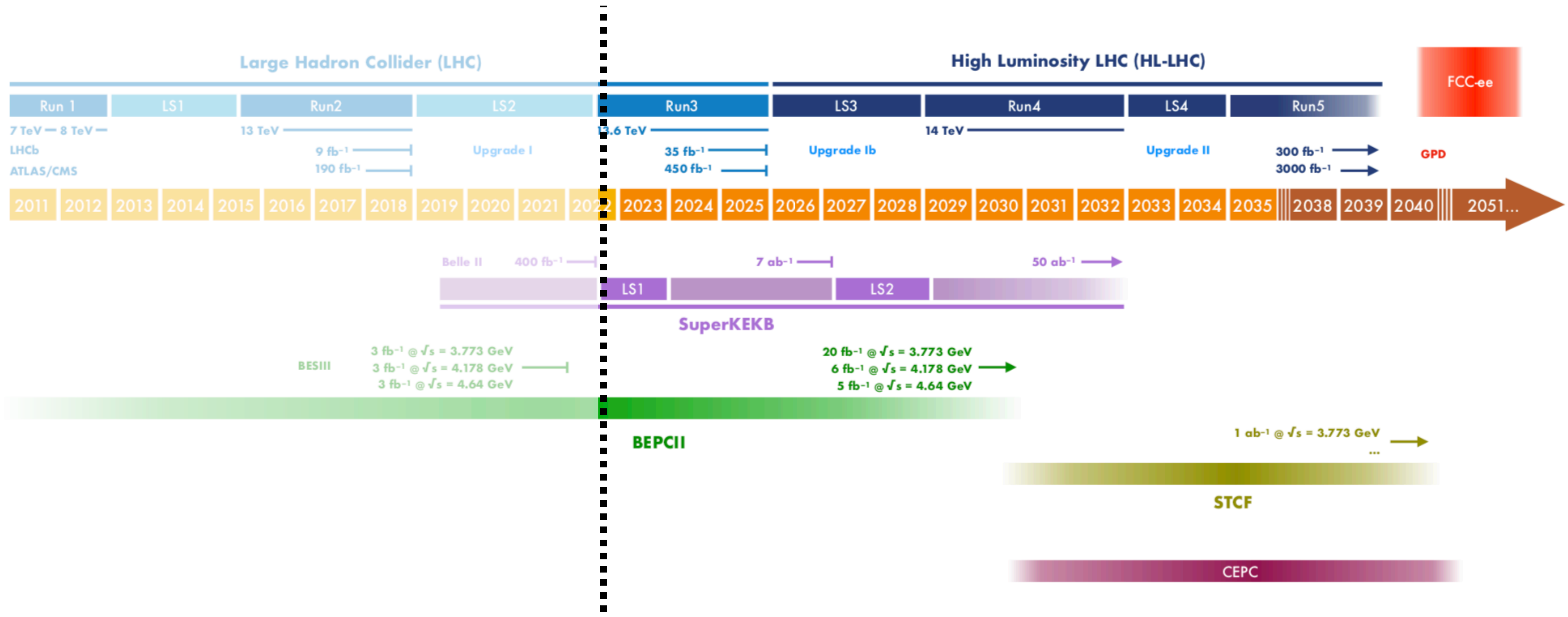
Anomalies

- Regardless of whether or not their statistical significance will increase, they remind us the genuine discovery potential of flavour (remember GIM?).

- To fully exploits this potential we need advancement on both experimental and theoretical side, to push precision to the next level.



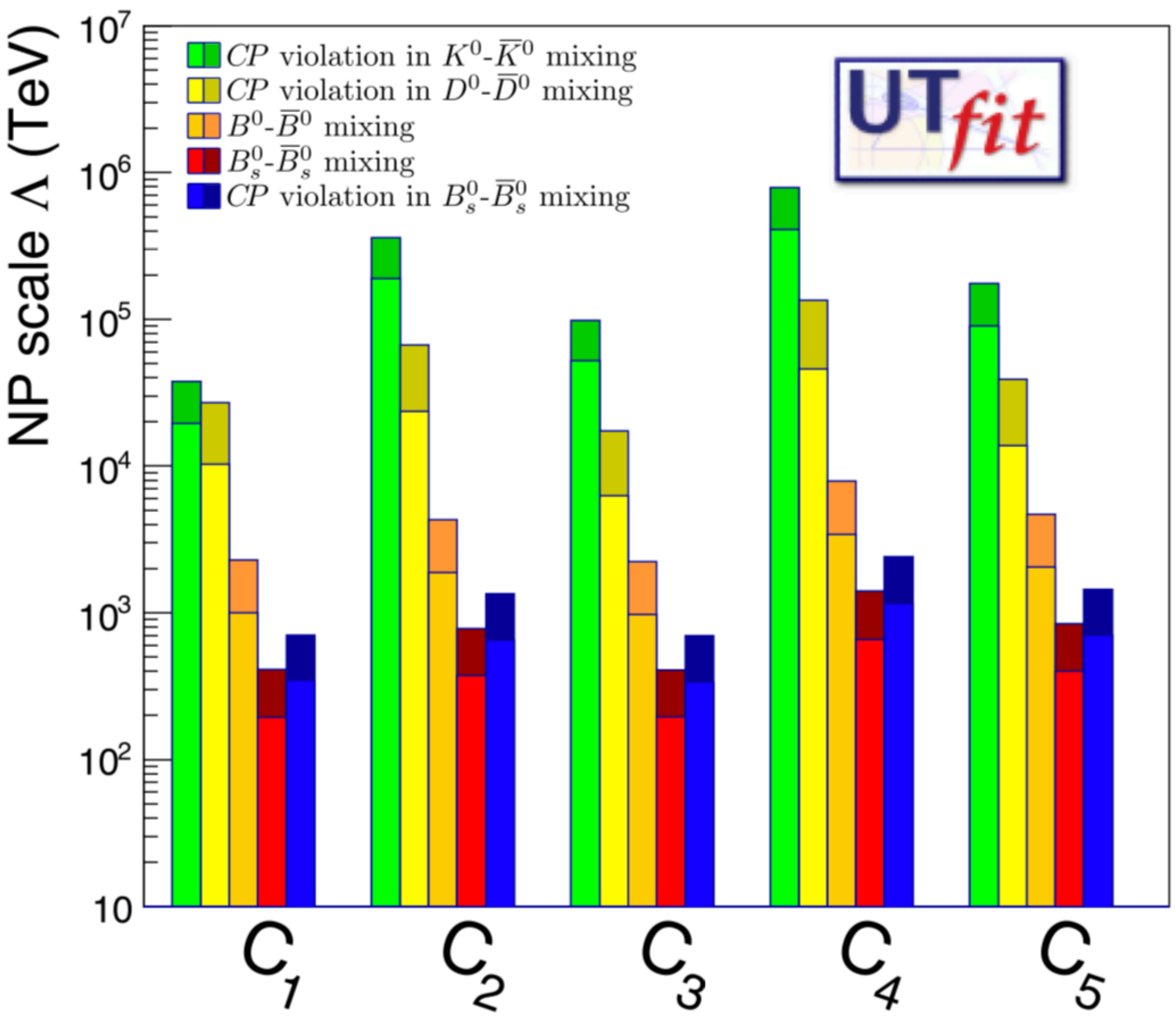
Timeline



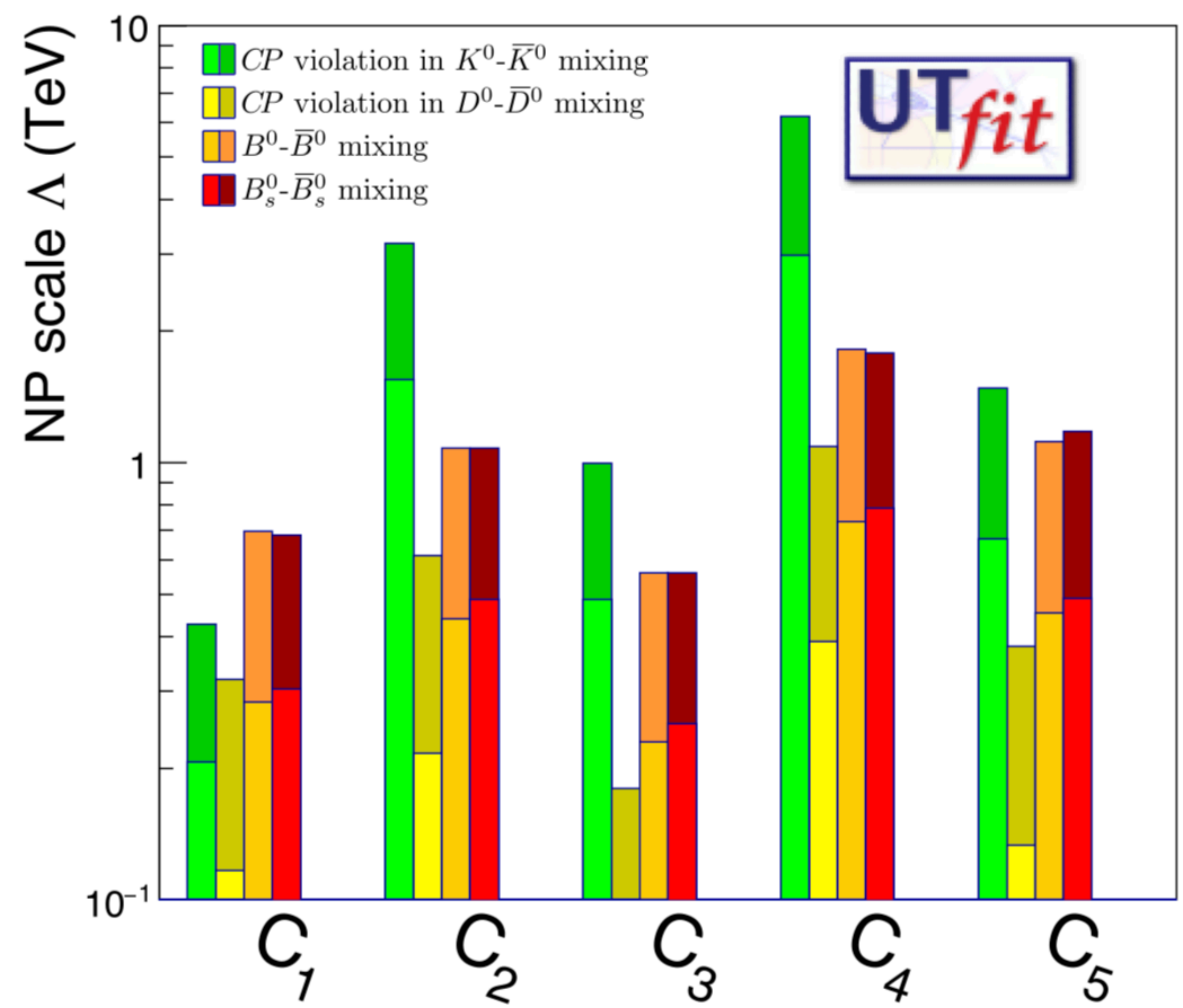
Important to stress LHCb and Belle II (and GDPs) complementarity. They will check each other across key observables leveraging on different strengths.
[arXiv:1812.07638, arXiv:2207.06307]

Impact on the flavour reach

[arXiv:2208.05403]



Arbitrary flavour structure,
NP strongly coupled



Minimal flavour violation,
NP weakly coupled

Summary

- Flavour physics, a most compelling probe for BSM dynamics.
- Multiple dedicated experiments with complementary capabilities online for the first time
- A broad and diverse program of a plethora of measurements is ahead. Unique, probably unrepeatable, opportunity.

Backup

Luminosity projections

Goal: 50 fb^{-1} — Goal: 300 fb^{-1}

LHCb — Consolidation — Upgrade II

Run 3			LS3			Run 4				LS4		Run 5				LS5	Run 6	
2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2039	2040	2041	2042