Belle II and anomalies: what's new, what's next?

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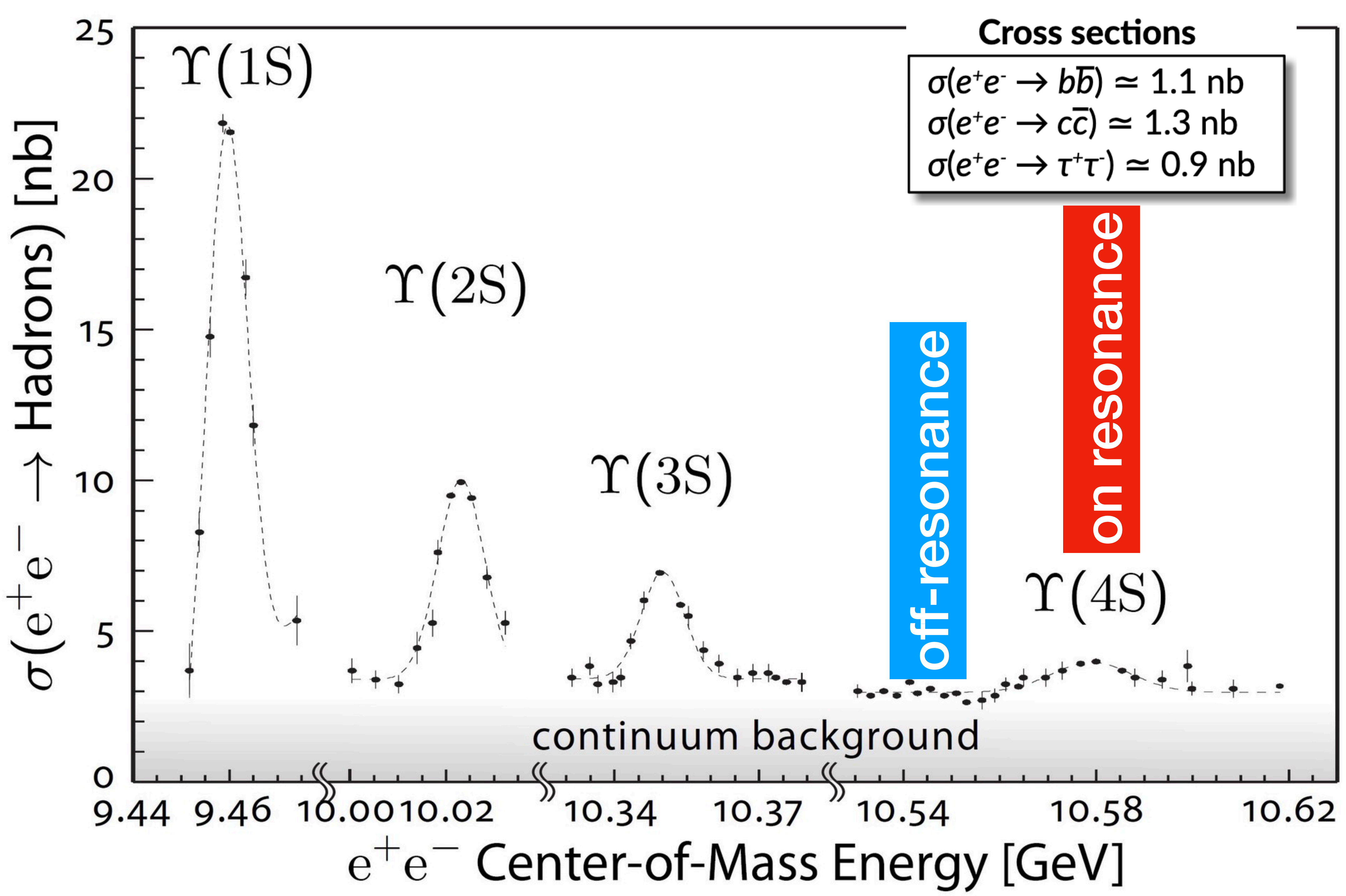
on behalf of the Belle II collaboration

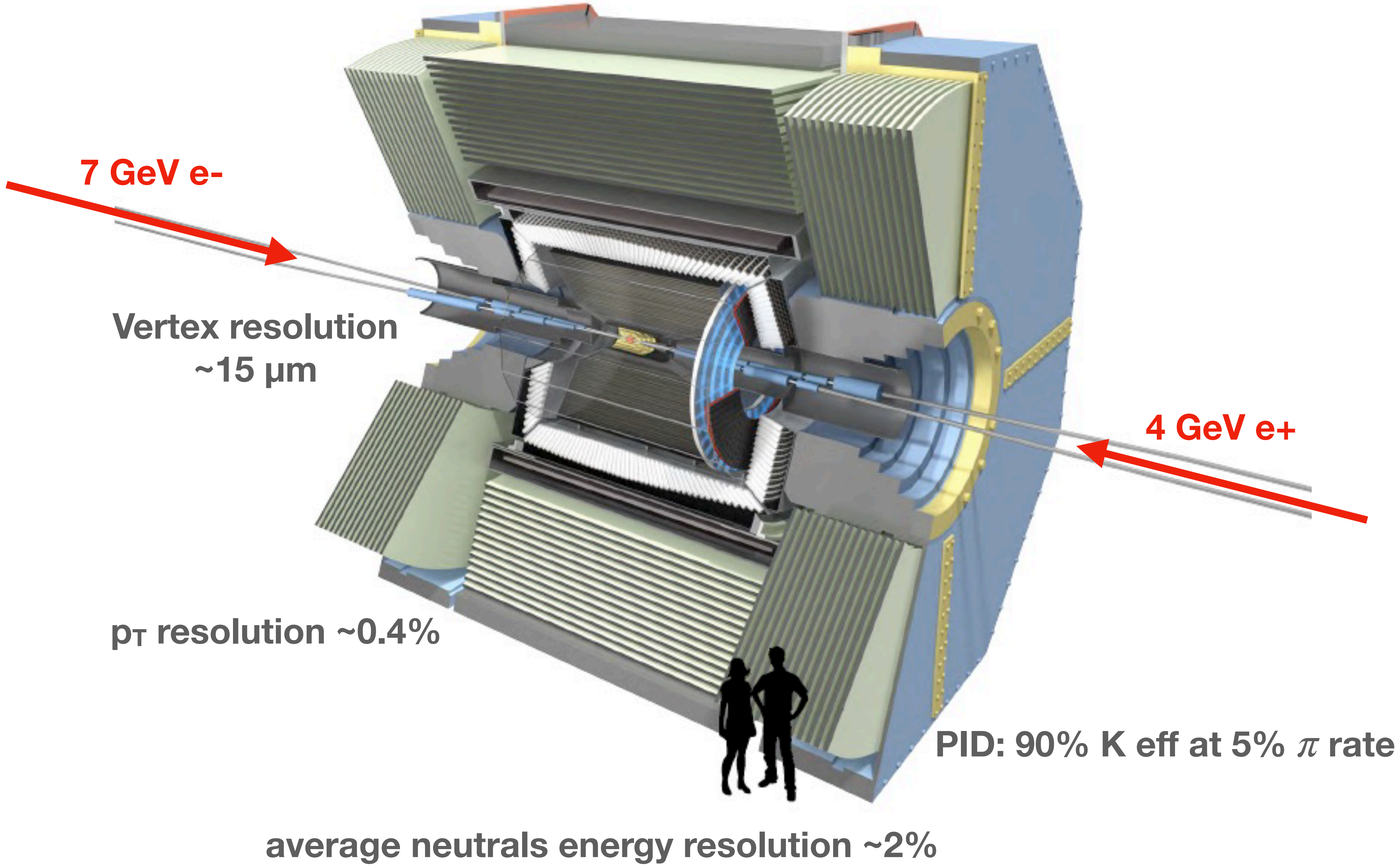
Siegen, 11 April 2024

The journey so far

- Belle II: mostly running on/near $\Upsilon(4S)$ resonance, with a short scan above $\Upsilon(4S)$
- Can include the Belle data: $\Upsilon(1-5S)$

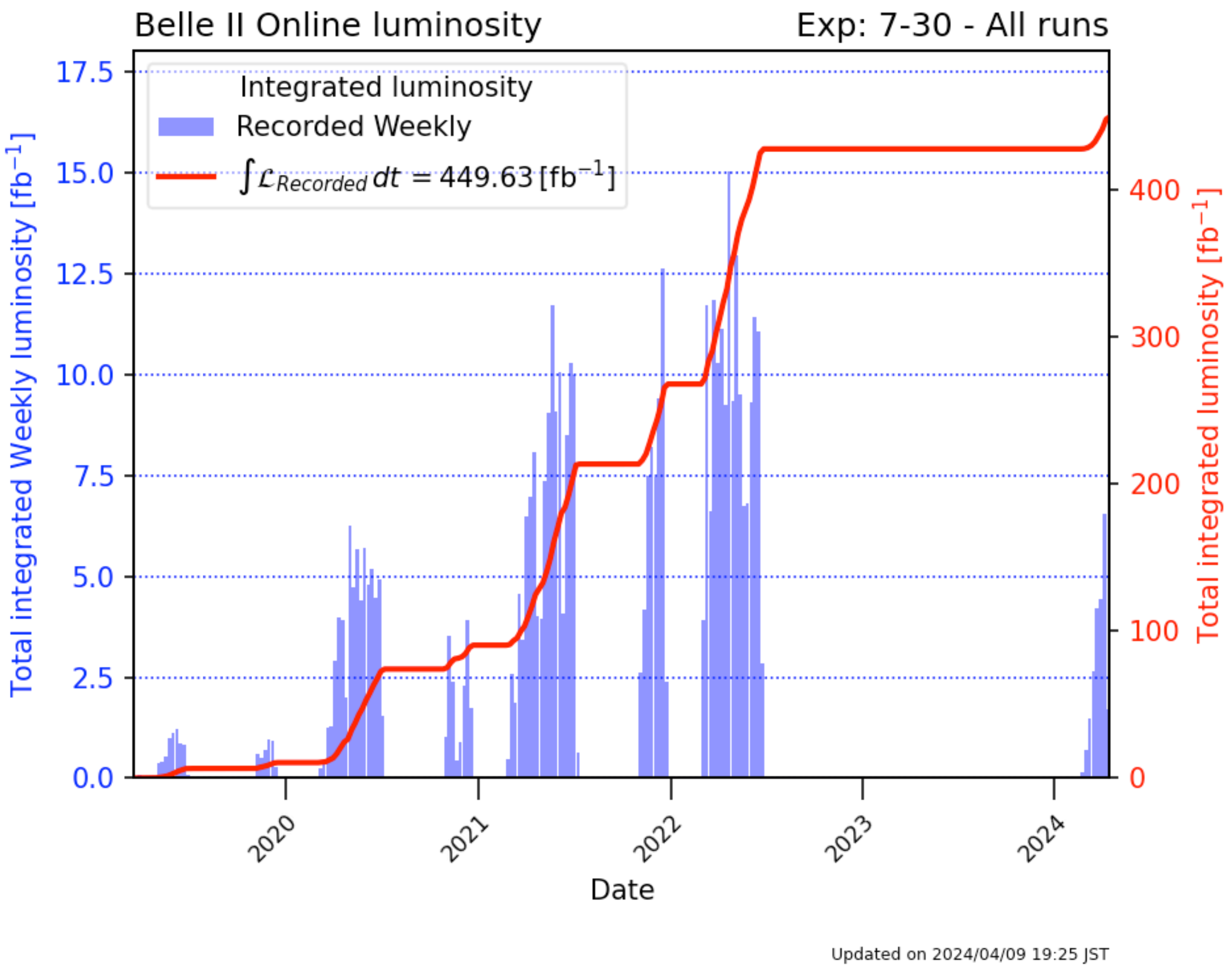


~4π coverage
optimal for missing energy



The journey so far

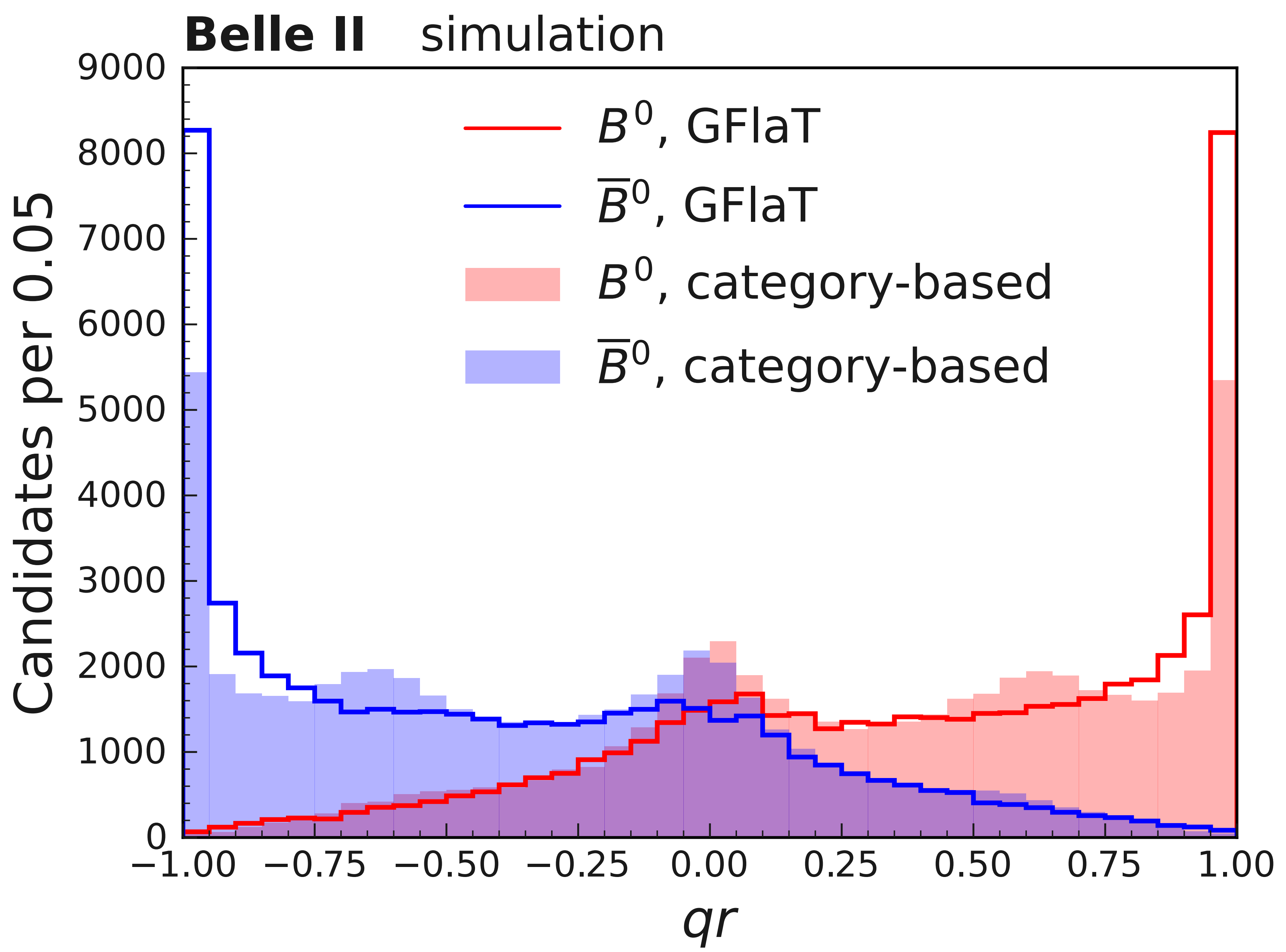
- World record peak luminosity in summer 2022: 4.7×10^{34}/cm²/s
- Progress limited by sudden beam losses and other accelerator issues
- LS1: machine improvements & complete the vertex detector
- **The data taking has resumed recently**
- Main objectives for 2024:
  - Reach and maintain the peak luminosity of 10^{35}/cm²/s
  - Cross the 1ab^{-1} milestone
  - Prove the effectiveness of the work done in LS1



Not just more data: improvement in the analysis tools

Improving the tagging: beauty

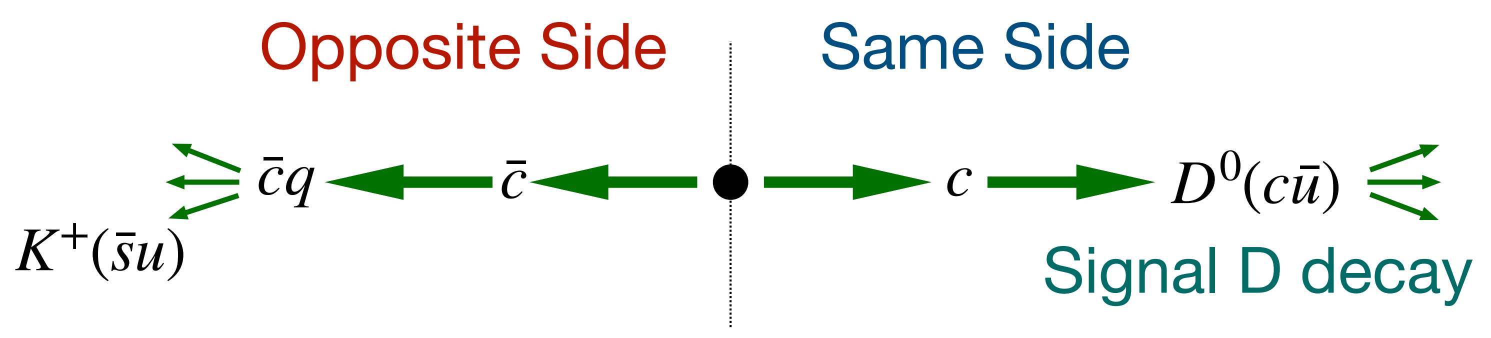
- **Conventional category-based tagger** (by charge of the lepton/kaon from the other B): effective tagging efficiency ~30%
- Flavour tagging using machine-learning techniques with the full event information (PID, tracking, kinematics) for the "rest of the event"
  - New **GNN-based tagger GFlaT** [2402.17260] with 37% efficiency
  - Works best when leptons and/or kaons present in the ROE, less well for pion-only events

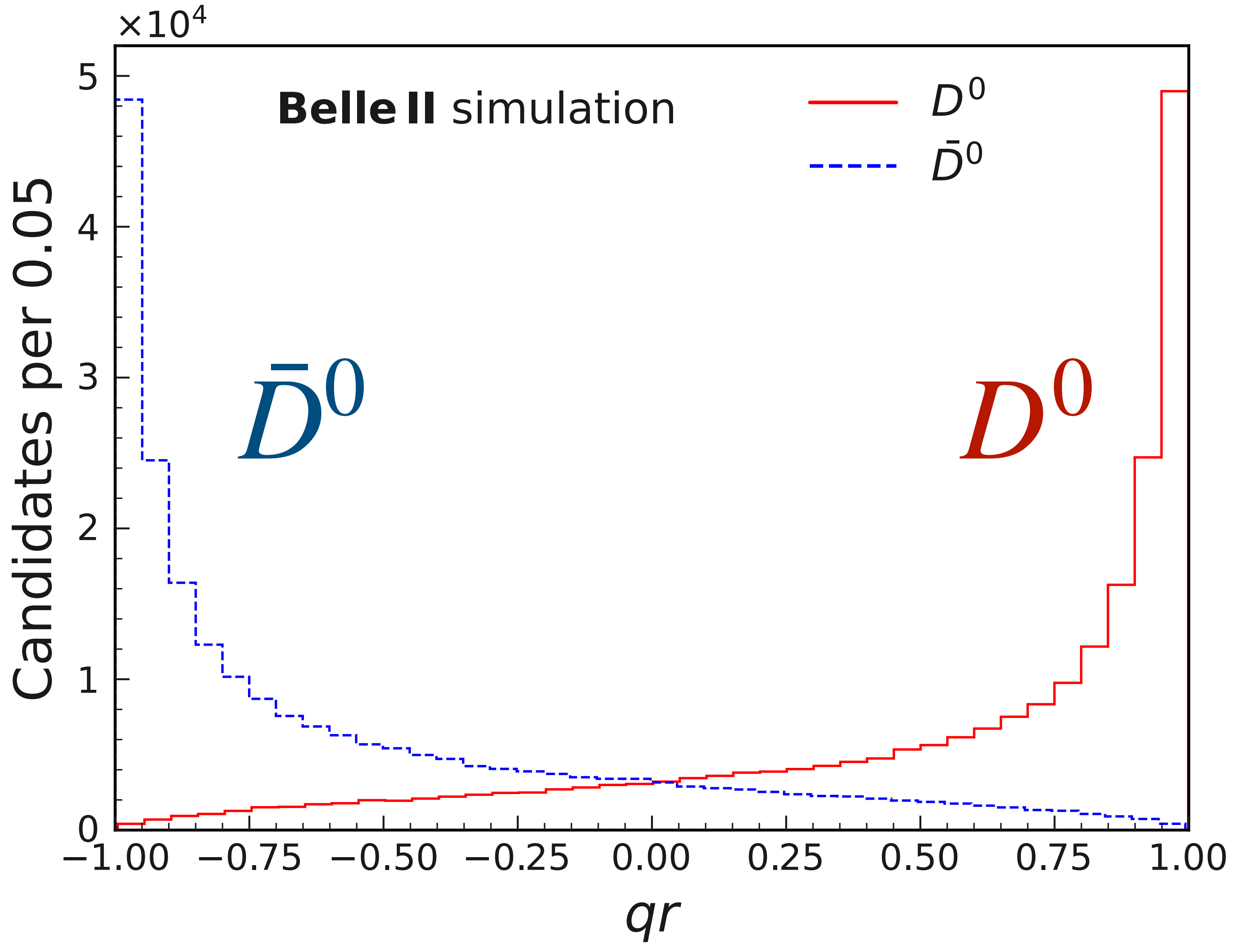


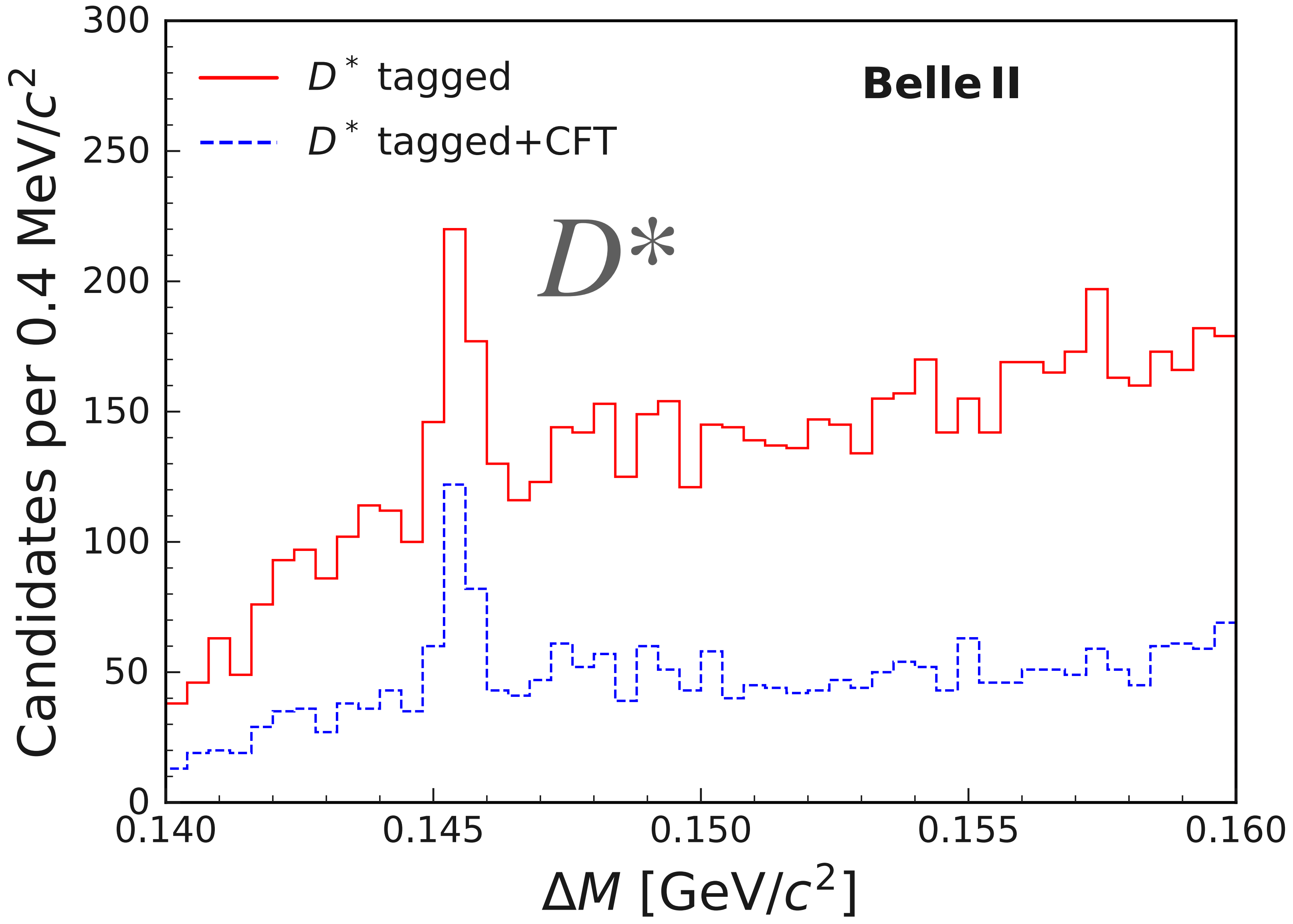
- Prospects for improvement: requires better understanding of simulation

Improving the tagging: charm

- **Conventional method:** tag the charge of the pion from $D^{*\pm} \to D^0\pi^\pm$, or lepton from $B^- \to D^0\ell^-\nu$
  - Loss of statistics due to low production rates, soft pion efficiency etc: ~25% effective efficiency
- New **inclusive tagging** in $e^+e^- \to c\bar{c}$ with BDT algorithm [Phys. Rev. D 107, 112010 (2023)]
  - Uses OS and SS information
  - Effective tagging eff. ~48%
  - **Doubles the effective sample size** for CPV and charm mixing studies
  - Useful to **suppress backgrounds** in untagged analyses

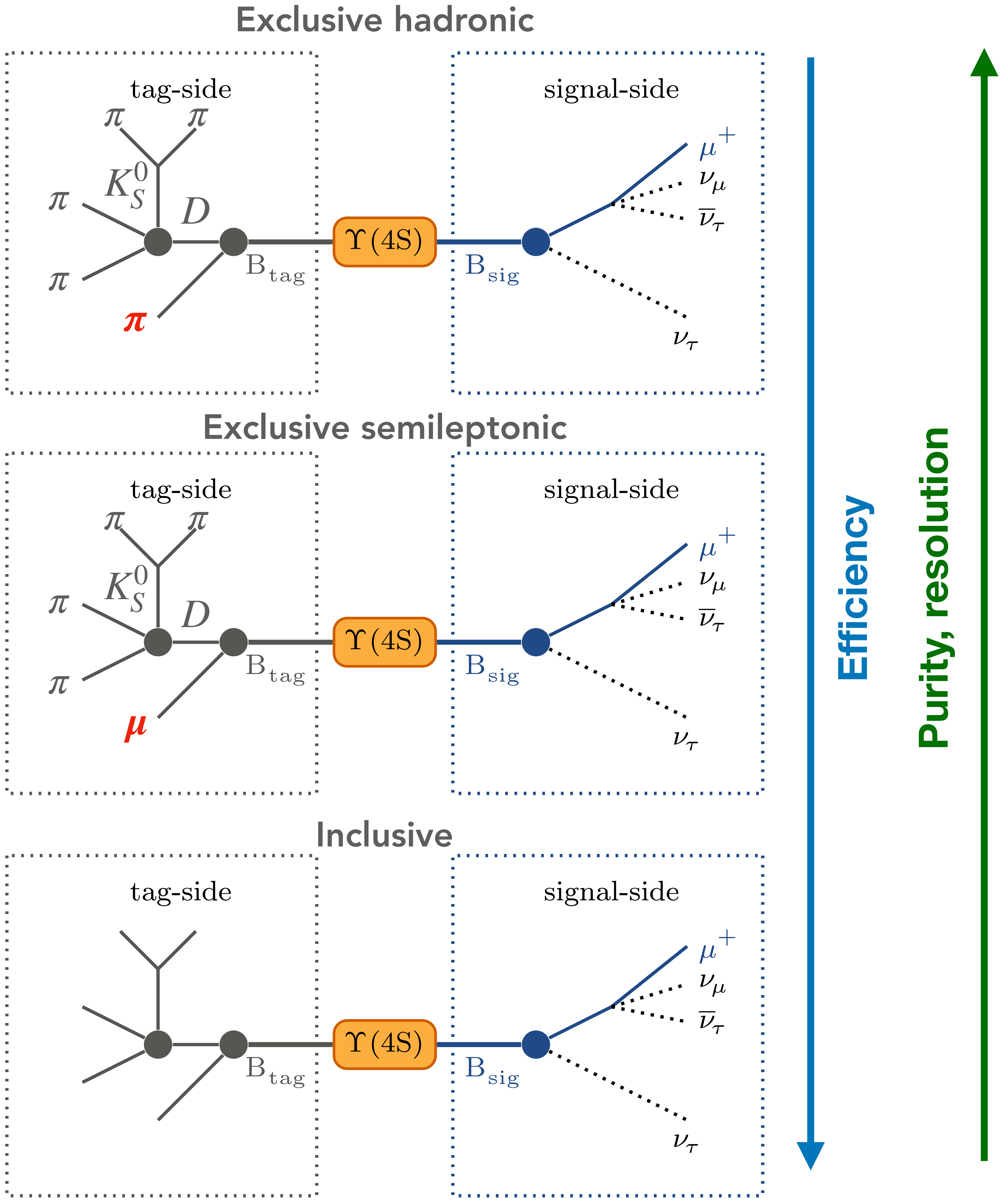






Missing-energy estimation

- **Conventional approach:** full reconstruction of the "other B" in a number of specific decay modes
  - Full event interpretation
  - Hadronic or semileptonic tag
- **Inclusive tagger:** reconstruct signal first, use the "rest of the event" for tagging
- Disagreement between data and simulated performance needs to be calibrated
- Constant improvements:
  - New tag decay modes added
  - BF and resonant structures of known decays re-measured to improve the simulation
  - Alternative ML tools explored (graph neural networks...)



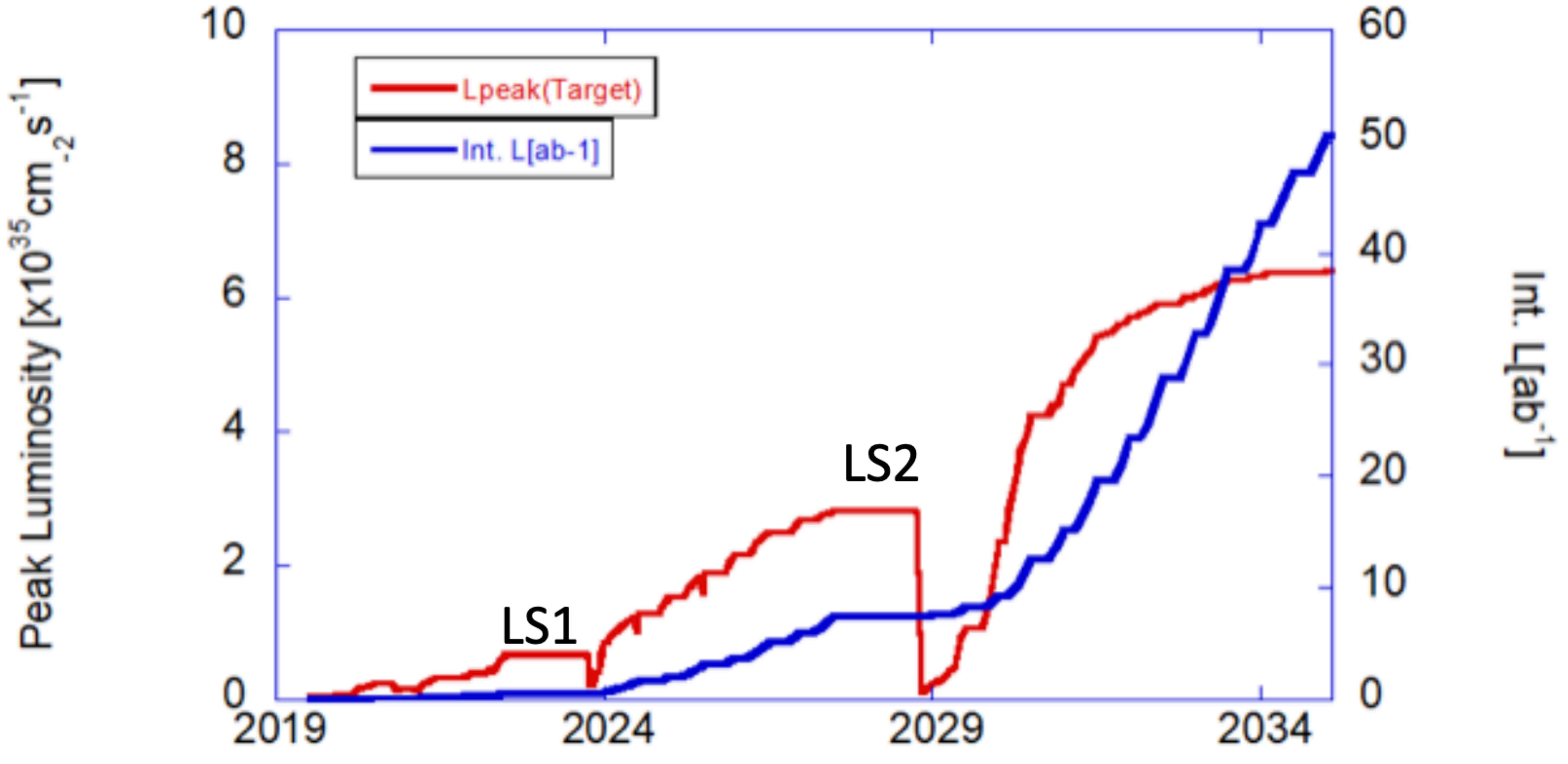
The stairway to flavour physicist's heaven

- **The eventual target is to collect 50 ab^{-1}, but:**

- Going beyond 2×10^{35}/cm^2/s requires a redesign of the interaction region and the vertex detector: beam background

- Envisaged LS2 in 2027-2028, no precise planning yet
  - May profit from this shutdown for other detector improvements

- The priority is to run at/near $\Upsilon(4S)$; special datasets at different energies might be collected in the future

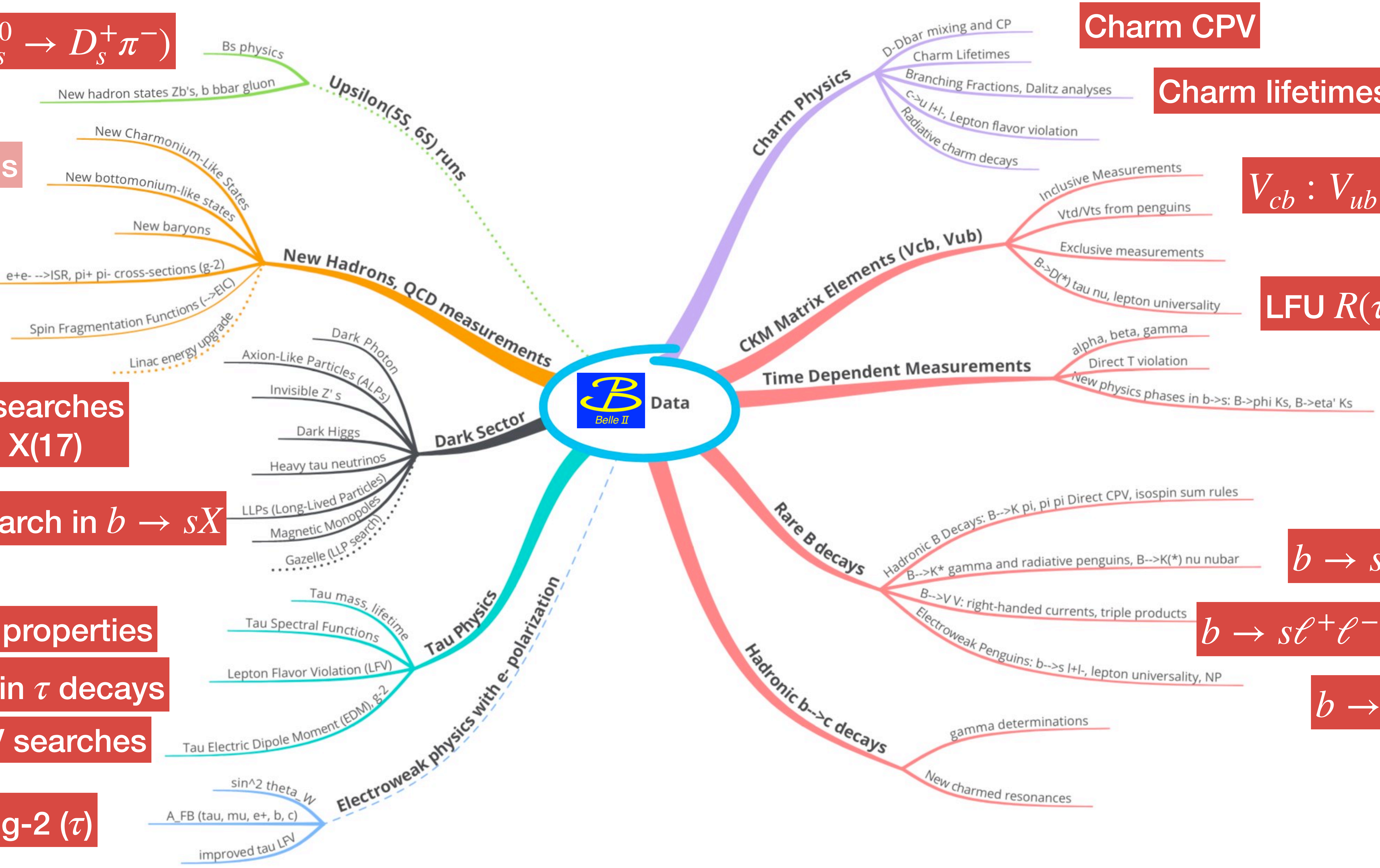


A *biased* collection of physics topics

Focus mostly on the topics **not** covered by Florian, Markus and Caspar

For physics prospects, a recent reference is the 2022 Snowmass report: 2207.06307

Belle II versus anomalies (broadly defined)



$\mathscr{B}(B_s^0 \to D_s^+ \pi^-)$

Exotic hadrons

muon g-2 inputs

direct searches incl. X(17)

resonance search in $b \to sX$

Tau properties

LFU in τ decays

LFV searches

g-2 (τ)

Charm CPV

Charm lifetimes

$V_{cb} : V_{ub}$

LFU $R(\tau/\mu)$

$b \to s\nu\bar{\nu}$ rates

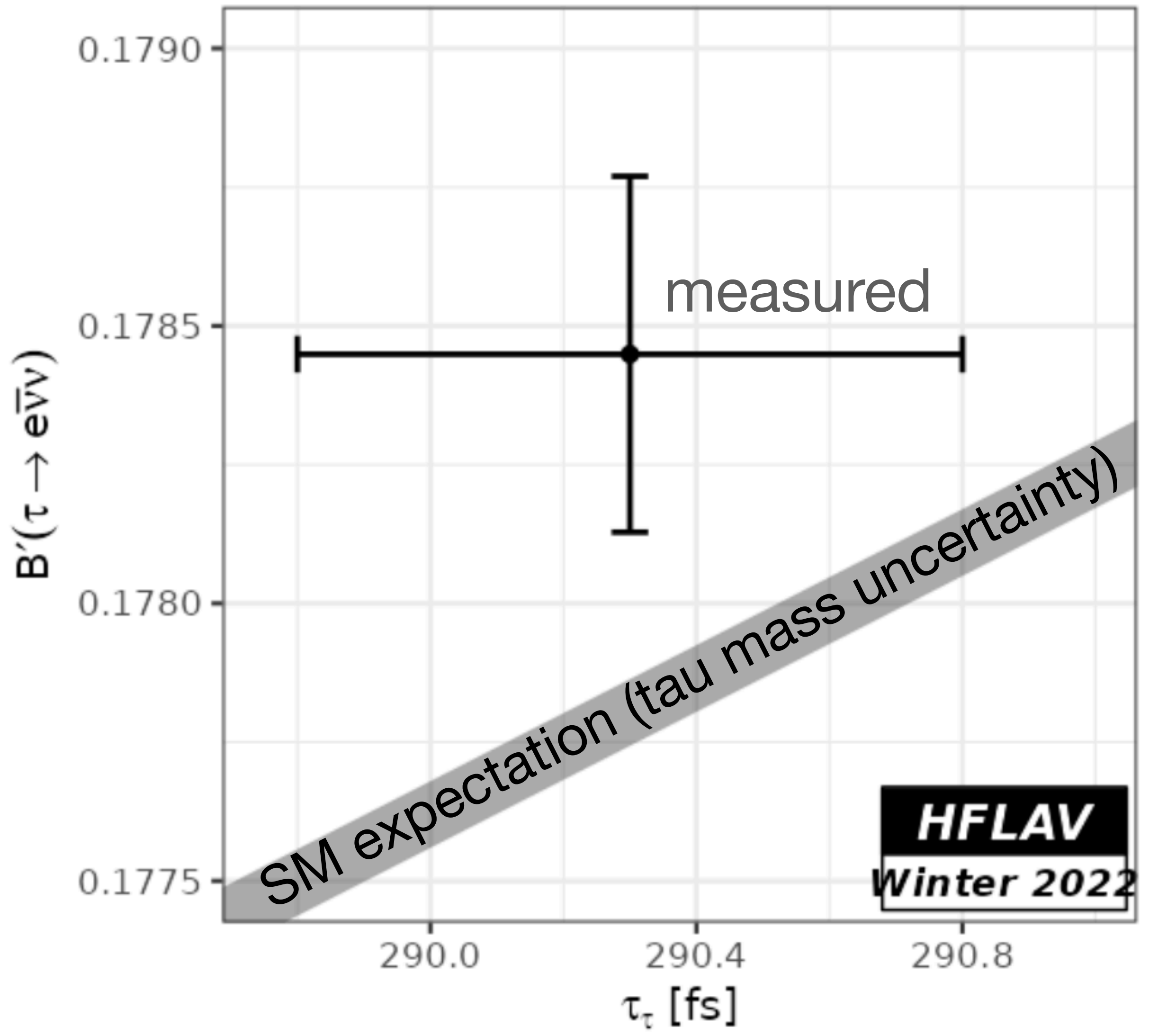
$b \to s\ell^+\ell^-$ and $b \to d\ell^+\ell^-$

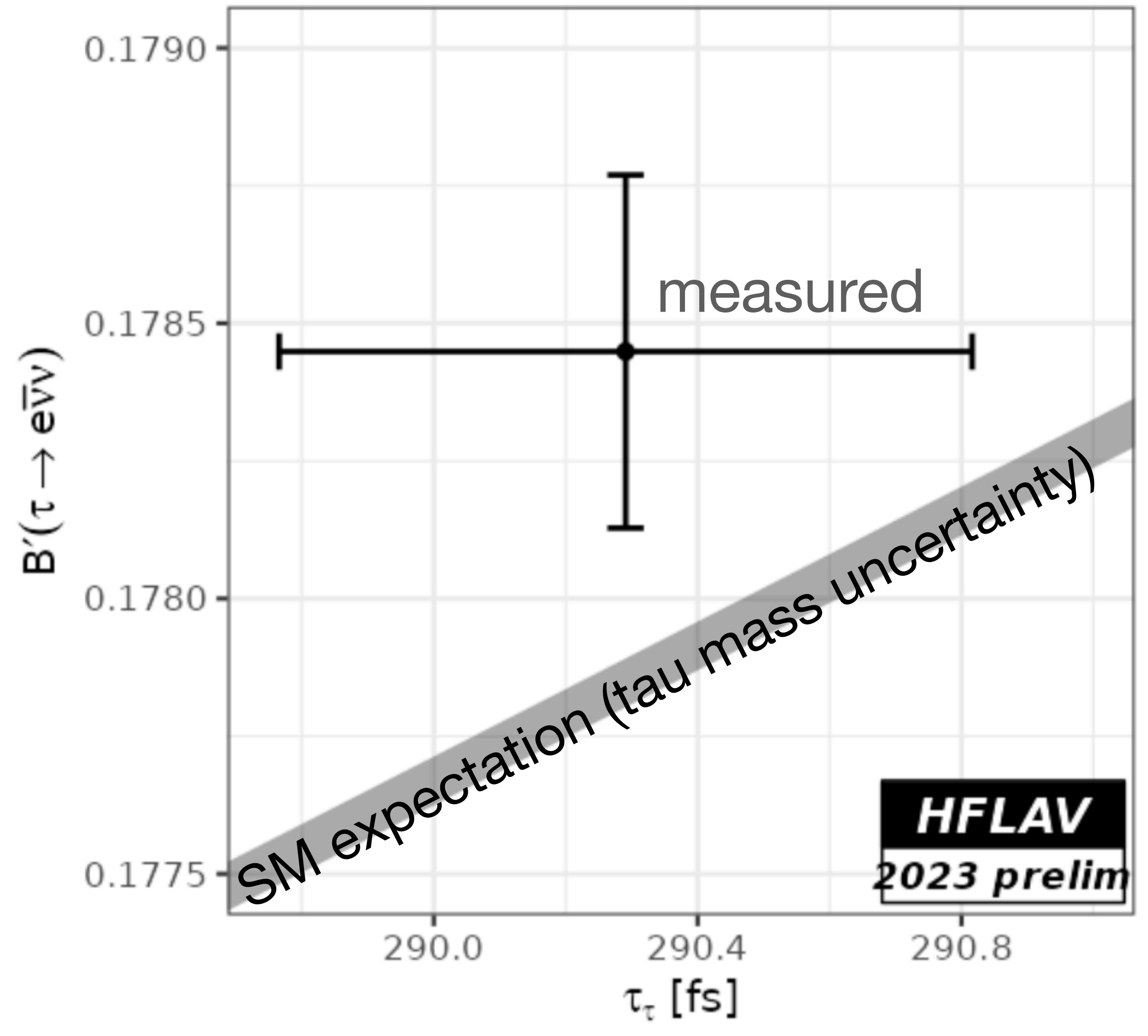
$b \to s\tau^+\tau^-$

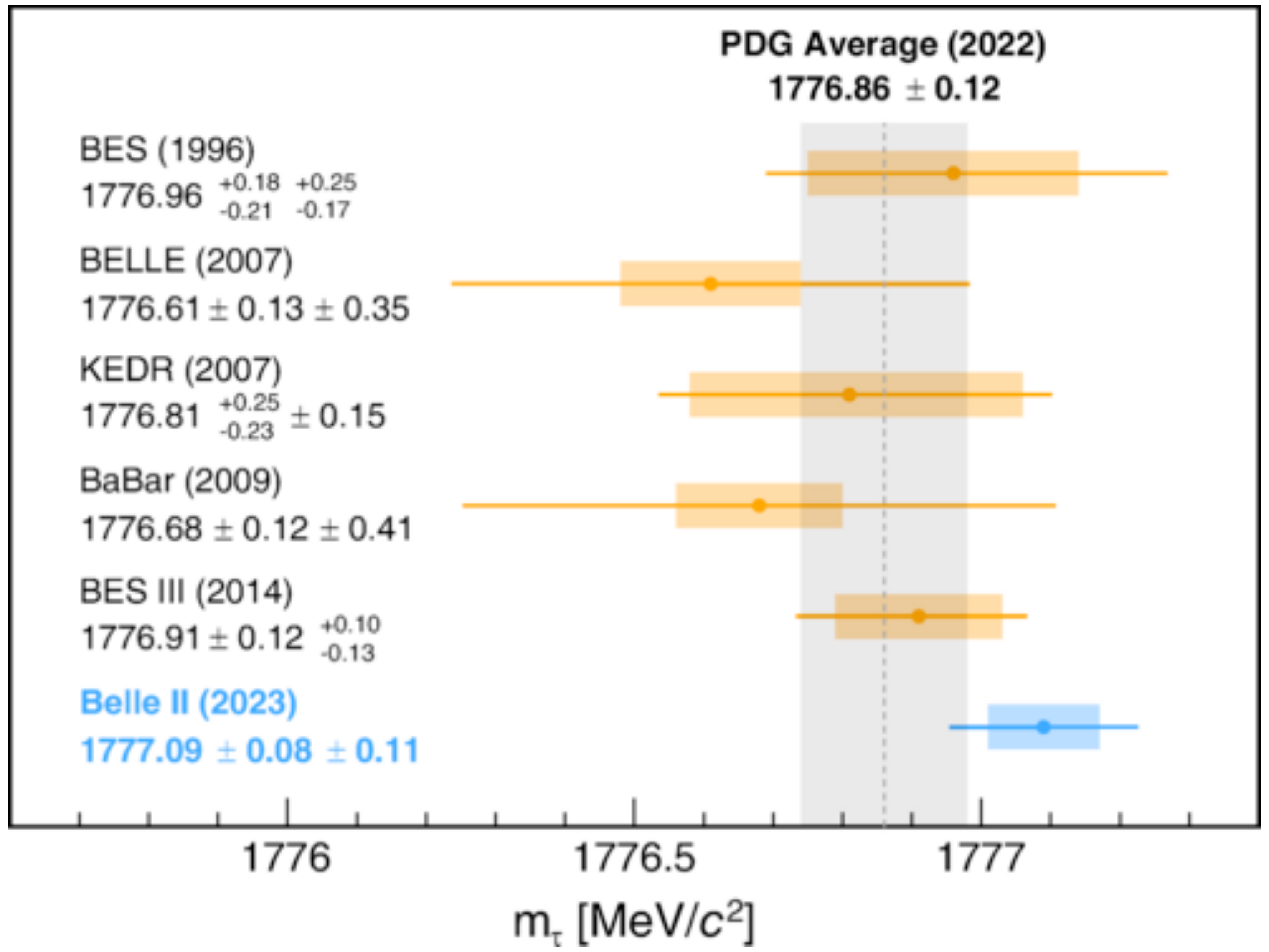
Tau properties

$$\mathcal{B}(\tau \to e\nu\bar{\nu}) \sim \mathcal{B}(\mu \to e\nu\bar{\nu})\frac{m_\tau^5}{m_\mu^5}$$

- Abundant $e^+e^- \to \tau^+\tau^-$ production
- **Tau mass:** pseudomass method with $e^+e^- \to \tau^+\tau^-, \tau \to 3\pi\nu$
  1777.09±0.08±0.11 MeV/c²
  most precise to date
  [Phys. Rev. D 108, 032006]
  - Largest syst: beam energy scale, momentum scale
    - Affected by the knowledge of Υ(4S) lineshape and B mass!







- Next step: **tau lifetime** (Belle result is world best)
  - Belle II will reduce both stat. and syst. uncertainties significantly, down to 0.2×10^{-15} s

Tau SM decays

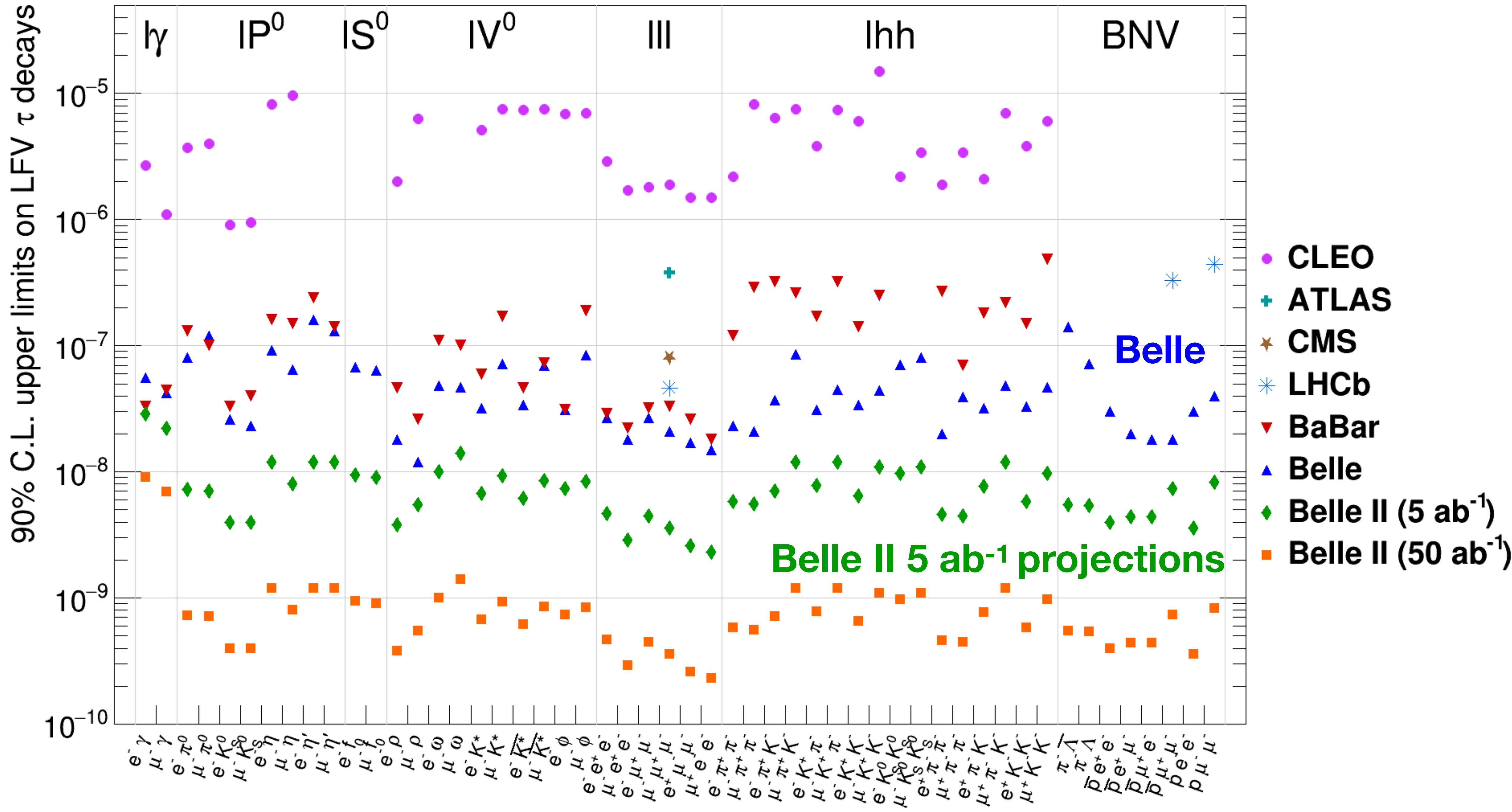
- **Lepton universality** in tau decays:
  - $\dfrac{\mathscr{B}(\tau \to \mu\nu\bar{\nu})}{\mathscr{B}(\tau \to e\nu\bar{\nu})}$ (mu/e universality) and $\dfrac{\Gamma(\tau \to \pi\nu)}{\Gamma(\pi \to \mu\nu)}$ (mu/tau universality)
- Sensitivity eventually limited by the control of PID performance, but can improve world average by a factor of ~few.

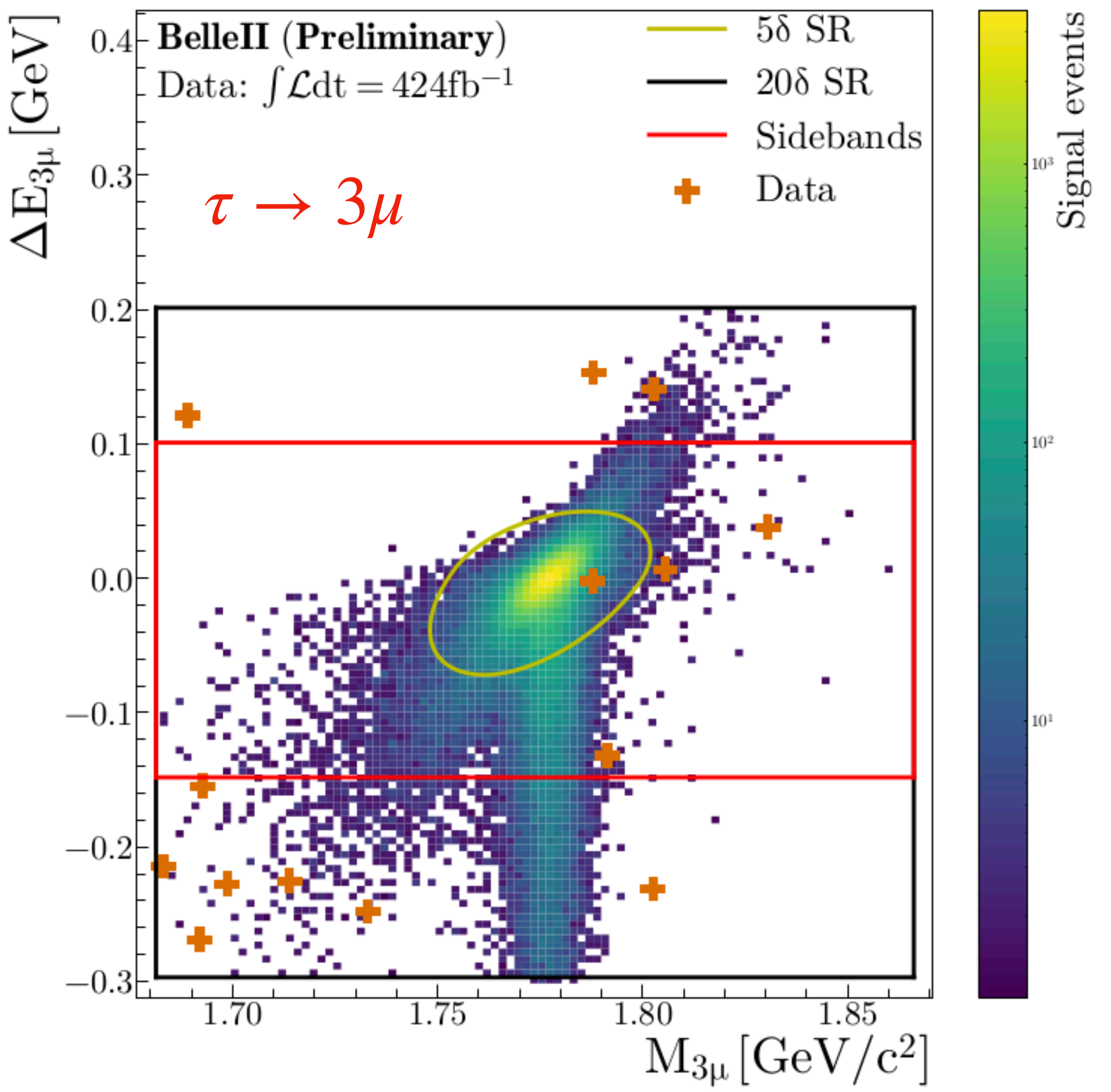
- **Michel parameters** (Lorentz structure of the $\tau \to \mu\nu\bar{\nu}$ decay): kink reconstruction at Belle allows to measure with ~100% uncertainty, precision down to few % expected with new algorithms & enlarged drift chamber at Belle II

- Input to the **Cabibbo angle anomaly**: $|V_{us}|$ from $\dfrac{\mathscr{B}(\tau \to K\nu)}{\mathscr{B}(\tau \to \pi\nu)}$
  - Projected reach down to ~1% sensitivity, depending on PID performance
- CPV measurements in tau decays...

LFV searches in τ decays

- The most stringent upper limits on **lepton-flavour-violating tau decays** come from the B factories
- Recent Belle II $\tau \to 3\mu$ search:
  - Tag $e^+e^- \to \tau^+\tau^-$ with 1-3 tracks on the tag side
  - Look for events with $E_{sig} - E_{beam} = 0$ near the τ mass
  - *Efficiency >2x better than Belle!*
  - UL: $\mathscr{B} < 1.9 \times 10^{-8}$ @90%CL
- Belle II projected reach: few $\times 10^{-9}$ with 10 ab-1 for most LFV channels
  - except for $\tau \to \ell\gamma$ modes (irreducible bkg due to $\tau \to \ell\nu\bar{\nu} + \gamma_{ISR}$)
    - This is where beam polarisation may help (about this later)
- Analyses of many other final states in progress
  - Also, searches for new bosons in $\tau \to \ell a$, HNL in $\tau \to \pi N$...





Penguins and friends

- The recent $B^+ \to K^+\nu\bar{\nu}$ analysis presented by Caspar. Expect observation with more data!
  - Clarifying the background properties is important
  - Future prospects: $B \to K^*\nu\bar{\nu}$, $B \to K_S^0\nu\bar{\nu}$, inclusive $B \to X_s\nu\bar{\nu}$, $B \to \pi(\rho)\nu\bar{\nu}$...
    - Spin-offs: BSM searches in $B \to K^{(*)}$ + invisible, charm decays e.g. $\Lambda_c^+ \to p\nu\bar{\nu}$ or $D \to \pi\nu\bar{\nu}$ (GIM-suppressed)
- **Experimental techniques (missing energy) can be applied to $B \to K^*\tau^+\tau^-$, $B \to \rho\tau^+\tau^-$ searches**
  - Expected sensitivity down to 5×10^{-4} BF, still far away from the SM rate
    - But close to the rate predicted by some BSM models explaining $b \to c\tau\nu$ anomalies
  - As well as LFV $b \to s\tau^\pm\ell^\mp$ searches, with sensitivity down to few $\times\, 10^{-6}$
    - similar BSM enhancements possible
- Let me reiterate the importance of understanding & improving the tagging performance

Penguins and friends

- Reach in $b \to s(d)e^+e^-$ and $b \to s(d)\mu^+\mu^-$ statistically limited compared to LHCb, but similar performance in muons and electrons helps for LFU tests.
  - Sensitivity to (semi-)**inclusive** $b \to s\ell^+\ell^-$
  - Very competitive in final states with neutrals e.g. $B^0 \to \pi^0 e^+e^-$, see recent Belle result

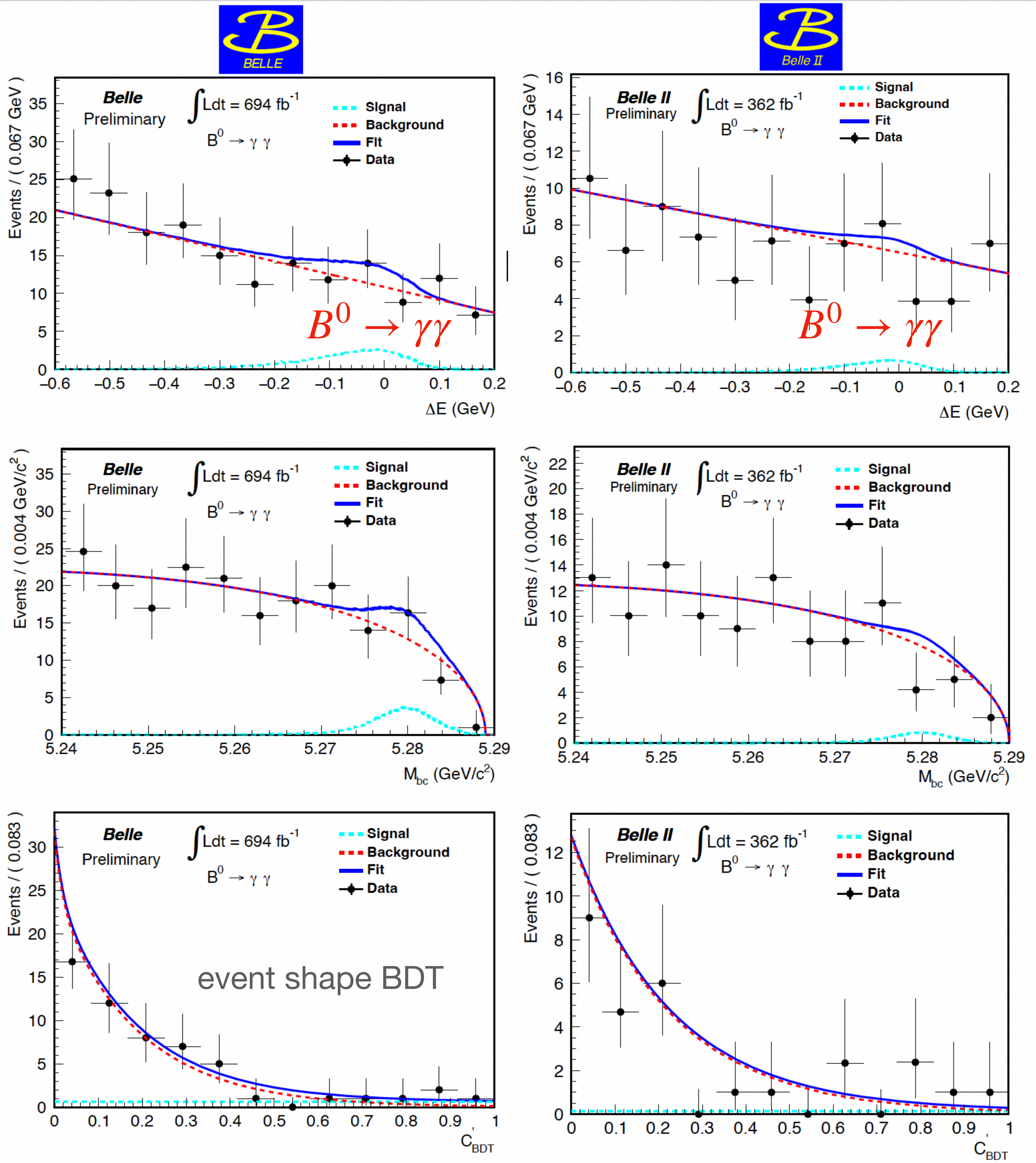
	N_{sig}	$\mathcal{B}^{\text{UL}}$ (10^{-8})
$B^0 \to \eta\ell^+\ell^-$	$0.5^{+1.0}_{-0.8}$	< 4.8
$B^0 \to \eta e^+e^-$	$0.0^{+1.4}_{-1.0}$	< 10.5
$B^0 \to \eta\mu^+\mu^-$	$0.8^{+1.5}_{-1.1}$	< 9.4
$B^+ \to \pi^+e^+e^-$	$0.1^{+2.5}_{-1.6}$	< 5.4
$B^0 \to \pi^0\ell^+\ell^-$	$-1.8^{+1.6}_{-1.1}$	< 3.8
$B^0 \to \pi^0 e^+e^-$	$-2.9^{+1.8}_{-1.4}$	< 7.9
$B^0 \to \pi^0\mu^+\mu^-$	$-0.5^{+3.6}_{-2.7}$	< 5.9

- Belle II is crucial to provide the measurements of **absolute branching fractions**, e.g. for normalisation modes used by LHCb such as $B \to K^{(*)}J/\psi$
  - Pre-requisite: better understanding of f_{+-}/f_{00} (relative B^+/B^0 production rates)

Diphoton

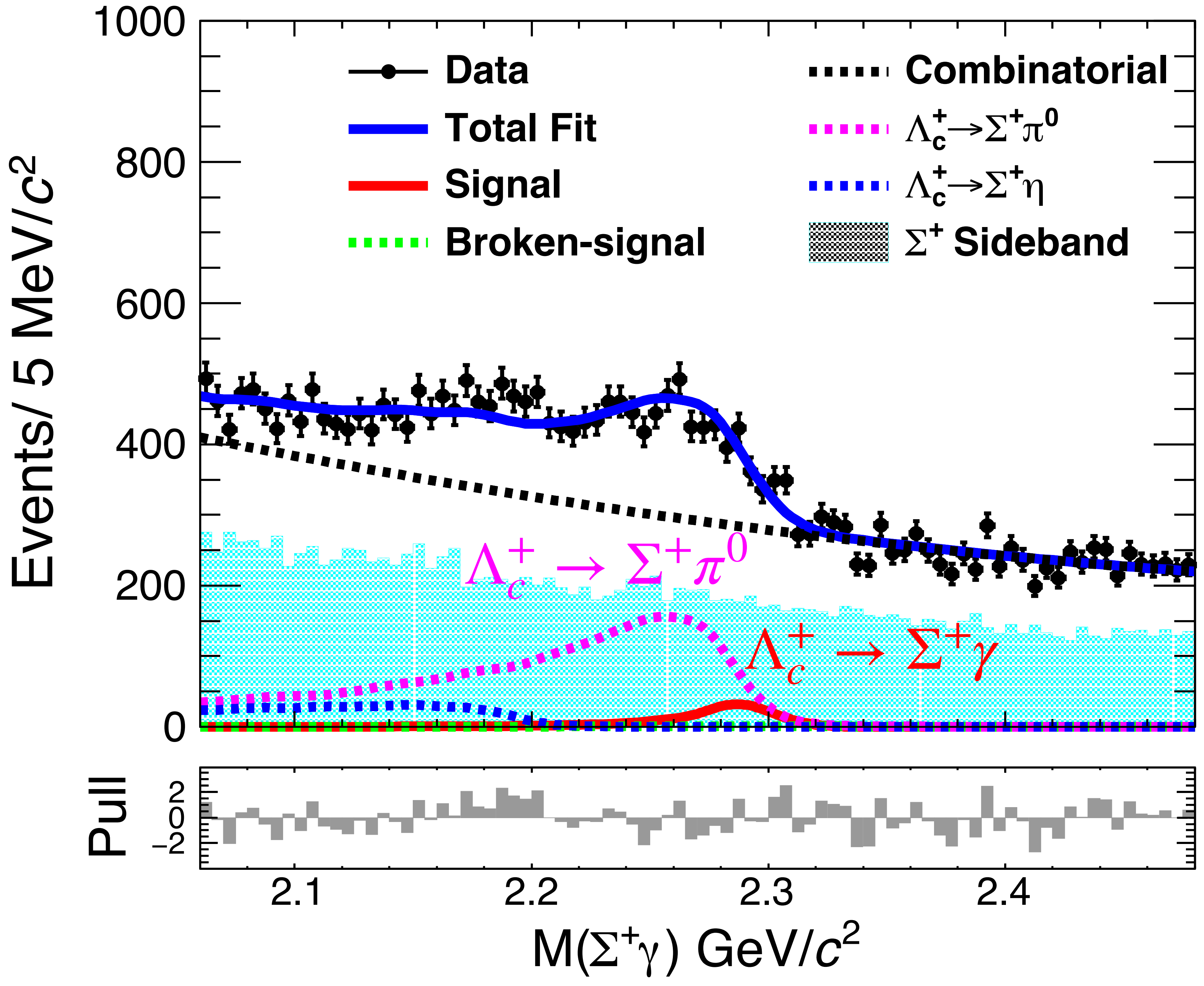
- Recent Belle+Belle II search for $B^0 \to \gamma\gamma$ (see Moriond talk): a very suppressed $b \to d$ transition
- UL $< 6.4 \times 10^{-8}$ @90% CL, only factor ~5 above the SM prediction
  - SM uncertainties are large (LD/SD interplay)
  - *Any exp input to help control the theory uncertainties?*
- Very interesting measurement with more data!

- $D^0 \to \gamma\gamma$ search in prospects: senstivity down to ~ 10^{-7} (factor ~10 above the SM rate)
- A less suppressed $B_s^0 \to \gamma\gamma$ can be searched if B_s^0 data collected



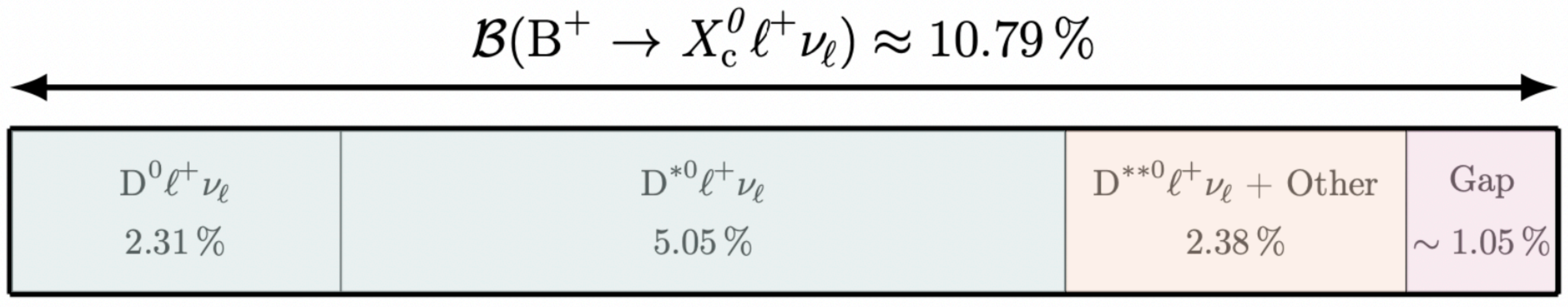
Radiative (charm) decays

- Many measurements of $b \to s\gamma$: *e.g.*
  - **photon polarisation** in $B \to K\pi\pi\gamma$ down to ~1% with more data
  - CP asymmetries in $B \to K^*\gamma$ at sub-percent precision
  - **Inclusive $b \to s\gamma$** rate at ~10% precision depending on E_γ threshold(eventually systematics-dominated)
- In the **charm sector**, the penguin $c \to u\gamma$ is very suppressed
  - The 4π geometry helps to reject $c \to u\pi^0$ backgrounds
  - W exchange $cd \to us\gamma$ (long-distance) is expected to have a larger rate
    - Interest to measure photon polarisation
- Belle did the <u>first search</u> for **radiative charm baryon decays** $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Xi_c^0 \to \Xi^0\gamma$
- BF limits at the 2×10^{-4} level, hope for observation at Belle II?
  - Theory predictions in few $\times\, 10^{-5}$ range

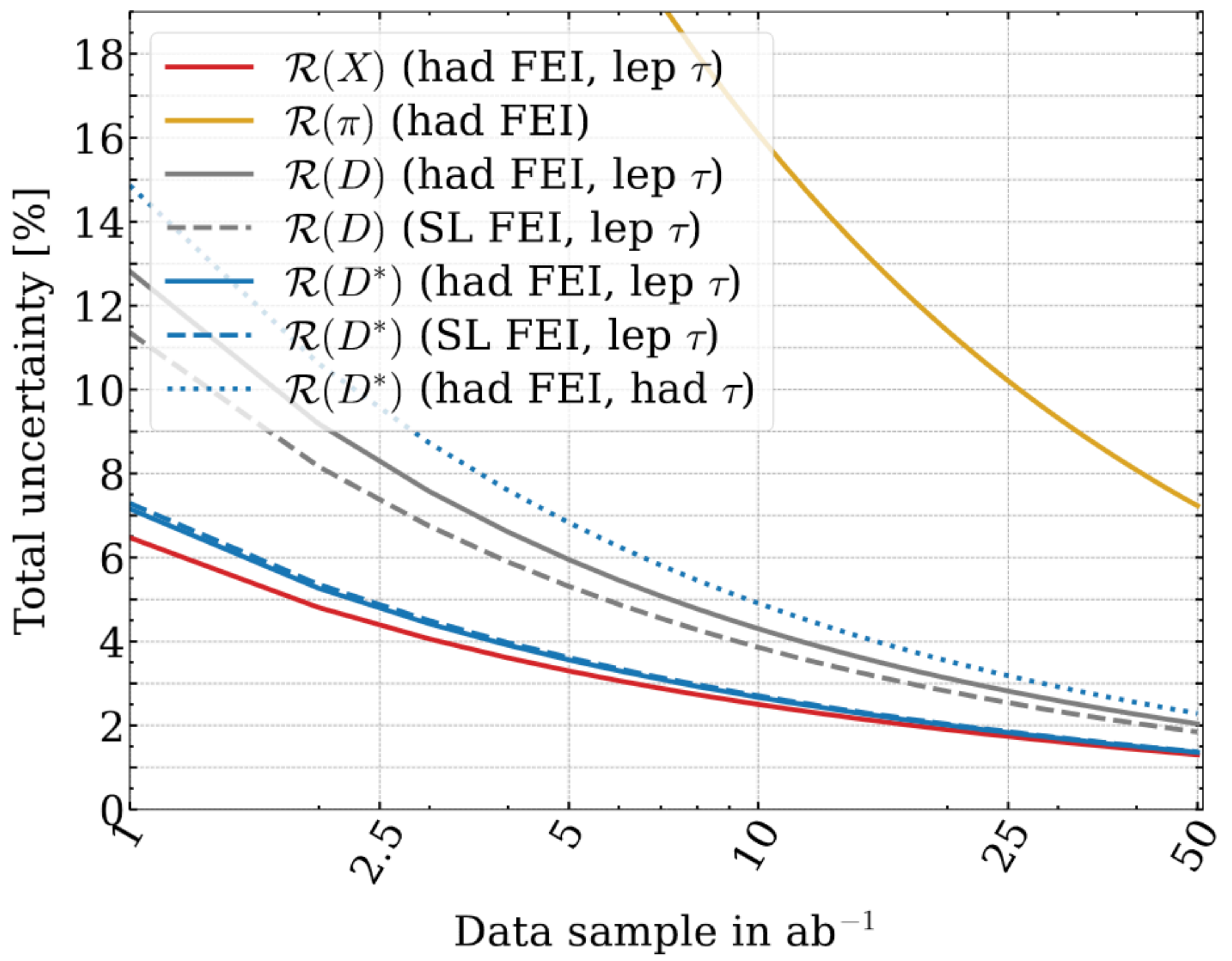


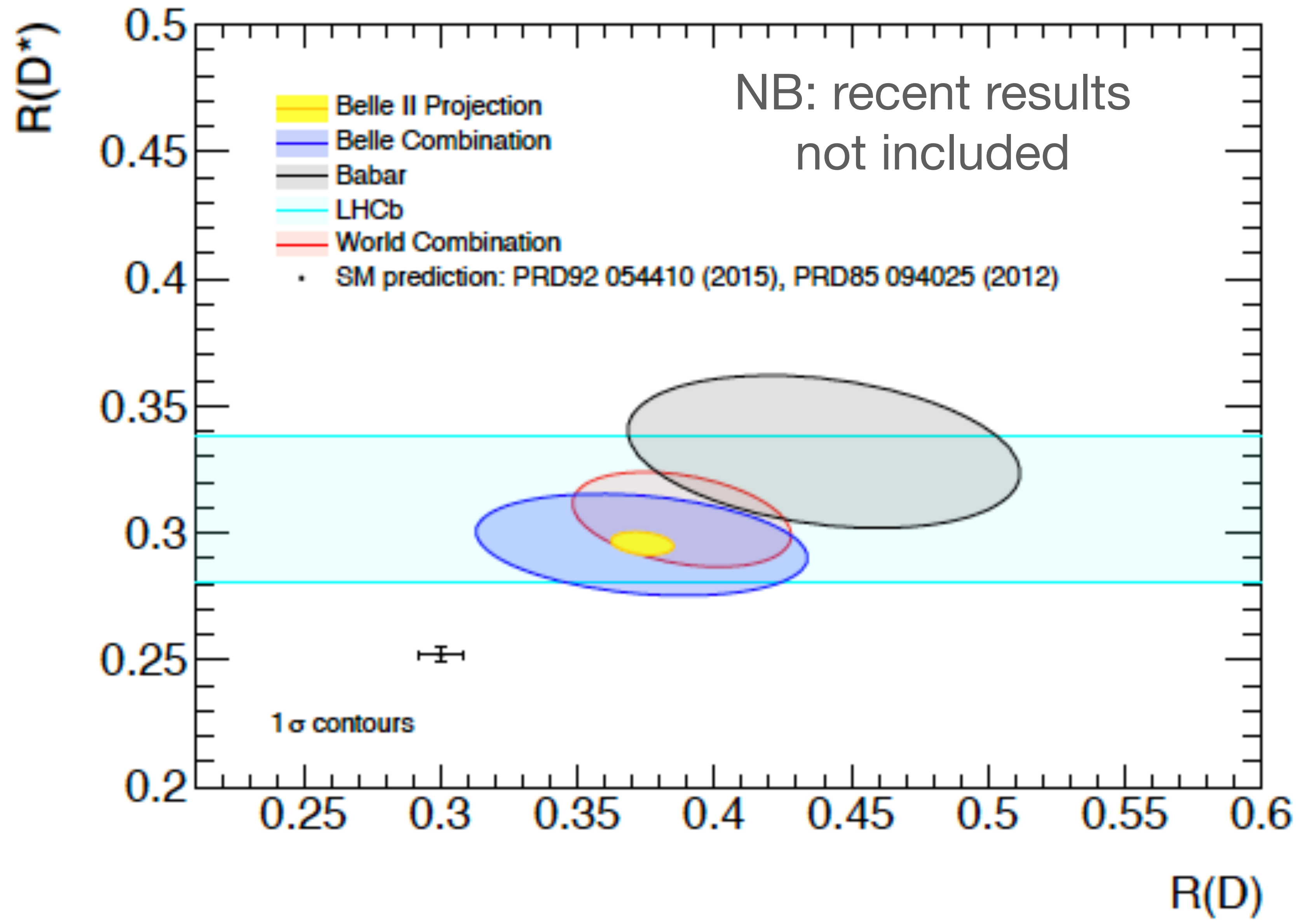
A few words on $b \to c\ell\nu$ and $b \to u\ell\nu$

- Closing the gap between inclusive and exclusive decays to corner the $|V_{cb}|$



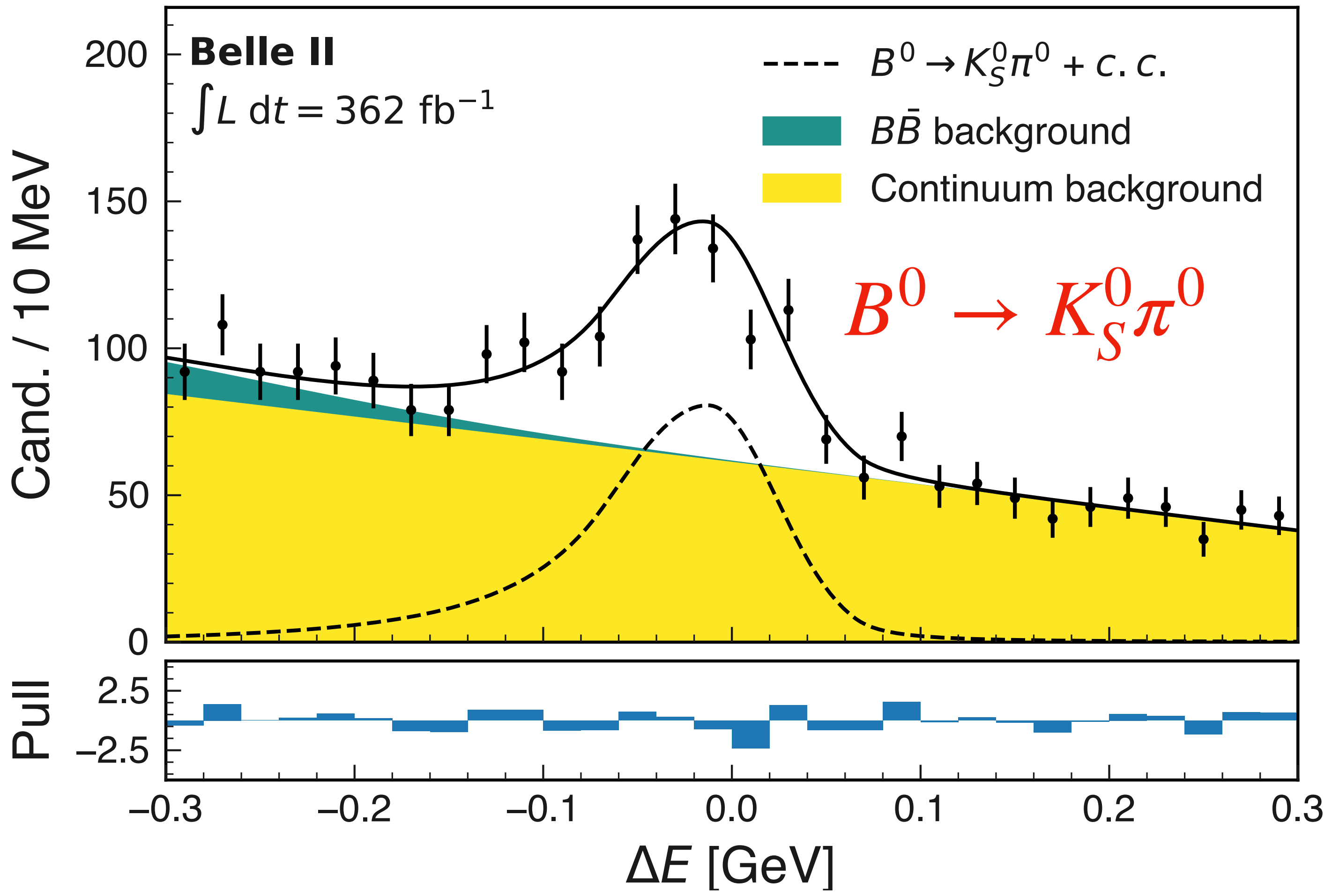
- $|V_{ub}|$ inclusive down to ~3-5% precision with 10ab^{-1} (*theory-dominated*), exclusive more precise
- Precision on $R_{D^{(*)}}$ down to few %
- High hope to observe $B^+ \to \mu^+\nu$ and improve significantly $B^+ \to \tau^+\nu$ measurement: both down to ~10% relative unc. with 10ab^{-1}
  - Benefit from inclusive tagging developed for $B^+ \to K^+\nu\nu$
  - Don't forget about $B^+ \to \mu^+\nu\gamma$ (see here)





CP violation in B decays

- **We enter the era of precision testing of the CKM unitarity**
- The unique feature of Belle II is the entangled B production and, therefore, high flavour-tagging efficiency
  - NB: search for non-perfect entanglement is an interesting QM test!
- World-best sensitivity achievable in final states with π^0, K_L^0 or K_S^0
- With 10 ab^{-1}, expected precision of
  - ~1% on $\sin 2\phi_1^{(eff)} \equiv \sin 2\beta^{(eff)}$ in tree-dominated $(c\bar{c})K^0$ or ~2% in loop-dominated $\eta' K^0$
    - See the recent result in $B^0 \to J/\psi K_S^0$ with early Belle II data (3x worse than LHCb Run1+2)
  - ~2.5° on $\phi_2 \equiv \alpha$ in $B \to \rho\rho$: Belle II the key player even with a few ab^{-1}!
  - ~2.5° on $\phi_2 \equiv \gamma$
- Narrowing down on the isospin sum rule in $B \to K\pi$ decays ("$K\pi$ puzzle"), where $A_{CP}(B \to K_S^0\pi^0)$ will be driven by Belle II (down to ~5% at 10 ab^{-1})
  - Recent Belle II result compatible with the SM: $I_{K\pi} = -0.03 \pm 0.13 \pm 0.04$
- CPV studies in multibody charmess B decays advantageous at Belle II: efficiency reasonably flat in phase-space

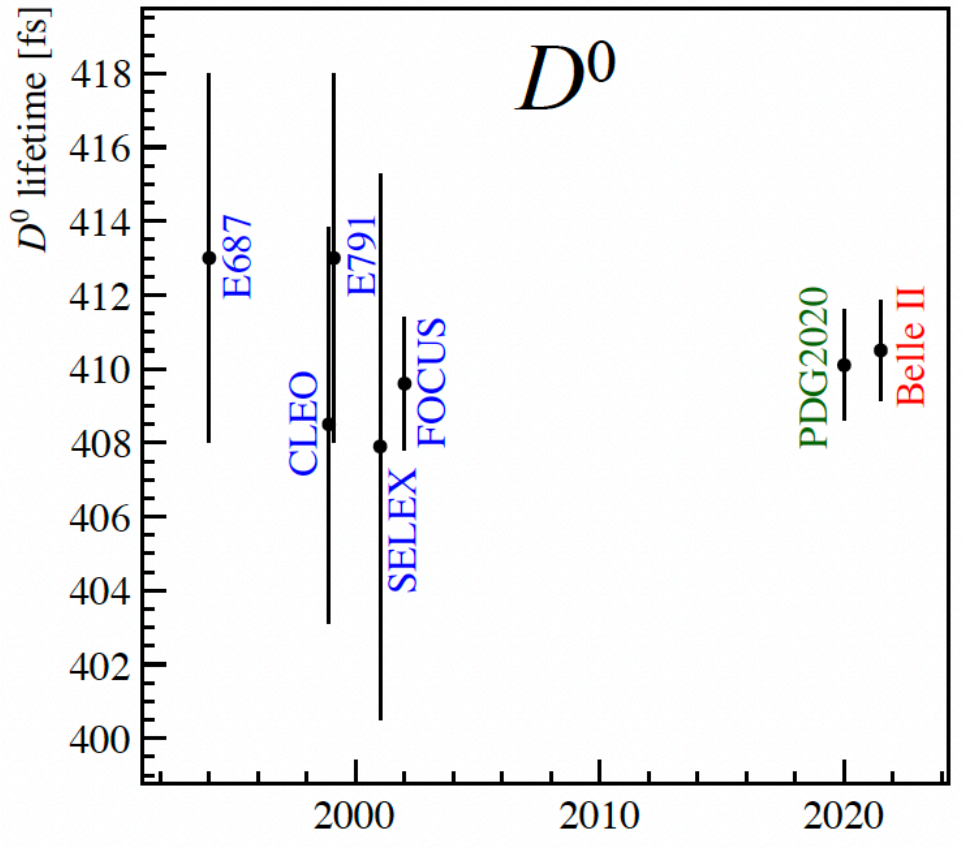


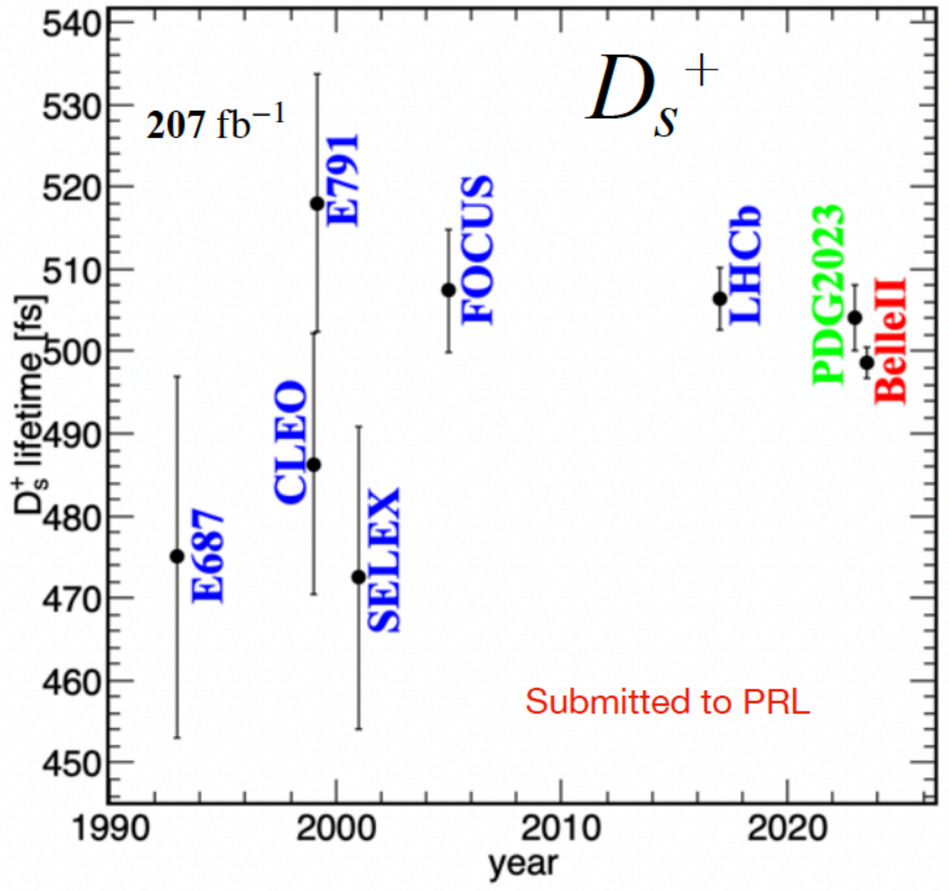
CPV in charm

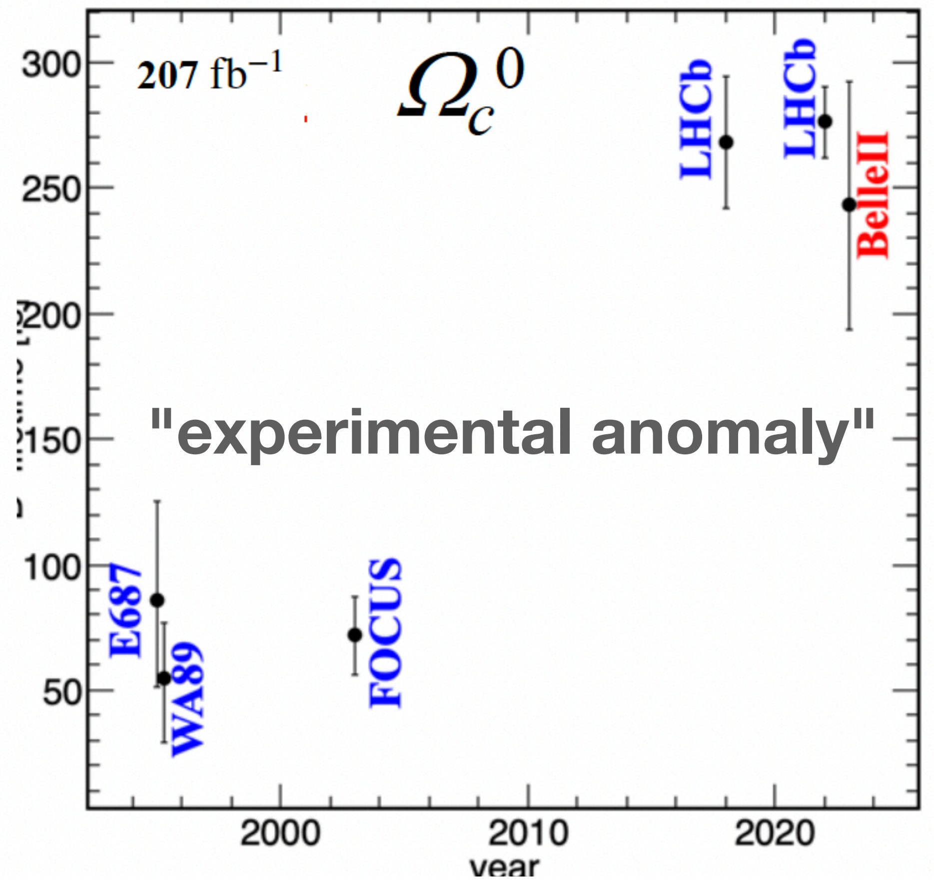
- Belle II uniquely positioned to probe CPV in final states with neutrals
  - Fully-charged and charged+1-neutral final states dominated by LHCb
- $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$ are well motivated
  - Projected sensitivity down to 0.07% (50 ab^{-1}) for $D^0 \to \pi^0\pi^0$ with the conventional D^* tag
    - but we have a much better tagger now!
    - still might be not enough to probe the $\mathcal{O}(10^{-4})$ effects
- Isospin **sum rule** by comparing CPV in $D^0 \to \pi^+\pi^-$, $D^0 \to \pi^0\pi^0$ and $D^+ \to \pi^+\pi^0$ decays: probe whether CPV is SM or beyond
- Absolute charm BFs and (rare) decays with neutrals will likely be the more important contribution

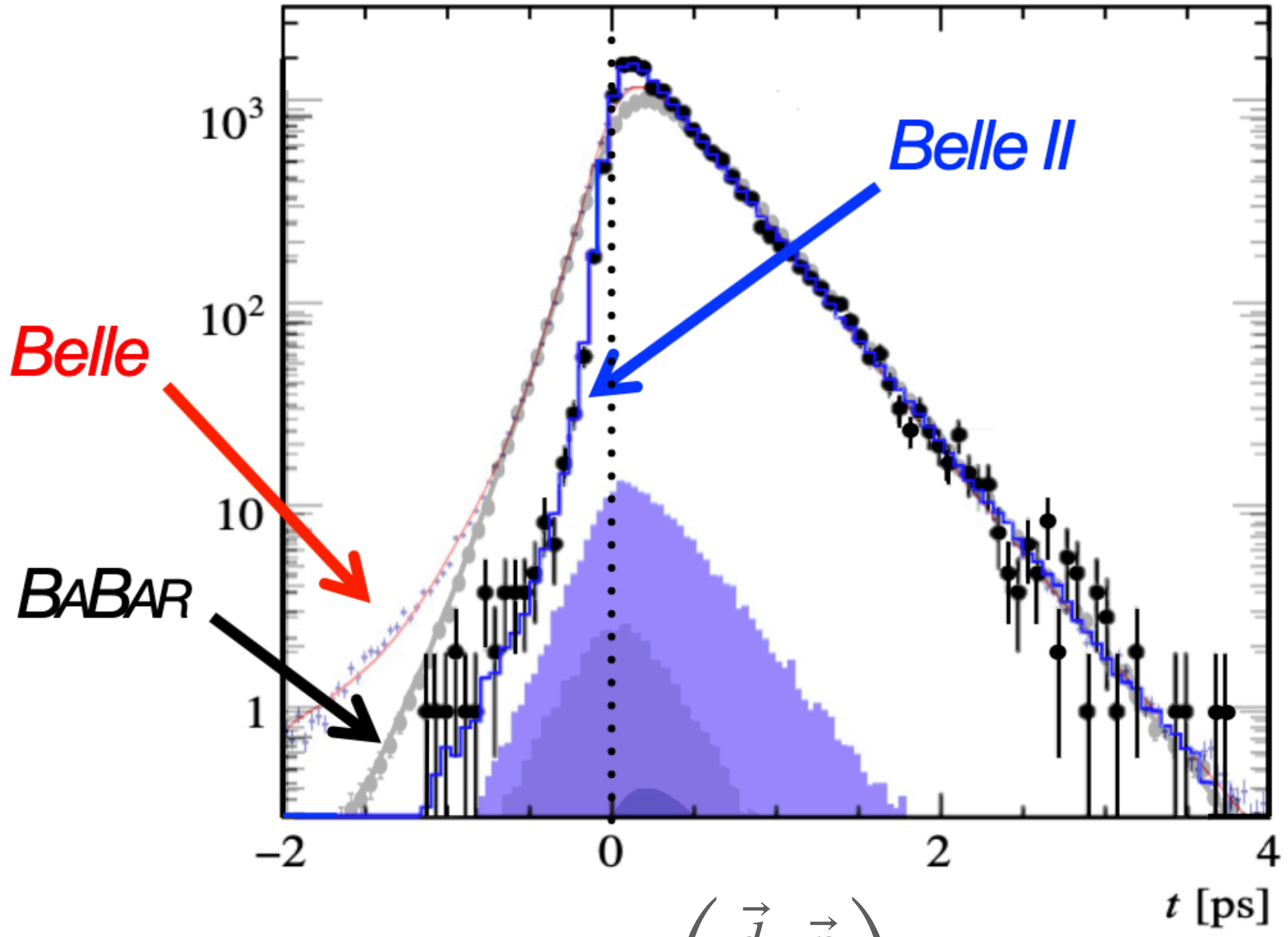
Decay another day

- **Precision lifetime measurements!**
- Decay-time resolution 2x better than Belle
- Fewer sculpting effects compared to the LHCb trigger

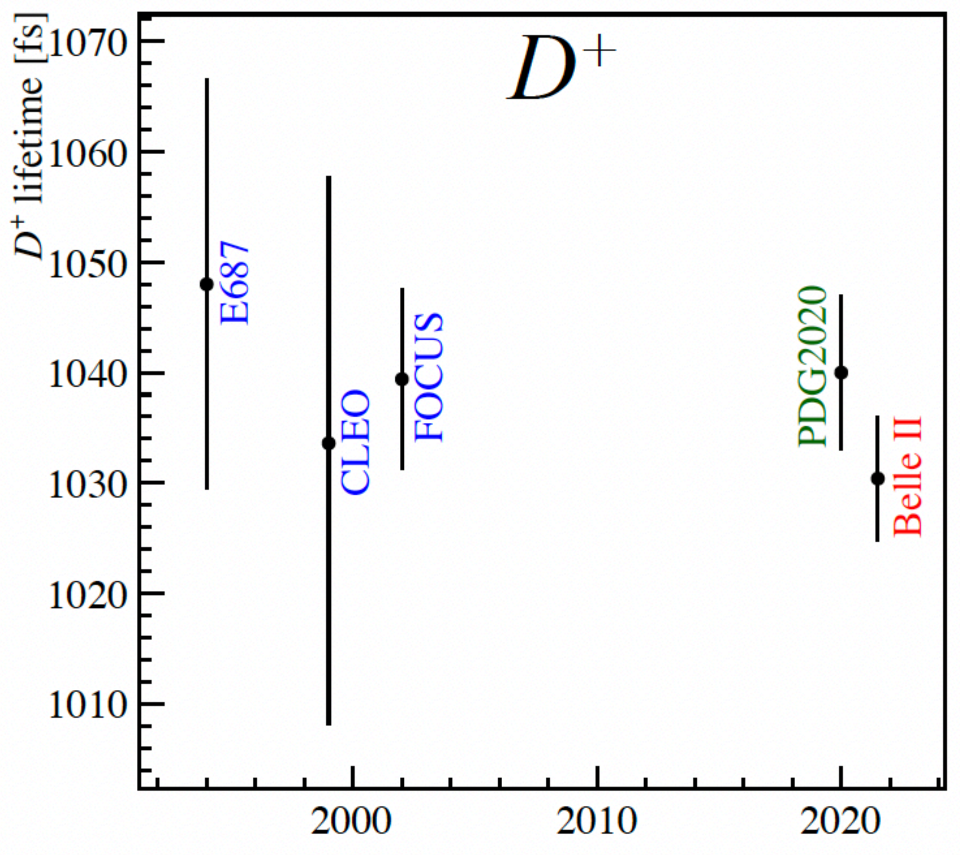


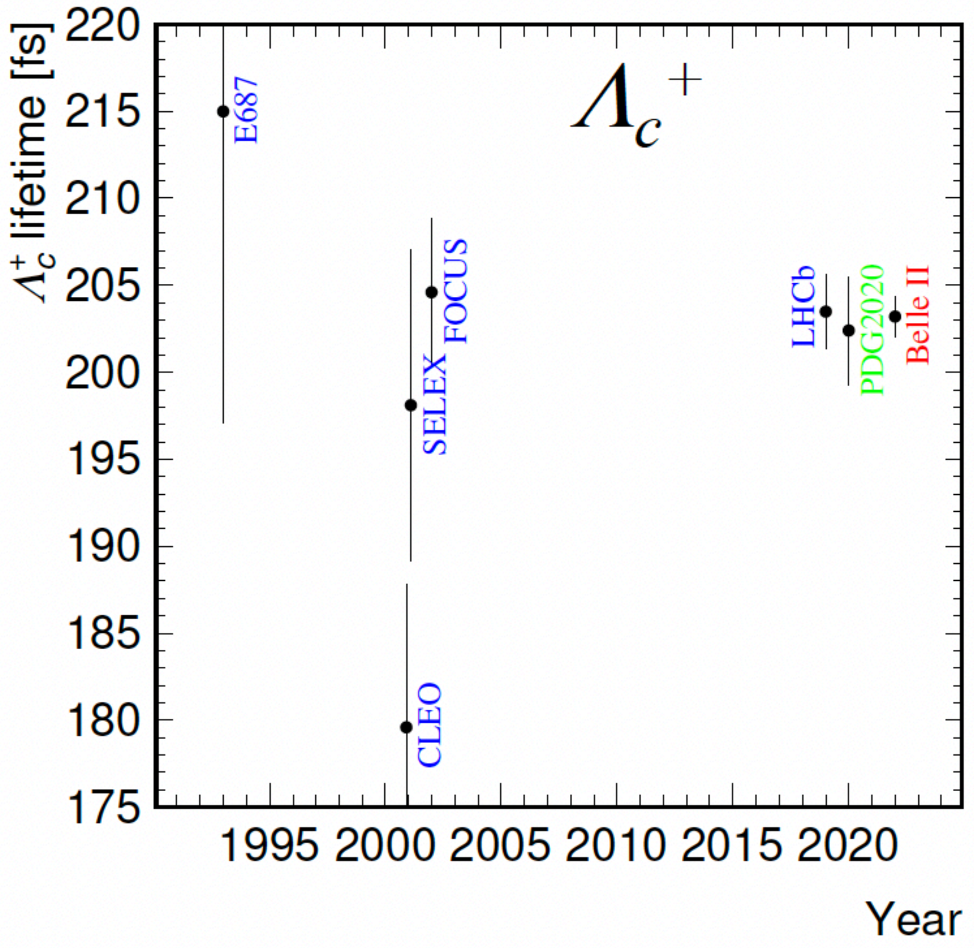






$$t = \left(\frac{\vec{d}\cdot\vec{p}}{p^2}\right) m$$

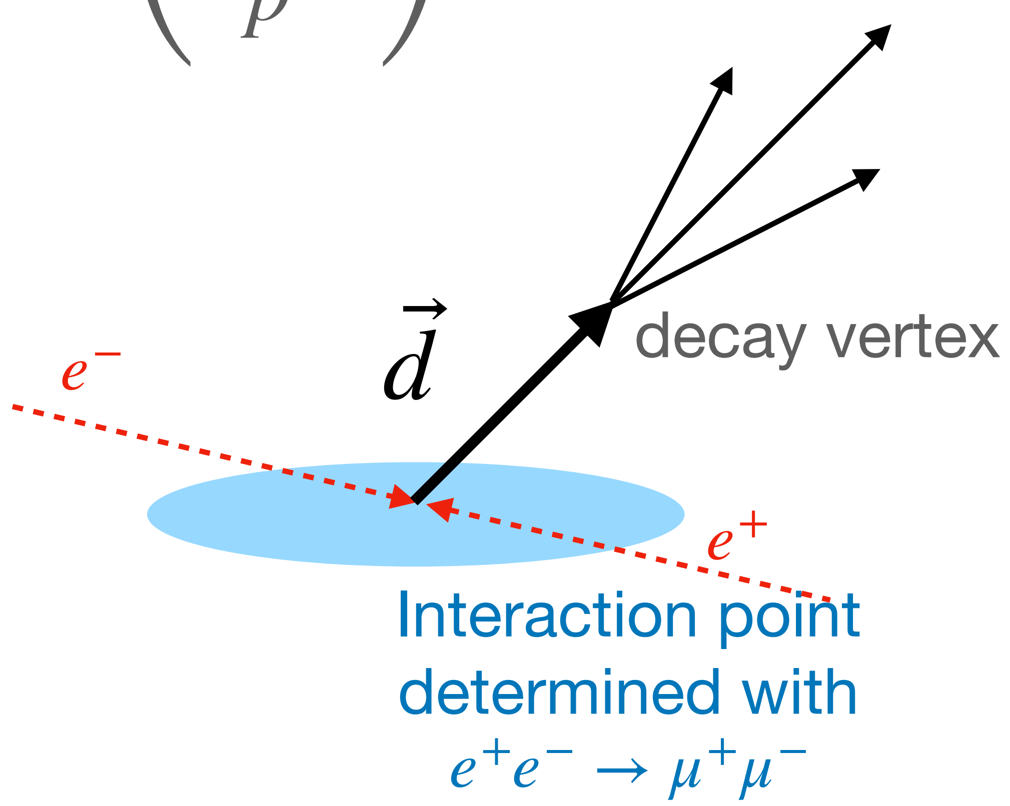




World best for all except Ω_c^0 and still statistically limited!

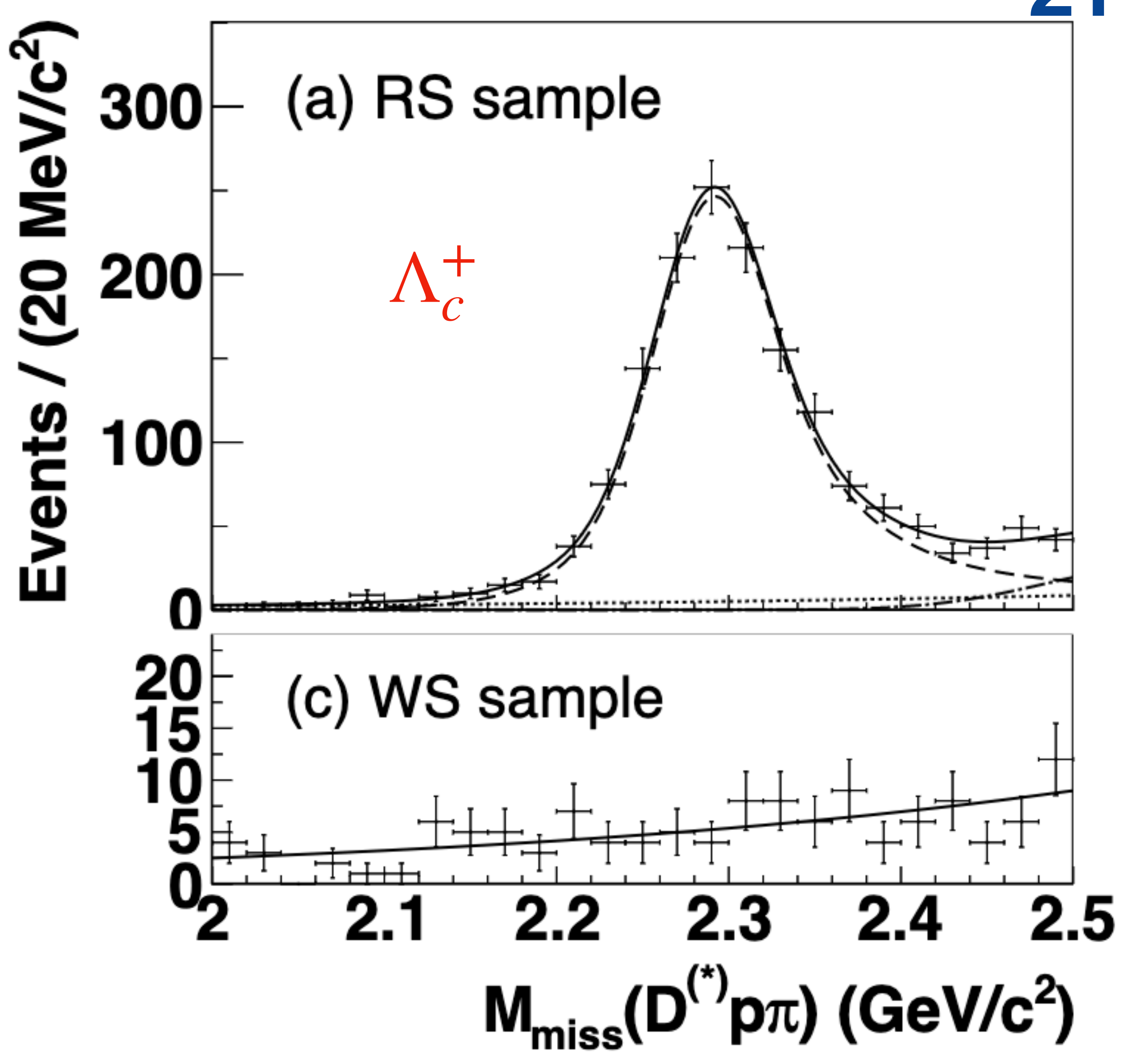
Much more precise than theory

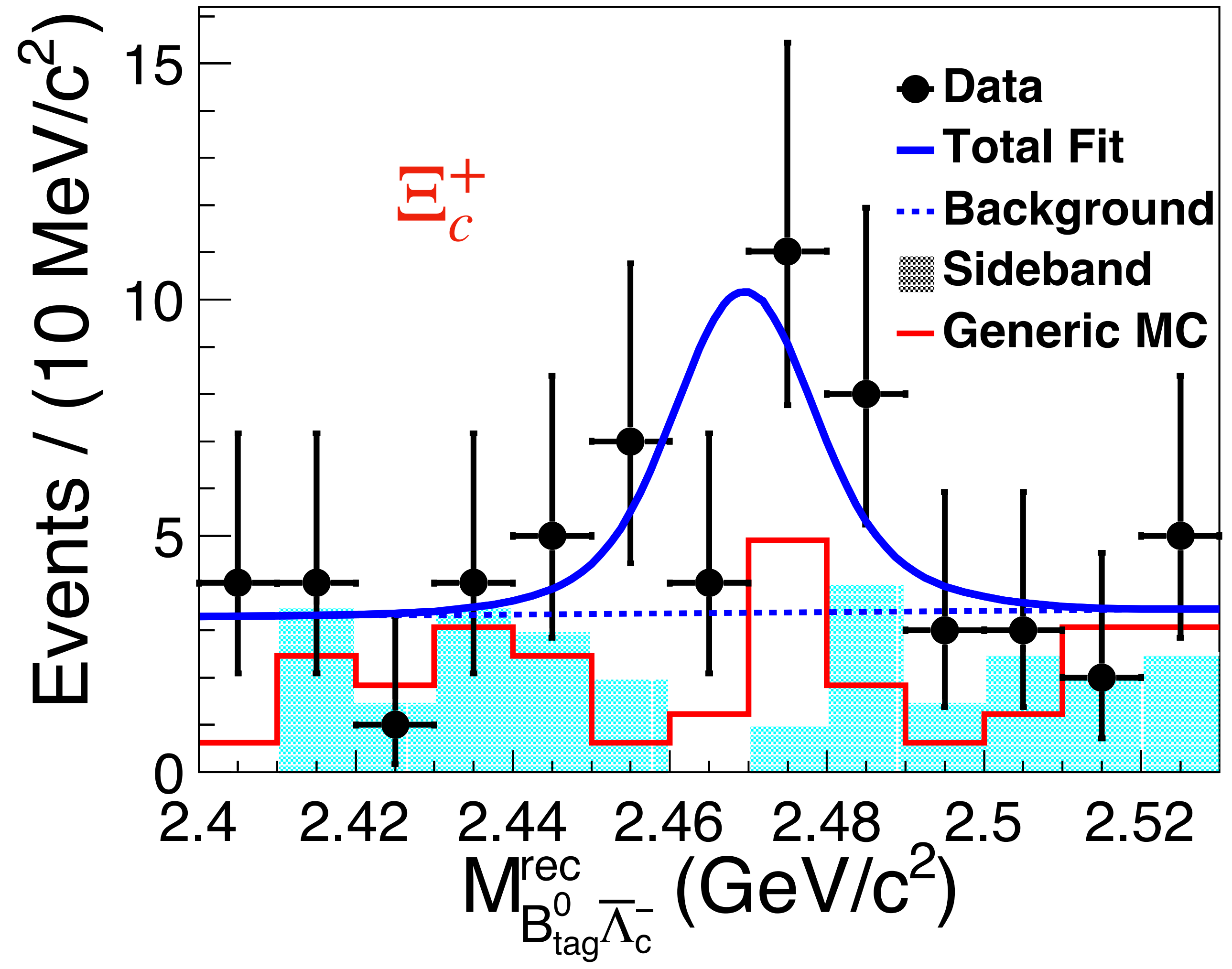
Systematics: detector alignment & resolution, backgrounds



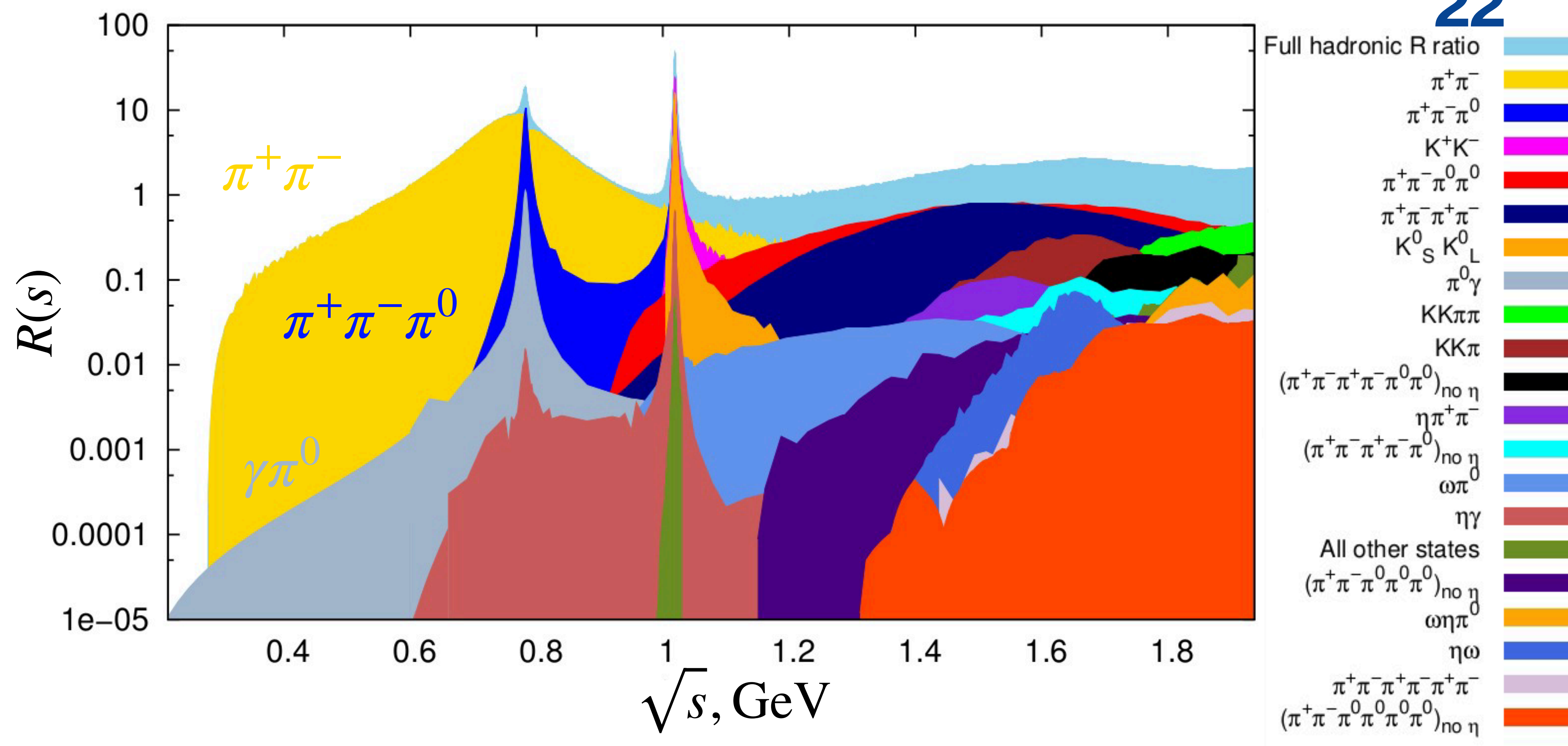
Inclusive charm baryons

- Two ways to obtain **inclusive** charm baryon datasets:
  - baryon-number, *s* and *c* conservation in e^+e^- collisions: $e^+e^- \to D^{(*)-}\bar{p}\pi^+\Lambda_c^+$
    - notable example: [Phys.Rev.Lett. 113 (2014) 4, 042002]
  - B-meson decays, $\bar{B}^0 \to \Xi_c^+\bar{\Lambda}_c^-$ with one baryon treated as recoil
    - notable example: [Phys.Rev.D 100 (2019) 3, 031101]
    - low statistics
- Useful to measure absolute BF, but in particular **decays with missing energy (semileptonic)**
- More results expected with these methods
  - Absolute BFs of Ξ_c/Ω_c imprecise or unknown (more data & better tagging helps!)
  - Note: BES III catching up by running on baryon-pair thresholds





Dipole moments



- **Muon g-2 inputs:** measure cross-section inputs to the HVP calculation
  - $\sigma(e^+e^- \to$ hadrons) below 1 GeV dominated by $e^+e^- \to \pi^+\pi^-$ and $e^+e^- \to \pi^+\pi^-\pi^0$
- New measurement of $\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$ using $\sigma(e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR})$ and the beam-energy constraint: see L. Corona at Moriond 2024 and 2404.04915
- Achieved accuracy of 2.2%, *moves the global fit up*
  - Dominant systematics: π^0 eff, PROKHARA MC generator (no NNLO ISR)
  - Measurements of $\sigma(e^+e^- \to \pi^+\pi^-)$ and others will come next
- **Tau EDM:** use spin correlation in $e^+e^- \to \tau^+\tau^-$, probe $\gamma\tau\tau$ vertex vs CP reversal
  - Belle result is the world best (precision $\sim 0.6 \times 10^{-17}$e*cm), 20 orders above SM
  - Belle II can improve further

"Chiral Belle" proposal

https://arxiv.org/abs/2205.12847

- What if we get a **polarised** electron beam?
  - ~70% polarisation can be a realistic target, without disruption the core physics programme (= no luminosity loss)
- **Electroweak measurements:** asymmetry in cross-sections with left- vs right-handed electrons
  - measure the neutral-current vector coupling or $\sin\theta_W$ at 10 GeV
- Access to **g-2 (tau)** down to the SM value, and improved EDM
  - changing the beam polarisation direction is required
- Improvement in **tau Michel parameters** measurement
- Reduced backgrounds in $\tau \to \ell\gamma$ search: SM backgrounds gets modified angular distribution
  - but what if the LFV process also gets modified? = access to helicity structure of new physics

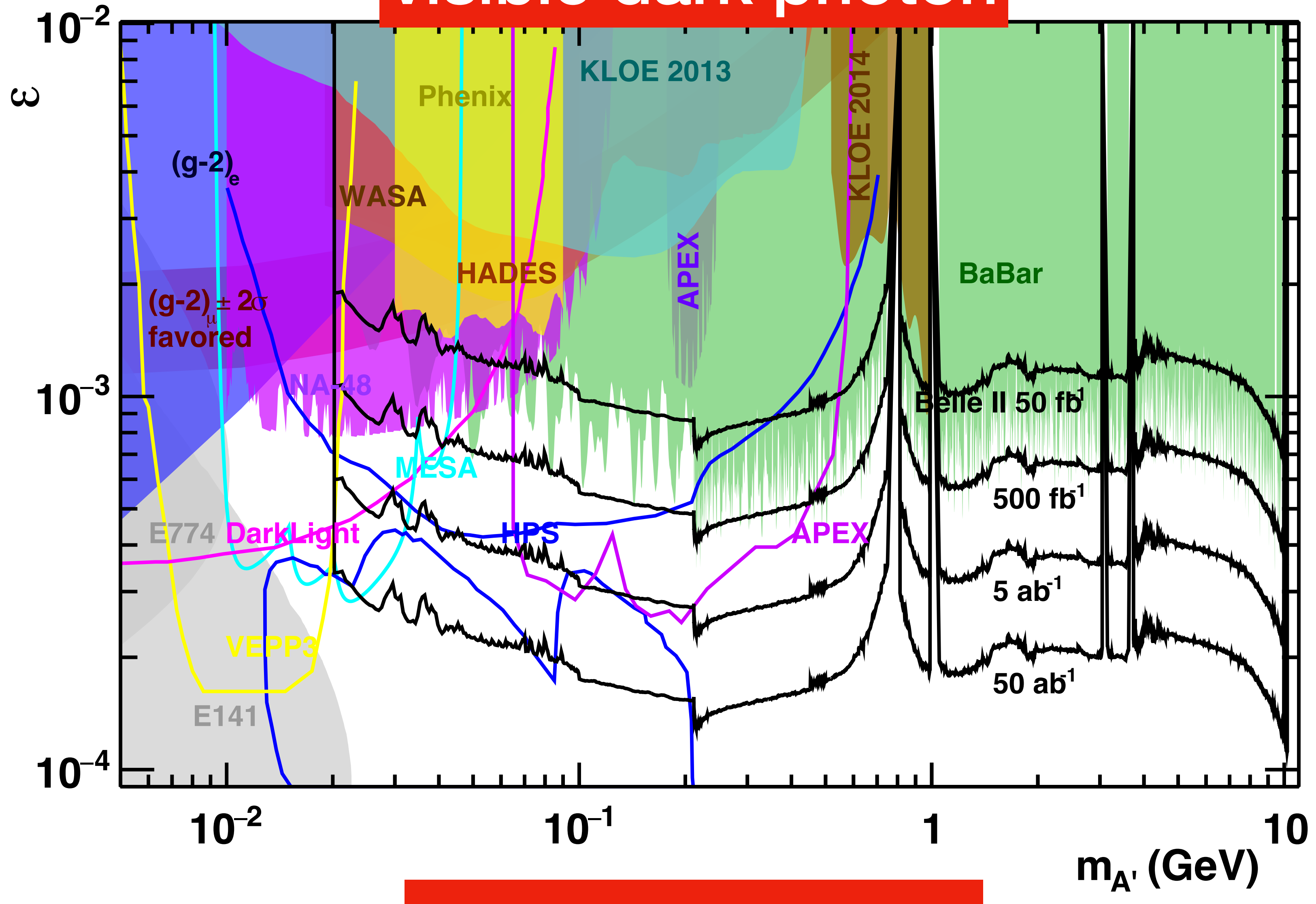
- **Feasibility studies ongoing.**

Catch me if you can

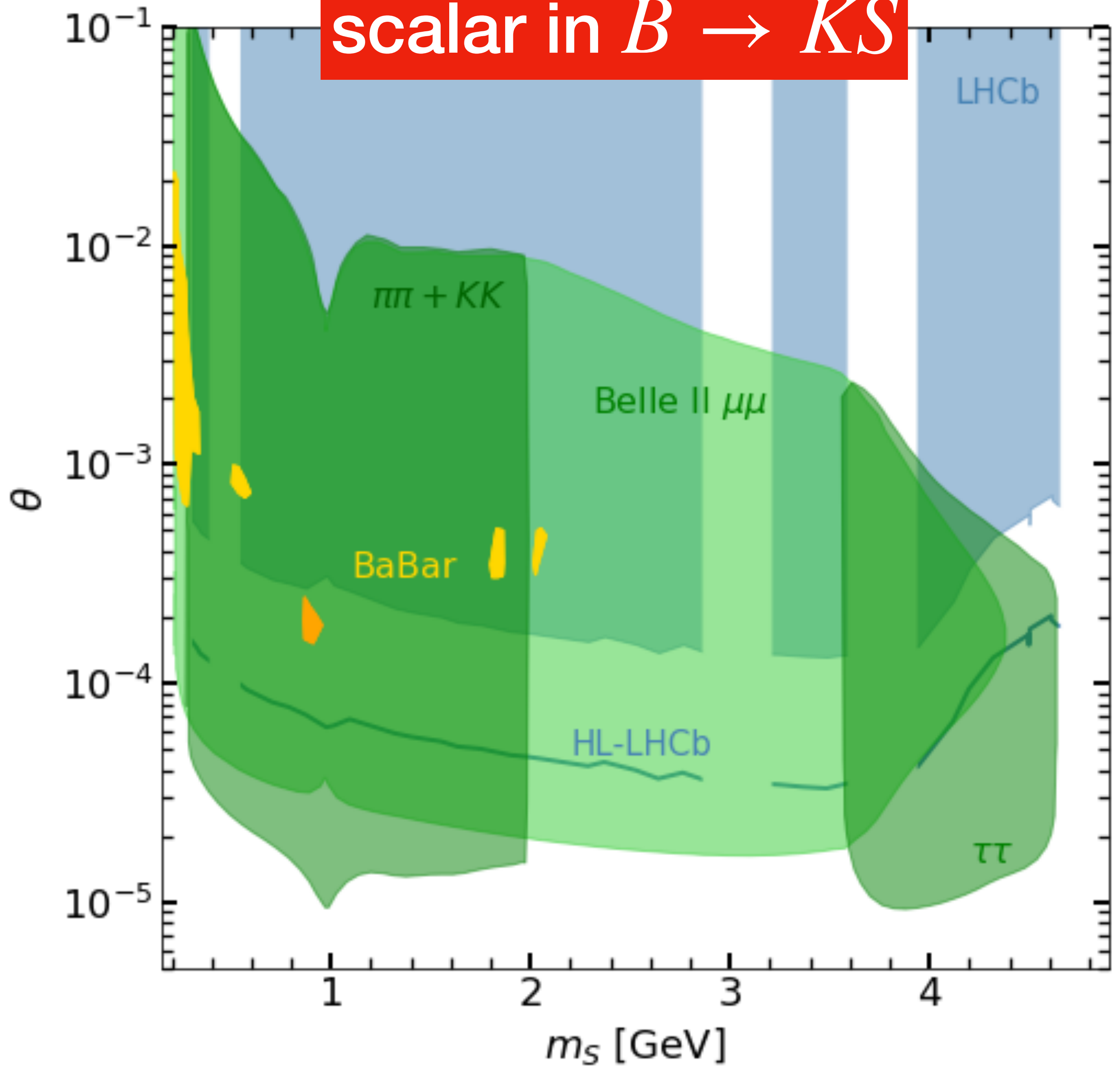
- A plethora of **direct** searches done, ongoing or planned:
  - Axion-like particles with $e^+e^- \to a\gamma$ and $a \to \gamma\gamma$, or $e^+e^- \to ae^+e^-$
  - Dark photons in various signatures: $e^+e^- \to \gamma X$, $e^+e^- \to \mu^+\mu^- X$, … – recent search
  - Z' in parameter space relevant for muon g-2
  - Dark matter candidates: long-lived particles, scalars in $B \to KS$…
  - Dilepton resonance: recent dimuon search; probing ATOMKI anomaly in dielectron
- **Expected world-best sensitivity for many signatures below 10 GeV**
- Searches that rely on missing energy depend severely on the detector performance
  - Ensuring the **hermeticity**: a small inefficiency in one subsystem can severely impact the reach
  - Cosmic-ray veto performance

Projections

visible dark photon



scalar in $B \to KS$



Summary

- There are many classes of "anomalies" where Belle II can contribute
  - or create new anomalies!

- A lot achieved with the data collected so far

- New ideas to improve the effective sensitivity even with existing data

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