



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

Vitalii Lisovskyi (Aix Marseille Univ, CNRS/IN2P3, CPPM)
on behalf of the Belle II collaboration

Siegen, 11 April 2024



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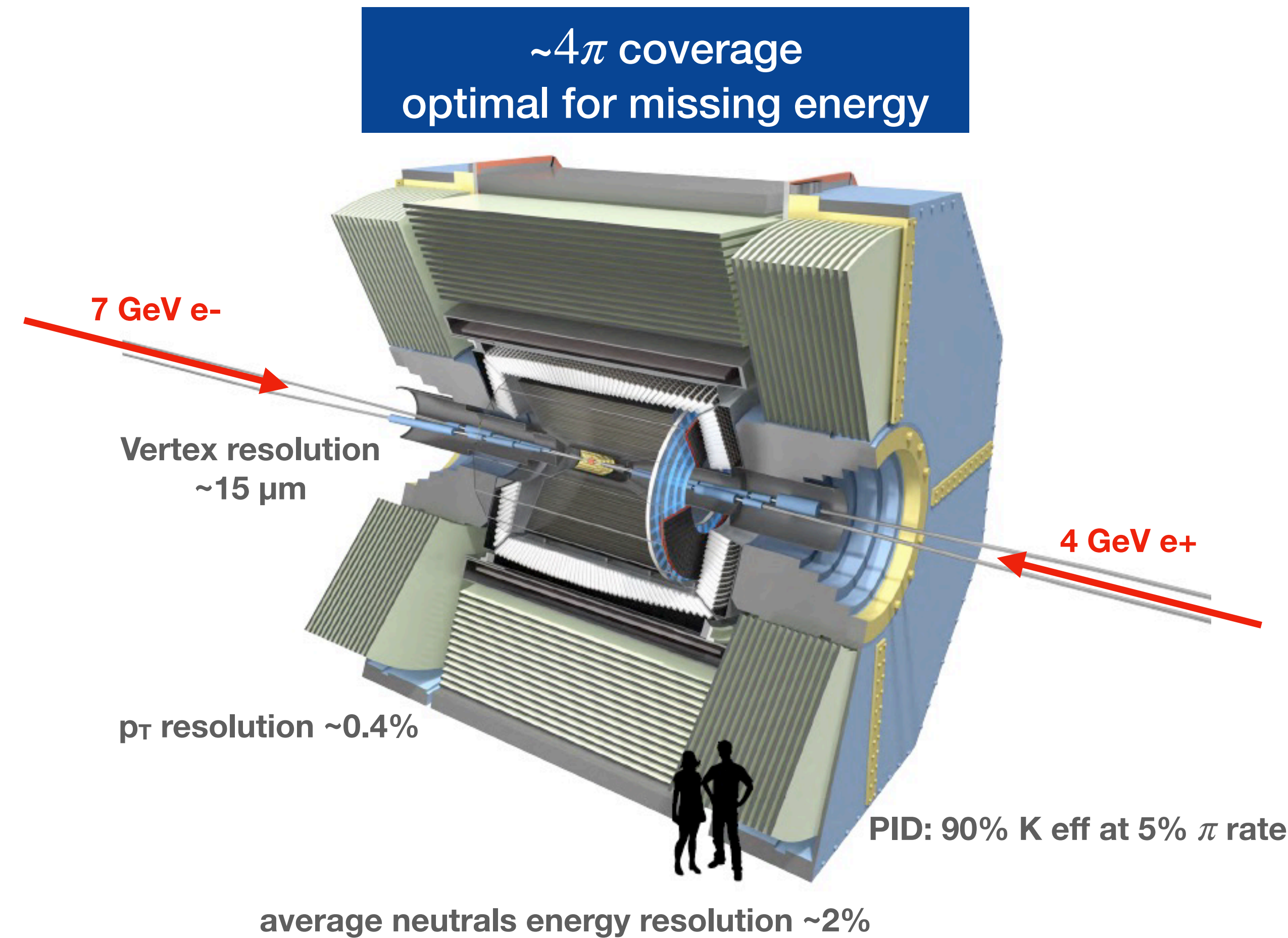
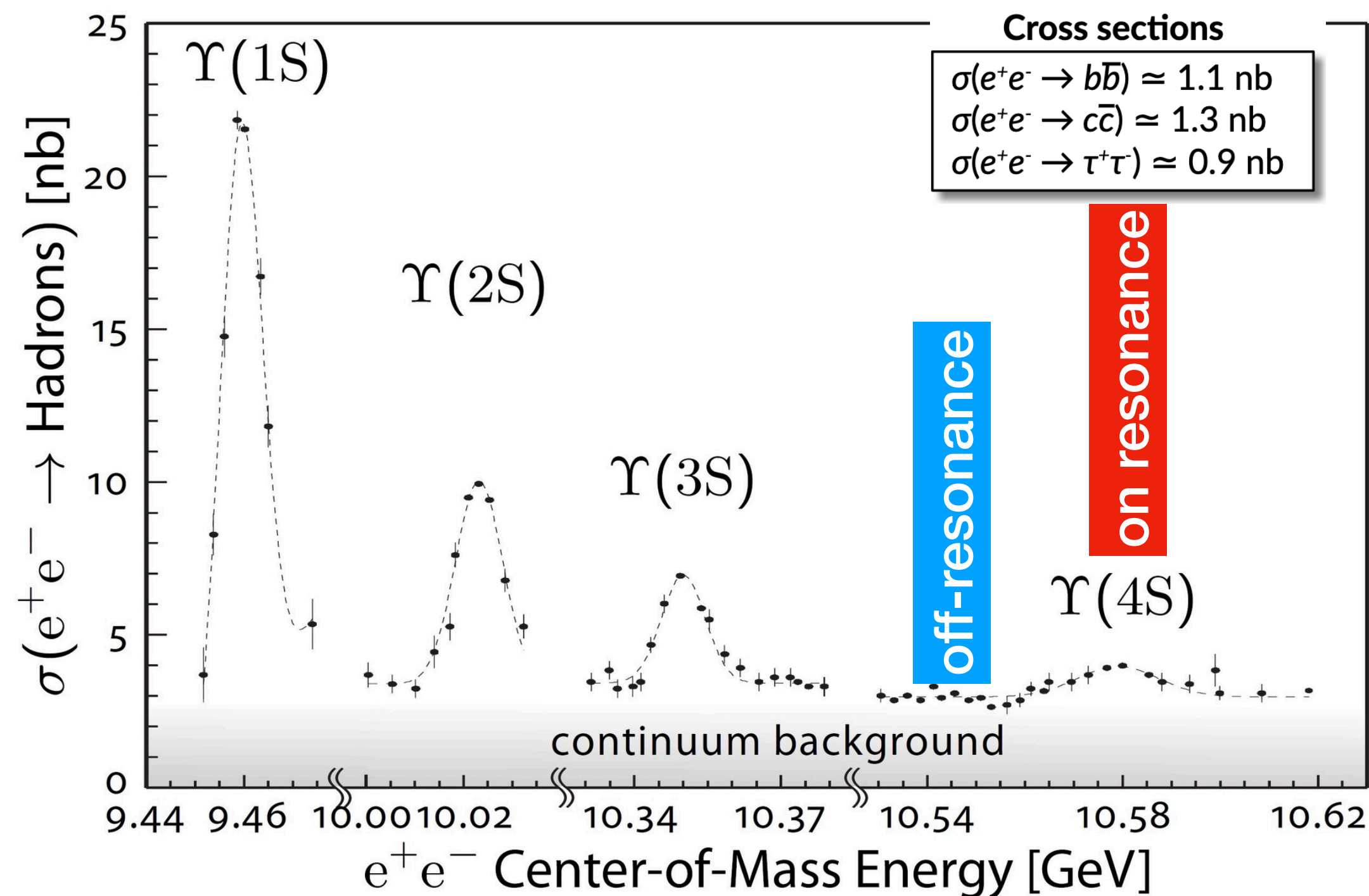
Impostor alert

When you lie on the application but still get the job



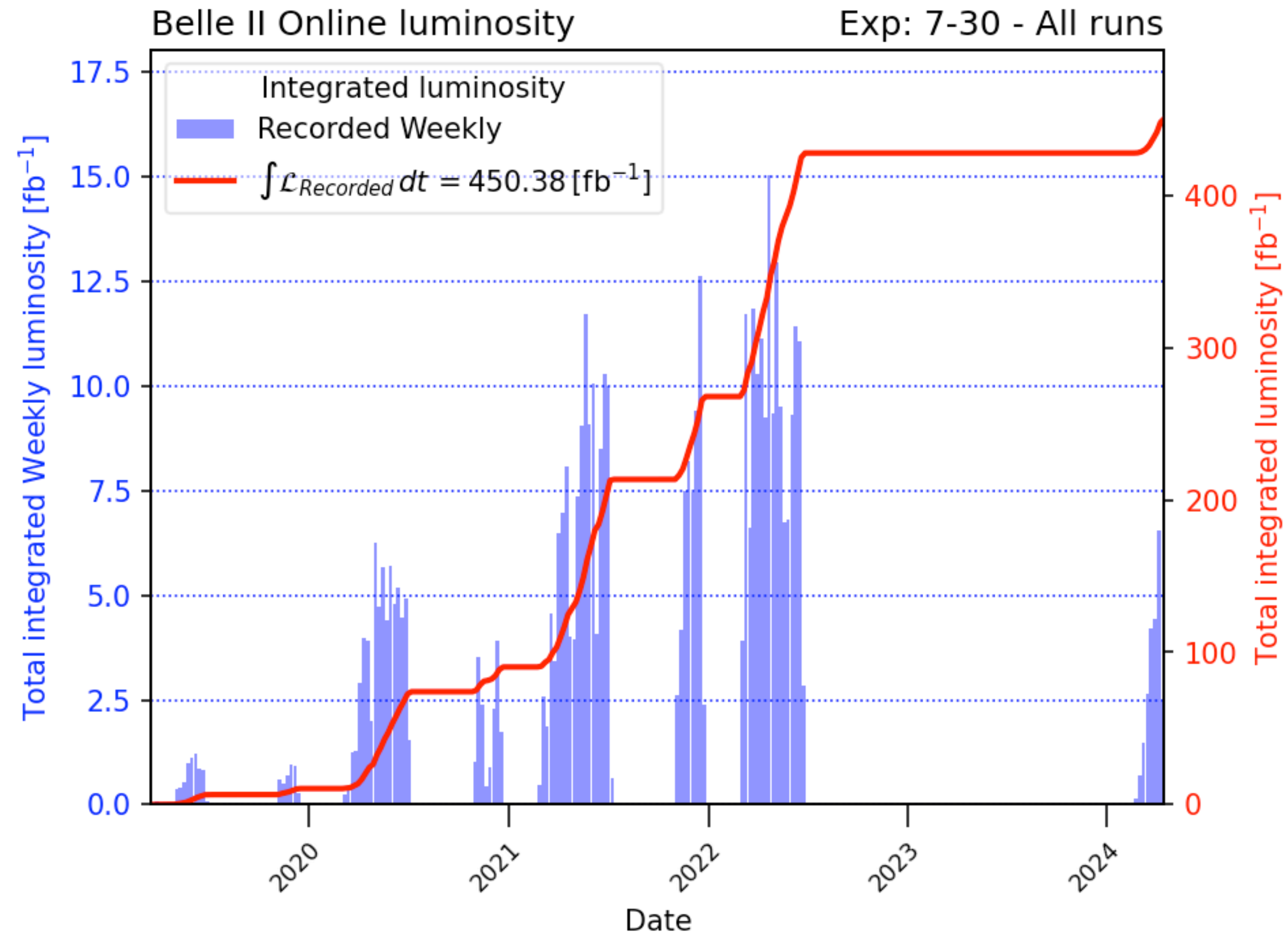
The journey so far

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



The journey so far

- World record peak luminosity in summer 2022: $4.7 \times 10^{34}/\text{cm}^2/\text{s}$
- 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 $10^{35}/\text{cm}^2/\text{s}$
 - Cross the 1ab^{-1} milestone
 - Prove the effectiveness of the work done in LS1

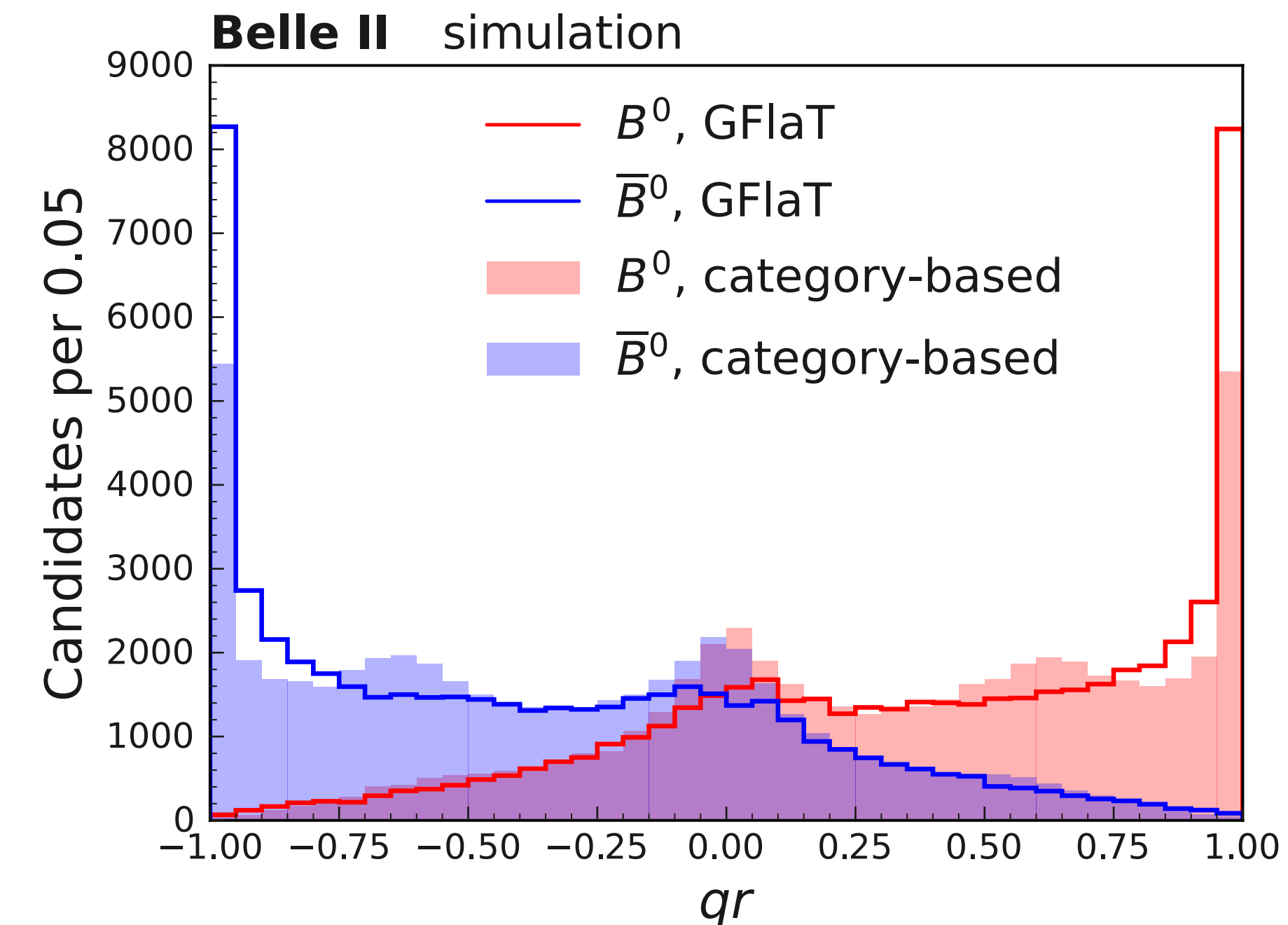


Updated on 2024/04/11 07:48 JST

Not just more data: improvement in the analysis tools

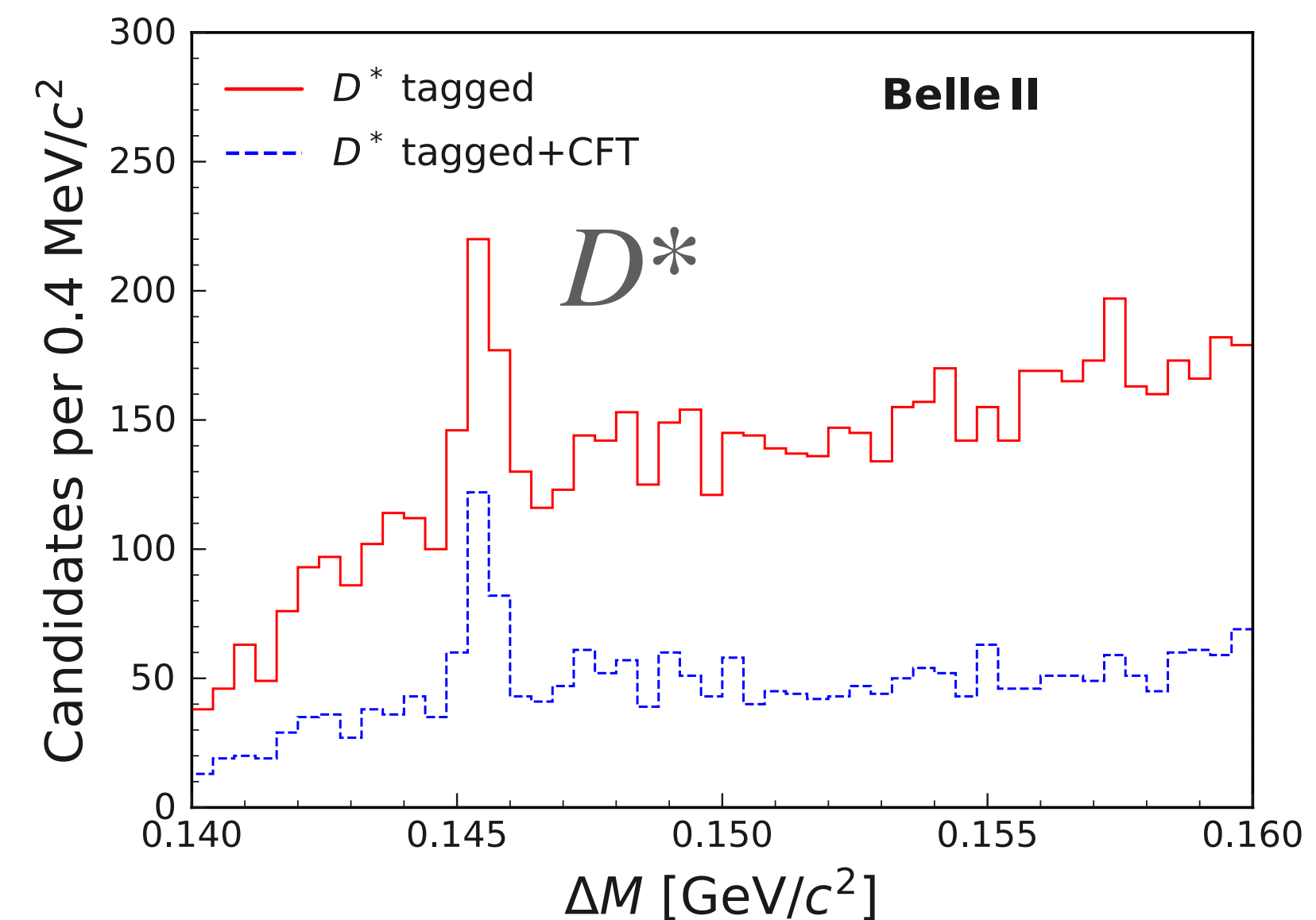
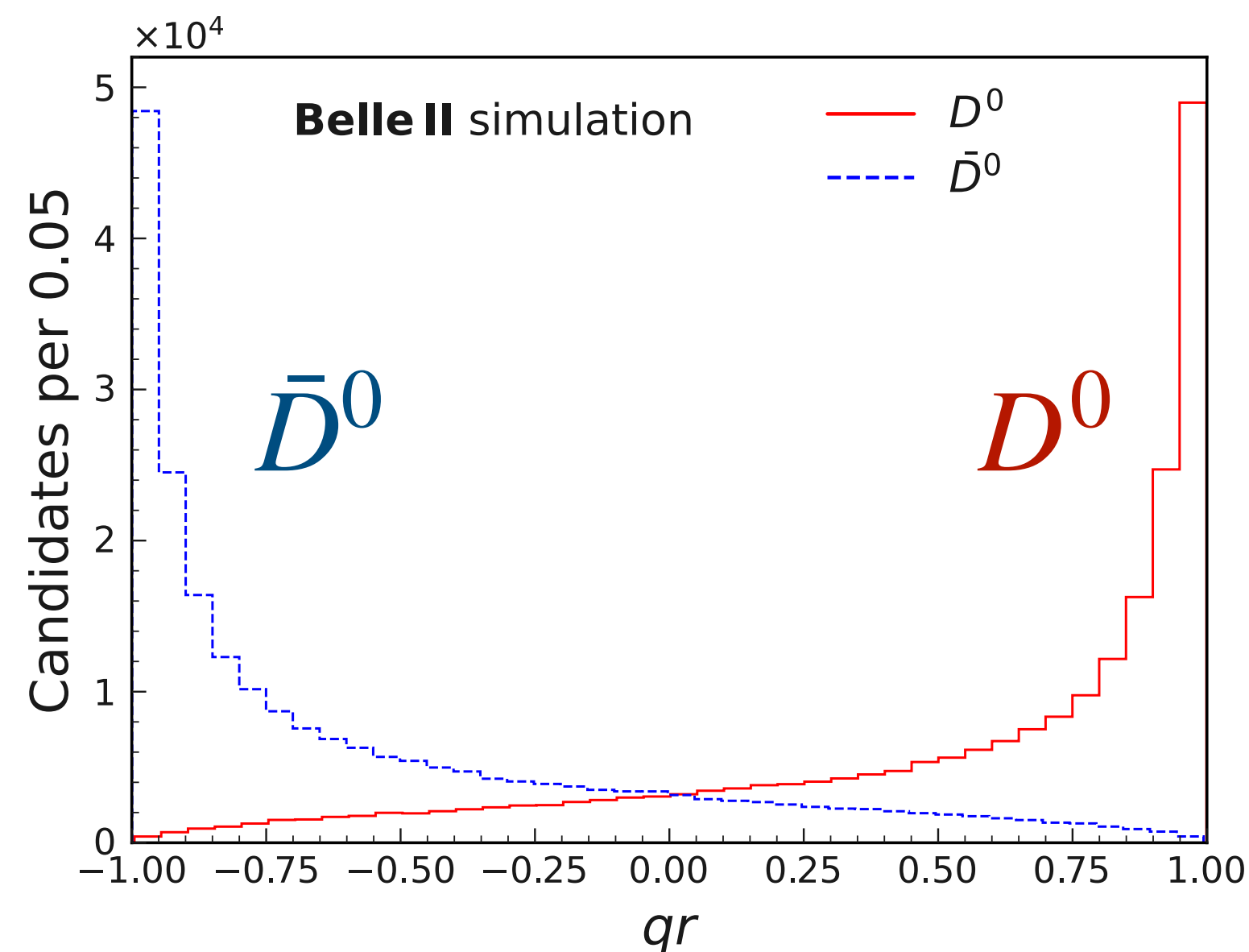
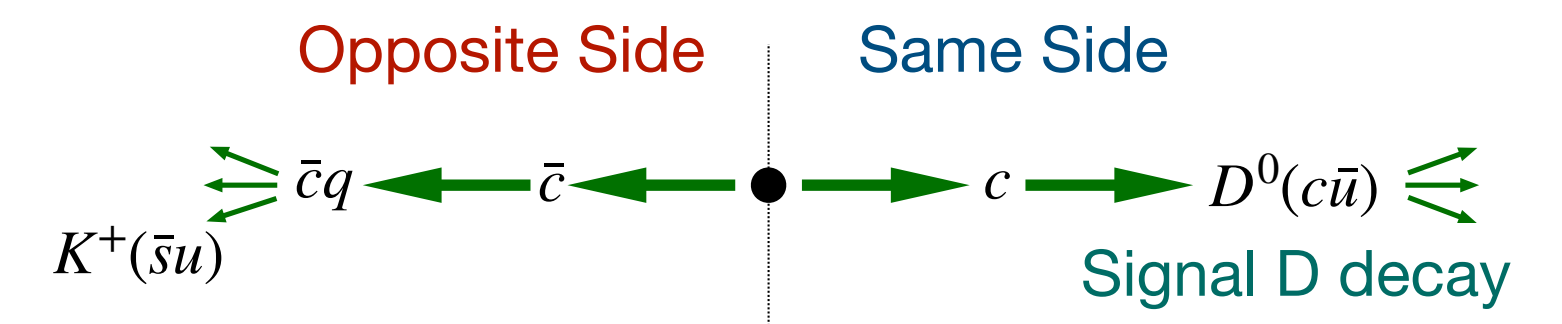
Improving the tagging: beauty

- **Conventional category-based tagger** (by charge of the lepton/kaon from the other B): effective tagging efficiency $\sim 30\%$
- 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



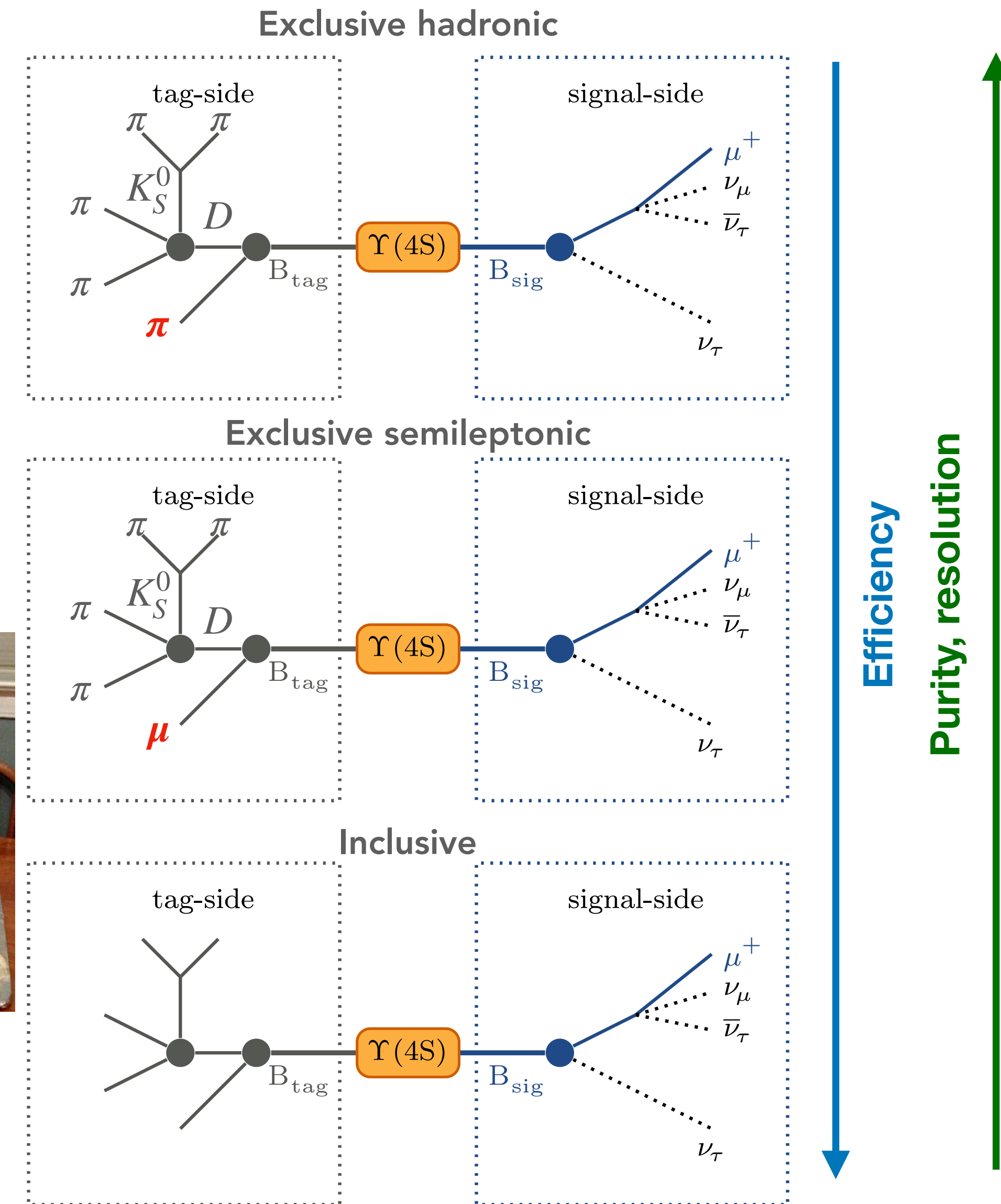
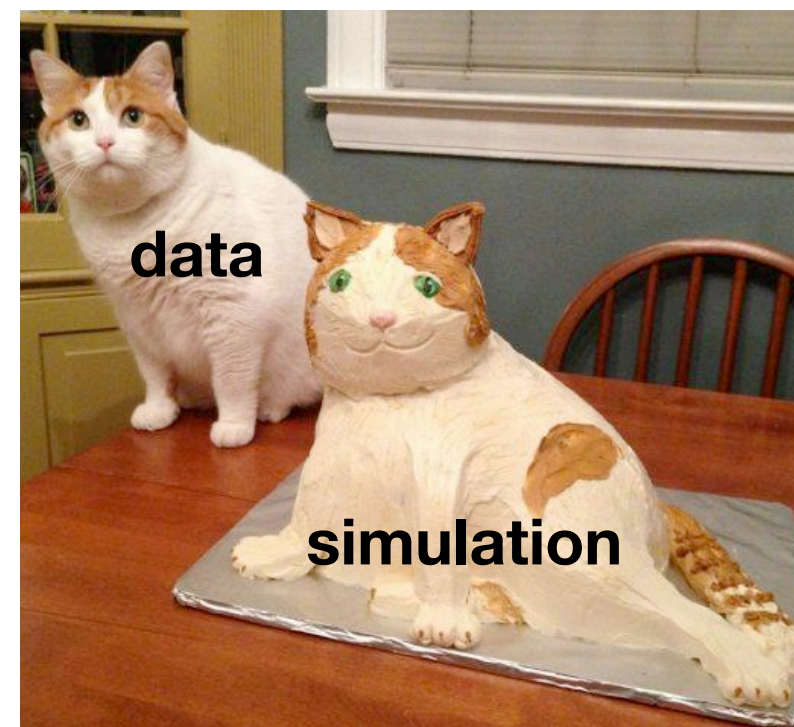
Improving the tagging: charm

- **Conventional method:** tag the charge of the pion from $D^{*\pm} \rightarrow D^0\pi^\pm$, or lepton from $B^- \rightarrow D^0\ell^-\nu$
 - Loss of statistics due to low production rates, soft pion efficiency etc: ~25% effective efficiency
- New **inclusive tagging** in $e^+e^- \rightarrow c\bar{c}$ 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



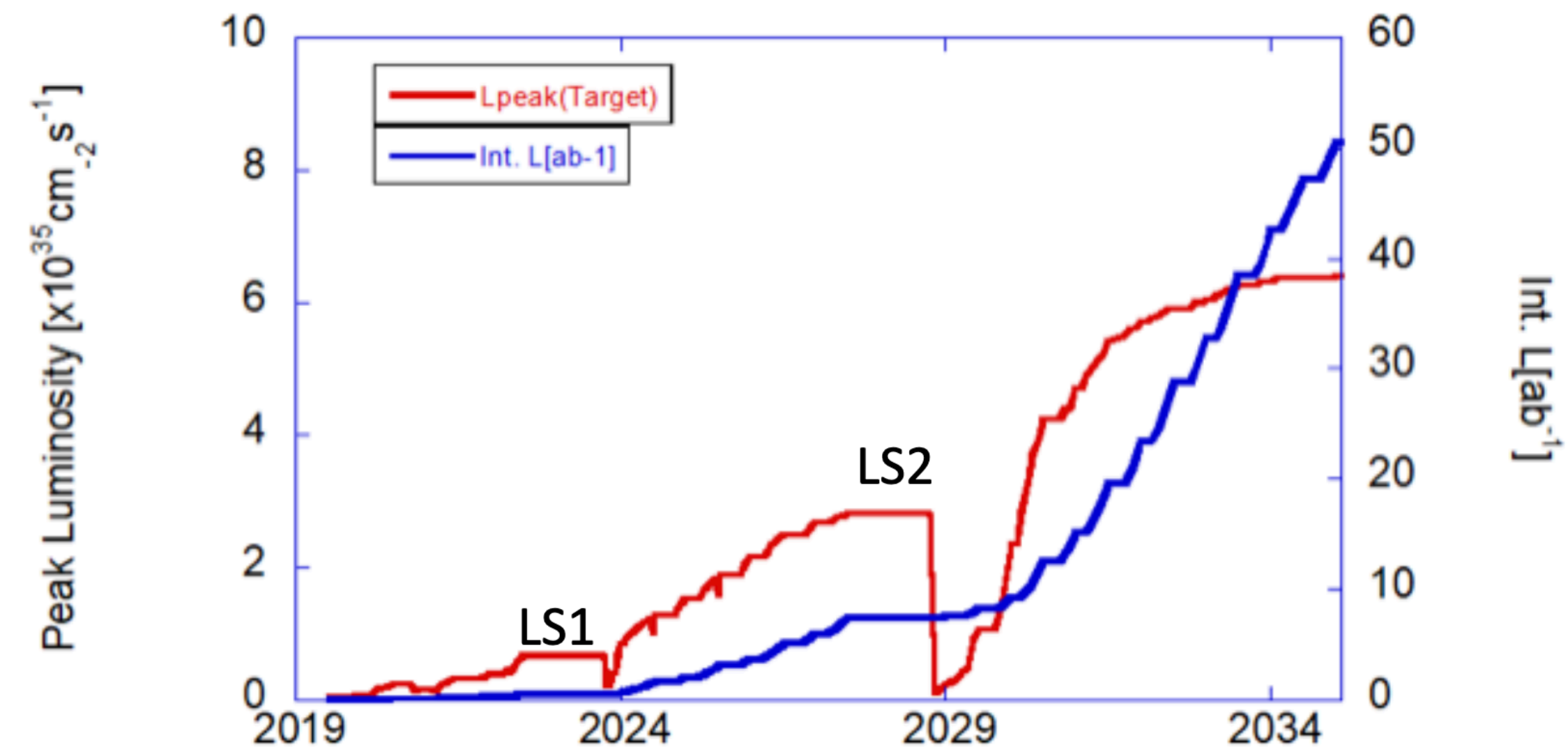
Missing-energy estimation

- 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 $2 \times 10^{35}/\text{cm}^2/\text{s}$ 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

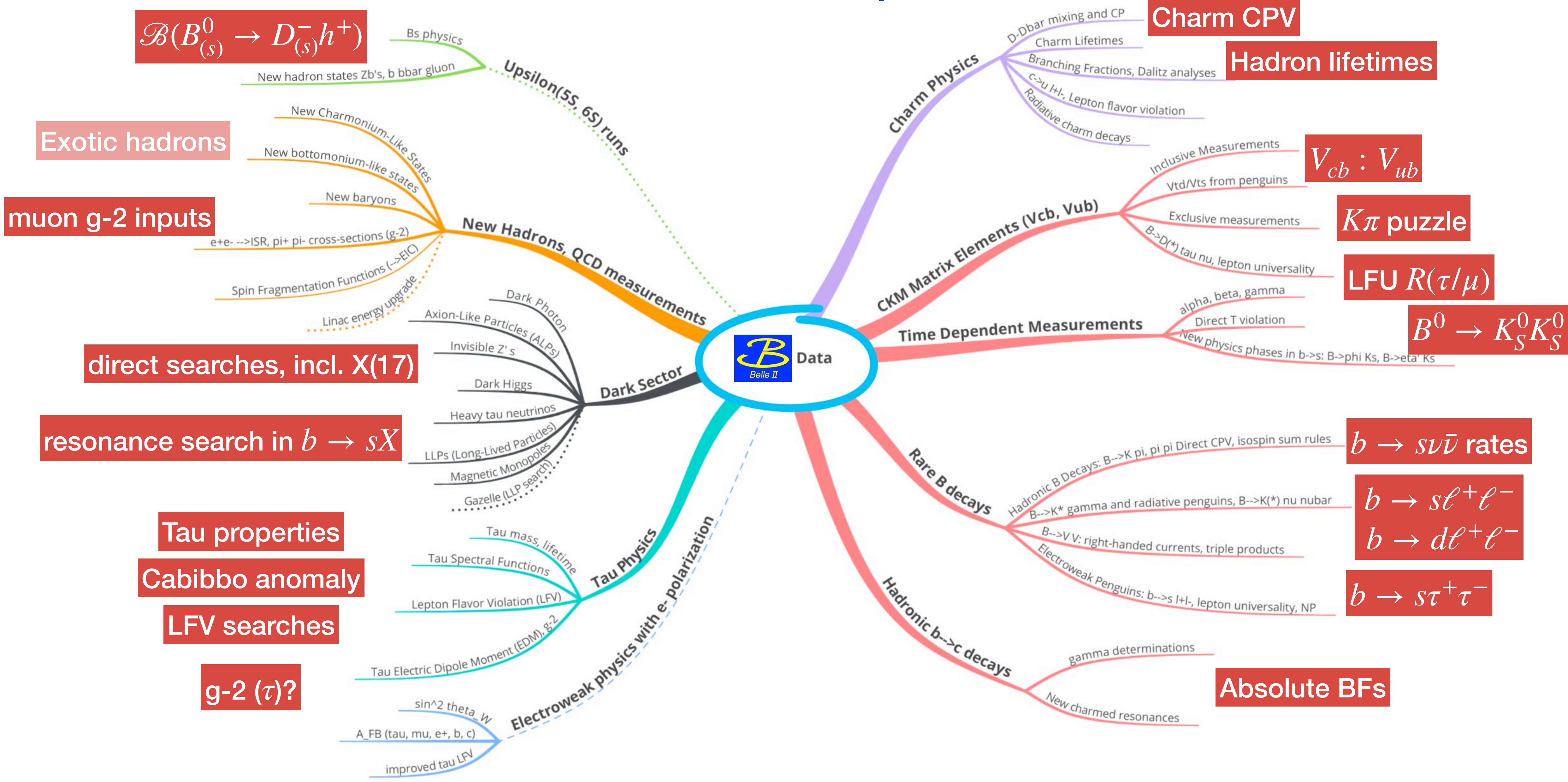


A biased collection of physics topics

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](#)

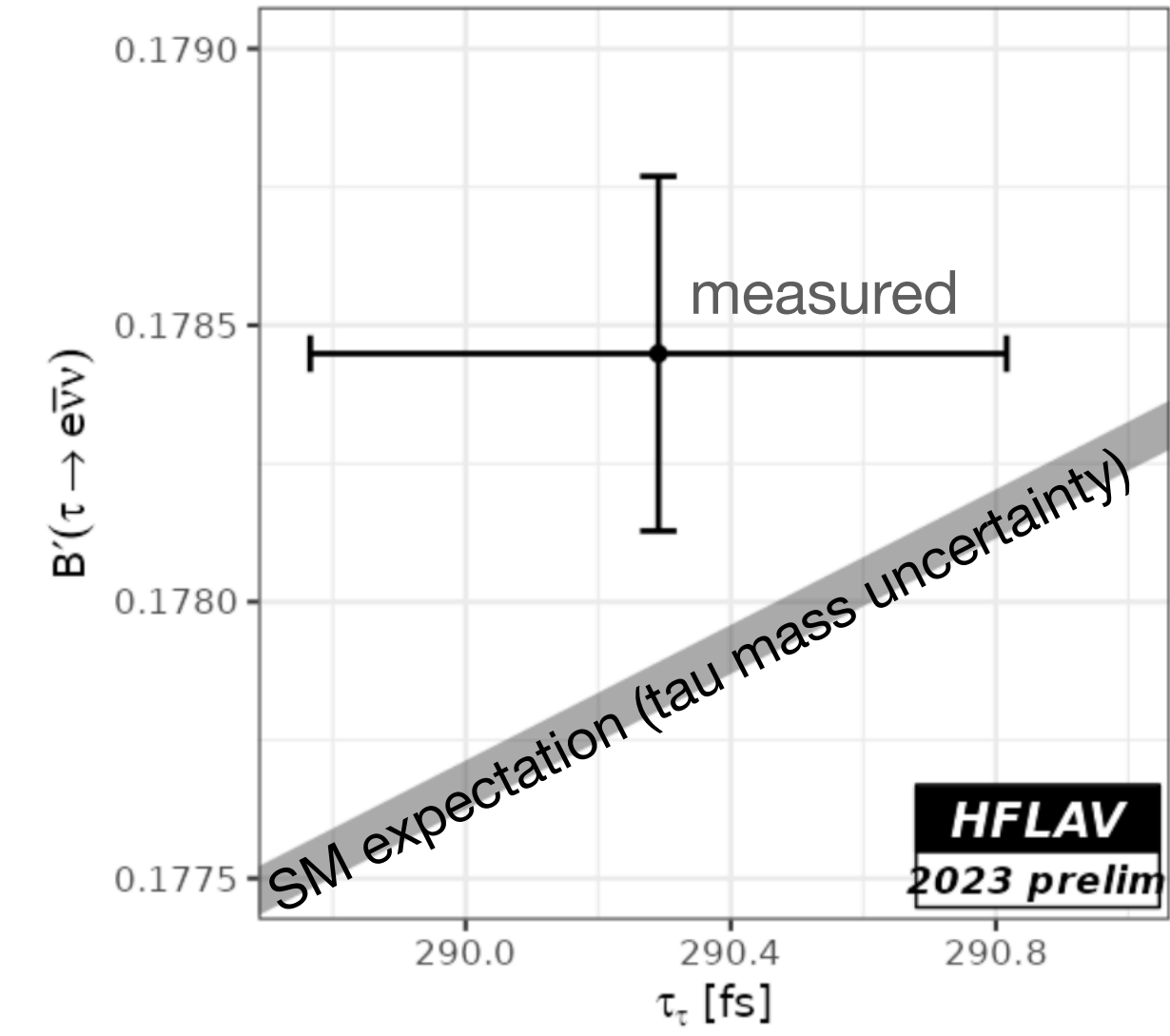
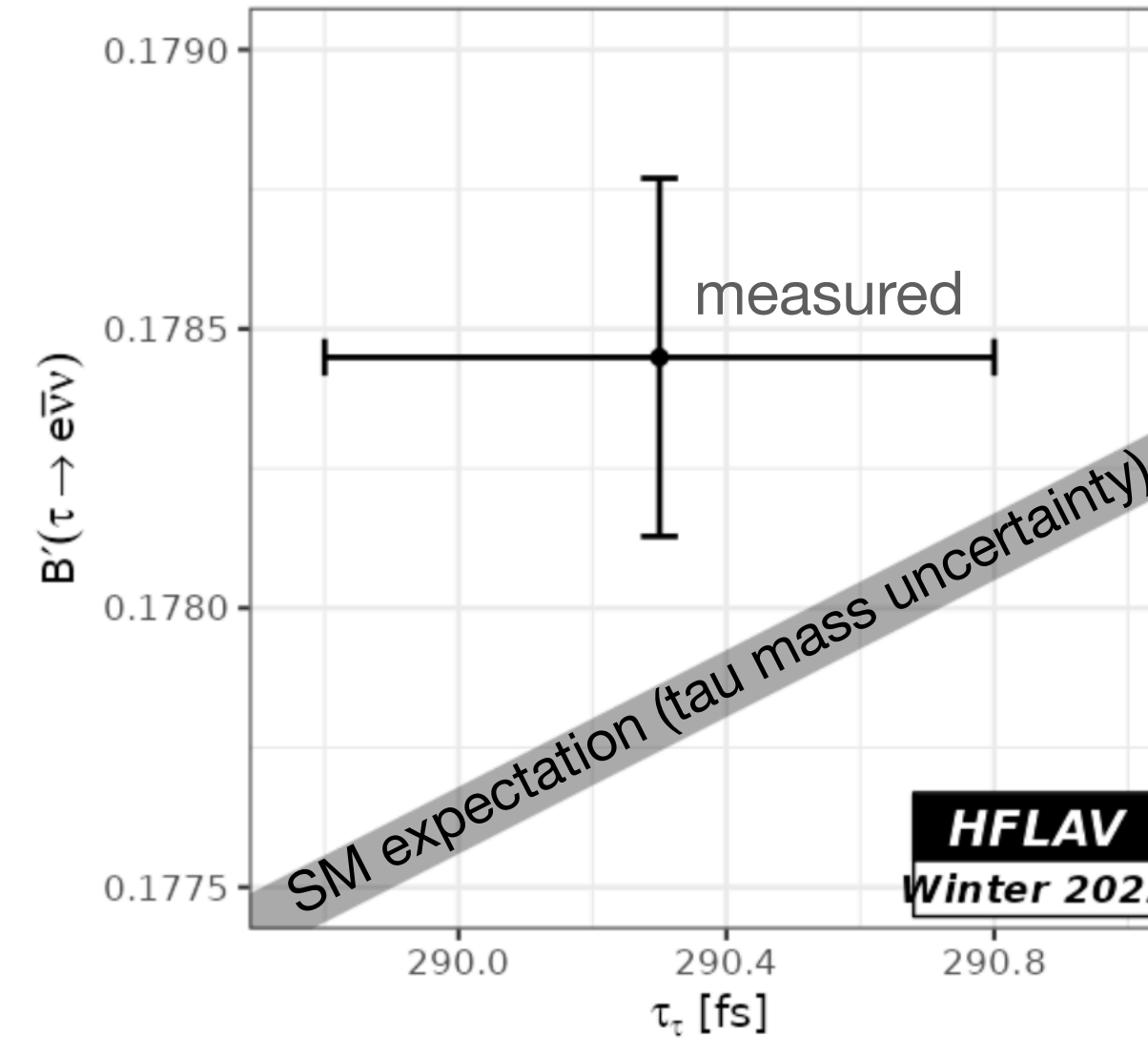
Belle II versus anomalies (broadly defined)



Tau properties

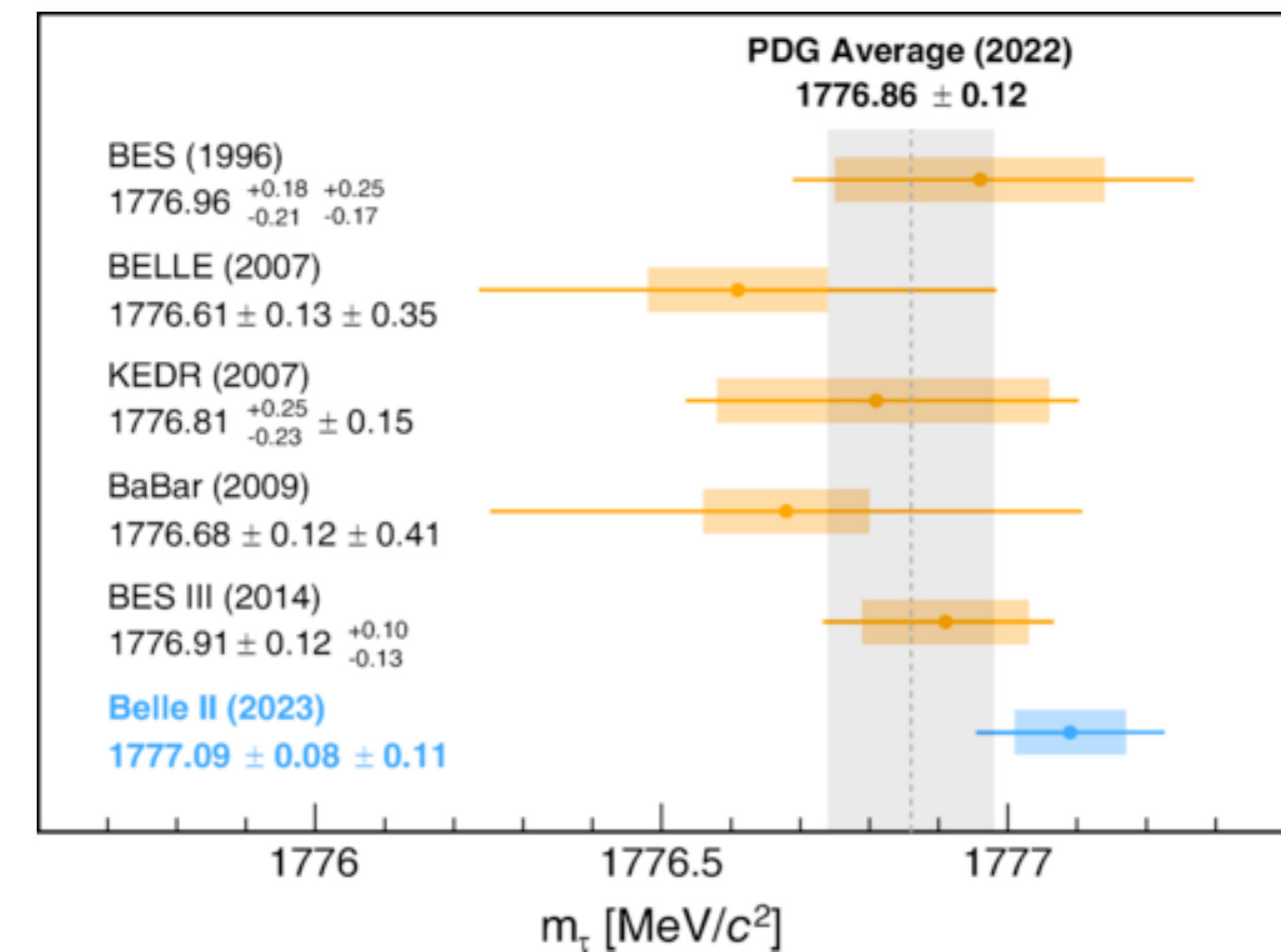
$$\mathcal{B}(\tau \rightarrow e\nu\bar{\nu}) \sim \mathcal{B}(\mu \rightarrow e\nu\bar{\nu}) \frac{m_\tau^5}{m_\mu^5}$$

- Abundant $e^+e^- \rightarrow \tau^+\tau^-$ production
- **Tau mass:** pseudomass method with $e^+e^- \rightarrow \tau^+\tau^-$, $\tau \rightarrow 3\pi\nu$
 $1777.09 \pm 0.08 \pm 0.11 \text{ MeV}/c^2$
 most precise to date
 [Phys. Rev. D 108, 032006]



- Largest syst: beam energy scale, momentum scale
 - Affected by the knowledge of $\Upsilon(4S)$ 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 $0.2 \times 10^{-15} \text{ s}$



- **Lepton universality** in tau decays:

- $\frac{\mathcal{B}(\tau \rightarrow \mu\nu\bar{\nu})}{\mathcal{B}(\tau \rightarrow e\nu\bar{\nu})}$ (mu/e universality) and $\frac{\Gamma(\tau \rightarrow \pi\nu)}{\Gamma(\pi \rightarrow \mu\nu)}$ (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 $\tau \rightarrow \mu\nu\bar{\nu}$ 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

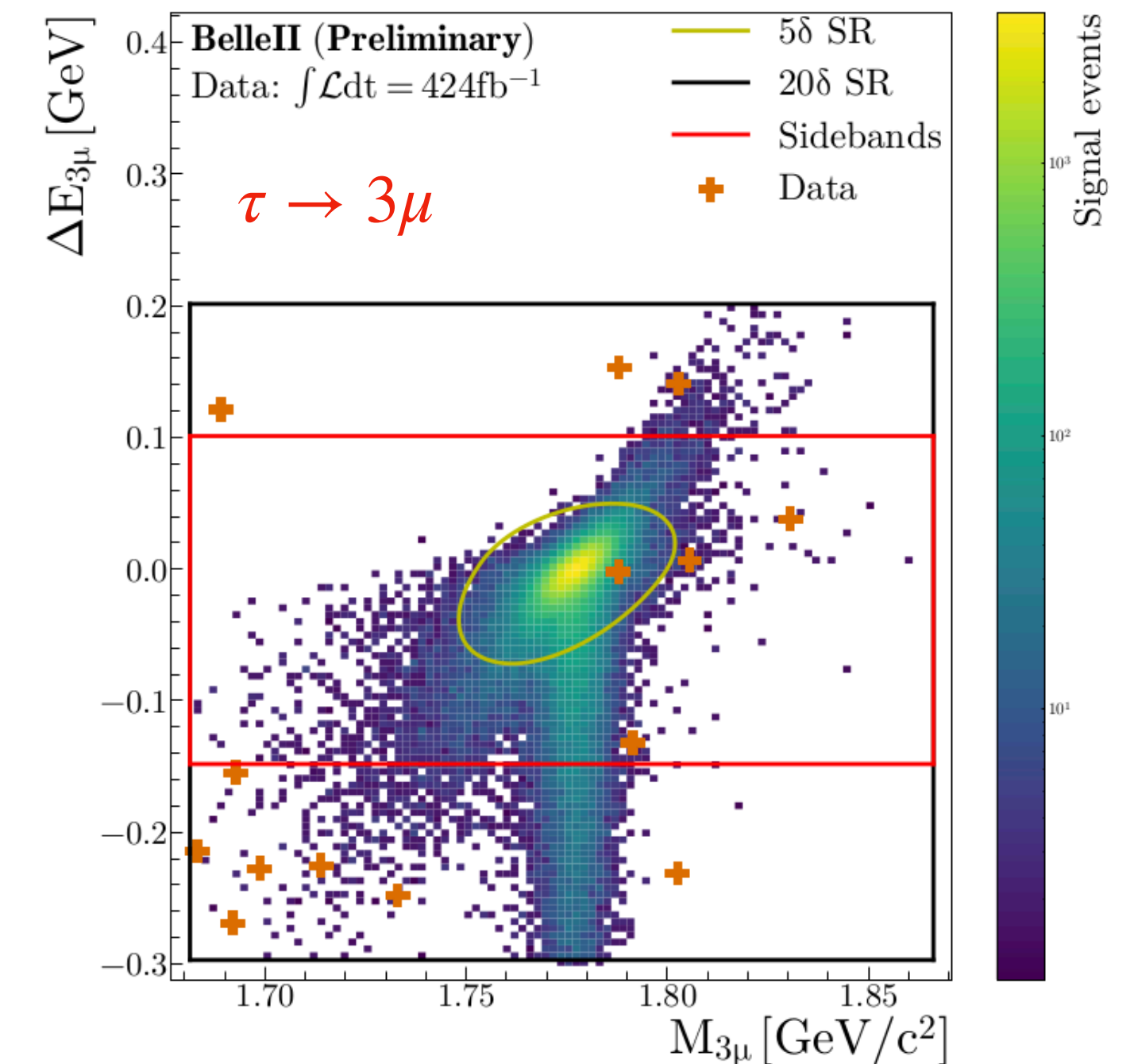
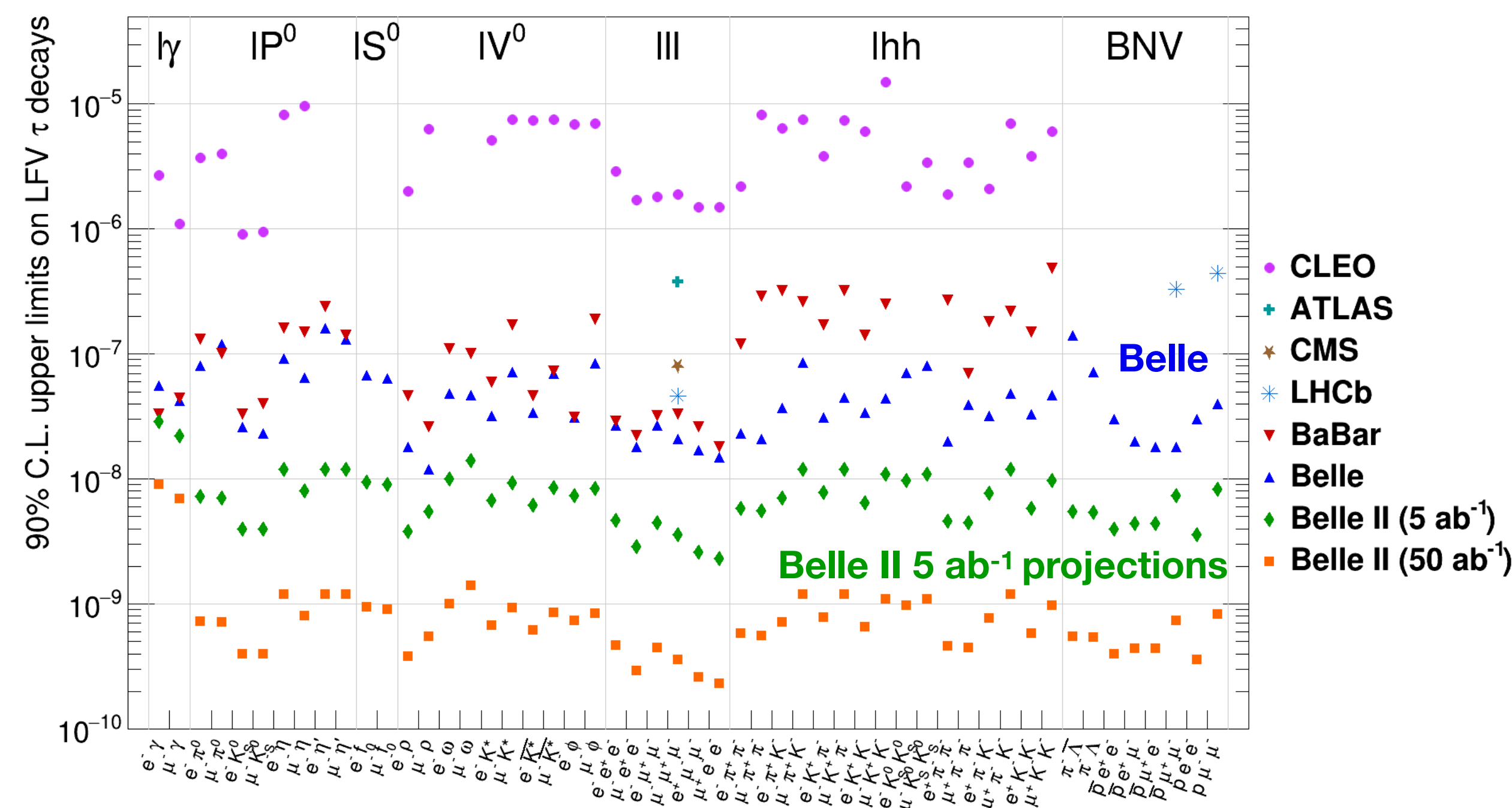
- Input to the **Cabibbo angle anomaly**: $|V_{us}|$ from $\frac{\mathcal{B}(\tau \rightarrow K\nu)}{\mathcal{B}(\tau \rightarrow \pi\nu)}$

- Projected reach down to few % sensitivity, depending on PID performance

- CPV measurements in τ 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 $\tau \rightarrow 3\mu$ search:
 - Tag $e^+e^- \rightarrow \tau^+\tau^-$ 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: $\mathcal{B} < 1.9 \times 10^{-8}$ @90%CL
- Belle II projected reach: $\text{few} \times 10^{-9}$ with 10 ab^{-1} for most LFV channels
 - except for $\tau \rightarrow \ell\gamma$ modes (irreducible bkg due to $\tau \rightarrow \ell\nu\bar{\nu} + \gamma_{ISR}$)
 - This is where beam polarisation may help (about this later)
- Analyses of many other final states in progress
 - Also, searches for new bosons in $\tau \rightarrow \ell a$, HNL in $\tau \rightarrow \pi N$...



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

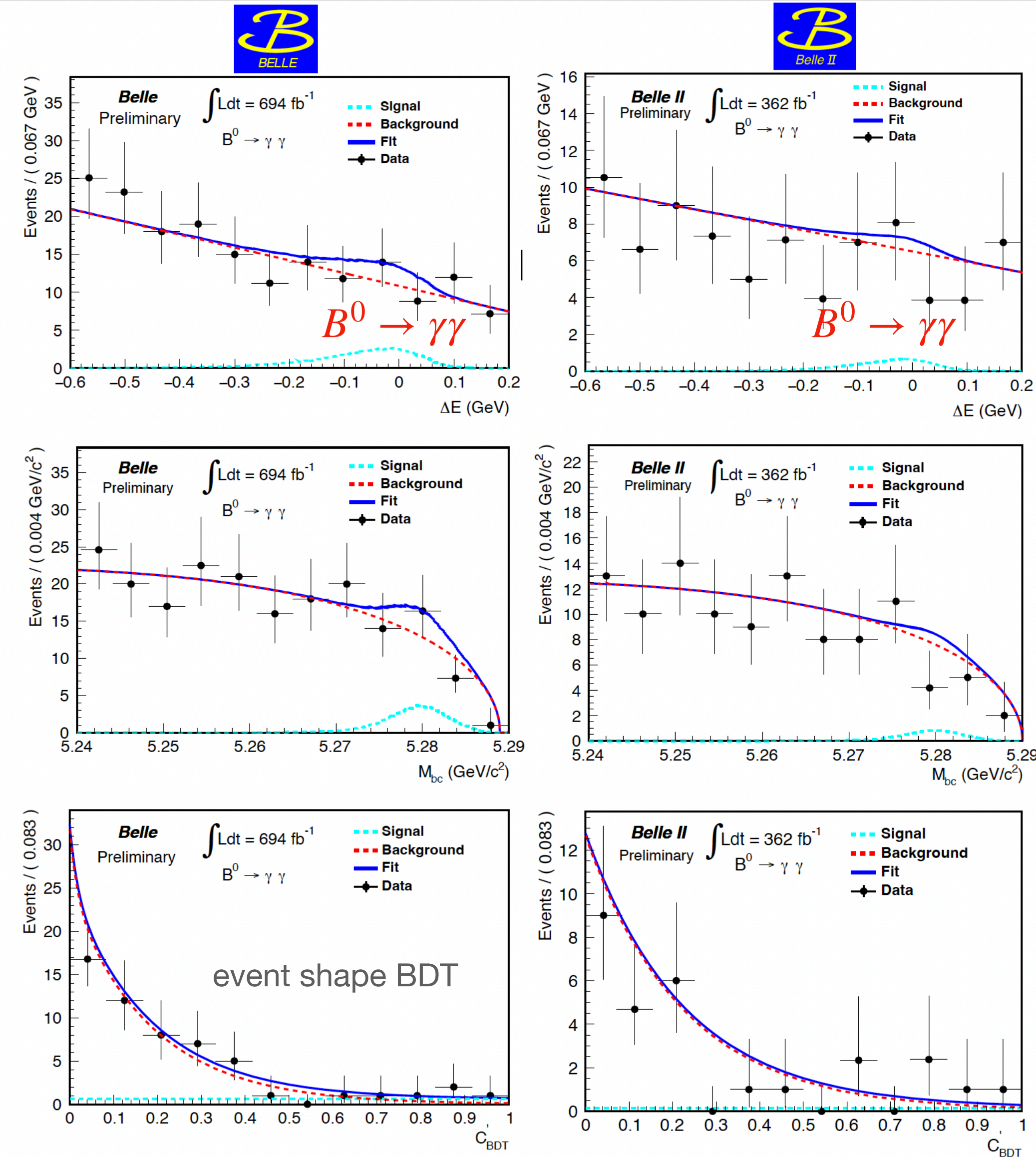
Penguins and friends

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

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

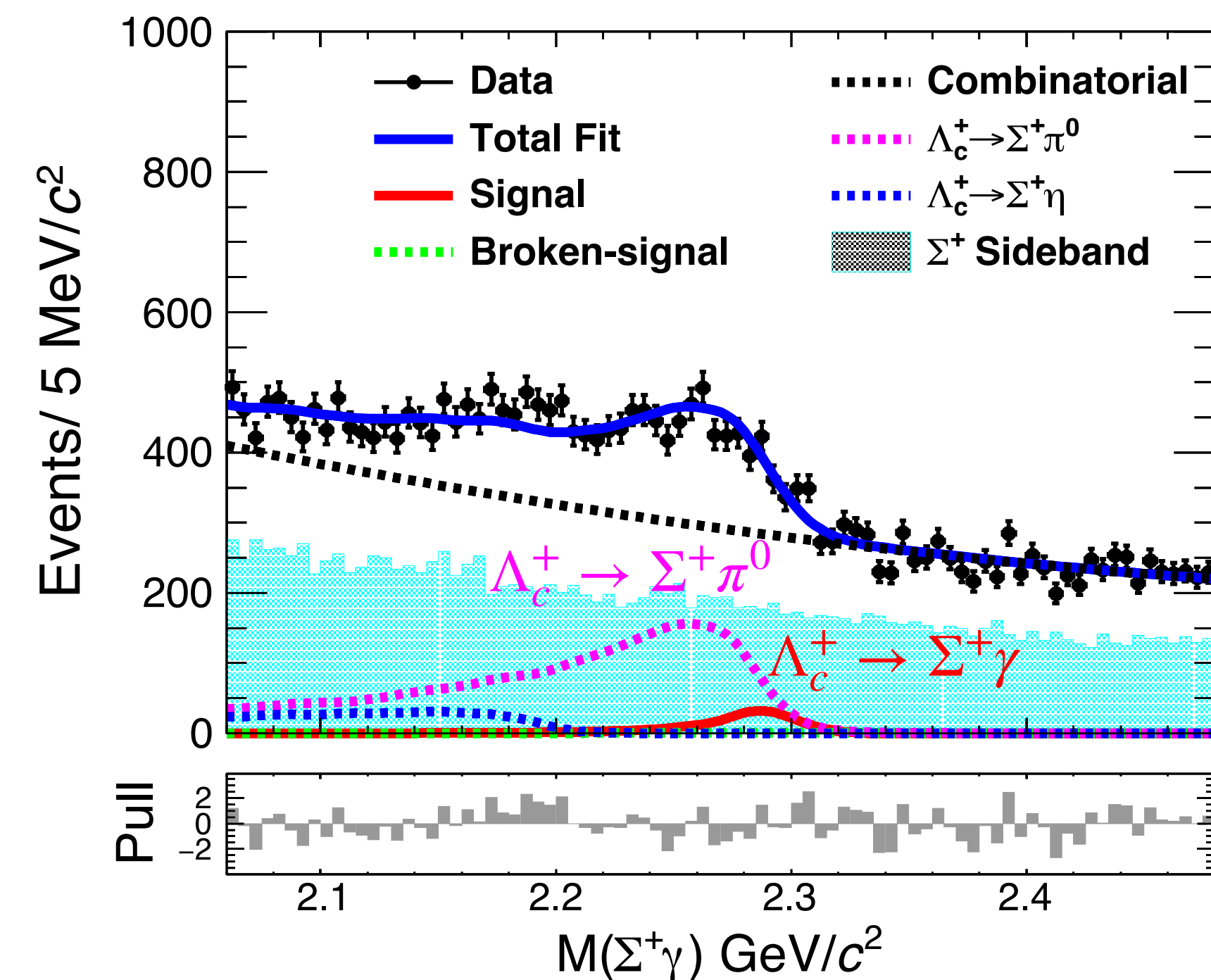
- Belle II is crucial to provide the measurements of **absolute branching fractions**, e.g. for normalisation modes used by LHCb such as $B \rightarrow K^{(*)}J/\psi$
 - Pre-requisite: better understanding of f_{+-}/f_{00} (relative B^+/B^0 production rates)

- Recent Belle+Belle II search for $B^0 \rightarrow \gamma\gamma$ (see Moriond talk): a very suppressed $b \rightarrow d$ 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!
- $D^0 \rightarrow \gamma\gamma$ search in prospects: sensitivity down to $\sim 10^{-7}$ (factor ~ 10 above the SM rate)
- A less suppressed $B_s^0 \rightarrow \gamma\gamma$ can be searched if B_s^0 data collected



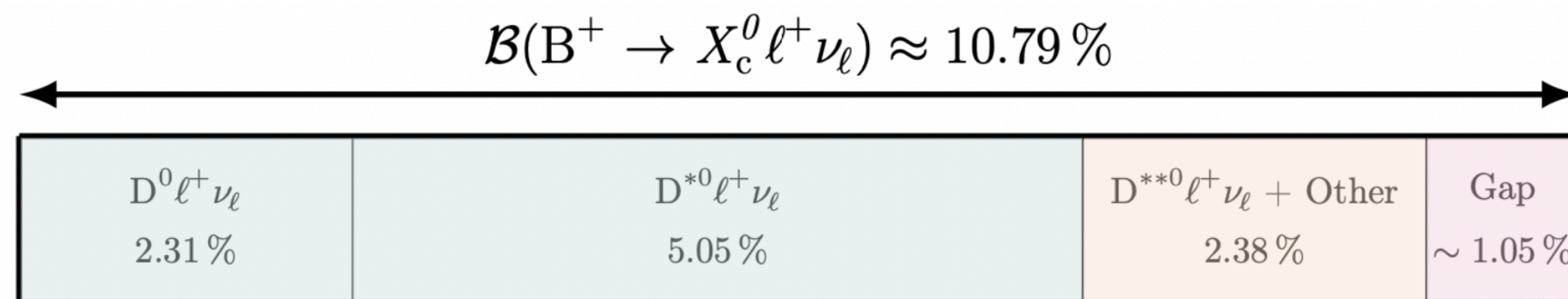
Radiative (charm) decays

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

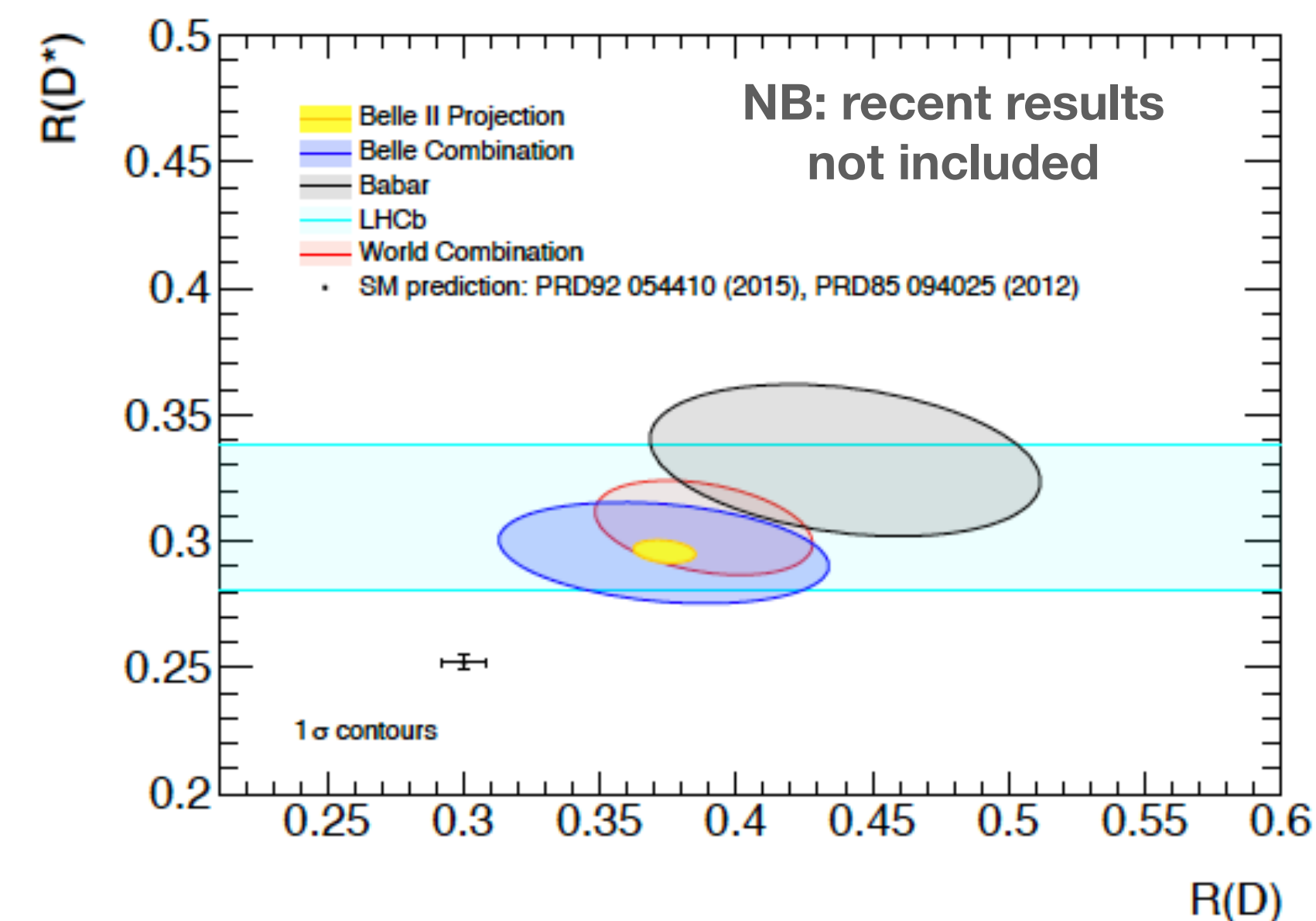
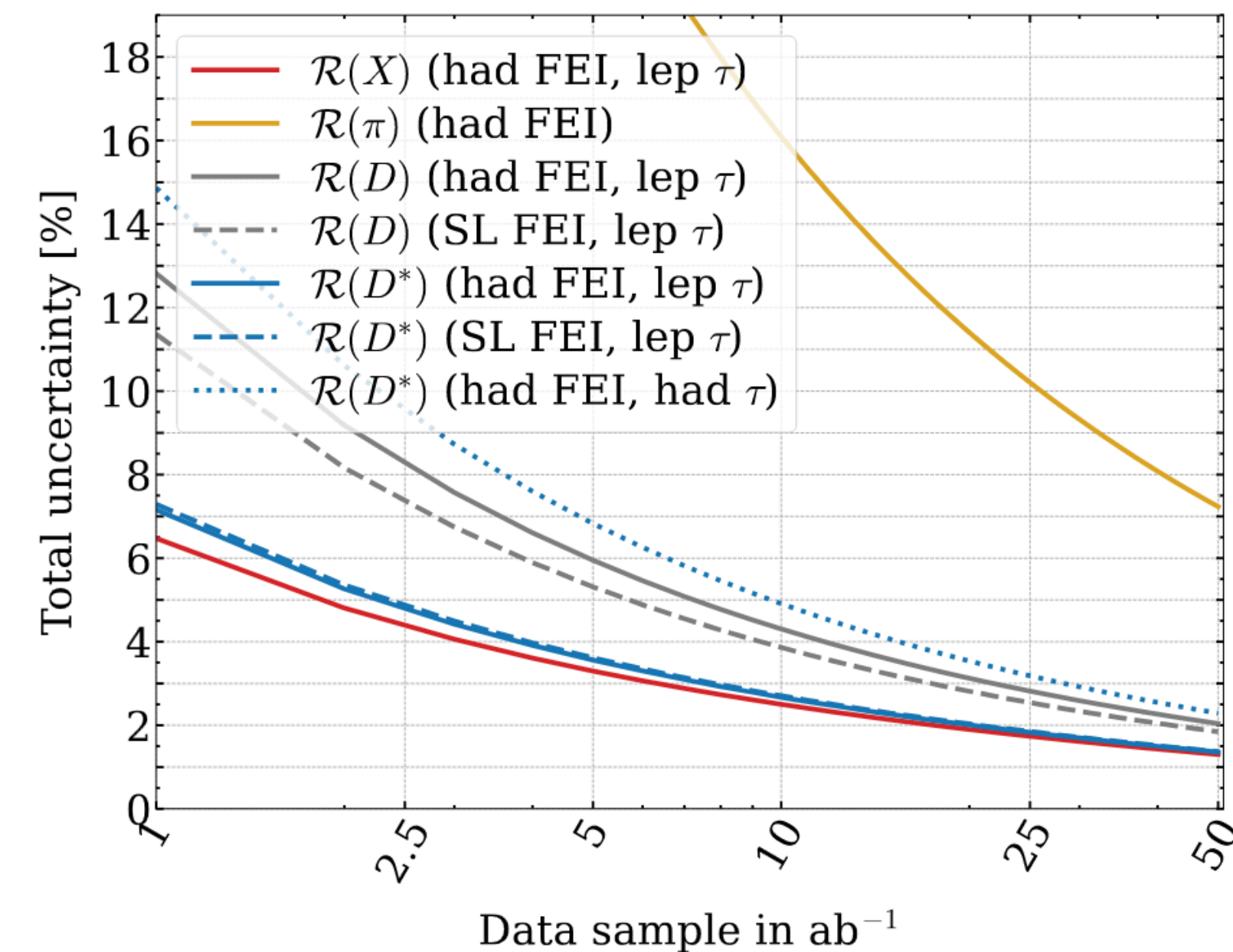


A few words on $b \rightarrow c\ell\nu$ and $b \rightarrow u\ell\nu$

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



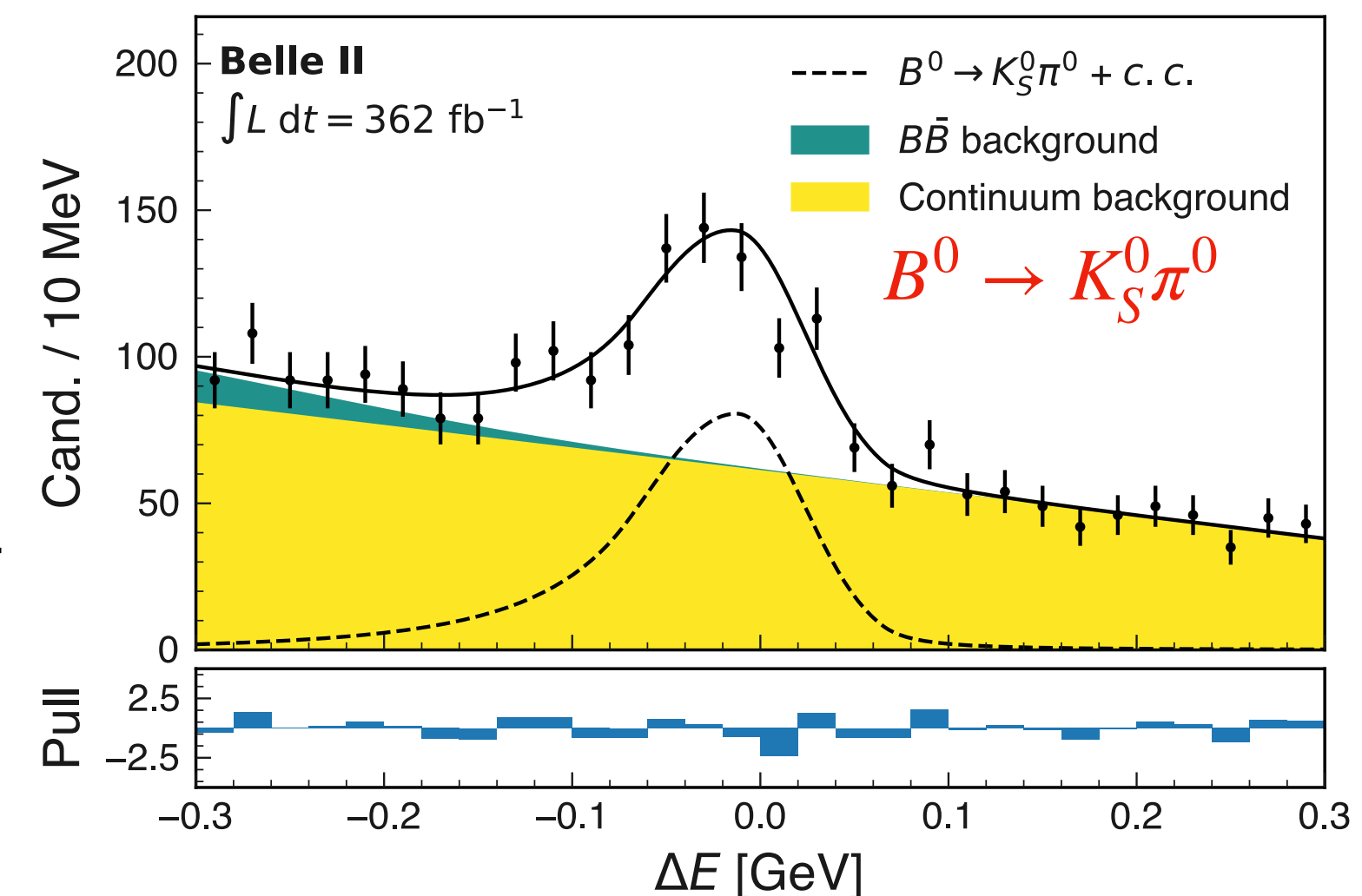
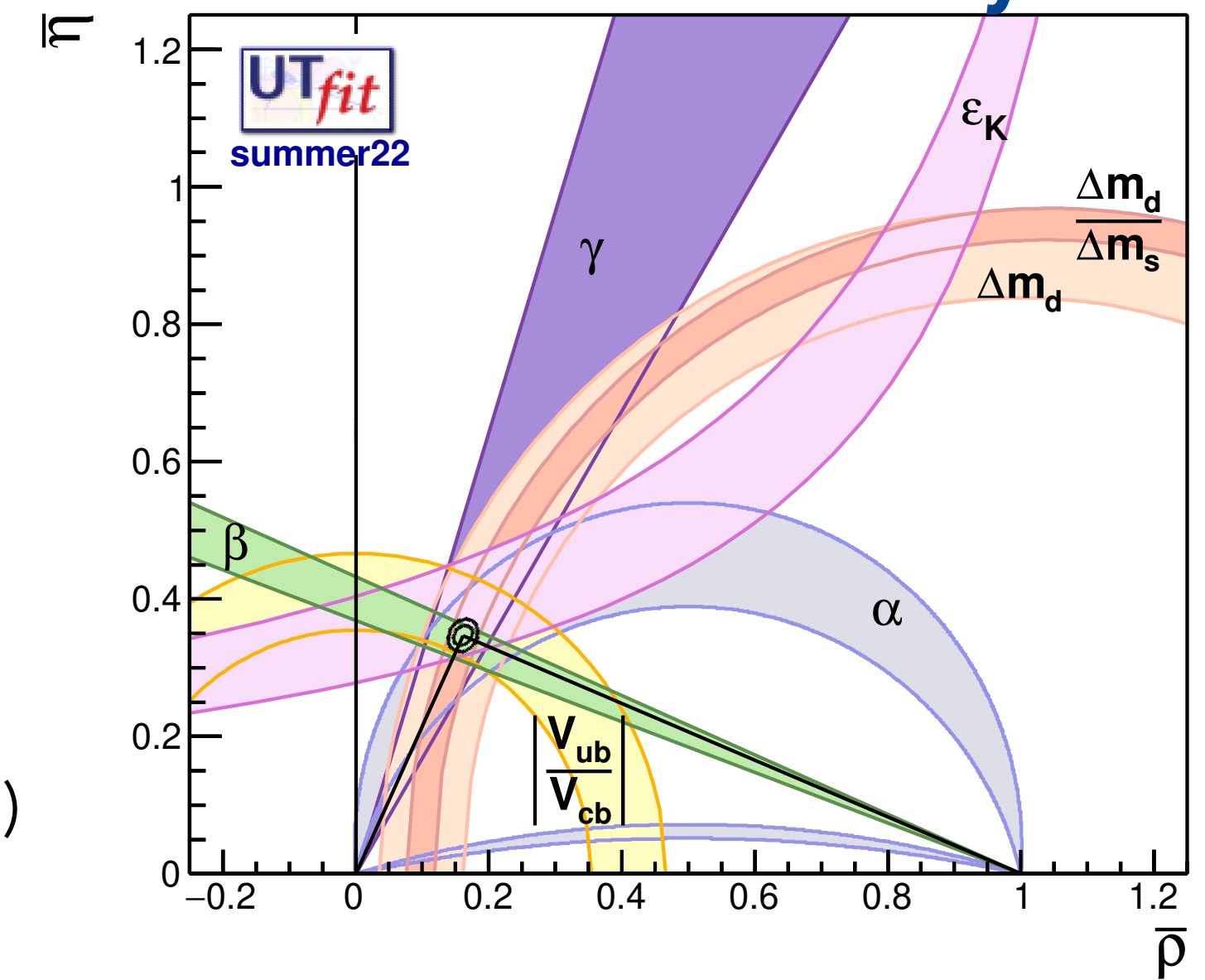
- $|V_{ub}|$ inclusive down to $\sim 3\text{-}5\%$ precision with 10ab^{-1} (*theory-dominated*), exclusive more precise
- Precision on $R_{D^{(*)}}$ down to few %
- High hope to observe $B^+ \rightarrow \mu^+ \nu$ and improve significantly $B^+ \rightarrow \tau^+ \nu$ measurement: both down to $\sim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



CP violation in B decays

- Trademark of Belle II: entangled B production → high flavour-tag 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} , expect precision of
 - $\sim 1\%$ on $\sin 2\phi_1^{(eff)} \equiv \sin 2\beta^{(eff)}$ in tree-dominated $(c\bar{c})K^0$ or $\sim 2\%$ in loop-dominated $\eta'K^0$
 - See the recent result in $B^0 \rightarrow J/\psi K_S^0$ with early Belle II data (3x worse than LHCb Run1+2)
 - $\sim 2.5^\circ$ on $\phi_2 \equiv \alpha$ in $B \rightarrow \rho\rho$: Belle II the key player even with a few ab^{-1} !
 - $\sim 2.5^\circ$ on $\phi_2 \equiv \gamma$
- Narrowing down on the isospin sum rule in $B \rightarrow K\pi$ decays ("Kπ puzzle"), where $A_{CP}(B \rightarrow K_S^0\pi^0)$ will be driven by Belle II (down to $\sim 5\%$ 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 charmless B decays advantageous at Belle II: efficiency reasonably flat in phase-space

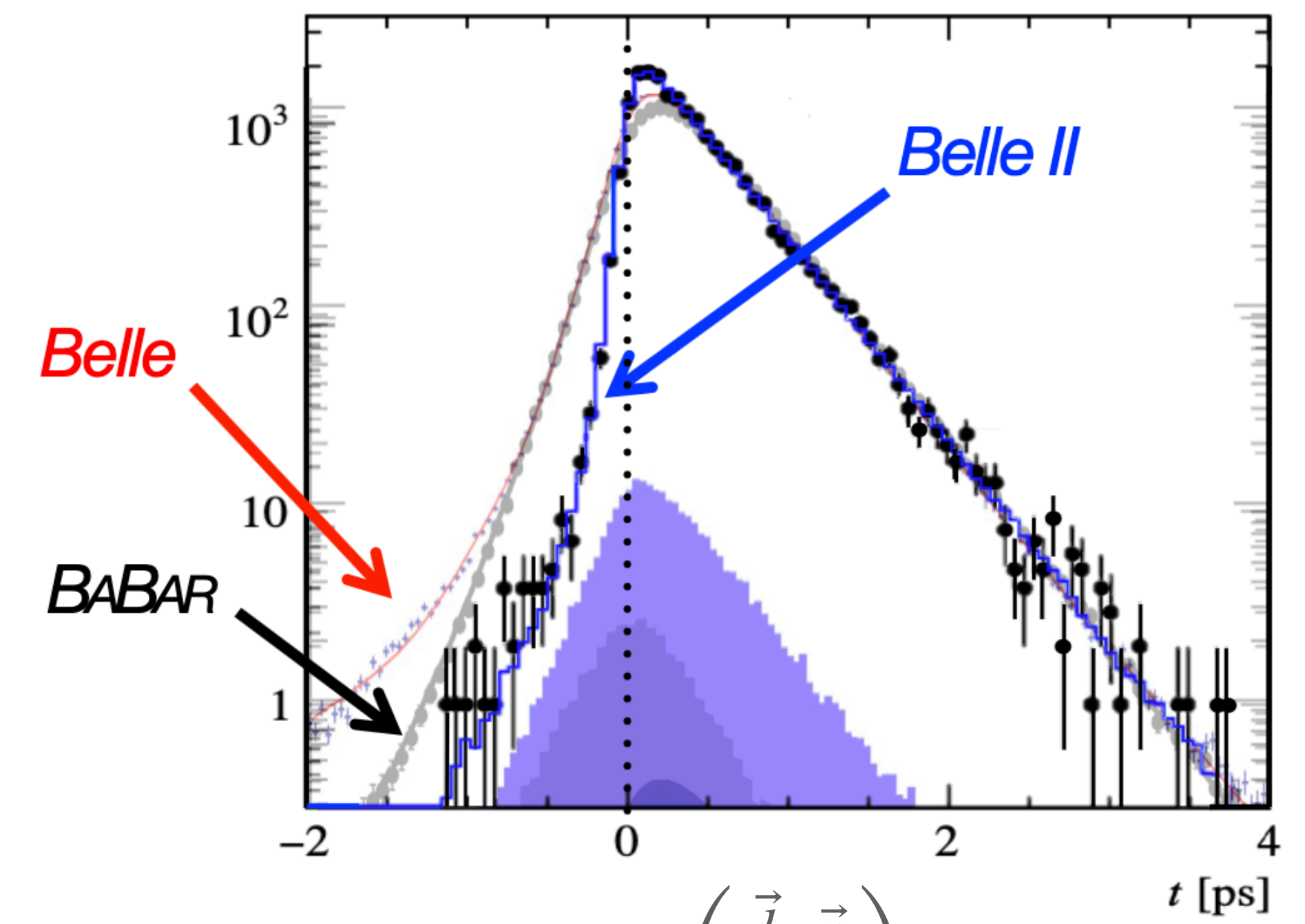
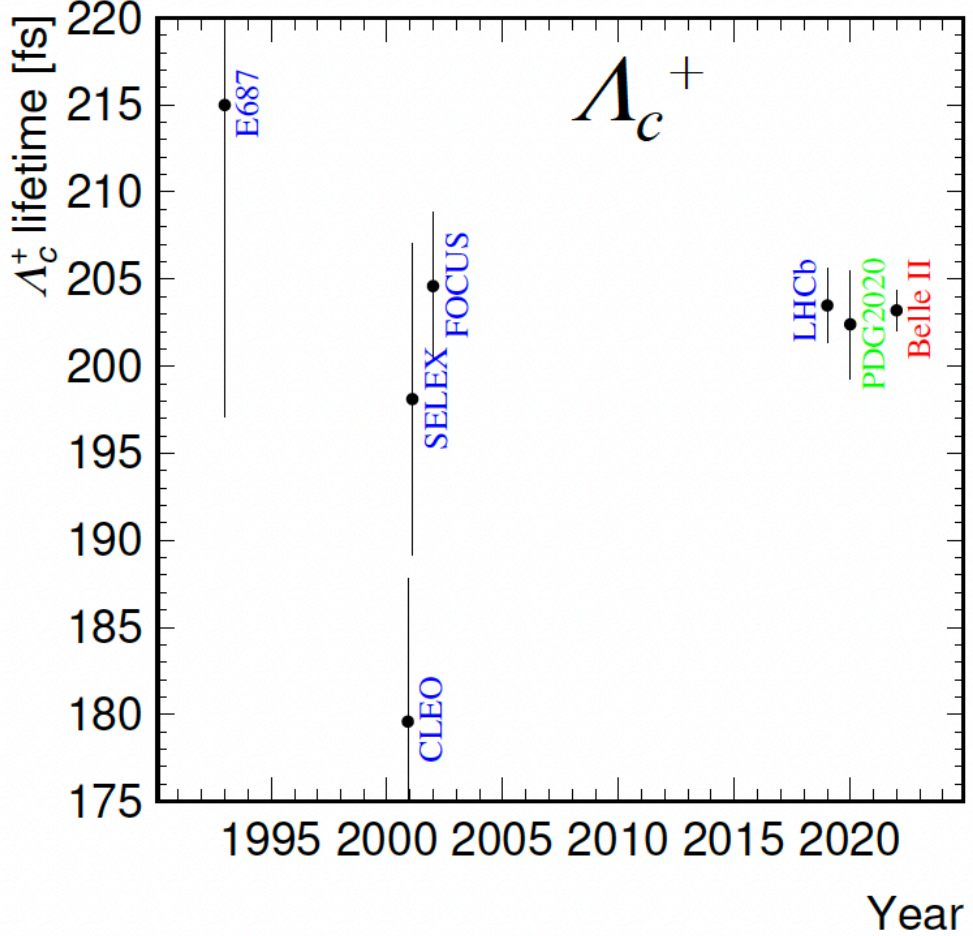
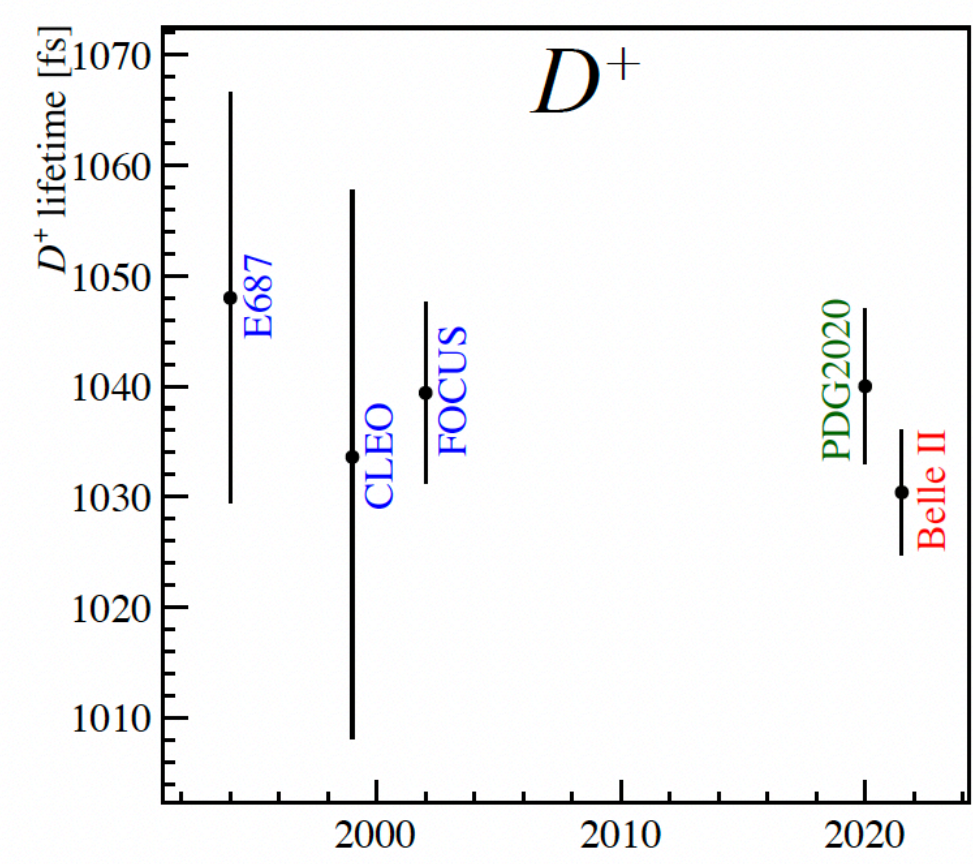
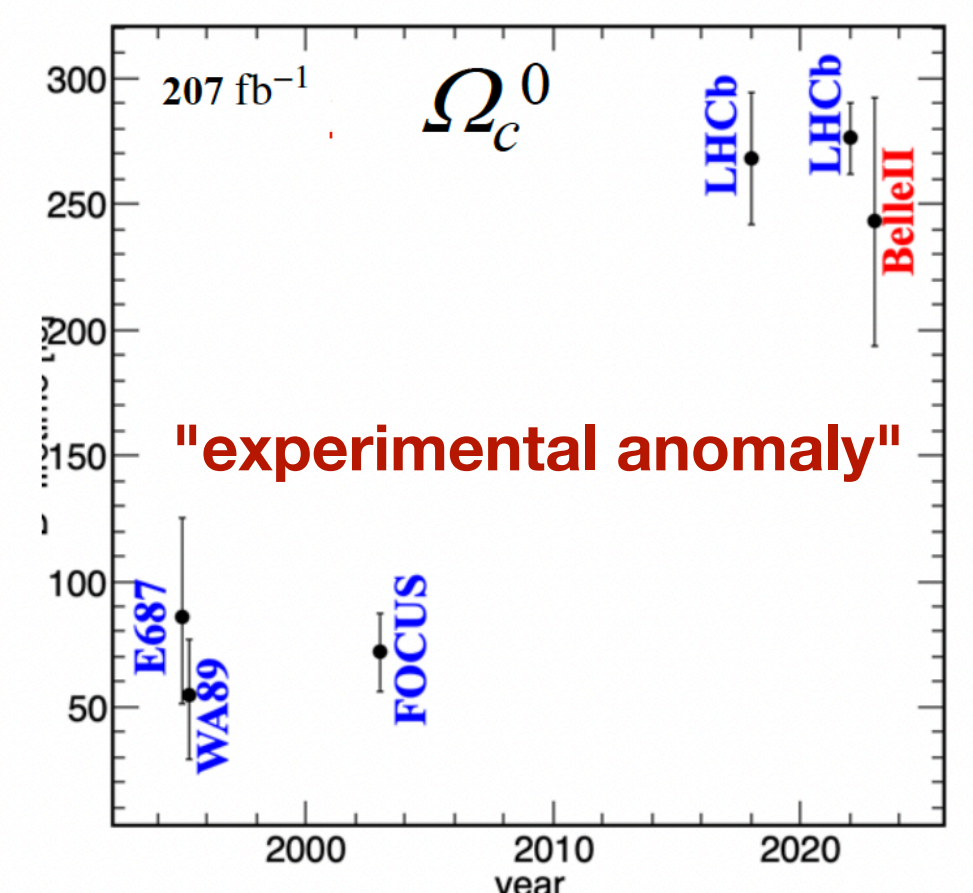
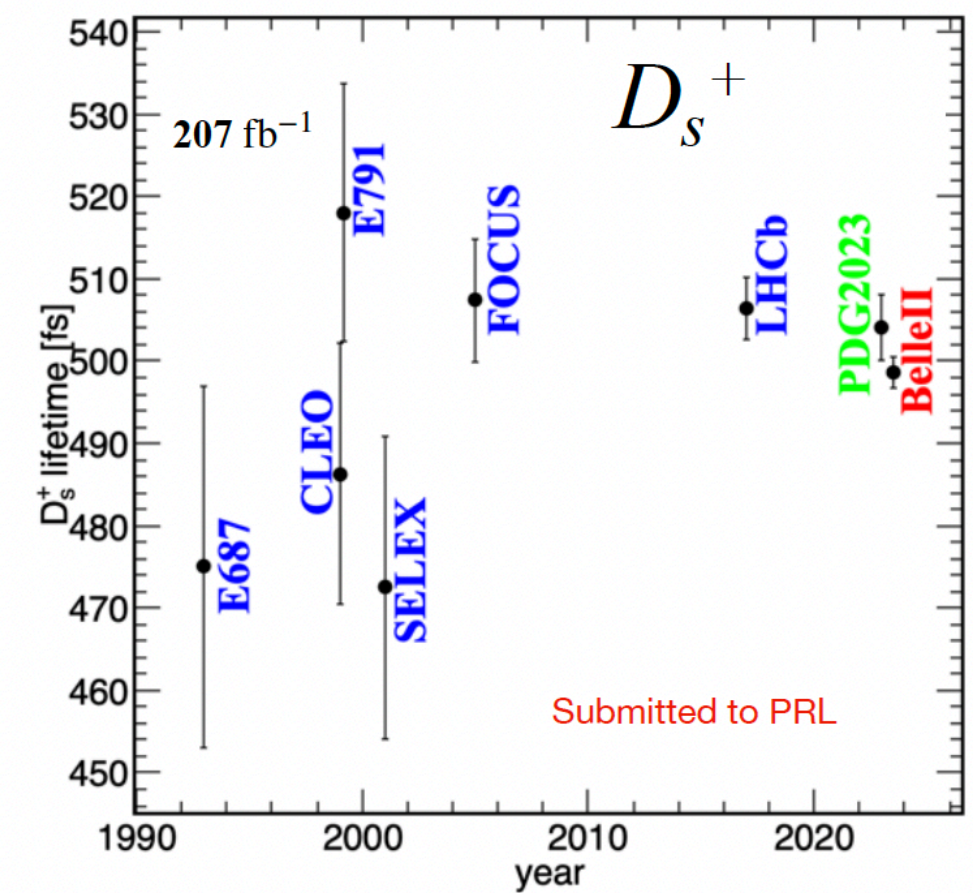
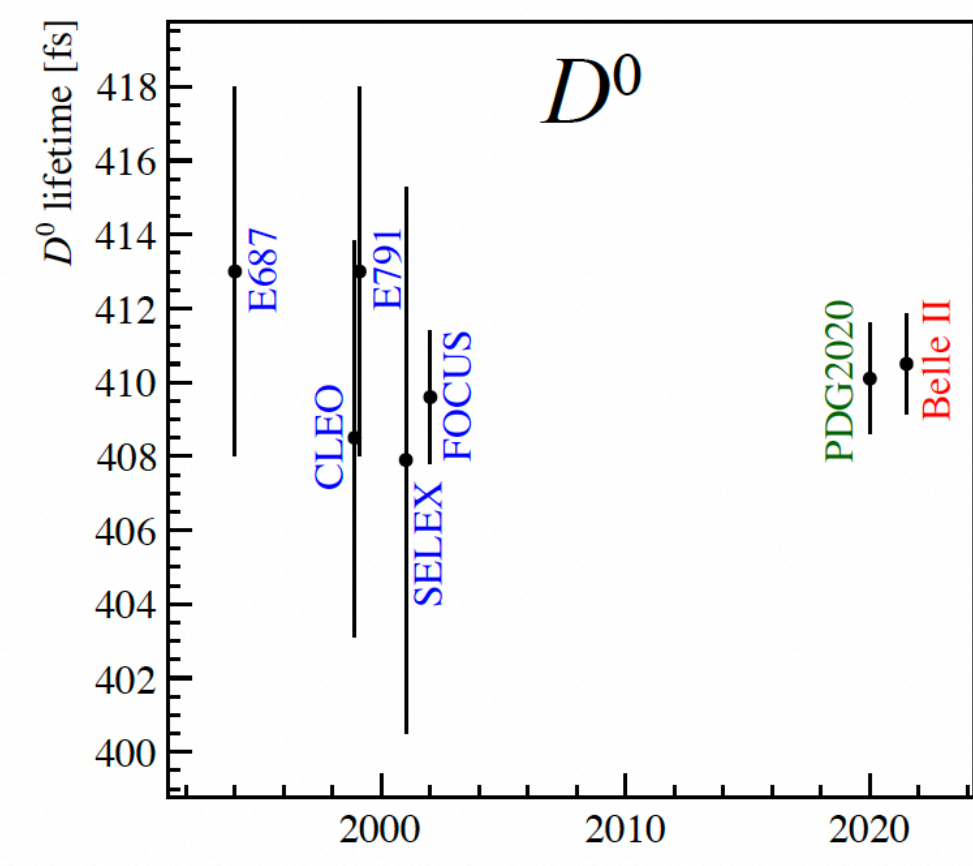
era of precision testing of the CKM unitarity



- Belle II uniquely positioned to probe CPV in final states with neutrals
 - Fully-charged and charged+1-neutral final states dominated by LHCb
- $D^0 \rightarrow \pi^0 \pi^0$ and $D^+ \rightarrow \pi^+ \pi^0$ are well motivated
 - Projected sensitivity down to 0.07% (50 ab^{-1}) for $D^0 \rightarrow \pi^0 \pi^0$ 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 $D^0 \rightarrow \pi^+ \pi^-$, $D^0 \rightarrow \pi^0 \pi^0$ and $D^+ \rightarrow \pi^+ \pi^0$ 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

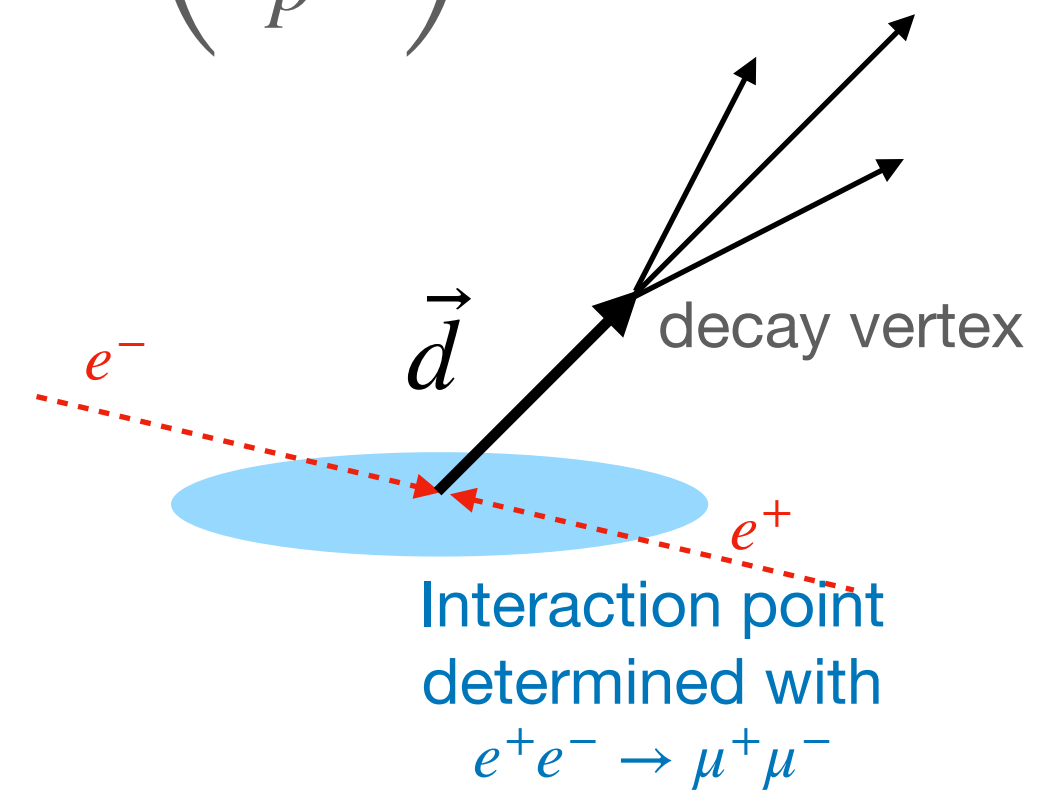
- Precision lifetime measurements!
- Decay-time resolution 2x better than Belle
- Fewer sculpting effects compared to the LHCb trigger



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

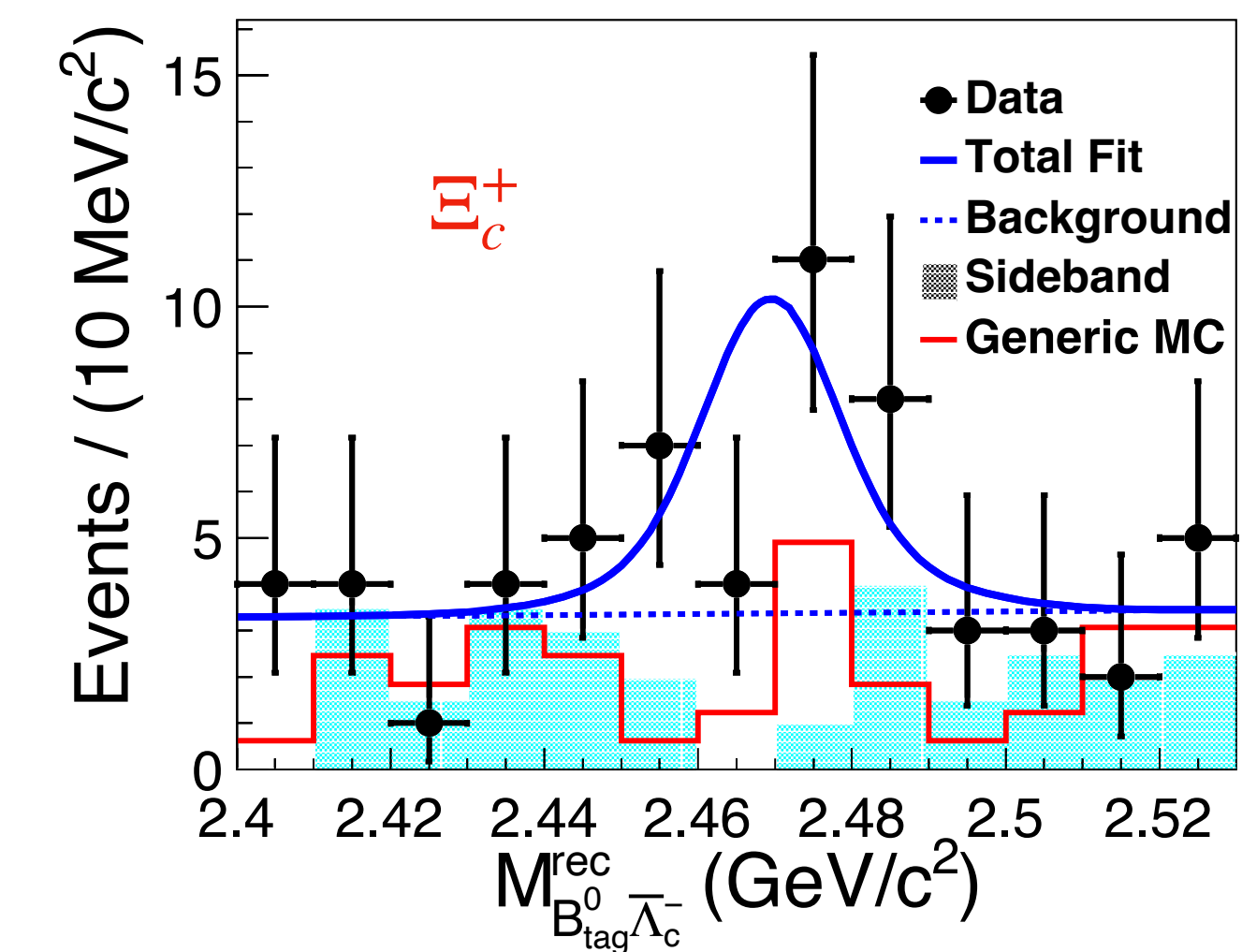
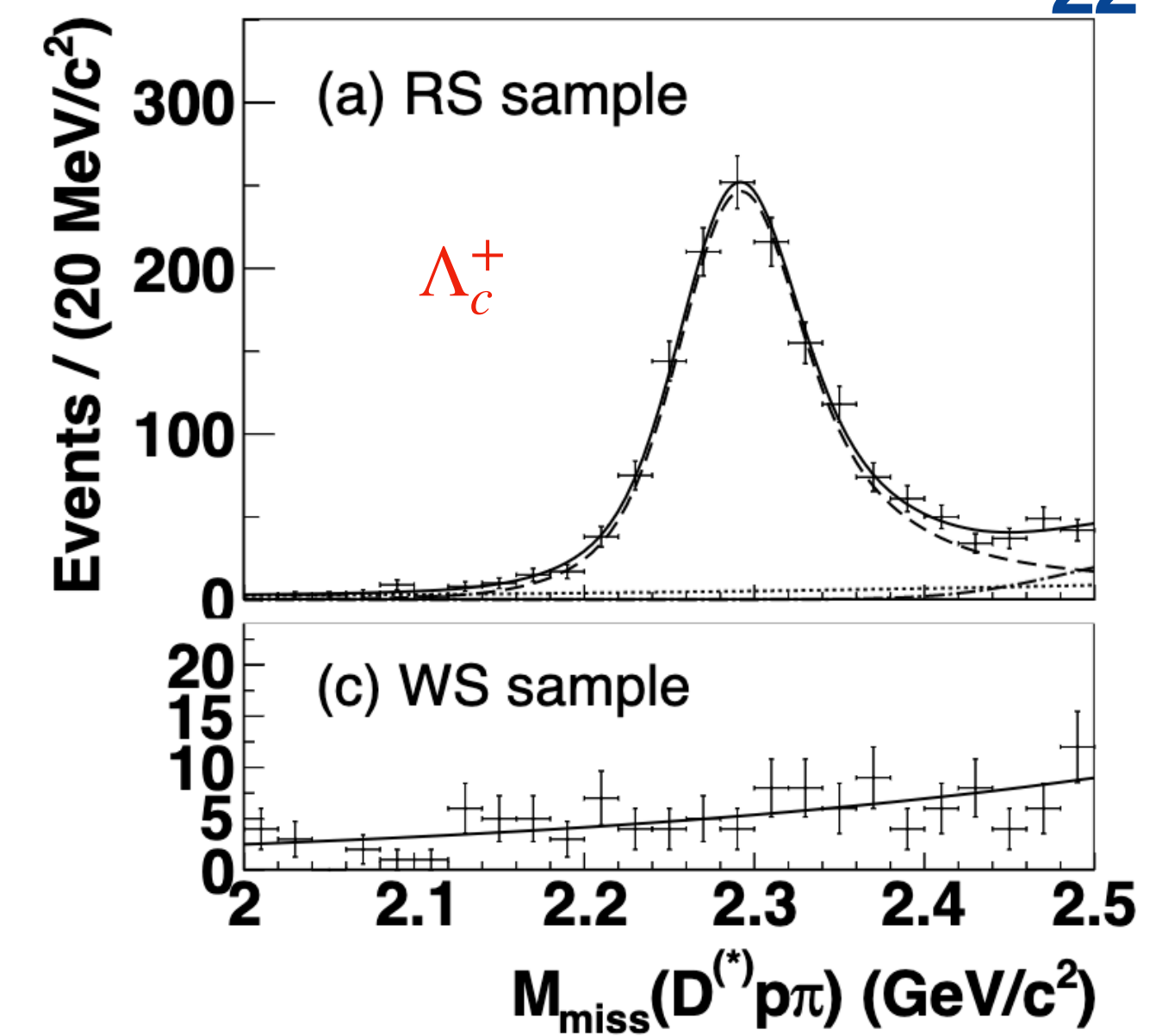
Much more precise than theory

Systematics: detector alignment & resolution, backgrounds



Inclusive charm baryons

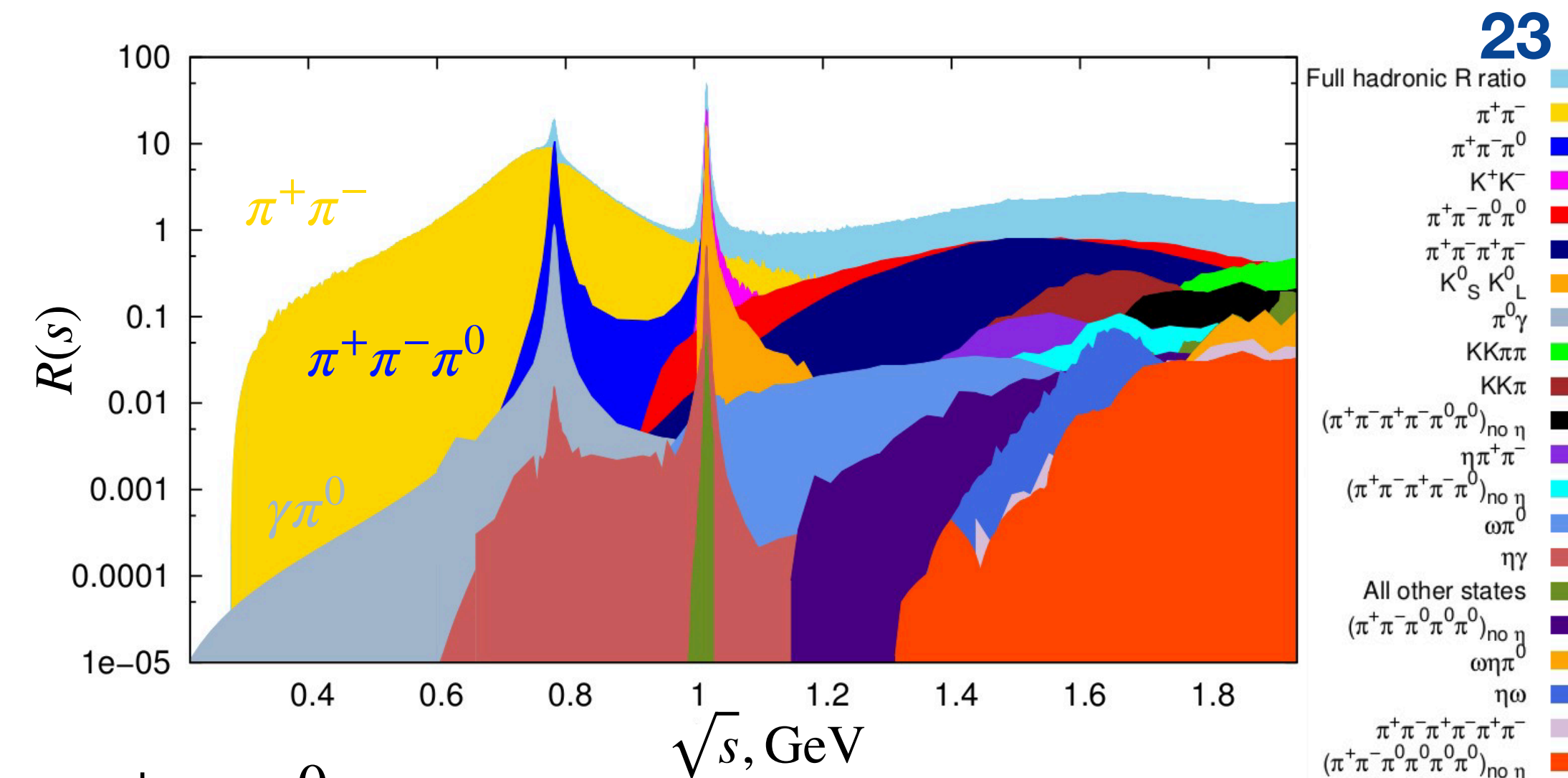
- Two ways to obtain **inclusive** charm baryon datasets:
 - baryon-number, s and c conservation in e^+e^- collisions:
 $e^+e^- \rightarrow D^{(*)-} \bar{p} \pi^+ \Lambda_c^+$
 - notable example: [Phys.Rev.Lett. 113 (2014) 4, 042002]
 - B-meson decays, $\bar{B}^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^-$ 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

- $\sigma(e^+e^- \rightarrow \text{hadrons})$ below 1 GeV dominated by $e^+e^- \rightarrow \pi^+\pi^-$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^0$



- New measurement of $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0)$ using $\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR})$ 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 $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ and others will come next
- **Tau EDM:** use spin correlation in $e^+e^- \rightarrow \tau^+\tau^-$, probe $\gamma\tau\tau$ vertex vs CP reversal
 - Belle result is the world best (precision $\sim 0.6 \times 10^{-17} e\cdot\text{cm}$), 20 orders above SM
 - Belle II can improve further

"Chiral Belle" proposal

<https://arxiv.org/abs/2205.12847>

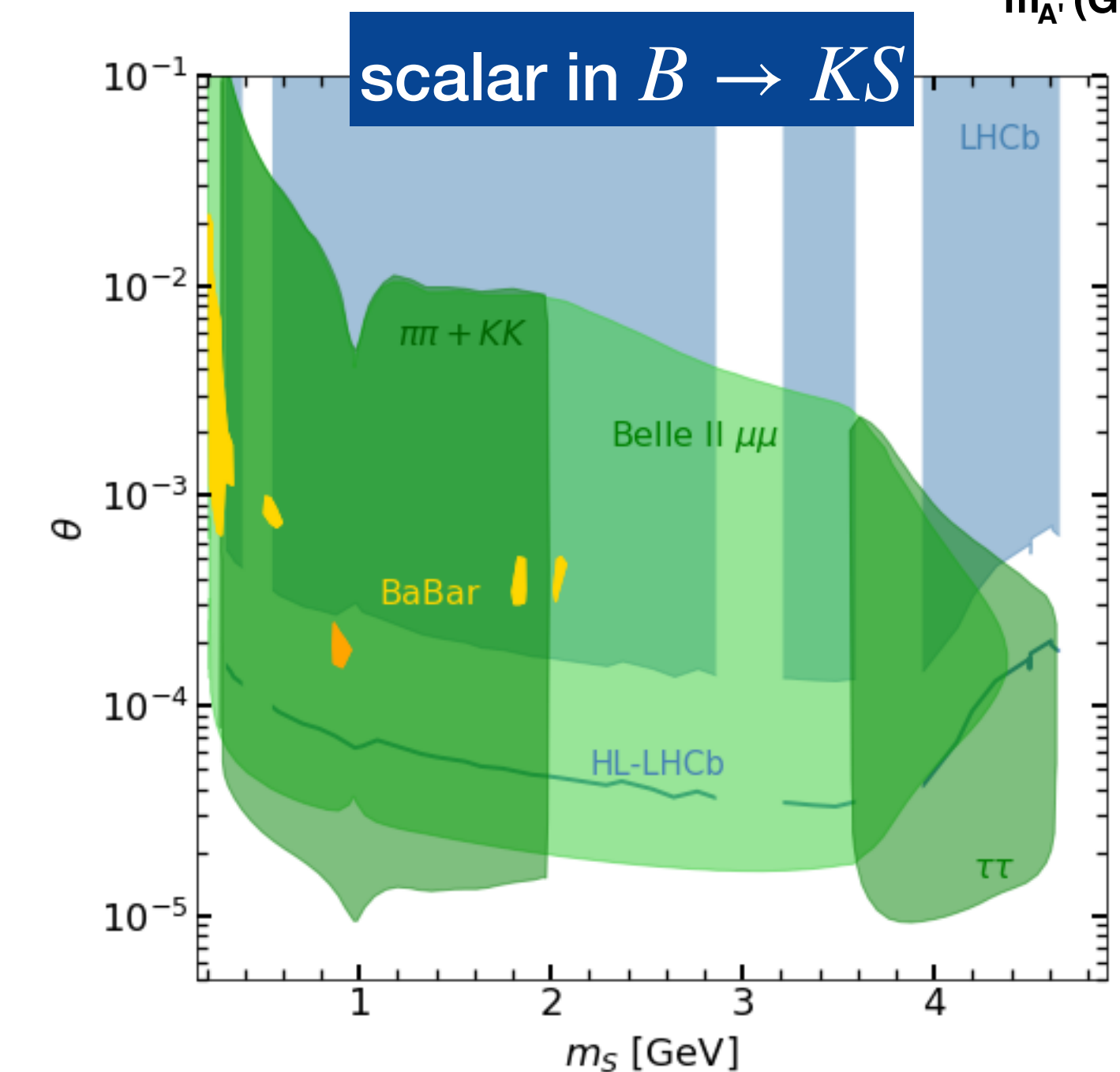
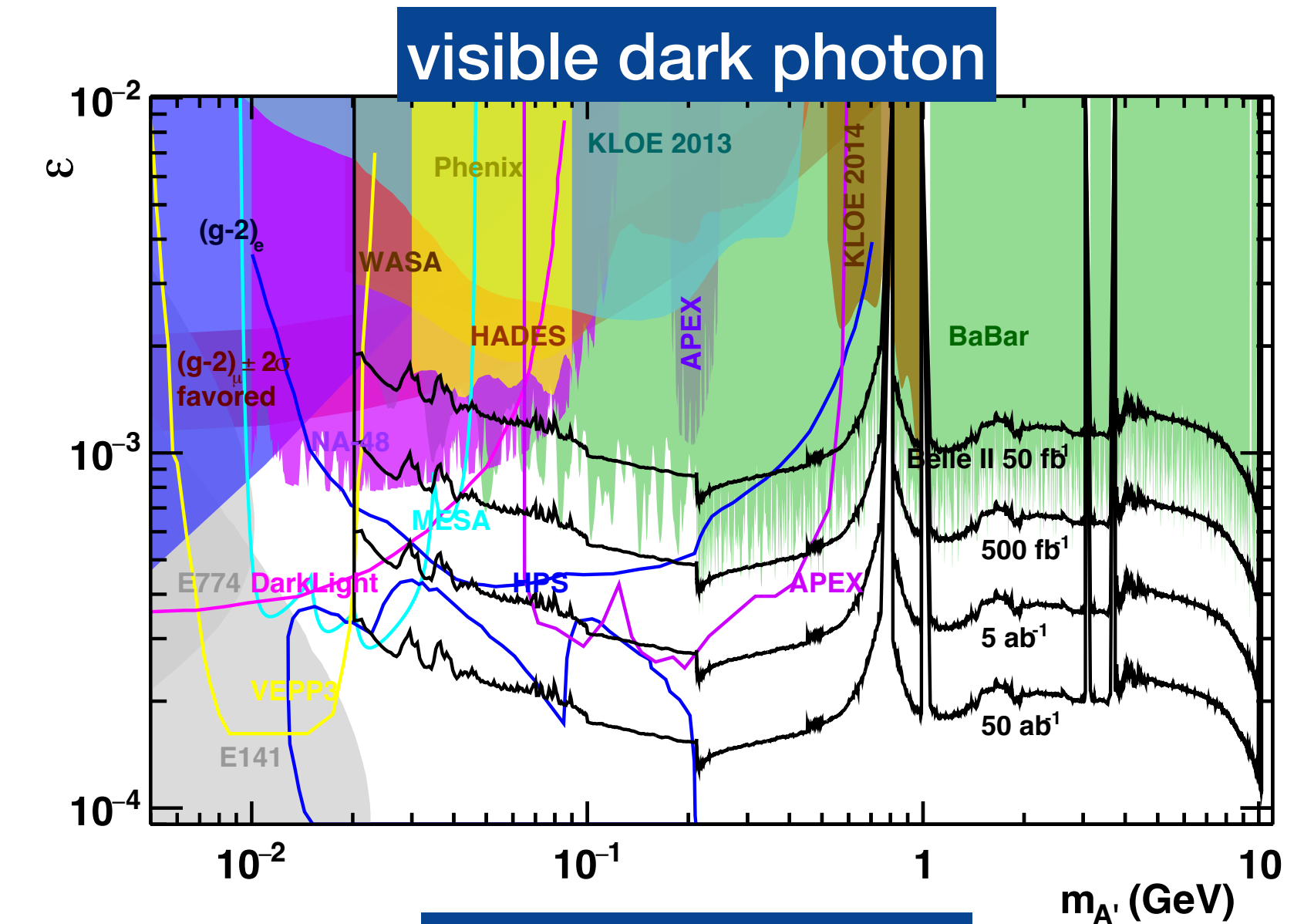
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- What if we get a **polarised** electron beam?
 - ~70% polarisation might be a realistic target, without disruption the core physics programme (~no luminosity loss)
- **Electroweak measurements:** asymmetry in cross-sections with left- vs right-handed 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 $\tau \rightarrow \ell \gamma$ 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 $e^+e^- \rightarrow a\gamma$ and $a \rightarrow \gamma\gamma$, or $e^+e^- \rightarrow ae^+e^-$
 - Dark photons in various signatures: $e^+e^- \rightarrow \gamma X$, $e^+e^- \rightarrow \mu^+\mu^-X$, ... - recent search
 - Z' in parameter space relevant for muon $g-2$
 - Dark matter candidates: long-lived particles, scalars in $B \rightarrow KS$...
 - 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



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

