Belle II — Intensity, the quark way

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The Standard Model success

These and many other questions fuel a strong and wide-spread prejudice that the SM is completed at high-energy by new particles and interactions

Two ways out

A more powerful collider (may not be sufficiently powerful or imminent)

Direct high-energy production of non-SM particles

Get smarter

Quantum probing of virtual non-SM particles that contribute to known lower-energy processes

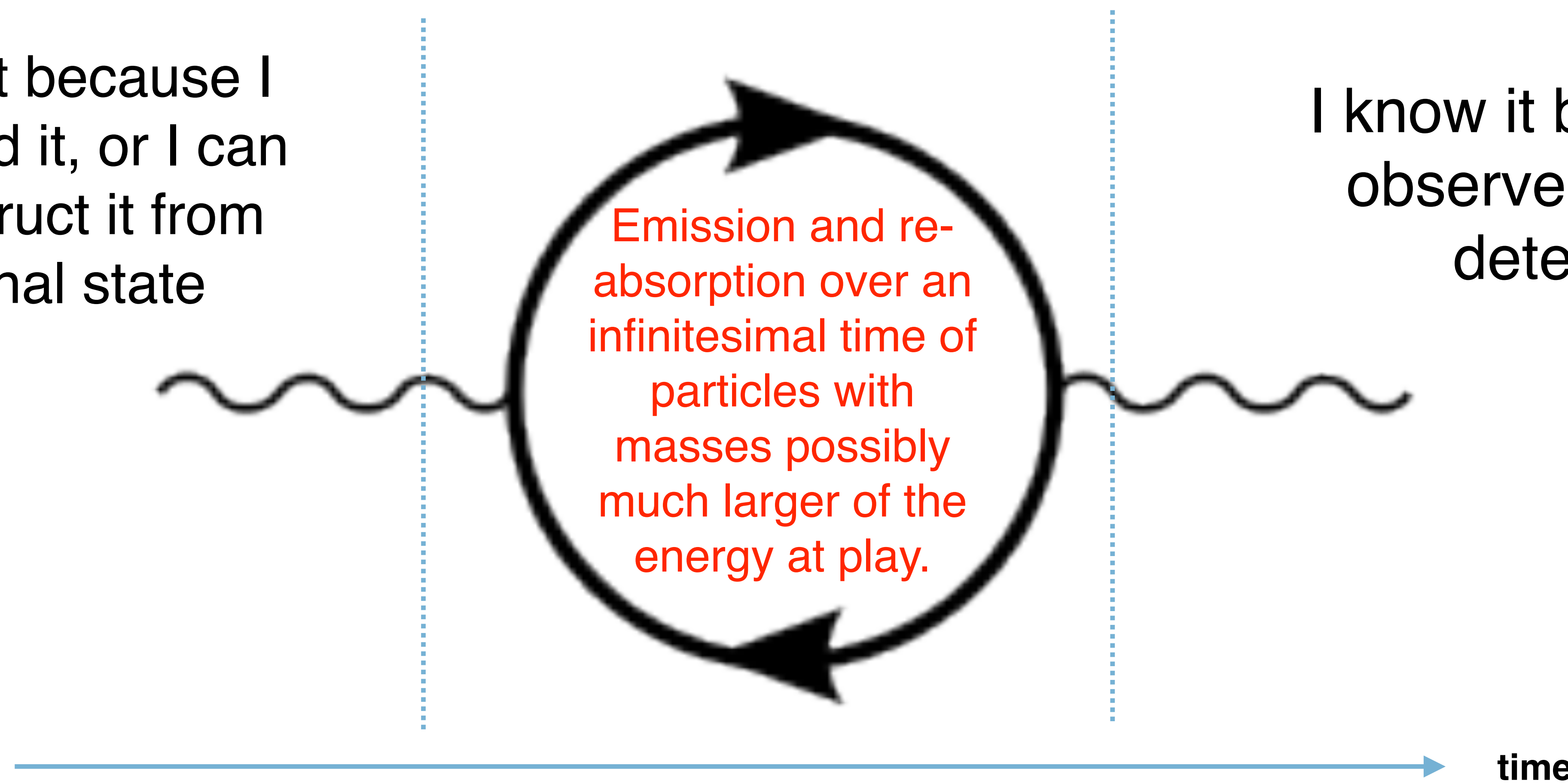
The precision frontier

Initial state

I know it because I produced it, or I can reconstruct it from the final state

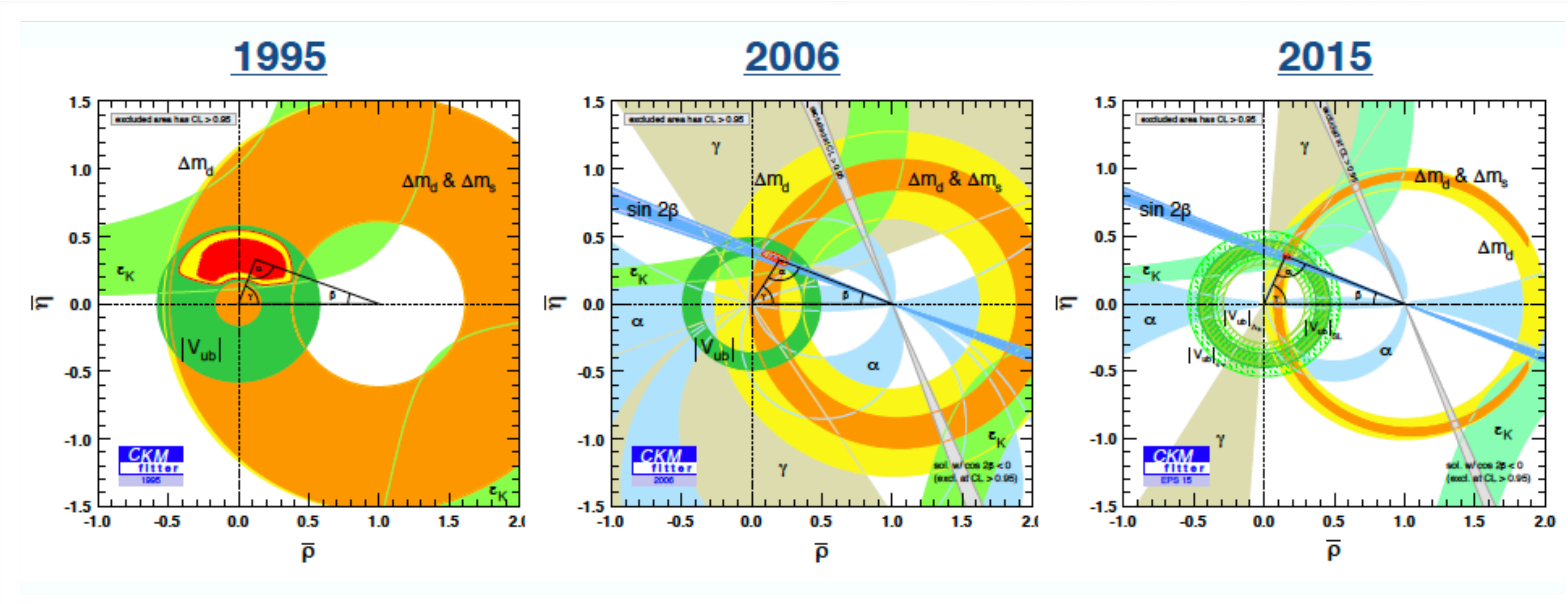
Final state

I know it because I observe it in the detector



O(GeV) **Very high mass** **O(GeV)**

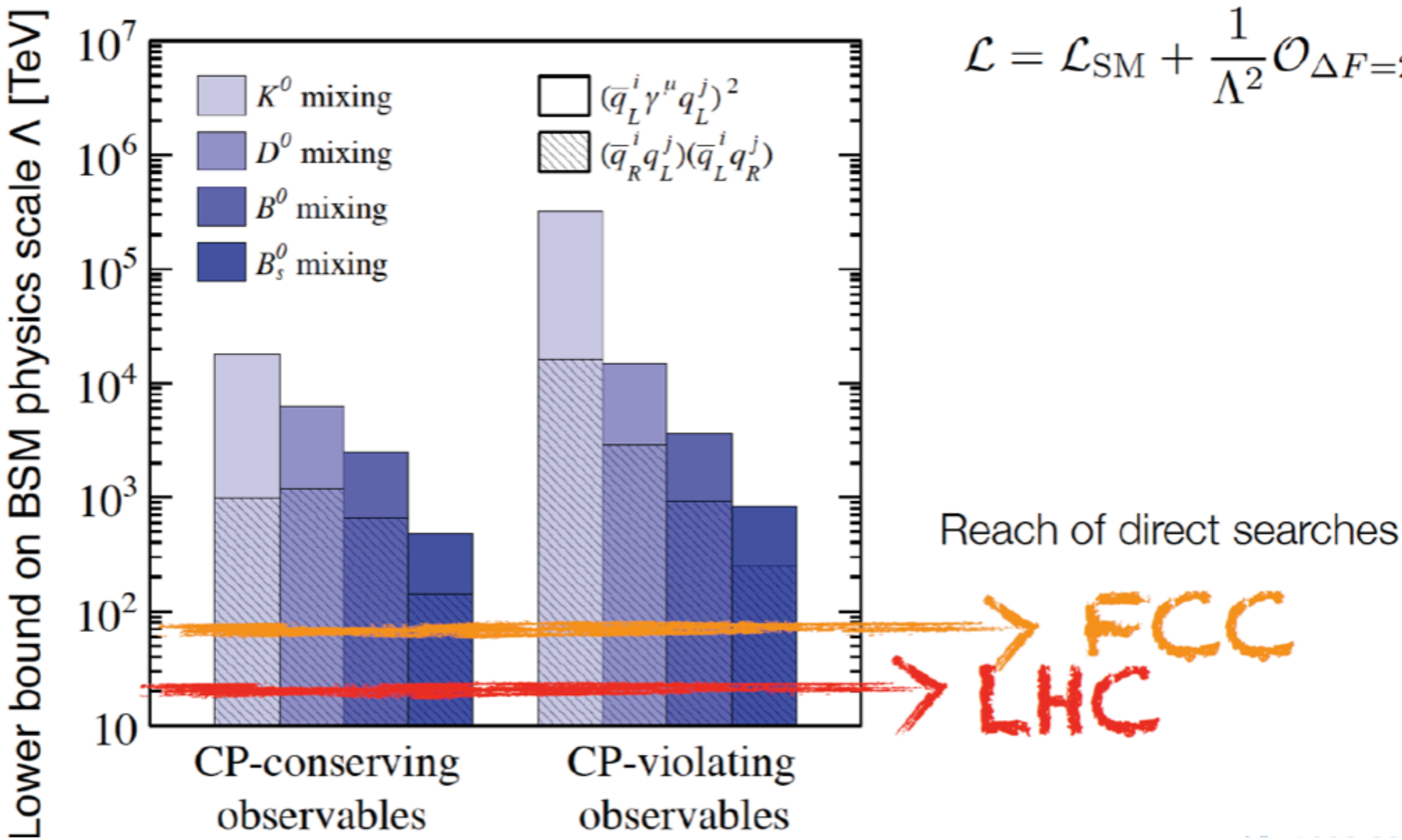
Flavor come a long way



CKM mechanism predicts all observations to within 10-15% uncertainties.

Explore suppressed processes, approach precision of favored ones.

But gotta finish the job



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{O}_{\Delta F=2}$$

Explore suppressed processes, approach precision of favored ones.

Who we are

SuperKEKB

Goal: 30x luminosity wrt KEKB thanks to nanobeams: squeeze beta fcn in the luminous region and minimize longitudinal beam overlap.

Modest (1.5x-2x) increase in currents. Large (20x) increase in beam cross section. Increase x-ing angle to 83 mrad

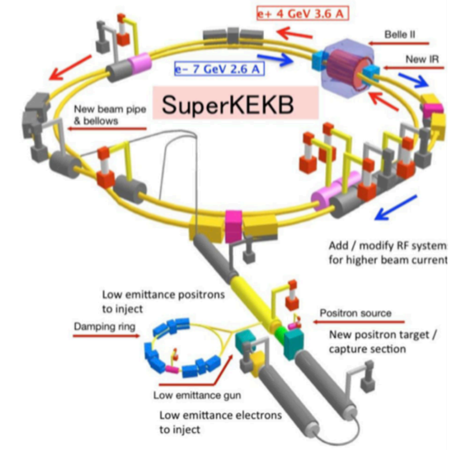
Achieving 50 nm vertical size requires low emittance and powerful and sophisticate final focus

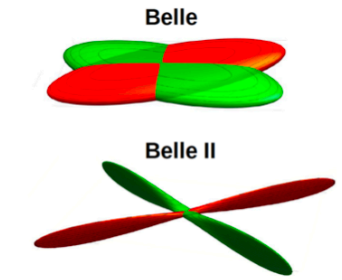
So far 10x below design, improving steadily

4.7×10^{34} cm^{-2} Hz record
(w/ currents 2-3x lower than at PEPII)

90% data taking efficiency 1–2 fb^{-1}/day, 8–12 fb^{-1}/week, 20–40 fb^{-1}/month.

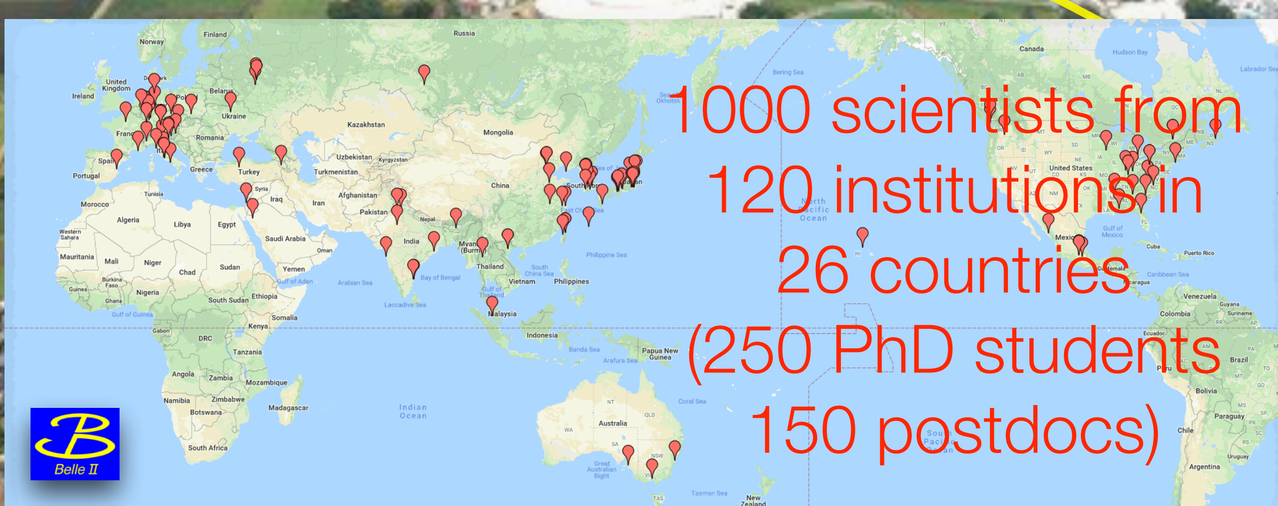
430 fb^{-1} collected (>50% of Belle, ~Babar).
Half of Babar's sample in just one year.





8

1 km



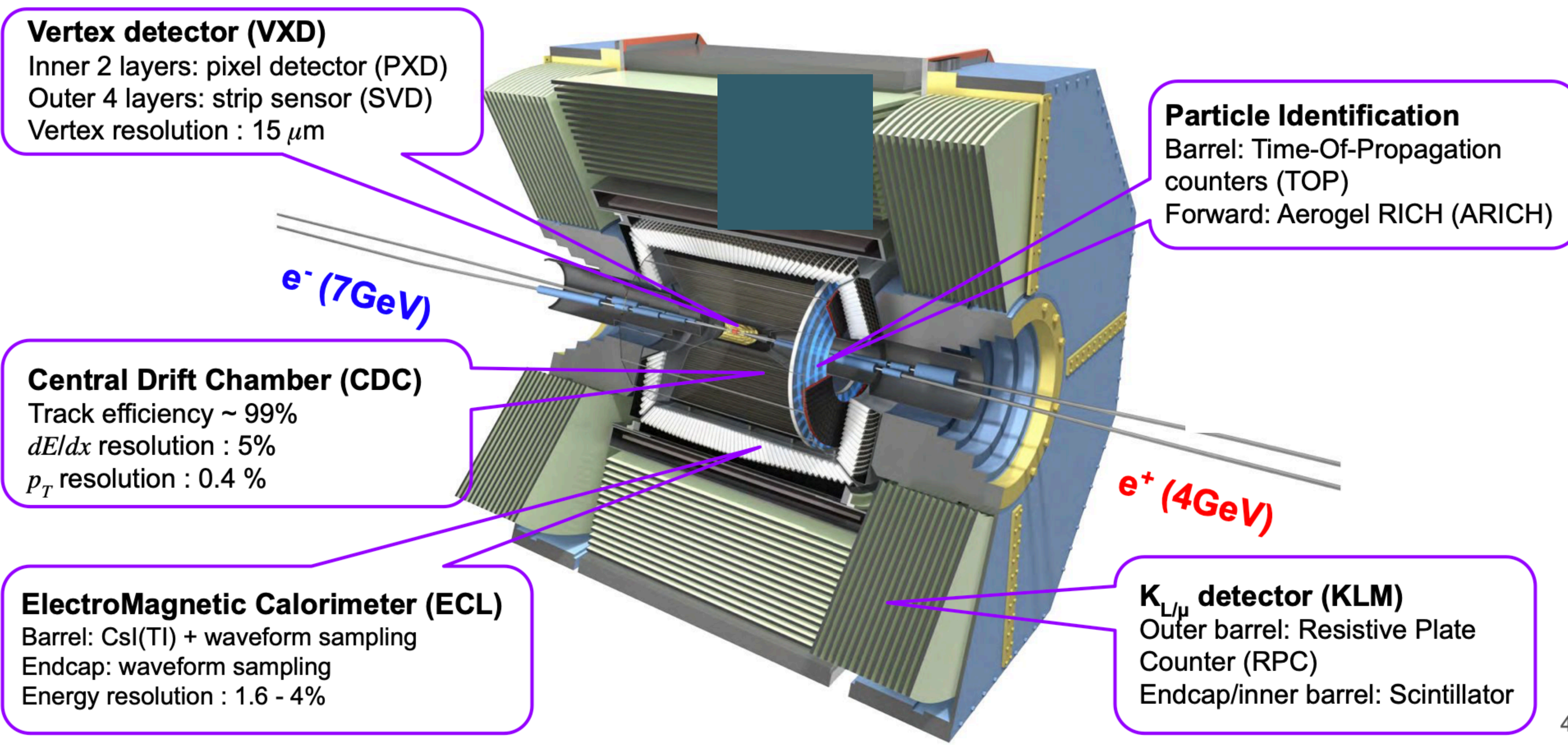
1000 scientists from 120 institutions in 26 countries (250 PhD students 150 postdocs)

7 GeV electrons on 4 GeV positrons at the Y(4S) mass. About 30 (now) to 600 (design) $B\bar{B}$, $D\bar{D}$, $\tau^+\tau^-$ *per second* —- with 3x background from light quarks

The instrument

It looks like the “old” Belle, but it is effectively a brand new detector

Only structure, magnet and calorimeter crystals are re-used

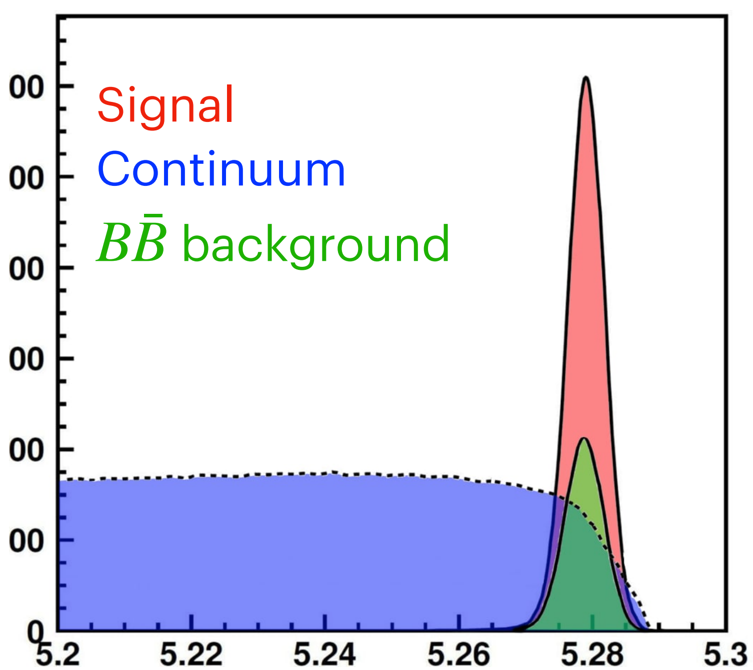


B factory analysis 101

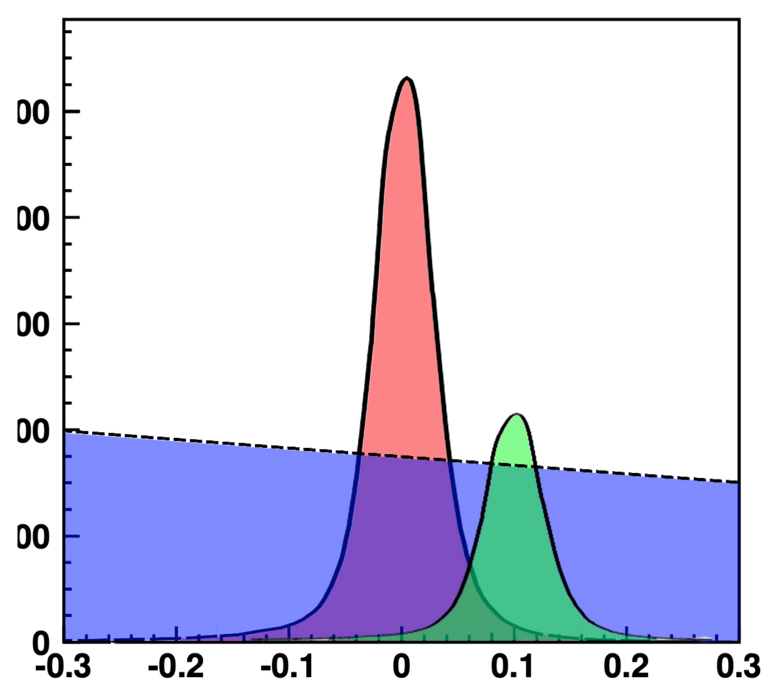
Point-like particles colliding at *BBbar* threshold:

Low background and knowledge of initial state: stringent kinematic constraints.

Extract signal using kinematics

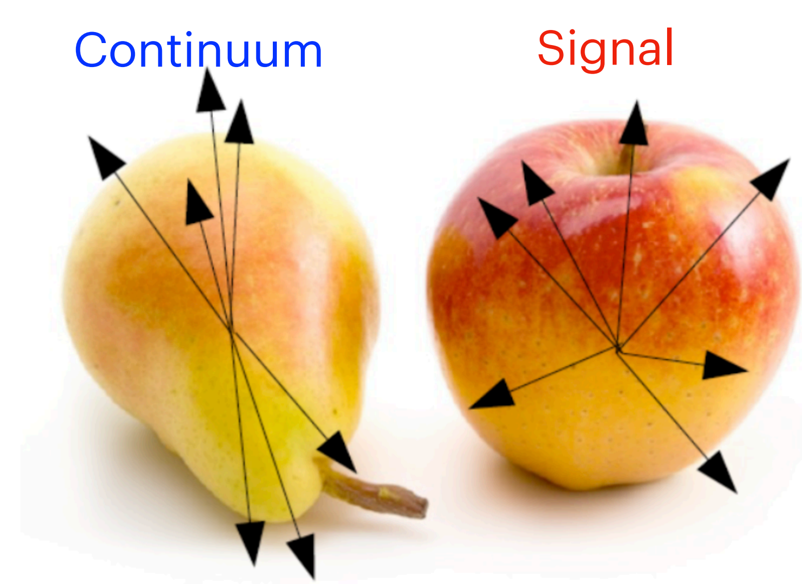


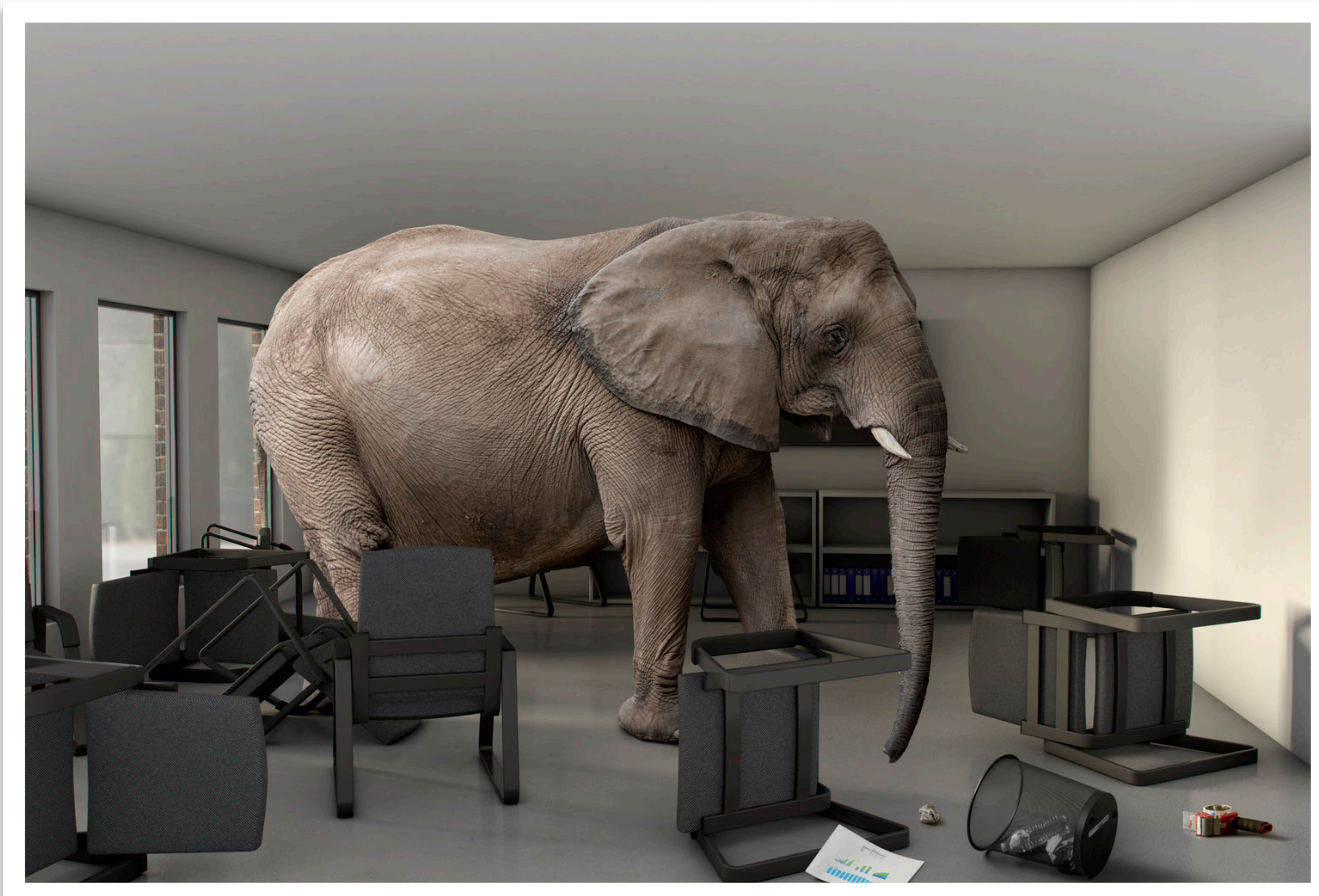
Invariant B mass with B energy replaced by half of the collision energy.



Difference between expected and observed B energy

..and event shape





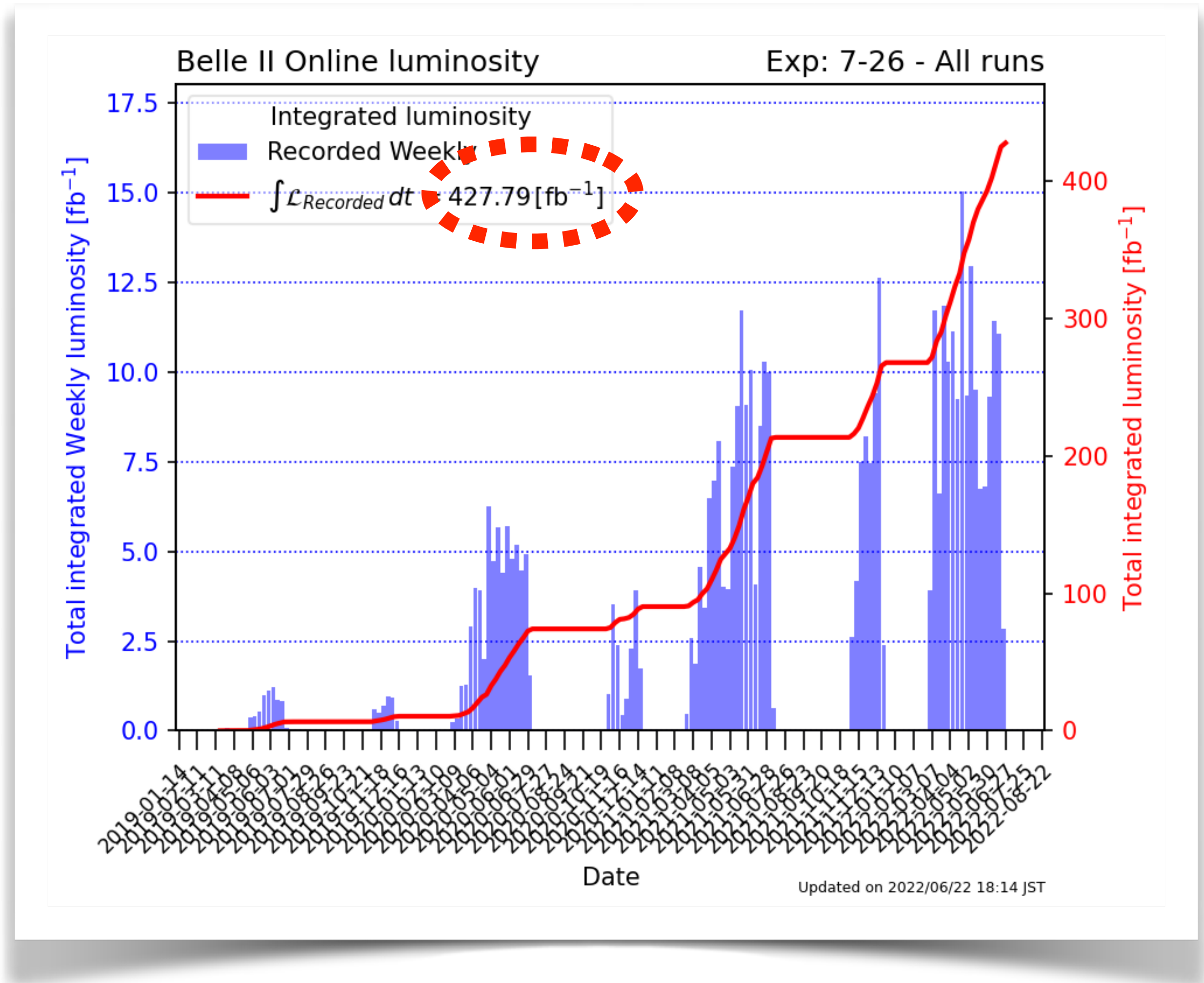
428 fb^{-1} after 4 years

Shortcomings in injection, collimation, beam stability, control of beam-backgrounds etc

SuperKEKB integrated luminosity ~10x off with respect to plans (Tip: SuperKEKB is exploring uncharted territory)

Issues getting addressed as we speak

Still, we only got a sample equivalent to Babar's and to 50% of Belle's so far

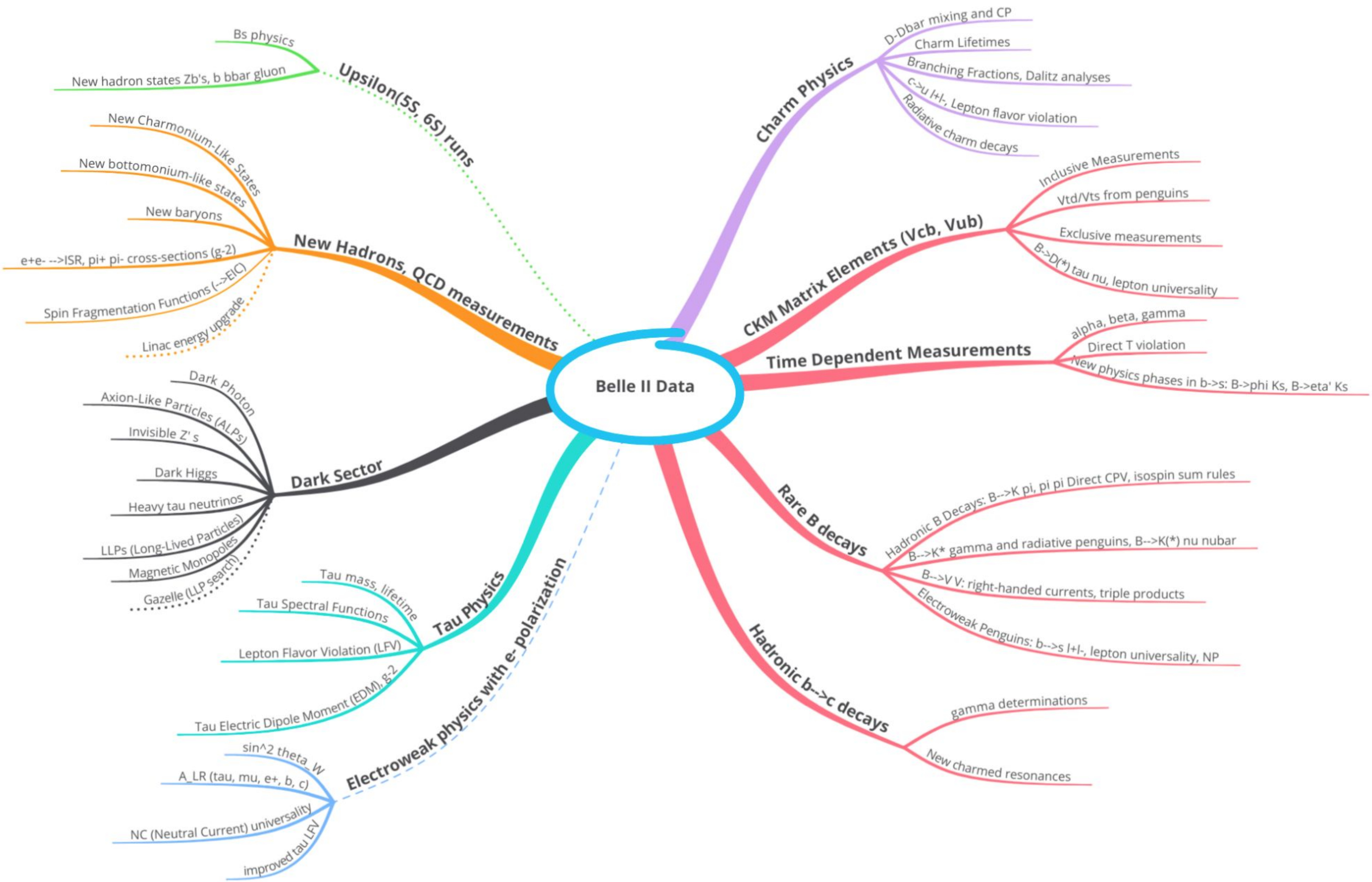


We have a newer and better detector than our predecessors

We have a larger and stronger collaboration than our predecessors

We benefit from 20+ years of progress in analysis and tools.

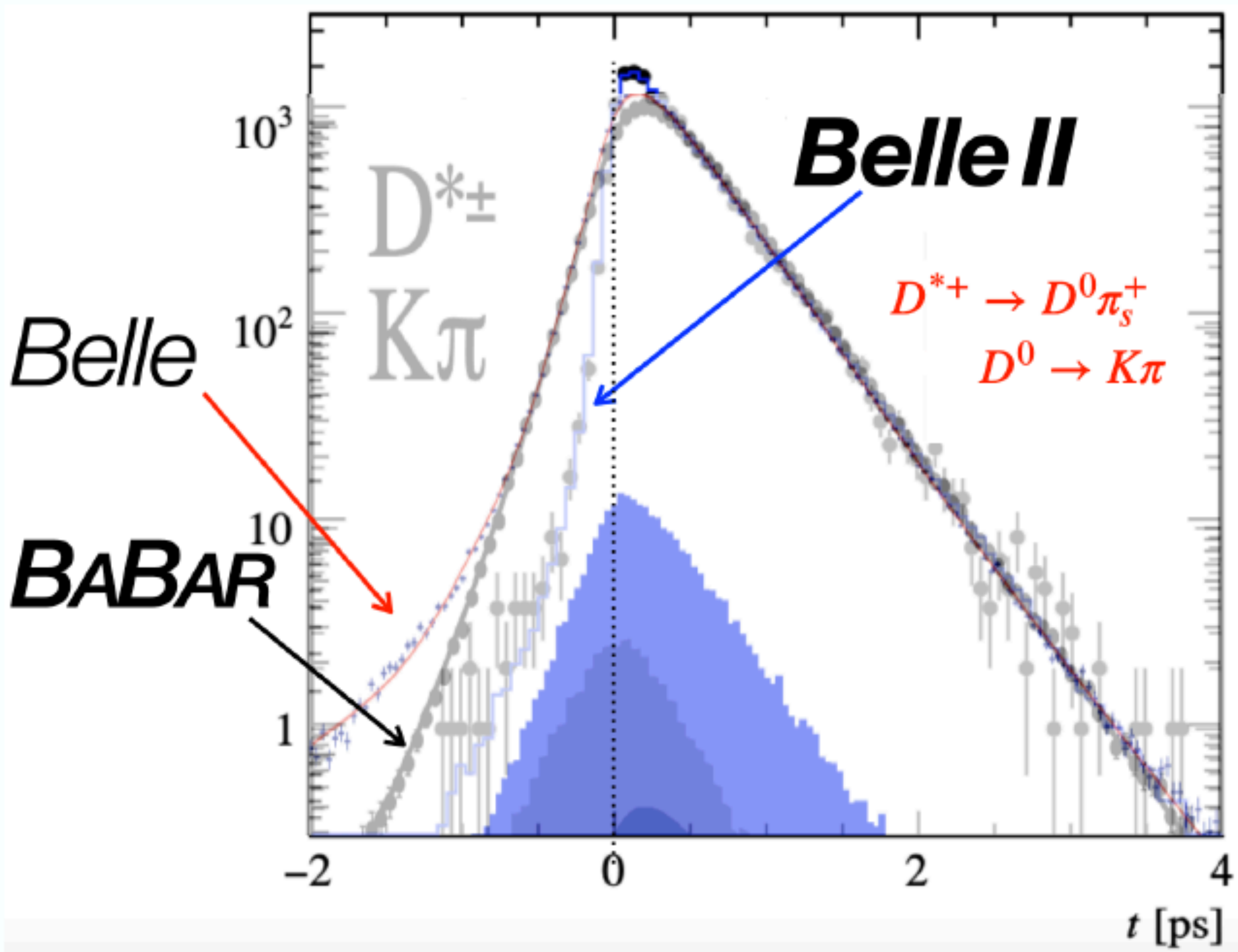
What we did so far



Ramping: in the past year, 40 new results that quadruple paper count

Today: sampler aimed at underlying relevant "common themes"

Pushing the detector envelope — vertexing



Greatly improved time resolution compared to previous B-factories.

Pushing the detector envelope — vertexing

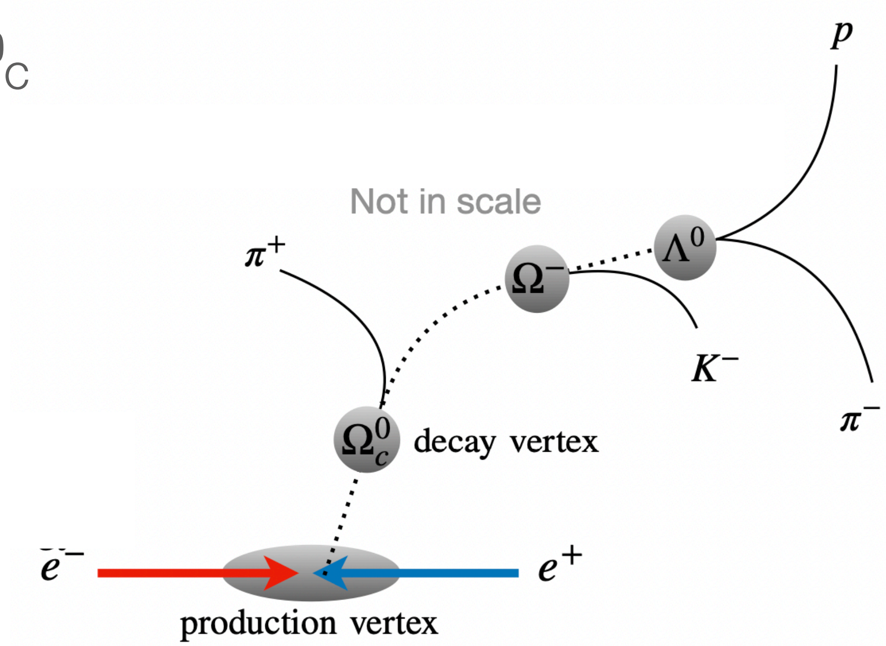
Systematic charmed lifetime program

$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs most precise Phys. Rev. Lett 127 (2021) 21801

$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs most precise Phys. Rev. Lett 127 (2021) 21801

$\tau(\Lambda_c^+) = 203.2 \pm 0.9 \pm 0.$ most precise Phys.Rev.Lett. 130 (2023) 071802

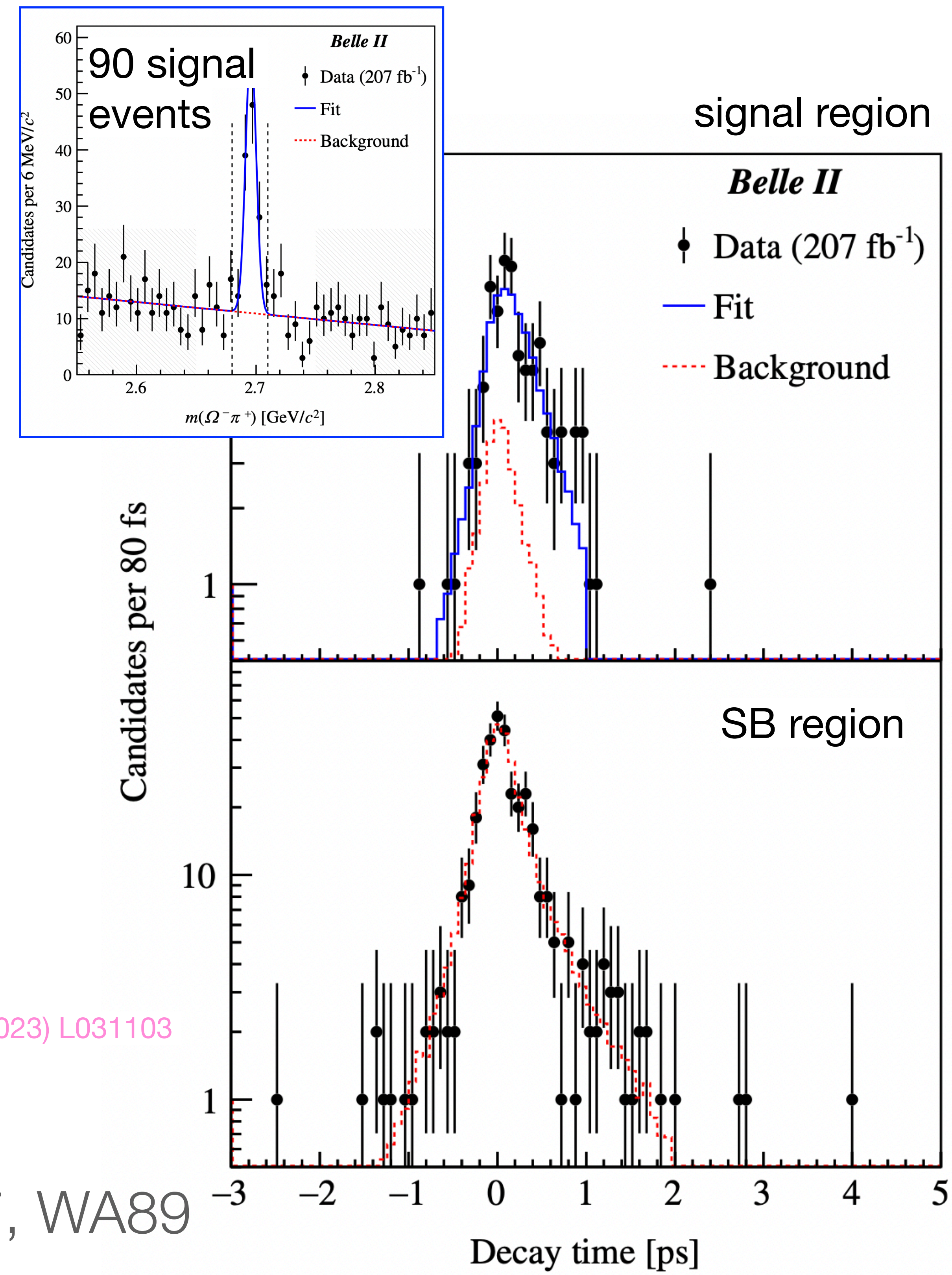
Latest entry: Ω^0_c



$$\tau(\Omega^0_c) = 243 \pm 48 \pm 11 \text{ fs}$$ Phys. Rev. D 107 (2023) L031103

Not the shortest-lived singly charmed baryon.

Consistent with LHCb. Not with FOCUS, E687, WA89



Pushing the envelope — *p* scale and collision energy

SuperKEKB is a τ factory too: sizable cross section and constrained kinematics

$\tau^- \to \pi^+\pi^-\pi^-\nu$ (signal) and

$\tau^+ \to$ 1 charged particle + (π^0) (other “side”)

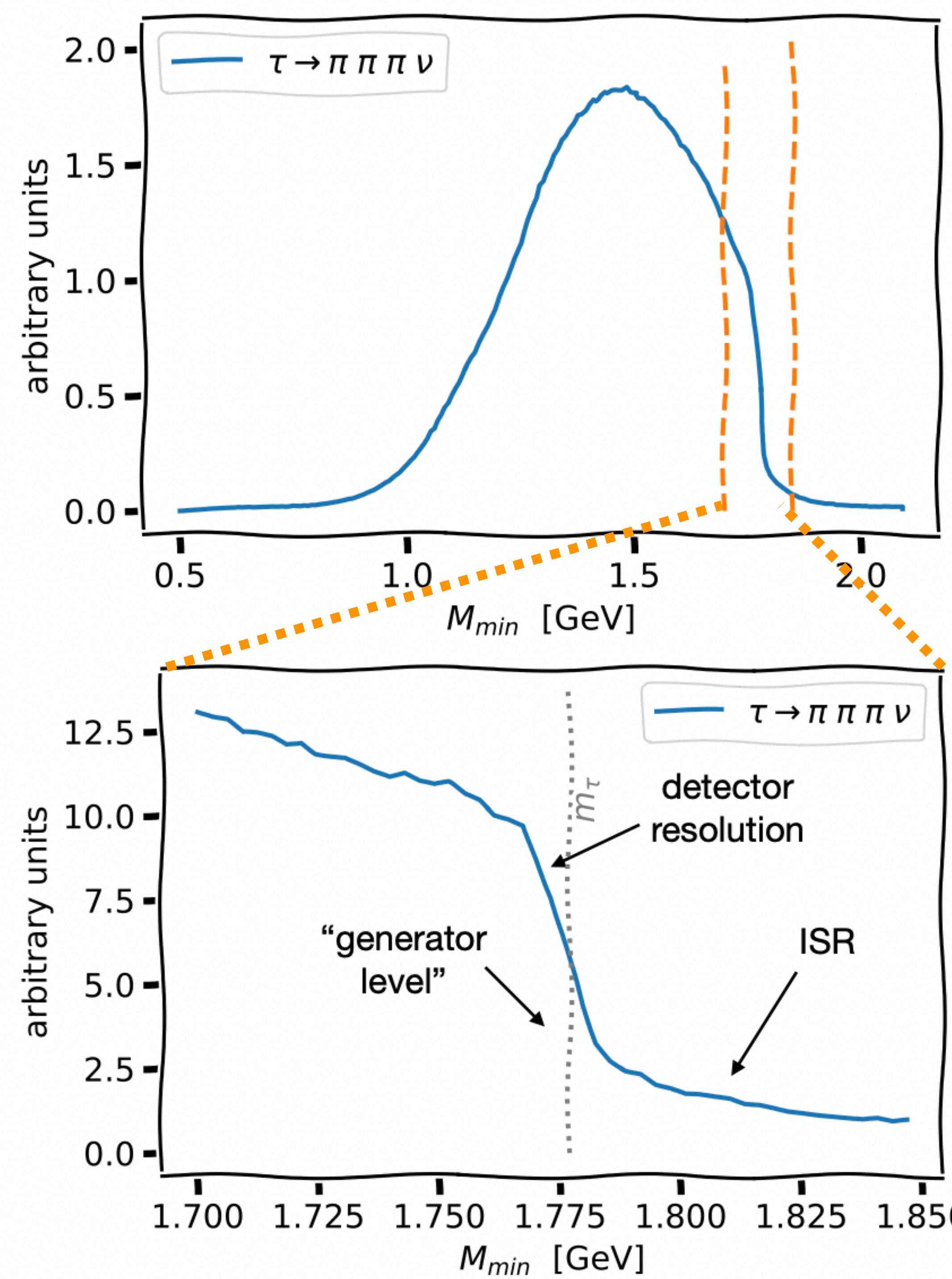
4 tracks. No additional high-energy photons

Empirical fit to reconstructed τ mass

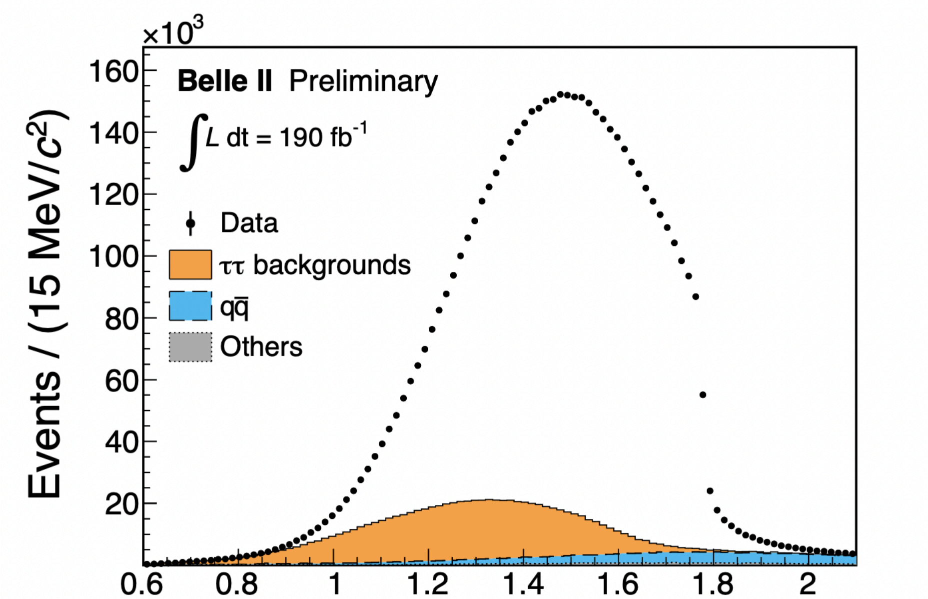
Assume τ-energy being 1/2 of collision energy and neutrino collinear with 3π syst.

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq m_\tau$$

Benchmark for precise knowledge of meomentum scale and collision energy

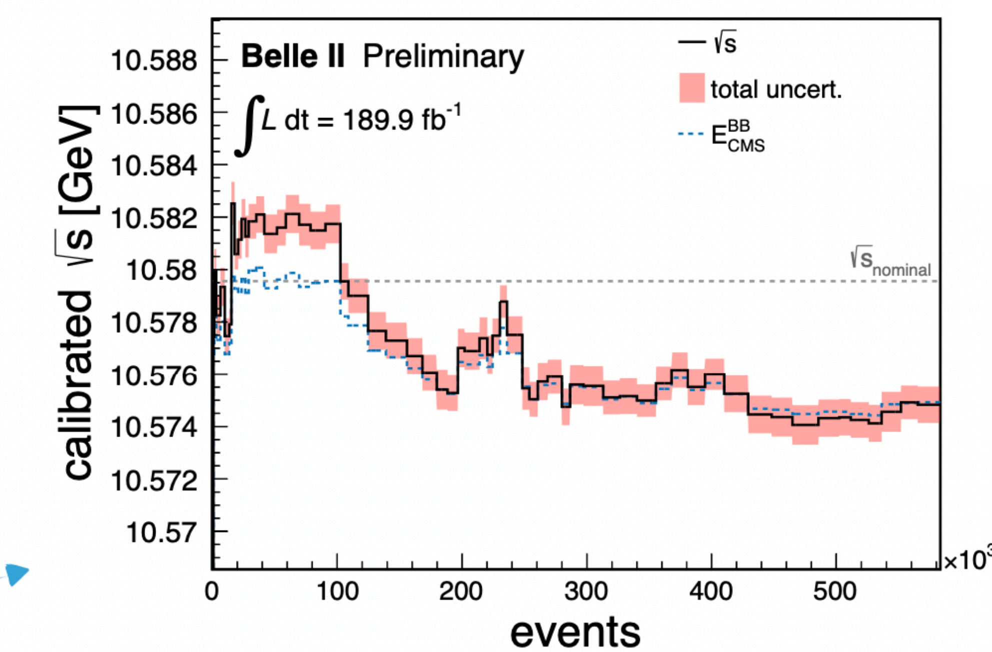


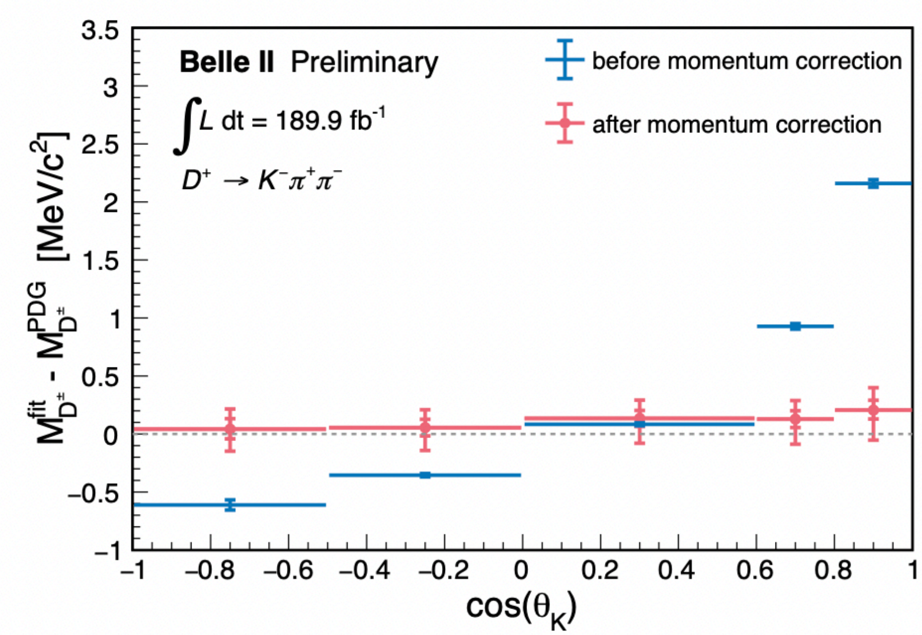
Systematics! Systematics! Systematics!



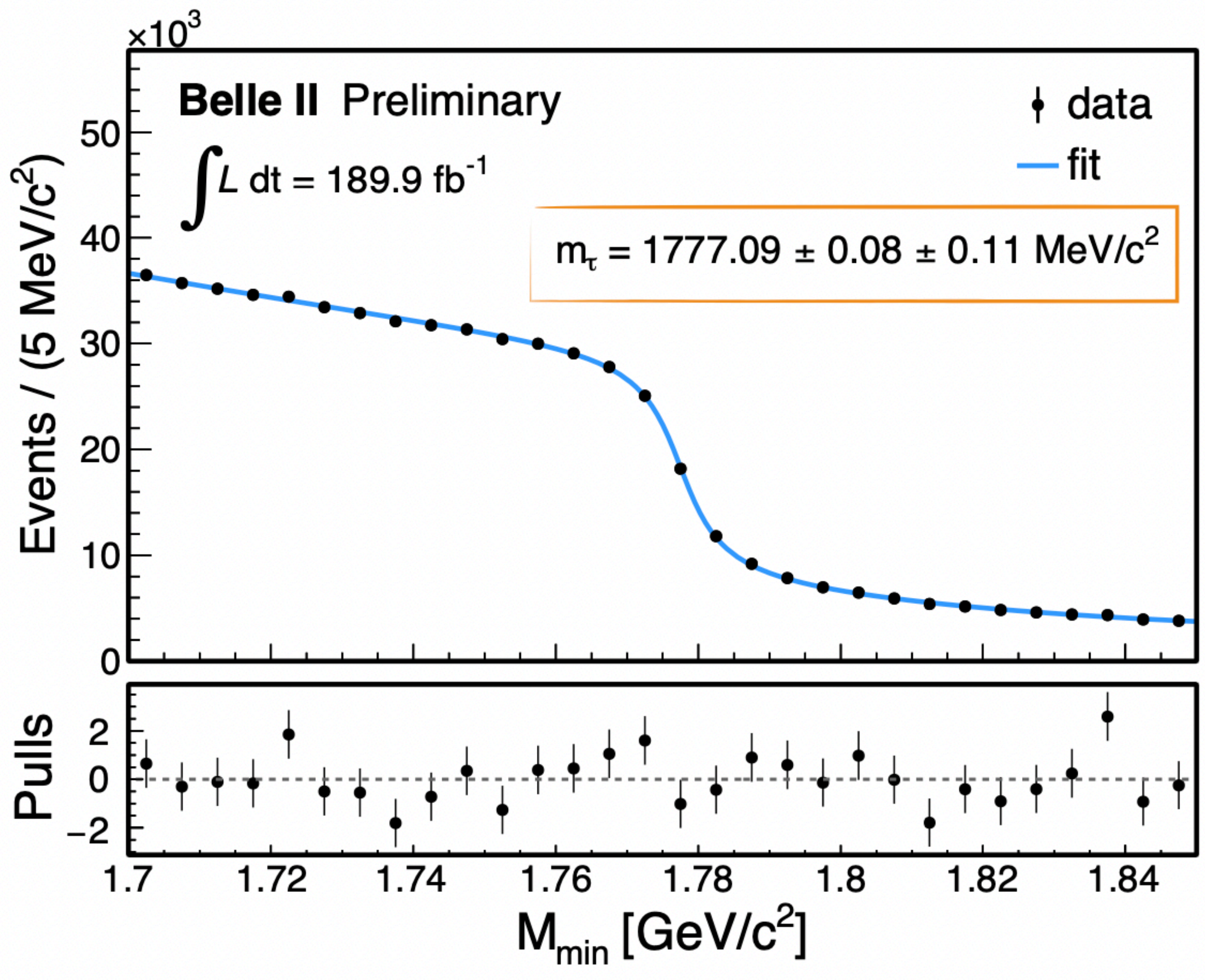
- $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq m_\tau$

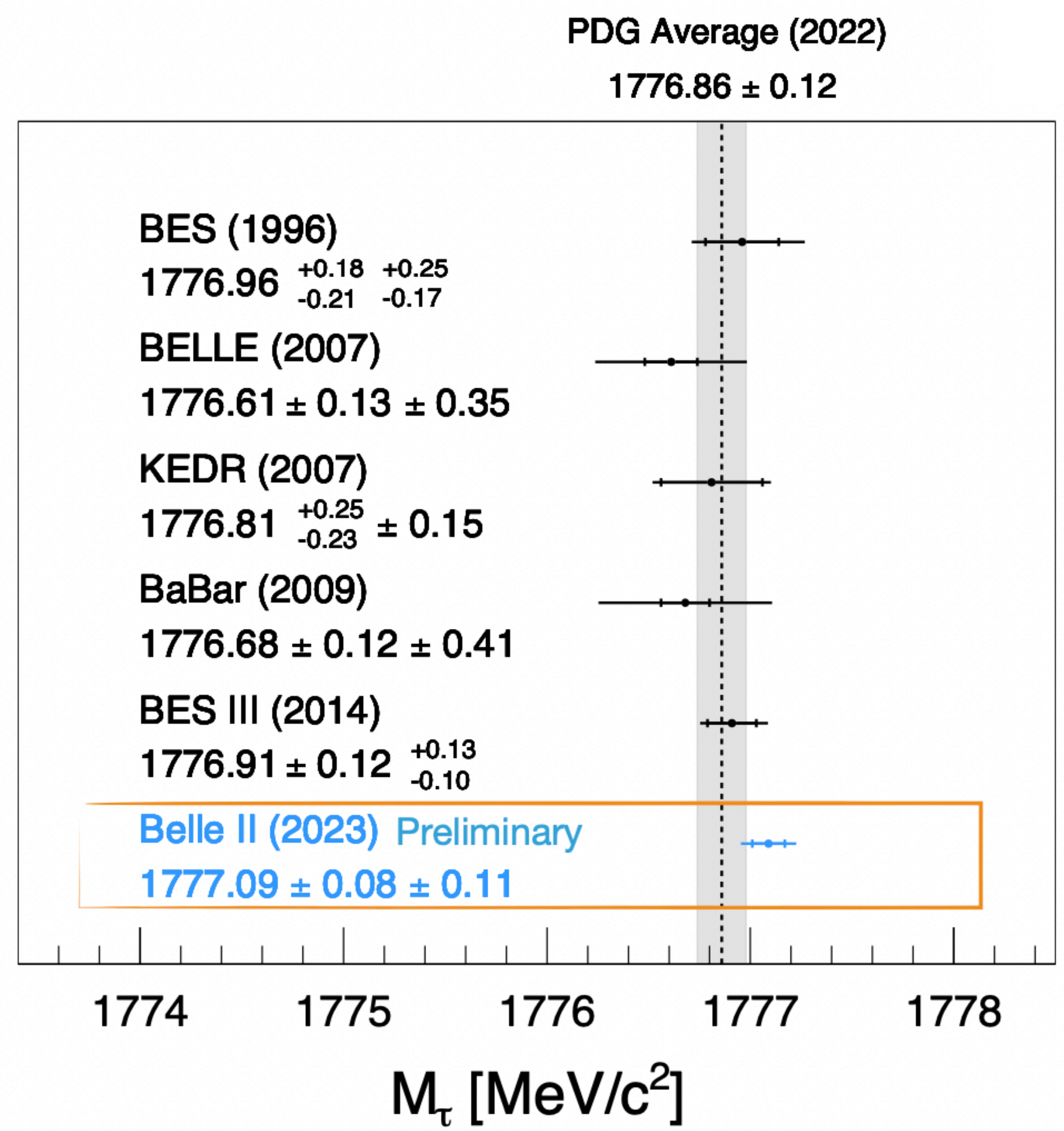
Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	$\leq$ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	$\leq$ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	$\leq$ 0.01
Neutral particle reconstruction efficiency	$\leq$ 0.01
Tracking efficiency correction	$\leq$ 0.01
Trigger efficiency	$\leq$ 0.01
Background processes	$\leq$ 0.01
Total	0.11





Tau-lepton mass result





Most precise to date

https://indico.in2p3.fr/event/29681/contributions/122507/attachments/76503/111032/04-SDreyer-v2.pdf

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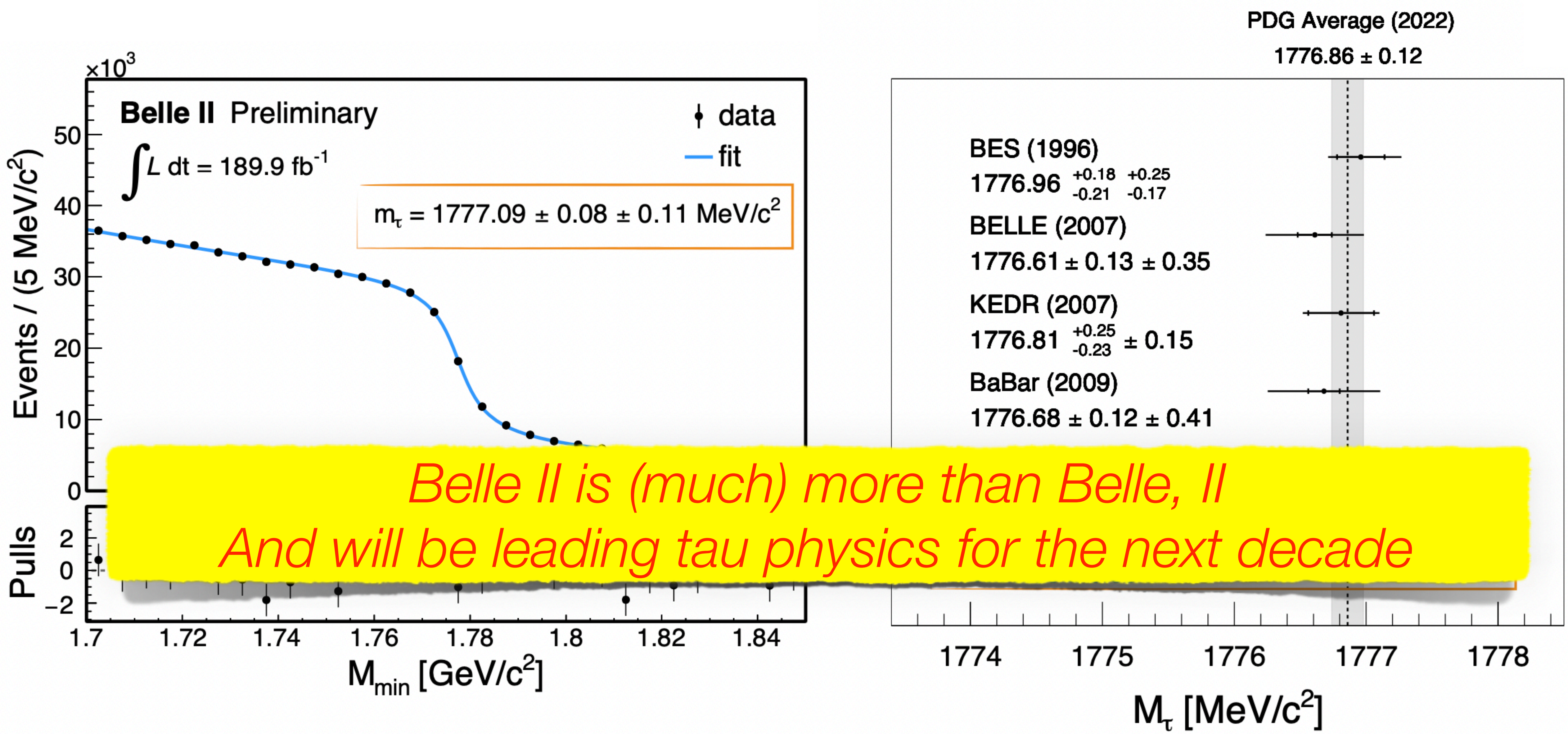


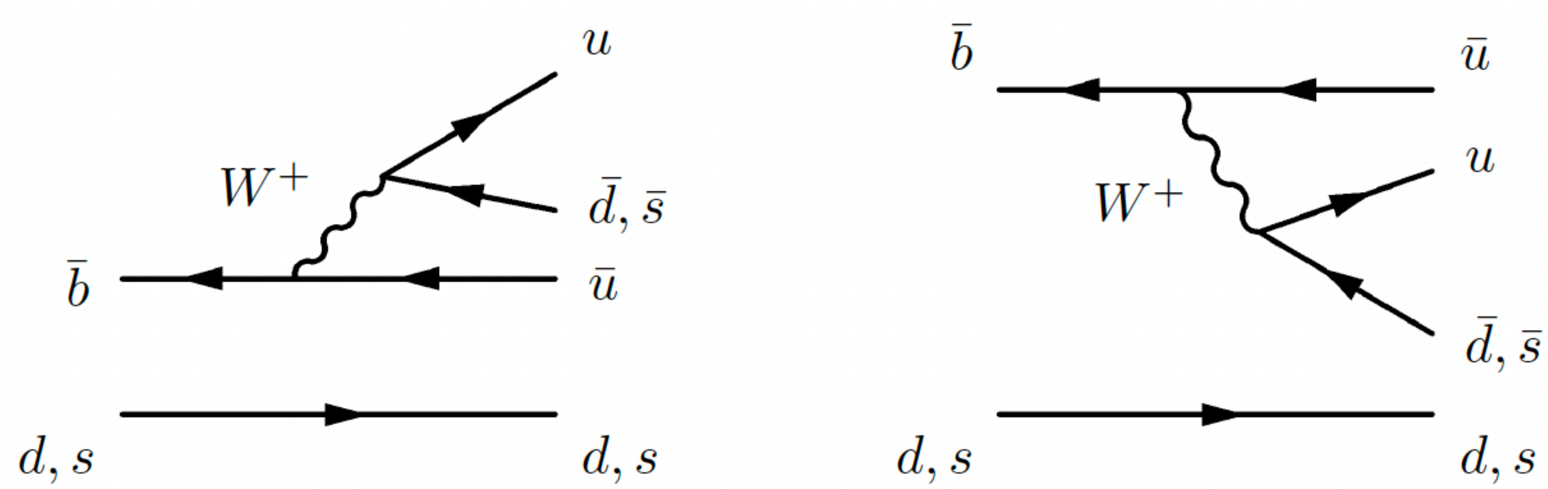
Belle II is (much) more than Belle, II
And will be leading tau physics for the next decade

Most precise to date

https://indico.in2p3.fr/event/29681/contributions/122507/attachments/76503/111032/04-SDreyer-v2.pdf

Testing the SM in hadronic B decays

Hadronic B decays are many. Plenty of CPV asymmetries to probe predictions



Testing the SM in hadronic *B* decays

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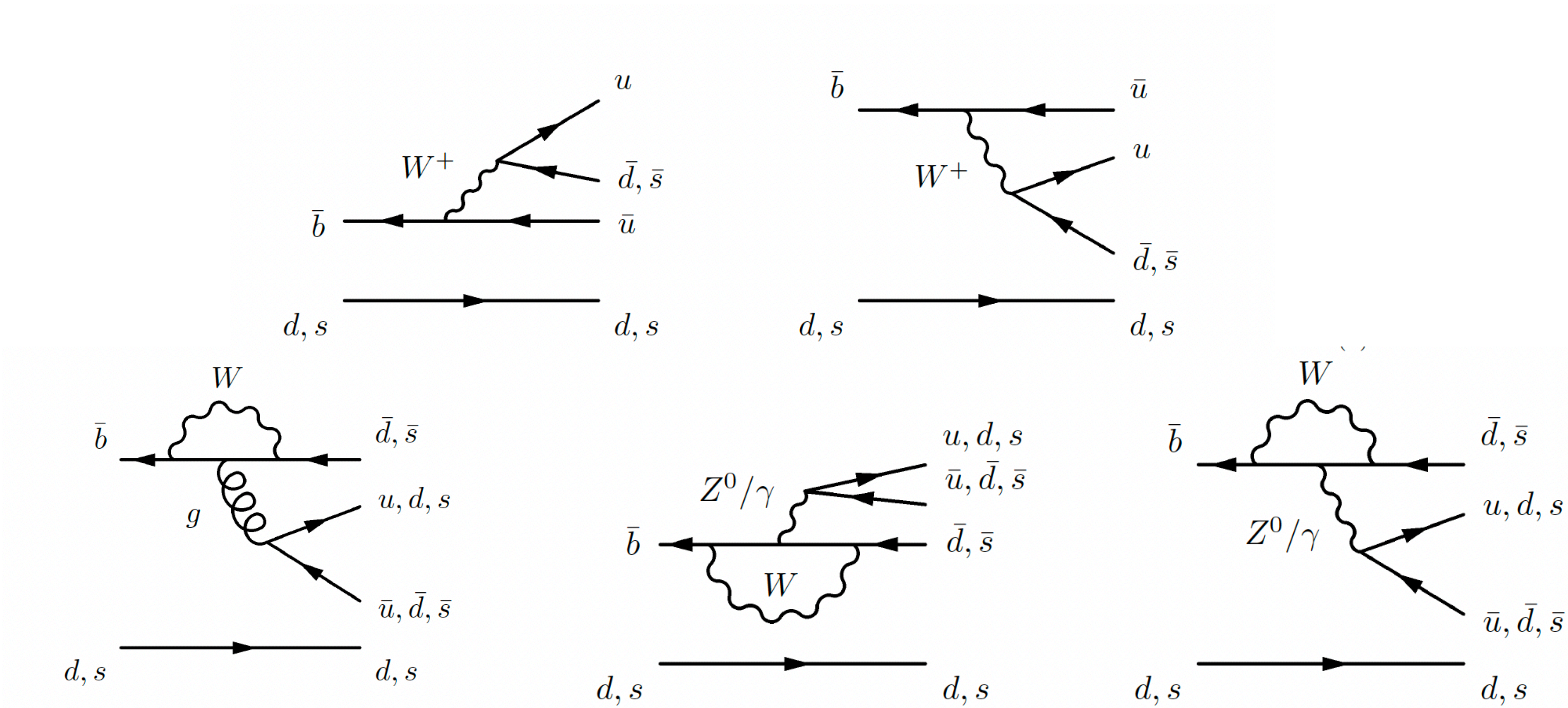


However, most are poor probes of BSM, since soft gluon exchanges make prediction intractable

Testing the SM in hadronic B decays

The $B \to K\pi$ family is an exception

Dynamical symmetries (isospin, heavy-quark, and SU(3) flavor) relate CP asymmetries and BF into a reliable and precise SM null test

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

(Phys.Lett. B627 (2005) 82-8)

Holds to 1% precision in the SM.

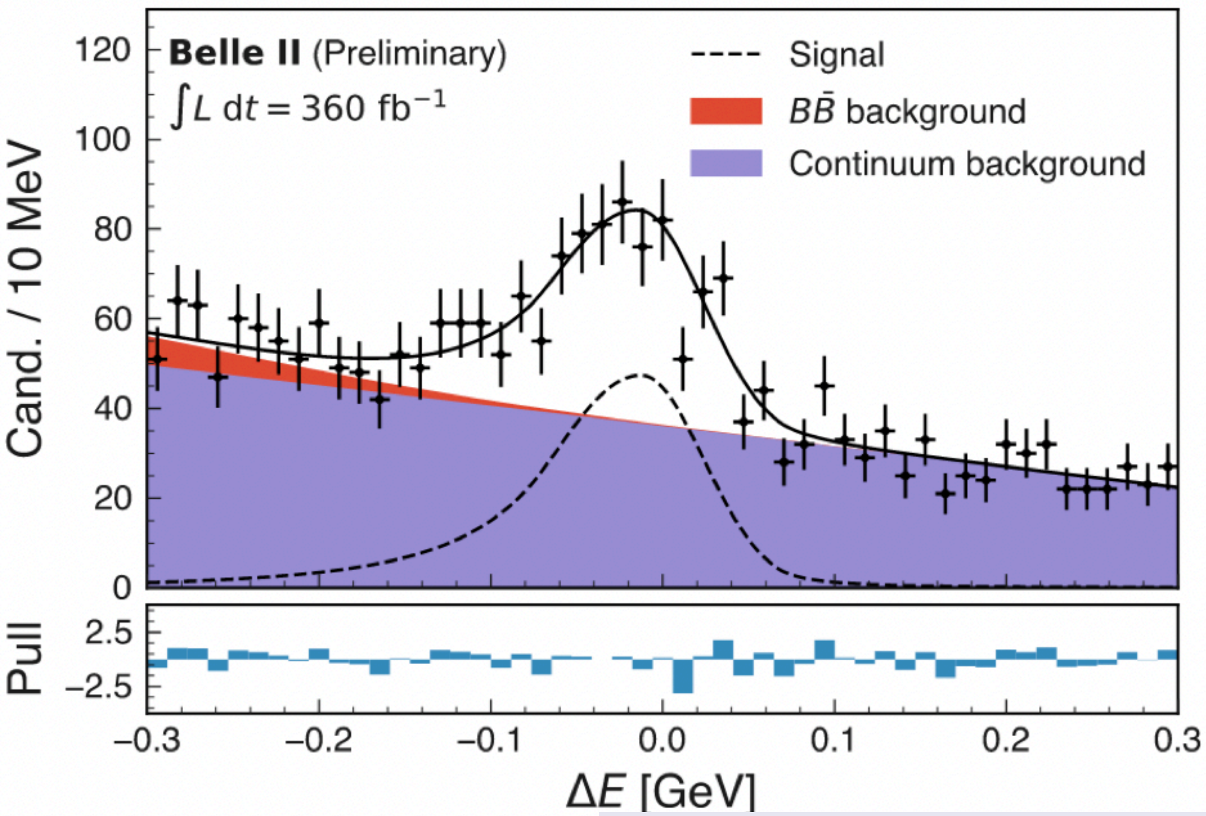
Current experimental precision is 11%, fully limited by $B^0 \to K^0\pi^0$

Unique to Belle II but hard: it's rare, it involves π^0 and K^0 (worse resolutions, worse vertex information) and know if B^0 or $\overline{B^0}$ was produced.

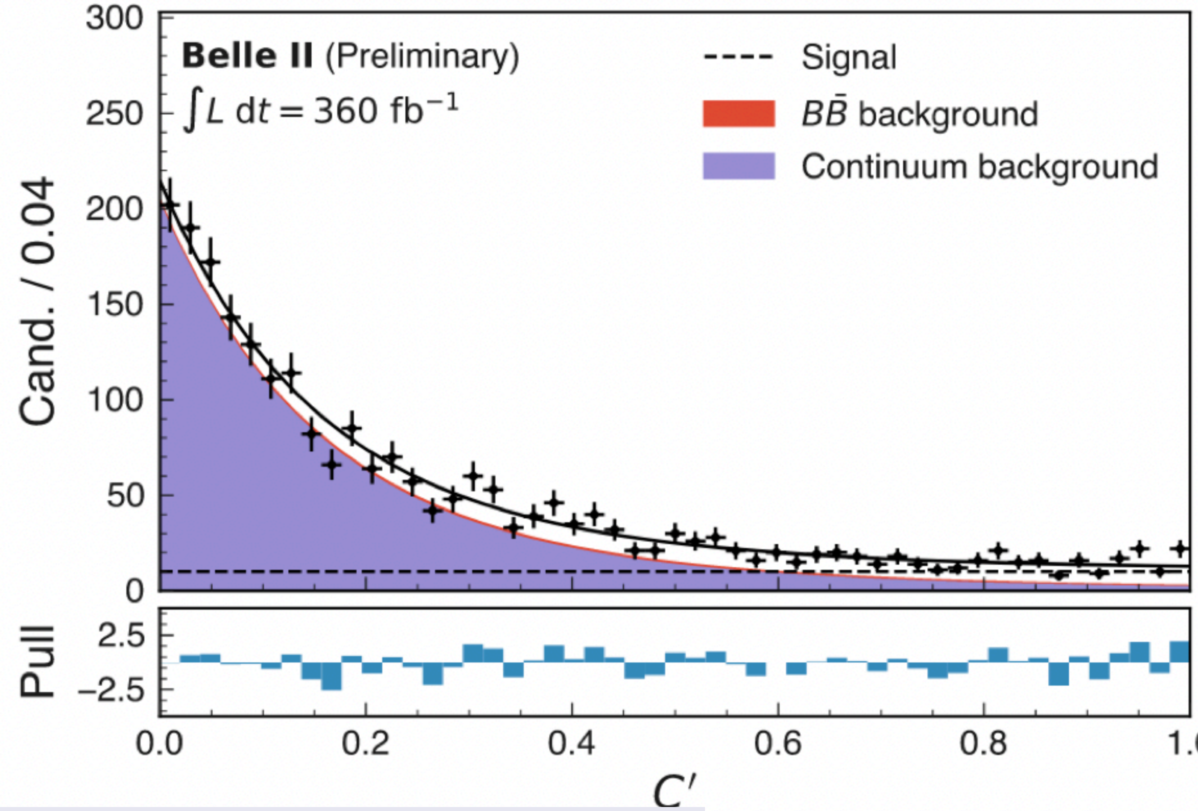
Tell signal (kinematics, vtx, event shape) from background from light-quarks

Isospin sum rule - analysis

Difference btw expected and observd B energy main signal extraction variable



Fit to decision-tree combination of discriminating variables separates bck



$$A_{K^0\pi^0} = -0.01 \pm 0.12(stat) \pm 0.05(syst)$$

$$\mathscr{B}(B^0 \to K^0\pi^0) = [10.5 \pm 0.6(stat) \pm 0.7(syst)] \times 10^{-6}$$

$$I_{K\pi} = -0.03 \pm 0.13(stat) \pm 0.05(syst)$$

Looks SM with 14% uncertainty. Competitive with world-average -0.13 ± 0.11 based on much larger samples by Belle and Babar

https://indico.in2p3.fr/event/29681/contributions/122496/attachments/76474/110993/03-HSagar-v1.pdf and https://arxiv.org/abs/2305.07555

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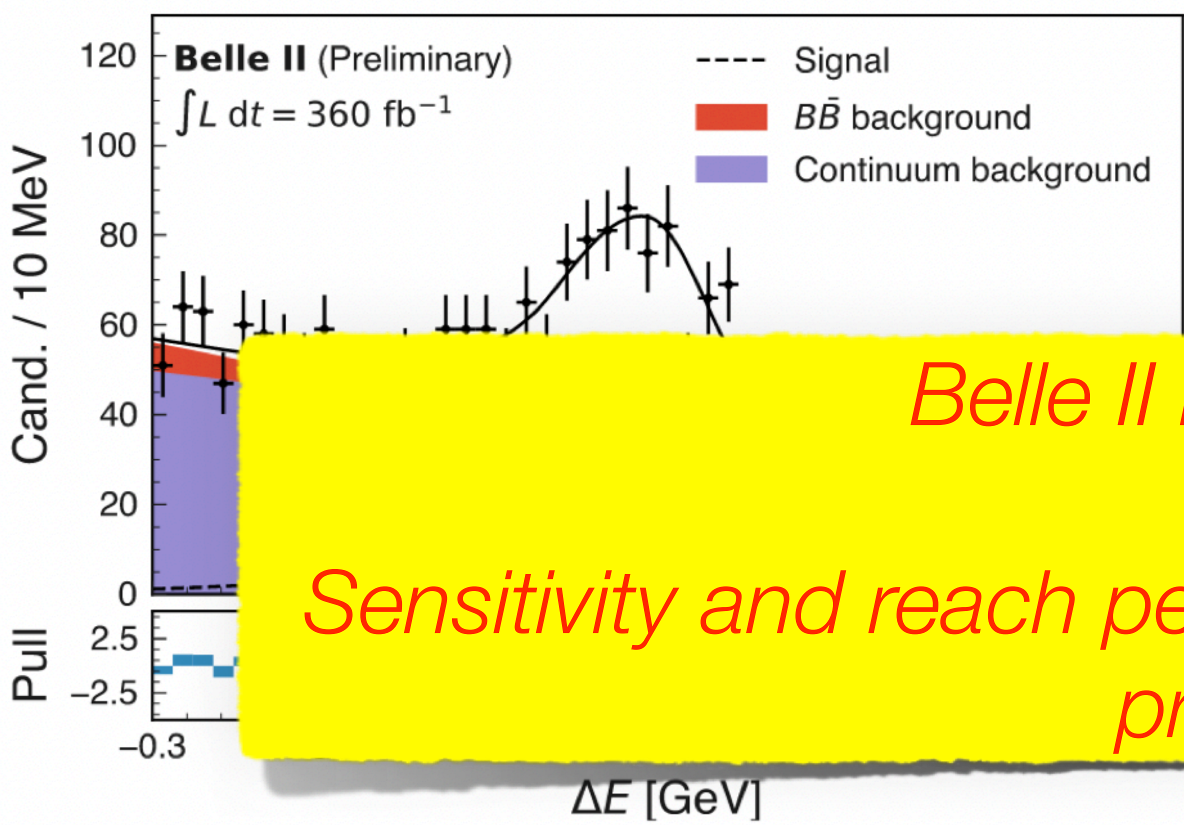

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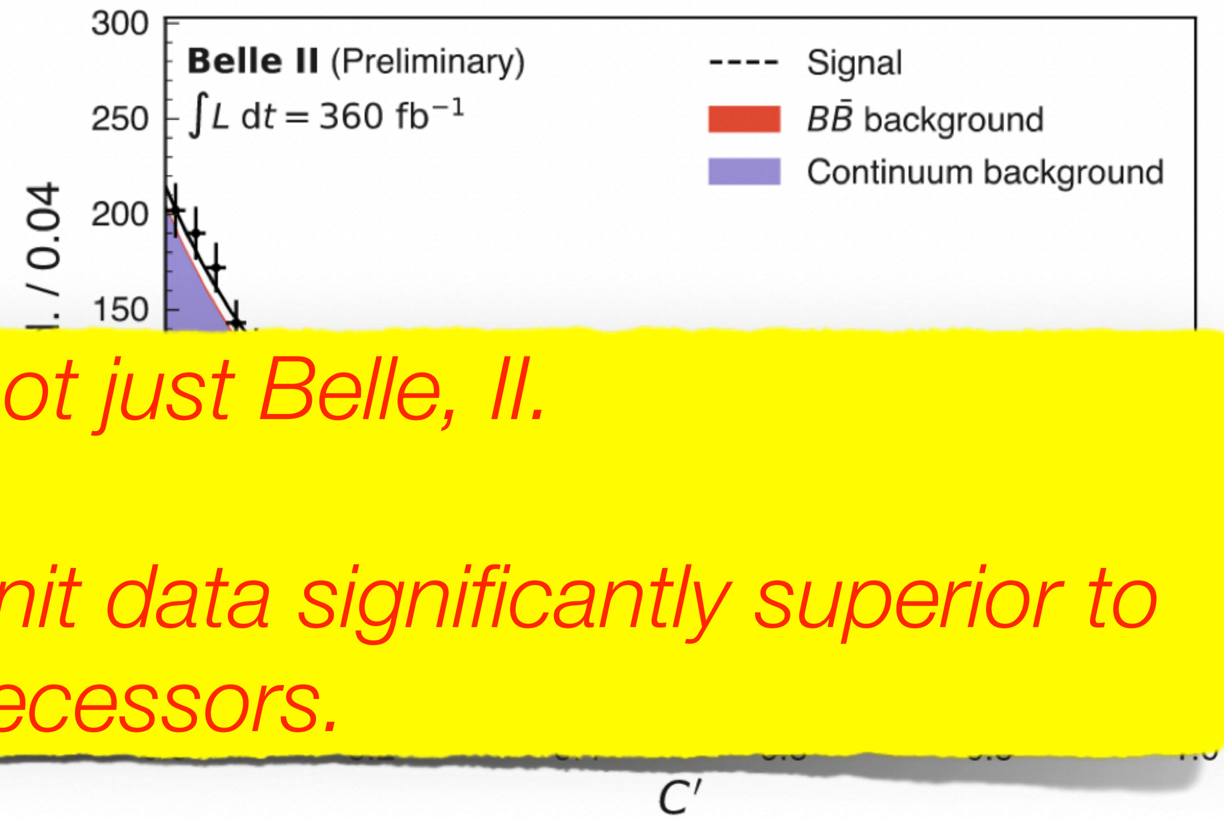

Belle II is not just Belle, II.

Sensitivity and reach per unit data significantly superior to predecessors.

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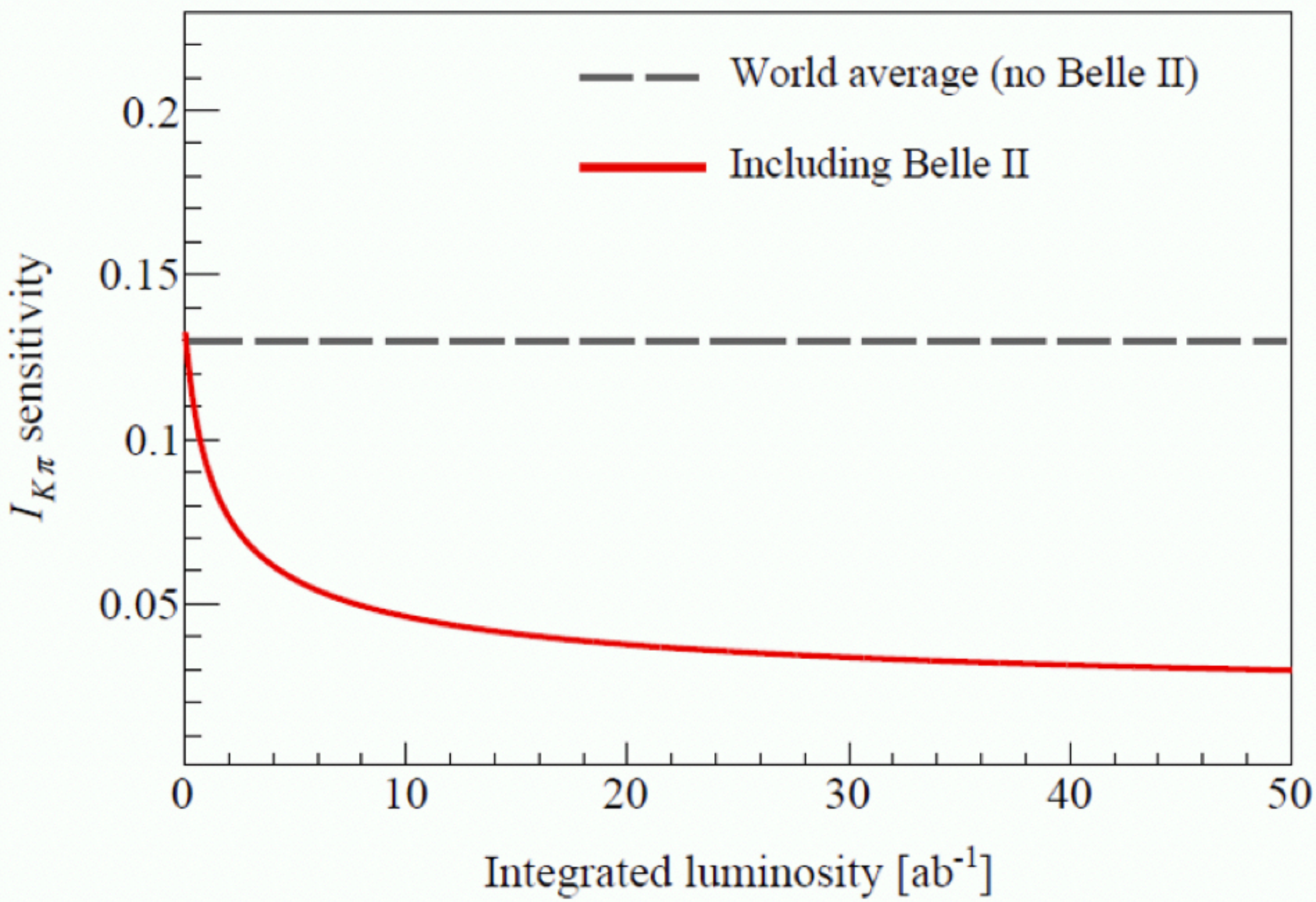
Isospin sum rule — Belle II impact

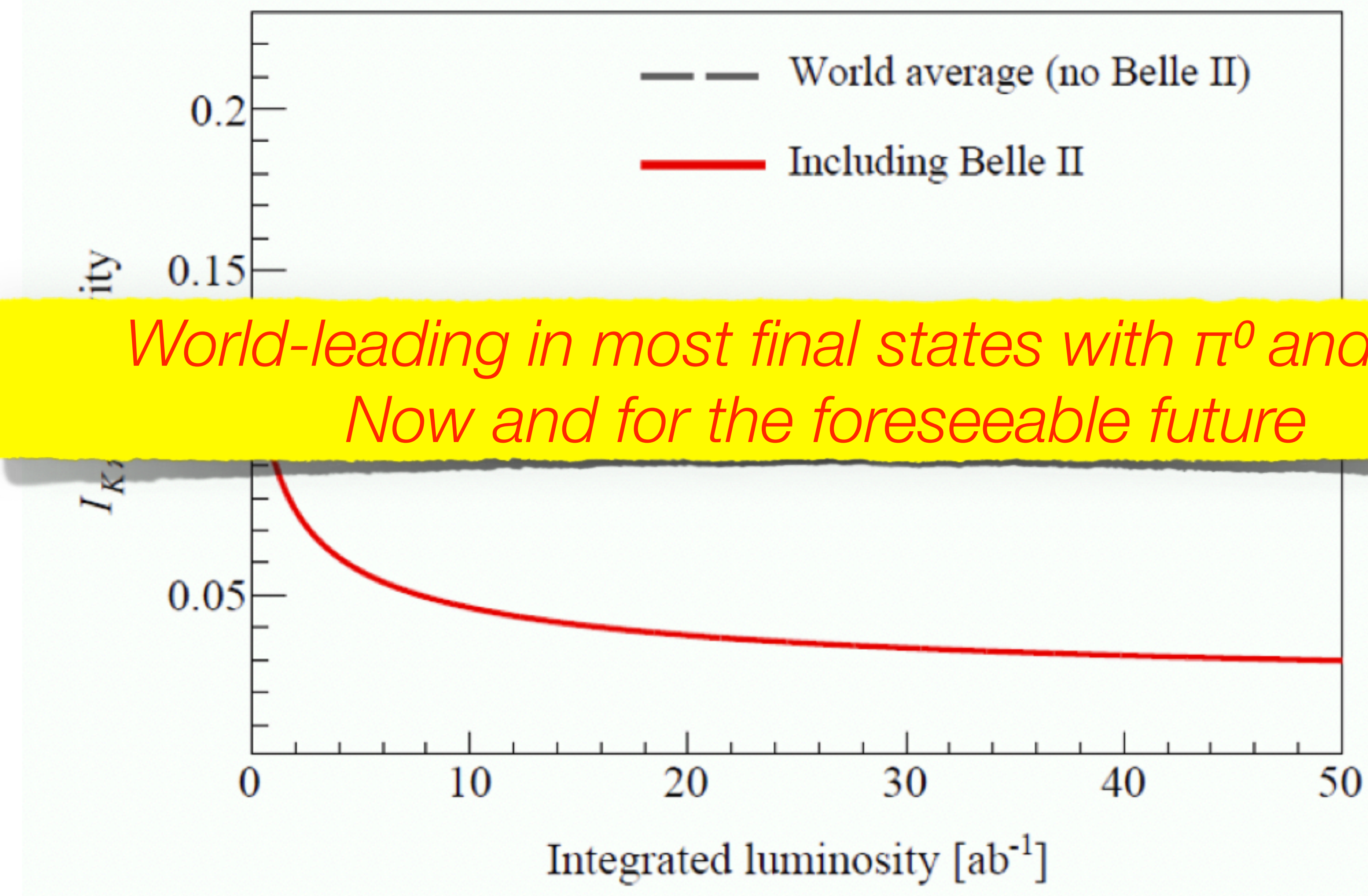
arxiv:2207.06307



Similar considerations apply to $B^0 \to \pi^0\pi^0$, $B^0 \to K^0K^0K^0$, $B^0 \to \eta' K^0$

Isospin sum rule — Belle II impact

arxiv:2207.06307



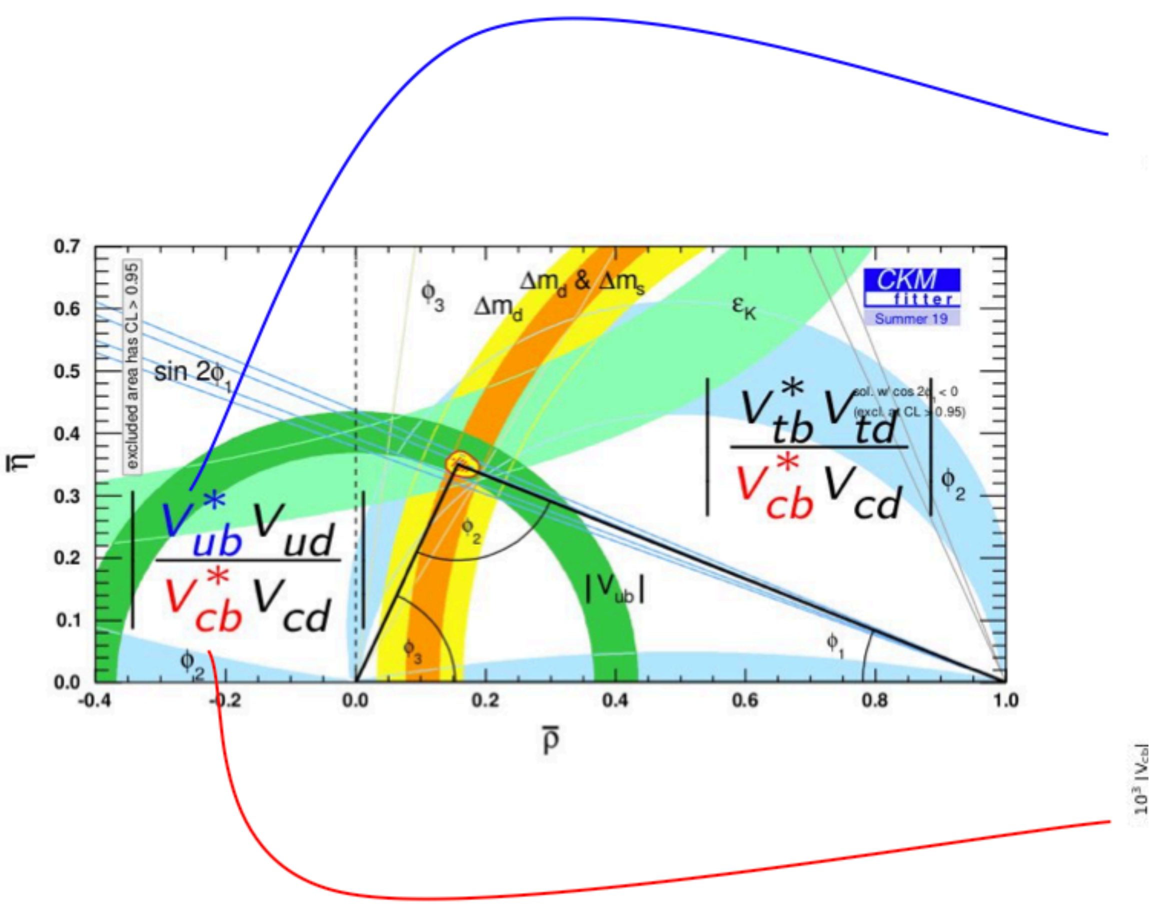
World-leading in most final states with π^0 and or K^0
Now and for the foreseeable future

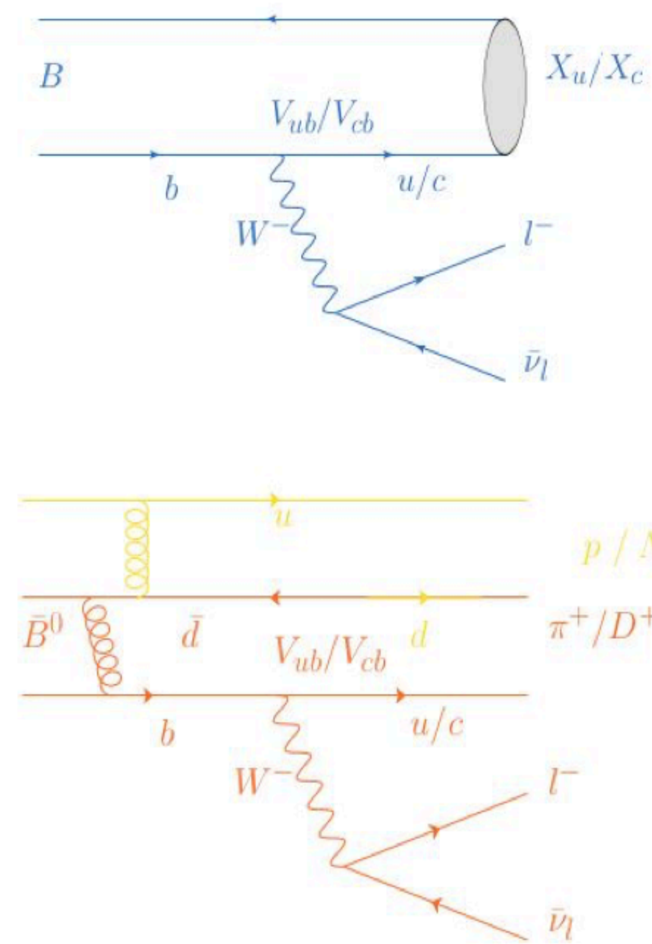
Similar considerations apply to $B^0 \rightarrow \pi^0\pi^0$, $B^0 \rightarrow K^0K^0K^0$, $B^0 \rightarrow \eta' K^0$

B-factory playground: semileptonic *B* decays

B → *[charm or u]* $\ell\nu$ determine sides of unitarity triangle. In plenty of ways:

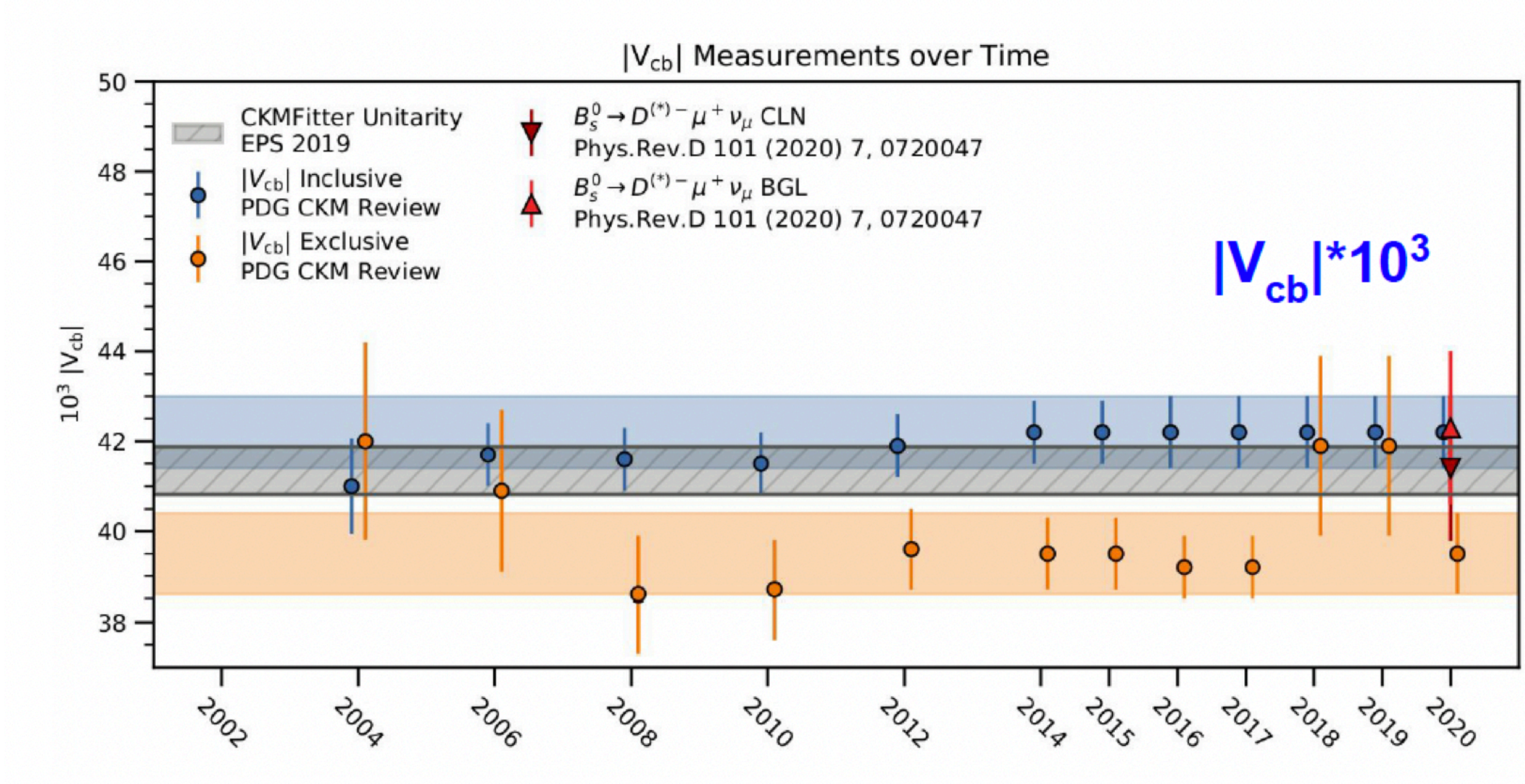
Reconstruct (or not) the other *B* in the event to suppress background. Use exclusive charm (D*, D…) or light (pi, rho) meson (easier measurement, tougher theory) or look at hadronic system inclusively (harder measurement, easier theory).





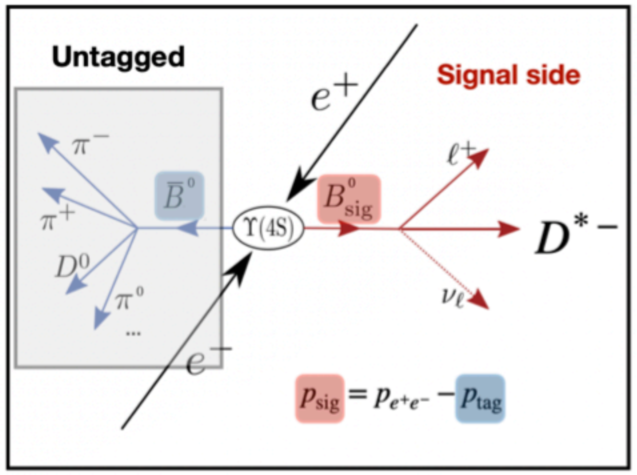
Then use theory/lattice transform BF or moments into |Vub| or |Vcb|

Things that should be equal differ…



Individual precision of about 3-5% crippled by systematic disagreement between inclusive and exclusive determinations

Back to basics — exclusive $|V_{cb}|$ from $B^0 \to D^{*-} \ell^+ \nu$



Untagged analysis focussing on experimentally **cleanest mode**:

$$\overline{B}^0 \to D^{*+} \ell^- \bar{\nu}_\ell$$
$$\hookrightarrow D^{*+} \to D^0 + \pi^+$$
$$\hookrightarrow D^0 \to K^- \pi^+$$

Extraction in **2D fit**:

$$\frac{d\Gamma}{dw \, d\cos\theta_\ell \, d\cos\theta_V \, d\chi} \propto |V_{cb}|^2 \times |F(w, \cos\theta_\ell, \cos\theta_V, \chi)|^2$$

This is what one measures using signal yields

Fully differential decay rate hard to measure in one shot.

Focus on one-dimensional partial decay rates

This is what one wants

“Form factors” incorporate the effects of strong interactions

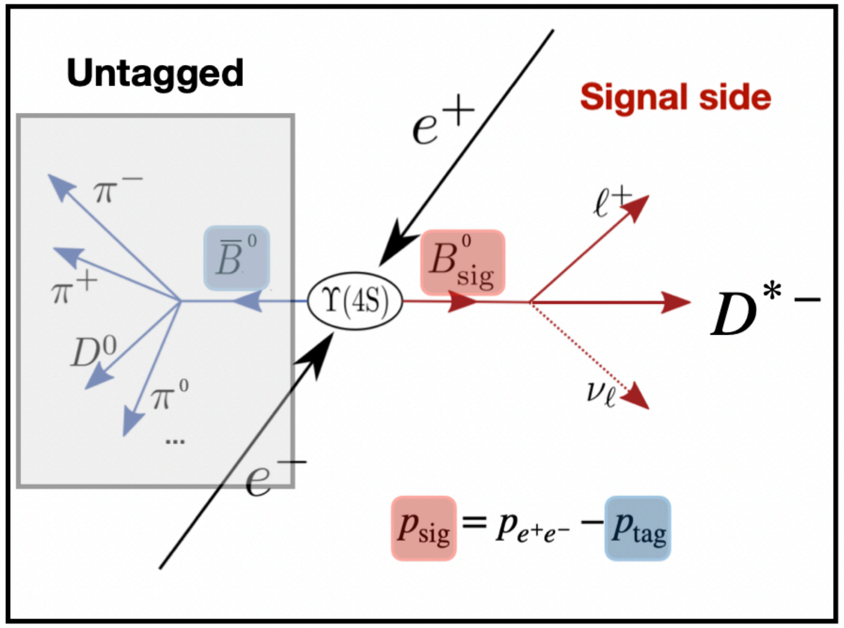
Experimentally one gets only the shape of the function.
Need at least one point from theory (lattice) to set normalization.
Various choices:

- fewer parameters but strong theory assumptions
- no theory assumption, but arbitrary # of parameters

Makes results model dependent

Recently experiments offer data distributions that can be fit with the various models. More flexibility but reliance on unfolding and proper usage of data by “others”.

The b-to-c quark coupling



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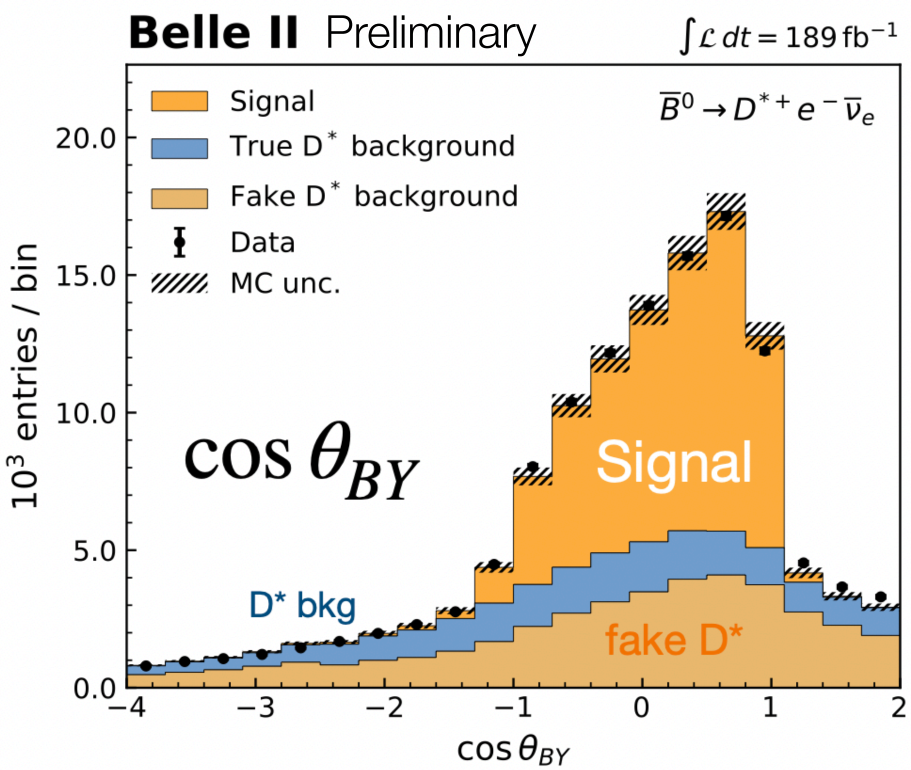
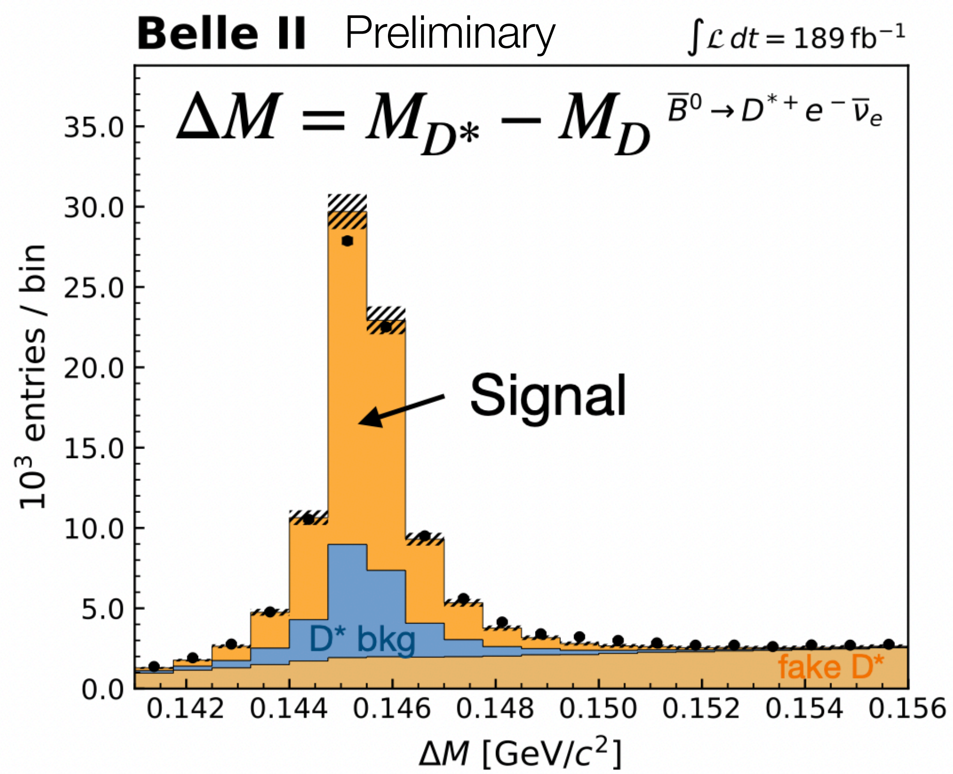


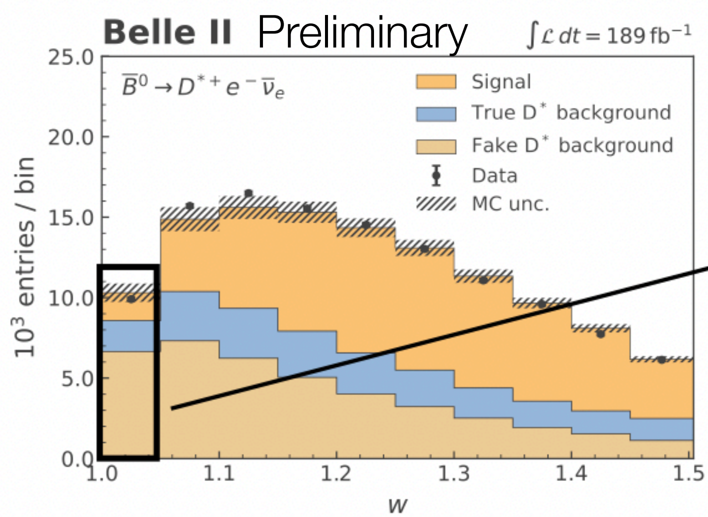
c.m. angle btw B and D*ell system



c.m. angle btw B and D*ell system

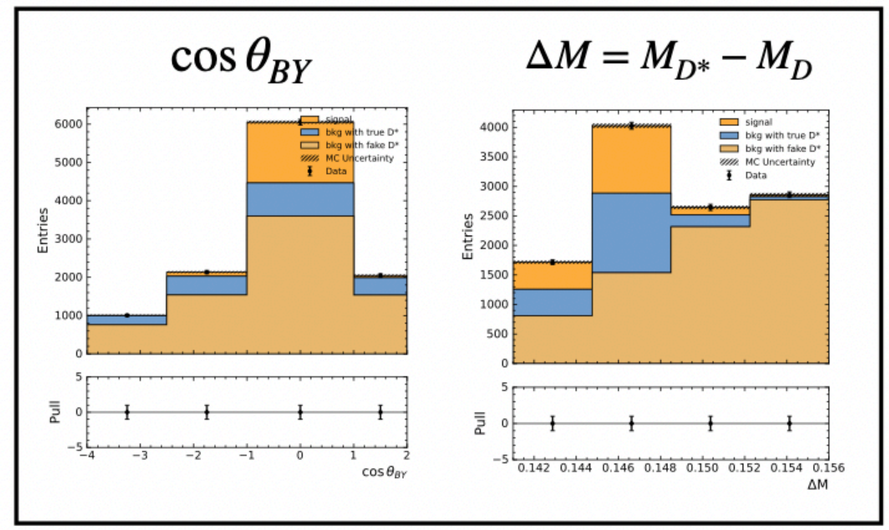
The b-to-c quark coupling

Also focus initially on **1D projections**:

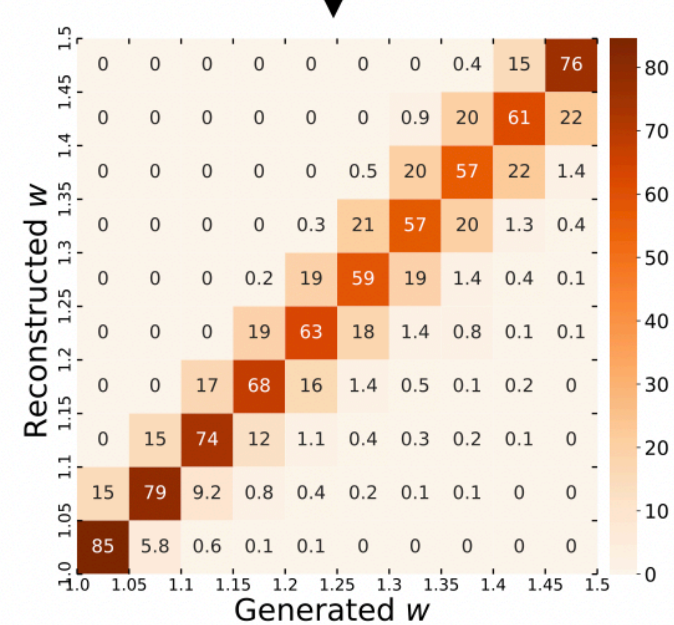


Fit

Preliminary



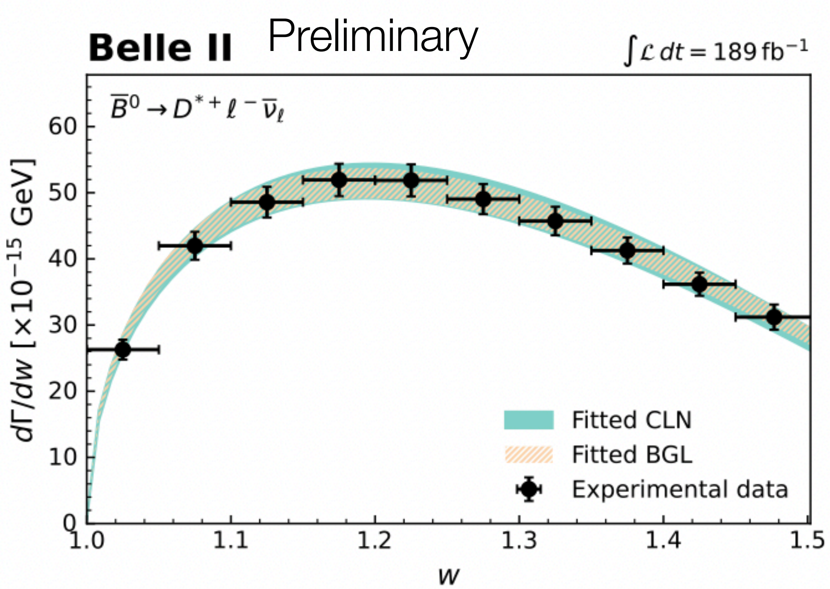
Correct for migration effects:



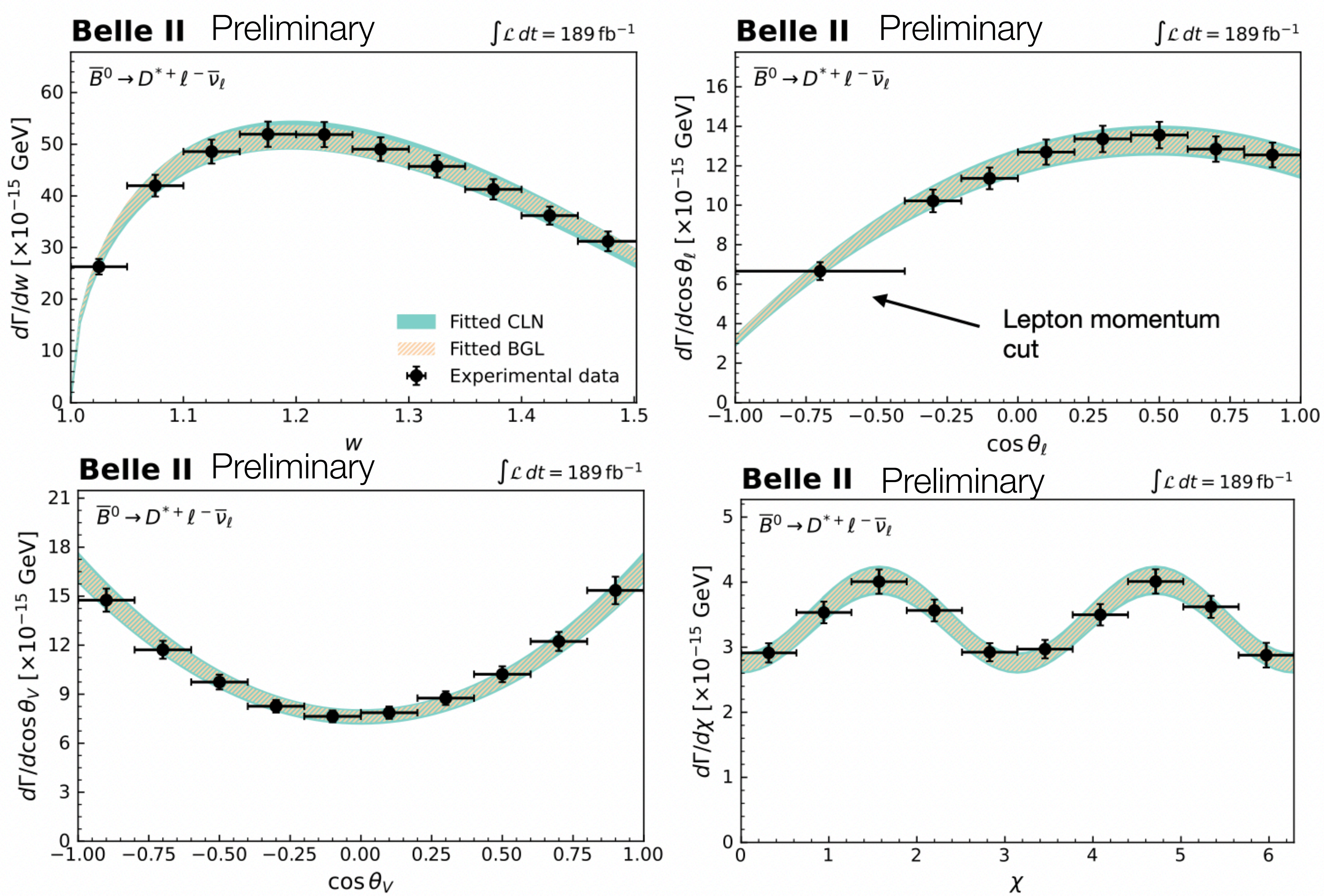
"Reco"

"True"

Correct for acceptance & efficiency



The b-to-c quark coupling



$$|V_{cb}|_{\mathrm{CLN}} = (40.2 \pm 0.3 \pm 0.9 \pm 0.6) \times 10^{-3}\,,$$
$$|V_{cb}|_{\mathrm{BGL}} = (40.6 \pm 0.3 \pm 1.0 \pm 0.6) \times 10^{-3}.$$

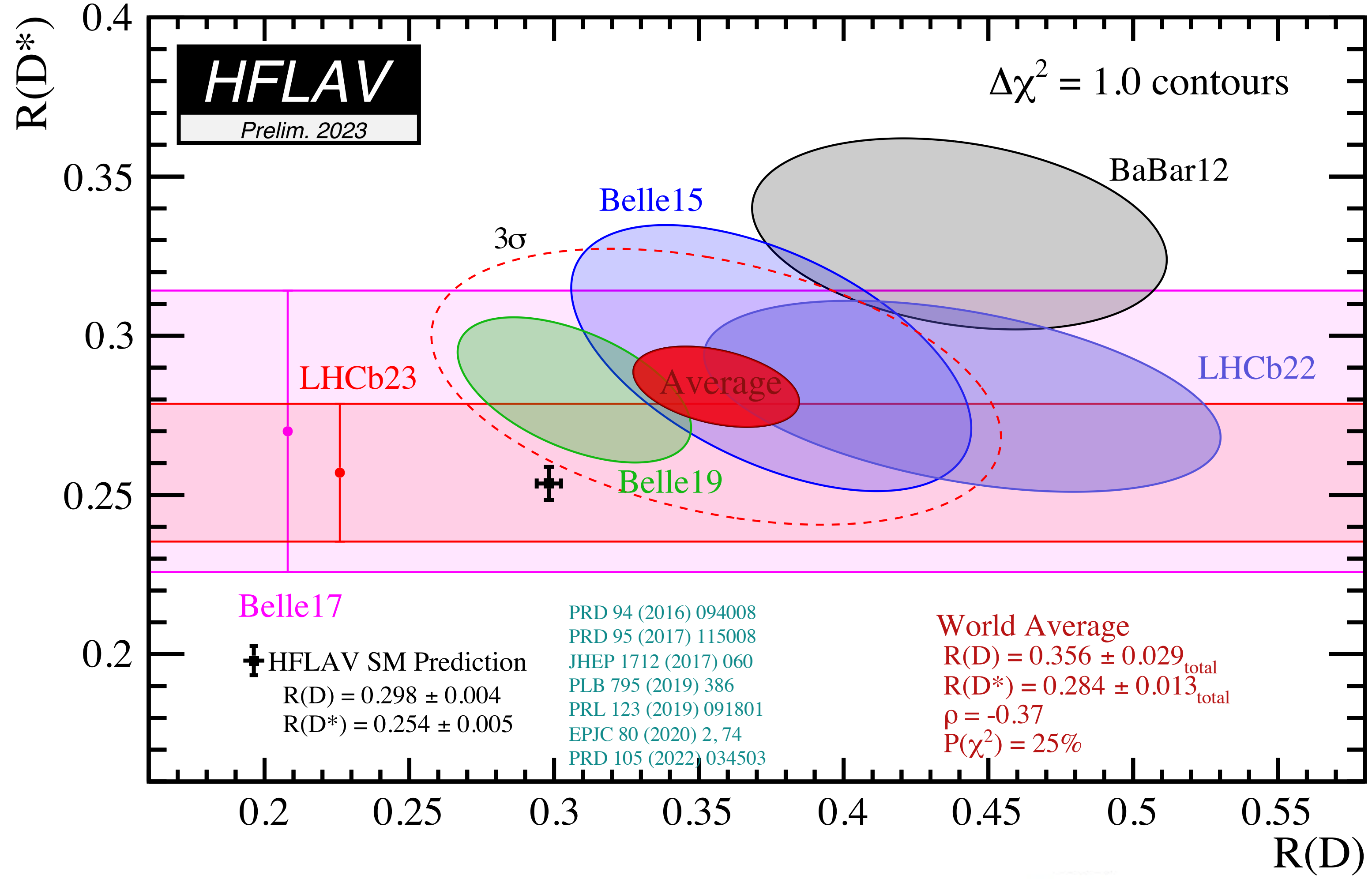
stat syst LQCD

Semileptonic brought us anomalies too…

$$R(D^*) \equiv \frac{\mathcal{B}(\bar{B} \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{*+}\ell^-\bar{\nu}_\ell)}$$

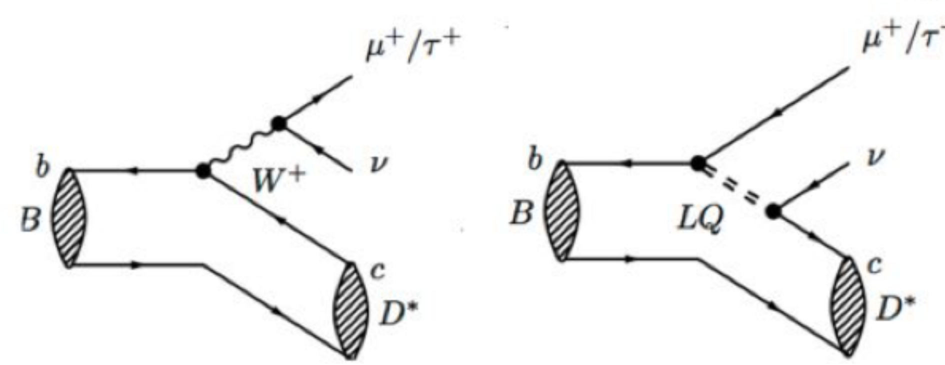
$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^{+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{+}\ell^-\bar{\nu}_\ell)}$$

Many experiments see 3σ tau excess in $b \to c$



$$A = A_0\left(\frac{c_{\rm SM}}{m_W^2} + \frac{c_{\rm NP}}{\Lambda^2}\right)$$

$$c_{\rm SM} \approx V_{\rm cb} \Rightarrow \frac{\Lambda^2}{c_{\rm NP}} \sim (3\ \text{TeV})^2$$

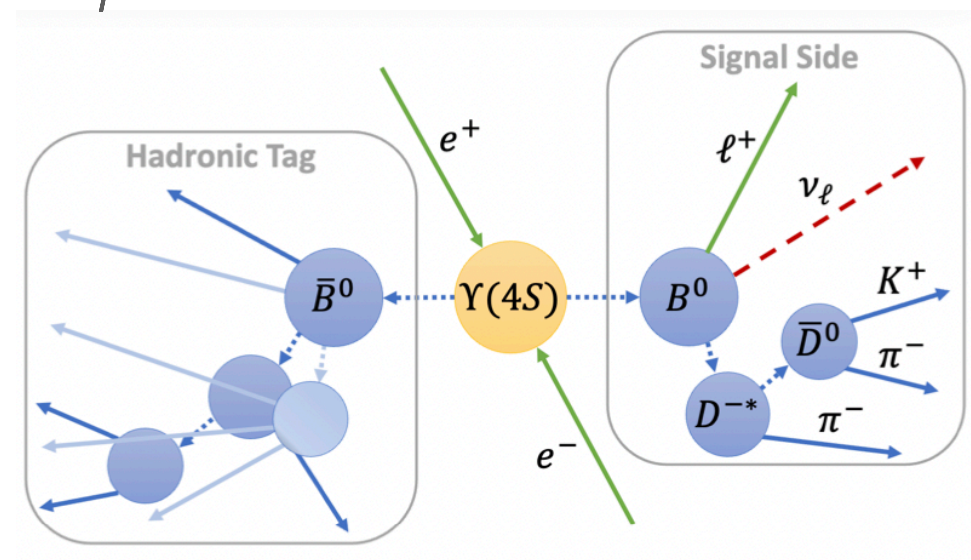


Multiple neutrinos, no narrow peak to fit in any distribution, multiple harsh bckgs

Significant advantages for Belle II

Muon-electron universality — exclusive

Seek lepton-flavor universality violation btw $B^0 \to D^{*-}\mu^+ \nu$ and $B^0 \to D^{*-}e^+ \nu$



Multibody: dynamics depends on ℓν mass q

Spin-1 D* channels the V - A properties of interaction and virtual W spin in a rich angular structure. Rate depends on 4 quantities

Recoil parameter $w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$

Sensitive to LFUV

$A_{FB}(w)$: $dx = d(\cos\theta_\ell)$ — propensity for ℓ± to travel in same direction of virtual W

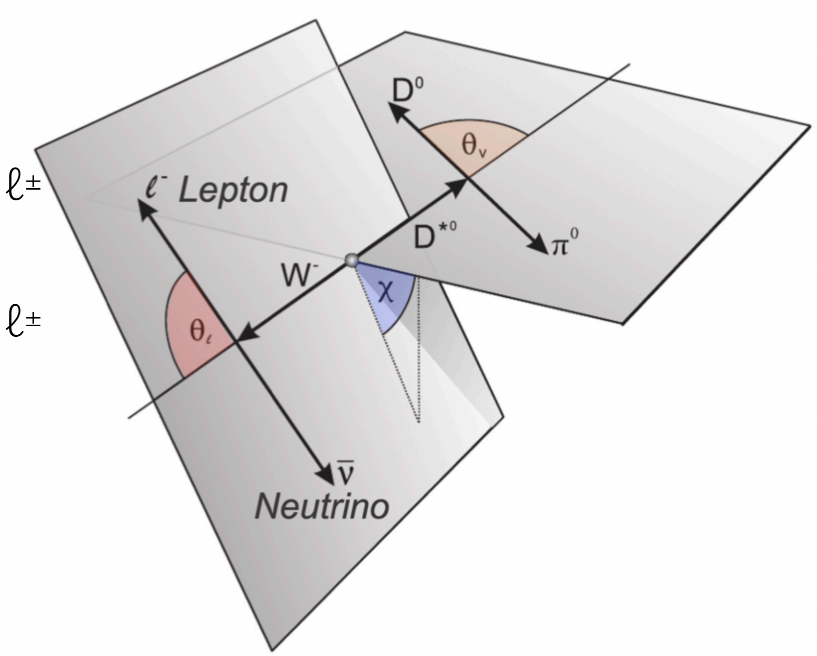
$S_3(w)$: $dx = d(\cos 2\chi)$ — propensity for alignment btw ℓ± and D*

$S_5(w)$: $dx = d(\cos\chi \cos\theta_V)$ — coupled propensity for alignment btw ℓ± and D wrt D*

Insensitive to LFUV (null test)

$S_7(w)$: $dx = d(\sin\chi \cos\theta_V)$ — coupled propensity for alignment btw ℓ± and D wrt D*

$S_9(w)$: $dx = d(\sin 2\chi)$ — propensity for alignment btw ℓ± and D*

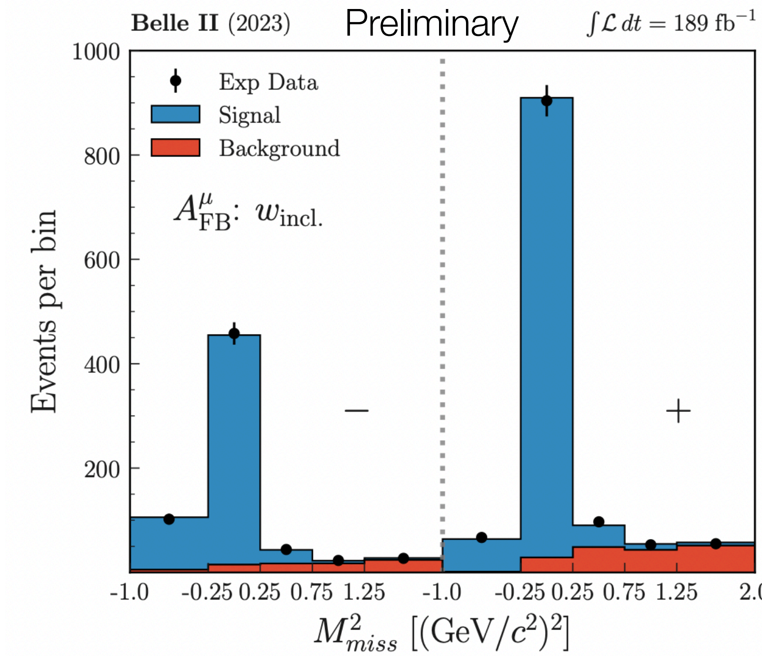


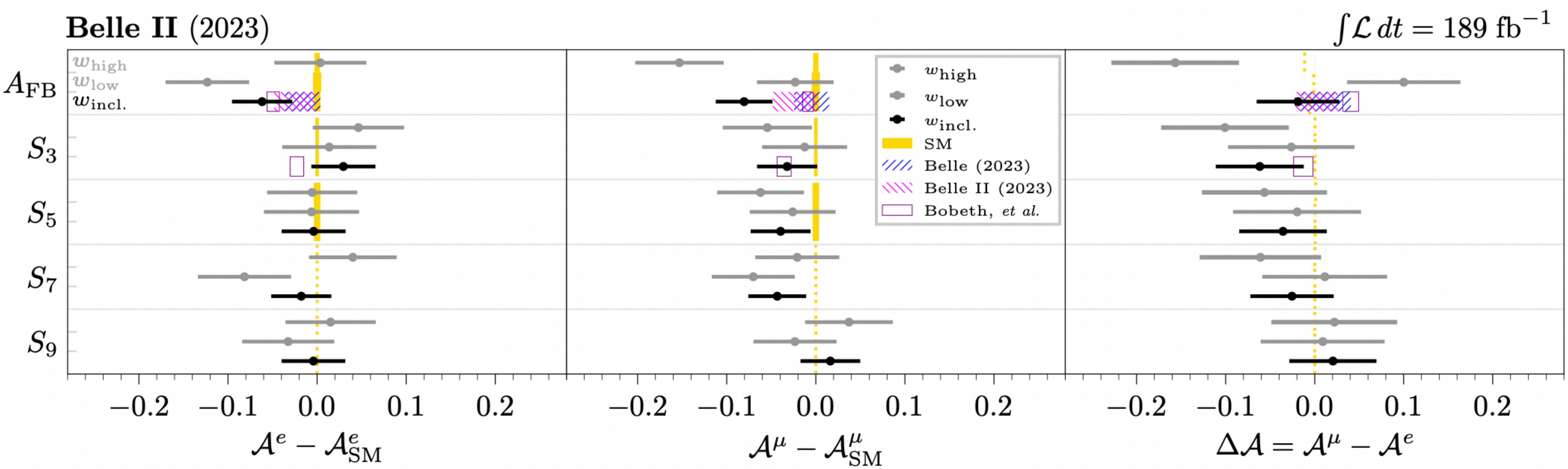
Differences of these asymmetries between e and *μ offer* sensitivity to lepton-flavor universality violation

Muon-electron universality exclusive

https://indico.in2p3.fr/event/29681/contributions/122501/attachments/76478/110997/YSF01-KKazuki-v1.pdf

Signal events determined with fits of the missing mass distribution (squared difference between 4-momentum of colliding particles and 4-momentum of all particles in the event) - peaks at zero (neutrino mass) for signal





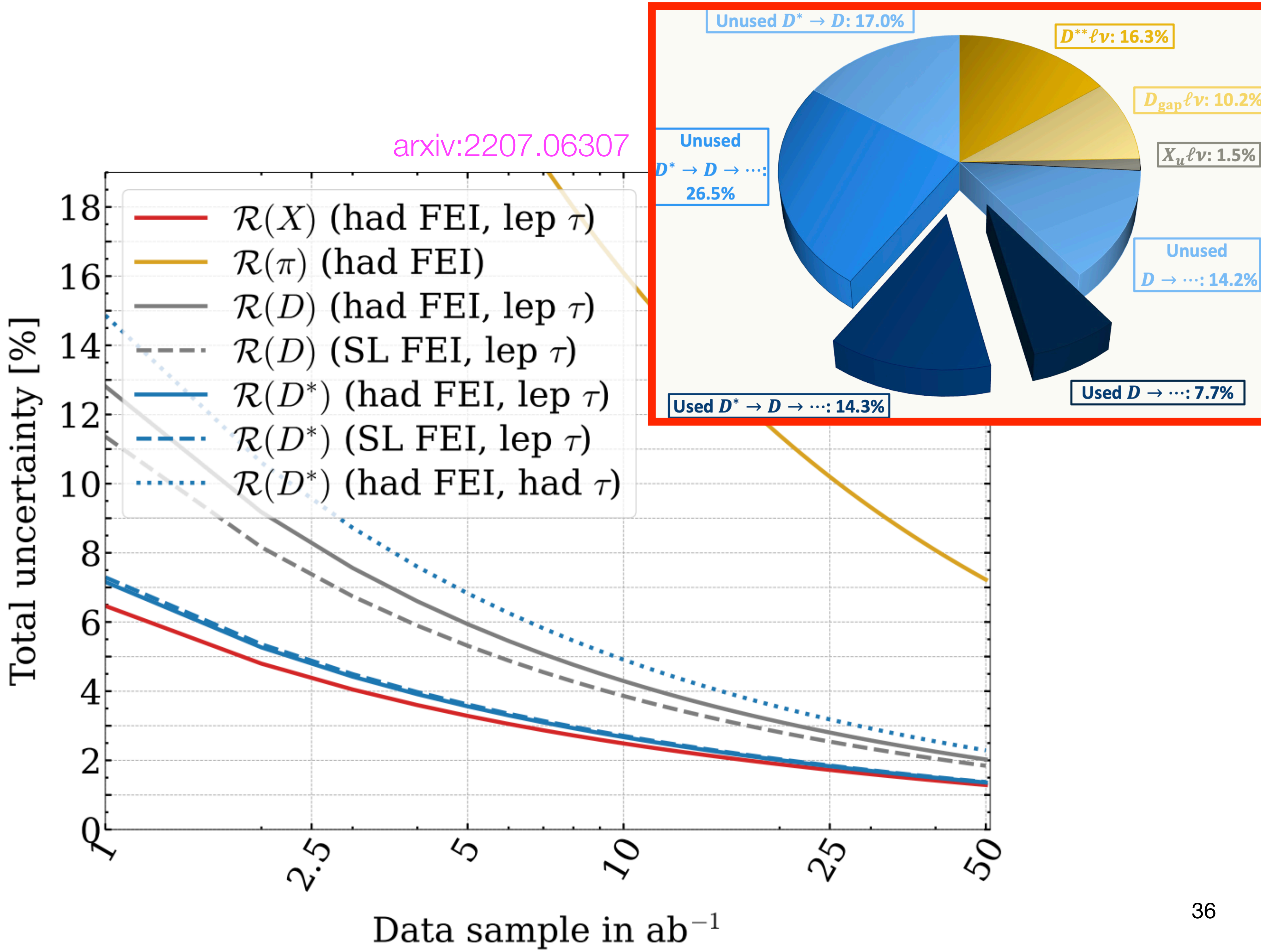
All SM within 5-10% uncertainties

Going inclusive — *R(X)*

R(D)

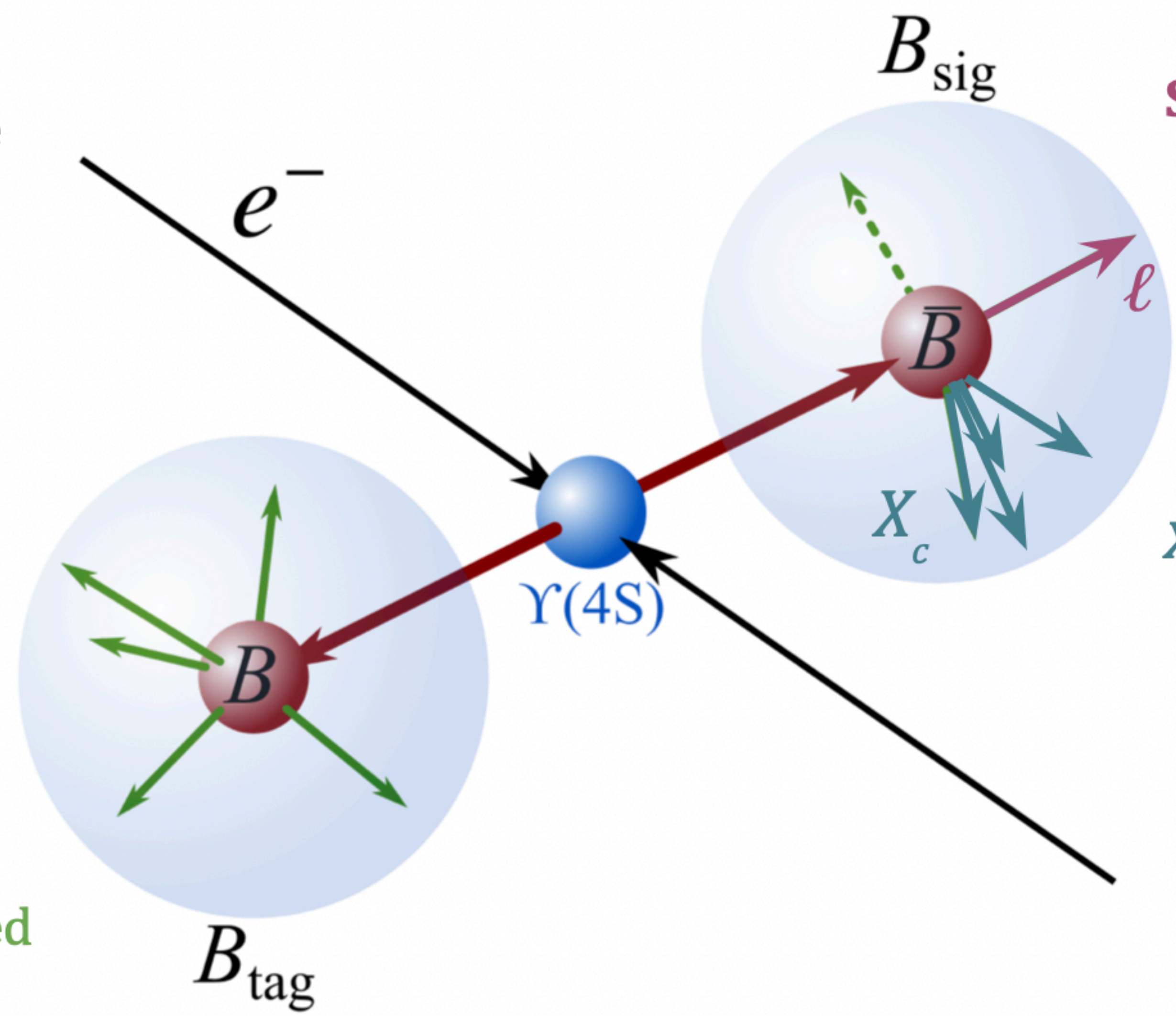
R(D)*

inclusive



Going inclusive — *R(X)*

Full event
Shape variables used to reduce continuum background with machine learning



Signal lepton:

- Exactly one lepton with high electron or muon likelihood

X_c system:

- Everything else in the event…
- …passing quality criteria

Tag-side *B* meson

- Fully reconstructed (hadronic modes)
- Best tag selected by classifier value

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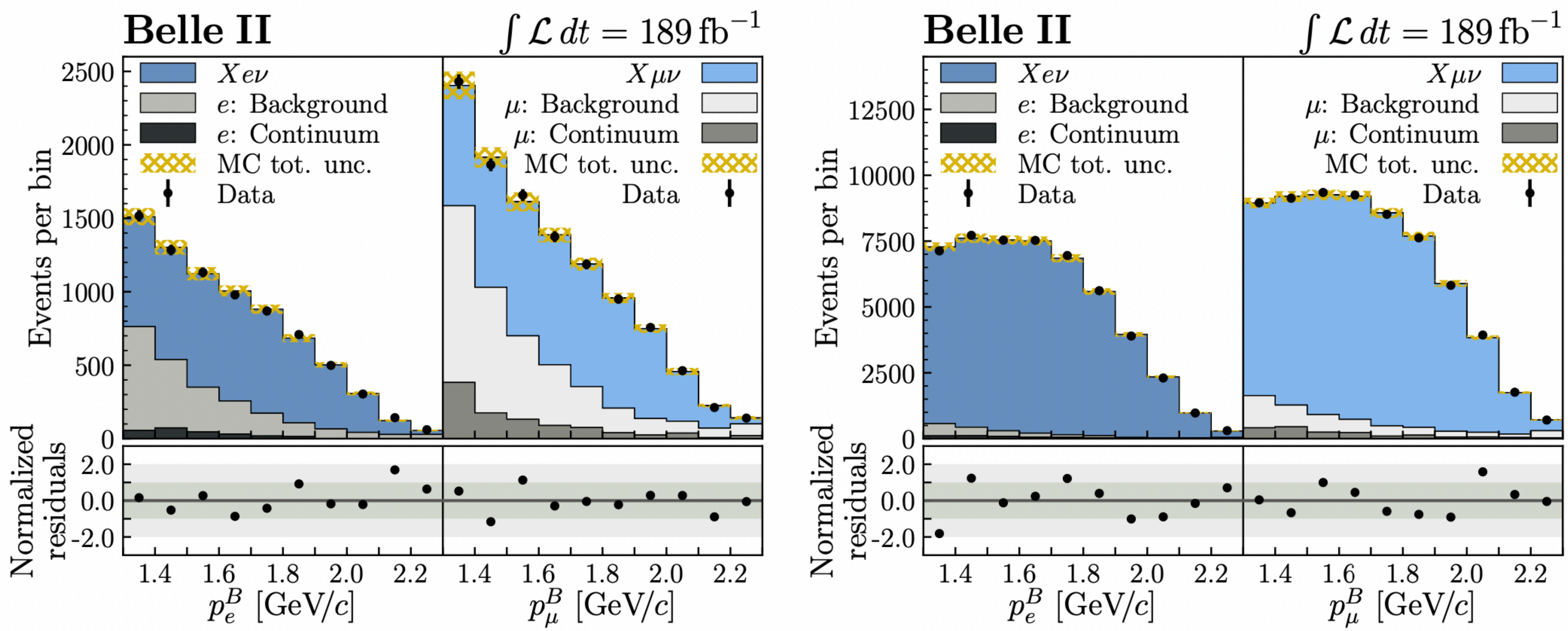
Constrain mismodeling in abundances and shapes of sample components is key

Muon-electron universality inclusive

Sample composition fit to lepton spectrum in signal and control regions

Control (Same-flavor B)

Signal (Different flavor B)



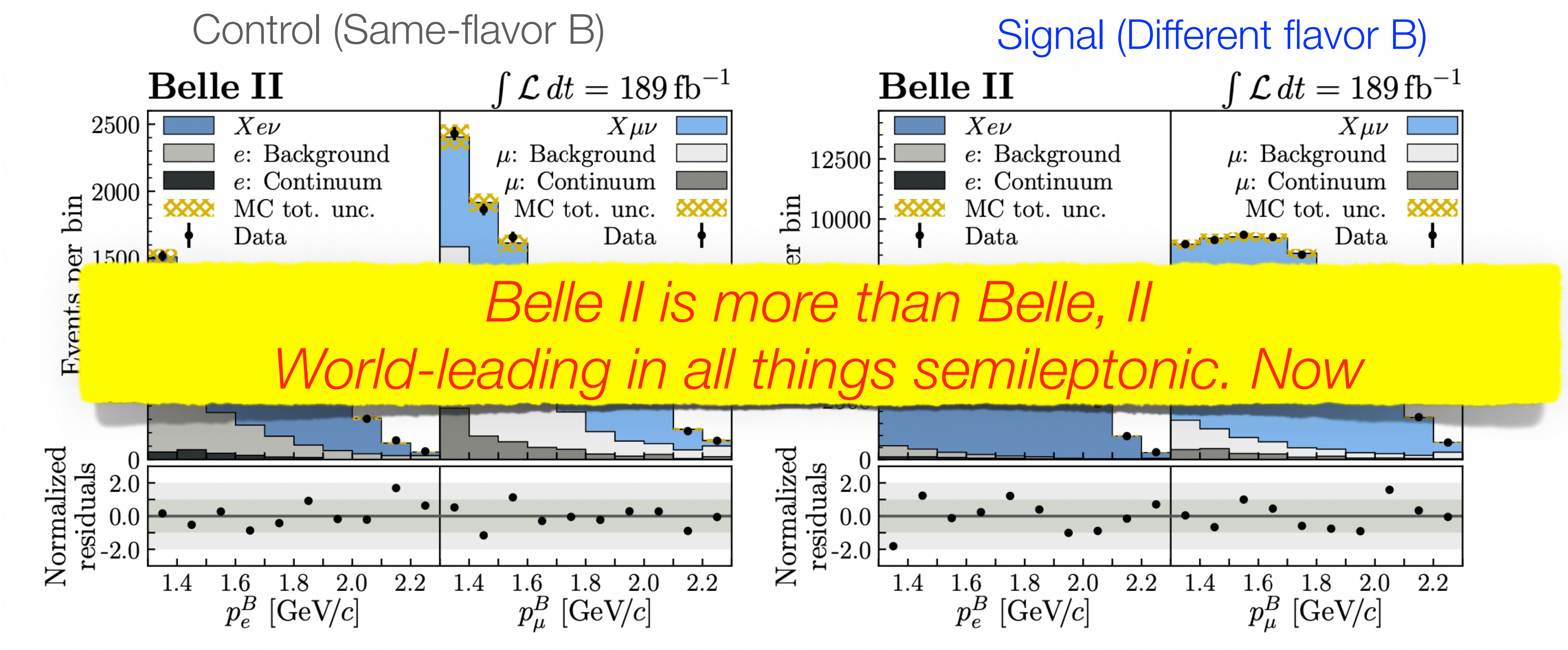
$R(X_{e\mu})$ = 1.033 ± 0.010 (stat) ± 0.019 (syst - mostly lepton ID)

First inclusive and most precise test of LFU in light leptons using SL decays.

arxiv:2301.08266

Muon-electron universality inclusive

Sample composition fit to lepton spectrum in signal and control regions



Belle II is more than Belle, II
World-leading in all things semileptonic. Now

$R(X_{e\mu}) = 1.033 \pm 0.010\ (\text{stat}) \pm 0.019\ (\text{syst}$ - mostly lepton ID)

First inclusive and most precise test of LFU in light leptons using SL decays.

arxiv:2301.08266

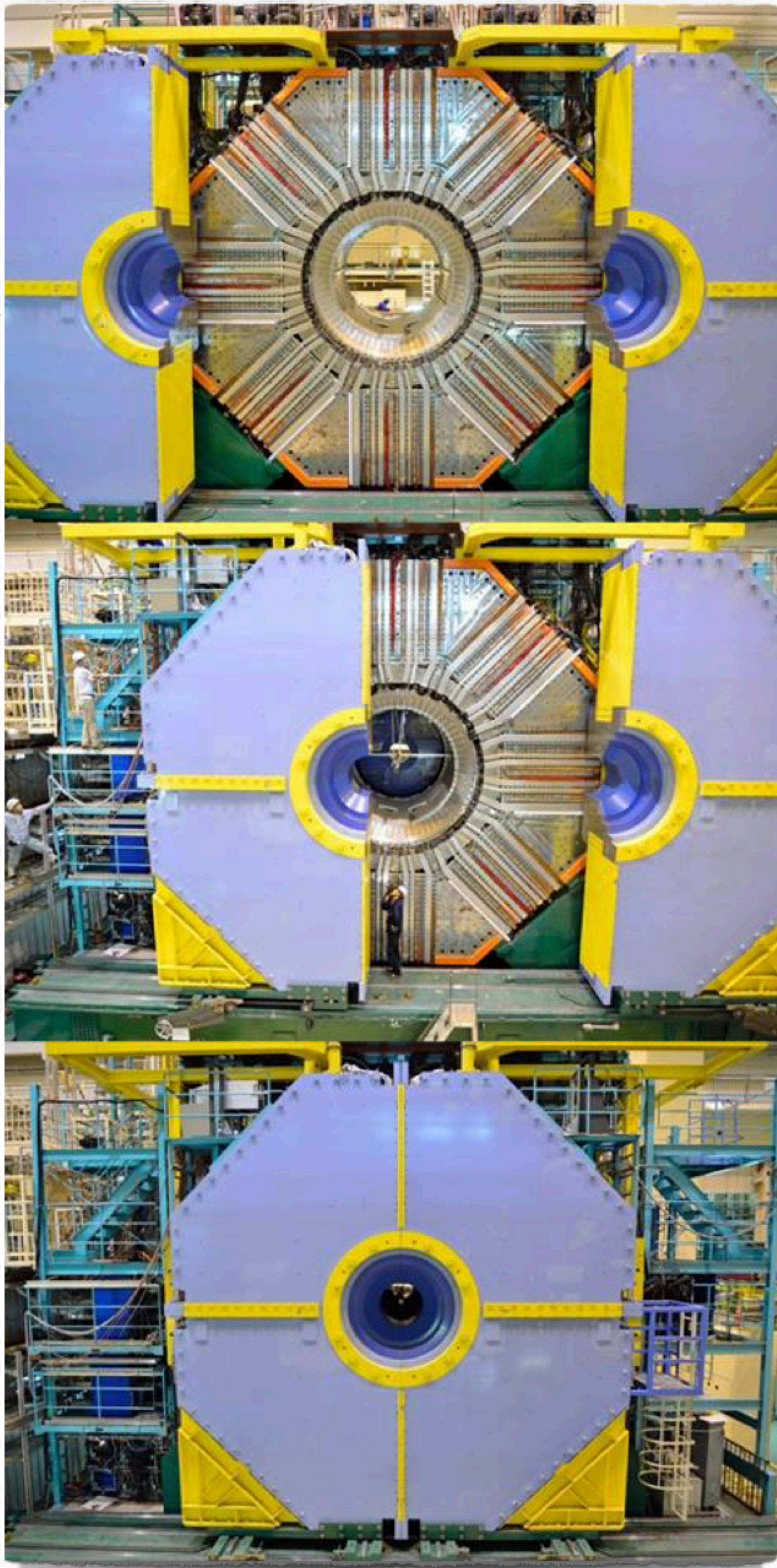
Epilogue

There's more to it

Journal-paper results approved in past 12 months

Energy-dependence of $B^{(*)}\bar{B}^{(*)}$ cross section — unique
Observation of $ee \to \omega\chi_b$ at 10.75 GeV — unique, PRL. **130**, 091902 (2023)
Test of light-lepton universality in $B \to D^*\ell\nu$ decays — unique
Test of light lepton universality in inclusive $B \to [X_c]\ell\nu$ decays — unique, arXiv: 2301.08266
Measurement of CKM angle γ using GLW — Belle + Belle II sample
Measurement of CKM angle γ using GLS — Belle + Belle II sample
Search for long-lived spin-0 mediator in b → s transitions— world leading
Measurement of of the τ mass — world leading
BF and ACP in $B^0 \to h^+h^{0-}$ decays and isospin sum rule — world leading
BF and ACP of $B^0 \to \pi^0\pi^0$ decays — competitive, arXiv: 2303.08354
ACP in $B^0 \to K^0_S K^0_S K^0_S$
|Vcb| using untagged $B \to D^*\ell\nu$ decays — competitive
CPV in $B^0 \to K^0\pi^0$ decays — competitive, arXiv: 2305.07555
CPV in $B^0 \to \phi K^0_S$
Novel method for charm flavor tagging — unique, arXiv: 2304.02042
B^0 lifetime and oscillations in $B^0 \to D^{(*)}h$ decays PRD **107**, L091102 (2023)
Search for a dark-sector ττ resonance in ee → ee ττ decays — world leading
Search for a dark-sector Z' to invisible — world leading, arXiv: 2212.03066
Search for τ → ℓ α — world leading PRL **130**, 181803 (2023)
Search for a dark γ and invisible darkHiggs in μμ+MET— world leading, PRL **130**, 071804 (2023)
Measurement of the Ω^0_c lifetime — PRD **107**, L031103 (2023)

(Plus a bunch of conference-note results)



Conclusion

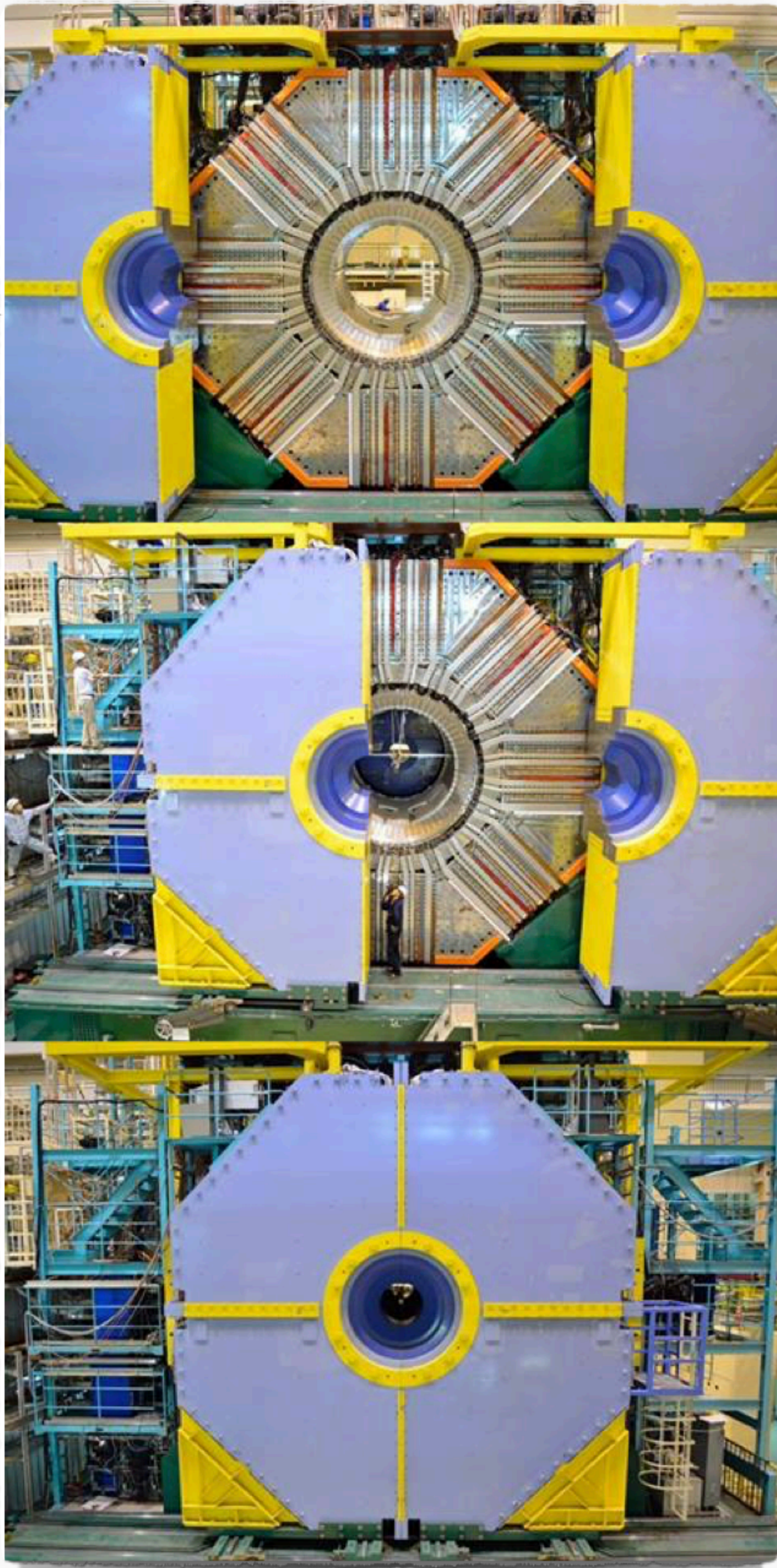
Quite special circumstances for flavor

- no BSM in high-p_T , anomalies in indirect tests
- Two state-of-art experiments, at the *Y(4S)* and in *pp*, running together over the next decade

Belle II accesses suite of compelling measurements that are unique and world leading

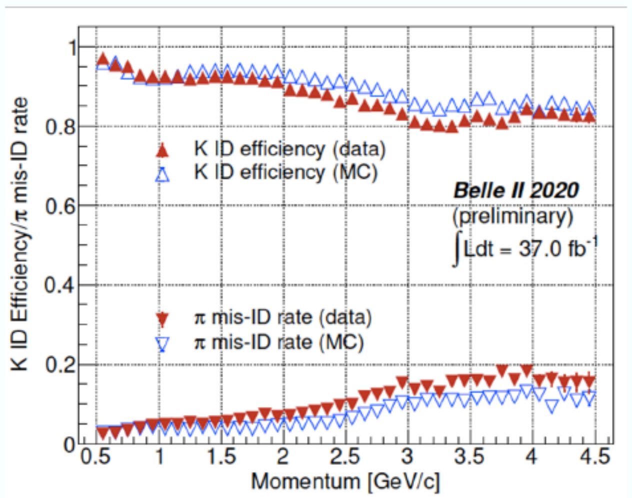
- saturate semileptonic τ-lepton and low-mass dark sector programs
- unique access to high-profile *B and D decay* measurements involving $\pi^0/\gamma/\nu$..

…this might be the last opportunity to do them

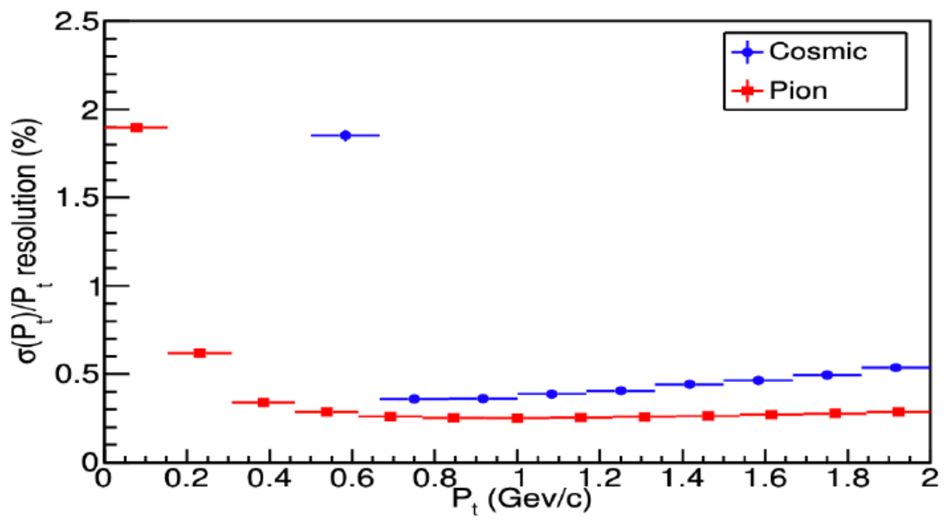


(Hopefully not) the end

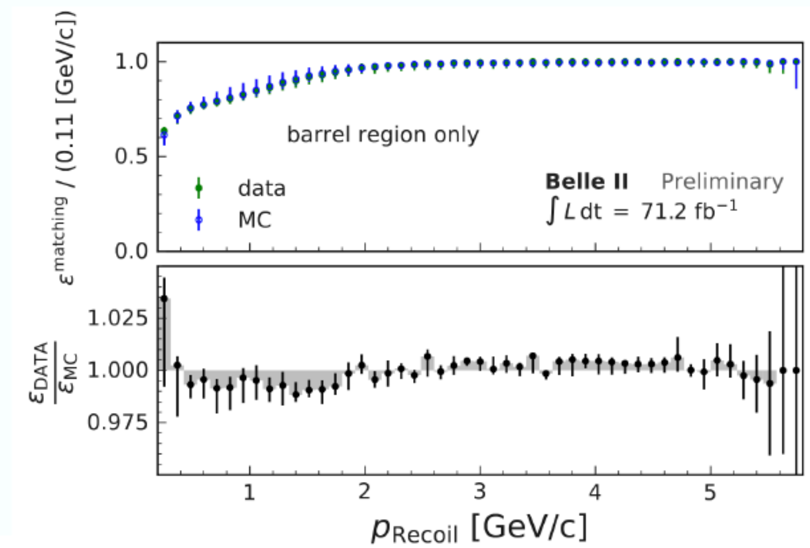
Performance



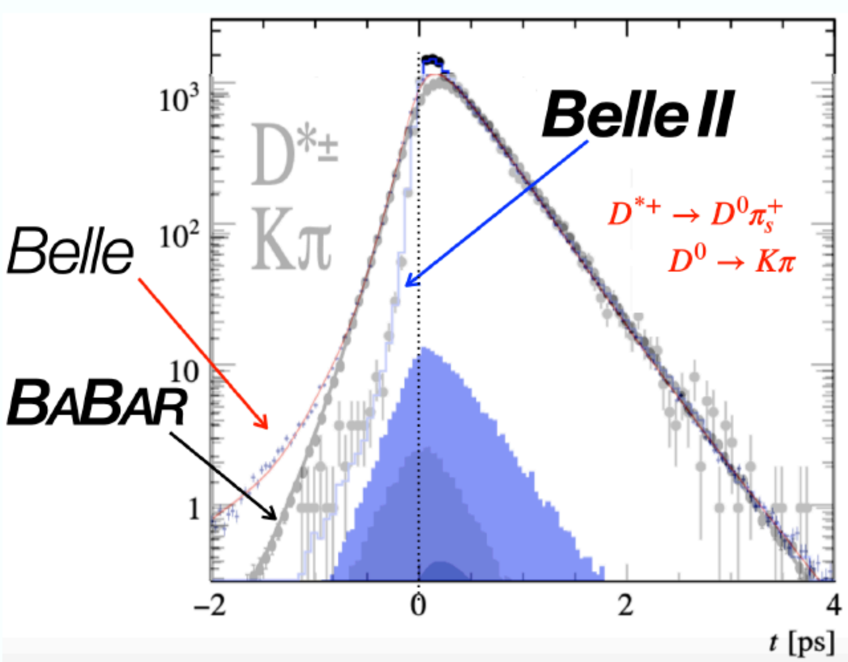
PID similar to Belle



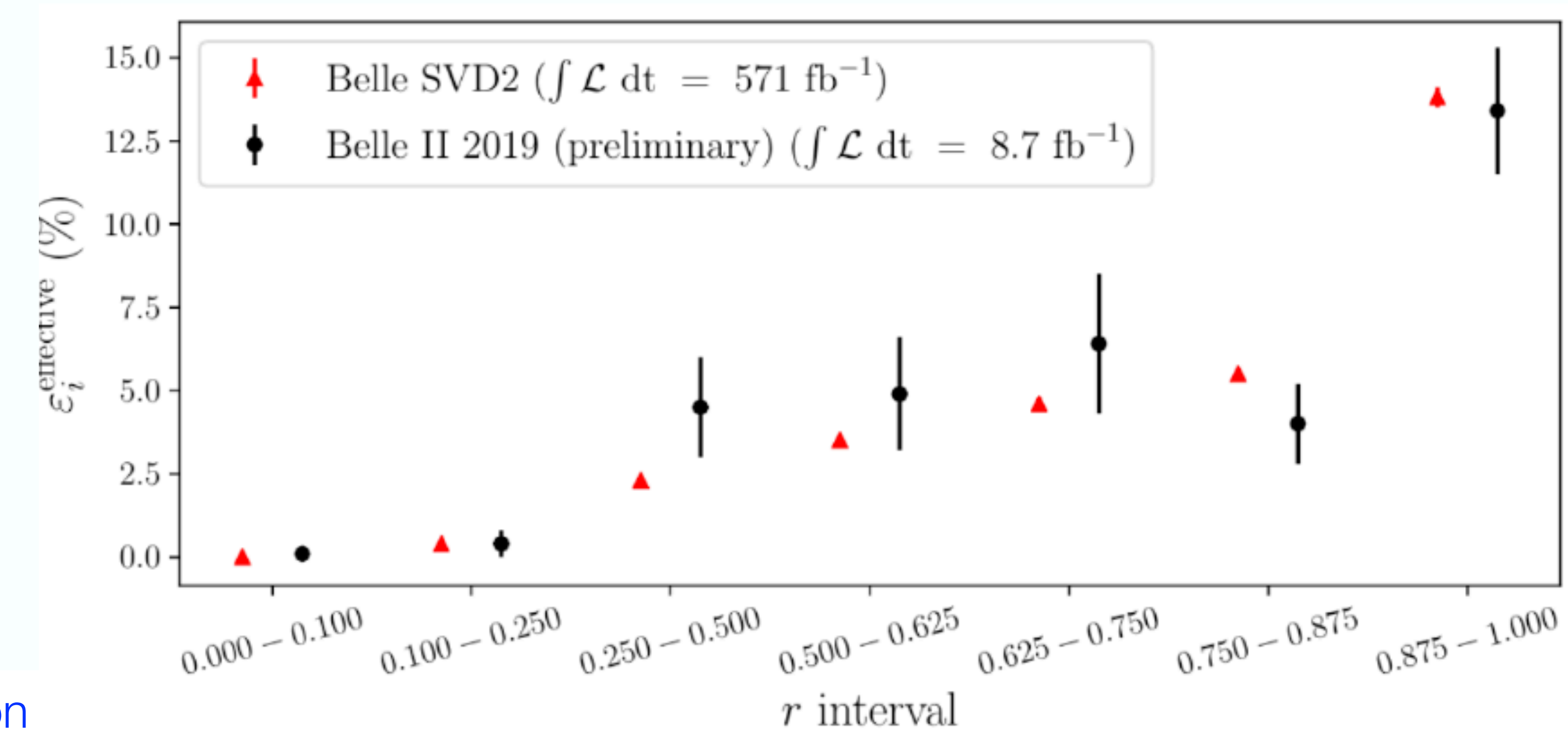
Momentum resolution 20% better than Belle



High photon efficiency,



Nearly 2x better decay-time resolution than Belle



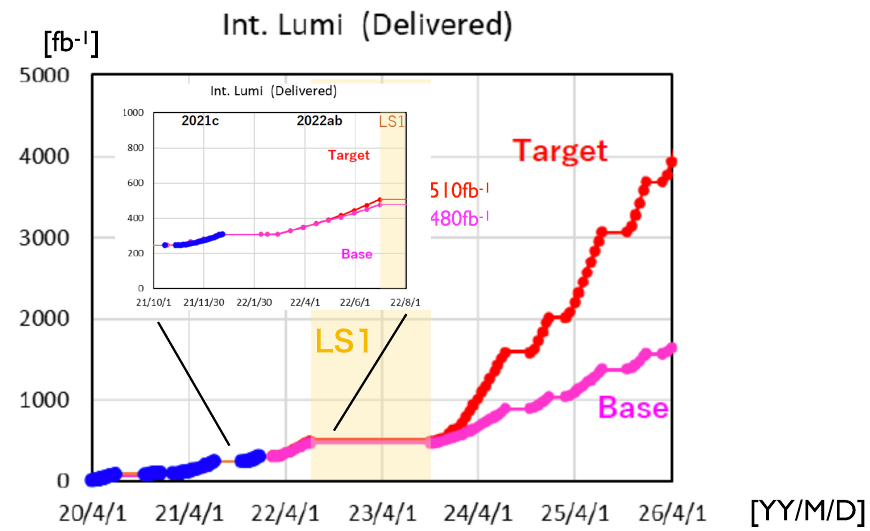
Tagging performance similar to Belle and improving

Future

Projection of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run



- We start long shutdown 1 (LS1) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvement works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond

Belle II Collaboration

Abstract

We describe the physics potential of the Belle II experiment with electron-positron data corresponding to integrated luminosities of 1 ab^{-1} to 50 ab^{-1}. We discuss Belle II's unique capabilities in reconstructing neutral particles, neutrinos and other "invisible" particles, and inclusive final states to probe non-standard-model physics. We project sensitivities for compelling measurements that are of primary relevance and where Belle II reach is unique or world leading.

arxiv:2207.06307

- Executive summary of Belle II/SuperKEKB White Papers, https://arxiv.org/abs/2203.10203
- Opportunities for Precision QCD at Belle II, https://arxiv.org/abs/2204.02280
- Charged Lepton Flavor Violation in the Tau Sector (joint paper of Belle II and other future experiments), https://arxiv.org/abs/2203.14919
- Dark Sector (joint paper of Belle II and other intensity frontier experiments), https://arxiv.org/abs/2207.00597
- Belle II Detector Upgrades White Paper, https://arxiv.org/abs/2203.11349
- Belle II User-based GRID analysis, https://arxiv.org/abs/2203.07564
- Beam Background Expectations for Belle II at SuperKEKB, http://arxiv.org/abs/2203.05731
- SuperKEKB Electron Polarization Upgrade White Paper, https://arxiv.org/abs/2205.12847
- Future HEP Computing Challenges (Belle II/DUNE joint paper), https://arxiv.org/abs/2203.07237
- Physics reach of a long-lived particle detector at Belle II, https://arxiv.org/abs/2105.12962