# Belle II — Intensity, the quark way

Diego Tonelli — INFN Trieste

*BNL Seminar, May 12, 2023*

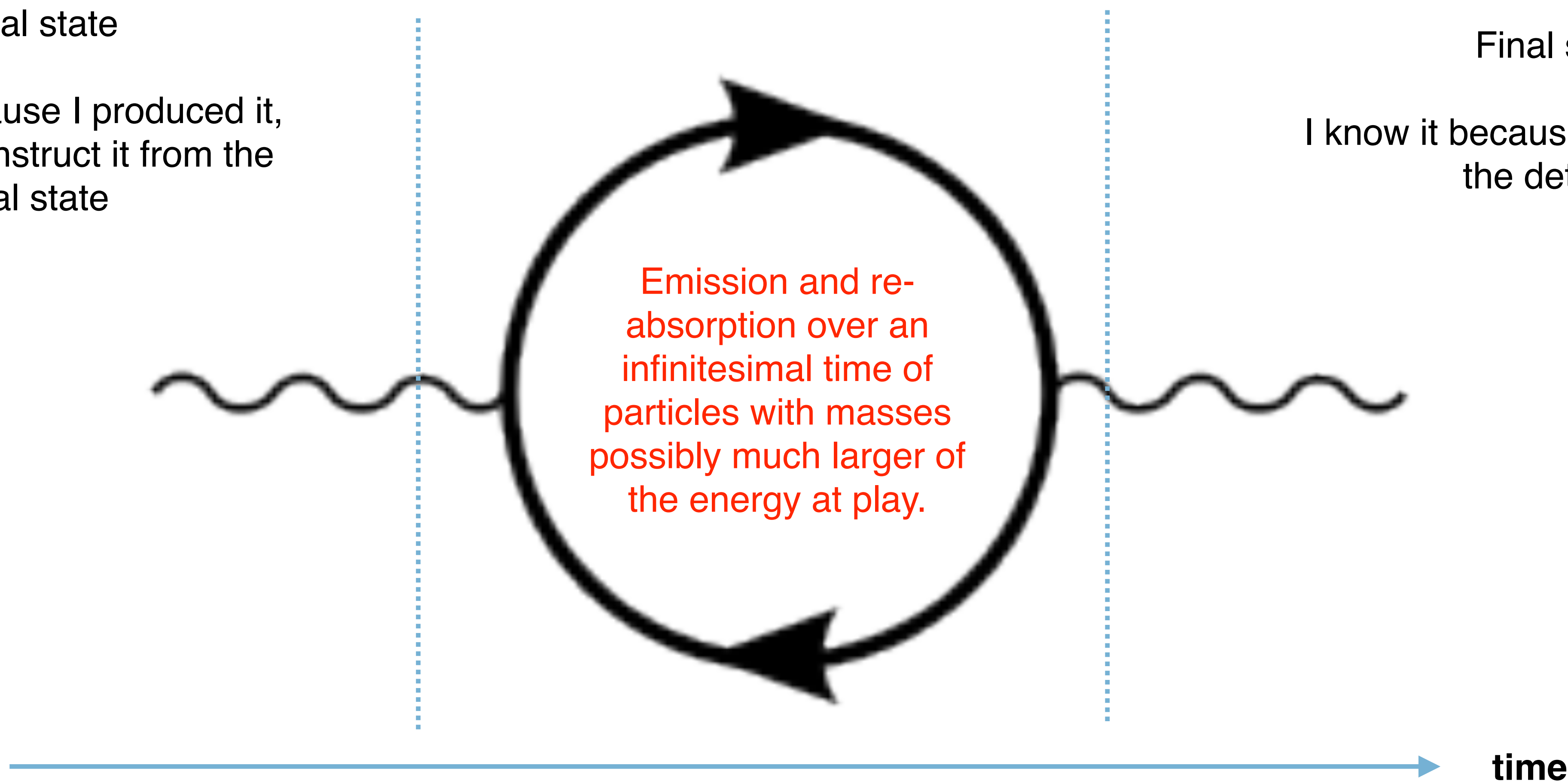
# The precision frontier

Initial state

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

Final state

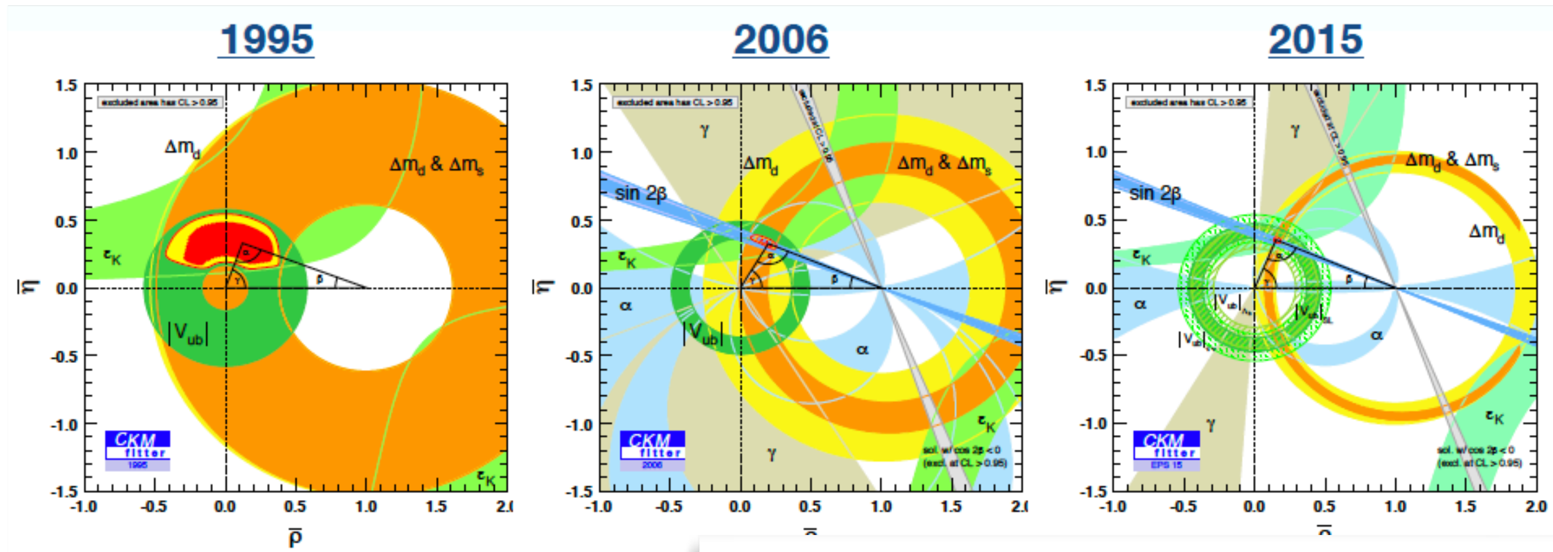
I know it because I observe it in the detector




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

# Why we do this

# Isn’t the fun already over?




## B-factories confirm matter-antimatter asymmetry; leads to 2008 Nobel Prize in Physics

See also: *Nobel press release* *SLAC Today* *Nature* *Science* *Symmetry Magazine*
Watch the Nobel lectures on video: Kobayashi, Maskawa, and Nambu

Ian Aitchison, Ray Cowan, and Owen Long for the BABAR Collaboration, Menlo Park, California, USA. Updated Monday, December 8, 2008

### Introduction

On October 7th, the Nobel committee announced that half of the 2008 Nobel Prize in Physics was awarded to Makoto Kobayashi and Toshihide Maskawa for their theory which simultaneously explained the source of matter/antimatter asymmetries in particle interactions and predicted the existence of the third

Recipients of the 2008 Nobel Prize in Physics. From left: Yoichiro Nambu (Enrico Fermi Institute, University of Chicago, USA), Makoto Kobayashi (High Energy Accelerator Research Organization (KEK), Tsukuba, Japan), and Toshihide Maskawa (Yukawa Institute for Theoretical Physics (YITP), Kyoto University, Japan).

Springer Link

Home > The European Physical Journal C > Article

Review | Open Access | Published: 19 November 2014

## The Physics of the B Factories

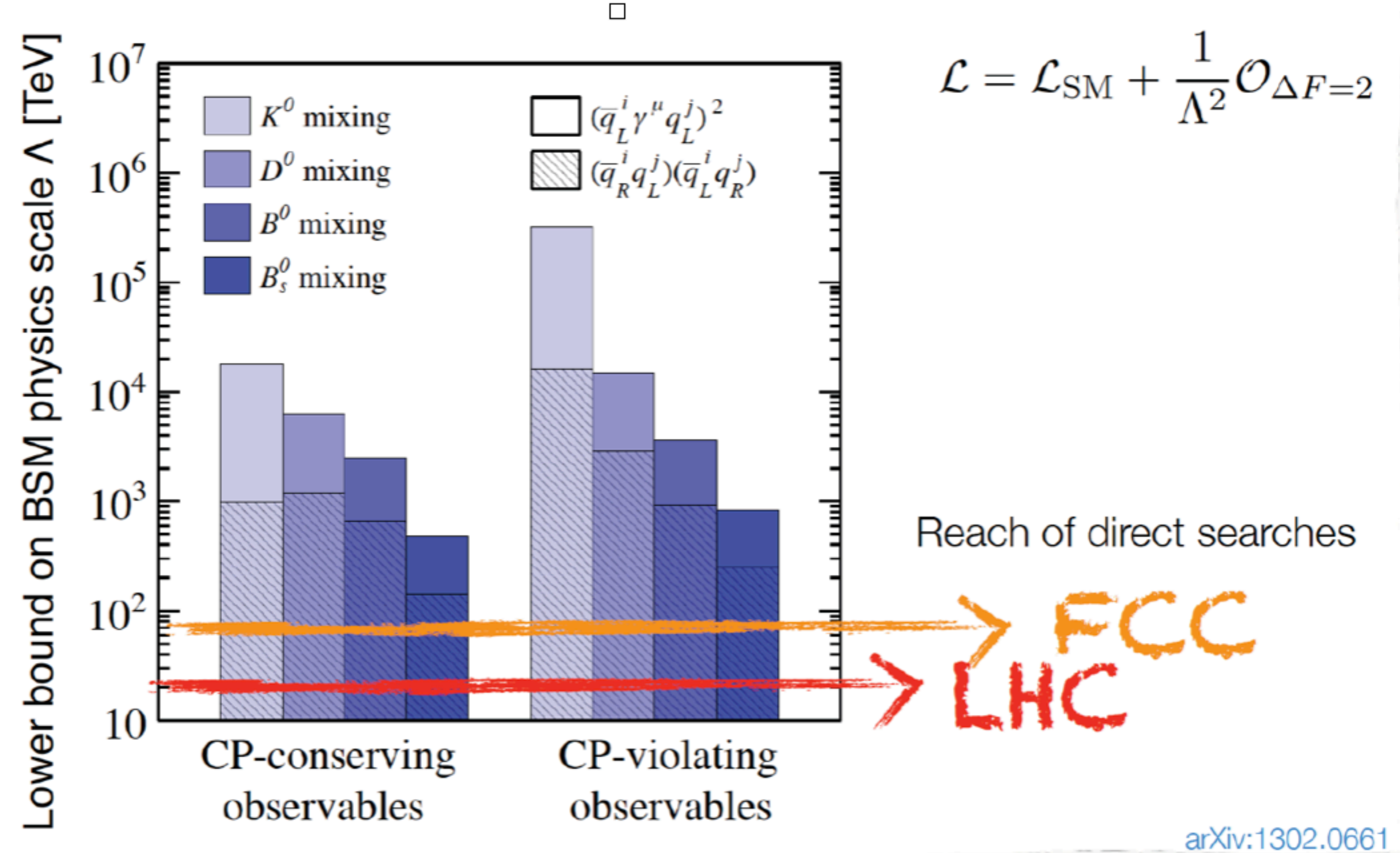
A. J. Bevan, B. Golob, Th. Mannel, S. Prell, B. D. Yabsley, H. Aihara, F. Anulli, N. Arnaud, T. Aushev, M. Beneke, J. Beringer, F. Bianchi, I. I. Bigi, M. Bona, N. Brambilla, J. Brodzicka, P. Chang, M. J. Charles, C. H. Cheng, H.-Y. Cheng, R. Chistov, P. Colangelo, J. P. Coleman, A. Drutskoy, ... D. Žontar

+ Show authors

*The European Physical Journal C* **74**, Article number: 3026 (2014) | Cite this article

# Gotta finish the job

CKM mechanism predicts all observations to within 10-15% uncertainties.
Closing the gap can inform us about what happens at very high scales



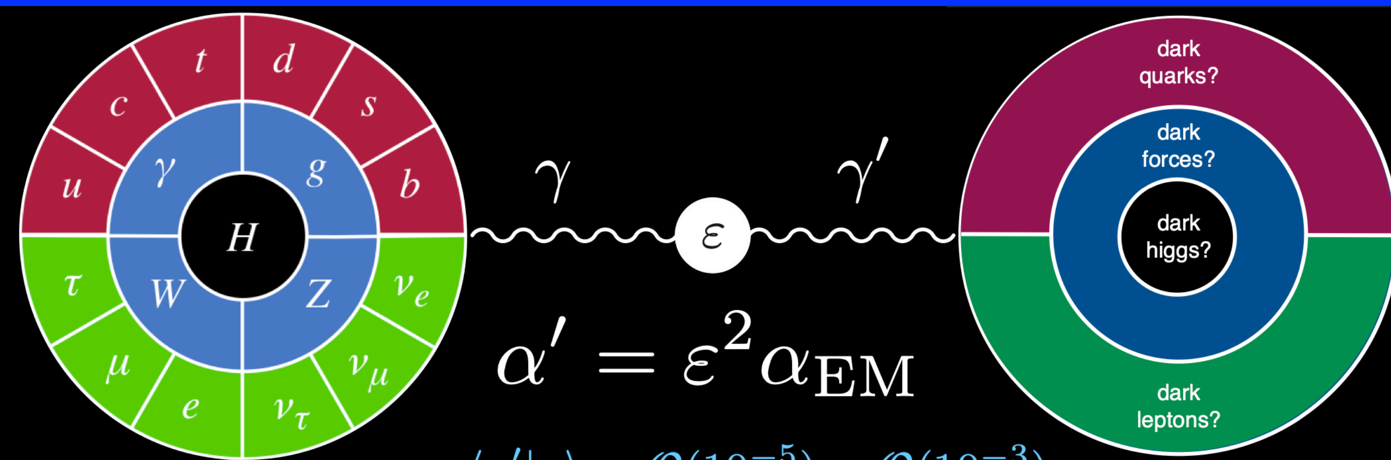

Explore suppressed processes approaching precision of favored ones.

# …and a whole new job just started..

Dark matter is likely to exist, and WIMP searches are empty handed.

Dark sectors solves to expt/pheno puzzles (e.g., strong CP)

Dark sector shares no charge with ordinary matter — it is inherently stable




$$\alpha' = \varepsilon^2 \alpha_{\mathrm{EM}}$$

$$\varepsilon \equiv \langle \gamma' | \gamma \rangle \approx \mathcal{O}(10^{-5}) - \mathcal{O}(10^{-3})$$

If the sectors are connected at some scale (e.g. if they are both part of a GUT), then quantum mechanical mixing, e.g., between the photon and dark photon, will occur resulting in feeble interactions between ordinary and dark matter—opening the door for DM below the EW scale.

Only a few options of DS-SM couplings do not violate SM symmetries, making systematic exploration possible

Much of the naturally interesting parameter space still unexplored

Belle II has unique reach in the MeV to few GeV range

# In a nutshell: if any nature's surprise is there…

We wanna be these guys

rather than those guys

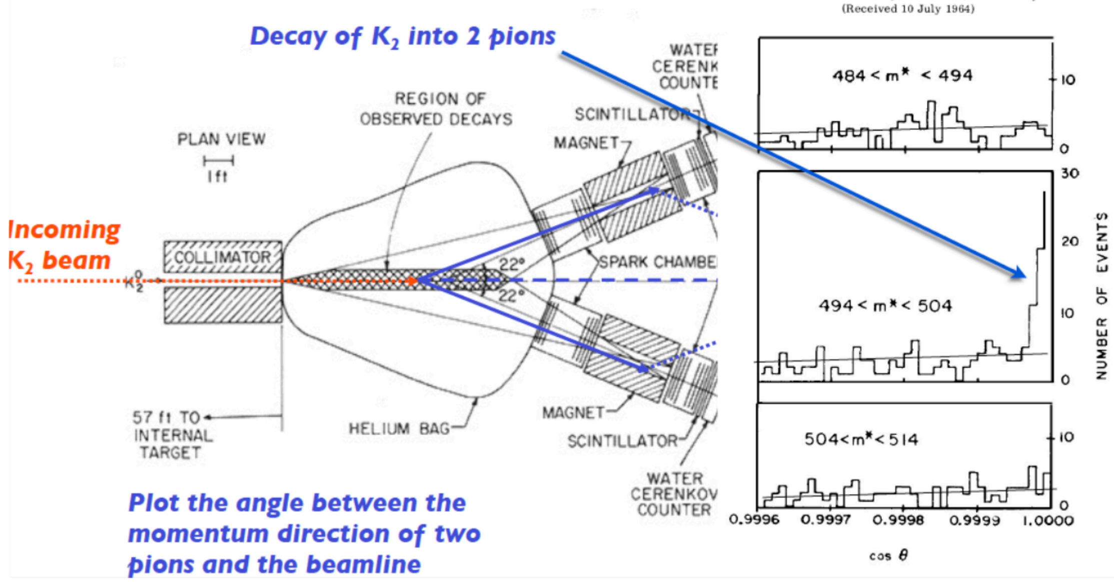
## Cronin and Fitch

Essential idea: Look for (CP violating) $K_2 \to \pi^+\pi^-$ decays 20 meters away from $K^0$ production point

EVIDENCE FOR THE 2π DECAY OF THE $K_2^0$ MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey

(Received 10 July 1964)

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## USSR had almost gotten there 3 years earlier..

"[…] A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky."
L. Okun, "Spacetime and vacuum as seen from Moscow"

VOLUME 6, NUMBER 10 PHYSICAL REVIEW LETTERS MAY 15, 1961

DECAY PROPERTIES OF $K_2^0$ MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.

(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our results on the charge ratio and the degree of the $2\pi$-decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in $K^0$ decay.

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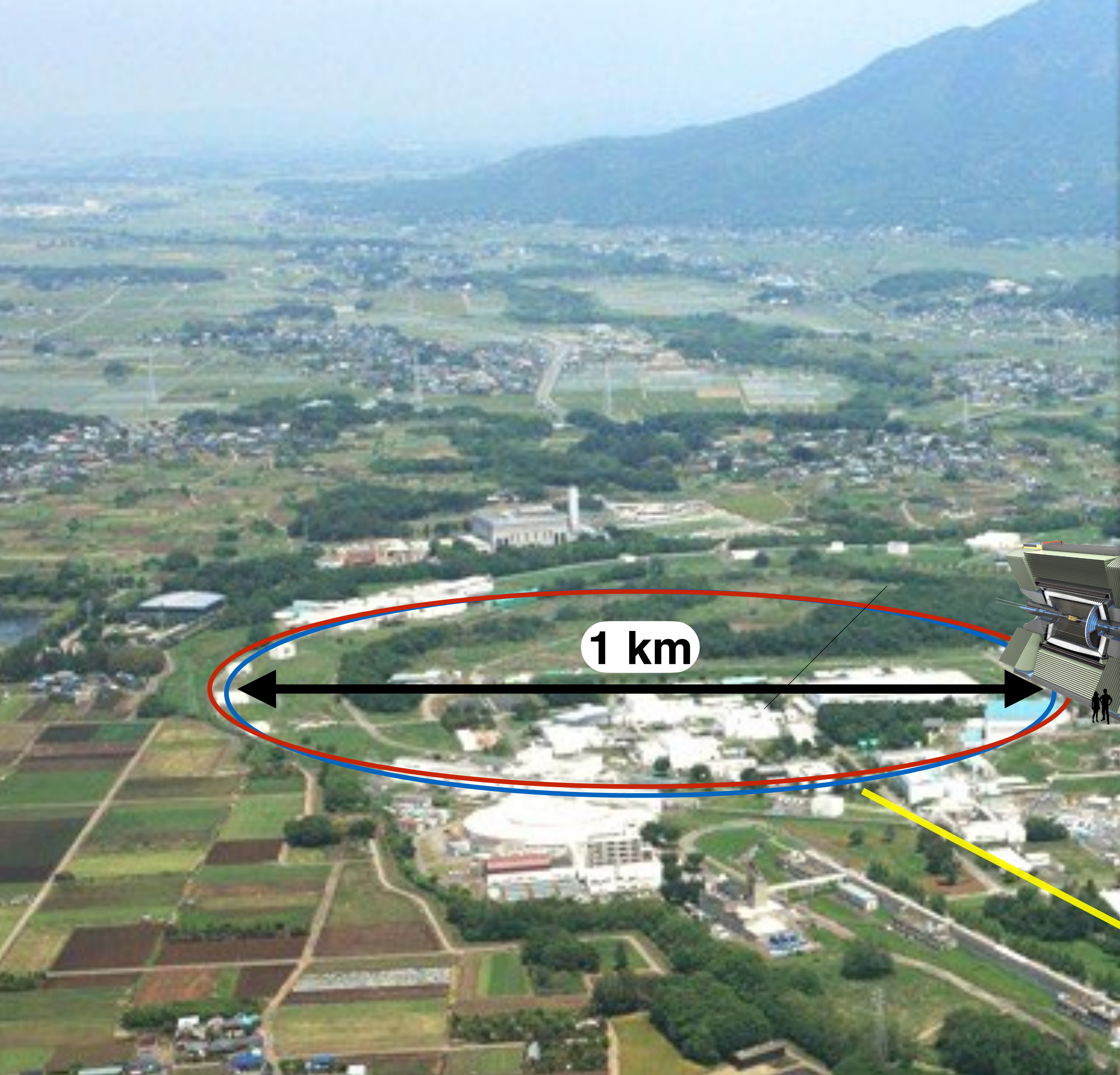
And even if there won't be no surprise, our exploration will guide and inform future research for decades (and it will be a lot of fun)

# Who we are

# The experiment




## 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

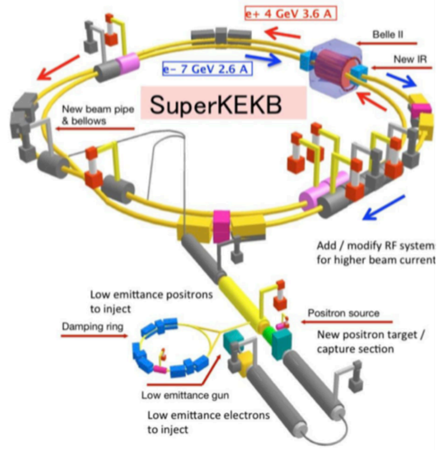
Achieving 50 nm vertical size requires low emittance and powerful and sophisticate final focus

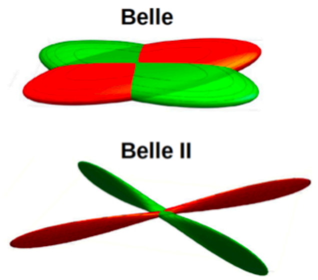
So far 10x below design, improving steadily

$4.7{\times}10^{34}\ cm^{-2}\ Hz$ 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.

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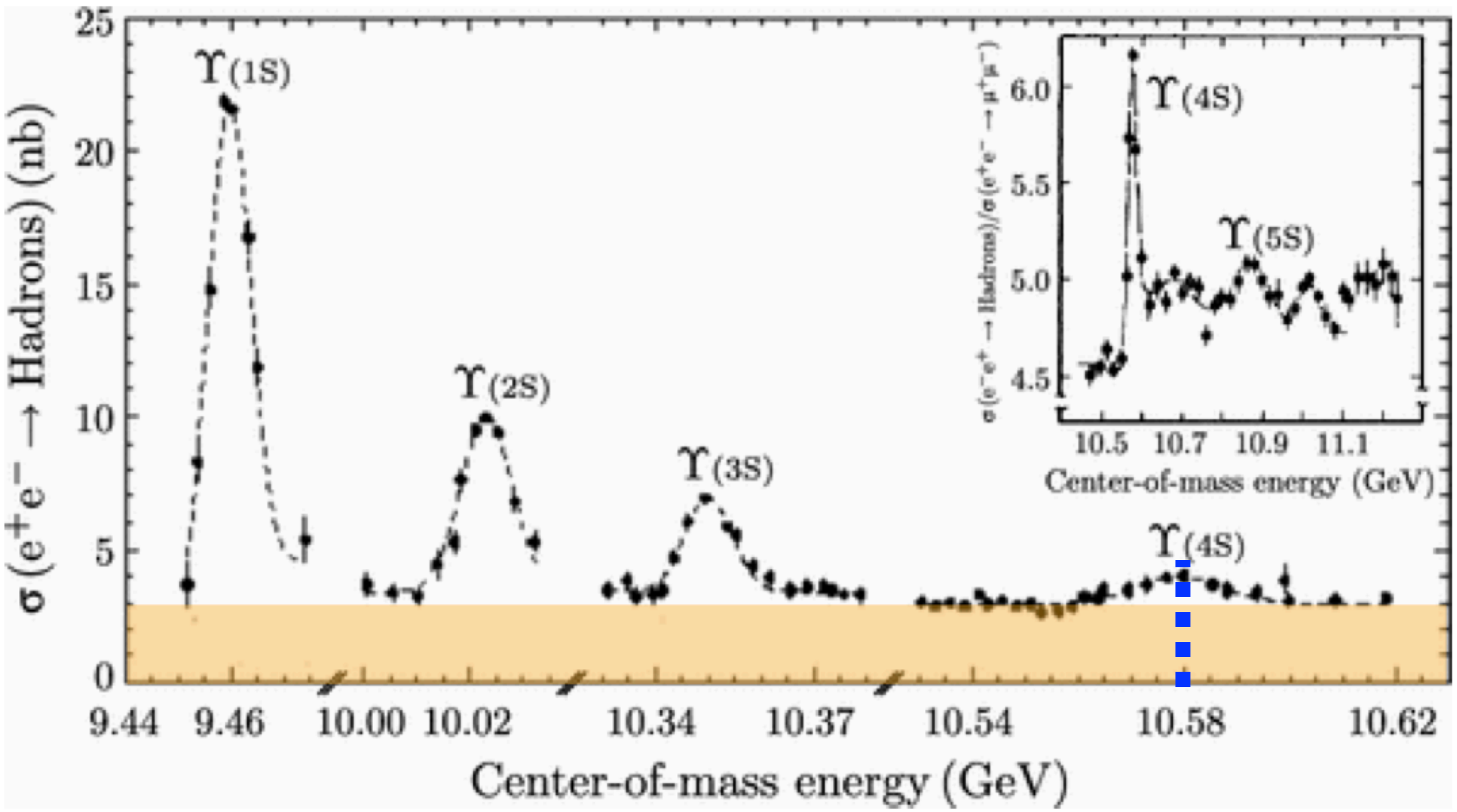
# Uber *B* (and *D*, and *τ*) factory

7 GeV electron on 4 GeV positron at, or around, the Υ(4S) mass



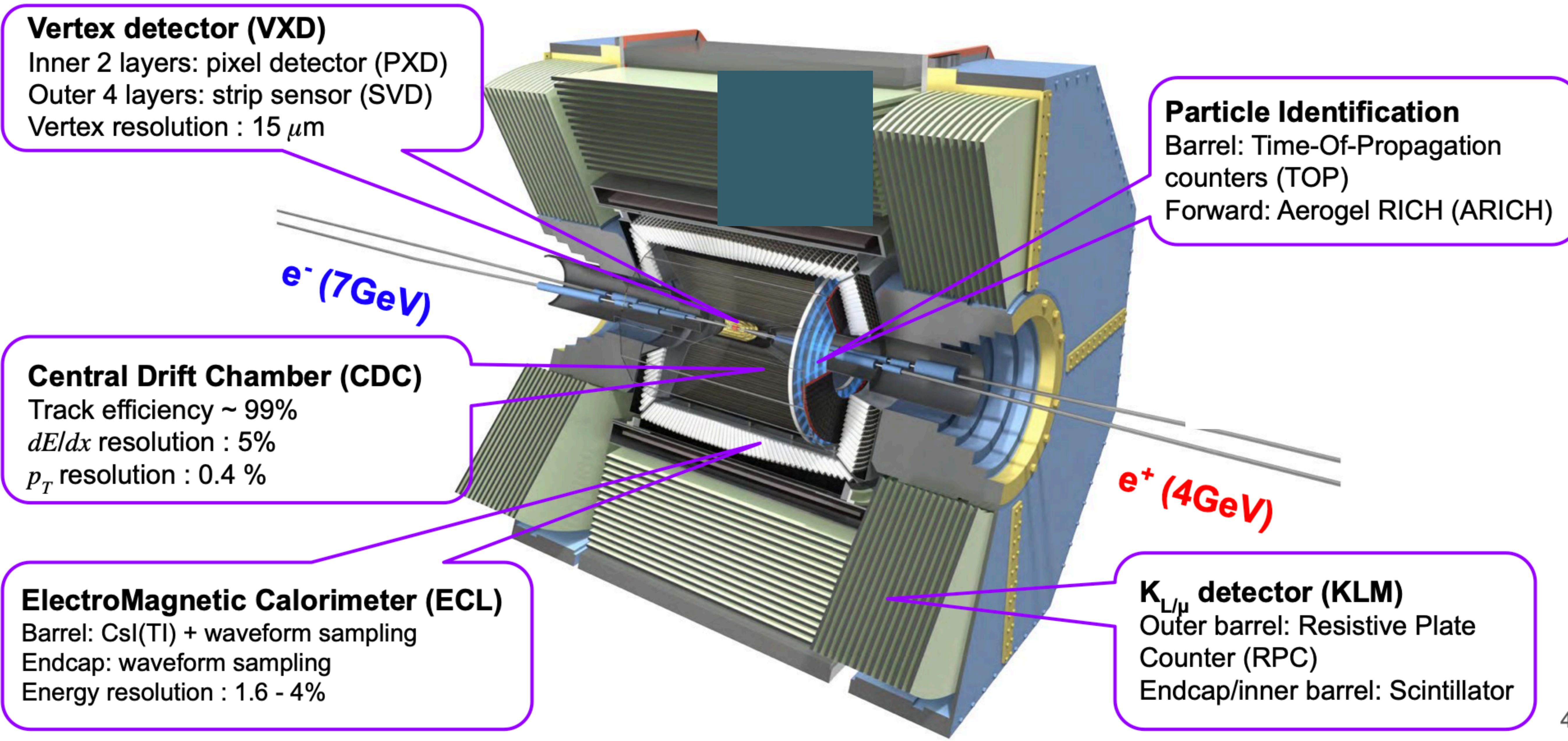

Most collisions are ee → ℓℓ. Discard based on particle multiplicity (but keep ττ and exotic/dark sector signatures!)

Others yield 30 (now) to 600 (design) *BB*, *DD* /second along with 3x light quarks

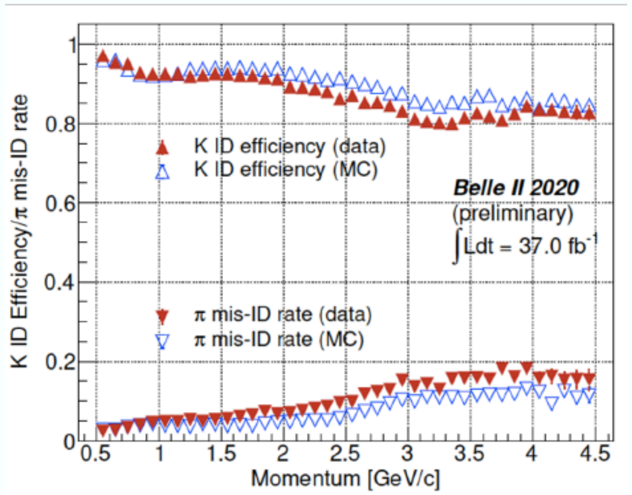
# The instrument

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

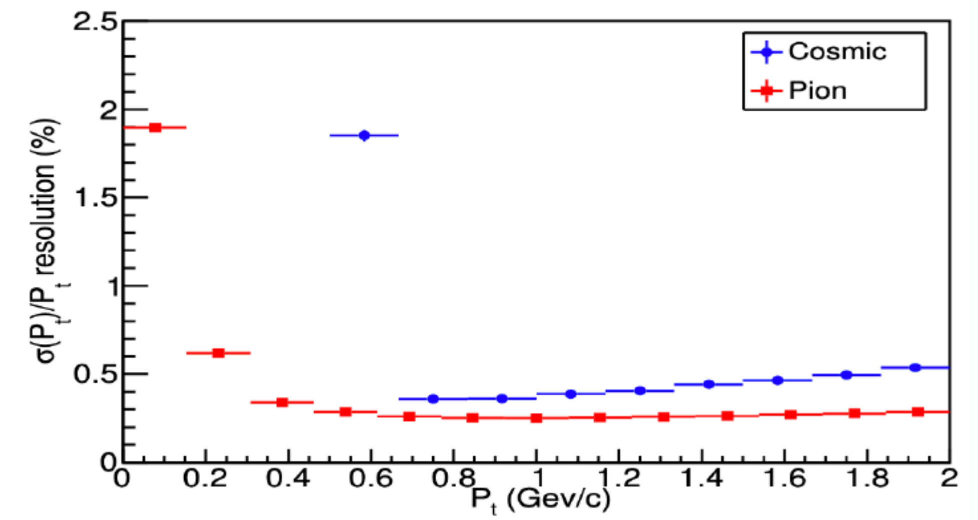
Only structure, magnet and calorimeter crystals are re-used



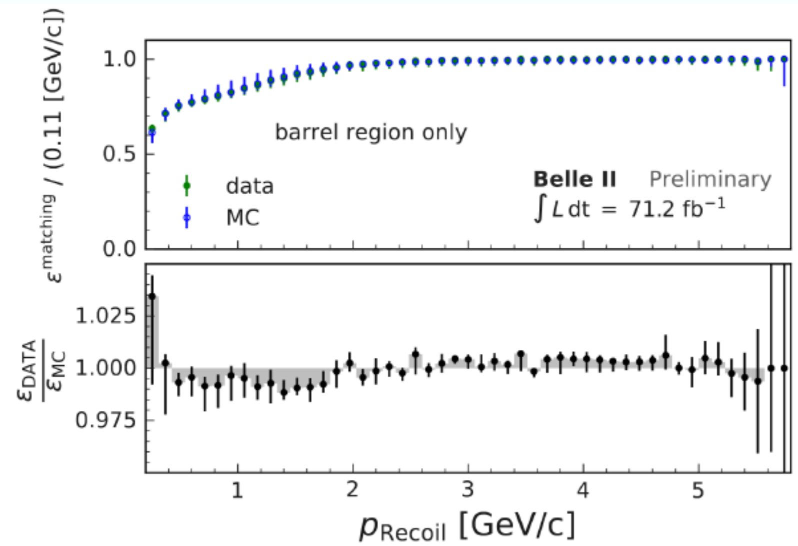
# Performance



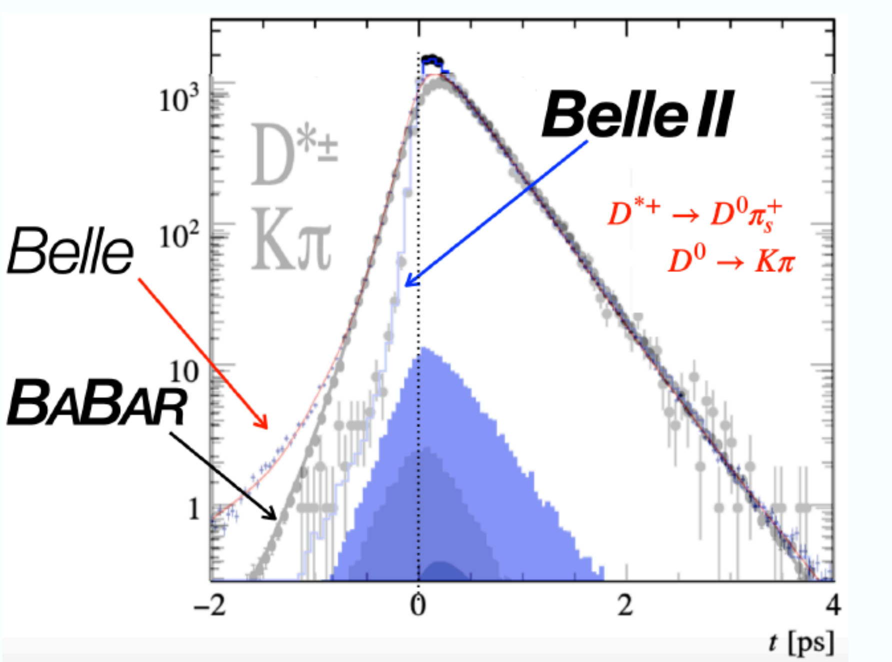

PID similar to Belle



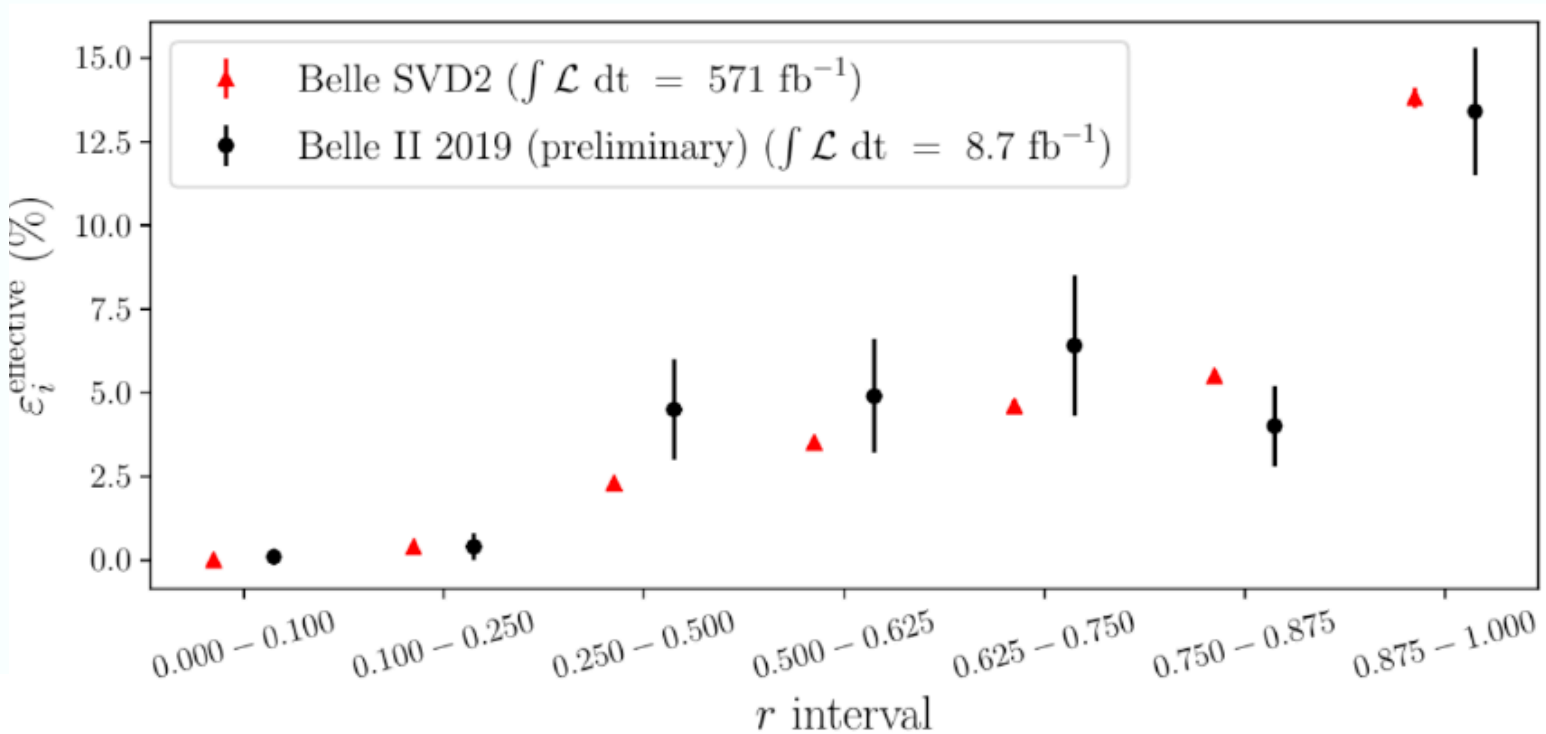

Momentum resolution 20% better than Belle




High photon efficiency,




Nearly 2x better decay-time resolution than Belle




Tagging performance similar to Belle and improving

# Strengths

Point-like particles colliding at *BBbar* threshold: low background and tight kinematic constraints.

Hermetic detector for reconstruction of neutrinos (semileptonic *B*, τ physics), along with invisible or inclusive final states.

Flavor-coherent *B* production — know neutral *B* flavor for 1/3 of neutral *B* for measurements involving time-evolution of oscillating neutral *B* mesons

Nonbiasing trigger for *B* and *D* physics: >95% efficiency and no sculpting of distributions (Dalitz plot analyses, smaller systematics, etc)

Good vertexing, good tracking, good PID, good photon and electron reconstruction, good $K_S$ and $K_L$ reconstruction with ~uniform performance over any final state and kinematic regime.

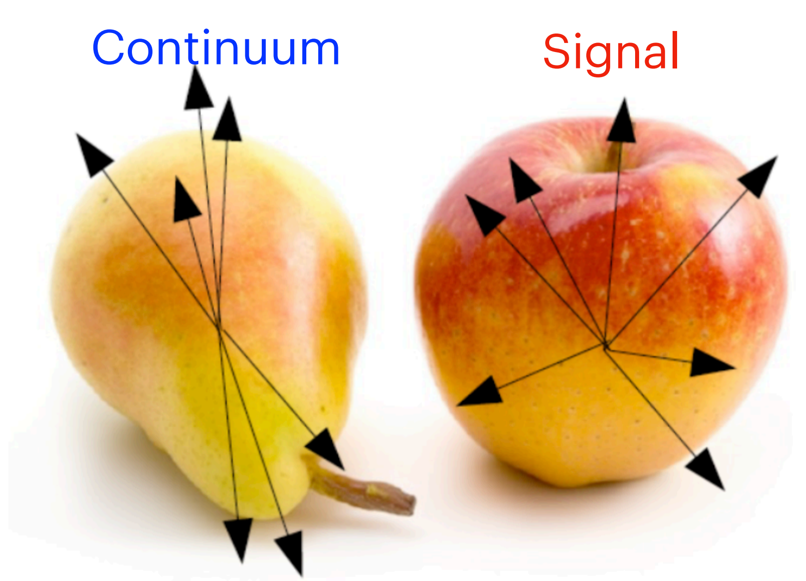
Dedicated low-multiplicity triggers offer unique sensitivity to dark-sector signals that could not be fully exploited at Belle/Babar

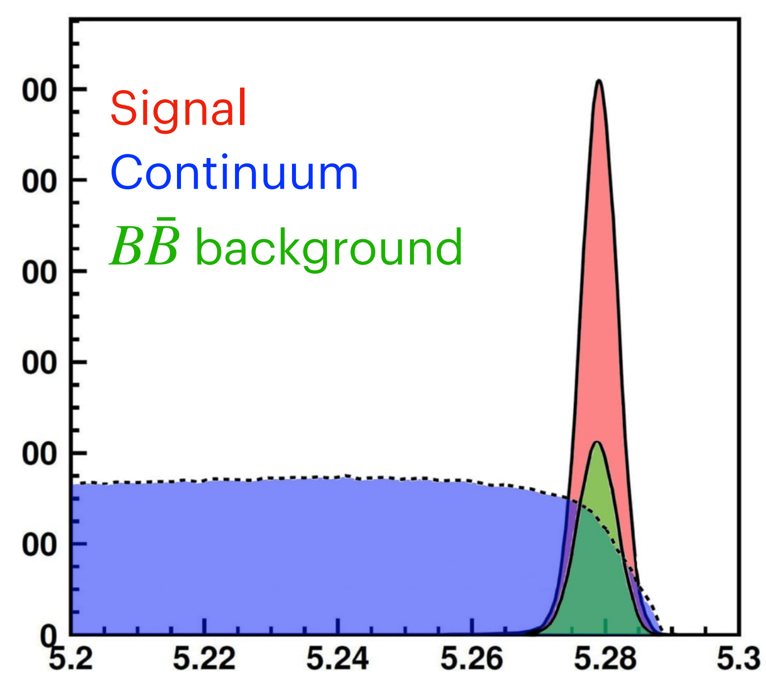
# *B* factory analysis 101

Hadronic events (about 10 tracks/clusters)

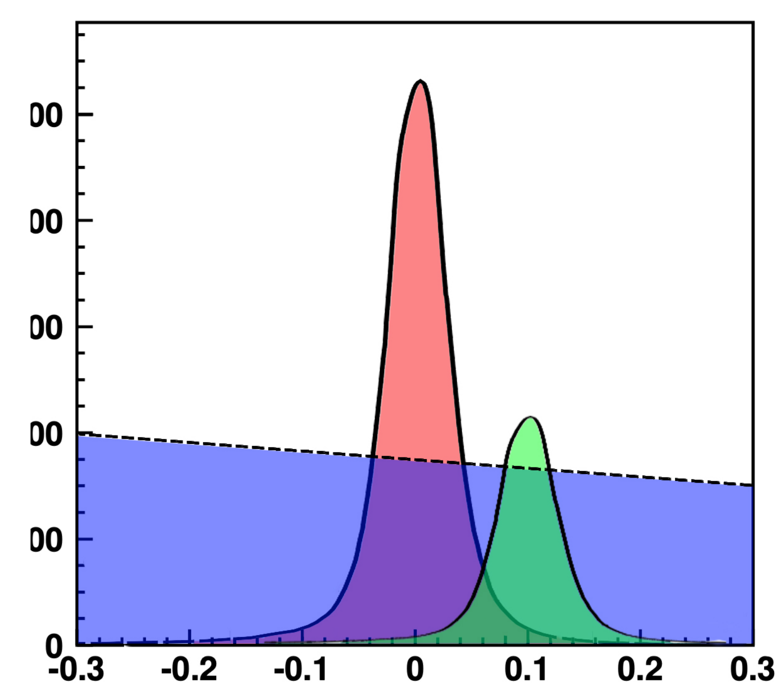
*B* produced at 50-500 per second, no background but low momenta (βγ ~0.3). Fly ~150 micron and decay.

Analysis exploits specifics of on-threshold production: event “shape” and beam-energy constrained kinematics.

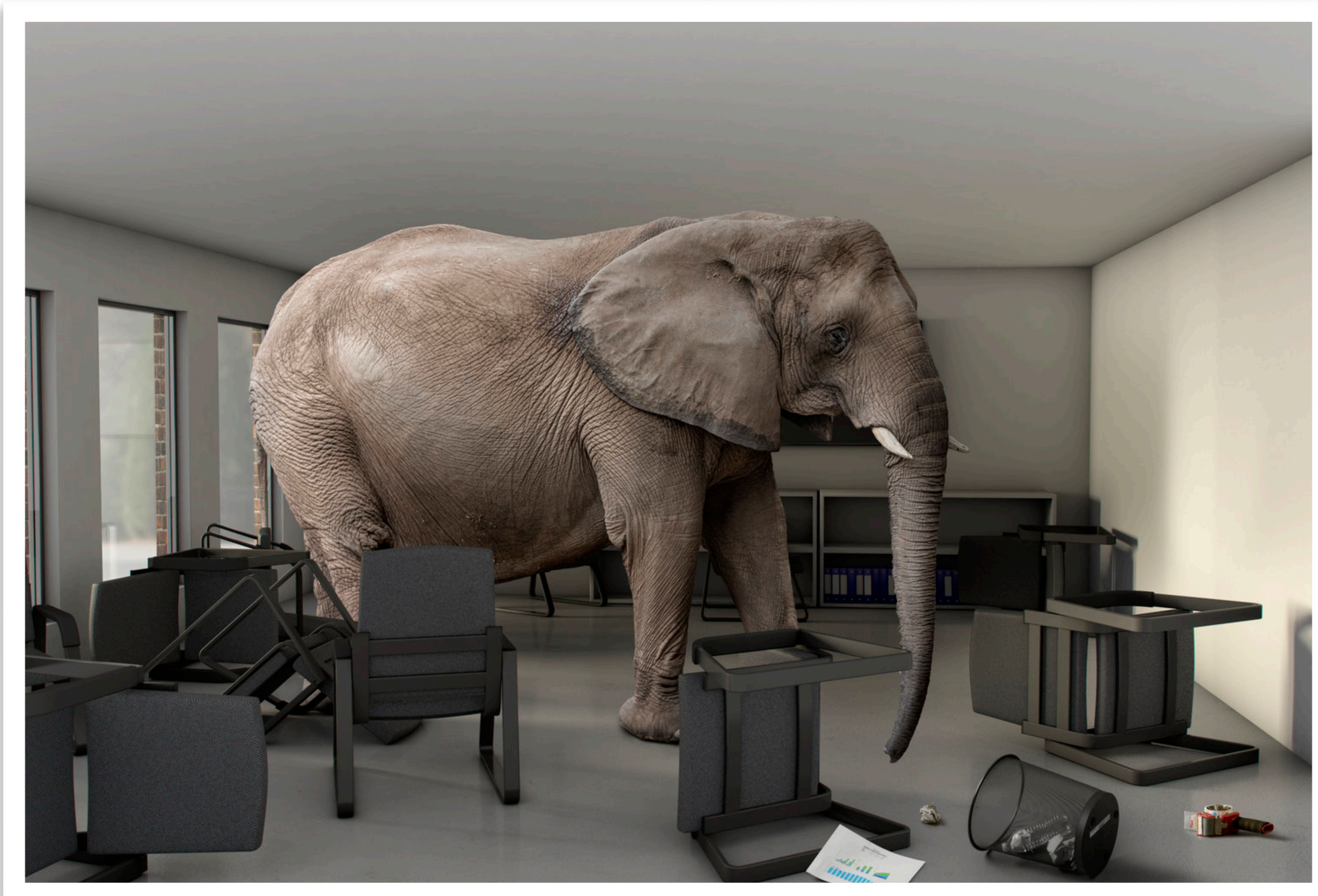



Invariant $B$ mass with $B$ energy replaced by half of the collision energy.




Difference between expected and observed B energy



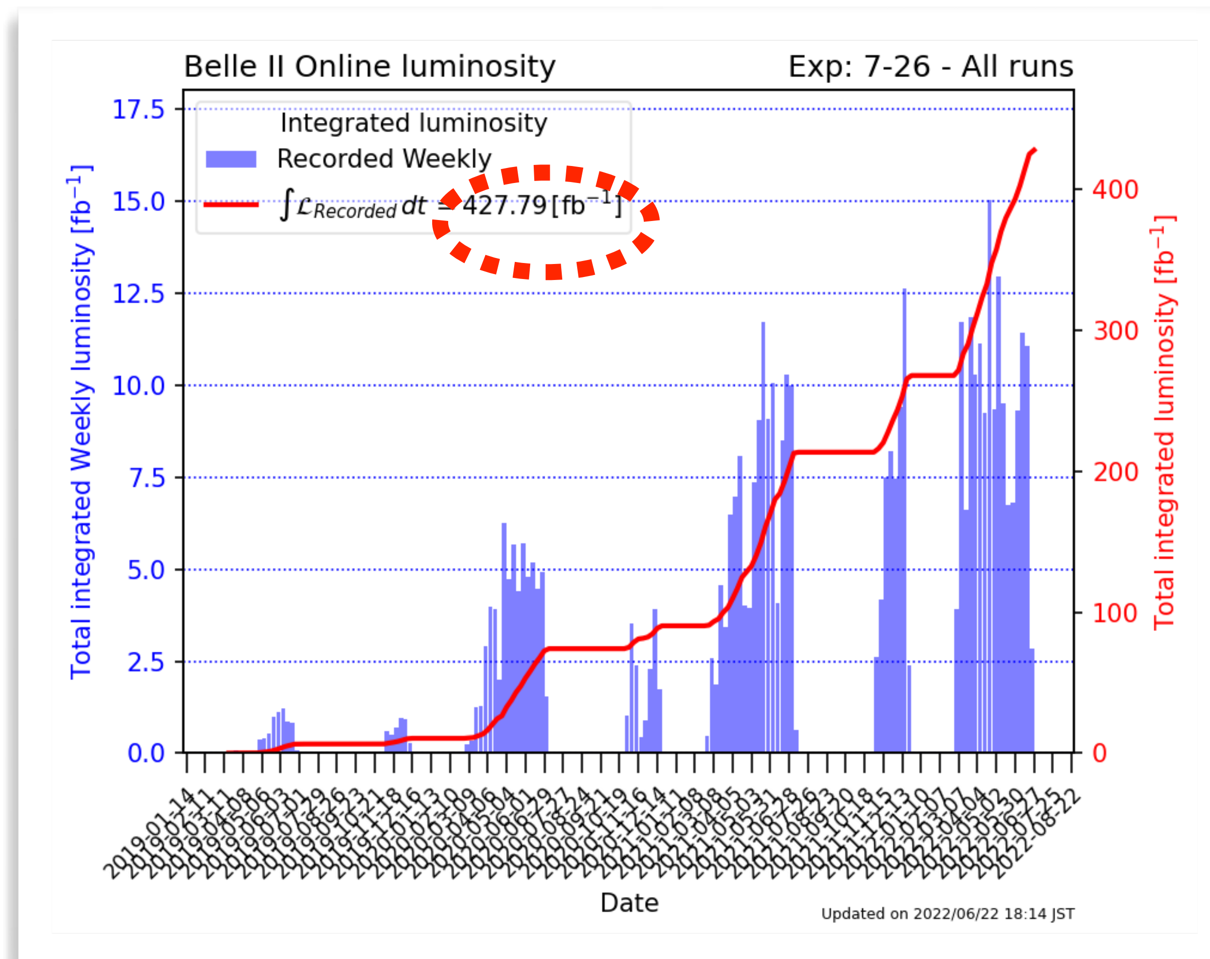
# 428 $fb^{-1}$ after 4 years

Shortcomings in injection, collimation, beam stability, control of beam-backgrounds etc made SuperKEKB luminosity 10x off with respect to plans

Tip: SuperKEKB is exploring uncharted territory.

Many getting addressed as we speak.

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




Is Belle II actually Belle 1/2? And 10 years after, on top of it?

# Against common sense — the bumble-bee approach

*"Until Belle II data set surpasses Belle's, not much physics to do"*

« Tout d'abord poussé par ce qui se fait en aviation, j'ai appliqué aux insectes les lois de la résistance de l'air, et je suis arrivé avec M. Sainte-Laguë à cette conclusion que leur vol est impossible ».

Antoine Magnan — Le vol des insectes — 1934

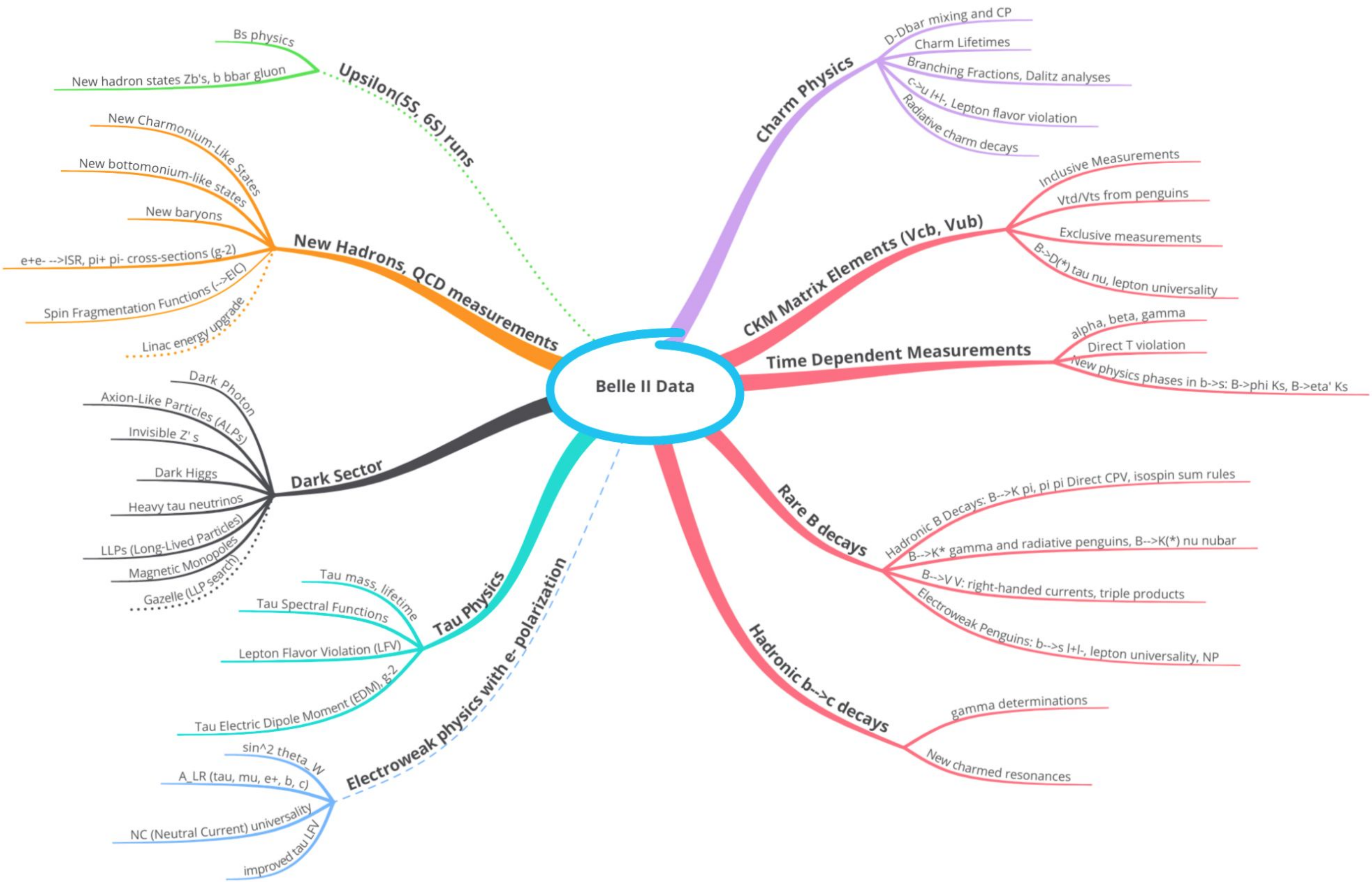
…but the bumble-bee did not know that scientific truth, and kept flying…

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




In the midst of physics ramping: in the past year, 40 new results and quadrupled paper count over previous total.

Today small sampler aimed at underlying relevant “common themes”

# Searching for BSM in $b \to sq\bar{q}$

Hadronic $B$ decays normally are poor probes of BSM as soft gluon exchanges make predictions intractable.

$B \to K\pi$ decays are an exception: dynamical symmetries (isospin, heavy-quark, and SU(3) flavor) relate CP asymmetries and BF into a reliable SM relation

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

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

Holds to 1% precision in the SM.

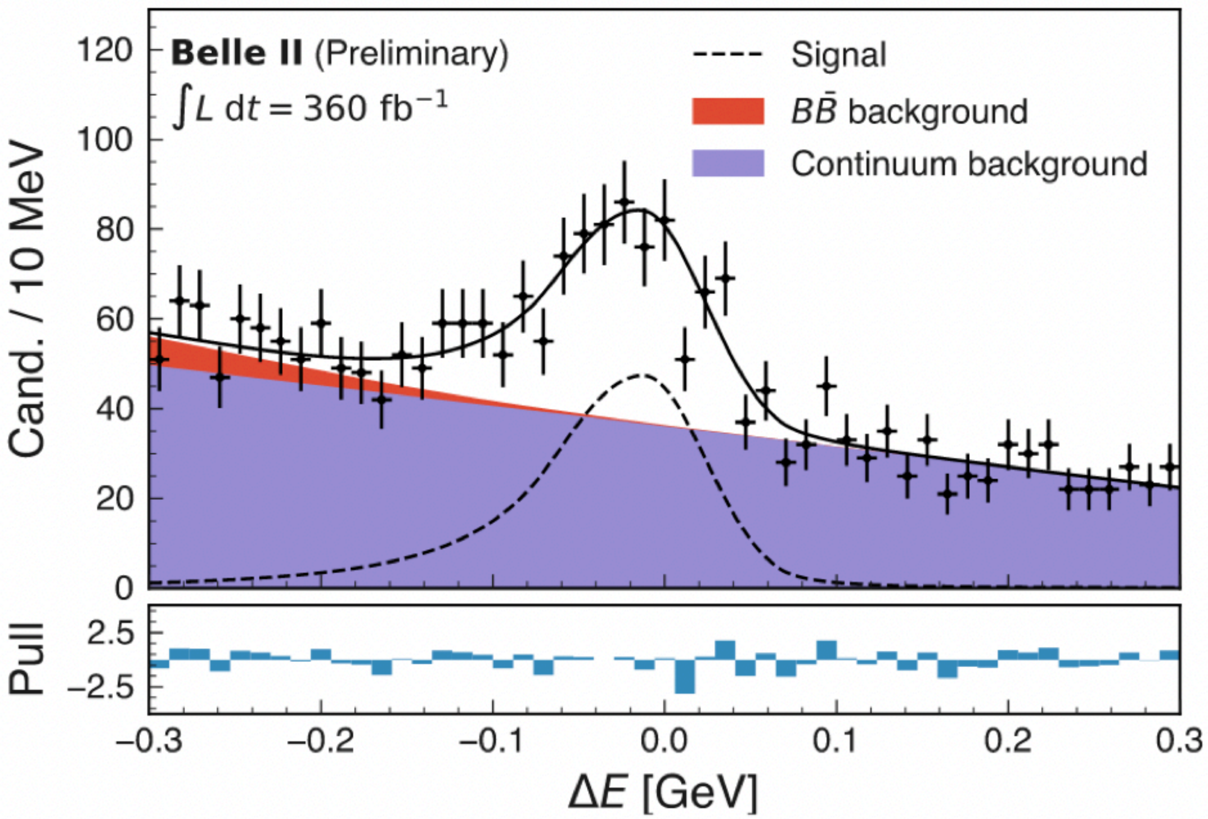
Current experimental precision is 11%, fully limited by $B^0 \to K^0\pi^0$

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

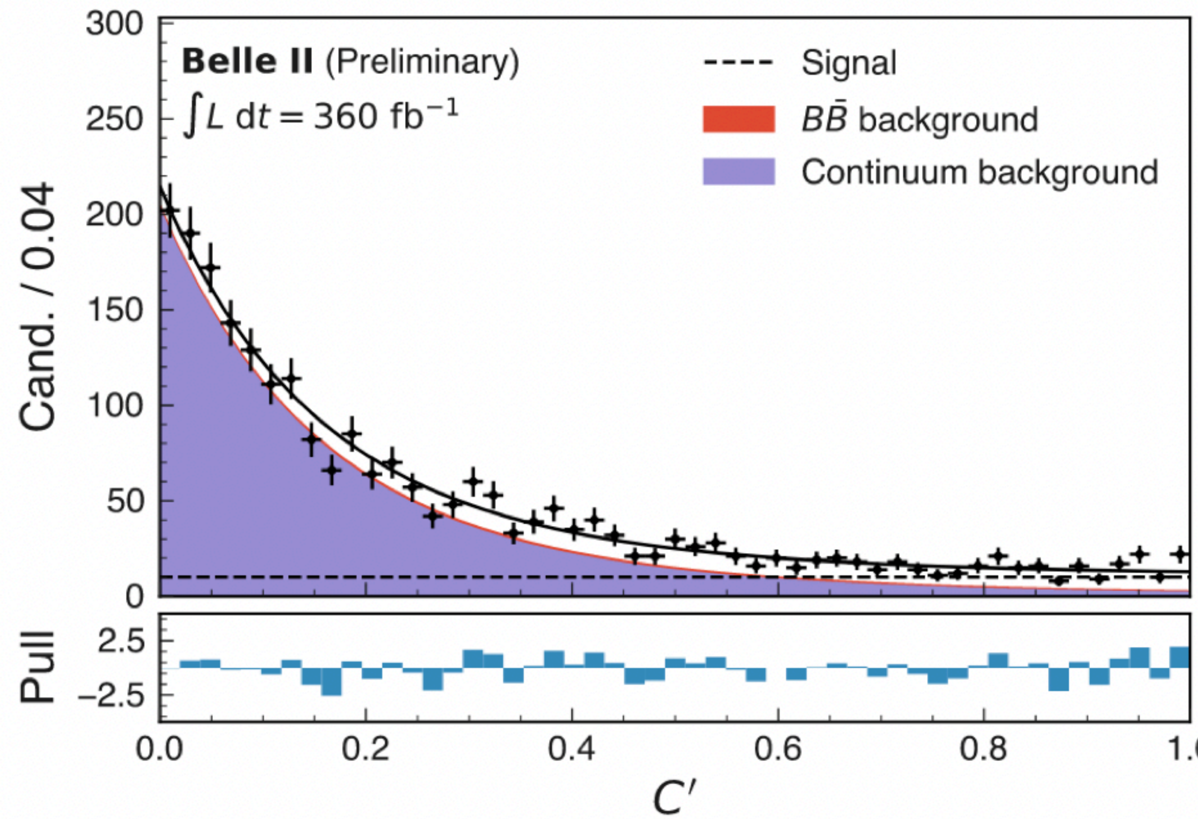
Tell signal (kinematics, vtx, event shape) from background from light-quarks

# 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

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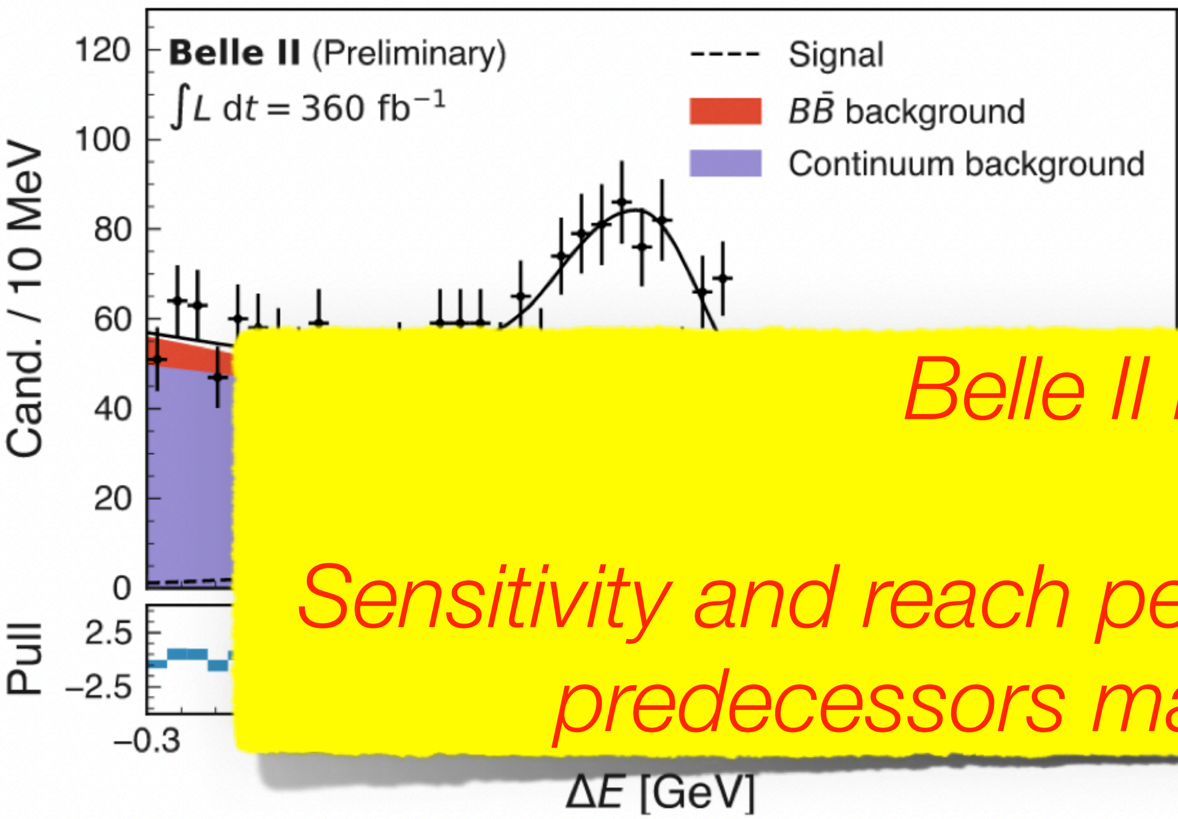


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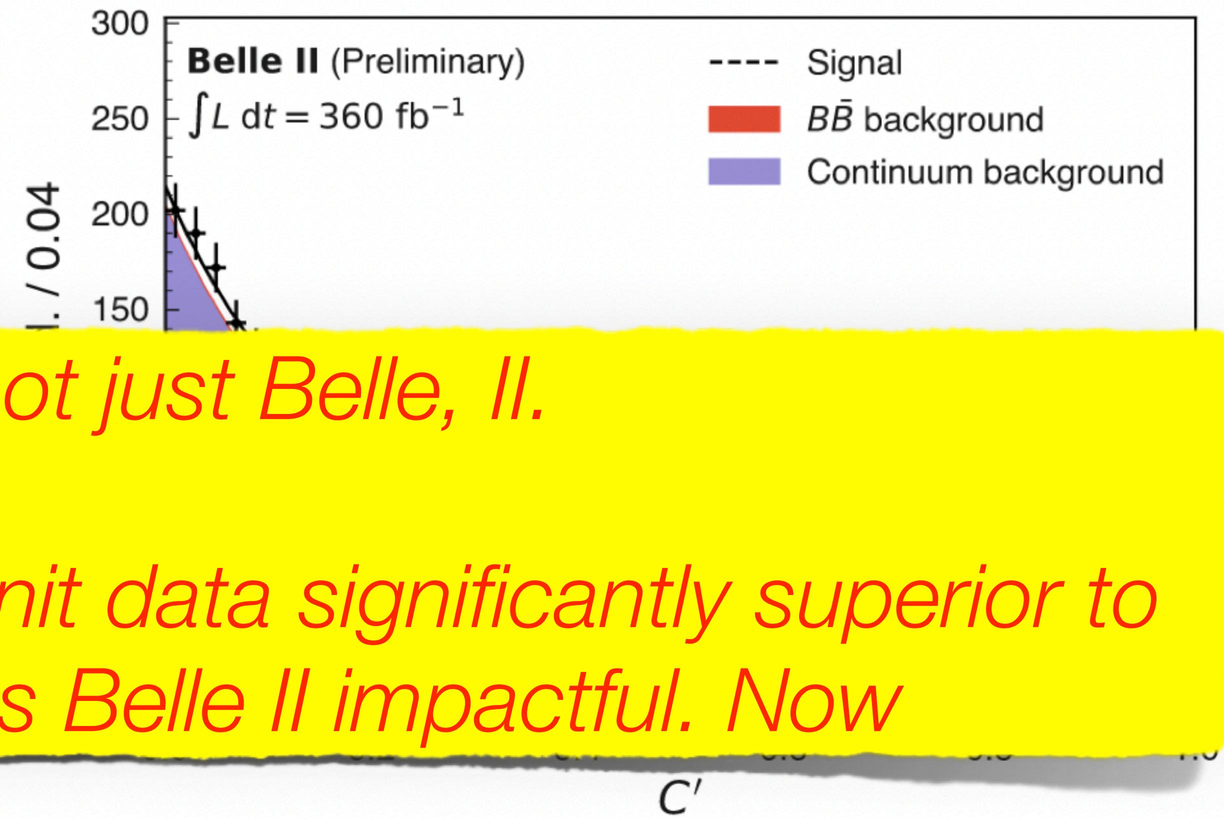


*Belle II is not just Belle, II.*

*Sensitivity and reach per unit data significantly superior to predecessors makes Belle II impactful. Now*

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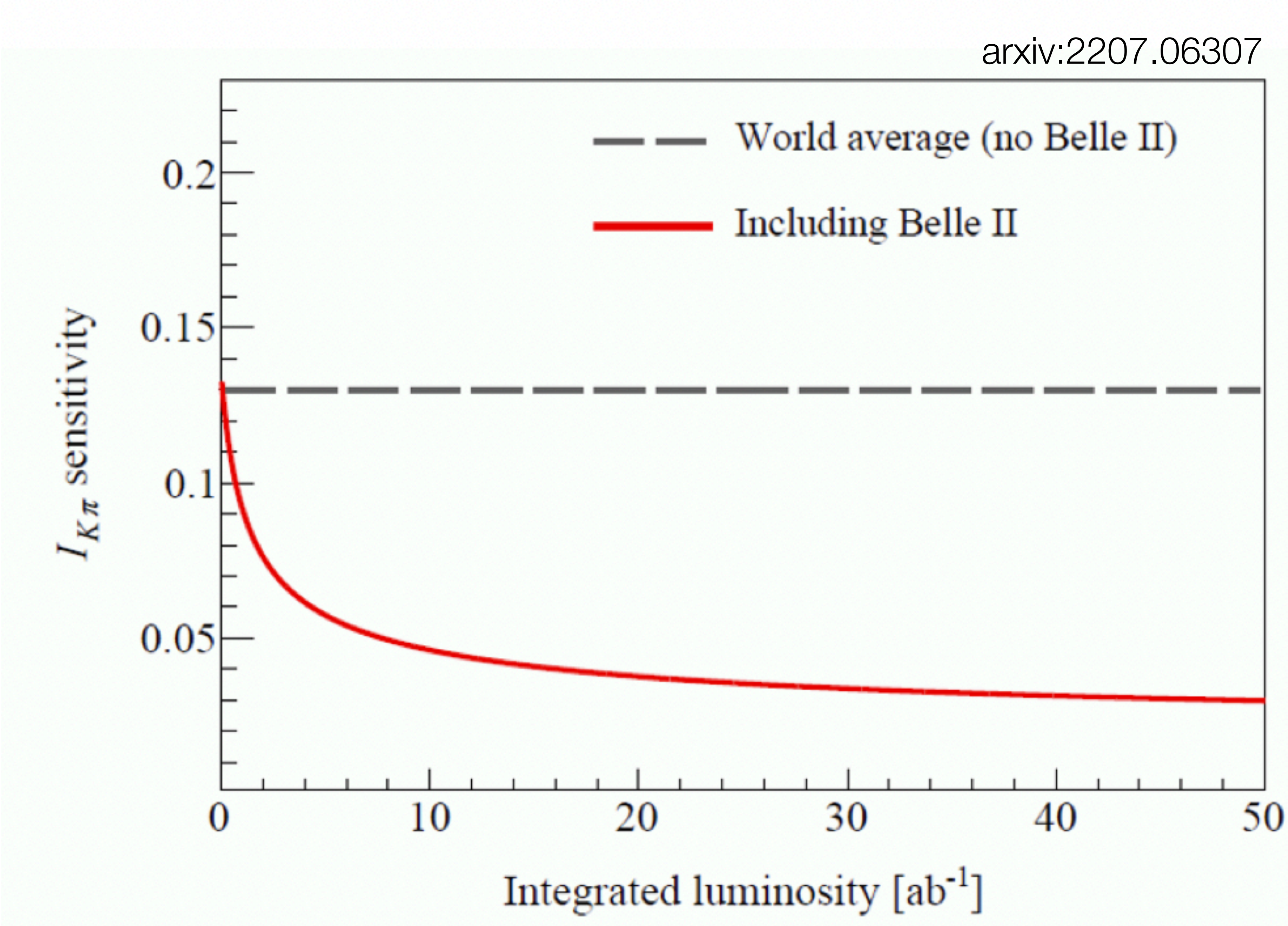
# Isospin sum rule — Belle II impact




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

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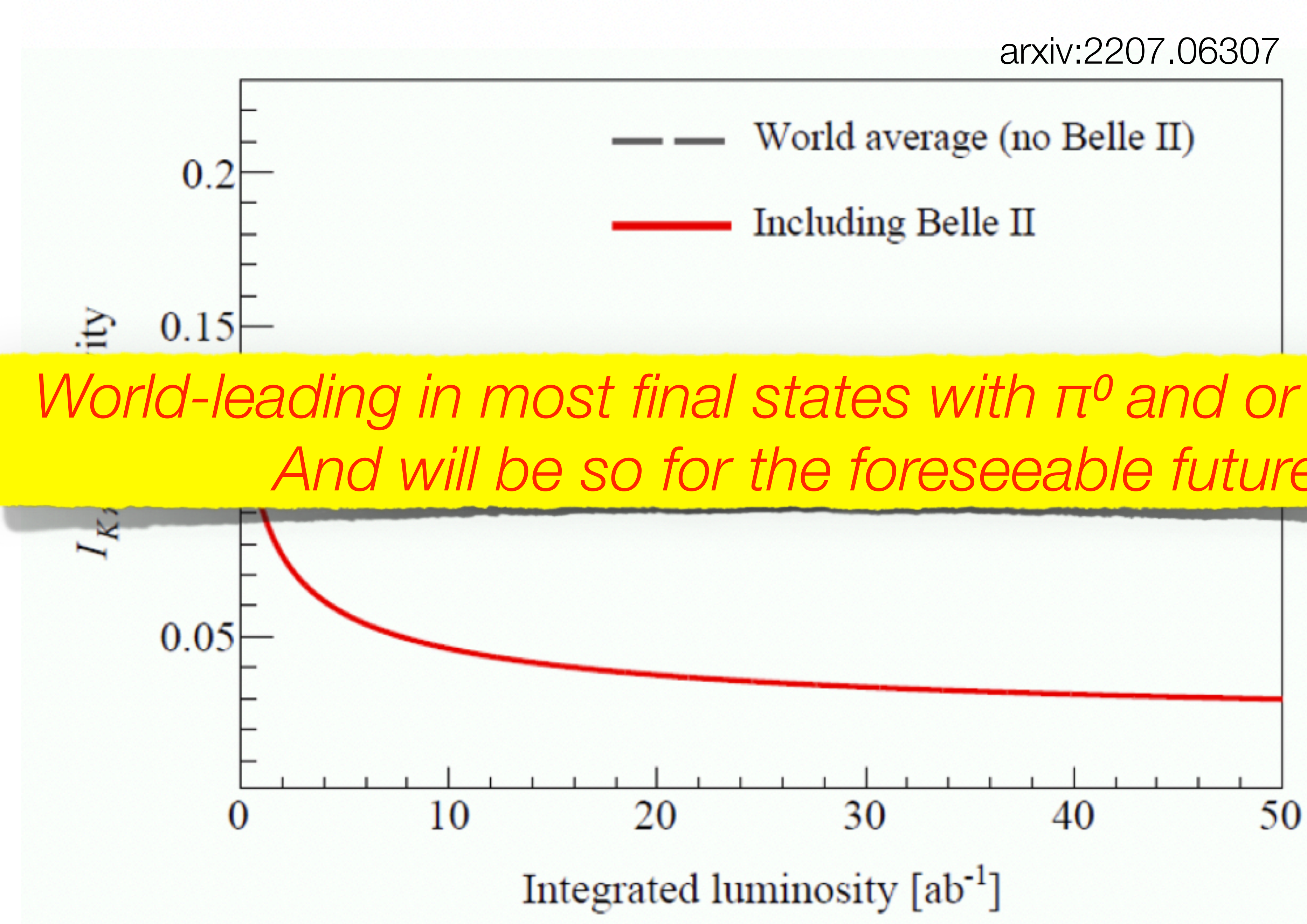



*World-leading in most final states with $\pi^0$ and or $K^0$. Now. And will be so for the foreseeable future*

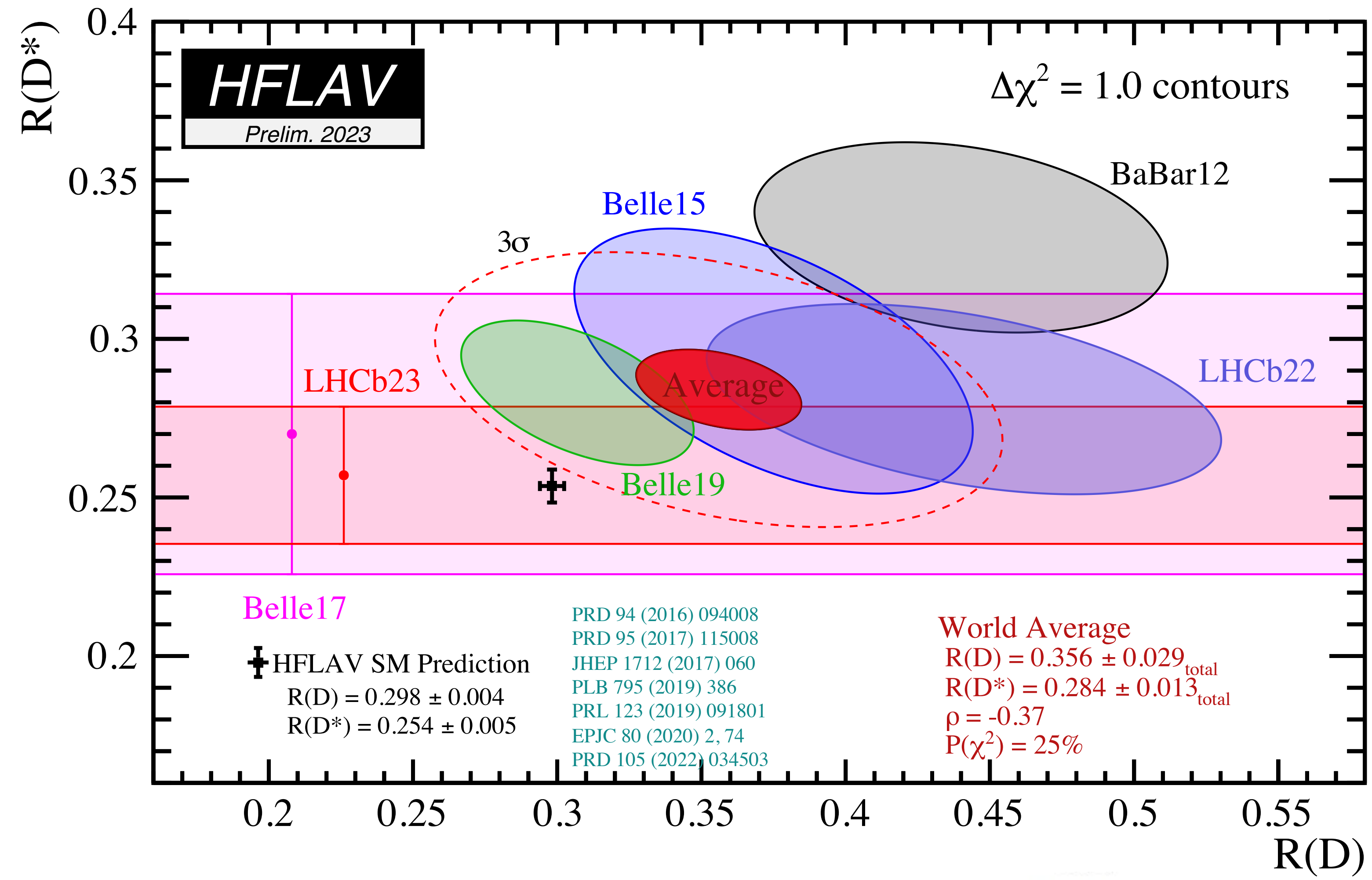
Similar considerations apply to $B^0 \rightarrow \pi^0\pi^0$, $B^0 \rightarrow K^0K^0K^0$, $B^0 \rightarrow \eta' K^0$

# Anomalies…*R(D)* and *R(D*)*

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

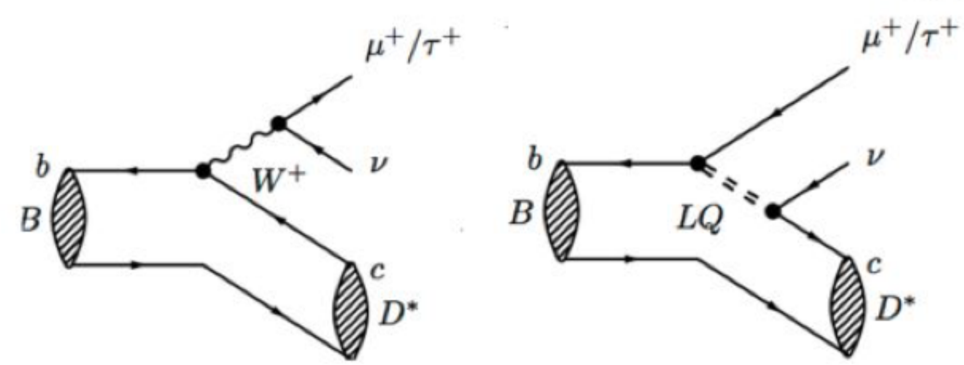
$$R(D) \equiv \frac{\mathcal{B}(\bar{B} \to D^{+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{+}\ell^-\bar{\nu}_\ell)}$$

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




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

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



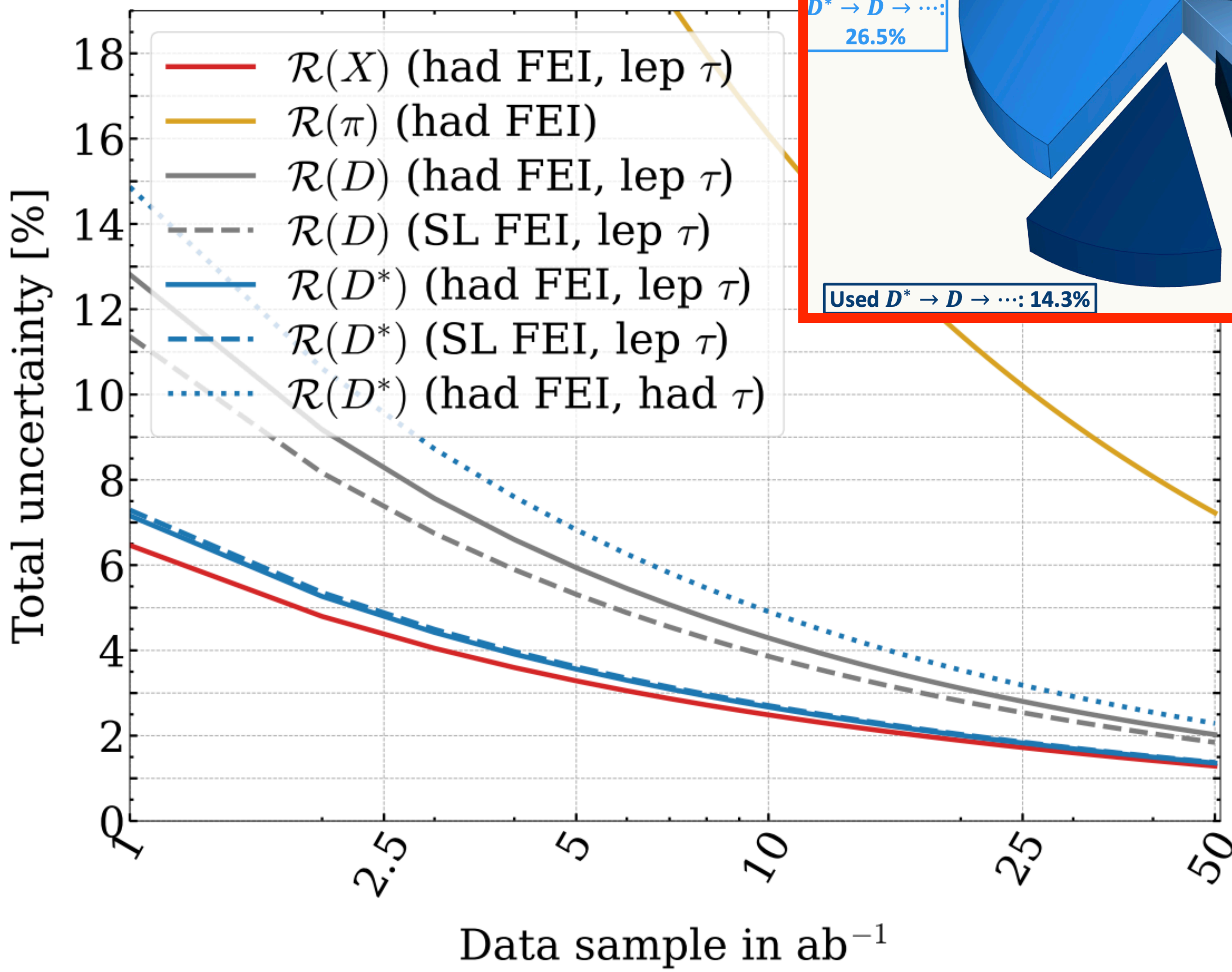

Multiple neutrinos, no narrow peak to fit in any distribution, multiple harsh backgrounds. Strong advantages for Y(4S) environment

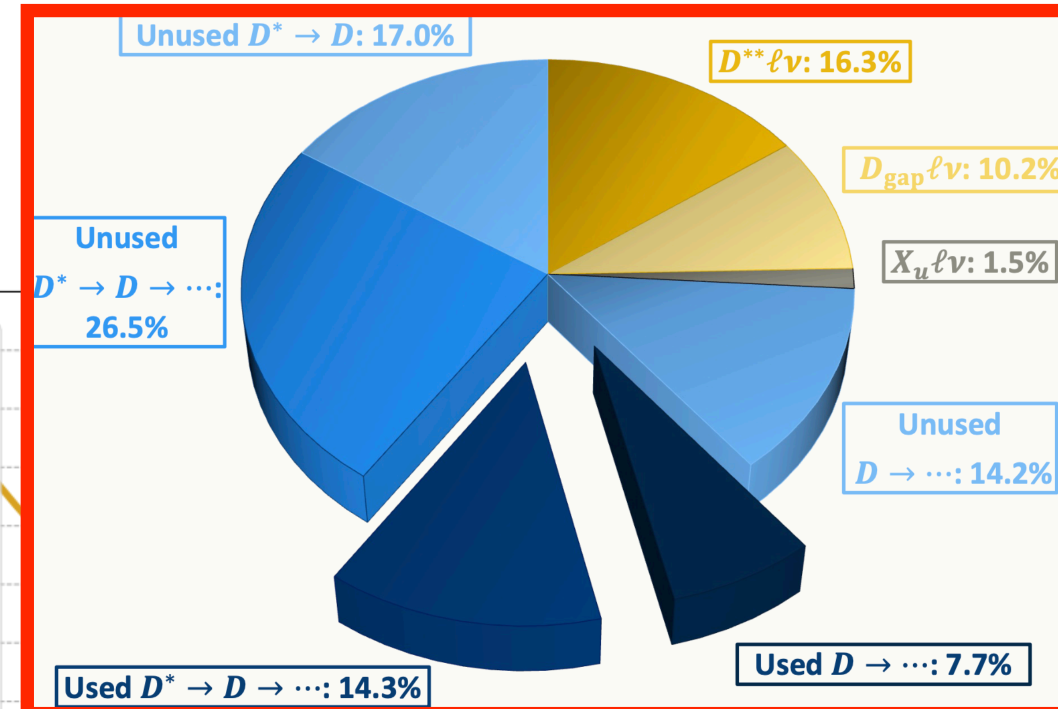
# Going inclusive — *R(X)*

R(D)

R(D*)
inclusive

arxiv:2207.06307



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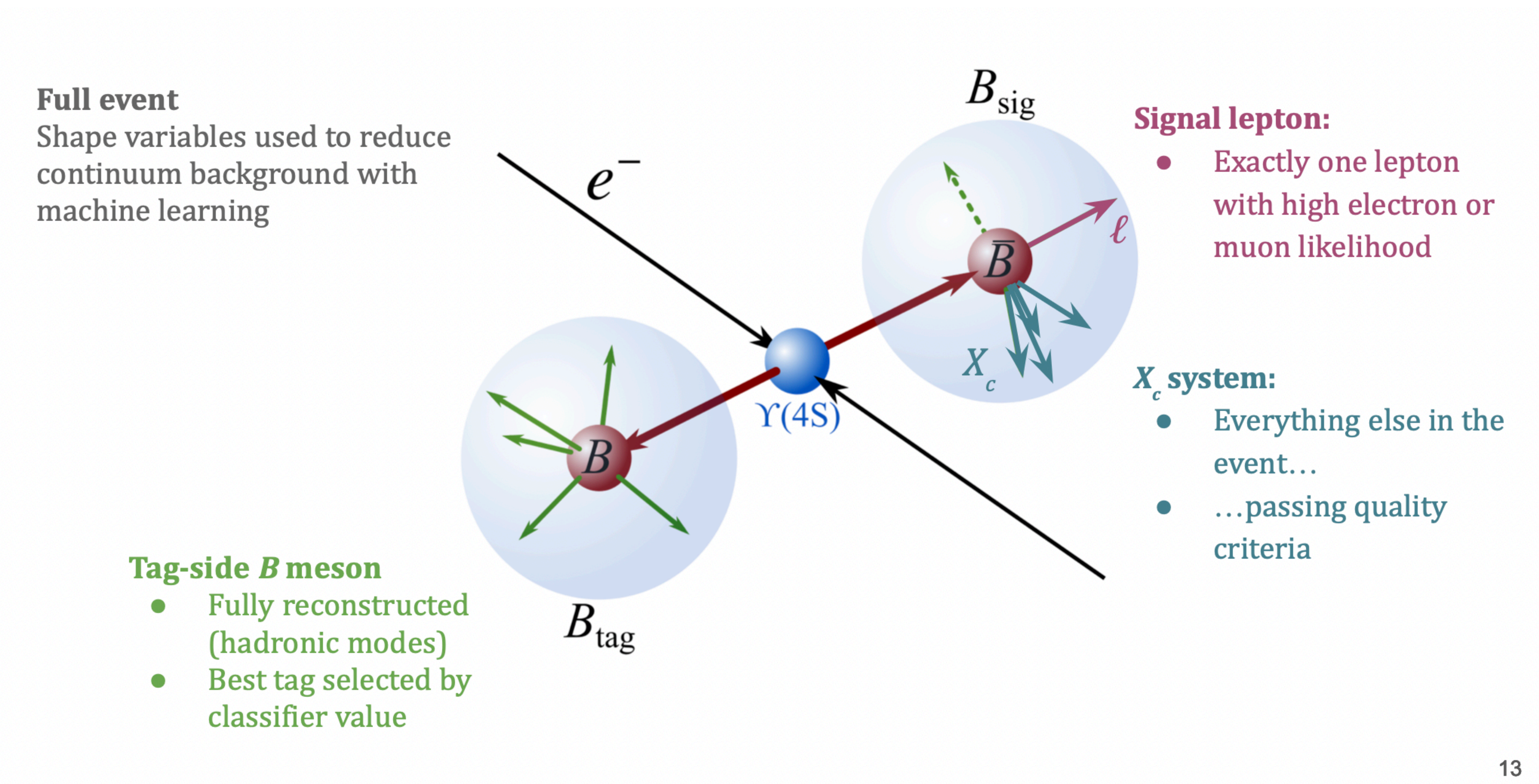


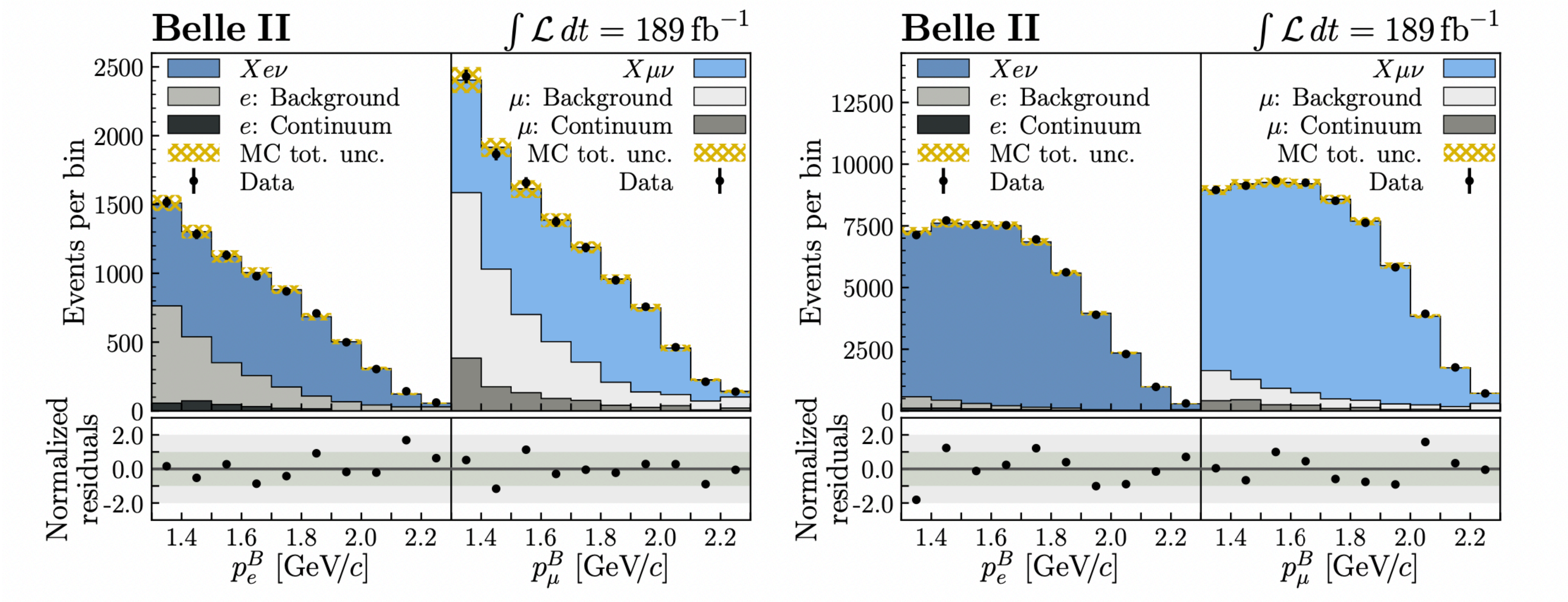

Essential to constrain mismodeling in abundances and shapes of all sample components

# First step - muon-electron universality

Sample composition fit to lepton spectrum in signal and control regions

Control (Same-flavor B)

Signal (Different flavor B)




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

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

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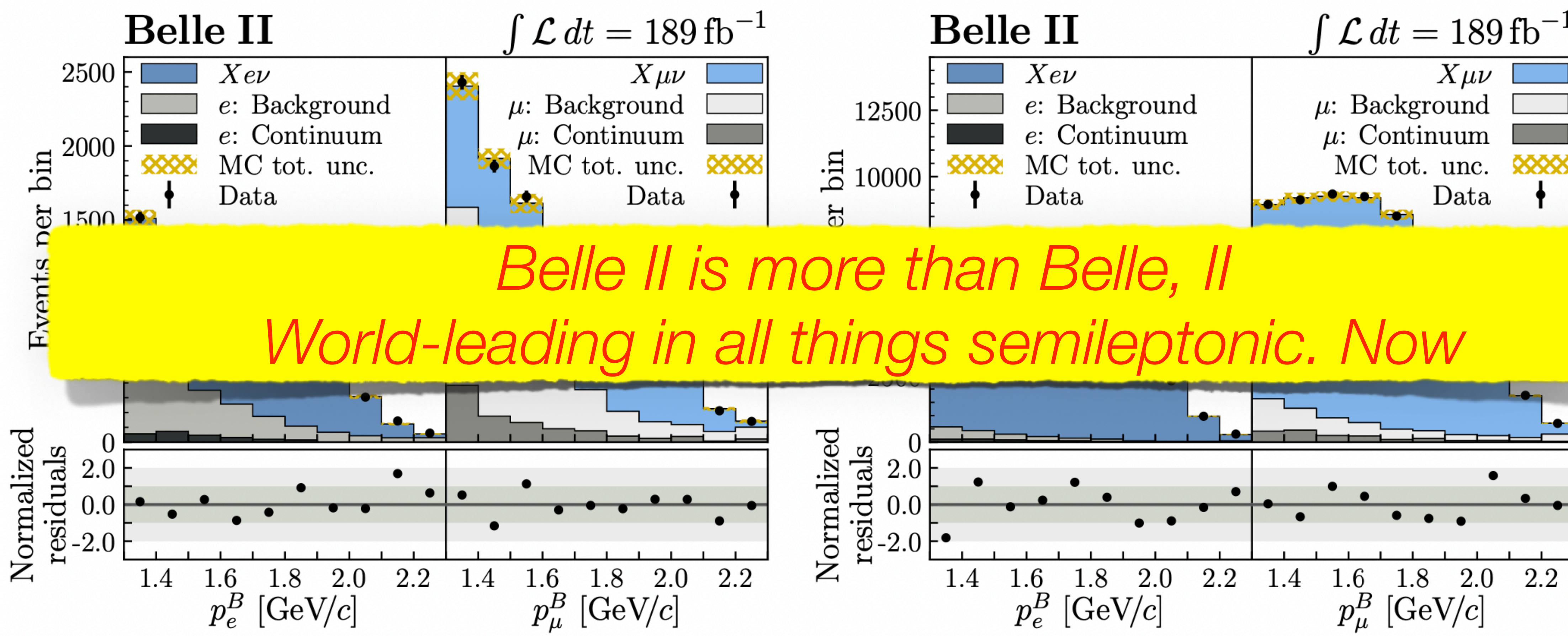


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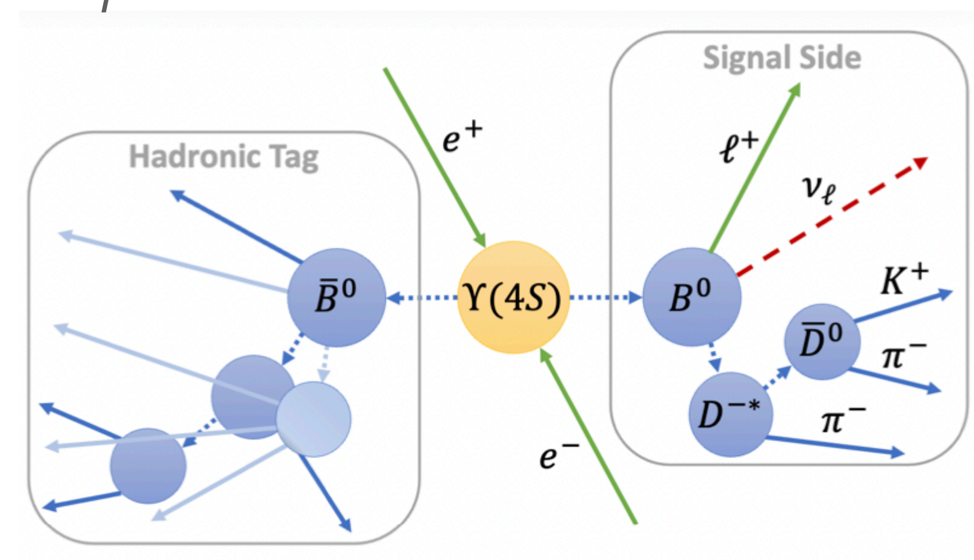
# Further light-lepton universality

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

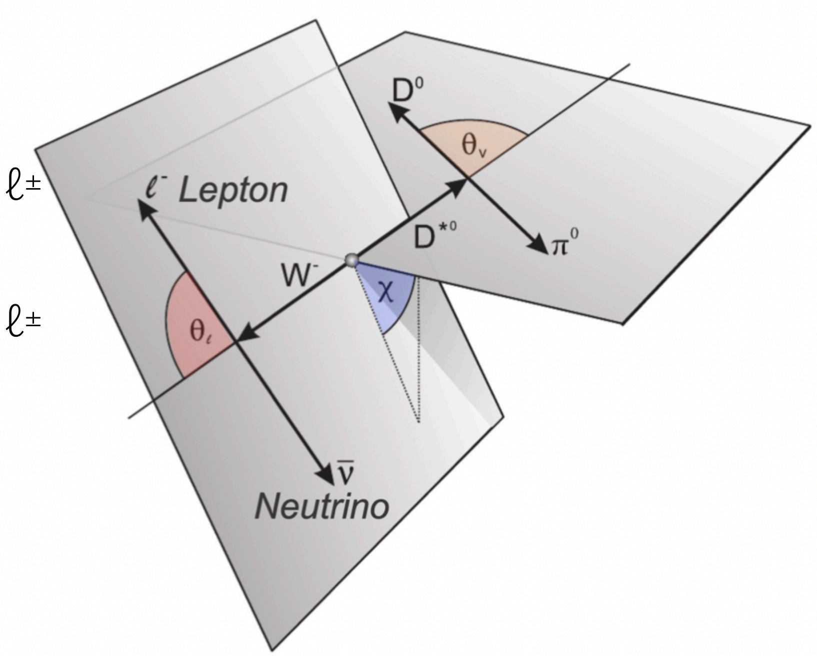
Recoil parameter $w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$

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*

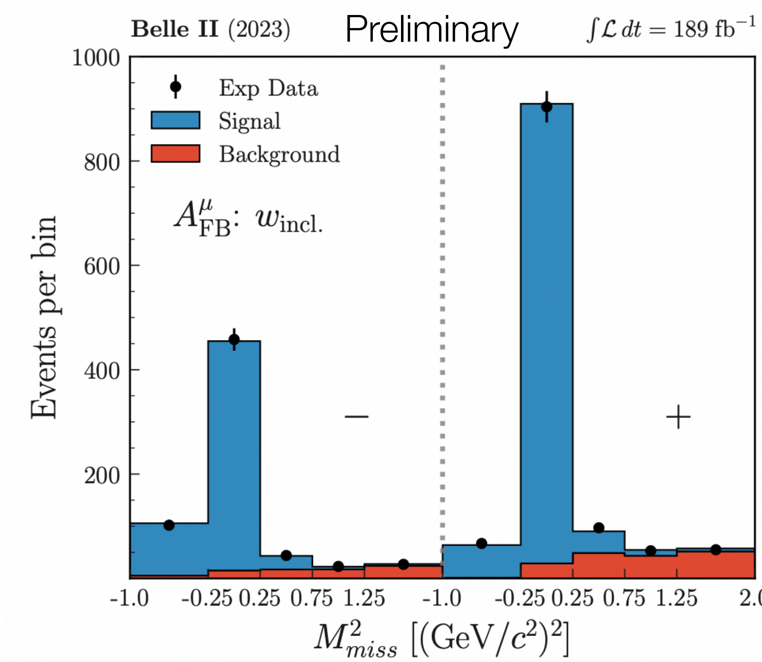


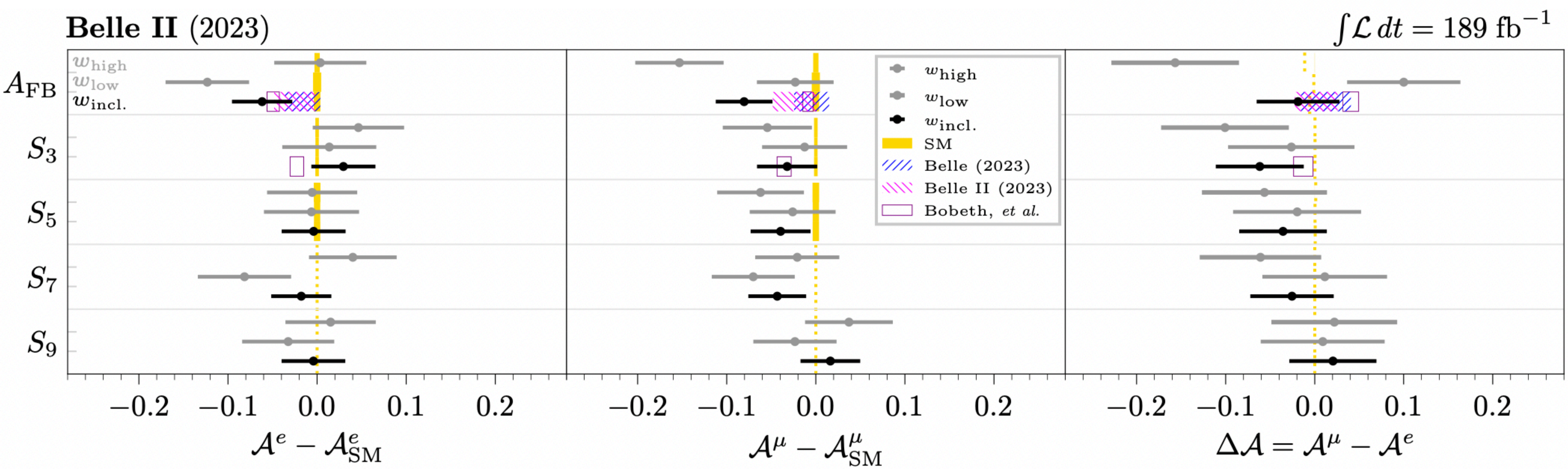

Differences of these asymmetries between e and *μ offer* sensitivity to lepton-flavor universality violation

# AFB++ results

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

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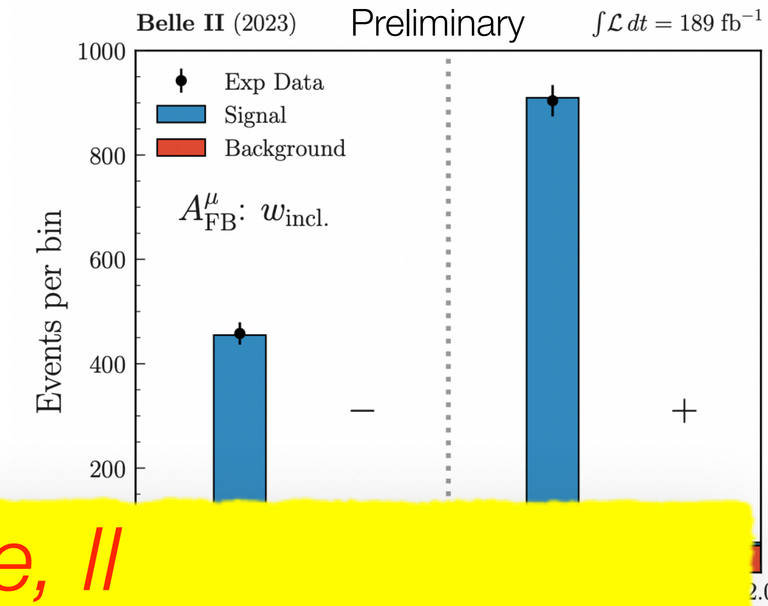
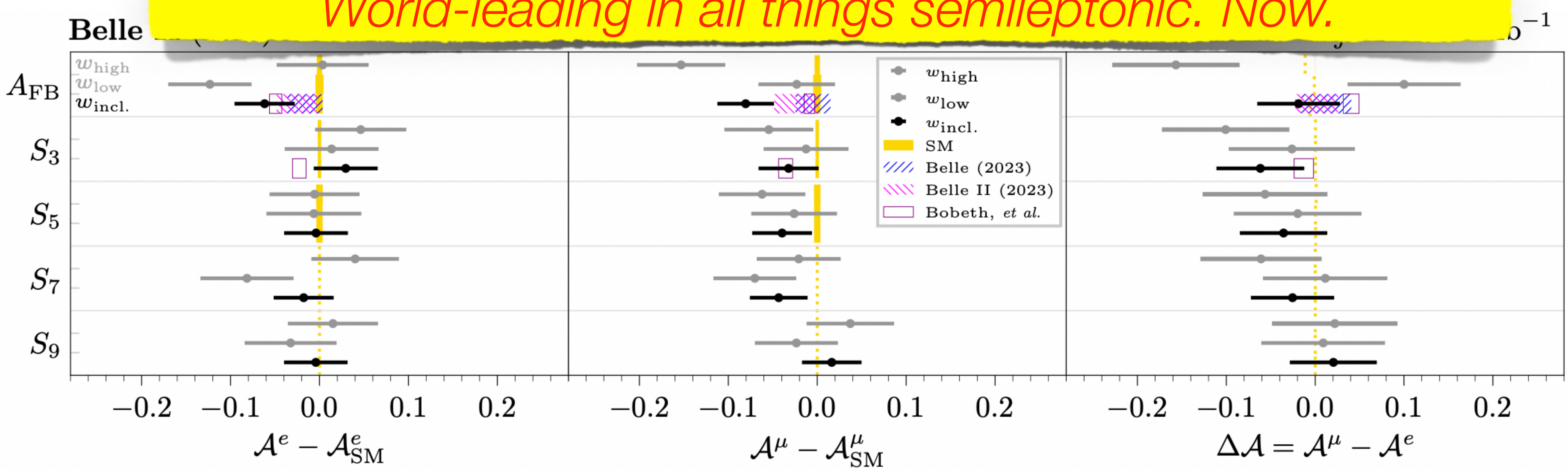



*Belle II is more than Belle, II*

*World-leading in all things semileptonic. Now.*




All SM within 5-10% uncertainties

# Beyond common sense - τ-lepton mass

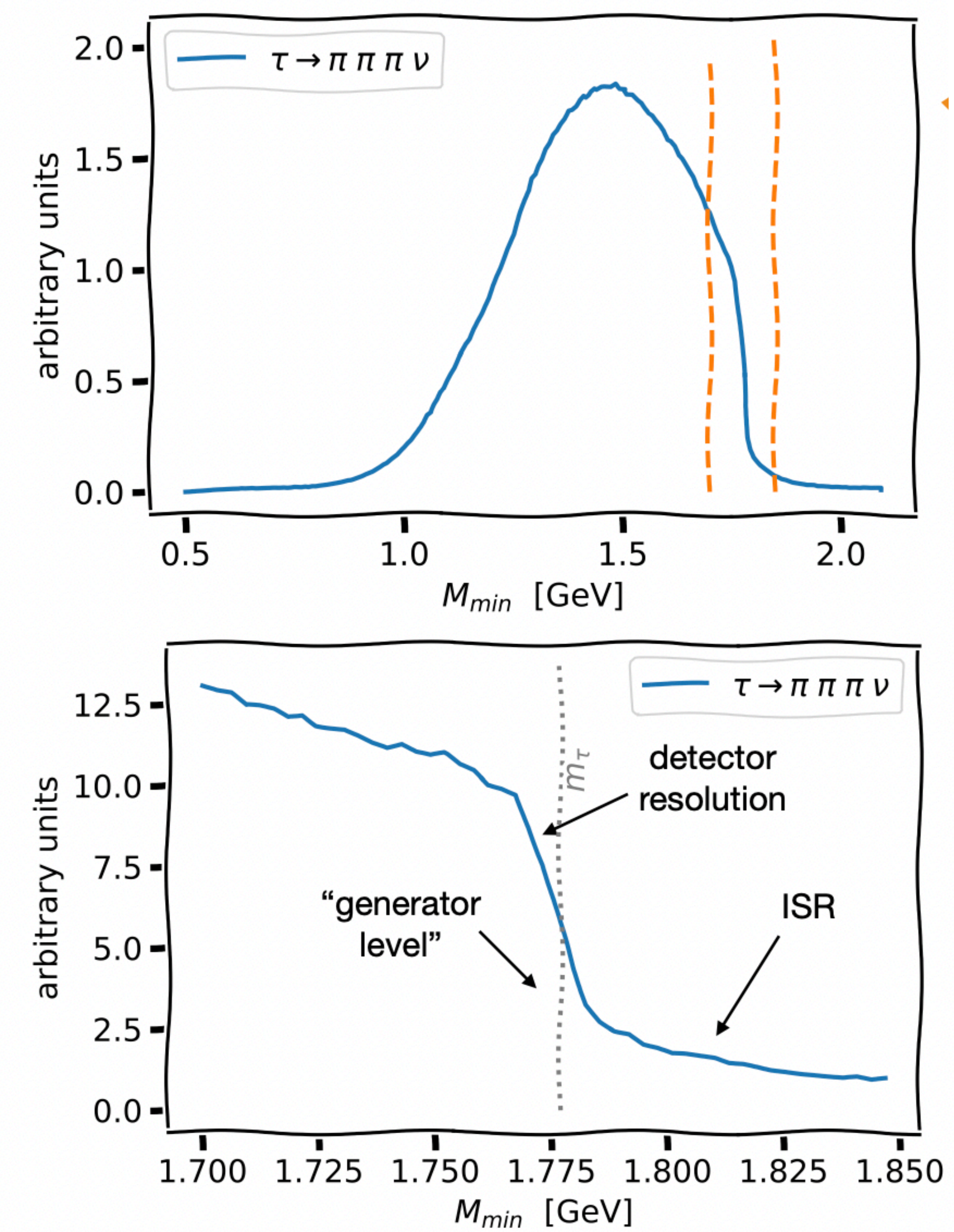
SuperKEKB is a τ factory too: sizable cross section and constrained kinematics

$\tau^- \to \pi^+\pi^-\pi^-\nu$ (signal) and $\tau^- \to \pi^+\pi^0\nu$

Four tracks. No additional high-energy photons

Empirical fit to distribution of pseudomass, Minimum value of the reconstructed τ mass where τ-energy is assumed to be 1/2 of collision energy

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



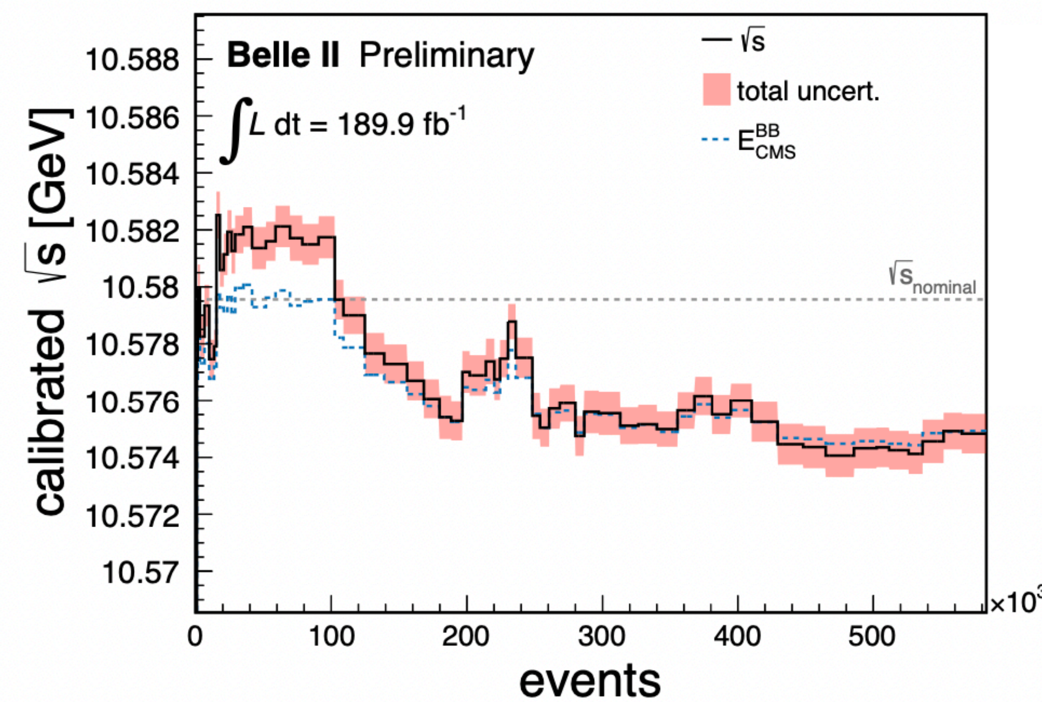

Benchmark for precision capabilities

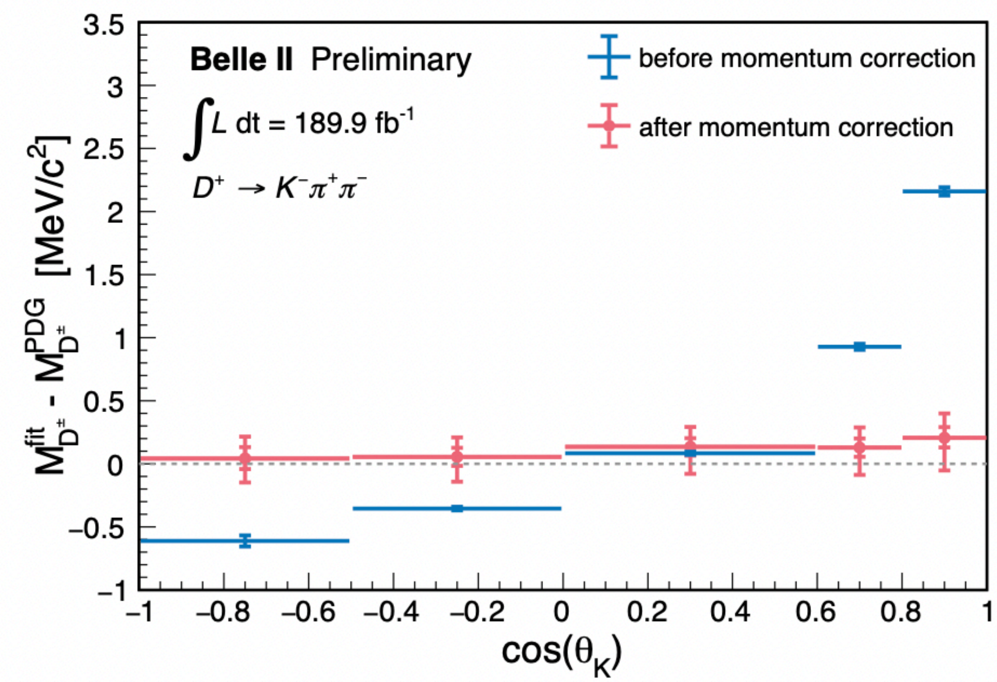
# Beyond common sense - tau mass

Boils down to control of systematic uncertainties

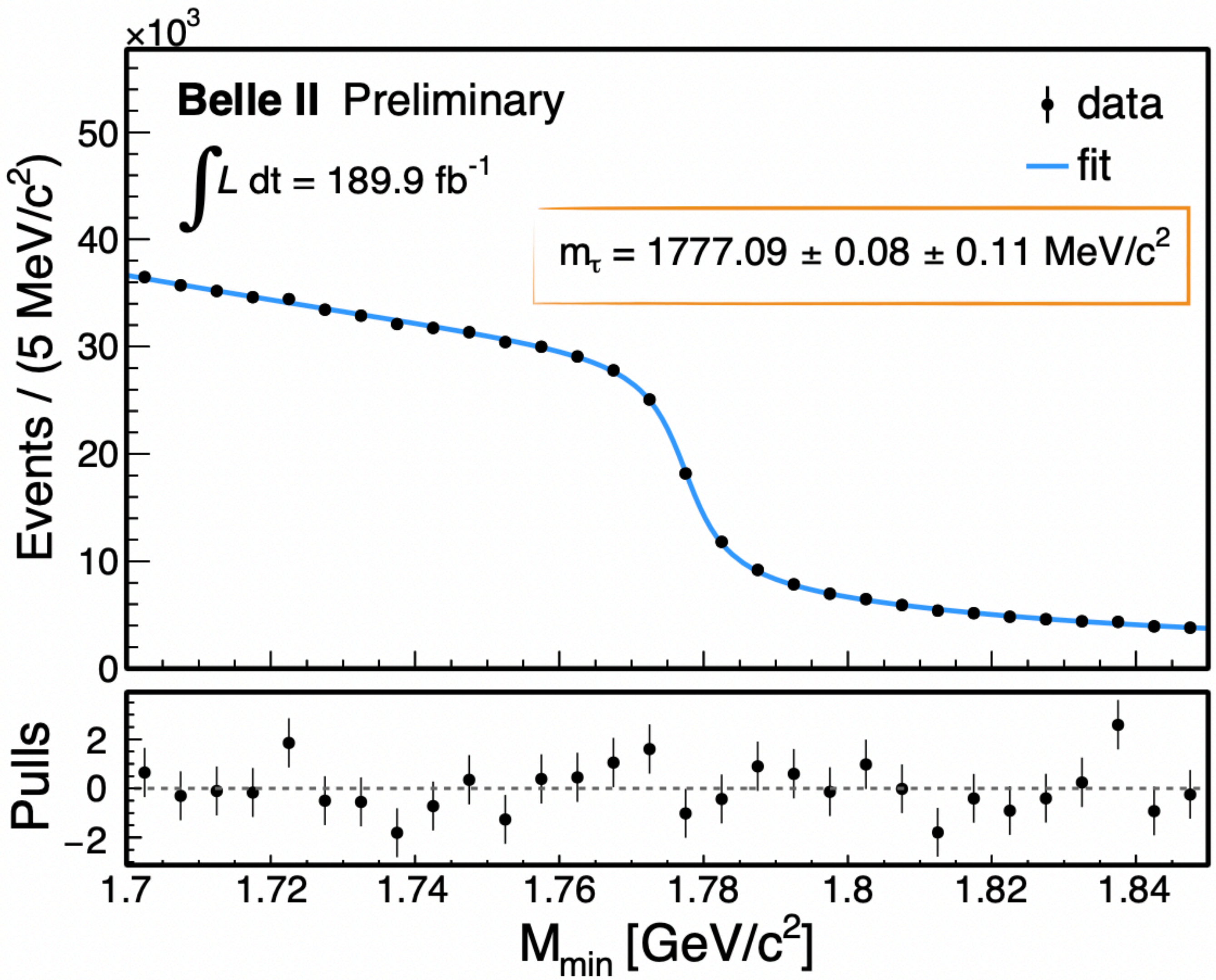
- $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq m_\tau$

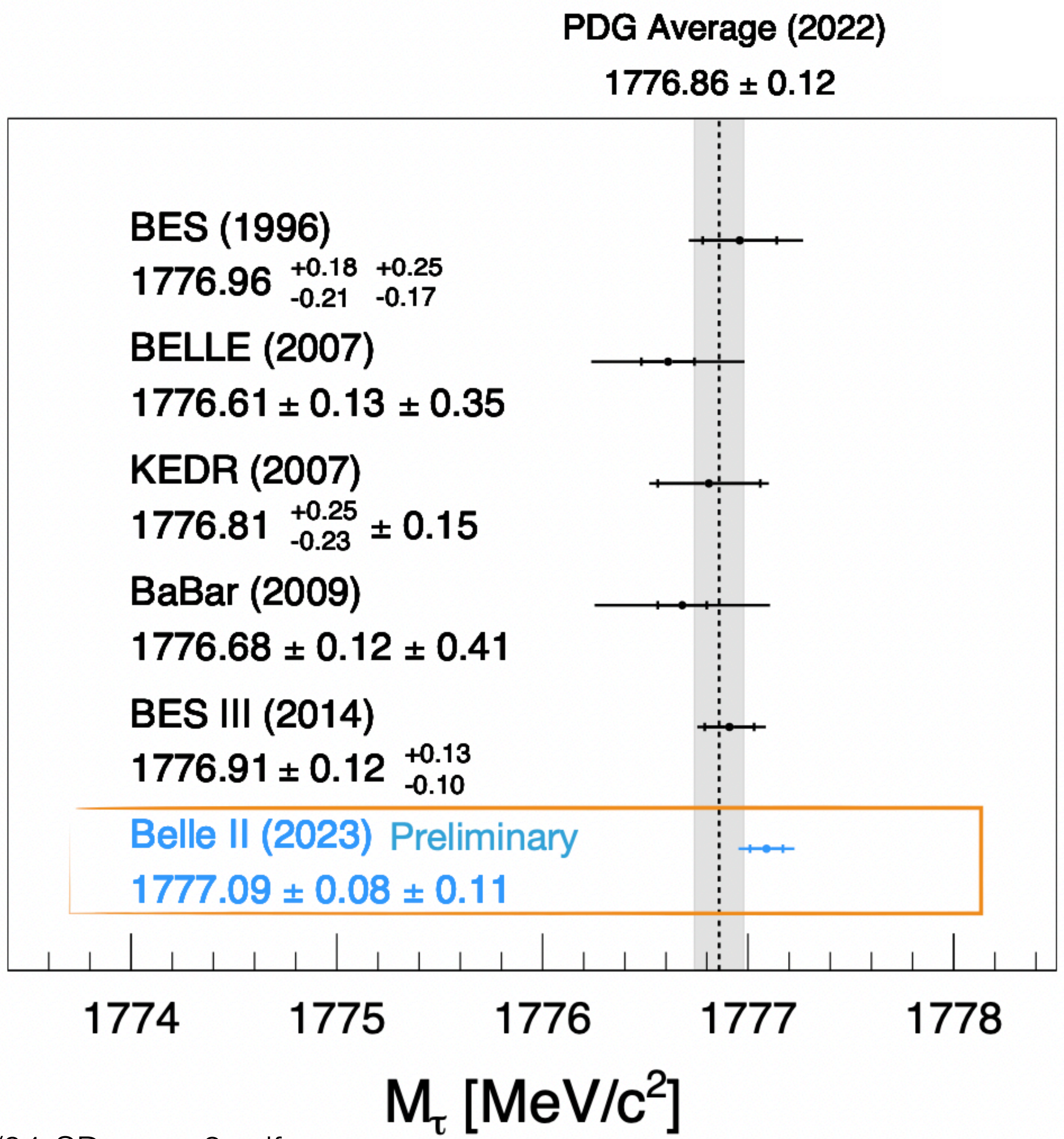
| Source | Uncertainty [MeV/$c^2$] |
|---|---|
| Knowledge of the colliding beams: | |
| Beam energy correction | 0.07 |
| Boost vector | $\lesssim 0.01$ |
| Reconstruction of charged particles: | |
| Charged particle momentum correction | 0.06 |
| Detector misalignment | 0.03 |
| Fitting procedure: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



# Beyond common sense - tau mass

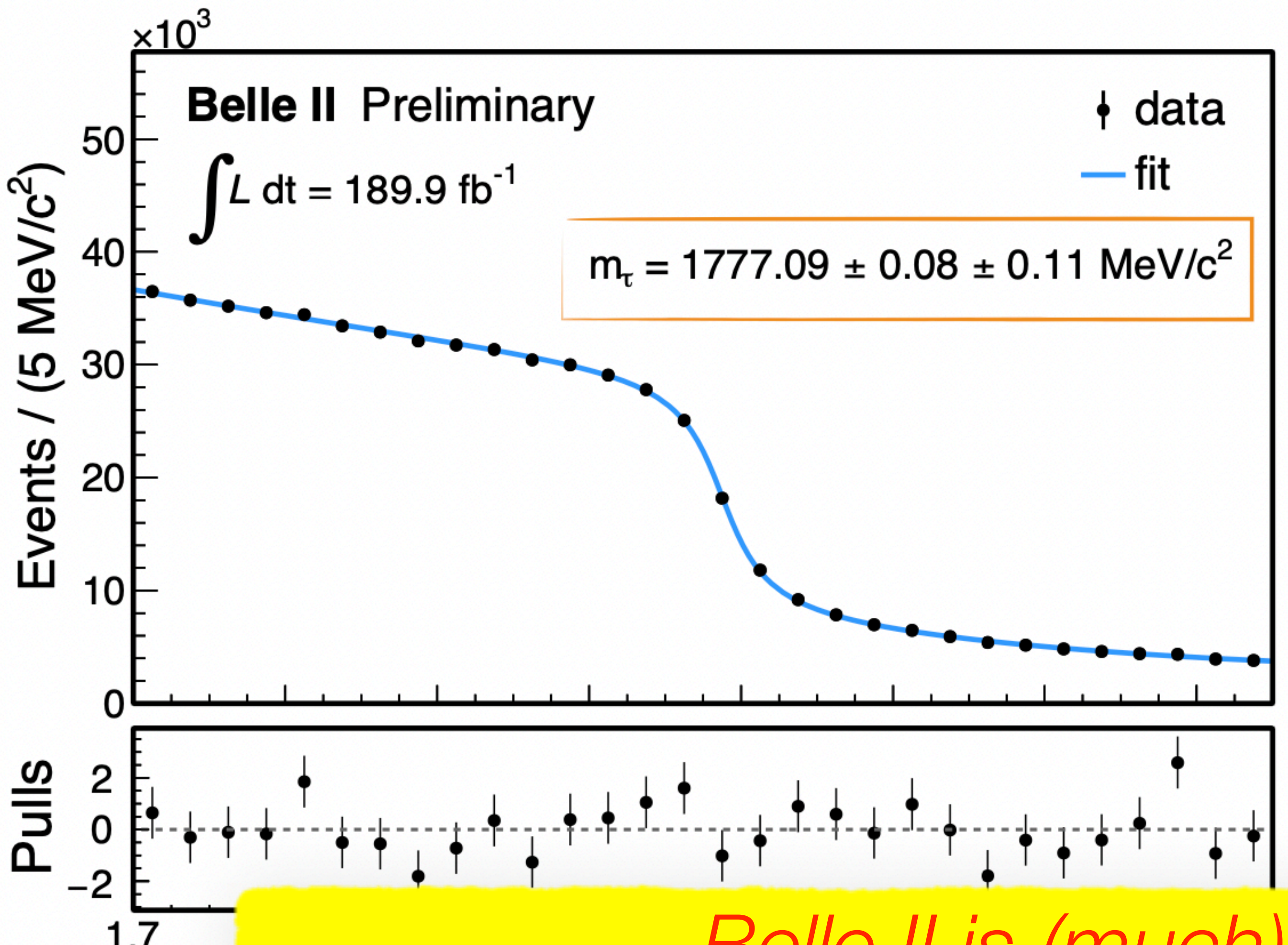


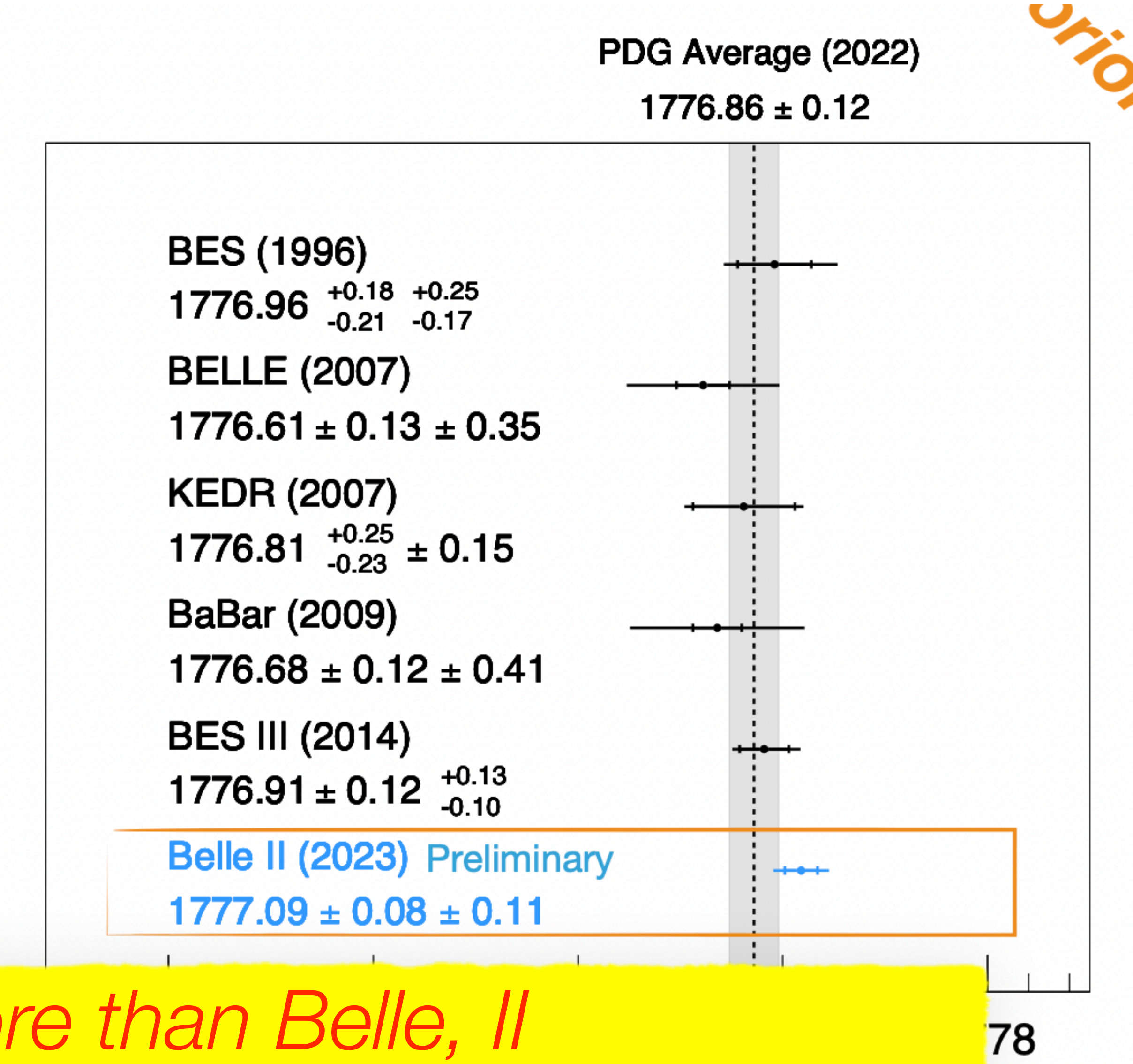




https://indico.in2p3.fr/event/29681/contributions/122507/attachments/76503/111032/04-SDreyer-v2.pdf

Most precise result to date

# Beyond common sense - tau mass




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

Most precise result to date

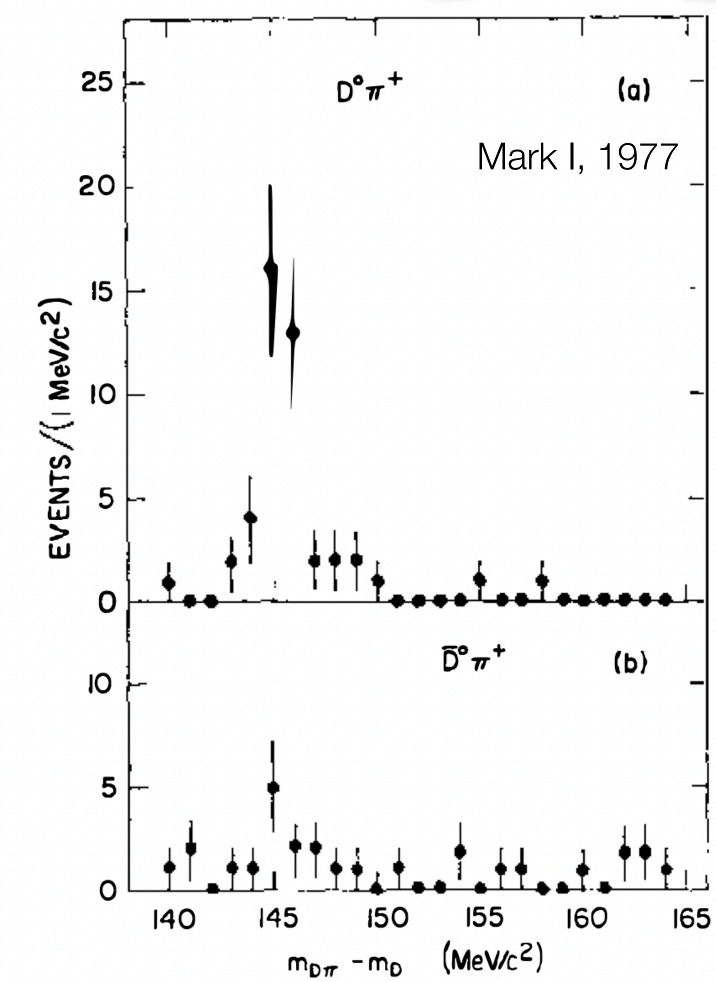
# Beyond common sense - charm flavor tagger

Time evolution of $D^0$ and $\bar{D}^0$ in common final states ($K_S\pi^+\pi^-$, $K^+K^-$, $\pi^+\pi^-$) probes BSM in D mixing and CPV

Final state says nothing on whether a $D^0$ or $\bar{D}^0$ was produced. Need to "tag" the flavor.

Since 1977: restrict to strong decay $D^{*+} \rightarrow D^0\pi^+$ where flavor and charge conservation allow associating the $\pi^+$ with $D^0$ and $\pi^-$ with $\bar{D}^0$

Industry standard at Belle, Babar, CDF II, LHCb etc..




D*-tag reduces 5x-20x the samples available for measurements.

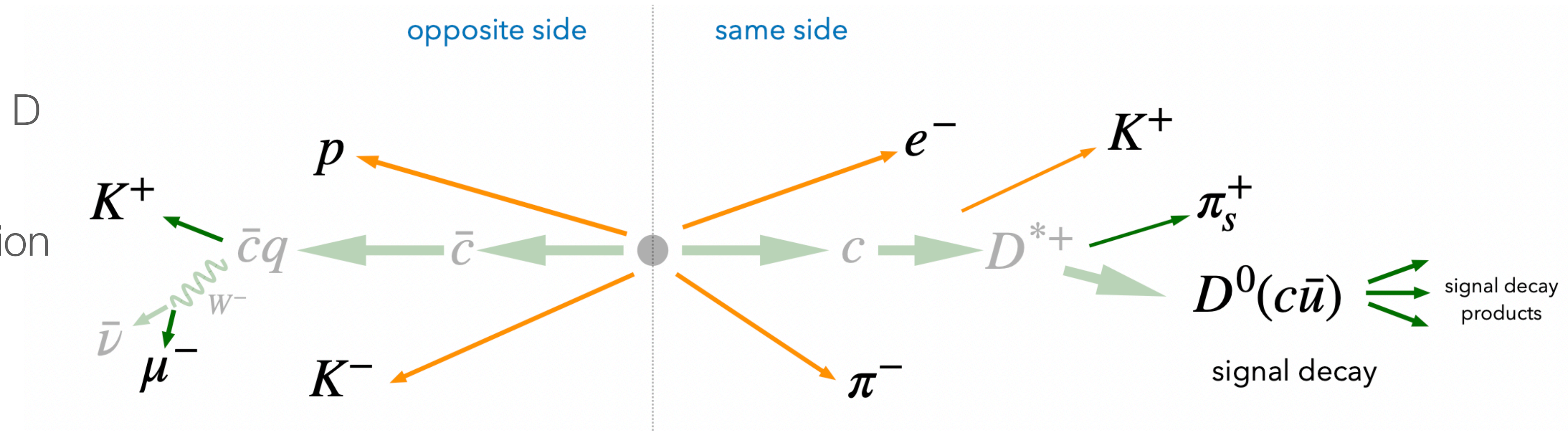
Belle II set on exploring an "holistic approach" that looks at many event features to reduce this reduction factor.

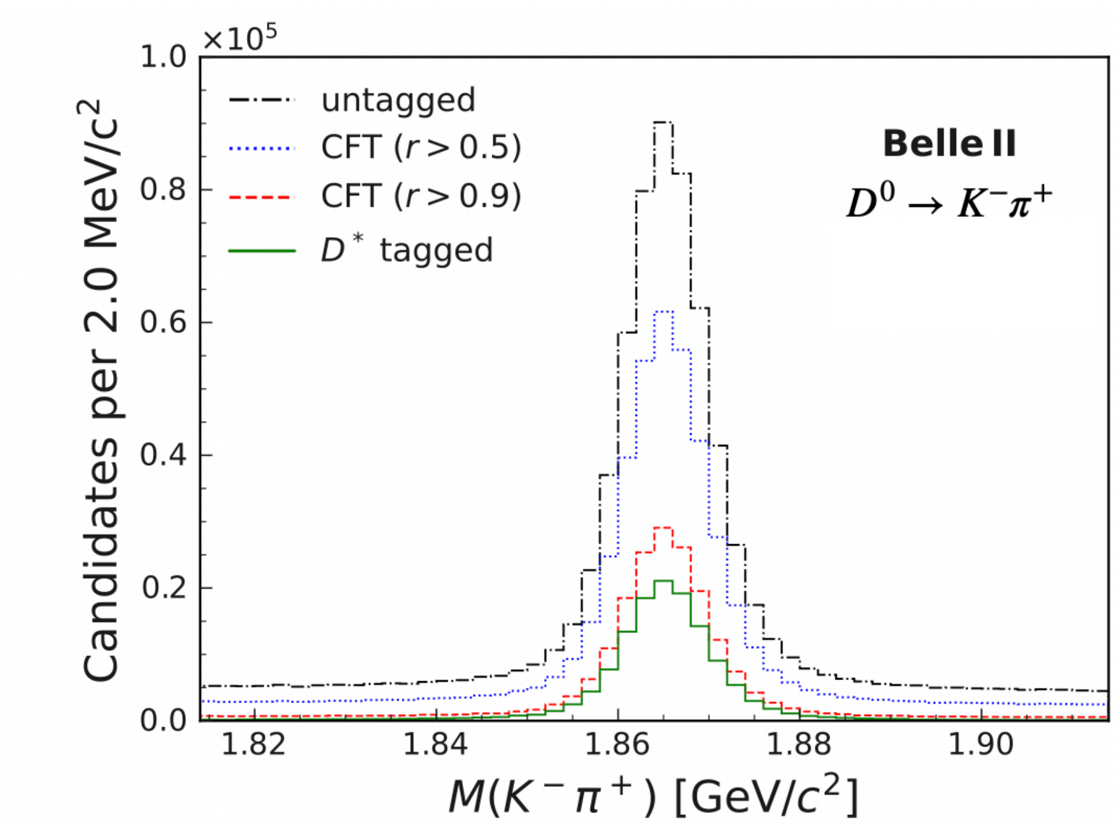
# Beyond common sense - charm flavor tagger

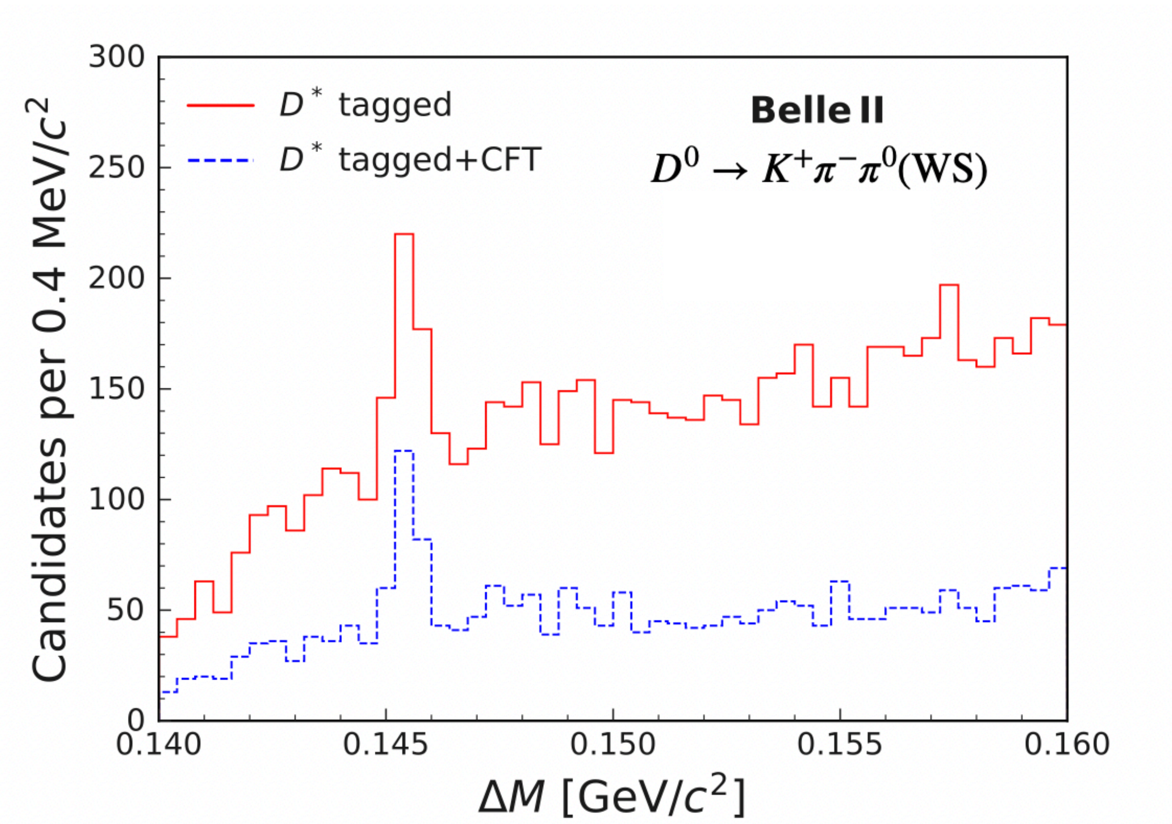
Look at particles collinear with signal D

Correlate kinematic features (recoil mass, distance) and PID using decision tree

Develop on MC, calibrate on data




Double sample size with respect to D*-tag.

arxiv:2304.02042

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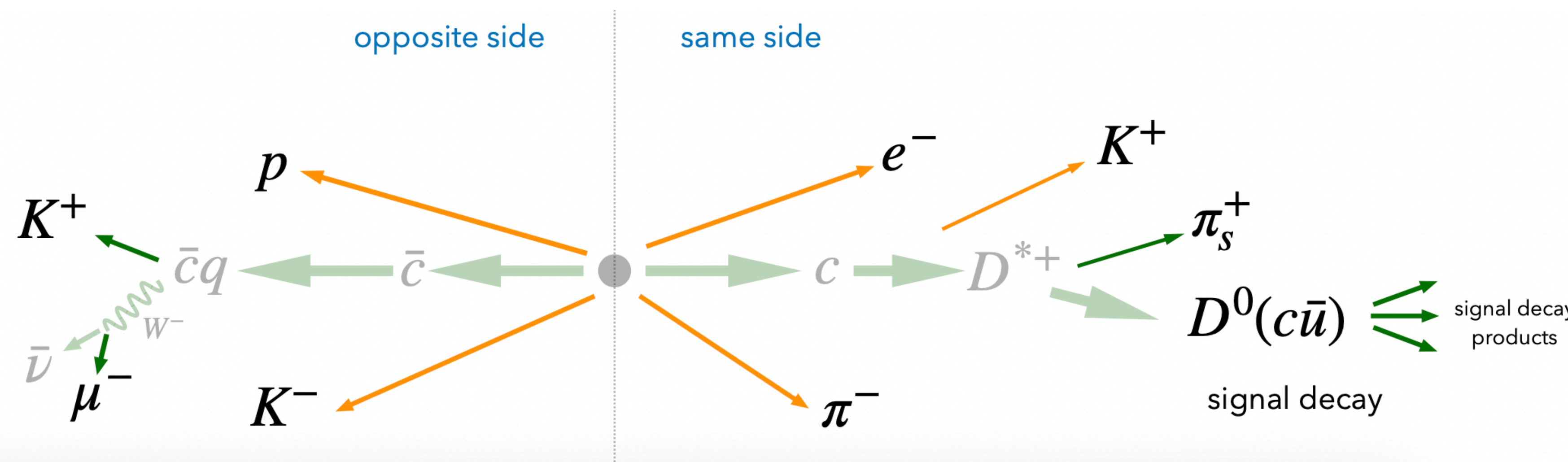
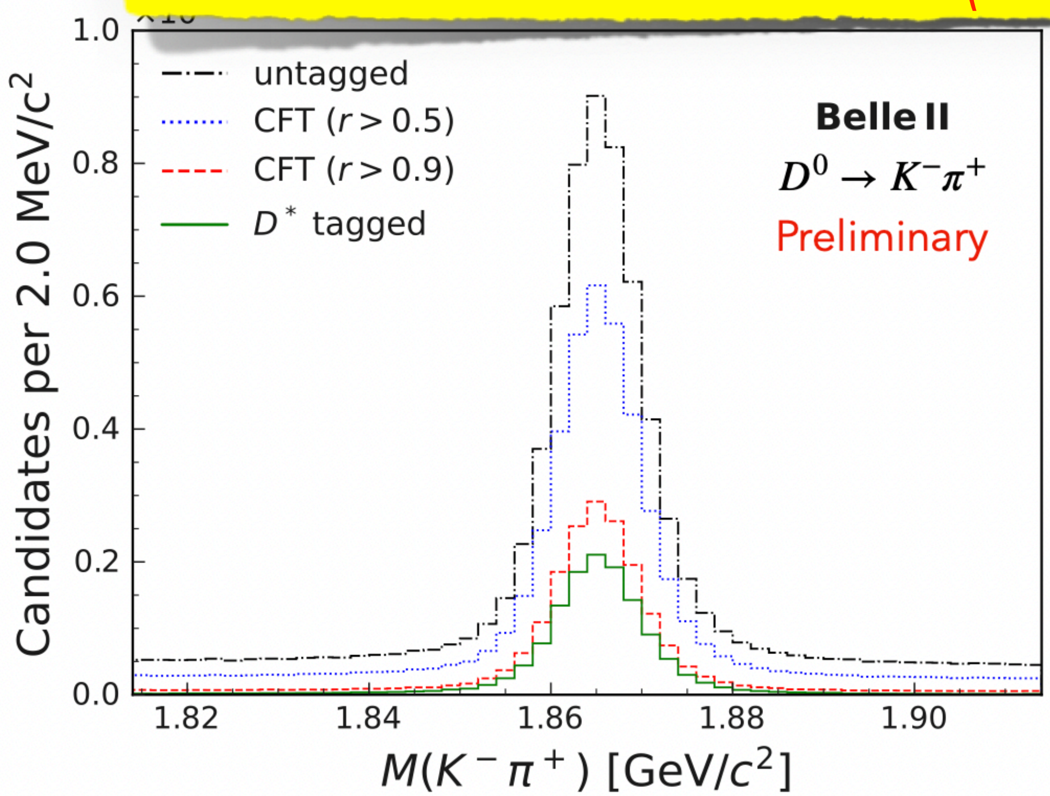
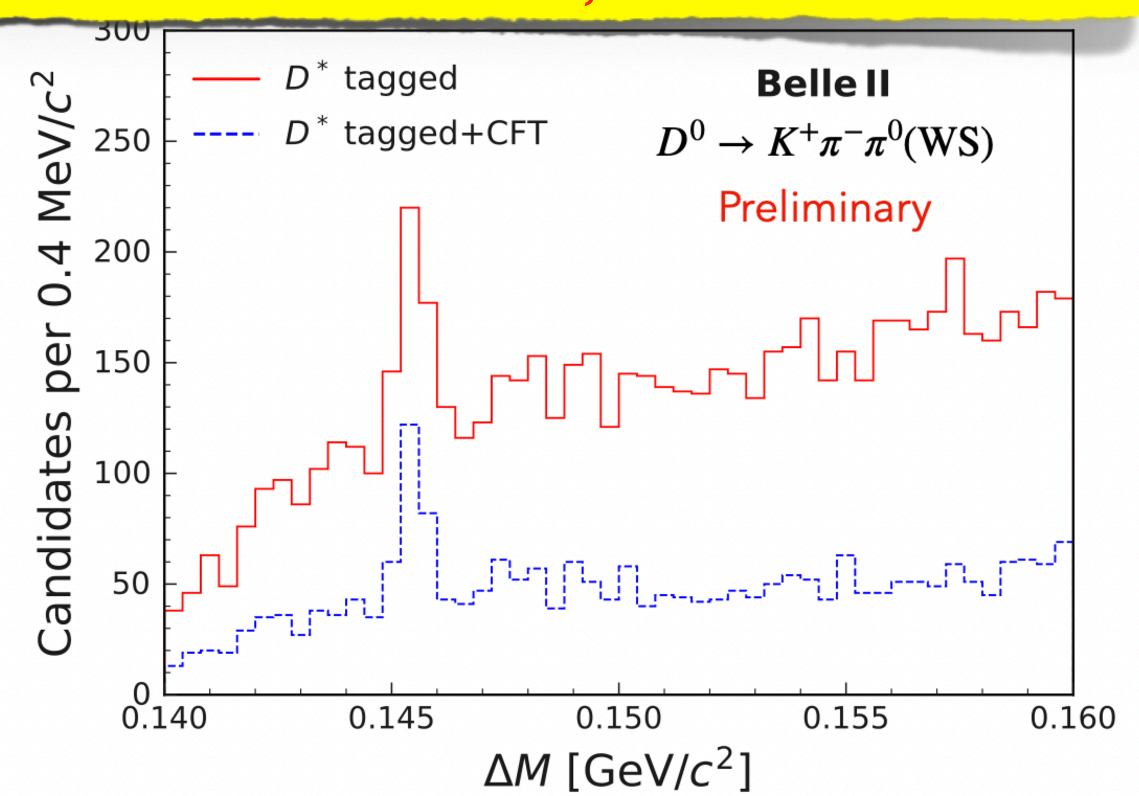



*Belle II is (much) more than Belle, II*

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# Directly searching for dark-sector particles

First search for long-lived particle at Belle II: spin-0 “S” particle from $b \to s$ transitions

8 channels: $B^+ \to K^+ S$ and $B^0 \to K^{*0} S$

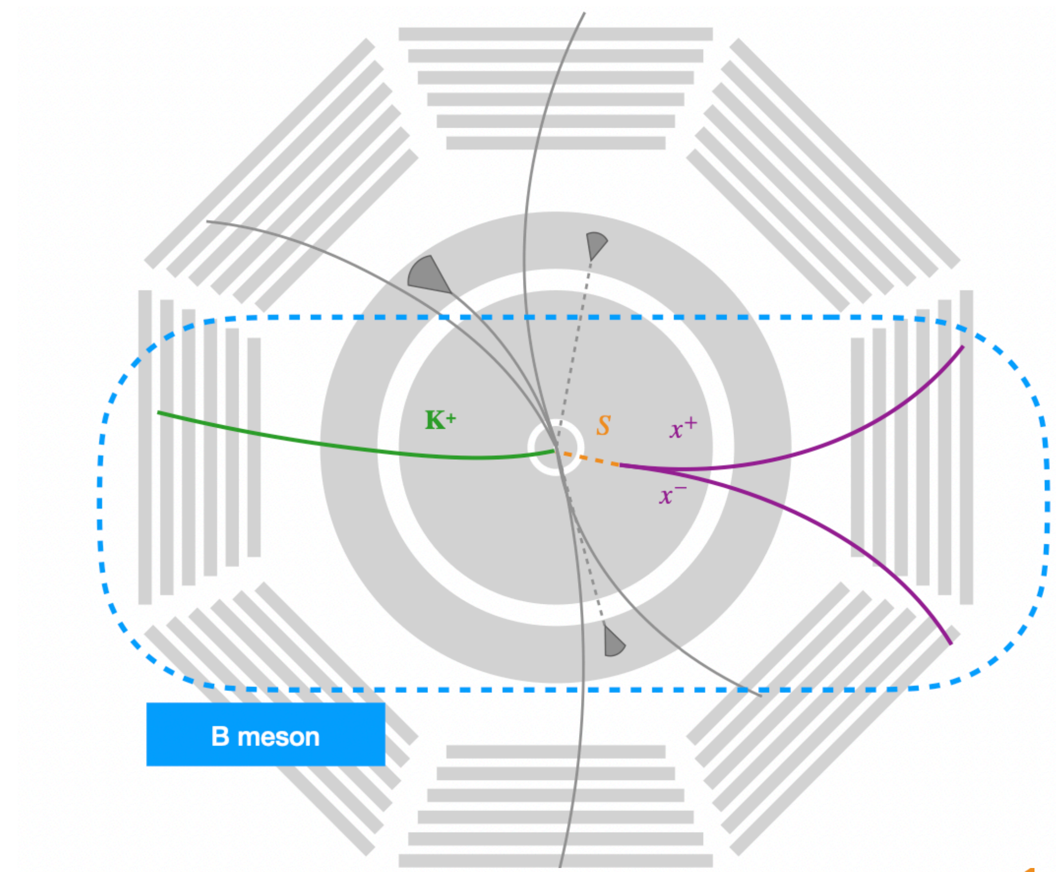
$S \to ee, \mu\mu, \pi\pi, KK$ with $0.001 < ct < 400$ cm

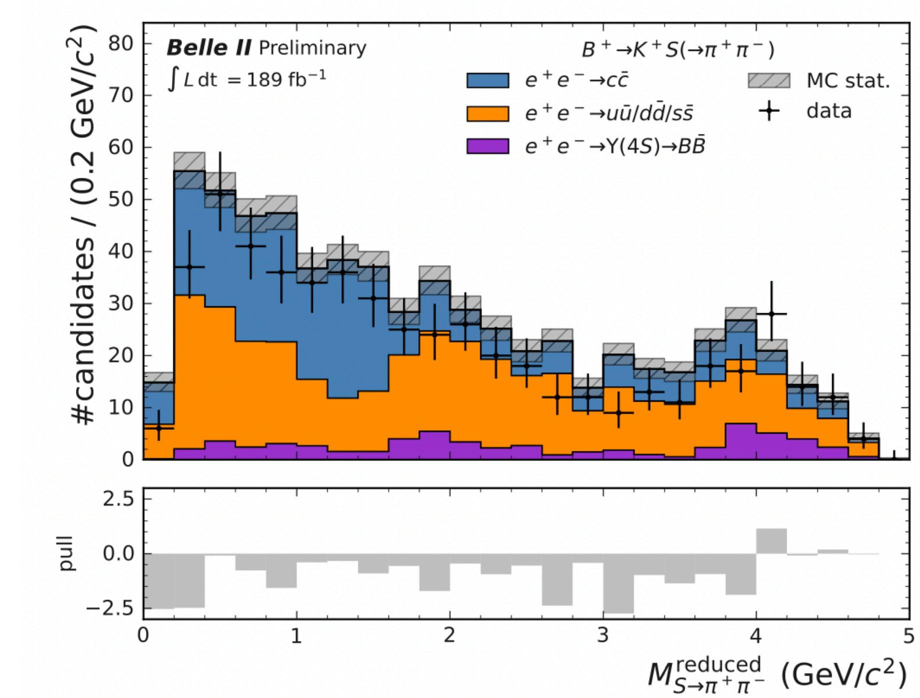
Look for fully reconstructed $B$ meson

Suppress continuum usingevent topology

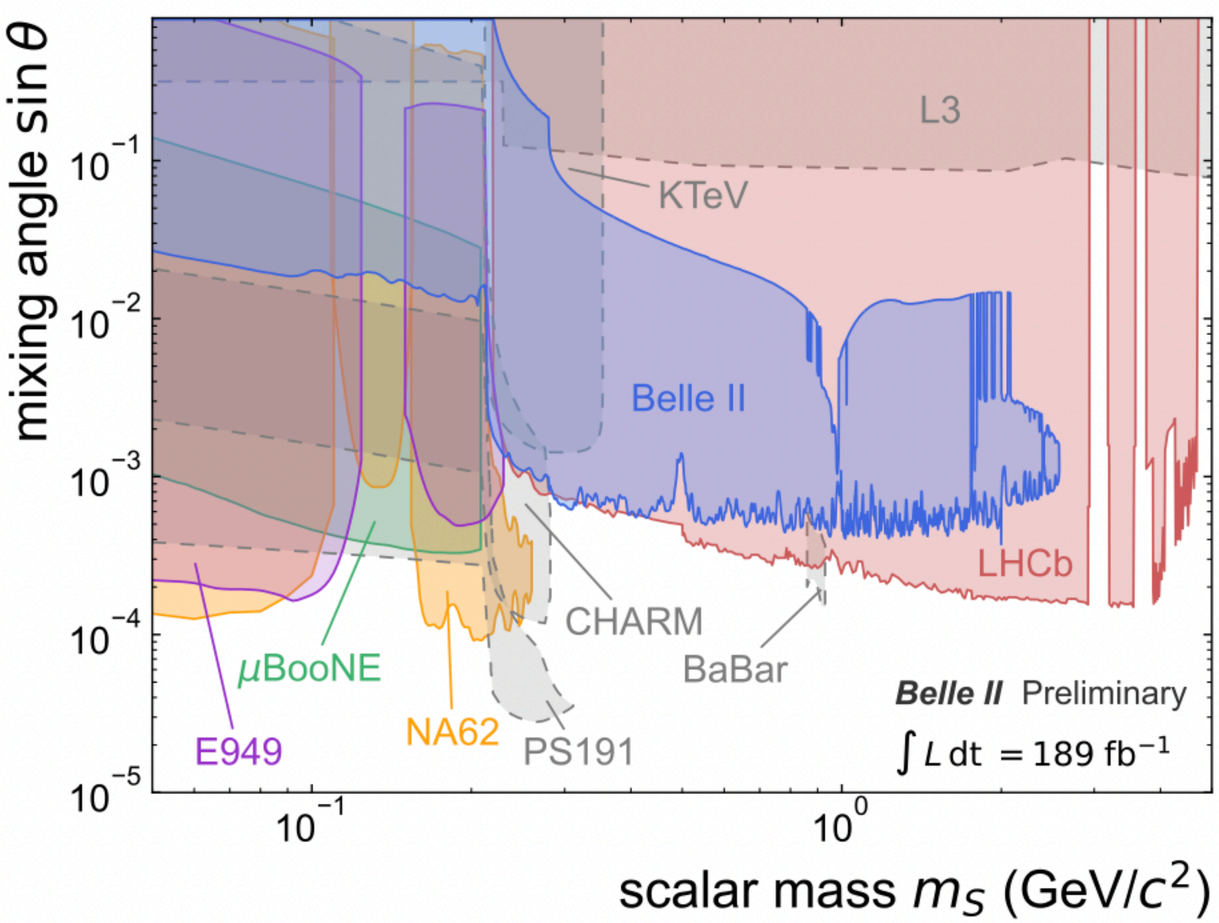
Veto Ks and use it as calibration control/ sample

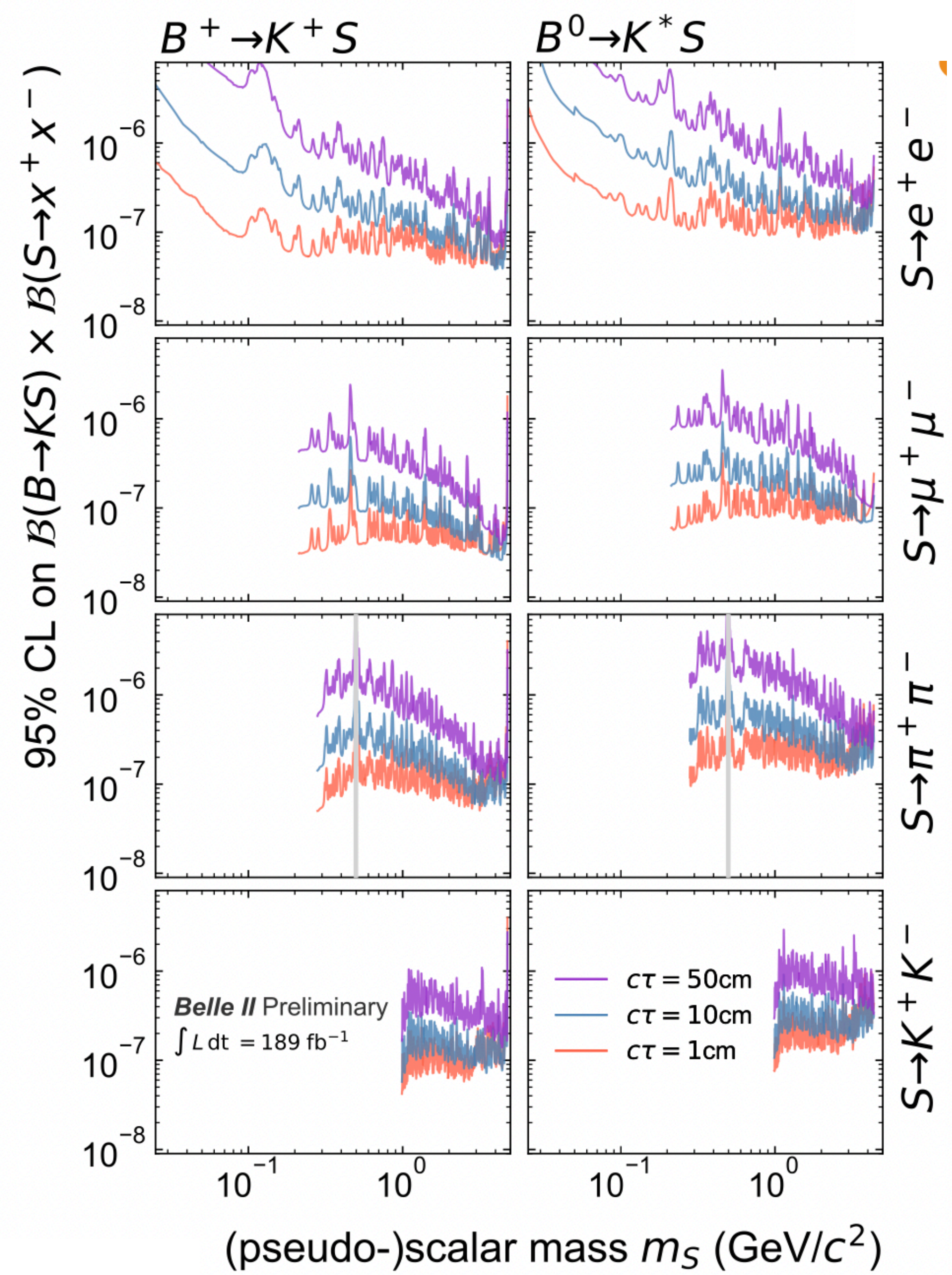
Suppress other peaking backgrounds by going displaced



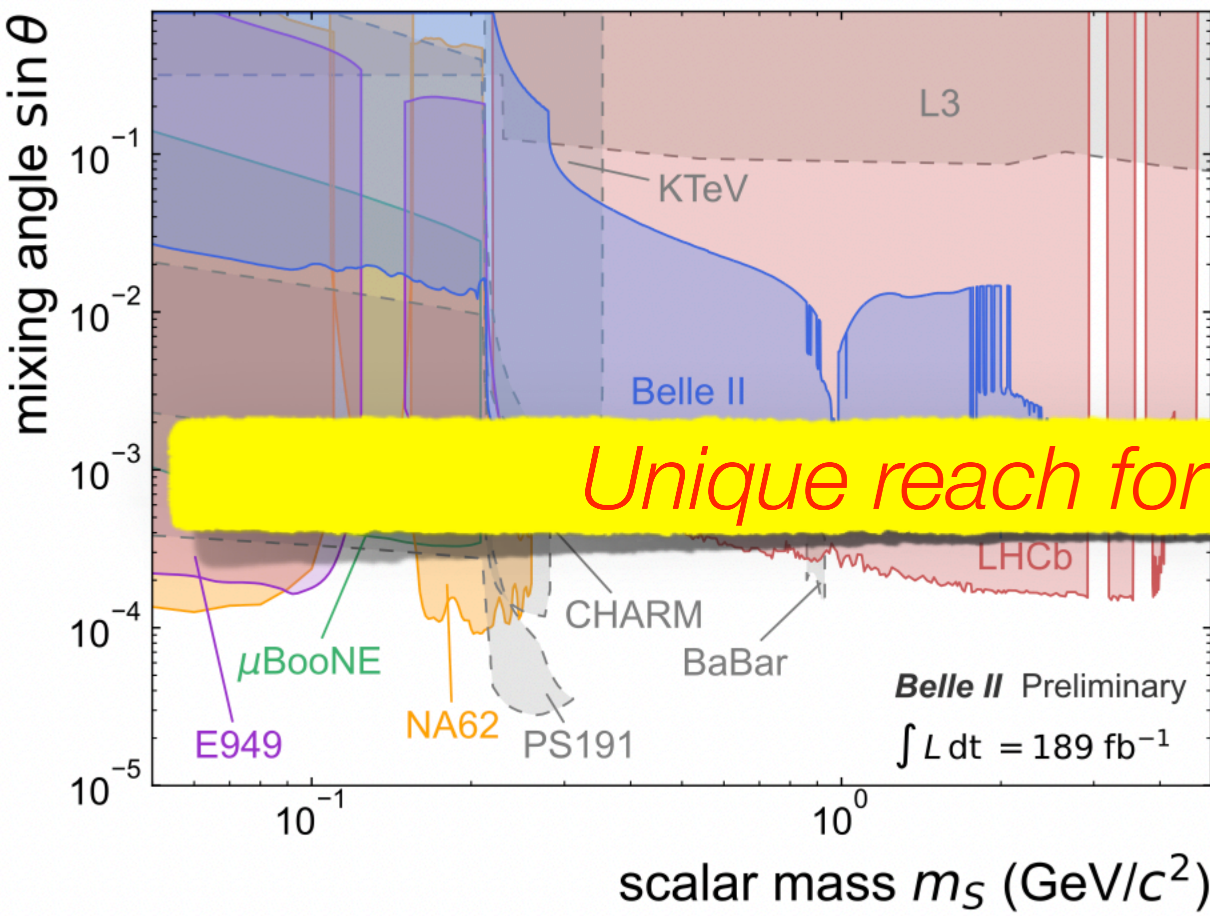
# Direct searches result

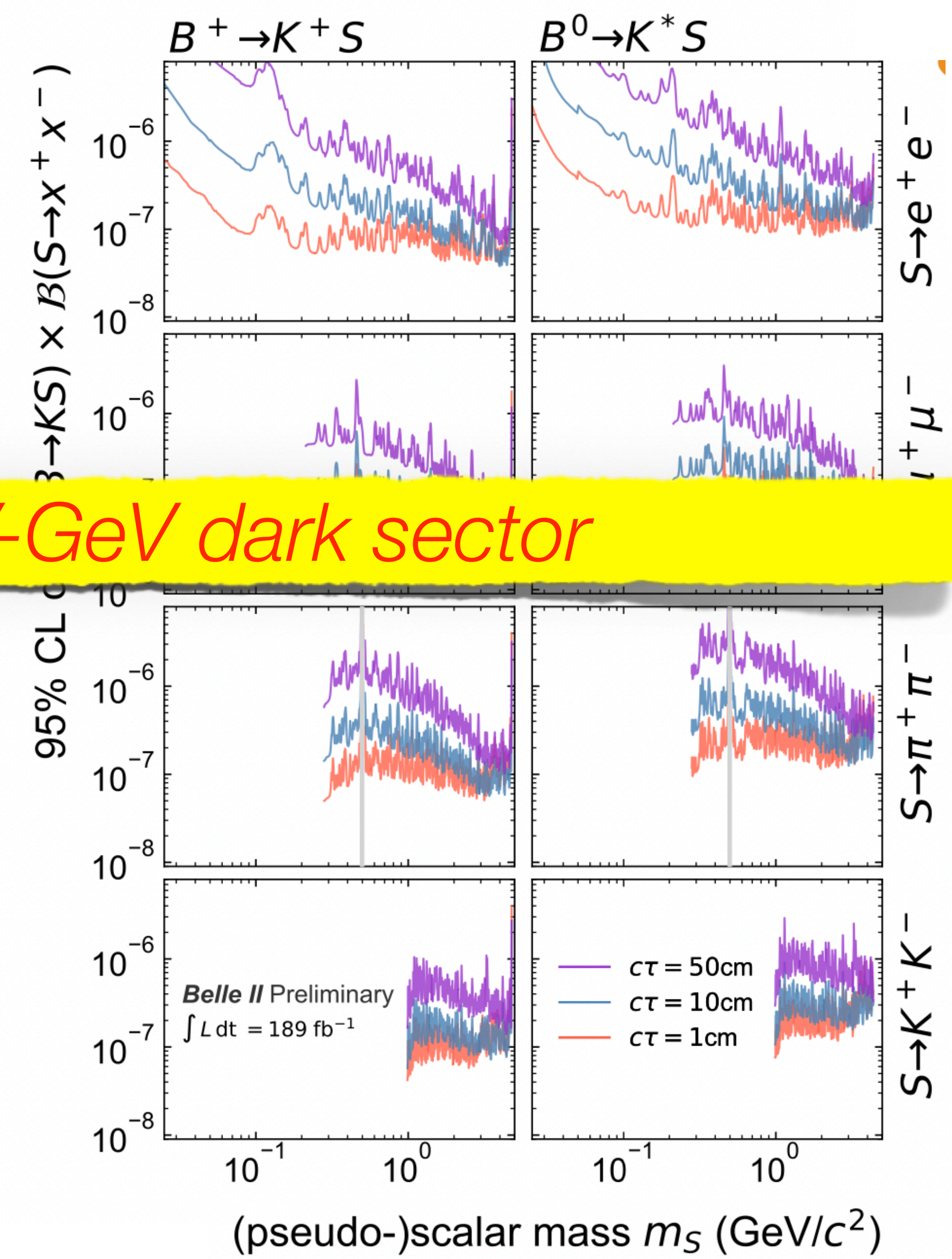



First limits for exclusive hadronic final states and most constraining direct search for K(*)ee

# Direct searches result




*Unique reach for MeV-GeV dark sector*

First limits for exclusive hadronic final states and most constraining direct search for K(*)ee

# Epilogue

# Conclusion

Quite special circumstances for flavor:

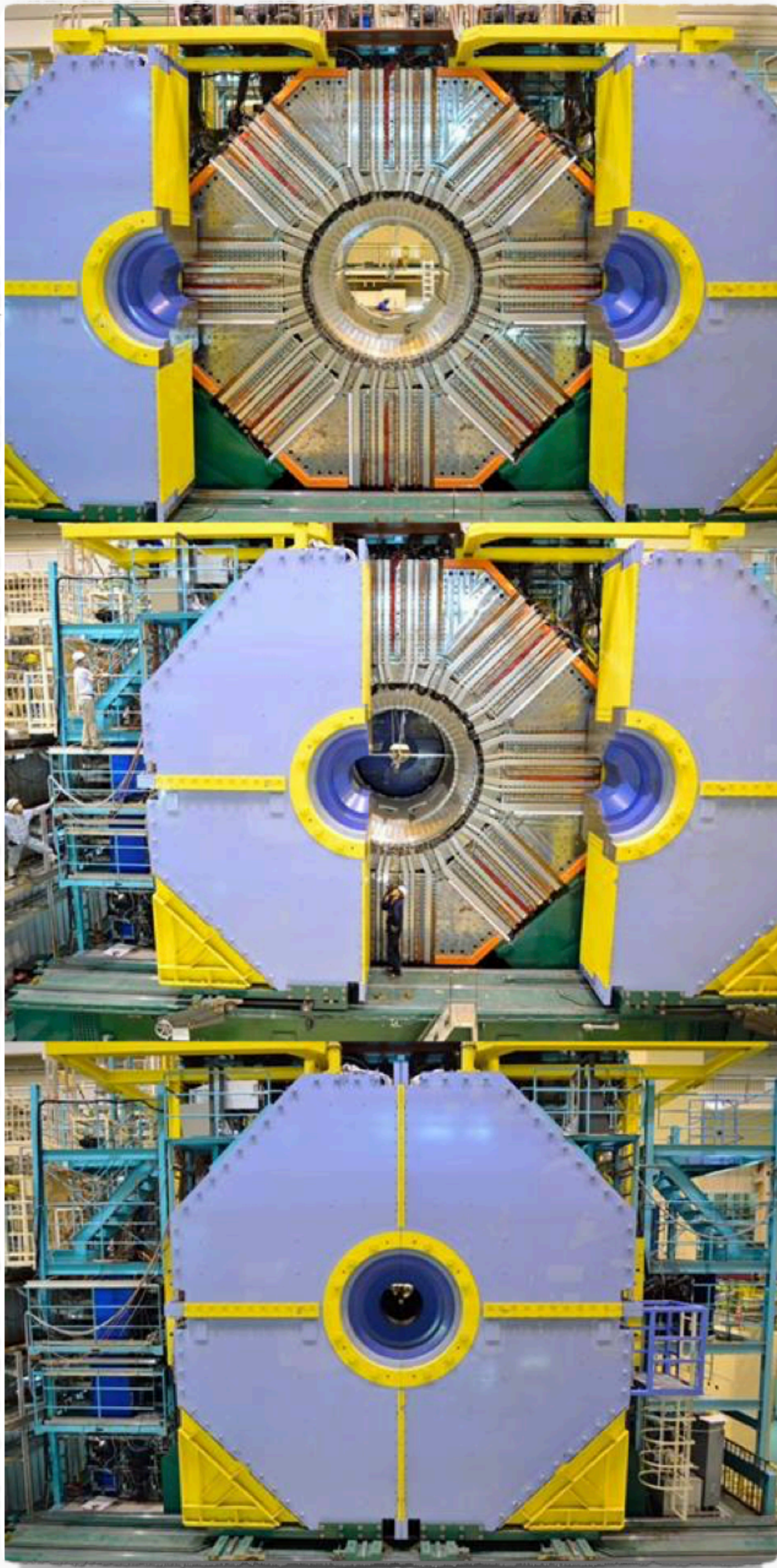
- no BSM in high-$p_T$, anomalies in indirect searches
- Two state-of-art experiments, at the *Y(4S)* and in *pp*, running together over the next decade

Complementarity is real.

Belle II: accesses suite of compelling measurements that are unique and world leading, now.

- saturate SL, τ, and low-mass DS programs
- unique access to high-profile *B/D* measurements involving $\pi^0/\gamma/\nu/$

…might be the last opportunity to do them



# Epilogue

50 years ago, flavor processes in Japan exposed striking evidence for “new” physics …but this went unnoticed in the Western world….

Prog. Theor. Phys. Vol. 46 (1971), No. 5

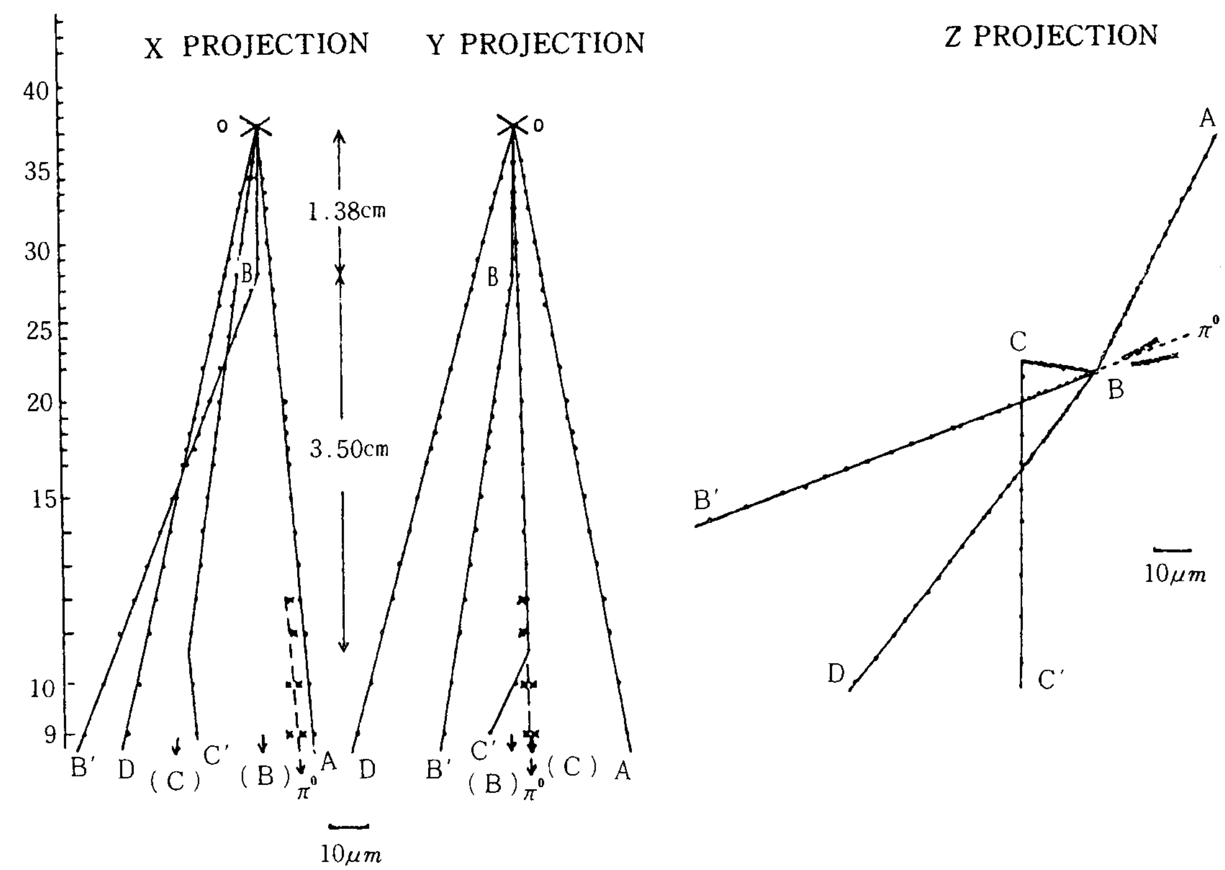
**A Possible Decay in Flight of a New Type Particle**

Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA*

*Institute for Nuclear Study University of Tokyo*

**Yokohama National University*

August 9, 1971




1971 — Evidence of kinks from decays of long-lived heavy particles in cosmic rays recorded with emulsions.

# Epilogue

50 years ago, flavor processes in Japan exposed striking evidence for "new" physics …but it went unnoticed in the Western world….

May Belle II give us a second opportunity?

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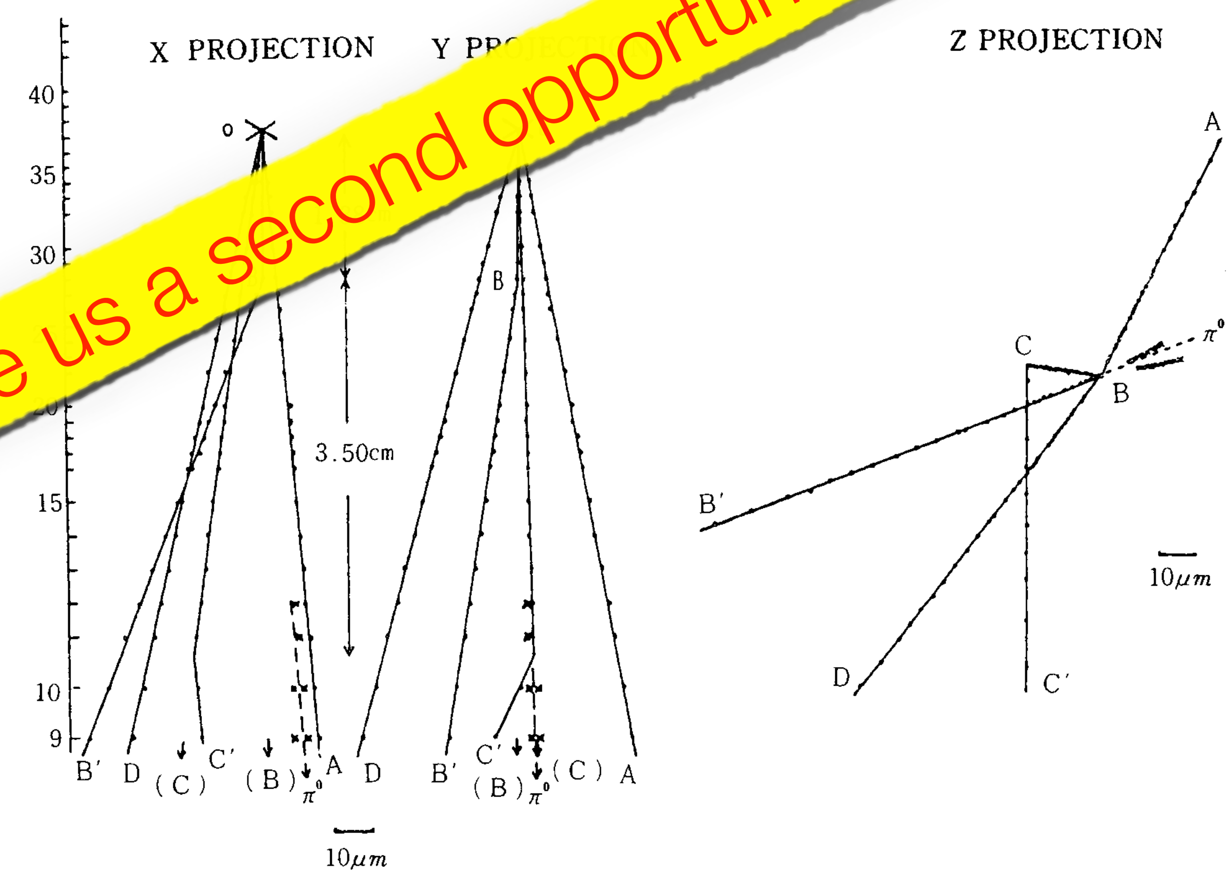



1971 — Evidence of kinks from decays of long-lived heavy particles in cosmic rays recorded with emulsions.

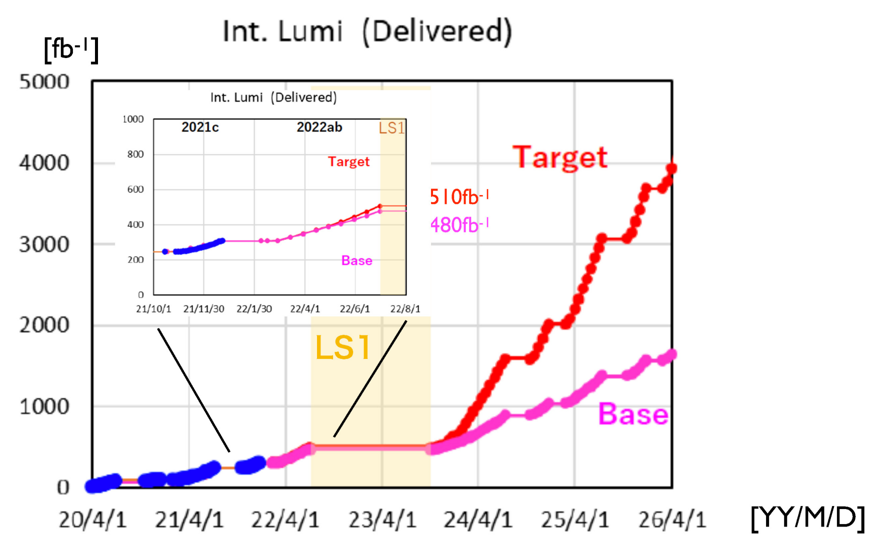
# (Hopefully not) the end

# 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.