Latest results from Belle and Belle II

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for the Belle and Belle II Collaborations

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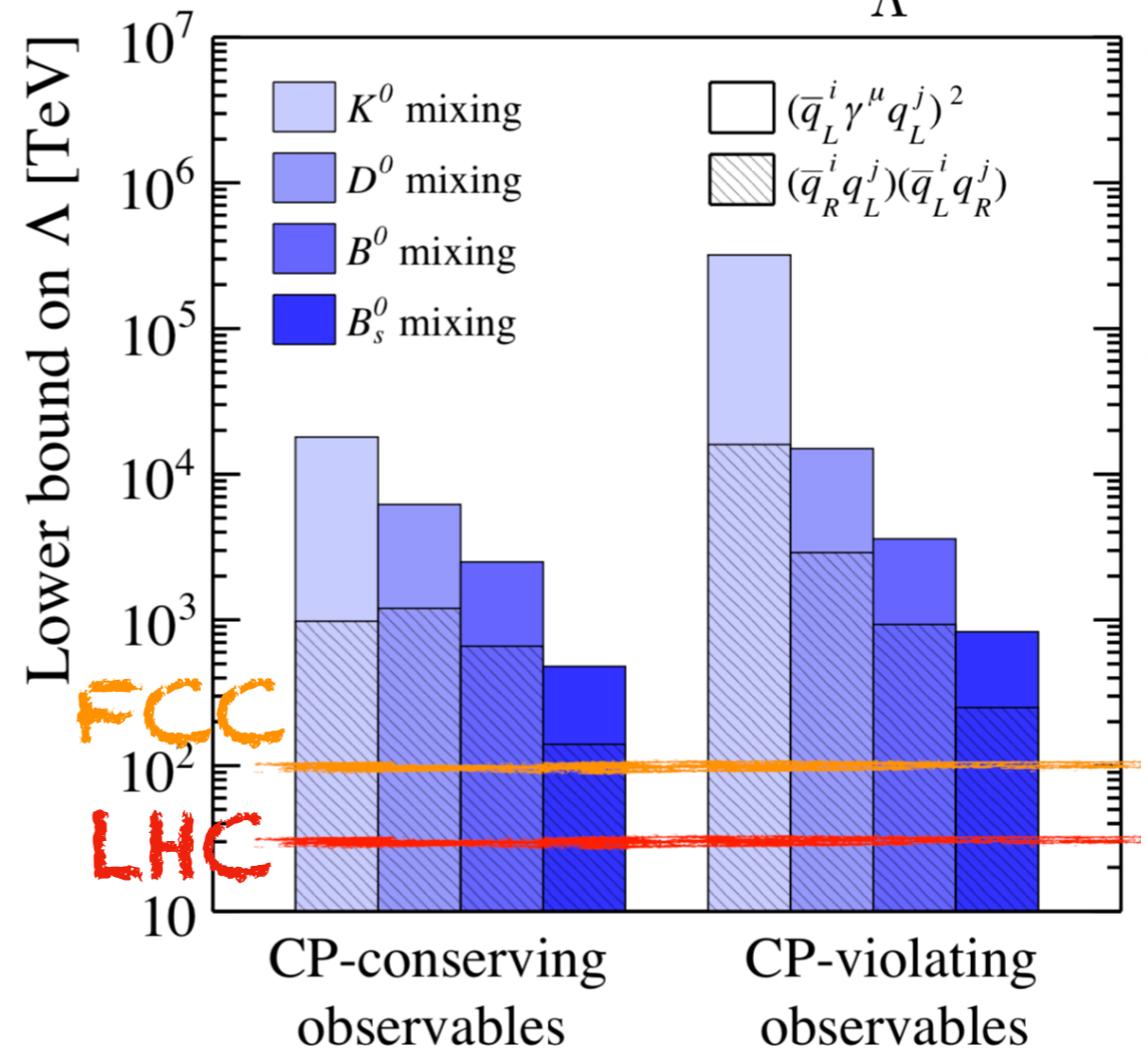
Probing the next scale

The standard model is incomplete.

Flavour physics to access higher scales than those directly reachable at current or futures colliders to search for UV extension.

Systematic approach to probe many redundant observables and look for emerging patterns that signal unexpected physics.

Name of the game is precision

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

[arXiv:1302.0661]

Lower bound on Λ [TeV]

- K^0 mixing
- D^0 mixing
- B^0 mixing
- B_s^0 mixing
- $(\bar{q}_L^i \gamma^\mu q_L^j)^2$
- $(\bar{q}_R^i q_L^j)(\bar{q}_L^i q_R^j)$

FCC

LHC

CP-conserving observables   CP-violating observables

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Boosting the reach

KEKB (1999-2010) ➠ SuperKEKB (2019-present).
Energy-asymmetric e^+e^- collisions at the *Y(4S)*
Unprecedented luminosity, 5.1×10^{34} cm^{-2} s^{-1} world record last December.

Belle (II) hermetic detector,
ideal for missing-energy final states.
Excellent vertexing and tracking.
Good PID and neutrals.

Belle II looks like "old" Belle, but
effectively a brand new instrument:
has better or same performance
within an harsher environment

About 800M B$\overline{\text{B}}$ pairs on tape for Belle.
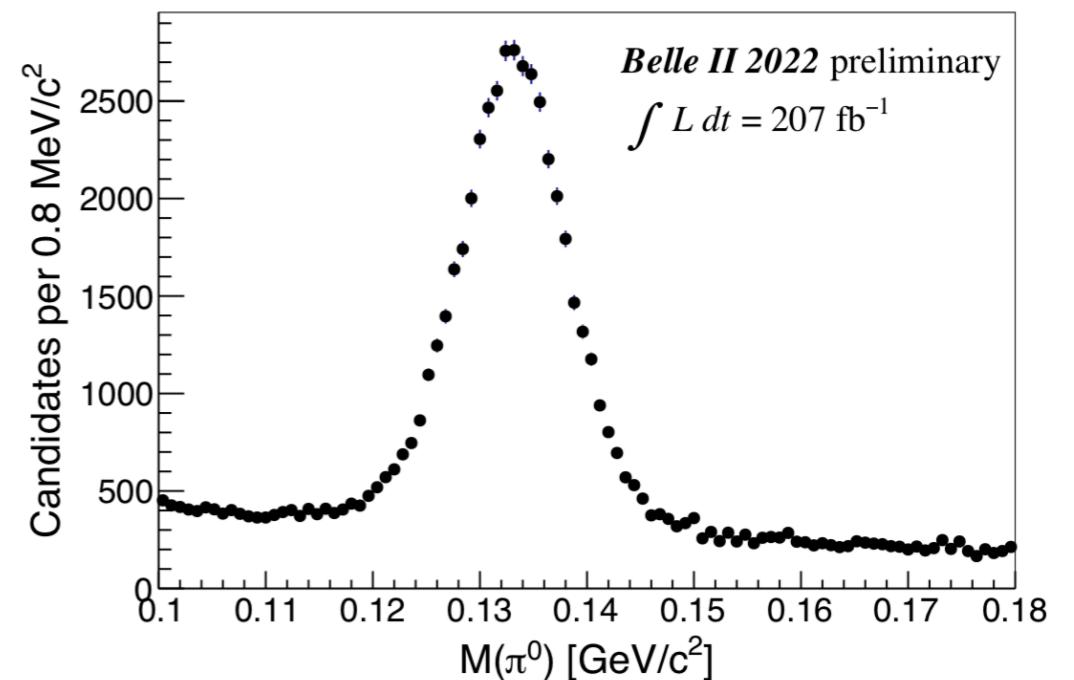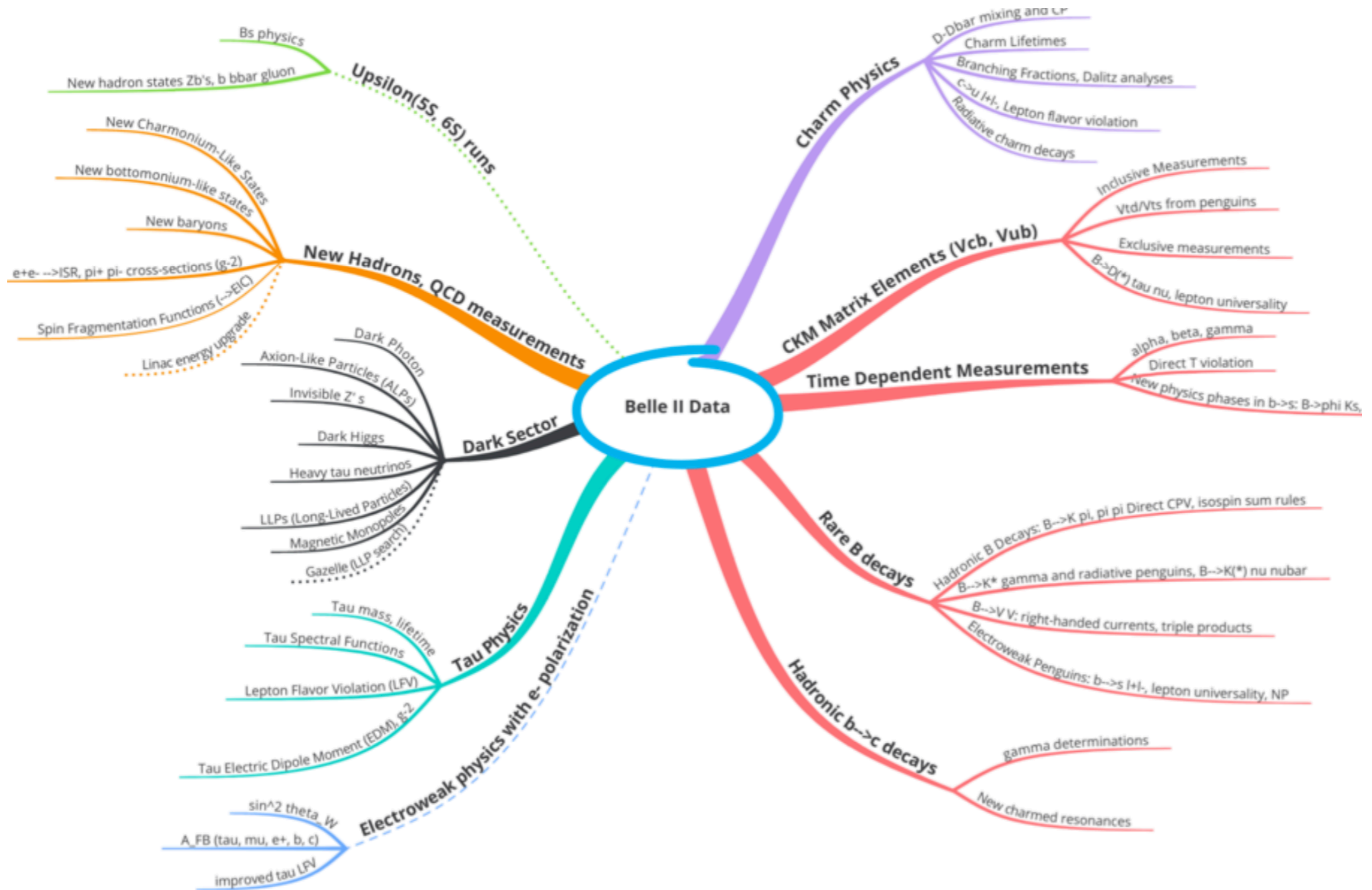Belle II roughly half, with higher quality.
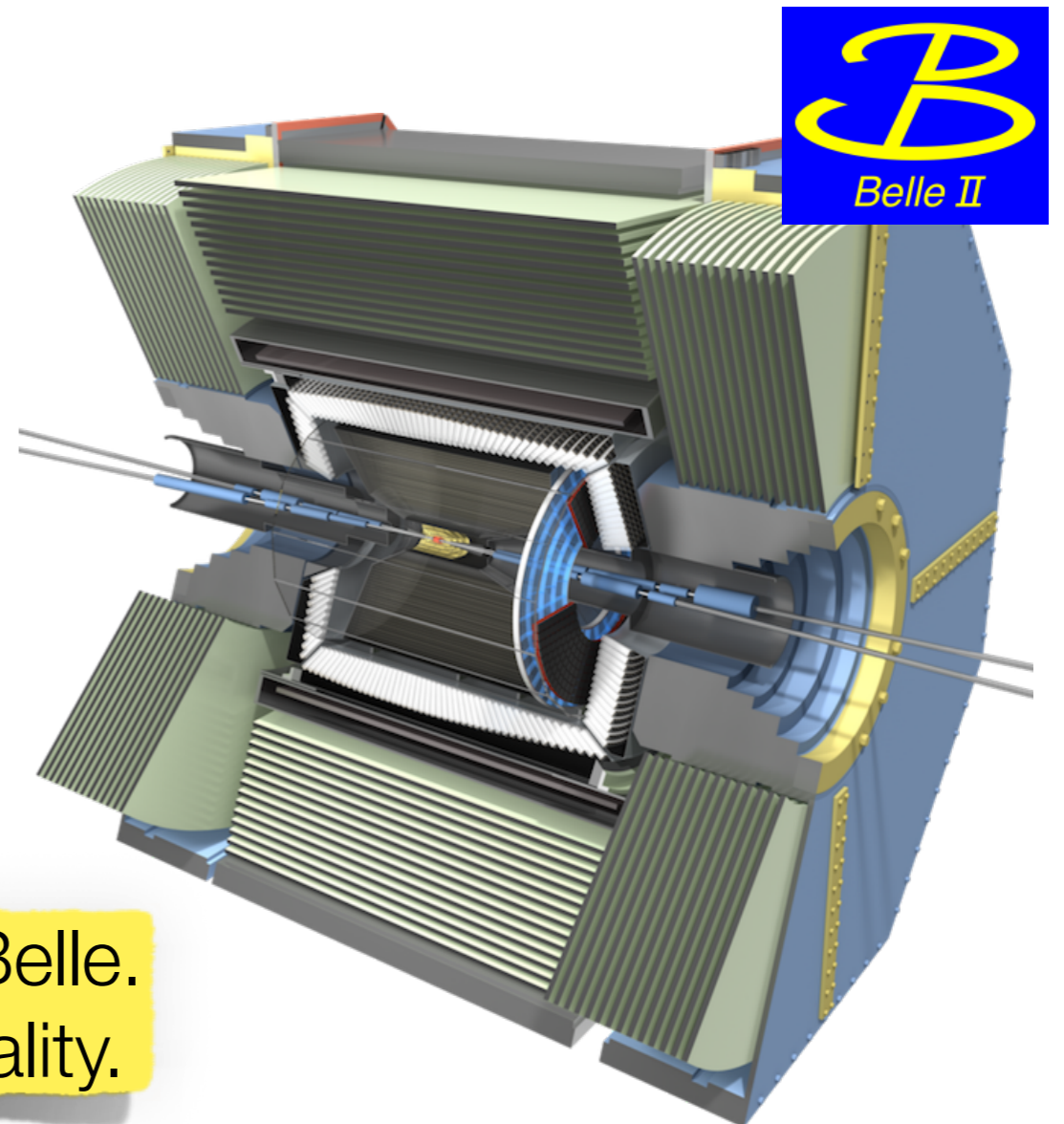
Performance

Net effect of better vertexing (PXD) and greatly-reduced size of the SuperKEKB interaction region (nano-beam scheme).
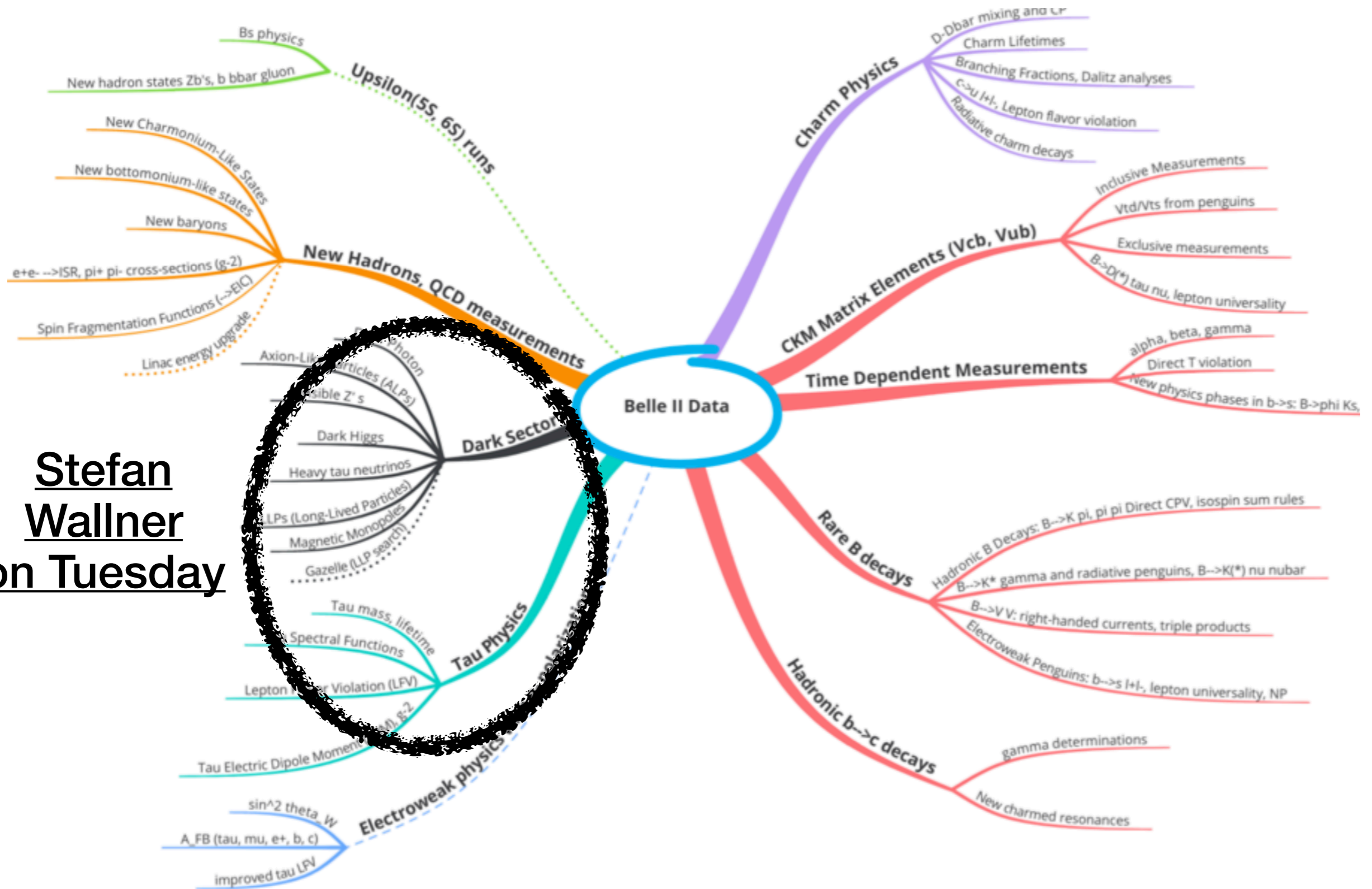

High photon efficiency
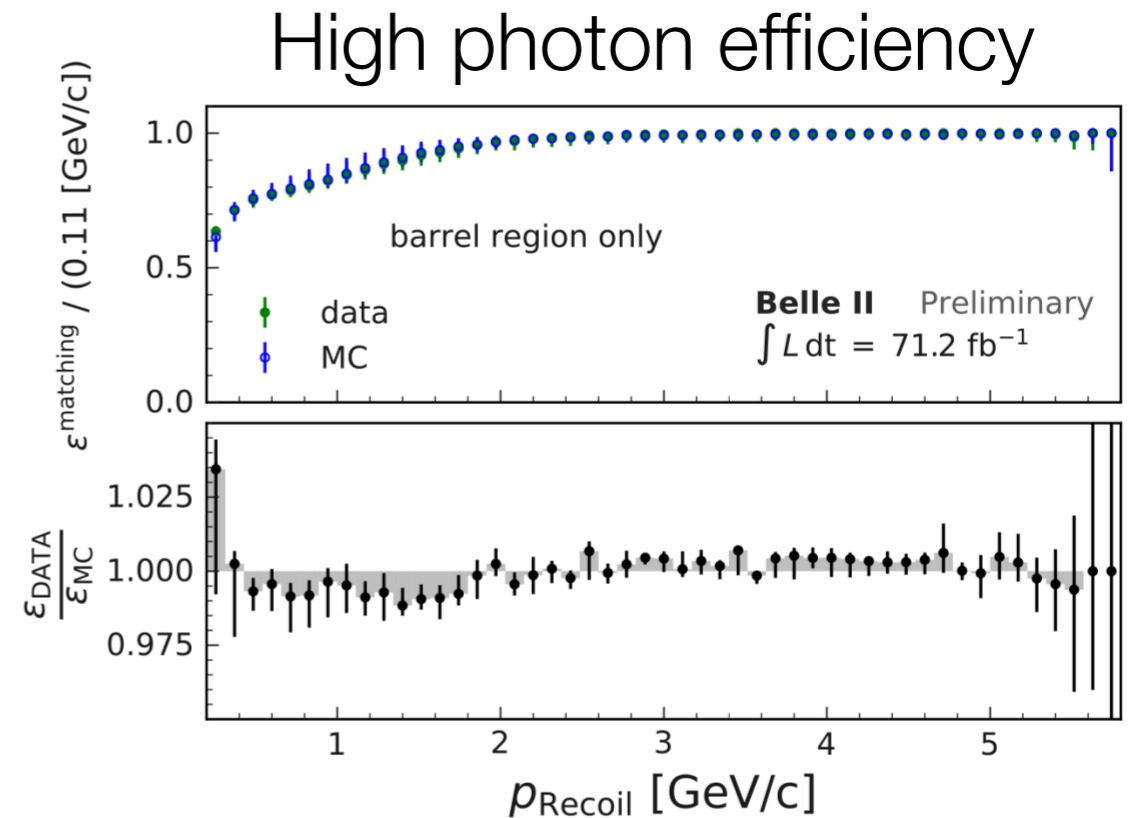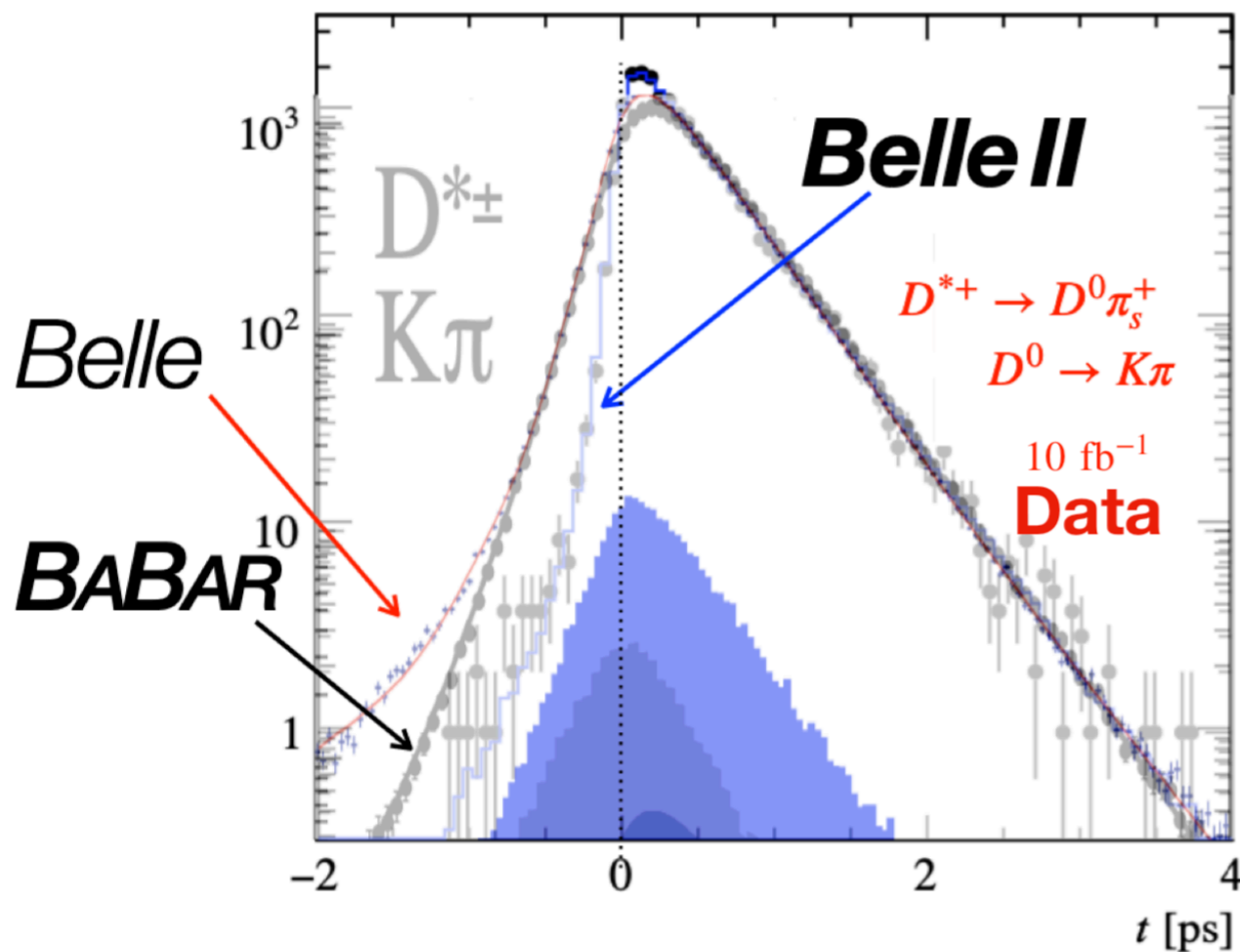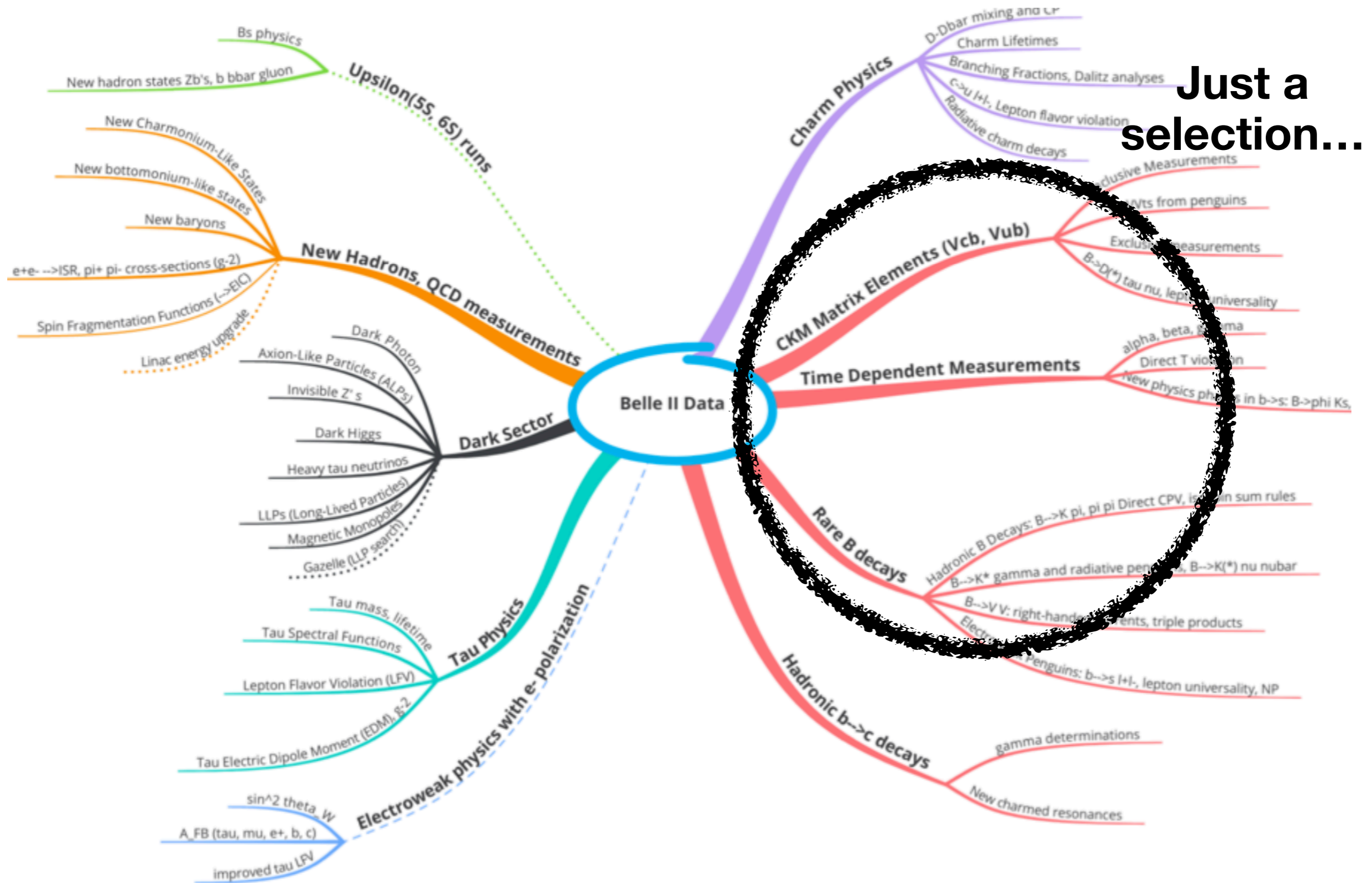

Good neutral reconstruction

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A diversified physics program

[arXiv:2207.06307]

A diversified physics program

A diversified physics program

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Strengthening the unitarity test

Quarks change flavour exchanging W bosons: the couplings are elements of a unitary matrix in the SM (Cabibbo-Kobayashi-Maskawa)
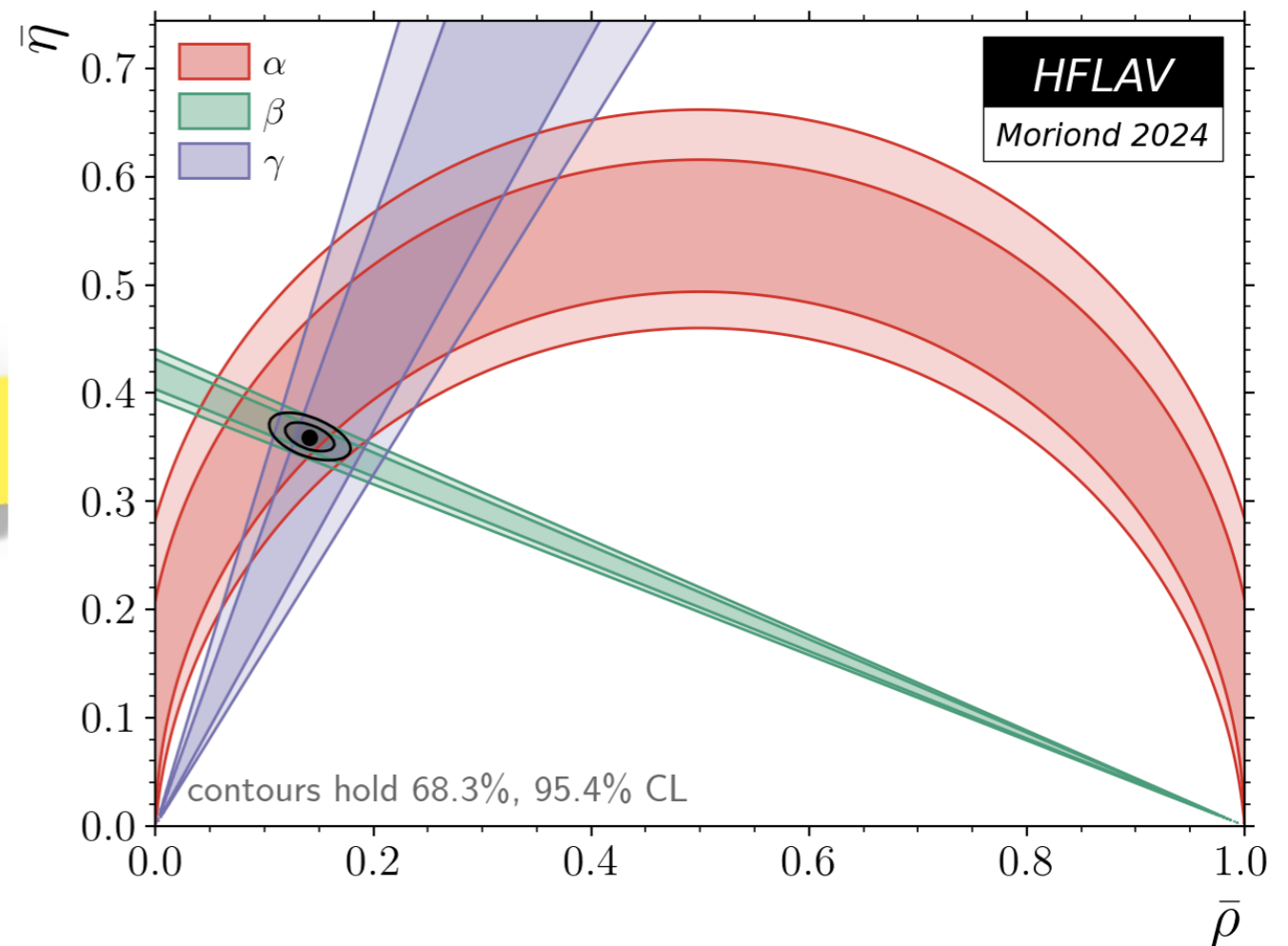
Unitarity represented by a triangle in a complex plane: angles must sum to 180 degrees.

Angle α (aka ϕ_1) the least known.

Determined with a global analysis of CP asymmetries and BR of charmless decays
$B \to \rho^+\rho^-, \rho^+\rho^0, \rho^0\rho^0$
$B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$
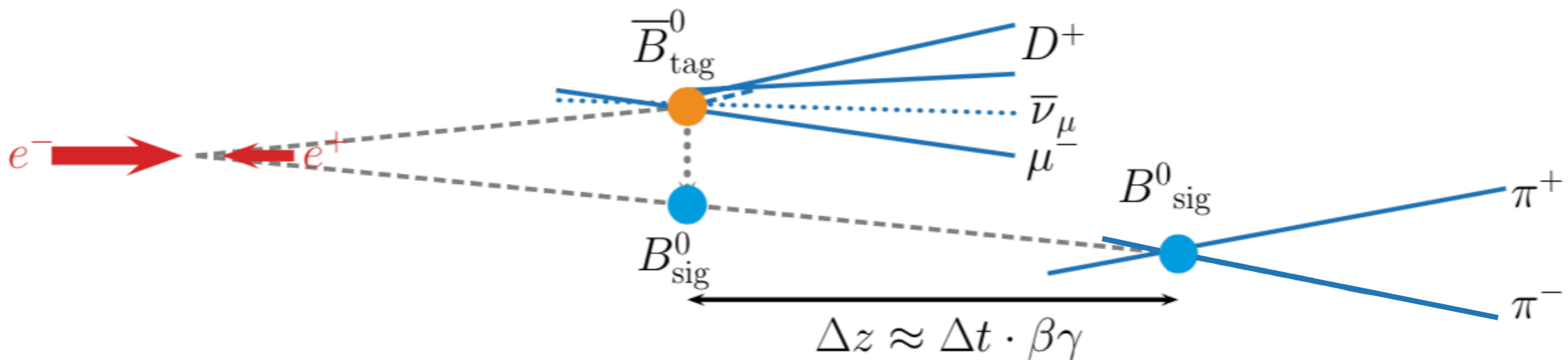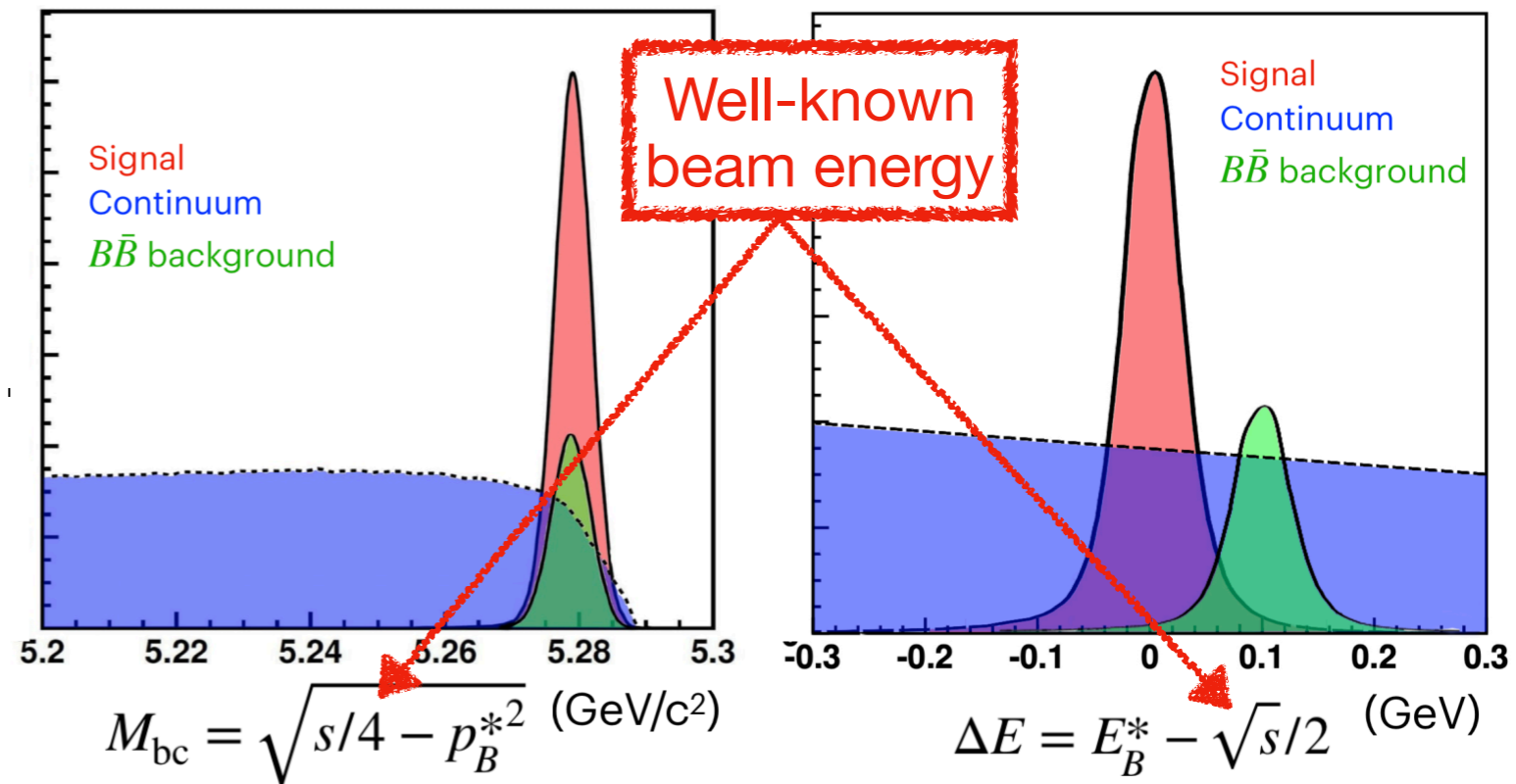related by isospin symmetry, to suppress hadronic unknowns.

Unique opportunity for Belle II to efficiently access all final states

B-factory 101

Threshold *B* production from point-like colliding particles, $e^+e^- \to Y(4S) \to B\bar{B}$: **kinematic well constrained**.

The asymmetric collision gives the boost to **measure the displacement** (decay-time difference, *Δt*) and **tag the flavour.**

Signal
Continuum
$B\bar{B}$ background

Well-known beam energy

Signal
Continuum
$B\bar{B}$ background

$$M_{\rm bc} = \sqrt{s/4 - p_B^{*2}} \ \text{(GeV/c}^2)$$

$$\Delta E = E_B^* - \sqrt{s}/2 \ \text{(GeV)}$$

$\overline{B}^0_{\rm tag}$

D^+

$\overline{\nu}_\mu$

μ^-

e^- e^+

$B^0_{\rm sig}$

$B^0_{\rm sig}$

π^+

π^-

$$\Delta z \approx \Delta t \cdot \beta\gamma$$

Charmless decay challenges

Fully-hadronic final state with high-momentum light mesons.

> Need to fight against "continuum" production. Background $O(10^6)$ larger than signal.
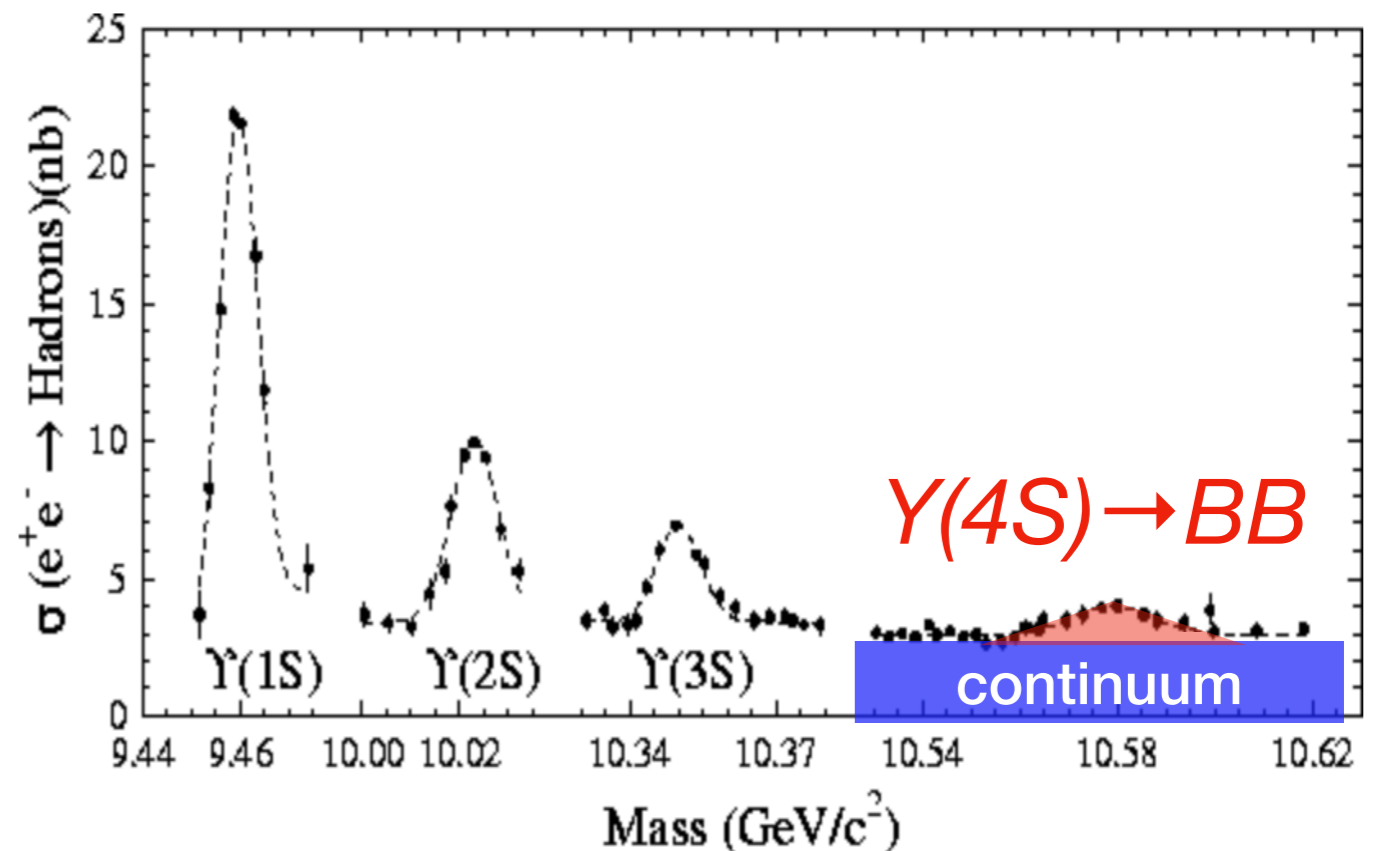
Exploit discriminating event topology: **continuum features a jet-like structure, while *B* decays isotropically at rest**.

Boost event-classification with machine learning algorithms (BDT, NNet).

$q\bar{q}$ events $B\bar{B}$ events
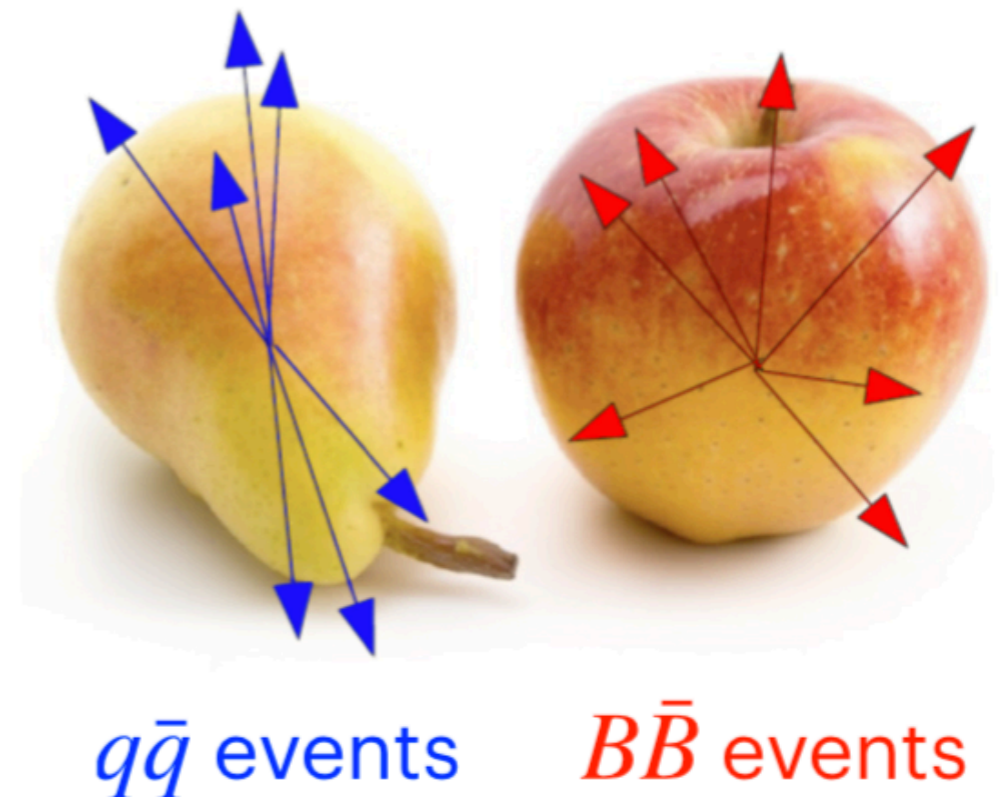
$B^0 \rightarrow \pi^0\pi^0$

Only four photons in the final state, no vertex to identify the signal.

Continuum suppressed with dedicated BDT.
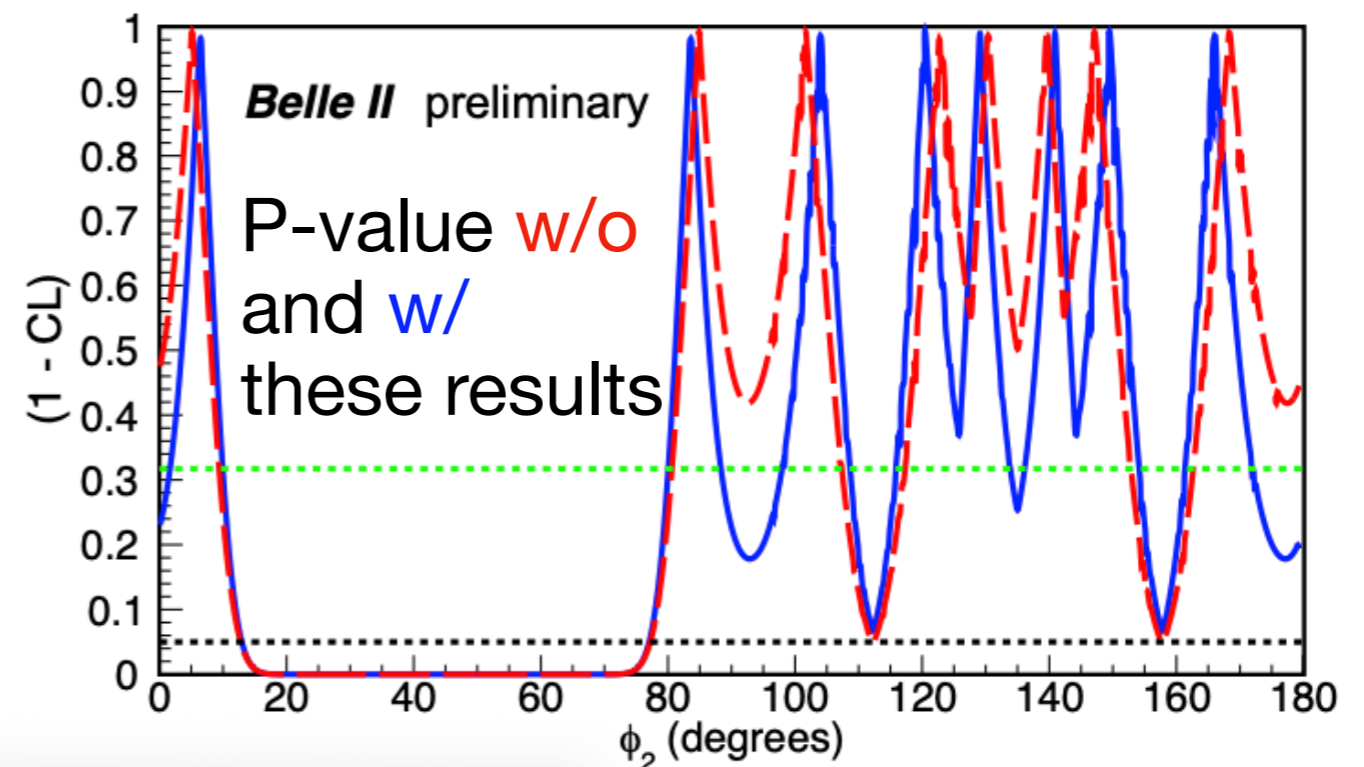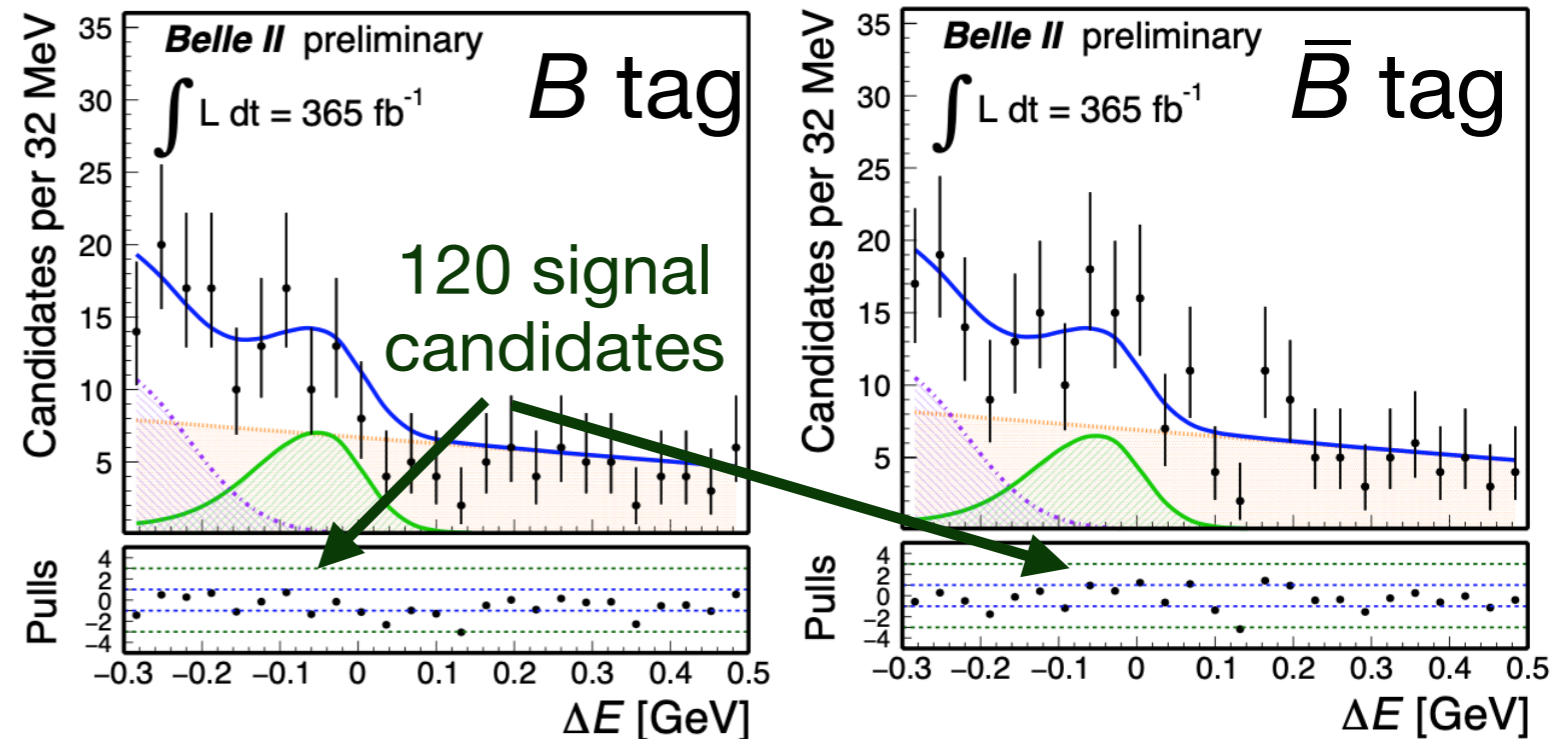Tag the flavour to measure the CP asymmetry.
Extract signal from a 4D fit (Mbc, ΔE, BDT, tag-quality).

BR = $(1.25 \pm 0.23) \times 10^{-6}$
$A_{CP} = (0.03 \pm 0.30)$

Compatible with and better than previous results.

120 signal candidates

P-value w/o and w/ these results

Large impact on α from $B \rightarrow \pi\pi$

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$B^0 \to \rho^+ \rho^-$

Effectively like three decays, according to allowed angular momenta between ρ's (vector mesons). Need the fraction of longitudinally polarised decays: fit distributions of decay angles.
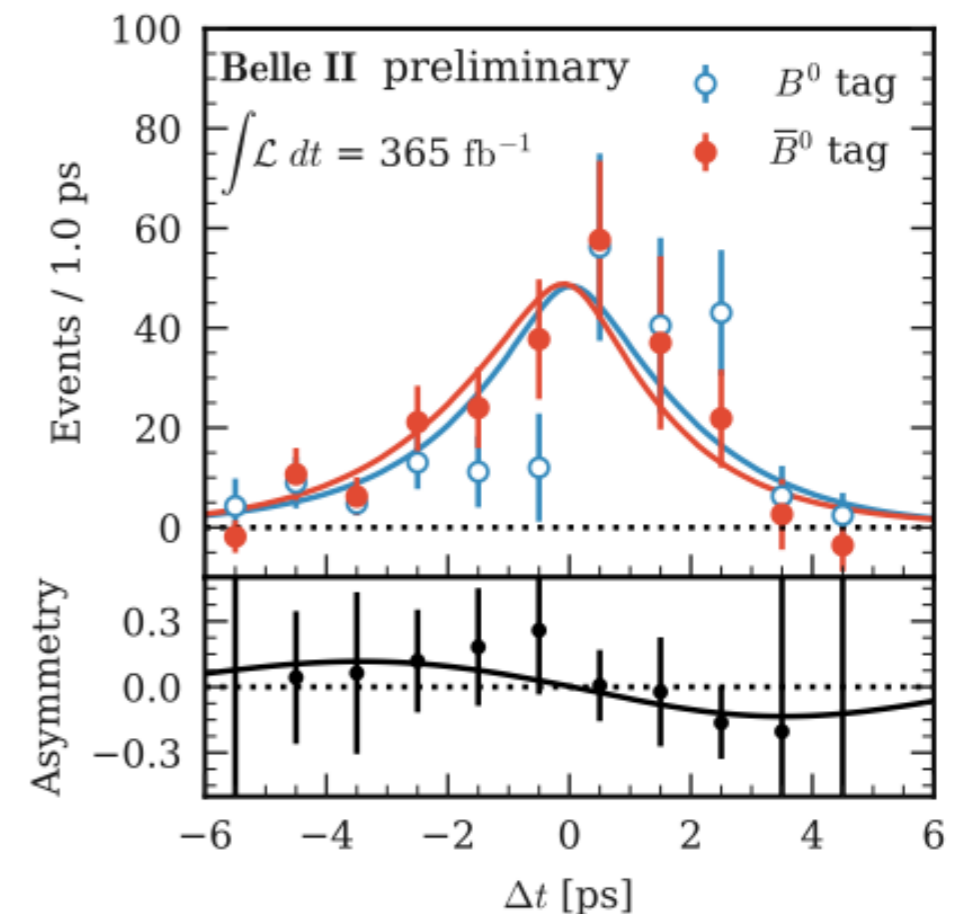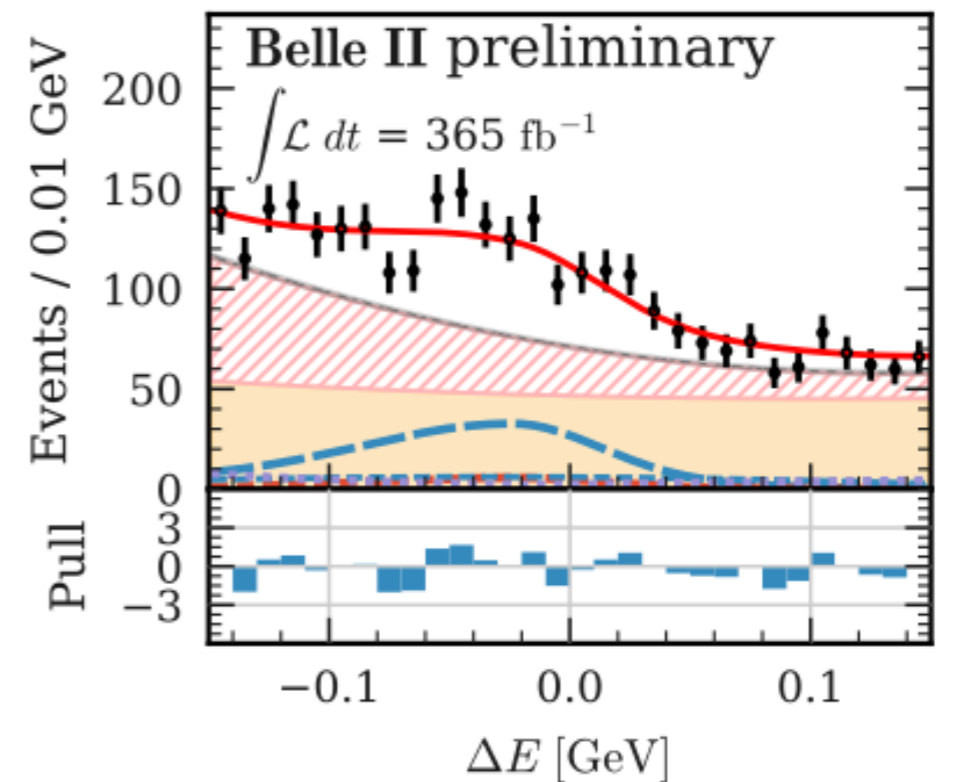
Suppress continuum with NNet and tag the flavour to measure the CP asymmetries as a function of Δt
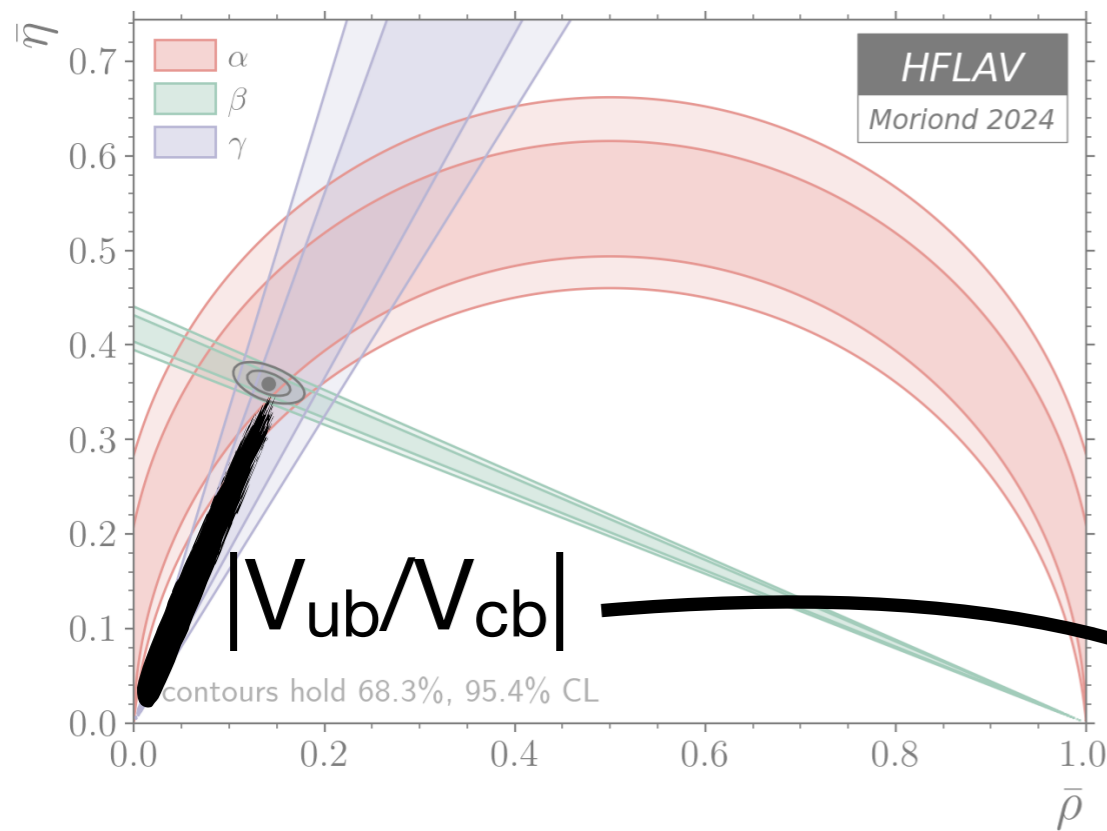
$$A_{CP} = -0.26 \pm 0.21$$
$$S_{CP} = -0.02 \pm 0.13$$

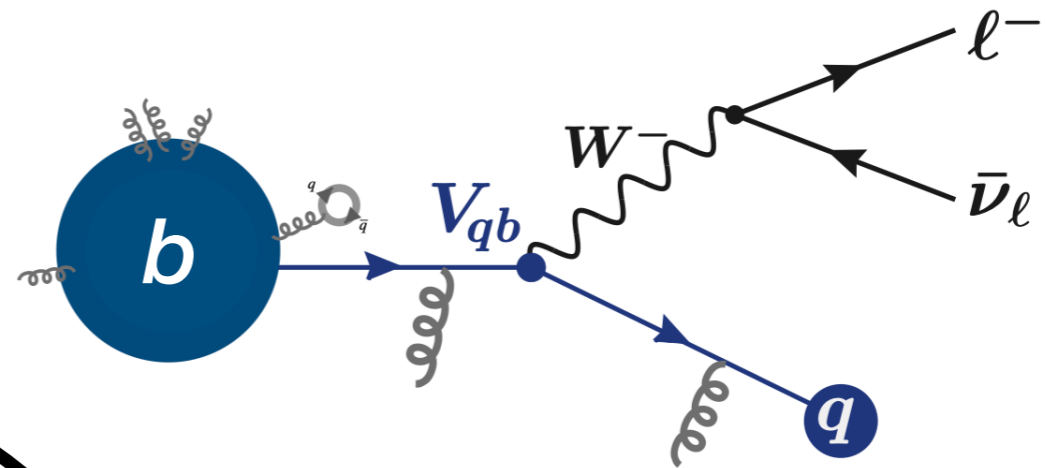Obtain a 10% improvement on α when including these results:

$$\alpha = \left(92.6^{+4.5}_{-4.8}\right)^\circ$$

Belle II preliminary
$\int \mathcal{L}\, dt = 365 \text{ fb}^{-1}$

Events / 0.01 GeV
Pull
ΔE [GeV]

Belle II preliminary
$\int \mathcal{L}\, dt = 365 \text{ fb}^{-1}$

B^0 tag
$\bar{B}^0$ tag

Events / 1.0 ps
Asymmetry
Δt [ps]

Measuring the sides…

Strengths of *b*-to-*c* and *b*-to-*u* couplings measured through semileptonic decay

$|V_{ub}/V_{cb}|$

Longstanding tension between inclusive (anything in the hadronic final state) or exclusive (D, D*,…) results.
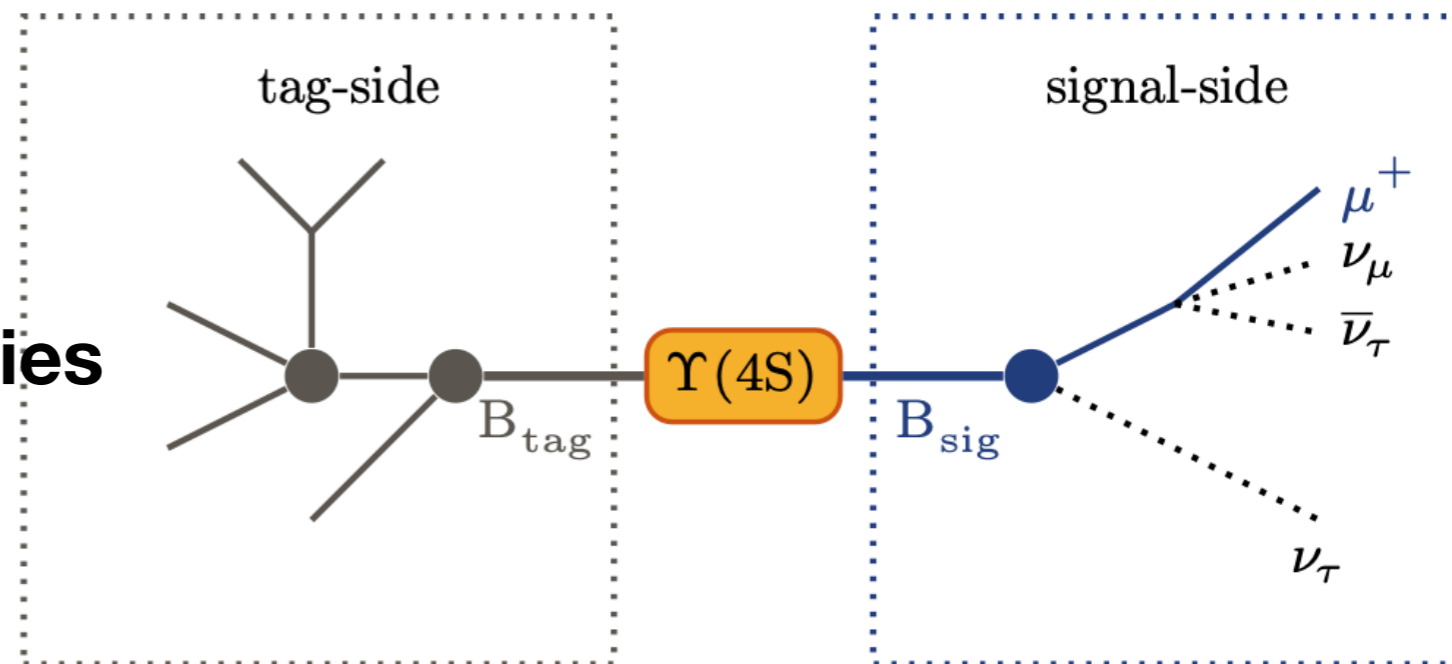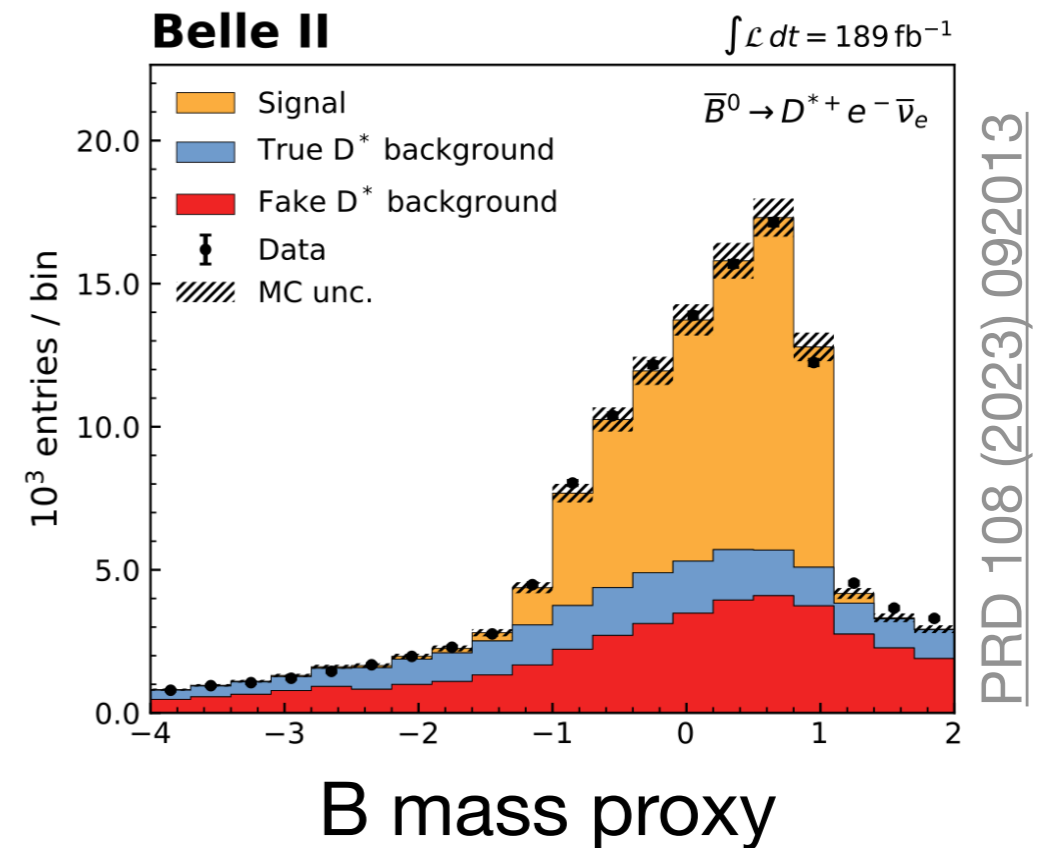About **3 standard deviations.**
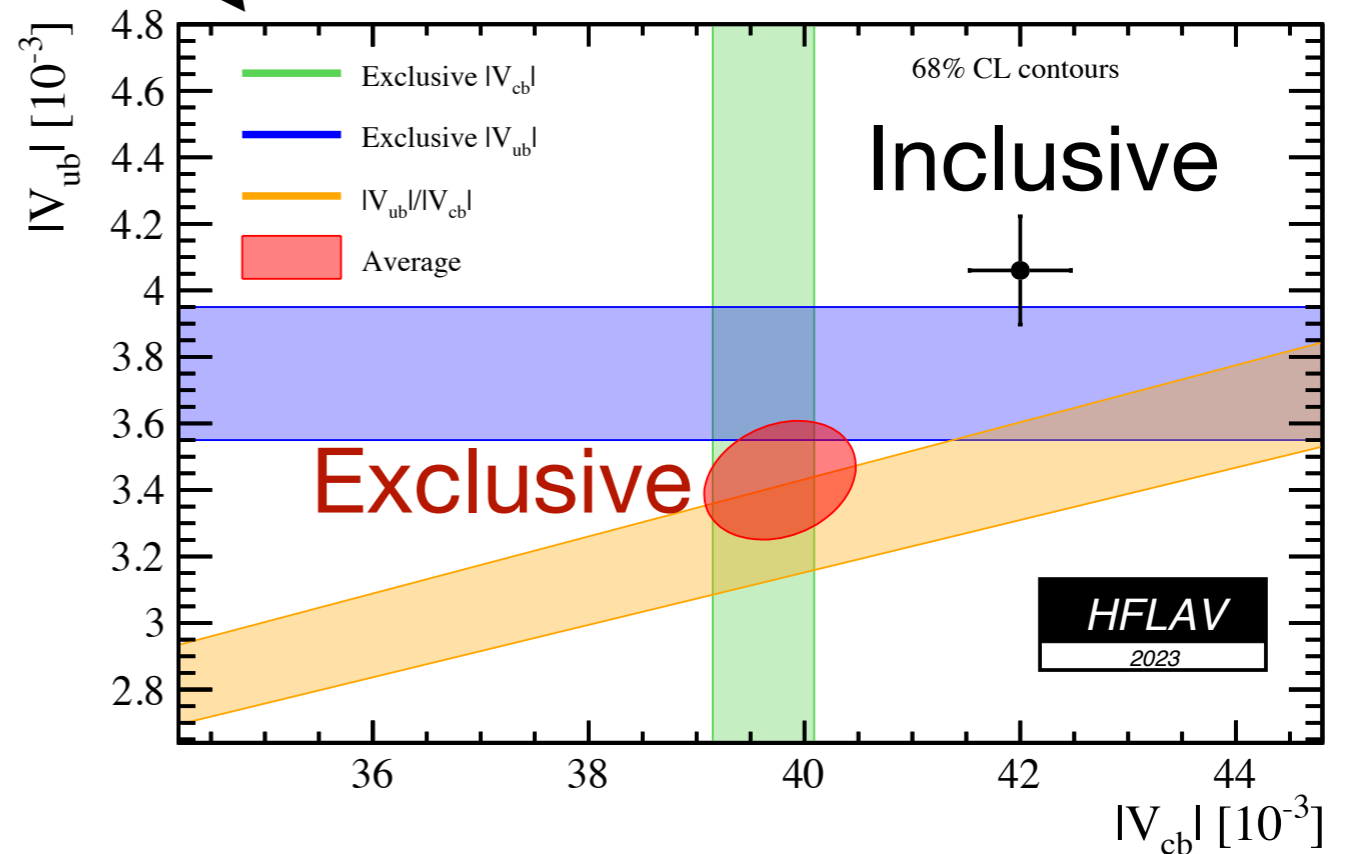
Intermezzo: dealing with missing energy

Energy of the B meson well known, missing the momentum direction.

When missing only a neutrino can approximate the kinematic with enough resolution.

Otherwise, measure the missing energy by reconstructing the accompanying B momentum, so-called **B-tagging.**

Hadronic decays feature the **best information, but efficiencies are typically lower than 1%** — even exploiting machine learning [Comp. Soft. Big Sci 3, 6 (2019)]

Belle II $\int \mathcal{L} \, dt = 189 \, \text{fb}^{-1}$

$\bar{B}^0 \to D^{*+} e^- \bar{\nu}_e$

Signal
True D^* background
Fake D^* background
Data
MC unc.

10^3 entries / bin

B mass proxy

PRD 108 (2023) 092013

tag-side

signal-side

$\Upsilon(4S)$

B_{tag} B_{sig}

μ^+
ν_μ
$\bar{\nu}_\tau$
ν_τ

Measuring the sides… at Belle (II)

New exclusive measurement (tagged) form Belle exploiting full differential information from B→D*lν decays for the first time

$$|V_{cb}| = (41.0 \pm 0.7) \times 10^{-3}$$ [PRL 133 (2024) 131801]

Compatible with inclusive (on the right path to resolve the tension?)
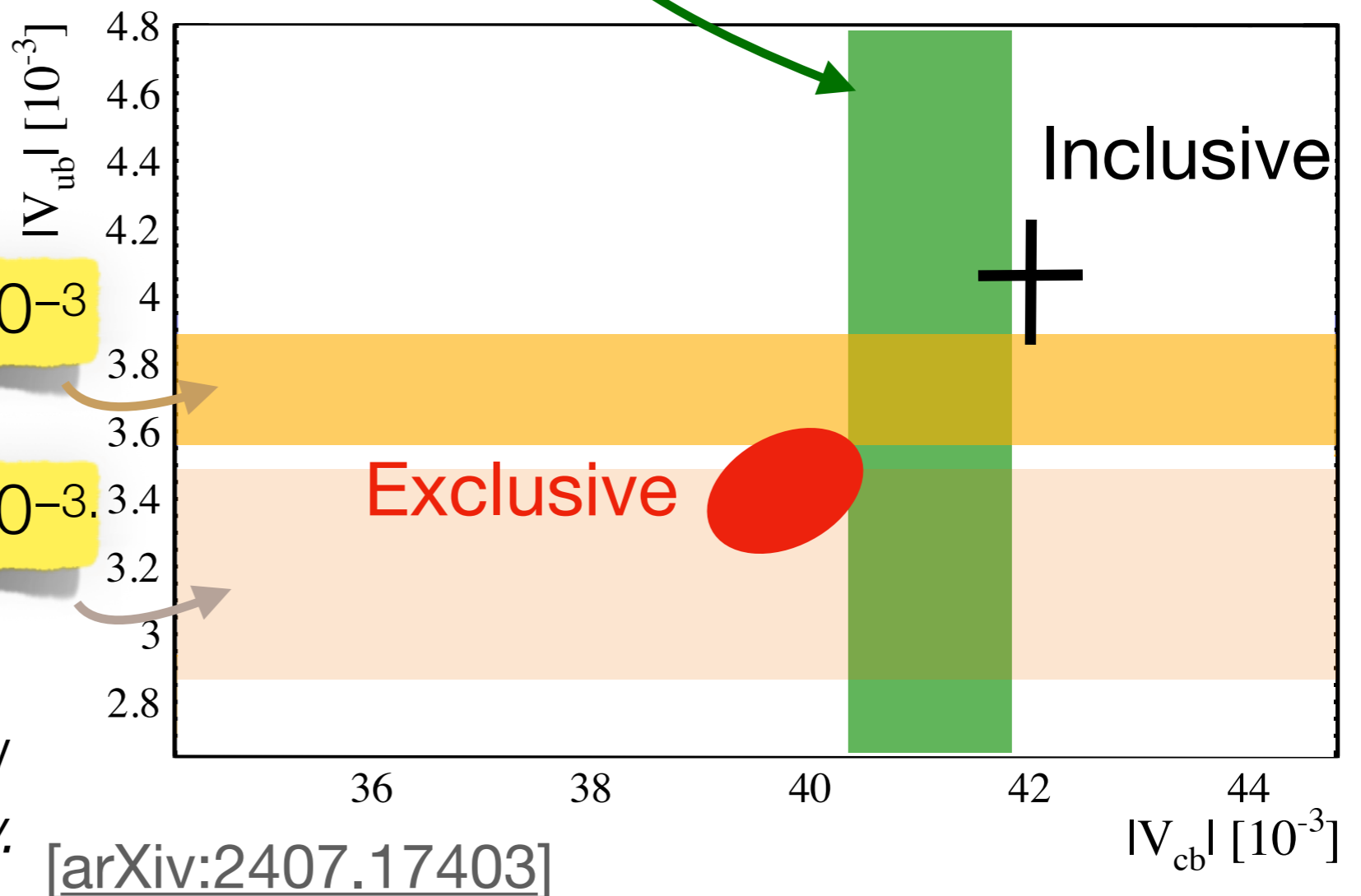
New exclusive results from Belle II (untagged):
B→πlν

$$|V_{ub}| = (3.73 \pm 0.16) \times 10^{-3}$$

B→ρlν

$$|V_{ub}| = (3.19 \pm 0.33) \times 10^{-3}$$

Pion modes reduce the tension, large uncertainty with ρ. *Theory inputs key.*

[arXiv:2407.17403]

Inclusive

Exclusive

$|V_{ub}|$ [10^{-3}]

$|V_{cb}|$ [10^{-3}]

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Evidence of $B \to \tau\nu$

Ideal probe for $|V_{ub}|$, but helicity suppressed.
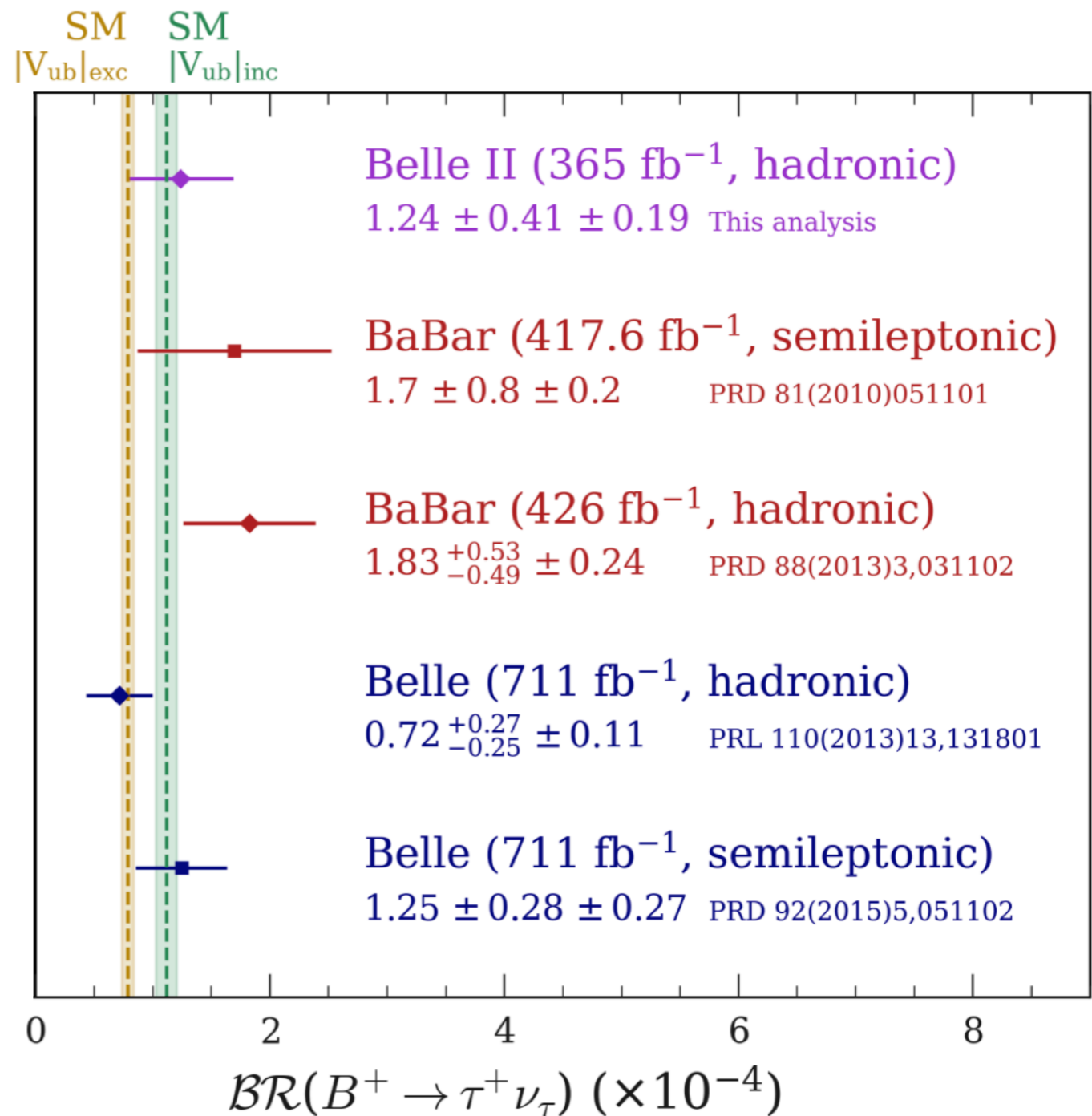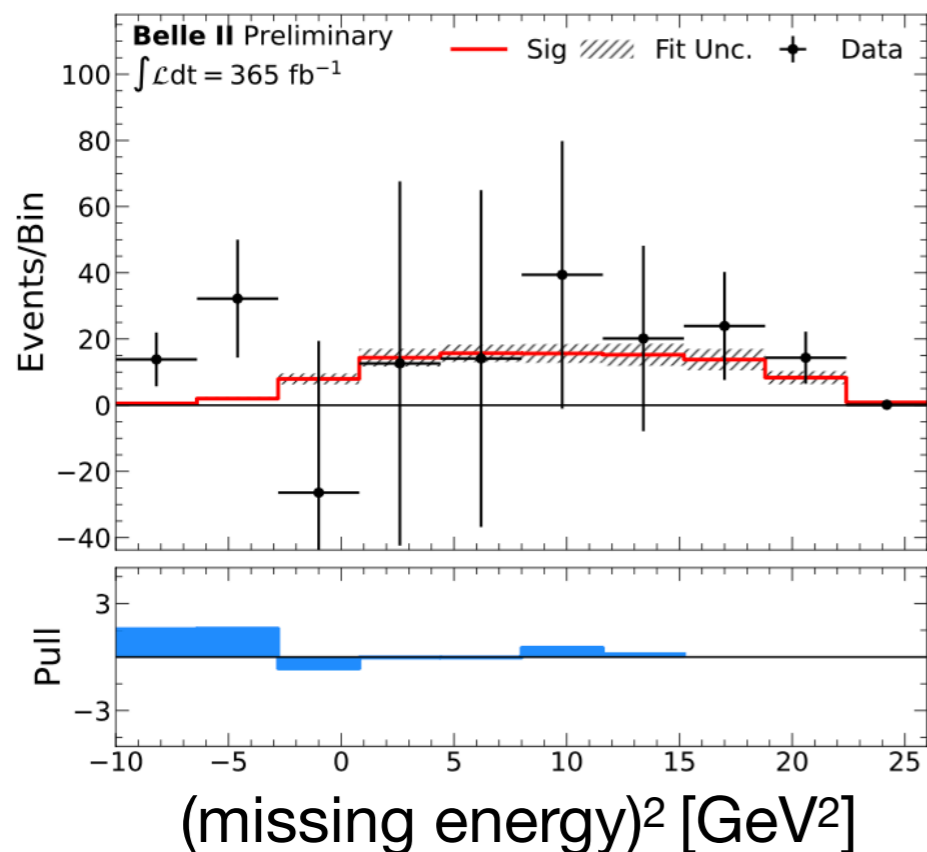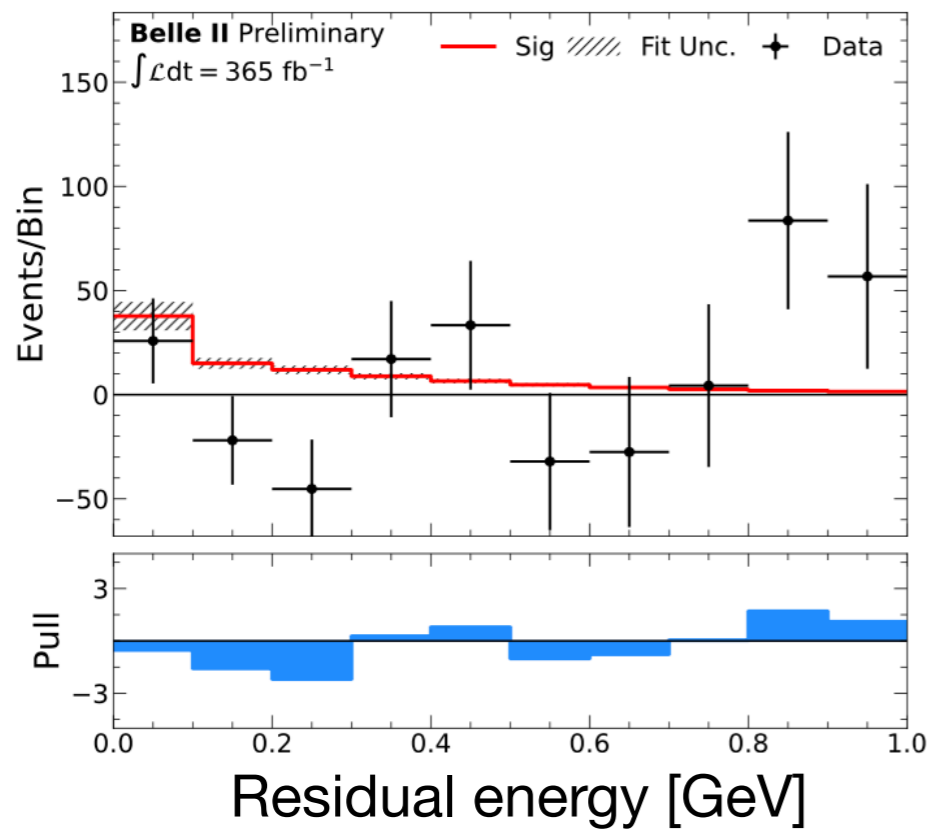Evidence from Babar/Belle, but not yet observed.

Hadronic tag. Reconstruct the tau decays into leptons, a pion, or a ρ. At least 3 neutrinos, large missing energy and nothing else: no residual energy in the calorimeter.

Hadronic tag

nothing else

B^-

B^+

Signal (tau decay)
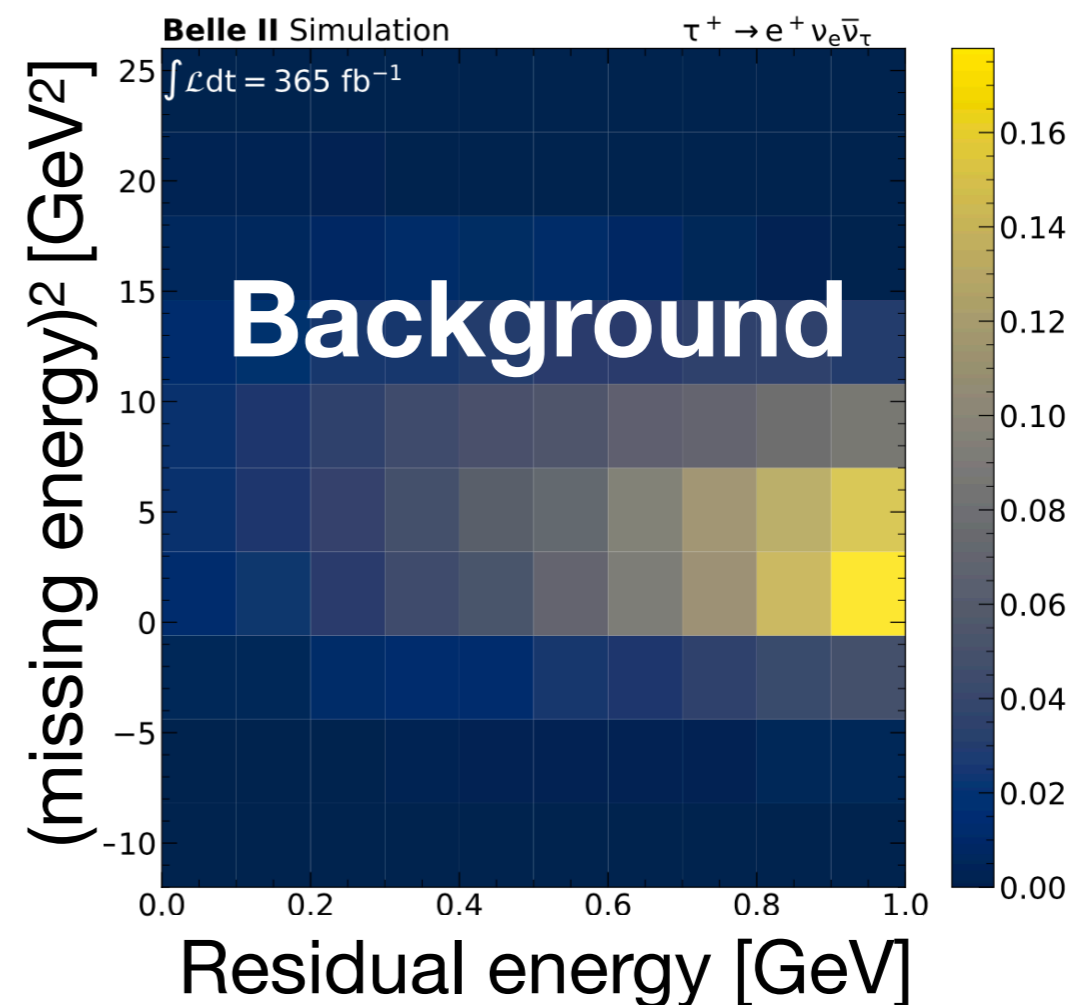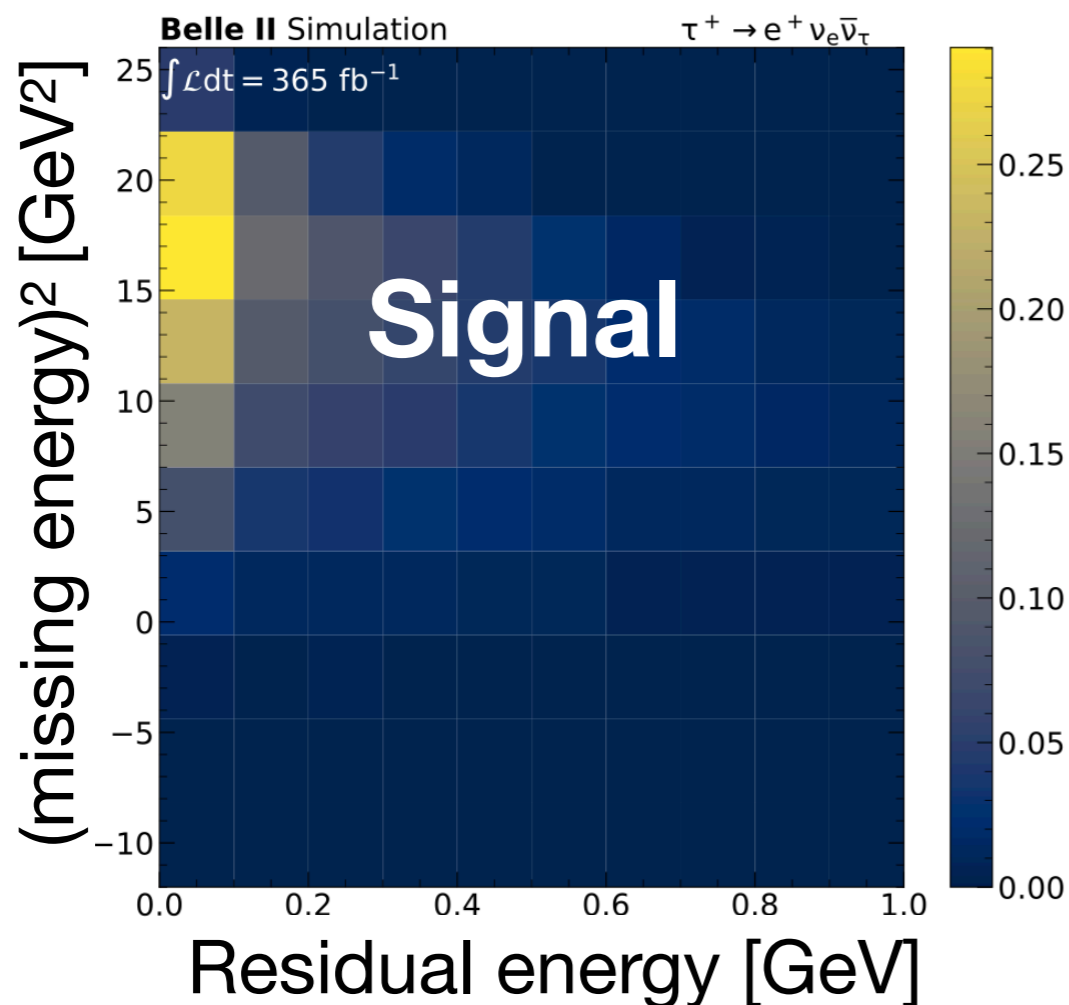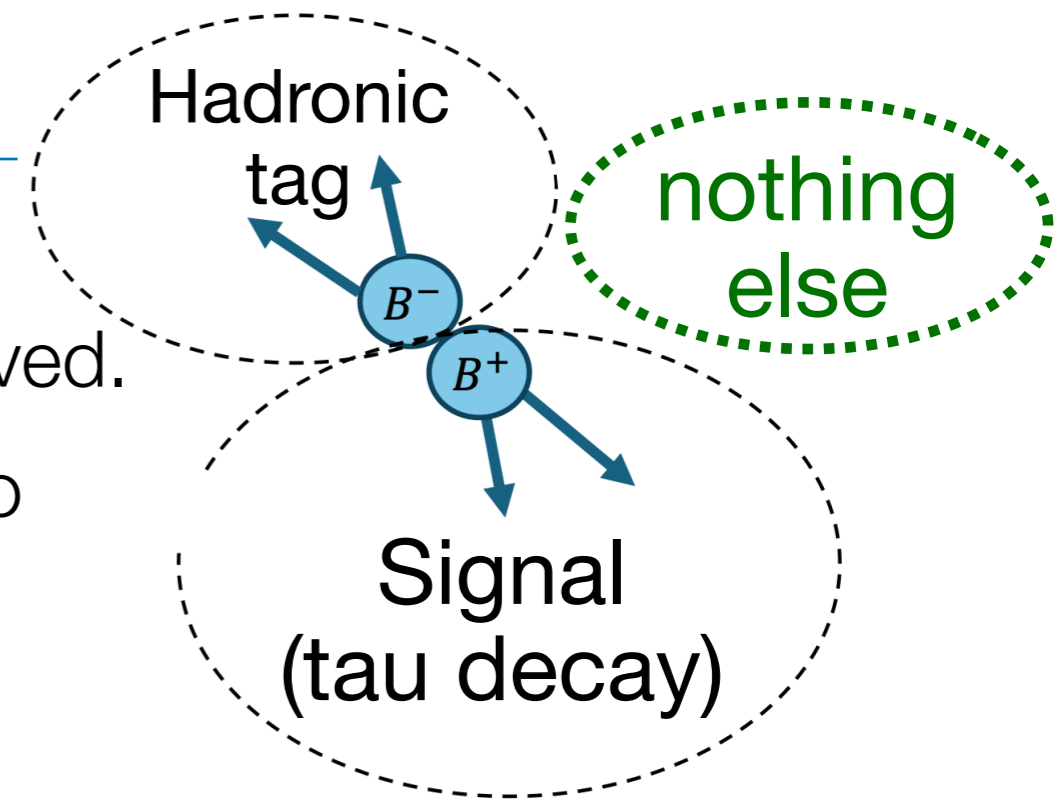
Evidence of $B \to \tau \nu$

[in preparation]

Residual energy [GeV]

(missing energy)^2 [GeV^2]

SM $|V_{ub}|_{exc}$ SM $|V_{ub}|_{inc}$

Belle II (365 fb^{-1}, hadronic)
$1.24 \pm 0.41 \pm 0.19$ This analysis

BaBar (417.6 fb^{-1}, semileptonic)
$1.7 \pm 0.8 \pm 0.2$ PRD 81(2010)051101

BaBar (426 fb^{-1}, hadronic)
$1.83 ^{+0.53}_{-0.49} \pm 0.24$ PRD 88(2013)3,031102

Belle (711 fb^{-1}, hadronic)
$0.72 ^{+0.27}_{-0.25} \pm 0.11$ PRL 110(2013)13,131801

Belle (711 fb^{-1}, semileptonic)
$1.25 \pm 0.28 \pm 0.27$ PRD 92(2015)5,051102

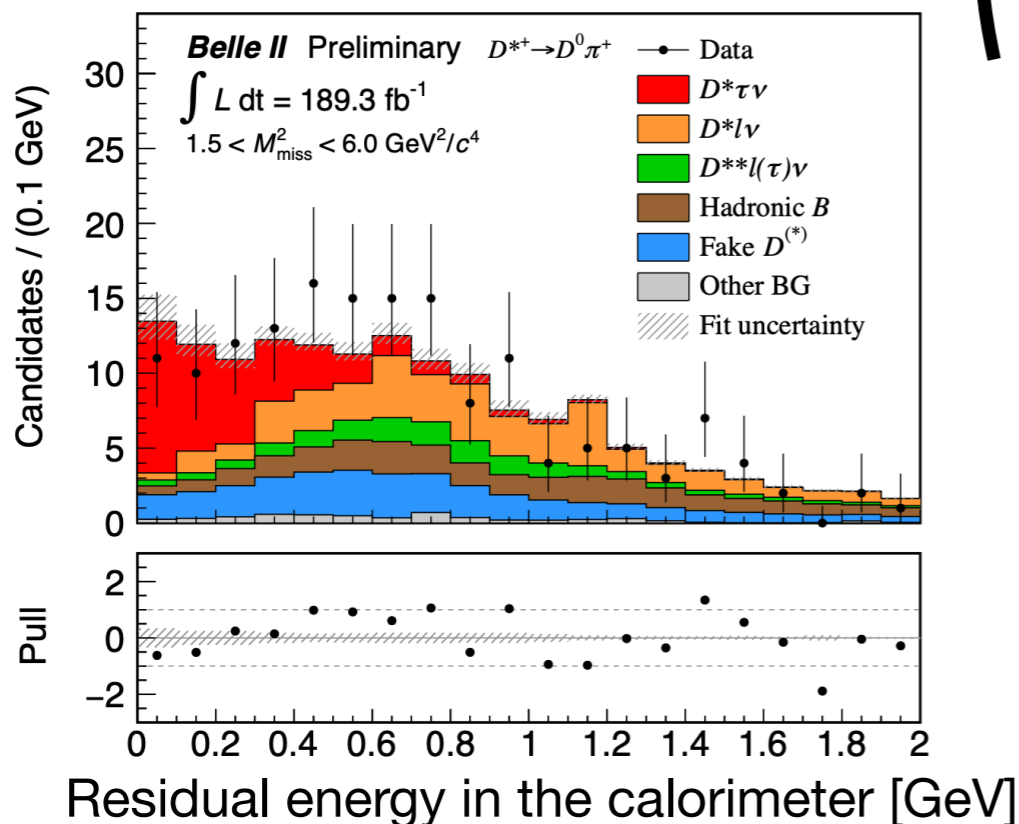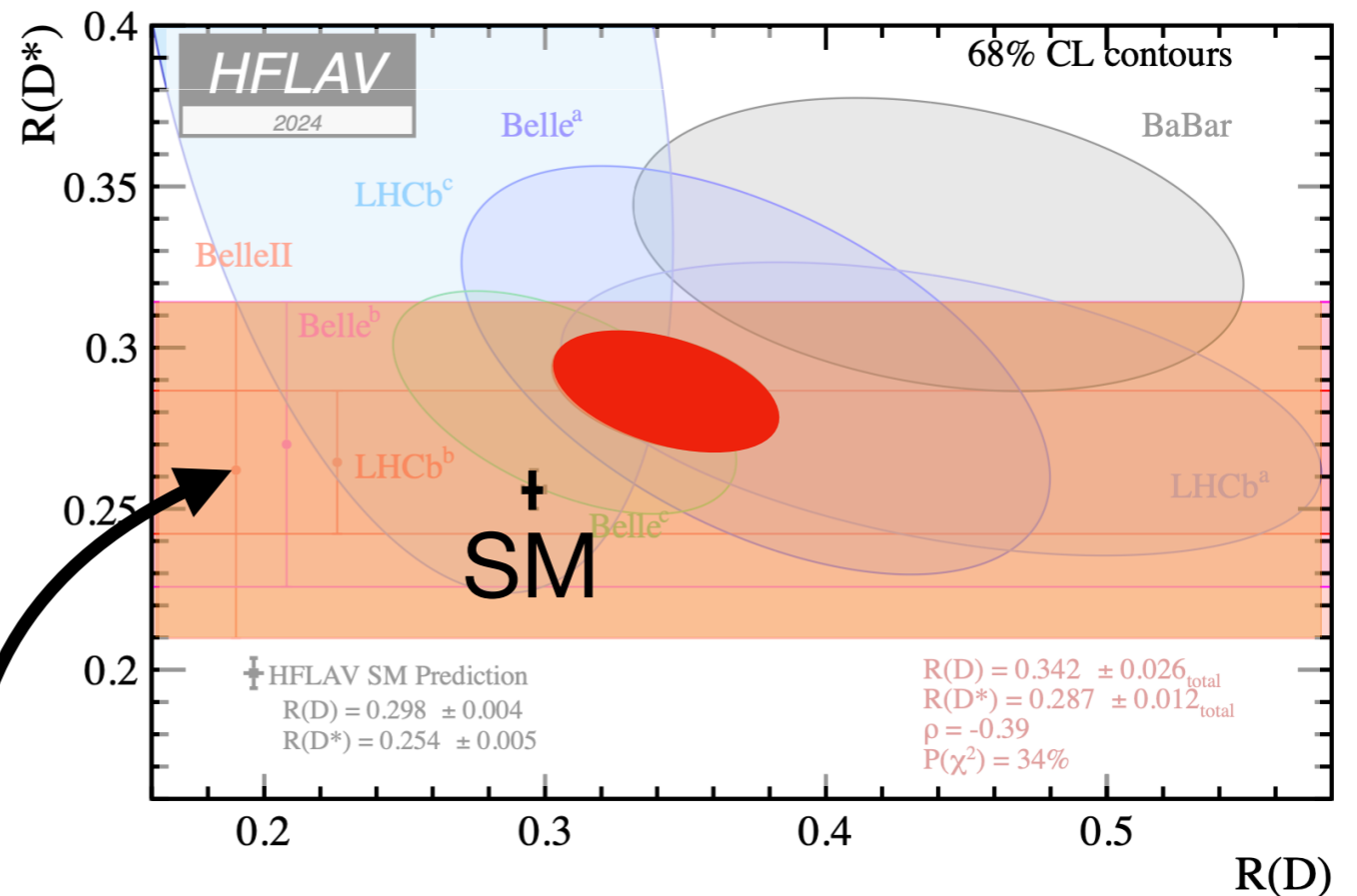$\mathcal{BR}(B^+ \to \tau^+ \nu_\tau)$ $(\times 10^{-4})$

Agrees with SM and previous results

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Testing accidental SM symmetries

In the SM, W boson couples equally to all leptons. Evidence for a consistent pattern: larger coupling for tau measured with

$$R\left(D^{(\star)}\right) \equiv \frac{\mathscr{B}(B \to D^{(\star)}\tau\nu)}{B \to D^{(\star)}\ell\nu}$$

Hadronic-tagged analysis provides comparable precision to equivalent Belle result with ¼ the sample

$$R(D^{\star}) = 0.26 \pm 0.04^{+0.04}_{-0.03}$$

[PRD 110 (2024) 072020]

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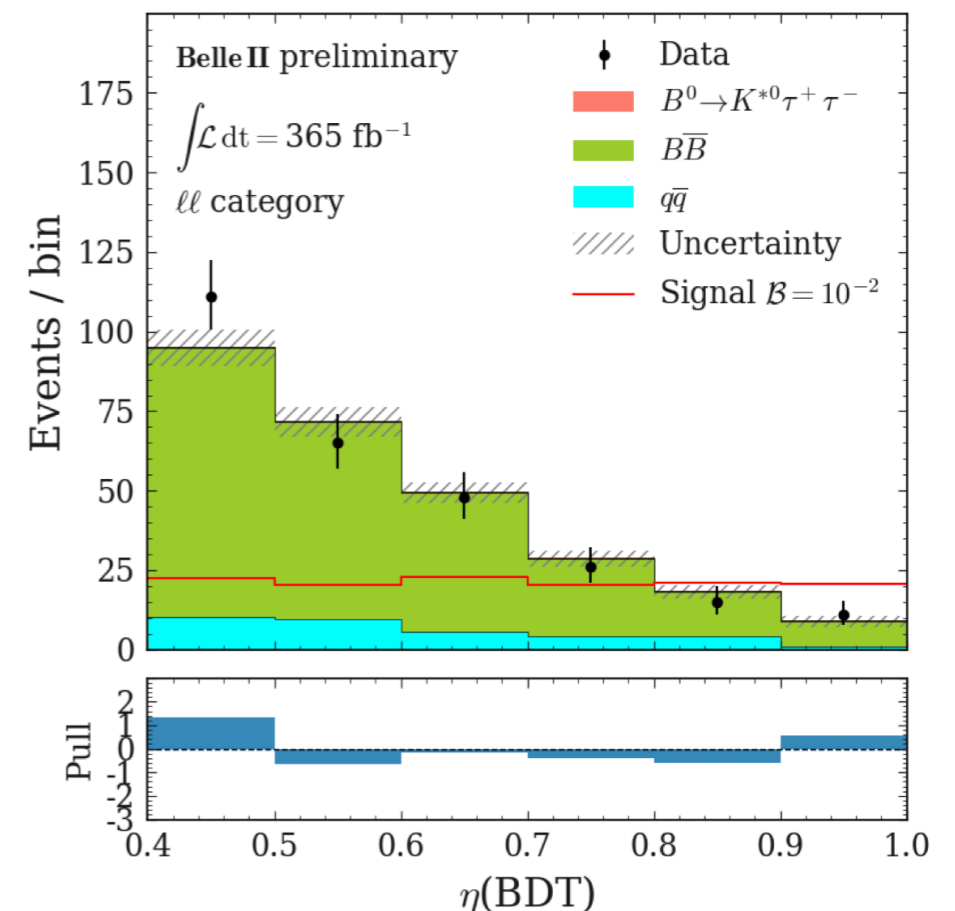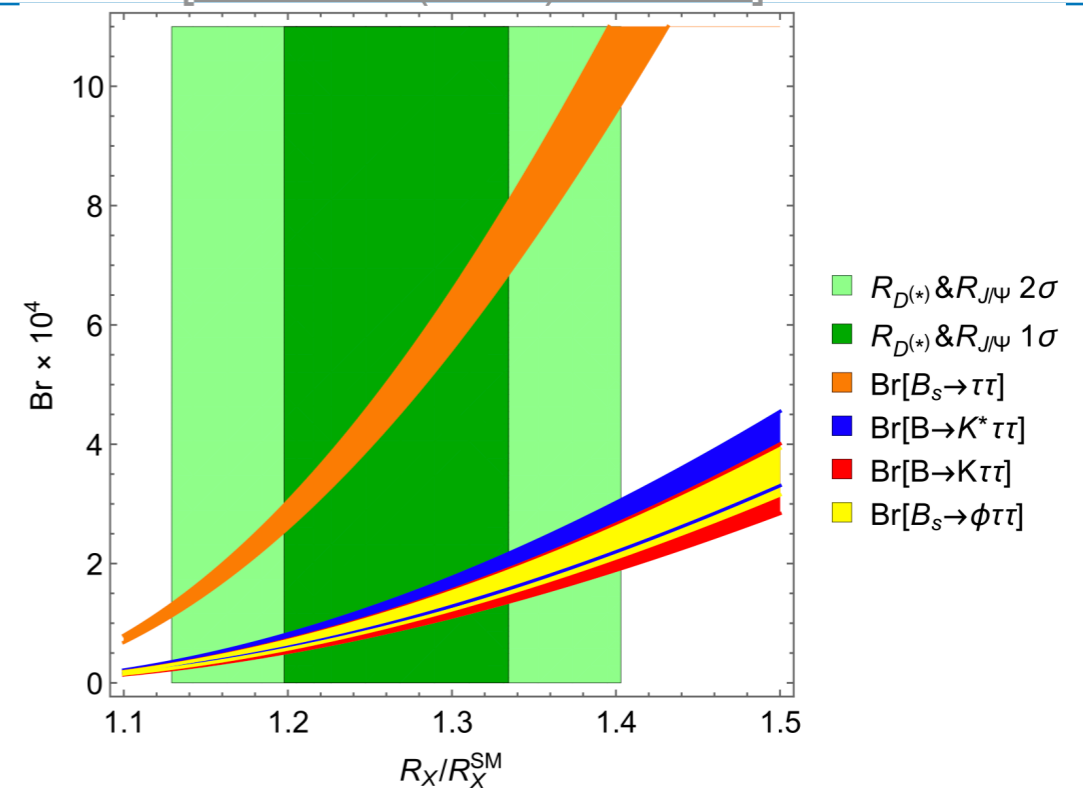# Search for $B \to K^* \tau \tau$

[PRL 120 (2018) 181802]

Change flavours but not charge: very suppressed in the SM. Models accommodating R(D*) anomaly predict a large enhancement.

Belle II: search combining 4 categories depending on tau decays (lepton-lepton, lepton-pion, pion-pion, rho-X)

BDT using missing energy, residual energy, invariant mass of the tau pair, … No signal found.

BF < 1.8 ×10⁻³ @ 90% CL

Limit twice improved over Belle.

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Search for $B \to K_S \tau l$ [arXiv:2412.16470]

Violates charge-lepton number conservation: forbidden in the SM. Again, model accommodating R(D*) anomaly predicts rates close to current experimental sensitivity

Combined Belle+Belle II sample to boost sensitivity. Hadronic tag and use recoiling mass as discriminating variable.
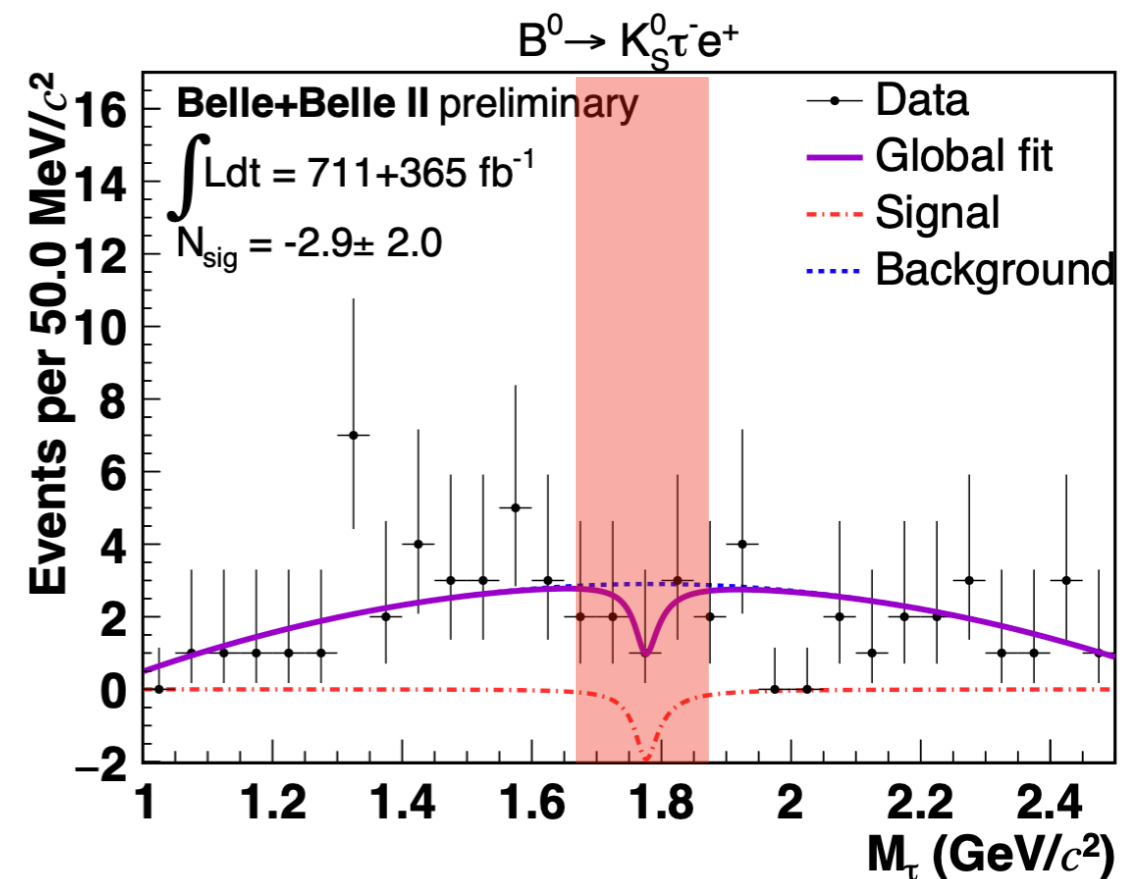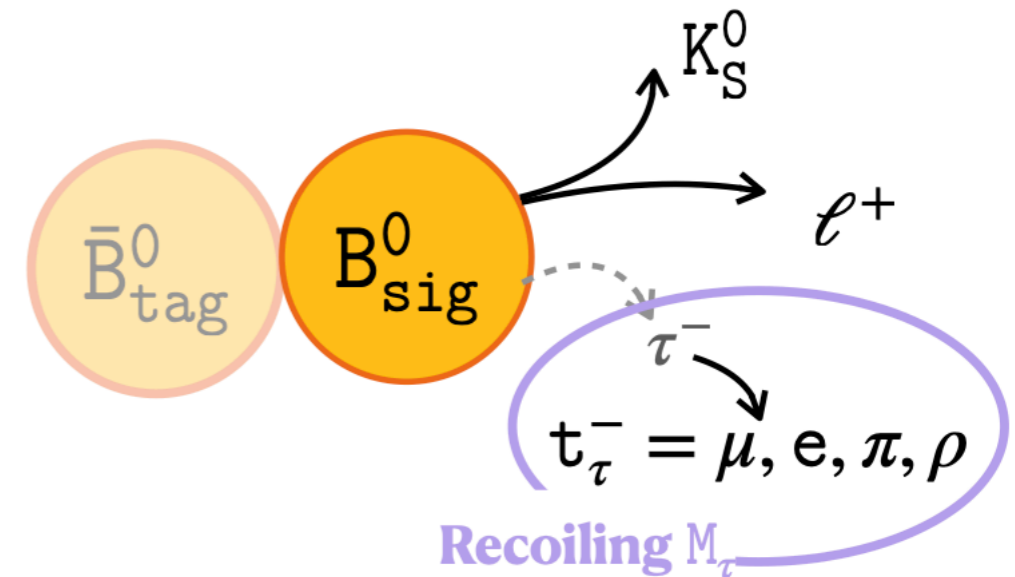
No signal found, upper limit @90% CL

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$

Not only beauty

List of recent results from charm and others (but tau and dark sector that are in Stefan talk)

Summary

Flavour physics is a powerful probe for pursuing physics beyond the SM and informing direct searches at energy frontier.

SuperKEKB and Belle II are pushing the intensity frontier to uncharted territories. Proving to be challenging.

Unique results. Improving unitarity tests of quark-mixing matrix, **efficiently accessing all final states, including with neutrals. Dealing with missing energy**, putting stringent limits for model buildings

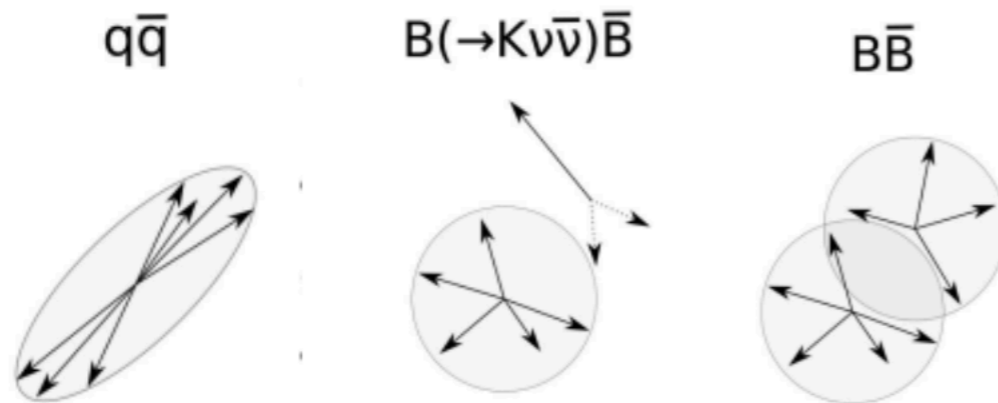Belle II results with smaller current data set than Belle. Yet, comparable or better.
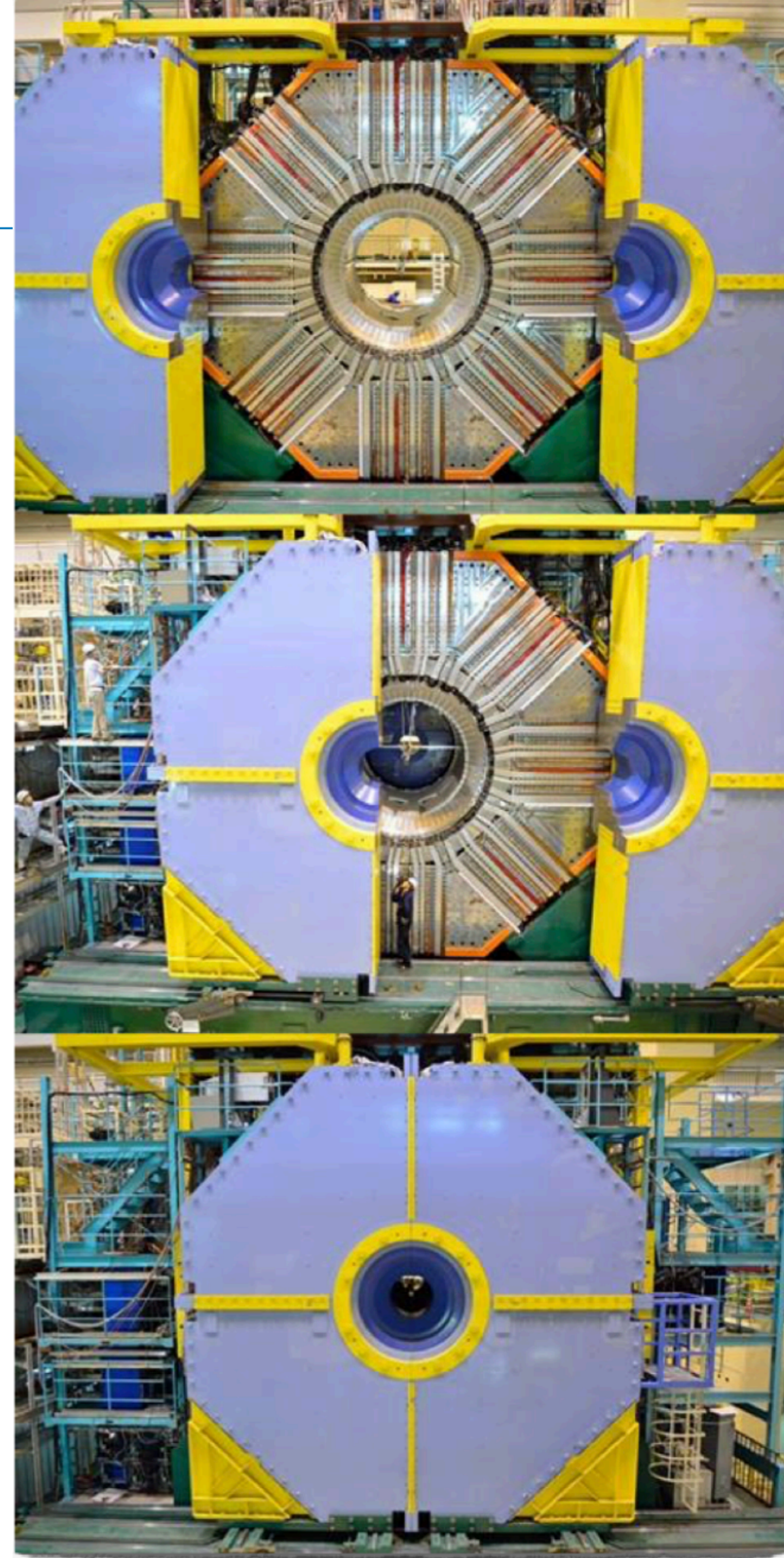
Backup

Evidence for $B \to K\nu\nu$

- **Theoretically clean and third generation sensitive** $b \to s ll$ **transition**

- **Inclusive tag developed that exploits topology**
  - **8% efficiency**

- **Fit to invariant mass of neutrinos (q²) and classifier**
  - **Checked and combined with lower efficiency hadronic B tag**

$$B(B^+ \to K^+ \nu\bar{\nu}) = \left(2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right) \times 10^{-5}$$
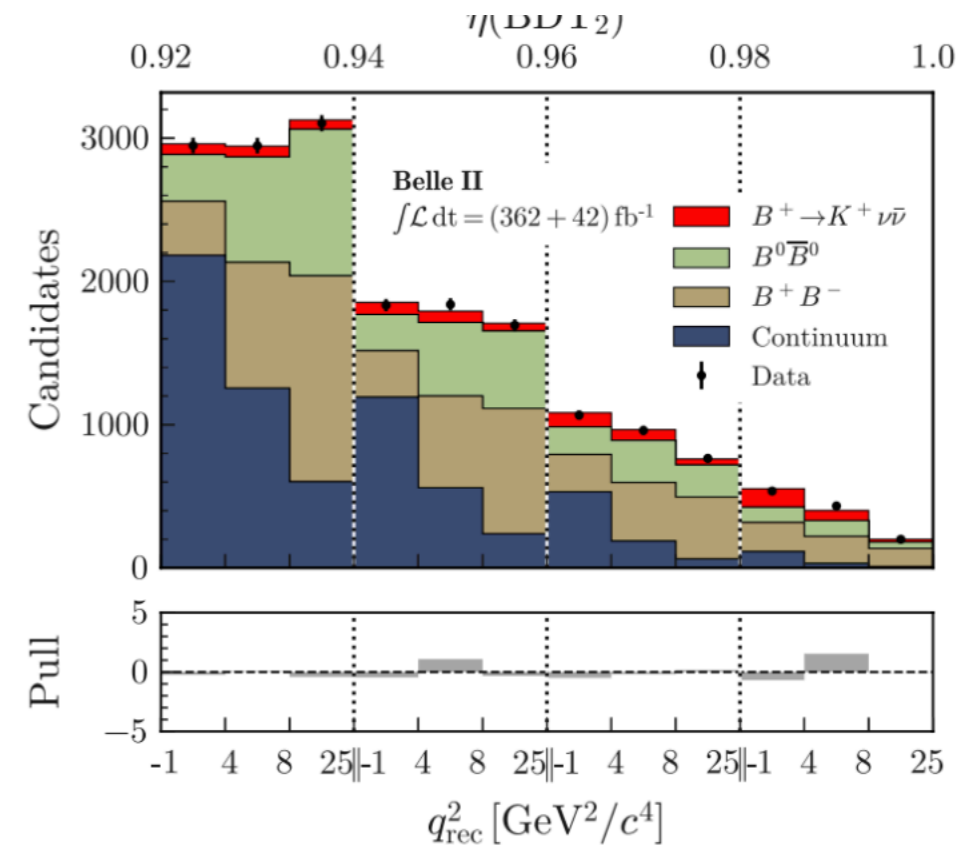
**Evidence @ 3.5σ
Tension with SM prediction of
0.6×10⁻⁵ @ 2.7σ**