Latest results from Belle and Belle II

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for the Belle and Belle II Collaborations

61st International Winter Meeting on Nuclear Physics — Bormio — Jan 30th, 2025

Probing the next scale

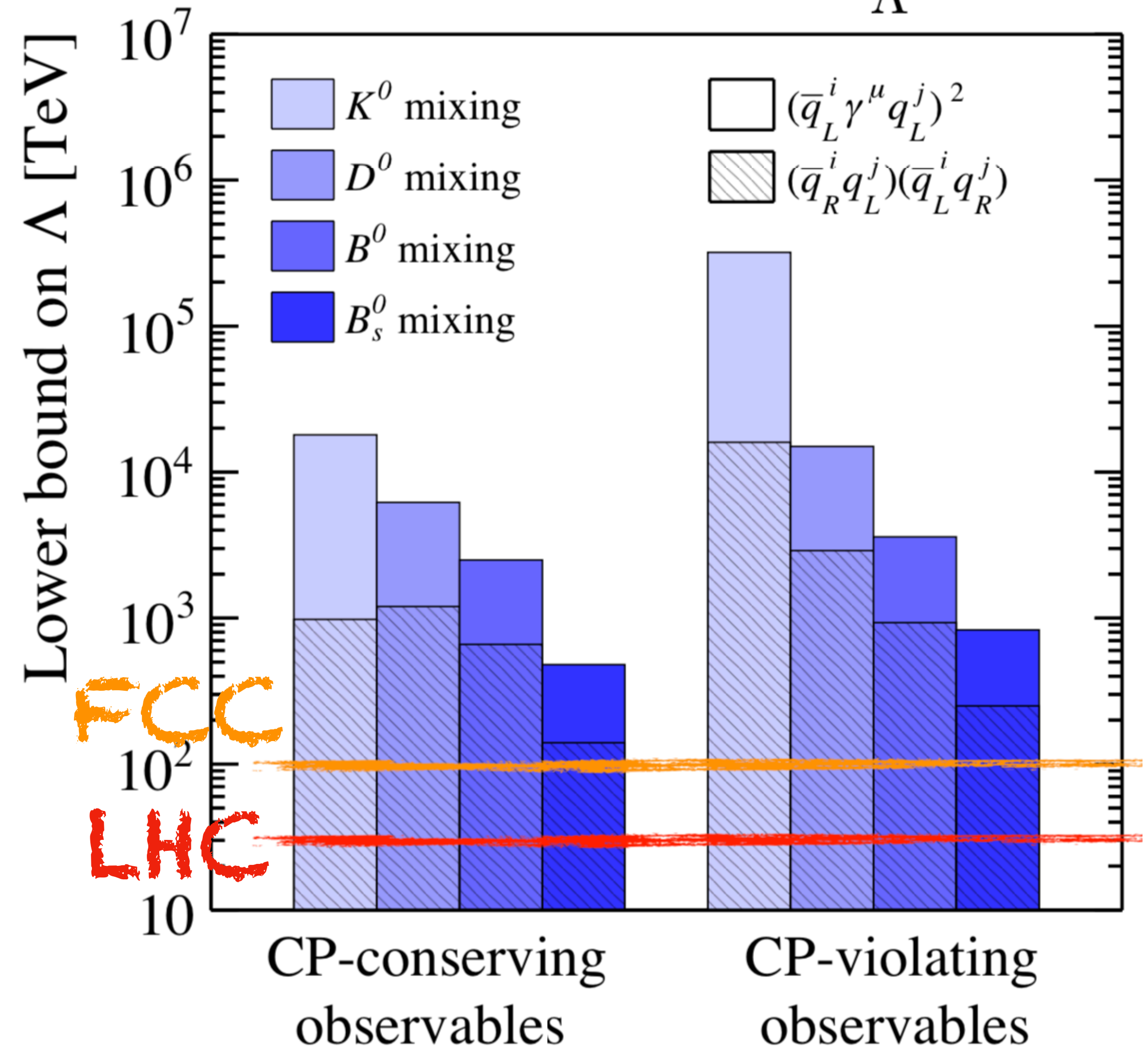
The standard model is incomplete.

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

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



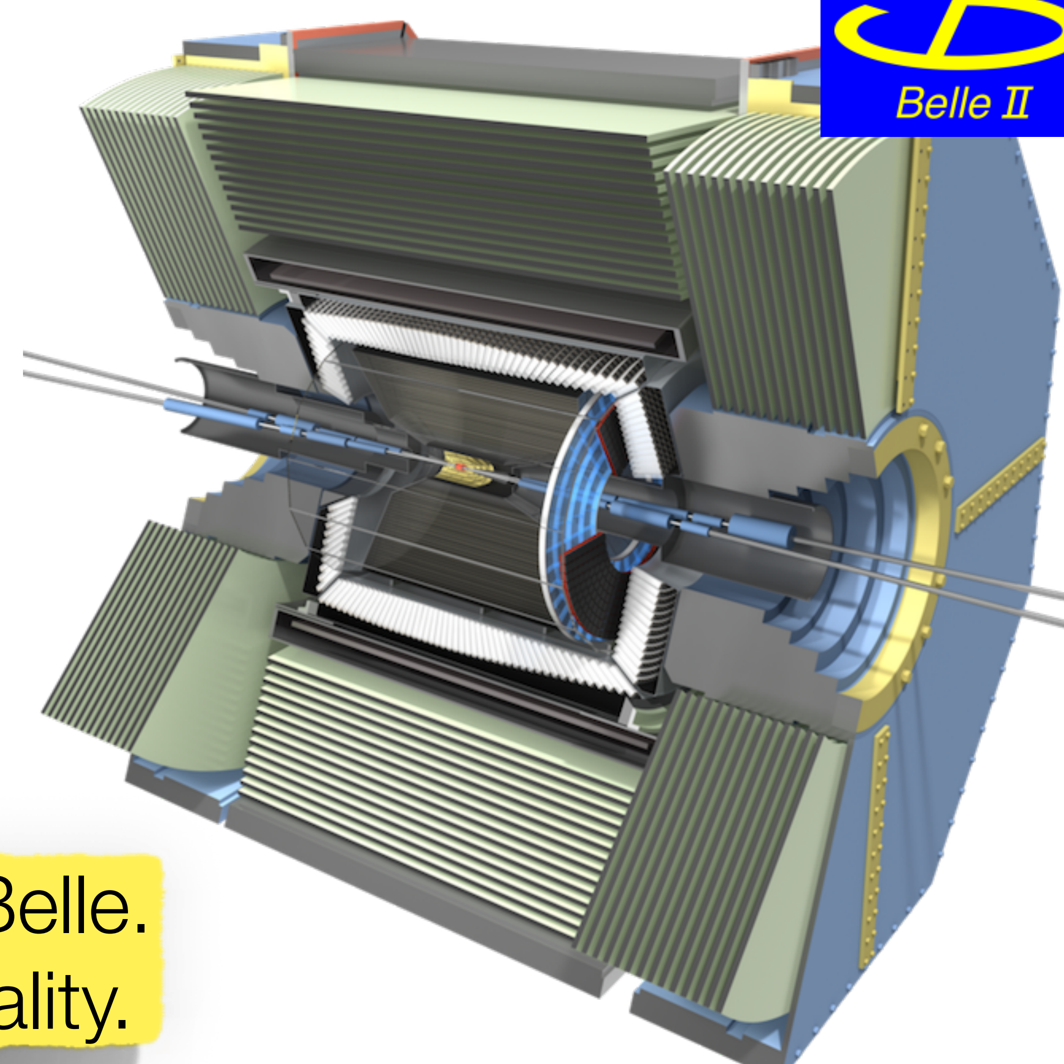
[arXiv:1302.0661]

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.

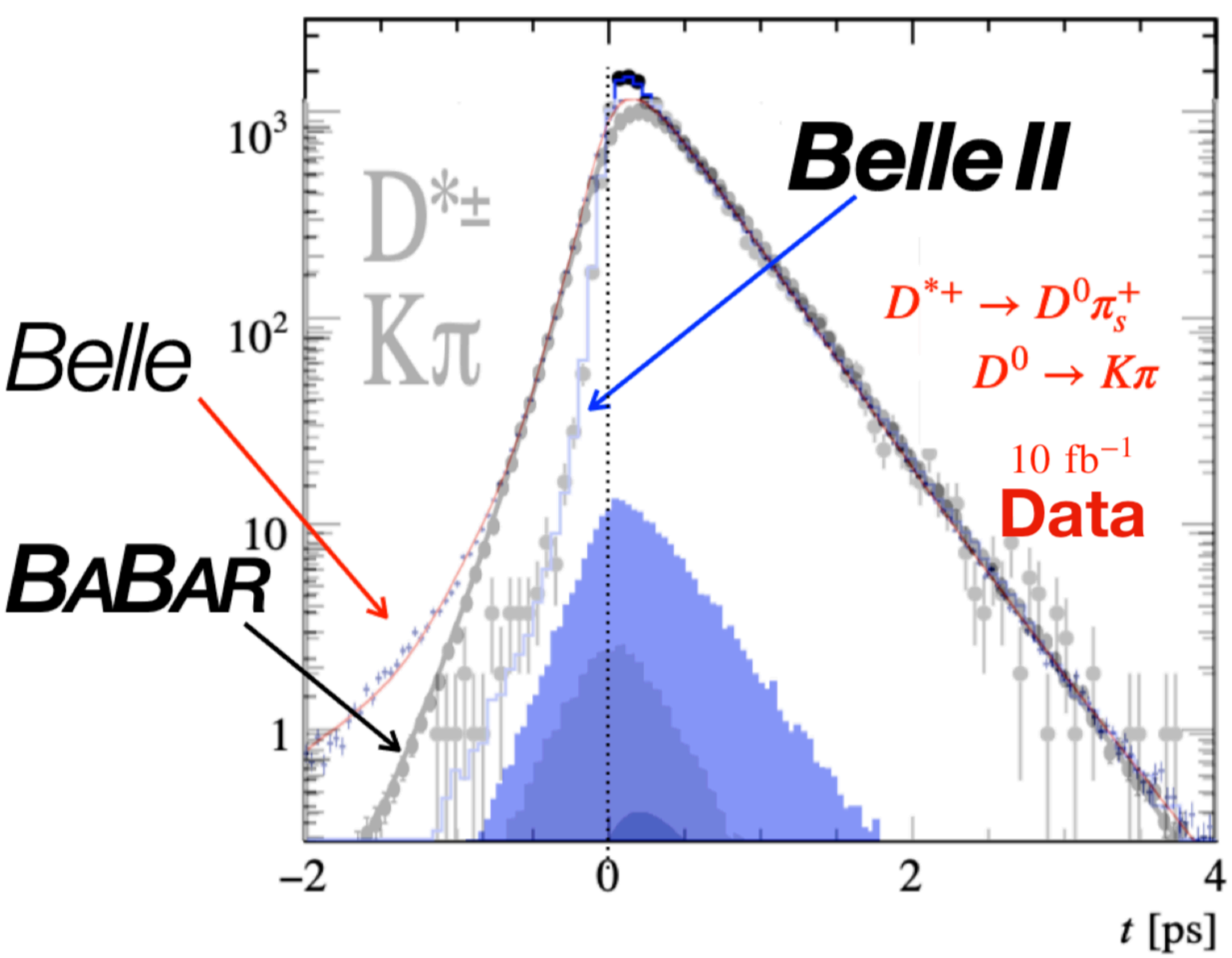
Belle II looks like “old” Belle, but
effectively a brand new instrument:
has better or same performance
within an harsher environment



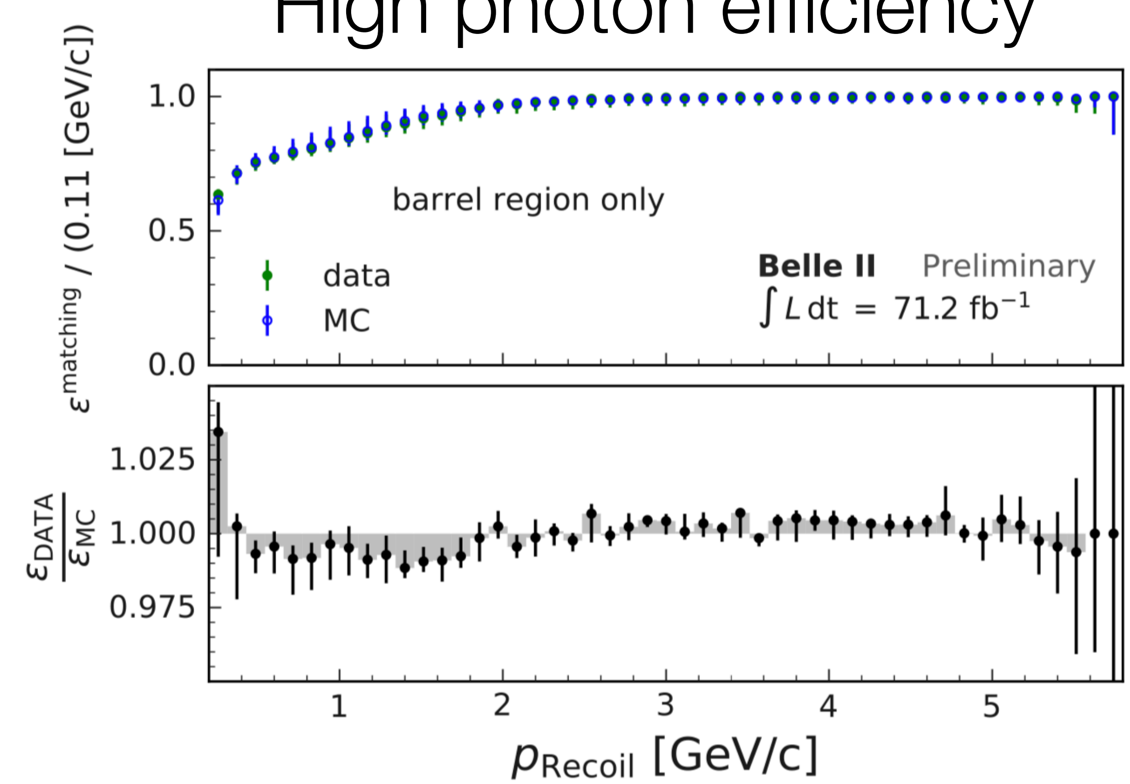
About 800M $B\bar{B}$ pairs on tape for Belle.
Belle II roughly half, with higher quality.

Performance

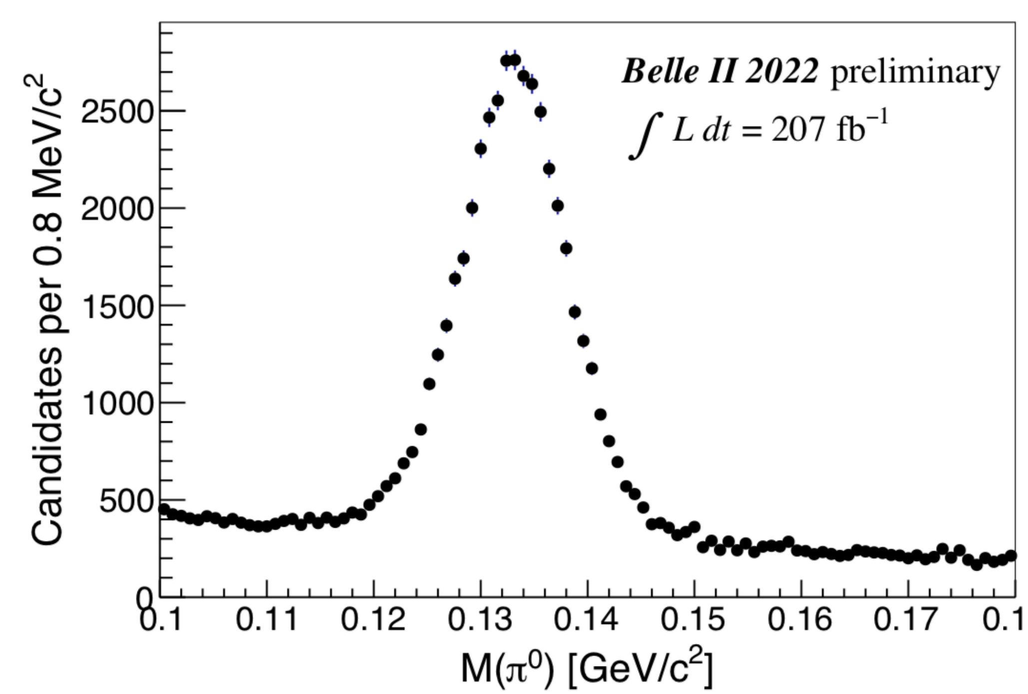
Net effect of better vertexing (PXD) and greatly-reduced size of the SuperKEKB interaction region (nano-beam scheme).



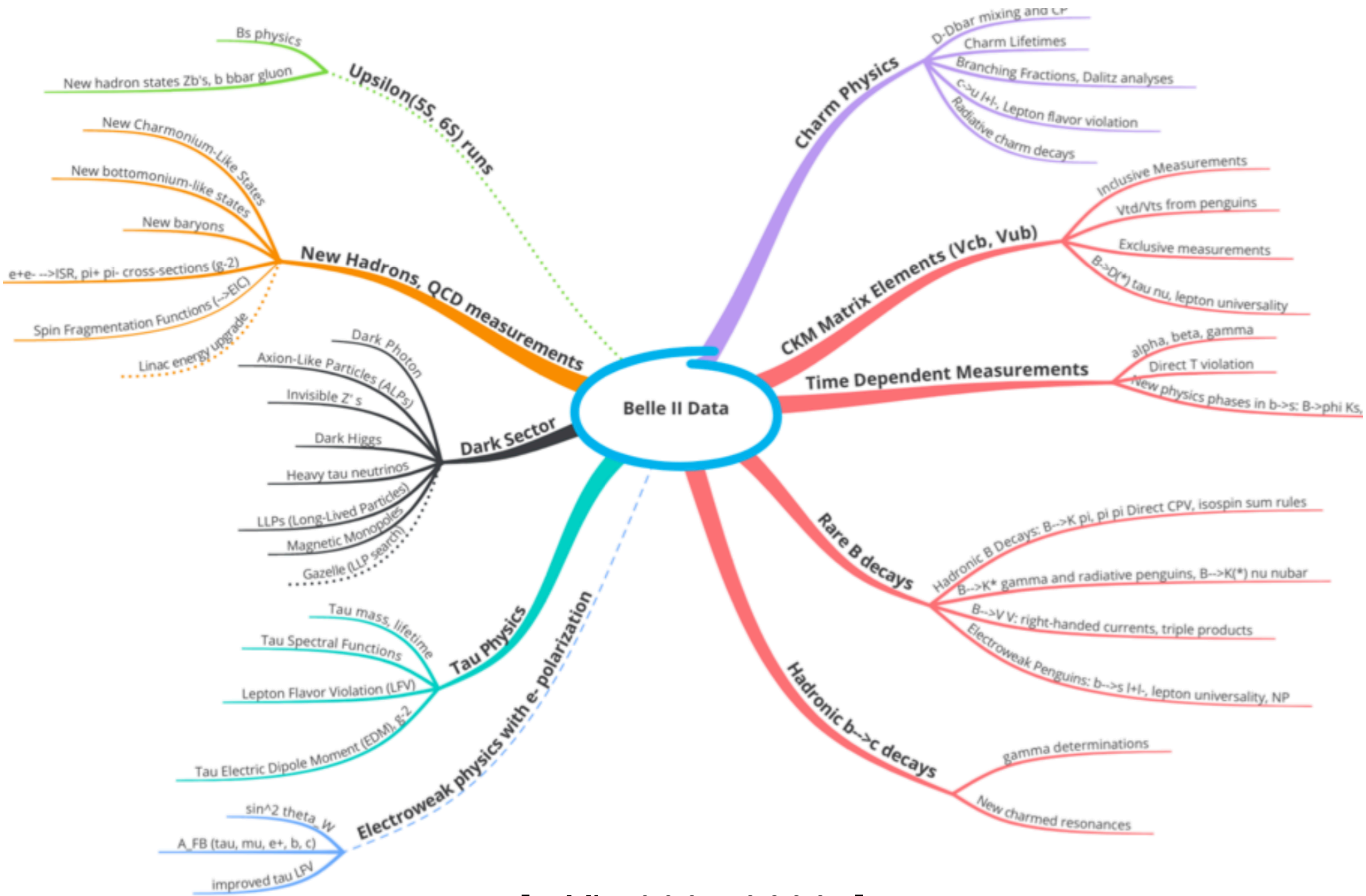
High photon efficiency



Good neutral reconstruction

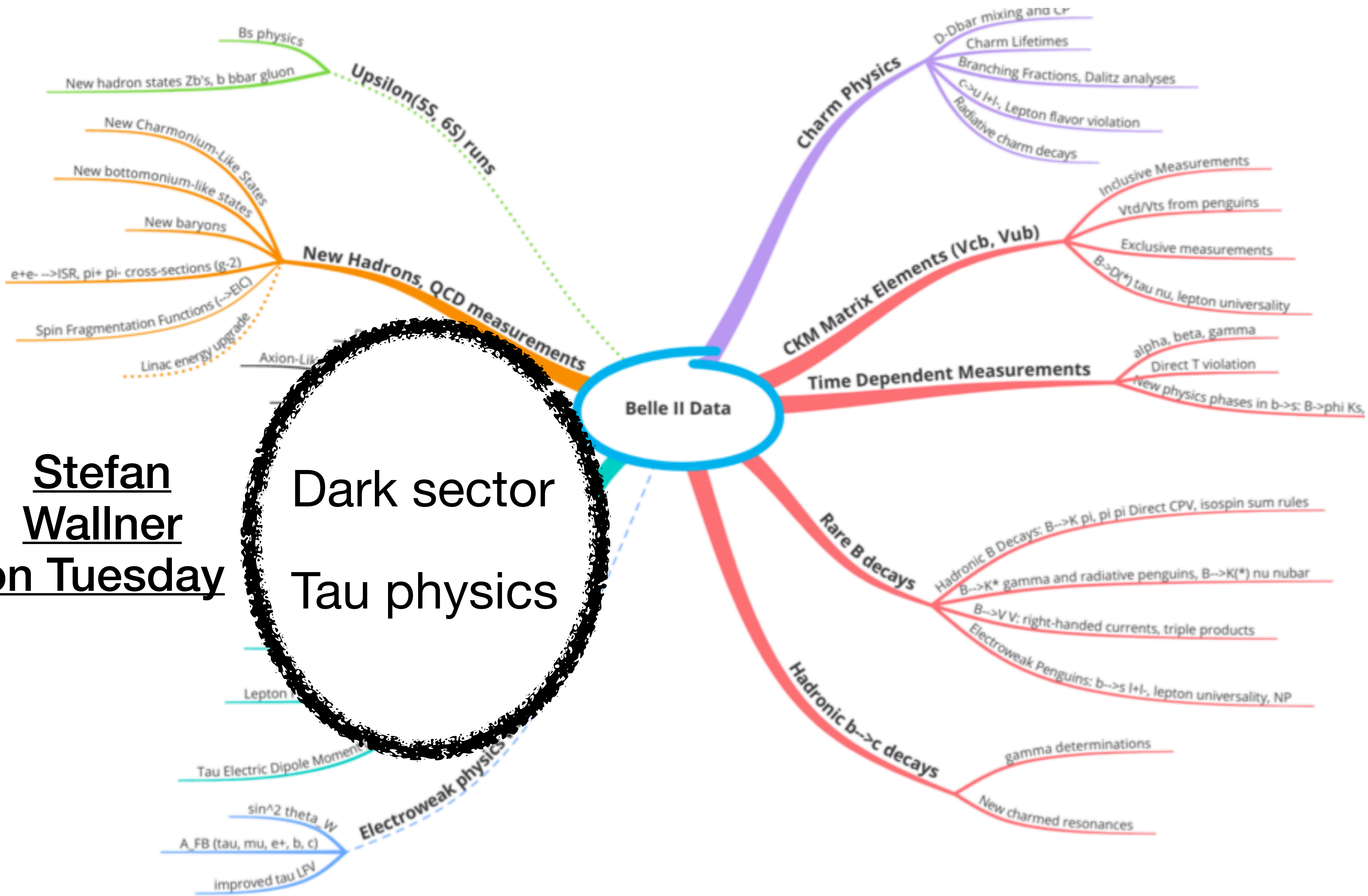


A diversified physics program



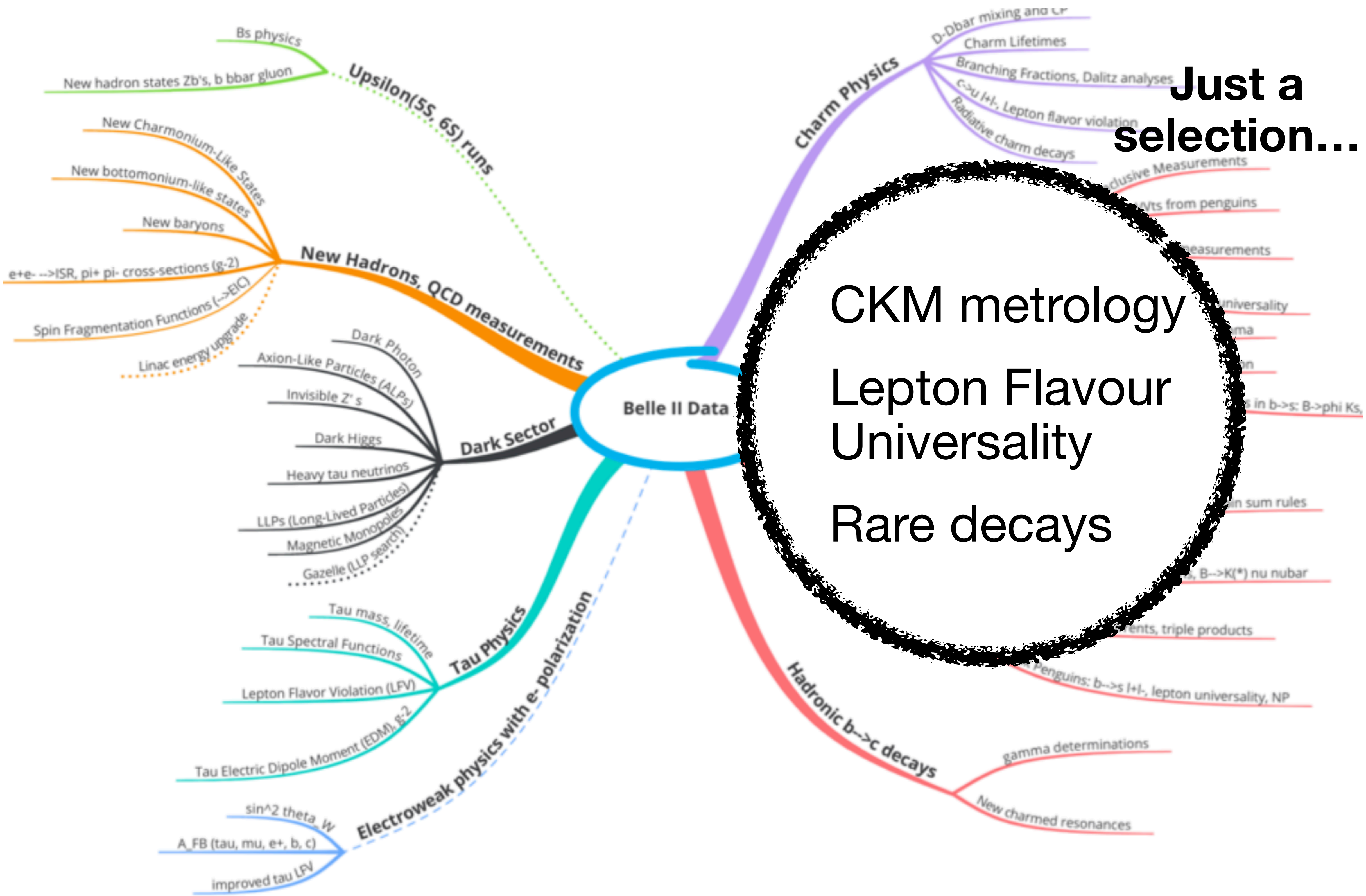
[arXiv:2207.06307]

A diversified physics program



Stefan Wallner on Tuesday

A diversified physics program



Just a selection…

CKM metrology

Lepton Flavour Universality

Rare decays

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.

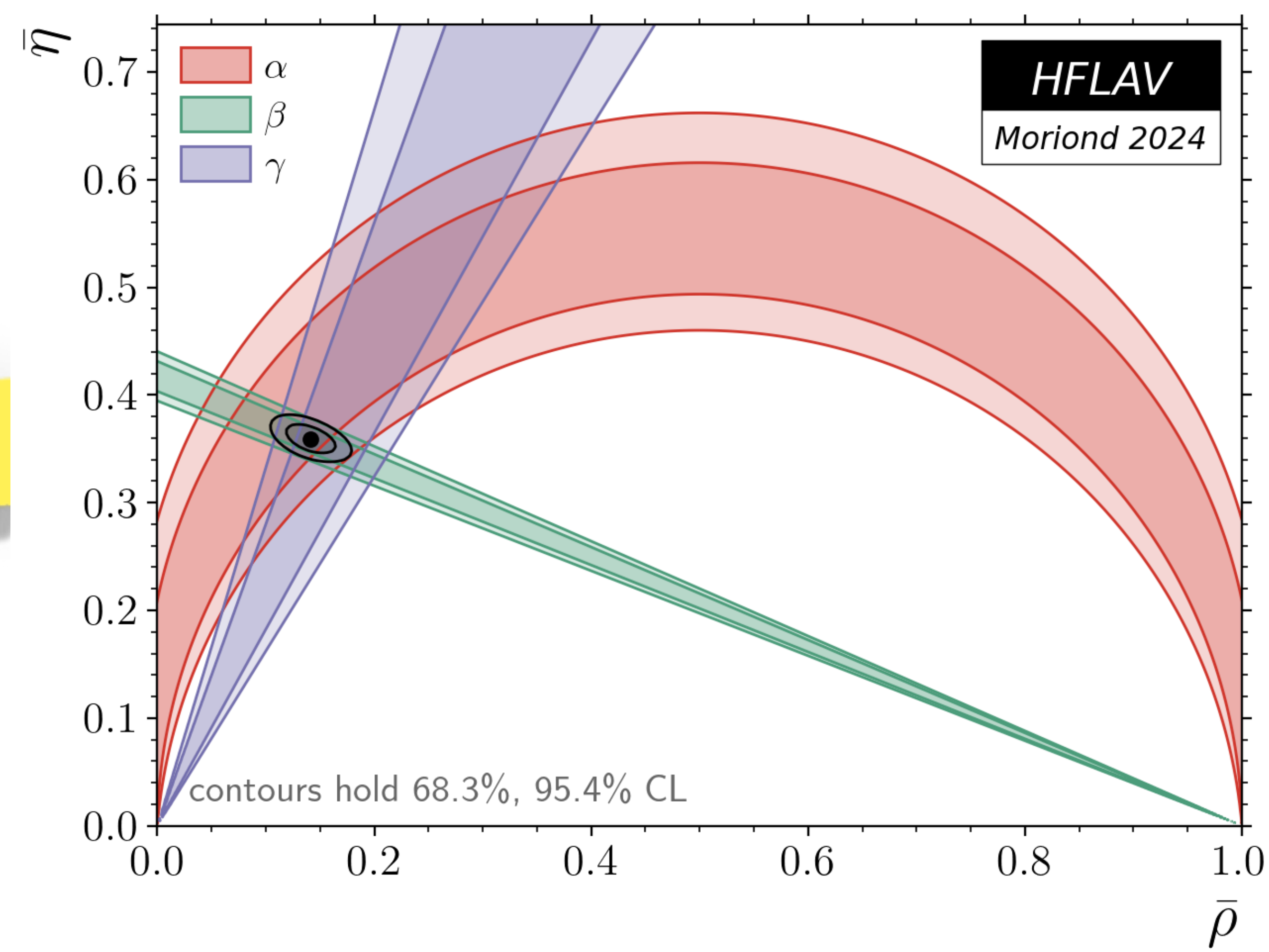
Angle α (aka ϕ_1) the least known.

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.

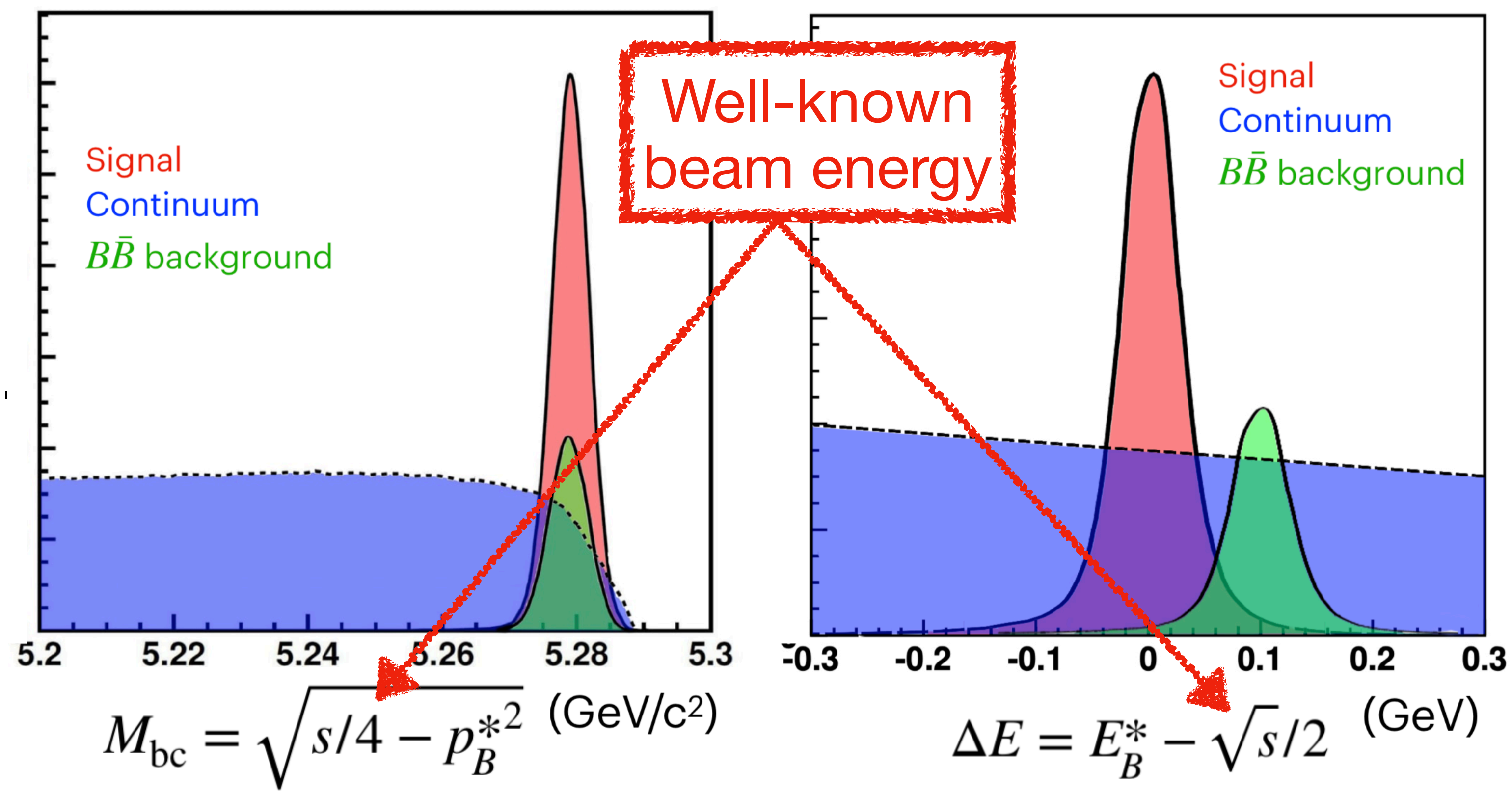


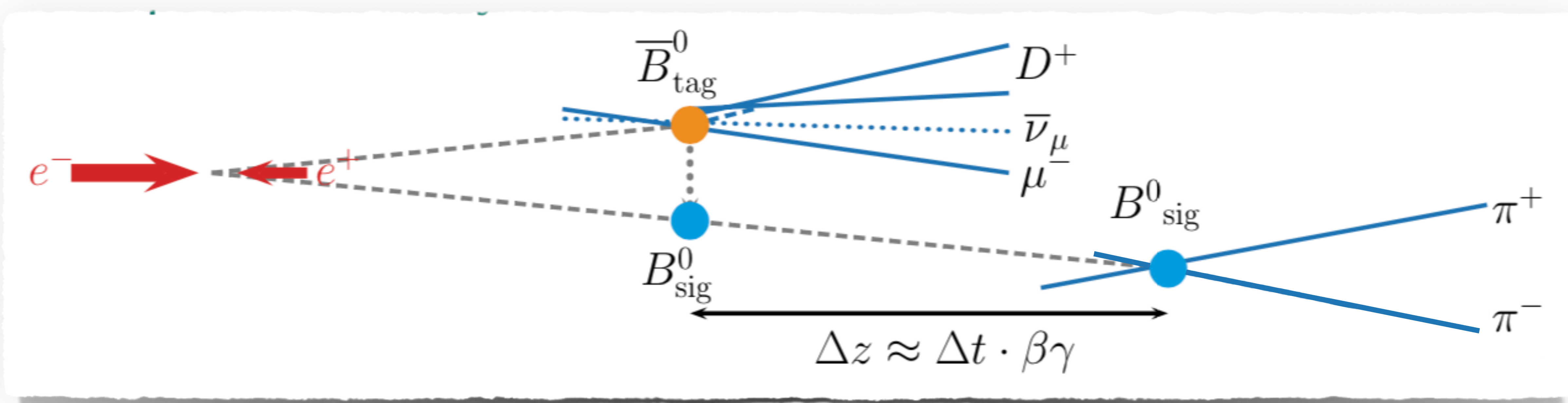
Unique opportunity for Belle II to efficiently access all final states

B-factory 101

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

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

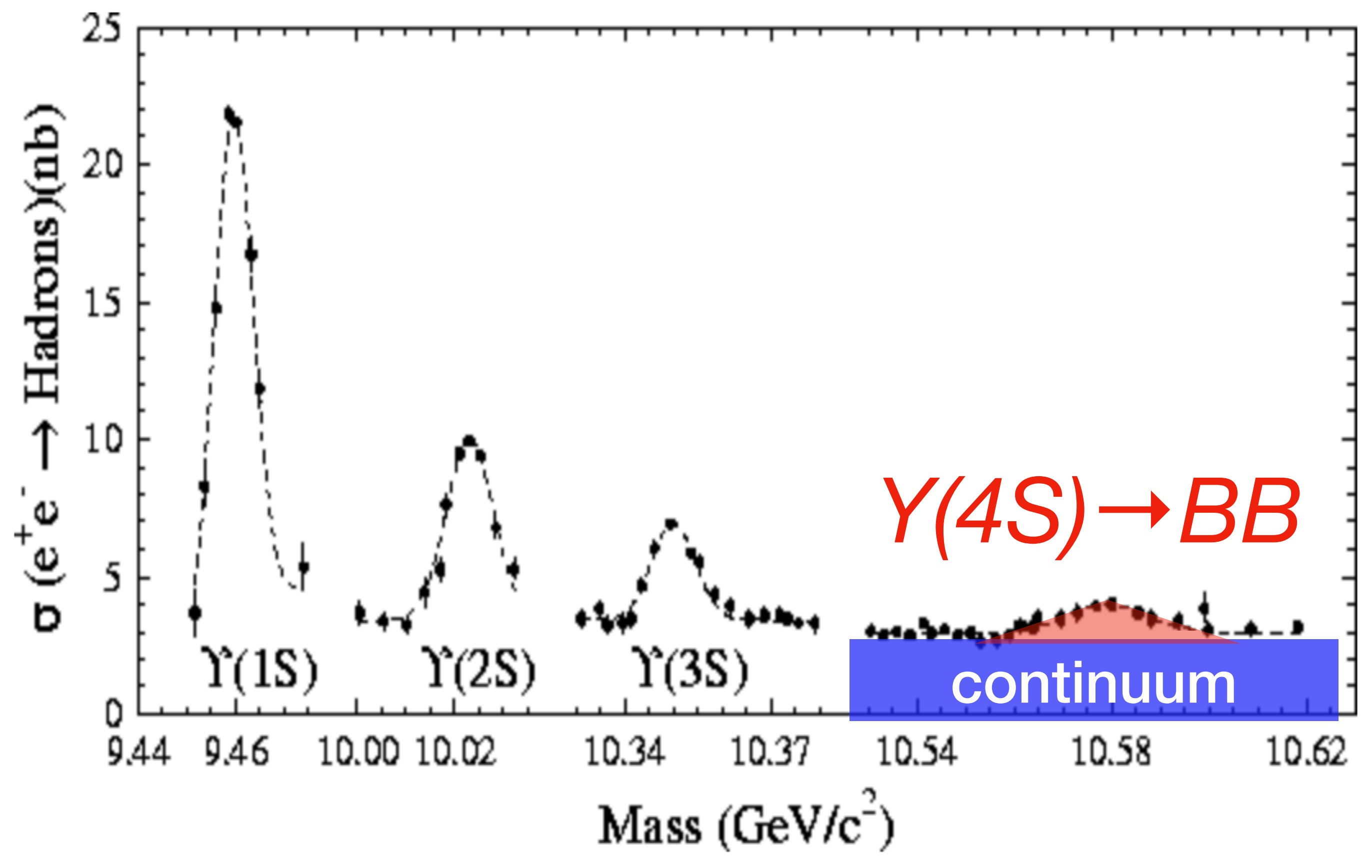




Charmless decay challenges

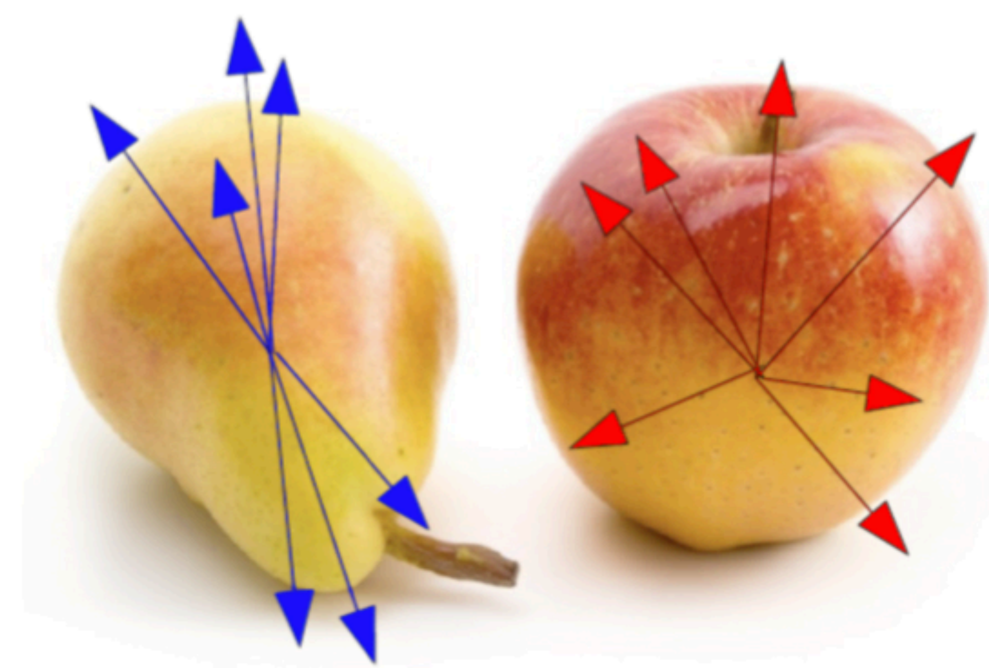
Fully-hadronic final state with high-momentum light mesons.

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).



$B^0 \to \pi^0\pi^0$

[arXiv:2412.14260]

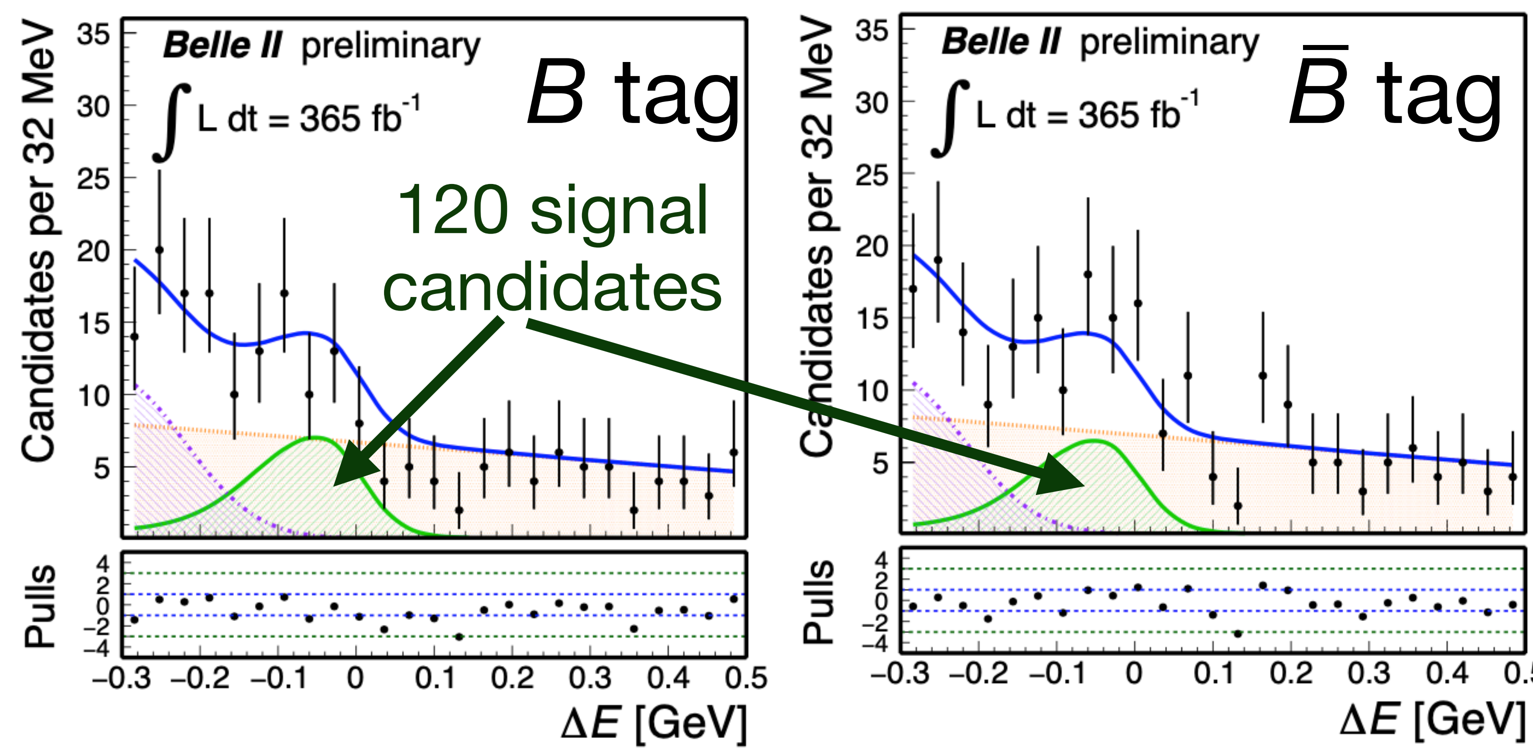
Only four photons in the final state, no vertex to identify the signal.

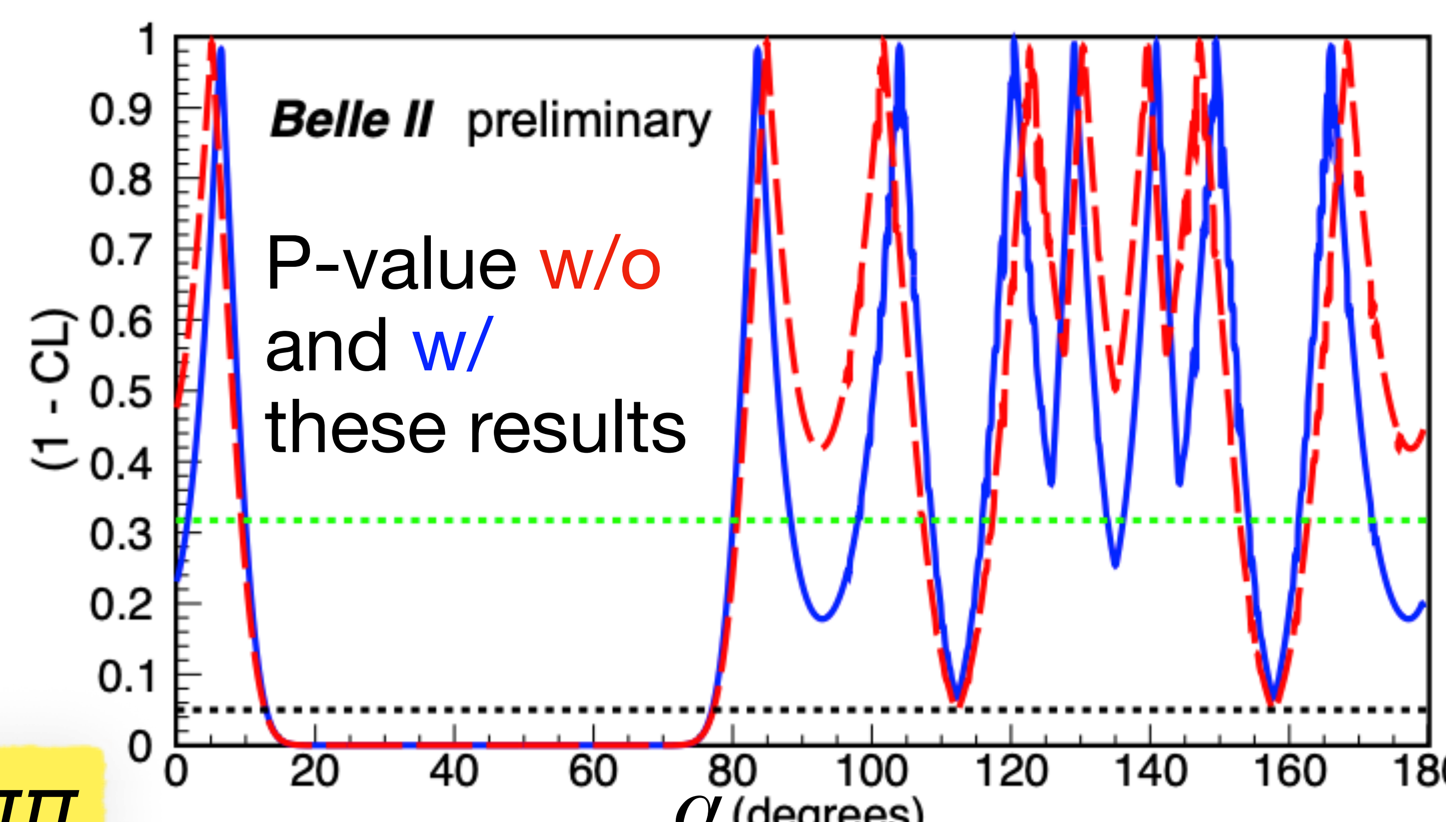
Continuum suppressed with dedicated BDT.
Tag the flavour to measure the CP asymmetry.
Extract signal from a 4D fit (Mbc, ΔE, BDT, tag-quality).

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

Compatible with and better than previous results.

Large impact on α from $B \to \pi\pi$

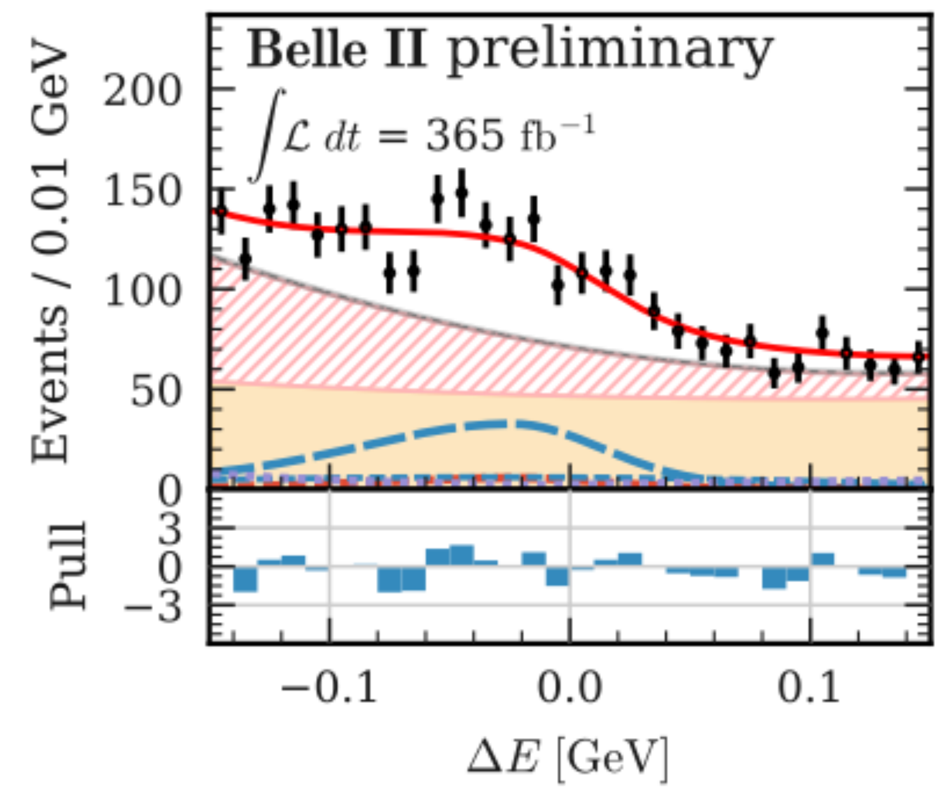




$B^0 \to \rho^+\rho^-$

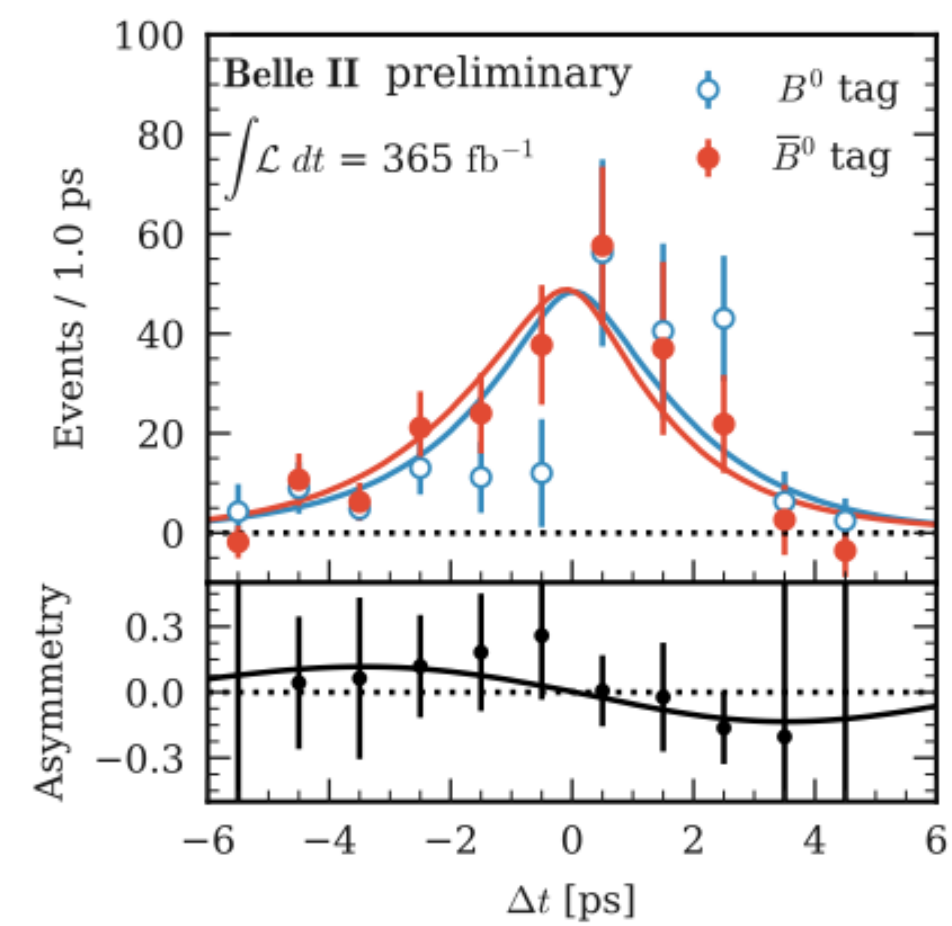
[arXiv:2412.19624]

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

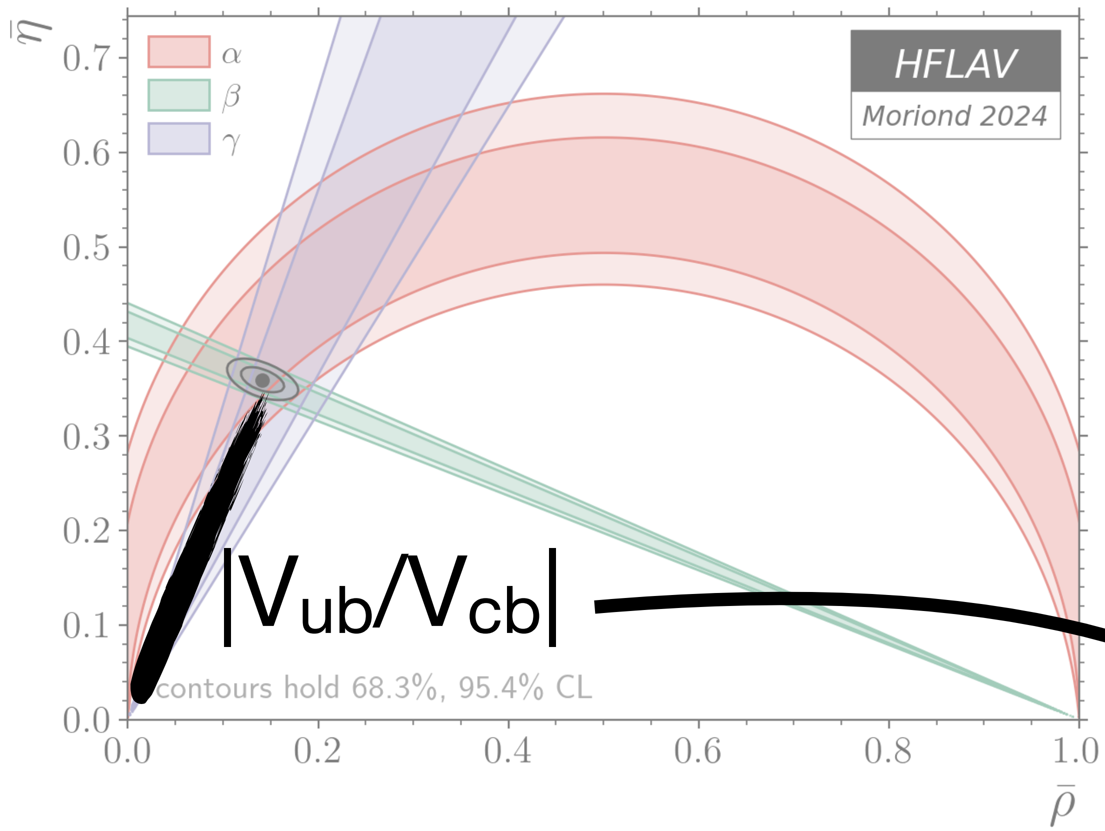
$A_{CP} = -0.26 \pm 0.21$
$S_{CP} = -0.02 \pm 0.13$



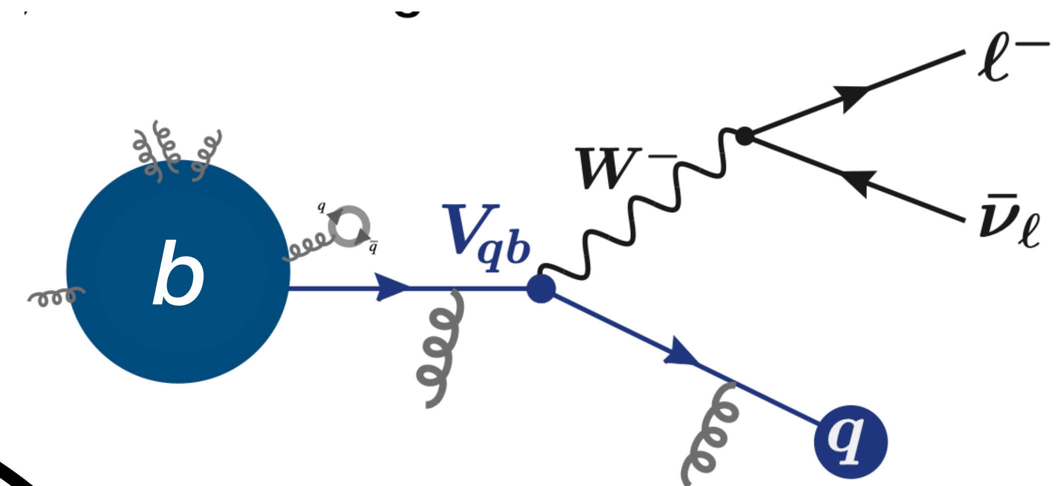
Obtain a 10% improvement on WA for α when including these results:

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

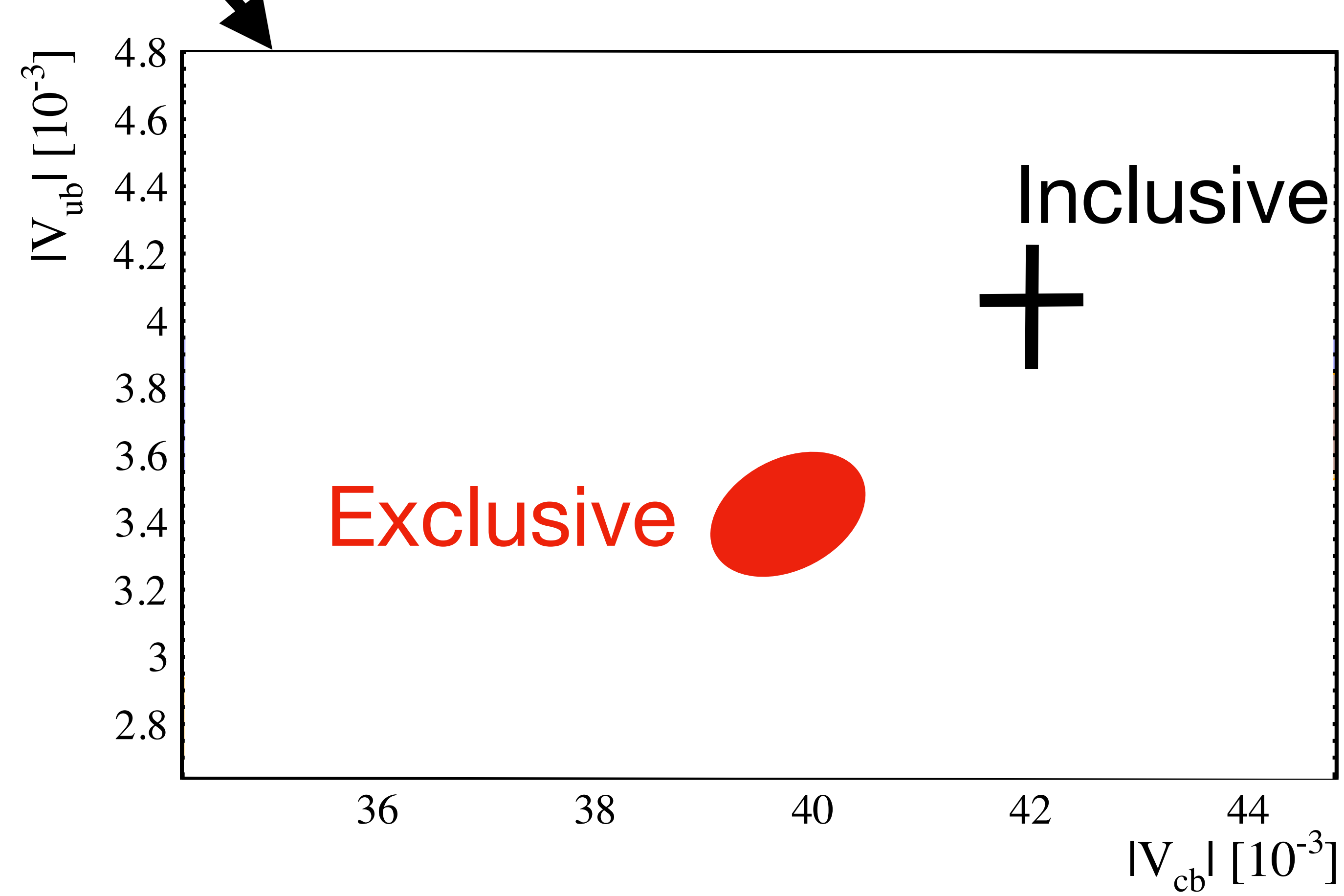
Measuring the sides…



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



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



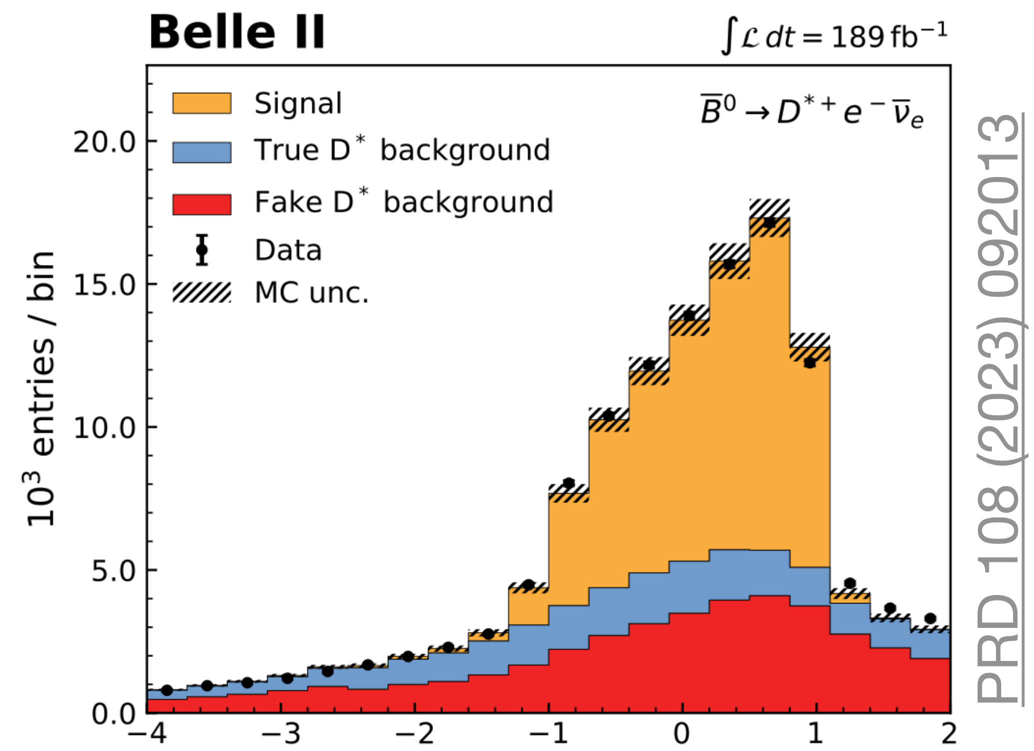
Intermezzo: dealing with missing energy

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

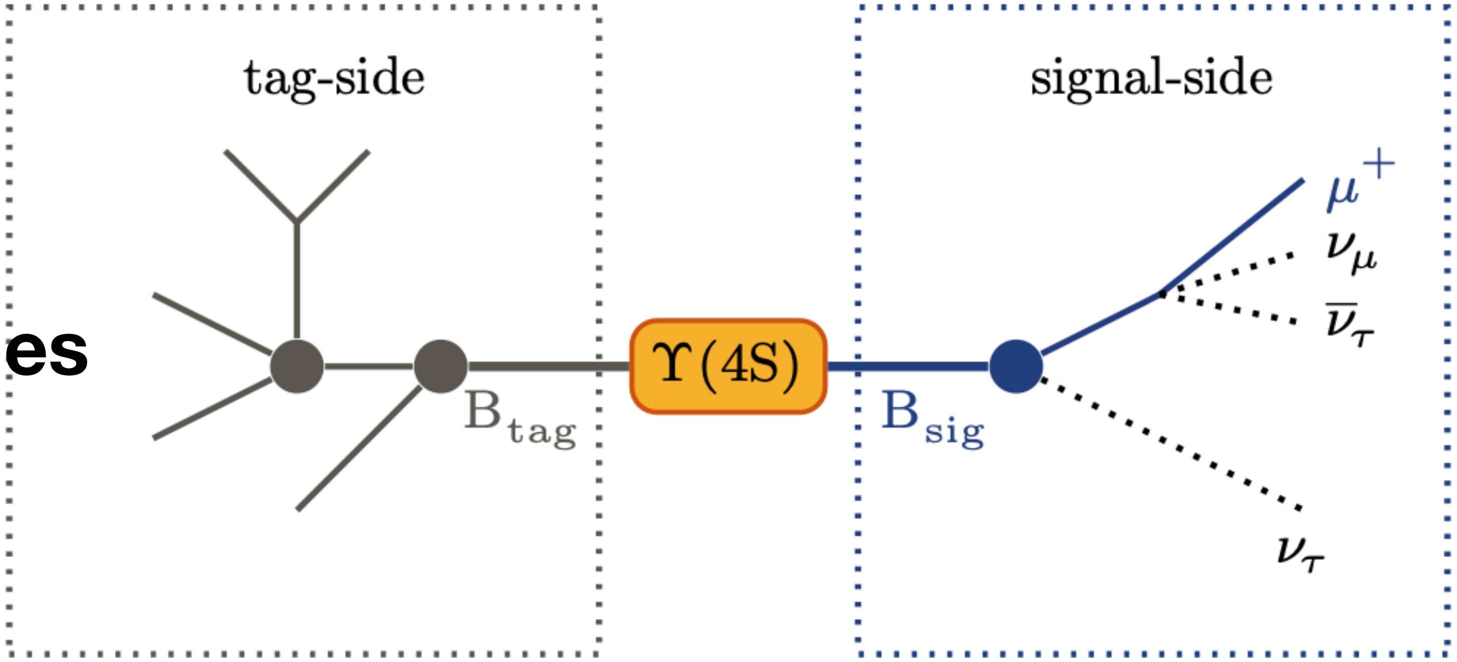
When missing only a neutrino can approximate the kinematic with enough resolution.

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)]



B mass proxy



Measuring the sides… at Belle (II)

New exclusive measurement (tagged) form Belle exploiting full differential information from $B \to D^* l \nu$ 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):

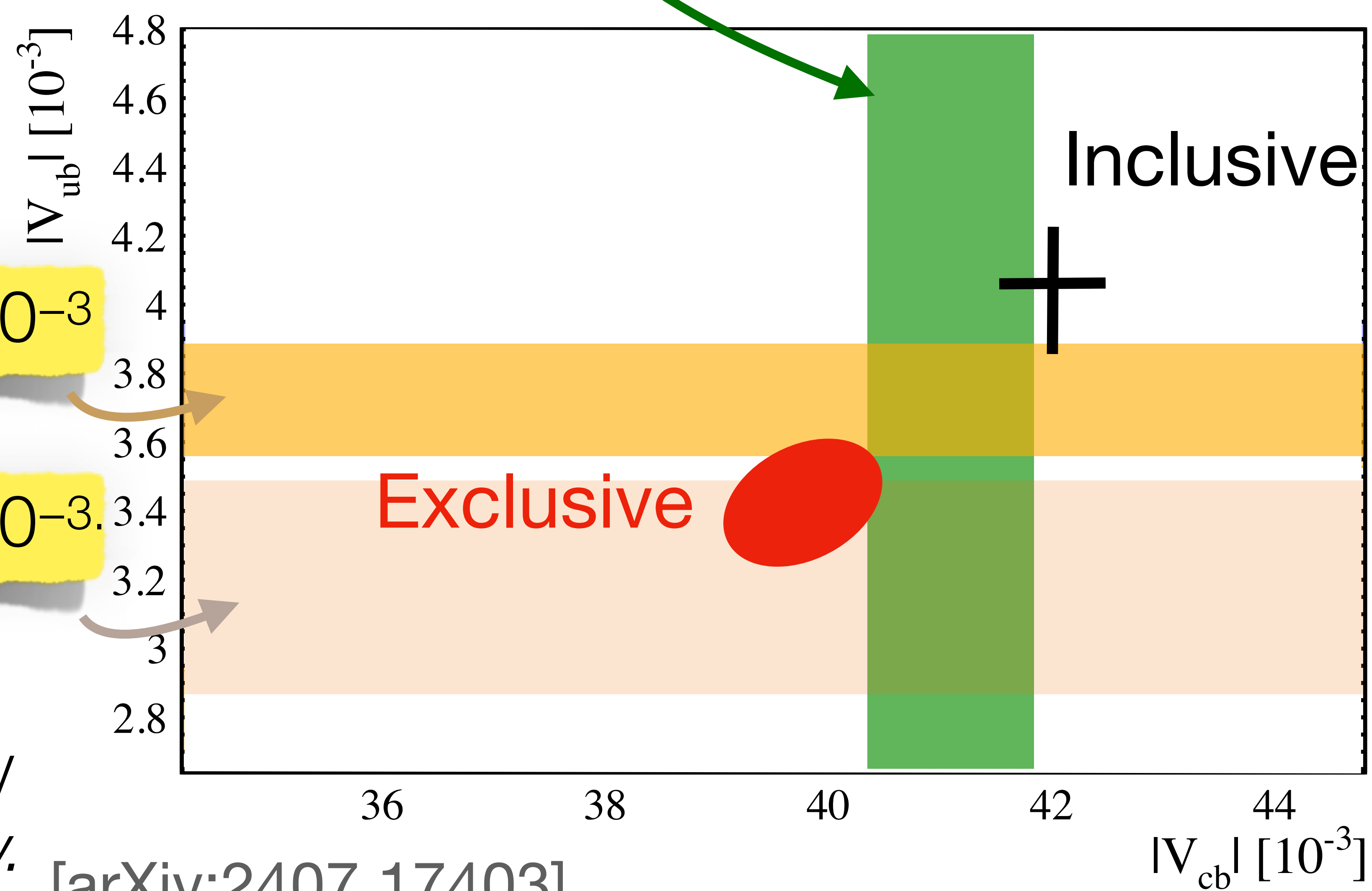
$B \to \pi l \nu$

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

$B \to \rho l \nu$

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

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

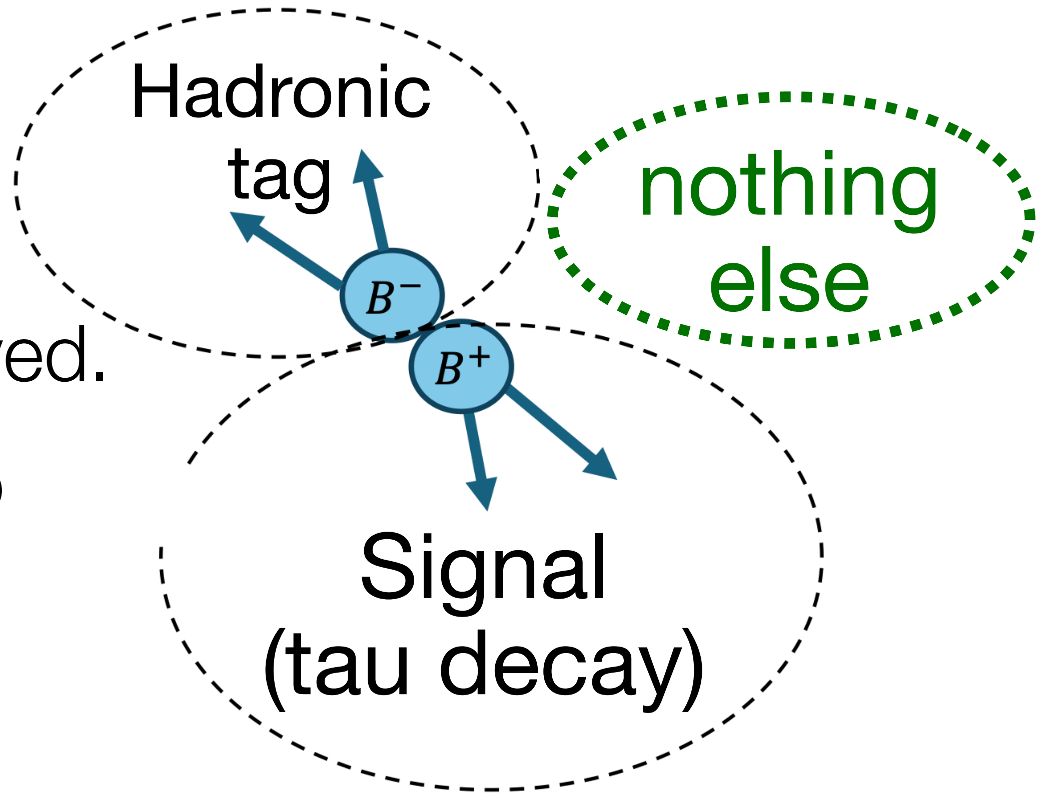


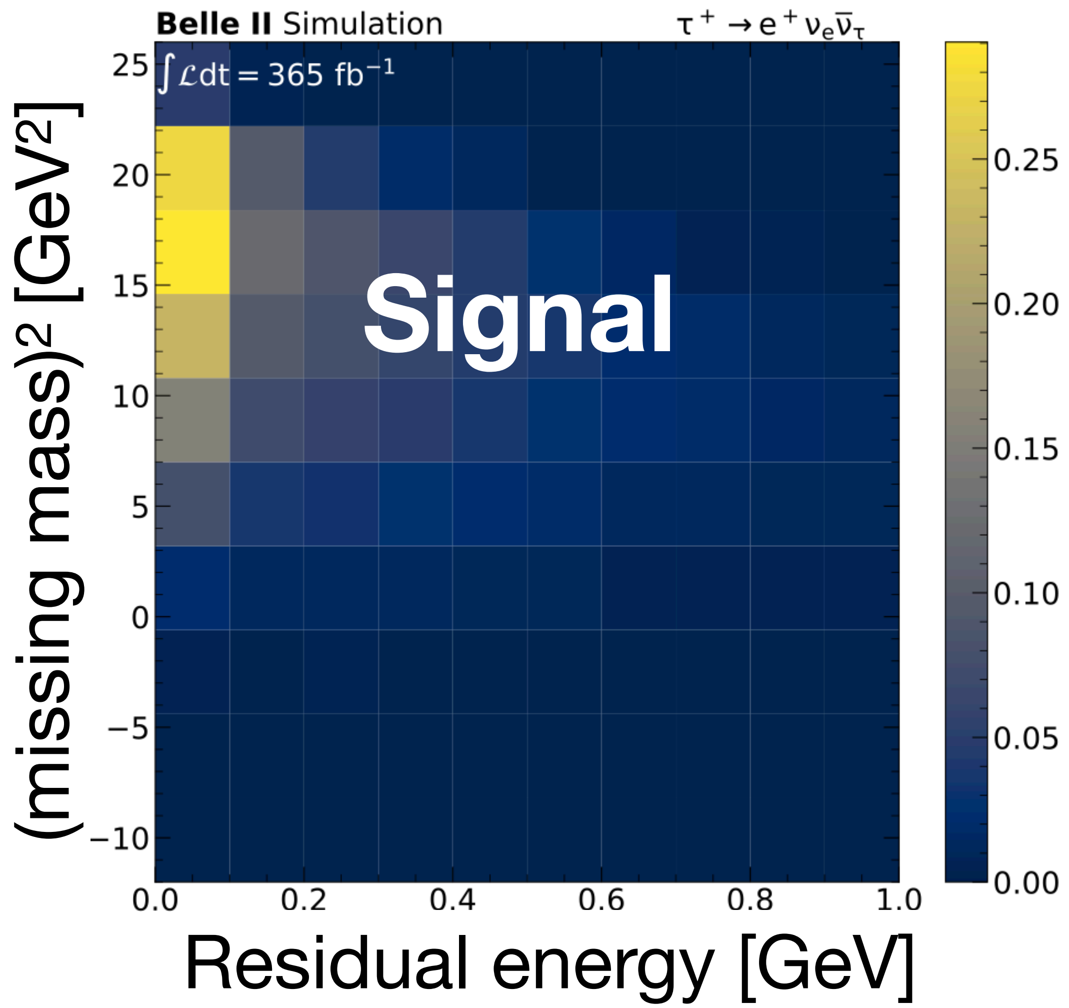
[arXiv:2407.17403]

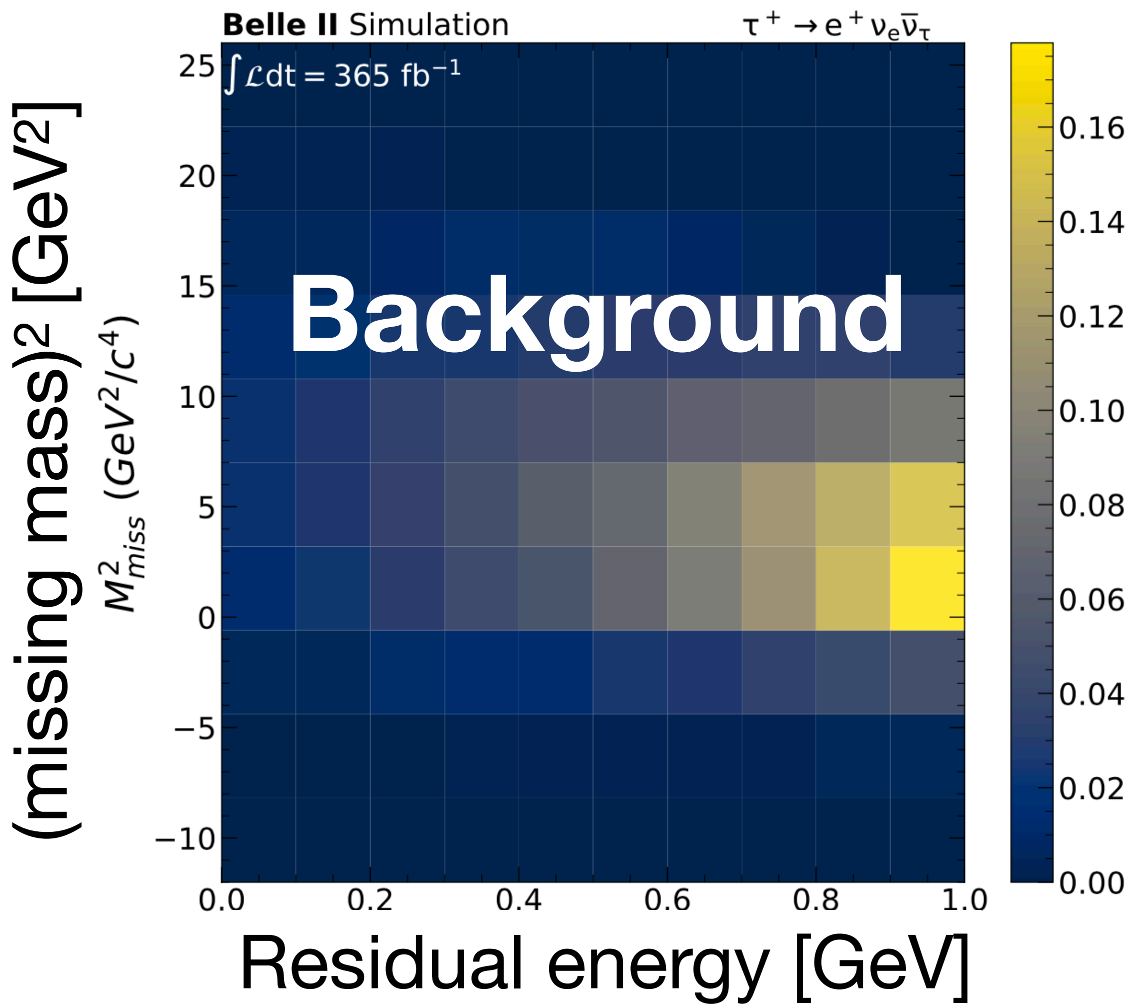
Evidence of $B \to \tau \nu$

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 mass and nothing else: no residual energy in the calorimeter.

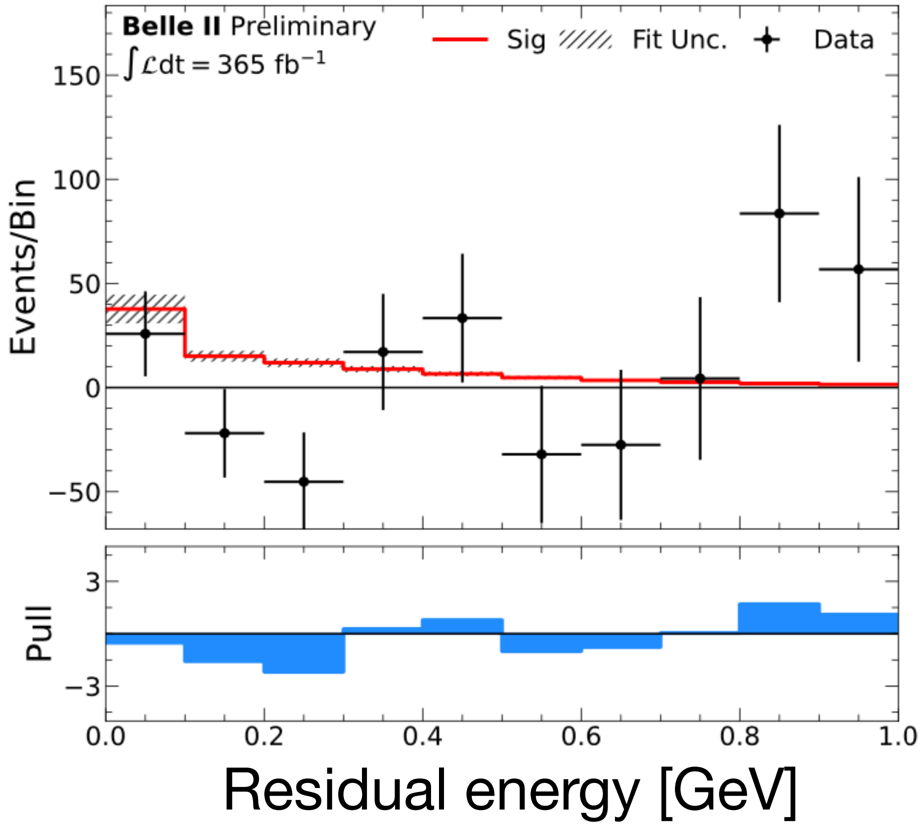


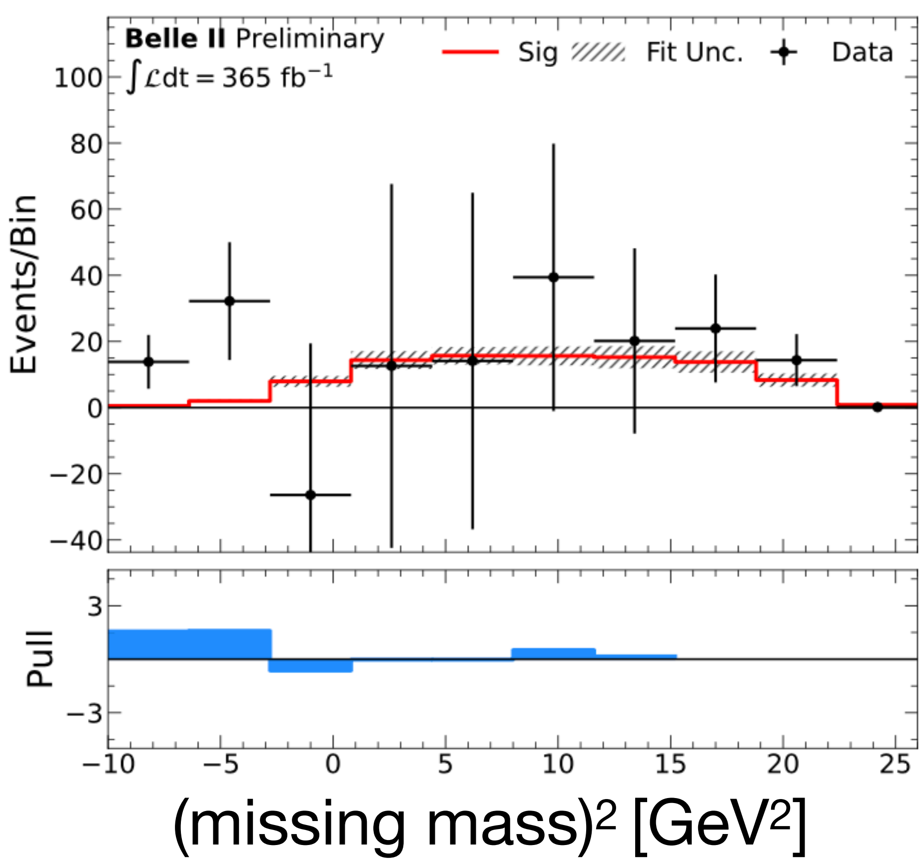


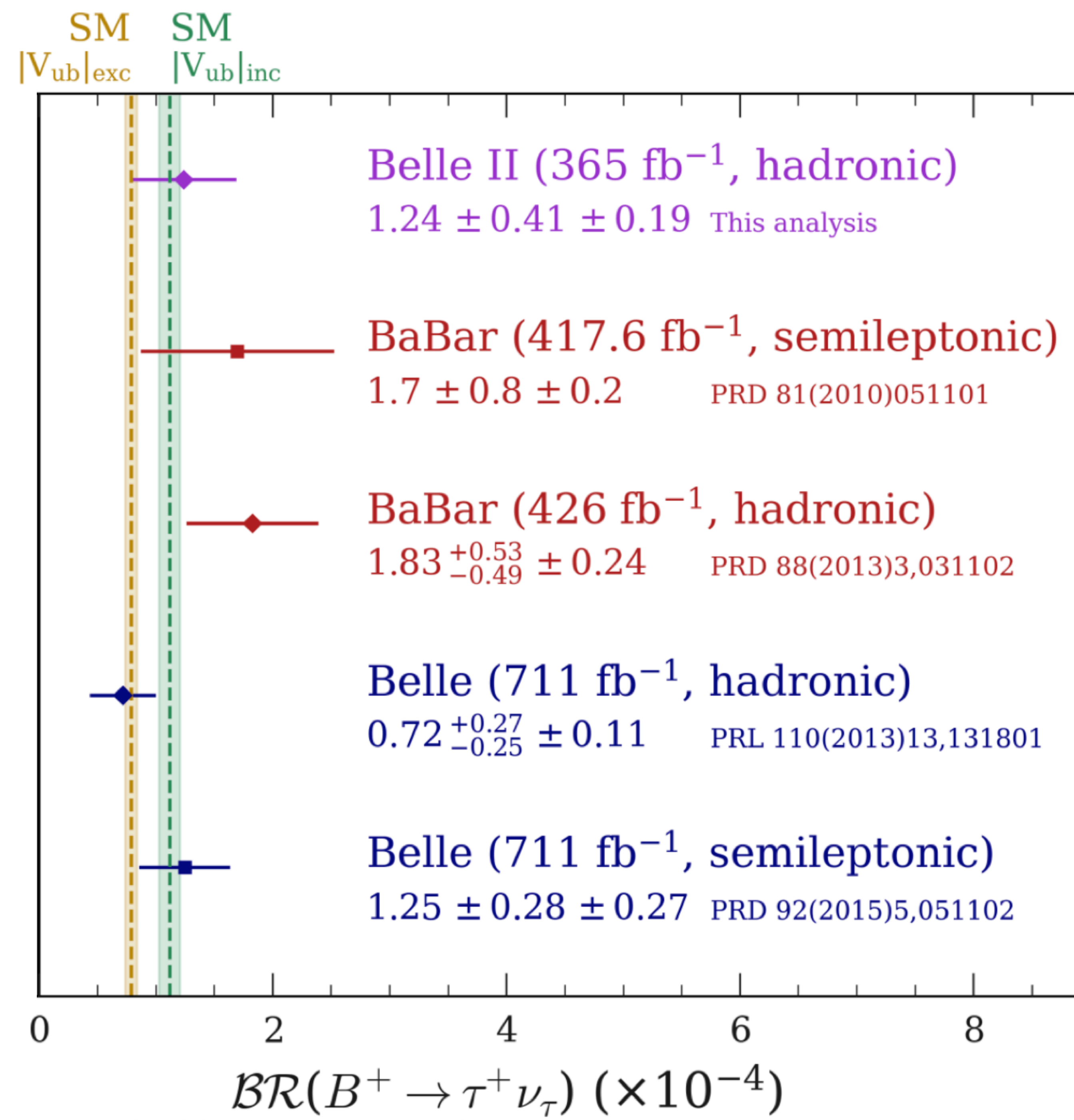


Evidence of $B \to \tau \nu$

[in preparation]





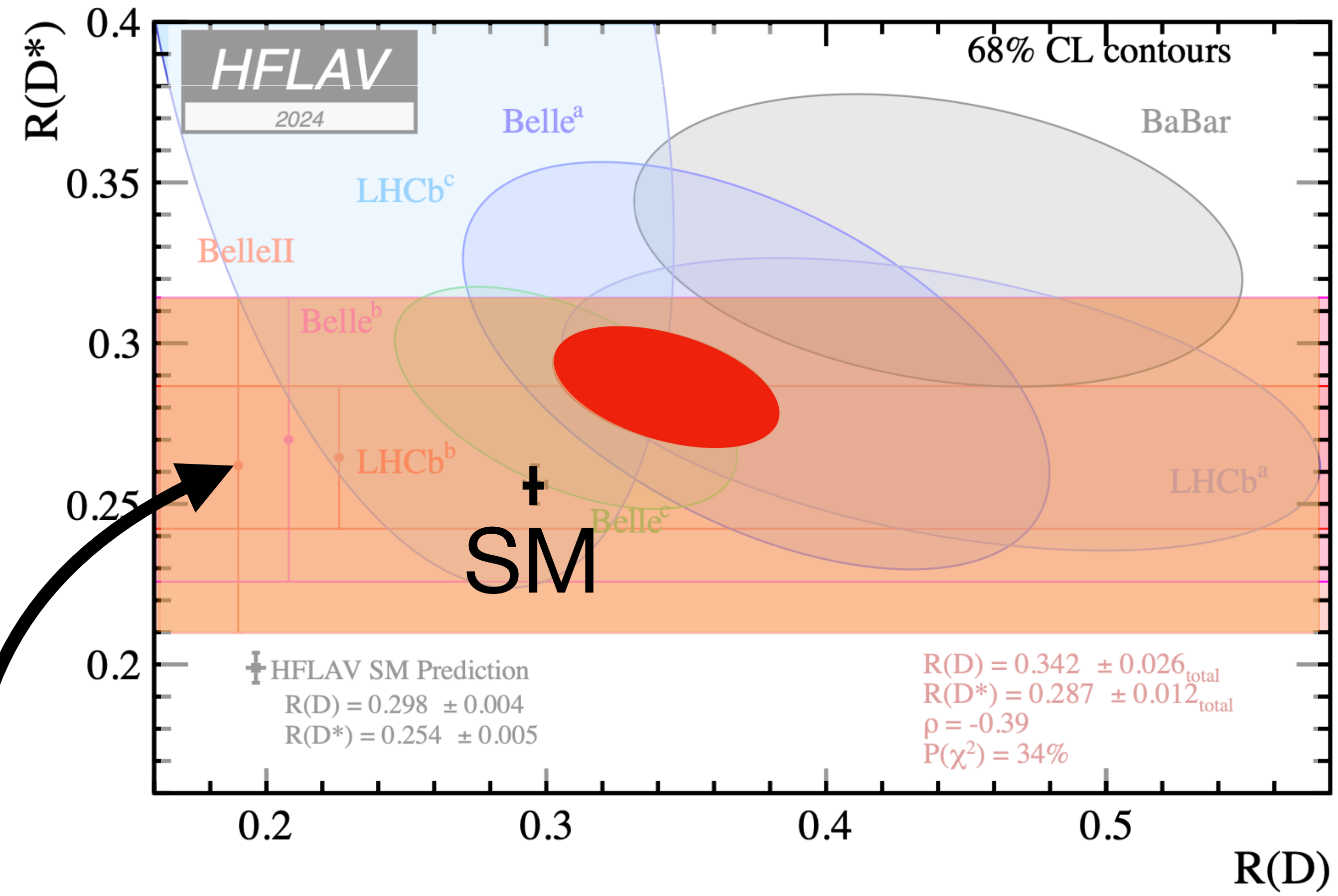


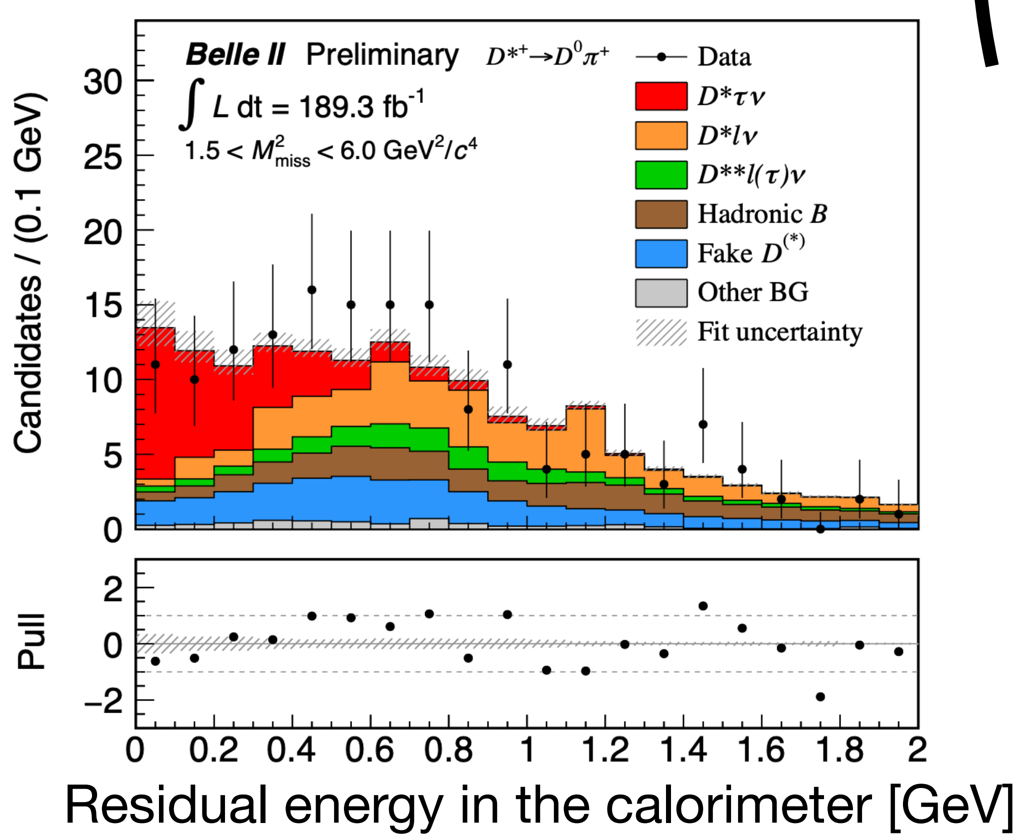
Agrees with SM and previous results

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

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





Hadronic-tagged analysis provides comparable precision to equivalent Belle result with 1/4 the sample

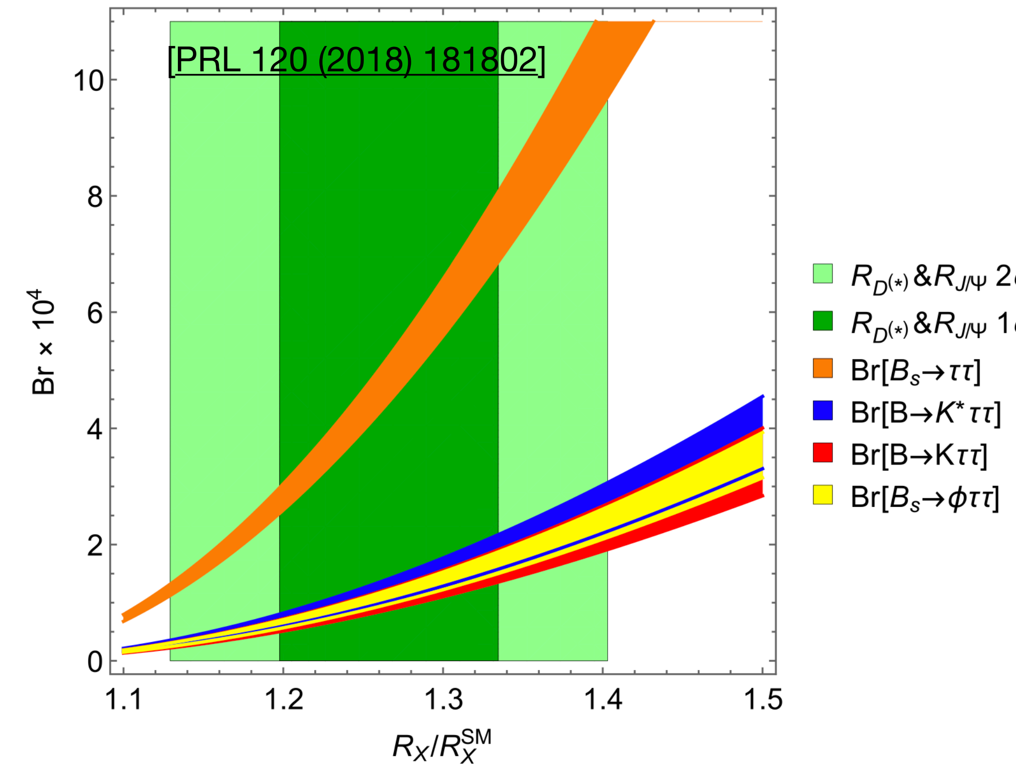
$$R(D^{\star}) = 0.26 \pm 0.04^{+0.04}_{-0.03}$$

[PRD 110 (2024) 072020]

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

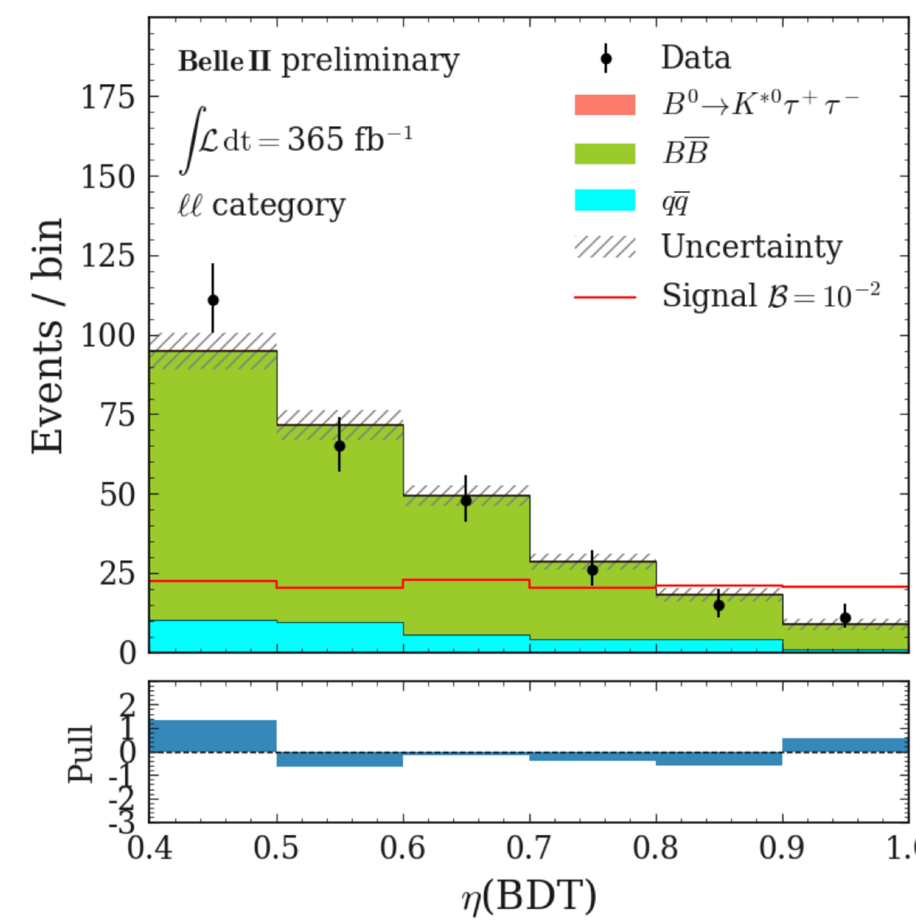
[in preparation]

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.



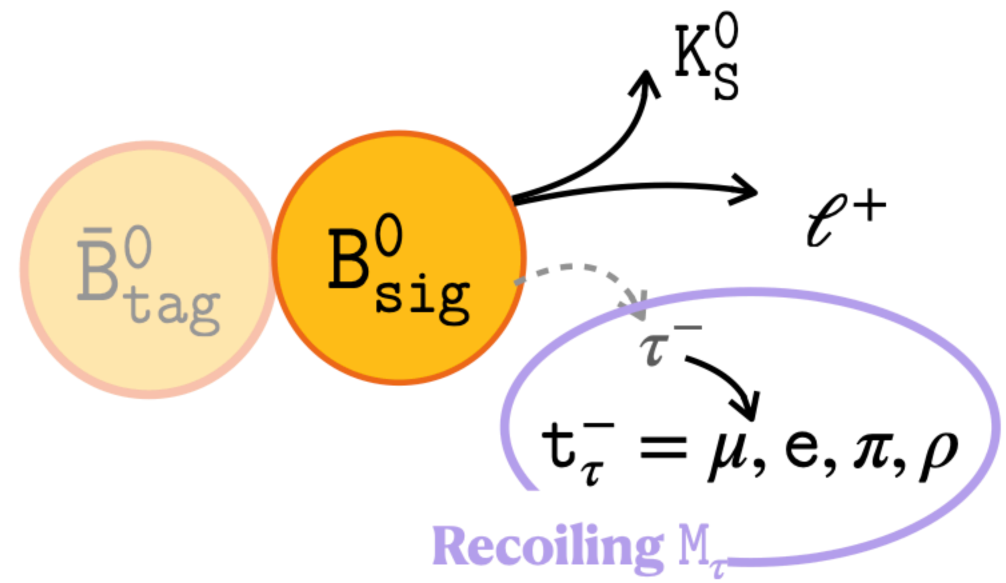
BF < 1.8×10^{-3} @ 90% CL

Limit twice improved over Belle.

Search for $B \to K_S\, \tau\, l$

[arXiv:2412.16470]

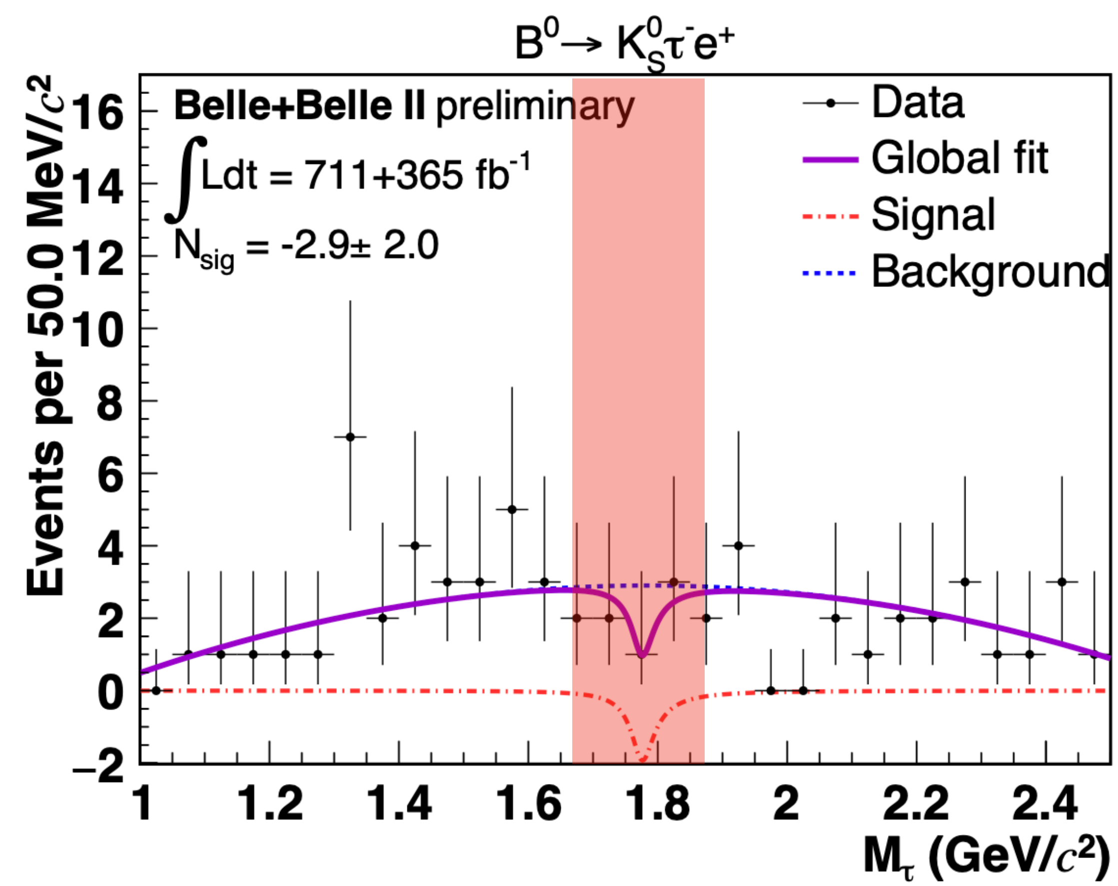
Violates charge-lepton number conservation: forbidden in the SM. Again, model accommodating R(D*) anomaly predicts rates close to current experimental sensitivity.



Combined Belle+Belle II sample to boost sensitivity. Hadronic tag and use recoiling mass as discriminating variable.

No signal found, upper limit @90% CL

$$\mathcal{B}(B^0 \to K^0_S \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^0_S \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^0_S \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K^0_S \tau^- e^+) < 0.8 \times 10^{-5}$$



And much more…

Several recent results not covered here

- Observation of $B^0 \to J/\psi\omega$ https://arxiv.org/abs/2412.12338
- Observation of 3 new Ξ_c decays https://arxiv.org/abs/2412.10677
- Measurement of inclusive BF($B_s \to DX$) https://arxiv.org/abs/2412.10677
- $B \to K^*\gamma$ decay properties https://arxiv.org/abs/2411.10127
- CPV in $D^0 \to K_S K_S$ https://arxiv.org/abs/2411.00306
- D mixing with $D^0 \to K_S\pi\pi$ https://arxiv.org/abs/2410.22961
- Observation of CPV in $B \to J/\psi\pi^0$ https://arxiv.org/abs/2410.08622
- Search for CPV in $D_{(s)} \to K_S K\pi\pi$ https://arxiv.org/abs/2409.15777
- CPV in $B^0 \to K_S\pi\gamma$ https://arxiv.org/abs/2407.09139
- Decay properties of $B \to \rho\gamma$ https://arxiv.org/abs/2407.08984
- BF of $B \to DKK^{(*)}$ and $B \to DD_s$ https://arxiv.org/abs/2406.06277
- Decay properties of $\Xi_c \to \Xi^0 \pi^0$, $\Xi^0\eta^{(')}$ https://arxiv.org/abs/2406.04642
- Energy dependence of $ee \to B^{(*)}B^{(*)}$ x-sec https://arxiv.org/abs/2405.18928
- Search for $B \to \gamma\gamma$ https://arxiv.org/abs/2405.19734
- Belle+Belle II γ combination https://arxiv.org/abs/2404.12817
- Measurement of BF($B \to D^0\rho$) https://arxiv.org/abs/2404.10874

… and counting, see the complete list

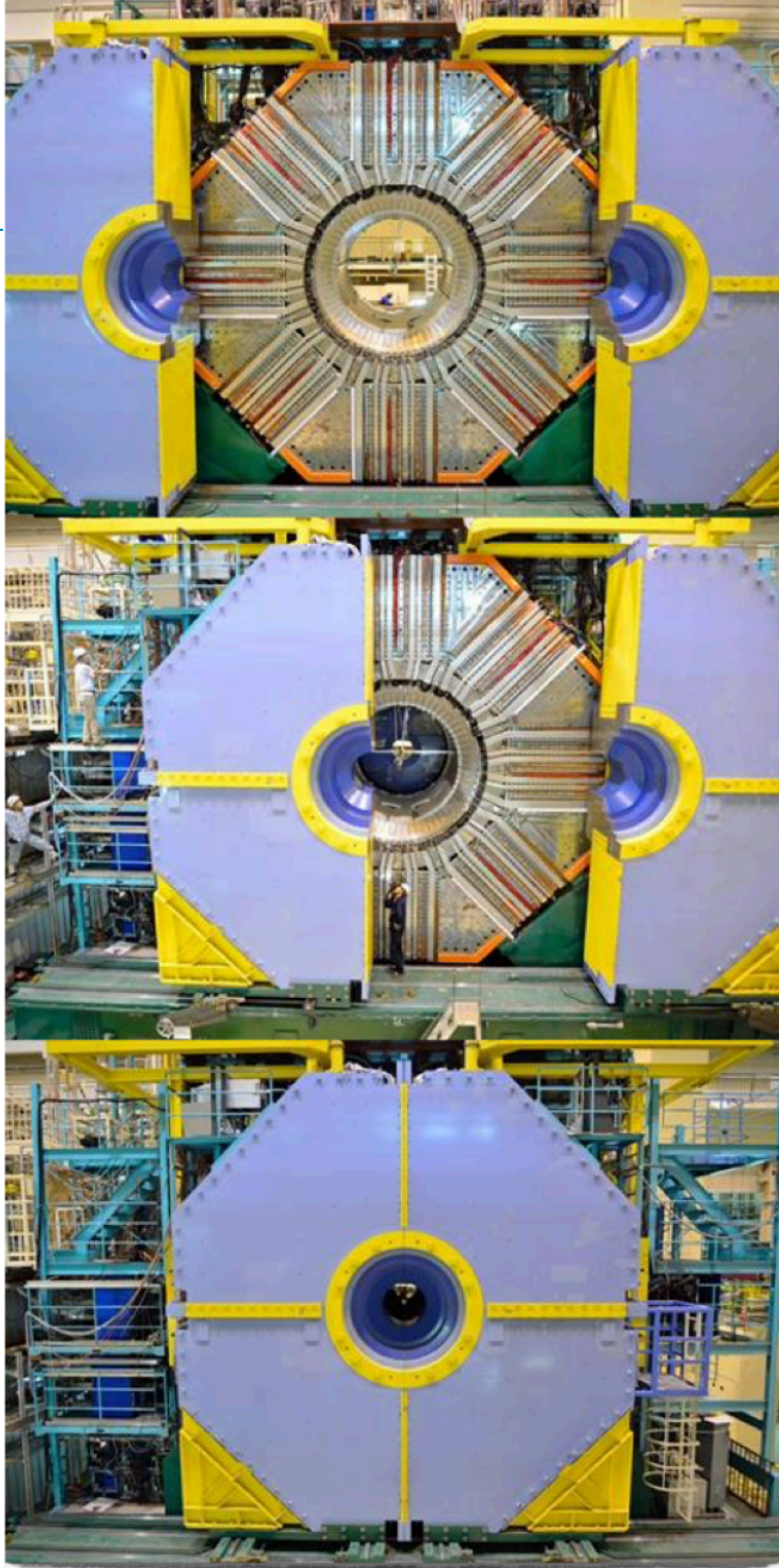
Summary

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 building.

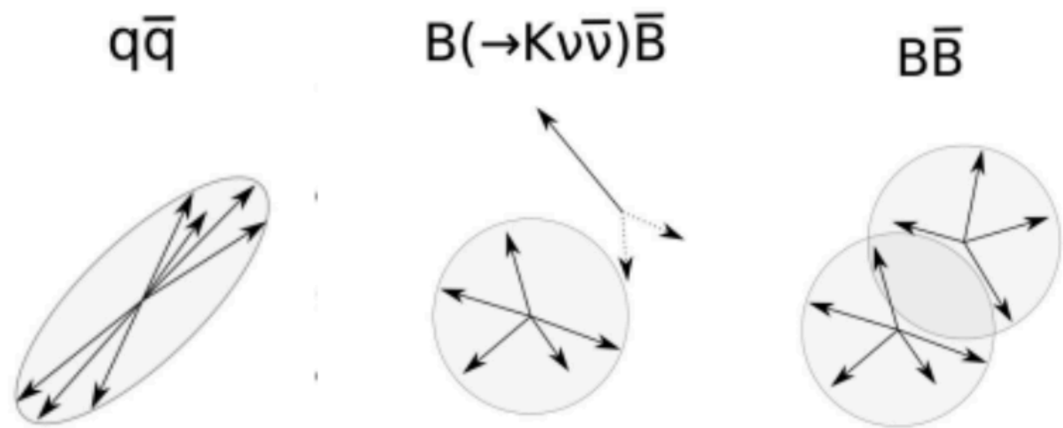
Belle II results with smaller current data set than Belle. Yet, competitive or better.



Backup

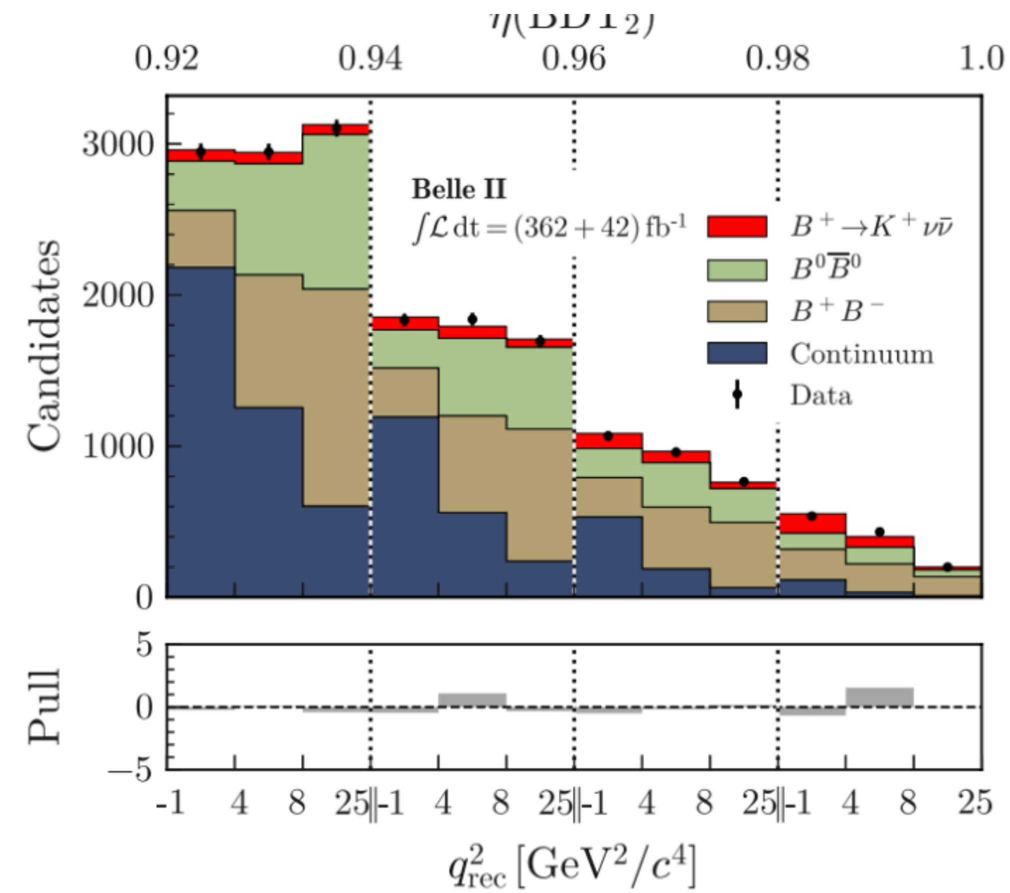
Evidence for $B \to K\nu\nu$

- Theoretically clean and third generation sensitive $b \to sll$ transition
- Inclusive tag developed that exploits topology
  - 8% efficiency



- Fit to invariant mass of neutrinos (q^2) and classifier
  - Checked and combined with lower efficiency hadronic *B* tag

$$\mathbf{B}(B^+ \to K^+ \nu\bar{\nu}) = \left(2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})\right) \times 10^{-5}$$



Evidence @ 3.5σ
Tension with SM prediction of 0.6×10^{-5} @ 2.7σ