McGill

Belle II

A Guided Tour of Belle II

Raynette van Tonder
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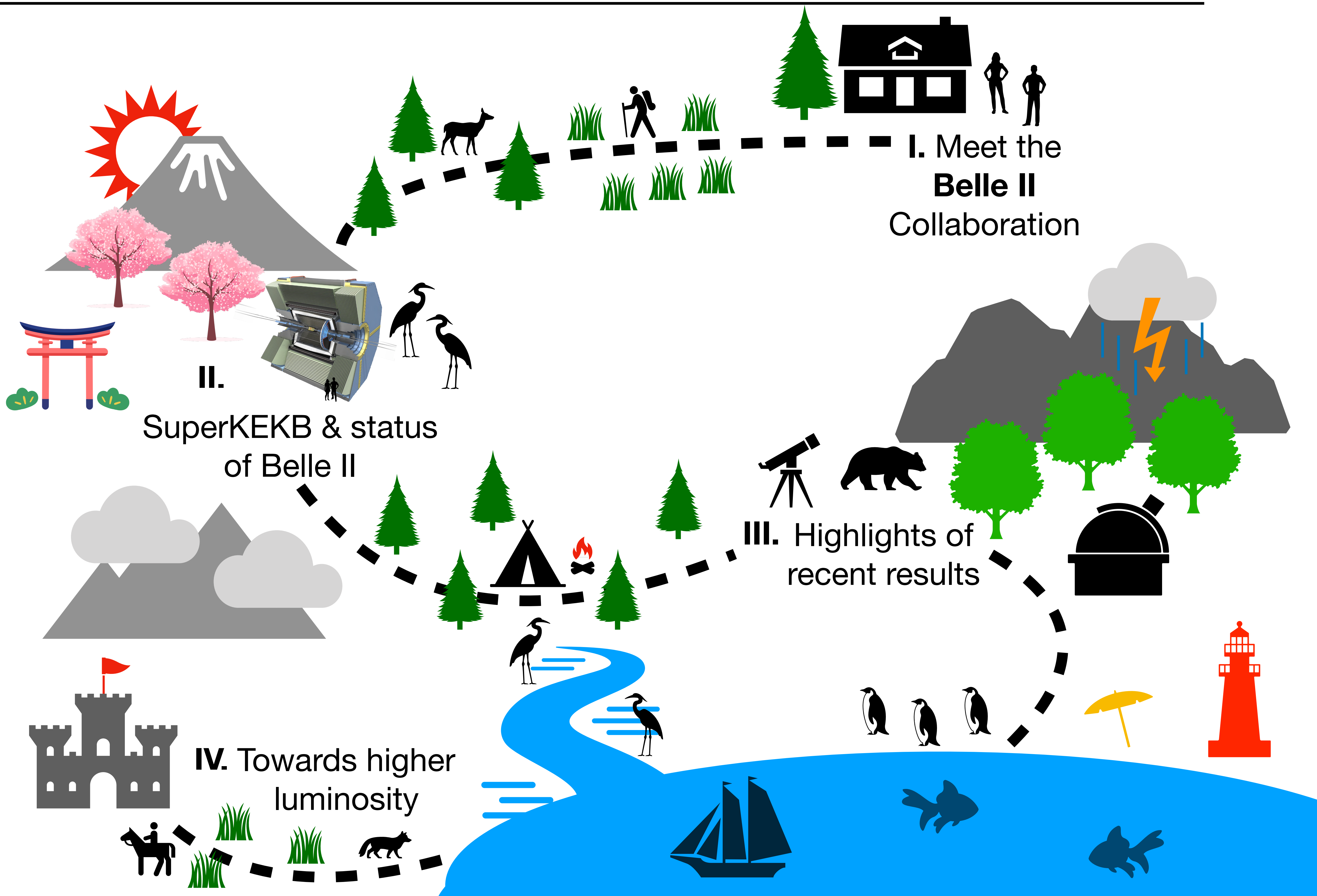
Travel guide for today



Meet the people!

Collaboration map

- The Belle II Collaboration comprises 1158 researchers from 124 institutes in 28 countries!

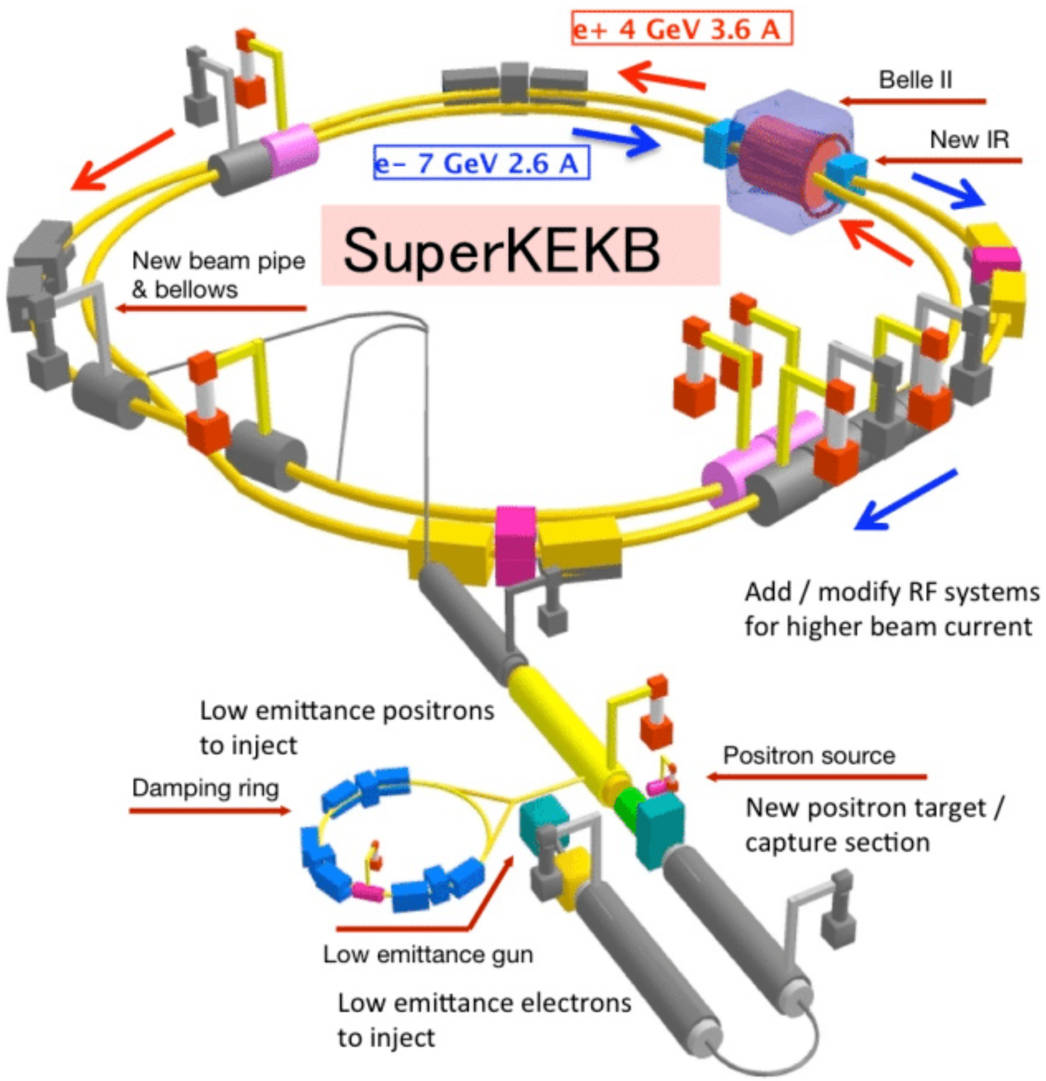
43rd Belle II General Meeting
10-14 Oct 2022, Rome

From KEKB to SuperKEKB

$\mathscr{L}_{\text{Belle}} = 2.11 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$

x30!

Goal: Achieve instantaneous luminosity of $\mathscr{L}_{\text{Belle II}} = 6 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$



How to increase luminosity:

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\,\zeta_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Lorentz factor

Beam current **x 1.5**

Beam-beam parameter

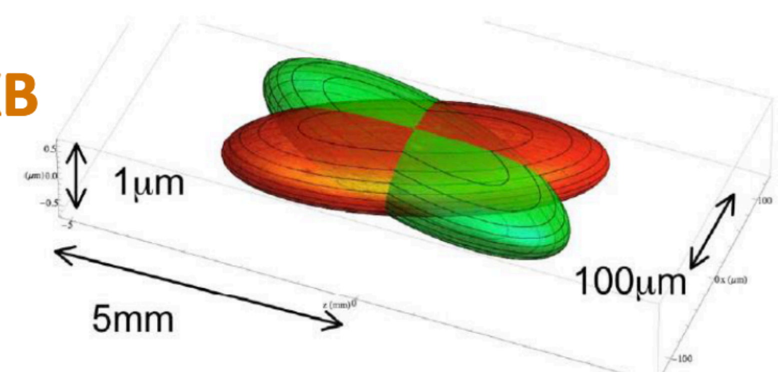
Beam size

Vertical β function **x 1/20**

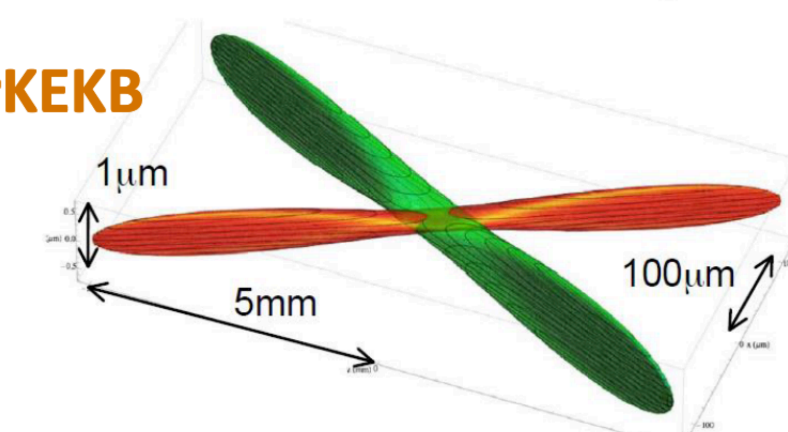
Geometric factors

Nano-beam scheme: Squeeze vertical beam spot size down to ≈ 50 nm using superconducting focusing magnets.

KEKB

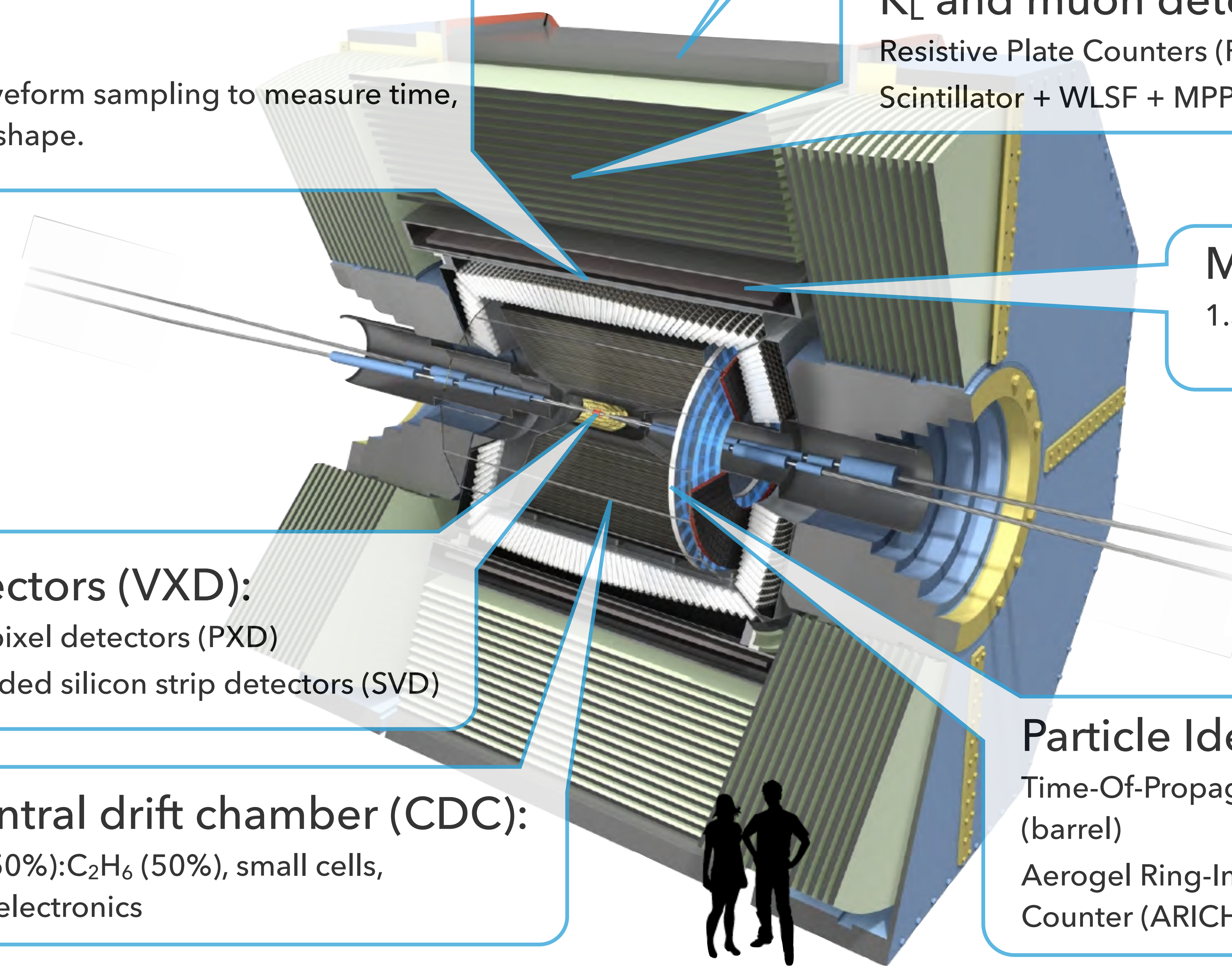


SuperKEKB



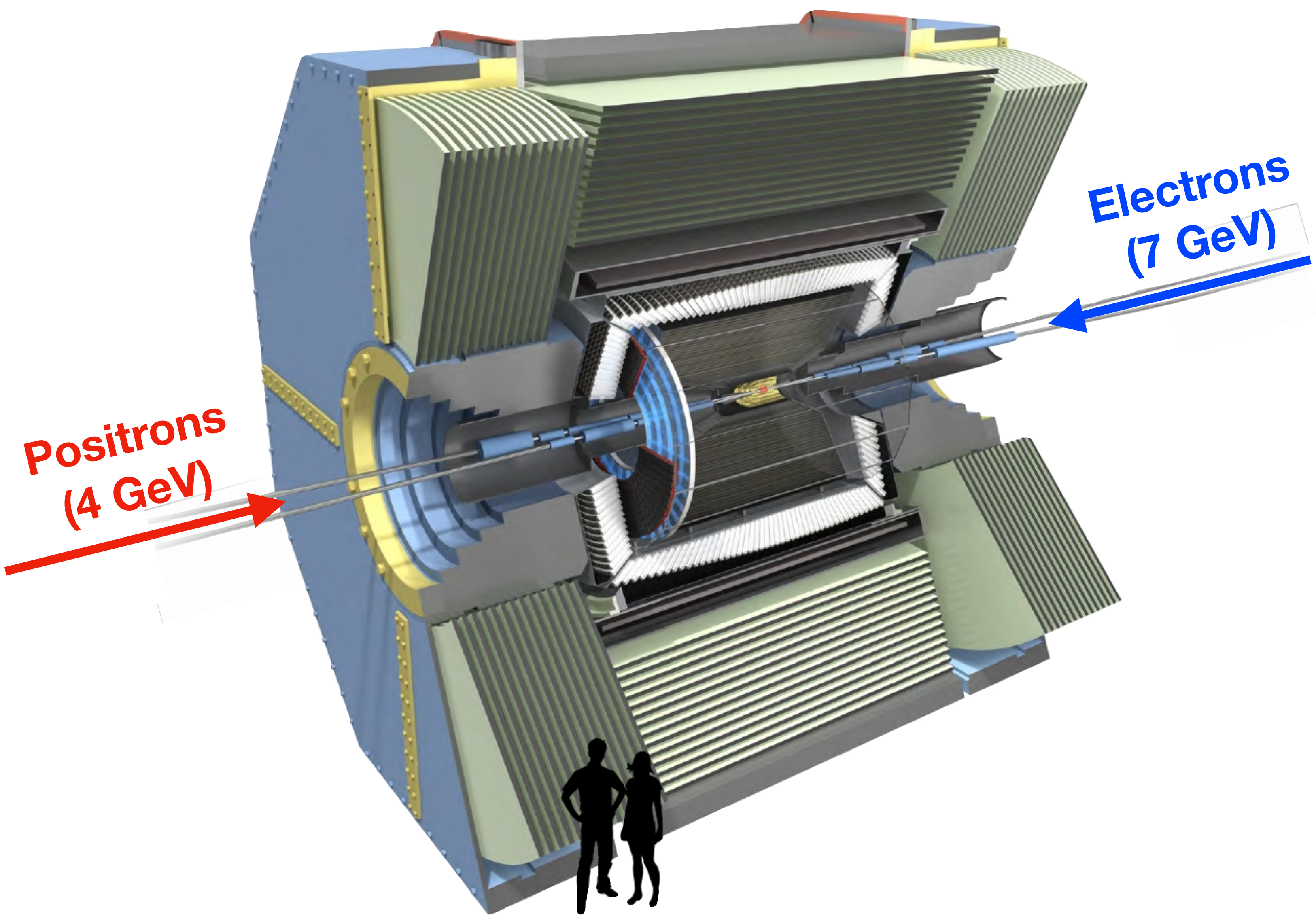

Mt. Tsukuba
Belle II
Detector
SuperKEKB
(HER + LER)
Damping ring
(e^+)
Linac
Japan
Belle II
Tsukuba
/ KEK
Tokio
KEK Tsukuba
Campus

It looks like Belle, but practically it's a brand new detector!



Did somebody order B mesons?

- An ideal laboratory to study rare decays or decays with missing energy



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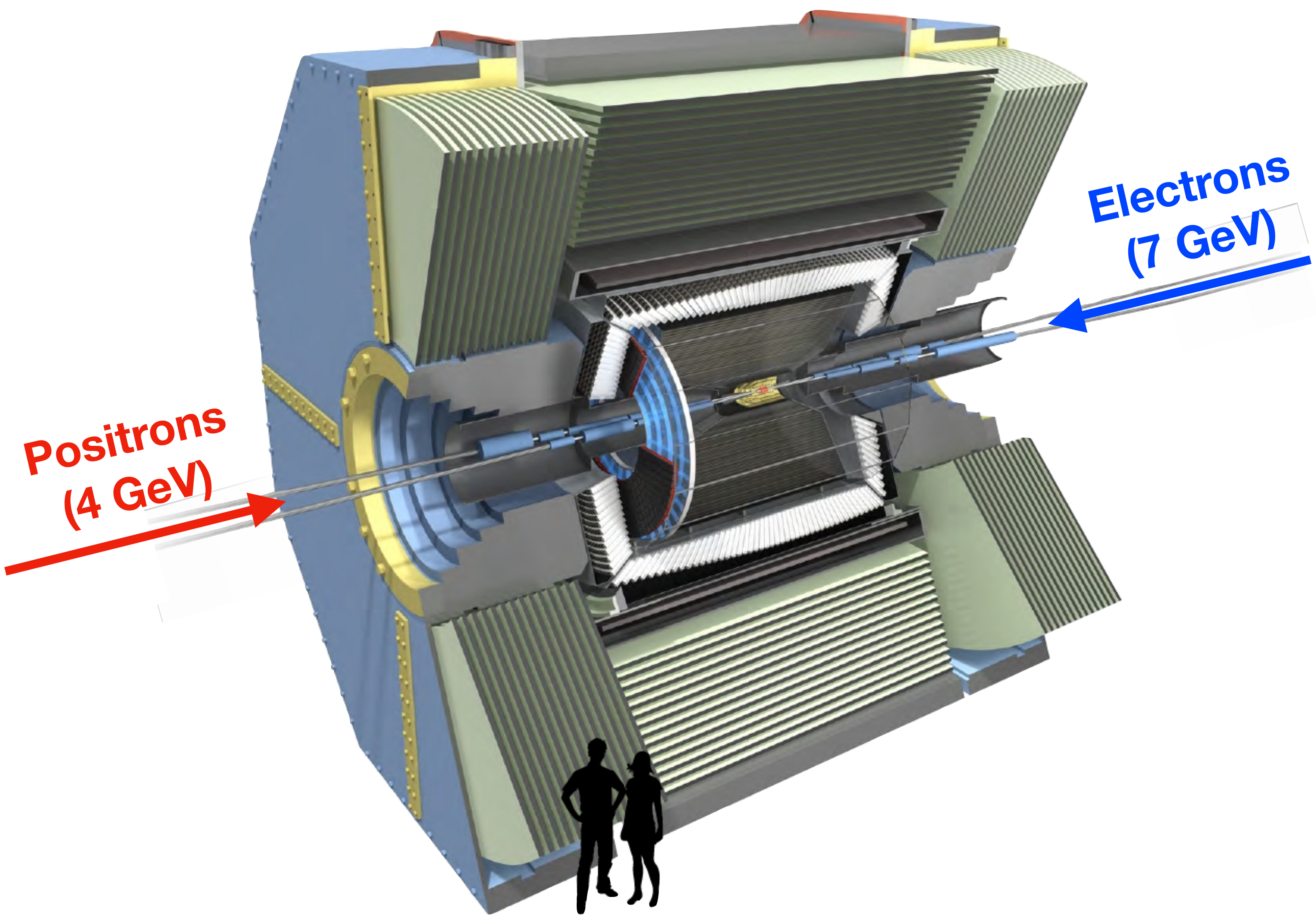

Collide electrons and positrons at a **centre of mass energy** of about twice the B meson mass:

$$\sqrt{s} = 10.58 \text{ GeV}$$

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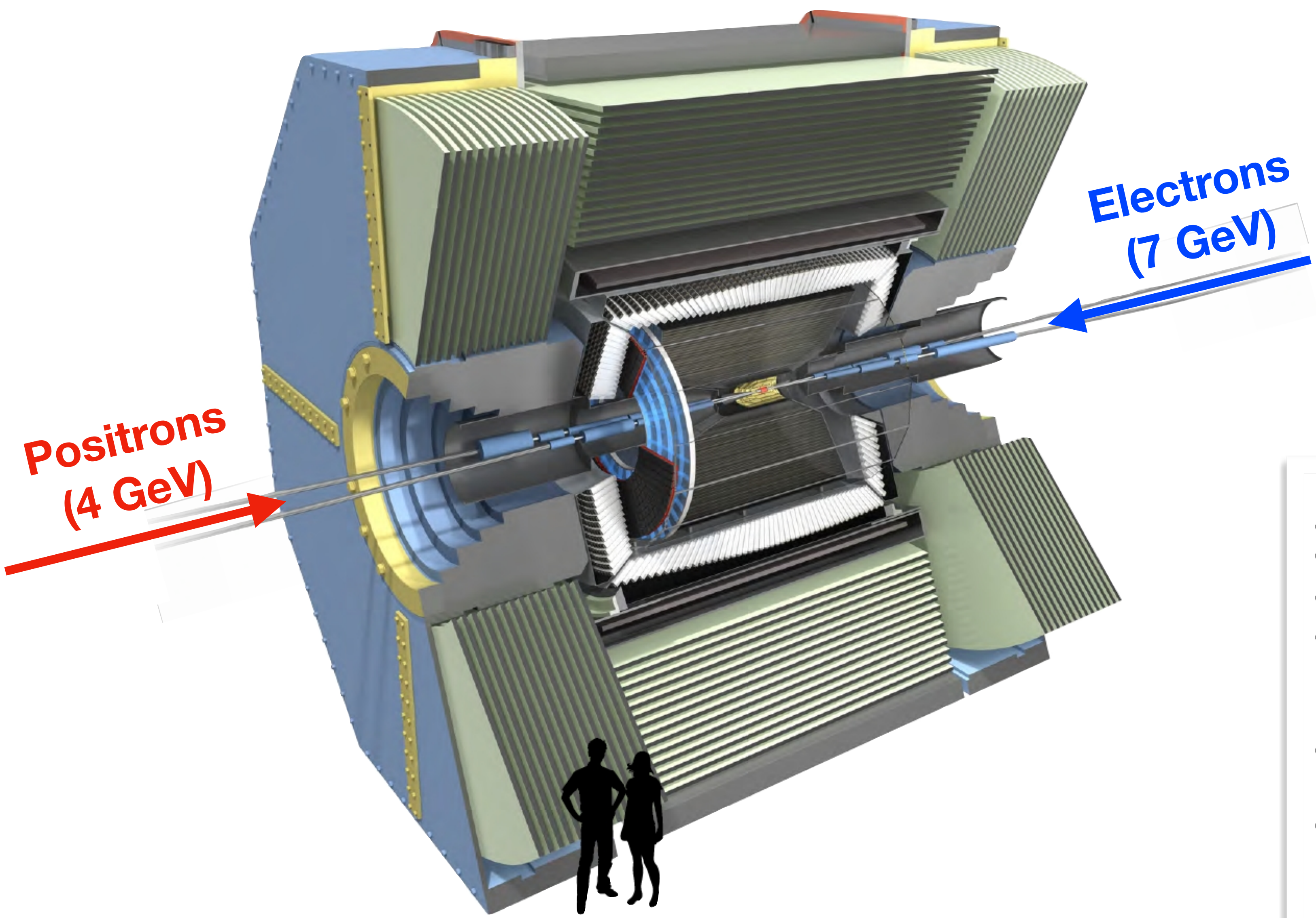

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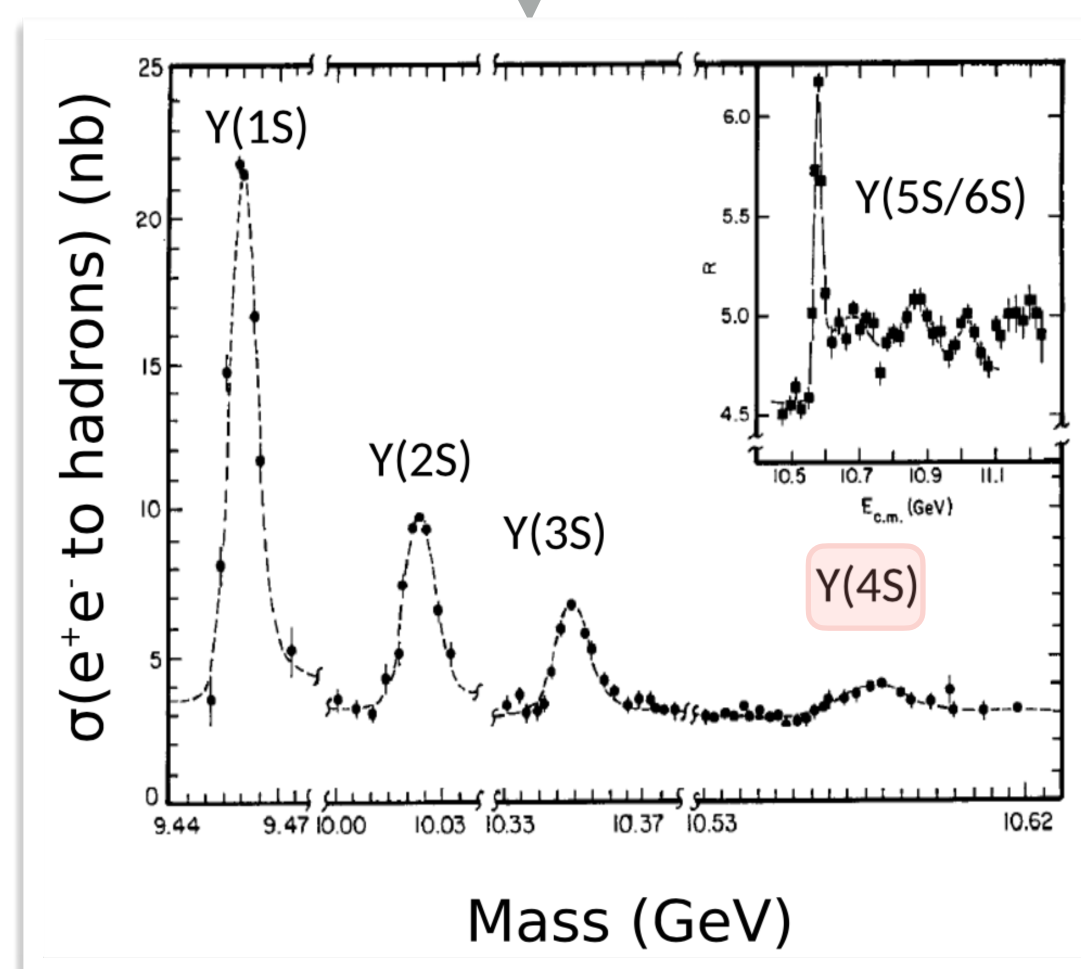

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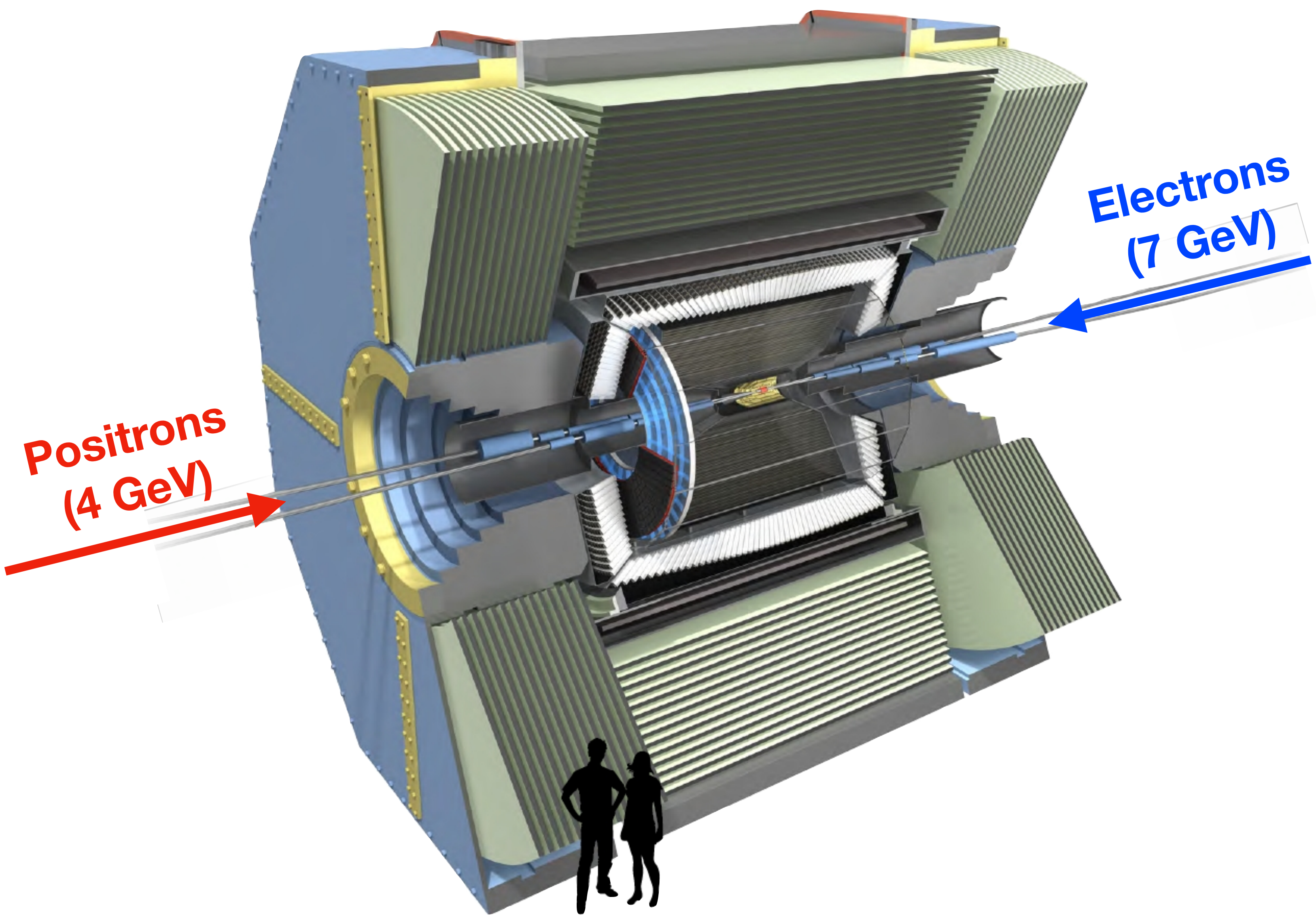

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$$\sqrt{s} = 10.58\ \mathrm{GeV}$$

$$\downarrow$$

$$\Upsilon(4S)$$

$$\langle b\bar{b} \rangle$$

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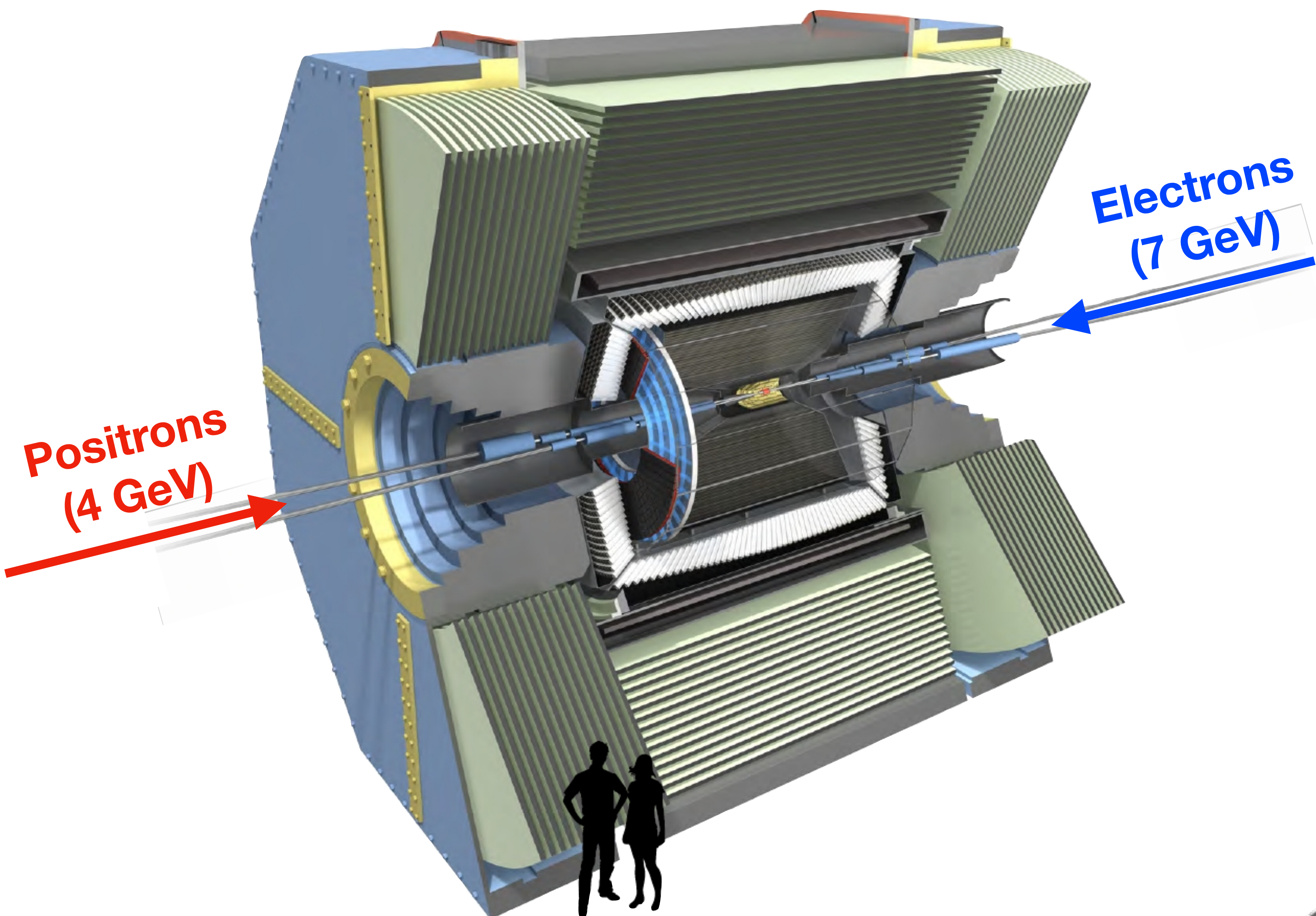

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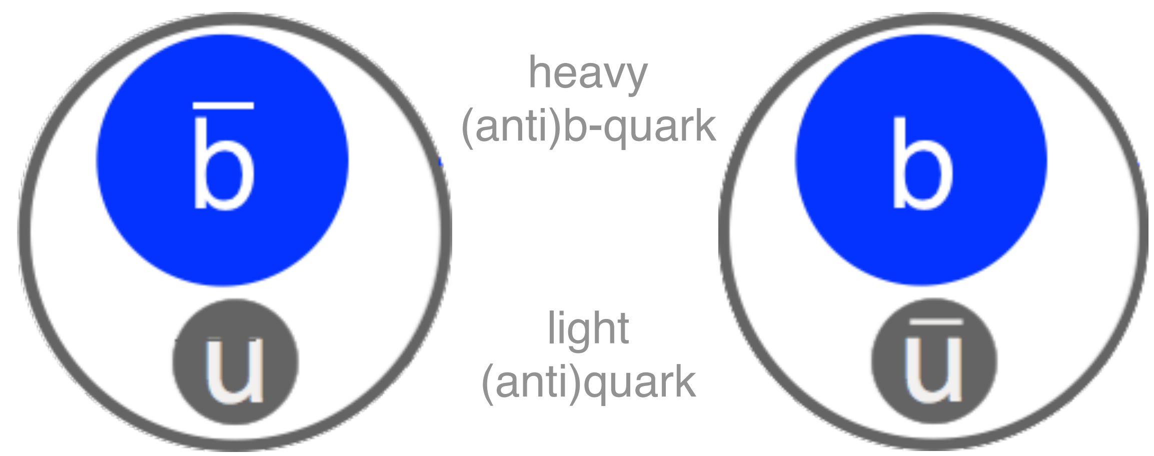
$$\langle b\bar{b} \rangle$$

B meson | **anti-B meson**



Advantages: Precisely known initial state, unique event topology & experimentally clean environment

First Belle II collision: 26 April 2018 00:38 GMT+09:00

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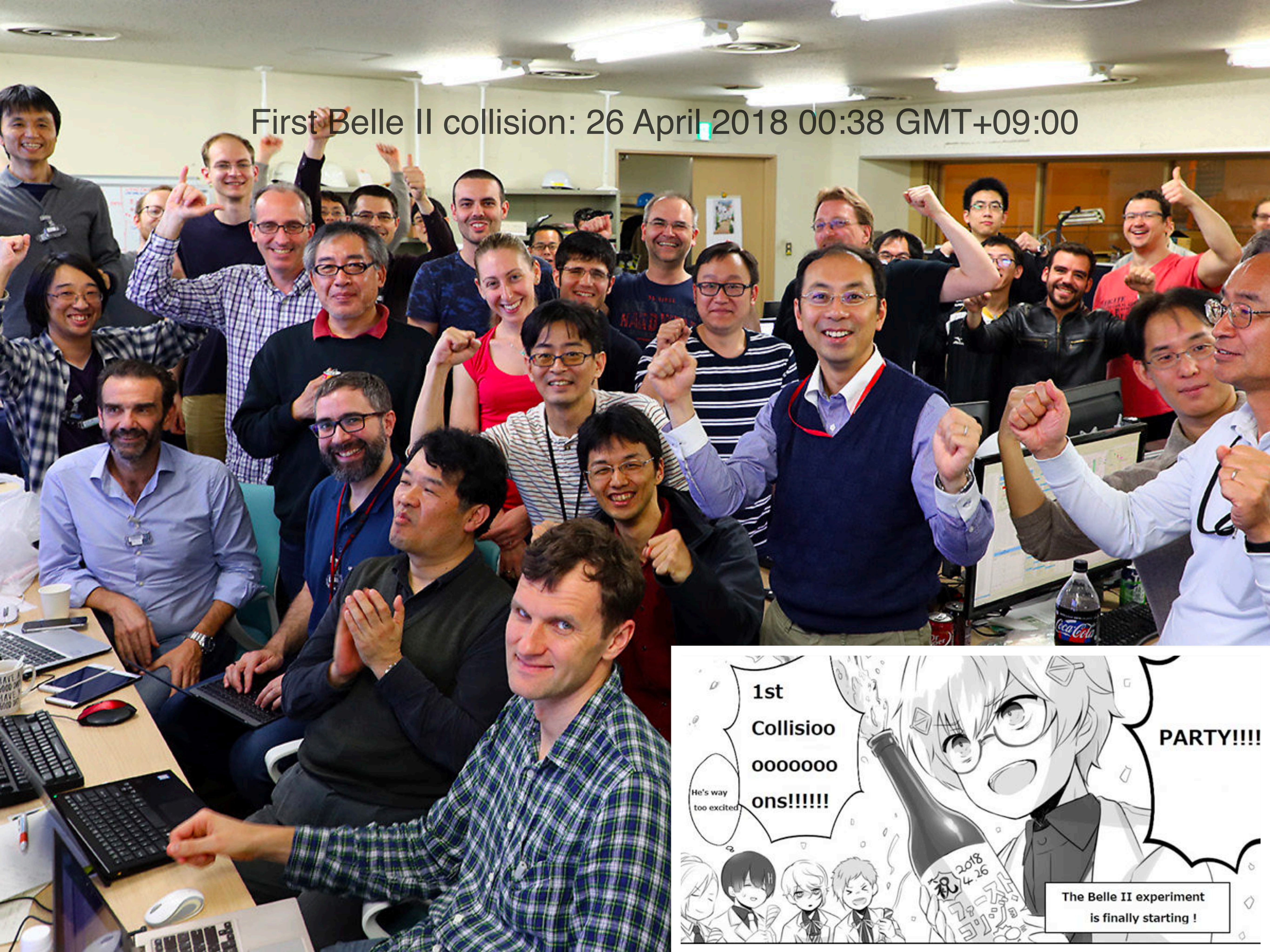
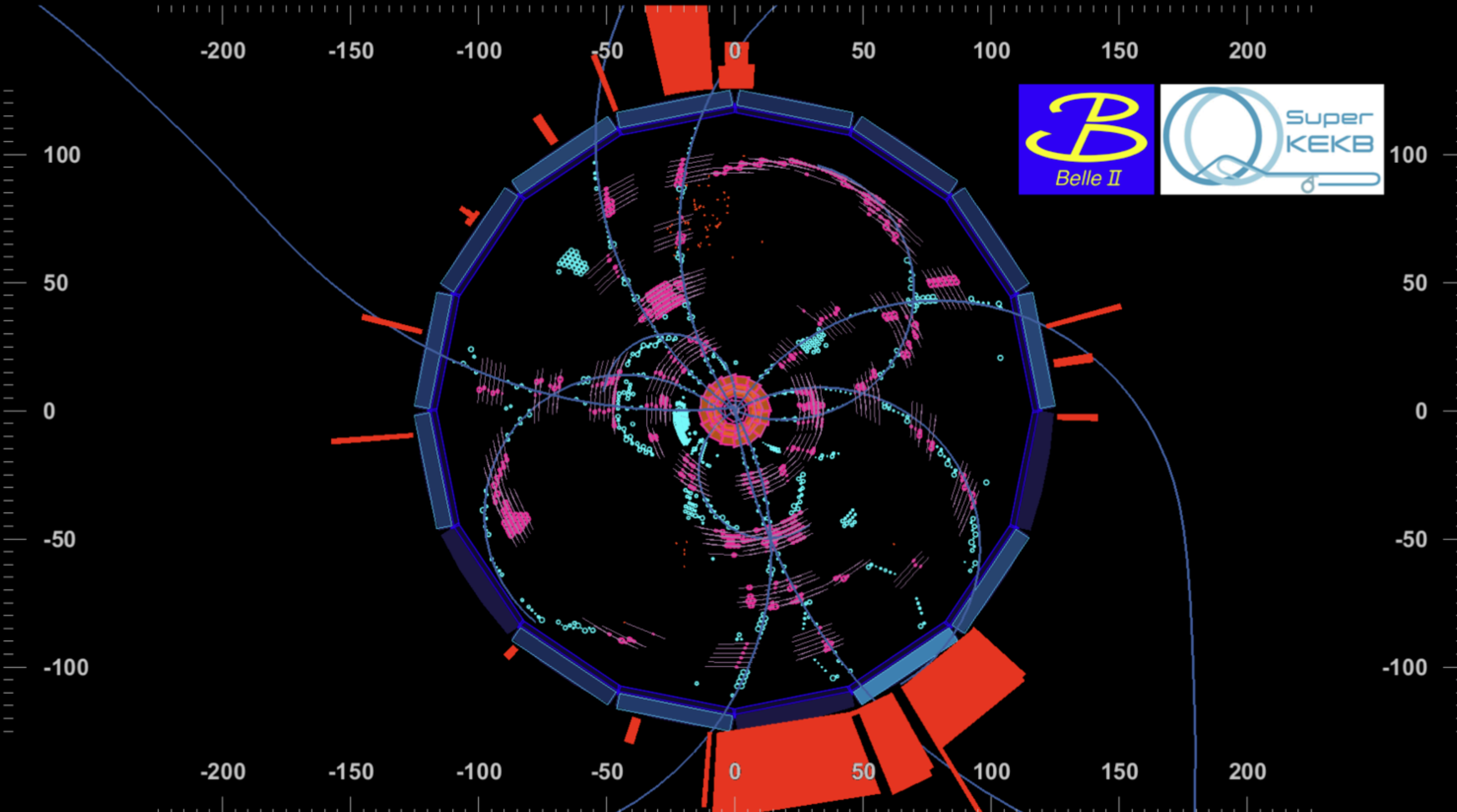
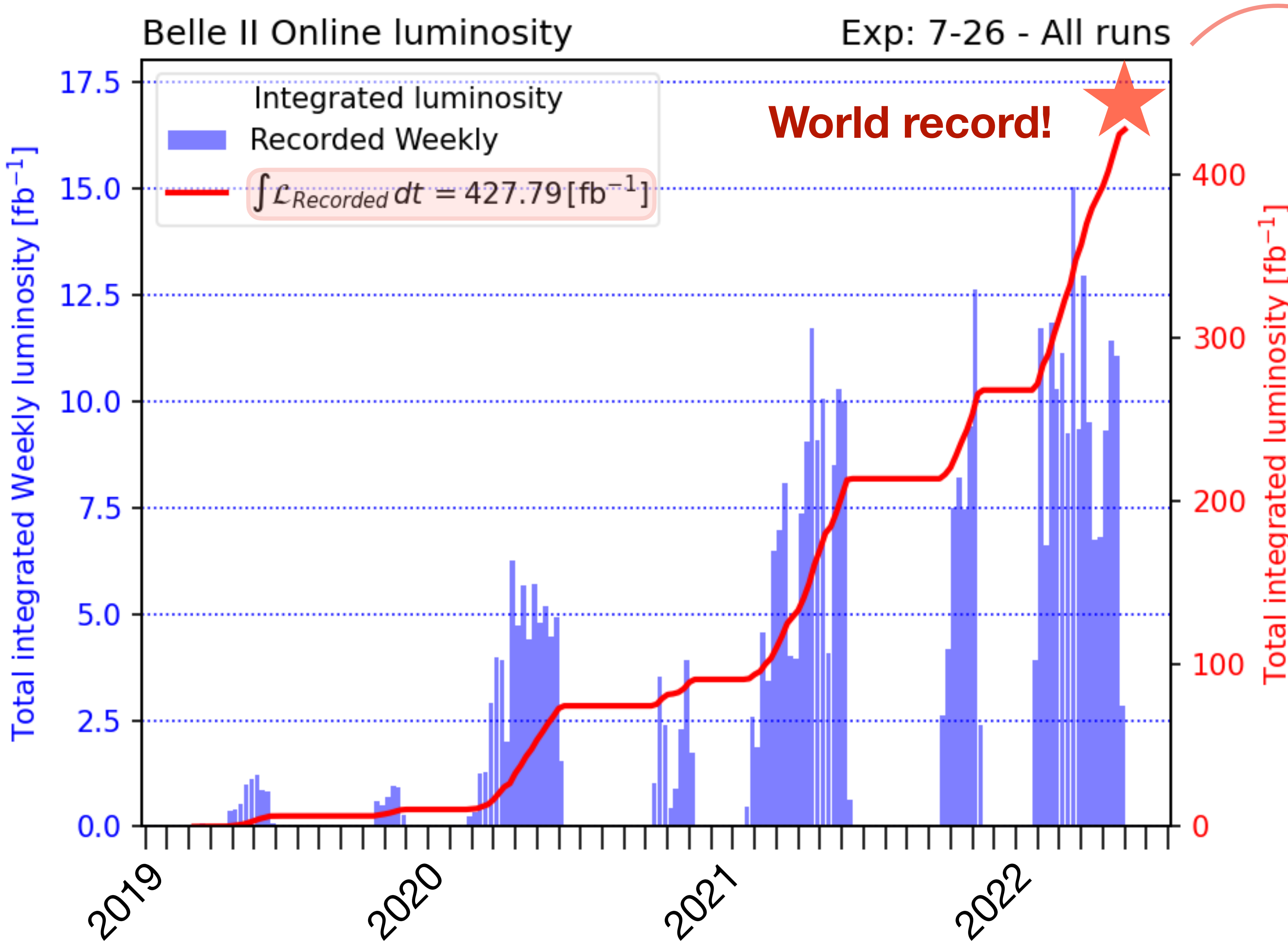



Belle II
SuperKEKB
-200
-150
-100
-50
0
50
100
150
200
100
50
0
-50
-100

Luminosity status

Online Luminosity

- Belle II has recorded a **total integrated luminosity** of 428 fb^{-1} since March 2019
  - (Belle 988 fb^{-1}, BaBar 513 fb^{-1})
- Current status: **Long Shutdown 1 (LS1)** to install two-layer pixel detector and machine maintenance **until Fall 2023!**



Instantaneous luminosity:
L_{peak} = 4.7 x 10^{34} cm^{-2} s^{-1}

Integrated luminosity:

~362 fb^{-1} recorded at $\Upsilon(4S)$

~42 fb^{-1} recorded 60 MeV below $\Upsilon(4S)$ (background studies)

~19 fb^{-1} recorded at 10.8 GeV (exotic hadron searches)

Physics program

Belle II Physics Book

Snowmass White Paper

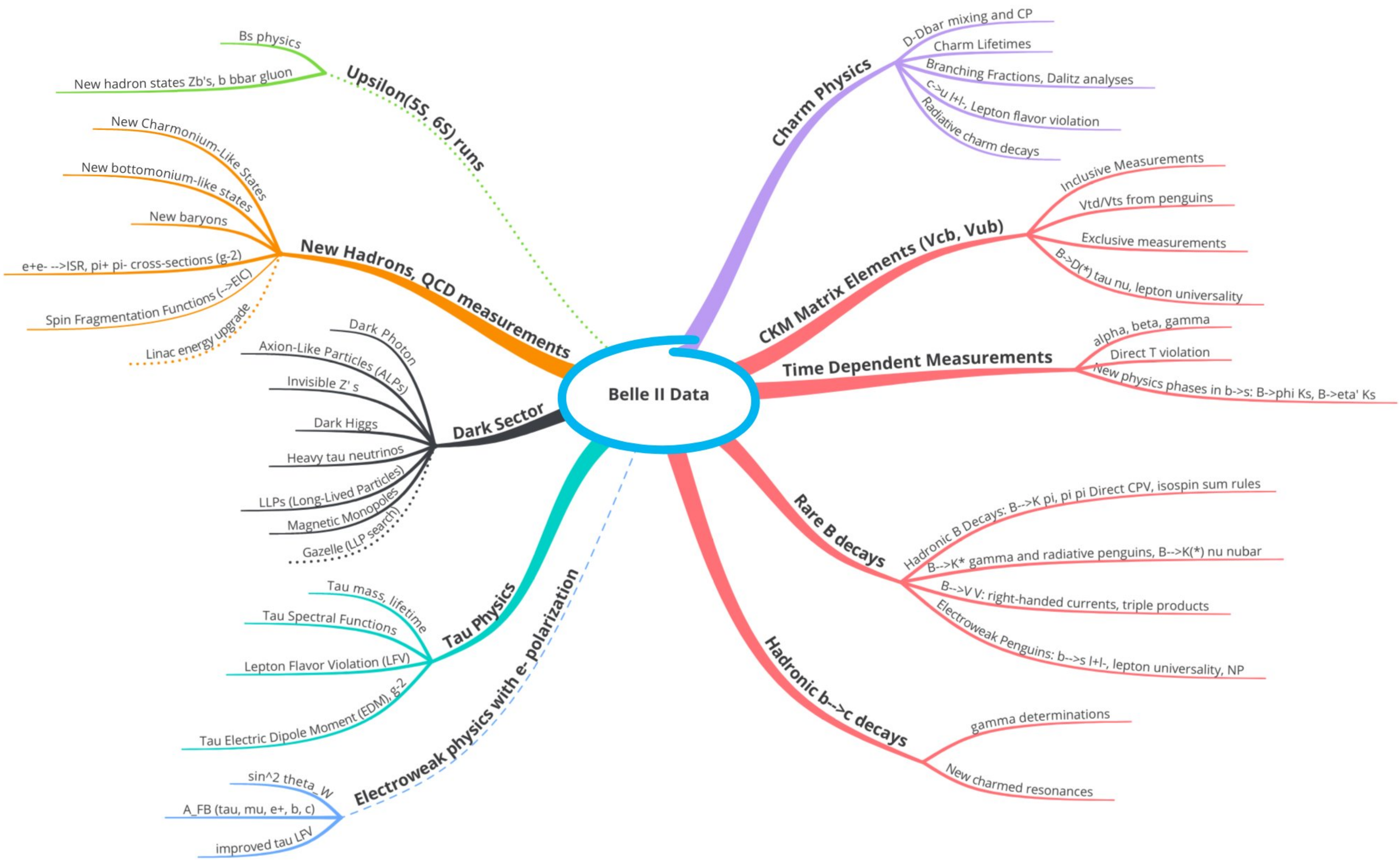


Image credit: T. Browder

Highlights of recent results

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Snowmass White Paper

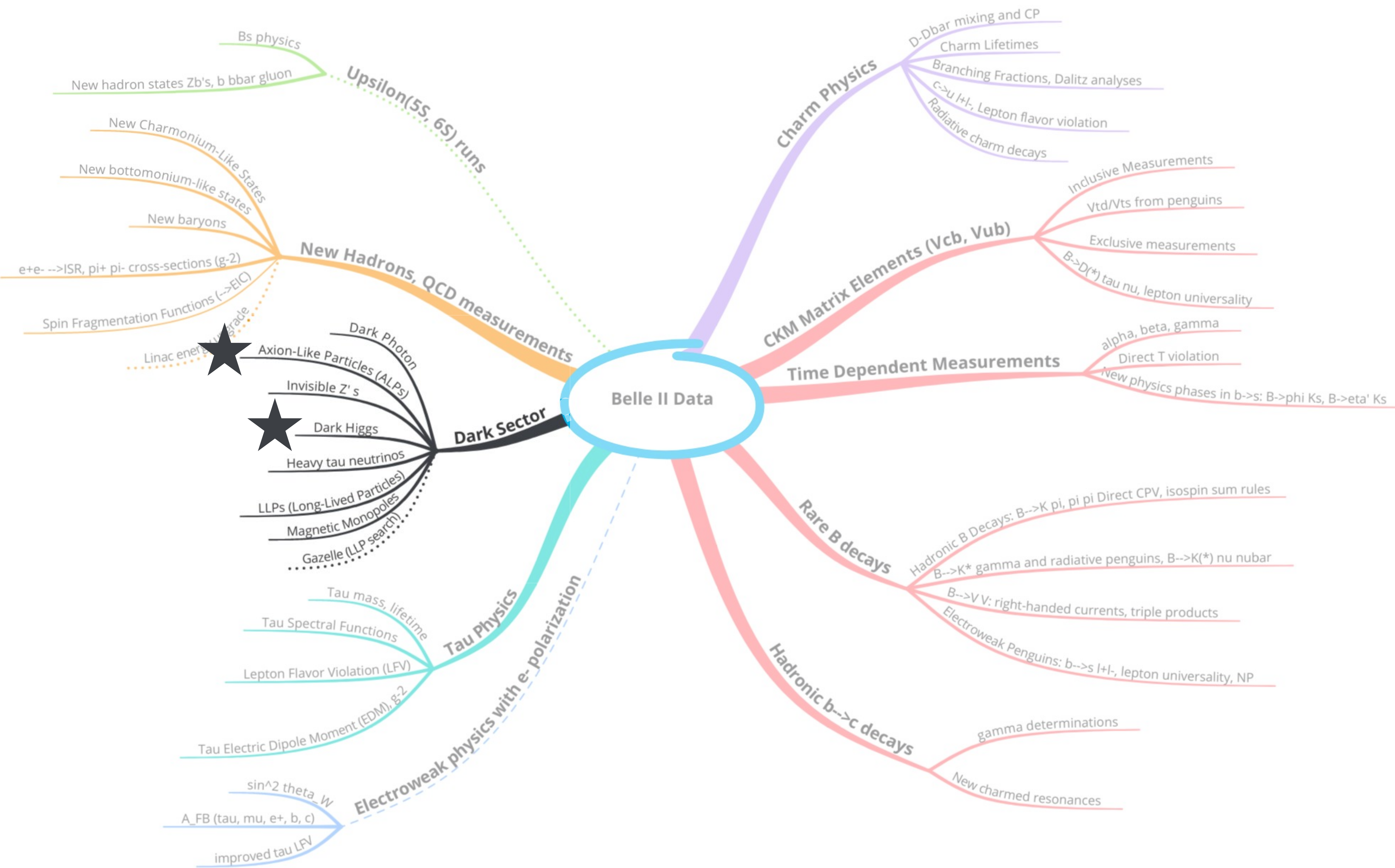
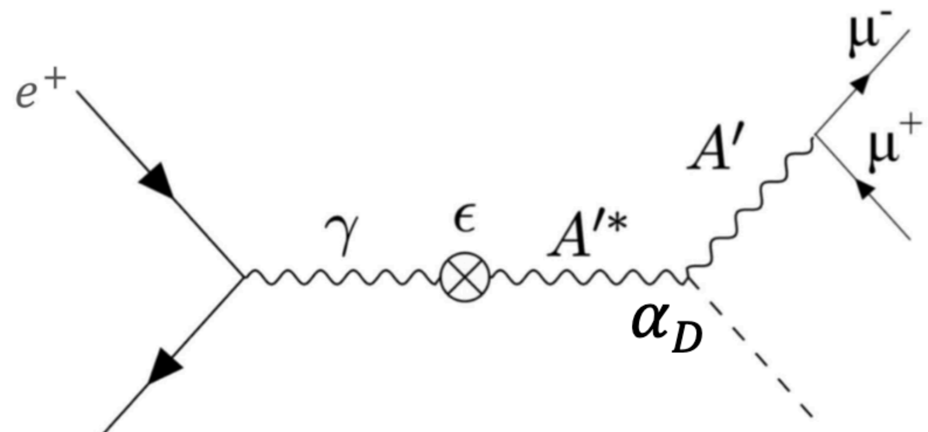


Image credit: T. Browder

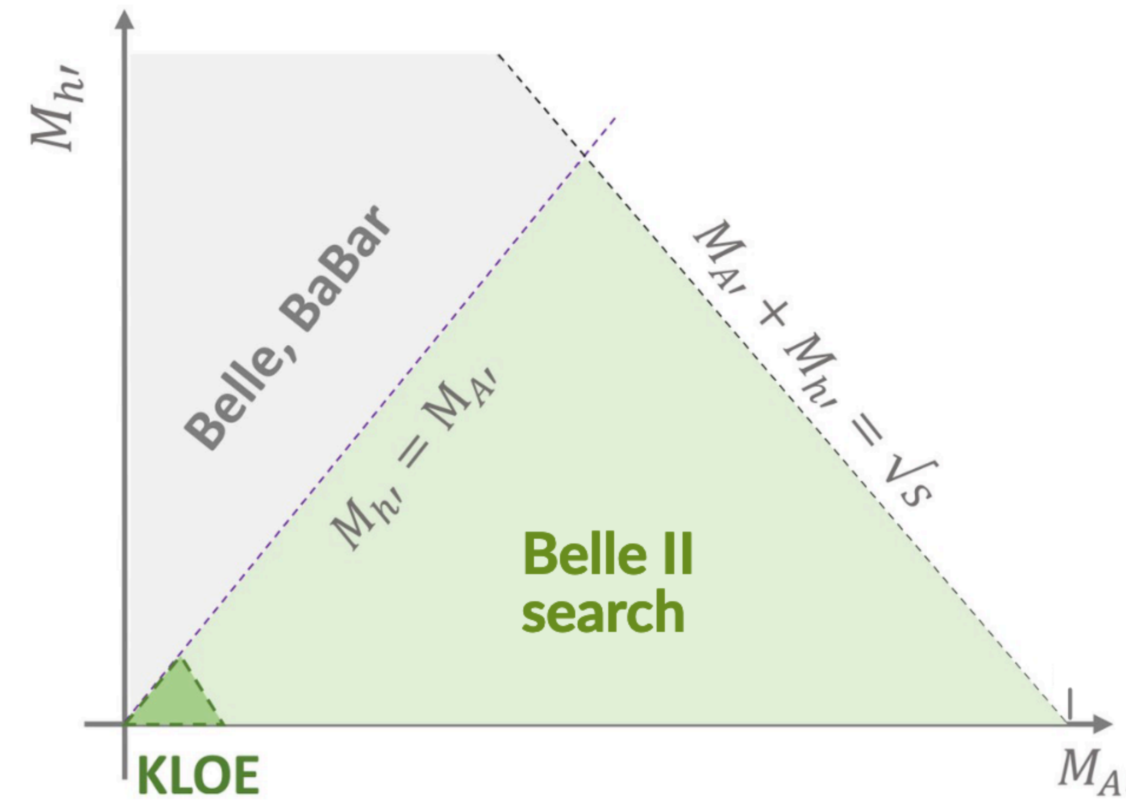
Dark Higgsstrahlung: $e^+e^- \rightarrow A'h'$

arXiv:2207.00509

- **Dark photon** : Couples to SM particles via kinematic mixing parameter ϵ
- **Dark Higgs:** Does not mix with SM Higgs & couples to A' via α_D



$\sigma \sim \epsilon^2 \times \alpha_D$



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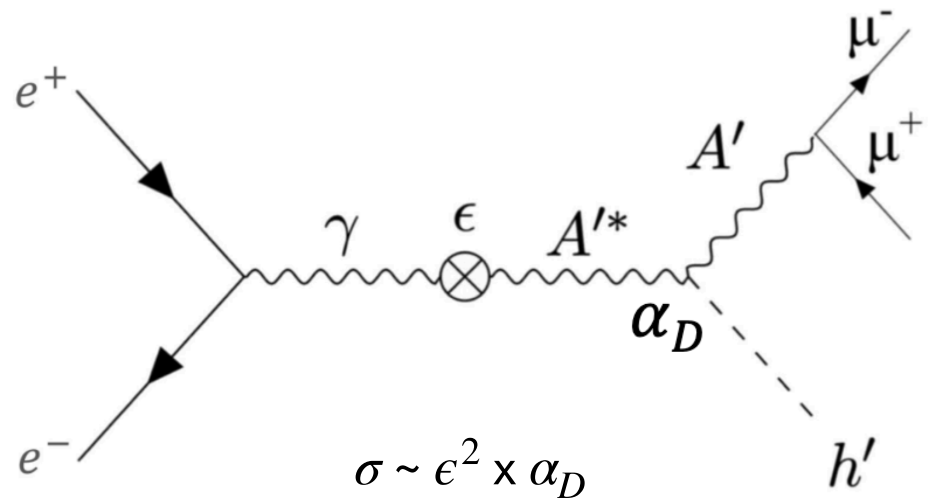
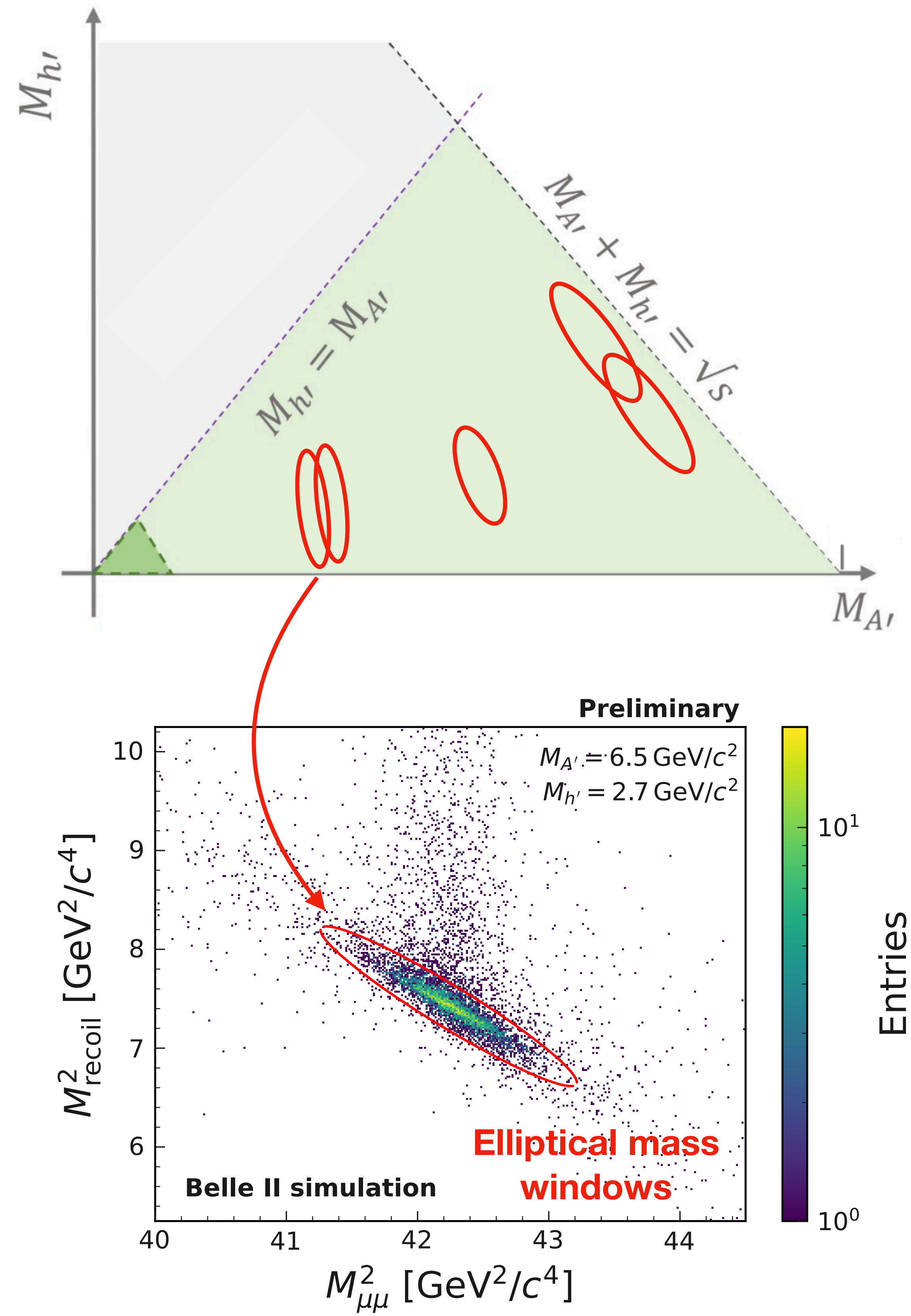


- **Signature:** Two oppositely charged muons & missing energy
- Scan for excess in 9000 elliptical mass windows within the allowed region



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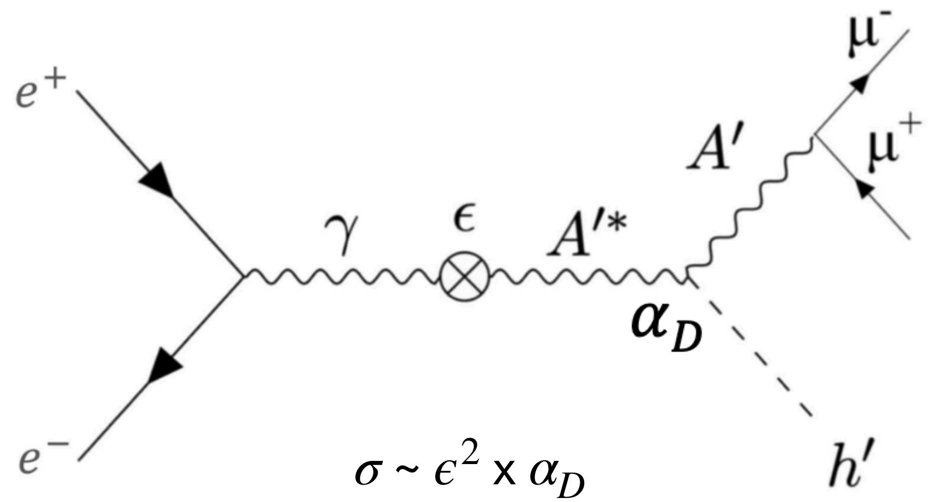
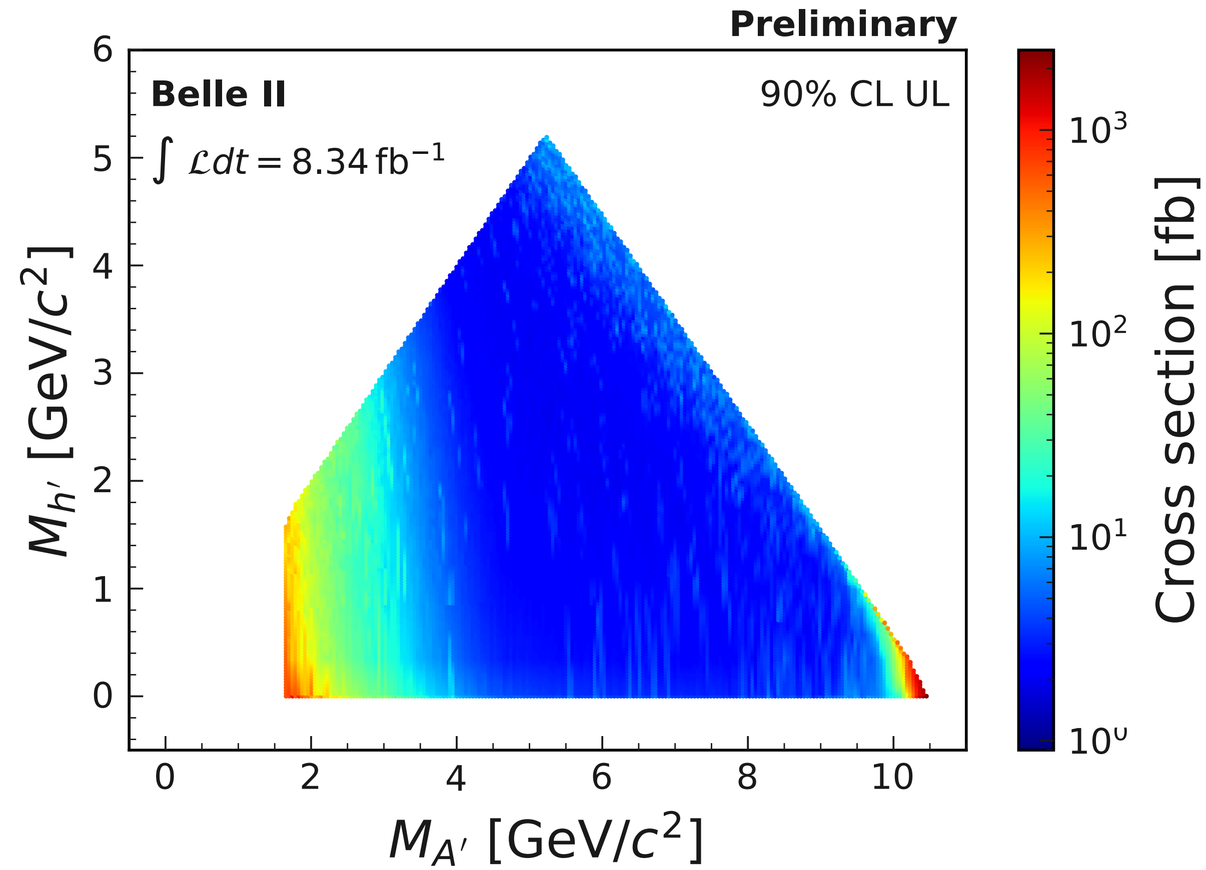
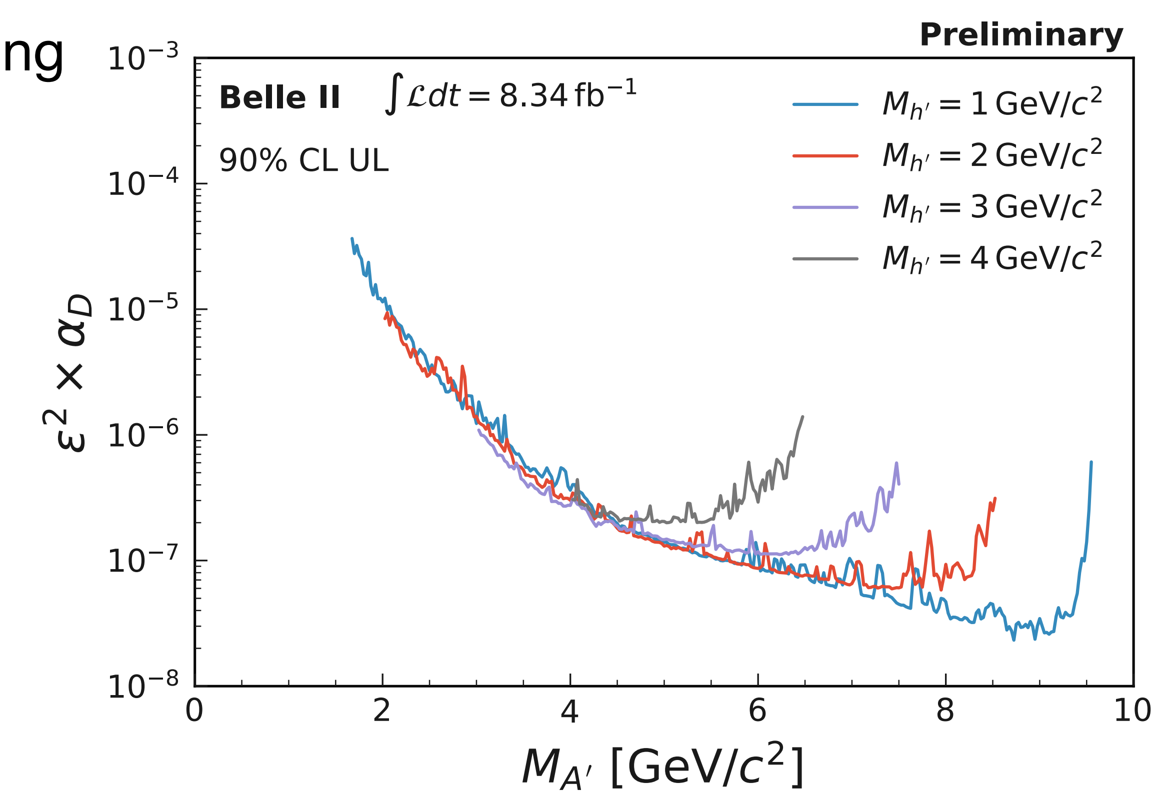




- **Signature:** Two oppositely charged muons & missing energy
- Scan for excess in 9000 elliptical mass windows within the allowed region
- Observed no excess above expected background

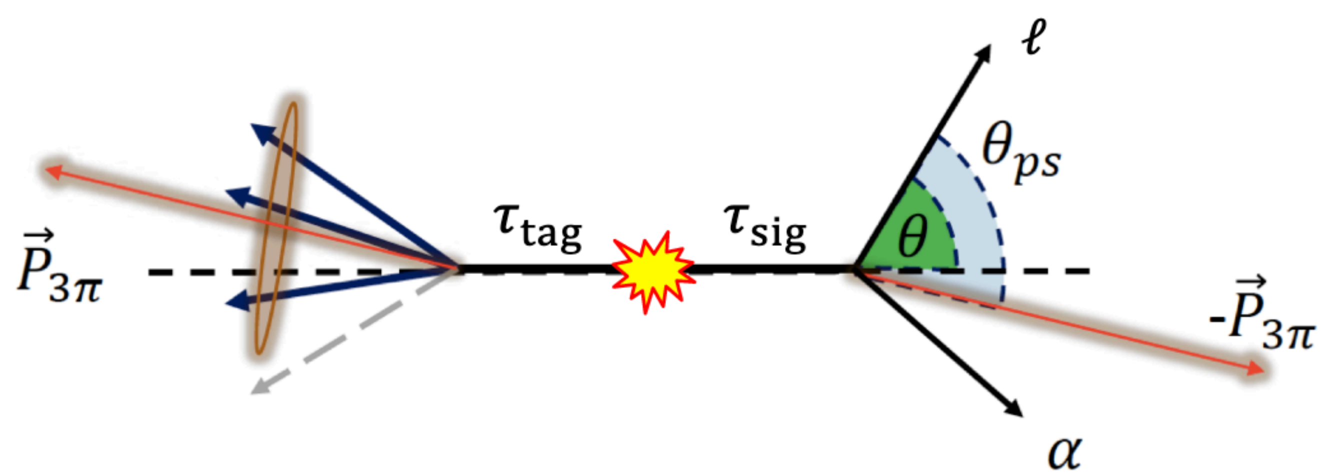


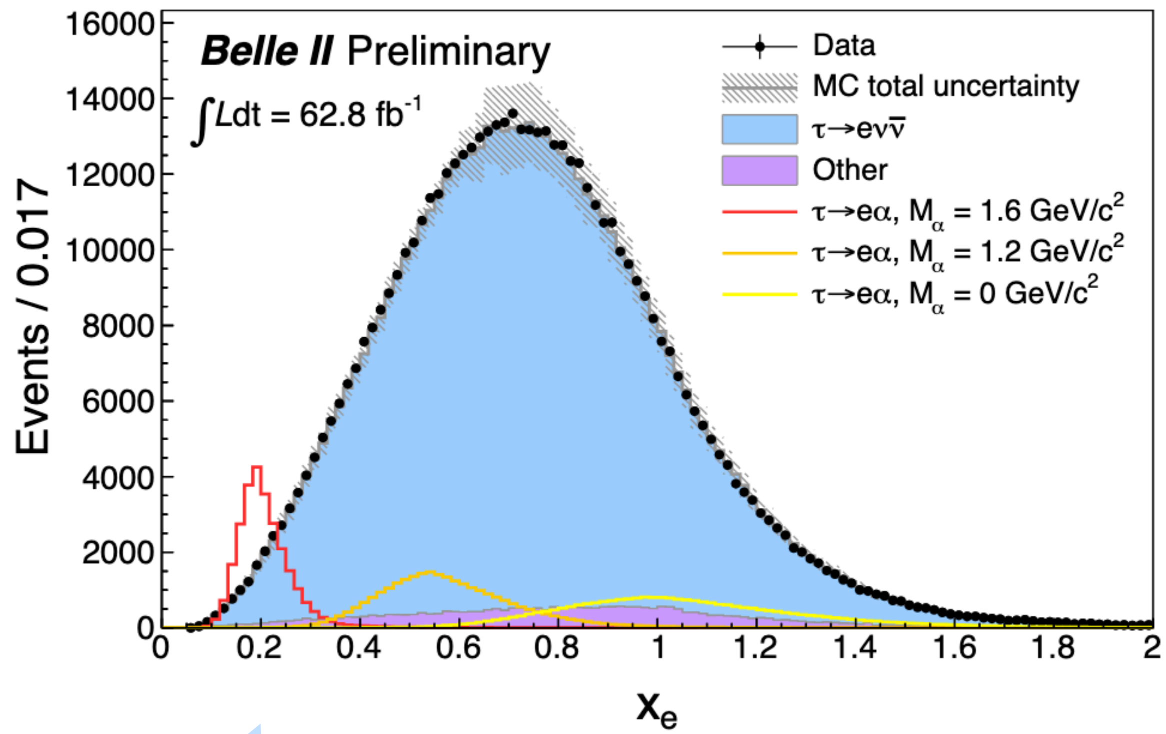
World leading limits on ϵ^2 x α_D for 1.65 < A' < 10.51 GeV/c^2

Search for $\tau^+ \to \ell^+\alpha$ (α = invisible boson)

F. Tenchini @ichep

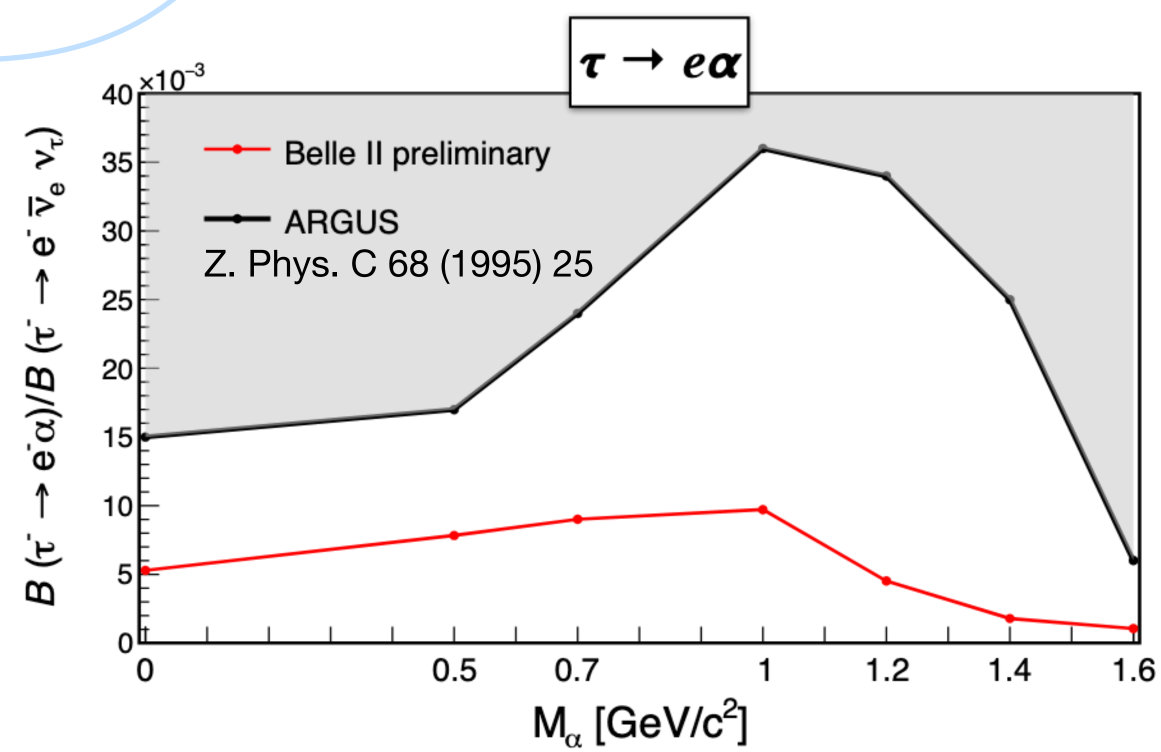
- Invisible LFV particles can emerge from new physics models e.g. light ALP JHEP 09 (2021) 173
- Tag $e^+e^- \to \tau^+\tau^-$ using $\tau \to 3\pi\nu$, then search for excess above the $\tau \to \ell\nu\nu$ spectrum





- The **event signature** is a peak in the $x_\ell \equiv E_\ell/2m_\tau$ distribution in the rest τ_{sig} frame
  - A pseudo rest frame for τ_{sig} is reconstructed from the $\vec{p}_{3\pi}$ of the τ_{tag} decays

$$(E_{\text{pseudo}}, \hat{p}_{\text{pseudo}}) = \left(\frac{E_{\text{beam}}}{2}, \frac{\sum_{3\pi}\vec{p}}{|\sum_{3\pi}\vec{p}|}\right)$$



Most stringent constraint on the BR to date!

Highlights of recent results

Belle II Physics Book

Snowmass White Paper

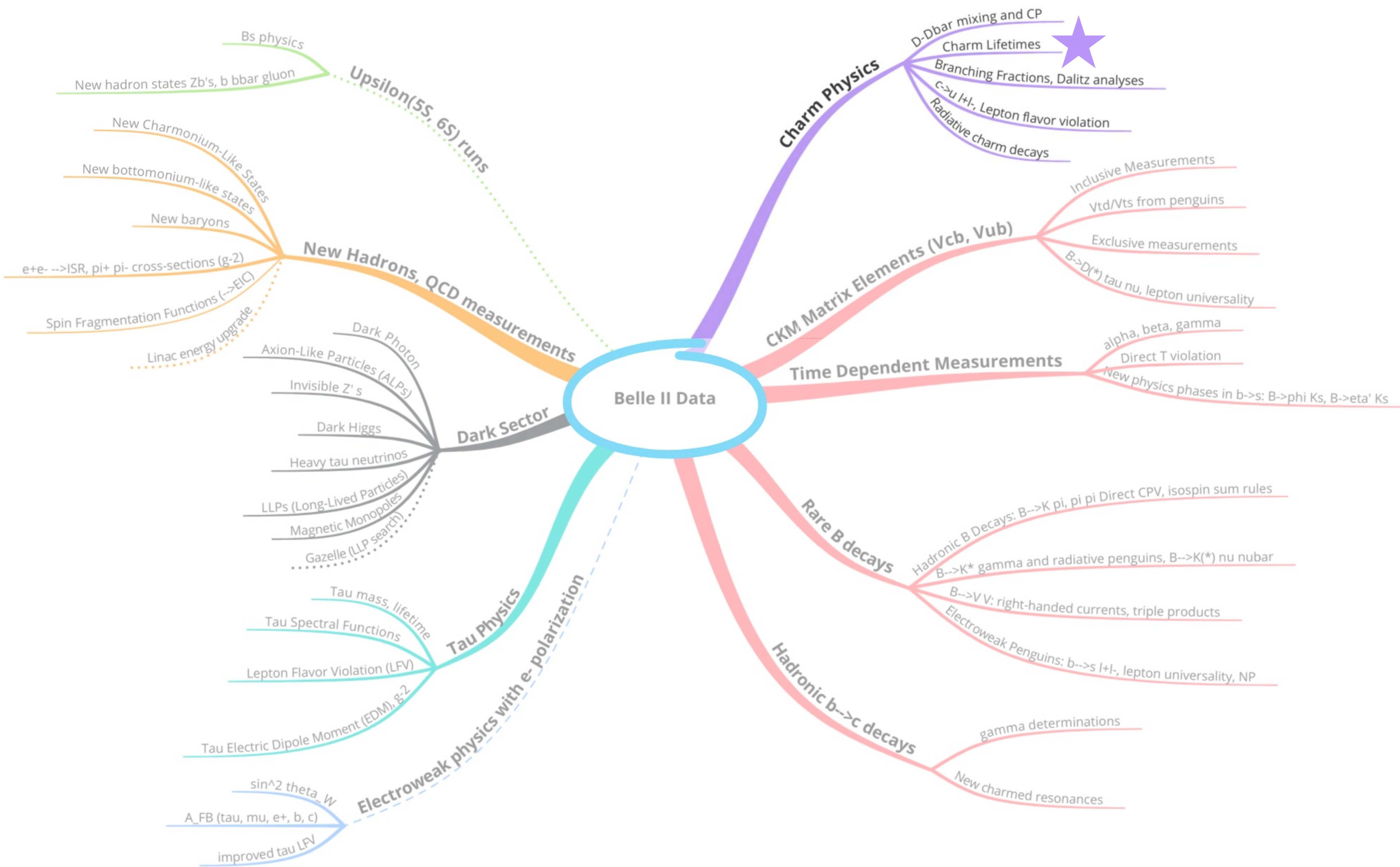
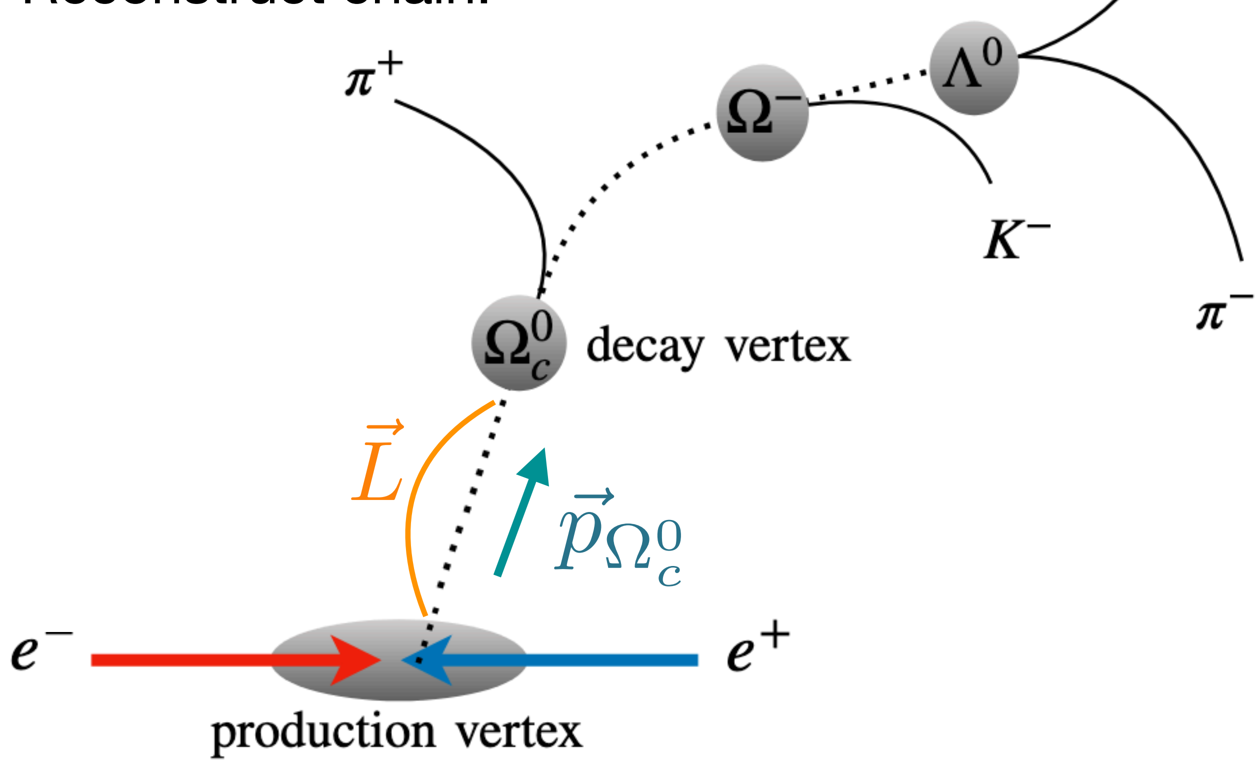


Image credit: T. Browder

Ω_c^0 lifetime measurement

arXiv:2208.08573

- Recent LHCb results have changed the hierarchy of singly charmed baryons
- Belle II analysis considers $e^+e^- \to c\bar{c}$ events taken near $\Upsilon(4S)$ resonance
- Reconstruct chain:



- Extract lifetime from a fit to (t, σ_t) where the decay time is given by:

$$t = \frac{m_{\Omega_c^0} \vec{L} \cdot \vec{p}_{\Omega_c^0}}{|\vec{p}_{\Omega_c^0}|^2}$$

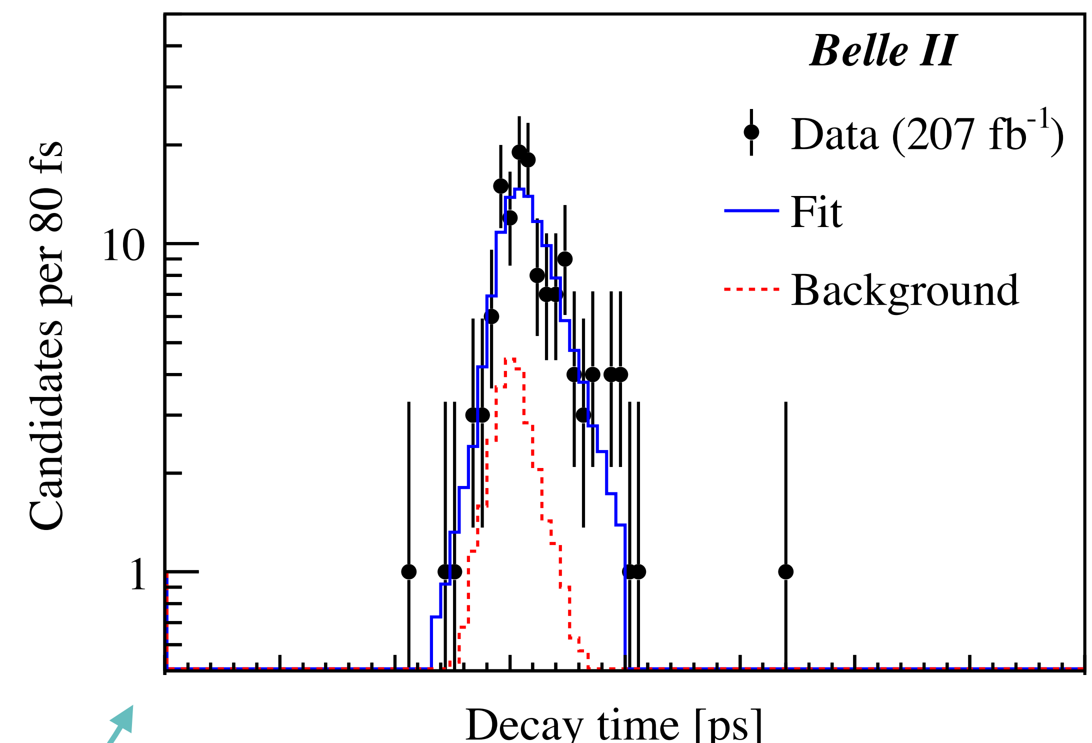
- Leading systematics: background modelling

Pre- and post-LHCb hierarchy:

$$\tau(\Omega_c^0) < \tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Xi_c^+)$$

$$\downarrow$$

$$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$$

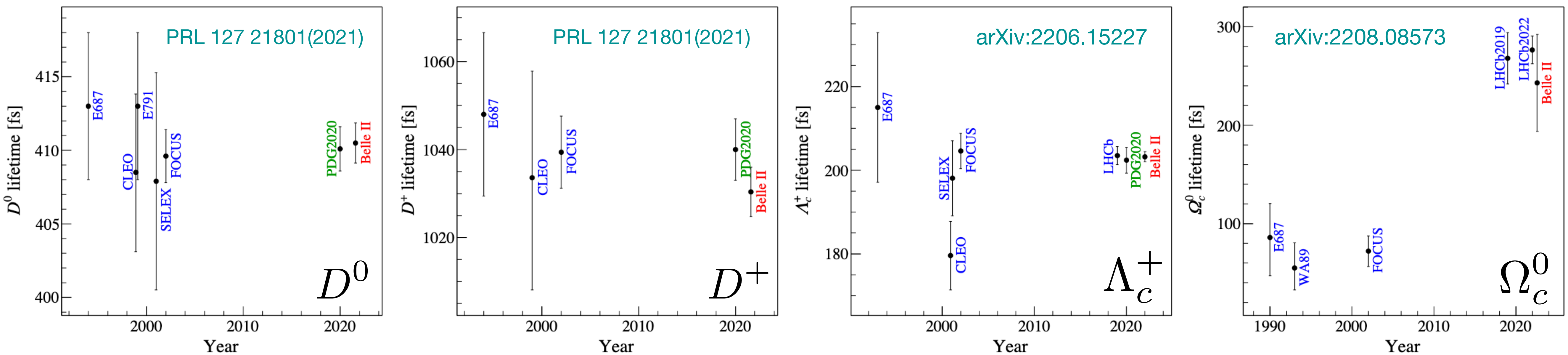


$$\tau_{\Omega_c^0} = (243 \pm 48 \pm 11)\ \text{fs}$$

Belle II confirms the LHCb results…

Charm hadron lifetimes

N. Nellikunnummel @ichep



- Absolute lifetime measurements of charm hadrons at Belle II thus far:
  - **Improved knowledge** of D lifetimes after ~20 years
  - **World's most precise measurements** of D^0, D^+ and Λ_c^+ lifetimes
  - **Independent confirmation** of LHCb's result indicating that Ω_c^0 is not the shortest-lived weakly decaying charm baryon
- Results limited by statistics expected to **improve with larger samples** and **additional decay modes**
- Tiny systematic uncertainties (e.g., sub-% for D^0) establish **excellent detector performance**
- **Paves the way for future lifetime measurements…**

Highlights of recent results

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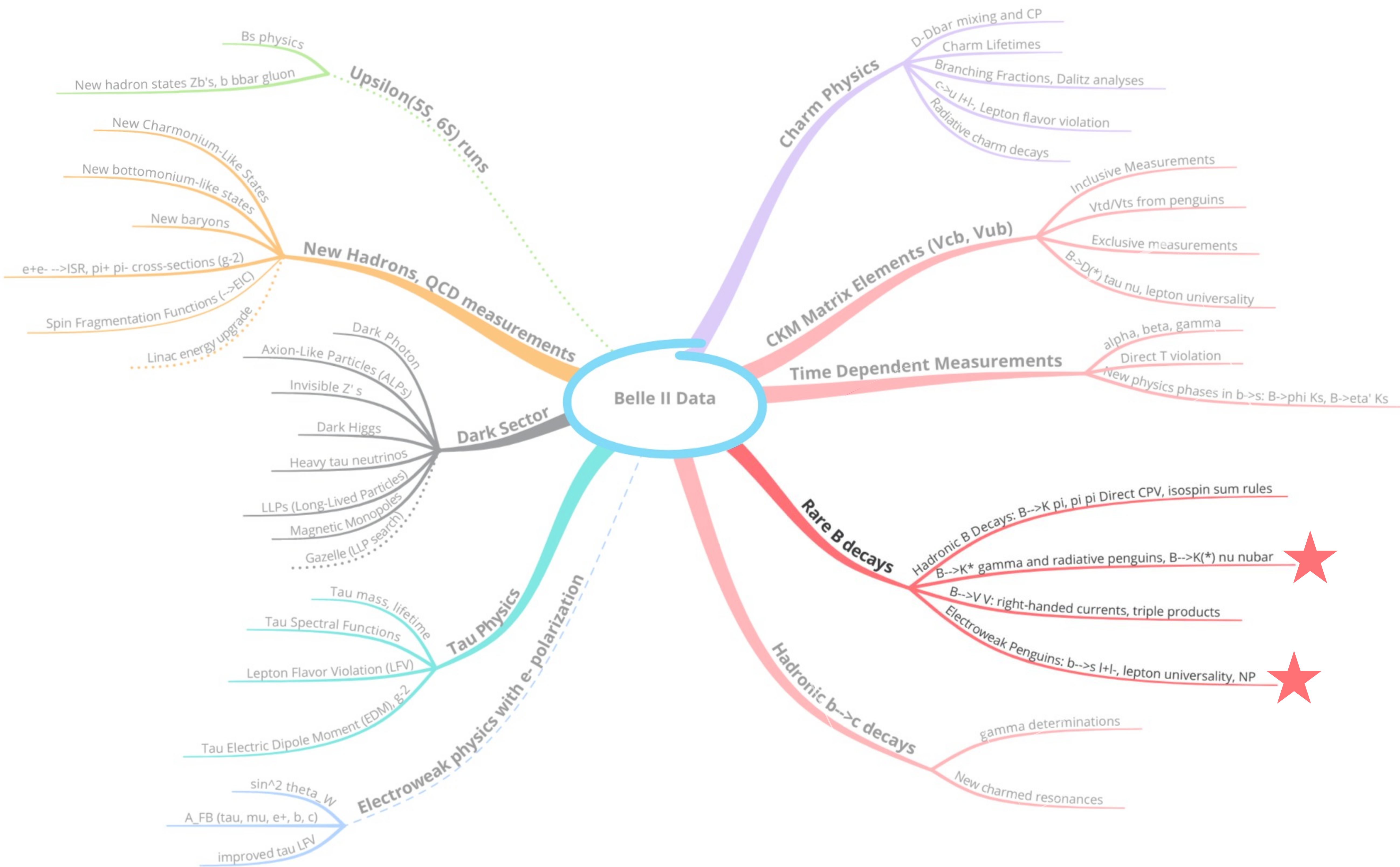

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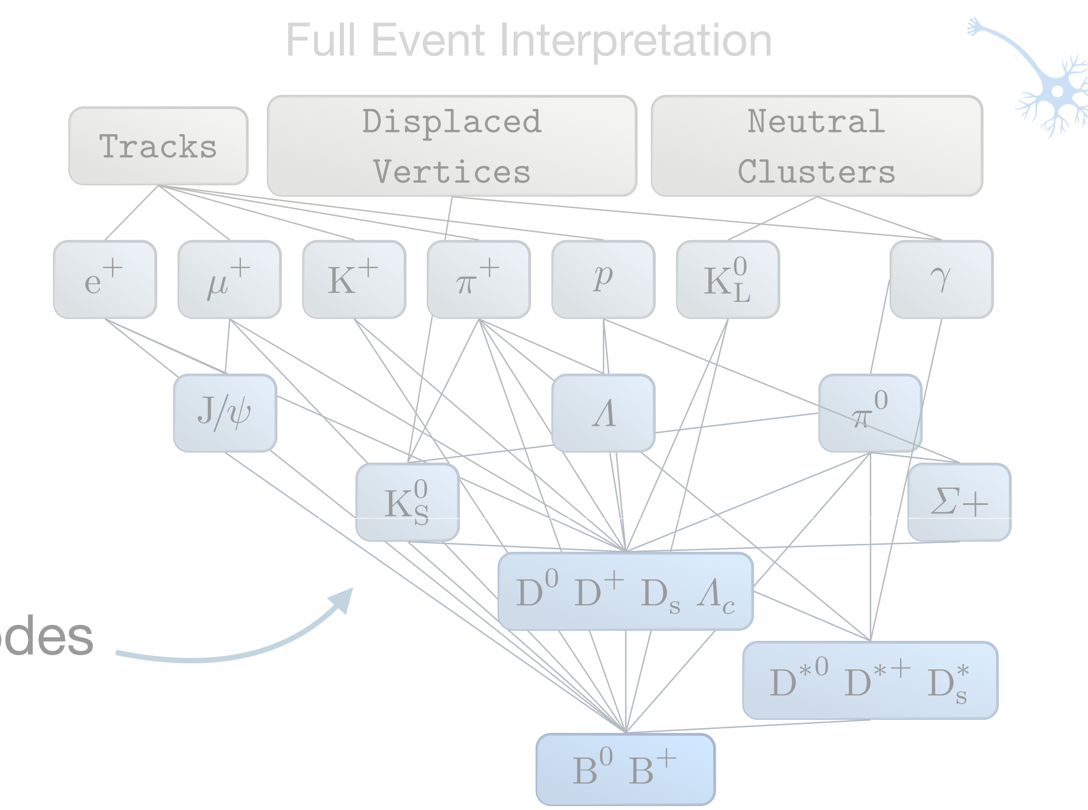
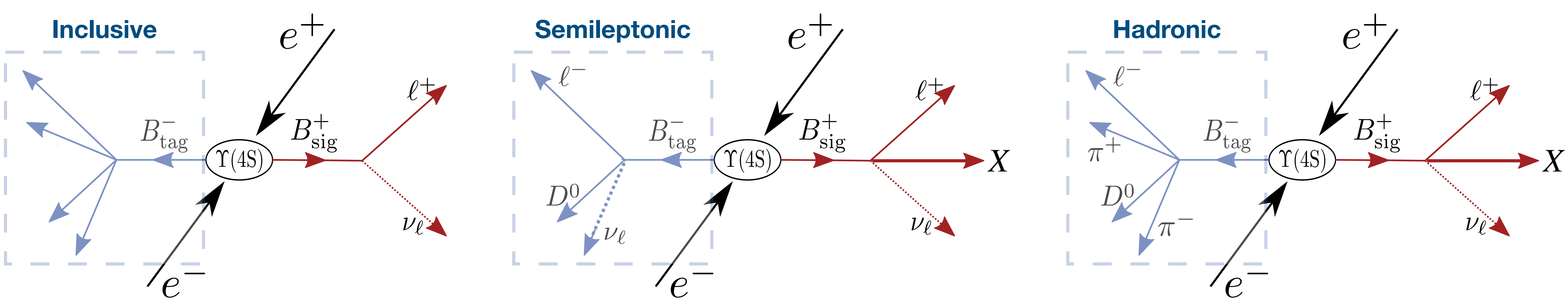
Reconstruction techniques

arXiv:1807.08680

- Decays with **missing final state particles** are experimentally challenging to reconstruct
- Exploit Belle II's **unique event topology**:
  - Information from companion B meson (B_{tag}) and conservation laws provide insights about signal B
- **Tagged approaches** reconstruct candidates with a hierarchical multivariate technique via $\mathcal{O}(10^3)$ decay modes
  - Small efficiency compensated by large integrated luminosity





$\epsilon = \mathcal{O}(100)\%$ Tagging efficiency, backgrounds $\epsilon = \mathcal{O}(0.1)\%$

Purity of tagged samples, available observables

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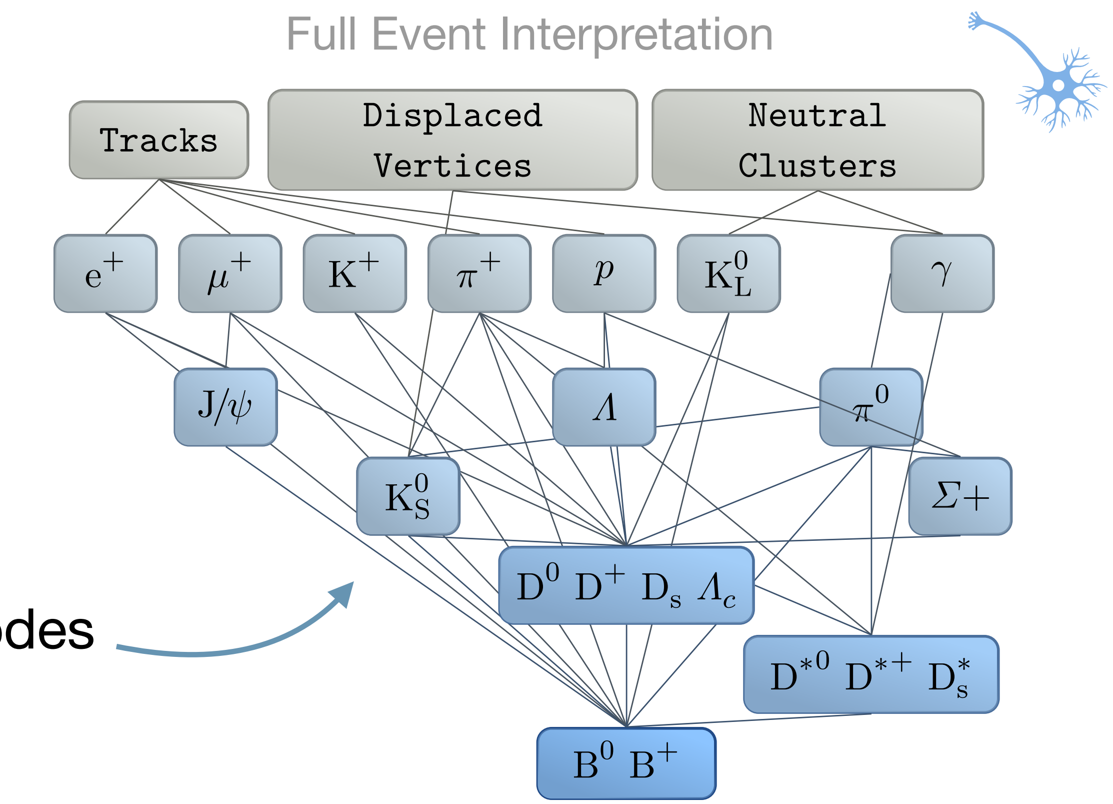

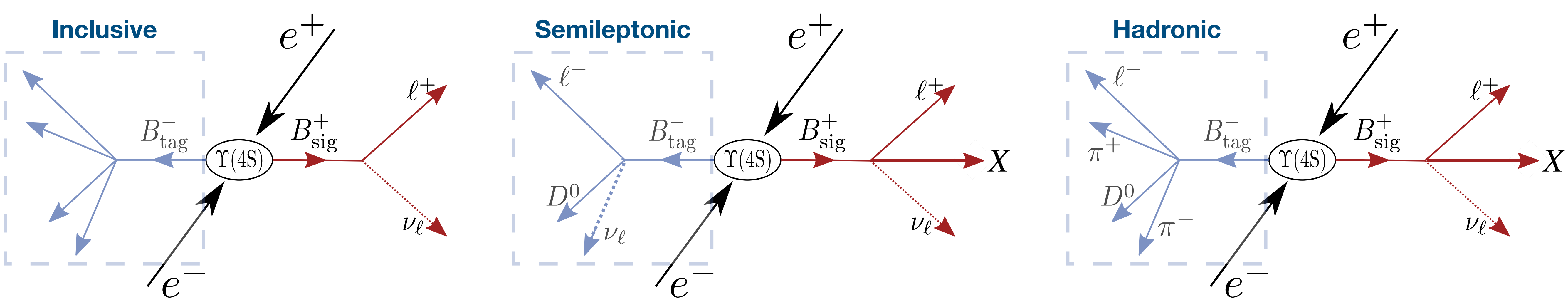

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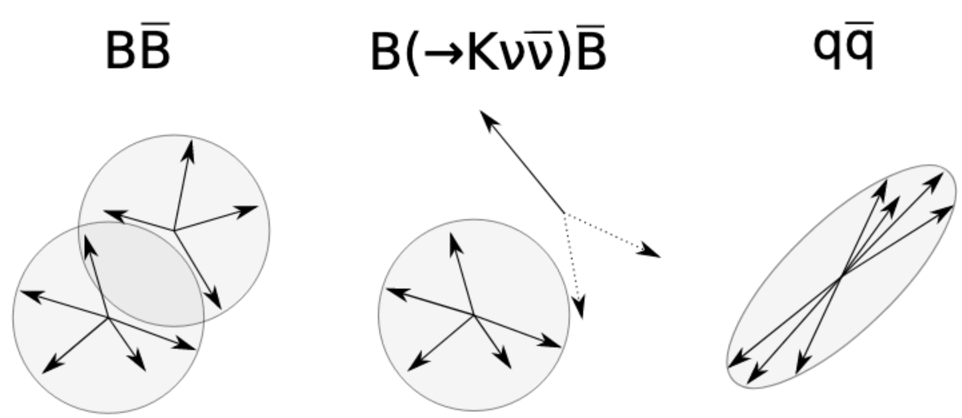
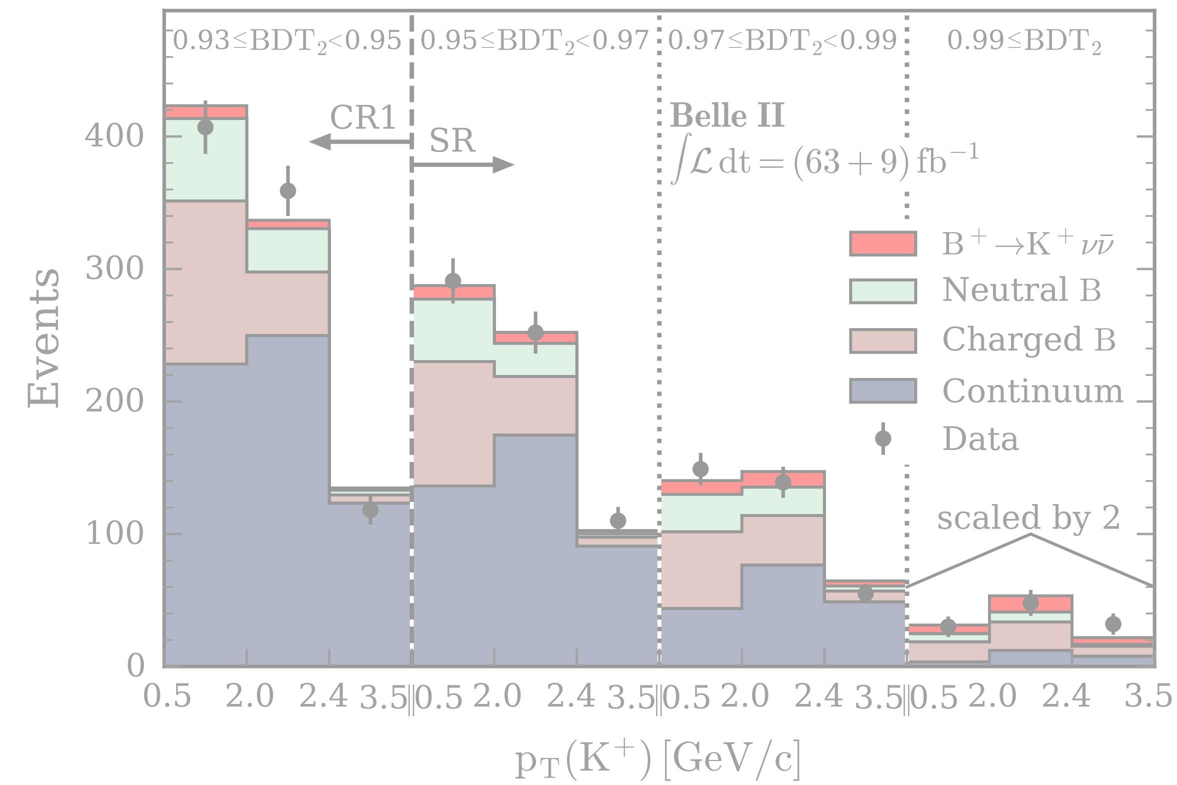
Purity of tagged samples, available observables

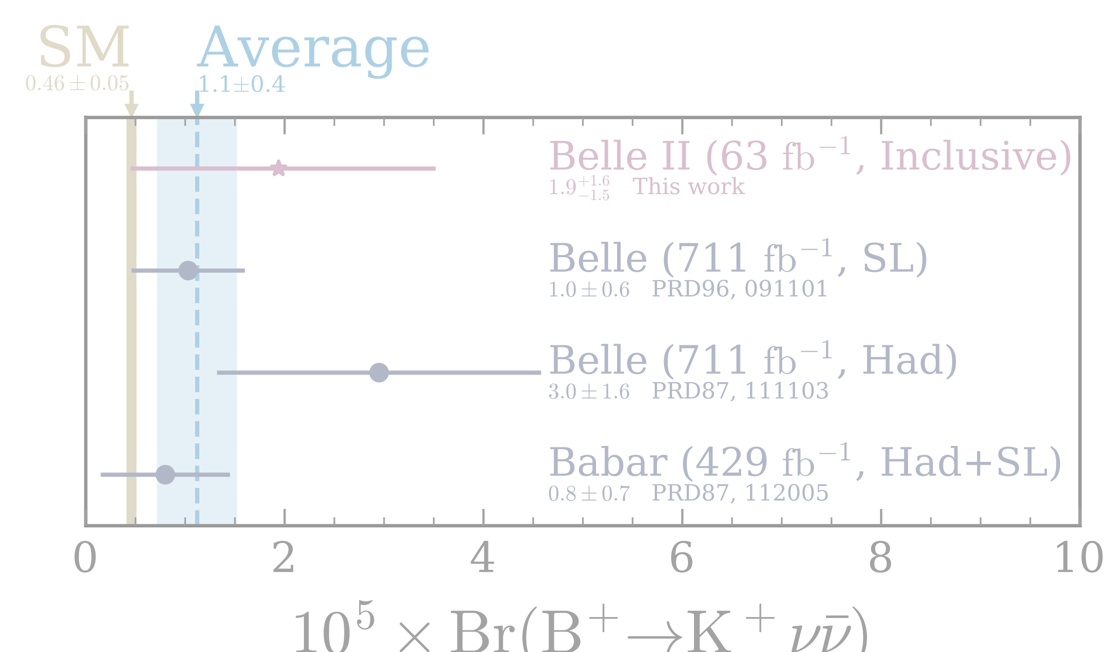
Search for $B^+ \to K^+ \nu\bar{\nu}$

PRL 127, 181802 (2021)

- Challenging due to **multiple missing particles** on the signal side
- New analysis strategy based on an **inclusive reconstruction** approach
- **Increased signal efficiency** ϵ_{sig} ~ 4% but larger background contributions
- Exploit distinctive topological features with BDTs to **select events and suppress backgrounds**







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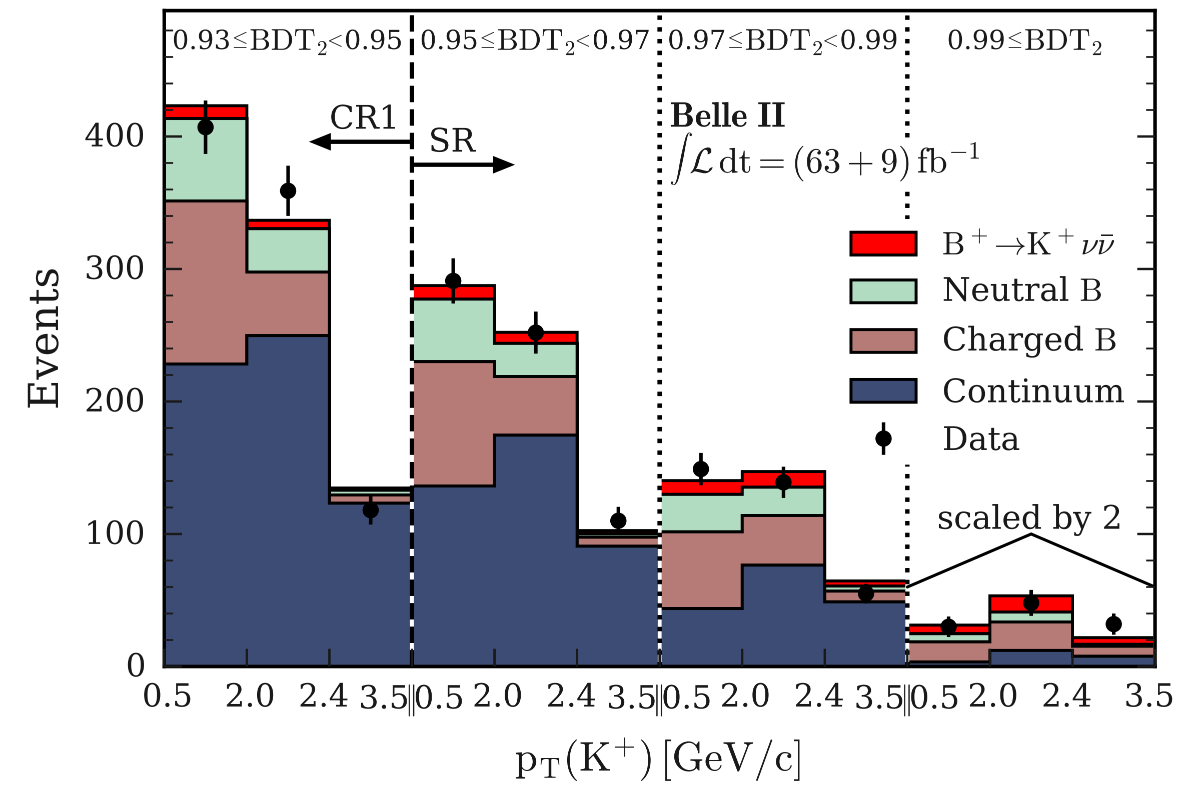

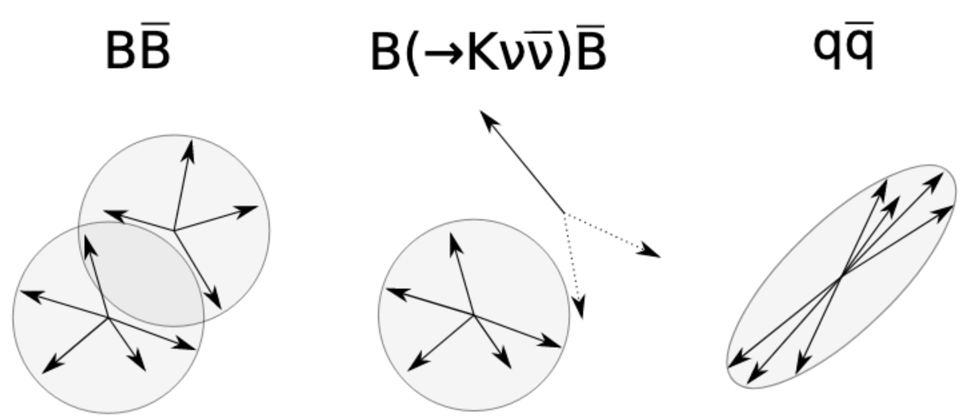

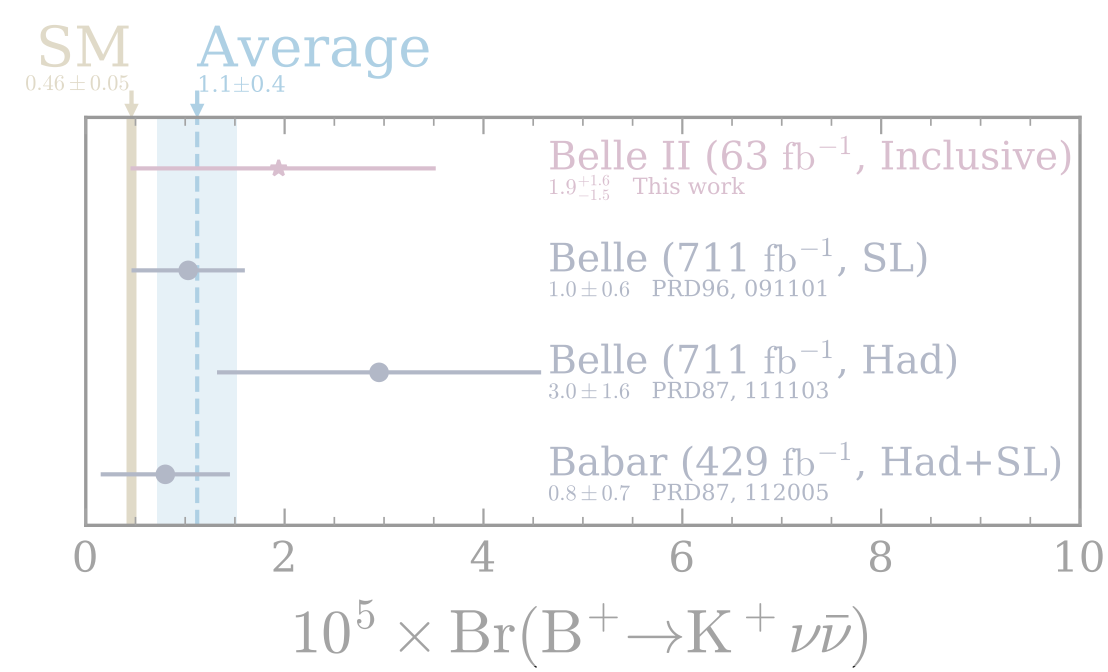

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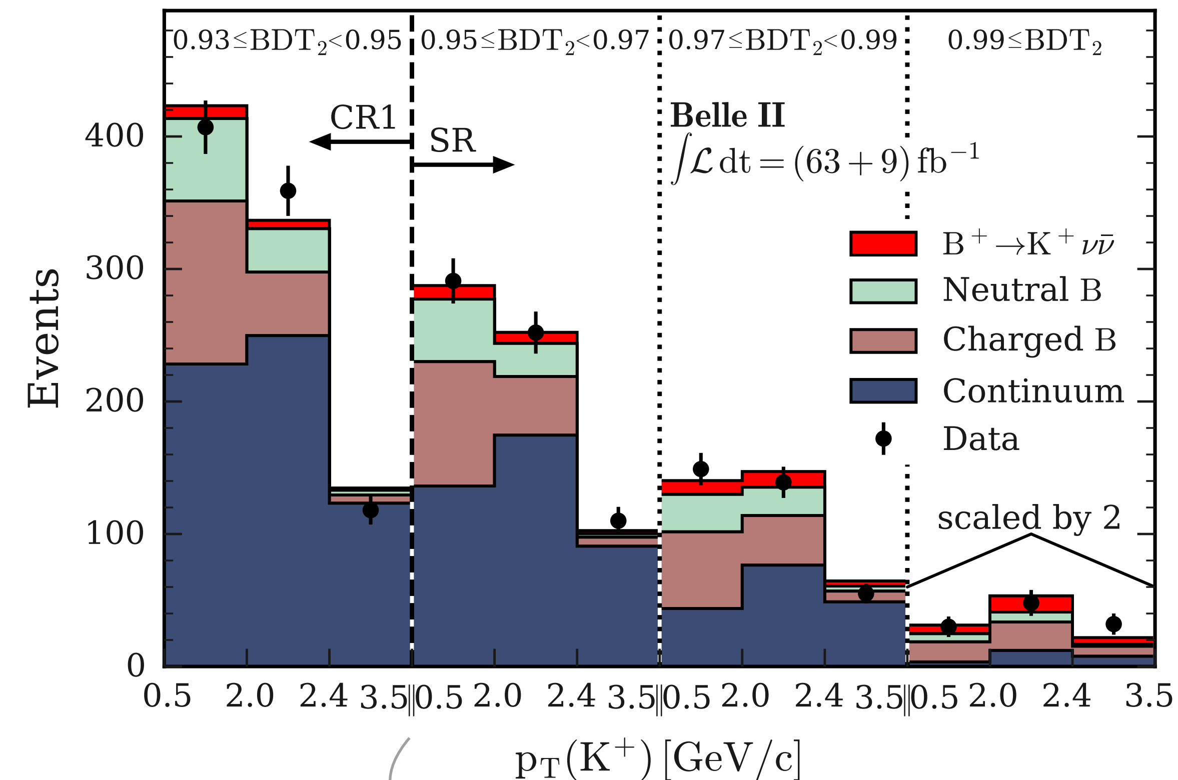
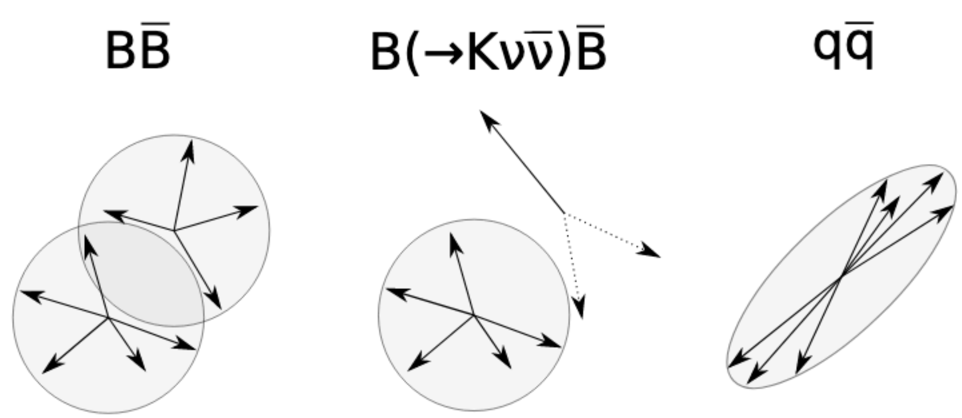
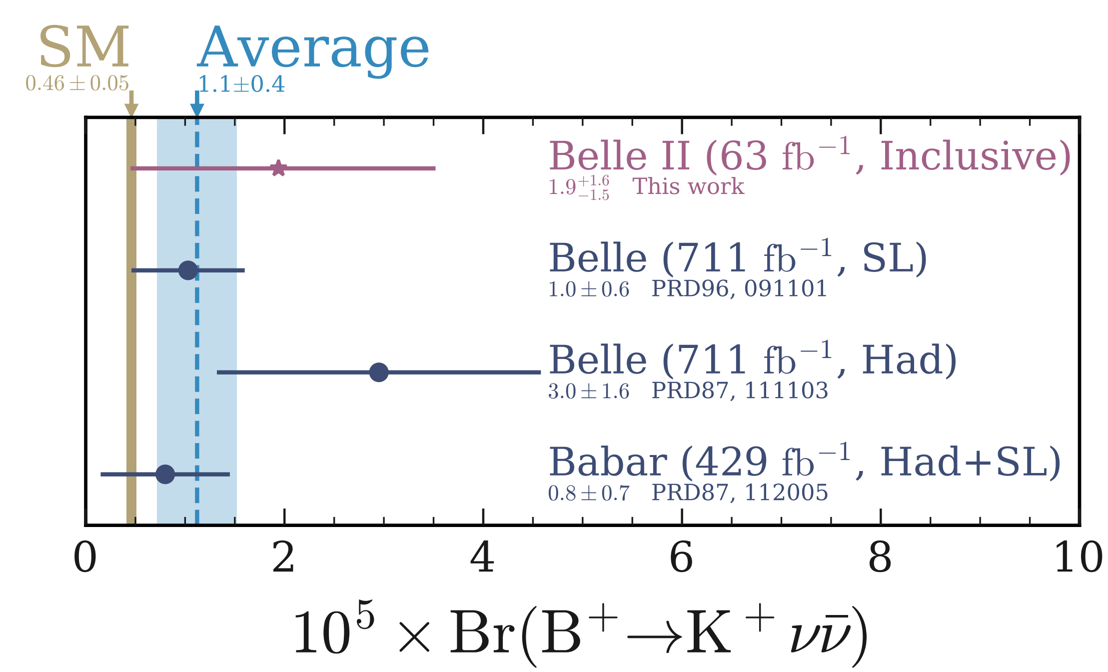


No excess excess above expected background





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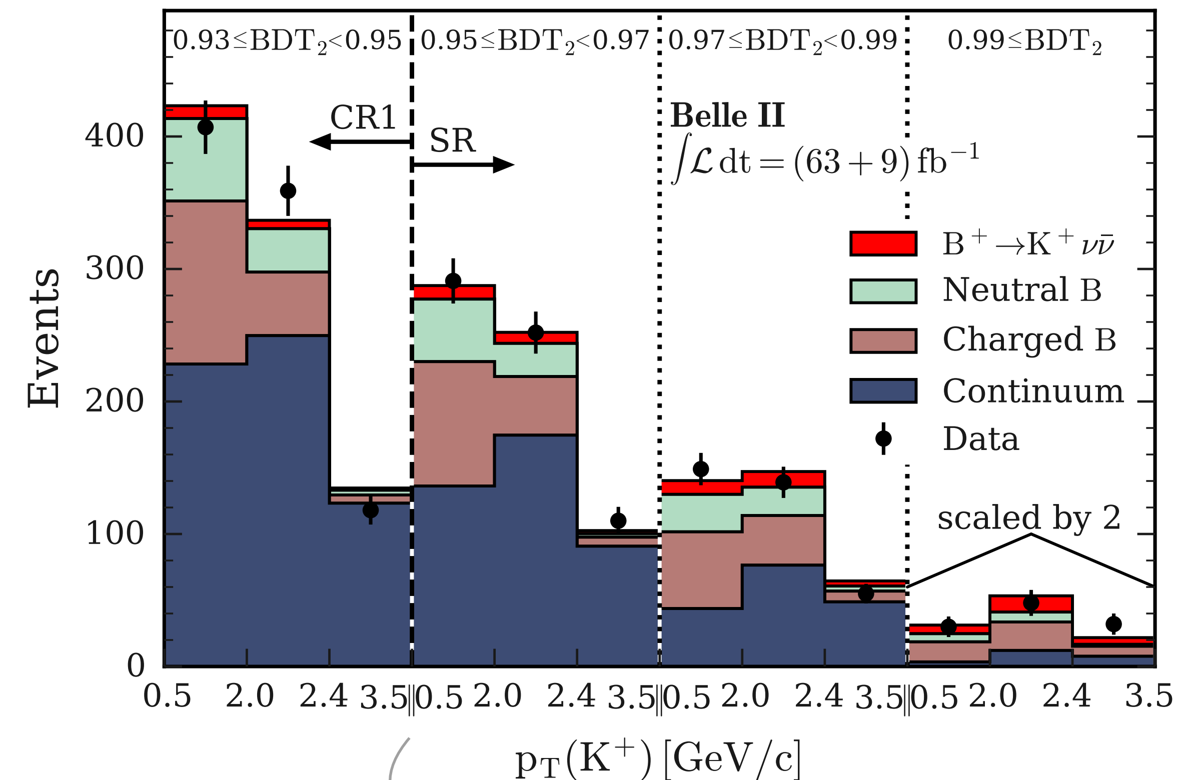

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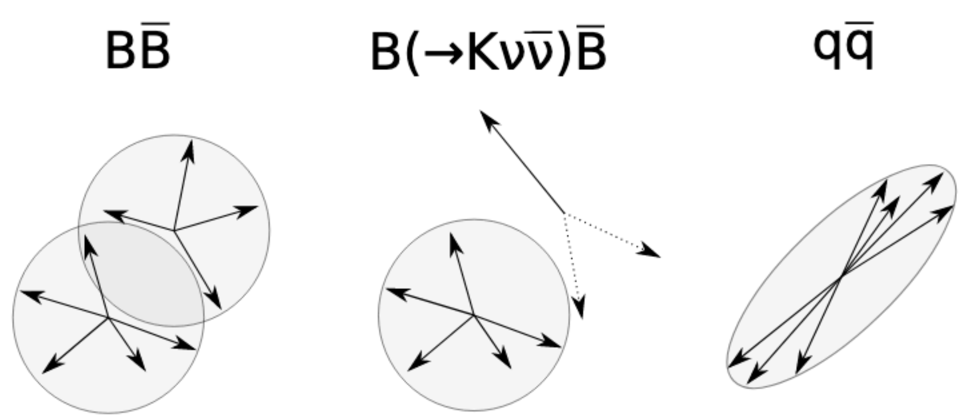
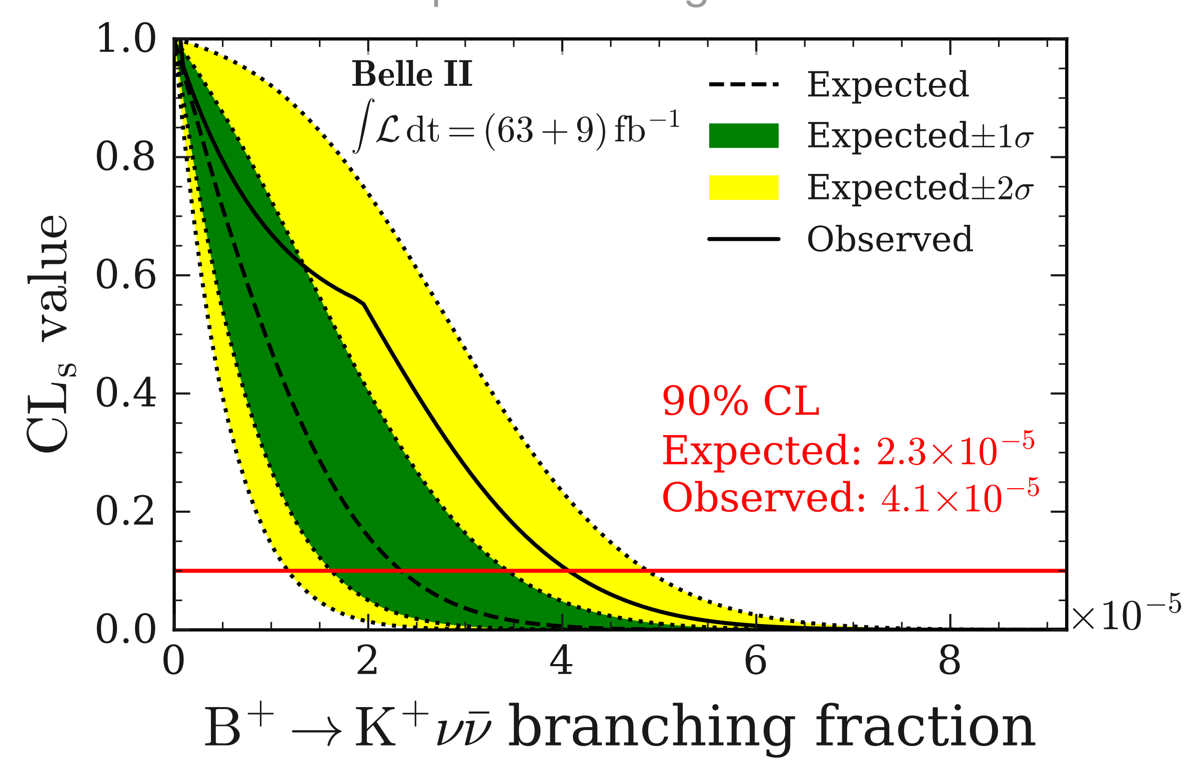




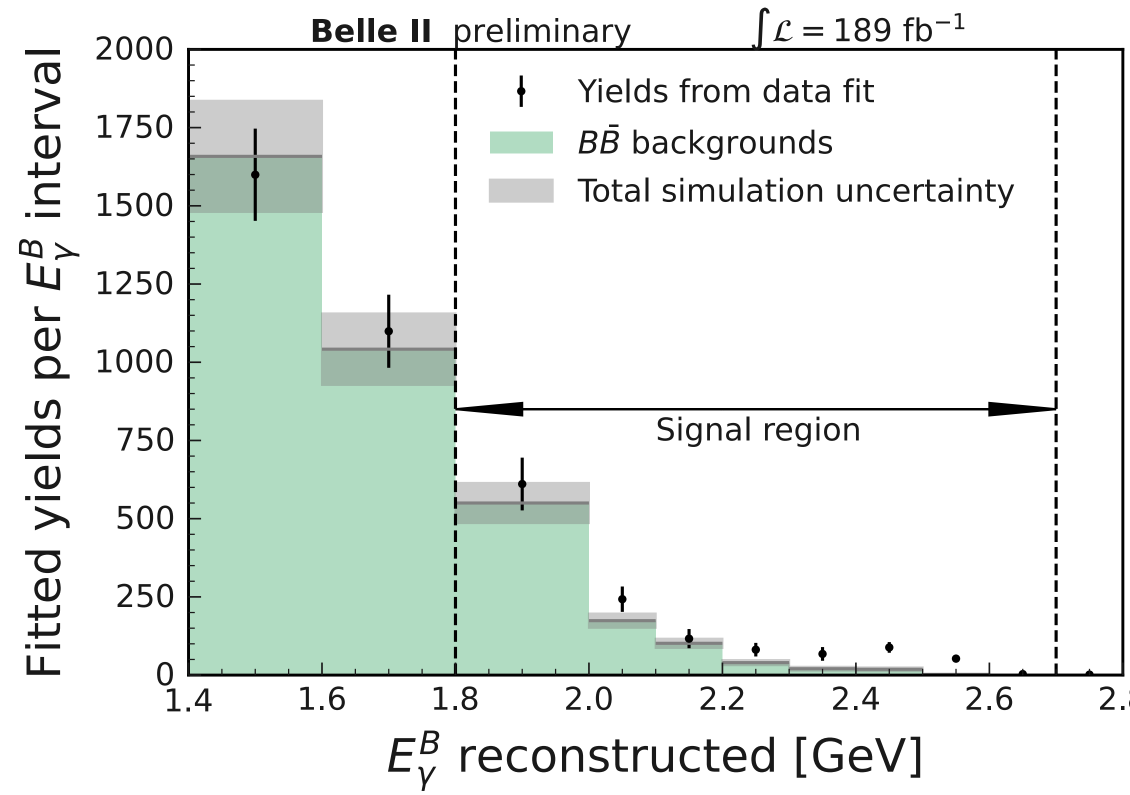
- **Further improvements are underway:**
  - Extend/improve classifiers using neural networks
  - Additional channels (e.g., $B^0 \to K^{*0}\nu\bar{\nu}$)
  - More data!

Branching fraction of $B \to X_s\gamma$

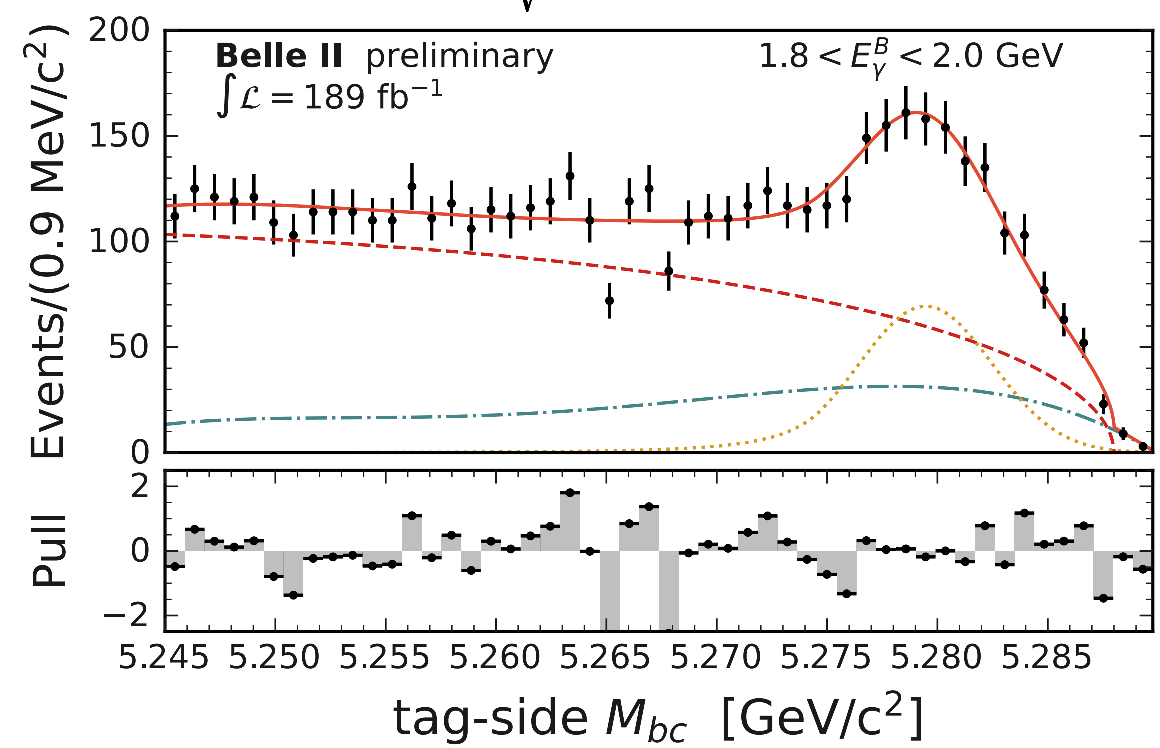
arXiv:2210.10220

Inclusive analysis:
Consider all $b \to s\gamma$ final states

- Reconstruction with **hadronic tagging** allows for access to photon energy in B rest frame E_γ^B
- **Large backgrounds** challenging to suppress without sacrificing "inclusiveness"
- Subtract background with **two-step procedure**:
  1. Fit the tag-side beam constrained mass M_{bc} to determine well-reconstructed B_{tag} candidates



$$M_{bc} = \sqrt{E_{\text{beam}}^2 - p_B^{*2}}$$



Branching fraction of $B \to X_s\gamma$

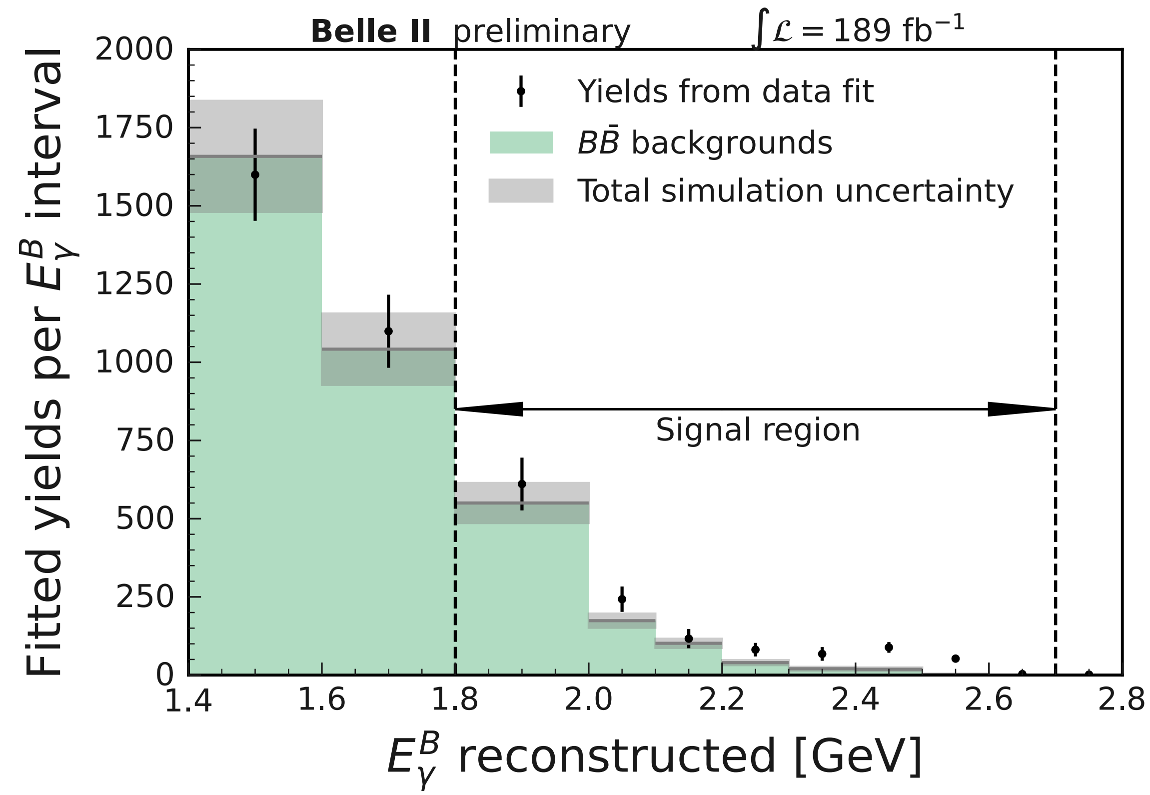
arXiv:2210.10220

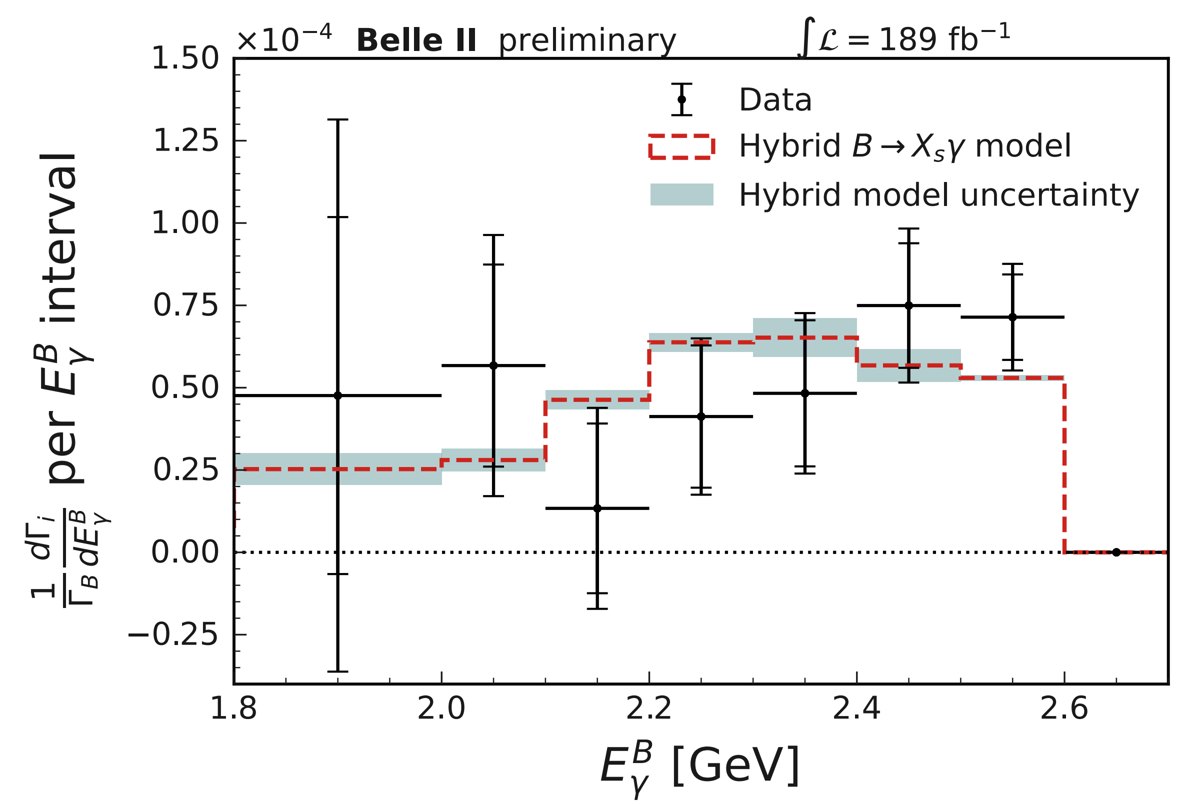
Inclusive analysis:
Consider all $b \to s\gamma$ final states

- Reconstruction with **hadronic tagging** allows for access to photon energy in B rest frame E_γ^B
- **Large backgrounds** challenging to suppress without sacrificing "inclusiveness"
- Subtract background with **two-step procedure**:
  1. Fit the tag-side beam constrained mass M_{bc} to determine well-reconstructed B_{tag} candidates
  2. Subtract $B\bar{B}$ background with a good B_{tag}

E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ $[10^{-4}]$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)
2.1	2.49 ± 0.46 (stat.) ± 0.35 (syst.)

Comparable precision with BaBar!





Highlights of recent results

Belle II Physics Book

Snowmass White Paper

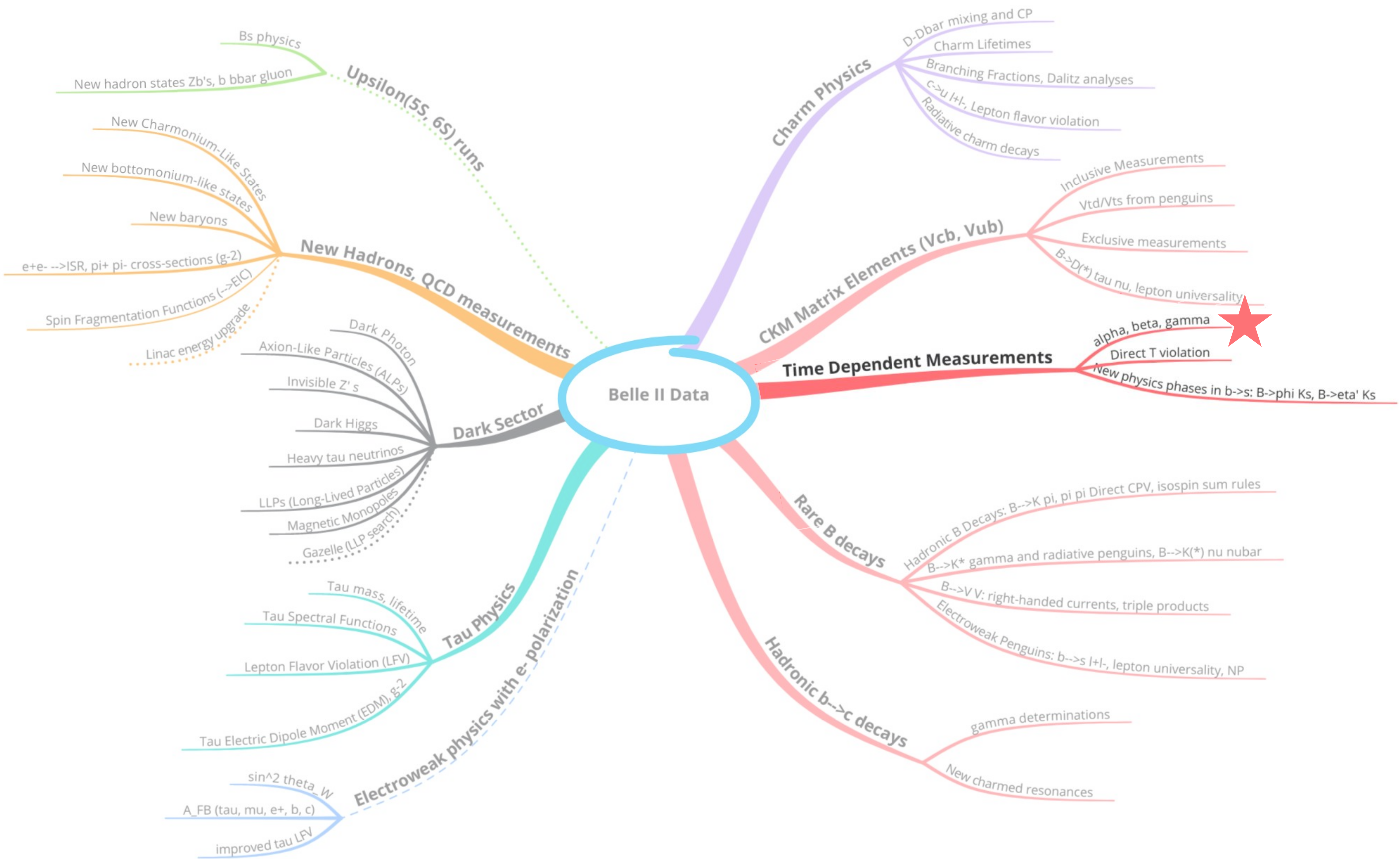


Image credit: T. Browder

CKM Unitarity triangle

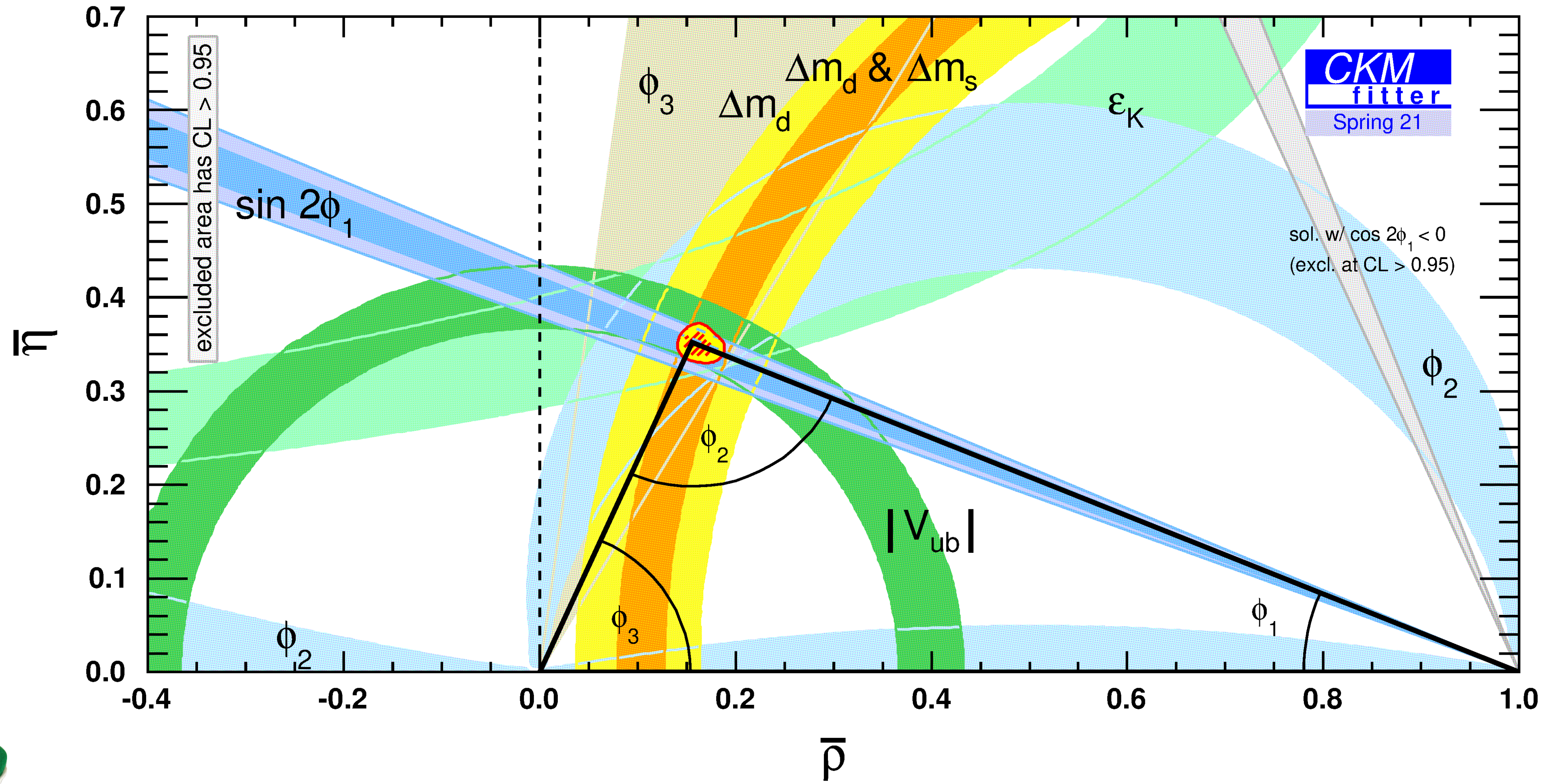
Overconstrain Unitarity condition

→ A potent test of Standard Model

$CC^\dagger = 1$

$$V_{ud}V_{ub}^* + V_{td}V_{tb}^* + V_{cd}V_{cb}^* = 0$$

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$



Almost all information on UT sides and angles comes from B-physics…

Measuring ϕ_1: time dependent analyses

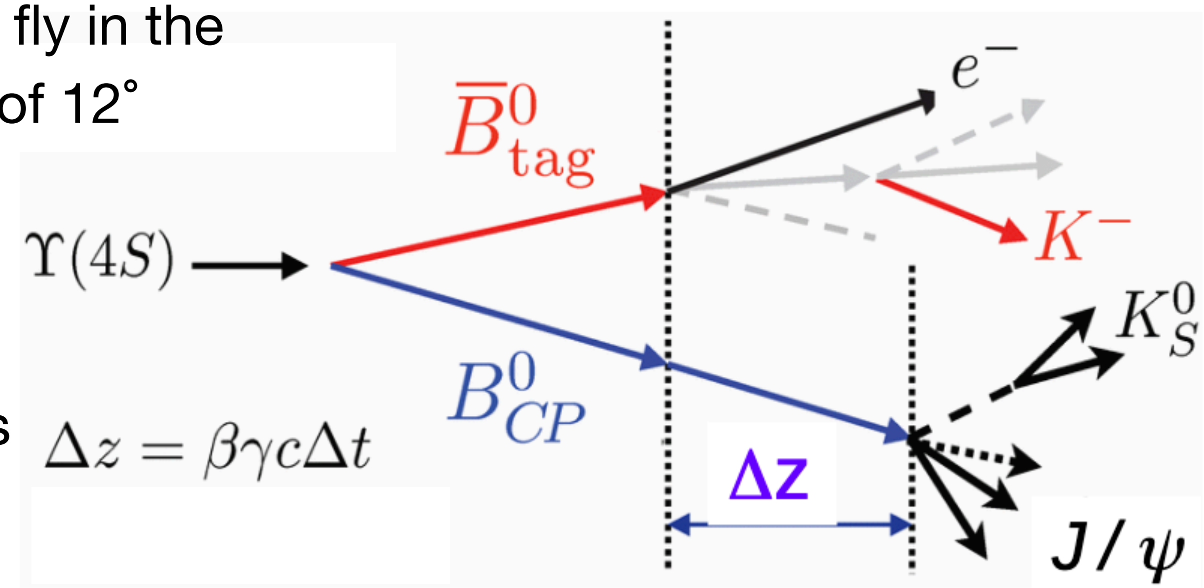
Time-dependent decay rate:

$$\Gamma(\Delta t, q; B_{CP} \to f_{CP}) \propto \exp\left(-\frac{|\Delta t|}{\tau_{B^0}}\right)\left[\mathcal{A}\cos(\Delta m_d \Delta t) + q\mathcal{S}\sin(\Delta m_d \Delta t)\right]$$

- Δt ... signed difference of the two B decay times
- q ... flavor of the B: $B^0(q{=}-1)$ or $\bar{B}^0(q{=}+1)$

τ_{B^0}: B^0 lifetime
Δm_d: B^0-$\bar{B}^0$ mixing
$\mathcal{A}$: direct CPV
$\mathcal{S}$: mixing-induced CPV
$\mathcal{S} = \sin 2\phi_1$ in the SM for $b \to c\bar{c}s$

- Due to the **asymmetric beam energies** B mesons fly in the direction of the e^- beam with a maximal deviation of 12°
- B^0_{CP}: fully reconstructed flavour eigenstate
- $\bar{B}^0_{tag}$: provides vertex and flavour information
  - Dedicated **flavour tagging algorithm** identifies $\bar{B}^0_{tag}$ flavour using all particles not belonging to B^0_{CP}
  - **Precise vertex reconstruction** provides crucial knowledge of Δt resolution



<Δz> ~ 130 μm at Belle II

$$\Delta t = \frac{(\vec{v}_{CP} - \vec{v}_{tag}) \cdot \vec{n}_{\text{boost}}}{\gamma\beta c}$$

Image credit: J. Skorupa

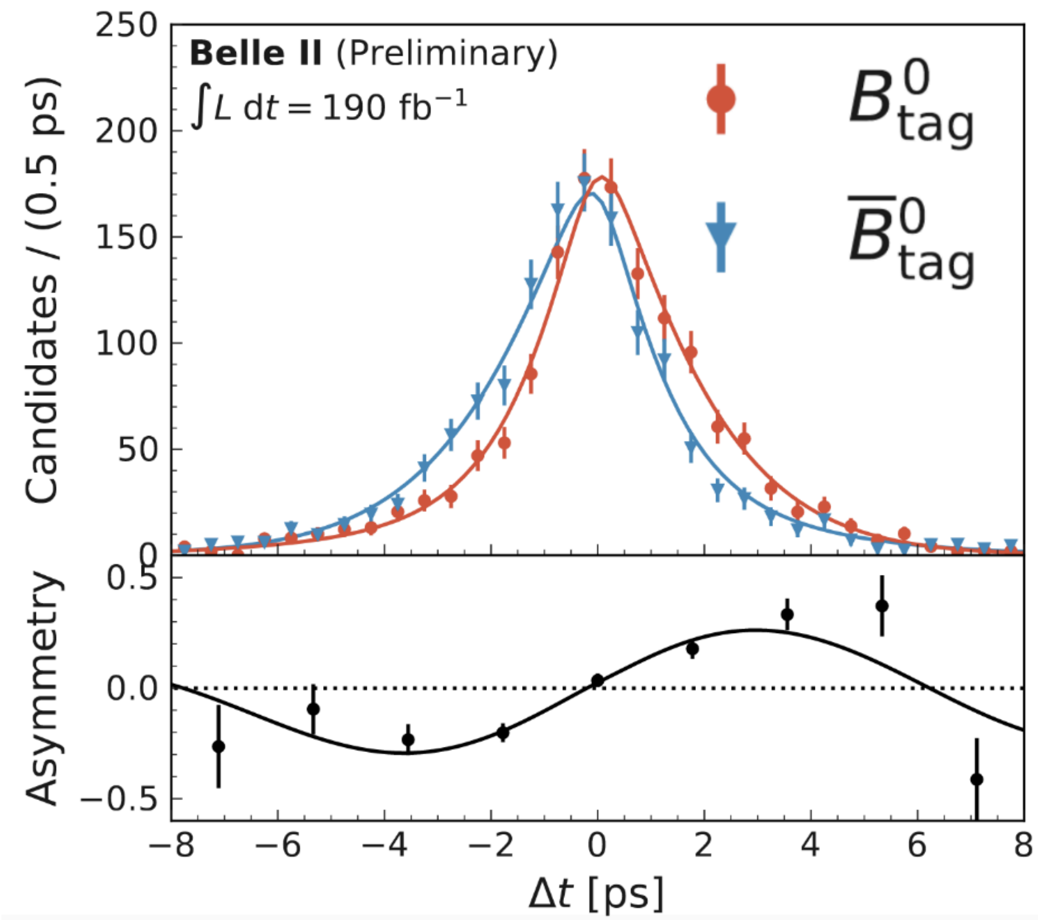
Measuring ϕ_1

C. La Licata @ichep

$B^0 \to J/\psi K_s^0$

- Golden channel for sin $2\phi_1$ measurement, largely background free
- Resolution function parameters calibrated with $B \to D^{(*)-}\pi^+$ events
- Subtract background by fitting $\Delta E = E_B^* - E_{\text{beam}}$
- K_L and other $c\bar{c}$ resonances to be added

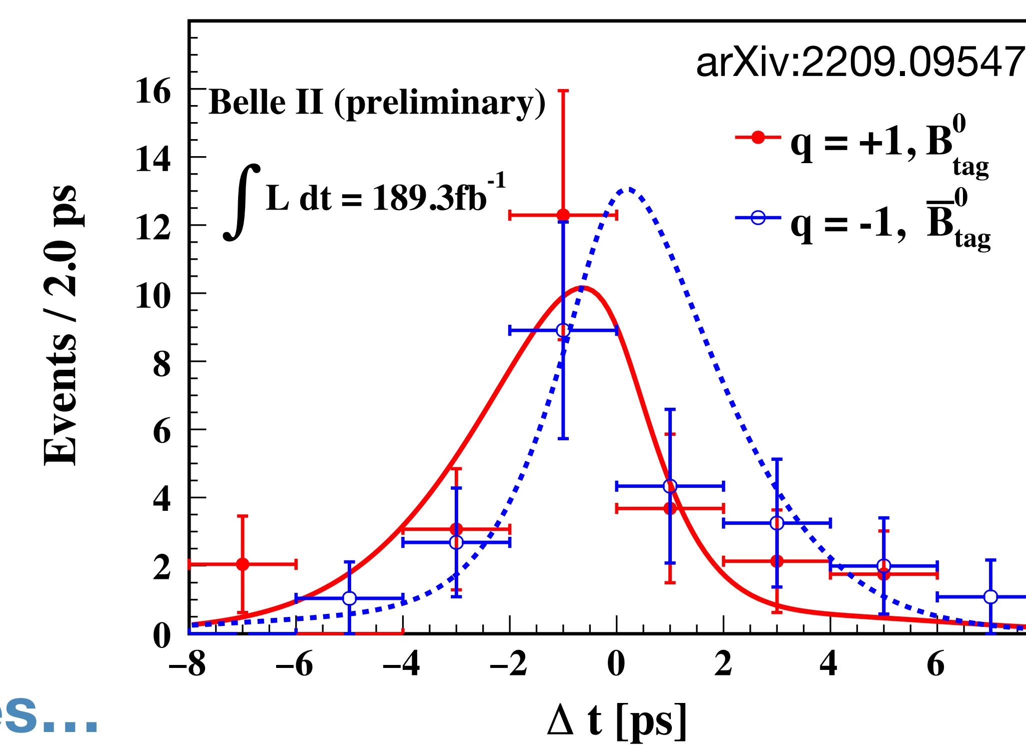
$$\mathcal{S} = 0.720 \pm 0.062 \pm 0.016$$
$$\mathcal{A} = 0.094 \pm 0.044^{+0.042}_{-0.017}$$



$B^0 \to K_s^0 K_s^0 K_s^0$

- Challenging vertexing with no prompt tracks
  - Only reconstruct $K_s \to \pi^+\pi^-$ and extrapolate back
- Extract signal from simultaneous fit: background suppression BDT, $M_{K_sK_sK_s}$ and M_{bc}

$$\mathcal{S} = -1.86^{+0.91}_{-0.46} \pm 0.09$$
$$\mathcal{A} = -0.22^{+0.30}_{-0.27} \pm 0.04$$



Both analyses dominated by statistical uncertainties…

Measuring ϕ_2: $B^0 \to \pi^0\pi^0$

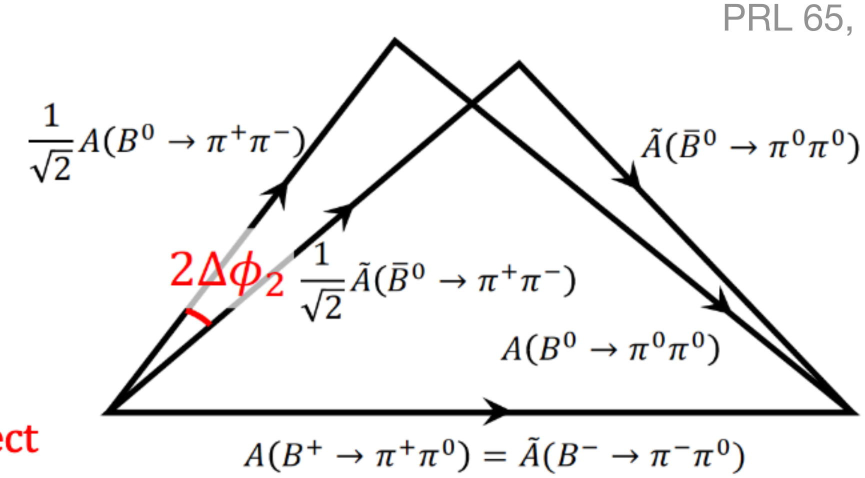
J. Skorupa @ichep

$\mathcal{A}_{\pi\pi}$ ($B \to \pi\pi$ mediated by $b \to u\bar{u}d$ tree) is an essential input to determine ϕ_2.

- $\mathcal{S}_{\pi\pi} = -\eta_{CP}\sqrt{1-\mathcal{A}_{\pi\pi}^2}\,\sin(2\phi_2 + 2\Delta\phi_2)$.

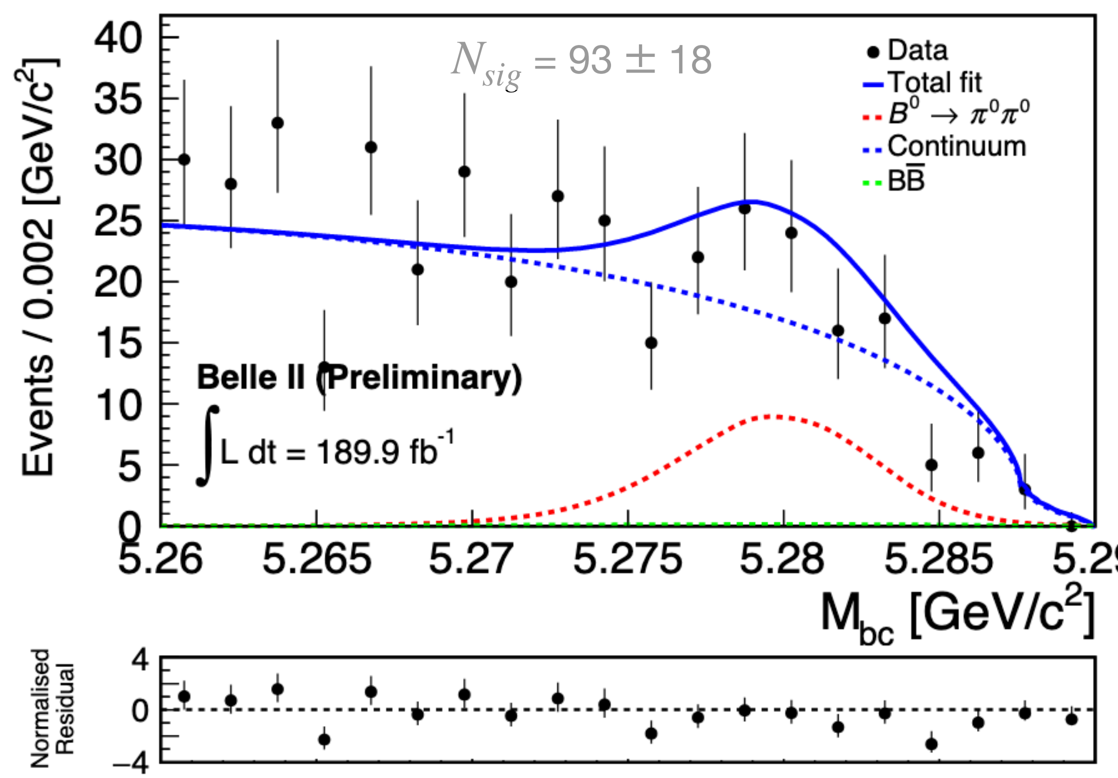
$b \to d u\bar{u}$ loop effect

PRL 65, 3381 (1990)



- Most challenging $\pi^0\pi^0$ mode, very hard for LHCb
- Suppress photon background with dedicated MVA to ensure pure $\pi^0 \to \gamma\gamma$ sample
- Extract data-simulation calibration factors using $B^0 \to D^*(\to K^-\pi^+\pi^0)\pi^0$ control channel
- Signal yield from 3D simultaneous fit: background suppression BDT, ΔE and M_{bc}

$$\mathcal{A}_{\pi\pi} = 0.14 \pm 0.46 \pm 0.07 \pm 0.04$$
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.27 \pm 0.25 \pm 0.17) \cdot 10^{-6}$$



WA: $\mathcal{A}_{\pi\pi} = 0.33 \pm 0.22$

$\mathcal{B} = (1.59 \pm 0.26) \cdot 10^{-6}$

Competitive with Belle using only 1/3 of data set!

Highlights of recent results

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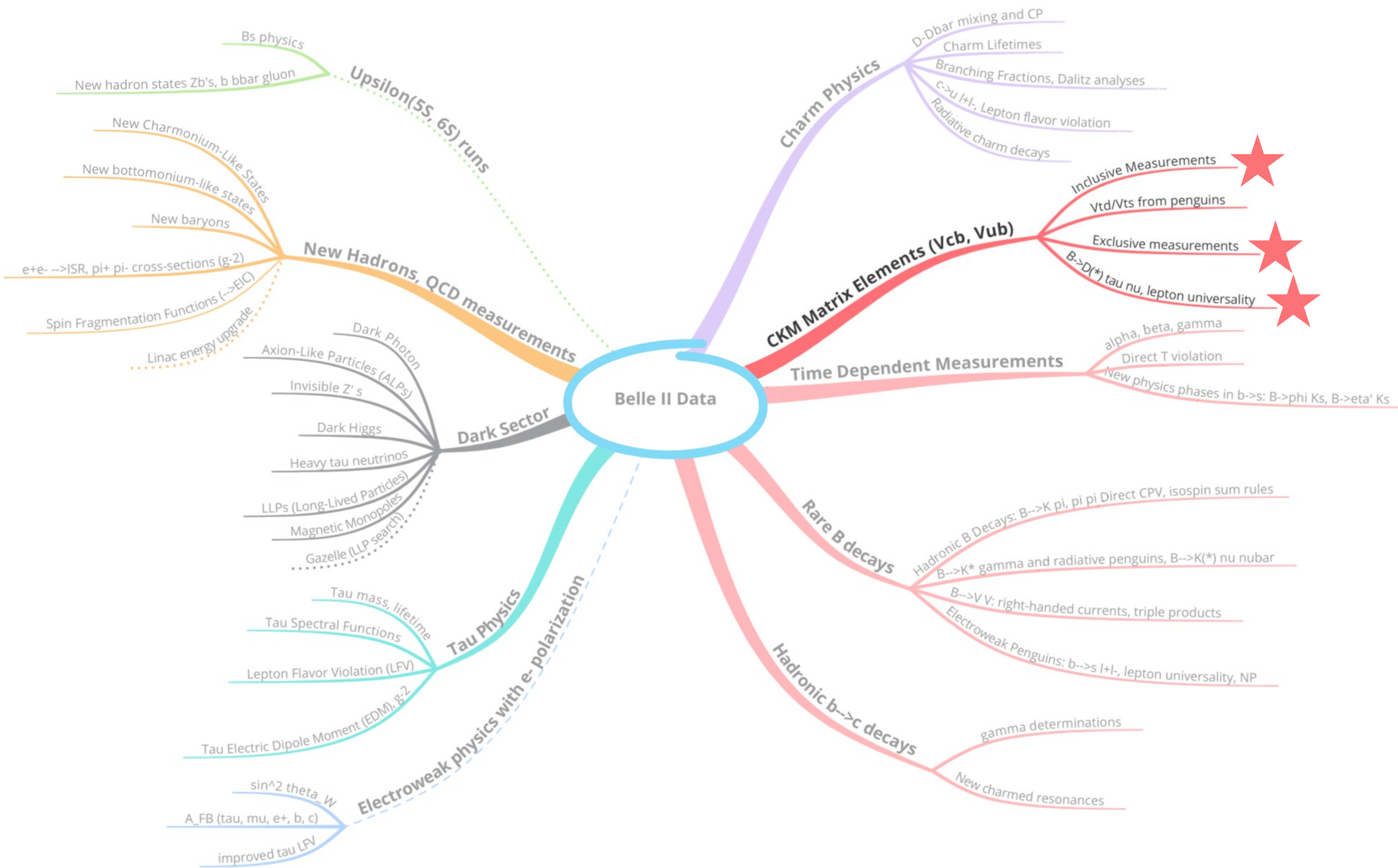
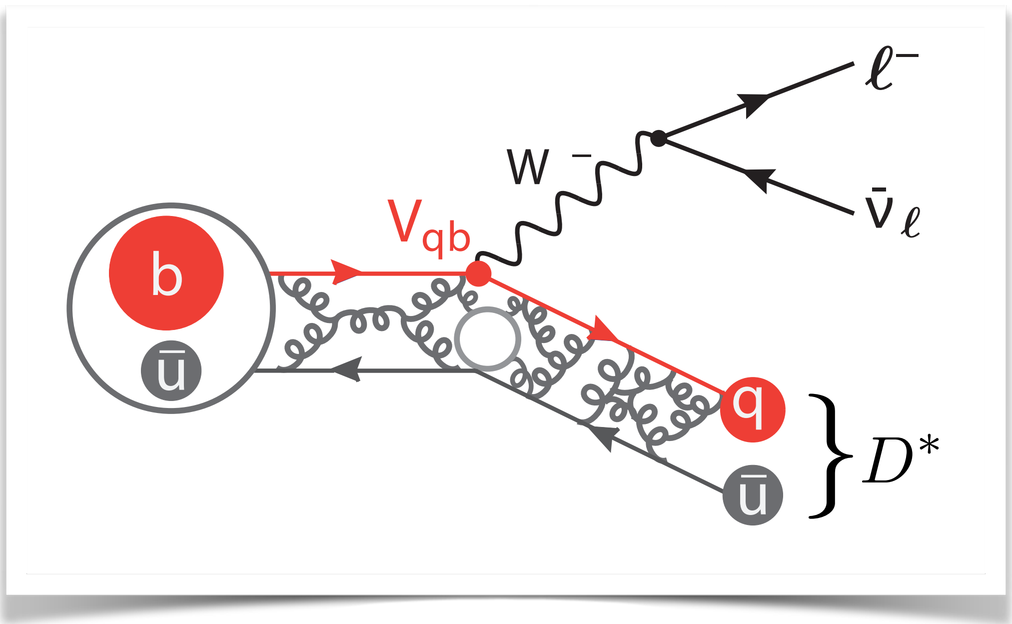


Image credit: T. Browder

How does one measure $|V_{cb}|$ & $|V_{ub}|$?



Exclusive $|V_{ub}|$

$$\bar{B} \to \pi \ell \bar{\nu}_\ell, \Lambda_b \to p \mu \bar{\nu}_\mu$$

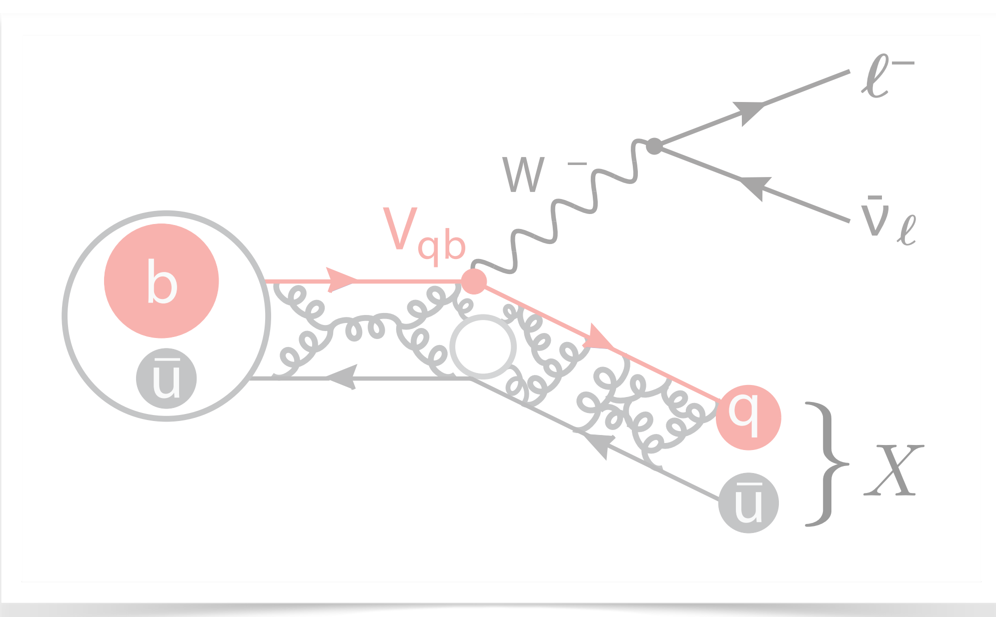
Exclusive $|V_{cb}|$

$$\bar{B} \to D \ell \bar{\nu}_\ell, \bar{B} \to D^* \ell \bar{\nu}_\ell$$

Needs **input** from non-perturbative methods:

$$\mathcal{B} \propto |V_{qb}|^2 f^2$$

Form Factors



Inclusive $|V_{ub}|$

$$\bar{B} \to X_u \ell \bar{\nu}_\ell$$

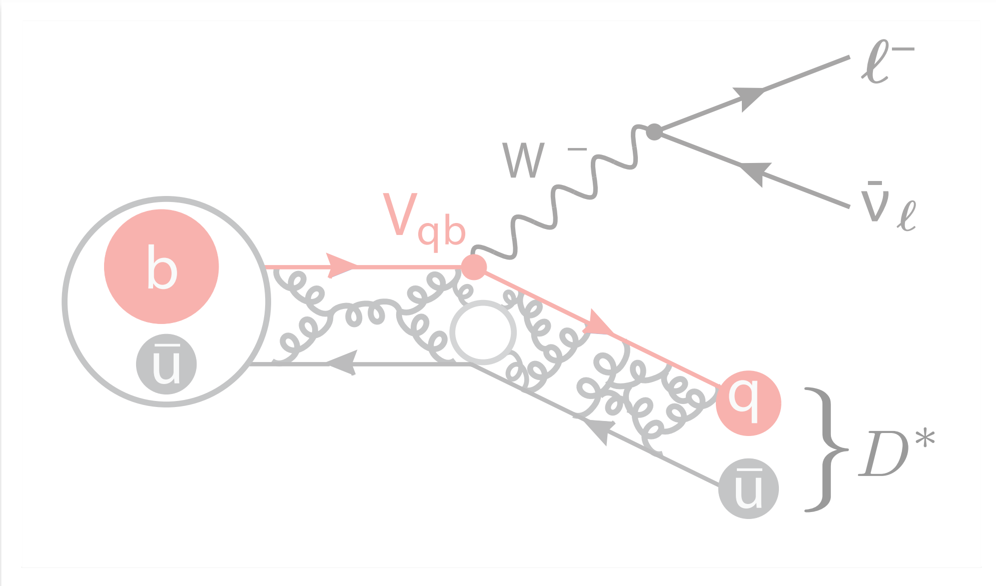
Inclusive $|V_{cb}|$

$$\bar{B} \to X_c \ell \bar{\nu}_\ell$$

Total decay rate **determined** from Heavy Quark Expansion (HQE)

$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q \, \ell \, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \dots \right]$$

How does one measure |V$_{cb}$| & |V$_{ub}$|?



Exclusive |V$_{ub}$|

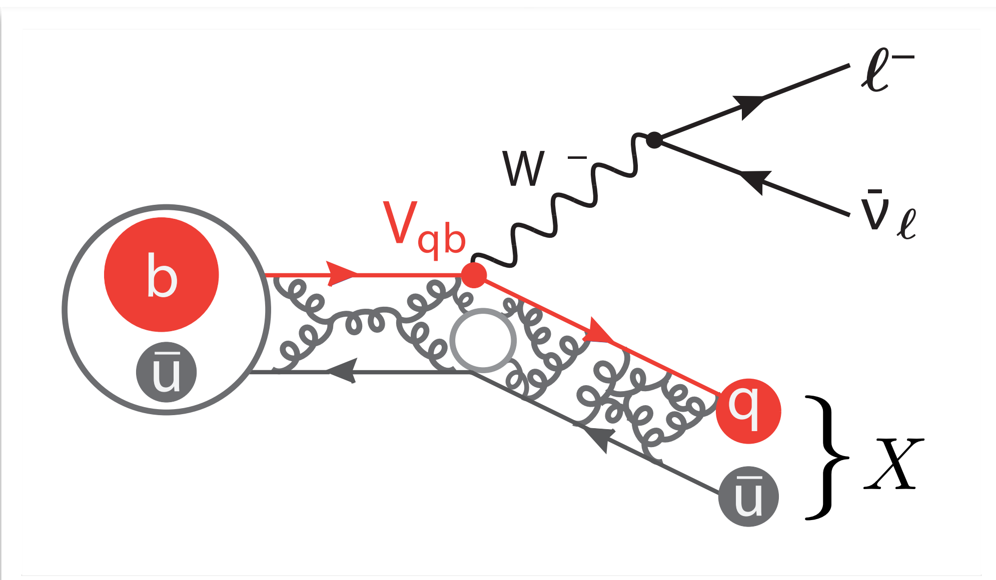
$\bar{B} \to \pi \ell \bar{\nu}_\ell, \Lambda_b \to p \mu \bar{\nu}_\mu$

Exclusive |V$_{cb}$|

$\bar{B} \to D \ell \bar{\nu}_\ell, \bar{B} \to D^* \ell \bar{\nu}_\ell$

Needs **input** from non-perturbative methods:

$\mathcal{B} \propto |V_{qb}|^2 f^2$ ← Form Factors



Inclusive |V$_{ub}$|

$\bar{B} \to X_u \ell \bar{\nu}_\ell$

Inclusive |V$_{cb}$|

$\bar{B} \to X_c \ell \bar{\nu}_\ell$

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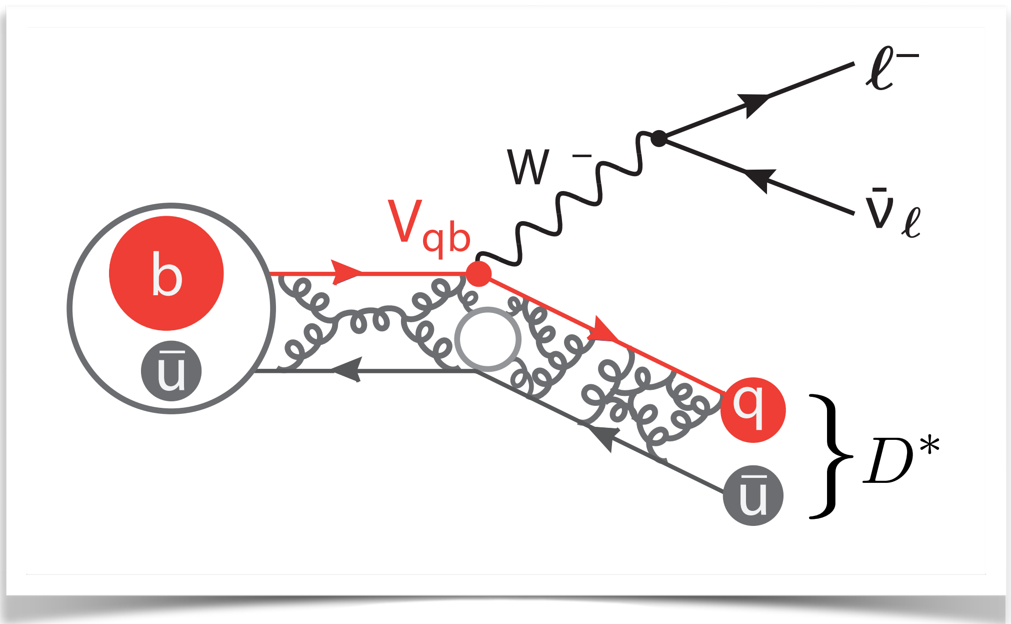
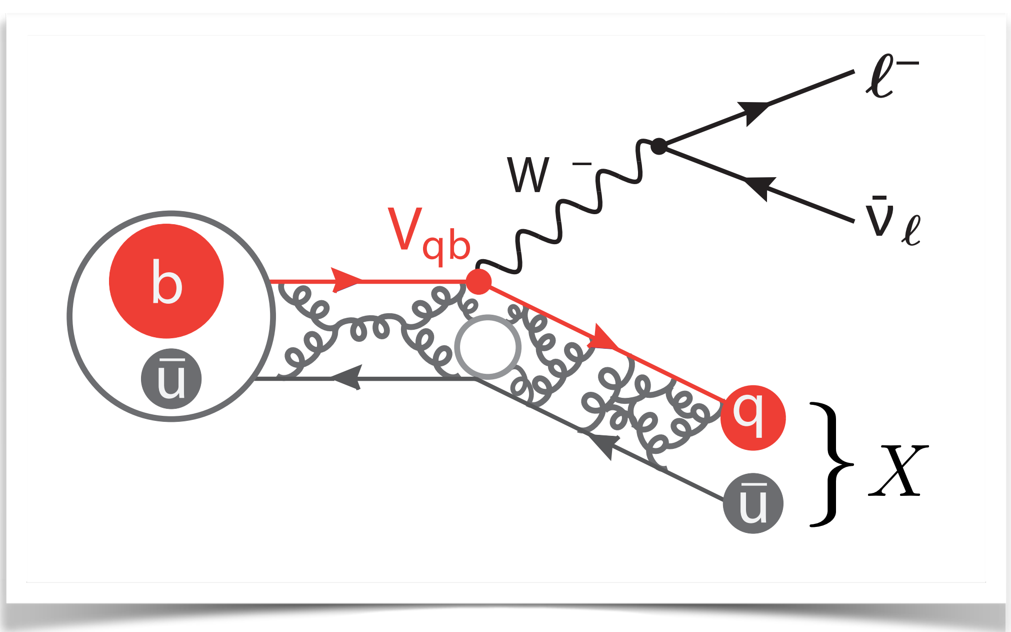
$$\mathcal{B} = |V_{qb}|^2 \left[\Gamma(b \to q\, \ell\, \bar{\nu}_\ell) + 1/m_{c,b} + \alpha_s + \ldots \right]$$

How does one measure $|V_{cb}|$ & $|V_{ub}|$?





Exclusive $|V_{ub}|$

$\bar{B} \to \pi \ell \bar{\nu}_\ell, \Lambda_b \to p \mu \bar{\nu}_\mu$

Exclusive $|V_{cb}|$

$\bar{B} \to D \ell \bar{\nu}_\ell, \bar{B} \to D^* \ell \bar{\nu}_\ell$

Measured
Branching Fraction

$$|V_{qb}| = \sqrt{\frac{\mathcal{B}(B \to X_q \ell \bar{\nu}_\ell)}{\tau \Gamma(B \to X_q \ell \bar{\nu}_\ell)}}$$

Prediction from
Theory but often also constrained
from **measured differential distributions**

Theory from non-perturbative Methods:

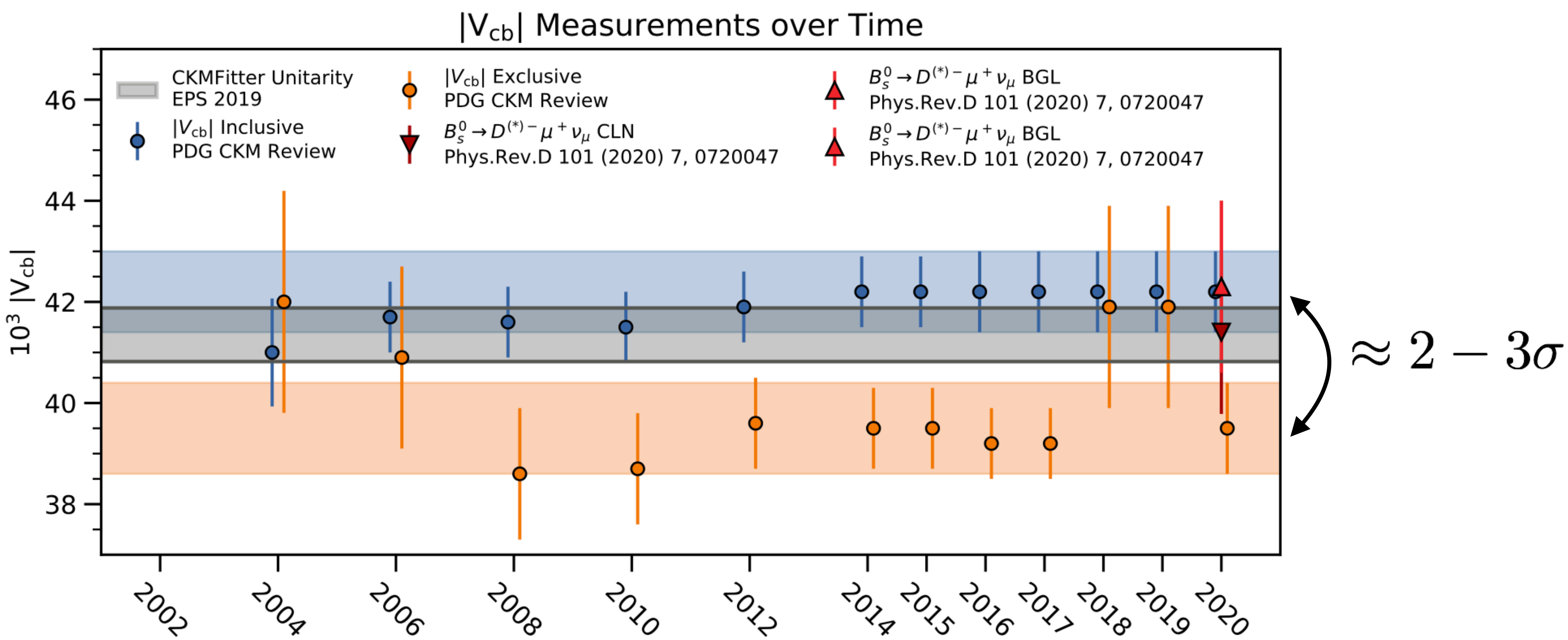
* Lattice QCD (high q^2)
* QCD Sum rules (low q^2)

Current status: A longstanding

$|V_{cb}|$

Inclusive

Exclusive



$|V_{ub}|$

Inclusive

Exclusive

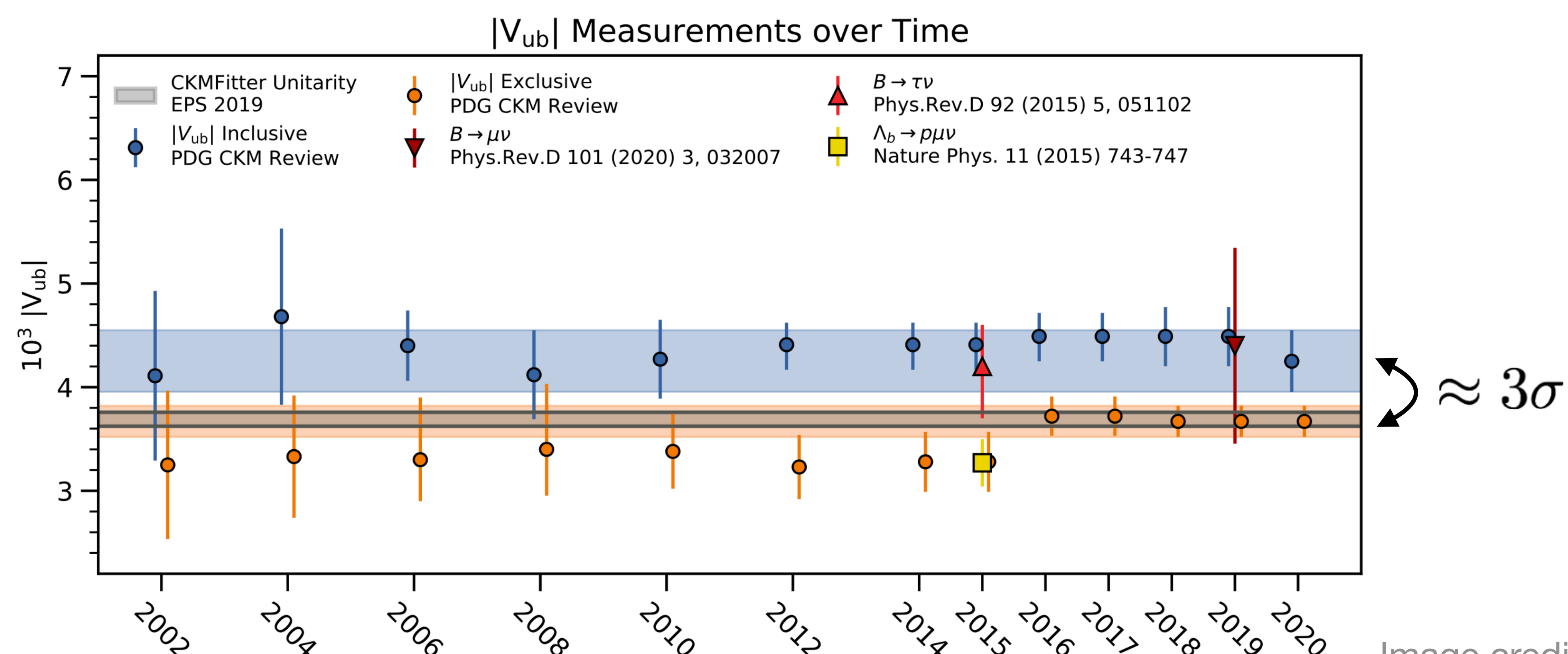
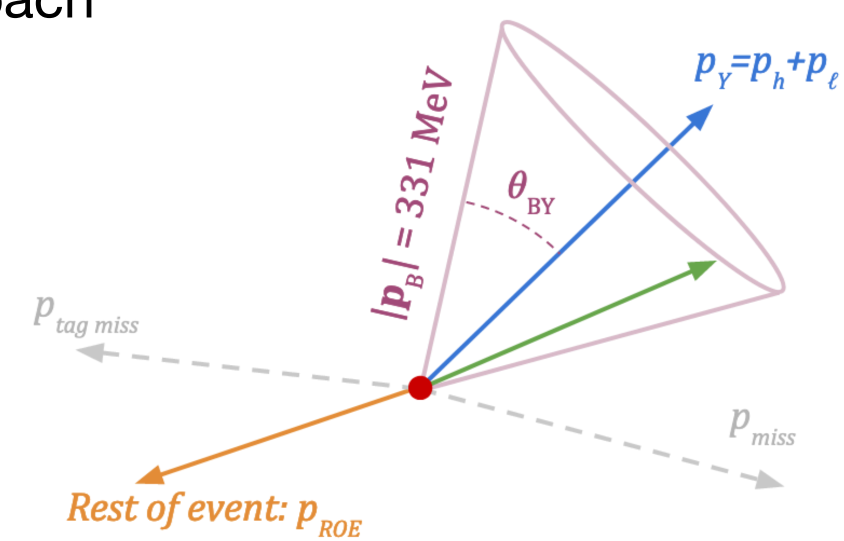


Image credit: M. Prim

Untagged $|V_{ub}|$

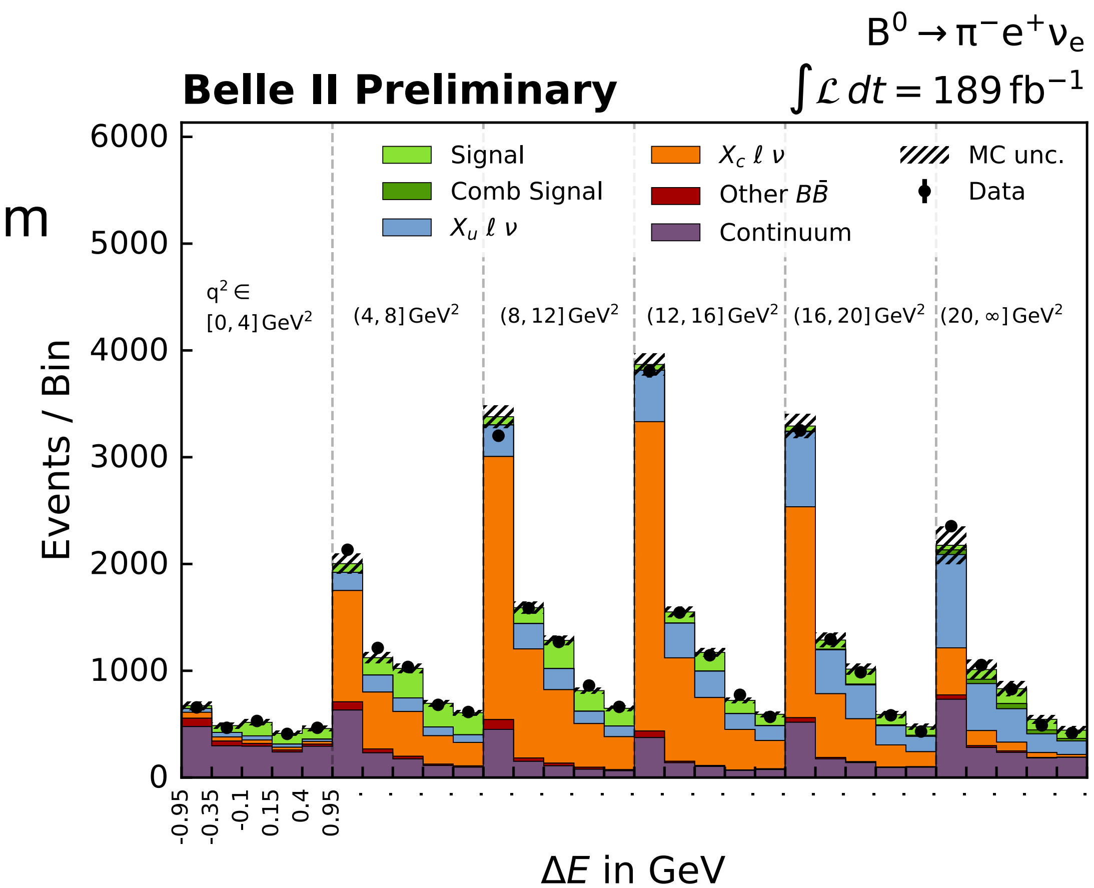
arXiv:2210.04224

- Reconstruct $B^0 \to \pi^- \ell^+ \nu_\ell$ with inclusive tagging
- **Main challenge:** large backgrounds from continuum and other semileptonic decays
  - Reject with dedicated BDT
- Estimate p_B using a modified ***diamond frame*** approach



- Extract signal via binned 2D fit using ΔE and M_{bc} in bins of $q^2 = (p_B - p_\pi)^2 = (p_\ell + p_\nu)^2$
- **Fit differential decay width** to BCL expansion with FNAL/MILC lattice QCD constraints included as nuisance parameters

$$|V_{ub}| = (3.54 \pm 0.12 \pm 0.15 \pm 0.16) \cdot 10^{-3}$$



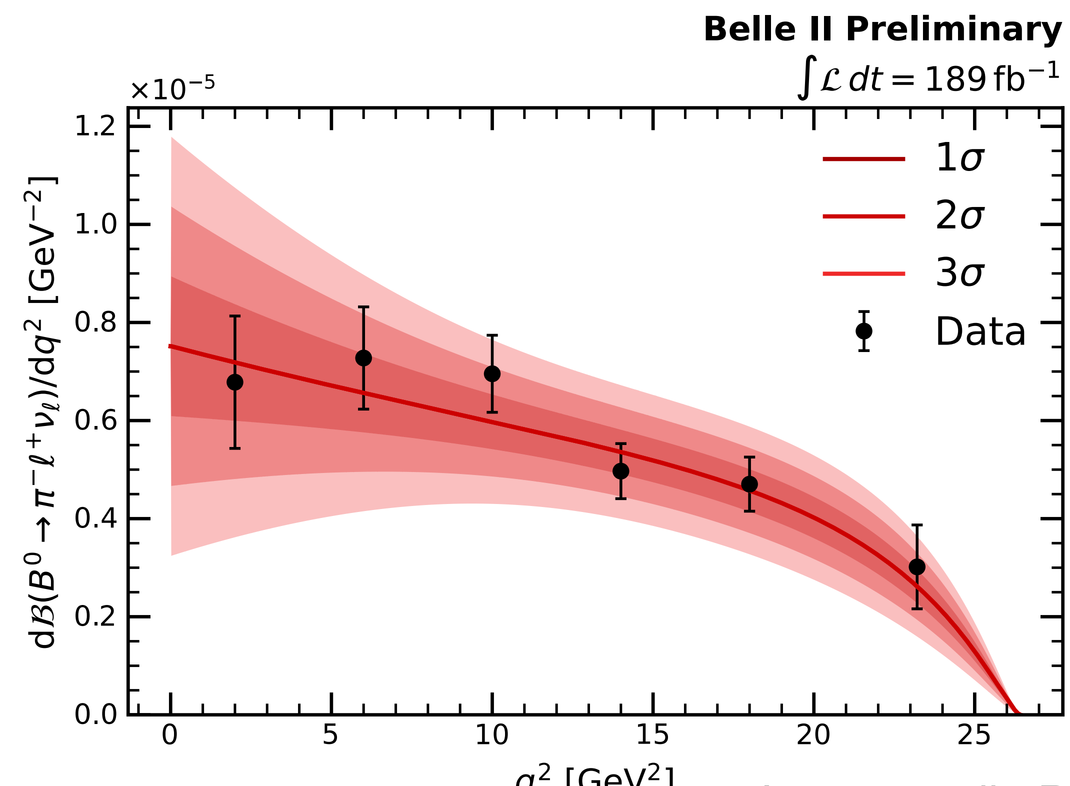


Image credit: P. Lewis

Untagged $|V_{cb}|$

arXiv:2210.13143

- Reconstruct $B^0 \to D^-(\to K^+\pi^-\pi^-)\ell^+\nu_\ell$ and $B^+ \to \bar{D}^0(\to K^+\pi^-)\ell^+\nu_\ell$ with inclusive tagging
- **Main challenge:** large backgrounds from $B \to D^*\ell\nu_\ell$ decays
  - **Reduce by reconstructing slow pions** with p < 0.35 GeV and rejecting events where $m_{D^*} - m_D \in$ [140, 150] MeV
- Estimate p_B again using a modified ***diamond frame*** approach
- Fit the angle between B and Y($D\ell$) to extract signal:

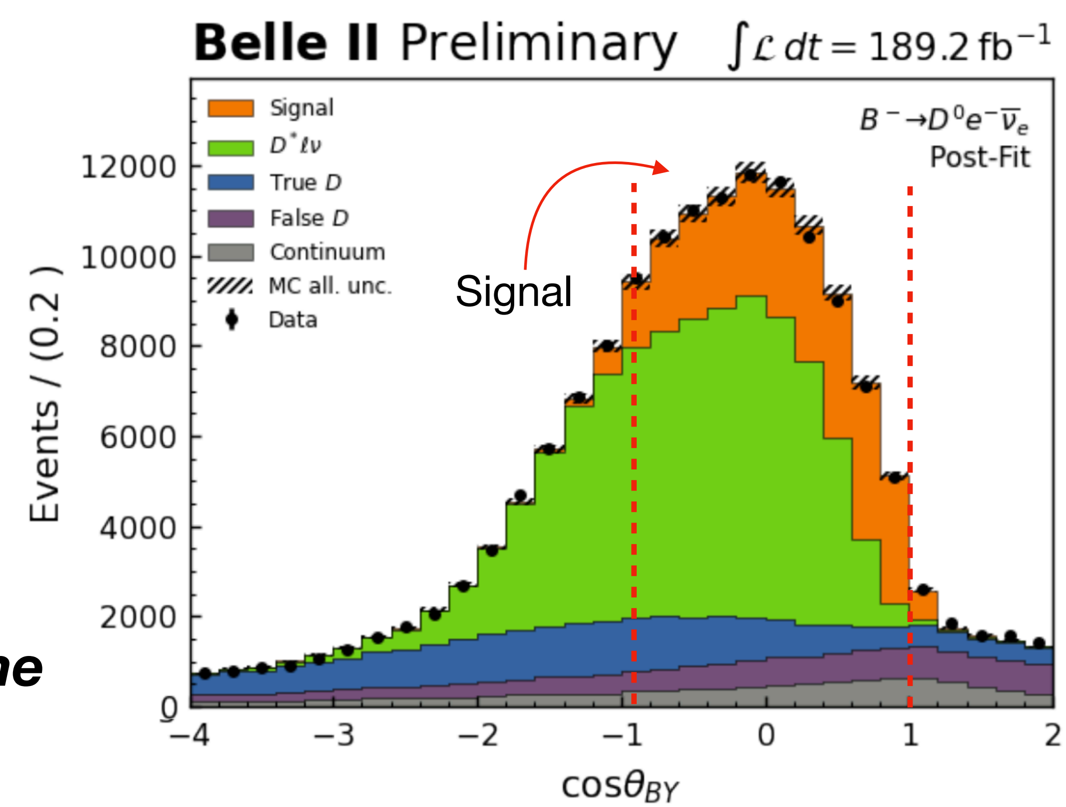
$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|p_B^*||p_Y^*|}$$

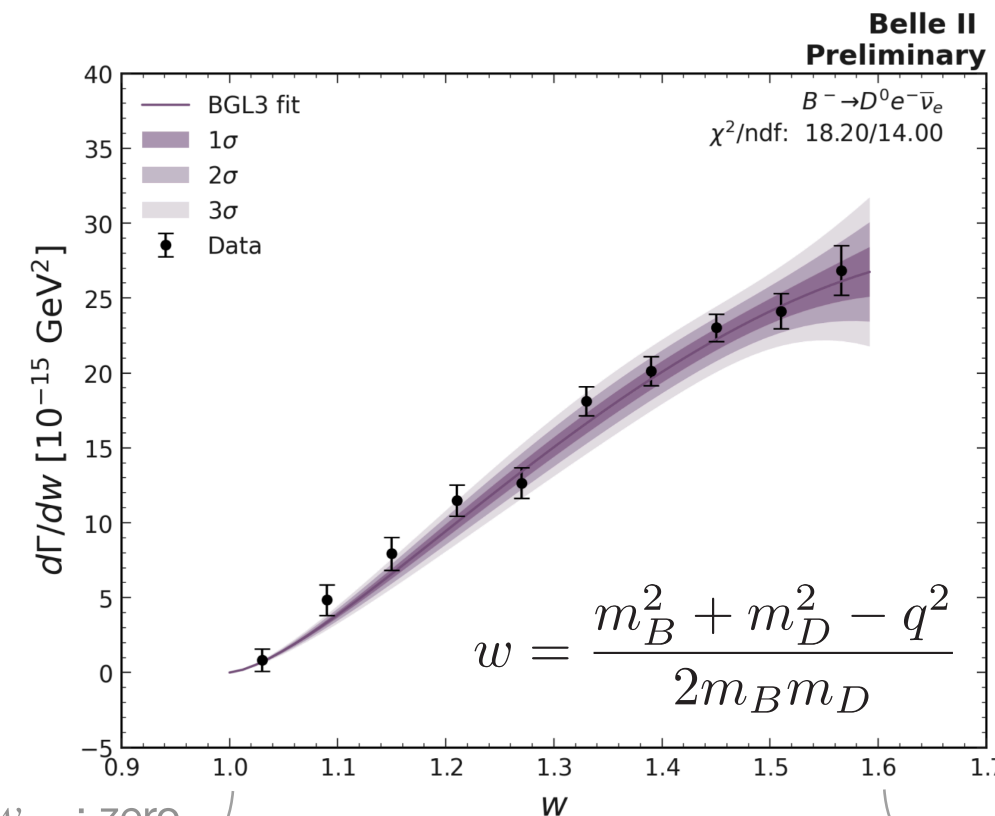
- **Fit differential decay width** using BGL (N = 3) parametrization with FNAL/MILC and HPQCD lattice QCD constraints included as nuisance parameters

$$\eta_{\mathrm{EW}}|V_{cb}| = (38.53 \pm 1.15) \cdot 10^{-3}$$

Electroweak corr. factor $\simeq 1$

~ 3% error comparable to past measurements





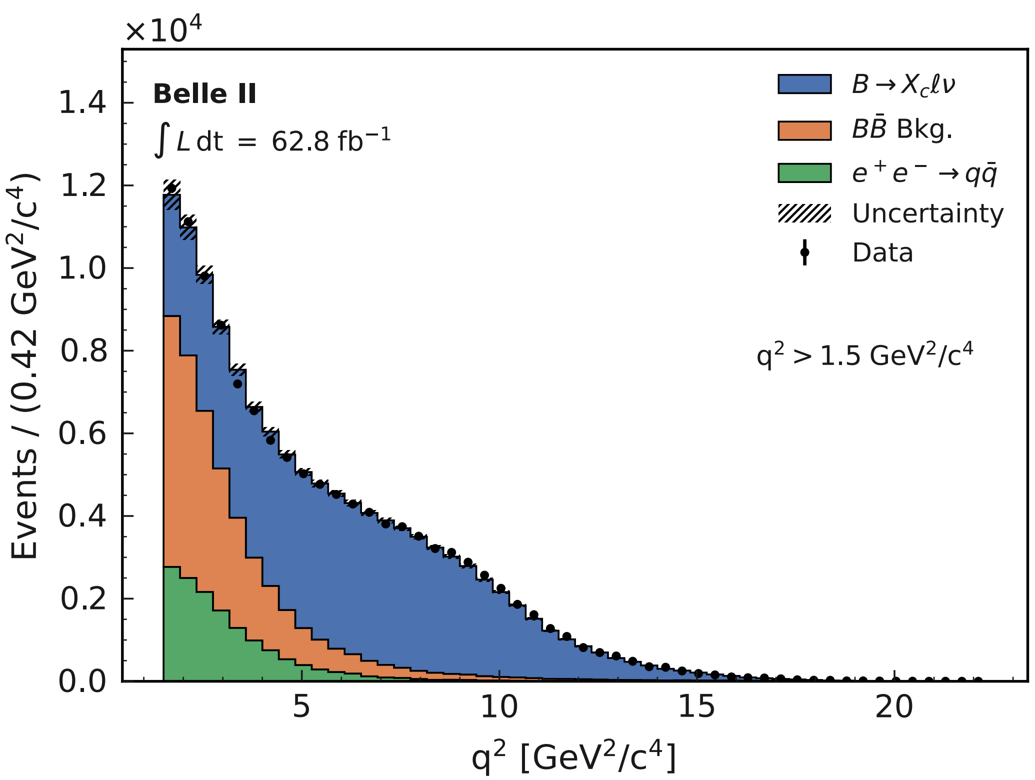
w_{min}: zero recoil

w_{max}

New incl. |V$_{cb}$| from q^2 moments

arXiv:2205.06372

- **Novel theoretical approach** to determine incl. |V$_{cb}$| with a reduced set of higher order HQE parameters at $\mathcal{O}(1/m_b^4)$ in a completely data-driven approach JHEP 02 177 (2019)
- Requires the reconstruction of q^2 for $B \to X_c \ell \nu_\ell$ decays
  - Only possible through **hadronic tagging** at B-factories!
- **Main challenge**: non-resonant $X_c \ell \nu_\ell$ 'gap' modelling



How to measure moments:

Calibrated q^2 dist. accounting for data/MC differences

Residual bias corr. factor

$$\langle q^{2n} \rangle = \frac{\sum w_i(q^2)(q^{2n}_{\mathrm{calib},i})}{\sum_i w_i(q^2)} \times \mathcal{C}_{\mathrm{cal}} \times \mathcal{C}_{\mathrm{acc}}$$

Background subtraction weights

Correct for resolution & selection effects

New incl. |V$_{cb}$| from q^2 moments

JHEP 10 (2022) 068

- **Novel theoretical approach** to determine incl. |V$_{cb}$| with a reduced set of higher order HQE parameters at $\mathcal{O}(1/m_b^4)$ in a completely data-driven approach JHEP 02 177 (2019)
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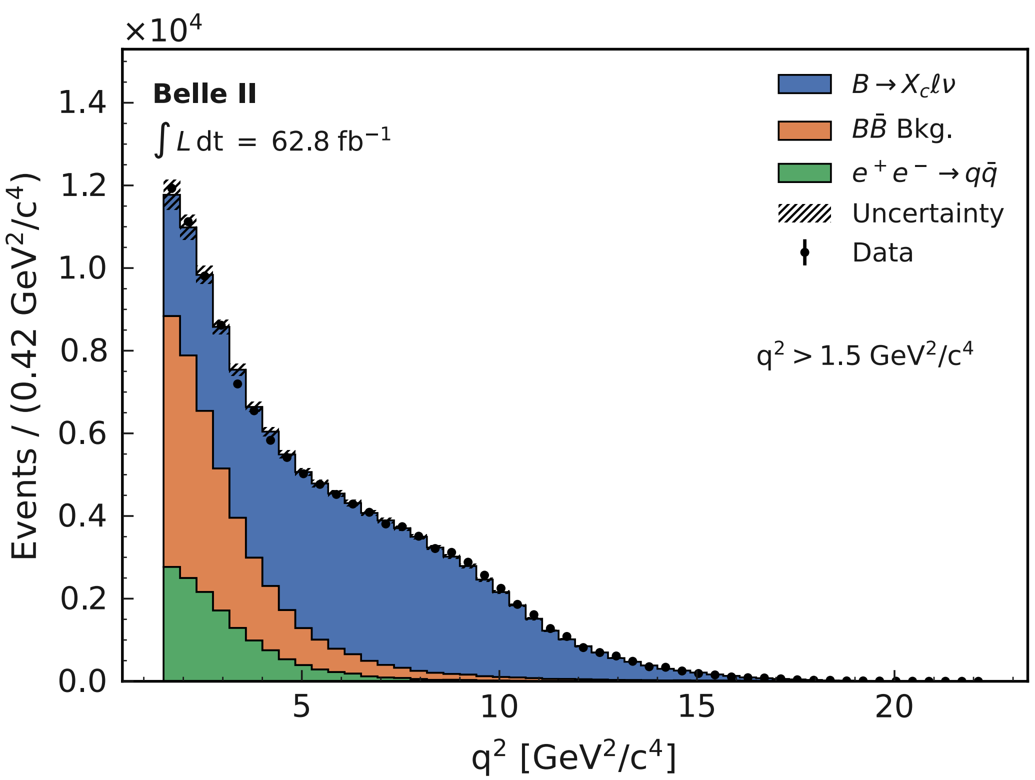
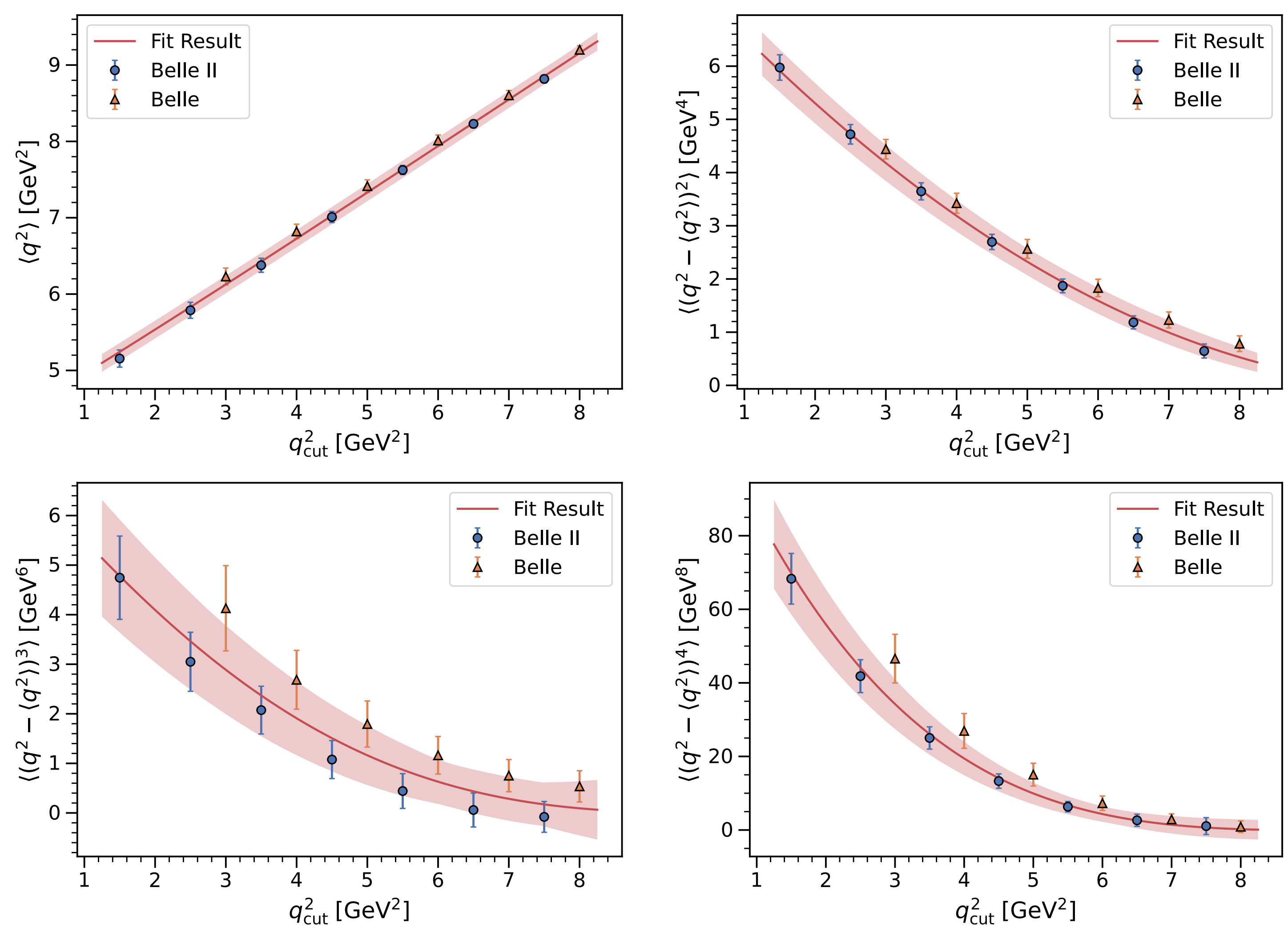


- Combined Belle & Belle II fit:

FYI my PhD analysis



$$|V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$$

Incl. vs Excl. puzzle remains…

Test of LFU: $R(X_{e/\mu})$

H. Junkerkalefeld @ichep

- Inclusive cross-check of the current **R(D*) tension** is crucial:

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$

- No measurement from Belle or BaBar…
- **First step:** $R(X_{e/\mu})$ LFU testing with light leptons using hadronic tagging

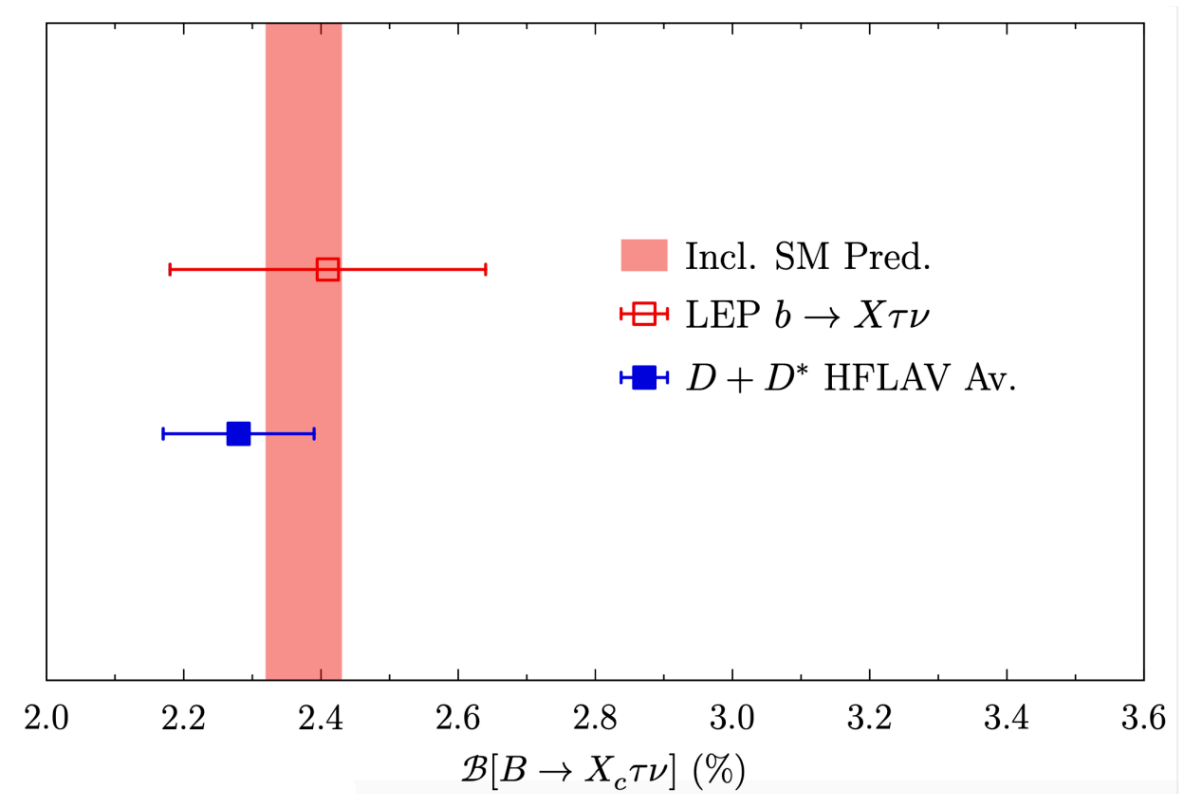
$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$$

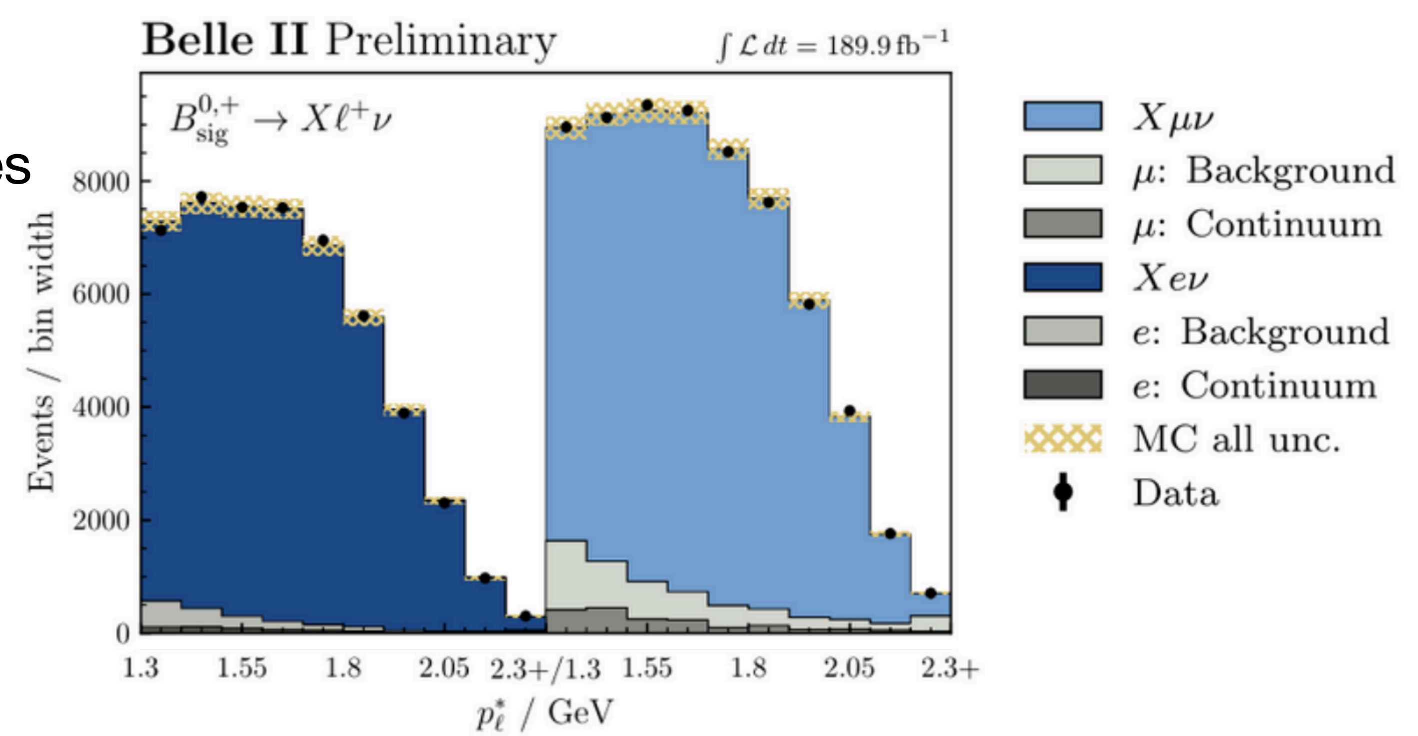
- Obtain the $X\ell\nu$ yields by a **simultaneous binned likelihood fit** of the e and μ templates to individual p_ℓ^* distributions

$$R(X_{e/\mu}) = 1.033 \pm 0.010 \pm 0.020$$

Compatible with SM prediction of 1.006 ± 0.001 with 1.2σ

First test of (e/μ) LFU in incl. $B \to X\ell\nu$!

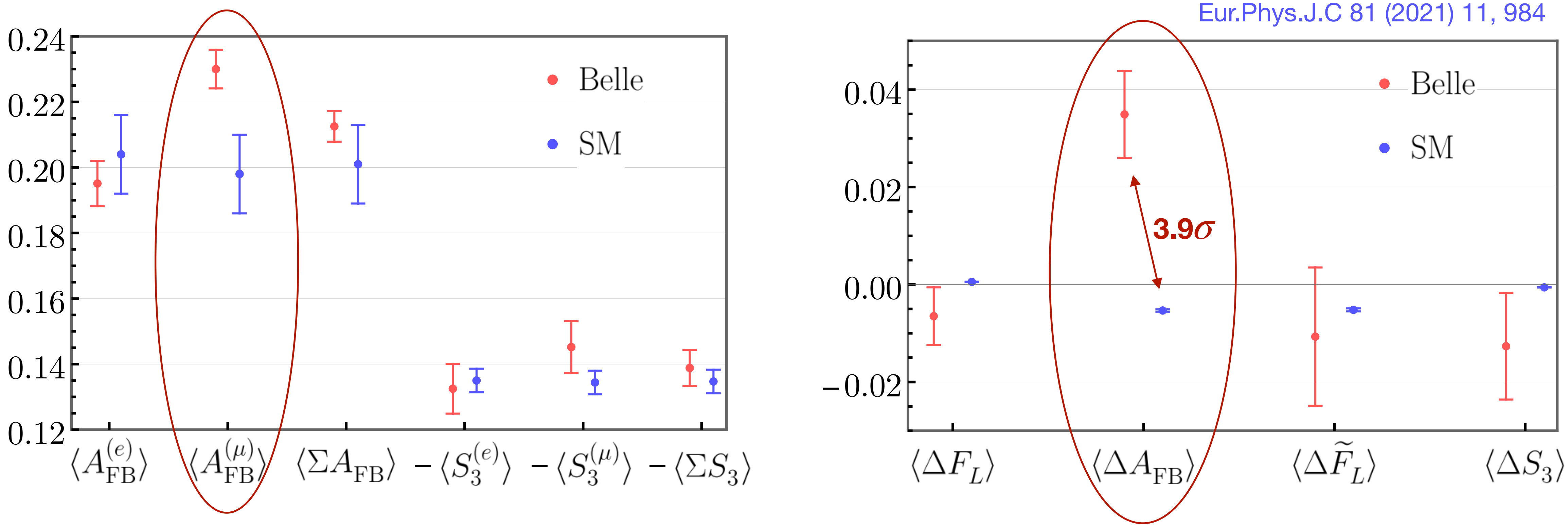




Forward-backward asymmetry

Current measurements of A_{FB} from $B^0 \to D^{*-}\ell^+\nu_\ell$ decays display a **discrepancy** with the SM prediction

Eur.Phys.J.C 81 (2021) 11, 984



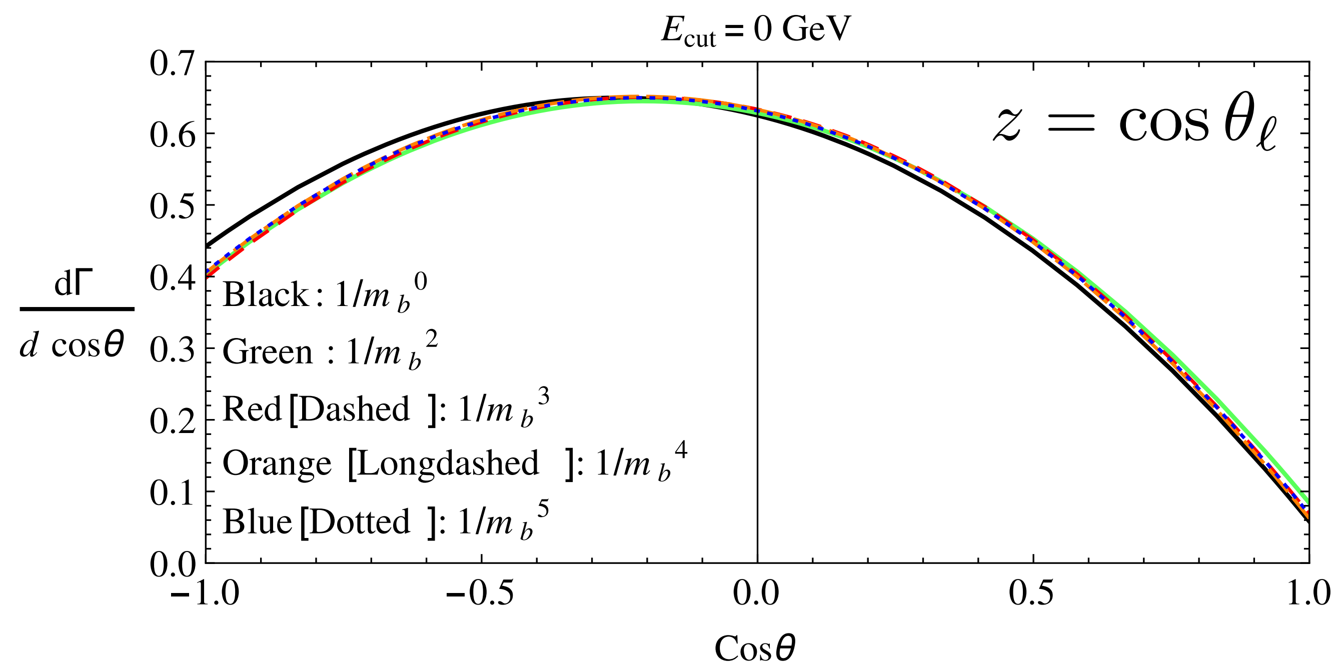
- **First** measurement of A_{FB} from **inclusive** $B \to X\ell\nu_\ell$ decays would provide an **orthogonal, complementary** study JHEP 04 (2016) 131
  - $X_u\ell\nu_\ell$ component **easily subtracted** in the HQE with **smaller uncertainties** than traditional MC approach arXiv:2205.03427 & JHEP 09 (2021) 51
- Additional information on HQE parameters leads to **greater sensitivity** in global fits, directly impacting precision on incl. $|V_{cb}|$

Incl. A_{FB} at Belle II

JHEP 04 (2016) 131

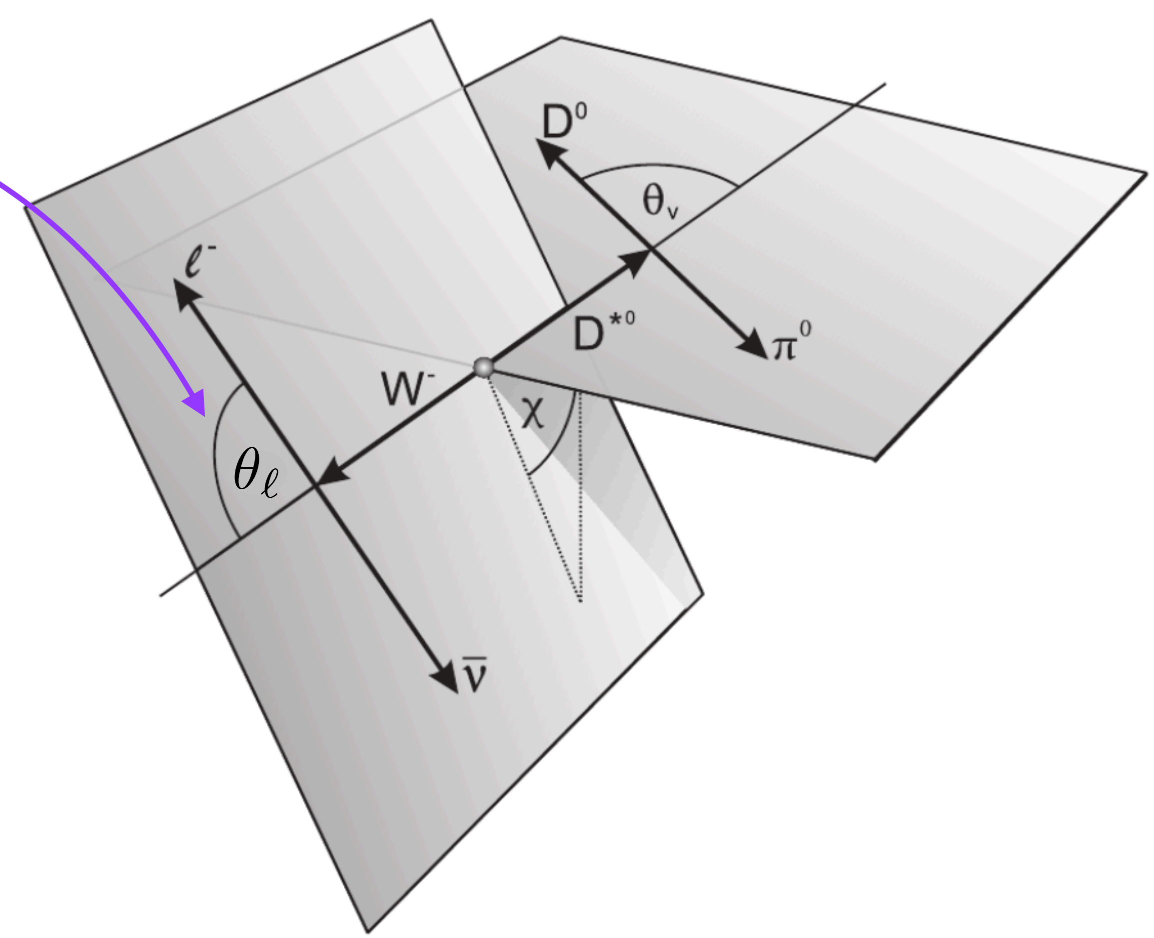
- Goal: Measure A_{FB} from **inclusive** $B \to X\ell\nu$ decays using **hadronic tagging**

$$\mathcal{A}_{FB} = \frac{1}{\Gamma}\left(\int_{-1}^{0} \mathrm{d}z \frac{\mathrm{d}\Gamma}{\mathrm{d}z} - \int_{0}^{1} \mathrm{d}z \frac{\mathrm{d}\Gamma}{\mathrm{d}z}\right)$$



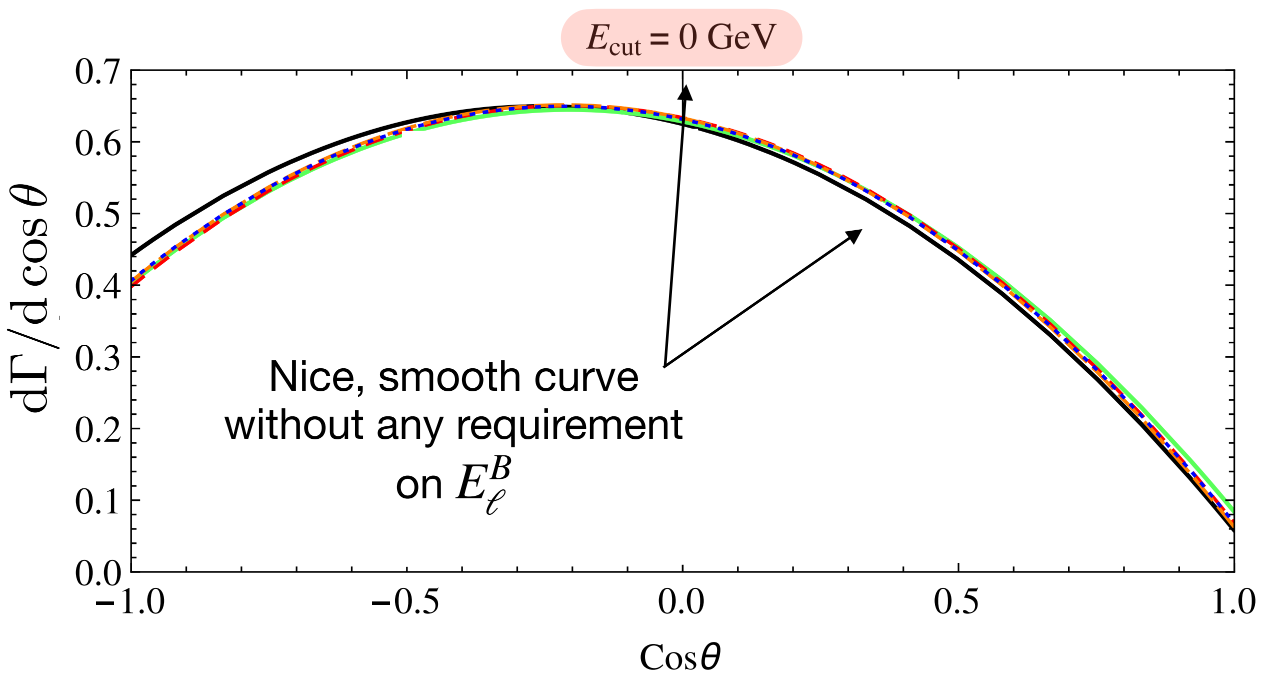
- Reconstruct:

$$z = \frac{E^B_{\nu_\ell} - E^B_\ell}{\sqrt{(E^B_{\nu_\ell} + E^B_\ell)^2 - q^2}}$$



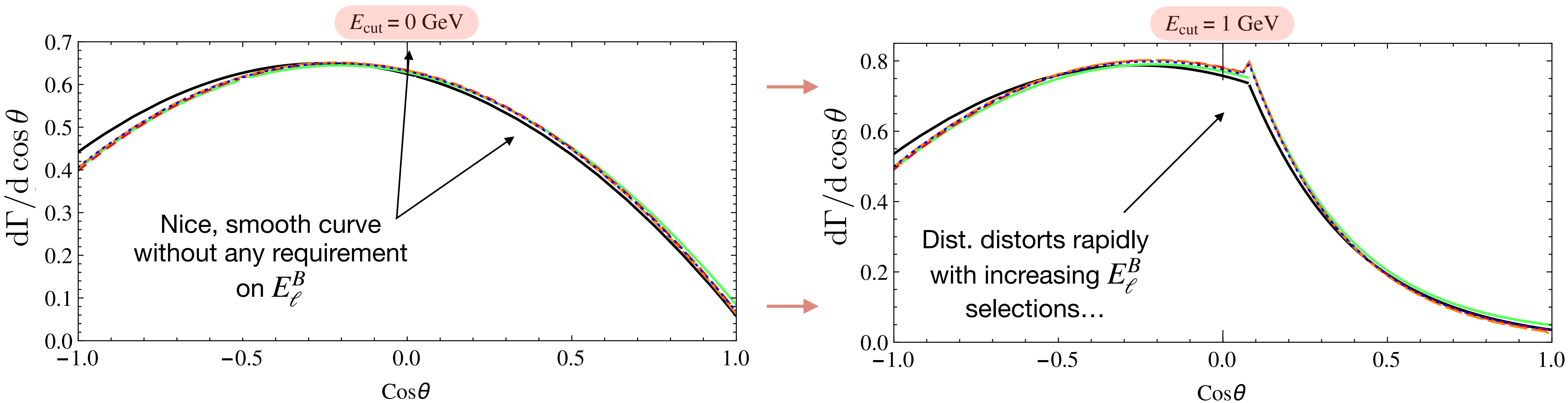
- Missing energy and q^2 **easily accessible** variables with tagged approach
- Separate electron and muon channels for further **LFU tests**

Impact of an E_ℓ requirement



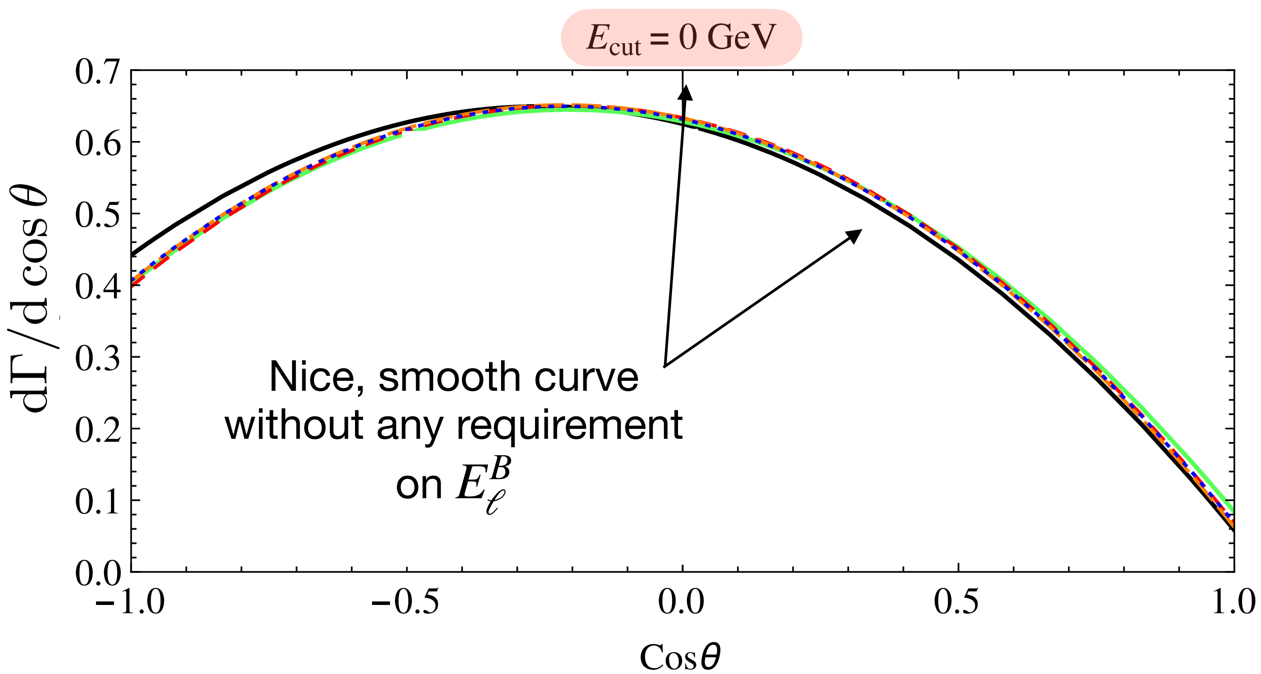
- A minimum energy is required for leptons to be successfully **reconstructed & identified** by the Belle II detector
- Higher E_ℓ selects a **less inclusive** sample

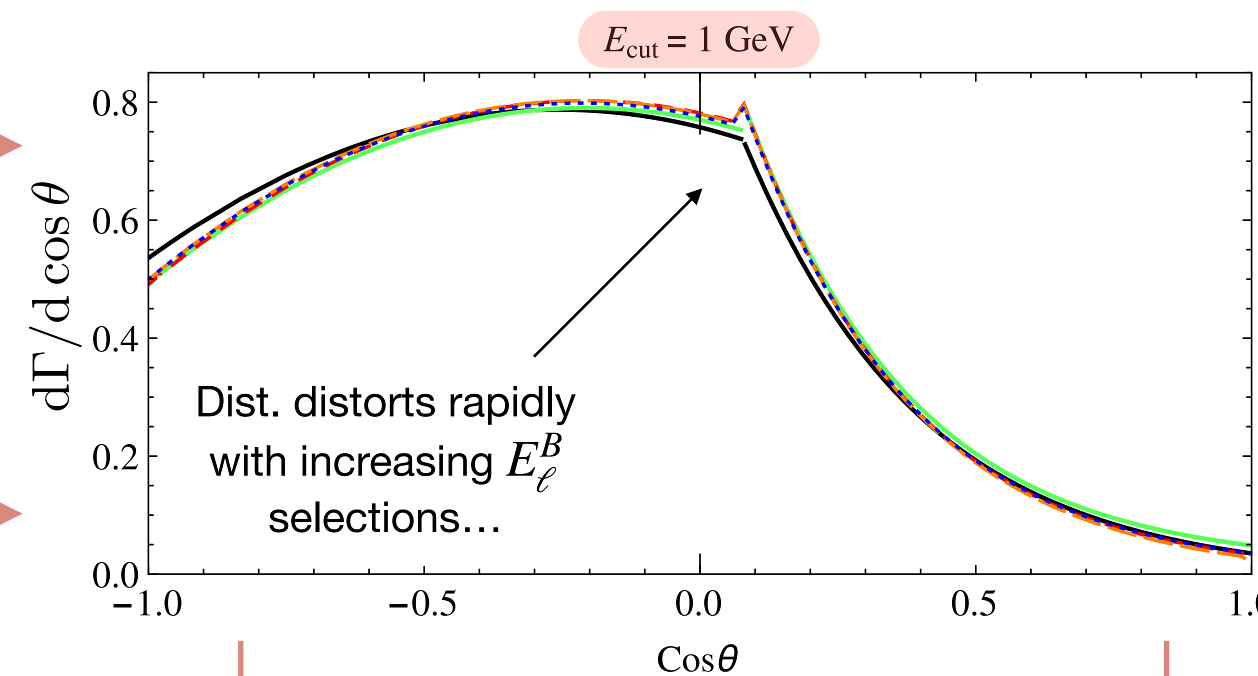
Impact of an E_ℓ requirement



- A minimum energy is required for leptons to be successfully **reconstructed & identified** by the Belle II detector
- Higher E_ℓ selects a **less inclusive** sample
- Imposing an E_ℓ requirement **introduces a kink**, which would smooth out due to detector resolution
- Potential challenges in **unfolding** reconstructed to the underlying distribution?

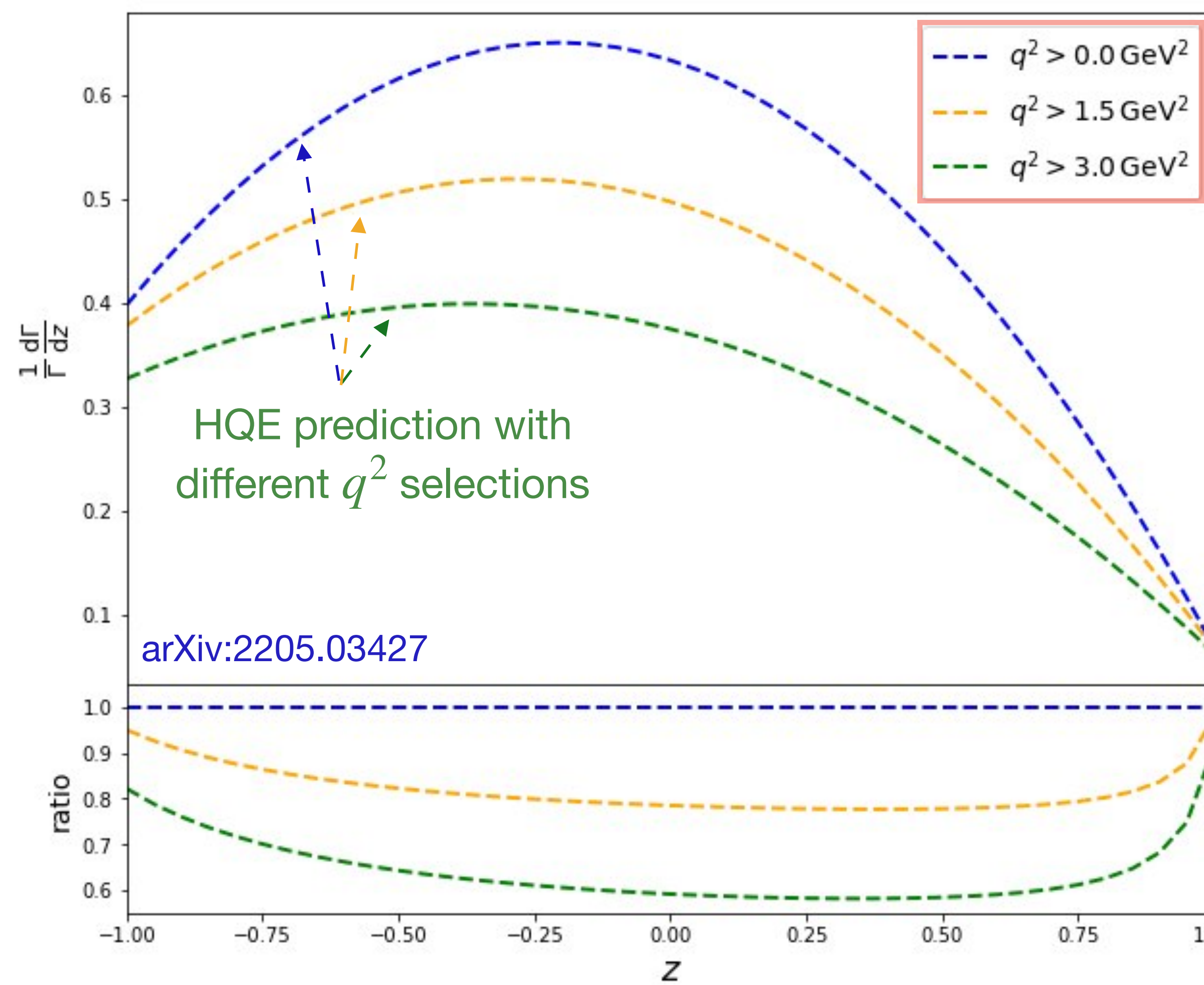
Impact of an E_ℓ requirement





- A minimum energy is required for leptons to be successfully **reconstructed & identified** by the Belle II detector
- Higher E_ℓ selects a **less inclusive** sample
- Imposing an E_ℓ requirement **introduces a kink**, which would smooth out due to detector resolution
- Potential challenges in **unfolding** reconstructed to the underlying distribution?

Suggestion:
Use a q^2 selection instead

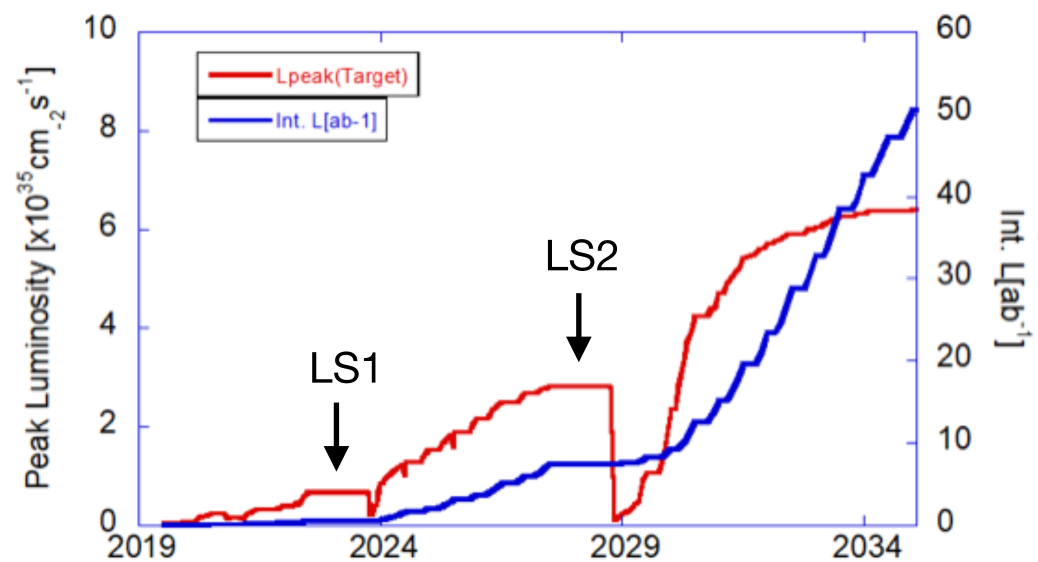


Towards higher luminosity:

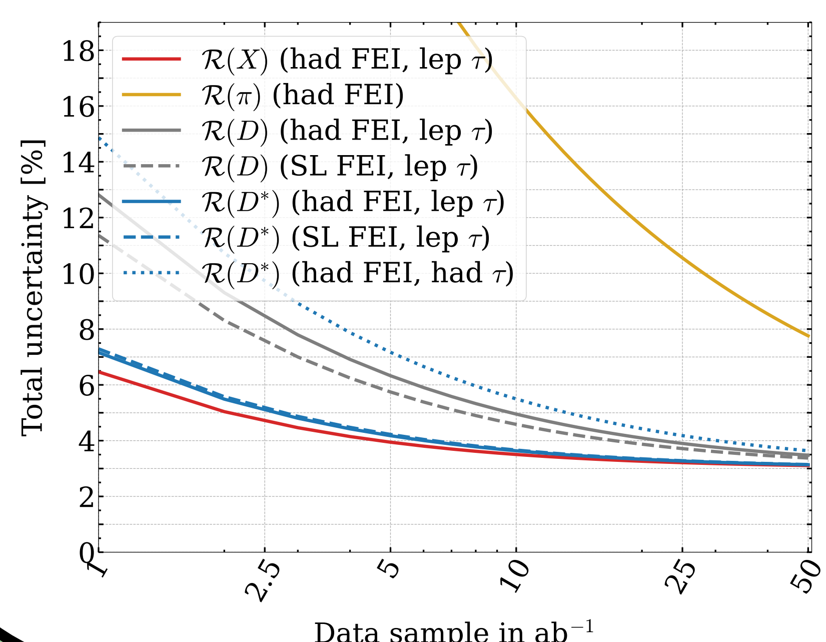
Belle II started its journey and offers a unique and fertile environment for flavour physics.

With 428 fb^{-1} LS1 data Belle II can already provide physics output with comparable precision to that of its predecessors.

Over the next decade, Belle II aims to collect a data set equivalent to ~ 50 ab^{-1}.



High quality results will soon start to impact world averages as data and precision increase.



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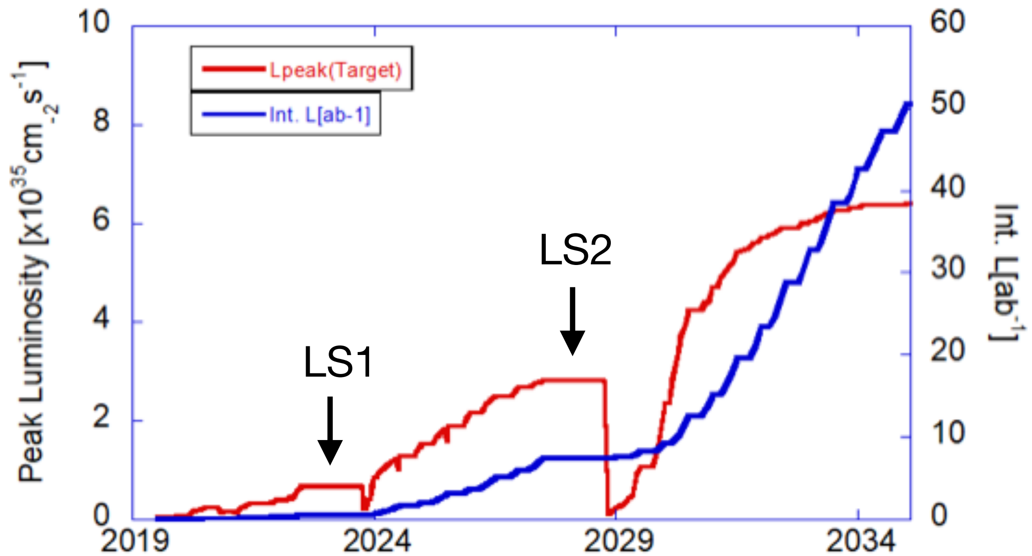

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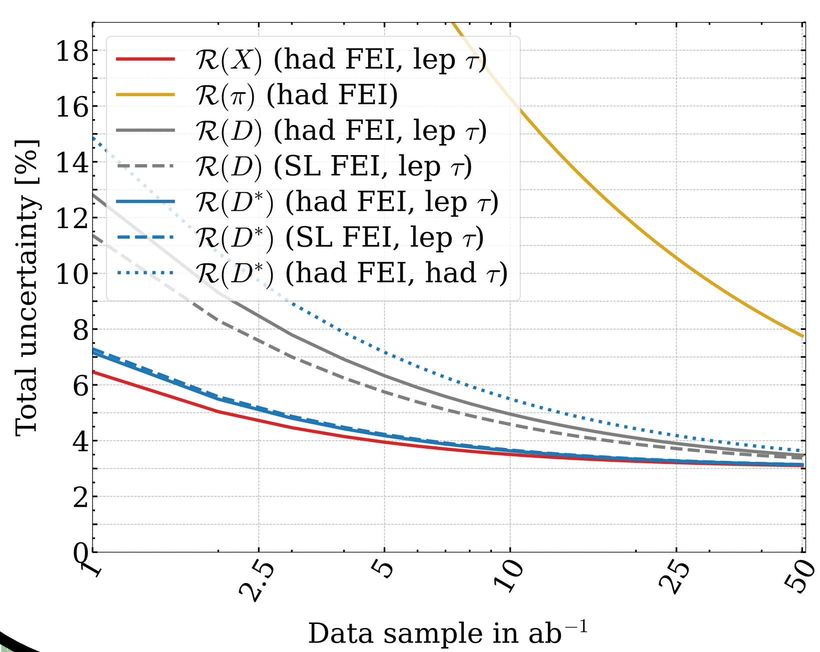
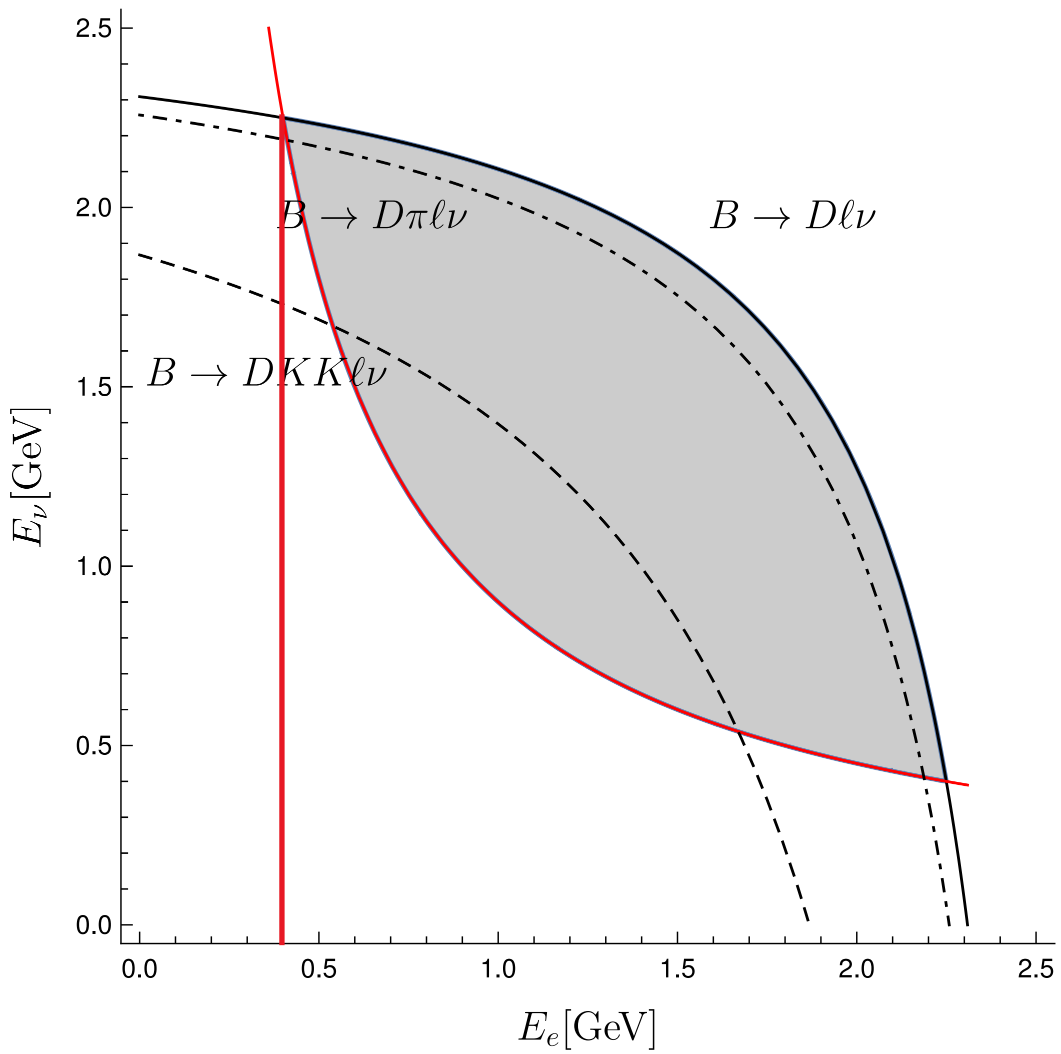
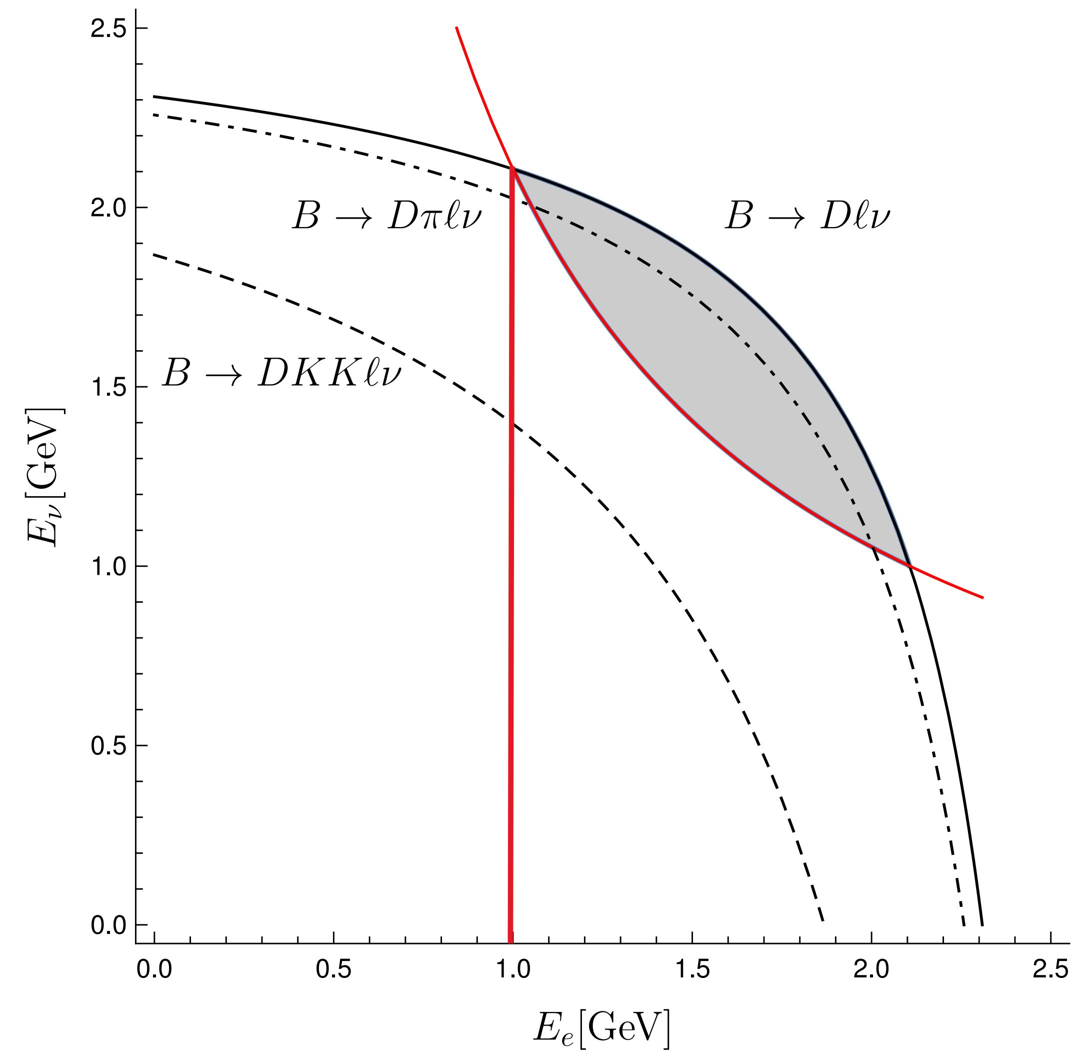


Thank you for your attention!

E_ℓ vs. q^2 selection criteria

[JHEP 02, 177 (2019)]





A requirement of $q^2 > 3.6\ \mathrm{GeV}^2$ is equivalent to imposing a selection of $E_\ell > 0.4\ \mathrm{GeV}$

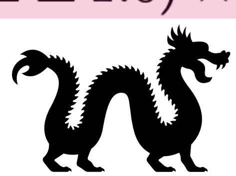
A requirement of $q^2 > 8.43\ \mathrm{GeV}^2$ is equivalent to imposing a selection of $E_\ell > 1.0\ \mathrm{GeV}$

$B \to X_c \ell \nu$ modelling & composition

$$\mathcal{B}(\mathrm{B}^+ \to X_c^0 \ell^+ \nu_\ell) \approx 10.79\,\%$$

$\mathrm{D}^0 \ell^+ \nu_\ell$	$\mathrm{D}^{*0} \ell^+ \nu_\ell$	$\mathrm{D}^{**0} \ell^+ \nu_\ell$ + Other	Gap
2.31 %	5.05 %	2.38 %	$\sim$ 1.05 %

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to X_c \ell \nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$



→ Fairly well known. Some iso-spin tension.

→ Broad states based on 3 measurements. (BaBar, Belle, DELPHI)

→ Some hints from the BaBar result.

Image credit: F. Metzner

A tale of two 'gap' models

Model 1:
Equidistribution of all final state particles in phase space

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D\,\ell^+\,\nu_\ell$	$(2.4 \pm 0.1) \times 10^{-2}$	$(2.2 \pm 0.1) \times 10^{-2}$
$B \to D^*\,\ell^+\,\nu_\ell$	$(5.5 \pm 0.1) \times 10^{-2}$	$(5.1 \pm 0.1) \times 10^{-2}$
$B \to D_1\,\ell^+\,\nu_\ell$	$(6.6 \pm 0.1) \times 10^{-3}$	$(6.2 \pm 0.1) \times 10^{-3}$
$B \to D_2^*\,\ell^+\,\nu_\ell$	$(2.9 \pm 0.3) \times 10^{-3}$	$(2.7 \pm 0.3) \times 10^{-3}$
$B \to D_0^*\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.8) \times 10^{-3}$	$(3.9 \pm 0.7) \times 10^{-3}$
$B \to D_1'\,\ell^+\,\nu_\ell$	$(4.2 \pm 0.9) \times 10^{-3}$	$(3.9 \pm 0.8) \times 10^{-3}$
$B \to D\pi\pi\,\ell^+\,\nu_\ell$	$(0.6 \pm 0.9) \times 10^{-3}$	$(0.6 \pm 0.9) \times 10^{-3}$
$B \to D^*\pi\pi\,\ell^+\,\nu_\ell$	$(2.2 \pm 1.0) \times 10^{-3}$	$(2.0 \pm 1.0) \times 10^{-3}$
$B \to D\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to D^*\eta\,\ell^+\,\nu_\ell$	$(4.0 \pm 4.0) \times 10^{-3}$	$(4.0 \pm 4.0) \times 10^{-3}$
$B \to X_c\ell\nu_\ell$	$(10.8 \pm 0.4) \times 10^{-2}$	$(10.1 \pm 0.4) \times 10^{-2}$

Model 2:
Decay via intermediate broad D^{**} state

Decay	$\mathcal{B}(B^+)$	$\mathcal{B}(B^0)$
$B \to D_0^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\pi\pi$)	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\pi\pi$)	$(0.03 \pm 0.03) \times 10^{-2}$	$(0.03 \pm 0.03) \times 10^{-2}$
$B \to D_0^*\pi\pi\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\pi\pi$)	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_1^*\pi\pi\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\pi\pi$)	$(0.108 \pm 0.051) \times 10^{-2}$	$(0.101 \pm 0.048) \times 10^{-2}$
$B \to D_0^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D\eta$)	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$
$B \to D_1^*\,\ell^+\,\nu_\ell$ ($\hookrightarrow D^*\eta$)	$(0.396 \pm 0.396) \times 10^{-2}$	$(0.399 \pm 0.399) \times 10^{-2}$

(Assign 100% BR uncertainty in systematics covariance matrix)