Recent highlights from Belle II

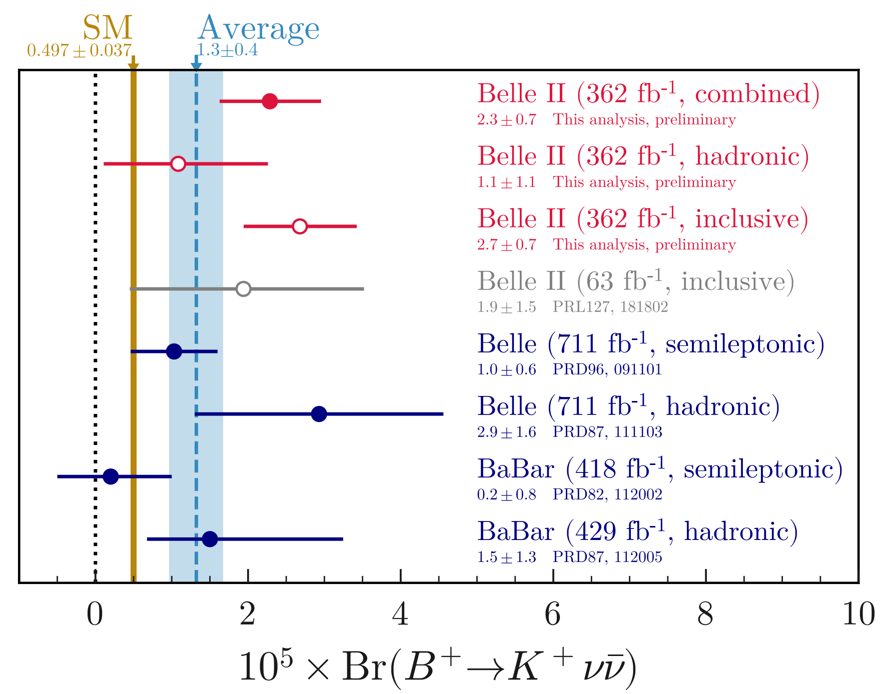
Raynette van Tonder
raynette.vantonder@mcgill.ca

2024 CAP Congress
Western University, London, ON
28 May 2024

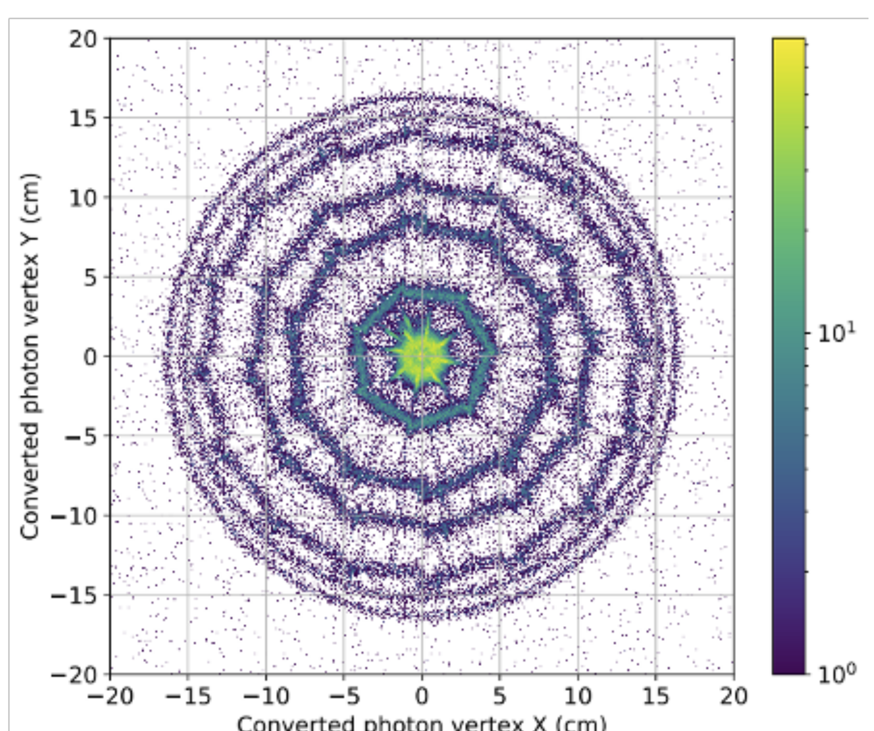
Outline for today

I. SuperKEKB & Belle II experimental status

II. Highlights of recent Belle II physics results



III. Ongoing & future work



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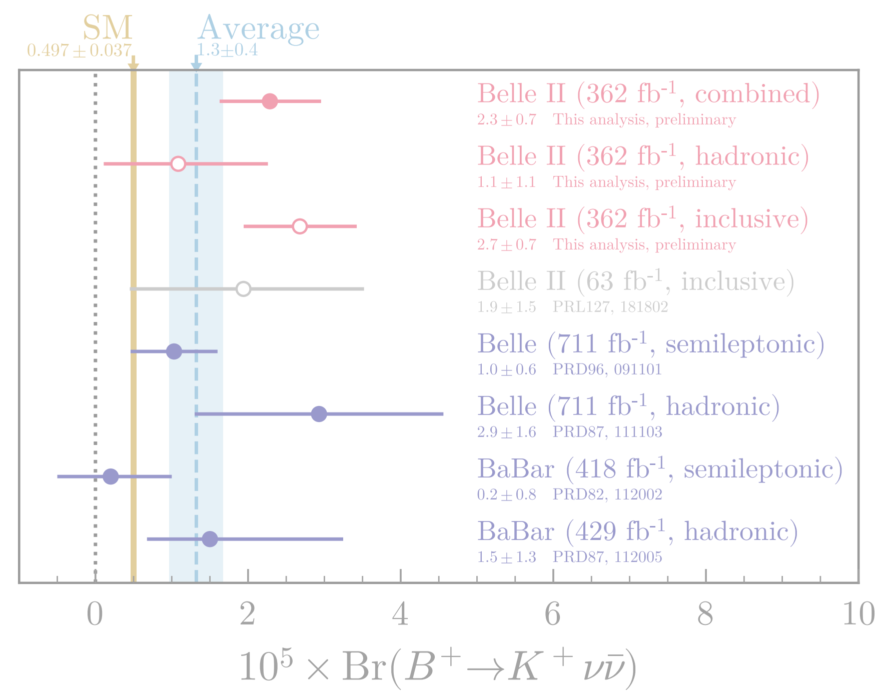

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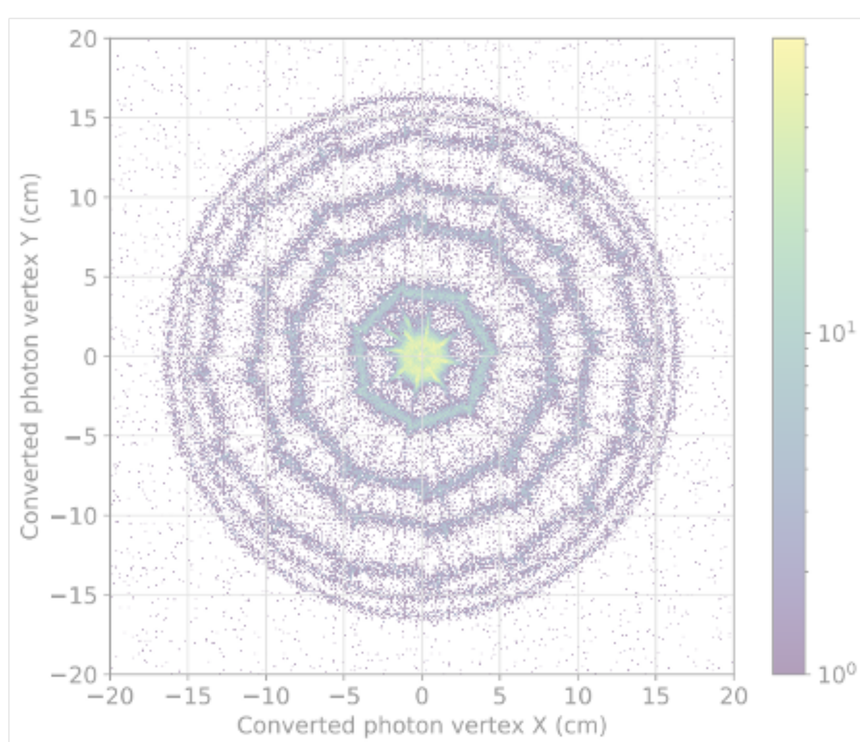
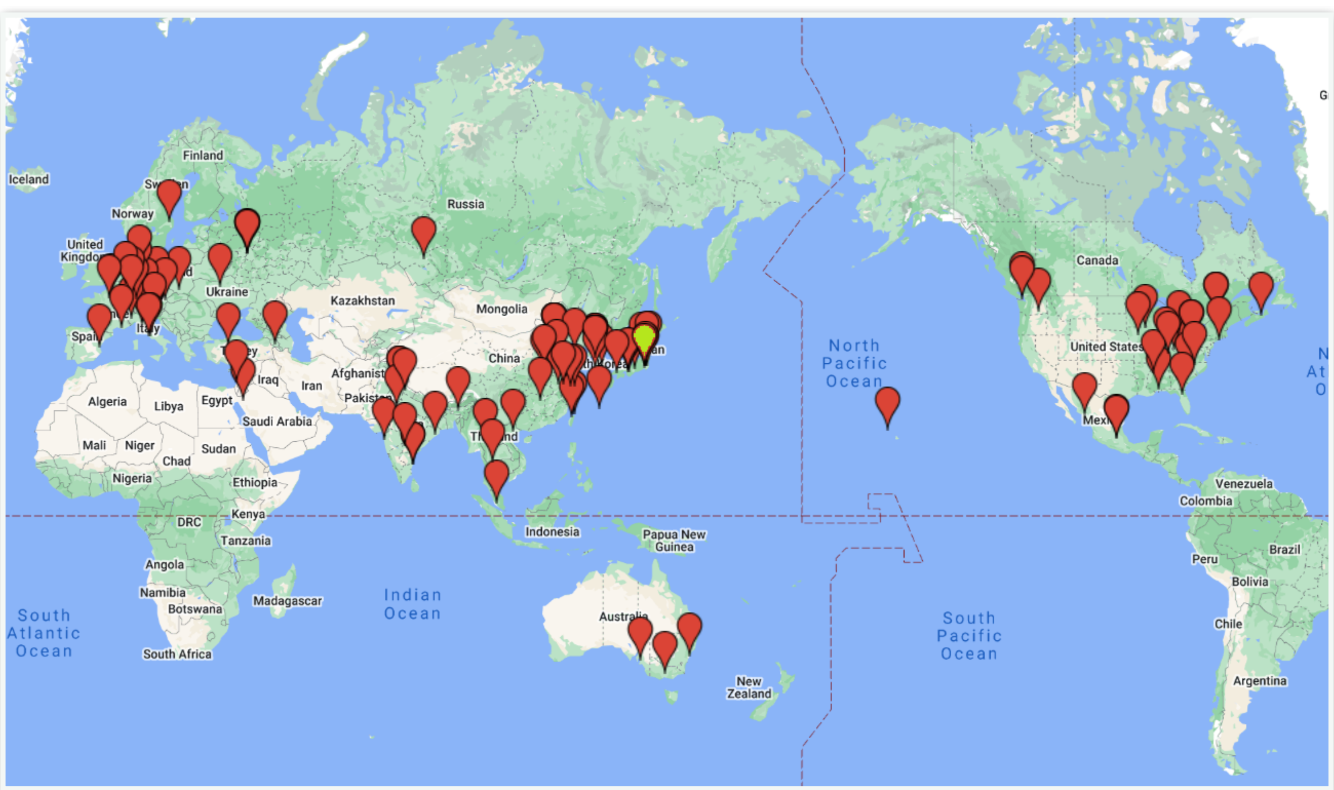


Belle II & Canadian Participation

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

- Seven Canadian institutes:
  - ➡ 15 grant eligible, 1 computing physicist, 4 postdocs, 12 graduate students, and 8 undergraduates.



U. British Columbia:
C. Hearty, J. McKenna, M. De Nuccio, R. Leboucher, M. Wakai, D. Crook, V. Sharma, K. Wang

U. Victoria:
M. Roney, R. Sobie, R. Kowalewski, T. Junginger, M. Ebert, T. Grammatico, A. Beaubien, N. Tessema, S. Gholipourverki, S. Taylor, Y. Peng

McGill:
A. Warburton, R. van Tonder, A. Fodor, T. Shillington, K. Chu

U. Manitoba:
S. Longo, J. Mammei, W. Deconinck, M. Gericke, I. Na, B. Blaikie, S. Saha, A. Tseragotin, A. Shakib, K. Reimer

U. Alberta:
S. Robertson

St. Francis Xavier:
H. Ahmed, E. Hunt, M. Penner

TRIUMF:
R. Baartman, T. Planche

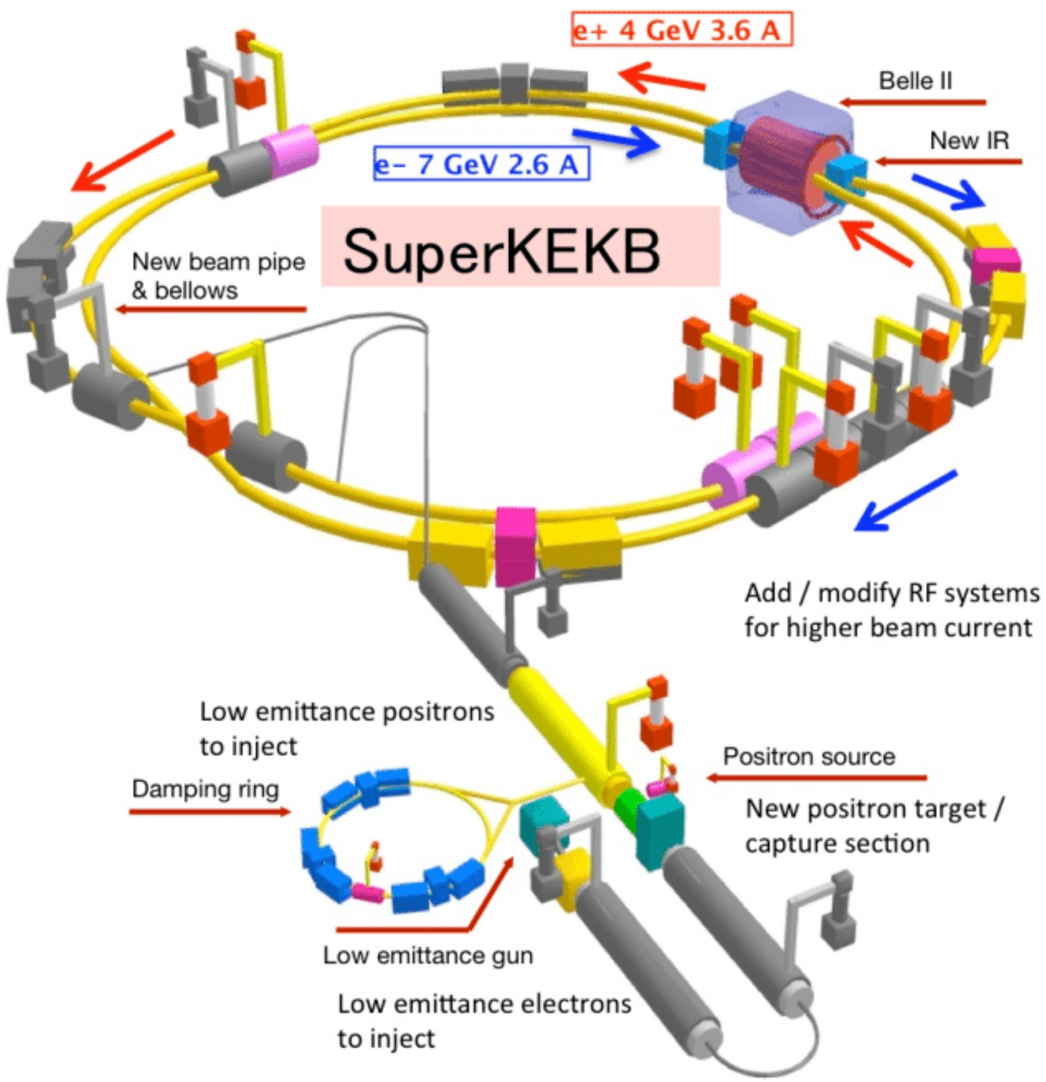
SuperKEKB in a nutshell

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

x30!

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

with record $4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$ already achieved!

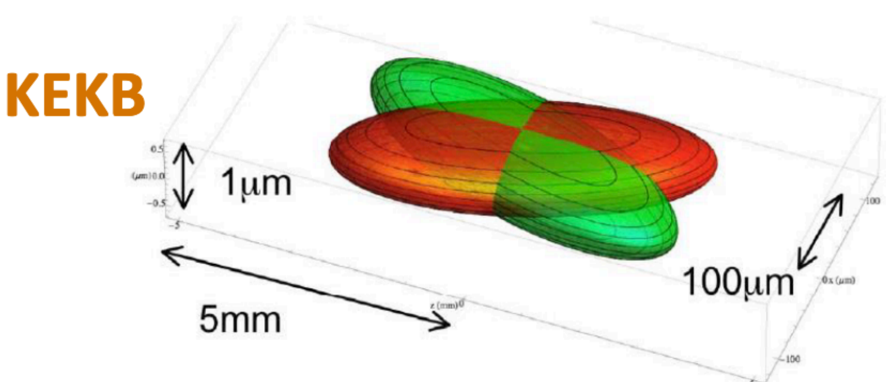


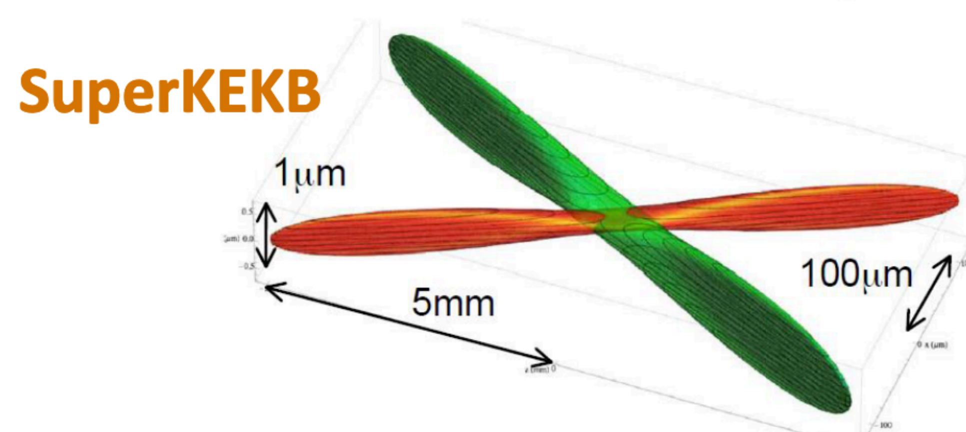
How to increase luminosity:

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

- Lorentz factor ($\gamma_\pm$)
- Beam size (σ_y^* / σ_x^*)
- Beam current ($I_\pm$) **x 1.5**
- Beam-beam parameter ($\zeta_{\pm y}$)
- Vertical $\boldsymbol{\beta}$ function (β_y^*) **x 1/20**
- Geometric factors (R_L / R_y)

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

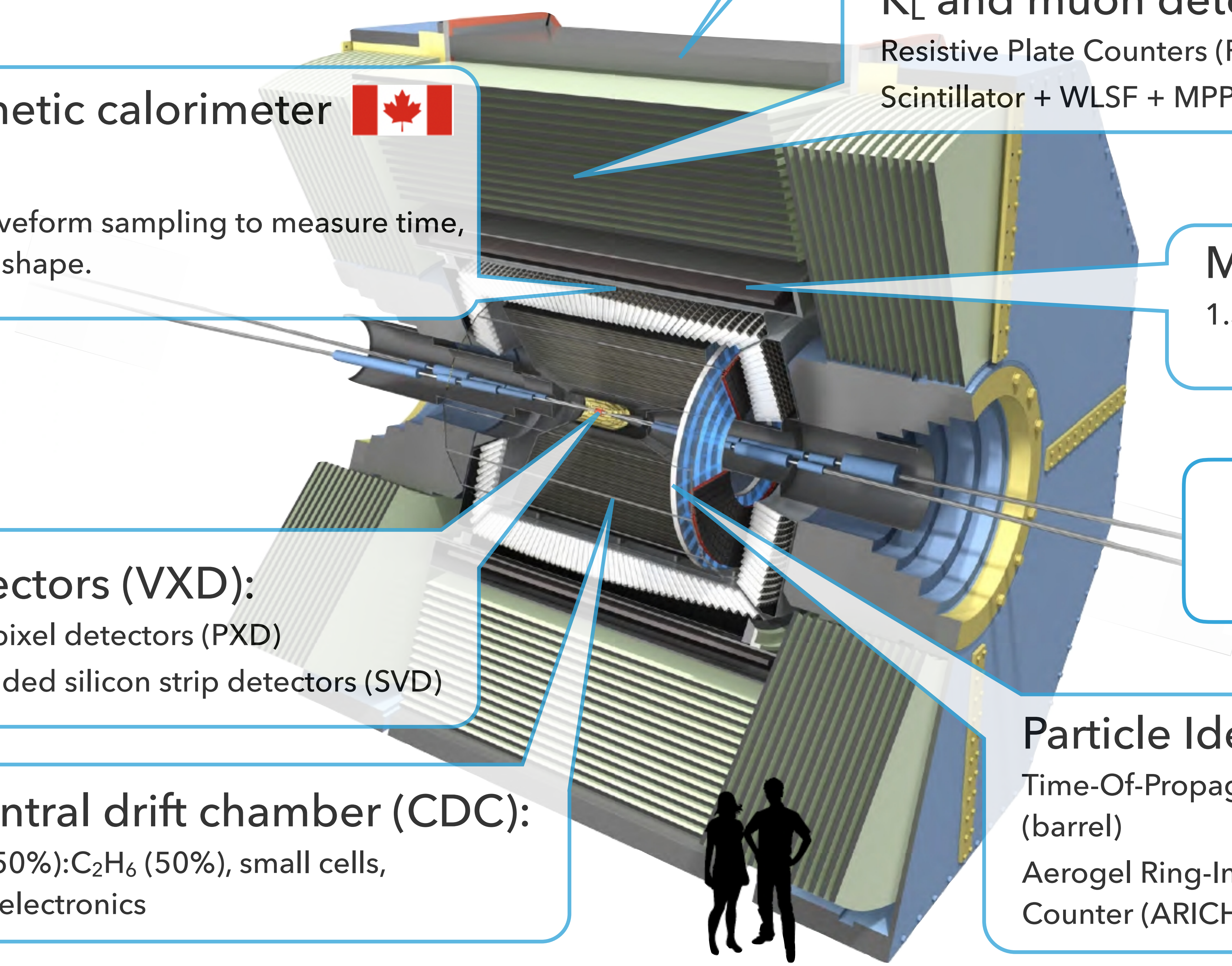





Mt. Tsukuba
Belle II
Detector
SuperKEKB
(HER + LER)
Damping ring
(e^+)
Linac
KEK Tsukuba
Campus
Japan
Belle II
Tsukuba
/ KEK
Tokio

Belle II Detector

- Operates as **magnetic spectrometer** with **high detection efficiency** for charged and neutral particles.



Re-utilized from Belle:
Only the structure, superconducting magnets, calorimeter crystals and KLM RPCs

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals, waveform sampling to measure time, energy, and pulse-shape.

Magnet:
1.5 T superconducting

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

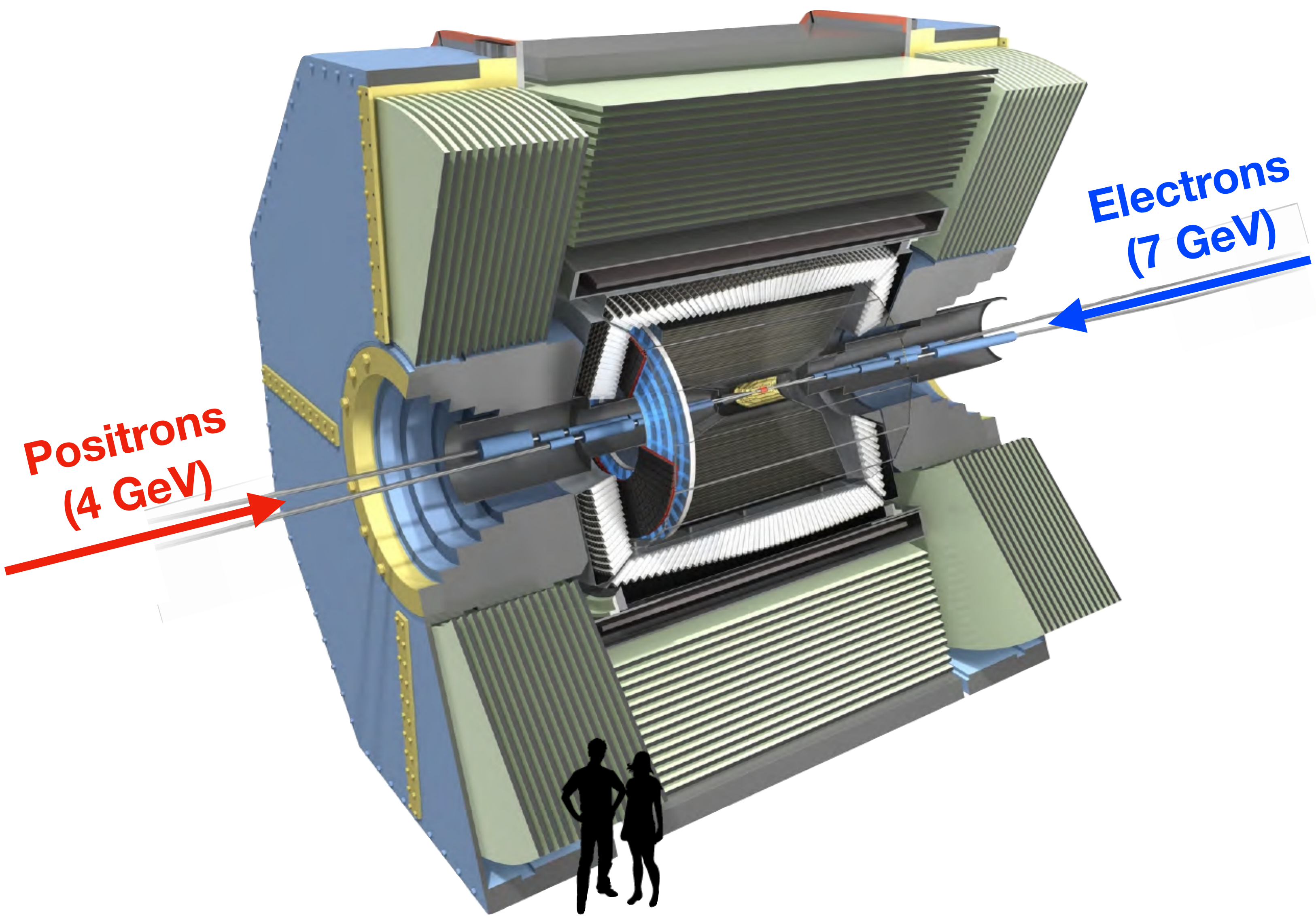
Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
$He(50\%):C_2H_6$ (50%), small cells, fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

B-meson production at B-Factories

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



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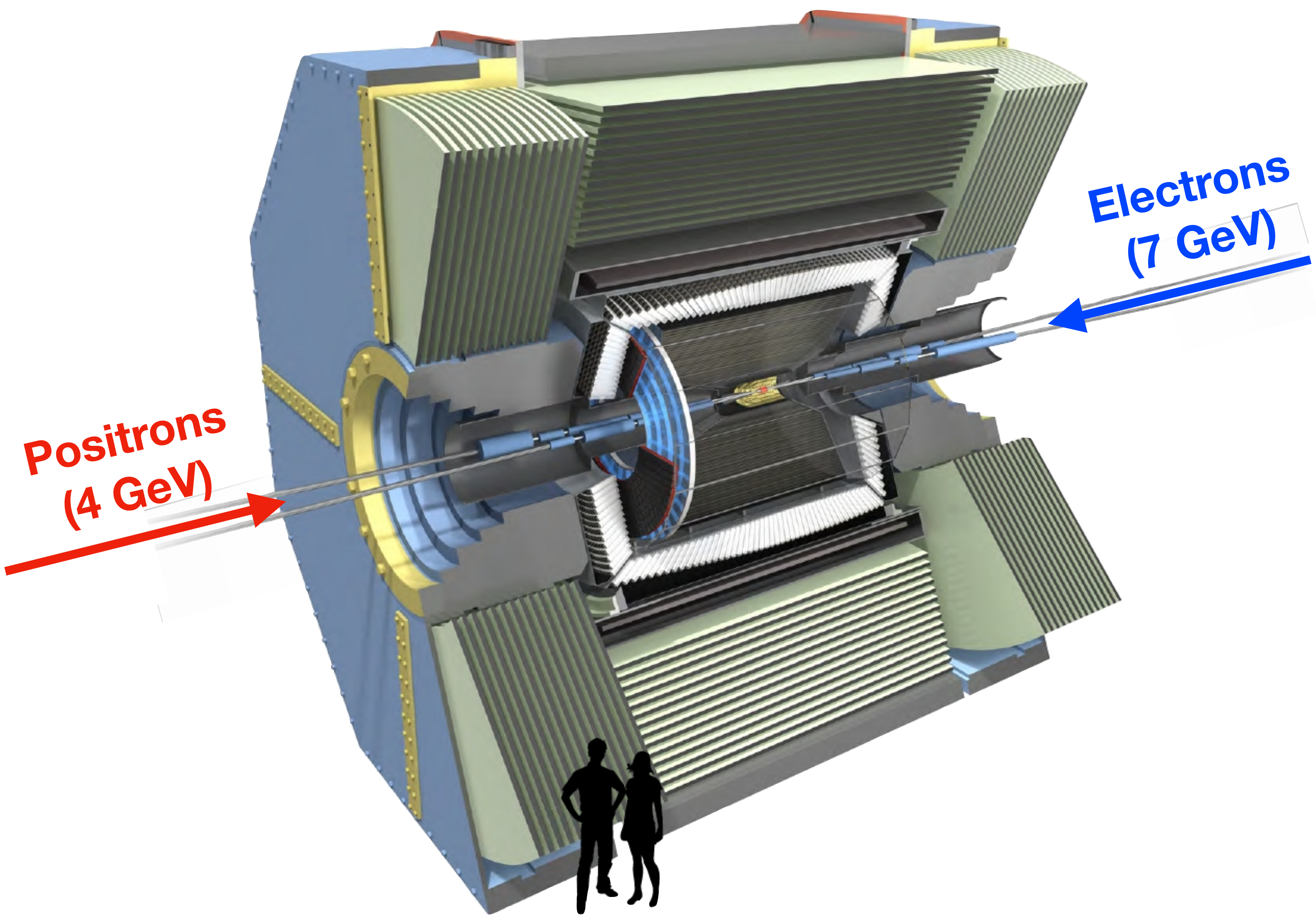

Collide electrons and positrons at a **centre of mass energy** of about twice the B meson mass:

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

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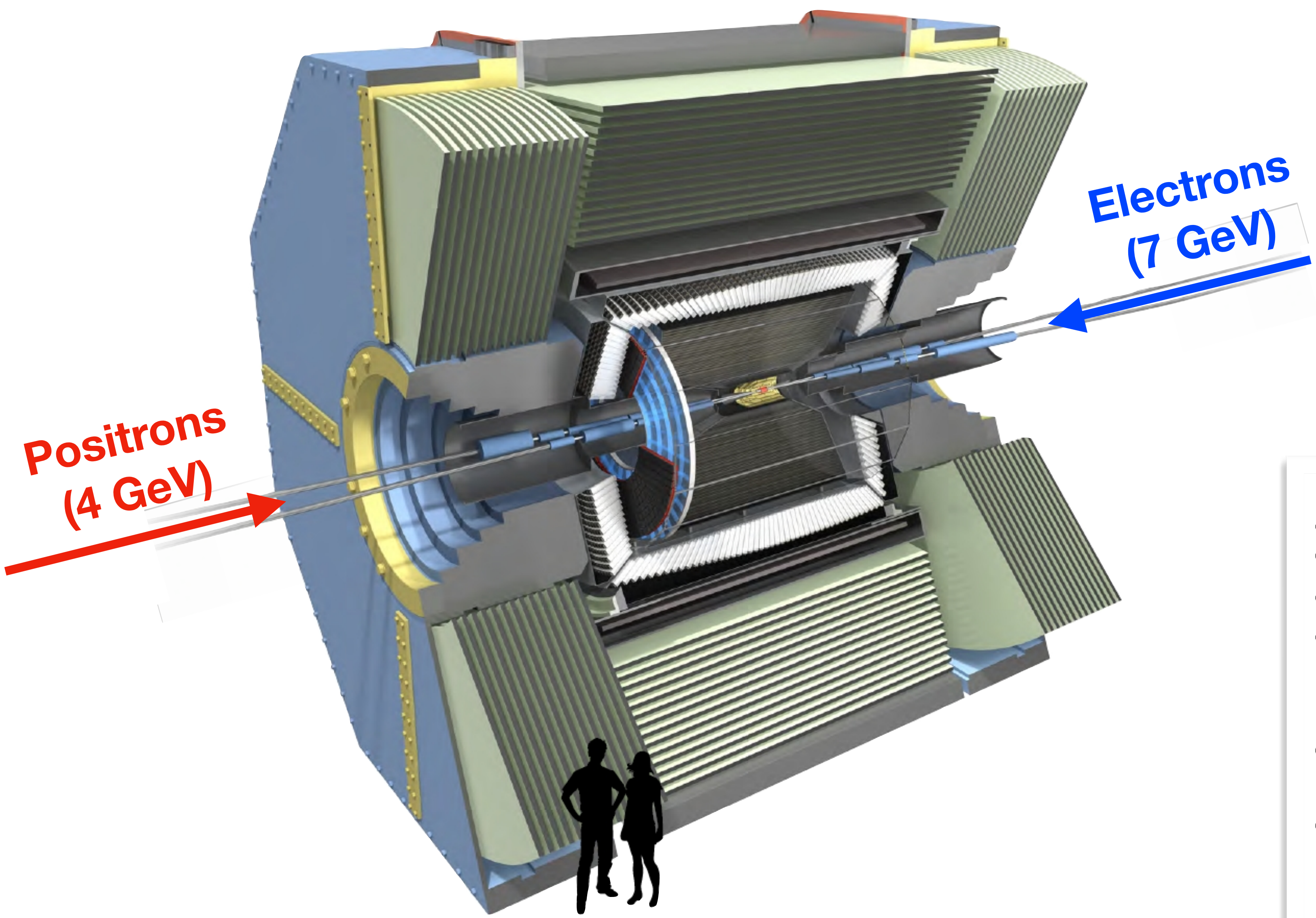

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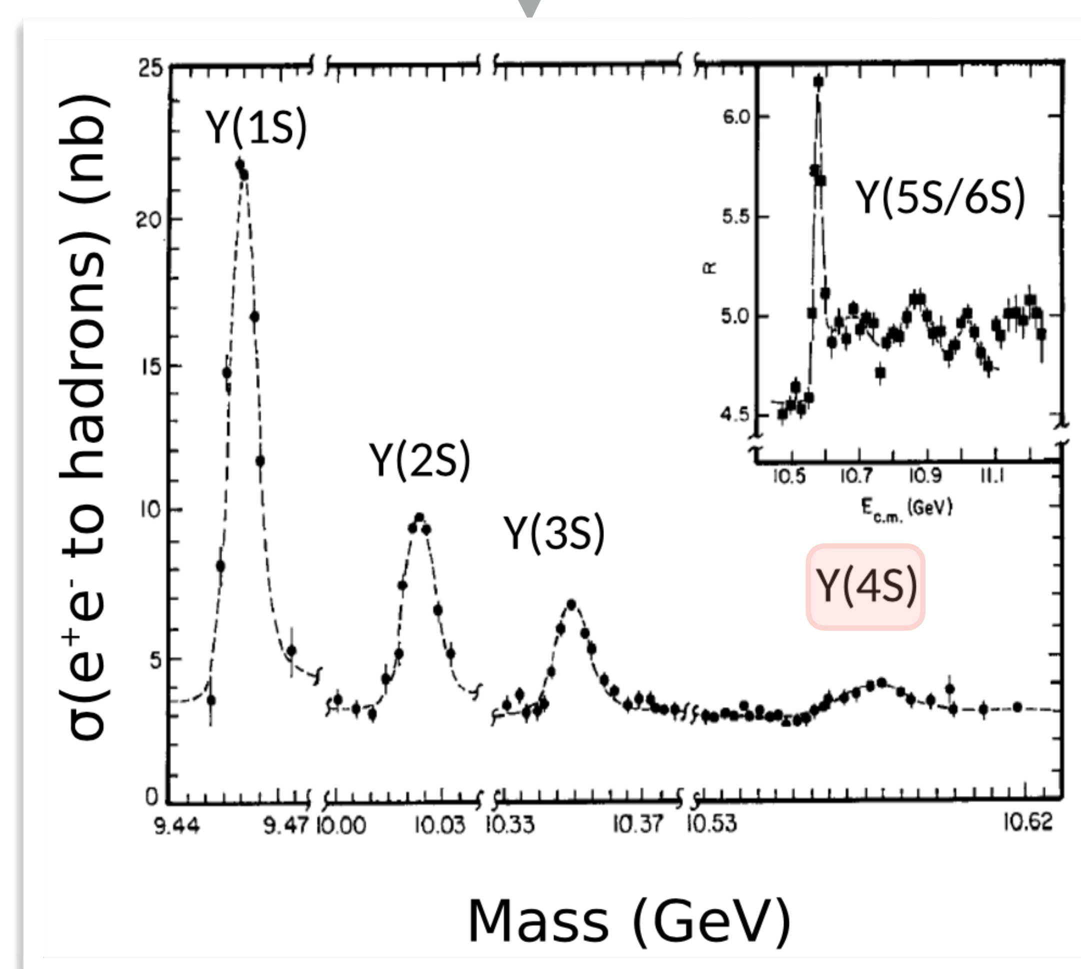

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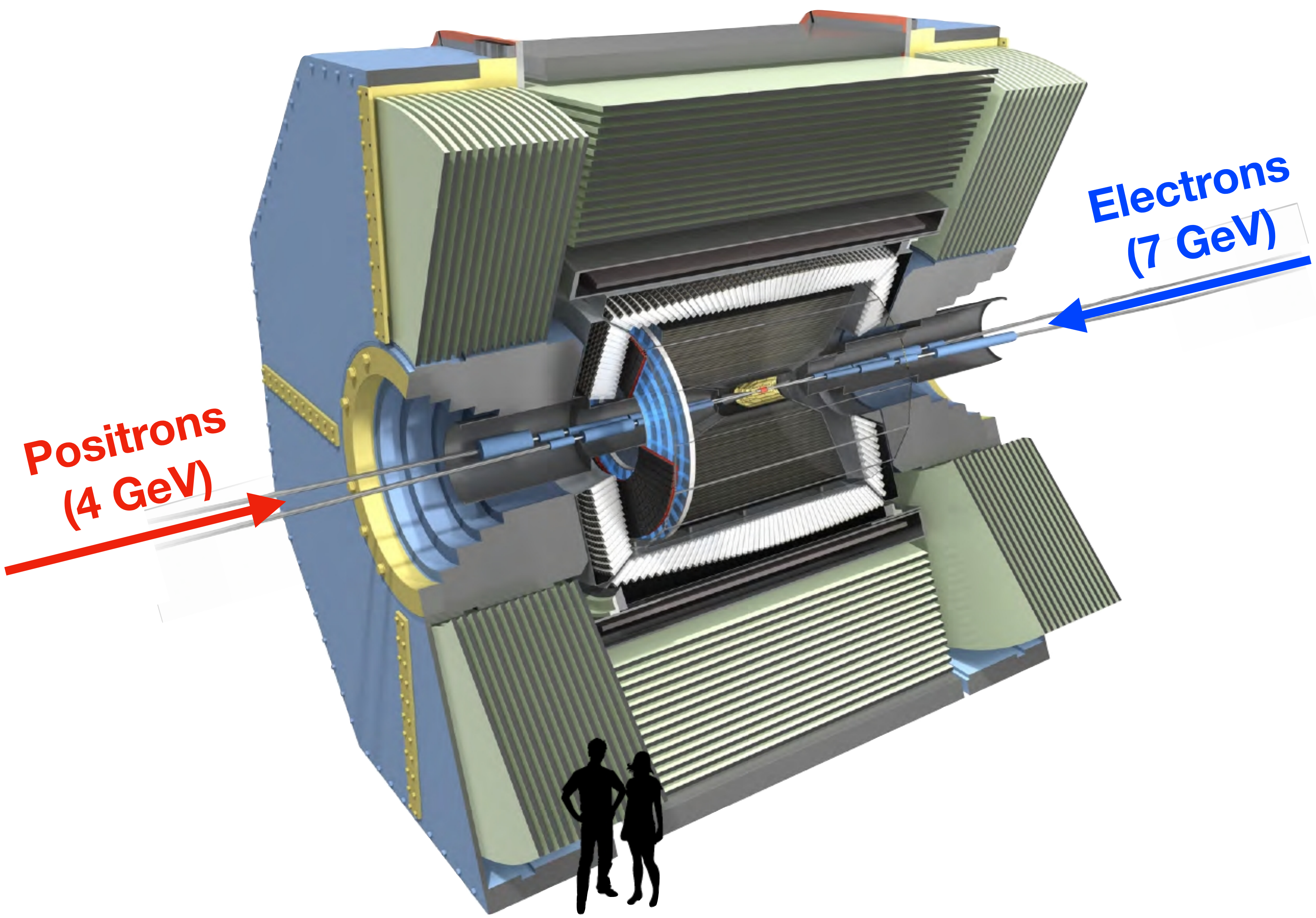

Collide electrons and positrons at a **centre of mass energy** of about twice the B meson mass:

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

$$\downarrow$$

$$\Upsilon(4S)$$

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

B-meson production at B-Factories

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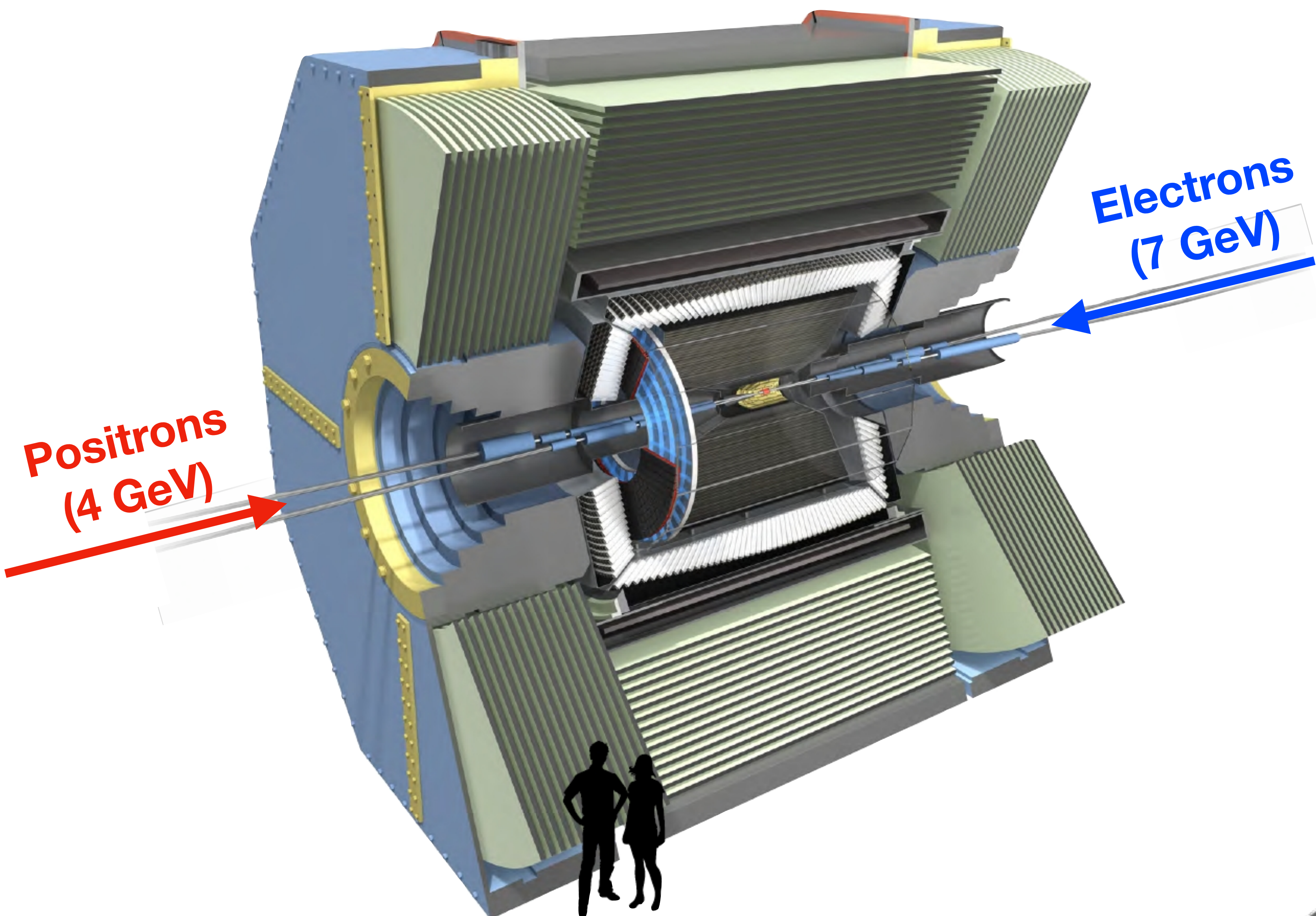

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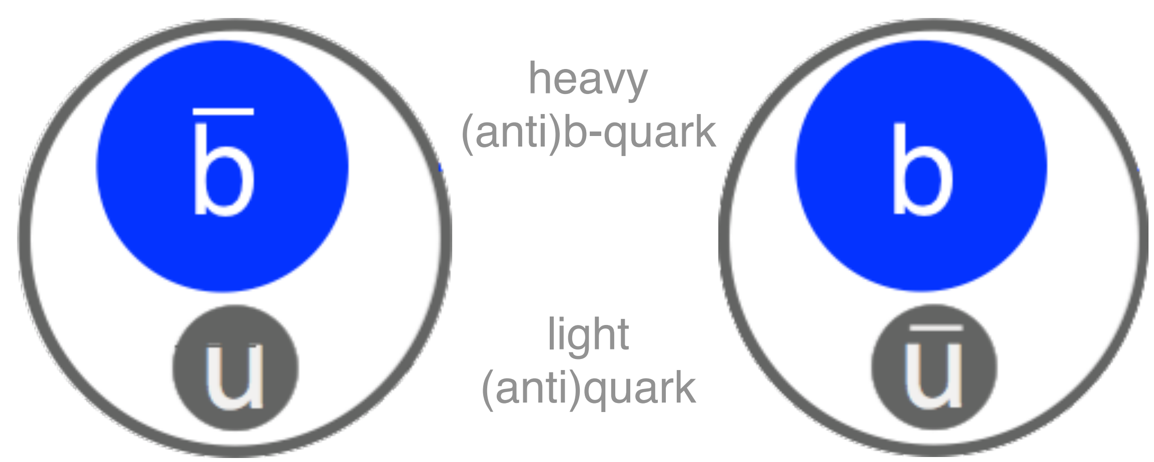
$$\Upsilon(4S)$$

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

B meson **anti-B meson**

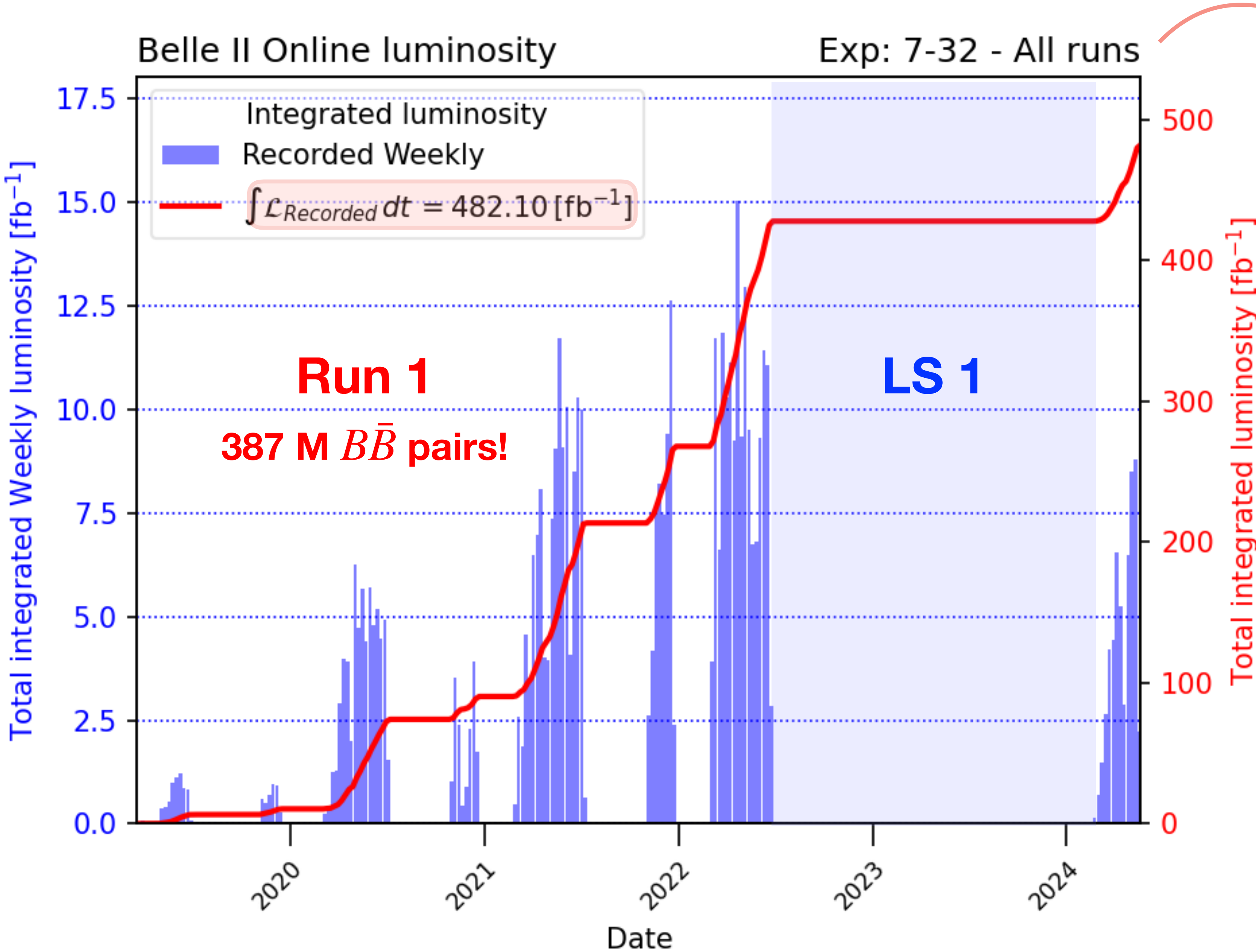


Advantages: Precisely known initial state, unique event topology & experimentally clean environment

Luminosity status

Online Luminosity

- Belle II has recorded a **total integrated luminosity** of 428 fb^{-1} since March 2019
  - Compared to previous B-Factories: Belle 988 fb^{-1} & BaBar 513 fb^{-1}
- Current status: **Run 2** started on **20 February 2024** after a long shutdown period to install two-layer pixel detector and machine maintenance.



World record!

Instantaneous luminosity:

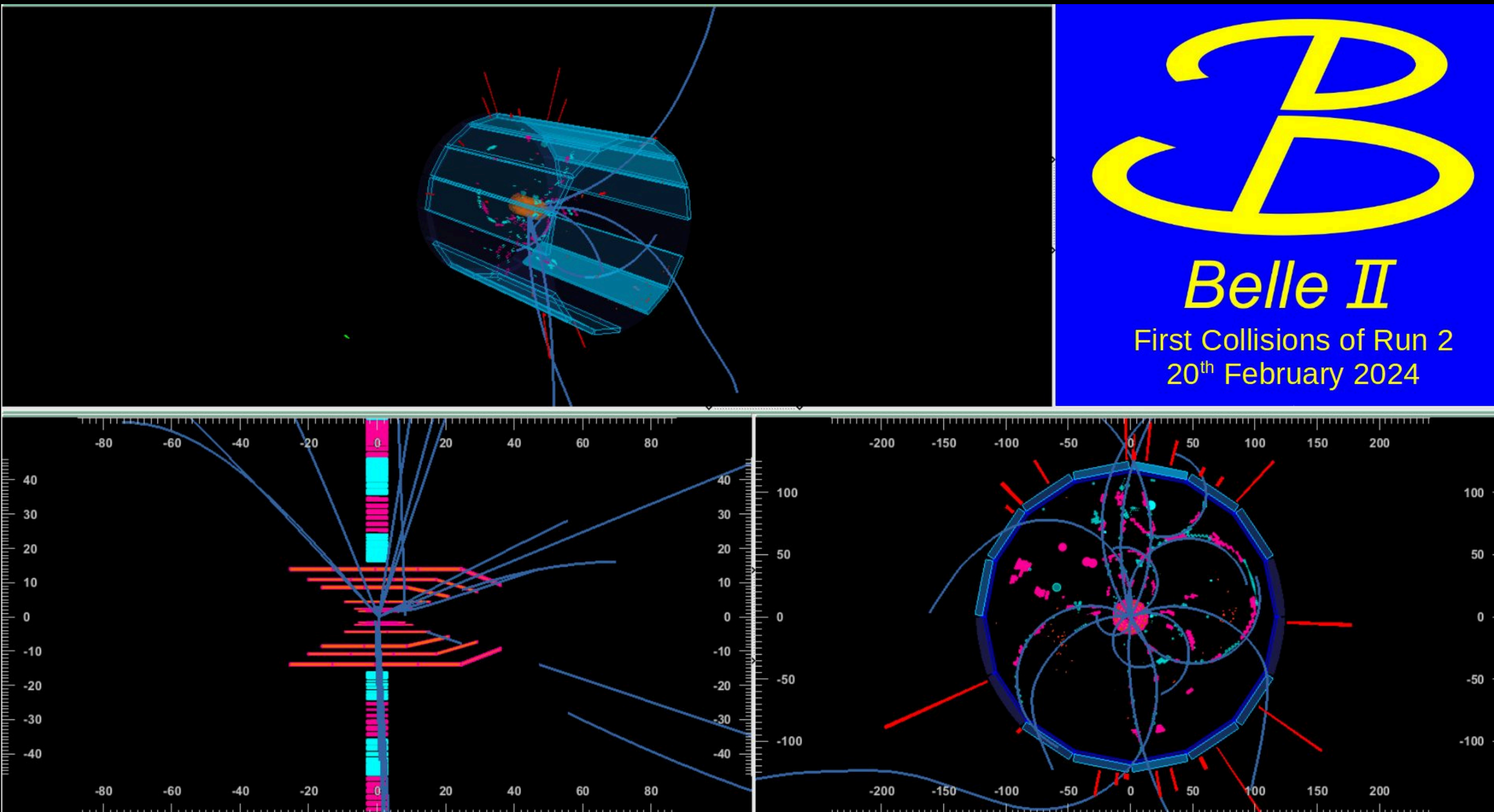
$L_{peak} = 4.7 \times 10^{34}\ cm^{-2}\ s^{-1}$

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)


Belle II
First Collisions of Run 2
20th February 2024

Physics program

Belle II Physics Book

Snowmass White Paper

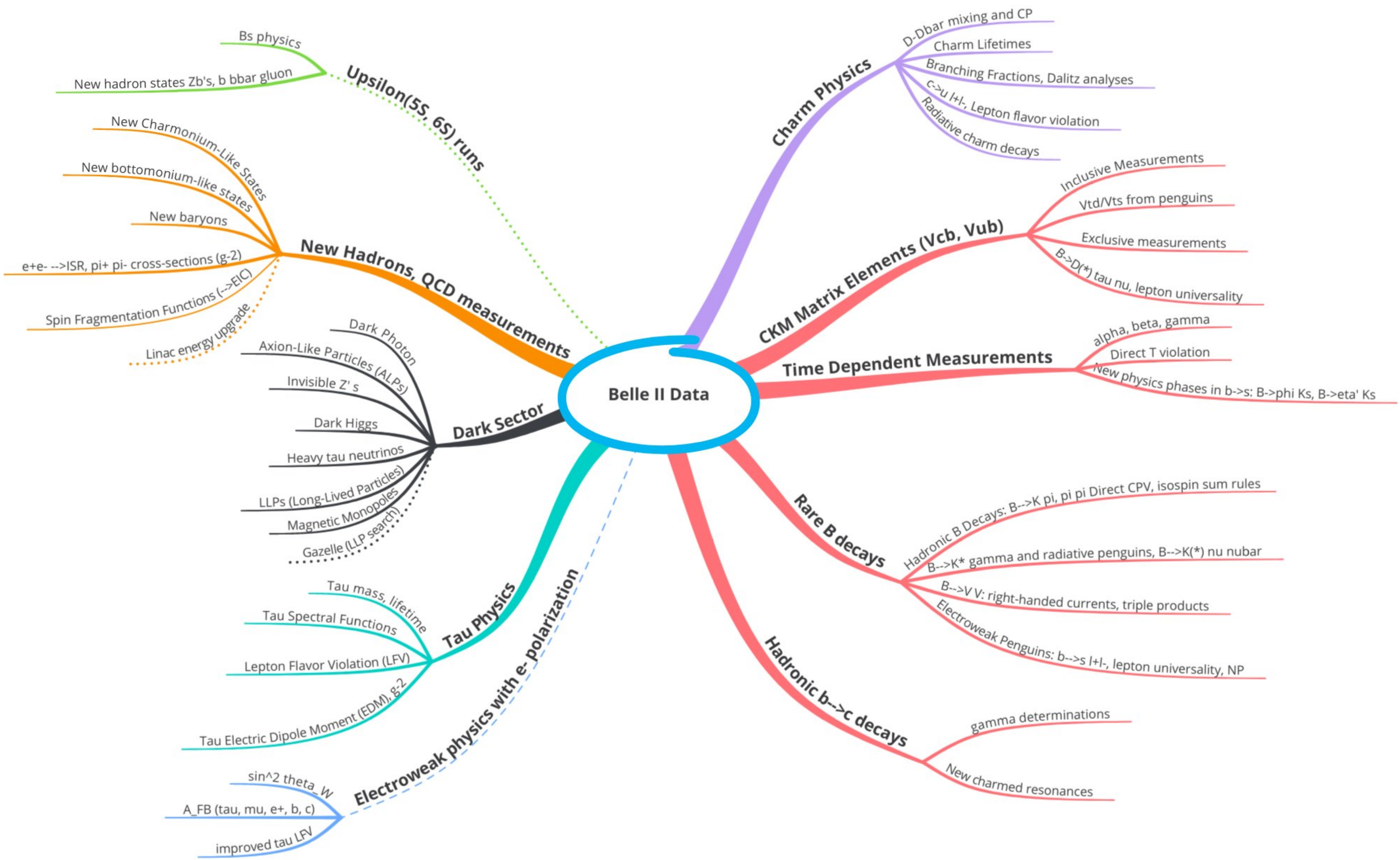


Image credit: T. Browder

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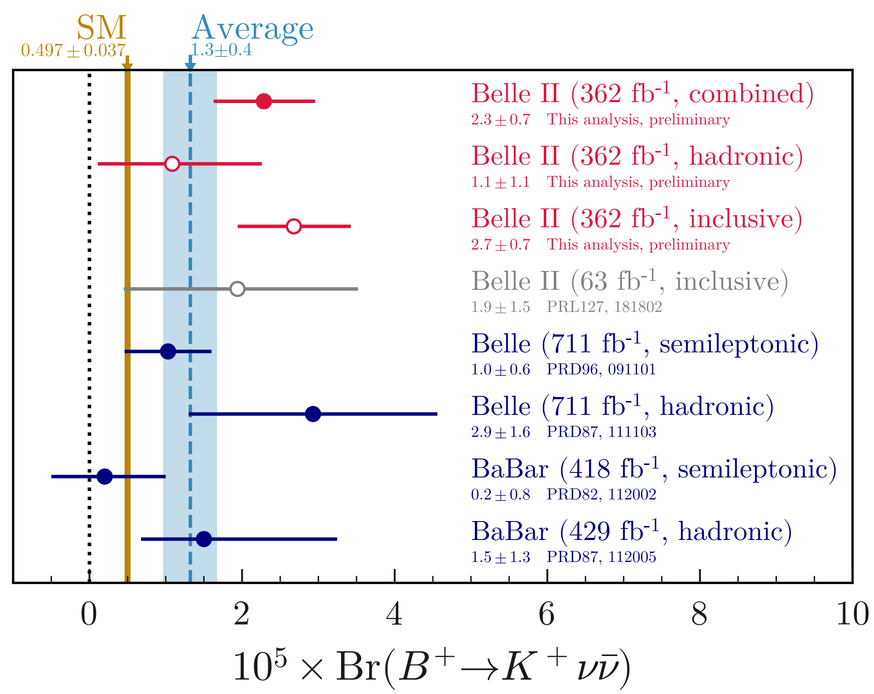

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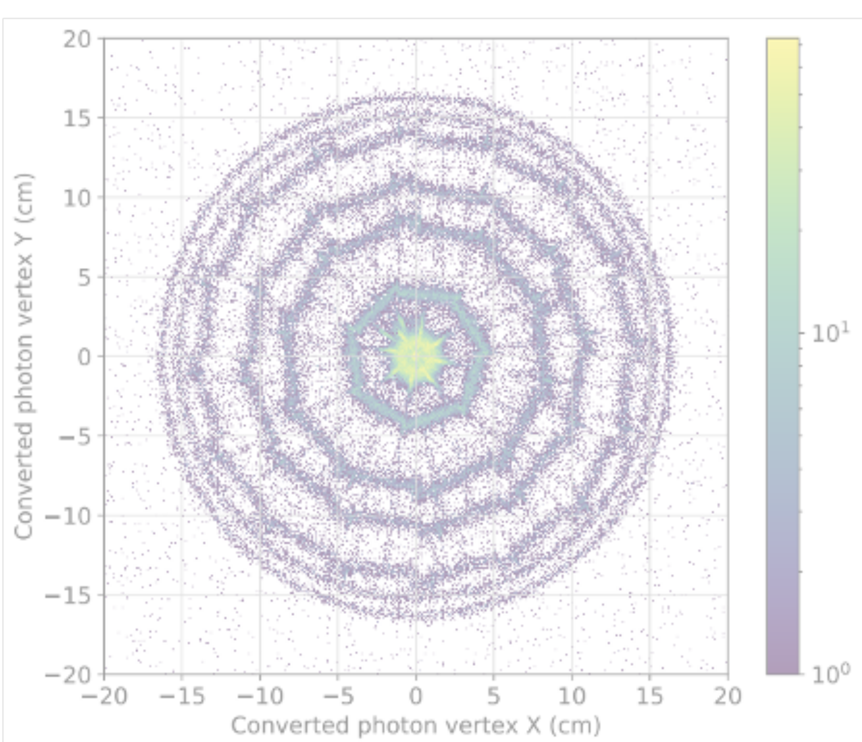
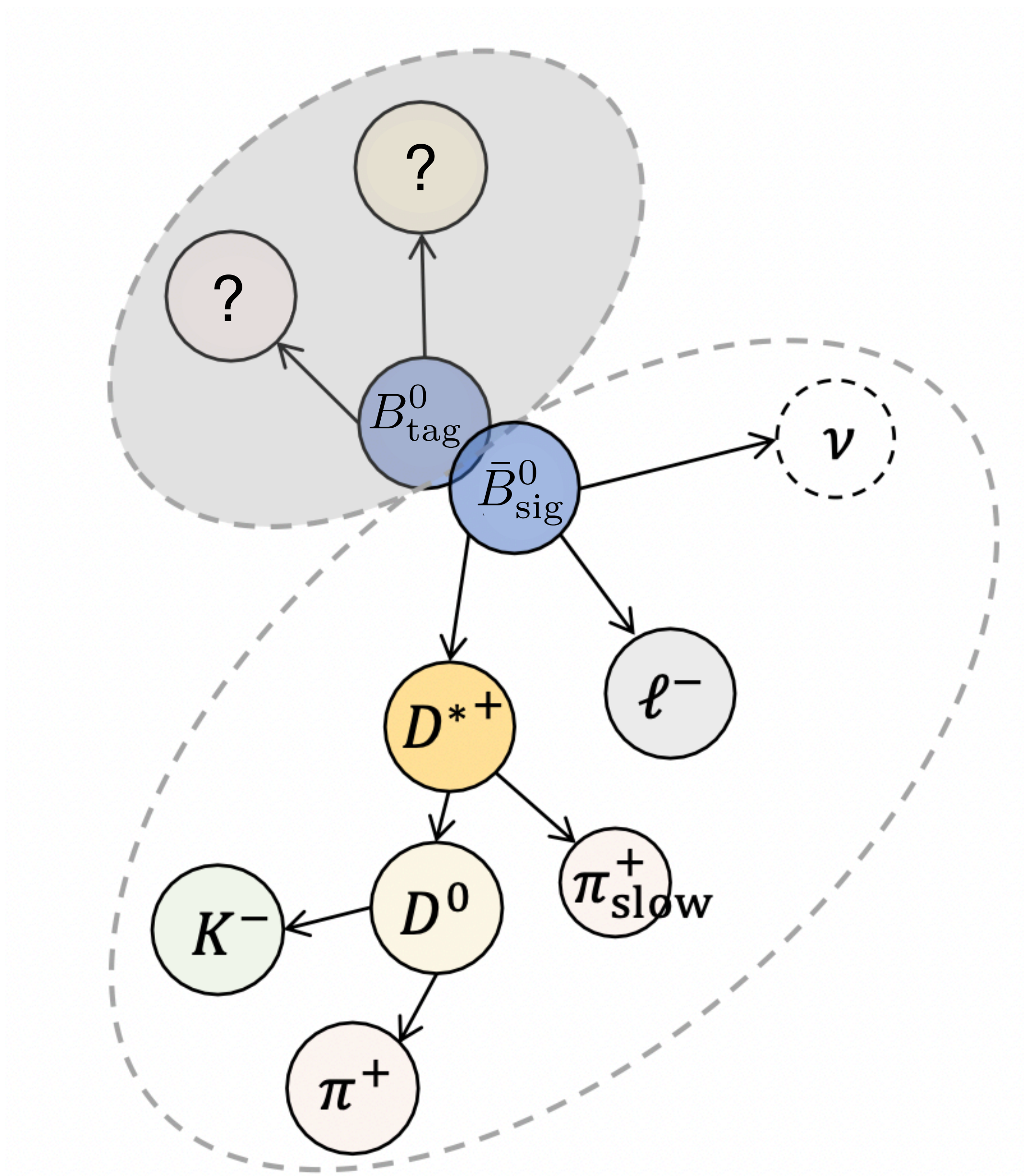


Reconstruction at B-Factories

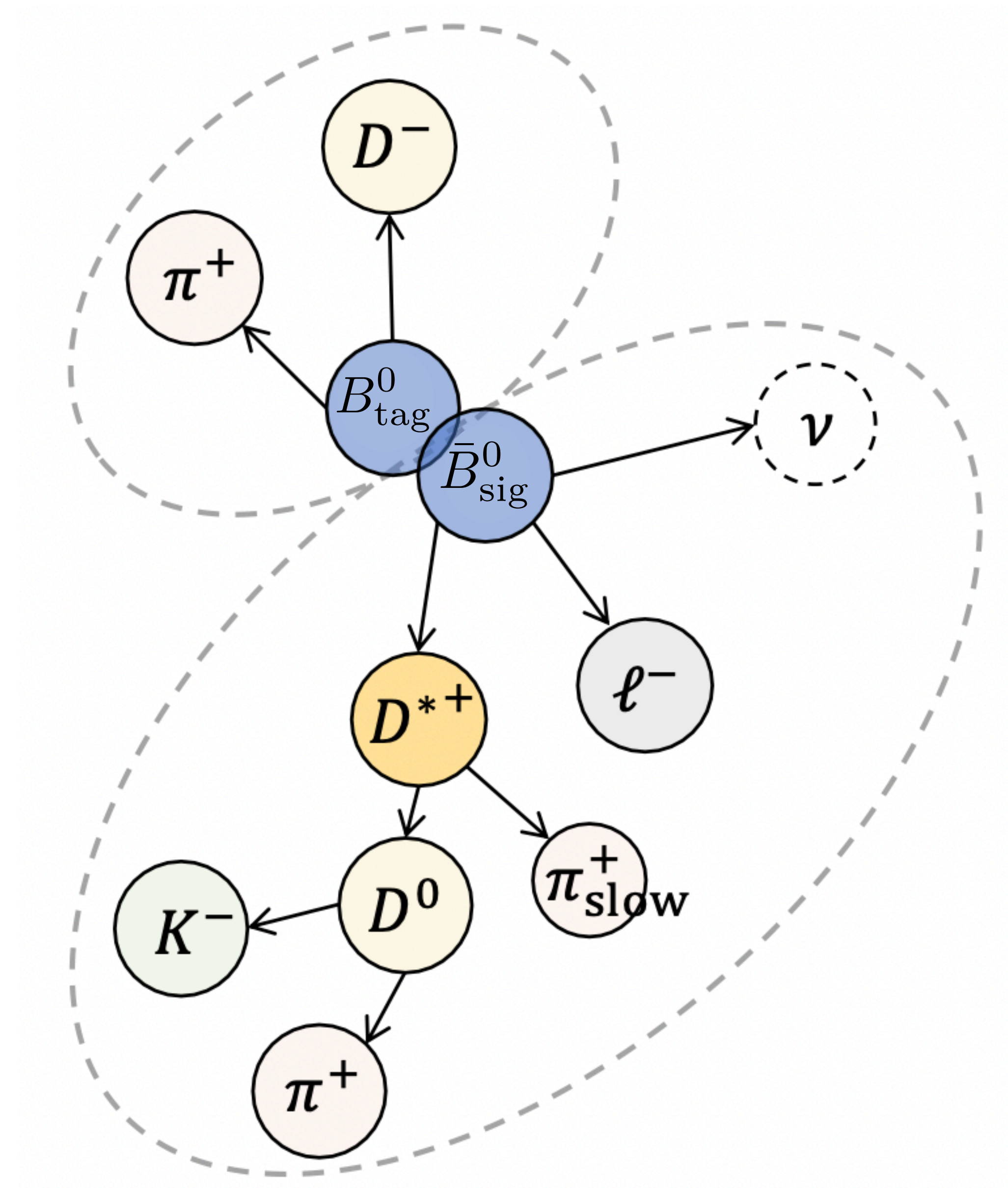
Inclusive/Untagged

Only reconstruct the signal B meson (B_{sig}).



Hadronic tagged

Reconstruct B_{tag} with (many) hadronic decay modes.



← Efficiency, backgrounds

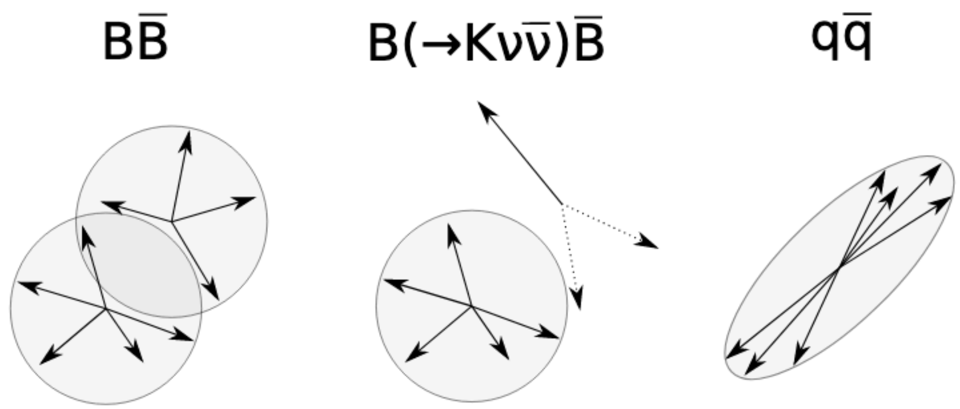
Purity, available observables →

Image credit: K. Kojima

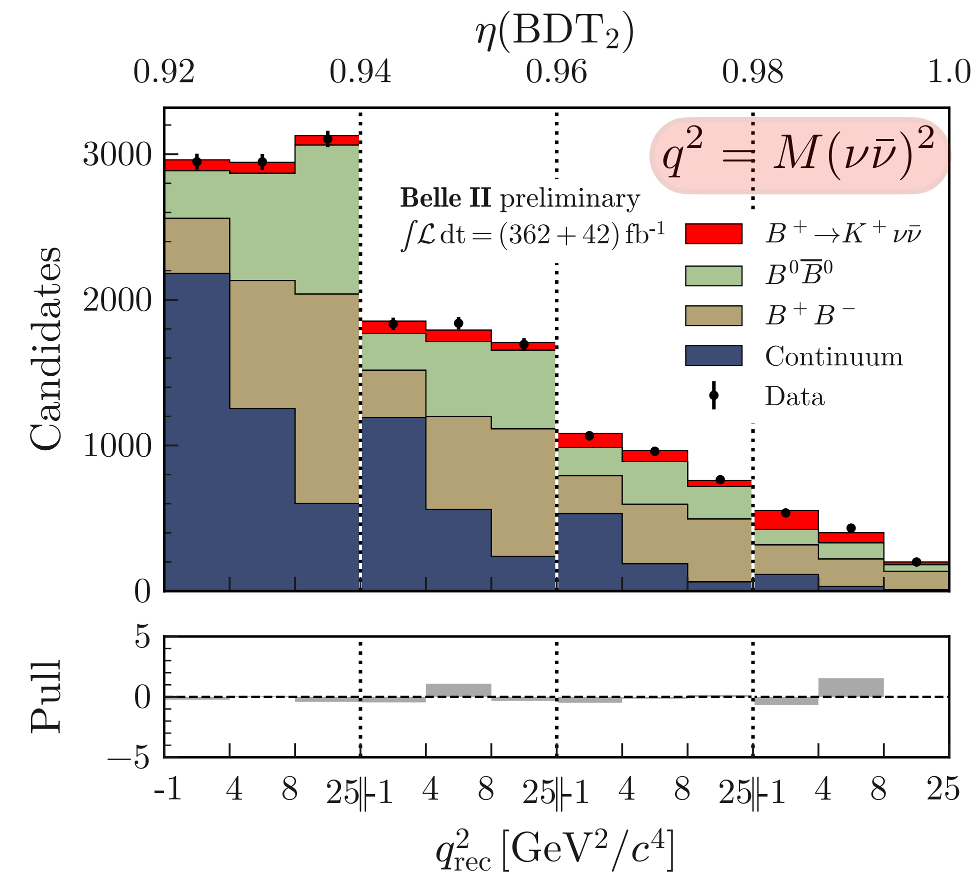
Evidence for $B^+ \to K^+ \nu \bar{\nu}$

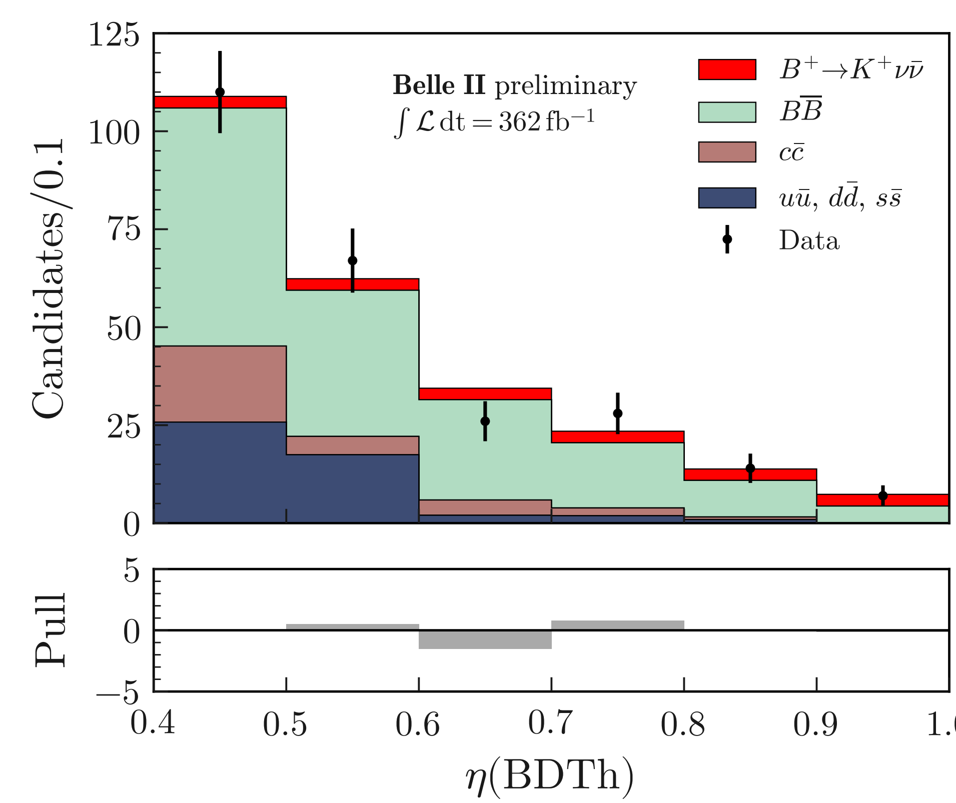
arXiv:2311.14647

- Very sensitive to beyond-Standard Model enhancements and complementary to $b \to s\ell^+\ell^-$.
- Experimentally challenging due to **multiple missing particles** on the signal side —only accessible at e^+e^- colliders!
- Two independent analyses, utilizing **inclusive and hadronic tagging** approaches, run in parallel.
- Both approaches exploit distinctive topological features with BDTs to **select events and suppress backgrounds**



- **Signal extraction strategies,**
  - Inclusive approach: Fit to signal classifier BDT_2 in bins of dineutrino mass-squared (q^2_{rec})
  - Tagged approach: Fit to signal classifier $\eta(\mathrm{BDTh})$





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

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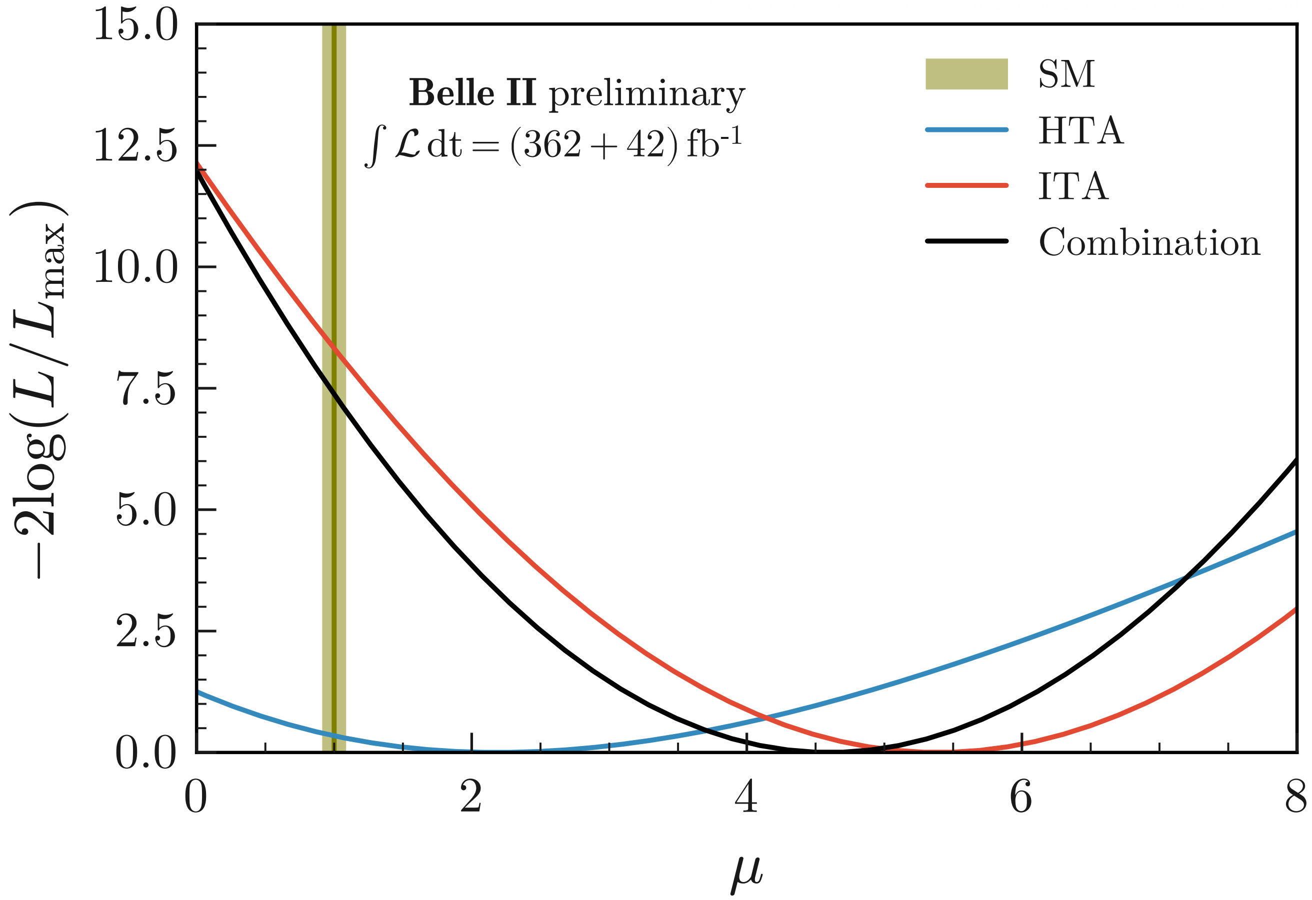
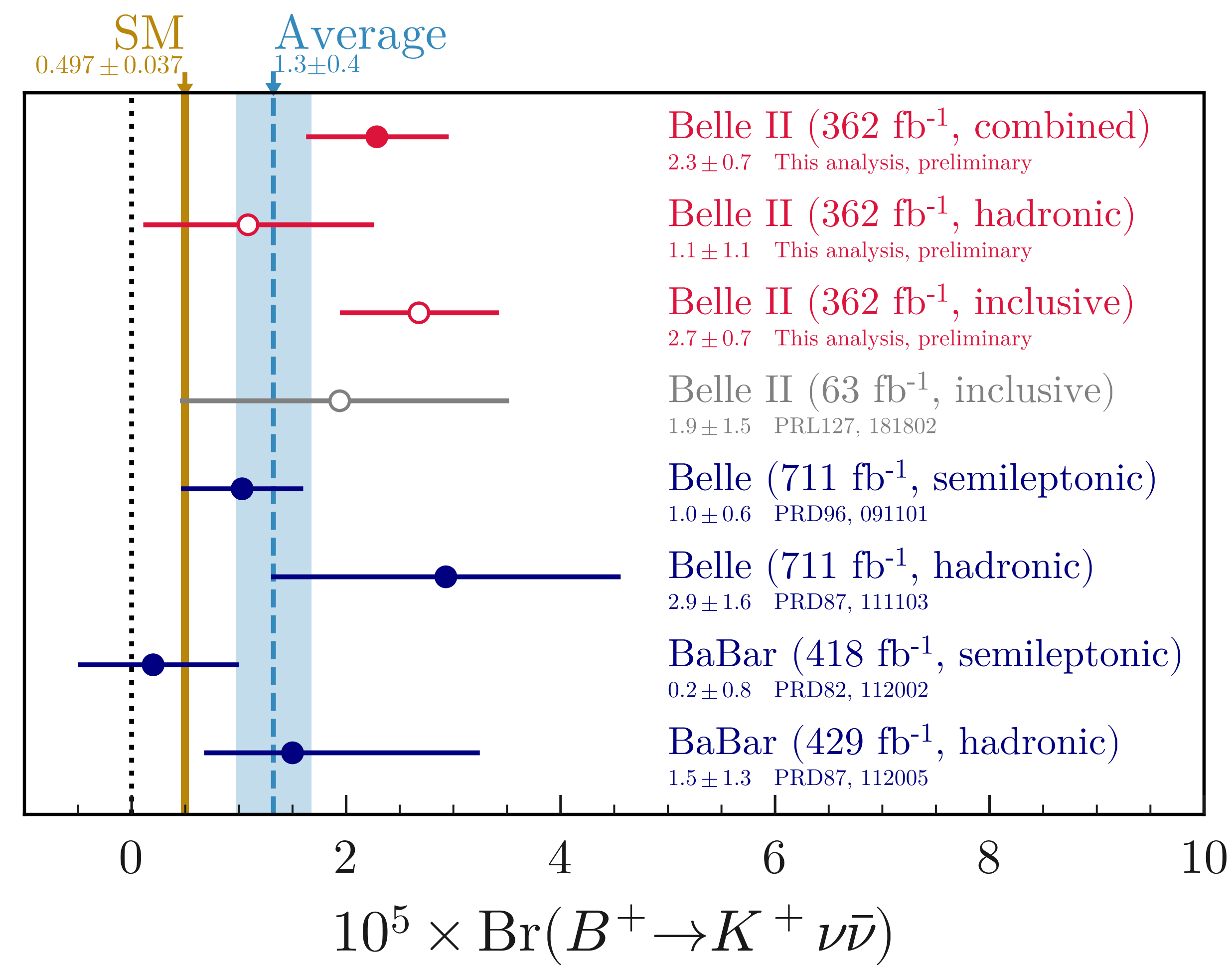
μ = measured BF / SM BF





Combined results:

Signal strength: $\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$

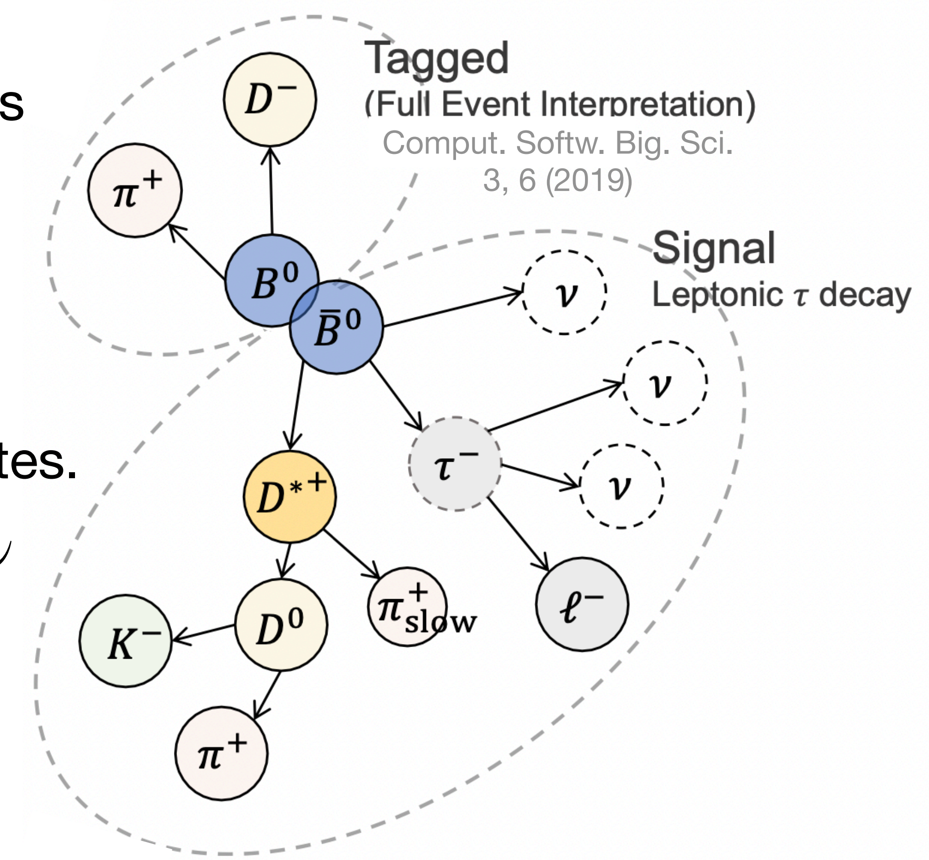
Branching ratio: $BR(B^+ \to K^+ \nu\bar{\nu}) = [2.4 \pm 0.5(\text{stat})^{0.5}_{-0.4}(\text{syst})] \times 10^{-5}$

First evidence of $B^+ \to K^+ \nu\bar{\nu}$ (3.5σ) with BR in excess of SM by 2.7σ

Measurement of $R(D^*)$

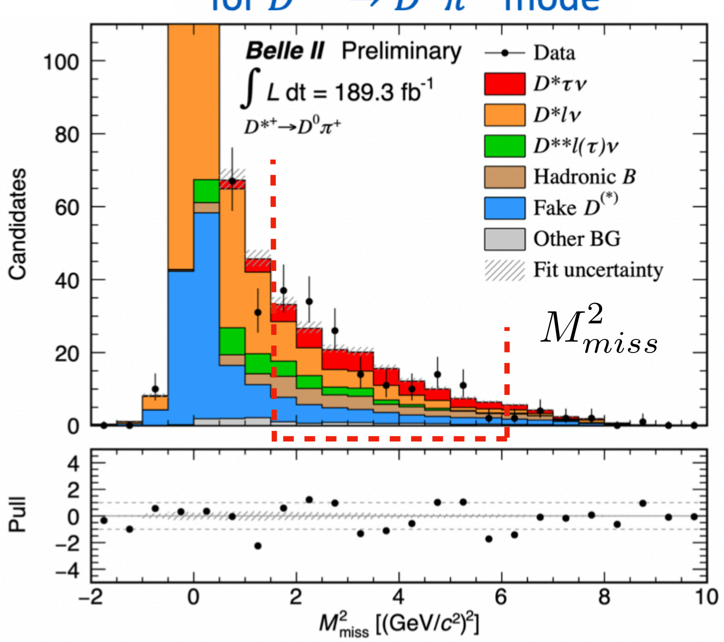
arXiv:2401.02840

Measure: $R(D^*) = \dfrac{\mathcal{B}(B \to D^* \tau \nu_\tau)}{\mathcal{B}(B \to D^* \ell \nu_\ell)}$ to cancel many systematics



- Consider three signal modes: $D^{*+} \to D^0\pi^+$ and $D^+\pi^-$, $D^{*0} \to D^0\pi^0$
- Identify lepton from $\tau \to \ell\nu\bar{\nu}$
- Completeness constraint require **no additional tracks** or π^0 candidates.
- **Main challenge:** understand significant & poorly known $B \to D^{**}\ell\nu$ background decays.
  - **Data-driven validation** of background and signal modelling based on studies of sideband regions.
- **Extract signal** with 2D fit to residual energy in the calorimeter E_{ECL} & mass of undetected neutrinos $M^2_{miss} = (p_{e^+e^-} - p_{B_{tag}} - p_{D^*} - p_\ell)^2$

Zoom of M^2_{miss} projection for $D^{*+} \to D^0\pi^+$ mode



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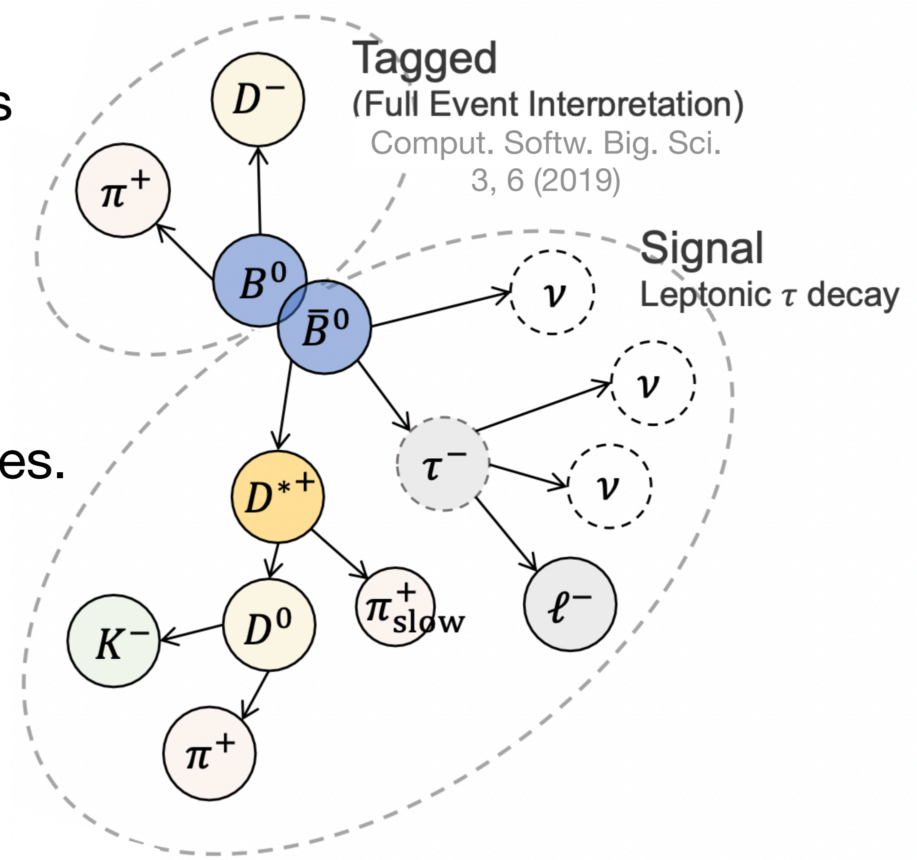

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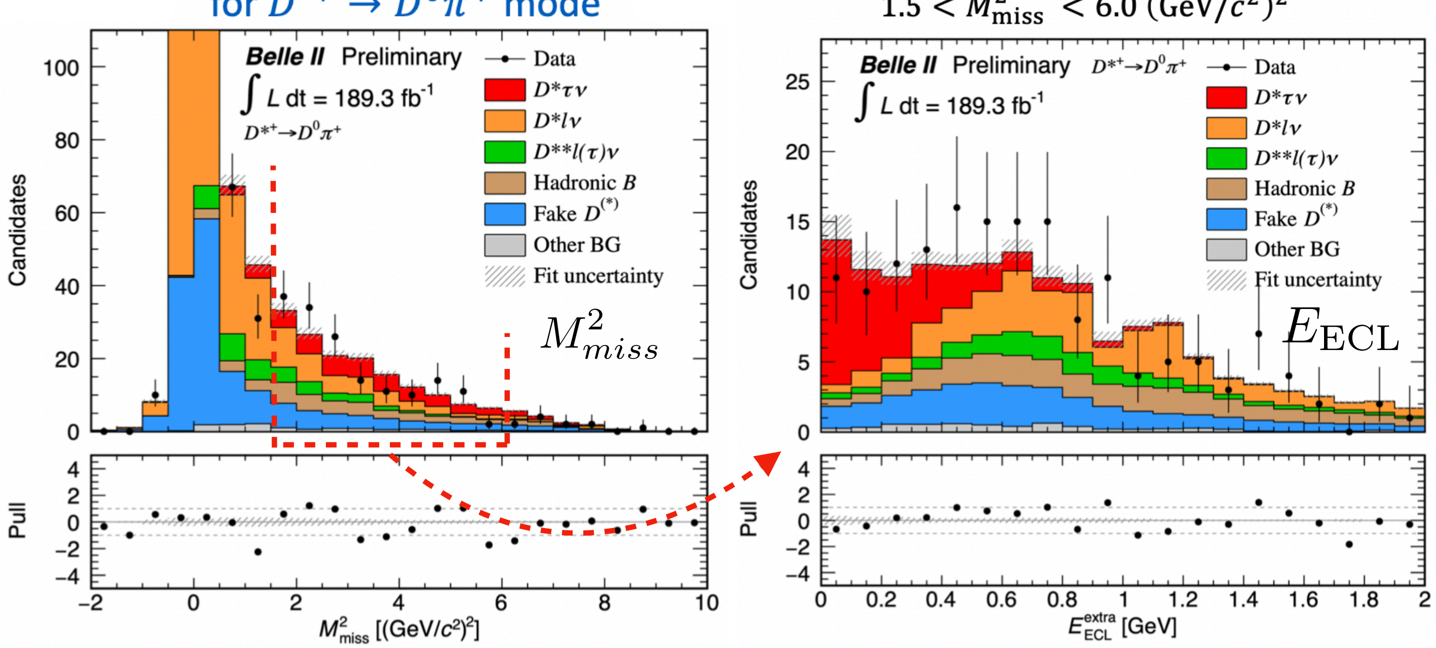
Zoom of $M^2_{\rm miss}$ projection for $D^{*+} \to D^0\pi^+$ mode

Signal-enhanced projection

$1.5 < M^2_{\rm miss} < 6.0\ (\text{GeV}/c^2)^2$



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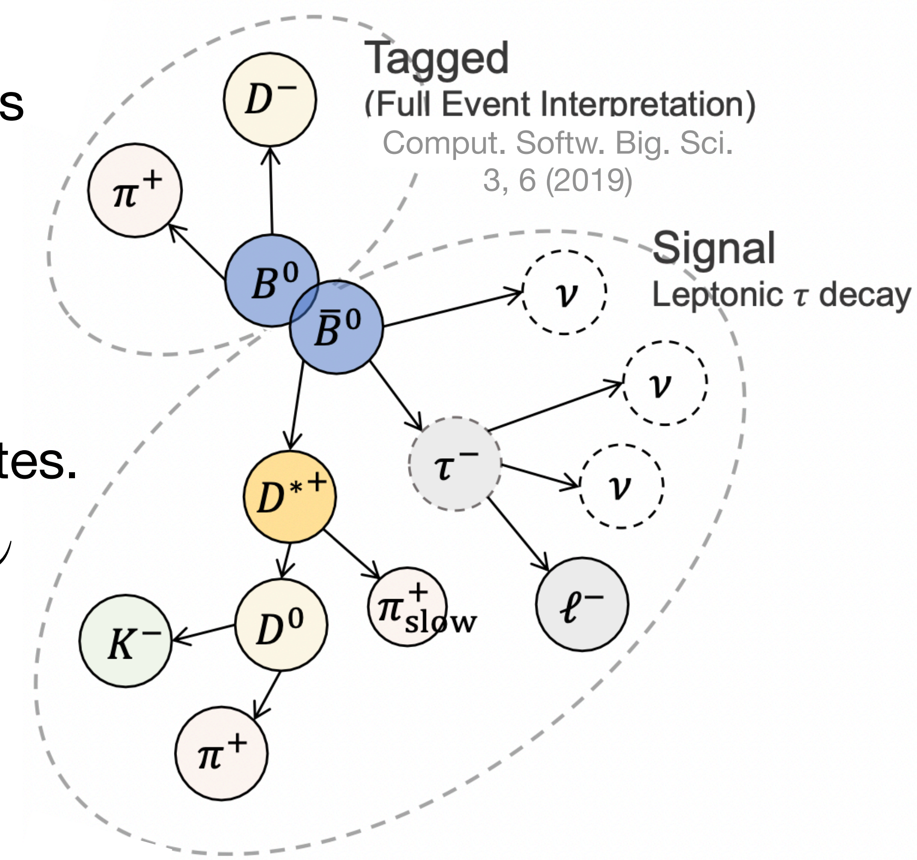

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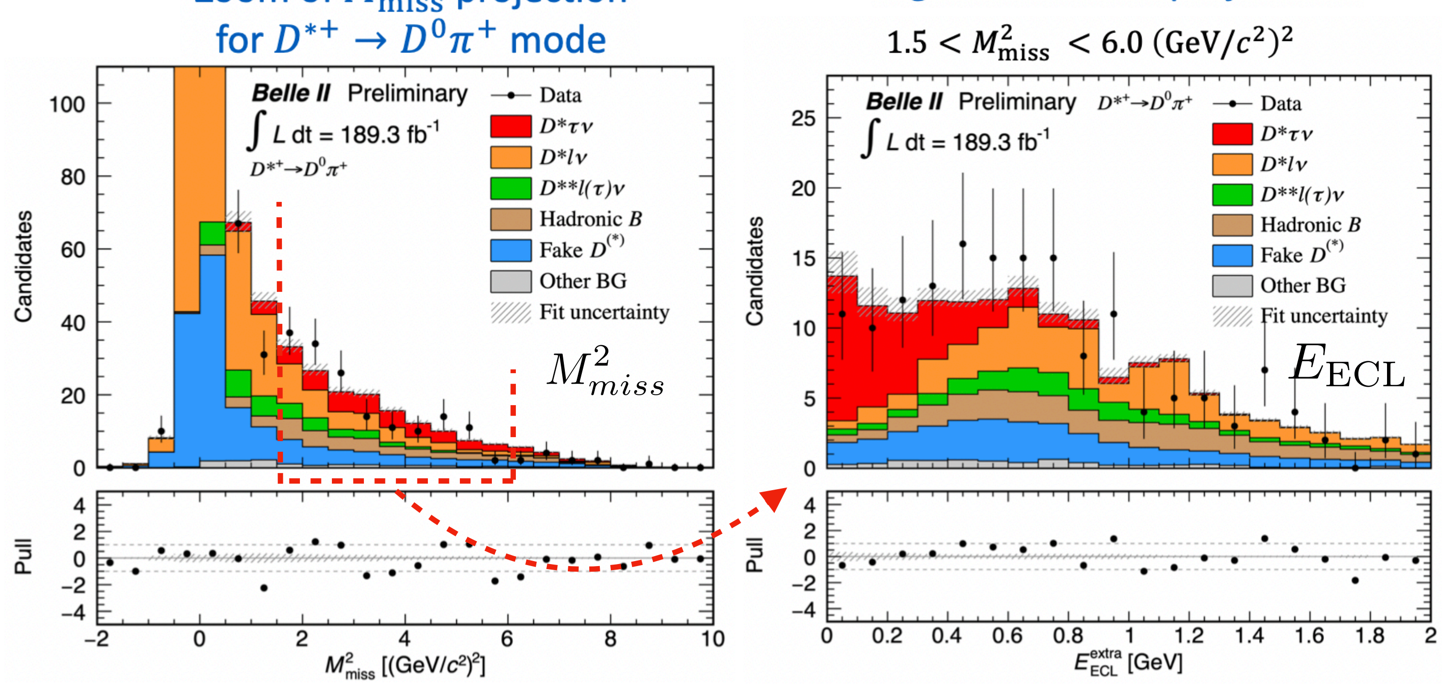

Leading systematics:
MC statistics, E_{ECL} PDF shape,
D^{**} modelling

$$R(D^*) = 0.262^{+0.041}_{-0.039}(\mathrm{stat.})^{+0.035}_{-0.032}(\mathrm{syst.})$$

SM prediction: $R(D^*) = 0.254 \pm 0.005$

HFLAV 23: $R(D^*) = 0.284 \pm 0.013$

Eur. Phys. J. C 81, 226 (2021)

Consistent with SM and previous measurements!

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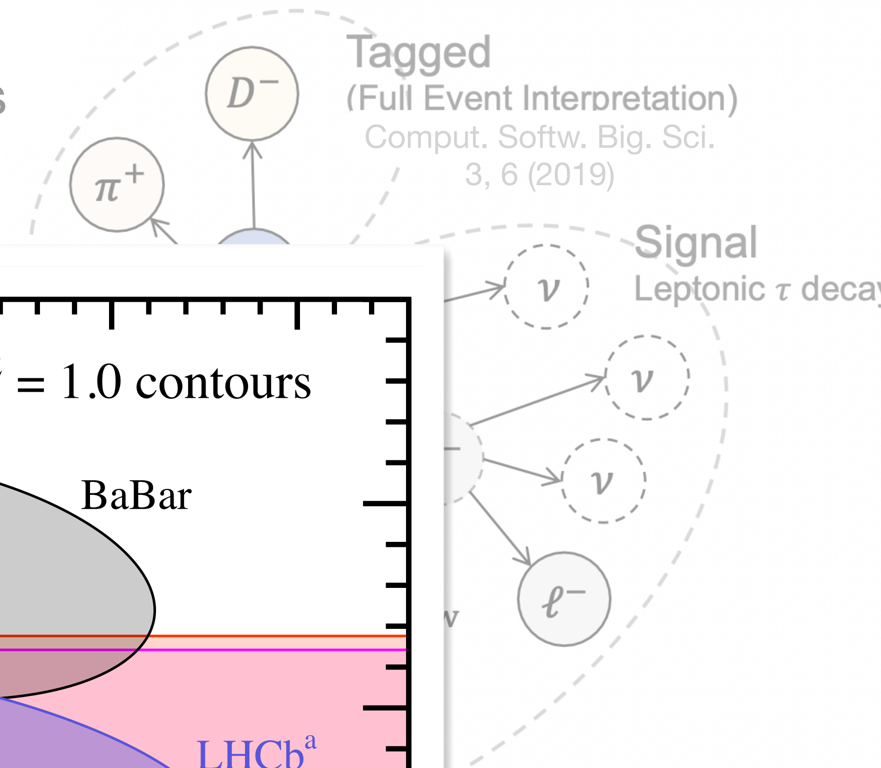

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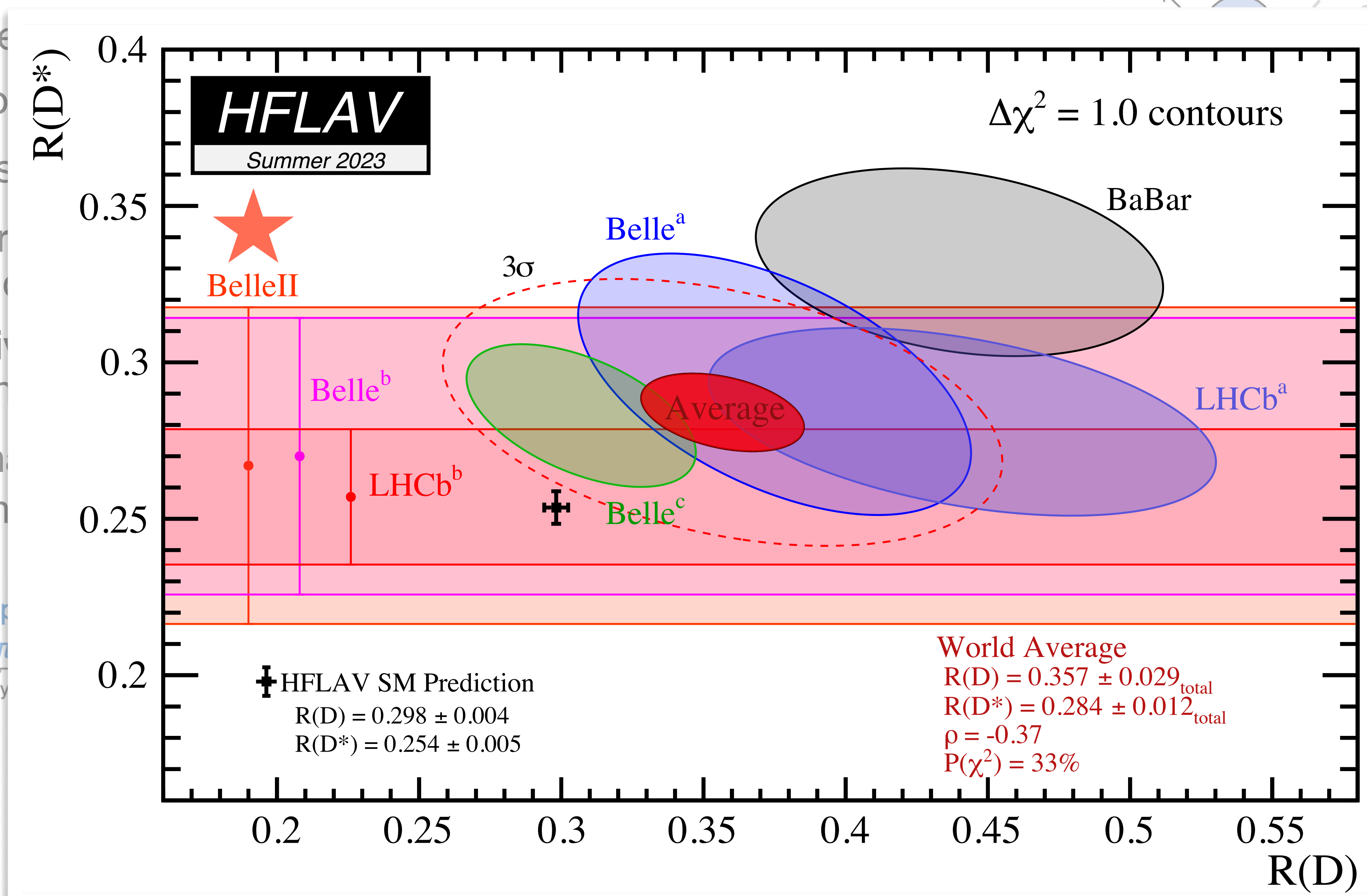

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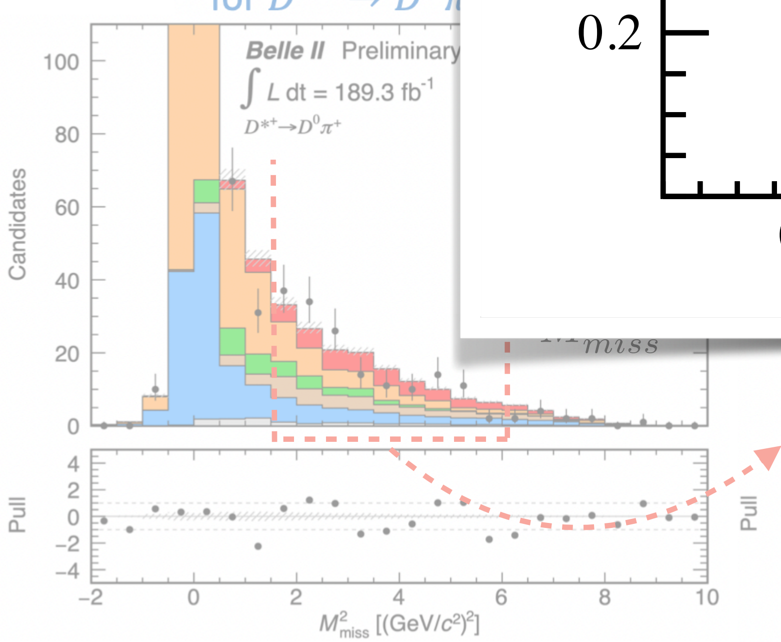

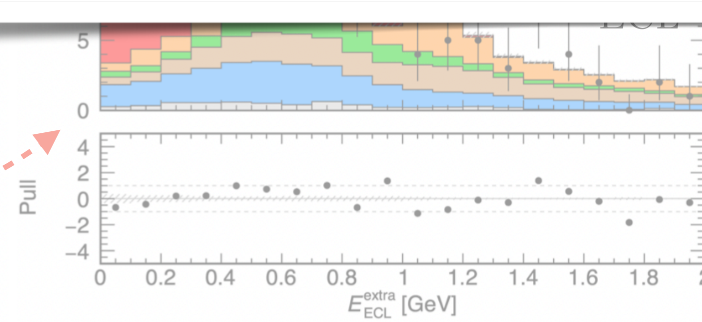

cs: shape,

$^{+0.035}_{-0.032}$(syst.)

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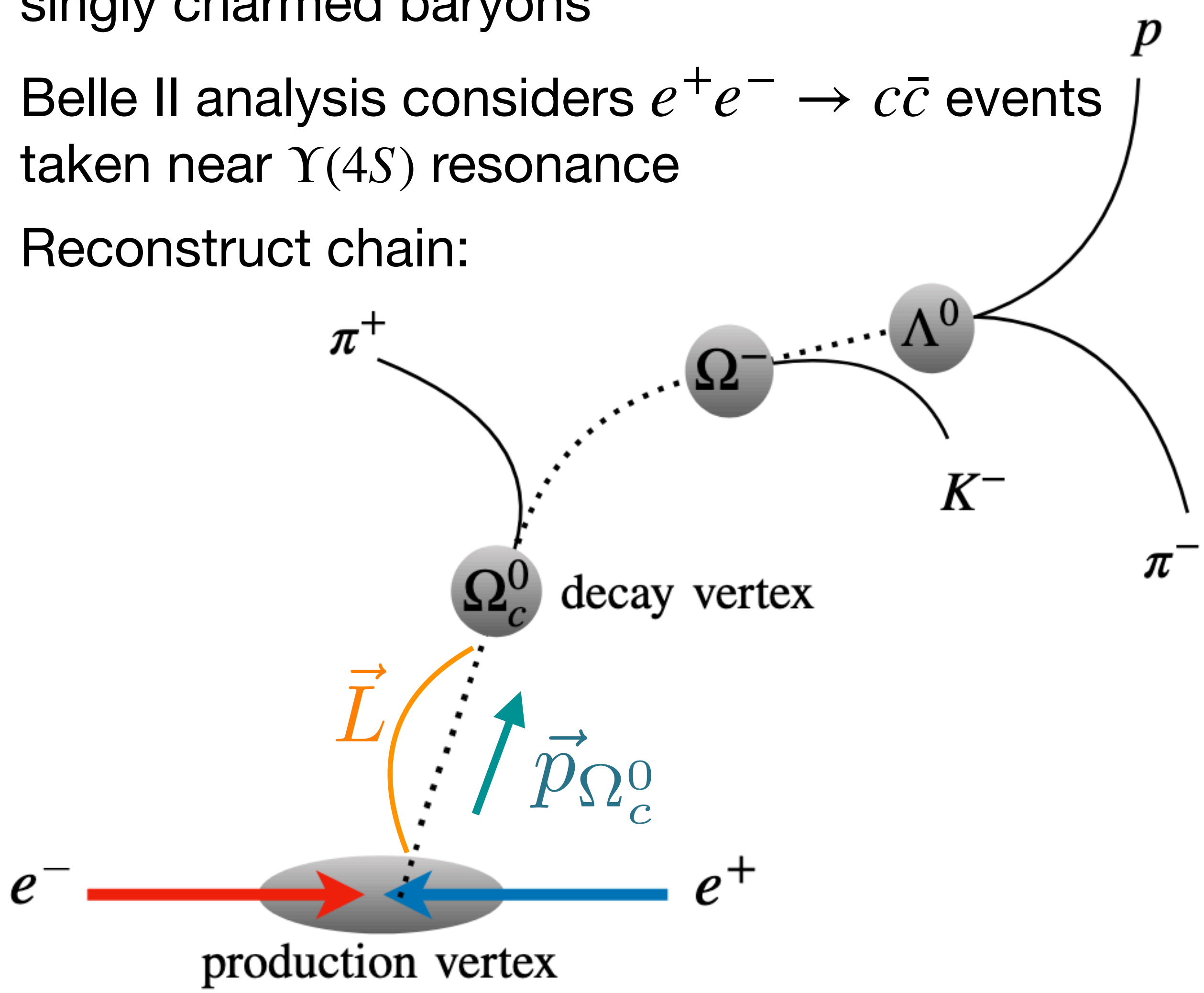
Eur. Phys. J. C 81, 226 (2021)

Consistent with SM and previous measurements!

Ω_c^0 lifetime measurement

PRD 107, L031103 (2023)

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



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

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

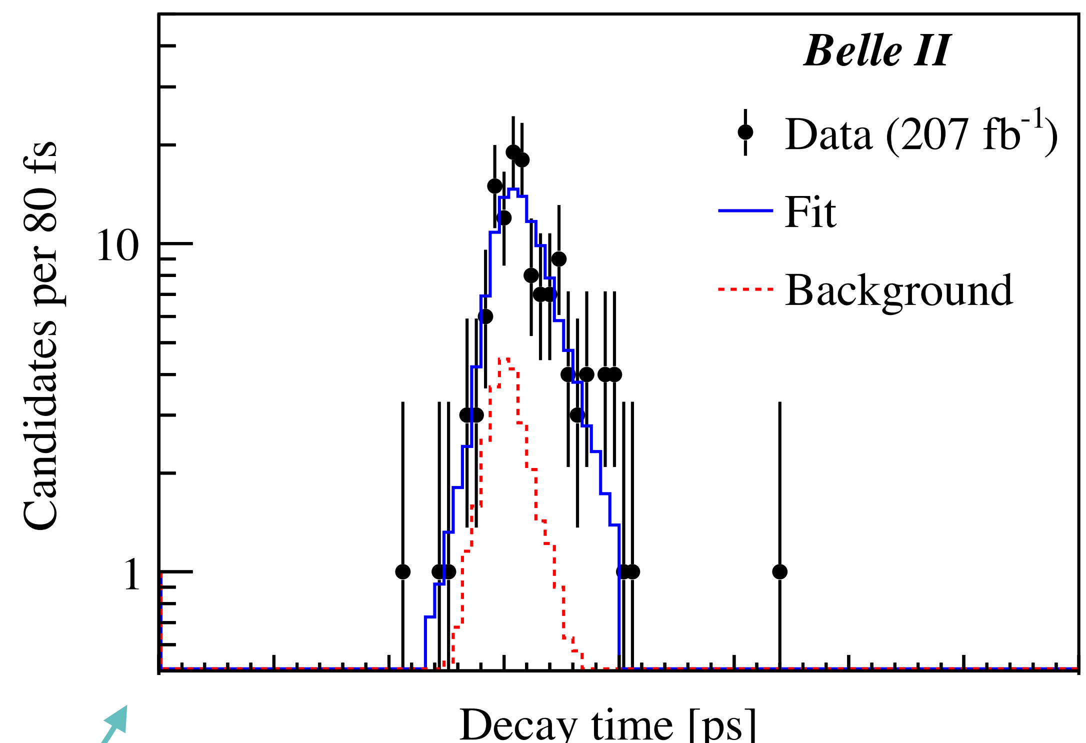
- Leading systematics: background modelling

Pre- and post-LHCb hierarchy:

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

↓

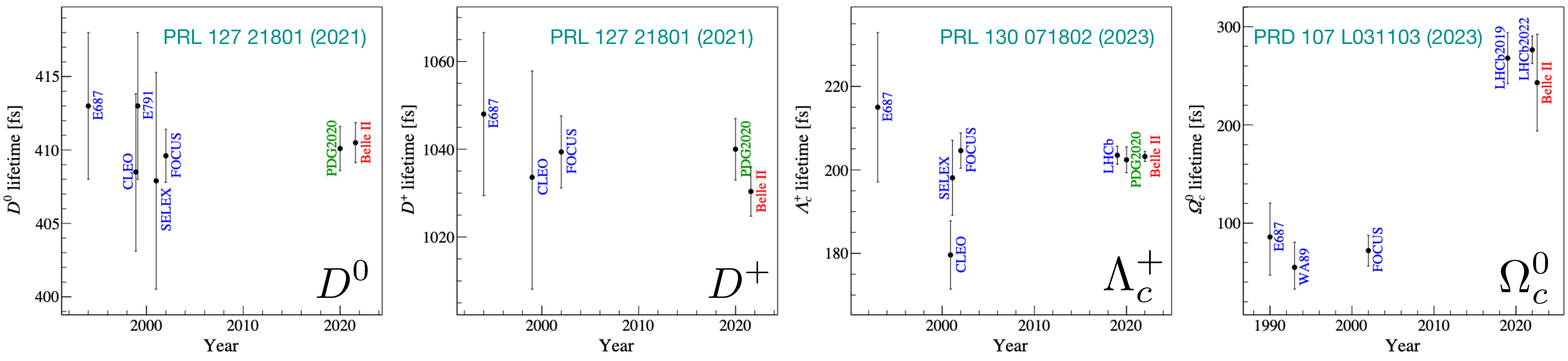
$\tau(\Xi_c^0) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+)$



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

Belle II confirms the LHCb results…

Charm hadron lifetimes

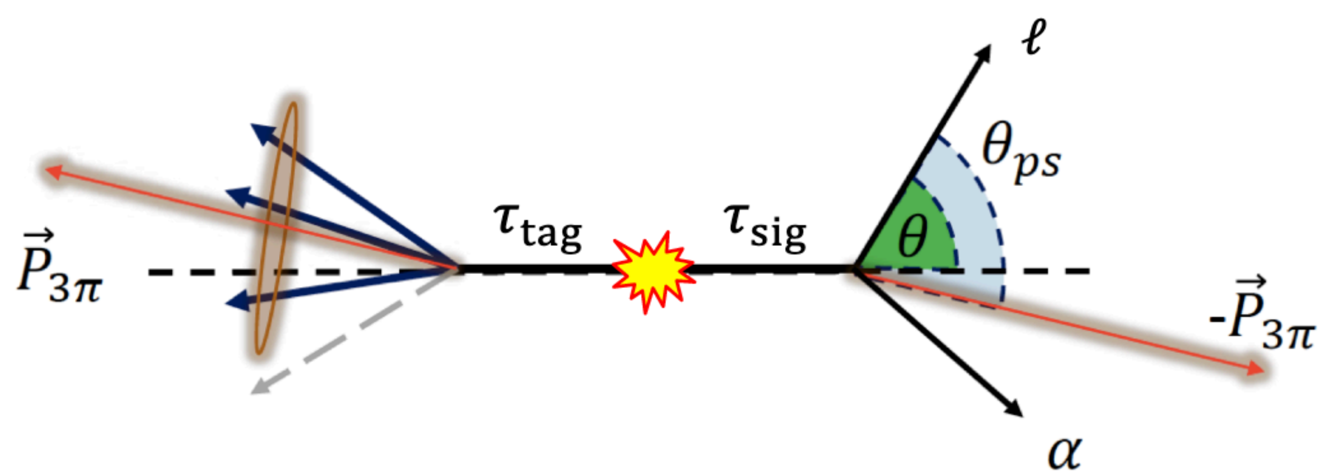


- Absolute lifetime measurements of charm hadrons at Belle II thus far:
  - **Improved knowledge** of D lifetimes after ~20 years
  - **World's most precise measurements** of D^0, D^+ and Λ_c^+ lifetimes
  - **Independent confirmation** of LHCb's result indicating that Ω_c^0 is not the shortest-lived 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…**

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

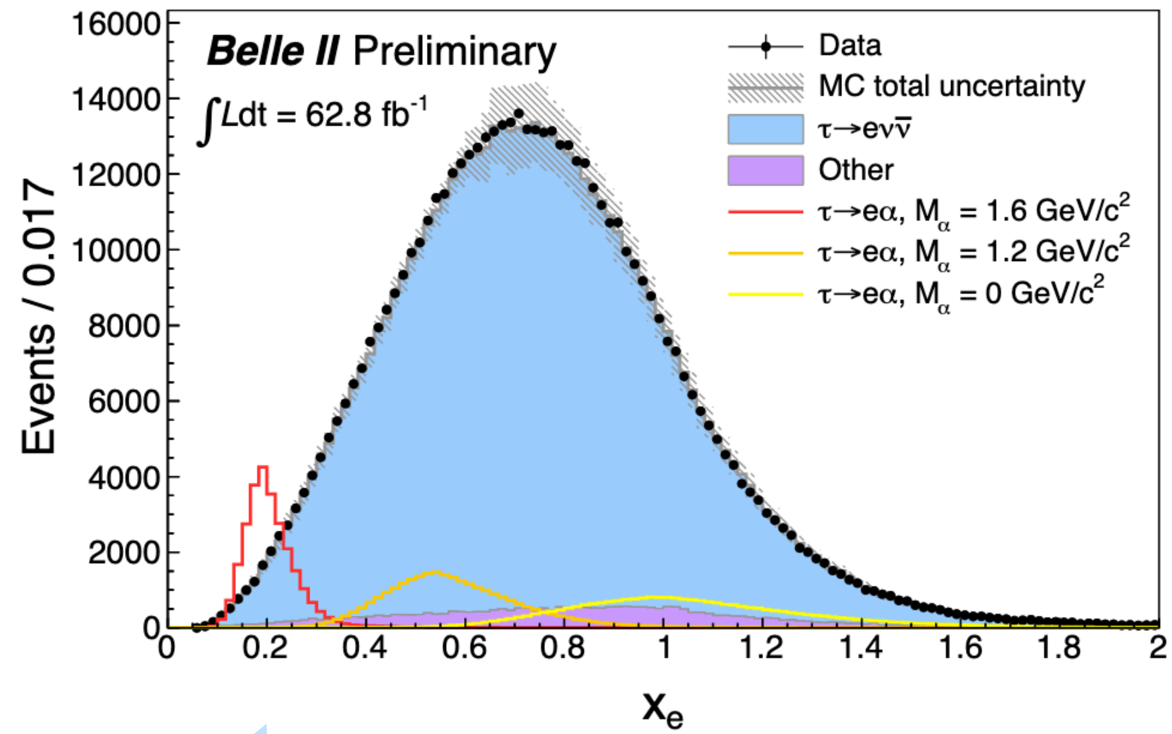
PRL 130 181803 (2023)

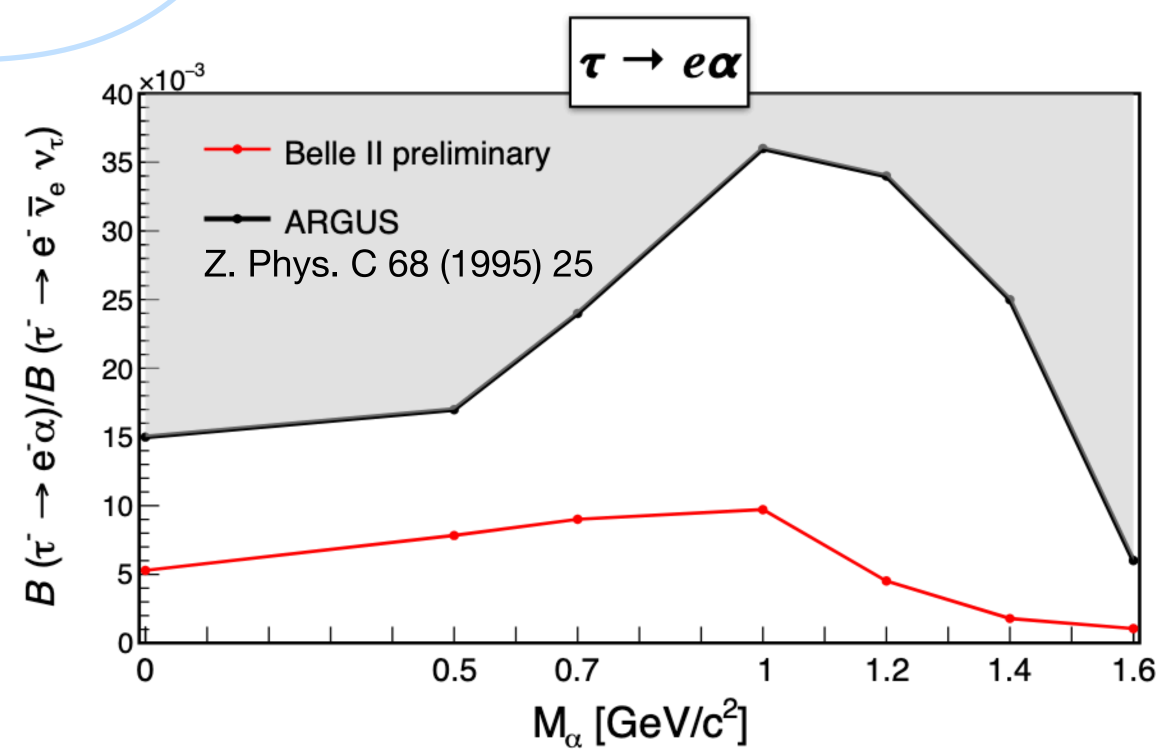
- Invisible LFV particles can emerge from new physics models e.g. light ALP JHEP 09 (2021) 173
- Tag $e^+e^- \to \tau^+\tau^-$ using $\tau \to 3\pi\nu$, then search for excess above the $\tau \to \ell\nu\nu$ spectrum



- 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

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



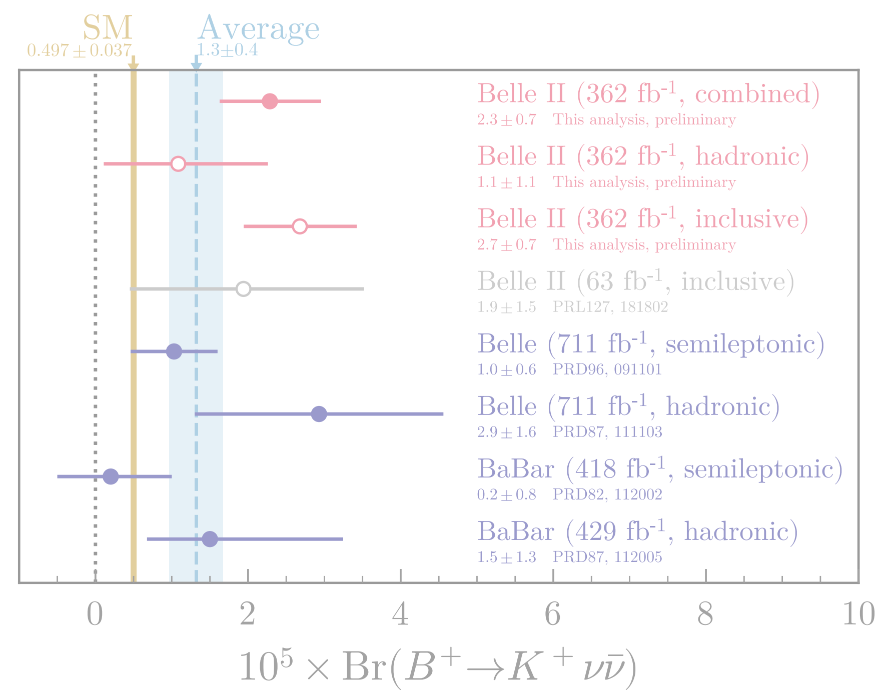


Most stringent constraint on the BR to date!

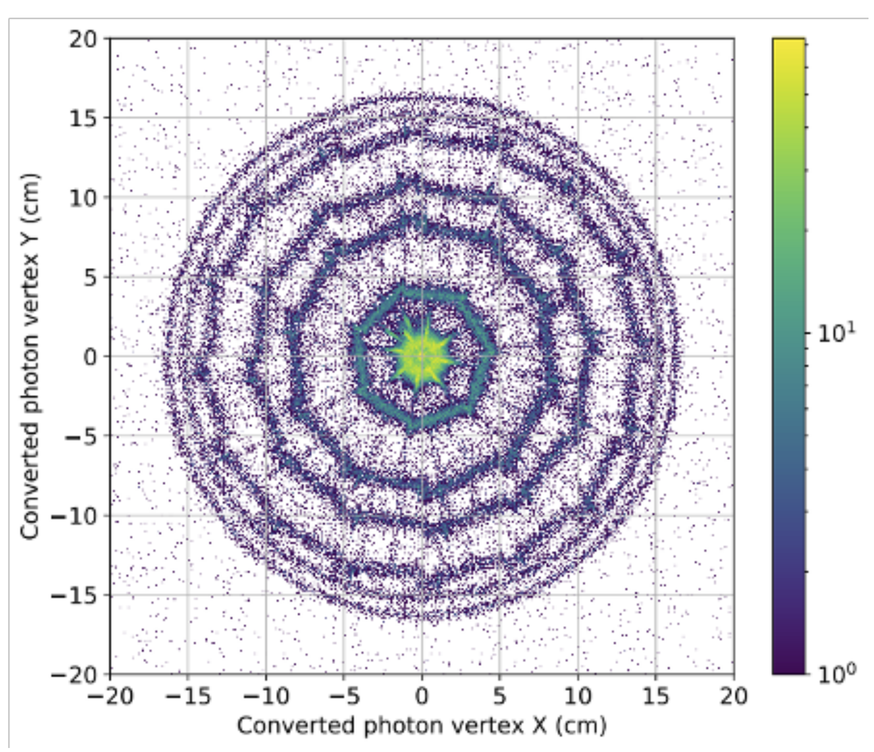
Outline for today

I. SuperKEKB & Belle II experimental status

II. Highlights of recent Belle II physics results



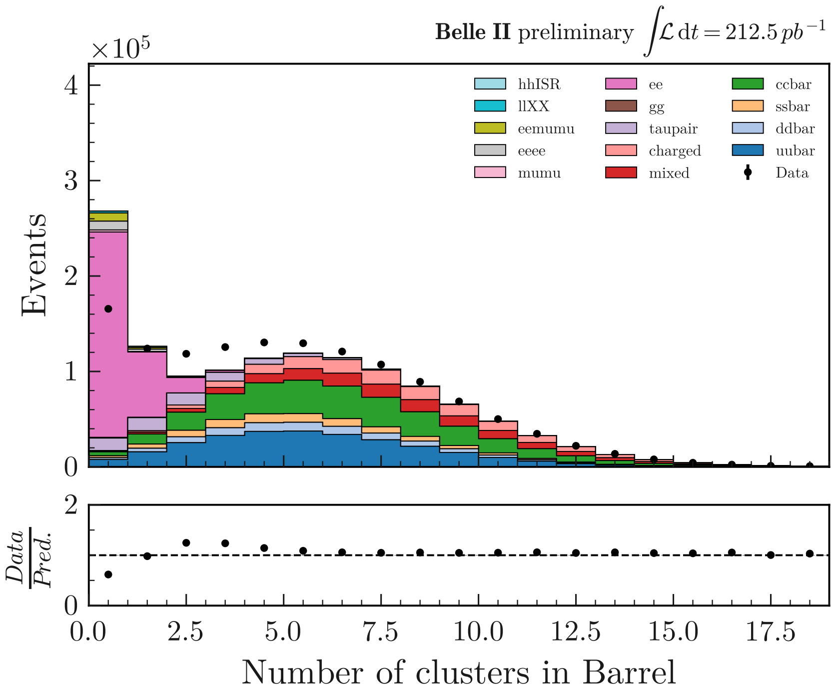
III. Ongoing & future work

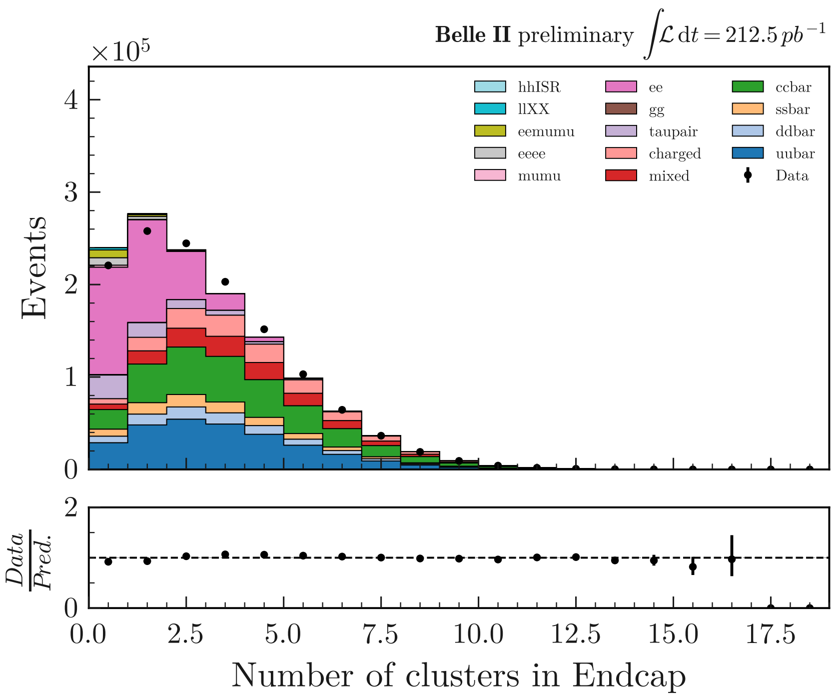


Belle II high-level trigger Bhabha reduction

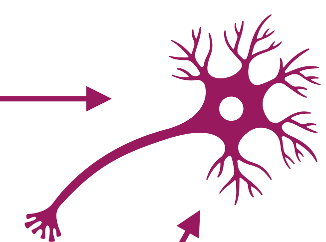
Robin Leboucher

- In most cases, the outcome of electron-positron collisions at SuperKEKB is not particularly interesting; mainly Bhabha $e^+e^- \to e^+e^-(\gamma)$ events.
- Implement new machine learning requirement to reduce high-level trigger Bhabha efficiency



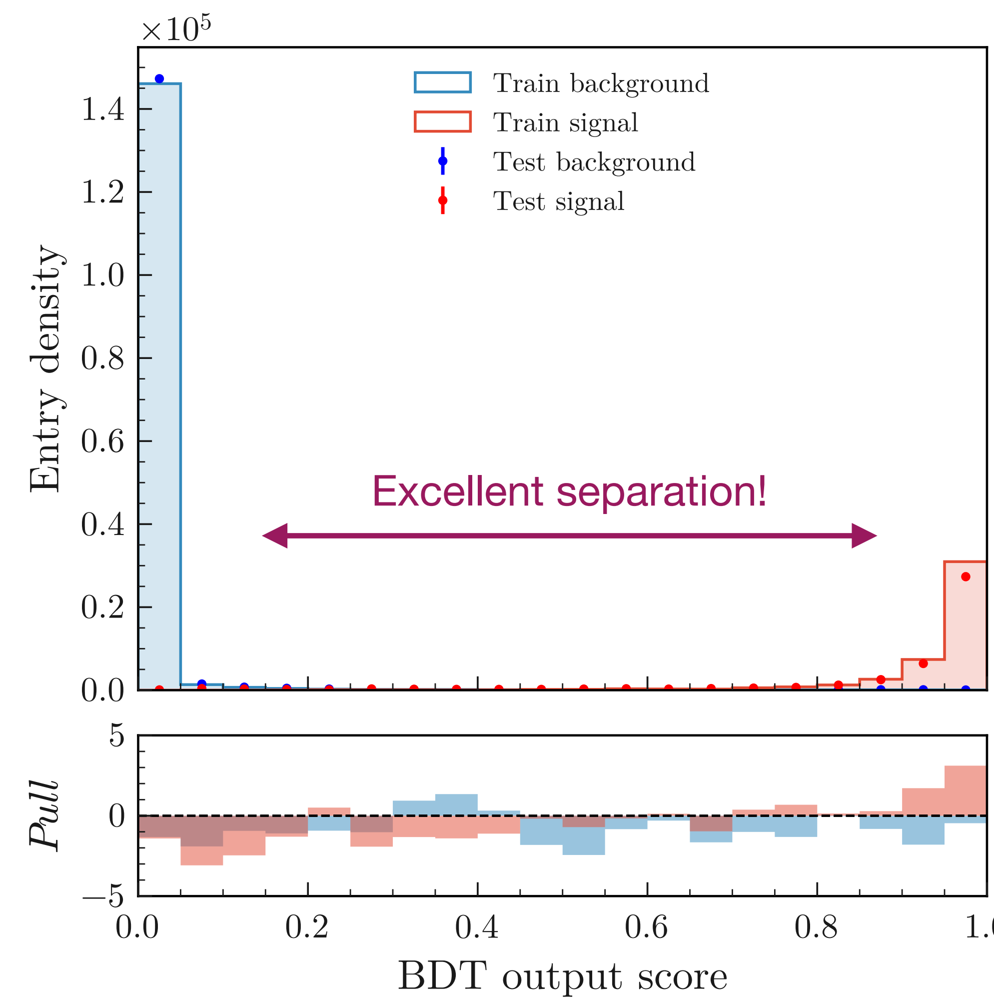


XGBoost



=

+ many more variables

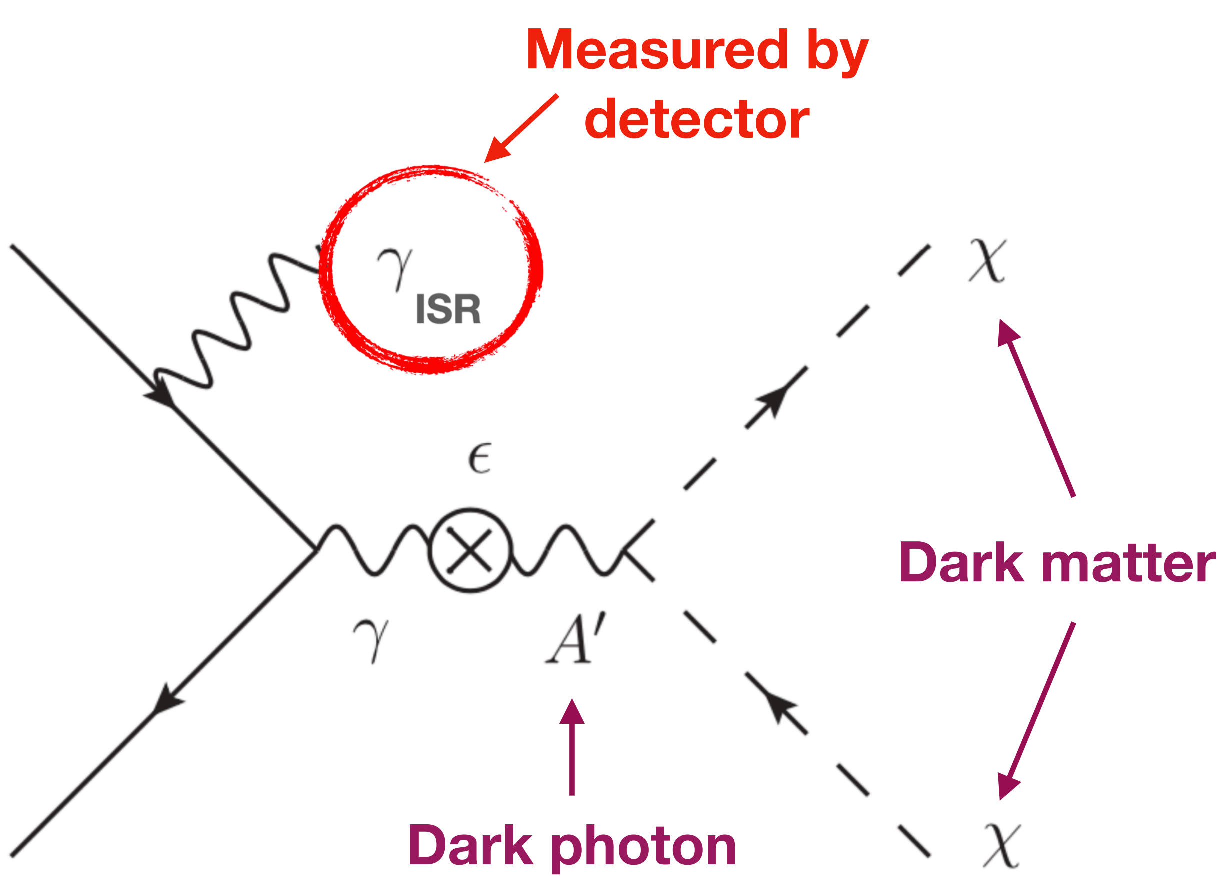


Classification accuracy:
94% for Bhabha events, and
99% for interesting physics processes.

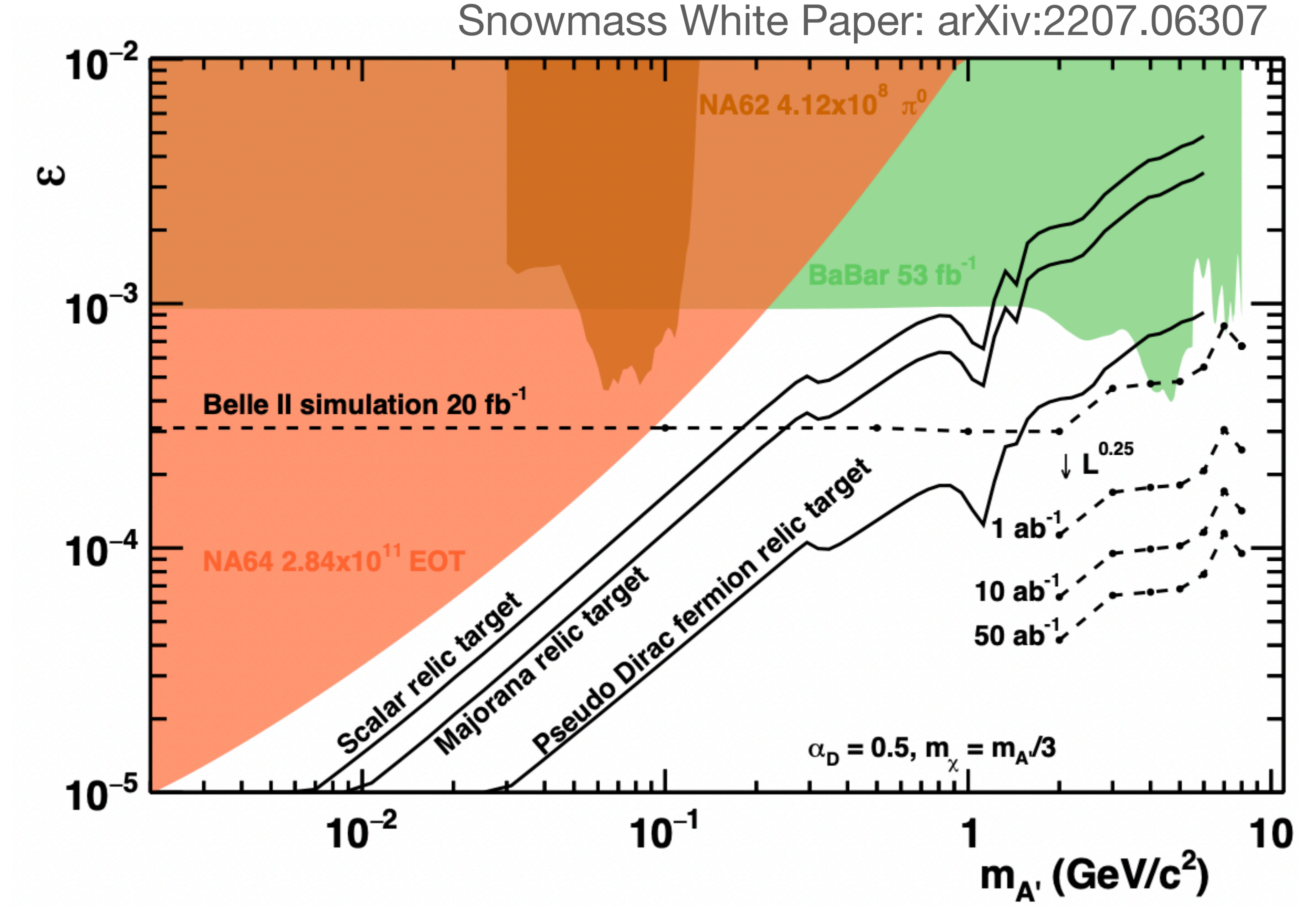
Dark photon search

Daniel Crook

- Dark photon is a spin-1 gauge boson that would mediate the dark EM force.
- Interacts through **kinetic mixing** with Standard Model photon.
- If dark photon is allowed kinematically to decay to dark matter, detector signature is a single high energy **photon**.
- Belle II will explore parameter space consistent with observed relic DM abundance.



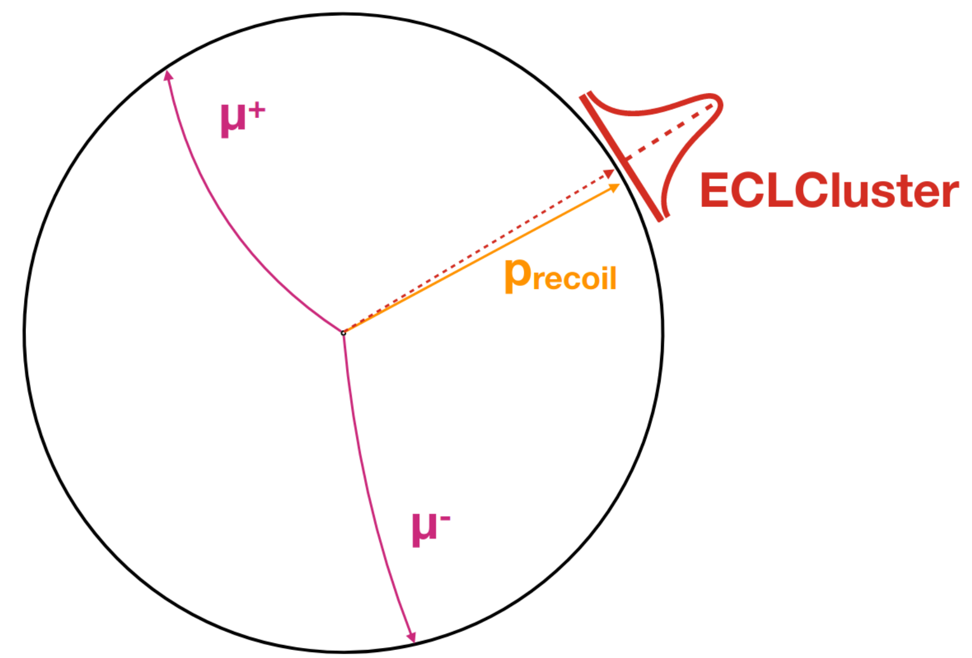
Snowmass White Paper: arXiv:2207.06307



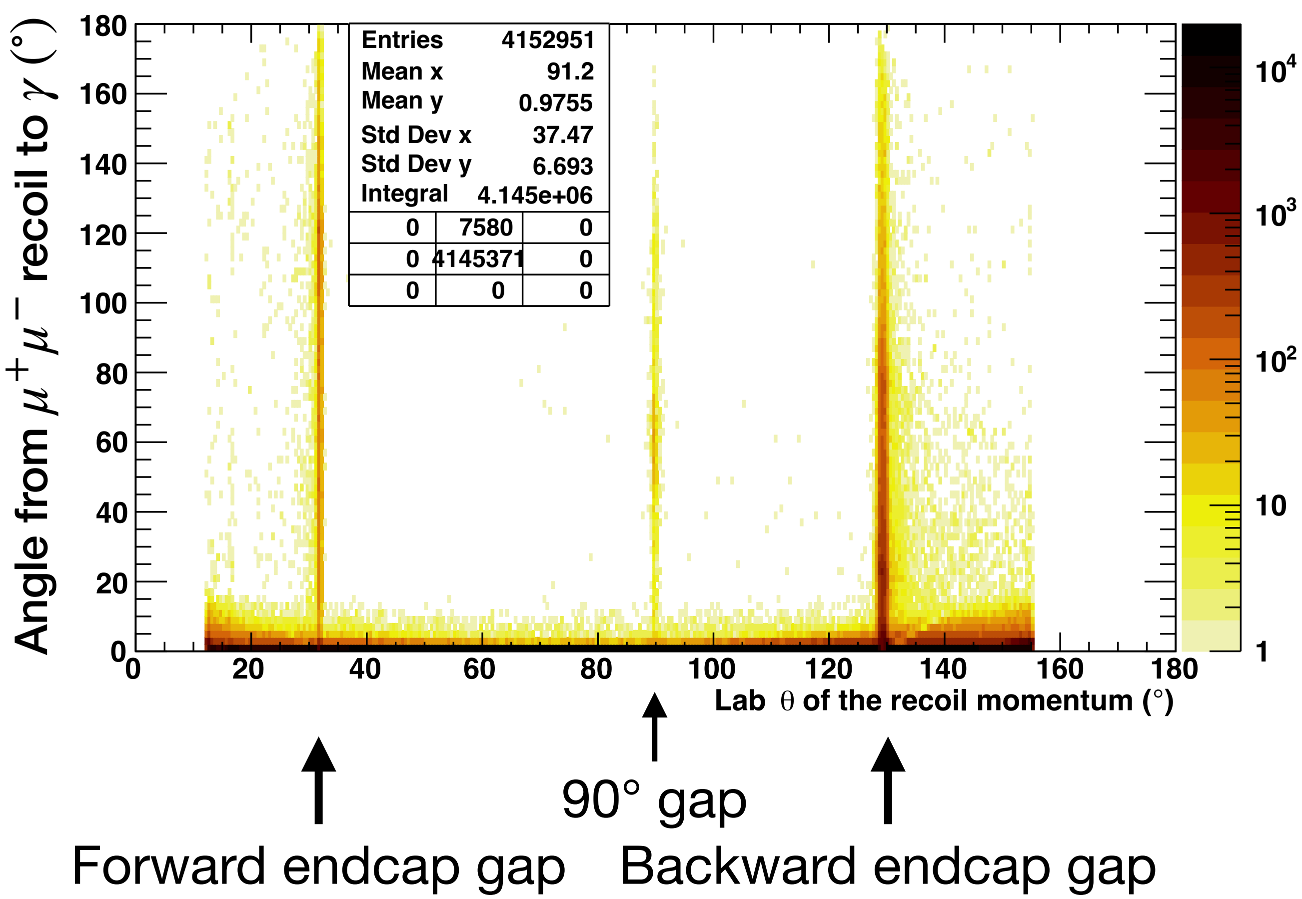
Dark photon search

Daniel Crook

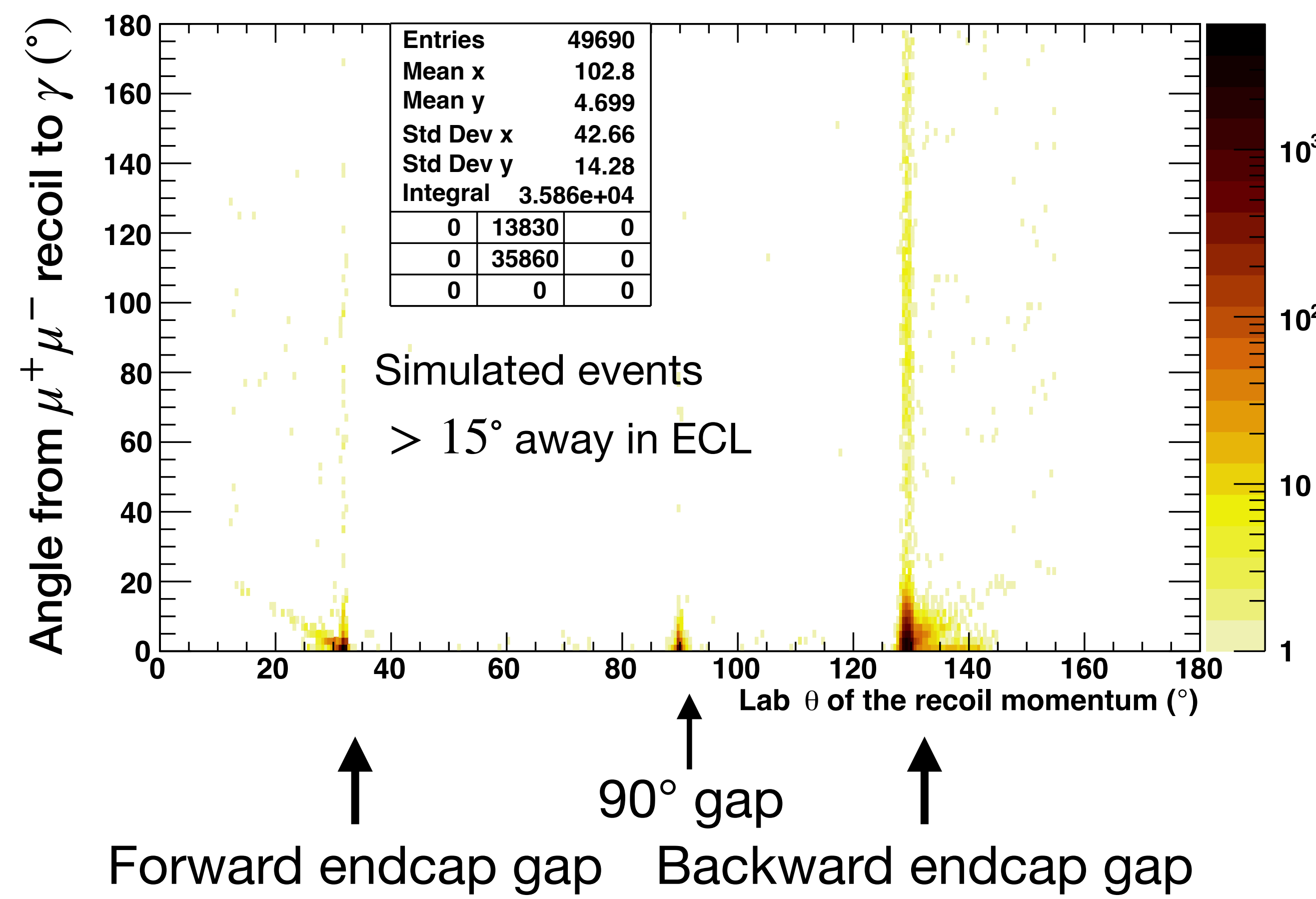
- **Major analysis background**: $e^+e^- \rightarrow \gamma\gamma(\gamma)$, with all but one out of acceptance or missed.
- Use $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ events to study Belle II sub-detector photon efficiency in data and simulation.
  - Estimate the momentum of the photon from the di-muon system. Search for a corresponding ECL or KLM cluster.
  - If either sub-detector sees a signal, the photon is detected.



Photon detector (ECL)



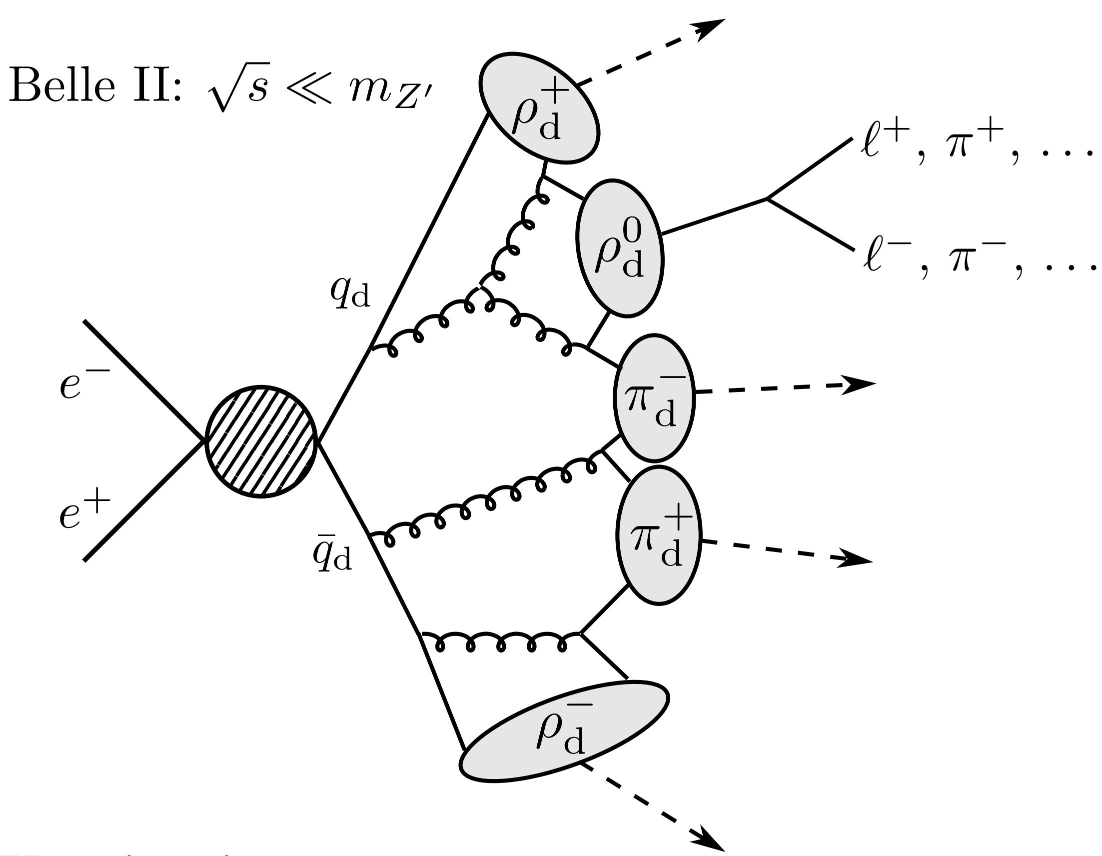
'Secondary' photon detector (KLM)



Dark shower search

Miho Wakai

- Strongly interacting dark sector coupled to Standard Model through a dark photon mediator.
- **Dark quarks form bound states**: dark pseudoscalars π_d^0, $\pi_d^\pm$ and vector mesons ρ_d^0, $\rho_d^\pm$
- **Dark pions are stable** and are the dark matter candidates.
- ρ_d^0 decays to the SM particles via a **virtual dark photon**.
  - Detector signature is displaced vertex with **two charged tracks.**



JHEP 12 (2022) 005

E. Bernreuther et al. Forecasting dark showers at Belle II

Example of a ρ_d^0 decay

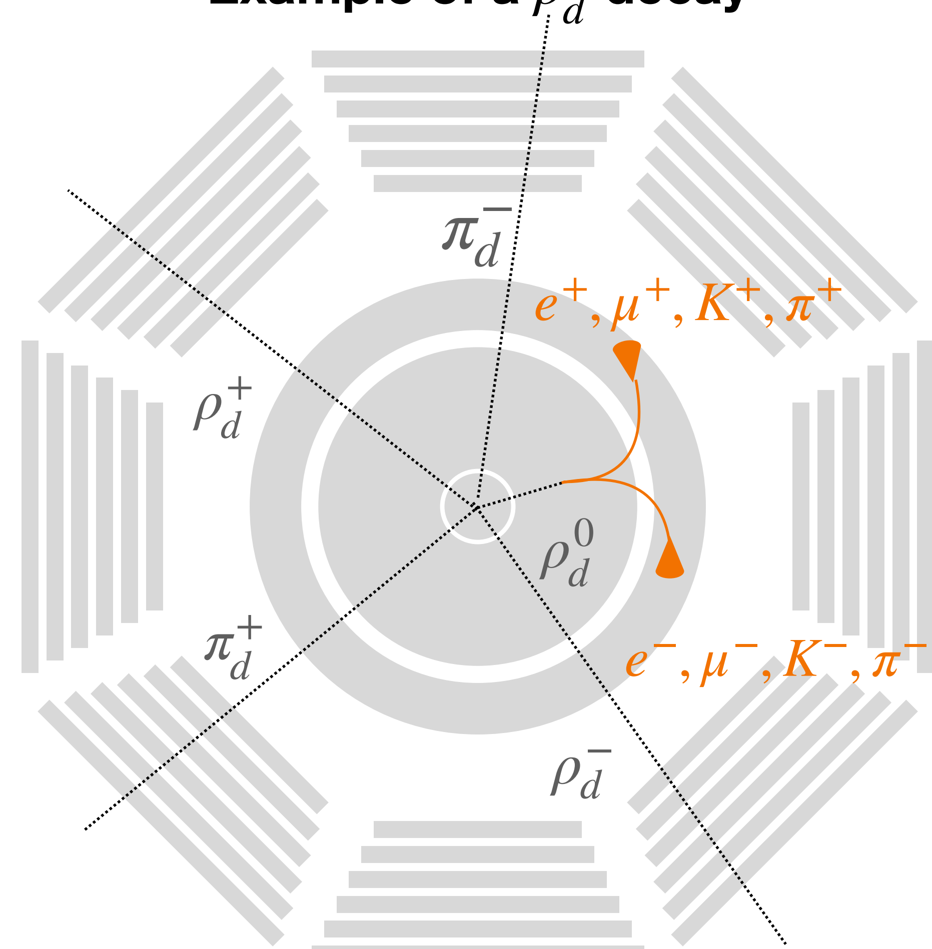
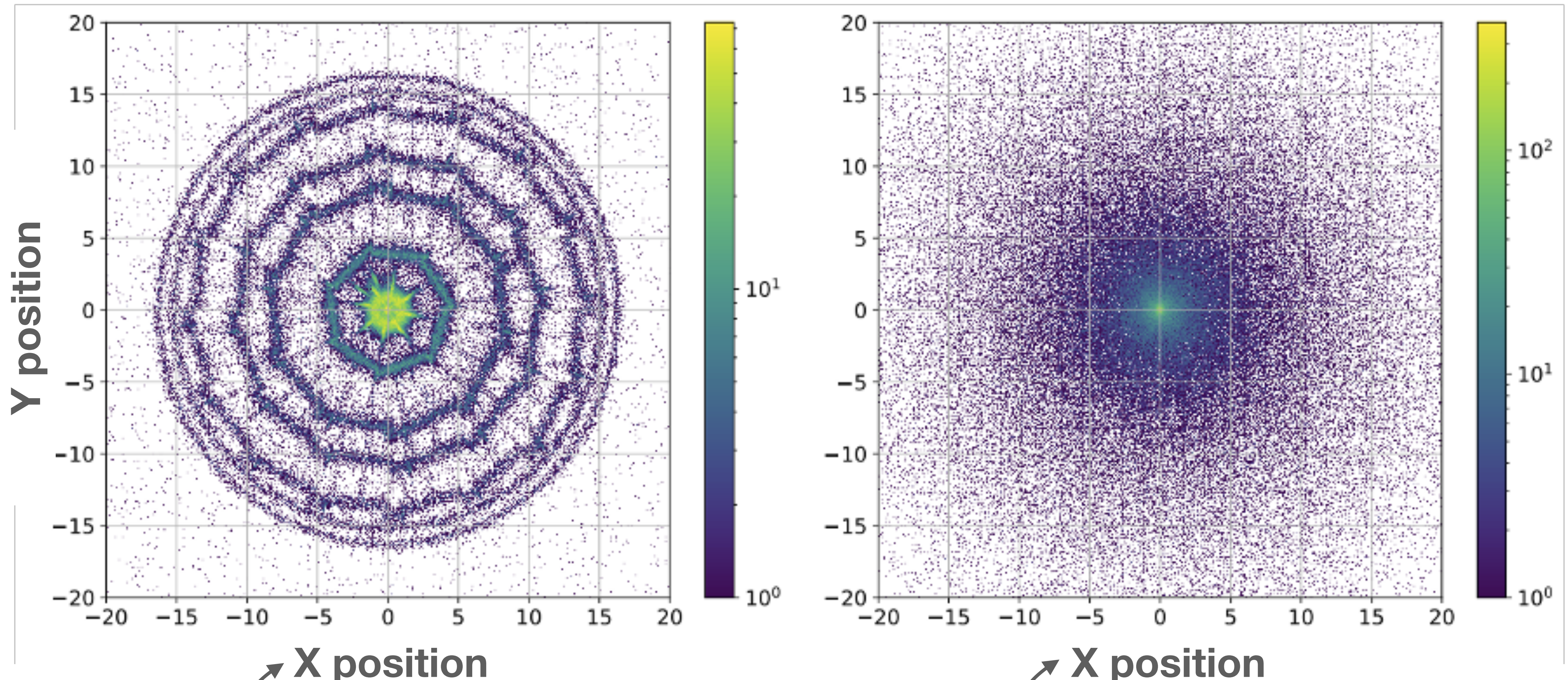


Image credit: Patrick Ecker

Dark shower search

Miho Wakai
&
Jaden Wang

- For low mass ρ_d^0, currently implementing machine learning (XGBoost library) to reduce background from photon conversion events.
- Currently achieving **96.1% accuracy.**



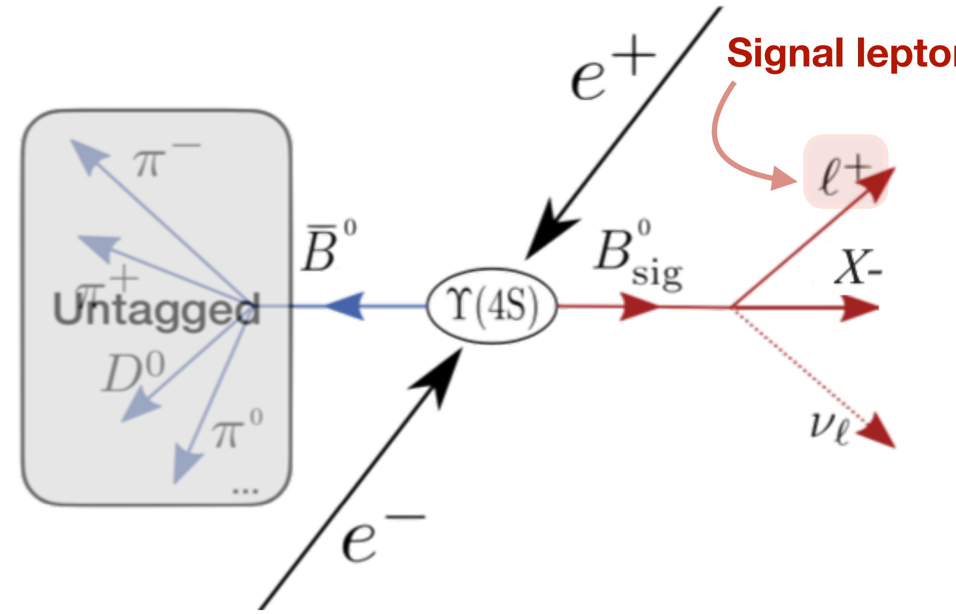
Photon conversions happen when interacting with material in detector

ρ_d^0 decays happens anywhere

Untagged analysis of inclusive $B \to X_u \ell \nu$

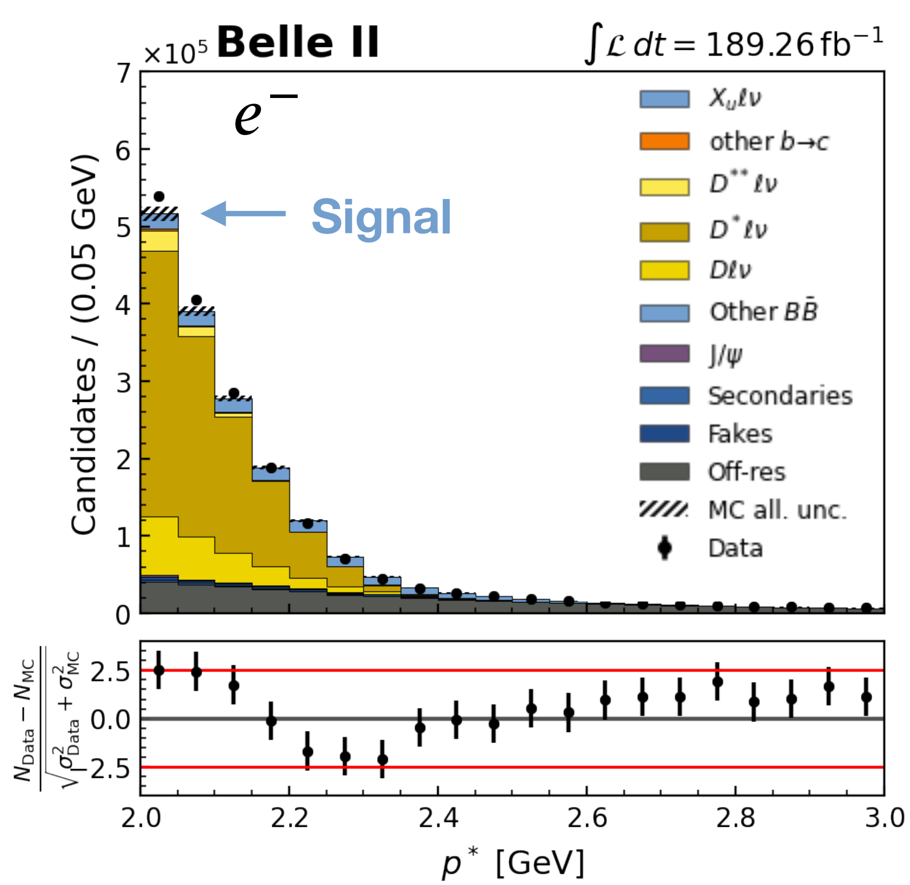
Andrea Fodor

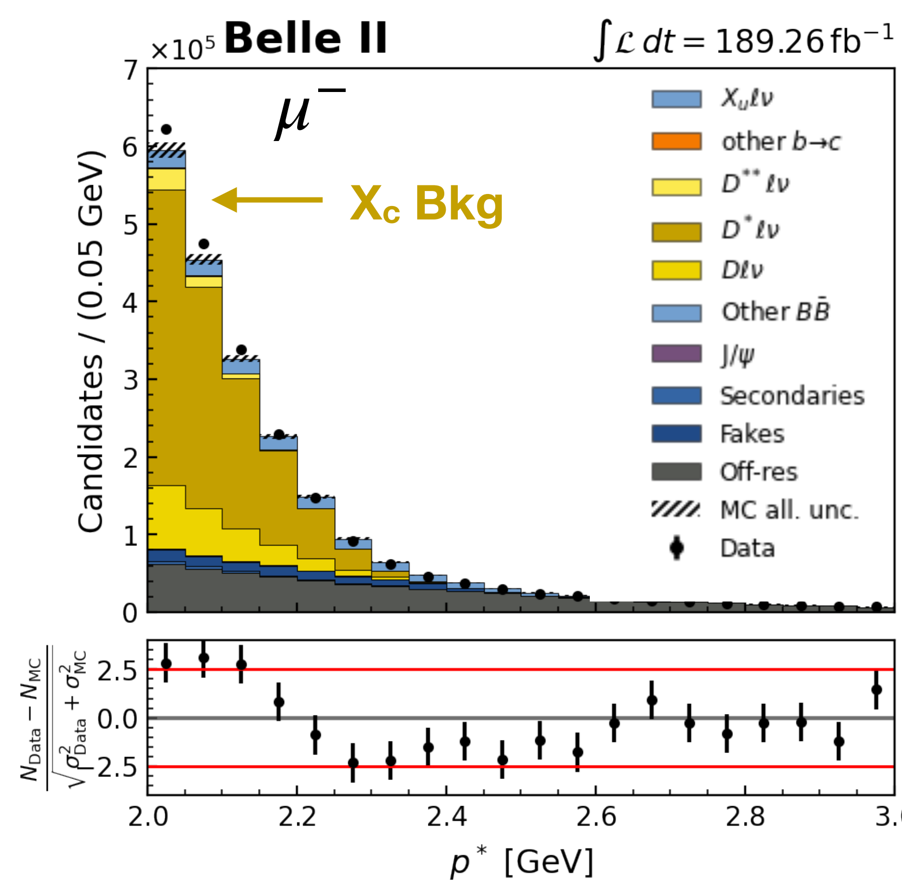
- Semileptonic decays of B mesons play a critical role in the determination of the CKM quark-mixing matrix elements $|V_{cb}|$ & $|V_{ub}|$.



- **Analysis goal:** measure the branching fraction of $B \to X_u \ell \nu$ decays via an **inclusive** analysis approach
  - *only the outgoing lepton is selected.*

- Looking in the **endpoint region of the lepton momentum** ($p^*_\ell > 2.0$ GeV) in the CM frame to avoid the dominant background from $B \to X_c \ell \nu$ decays.



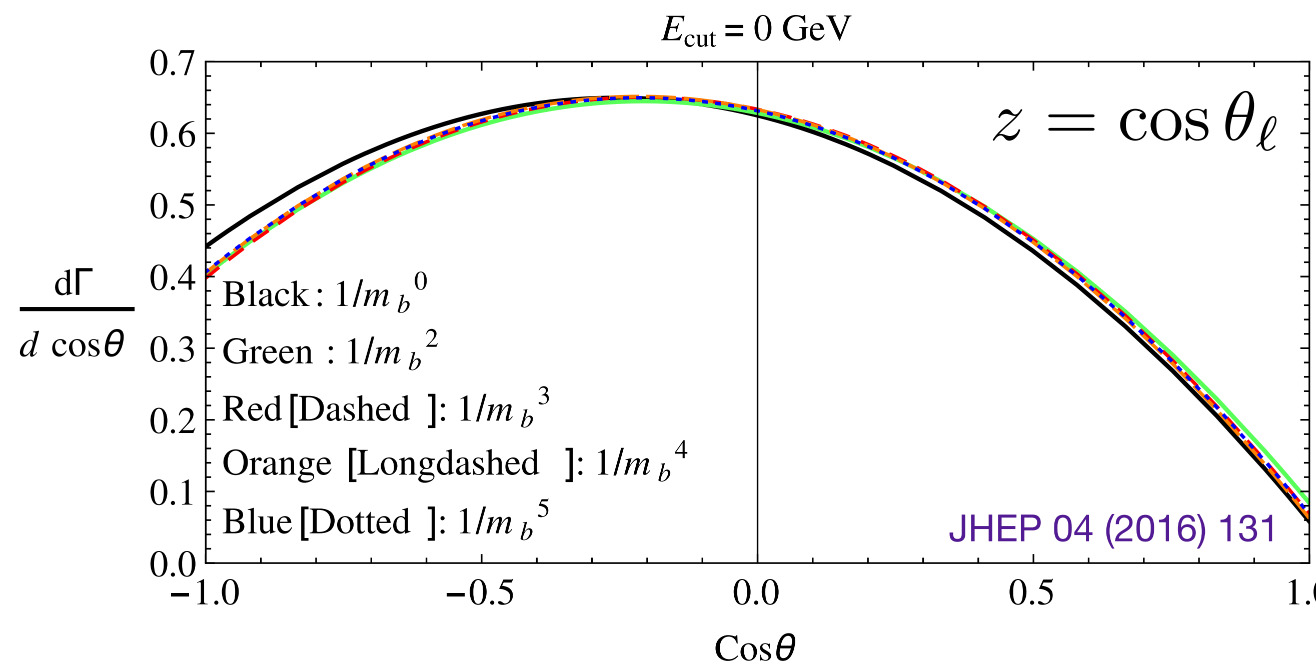


Forward-backward asymmetry in incl. $B \to X\ell\nu$

Raynette van Tonder

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

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

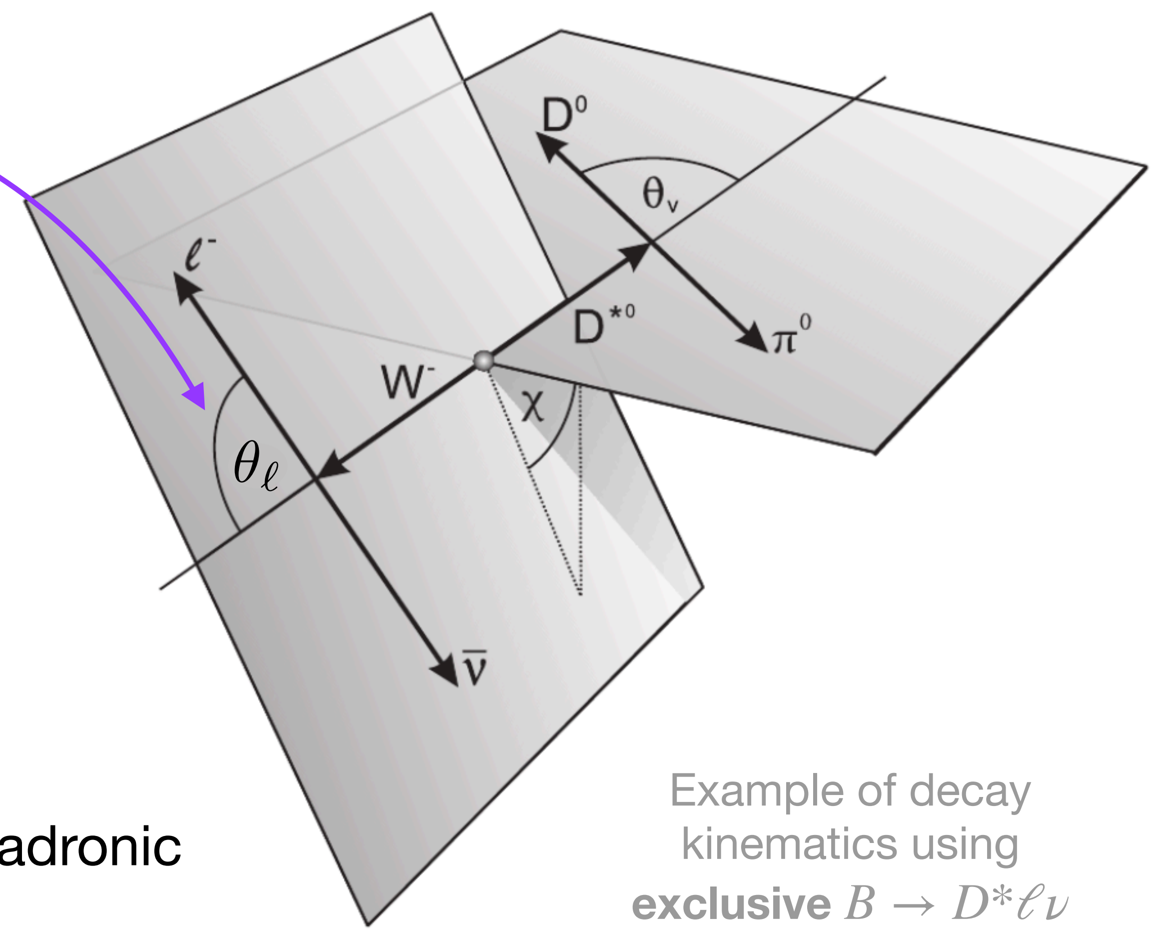


- Reconstruct:

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

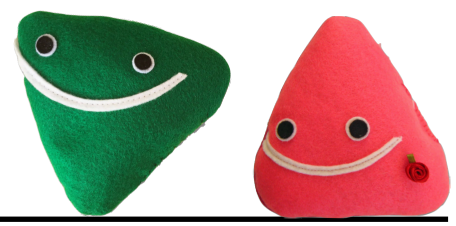
- Missing energy and q^2 **easily accessible** variables with tagged approach
- Separate electron and muon channels for further **LFU tests**
- Additional information leads to **greater sensitivity** in global fits for $|V_{cb}|$ **determinations**

☞ Improves uncertainties on the non-perturbative hadronic matrix elements in the heavy quark expansion

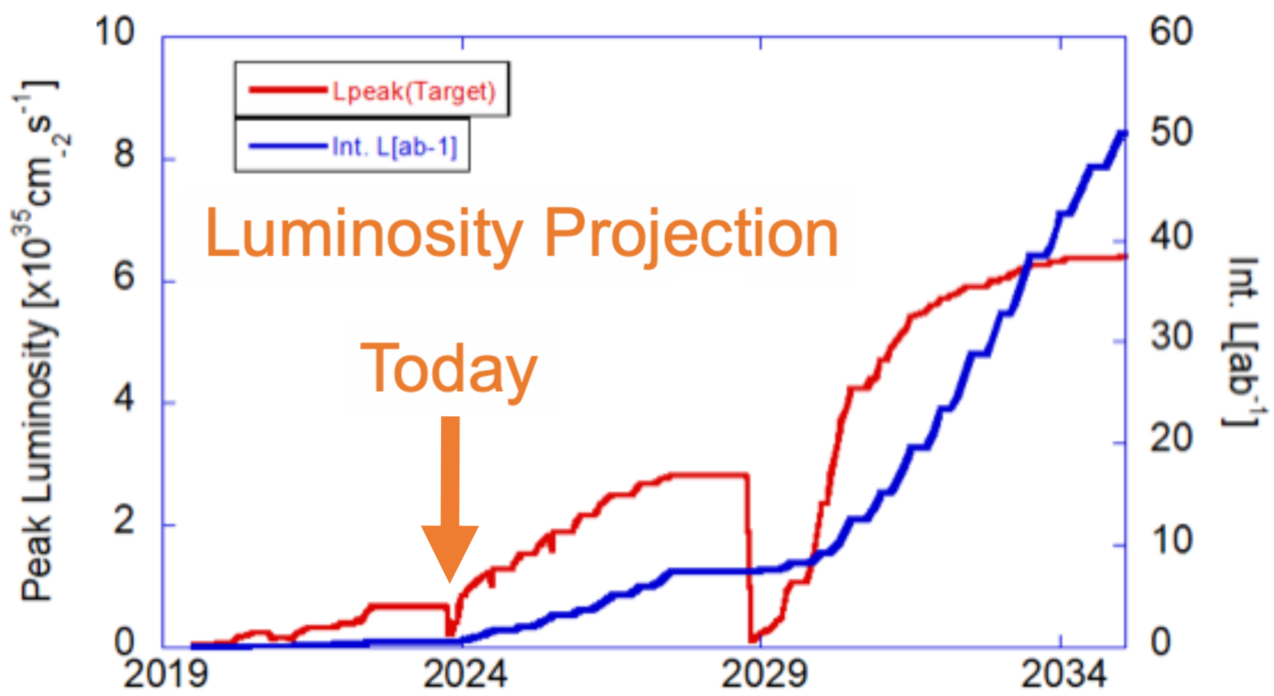


Example of decay kinematics using **exclusive** $B \to D^*\ell\nu$

Conclusion



- Belle II offers a **unique and fertile environment** for flavour physics.
- Multiple **world-leading results** published since arrival of first data.
  - Only presented a **subset of results.**
- Luminosity and physics output will continue to grow —especially with the the start of a **new data taking period!**



Many opportunities for new personnel interested in joining!