Belle II
Status and Prospects

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Physics Department, Brookhaven National Laboratory

XV Latin American Symposium on High Energy Physics
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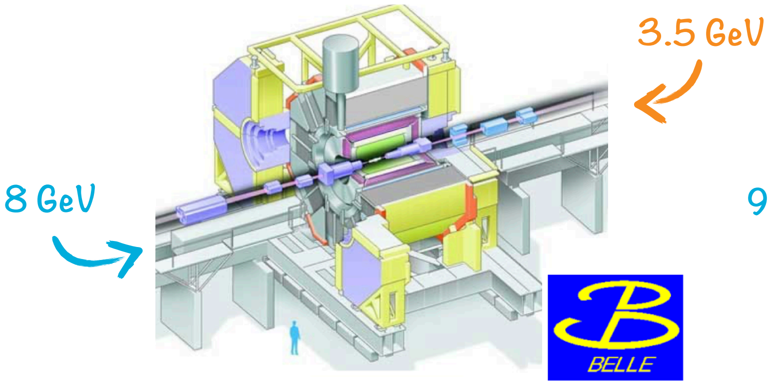
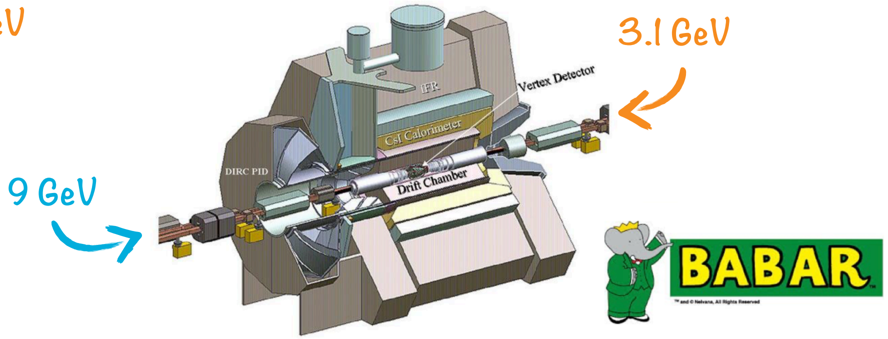
B-Factories

Features of a B-Factory

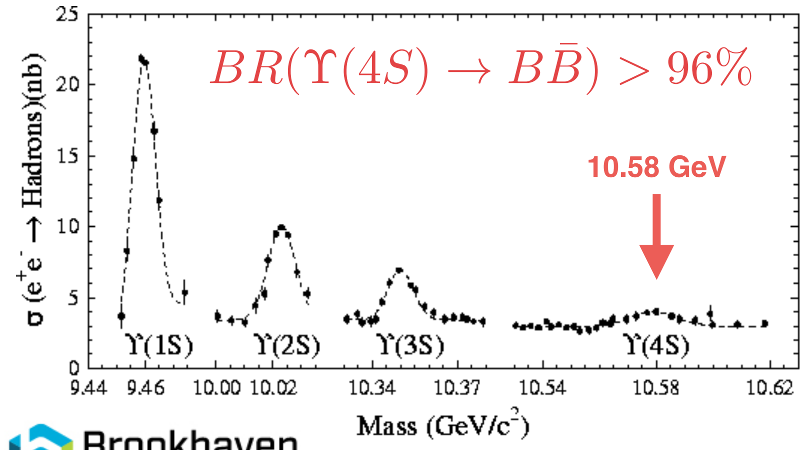


KEKB collider : 711 fb^{-1}@Y(4S)
[1999-2010]



SLAC-PEP II collider : 462 fb^{-1}@Y(4S)
[1999-2008]

- Well-defined initial state



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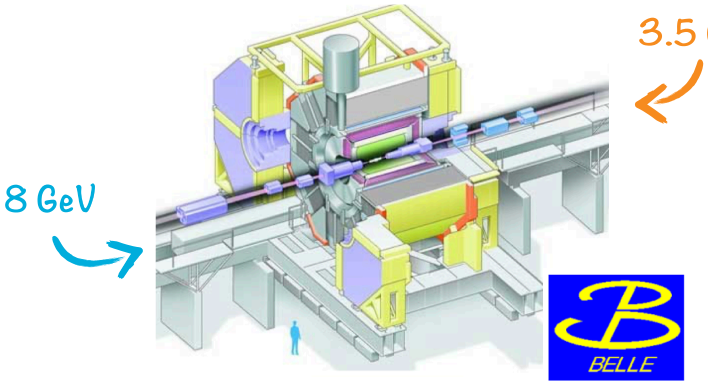
Features of a B-Factory



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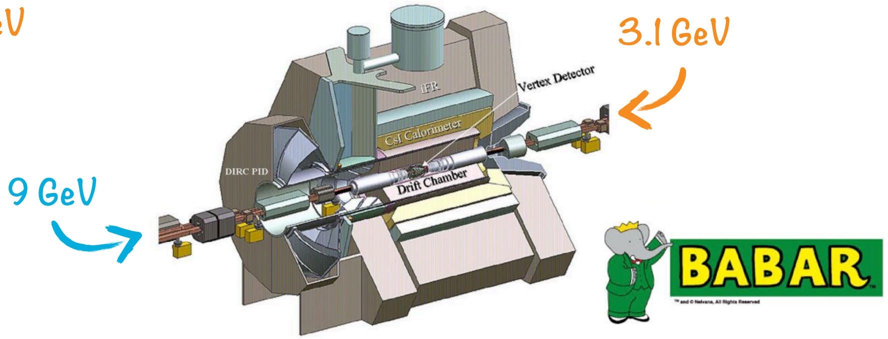
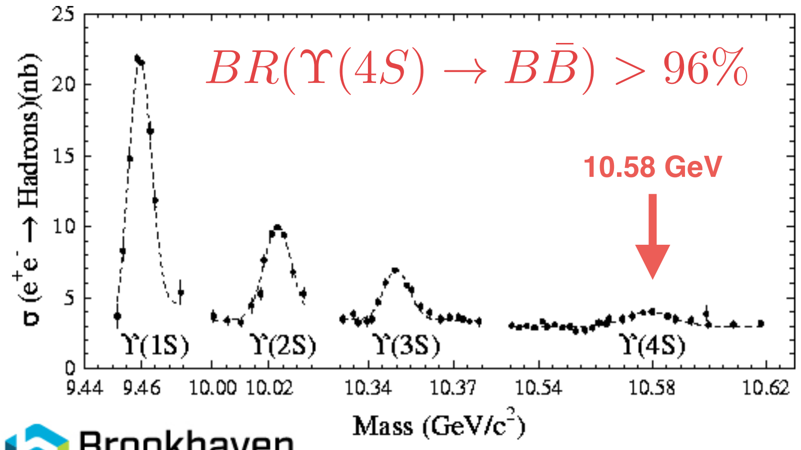
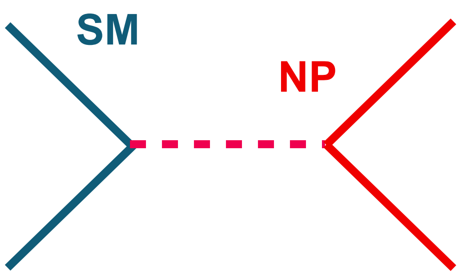


SLAC-PEP II collider : 462 fb^{-1}@Y(4S)
[1999-2008]

- Well-defined initial state
- High luminosity



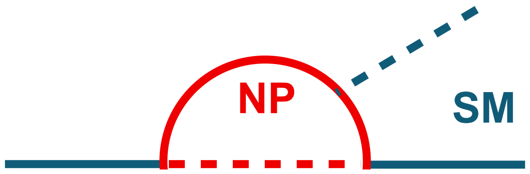
Energy frontier



Limited by beam energy

vs

Intensity frontier



Limited by statistics

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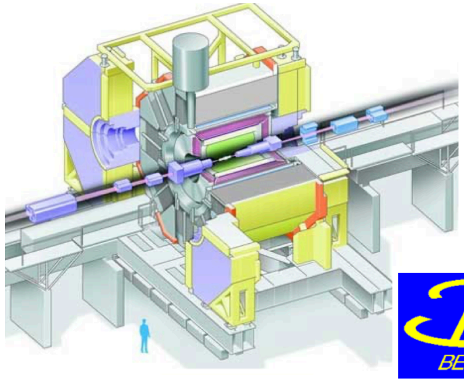
Features of a B-Factory

8 GeV

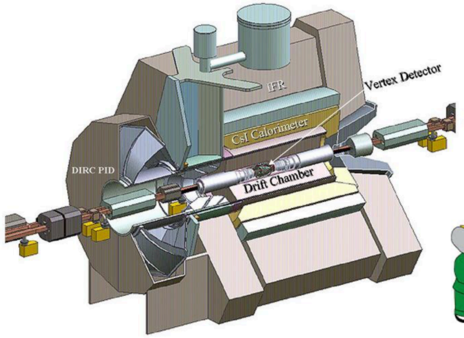
3.5 GeV



KEKB collider : 711 fb^{-1}@Υ(4S)
[1999-2010]

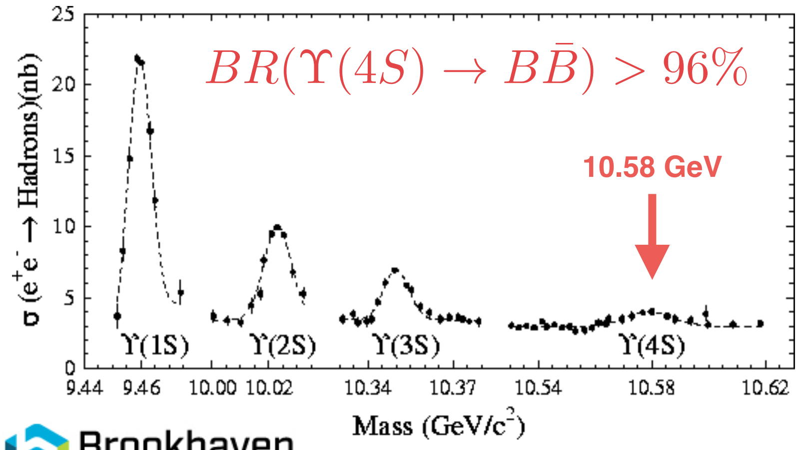
9 GeV

3.1 GeV

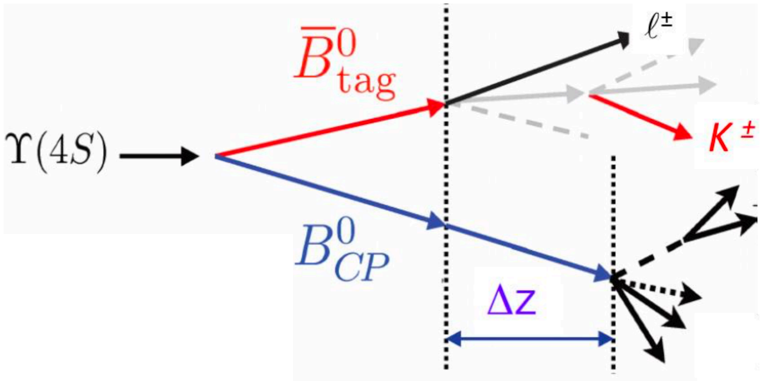


SLAC-PEP II collider : 462 fb^{-1}@Υ(4S)
[1999-2008]

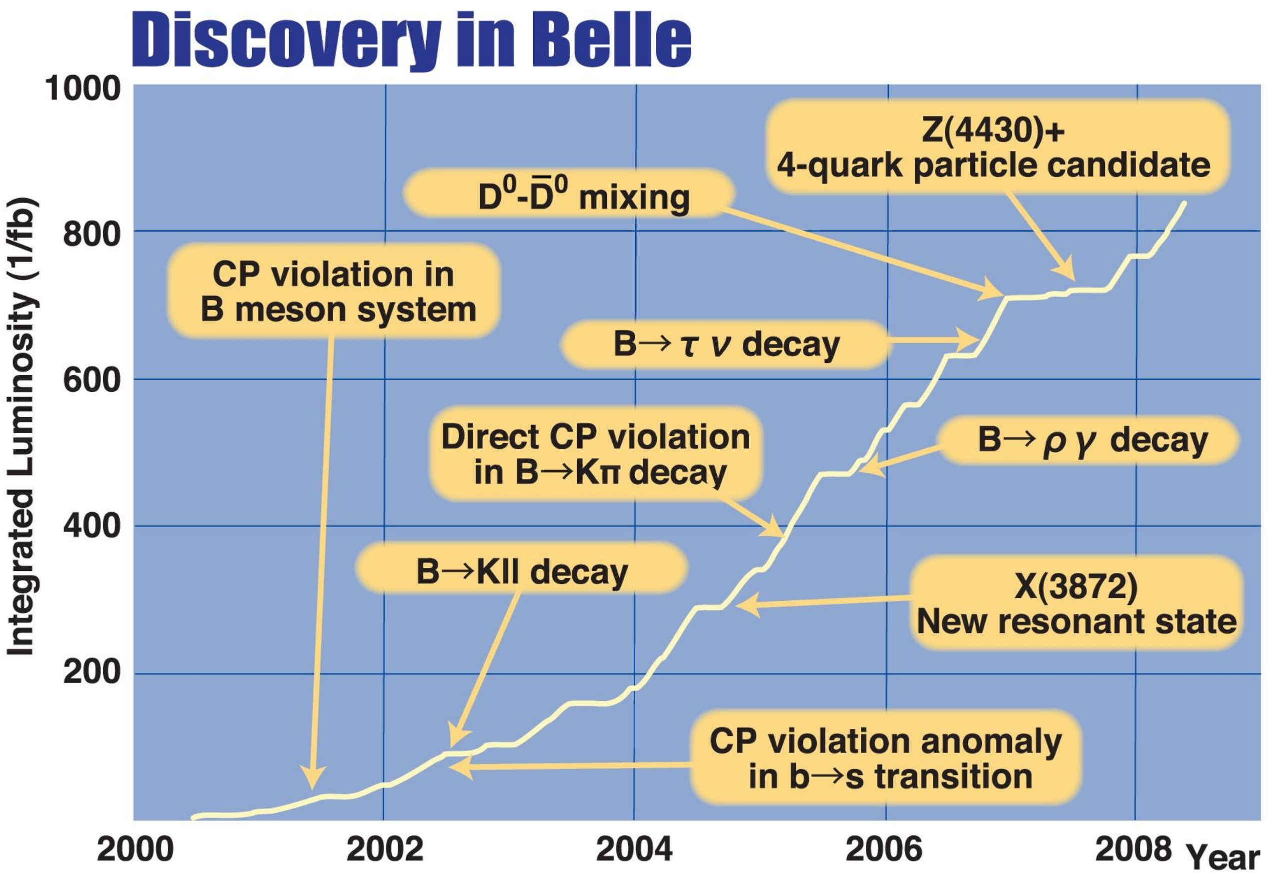
- Well-defined initial state
- High luminosity
- Asymmetric collisions



- Allows to make time dependent analysis of CP asymmetries



Highlights of the Belle Experiment



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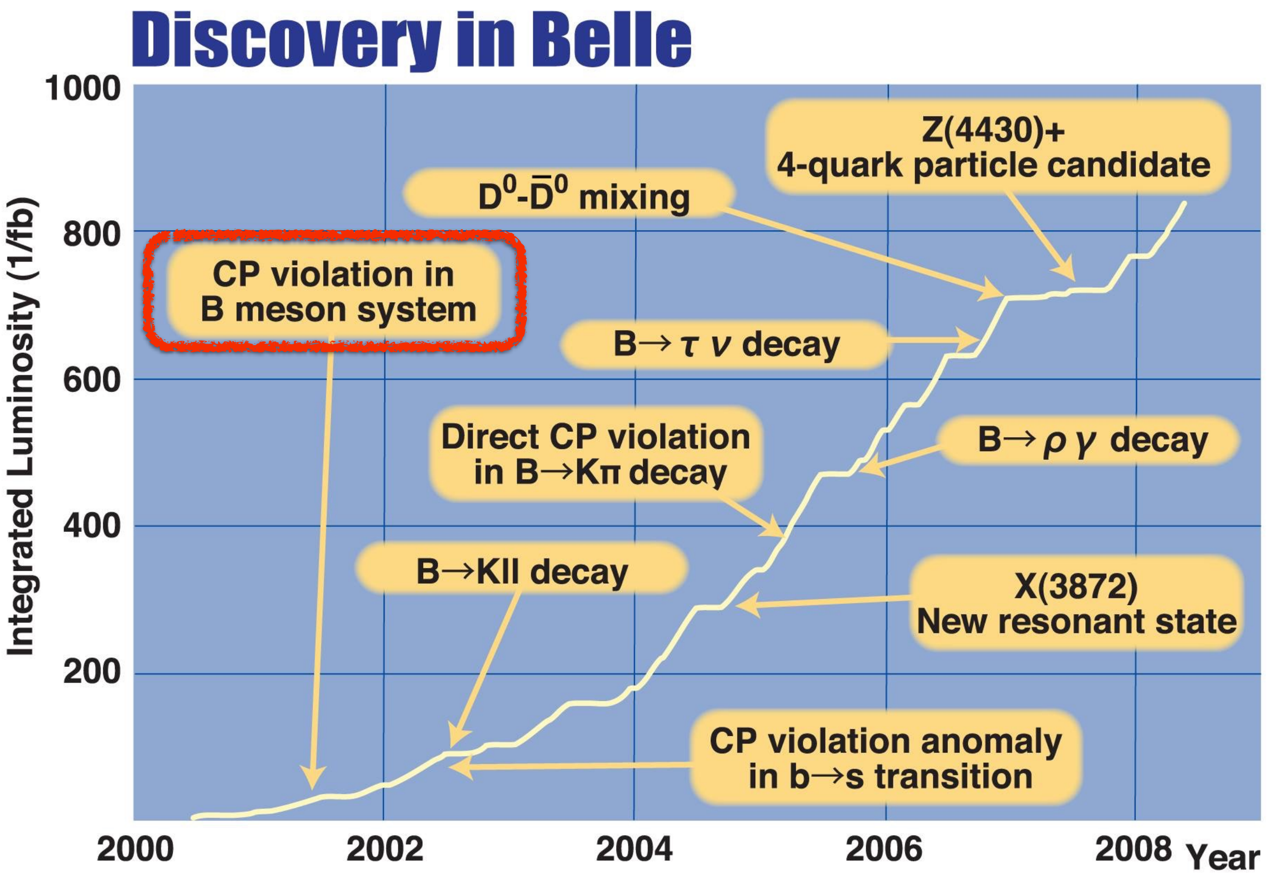
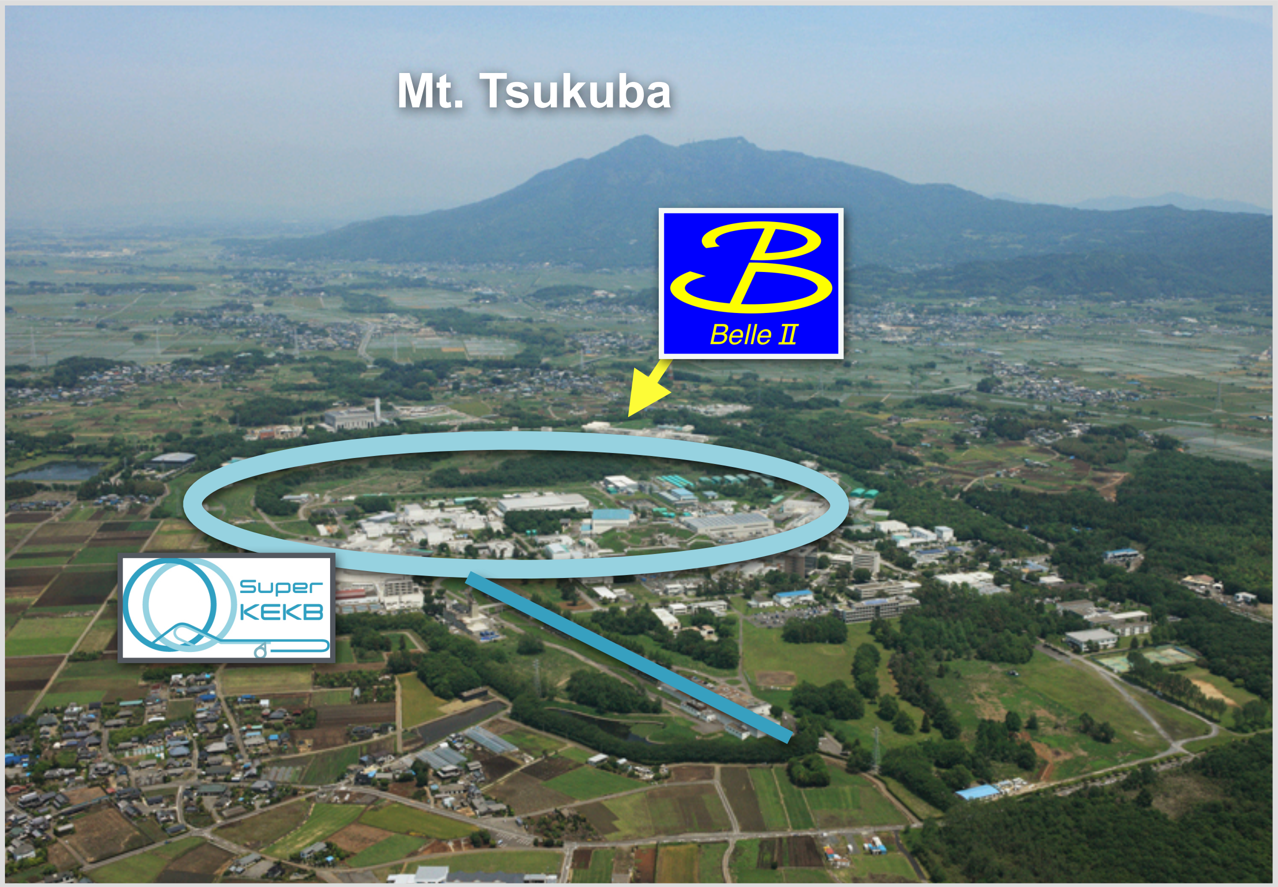
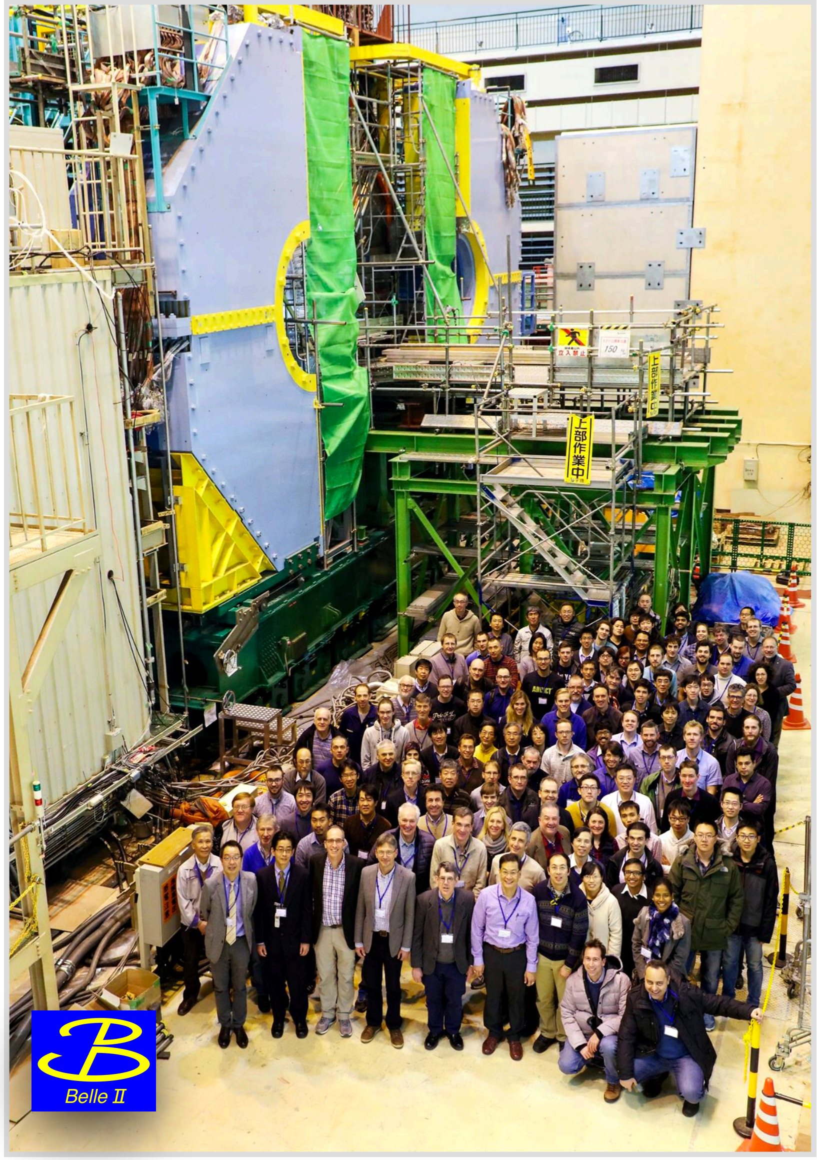


The Belle II Collaboration

1200 members, 125 institutions, 28 countries





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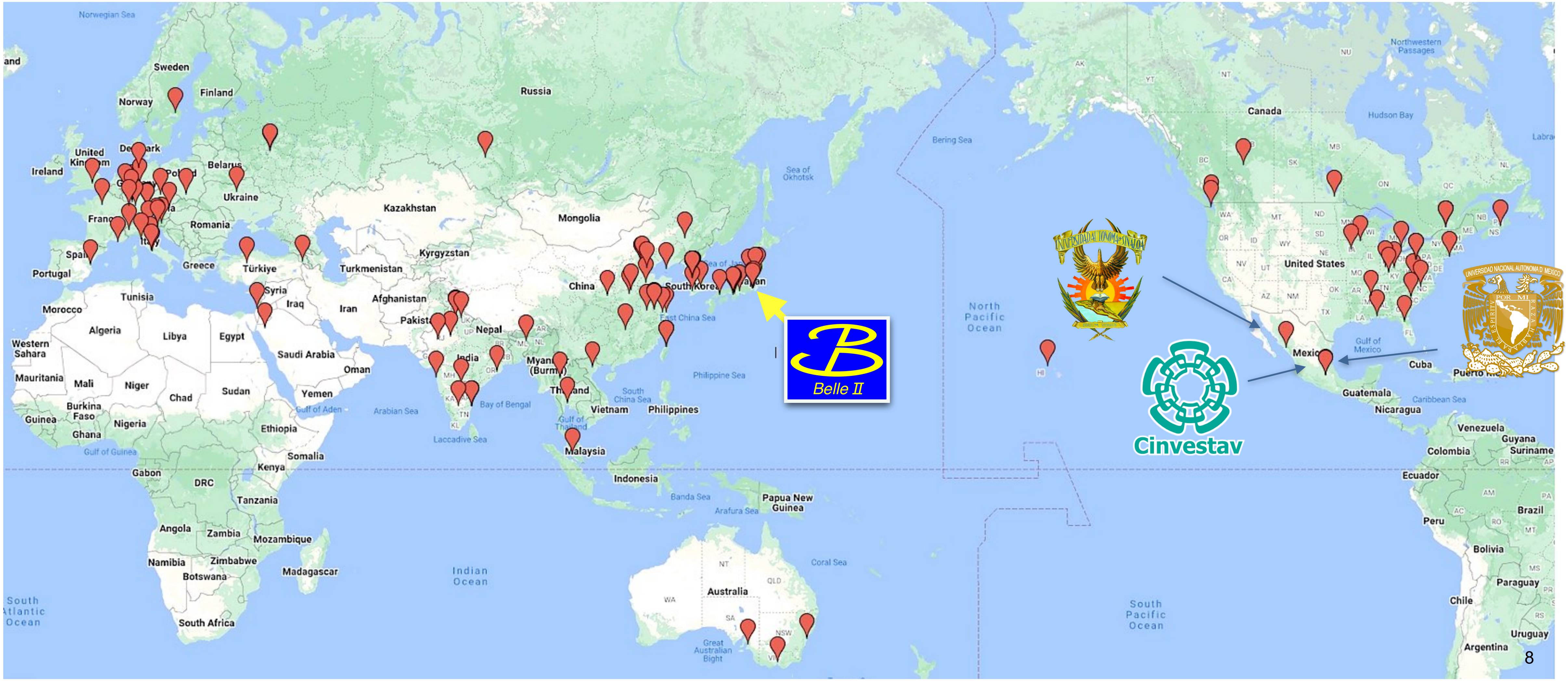

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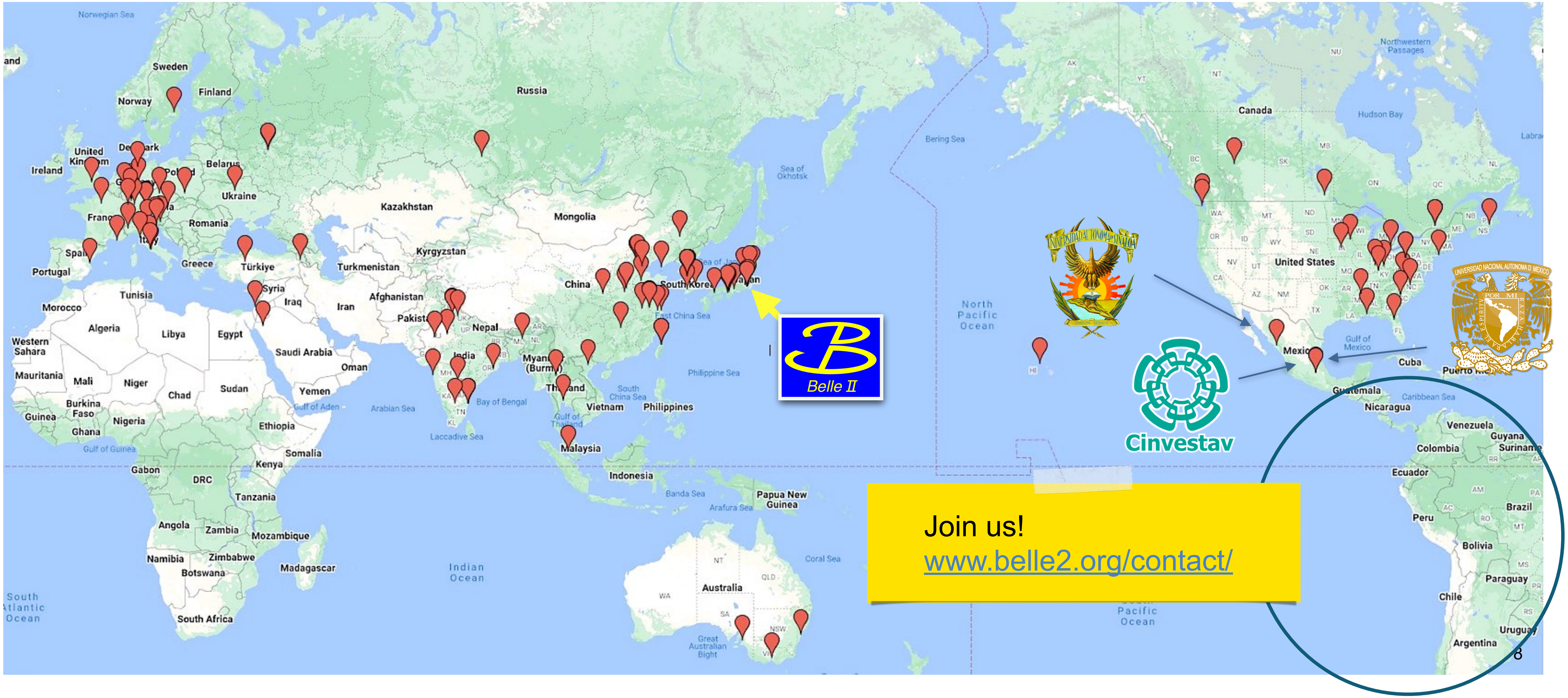
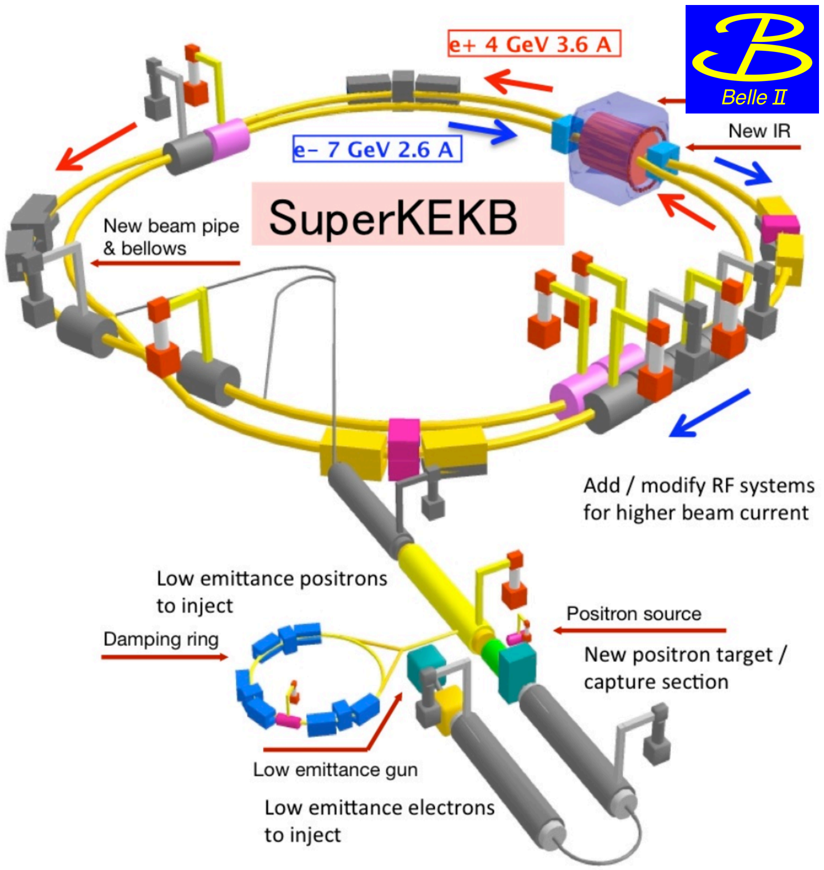


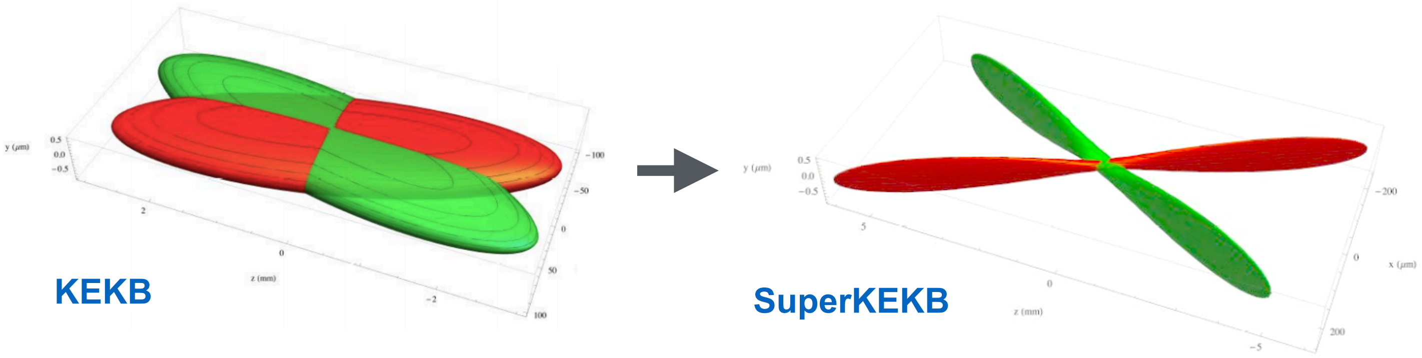
Join us!
www.belle2.org/contact/

SuperKEKB

- Goal: deliver multi ab^{-1} data set
  O(10) more than previous B factories

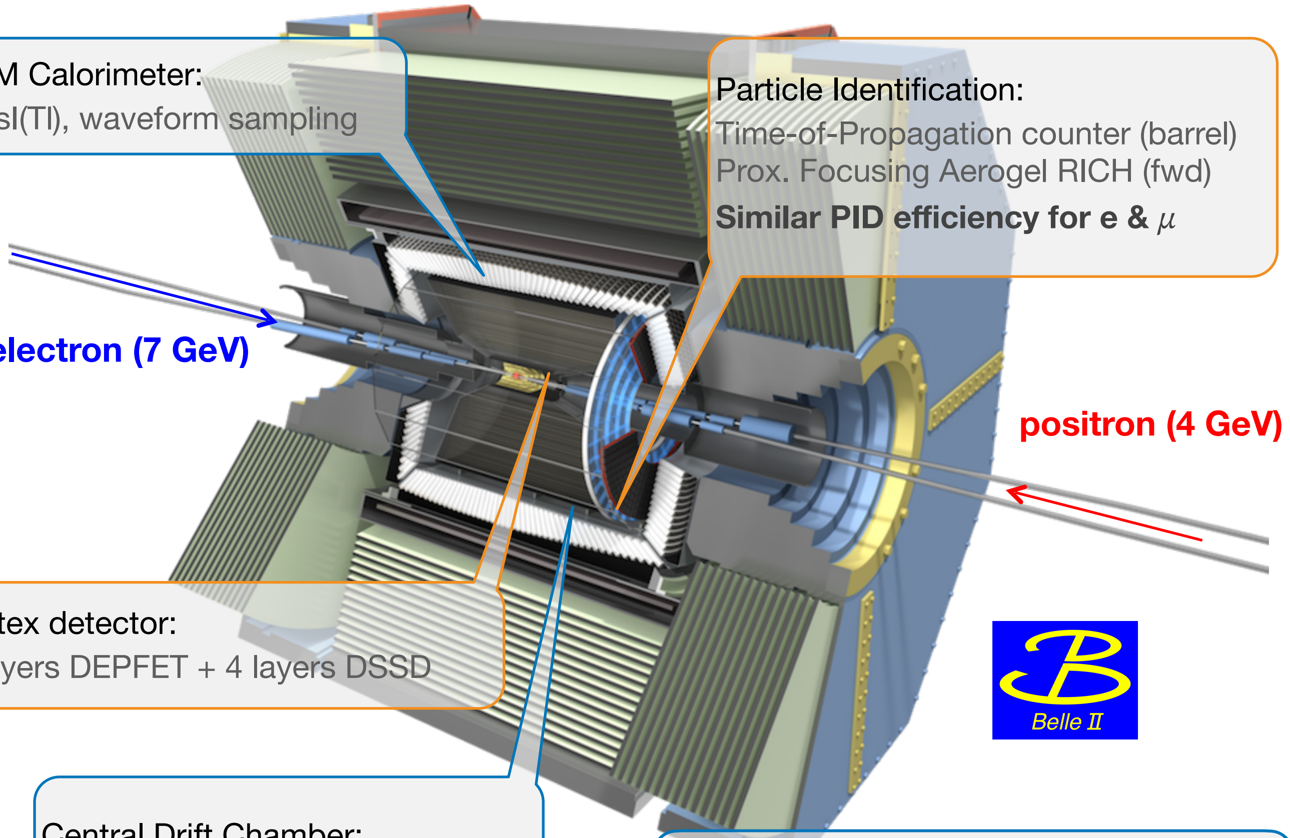


- "Nano-beams": vertical beam size is 50 nm at the IP



- Challenges at L=6.0x10^{35} cm^{-2} s^{-1}:
  - **Higher background** (Radiative Bhabha, Touschek, beam-gas scattering, etc.)
  - **Higher trigger rates** (High performance DAQ, computing)

Belle II in a Nutshell



EM Calorimeter:
CsI(Tl), waveform sampling

Particle Identification:
Time-of-Propagation counter (barrel)
Prox. Focusing Aerogel RICH (fwd)
Similar PID efficiency for e & μ

Vertex detector:
2 layers DEPFET + 4 layers DSSD

Central Drift Chamber:
He(50%):C_2H_6(50%), Small cells,
long lever arm, fast electronics

Readout (TRG, DAQ):
Max. 30kHz L1 trigger
~100% efficient for hadronic events
Dedicated low-multiplicity triggers

arXiv:1011.0352 [physics.ins-det]

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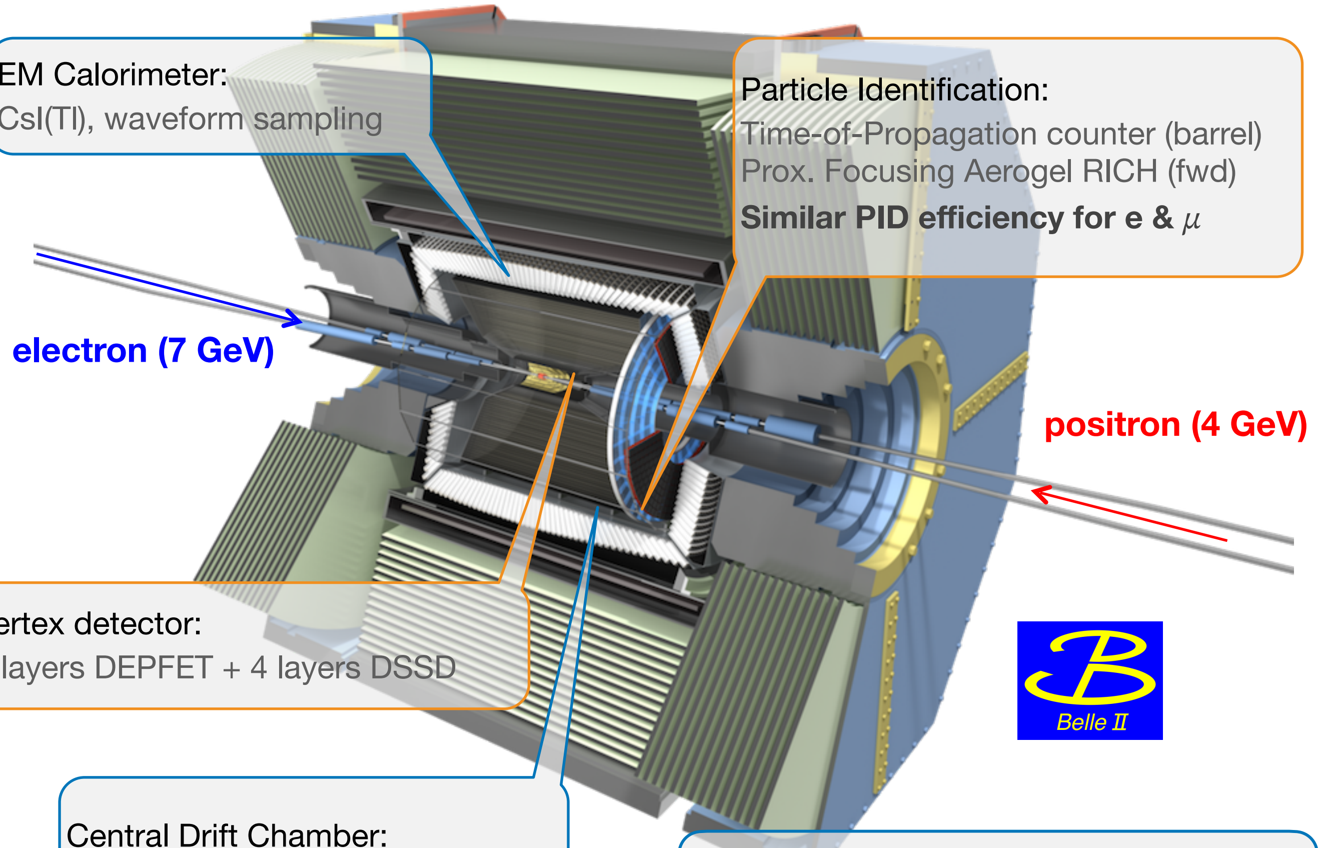

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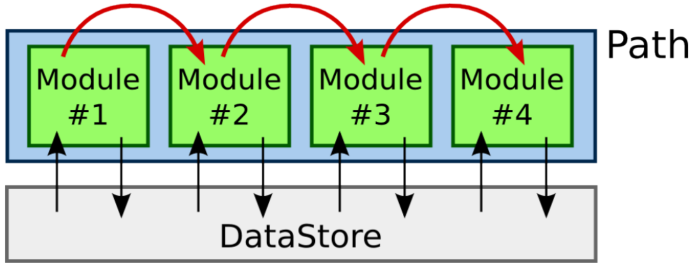
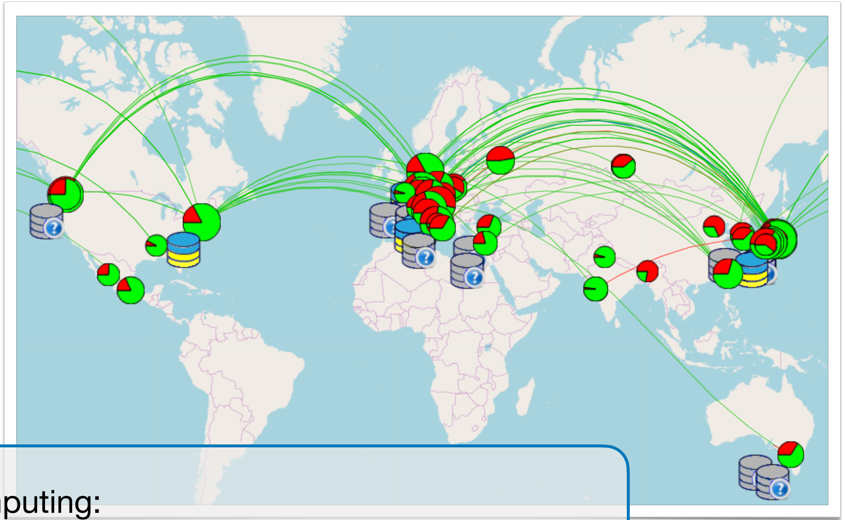
arXiv:1011.0352 [physics.ins-det]

Software:
Open-source algorithms for simulation, reconstruction, visualization, and analysis



Comput. Softw. Big Sci. 3 1 (2019)



Computing:
Distributed over the world via grid

EPJ Web Conf., 245 (2020) 11007

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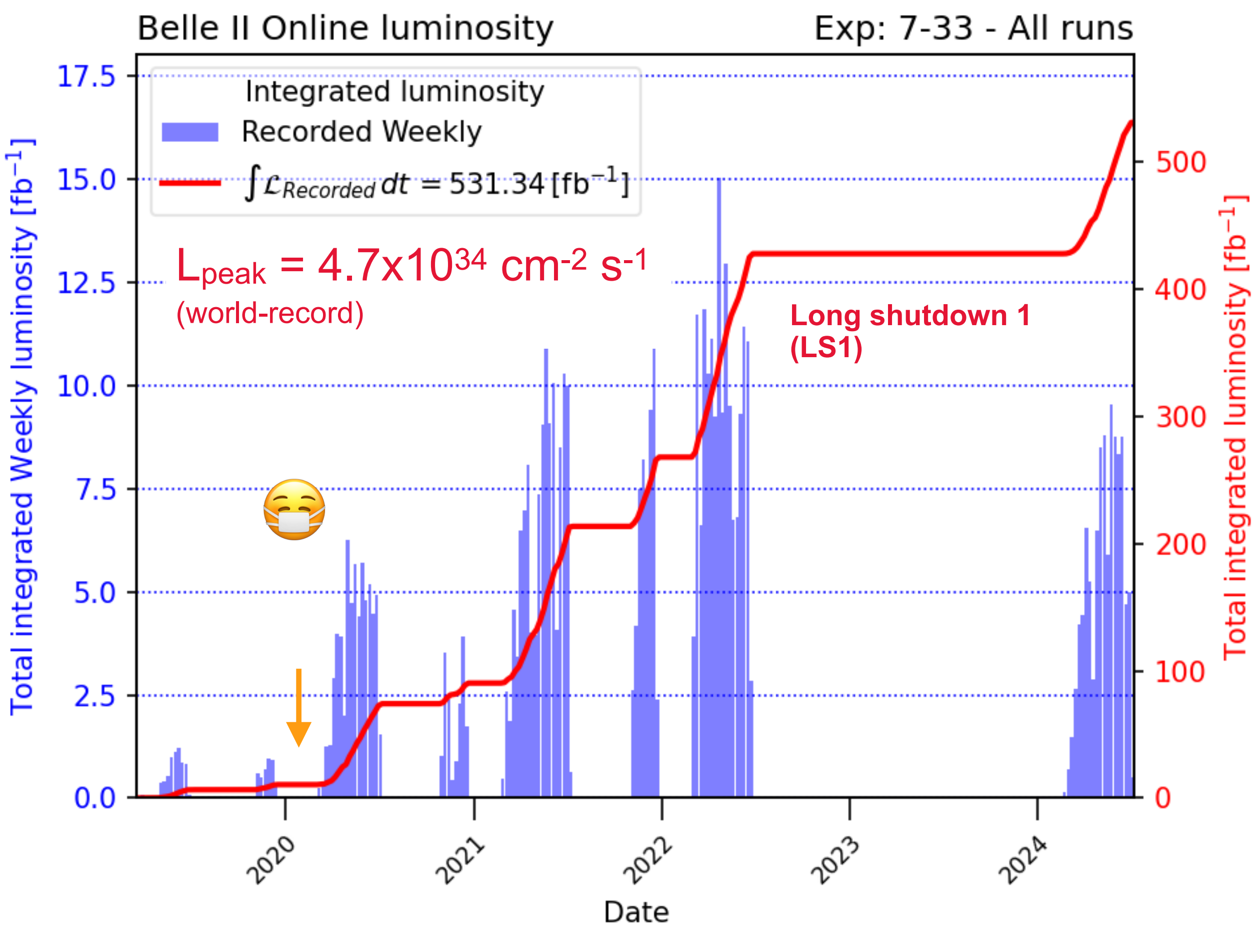
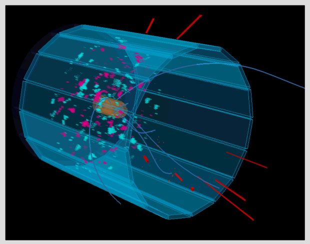
Integrated Luminosity



- **Super B-factory performance levels**
  - Instantaneous luminosity above the previous B factories, with lower beam currents than KEKB
- Long shutdown 1 during 2022 - 2024
  - Upgrade in the accelerator
  - Installation of full vertex detector
- Data taking restarted in 2024



evdisp.belle2.org

The Belle II Physics Program

- A unique environment for high-precision measurements and BSM searches
- The program covers measurements in B decays, charm, dark sector, etc.
- Several of them, unique to Belle II

- Today we will cover a small fraction of the results
  - A full list is available at belle2.org

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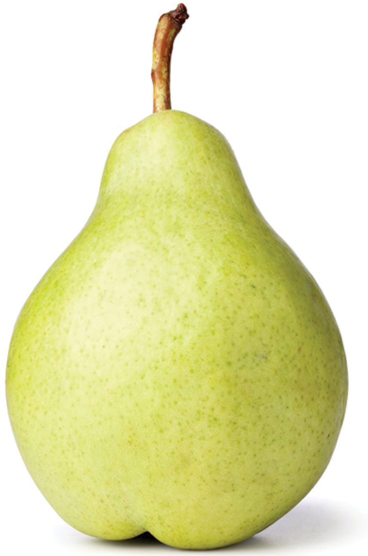
B-Physics

B-Factories 101: Event Shape and Kinematics

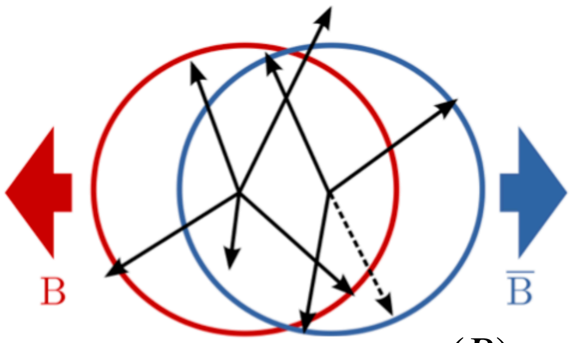
or



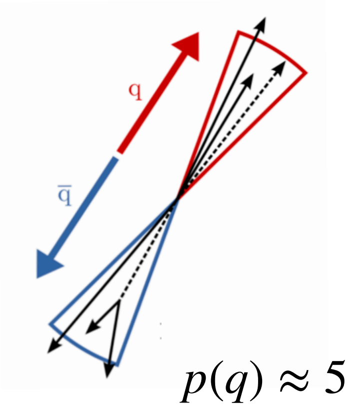
B-Factories 101: Event Shape and Kinematics

- $B\bar{B}$ events have a spherical shape, useful to discriminate them from $q\bar{q}$ events

$$\sqrt{s} = 10.58\ \text{GeV} \approx 2m_B$$



$p(B) \approx 0.3\ \text{GeV}/c$



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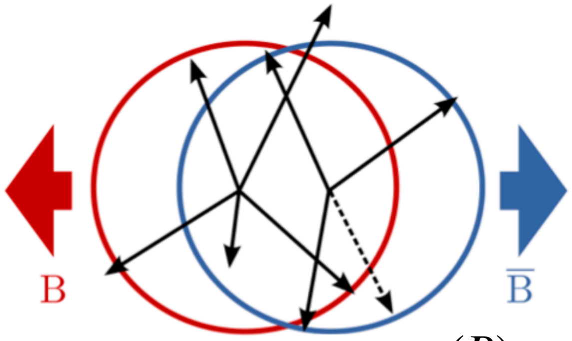

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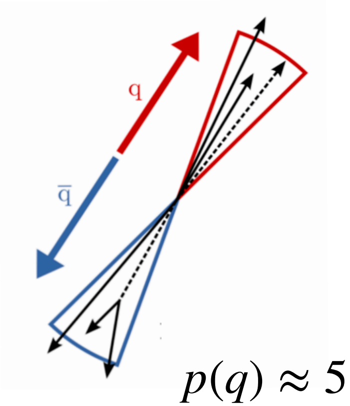
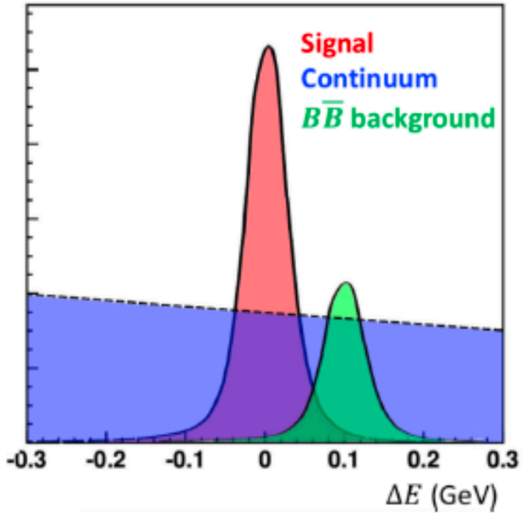


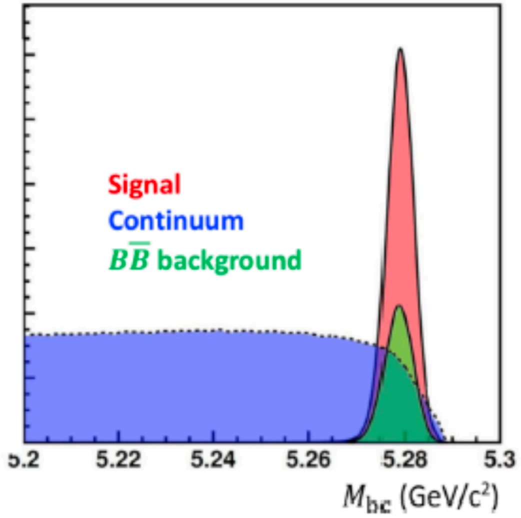
$p(q) \approx 5 \text{ GeV}/c$

- Kinematic constraints are used to separate signal from background and $q\bar{q}$ continuum

$$\Delta E = E_B - \sqrt{s}/2$$



$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{\,2}}$$



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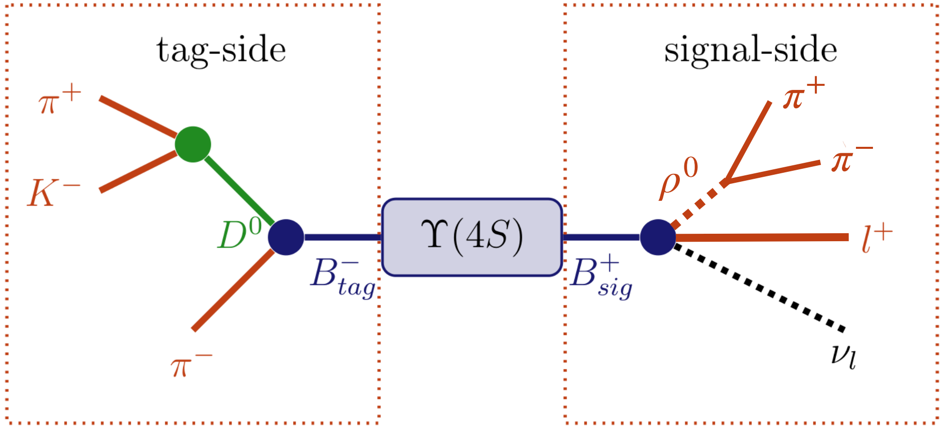
B-Factories 101: Tagging

Full event interpretation

- Reconstructs one of the B mesons (tag)
- Infers **strong kinematic constraints** for the remaining B meson in the event



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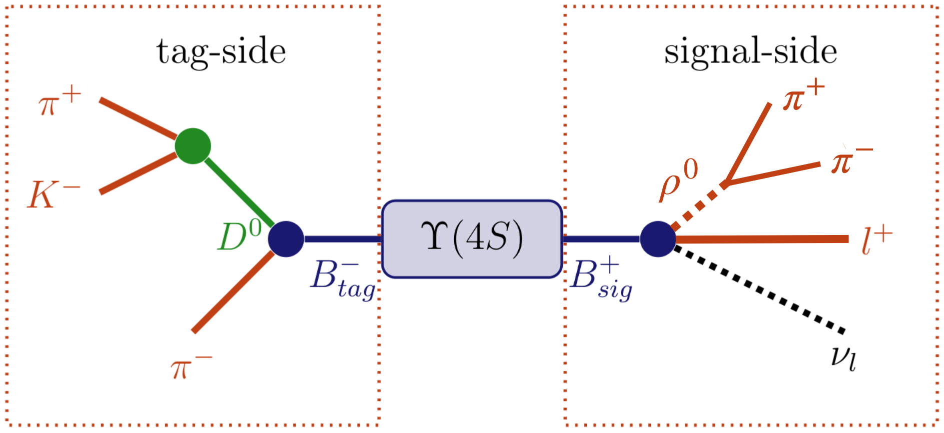

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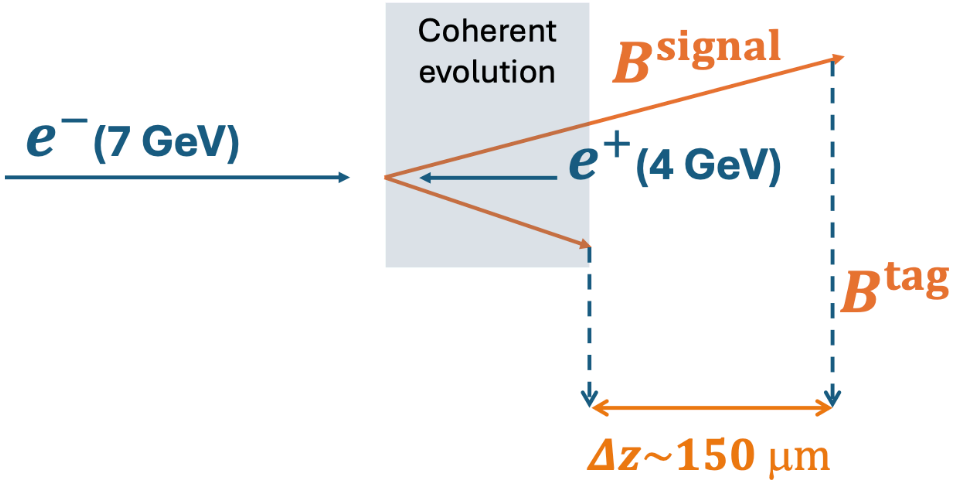
Flavor tagger

- Determine the flavor of **neutral** B mesons
- Quantum correlation allows identification of "signal B" flavor based on "tag B"



Belle II. Eur. Phys. J. C 82, 283 (2022)

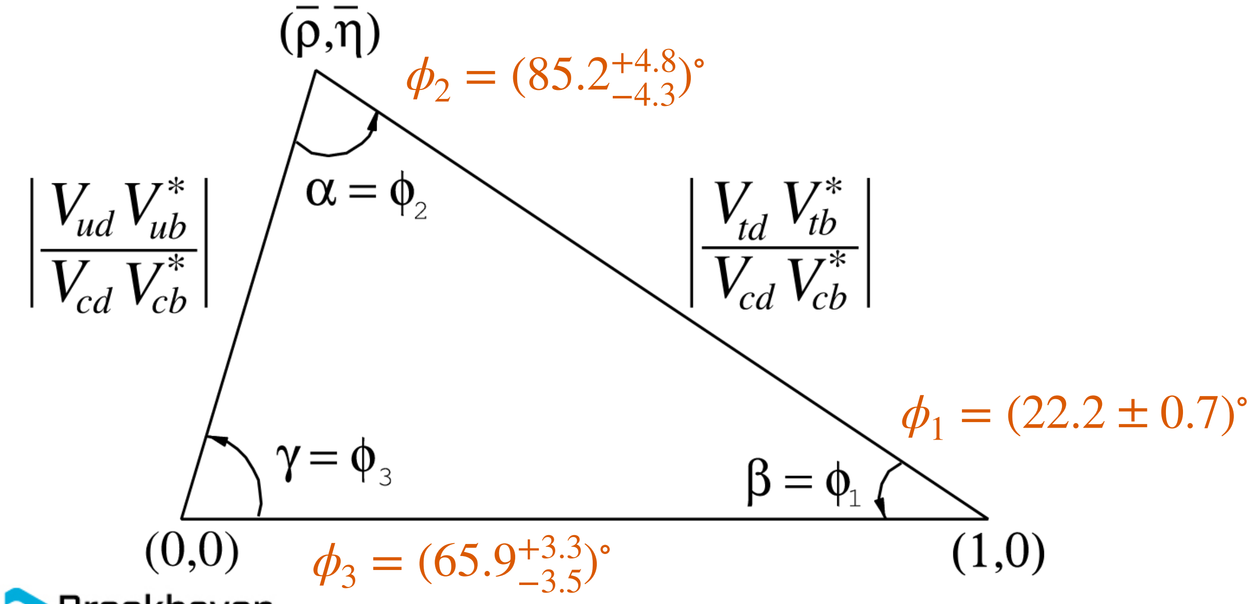
Analysis techniques unique to B factories

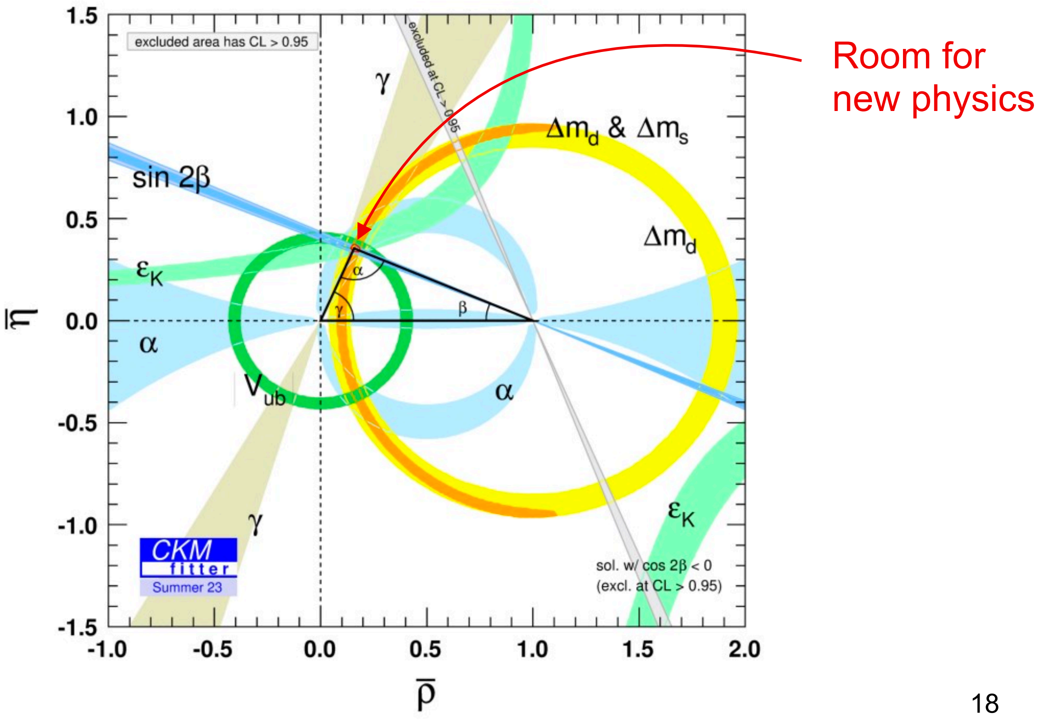
The CKM Matrix Unitarity

- Unitarity conditions can be represented as triangles
  - Three mixing angles and one CP violating phase

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

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





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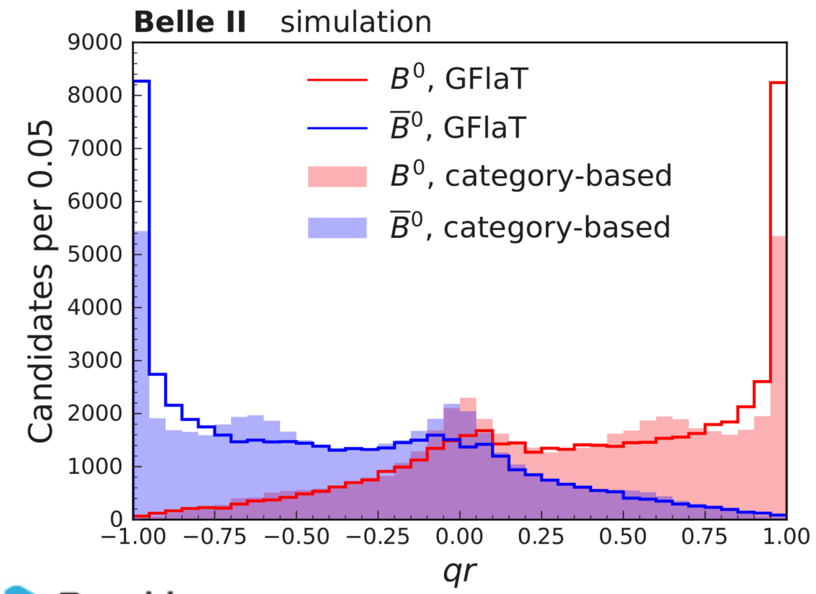
Graph-neural-network flavor tagging and ϕ_1

- A novel technique in Belle II to tag flavors:
  Graph-neural-network flavor tagging (GFlaT)
  - Accounts for relations between final-state particles
  - Calibrated using "self-tagging" B decays, like
    $B^0 \to D^{*-}\pi^+ \to \bar{D}\pi^-\pi^+ \to K^+\pi^-\pi^-\pi^+$



Improvement of 20% in effective tagging power vs previous algorithm

Phys. Rev. D 110, 012001 (2024)

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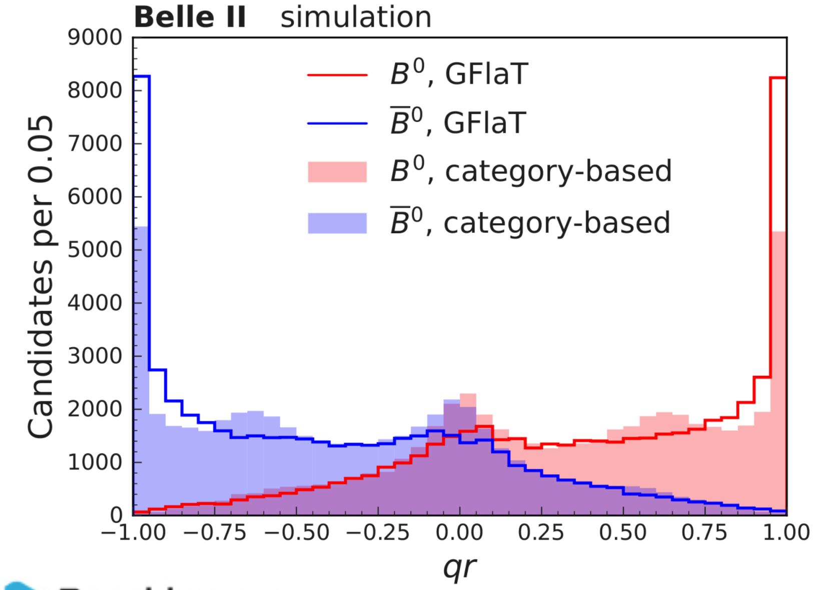


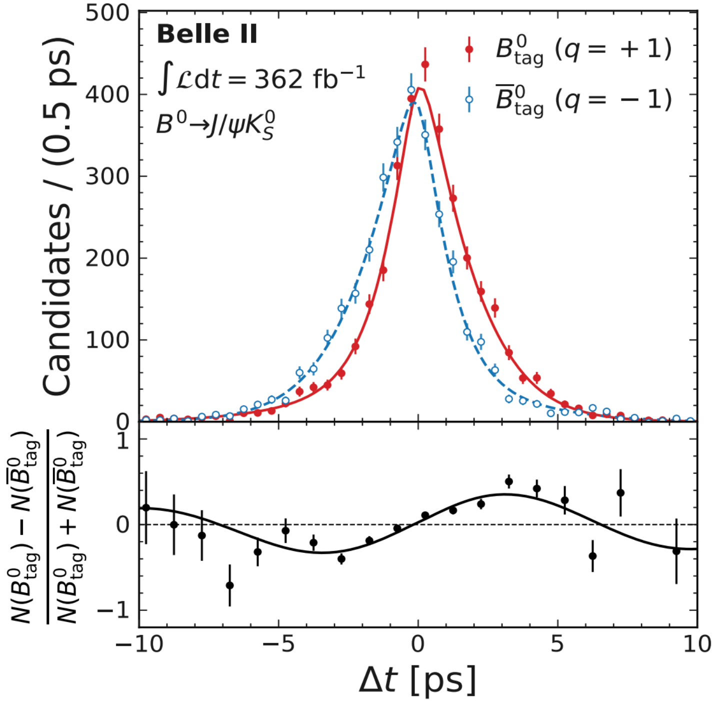
Improvement of 20% in effective tagging power vs previous algorithm

- Using as a benchmark the "golden channel" $B^0 \to J/\psi\, K_s^0$

$$A_{CP}^{B\to f}(\Delta t) \equiv \frac{\Gamma(B^0(\Delta t) \to f) - \Gamma(\bar{B}^0(\Delta t) \to f)}{\Gamma(B^0(\Delta t) \to f) + \Gamma(\bar{B}^0(\Delta t) \to f)}$$

$$= \boxed{S} \cdot \sin(\Delta m_d \Delta t) - \boxed{C} \cdot \cos(\Delta m_d \Delta t)$$

Mix-induced CPV Direct CPV $S = |\sin(2\phi_1)|$



$\phi_1 = (23.2 \pm 1.5 \pm 0.6)^\circ$

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Phys. Rev. D 110, 012001 (2024)

ϕ_2: $B^0 \to \pi^0\pi^0$

FPCP 2024
Paper in preparation

$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = \frac{\Gamma(\overline{B}^0 \to \pi^0\pi^0) - \Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(\overline{B}^0 \to \pi^0\pi^0) + \Gamma(B^0 \to \pi^0\pi^0)}$$

- Tree-level $b \to u\bar{u}d$ decays are sensitive to ϕ_2
  - loop $b \to d$ loop contributions add an extra phase $\Delta\phi_2$
- Determining ϕ_2 from $B \to \pi\pi$ decays, requires BRs and A$_{CP}$ of:

$$B^0 \to \pi^+\pi^-,\ B^+ \to \pi^+\pi^0,\ B^0 \to \pi^0\pi^0$$

[Phys. Rev. Lett. 65, 3381]

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ϕ_2: $B^0 \to \pi^0\pi^0$

[FPCP 2024](#)
Paper in preparation

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$$B^0 \to \pi^+\pi^-,\ B^+ \to \pi^+\pi^0,\ B^0 \to \pi^0\pi^0$$

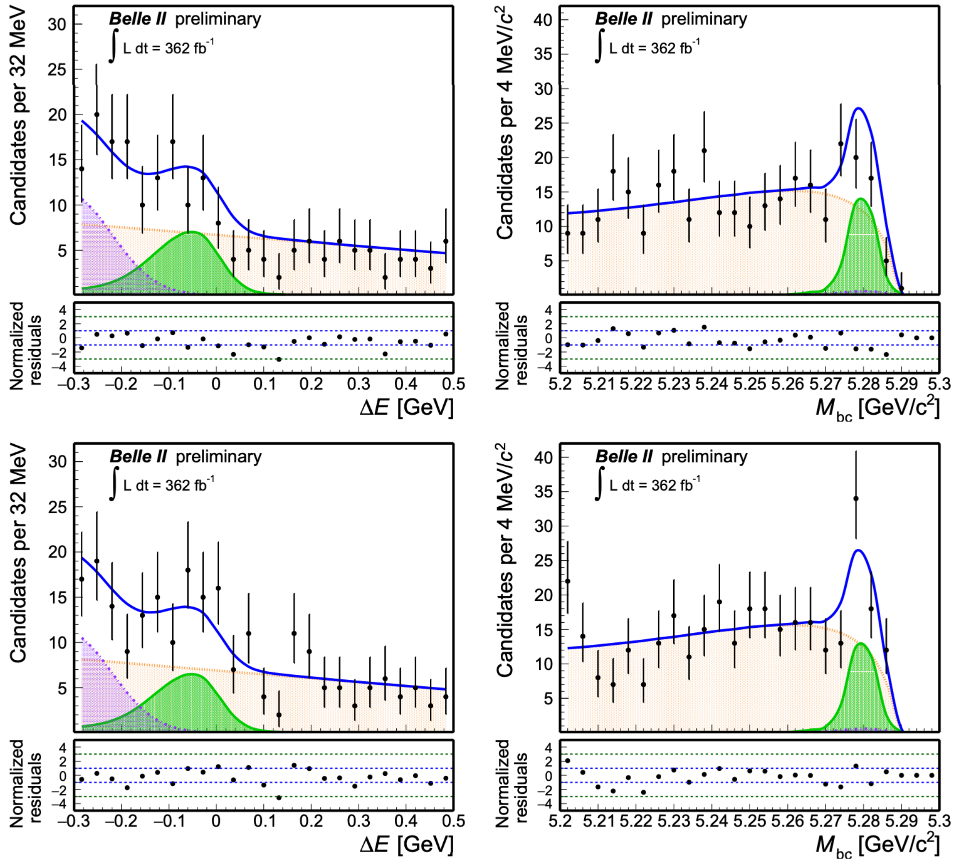
[Phys. Rev. Lett. 65, 3381]

- Updated measurement of $B^0 \to \pi^0\pi^0$at Belle II with full run 1 statistics
  - Experimentally challenging: 4 photons with no tracks
  - A BDT classifier to discriminate signal
  - Using the **graph flavor tagger** to determine signal flavor and measure CP asymmetry

$$\mathscr{B}(B \to \pi^0\pi^0) = (1.26 \pm 0.20 \pm 0.12) \times 10^{-6}$$

$$A_{CP}(B \to \pi^0\pi^0) = 0.06 \pm 0.30 \pm 0.05$$

World-best!



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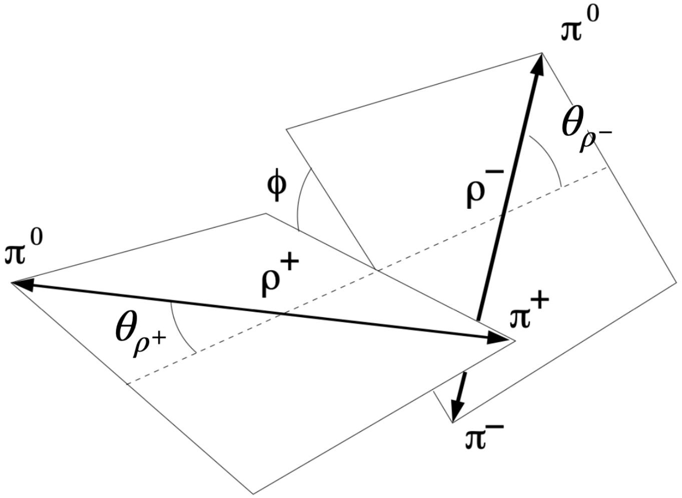
ϕ_2: $B^0 \to \rho^+\rho^-$

- Small loop contribution - golden model for the extraction of ϕ_2
- It is a pseudo scalar to vector-vector decay - longitudinal and transverse polarization states
  - The fraction of longitudinal polarization f_L determines the sensitivity of the CPV parameters
  - f_L is extracted from the helicity angles θ_ρ



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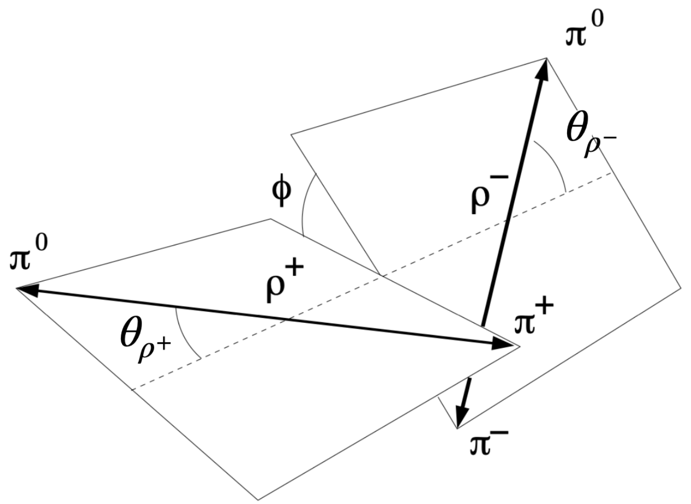
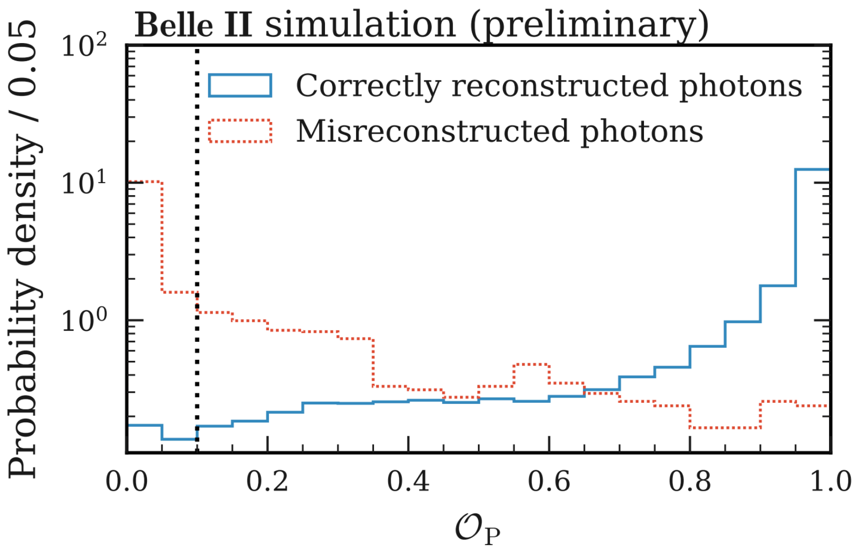
  - The fraction of longitudinal polarization f_L determines the sensitivity of the CPV parameters
  - f_L is extracted from the helicity angles θ_ρ
- Signal candidates reconstructed via $\rho^+ \to \pi^+(\pi^0 \to \gamma\gamma)$
- Selection via MVA techniques
  - Boosted Decision Tree (BDT) to classify real photons from hadronic showers
  - TabNet classifier for continuum suppression (CS)



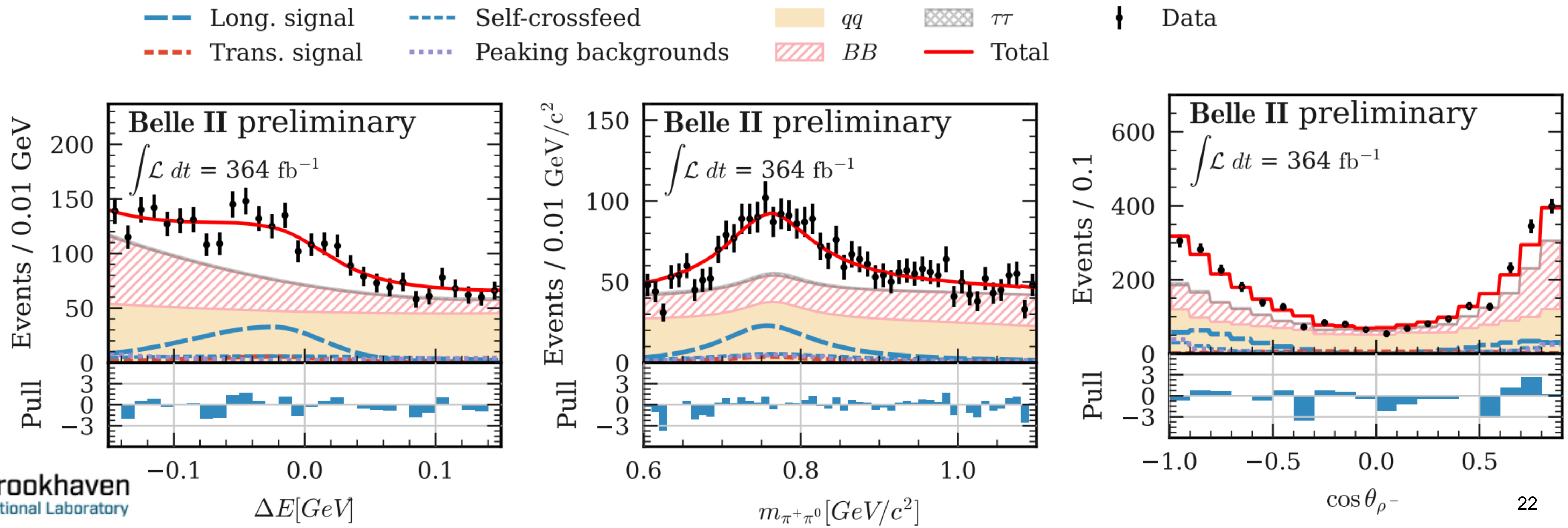


ϕ_2: $B^0 \to \rho^+\rho^-$

- Fit for branching ratio and f_L: ΔE, m_ρ, $cos\theta_\rho$, CS
- Systematic uncertainties dominated by π^0 efficiency and MC mismodeling

$$\mathscr{B}(B^0 \to \rho^+\rho^-) = (29.0^{+2.3}_{-2.2}{}^{+3.1}_{-3.0}) \times 10^{-6}$$
$$f_L(B^0 \to \rho^+\rho^-) = 0.921^{+0.024}_{-0.022}{}^{+0.017}_{-0.015}$$

Consistent with previous measurements



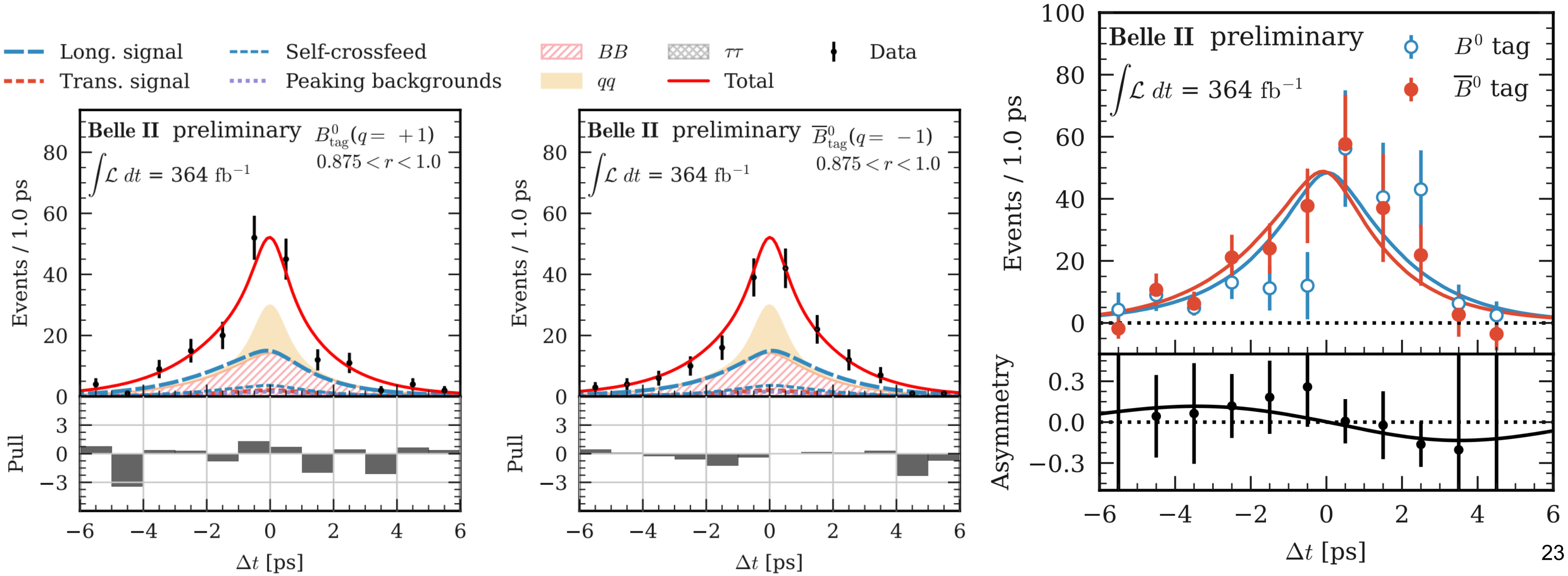
ϕ_2: $B^0 \to \rho^+\rho^-$

Paper in preparation

- Fit for CP asymmetries: ΔE, m_ρ, $cos\theta_\rho$
  + decay time difference between B_{sig} and B_{tag} (Δt) and flavor tagger

- Combining world averages of $B \to \rho\rho$: $\phi_2 = (92.6^{+4.5}_{-4.8})^\circ$

Improves sensitivity of ϕ_2 by 6.0%



$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

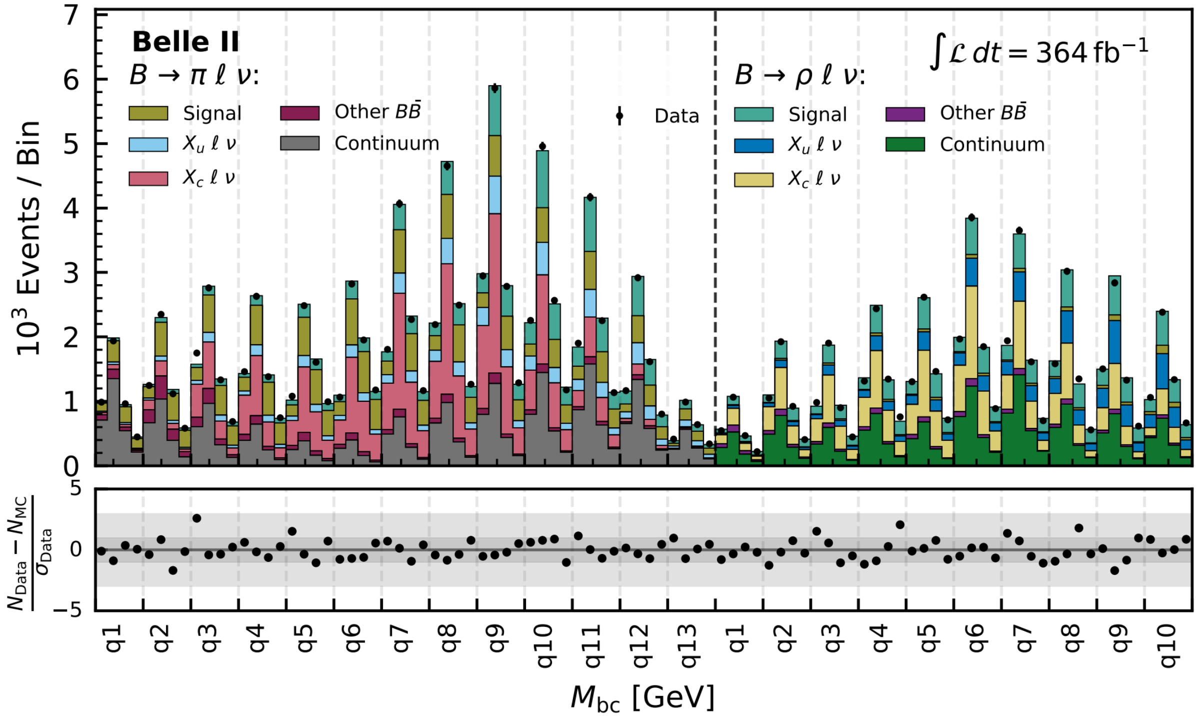
- The rate of $b \to u$ decays is proportional to $|V_{ub}|^2$; Determination by inclusive and exclusive methods differ by 2.5σ

[PDG 2023]

- Simultaneous study of the charmless semileptonic decays $B^0 \to \pi^- \ell^+ \nu$ & $B^+ \to \rho^0 \ell^+ \nu$
  - Extract signal yields from simultaneous fit to binned MC templates
- p_ν estimated from all reconstructed tracks and clusters
  - Then used to reconstruct M_{bc} & ΔE
- Background suppressed using BDTs

$$q^2 = (p_B - p_{\pi/\rho})^2$$

$$\mathscr{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathscr{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$



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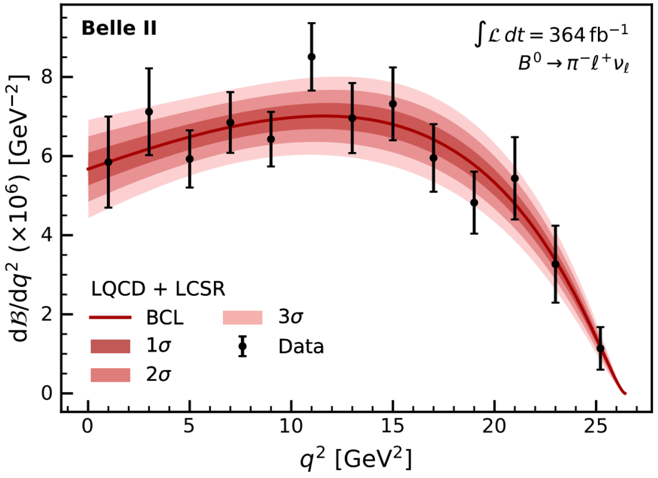
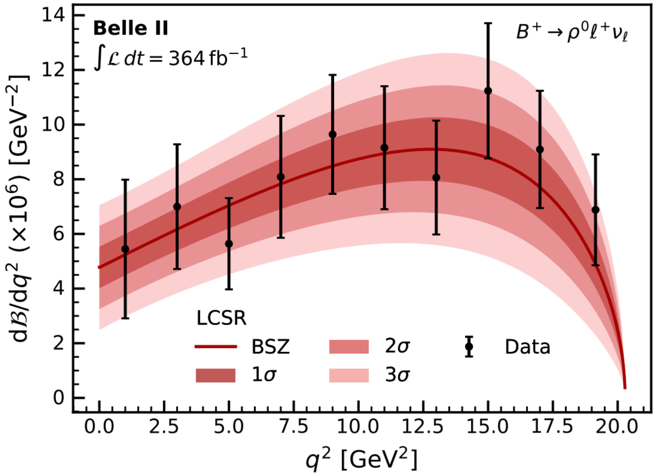
$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

arxiv:2407.17403
Submitted to PRD

- $|V_{ub}|$ extracted from the $q^2 = (p_B - p_{\pi/\rho})^2$ spectra with form factor determinations
  - Lattice QCD (LQCD) [Eur. Phys. J. C 82, 869 (2022)]
  - Light-cone sum rule (LCSR) [J. High Energ. Phys. 2021, 36 (2021), J. High Energ. Phys. 2016, 98 (2016)]





$$|V_{ub}|^{\mathrm{LQCD}}_{B\to\pi\ell\nu} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$$

(stat.) (syst.) (theo.)

$$|V_{ub}|^{\mathrm{LQCD+LCSR}}_{B\to\pi\ell\nu} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$$

$$|V_{ub}|^{\mathrm{LCSR}}_{B\to\rho\ell\nu} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$

- Consistent with world-average
- Comparable precisions with Belle/BaBar

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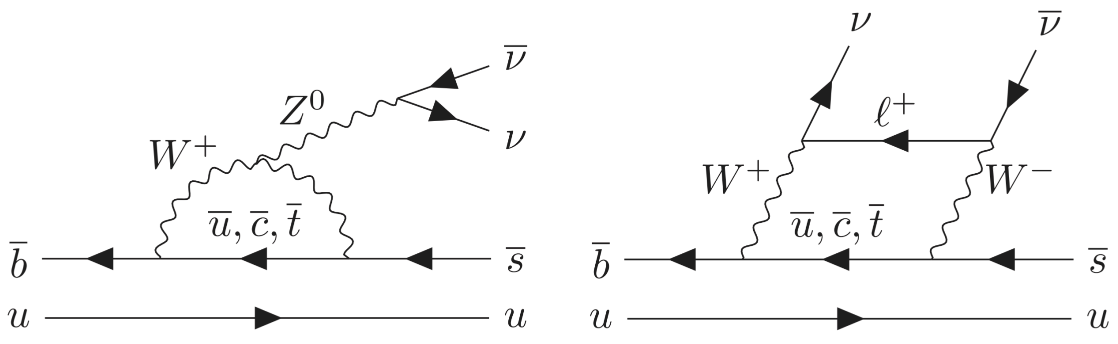
Rare B Decays

$B^+ \to K^+\nu\bar{\nu}$ decays

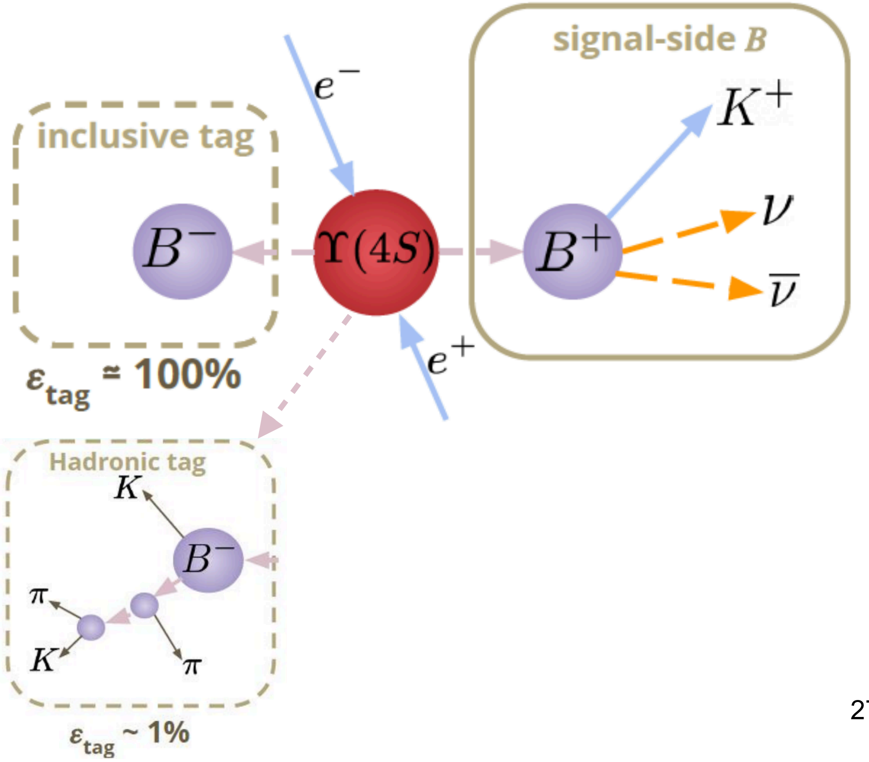
- Flavor-changing neutral current $b \to s\nu\bar{\nu}$ transitions suppressed in the SM due to the GIM mechanism
- Reliable prediction for the branching ratio in the SM

$$BR(B^+ \to K^+\nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$$ PRD 107, 014511 (2023)



- Can be modified by non-SM contributions
  - Leptoquarks
  - $B^+ \to K^+ +$ dark matter

- New approach: inclusive + hadronic B-tagging & MVA classifier
  - **Inclusive tag** increase signal efficiency by 35% vs exclusive tag
  - **Hadronic tag** for consistency check and 10% increase in precision for final combination



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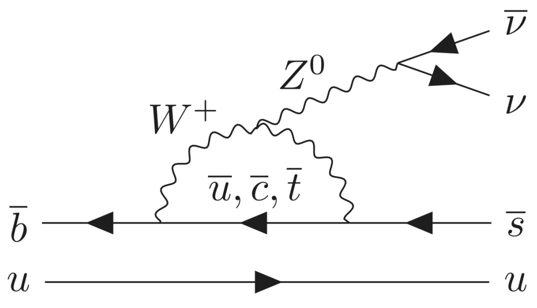
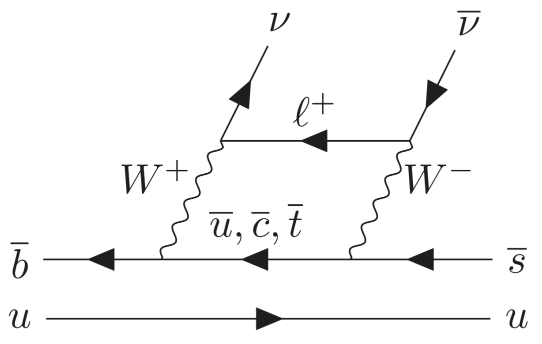
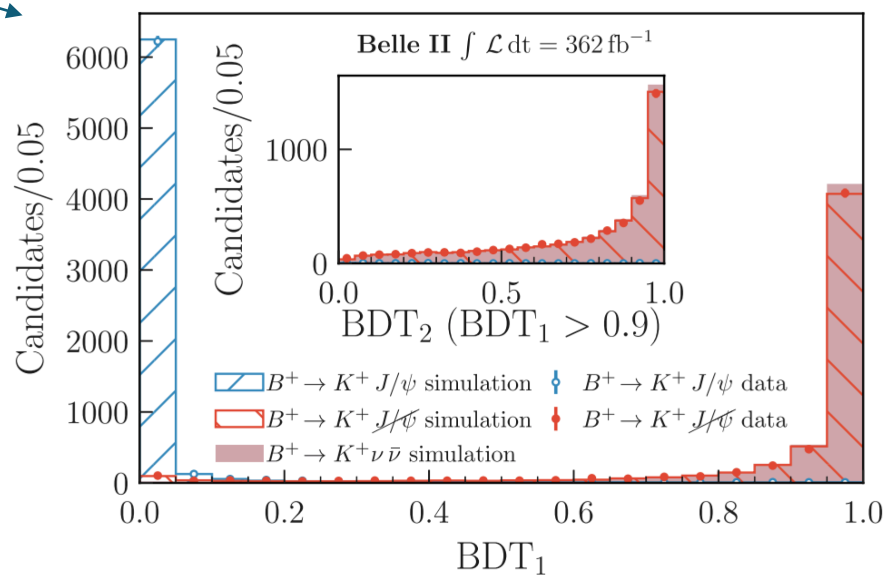




- Can be modified by non-SM contributions
  - Leptoquarks
  - $B^+ \to K^+$+ dark matter

- Validated with $B^+ \to K^+ + J/\psi$:



- New approach: inclusive + hadronic B-tagging & MVA classifier
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Evidence for $B^+ \to K^+ \nu\bar{\nu}$ decays

[Phys. Rev. D 109, 112006]

- Perform binned maximum likelihood fit

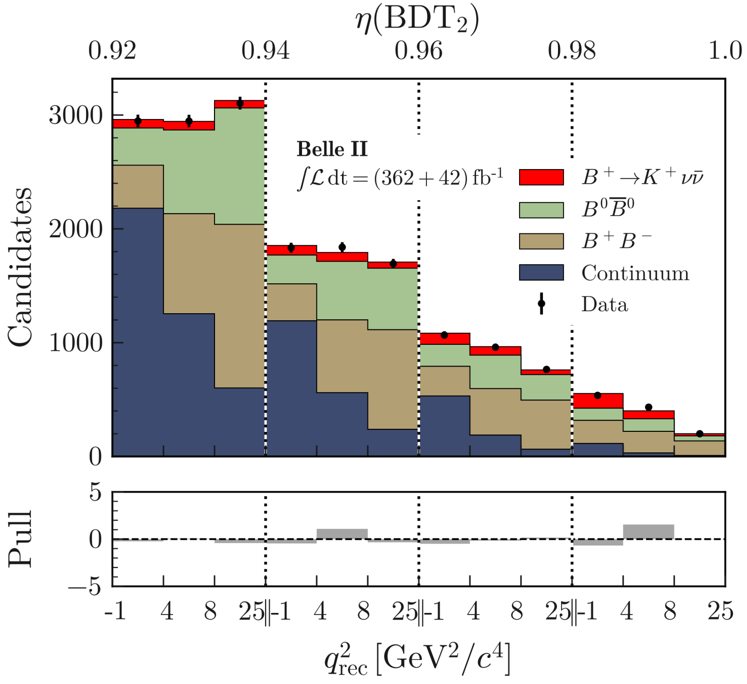
Inclusive tag: fit in bins of di-neutrino mass (q^2_{rec}) and classifier output:

ITA: $BR = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

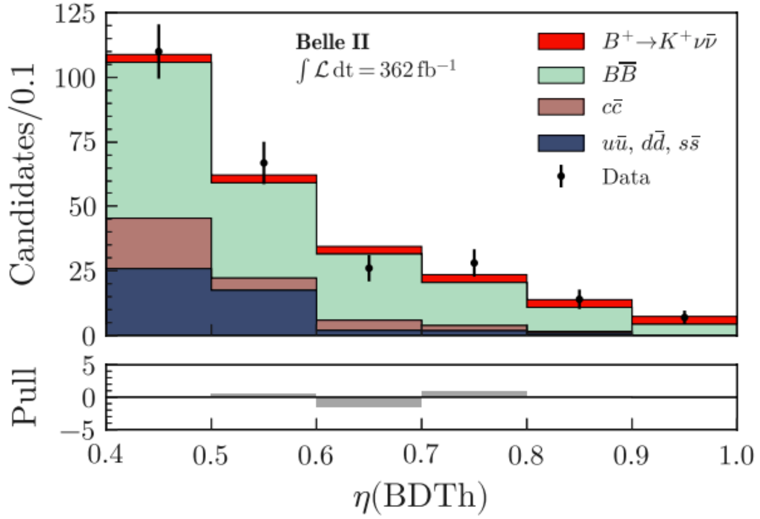
HTA: $BR = (1.1\ ^{+0.9}_{-0.8}\ ^{+0.8}_{-0.5}) \times 10^{-5}$

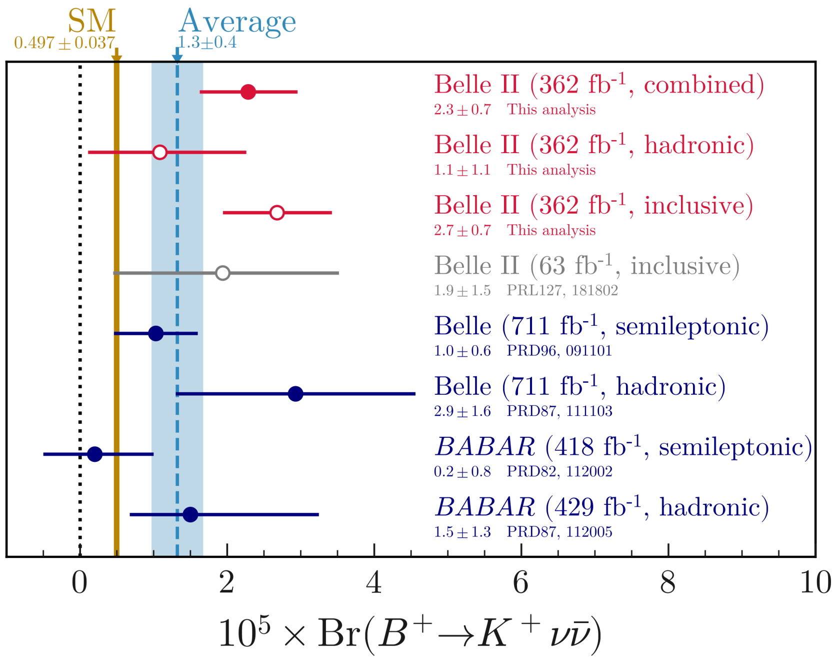
Combined: $BR = (2.3 \pm 0.5\ ^{+0.5}_{-0.4}) \times 10^{-5}$

Fit Result
- 3.5σ excess
- 2.7σ from SM



Hadronic tag: in bins of classifier output:





$B^0 \to K^{*0}\tau^+\tau^-$ decays

- FCNC suppressed in the SM

  $BR(B^0 \to K^{*0}\tau^+\tau^-) = (0.98 \pm 0.10) \times 10^{-7}$

- New physics models enhance the branching ratio significantly
  - Stronger BSM couplings to the third fermion generation

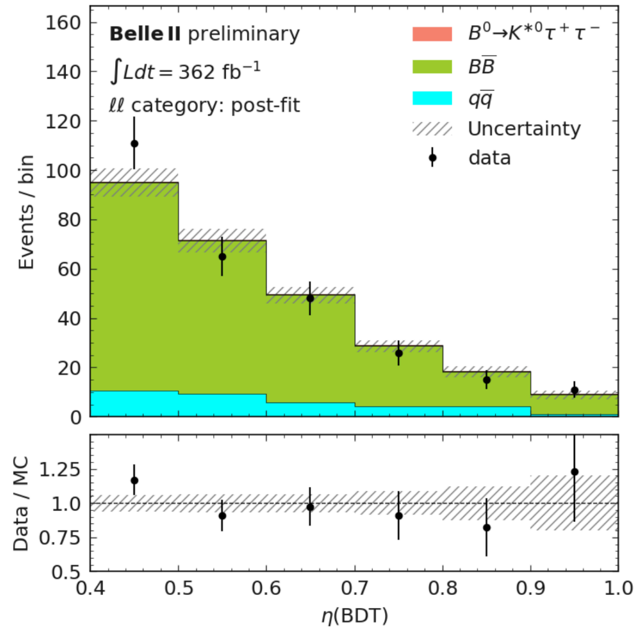
[Phys. Rev. Lett. 120, 181802]

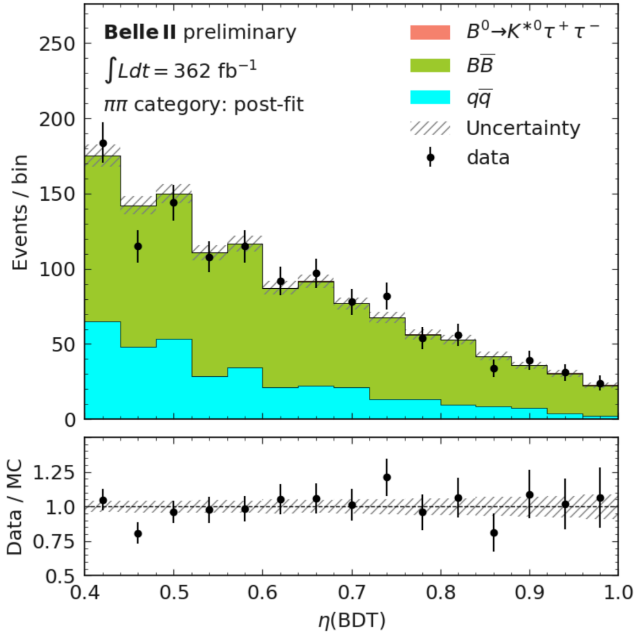
- Approach: τ reconstructed from $\tau \to \ell \bar{\nu}_\ell \nu_\tau$, $\tau \to \pi \nu_\tau$, $\tau \to \pi \rho_\tau$ & hadronic B-tagging
  - No signal peak & large backgrounds
- MVA classifier trained with kinematics of the event: missing energy, q^2, $M(K^* + \text{track})$, etc

$BR(B^0 \to K^{*0}\tau^+\tau^-) < 1.73 \times 10^{-3}$ at 90% C.L.

- Most stringent result to date for $b \to s\tau\tau$ transitions

Simultaneous fit to BDT output in all categories





2x better UL than Belle with half the statistics

Paper in preparation

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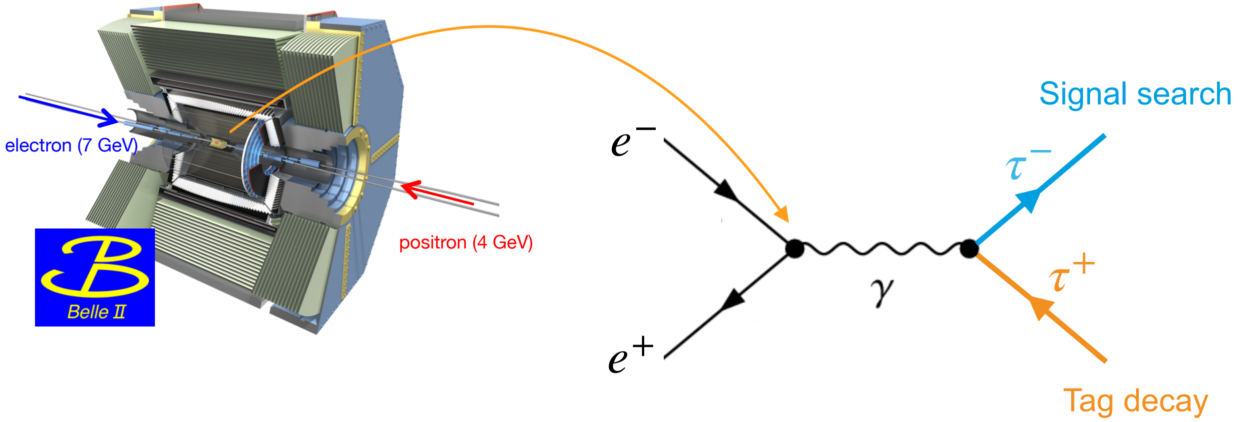
Tau Leptons

Belle II is a τ Factory too



- At Υ(4S):

  $\sigma(e^+e^- \to B\bar{B}) = 1.05 \text{ nb}$

  $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92 \text{ nb}$

- Suitable environment for the study of tau lepton decays
  - $\sim 4\pi$ angular coverage
  - Triggers for low multiplicity events
  - Similar PID performance for e, μ leptons and π, K mesons

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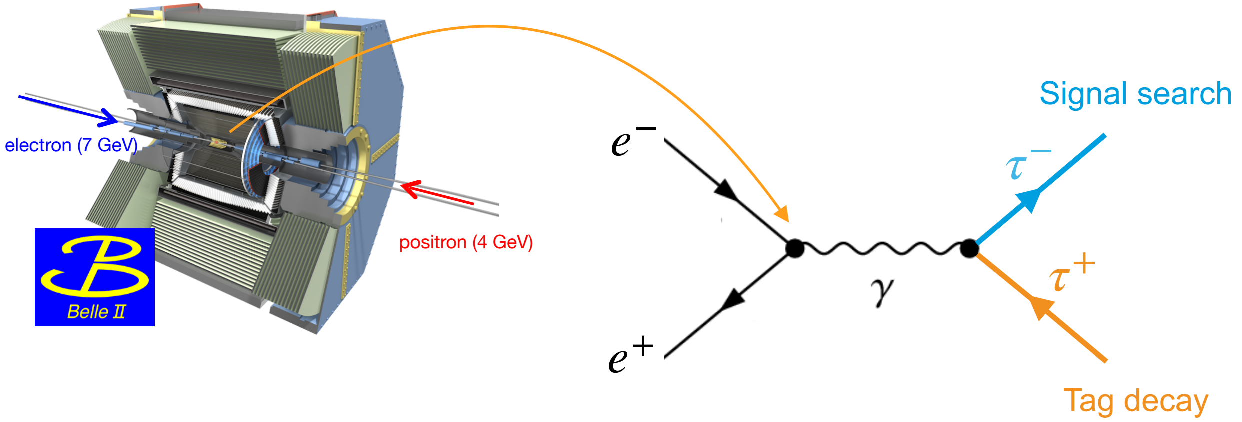

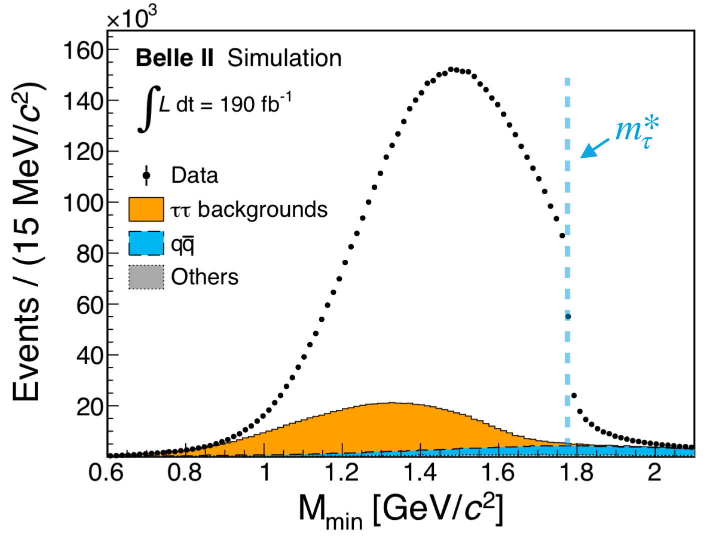

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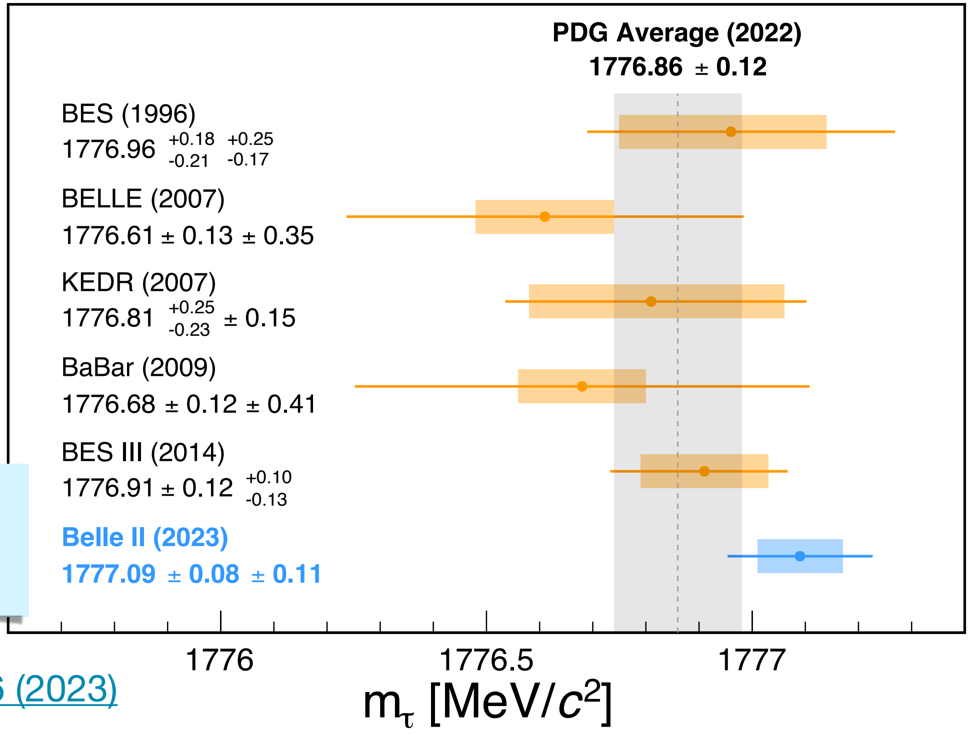
Most precise tau mass measurement to date!



Phys. Rev. D 108, 032006 (2023)

Tau Lepton Mass Measurement

- Measured in the decay mode $\tau \to 3\pi\nu$, using a pseudomass technique

- The tau mass can be calculated as

$$m_\tau^2 = (p_h + p_\nu)^2$$
$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\ \cos(\vec{p}_h, \vec{p}_\nu)$$

- As the direction of the neutrino is unknown, the approximation $\cos(\vec{p}_\nu, \vec{p}_h) = 1$ is taken, resulting in

  - $M_{\min}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p}_h|(E_\tau - E_h)\ < m_\tau^2$

- Then, the distribution of the pseudomass is fitted to an empirical edge function, and the position of the cutoff indicates the value of the mass

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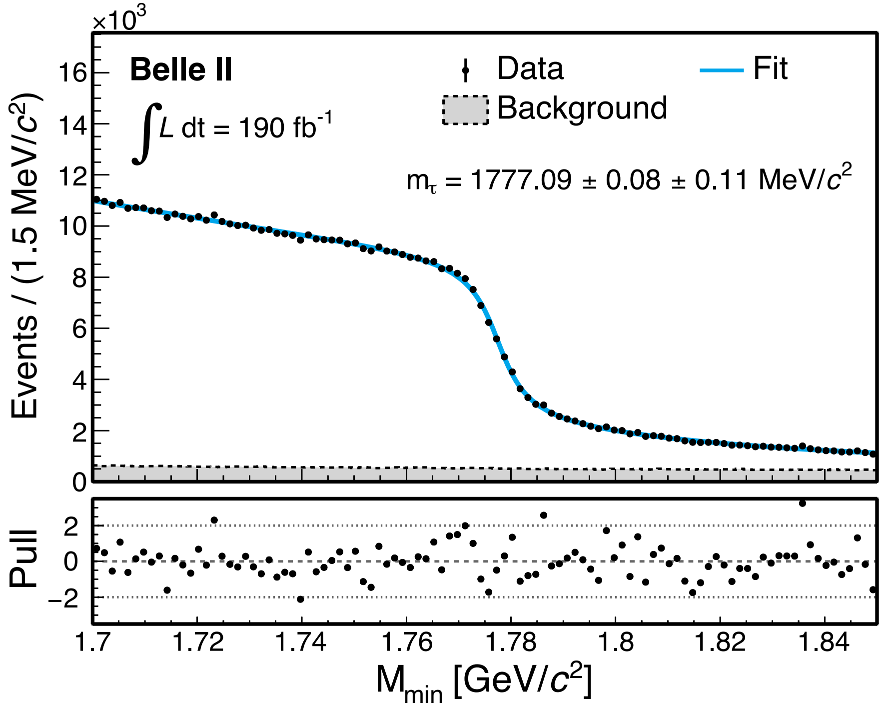
- Then, the distribution of the pseudomass is fitted to an empirical edge function, and the position of the cutoff indicates the value of the mass

P_{tracks}

$$M_{\min} = \sqrt{\boxed{M_{3\pi}^2} + 2\left(\boxed{\sqrt{s}/2} - E_{3\pi}^*\right)\left(\boxed{E_{3\pi}^* - P_{3\pi}^*}\right)}$$

E_{beam}



Phys. Rev. D 108, 032006 (2023)

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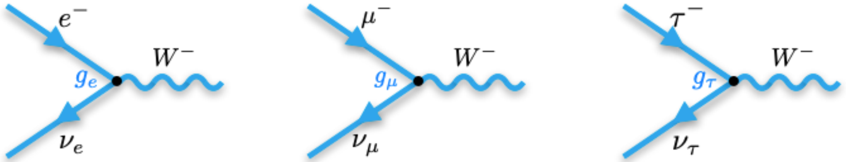
Lepton Flavor Universality Test

$g_e = g_\mu = g_\tau$?



- The coupling of leptons to W bosons is flavor-independent in the SM
- τ decays enable a test of μ – e universality
- Experimental challenge: particle ID

$$\left(\frac{g_\mu}{g_e}\right)^2 \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{\text{SM}}{=} 1$$

$$R_\mu = \frac{BR(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \overset{\text{SM}}{=} 0.9726$$

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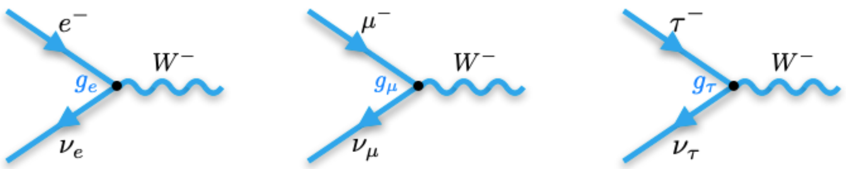

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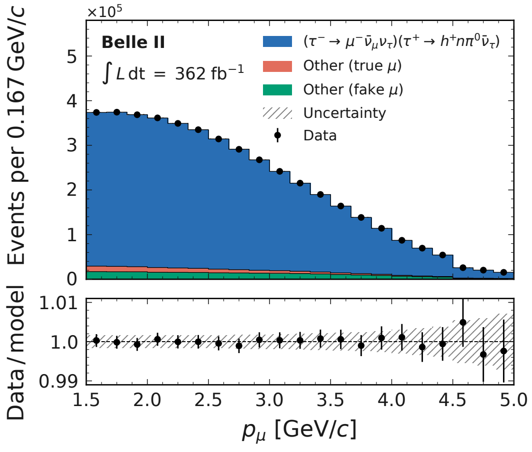
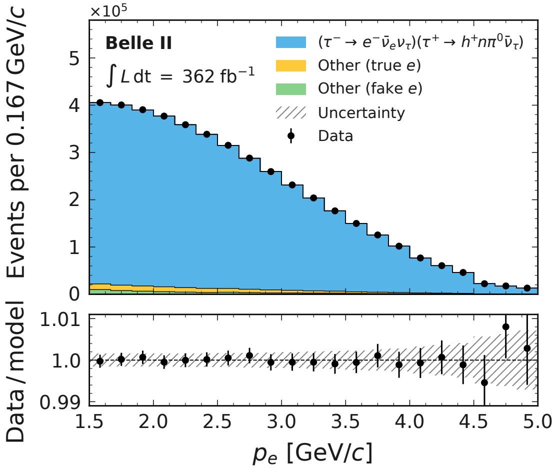
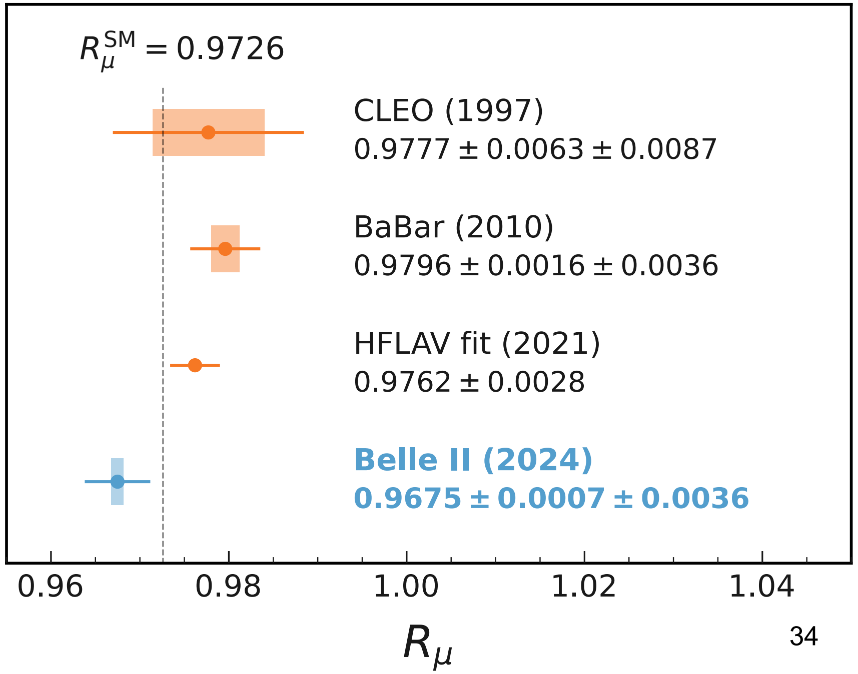
- Most precise test of universality in τ decays from a single measurement
- Consistent with the SM at 1.4σ







J. High Energ. Phys. 2024, 205 (2024)

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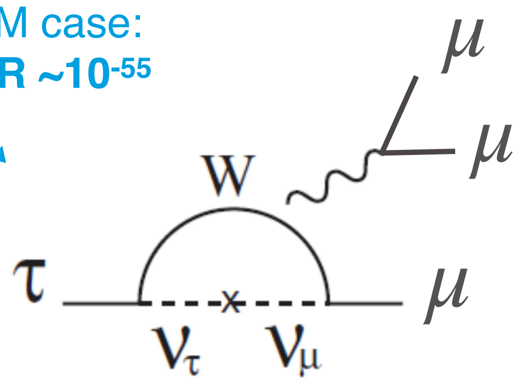
Lepton Flavor Violation

- Quarks change generations
- Neutrinos change flavor
  - Lepton Flavor Violation (LFV) is an established fact, but only in neutrinos
- What about charged leptons?
  - Neutrinos with mass → CLFV
  - But extremely suppressed

SM case:
BR ~10^{-55}



[Eur. Phys. J. C 79, 84 (2019)]

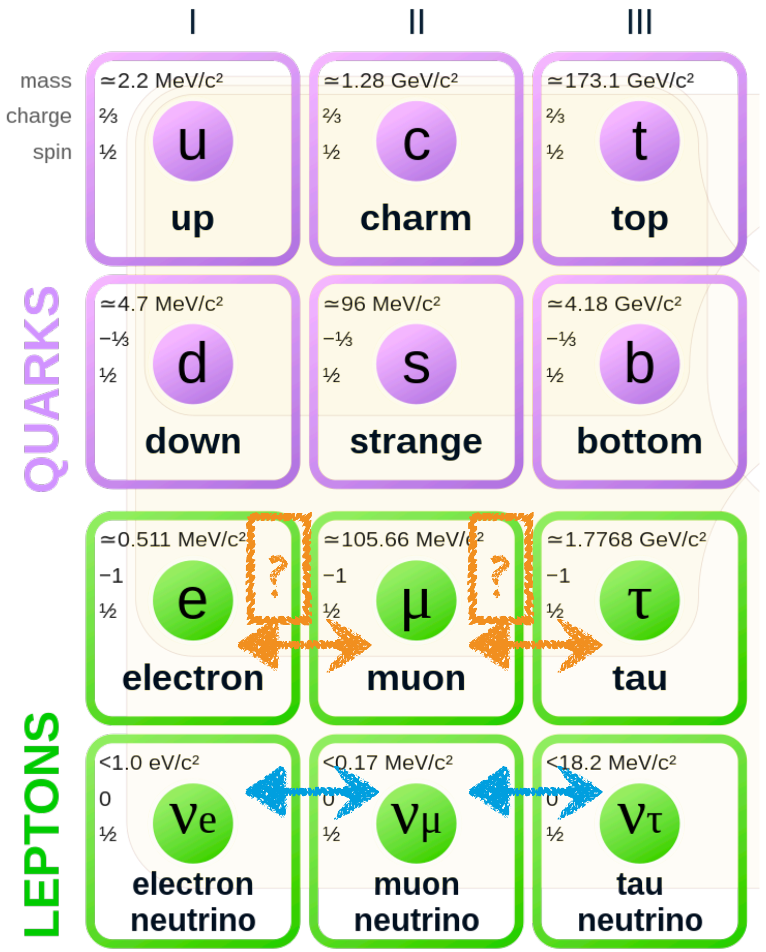


Figure: Wikipedia

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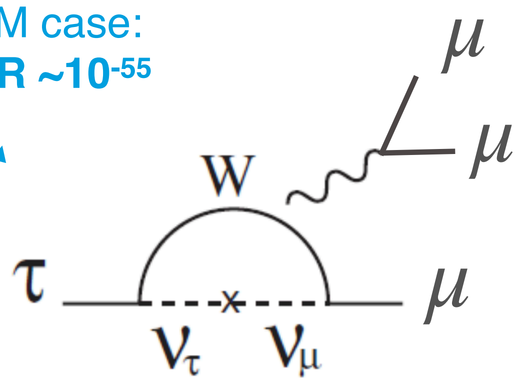
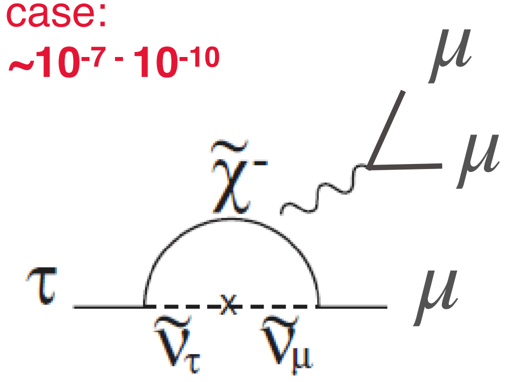
- **Observation of CLFV is a clear signature of New Physics!**

SM case:
BR ~10^{-55}



[Eur. Phys. J. C 79, 84 (2019)]

NP case:
BR ~10^{-7} - 10^{-10}



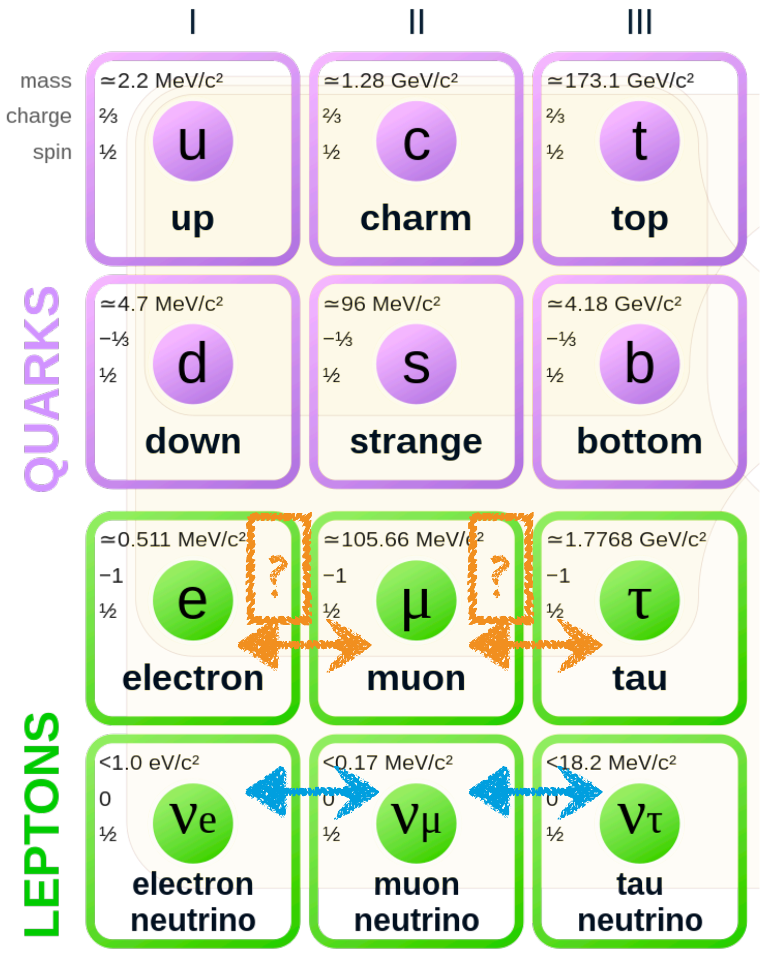


Figure: Wikipedia

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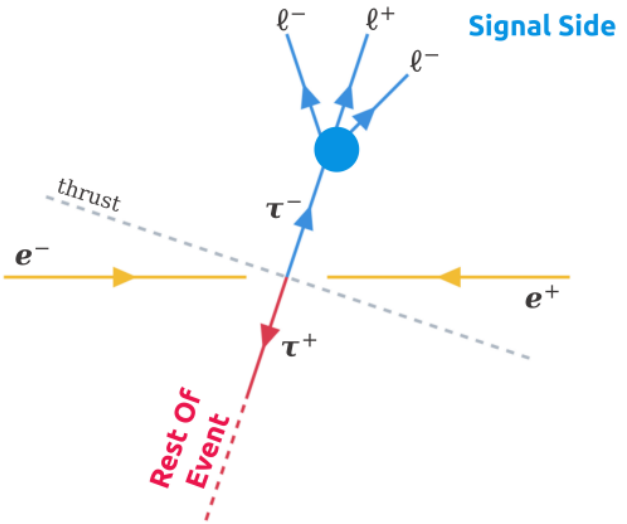
$\tau \to 3\mu$

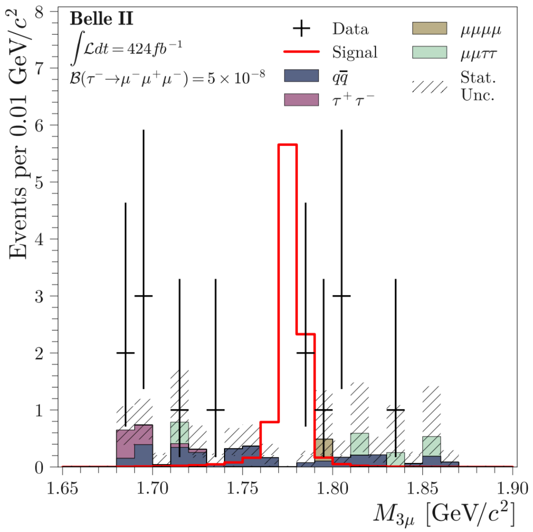
- Inclusive tagging: only the signal τ is reconstructed from 3 muons
- BDT-based selection with the rest of event
- Define a signal region in the $M_{3\mu}$, ΔE plane
  - One event after opening the box

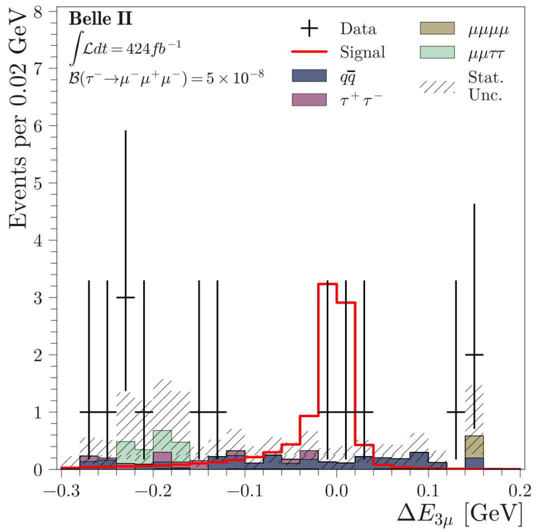
$\mathscr{B}(\tau^+ \to \mu^+\mu^-\mu^+) < 1.9 \times 10^{-8}$

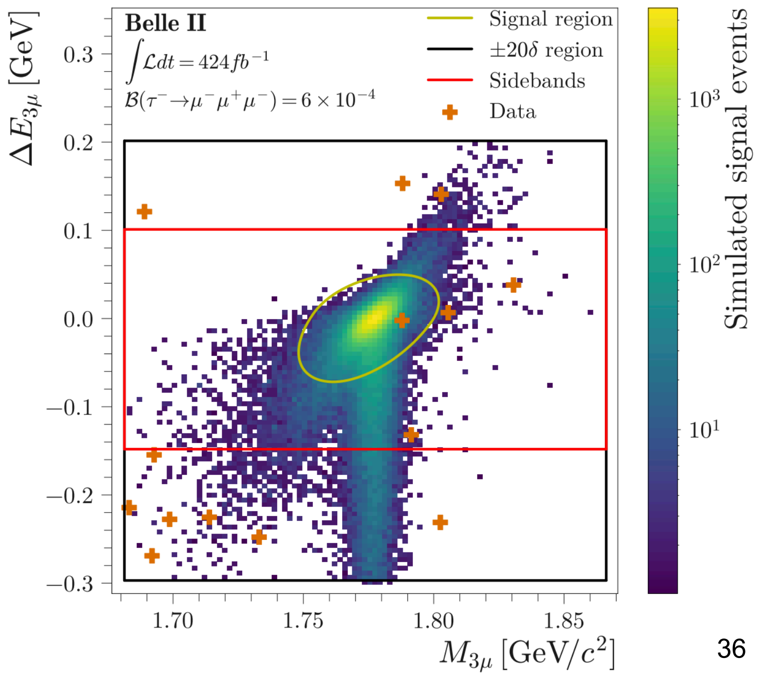
Most stringent limit to date despite smaller data sample



JHEP 09 (2024) 062



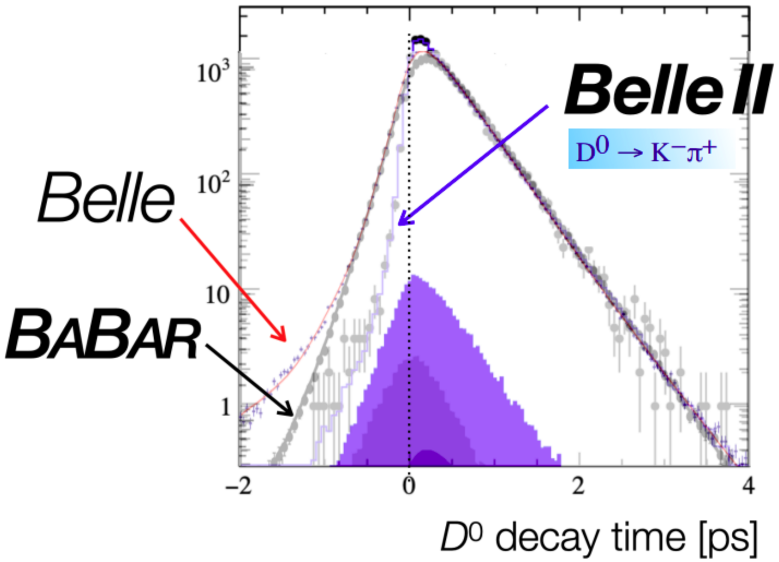




Charmed Hadrons

Precise charm lifetime measurements

- Belle II can measure absolute lifetimes with high precision
  - **Very good vertex resolution, small beam size**
  - Precise calibration of particle momentum
  - Excellent detector alignment



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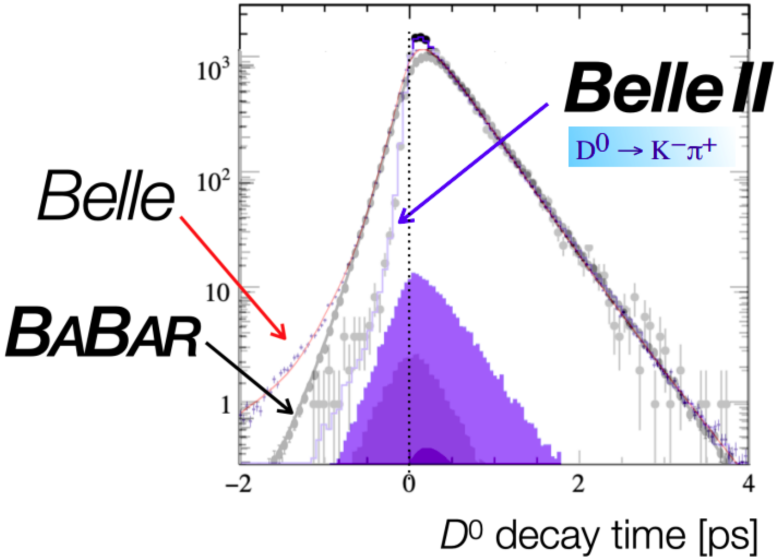
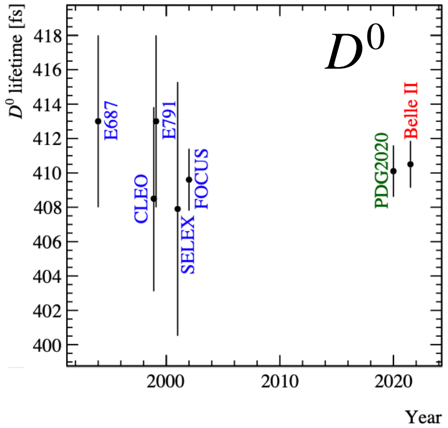
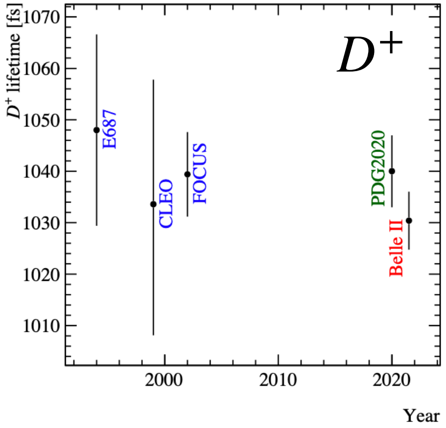


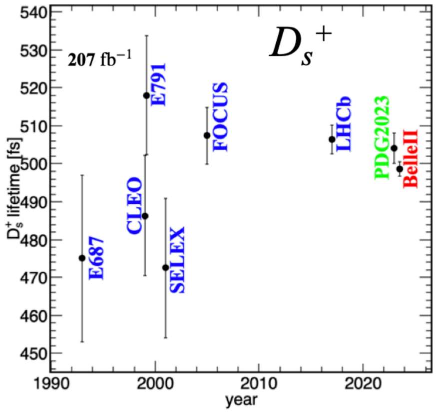
- World-leading measurements for D^0, D^+, D_s^+, Λ_c^+, confirmation of Ω_c^0

PRL.127.211801 (2021)

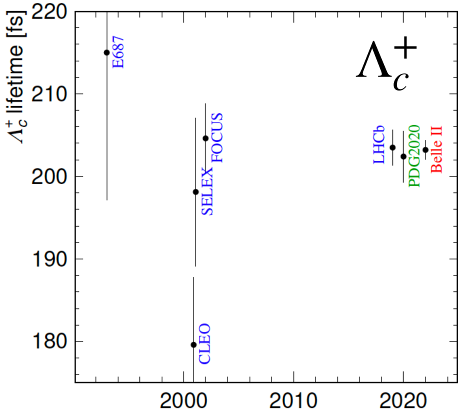




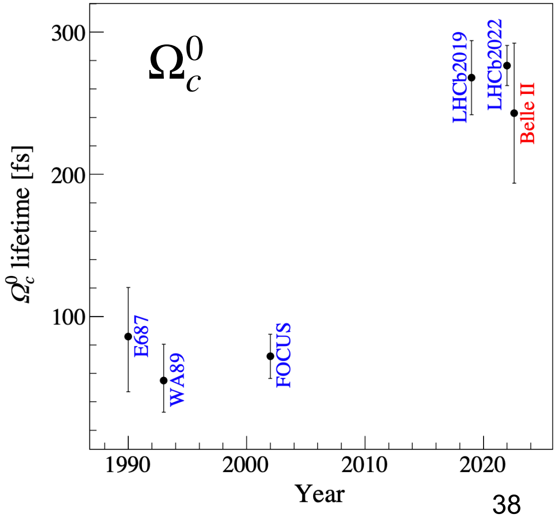
PRL.131.171803 (2023)



PRL.130.071802 (2023)



PRD.107.L031103 (2023)



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CP Violation in $D^0 \to K_s^0 K_s^0$

- Involves the interference of $c\bar{u} \to s\bar{s}$ and $c\bar{u} \to d\bar{d}$ transitions
  - A_{CP} may be enhanced to an observable level
- Current world-average limited by statistics
  - New measurement combining Belle & Belle II datasets

$$A_{CP}(D^0 \to K_S^0 K_S^0) = \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\bar{D}^0 \to K_S^0 K_S^0)}$$

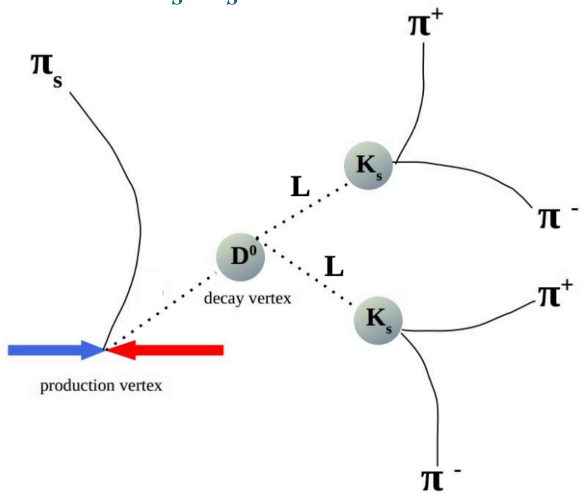
$$A_{\rm raw}^{K_S^0 K_S^0} = \frac{N(D^0 \to K_S^0 K_S^0) - N(\bar{D}^0 \to K_S^0 K_S^0)}{N(D^0 \to K_S^0 K_S^0) + N(\bar{D}^0 \to K_S^0 K_S^0)}$$

- Determination using $D^0 \to K^+K^-$ as control mode
  - $A_{CP}^{K_sK_s} = \left(A_{raw}^{K_sK_s} - A_{raw}^{KK}\right) + A_{CP}^{KK}$

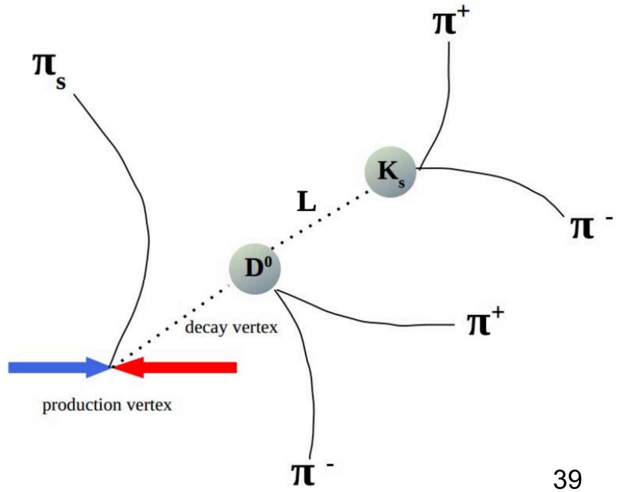
- Background rejection using the flight distance of the K_s^0 candidates

$$S_{min} = \log[\min(L_1/\sigma_{L_1}, L_2/\sigma_{L_2})]$$

$D^0 \to K_s^0 K_s^0$



$D^0 \to K_s^0 \pi^+\pi^-$



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CP Violation in $D^0 \to K_S^0 K_S^0$

Paper in preparation

- Signal extraction via simultaneous fit to $m(D^0\pi^+)$ and S_{min}
- **Tagging** the flavor via $D^{*+} \to D^0 \pi^+$
- Using 980 fb^{-1} of Belle data, and 428 fb^{-1} of Belle II data

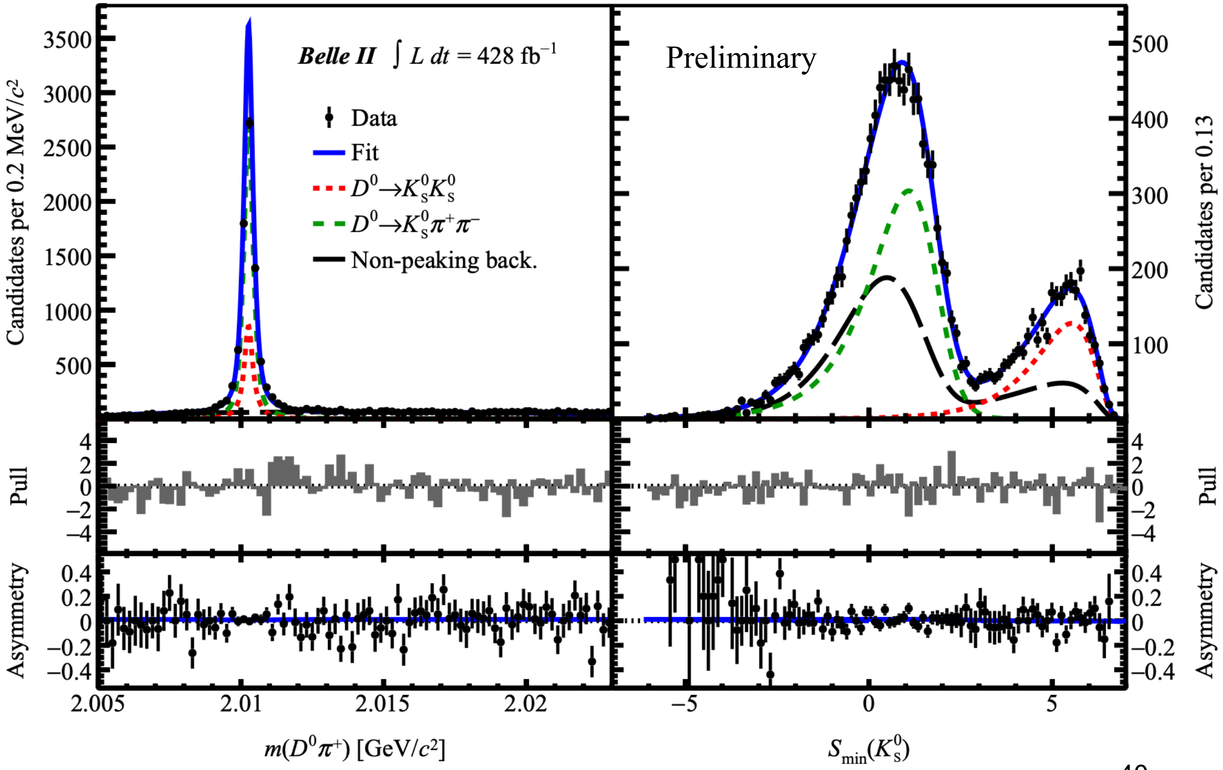
$A_{CP}(D^0 \to K_s K_s)$ *in Belle: (-1.1 ± 1.6 ± 0.1) %*

$A_{CP}(D^0 \to K_s K_s)$ *in Belle II: (-2.2± 2.3 ± 0.1) %*

$\boldsymbol{A_{CP}(D^0 \to K_s K_s)}$ ***(Belle + Belle II) = (-1.4 ± 1.3 ± 0.1) %***

- In agreement with previous results

Precision comparable to the world's best measurement from LHCb



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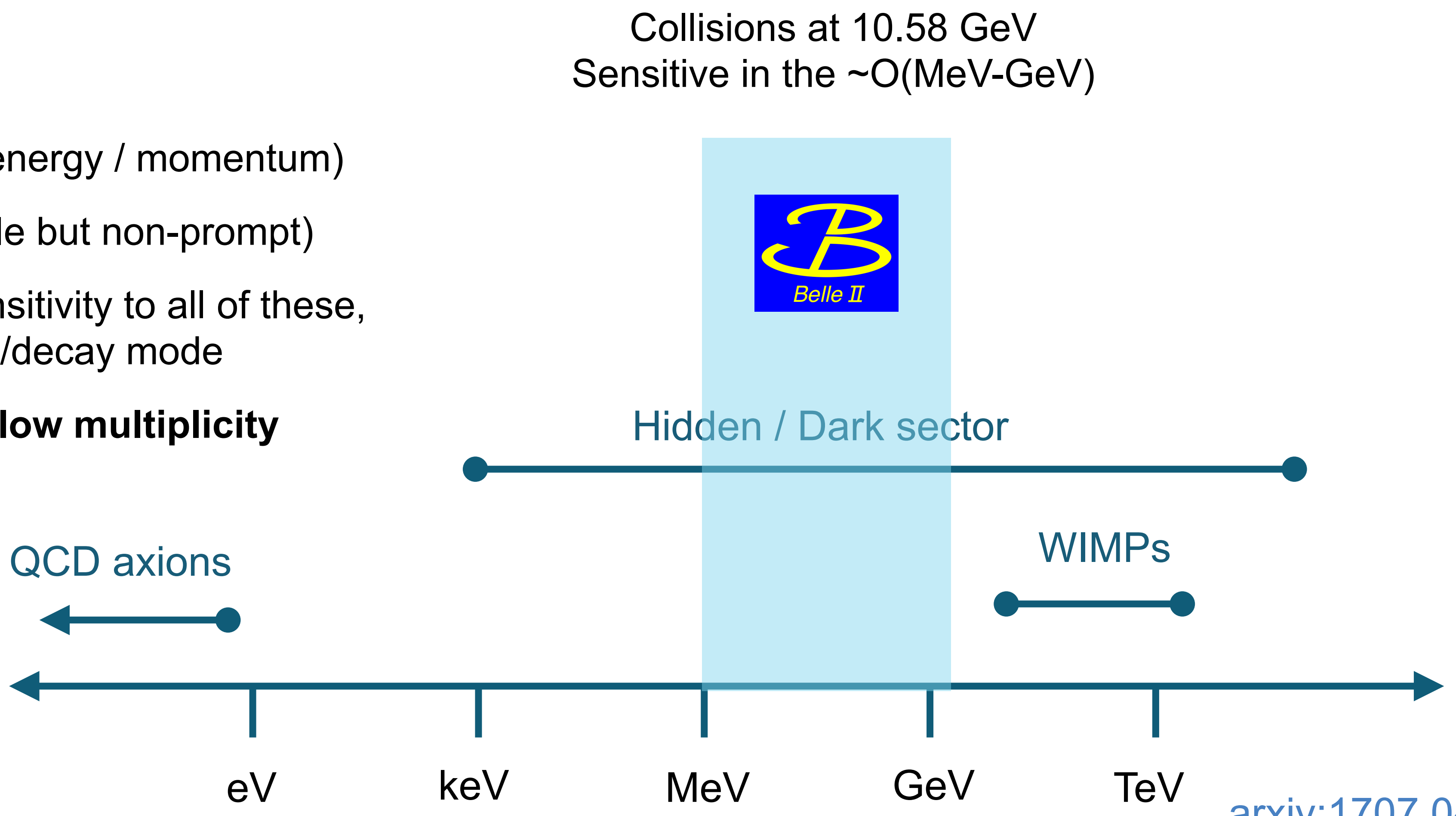
Dark Sector

Dark Sector searches at Belle II

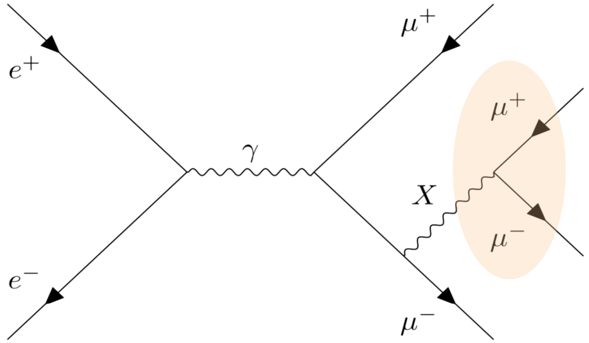
- Three possible cases
  - **Visible signatures**
  - **Invisible** (missing energy / momentum)
  - **"Long lived"** (visible but non-prompt)
- Belle II has potential sensitivity to all of these, depending on the model/decay mode
- **Dedicated triggers for low multiplicity**

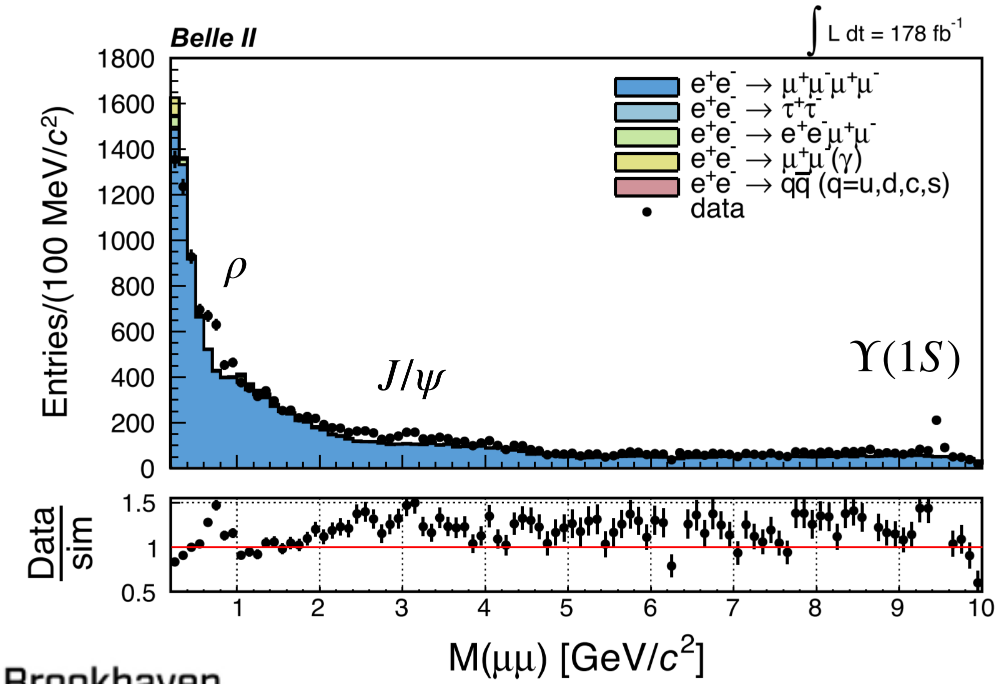


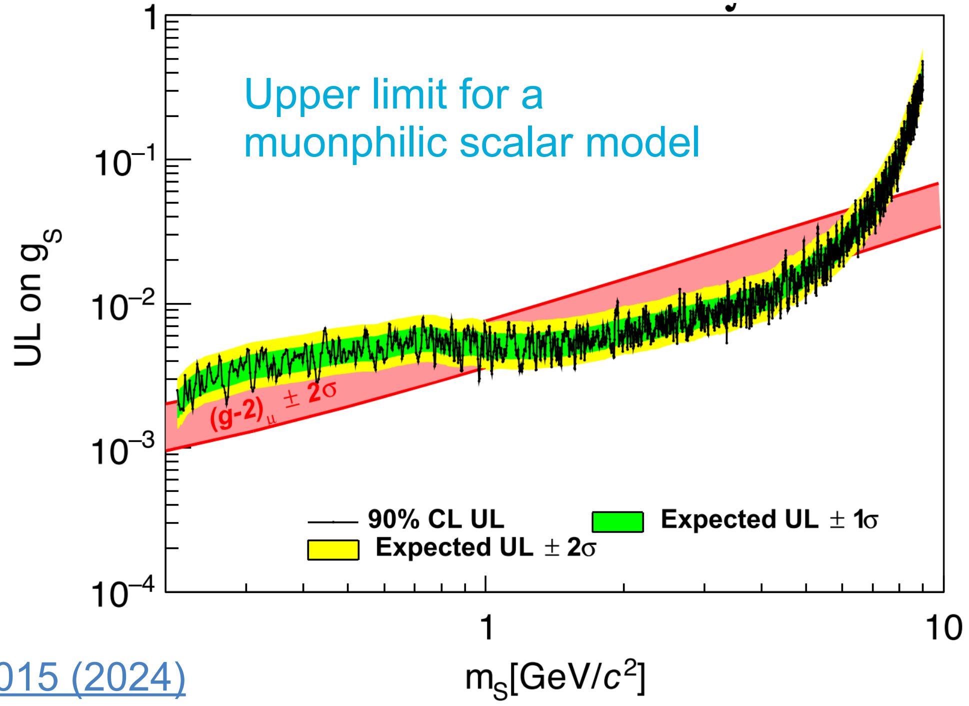
arxiv:1707.04591

Search for a $\mu\mu$ resonance in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

- Searching for 4 tracks, at least three identified as muons
  - No extra energy in the event
- Signal extraction via fit scan to $M_{\mu\mu}$
  - Signature is a narrow peak in the opposite-charge dimuon mass







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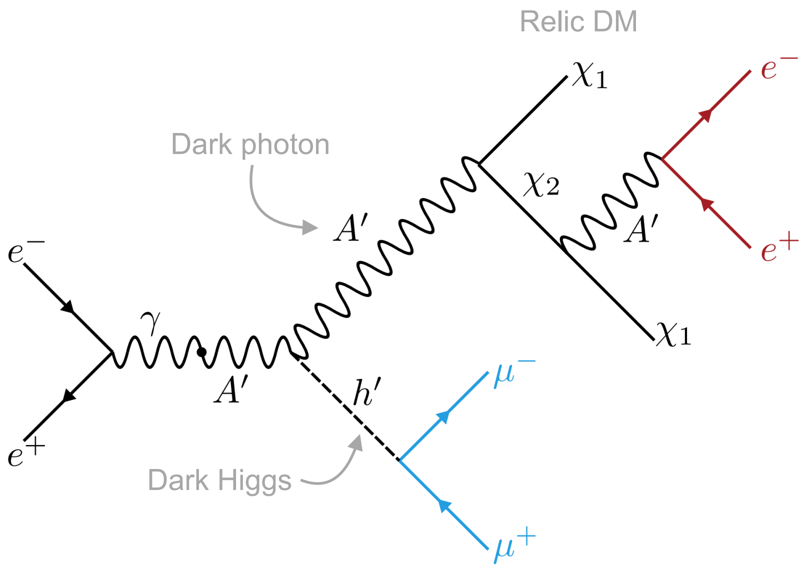
Phys. Rev. D 109, 112015 (2024)

Search for Inelastic Dark Matter

- Models with two dark matter particles χ_1, χ_2 and a massive dark photon A' motivated by cosmological limits
  - χ_1 - relic DM; χ_2 - Long-lived
  - Extended with a dark Higgs h' that gives mass to the photon



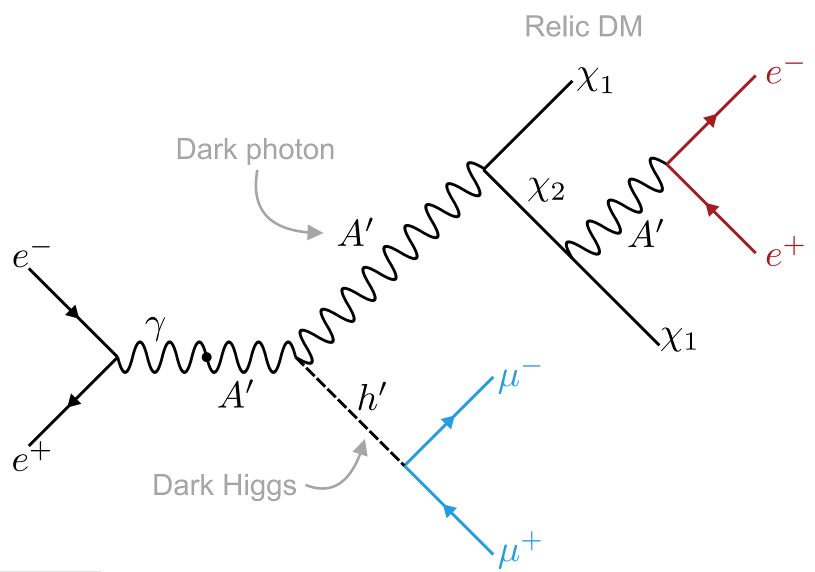
[J. High Energ. Phys. 2021, 146 (2021)]

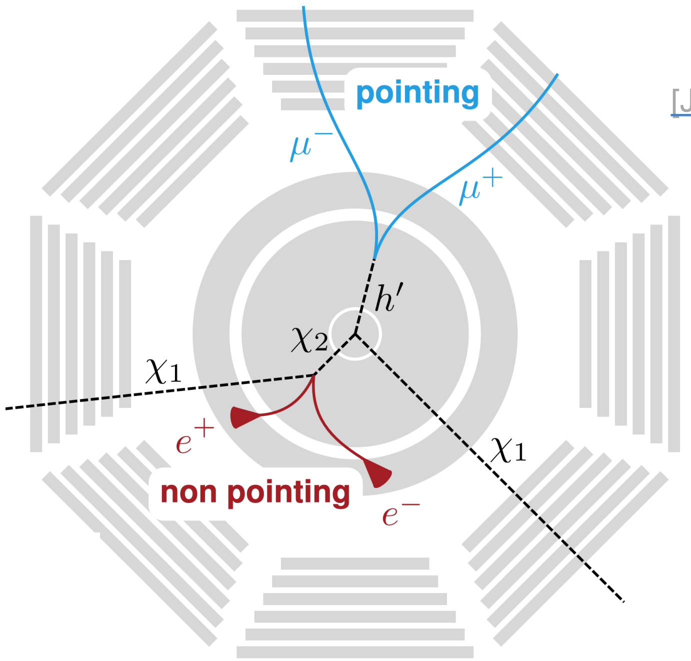
Search for Inelastic Dark Matter

- Models with two dark matter particles χ_1, χ_2 and a massive dark photon A' motivated by cosmological limits
  - χ_1 - relic DM; χ_2 - Long-lived
  - Extended with a dark Higgs h' that gives mass to the photon

- The signature is
  - 2 tracks forming a pointing displaced vertex
  - 2 tracks from a non-pointing displaced vertex
  - Missing energy

- Almost zero background





[J. High Energ. Phys. 2021, 146 (2021)]

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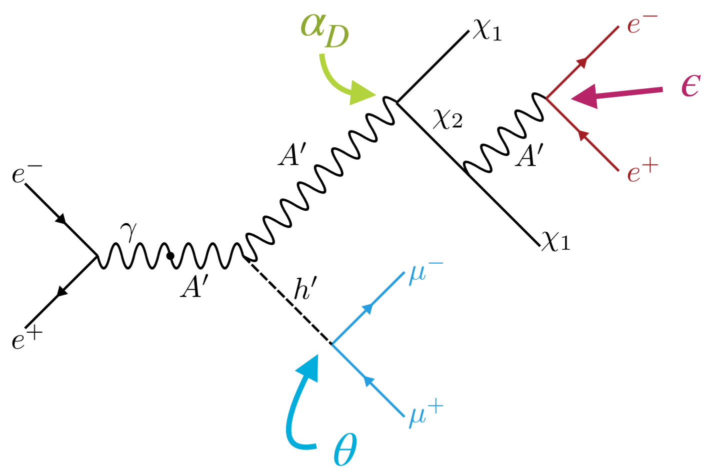
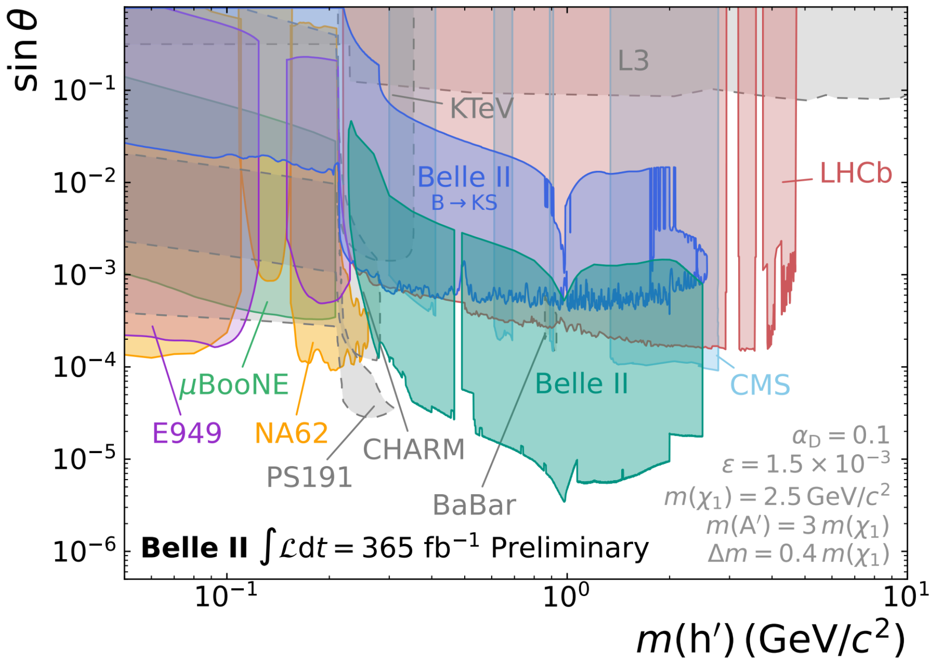
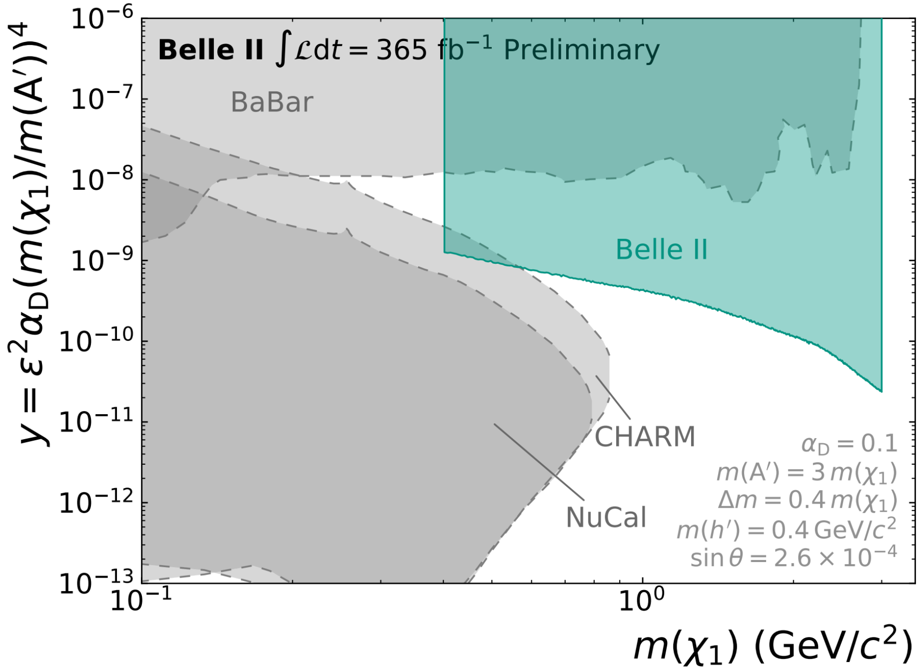
Search for Inelastic Dark Matter



- Expected background estimated in data from sidebands
- No significant excess found for any of the final states or combined
  - Setting 95% upper limits

Paper in preparation





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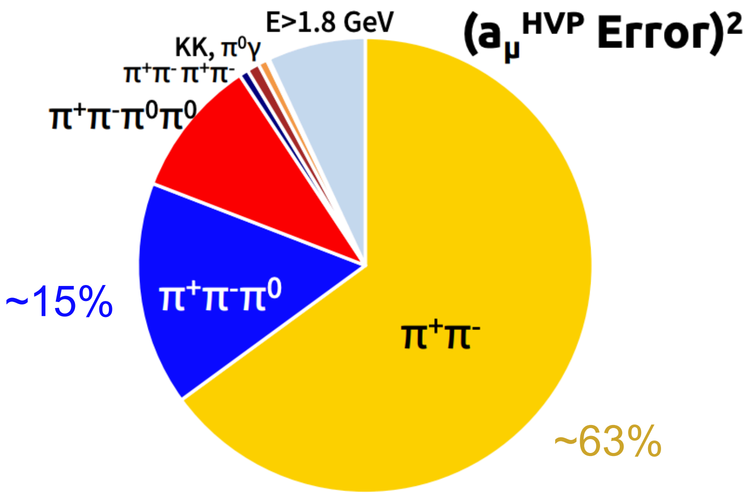
Belle II Input to HVP

$e^+e^- \to \pi^+\pi^-\pi^0$

- In the anomalous magnetic momentum of the muon determination

$$a_\mu^{\mathrm{SM}} = (g_\mu - 2)/2 = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLBL}}$$

- The theoretical uncertainty is dominated (>80%) by the leading-order Hadronic Vacuum Polarization (HVP)



$e^+e^- \to \pi^+\pi^-\pi^0$

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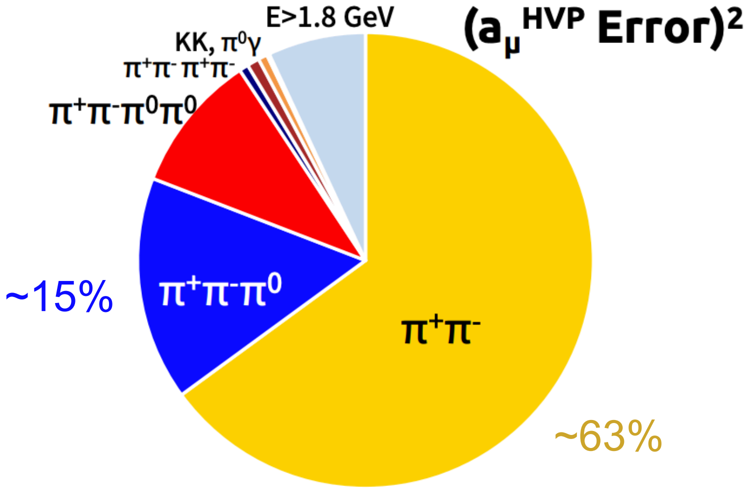
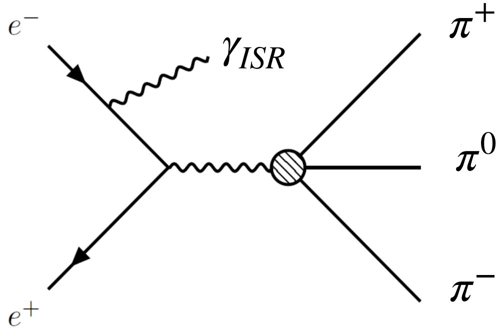
$$a_\mu^{\mathrm{SM}} = (g_\mu - 2)/2 = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLBL}}$$

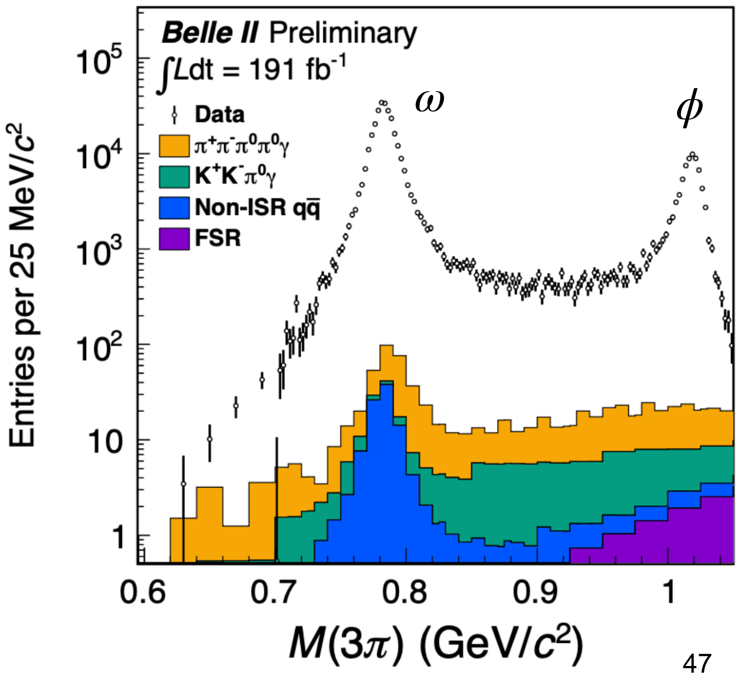
- The theoretical uncertainty is dominated (>80%) by the leading-order Hadronic Vacuum Polarization (HVP)

- In Belle II, the cross sections as a function of c.m. energy is measured using the initial state radiation (ISR) method

- Event selection: 2 tracks + 3 photons
  $e^+e^- \to \pi^+\pi^-(\pi^0 \to \gamma\gamma)\gamma_{ISR}$
- Fit to $M_{\gamma\gamma}$ spectrum in each $M_{3\pi}$ bin
- Residual background estimated from MC

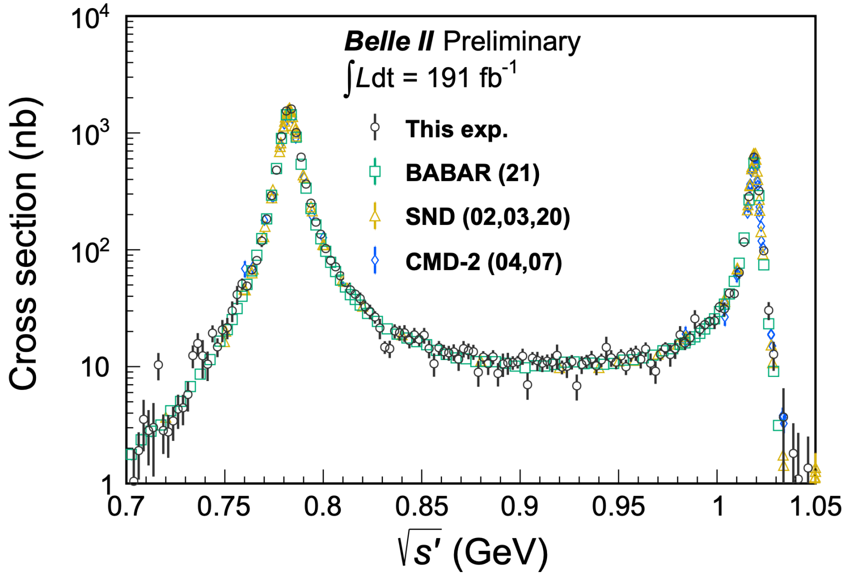






$e^+e^- \to \pi^+\pi^-\pi^0$

- Study in the energy range of 0.62 - 3.50 GeV
  - Cross section at low energy higher (~10%) than BaBar, CMD-2 and SND
  - At high energy (> 1 GeV), in agreement with BaBar

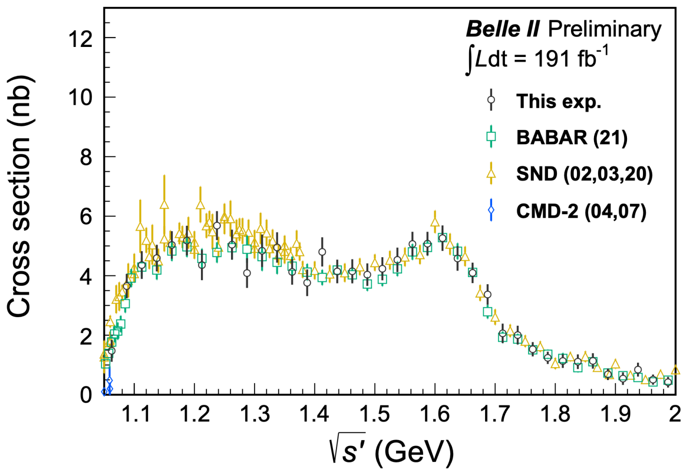


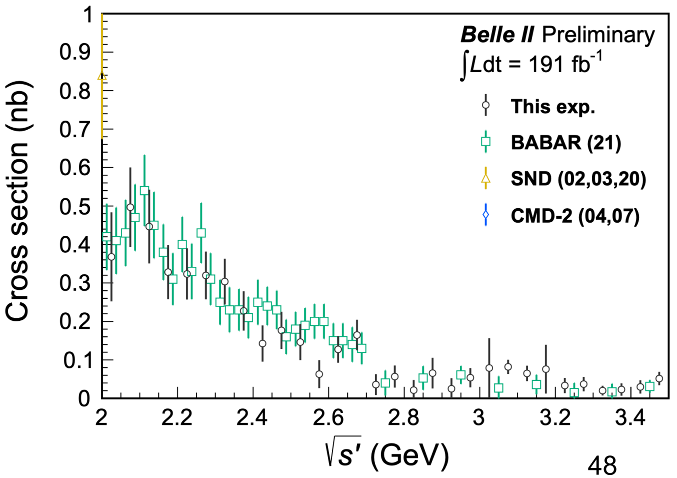
- Contribution to $a_\mu^{\rm HVP}$ in the 0.62 - 1.80 GeV energy range:

$$a_\mu^{\rm HVP,3\pi} = (48.91 \pm 0.23 \pm 1.07) \times 10^{-10}$$

6.5% higher than the global fit with 2.5σ significance

arXiv:2404.04915
Accepted in PRD for publication





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Summary

- Overview of the physics program at Belle II covering B physics, tau lepton, charmed hadrons & dark sector
  - Many more results at www.belle2.org
- With an early data set and unique capabilities, Belle II is delivering **world-best measurements** for several observables
  - Most results presented using 365 fb^{-1} on-resonance [arXiv.2407.00965]
- Run 2 will continue until the next upgrade of the detector, collecting several ab^{-1}
- **Stay tuned!** More results are coming

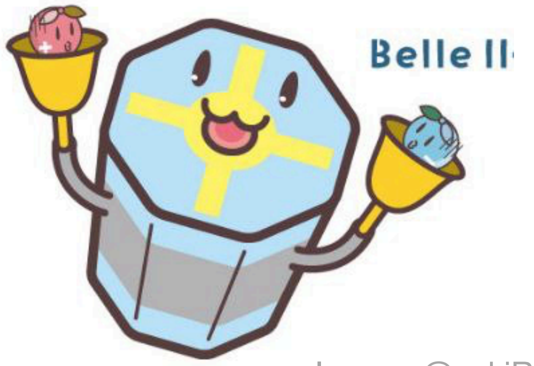
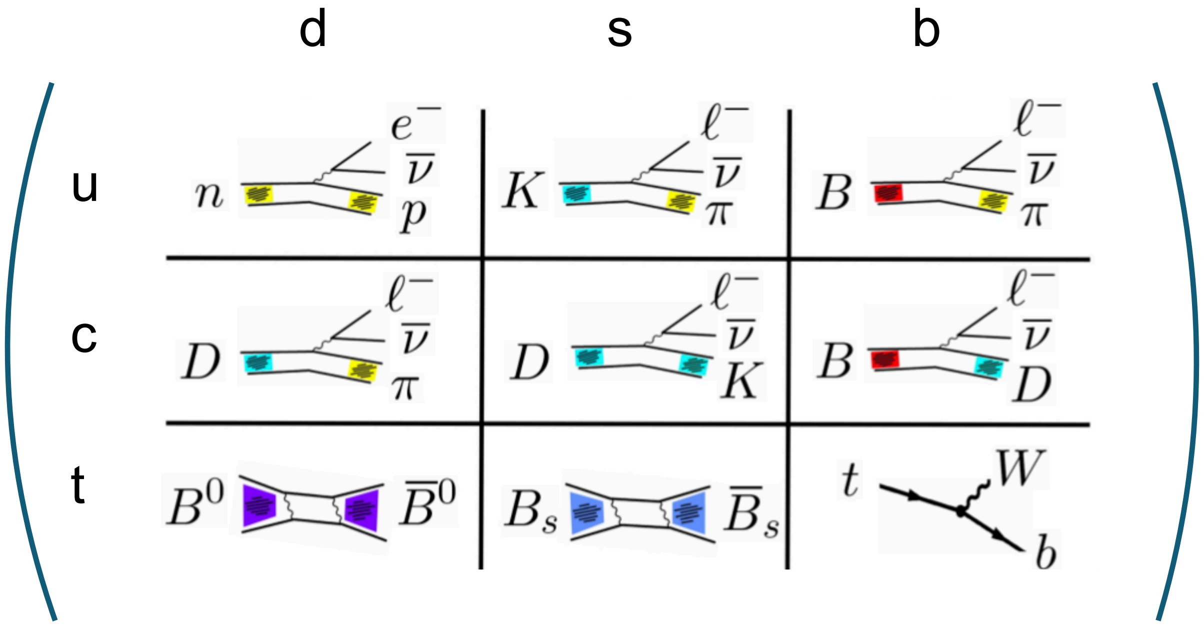
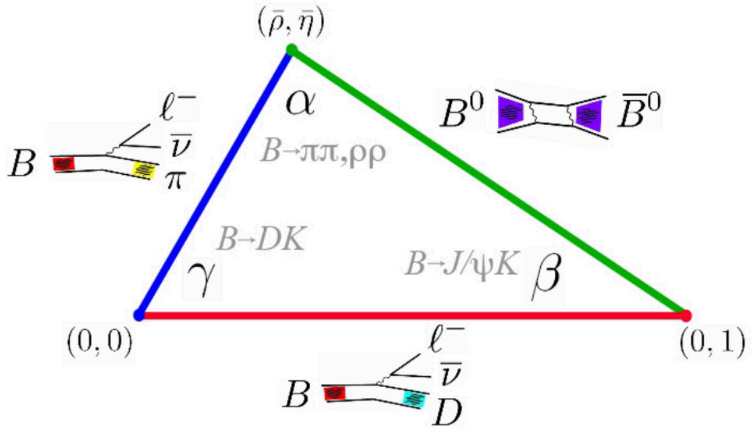


Image: @yukiRPM

Backup

Tests of CKM Matrix





$$\phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) = (22.2 \pm 0.7)^\circ$$

$$\phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) = (85.2^{+4.8}_{-4.3})^\circ$$

$$\phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) = (65.9^{+3.3}_{-3.5})^\circ$$

Figures: L. Silva, http://ckmfitter.in2p3.fr/www/docs/slides_ckmworkshop_2023.pdf

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

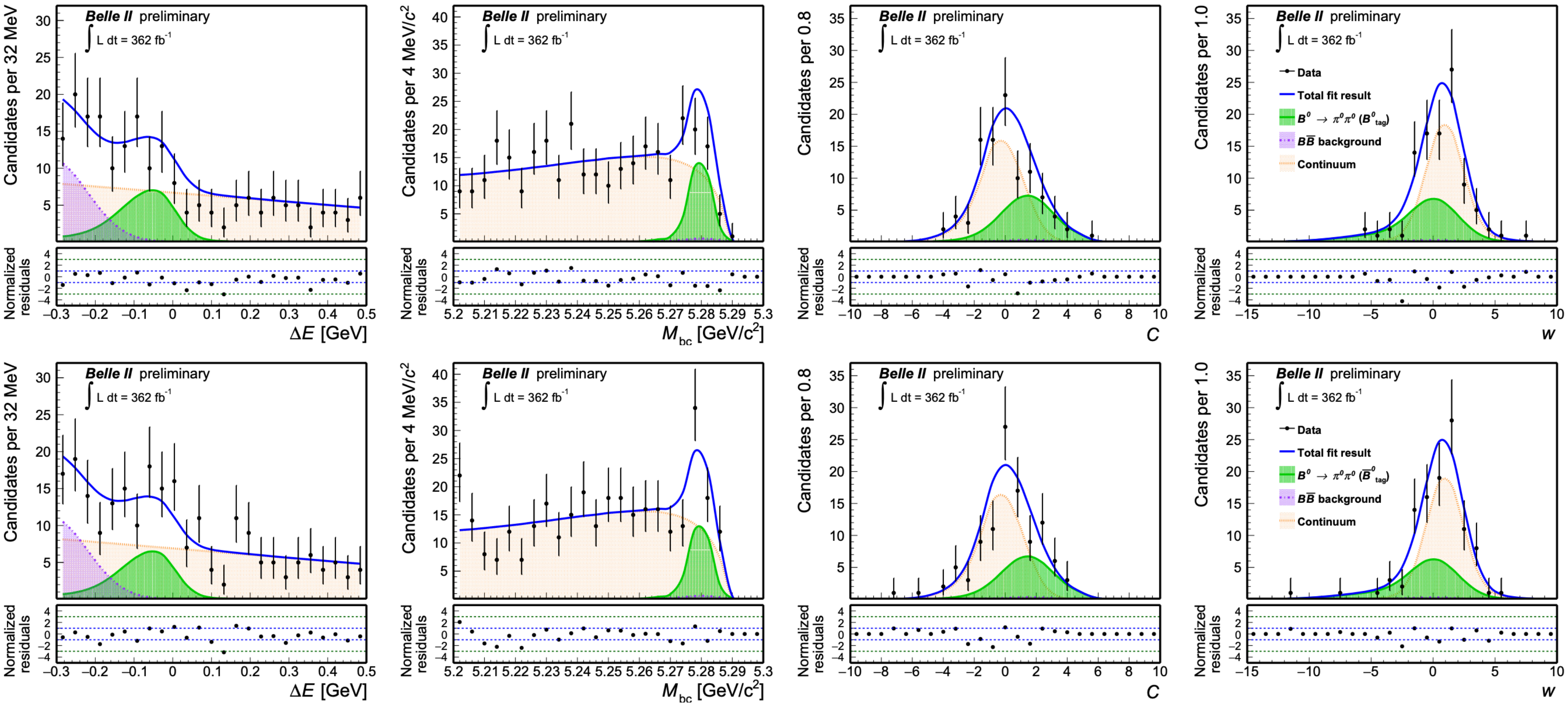
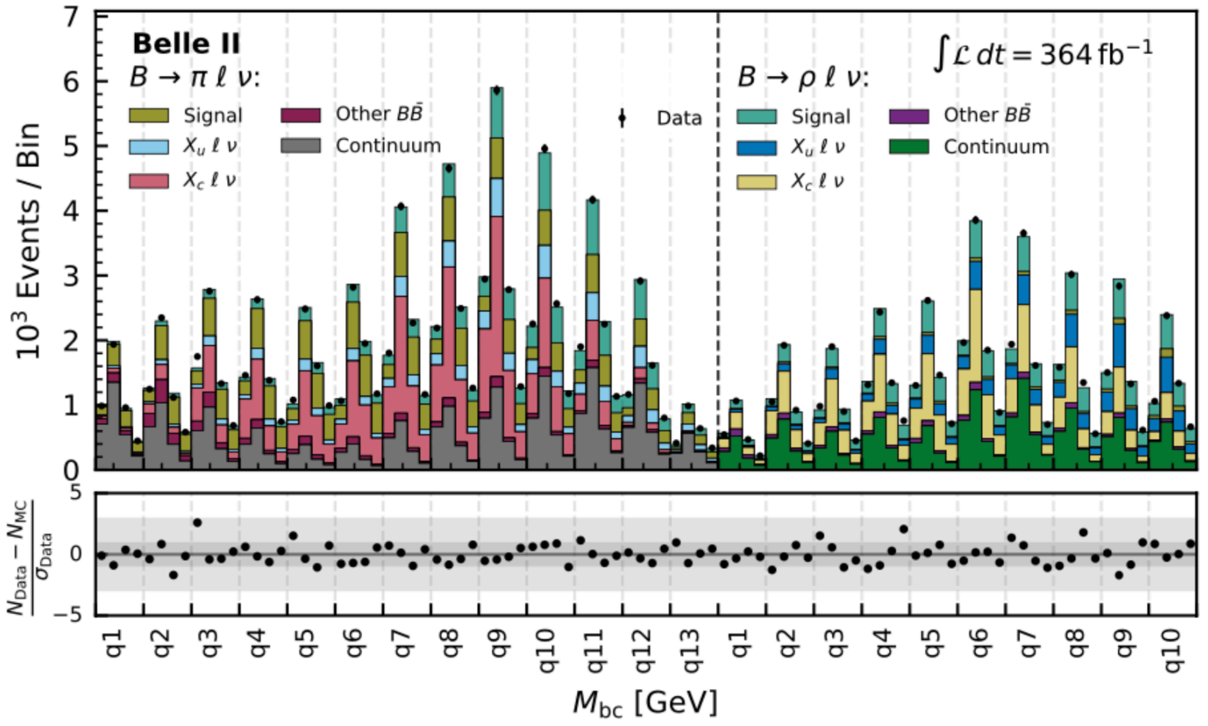
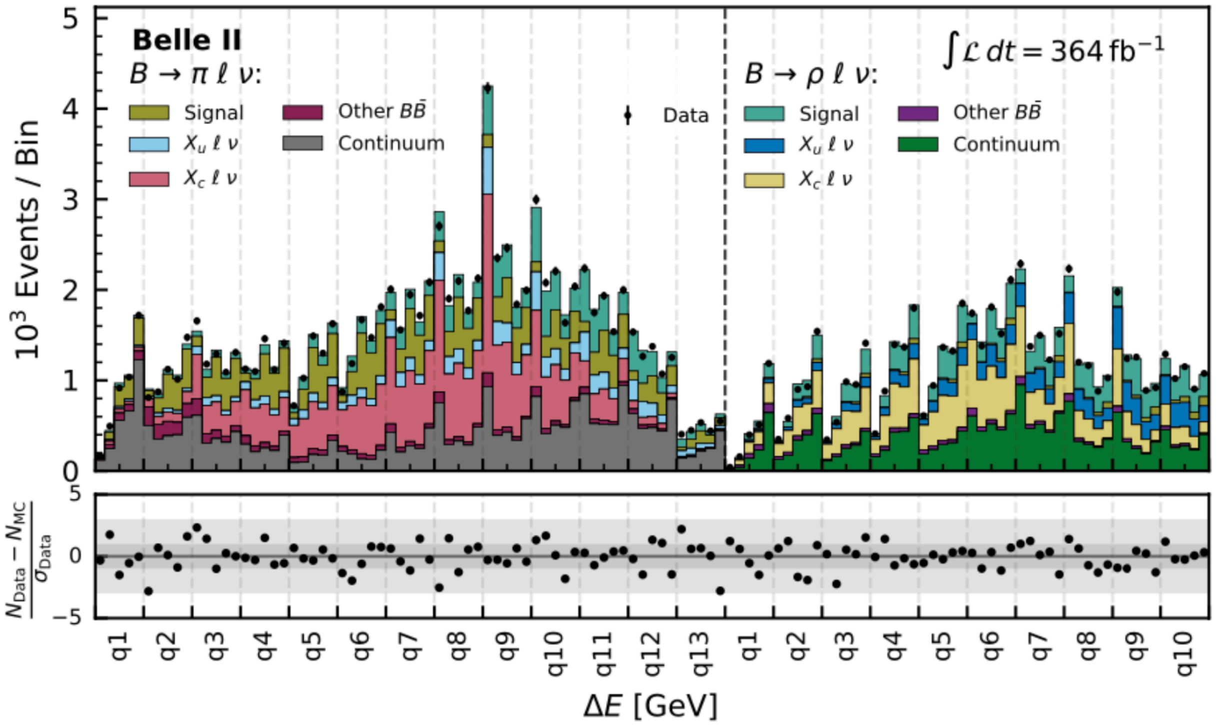


FIG. 2. Distributions of (left to right) ΔE, $M_{\rm bc}$, C, and w for the $B^0 \to \pi^0\pi^0$ candidates with (top) positive and (bottom) negative q tags. The result of the fit to the data is overlaid. The data distributions are signal-enhanced (see text). Pulls are shown below each distribution.

$|V_{ub}|$ from $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

$q^2 = (p_B - p_{\pi/\rho})^2$





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

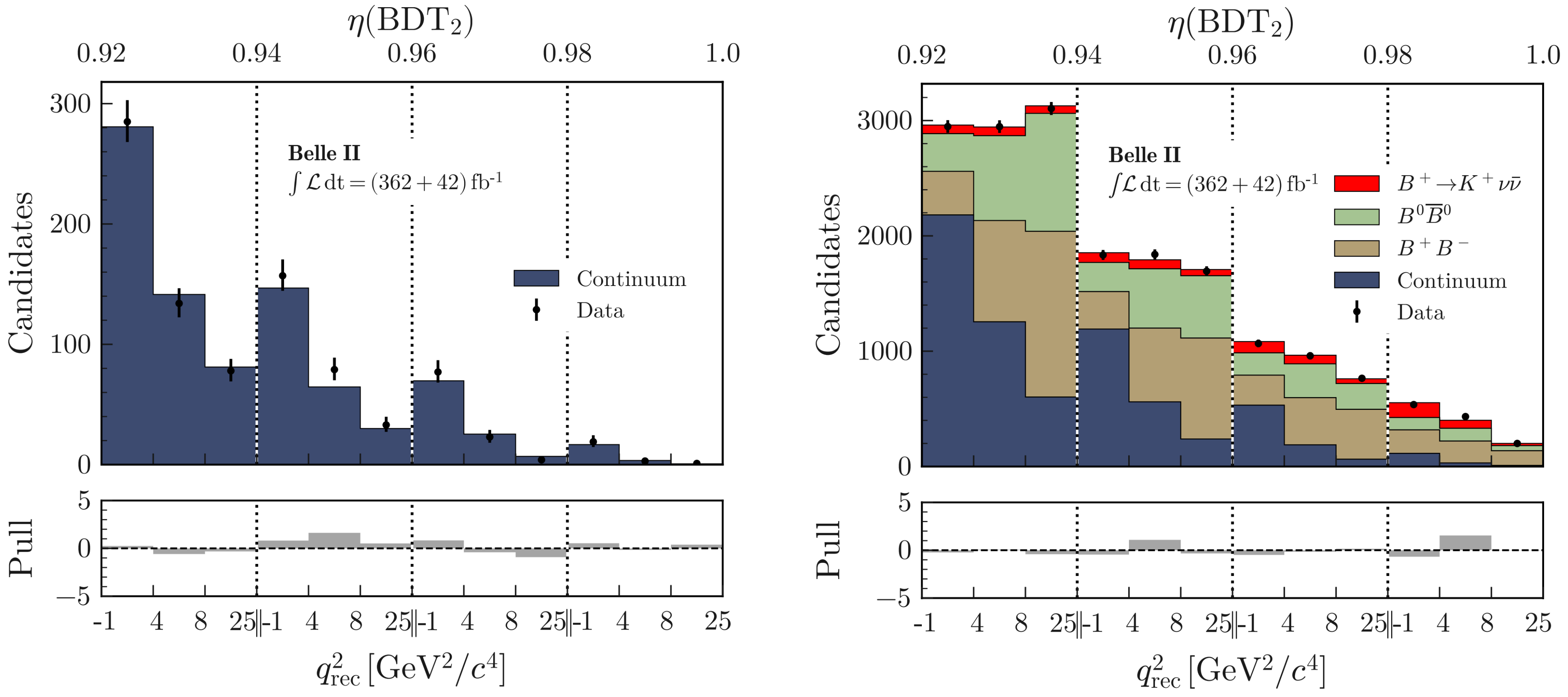
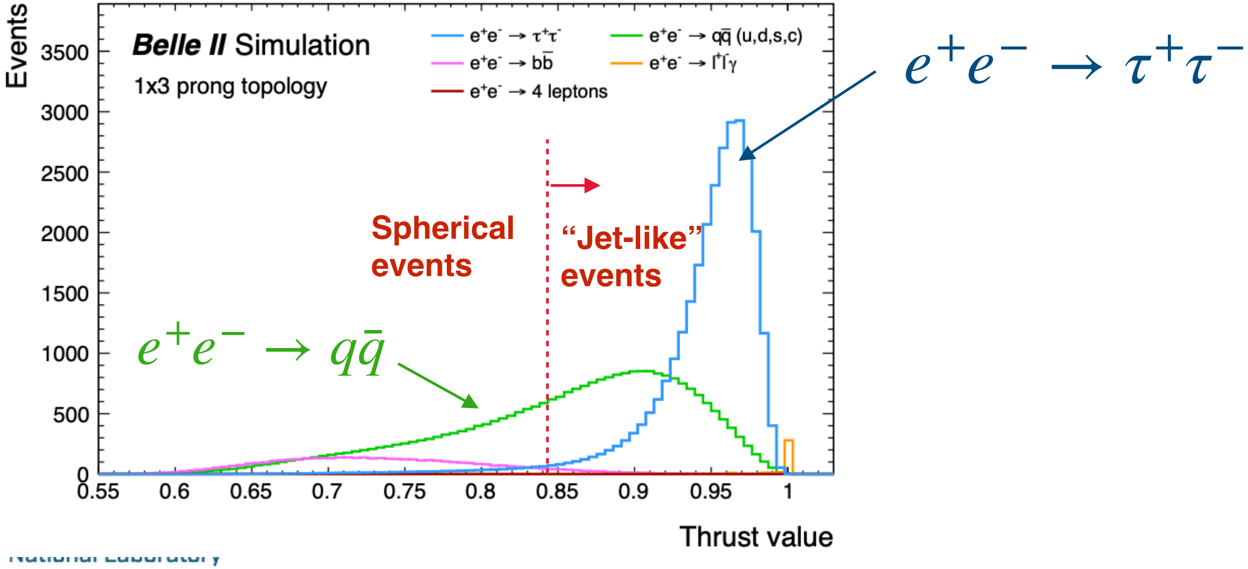
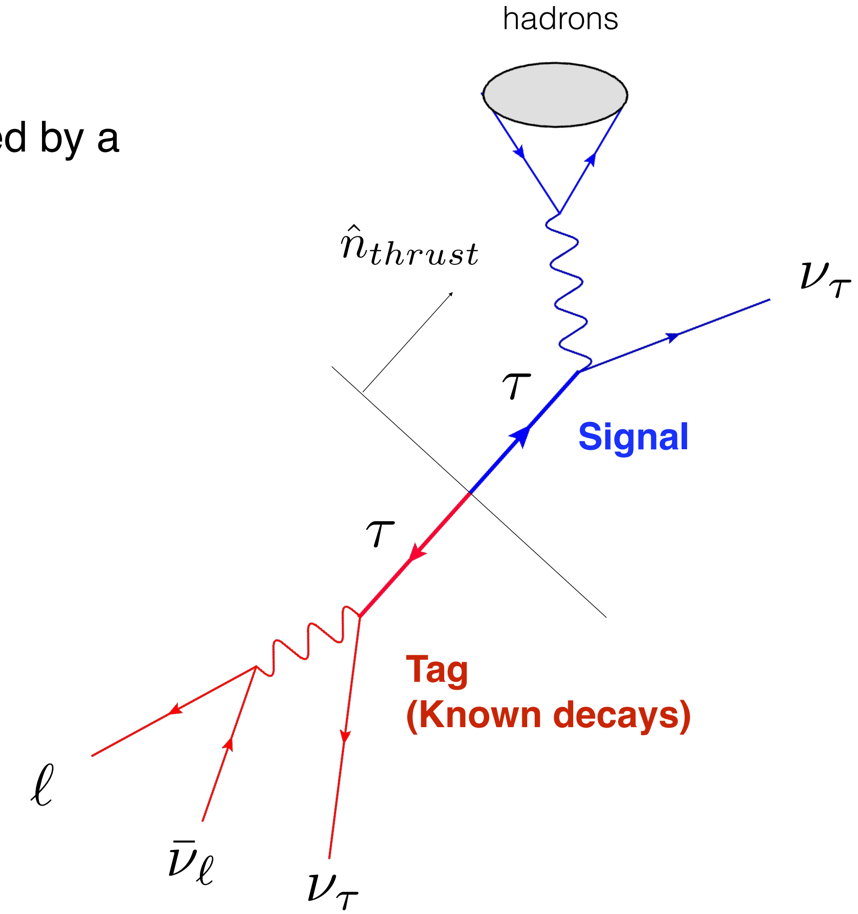


FIG. 15. Observed yields and fit results in bins of the $\eta(\mathrm{BDT}_2) \times q^2_{\mathrm{rec}}$ space obtained by the ITA simultaneous fit to the off- and on-resonance data, corresponding to an integrated luminosity of 42 and 362 fb^{-1}, respectively. The yields are shown individually for the $B^+ \to K^+\nu\bar{\nu}$ signal, neutral and charged B-meson decays and the sum of the five continuum categories. The yields are obtained in bins of the $\eta(\mathrm{BDT}_2) \times q^2_{\mathrm{rec}}$ space. The pull distributions are shown in the bottom panel.

How do we reconstruct taus at Belle II?

- A τ event is never reconstructed completely (we lose neutrinos), then we use features of the event to identify τ-pair candidates.
- Event is divided in two sides (signal and tag) using a plane defined by a **thrust axis**, build with all the final state particles:
- $$V_{thrust} = \frac{\sum_i |\vec{p}_i{}^{cm} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_i{}^{cm}|}$$
- Thrust axis: $\hat{n}_{thrust}$ such that V_{thrust} is maximum.





Tau Lepton Mass Measurement

- **Major improvements in the determination of the beam energy and charged particle momentum**

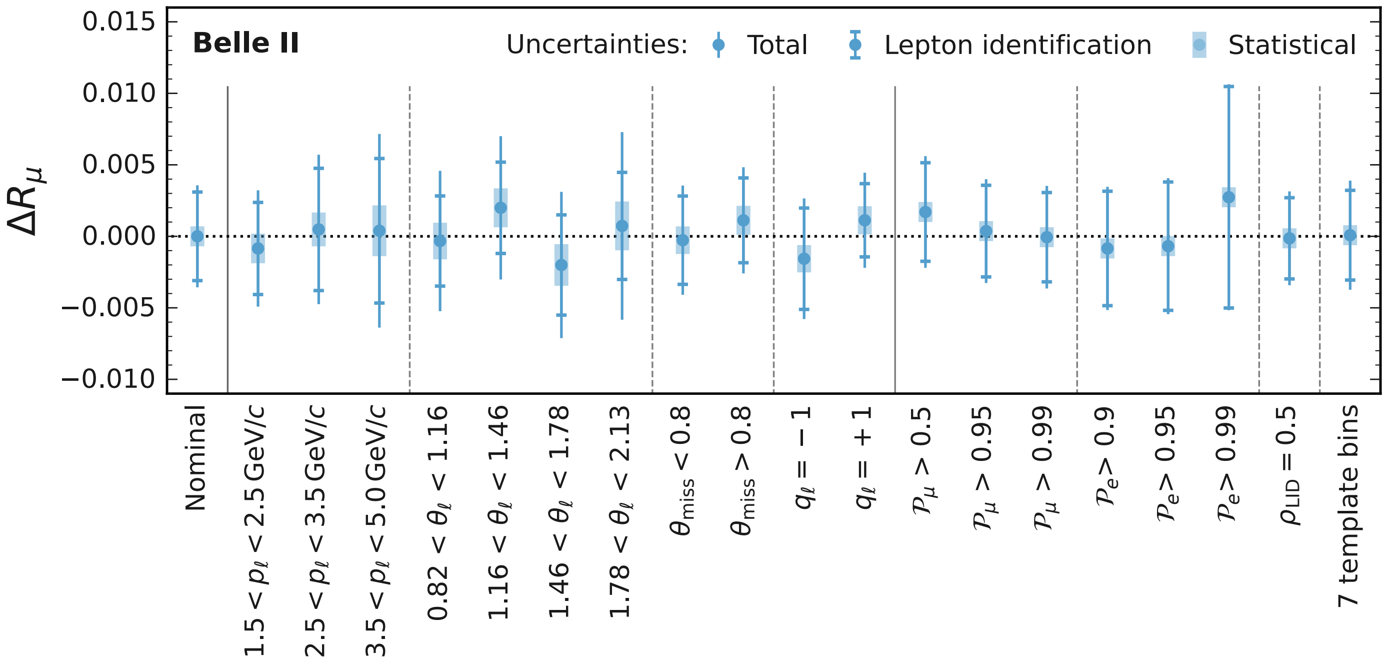
- Use energy of fully reconstructed B mesons (E^*_B) to calibrate $\sqrt{s}$
  - E^*_B only approximately equals $\sqrt{s}$, accounting extra corrections due to subtle effects from ISR photons, spread of the beam energy

- We use $D^0 \rightarrow K\pi$ to correct for the momentum of the tracks
  - Get phase-space dependent scale factors (SF) for K and π based on difference in peak position and PDG value of D^0

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

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

Tests of LFU at Belle II



Source	Uncertainty [%]
Charged-particle identification:	0.32
Electron identification	0.22
Muon misidentification	0.19
Electron misidentification	0.12
Muon identification	0.05
Imperfections of the simulation:	0.14
Modelling of FSR	0.08
Normalisation of individual processes	0.07
Modelling of the momentum distribution	0.06
Tag side modelling	0.05
π^0 efficiency	0.02
Particle decay-in-flight	0.02
Tracking efficiency	0.01
Modelling of ISR	0.01
Photon efficiency	< 0.01
Photon energy	< 0.01
Detector misalignment	< 0.01
Momentum correction	< 0.01
Trigger	0.10
Size of the simulated samples	0.06
Luminosity	0.01
Total	0.37

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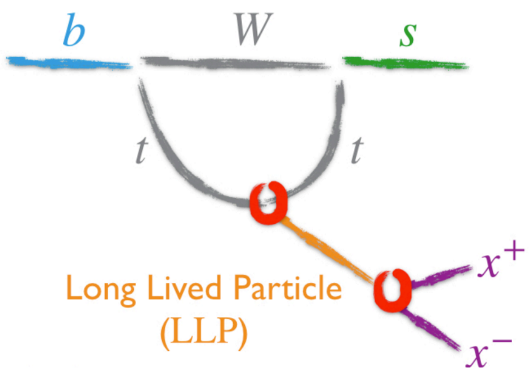
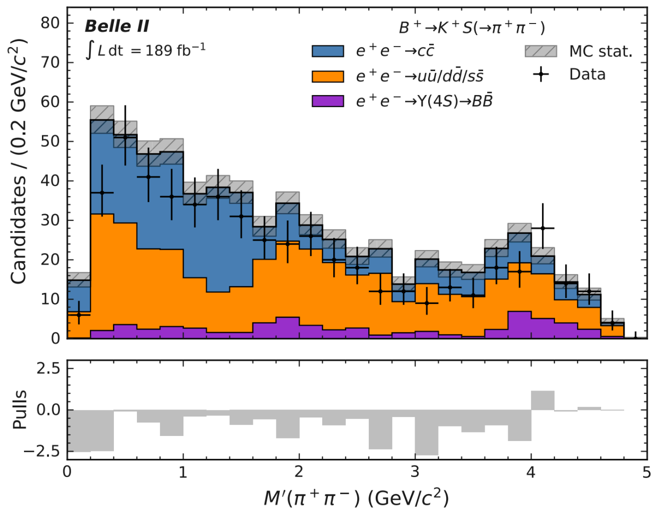
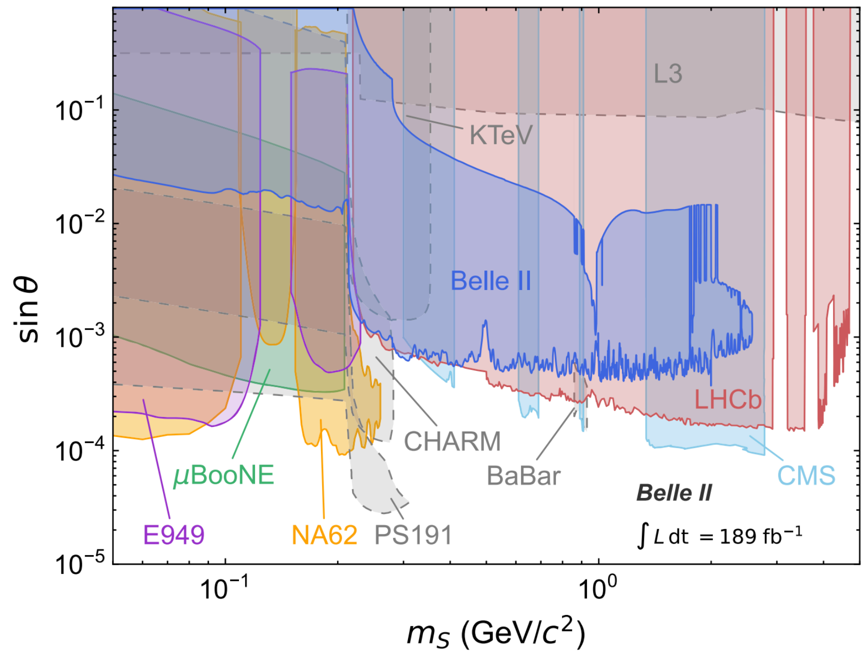
Search for long-lived particle in b → s transitions

- Proposed dark Higgs-like scalar which mixes with SM
- Bump hunt in reconstructed LLP mass
- Eight exclusive channels:
    - $B^+ \to K^+$ LLP
    - $B^0 \to [K^{*0} \to K^+\pi^-]$ LLP
        - LLP $\to x^+x^-$ for $x \in (e,\mu,\pi,K)$



- Main background: combinatorics in continuum, K_s^0 (mass region vetoed)
- Main result: exclusive model independent limits for (pseudo-)scalar LLP
- **First for decays into hadrons**





Phys Rev D. 108 L111104 (2023)

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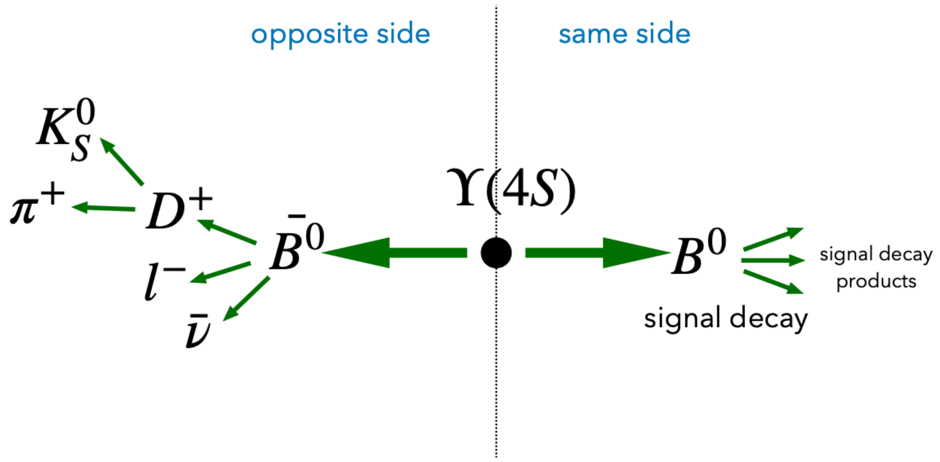
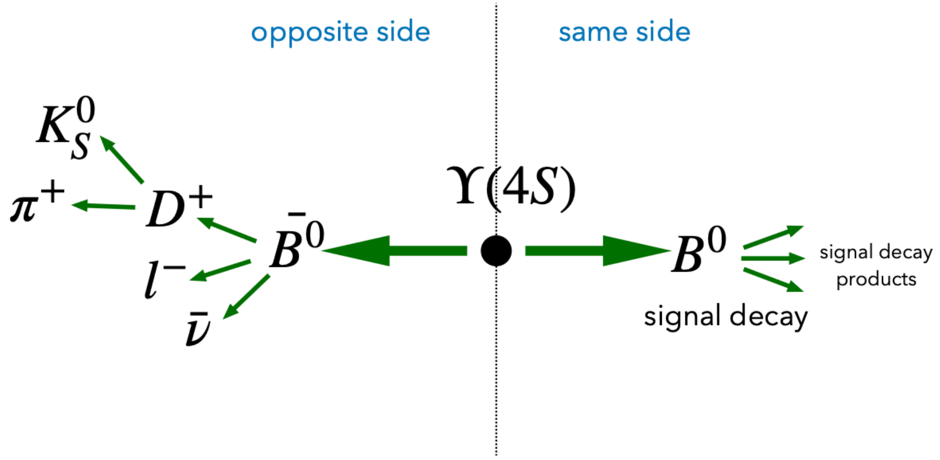
Charm Tagging

- A typical $B\bar{B}$ event
  - Quantum correlation allows identification of “signal B” flavor based on “tag B”

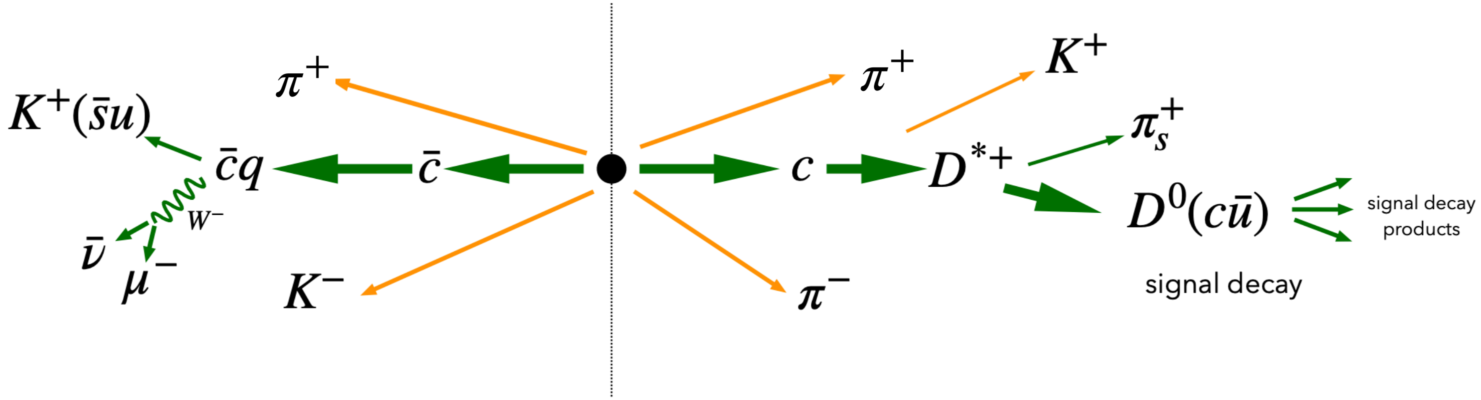


Charm Tagging

- A typical $B\bar{B}$ event
  - Quantum correlation allows identification of “signal B” flavor based on “tag B”



- Charm hadrons are different
  - No quantum correlation due to “fragmentation particles”
  - Using instead
    - $D^{*+} \rightarrow D^0 \, \pi^+$
    - $D^{*-} \rightarrow \bar{D}^0 \, \pi^-$



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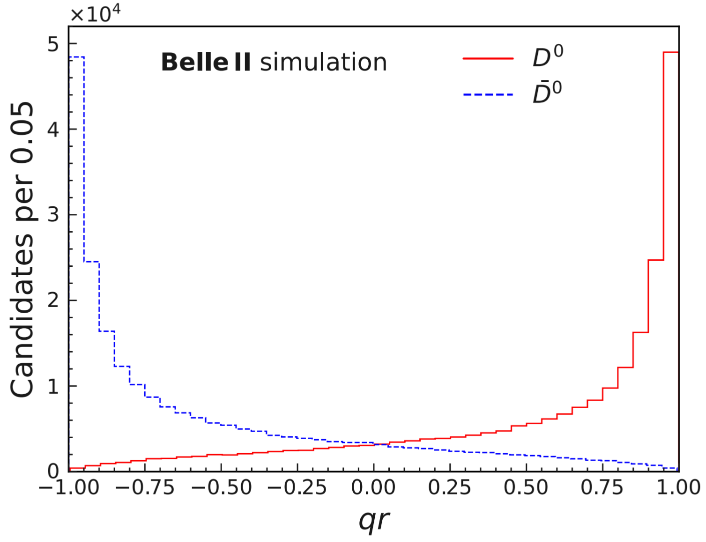
Charm Flavor Tagger

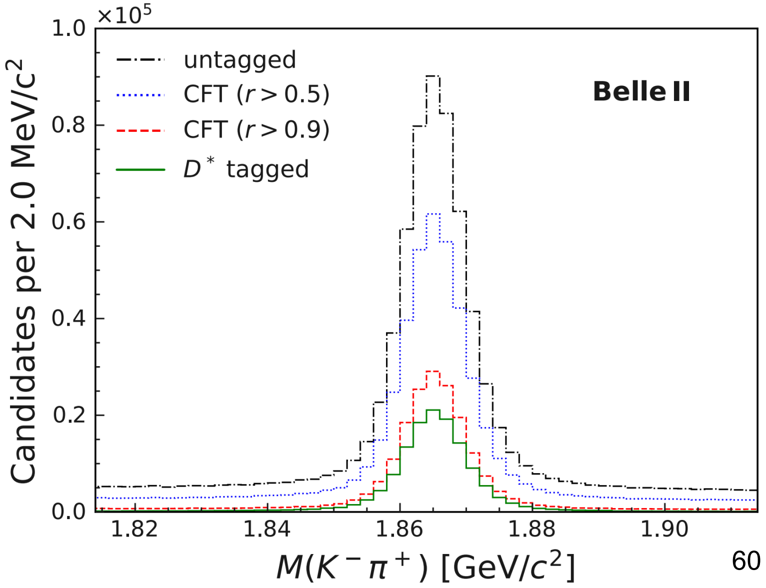
Phys. Rev. D 107, 112010



- A novel method to identify the flavor of neutral charmed mesons
- Exploits the correlation between the flavor of a reconstructed neutral D meson and the electric charges of the rest of the event
- Tagging decision q = +1 (-1) for $D^0(\bar{D}^0)$, with a dilution factor r
- Effective tagging efficiency

$$\epsilon_{\text{tag}} = (47.91 \pm 0.07 \pm 0.51)\,\%$$

- Approximately **doubles the effective size of data sets** for CP violation and charm mixing measurements



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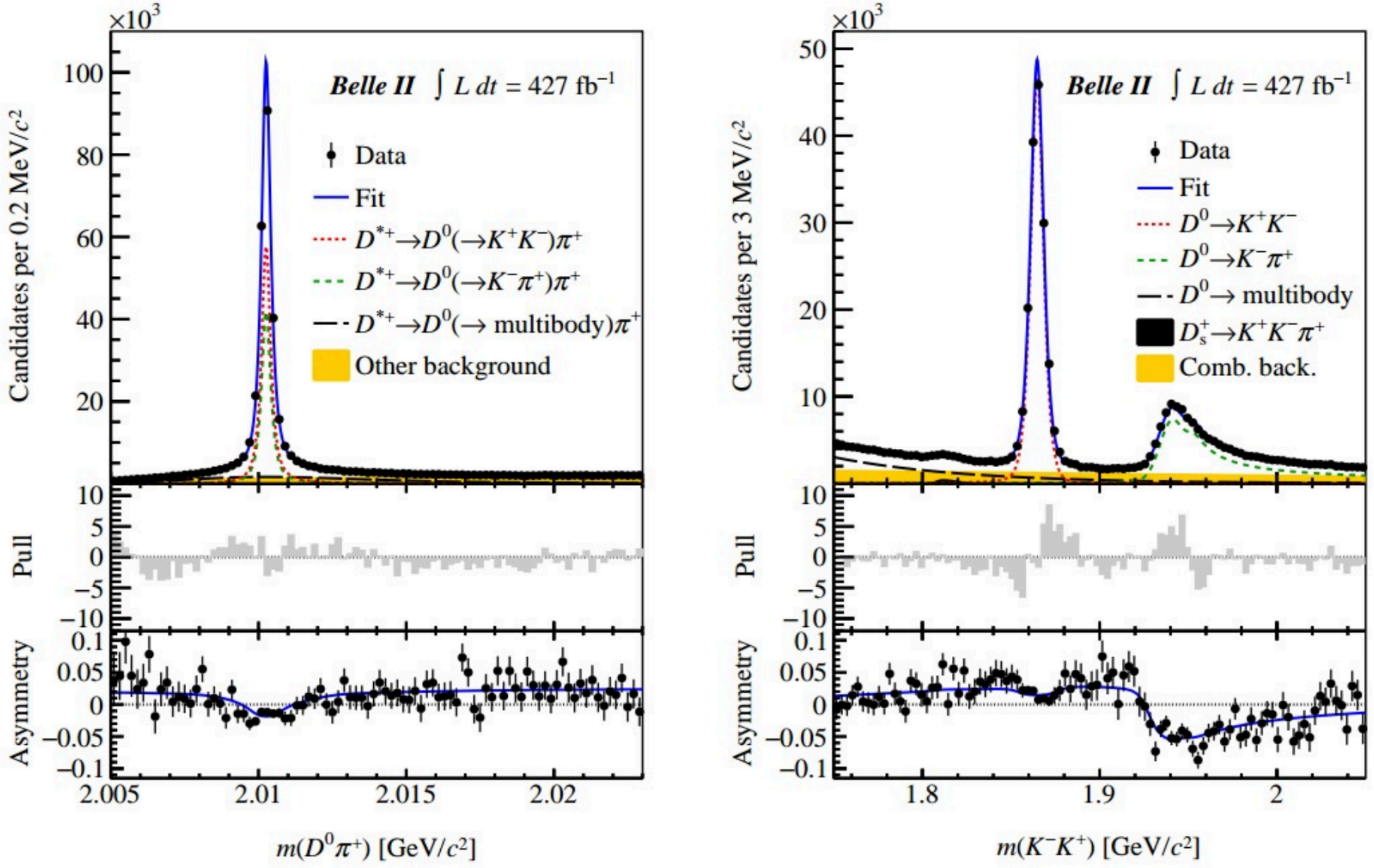
CP Violation in $D^0 \to K_s^0 K_s^0$

- Control mode $D^0 \to K_s^0 K_s^0$



$e^+e^- \rightarrow \pi^+\pi^-\pi^0$

- HVP contributions to g_μ-2

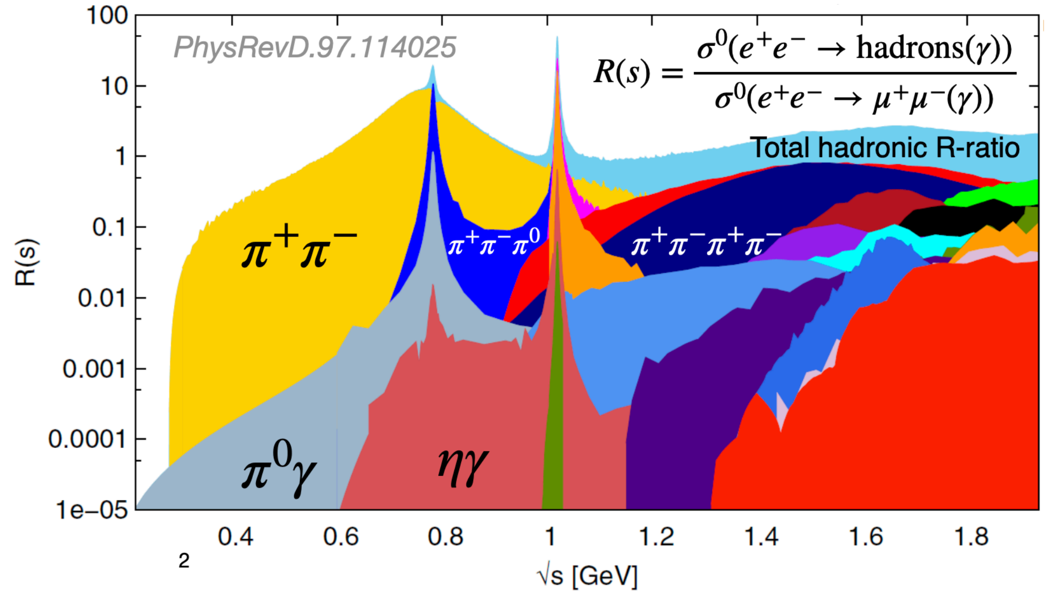
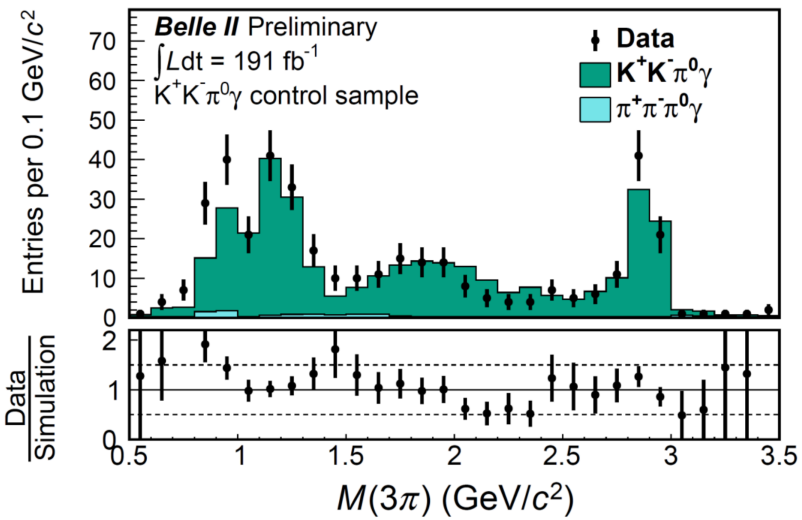


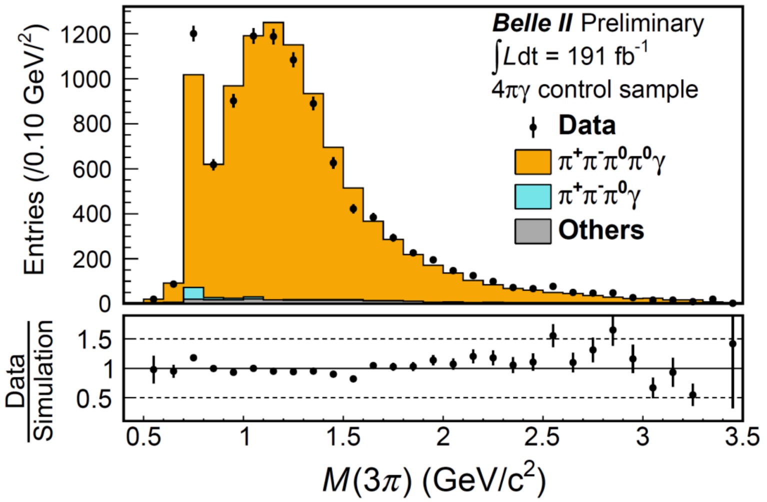
Table II. Summary of contributions to the systematic uncertainty in $a_\mu^{3\pi}$ (%).

Source	Systematic uncertainty (%)
Efficiency corrections	1.63
Monte Carlo generator	1.20
Integrated luminosity	0.64
Simulated sample size	0.15
Background subtraction	0.02
Unfolding	0.12
Radiative corrections	0.50
Vacuum polarization corrections	0.04
Total	2.19

NNLO QED generators are crucial

- Control modes:





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Simultaneous Determination of Exclusive & Inclusive $|V_{ub}|$

- Long standing 3σ discrepancy between **exclusive** and **inclusive** determination of $|V_{ub}|$
- New measurement using the full Belle dataset.
- Fitter corporates experimental observation of **$B \to \pi \ell \nu$** & other **$B \to X_u \ell \nu$** normalizations
- Various fit scenarios applied:
  - Combined or separate **$B^+ \to \pi^0 \ell \nu$** & **$B^0 \to \pi^+ \ell \nu$**
  - Input form factor constraint: **Lattice QCD (LQCD) + exp.** or **only LQCD**

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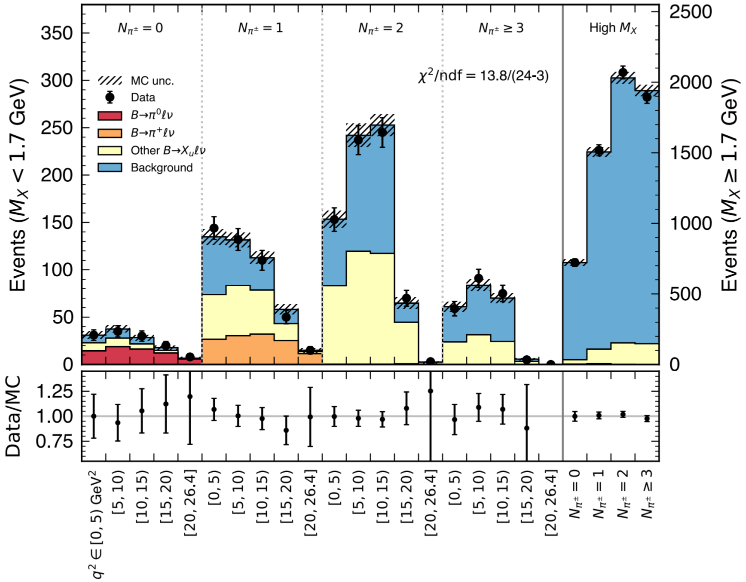
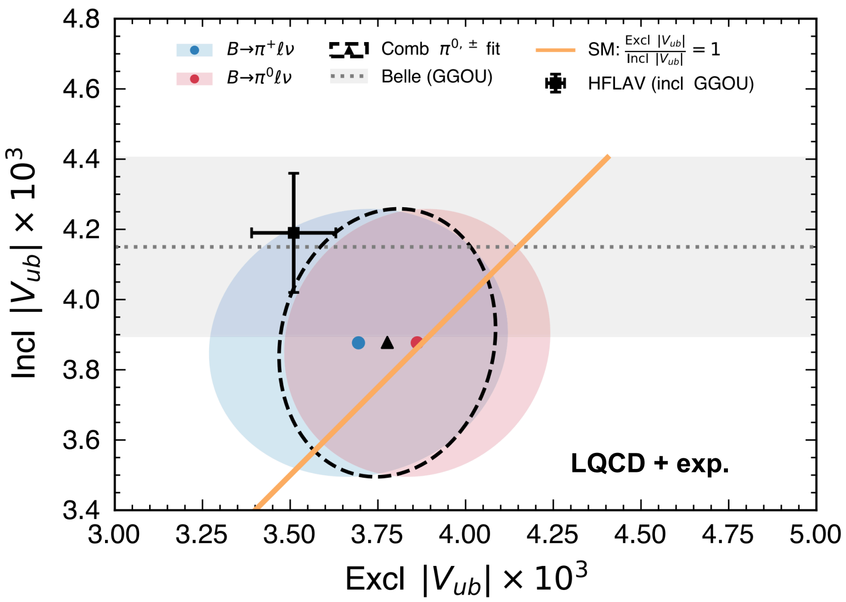
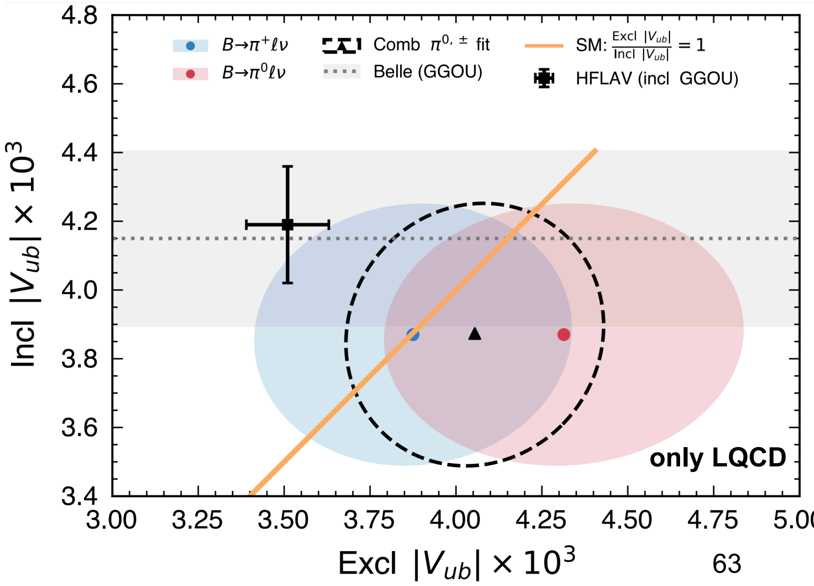
- New result is
  - consistent between excl and incl analyses
  - In agreement with CKM expectation







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