Belle II physics: a brief tour

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Outline

1. **The why:** flavour physics in e^+e^- and Belle II
2. **The what:** general methods and recent highlights
   - *B*-physics primer
   - *B*-physics
     - *CP* violation examples
     - Evidence for $B^+ \to K^+\nu\nu$
     - Search for $B^+ \to K^*\tau\tau$
   - More than *B* physics
     - τ lepton-flavour violation
     - hadronic cross sections for hadronic vacuum polarization to g−2
     - Exotic hadrons
3. **The future:** status and prospects for SuperKEKB and Belle II

Part I: the why

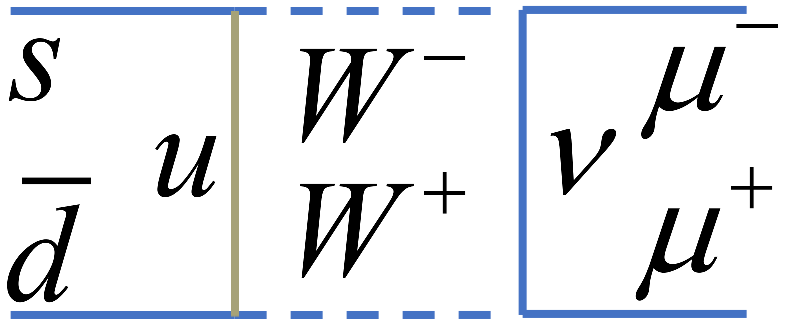
e^+e^- flavour physics and Belle II

Why flavour physics? – history of discovery

- Particle zoo of mesons and baryons discovered in 1950s and early 1960s lead to the quark model
  - up (u)
  - down (d)
  - strange (s)
- An allowed but rare decay such as

$$K_L^0(s\bar{d}) \rightarrow \mu^+\mu^-$$

was predicted **but not seen!**



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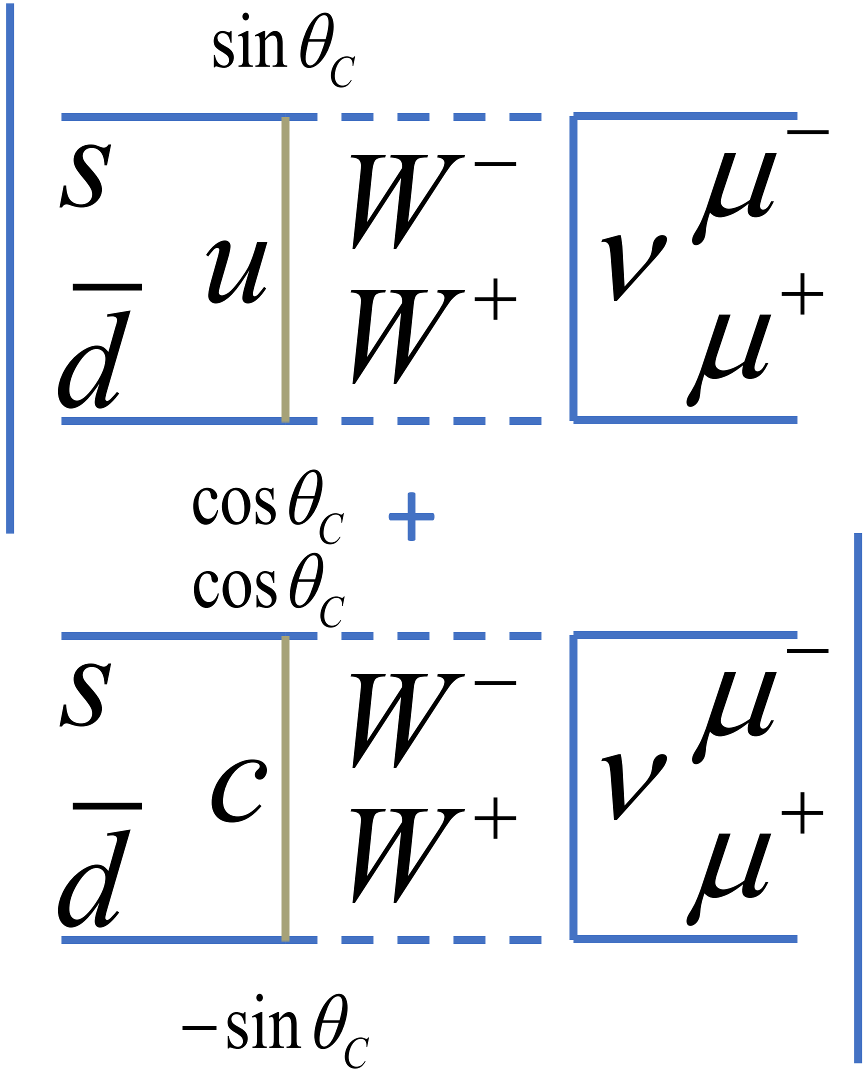


2 $\propto$ Rate ~ 0

Glashow

Iliopoulos

Maiani

Phys. Rev. **D** 2, 1285 (1970)

$m_c \sim 3\ m_K$

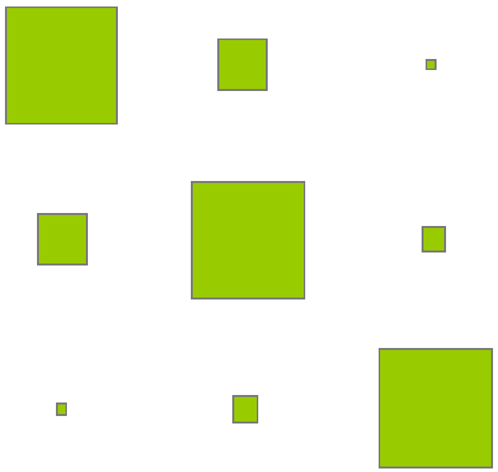
Such rare virtual processes tell you about higher energy particles

CKM matrix

- Two by two mixing matrix proposed by Cabibbo
  - Kobayashi-Maskawa proposed third generation to explain observed CP violation by Cronin and Fitch
- 3×3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase
- Intergenerational coupling disfavoured

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

Relative magnitude of elements



Responsible for CP violation

Visualising CP violation: the unitarity triangle

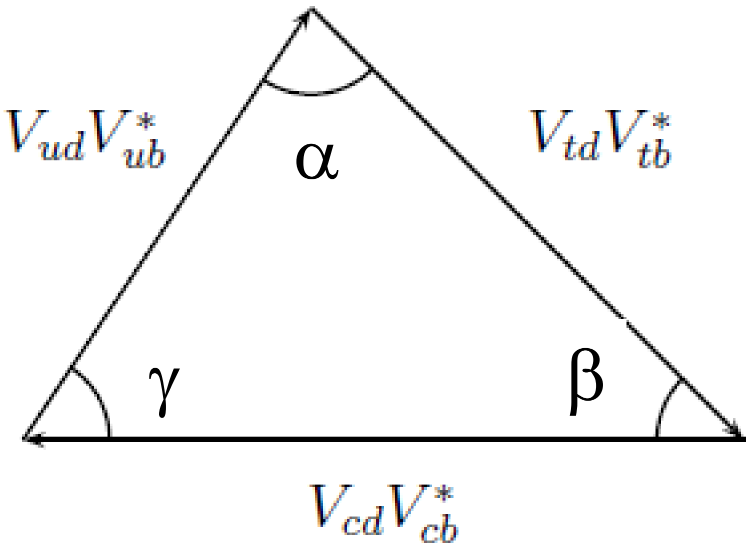
$\lambda = \sin\theta_c = 0.22$

1) $$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3\left[1-(\rho - i\eta)\right] & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

2) Exploit unitarity (1st and 3rd col.)

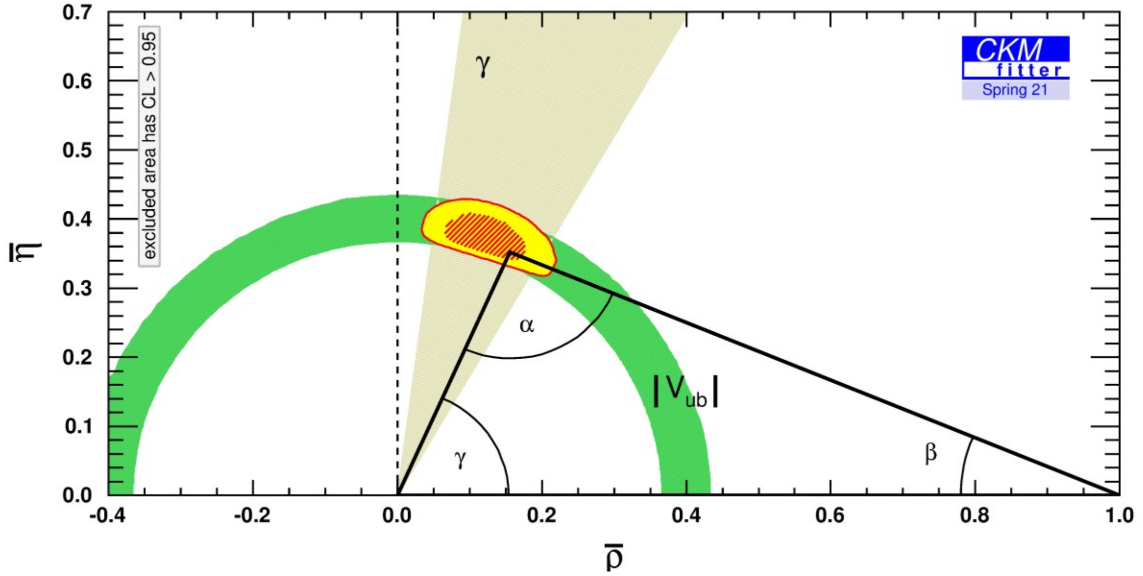
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

3)

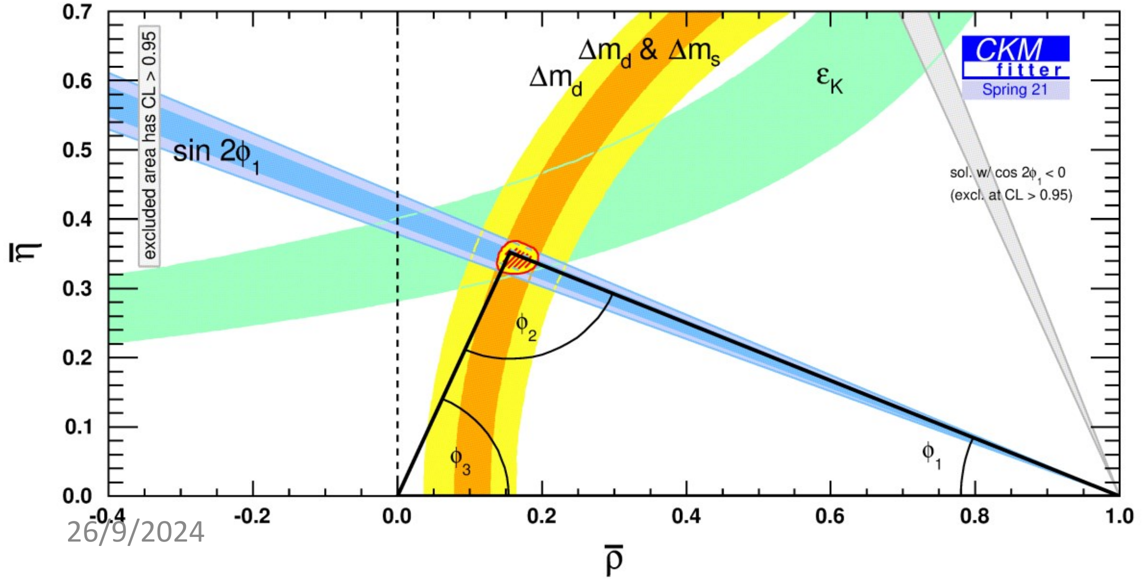


$$\phi_1 = \beta$$
$$= \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$
$$\simeq \arg\left(\frac{1}{1-\rho-i\eta}\right)$$

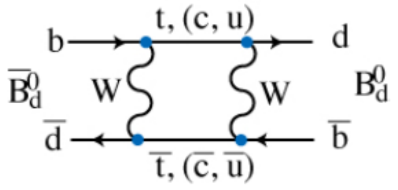
Over constraint – loop sensitivity



Tree level only



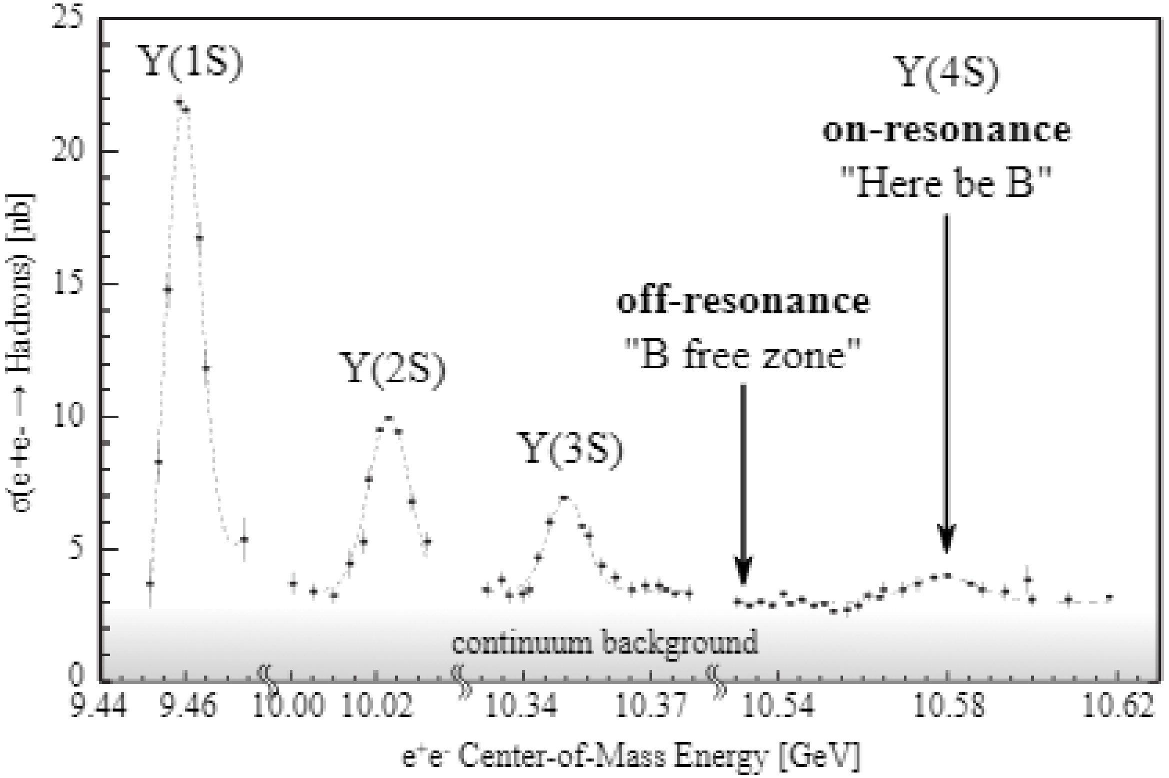
Loop-level only



NP at
O(>TeV)?

Why *B* physics at the Υ(4S)?

- The process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum



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- **Advantages compared to proton-proton**
  - Low average multiplicity – neutral reconstruction
  - Constrained kinematics – good missing momentum reconstruction
  - Correlated $B^0\bar{B}^0$ - high flavour-tagging efficiency
  - Open trigger – 100% efficient for almost all *B* decays

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  - Open trigger – 100% efficient for almost all *B* decays
- <u>**Disadvantages compared to proton-proton**</u>
  - **Cross section – 150,000 times smaller**
  - No B_s, B_c, or Λ_b produced – can run at Υ(5S) for B_s
  - No boost in the c.m. frame – **partially overcome by the asymmetric beams**

Detectors and data samples

- Belle + BaBar collected $0.71+0.43=1.14\ \mathrm{ab}^{-1}$ $\Upsilon(4S)$ samples
  - Many achievements: confirmation of KM mechanism, $b \to c\tau\nu$, direct CPV in B decay

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- SuperKEKB + Belle II@KEK, Tsukuba
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World record 4.7×10^{34} $cm^{-2}s^{-1}$**
  - Target 6×10^{35} $cm^{-2}s^{-1}$
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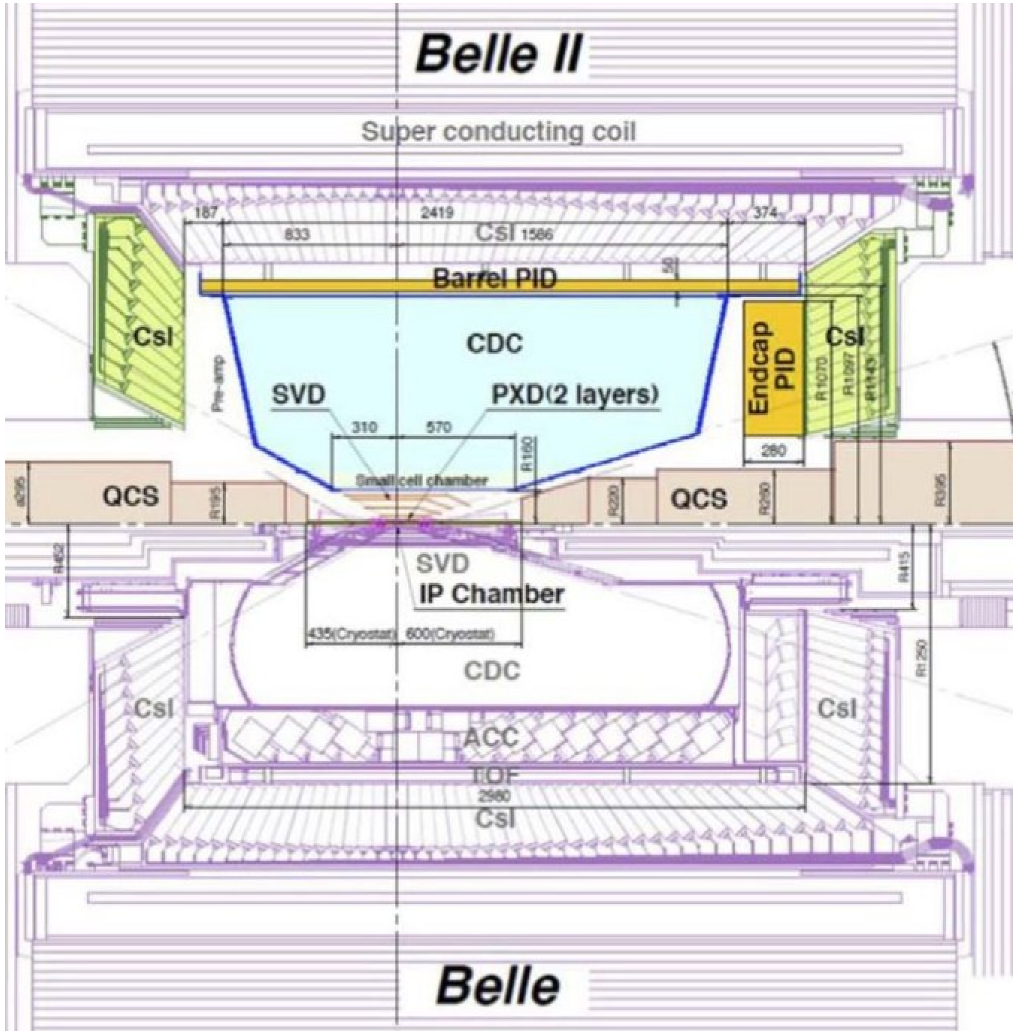
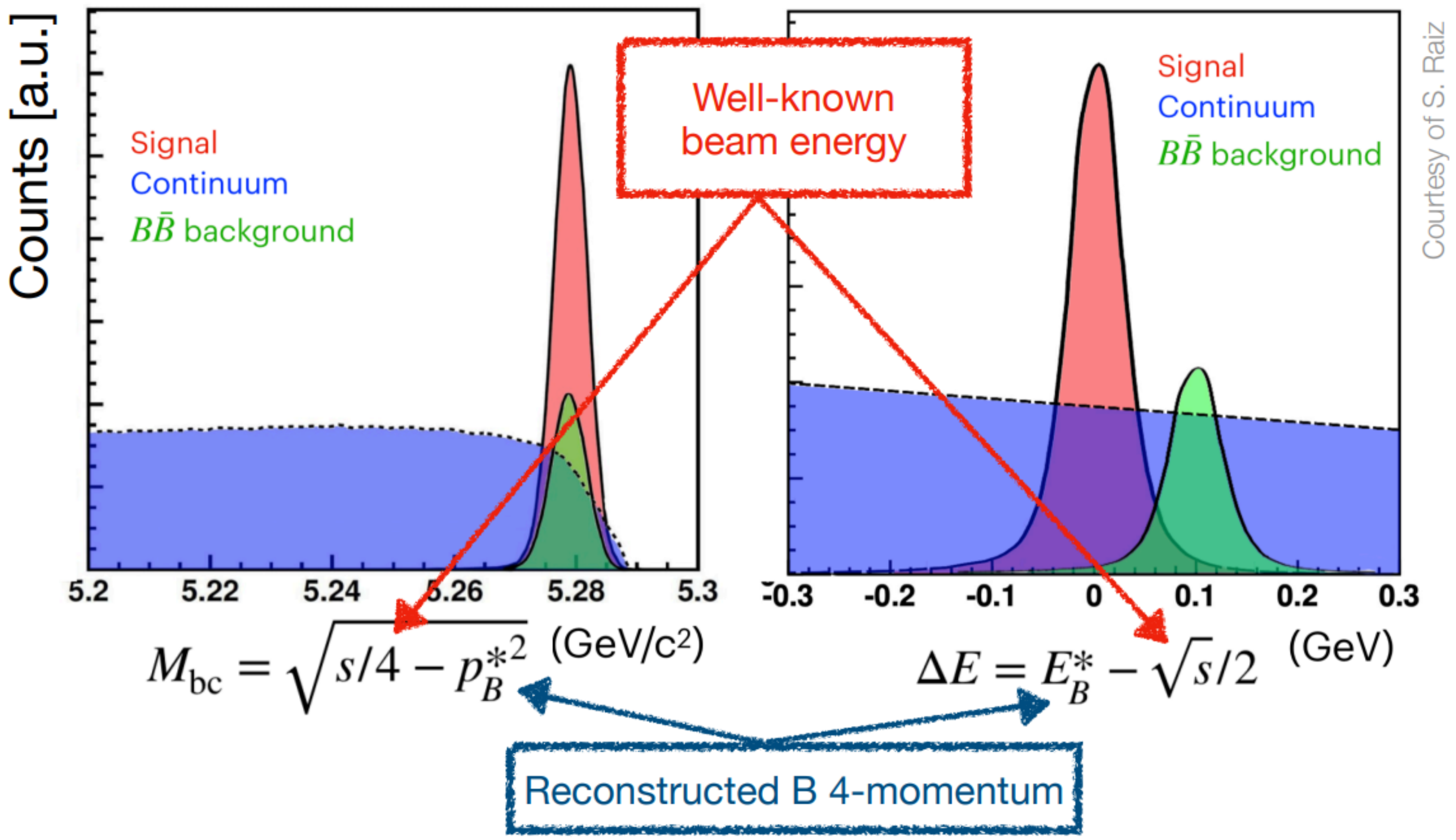


Part II: the what

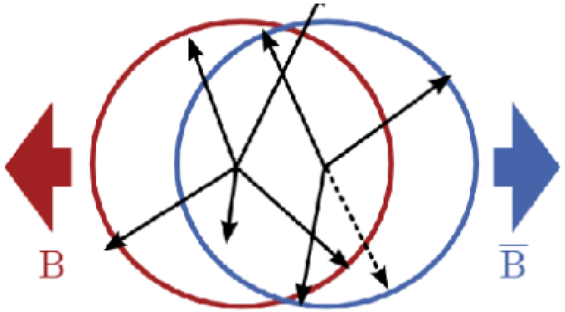
Recent highlights

B-factory analysis essentials 1 – beam constrained kinematics

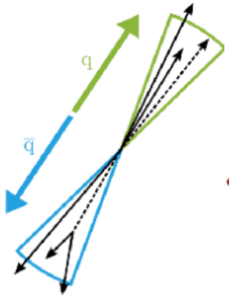


B-factory analysis essentials 2 – continuum suppression

- In the c.m. frame B mesons almost at rest when they decay
  - isotropic distribution of particles
- In the c.m. frame continuum qq back-to-back
  - jetlike distribution of particles



vs.



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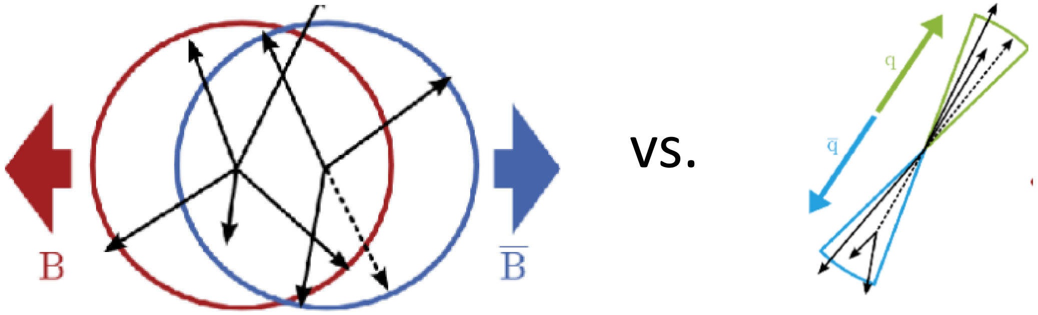
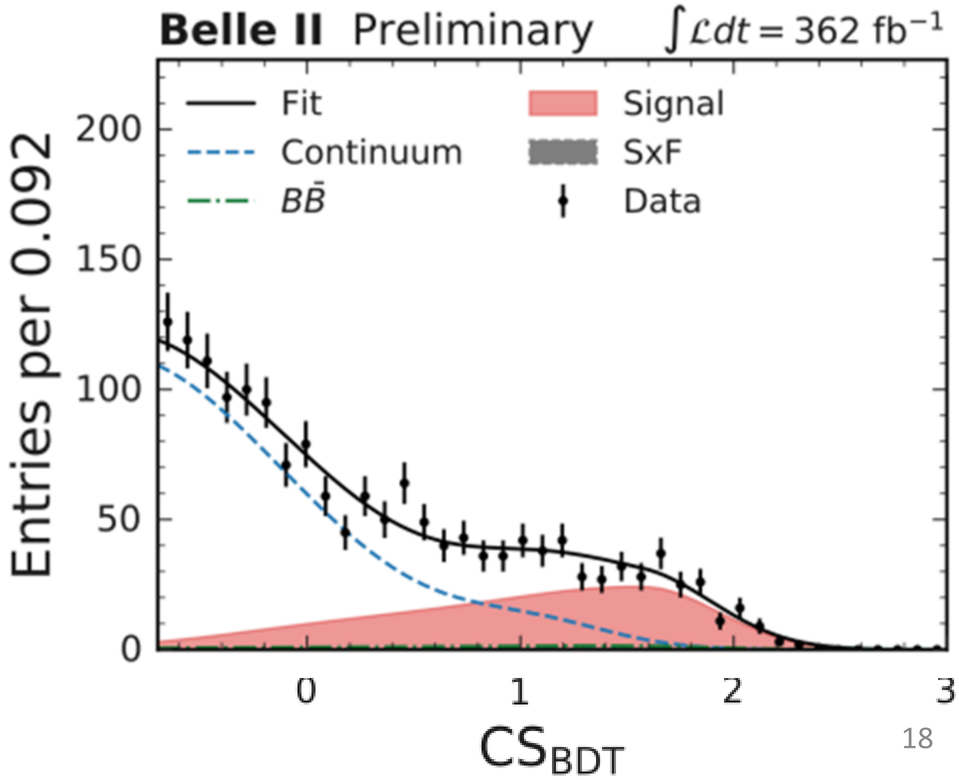
- Shape variables, e.g., thrust and Fox-Wolfram moments, help distinguish topologies
- Ideal task for machine-learning
- Output oft used as a fit variable





B-factory analysis essentials 3: hadronic tag

- Full-reconstruction of one B decay in a large number of high BF modes on one side
  - $B \rightarrow D^{(*)0}\, m\pi^{\pm} n\pi^{0}$, where $m \geq 1$ $n \geq 0$
- Reconstruct other B as signal with missing energy

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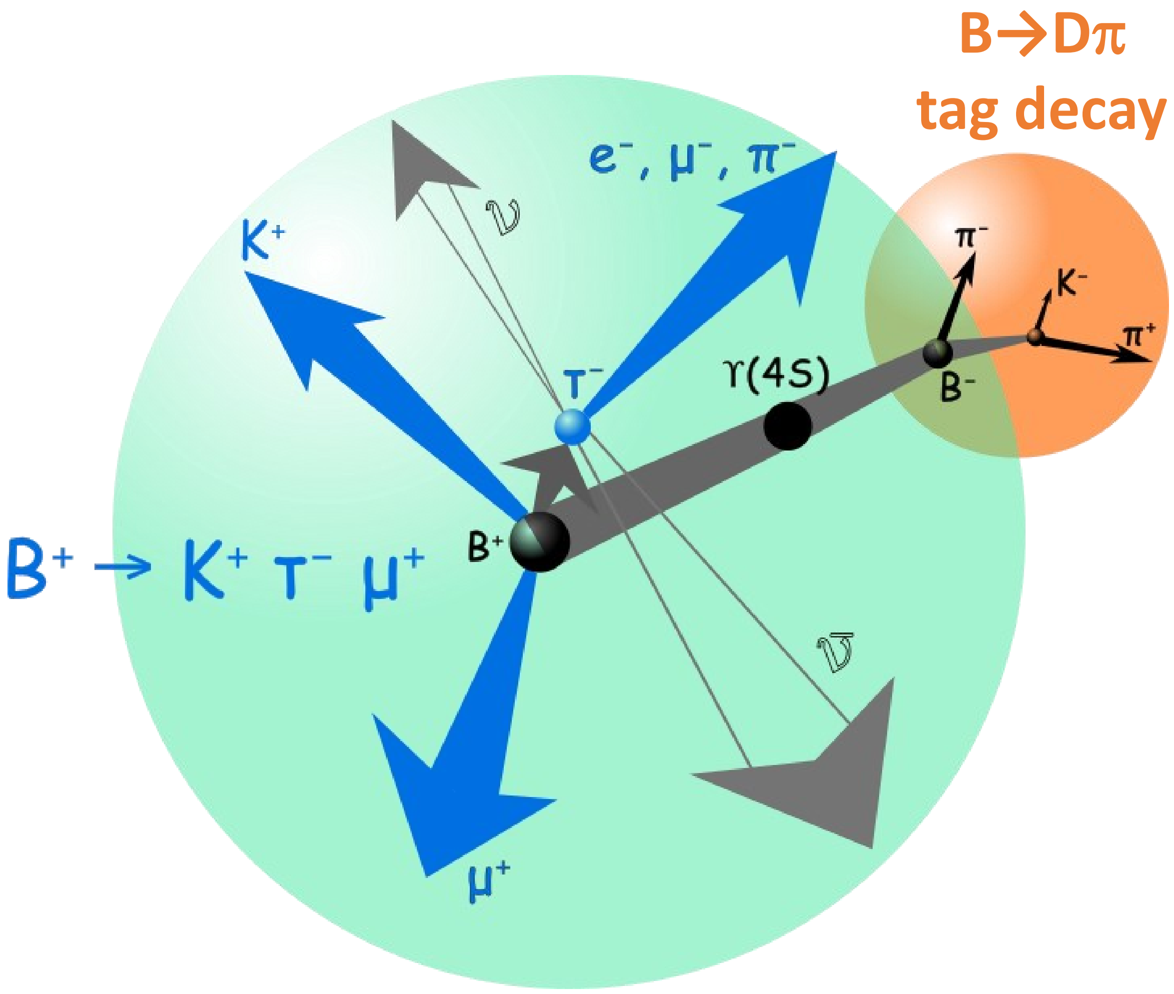

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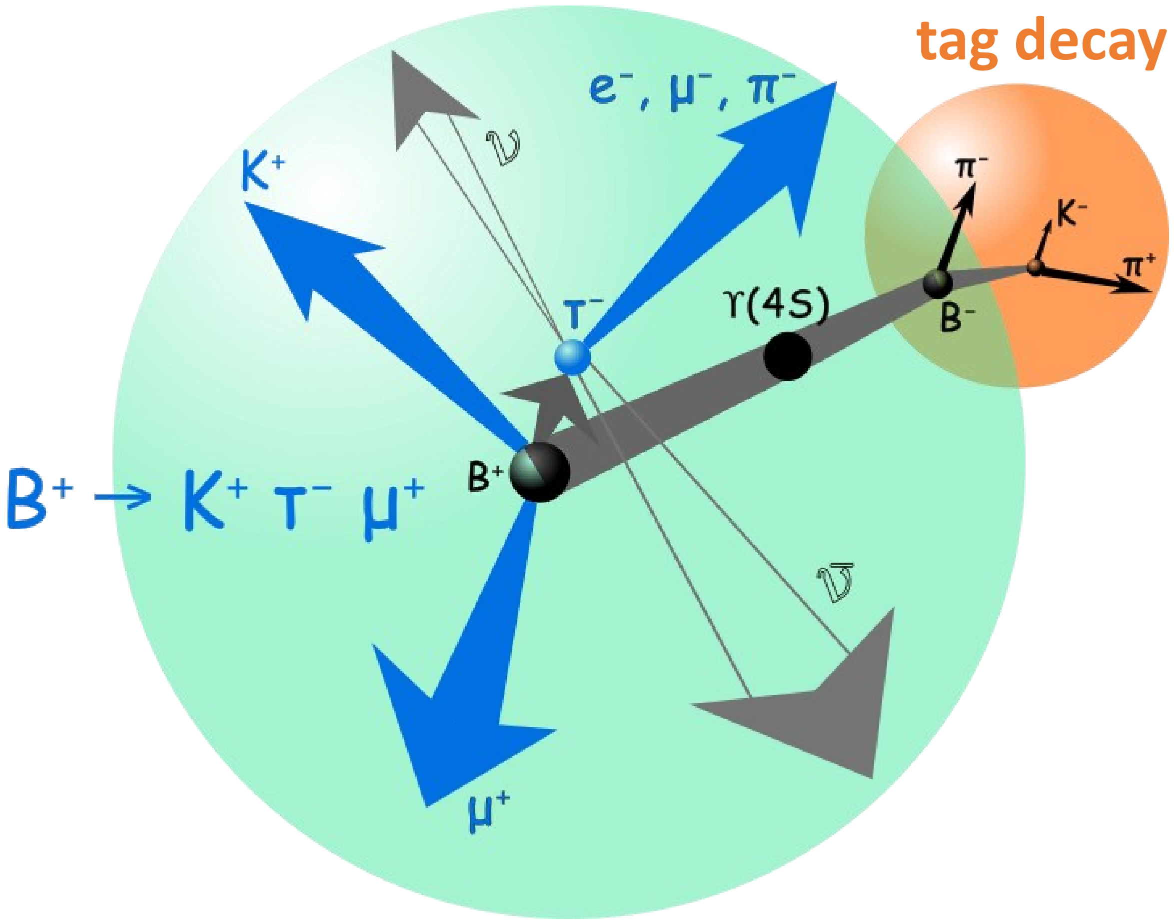
- Reconstruct other B as signal with missing energy
- Machine learning algorithm used to boost efficiency as much as possible
  - [Comput. Softw. Big Sci. 3 (2019) 1, 6]()
- Total efficiency < 1% but a powerful tool
- Requires calibration



B-factory analysis essentials 4 – vertexing and flavour tagging

$$\begin{tikzcd} B^0 \arrow[rr] \arrow[dr] & \arrow[d, phantom, "2\phi_1"] & f_{CP} \\ & \bar{B}^0 \arrow[ur] & \end{tikzcd} \quad \propto \; |V_{td}|^2 e^{2i\phi_1}$$

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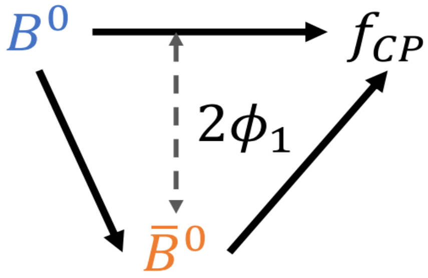

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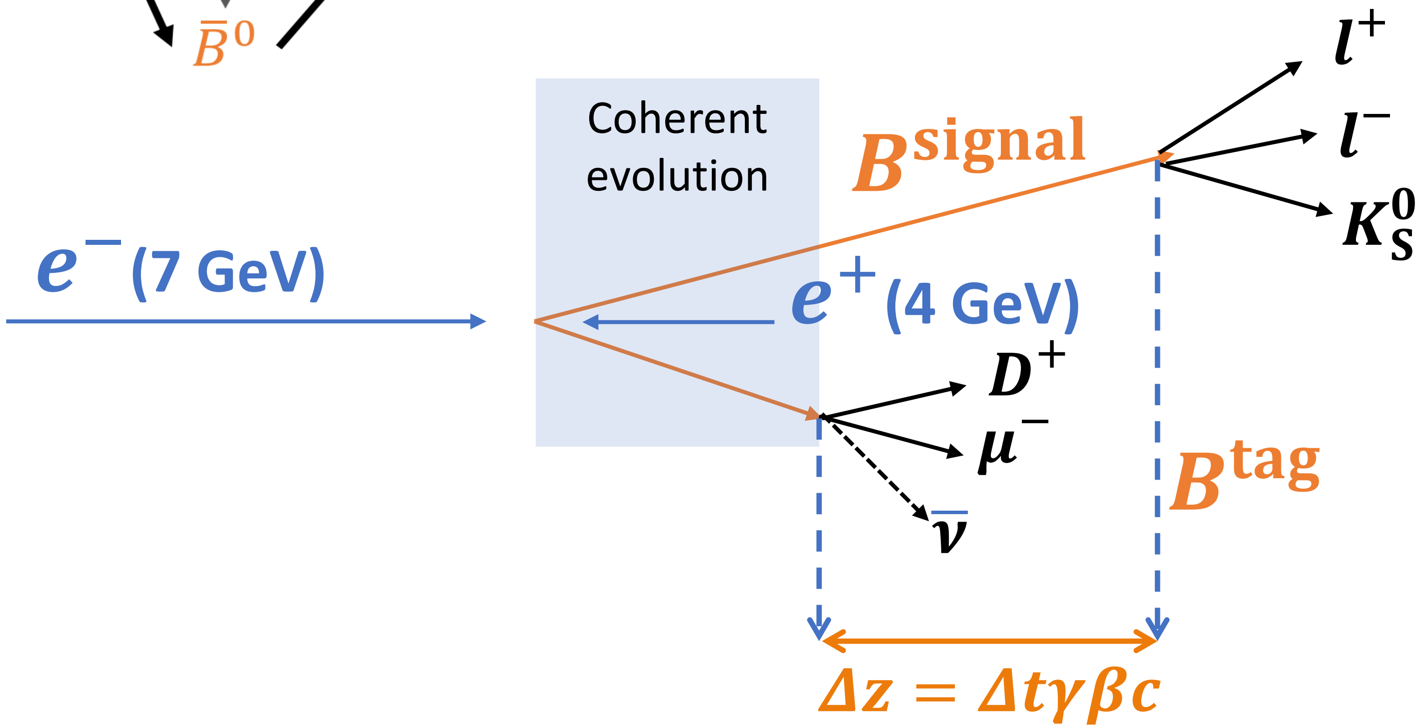

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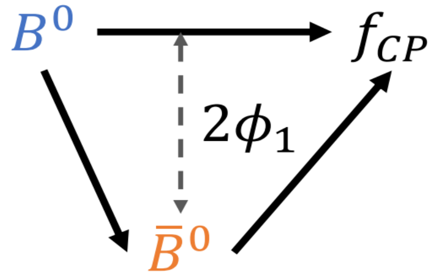

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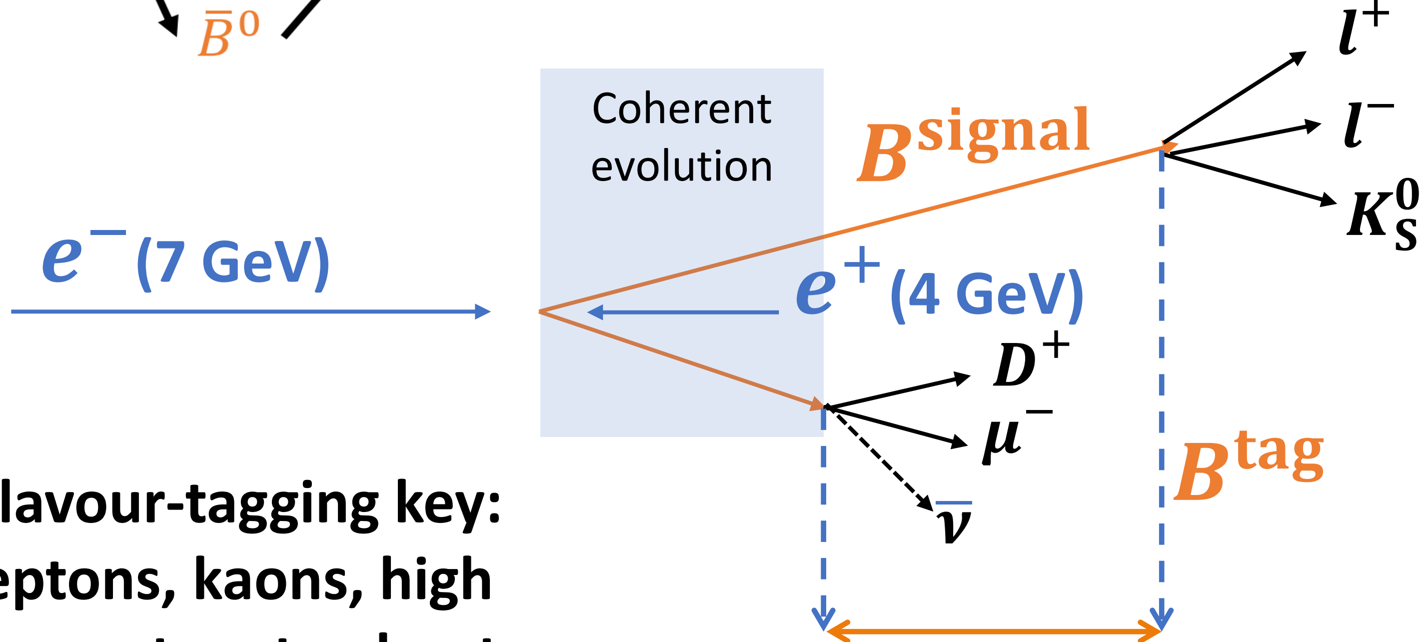
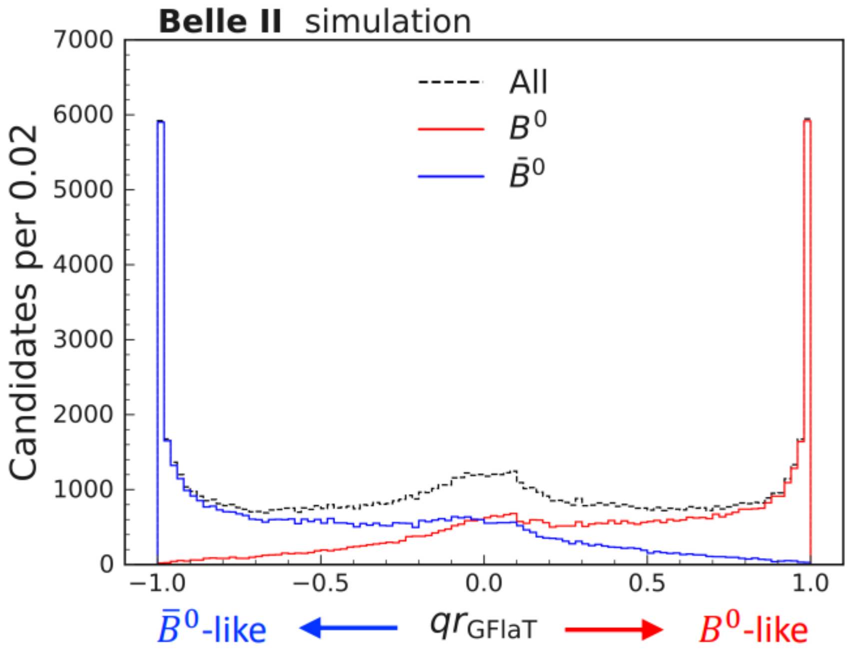


$$\Delta z = \Delta t \gamma \beta c$$

Flavour-tagging key: leptons, kaons, high momentum tracks etc



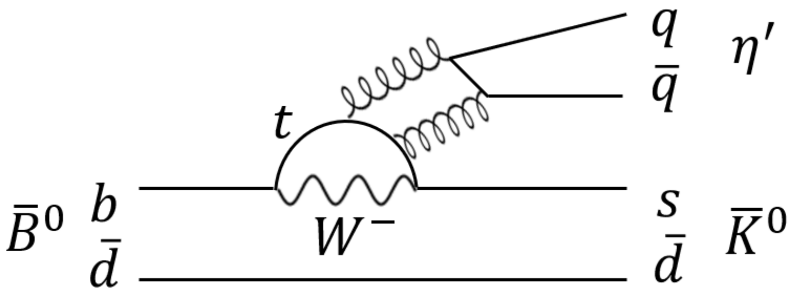
Graph-neural-network approach has improved our tagging by 18%

$$\epsilon(1-2\omega) = 37.4\%$$

arXiv:2402.03713 [hep-ex]

Time-dependent *CP* violation - $\boldsymbol{B^0 \to \eta' K_S^0}$

- Decay may also have a BSM phase as it is a gluonic penguin
    - alter the value of ϕ_1 from that measured in $b \to c\bar{c}s$ transitions such as $B^0 \to J/\psi K_S^0$



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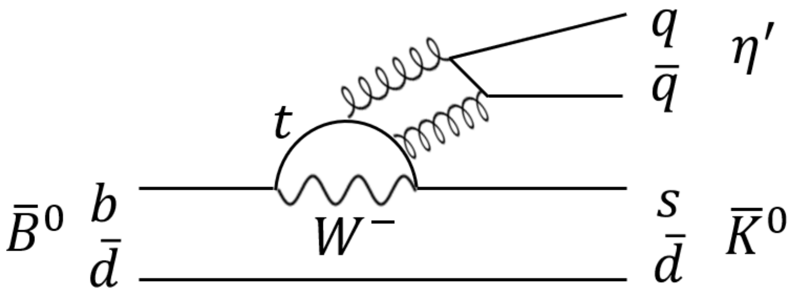
- Reconstructing $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho(\pi^+\pi^-)\gamma$ we select 829 ± 35 events in 362 fb^{-1} sample
  - 3D fit to ΔE, m_{BC} and continuum suppression output



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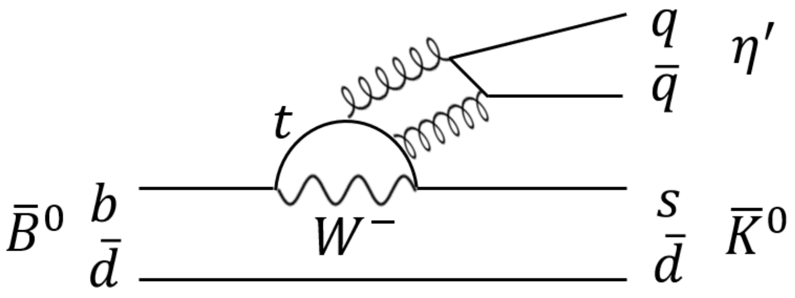
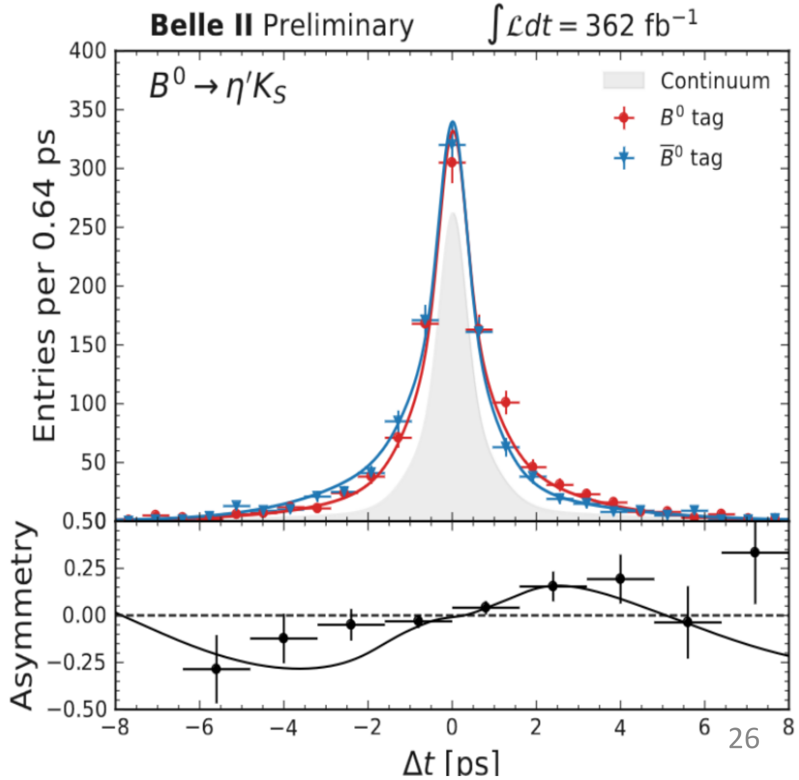
  - 3D fit to ΔE, m_{BC} and continuum suppression output
- **sin 2ϕ_1 = 0.67±0.10±0.04**
- Consistent with current HFLAV average and that from $b \to c\bar{c}s$ result

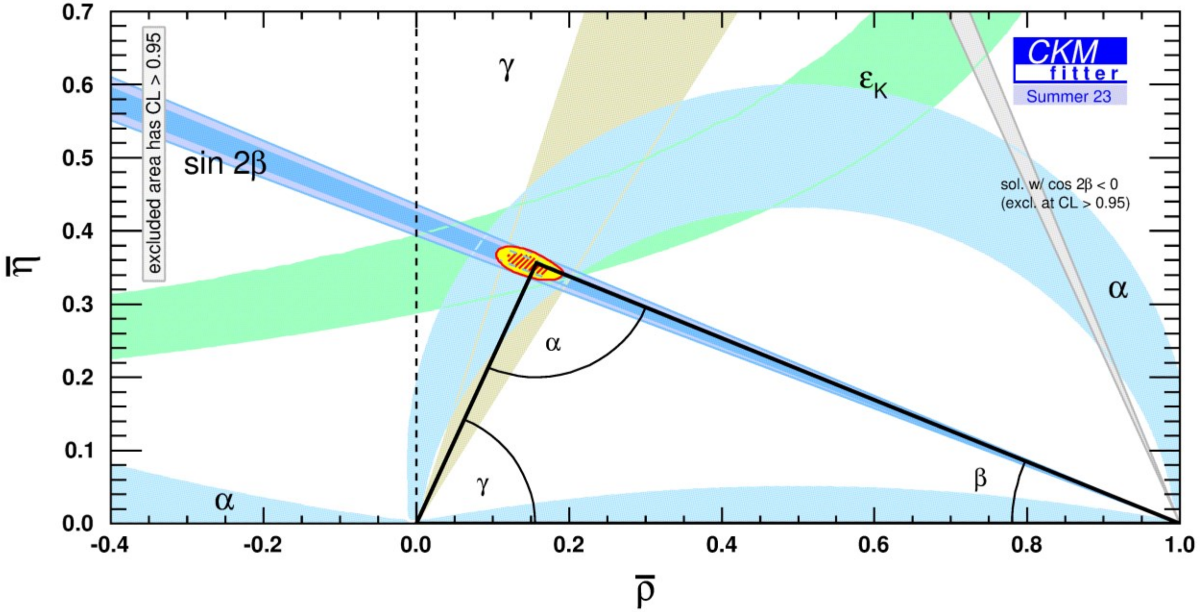




α/ϕ_2: $B^0 \to \pi^0\pi^0$

Paper in preparation

- α/ϕ_2 now the least precise angle of the unitarity triangle
- Isospin relations among all $B \to \pi\pi$ branching fractions and CP asymmetries provide constraints
  - **Gronau and London PRL 65 3381 (1990)**
- Weakest link: $\mathbf{B^0 \to \pi^0\pi^0}$



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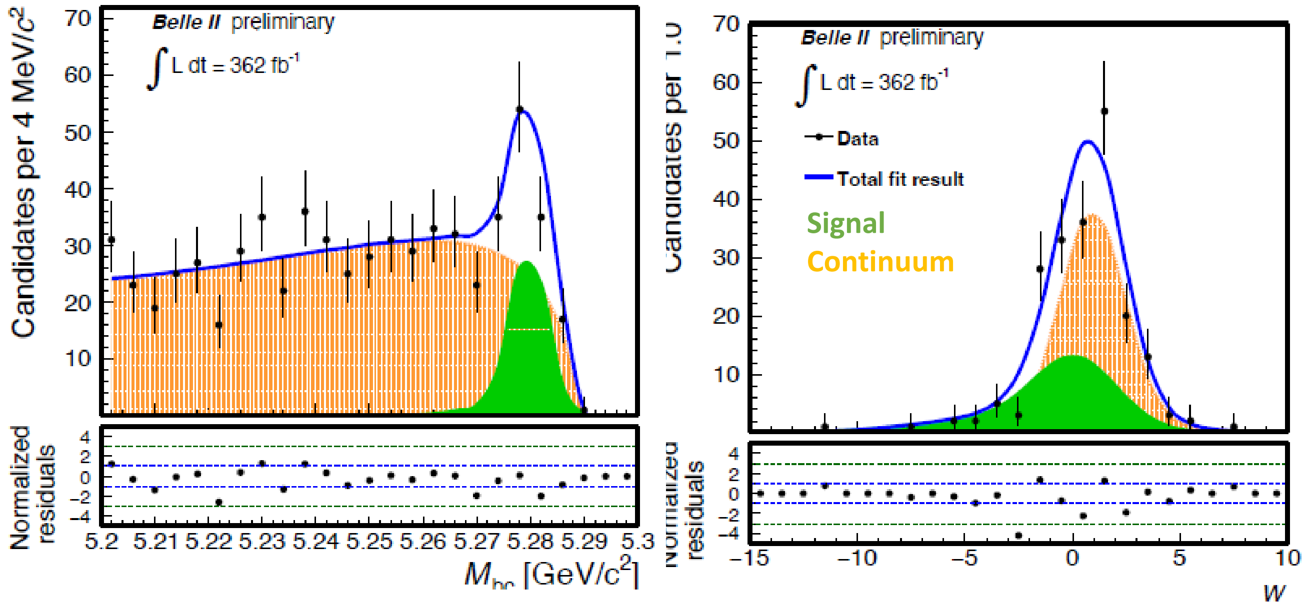
  - **Gronau and London PRL 65 3381 (1990)**
- Weakest link: $\mathbf{B^0 \rightarrow \pi^0\pi^0}$
- New result from Belle II
  - 4-D fit including tagging probability
  - Graph-neural-network based tagger
    - 18% more powerful than before
    - **arXiv:2402.17260 [hep-ex] (acc. PRD)**

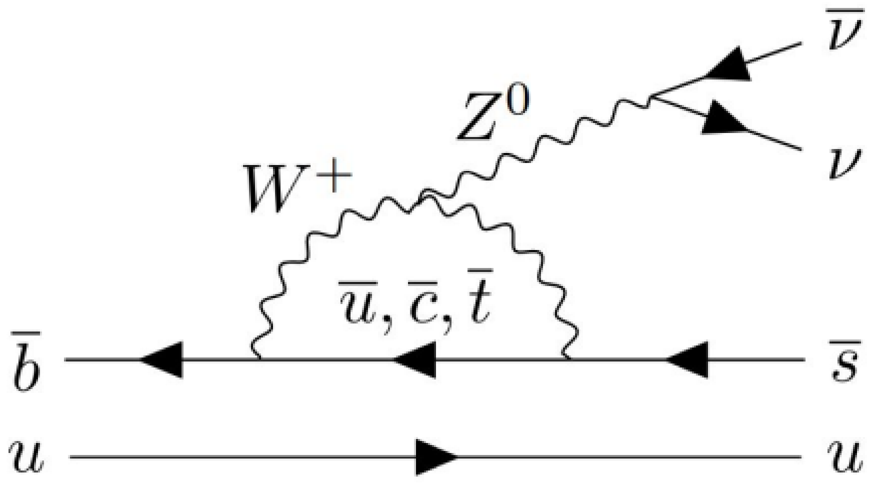


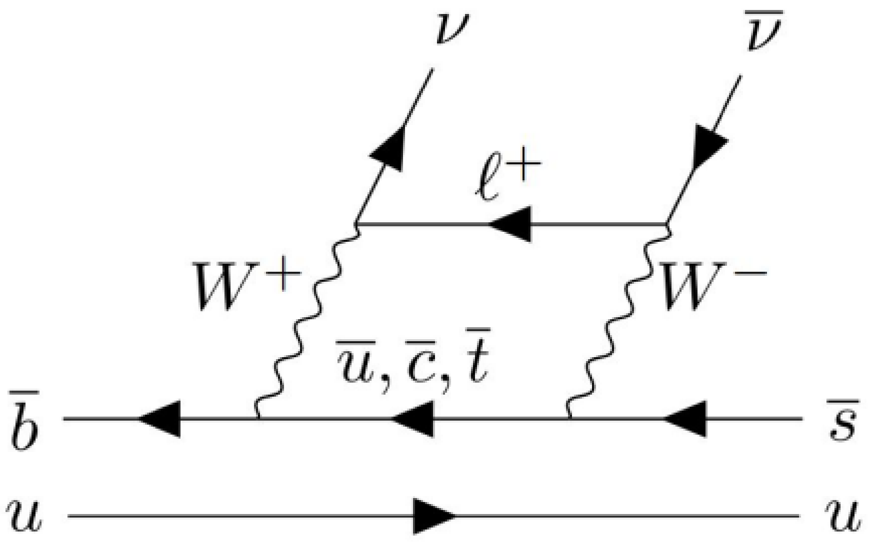
Beam-energy constrained $\pi^0\pi^0$ invariant mass

Transformed wrong-flavour-tag probability

$$\mathscr{B} = (1.26^{+0.20}_{-0.19} \pm 0.11) \times 10^{-6}$$
$$A_{CP} = 0.06 \pm 0.30 \pm 0.06$$

$B^+ \to K^+\nu\bar{\nu}$: Motivation





- Well known in SM but very sensitive to BSM enhancements – 3rd gen
  - $B(B \to K^+\nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]

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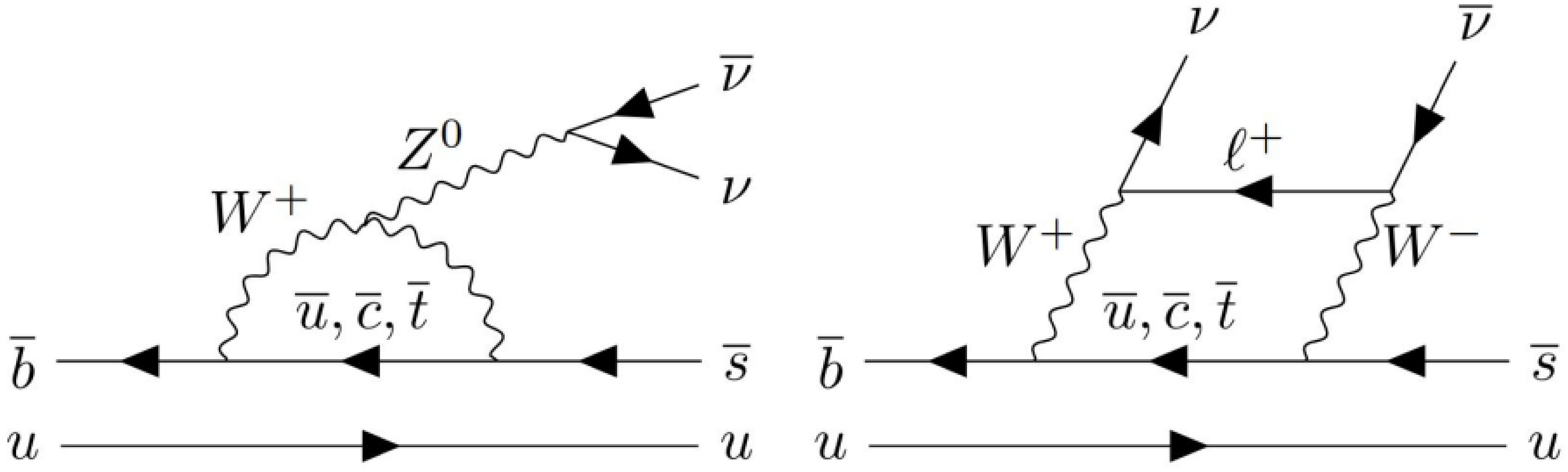

- Well known in SM but very sensitive to BSM enhancements – 3rd gen
  - $B(B \rightarrow K^+\nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Challenging experimentally
  - Low branching fraction with large background
  - No peak – two neutrinos leads to no good kinematic constraint

$B^+ \to K^+ \nu\bar{\nu}$: Analysis strategy

- Two methods: an inclusive tag (8% efficiency) and conventional hadronic tag (0.4% efficiency)
  - many common features except tag

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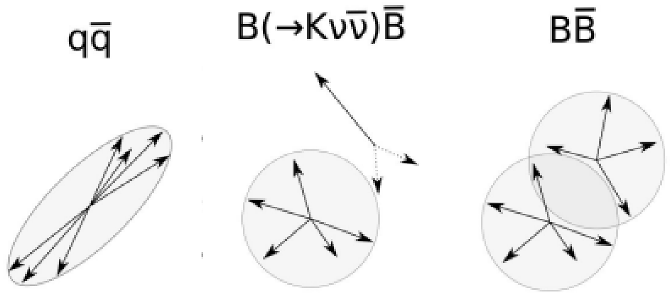
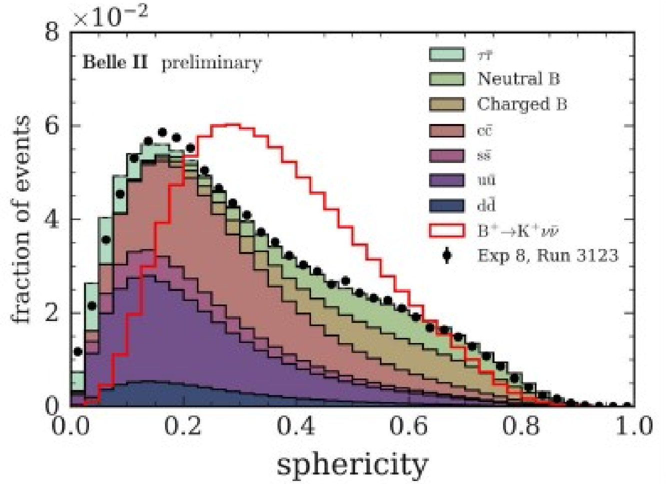


- Two methods: an inclusive tag (8% efficiency) and conventional hadronic tag (0.4% efficiency)
  - many common features except tag
- Use event variables to suppress background
  - Inclusive:
    1. preselect events where missing momentum and signal kaon well reconstructed
    2. First boosted decision tree (BDT1): 12 variables
    3. Second BDT2: 35 variables – 3 times sensitivity



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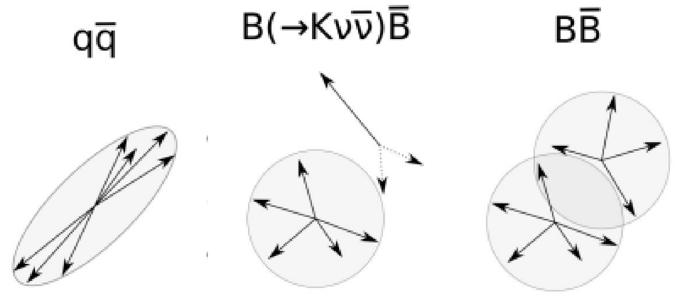

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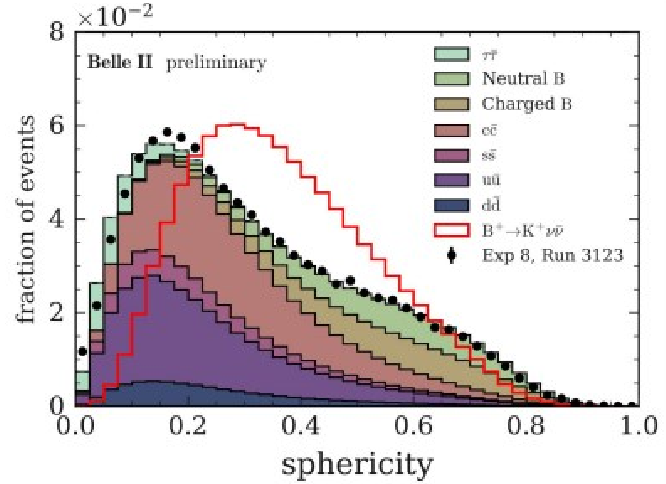
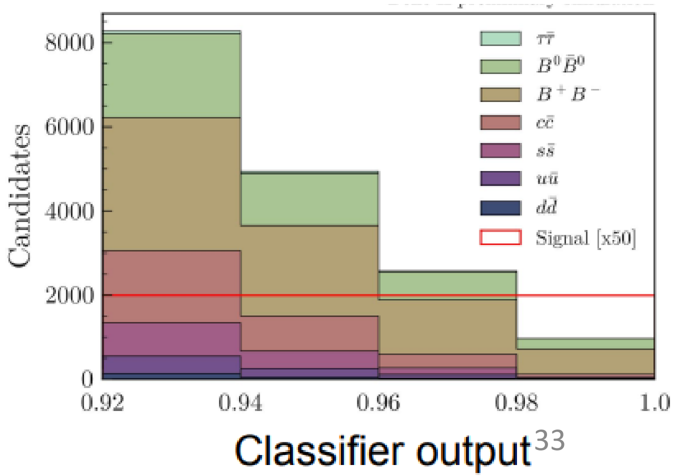
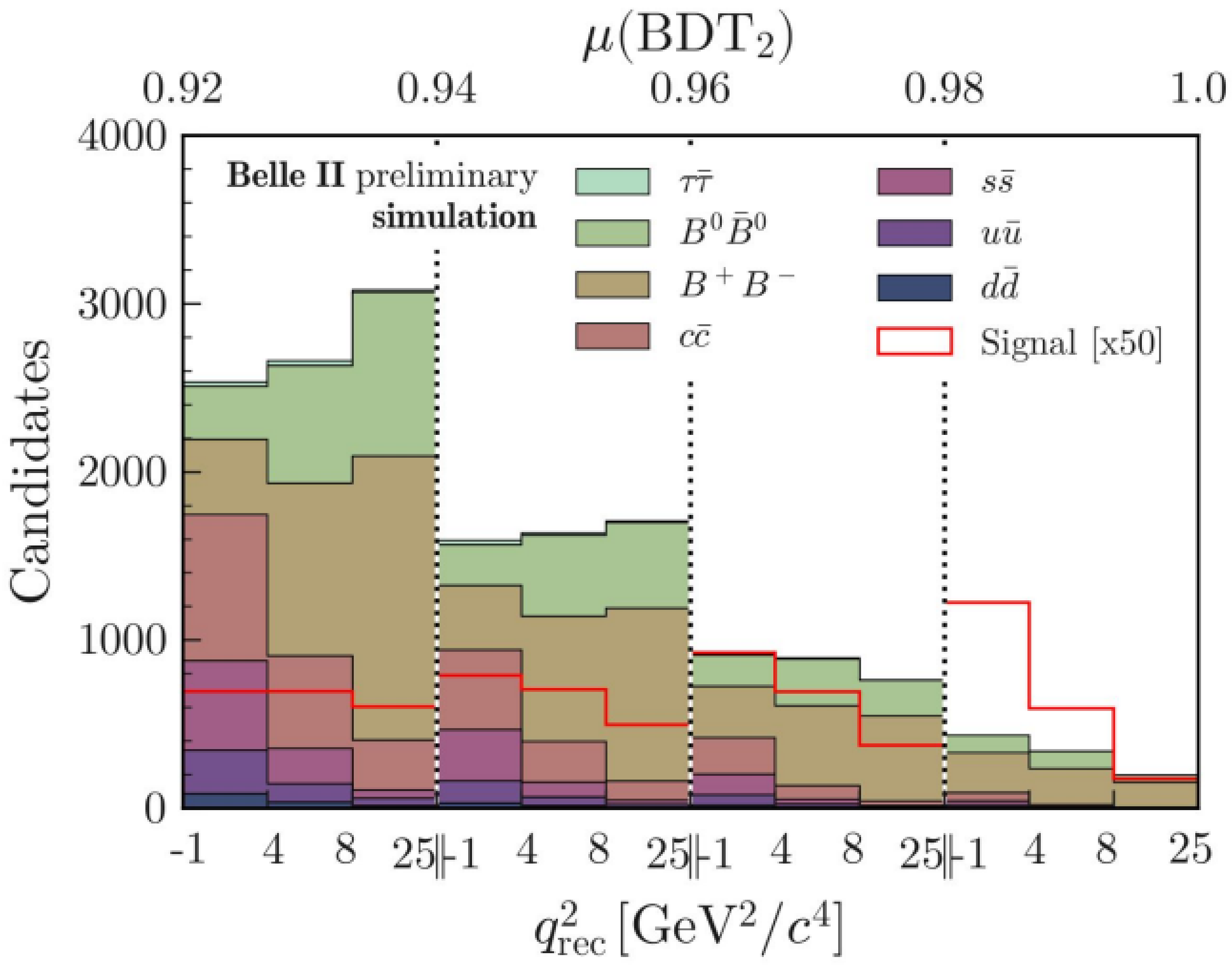
    4. BDT2 fit extraction variable in bins of $\nu\bar{\nu}$ mass-squared – q^2
  - Hadronic tag: single BDT for fit
    - key variable any additional calorimeter energy other than K+tag





$B^+ \to K^+\nu\bar{\nu}$: Inclusive signal extraction



(3 bins in q^2_{rec}) x (4 bins in $\mu(\mathrm{BDT}_2)$)

- 1 signal and 7 background templates from simulation
  - corrected using control samples
- Profile maximum likelihood fit inc. systematic uncertainties
- Continuum template constrained by off-resonance

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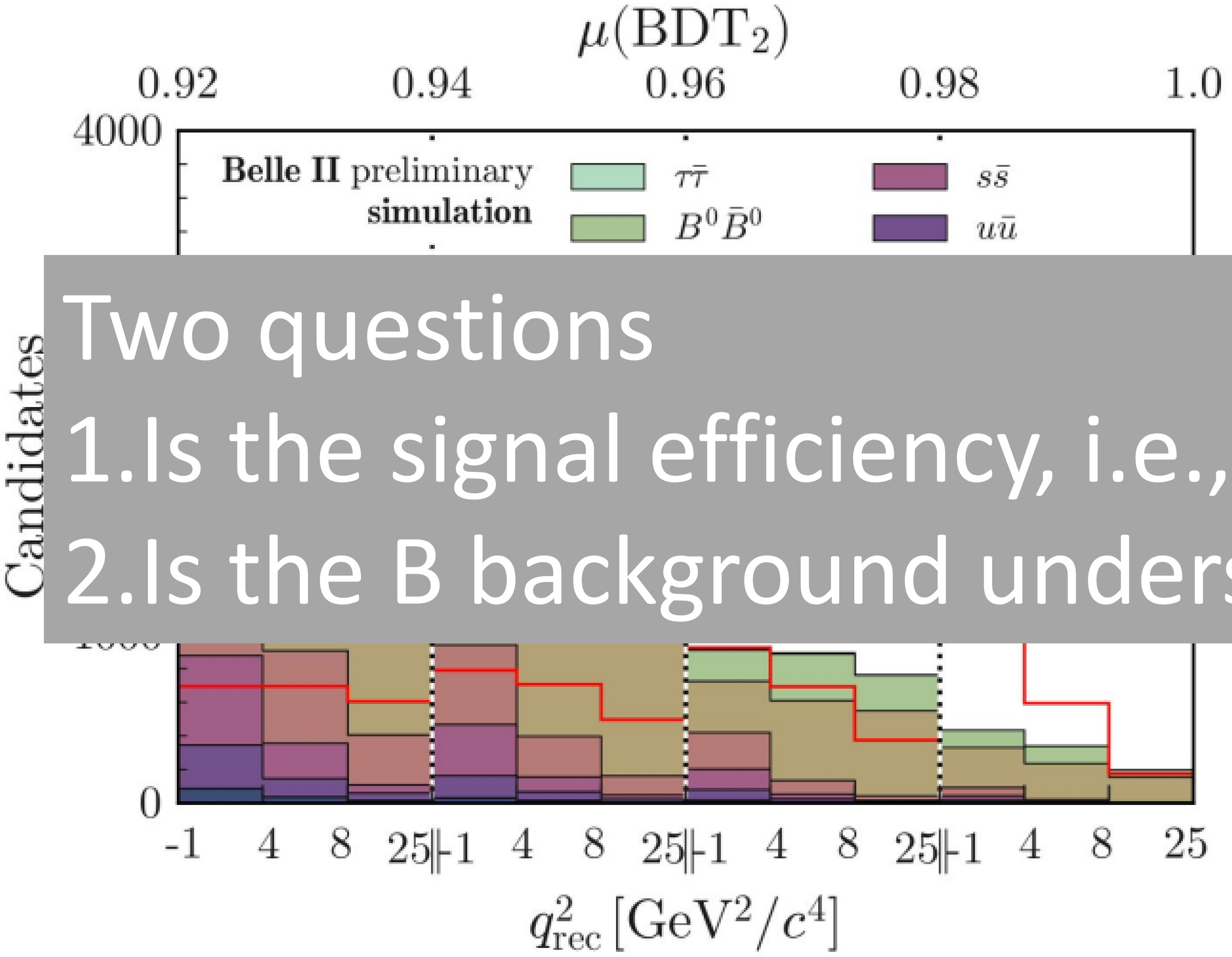

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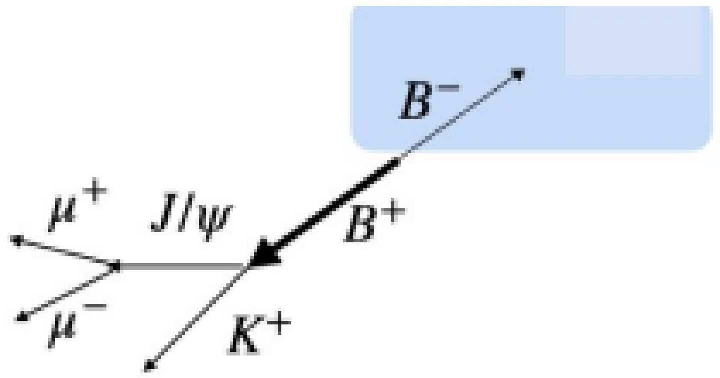
Two questions

1. Is the signal efficiency, i.e., BDT, well modelled?
2. Is the B background understood?

$B^+ \to K^+\nu\bar{\nu}$: Efficiency validation

Rest of the event



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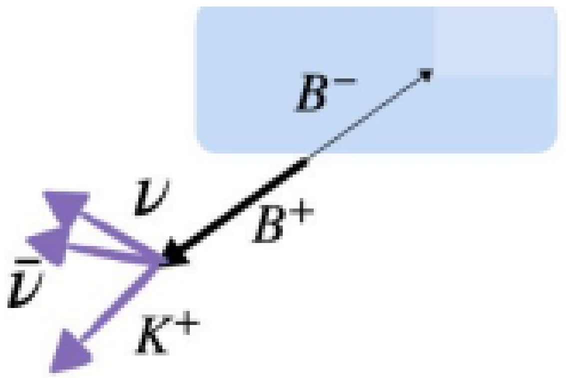
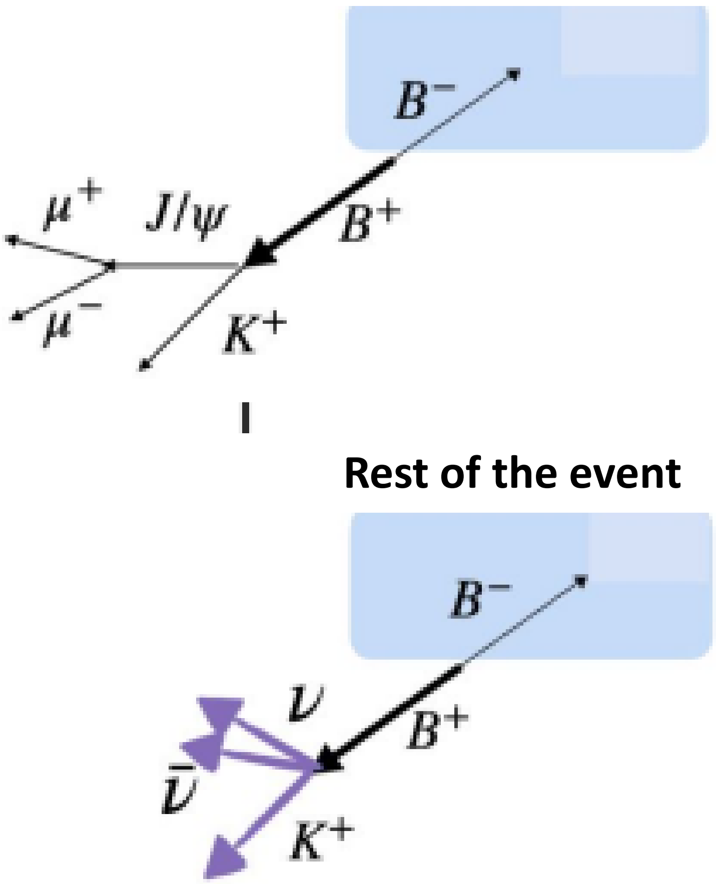
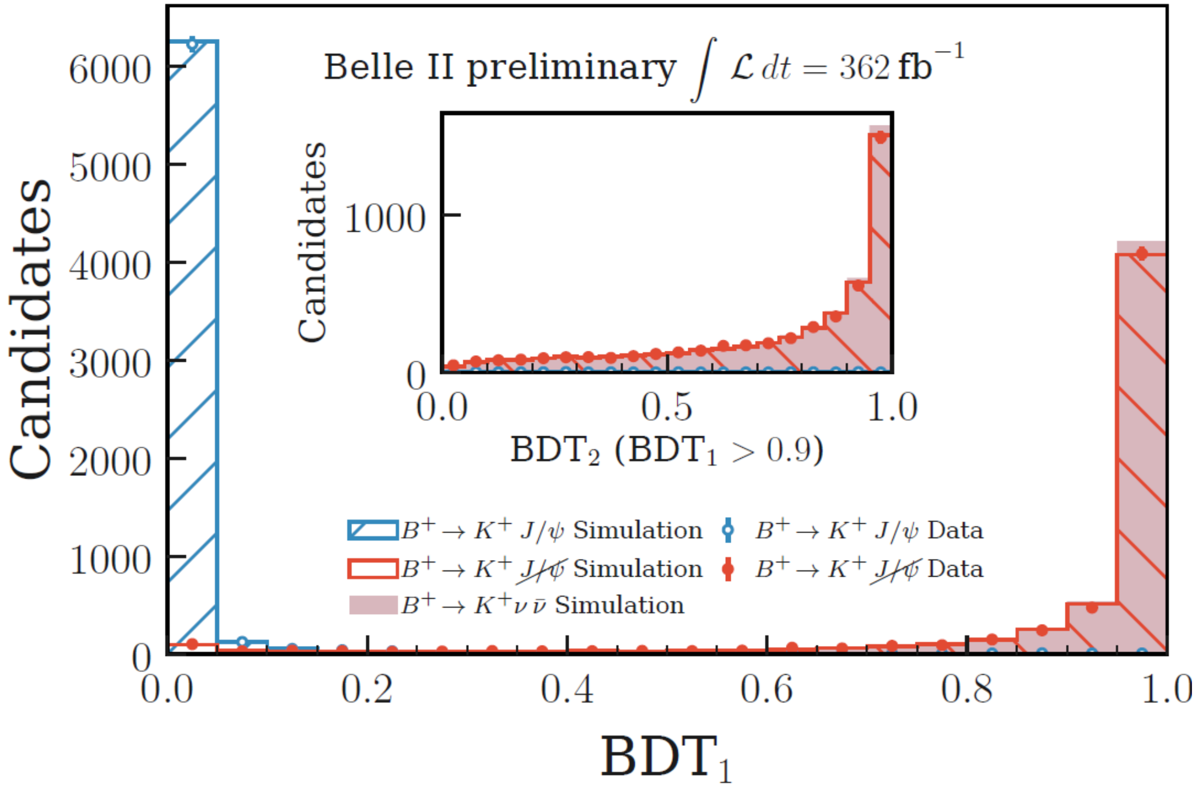


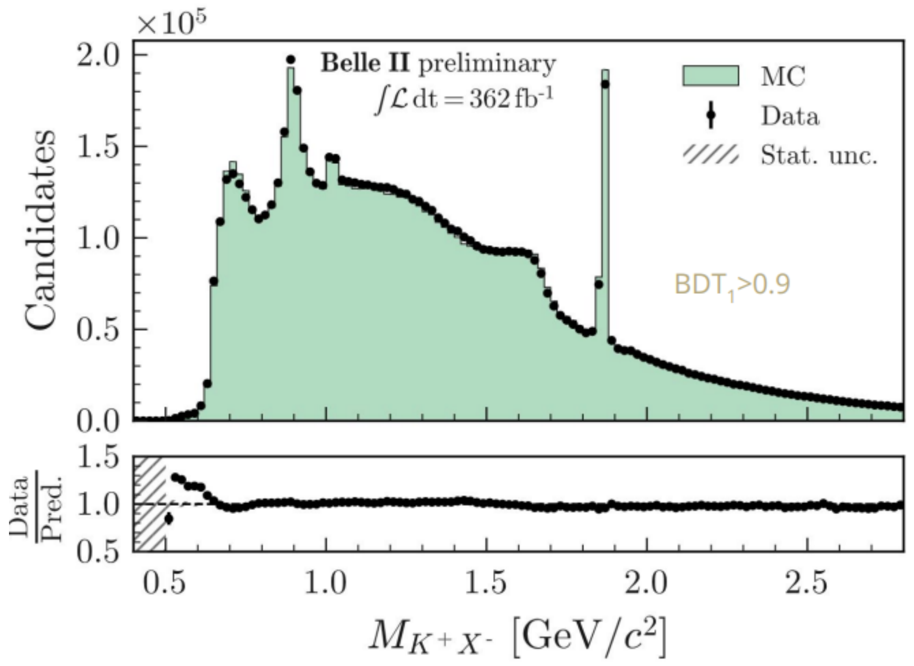
$B^+ \to K^+\nu\bar{\nu}$: Efficiency validation

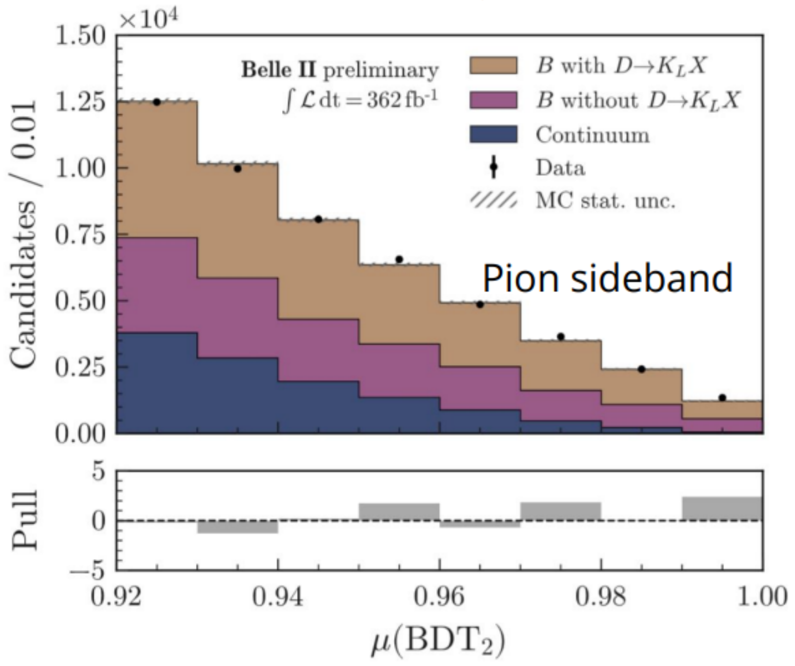




Ratio between selection on data and simulation for the control sample 1 with 3% uncertainty

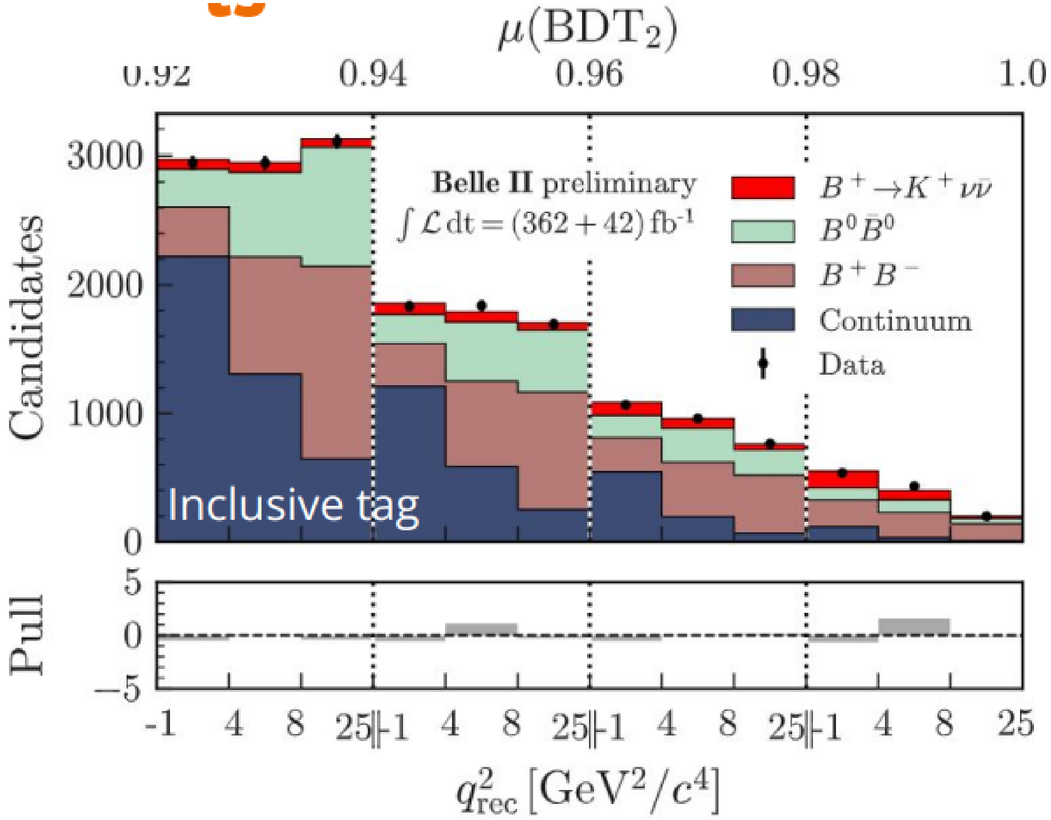
$B^+ \to K^+\nu\bar{\nu}$: >90% background from B→D(K^+X)lν + B →D(K_LX)K^+

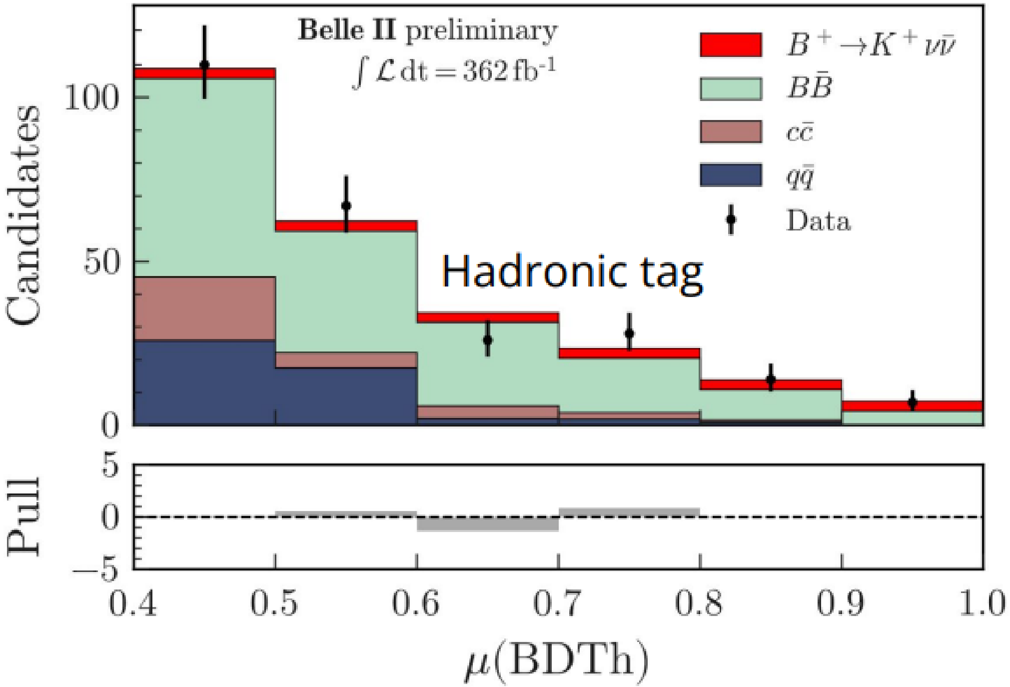




- KX system agrees well between data and MC
- Prompt K^+ production studied using prompt π^+ from $B^+ \to \pi^+X$ decays
- Systematic uncertainties on decay branching fractions, enlarged for D→K_LX and B →D**l ν

$B^+ \to K^+ \nu\bar{\nu}$: Results





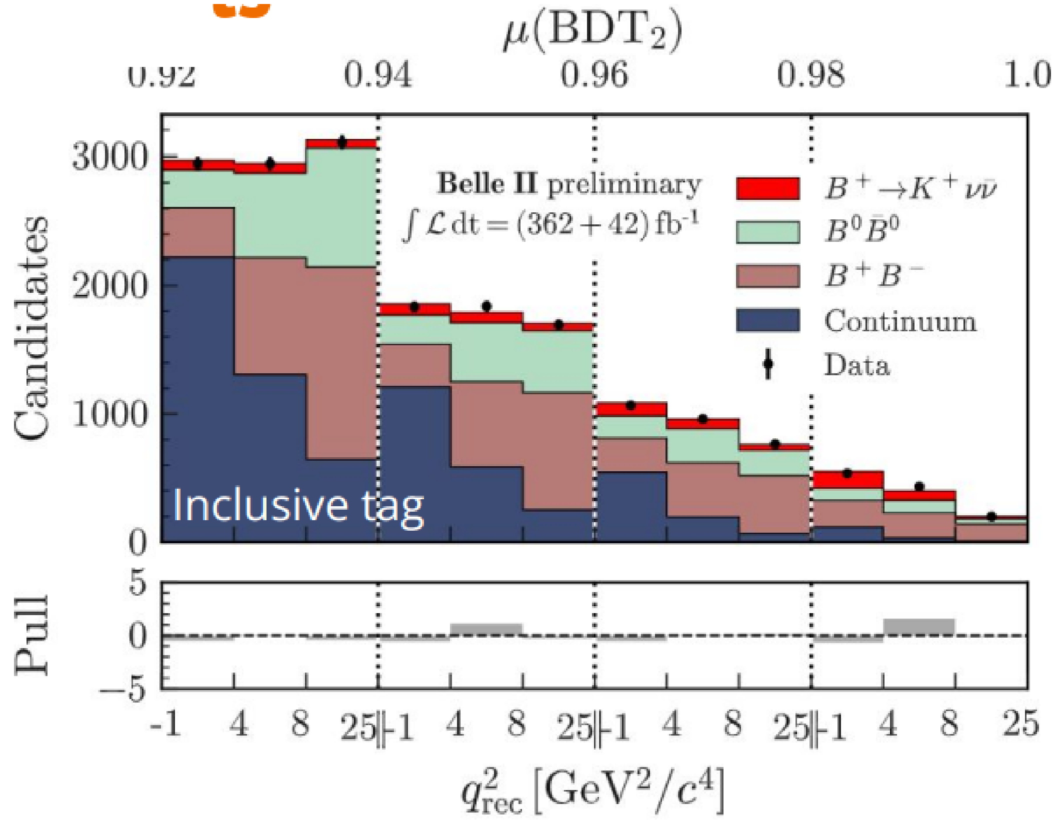
$$\mathrm{BF_{inc}} = (2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-5}$$

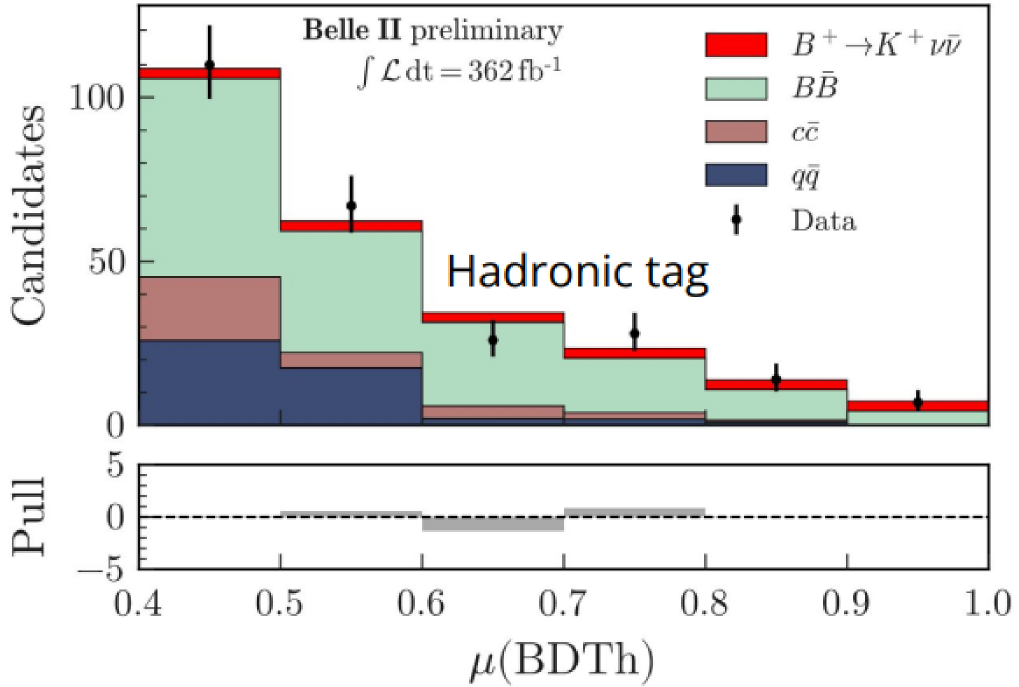
$$\mathrm{BF_{had}} = \left(1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})\right) \times 10^{-5}$$

$$\mathrm{BF_{comb}} = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$$

$B^+ \to K^+ \nu\bar{\nu}$: Results

[Published by PRD](#)
[arXiv:2311.14647](#) [hep-ex]





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$$\mathrm{BF_{comb}} = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}\,(\mathrm{syst})\right) \times 10^{-5}$$

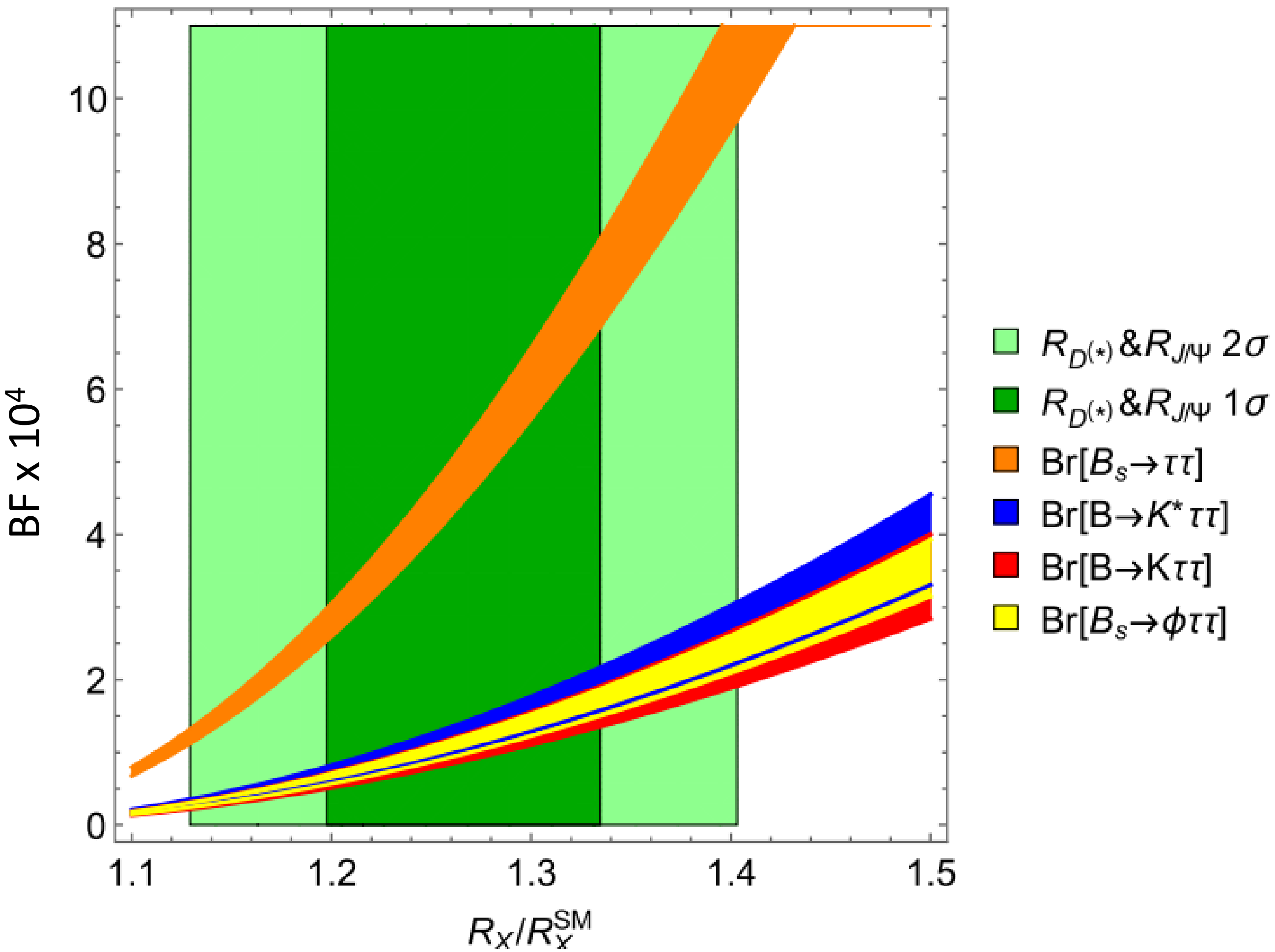
Combined result
Evidence @ 3.5σ
Tension with SM (0.6×10^{-5}) @ 2.7σ

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

Paper in preparation

- Very sensitive to explanations of the other anomalies
  - SM branching fraction prediction 10^{-7}

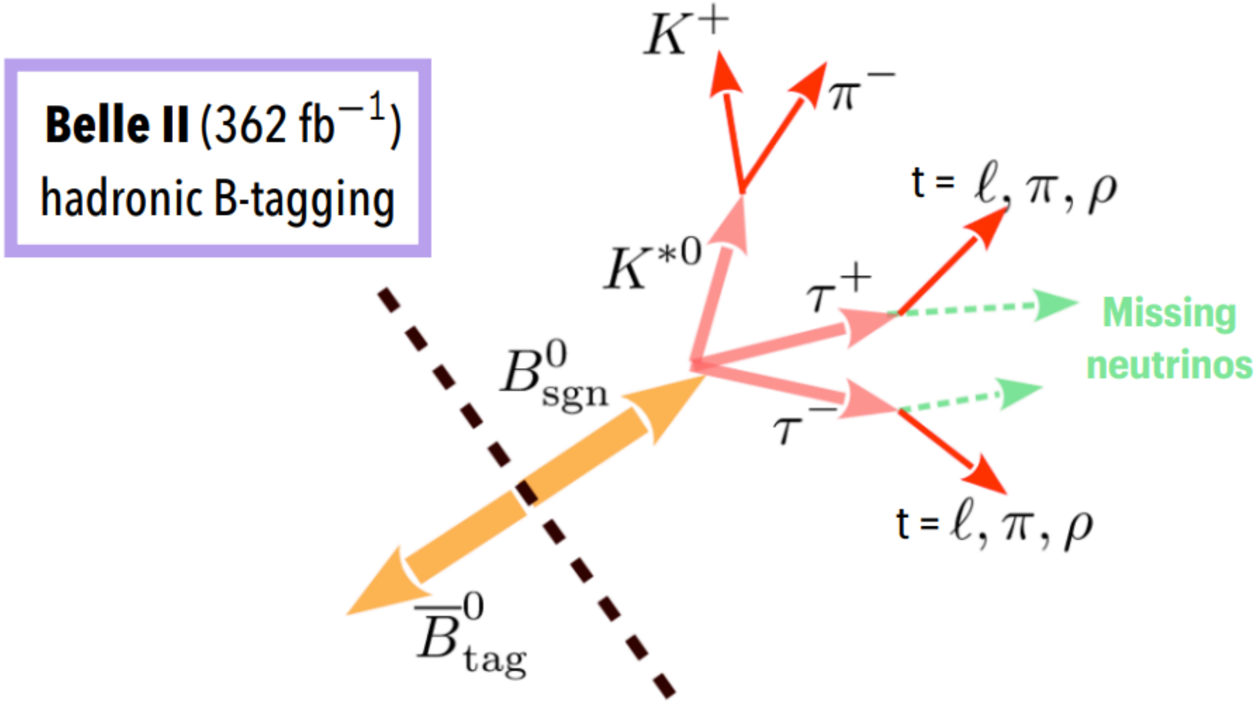
PRL **120**, 181802 (2018)



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

Paper in preparation

- Very sensitive to explanations of the other anomalies
  - SM branching fraction prediction 10^{-7}
- Hadronic B tagging
- Different of classes of tau decay
  - Missing energy, no additional energy in calorimeter,… into a **classifier that is fit to extract yield**
- Limit twice improved over Belle

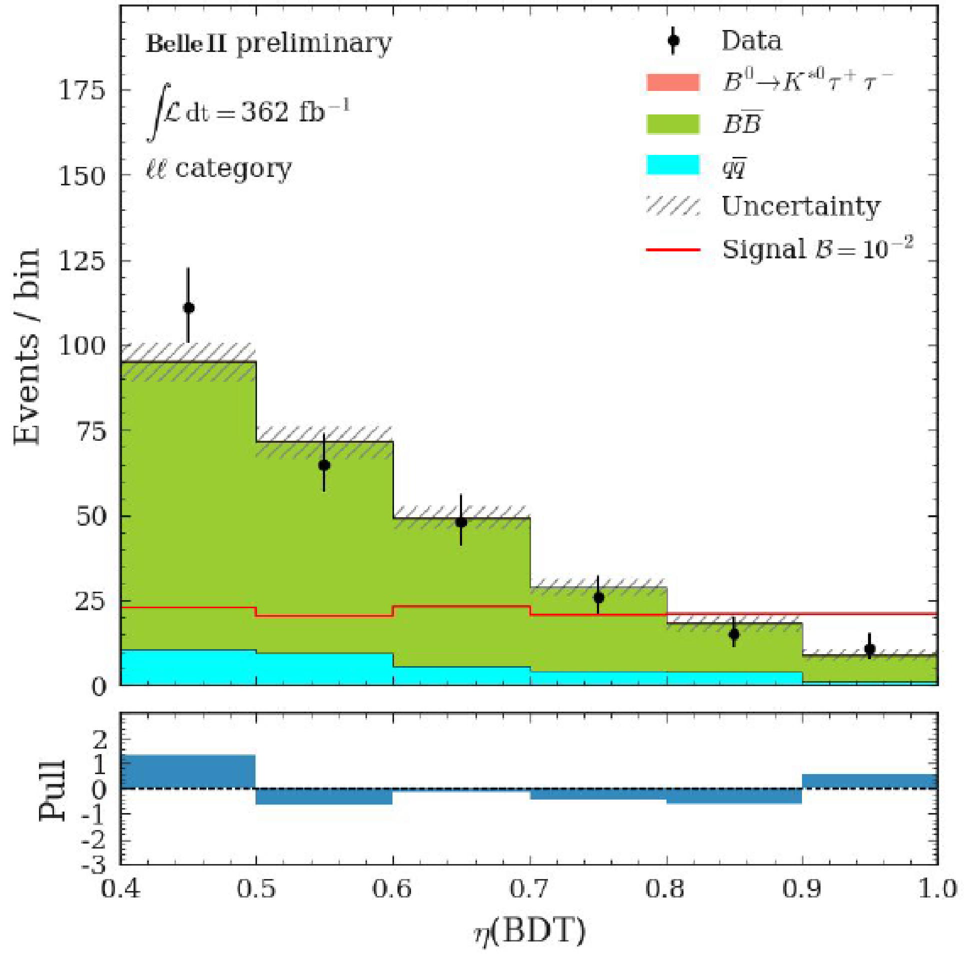


$B^0 \to K^{*0}\tau^+\tau^-$

Paper in preparation
NEW FOR ICHEP

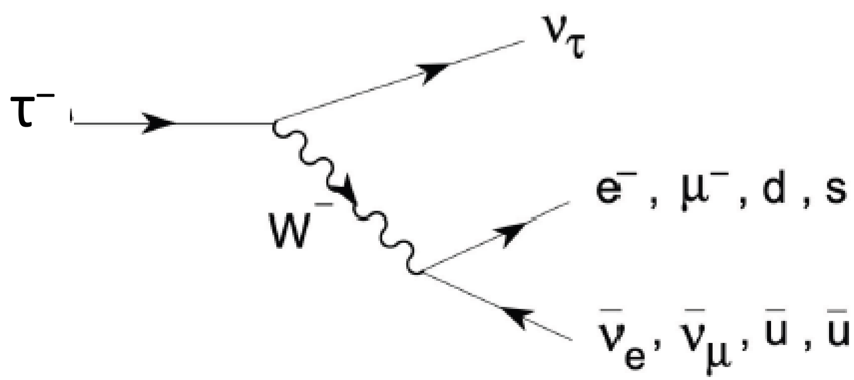
Talk by M. Liu

- Very sensitive to explanations of the other anomalies
  - SM branching fraction prediction 10^{-7}
- Hadronic B tagging
- Different of classes of tau decay
  - Missing energy, no additional energy in calorimeter,… into a **classifier that is fit to extract yield**
- **Limit twice improved over Belle**
  - **Improved tagging and signal efficiency**



$$BF(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$$ at 90% CL

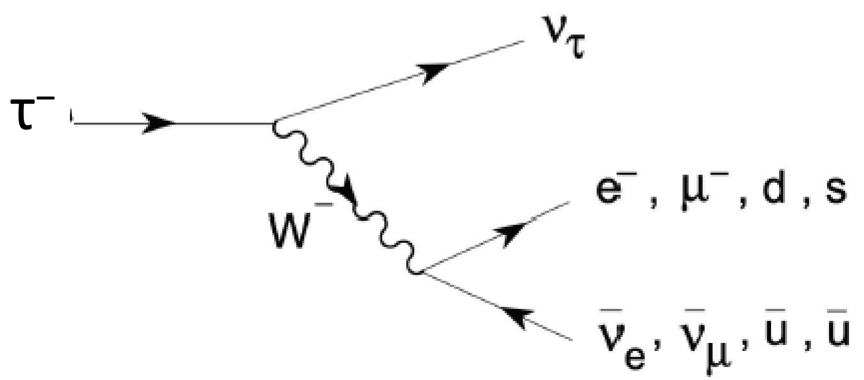
Tau physics motivation I

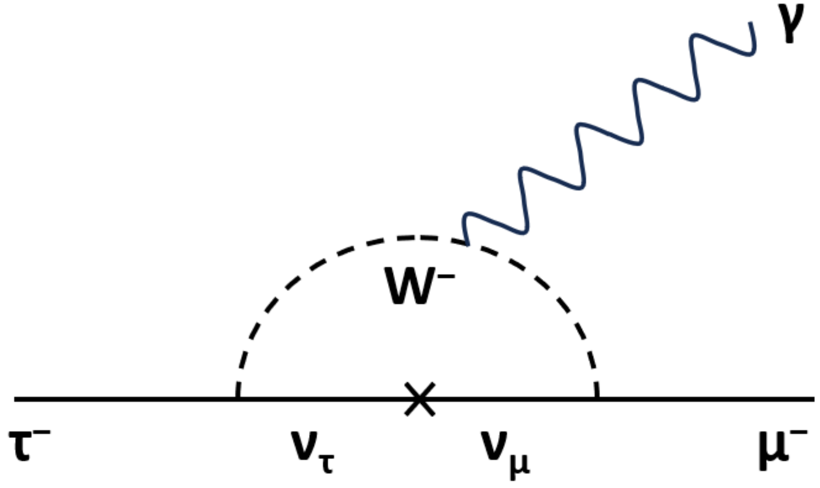


- 185 standard model decay modes studied
    - **principally hadronic final states**
- Unique laboratory to study weak interaction

Tau physics motivation I

- 185 standard model decay modes studied
  - **principally hadronic final states**
- Unique laboratory to study weak interaction
- Third-generation therefore beyond-SM-sensitivity anticipated
  - Any observation of lepton-flavour violation in **$\tau \to 3\mu$**, $\tau \to \mu\gamma$, $\tau \to l\phi$ etc **new physics**
  - SM highly suppressed
- Connections to g-2 and lepton universality violation in b decay

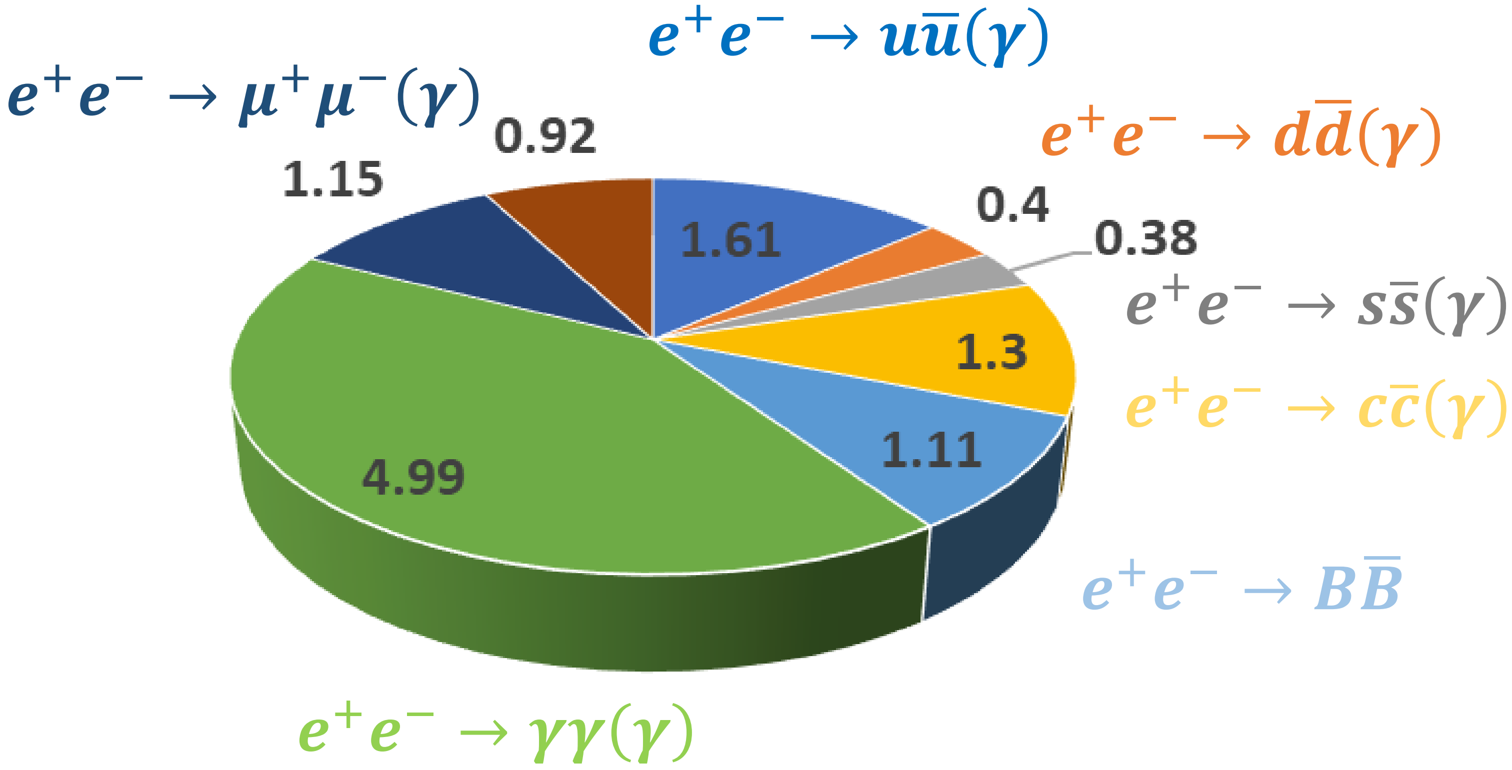




Why τ physics at the $\Upsilon(4S)$?

- The centre-of-mass energy of the B factories process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum

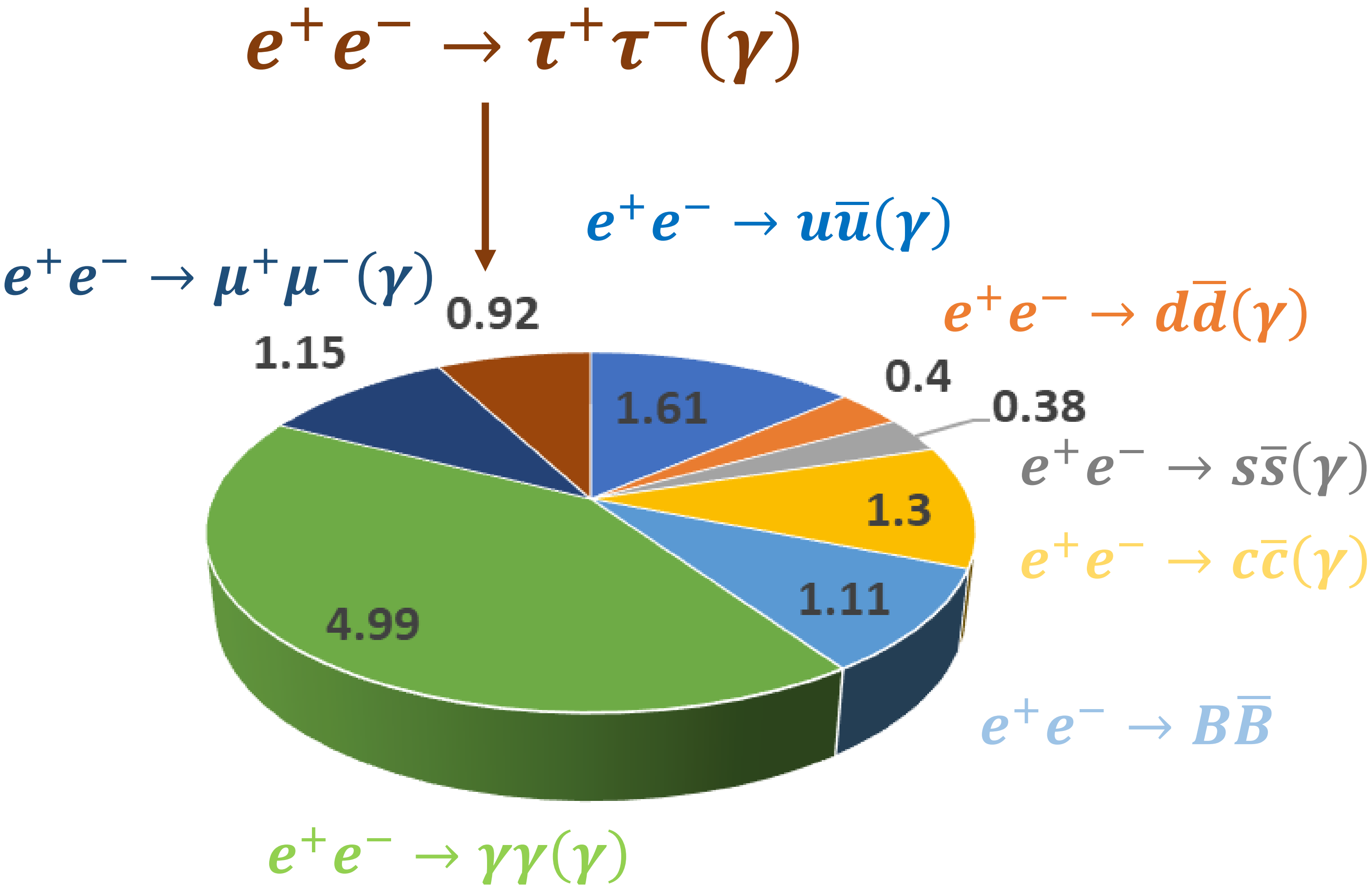
Non Bhabha cross section in nb



Why τ physics at the Υ(4S)?

- The centre-of-mass energy of the B factories process $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ has comparable cross section to $e^+e^- \to q\bar{q}, q = u, d, s, c$ a.k.a. continuum
- Similar cross section for $e^+e^- \to \tau^+\tau^-$
- 920 million tau pairs per ab^{-1} of integrated luminosity

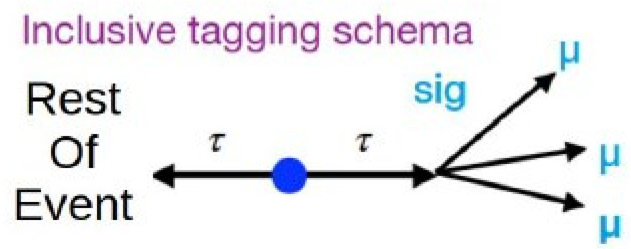
Non Bhabha cross section in nb



Submitted to JHEP
arXiV:2405.07386

$\tau \rightarrow 3\mu$– lepton flavour violation search

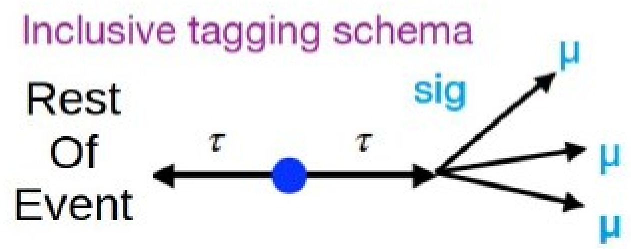
- Inclusive tag of the non-signal τ to increase efficiency – multivariate

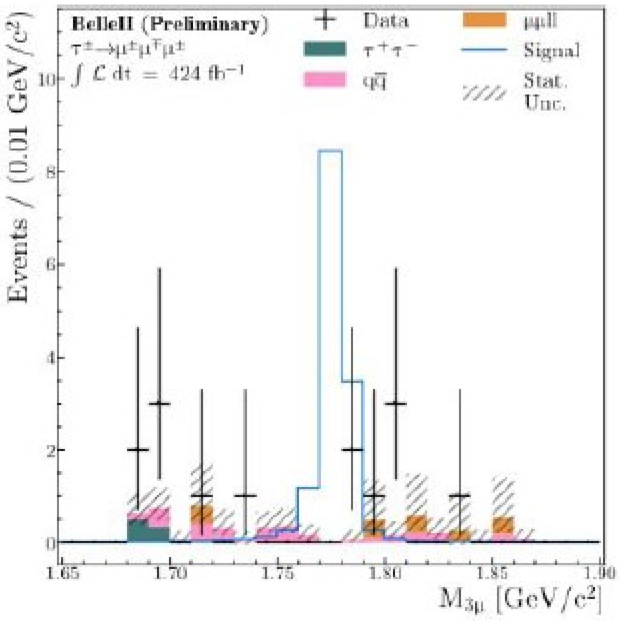


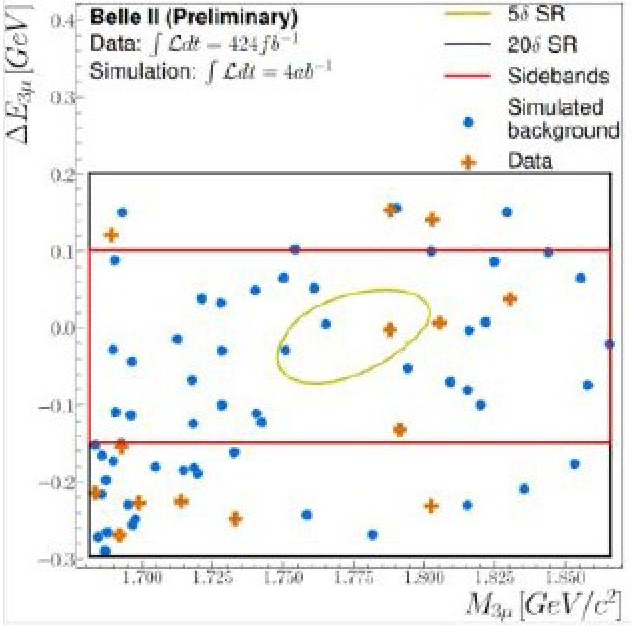
Submitted to JHEP
arXiV:2405.07386

$\tau \rightarrow 3\mu$– lepton flavour violation search

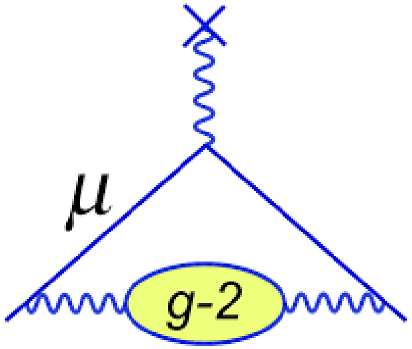
- Inclusive tag of the non-signal τ to increase efficiency – multivariate
- Cut 'n' count in 2D plane of
  - $M_{3\mu}$ and $\Delta E = E_{3\mu} - E_{beam}$ (in c.m.)
  - Sideband derived background estimate $0.5^{+1.4}_{-0.5}$ events
- One event observed
- World best limit
  - **BF < 1.9×10^{-8} (90% c.l.)**
- Area of competition
  - LHCb BF < 4.1×10^{-8} (Run 1 only)
  - CMS BF < 2.9×10^{-8} (Run 1+2)

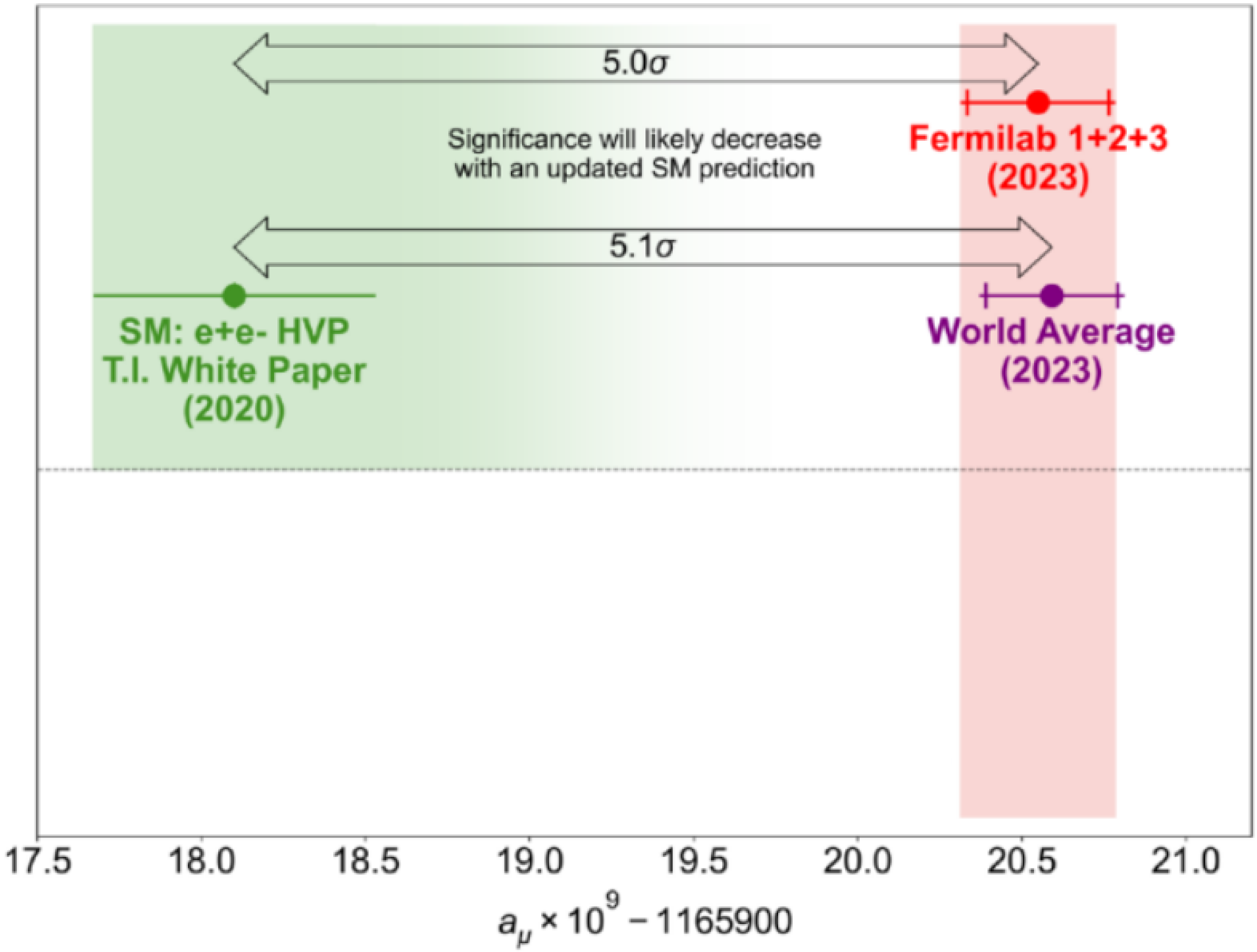






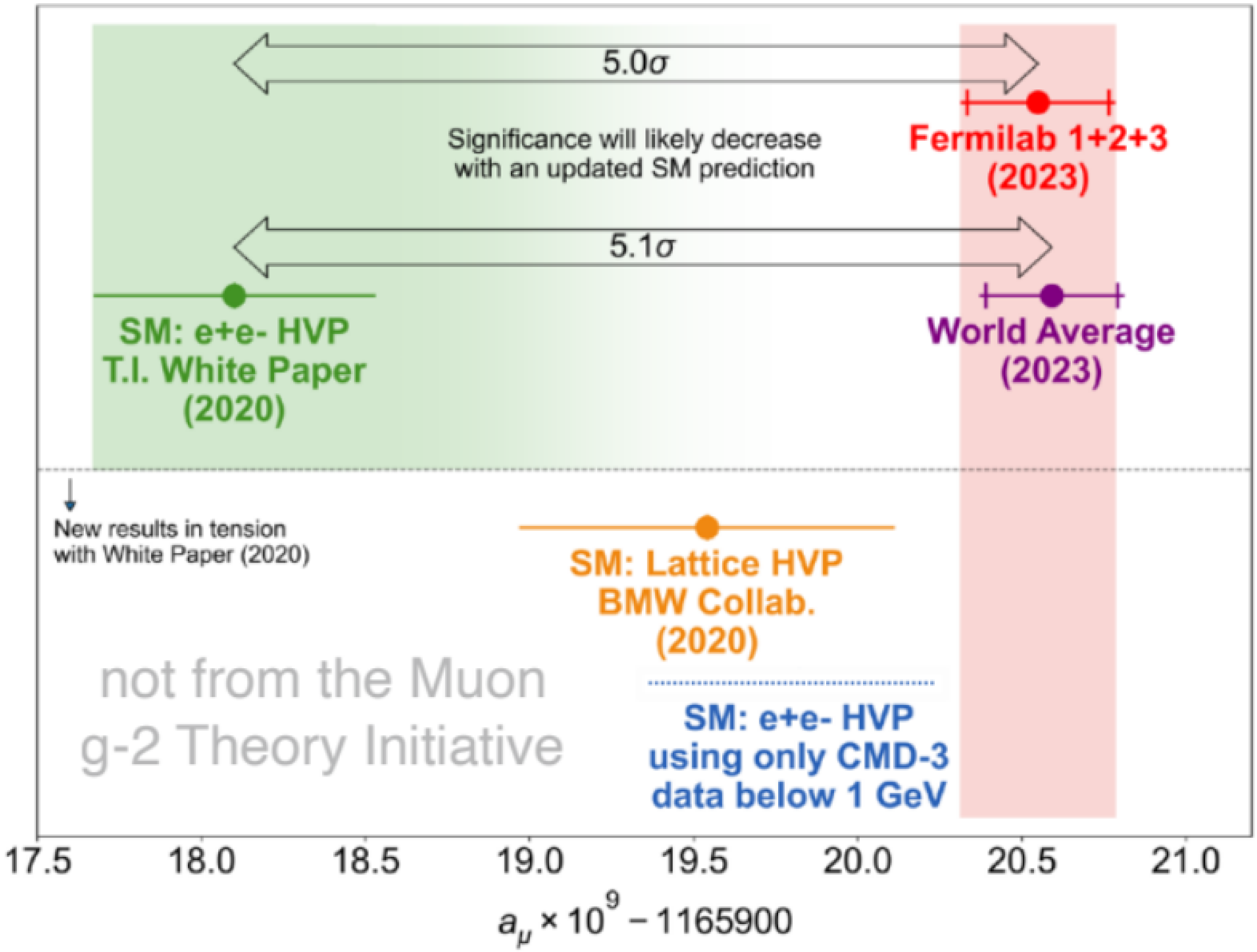
…away from heavy flavour muon g−2





Plot from A. Keshavarzi talk at Lattice 2023

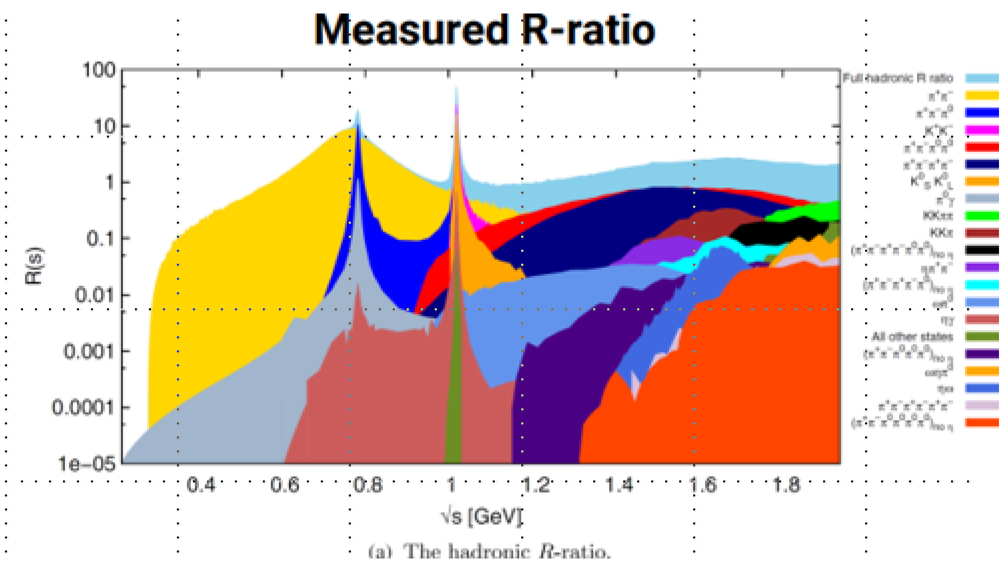
...away from heavy flavour muon g–2



Plot from A. Keshavarzi talk at Lattice 2023

$\sigma(e^+e^- \to \pi^+\pi^-\pi^0)$

[arXiv:2404.04915](https://arxiv.org/abs/2404.04915) [hep-ex]



Muon anomalous magnetic moment

$$a_\mu = \frac{g-2}{2} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{QCD}}$$

Hadron contribution term

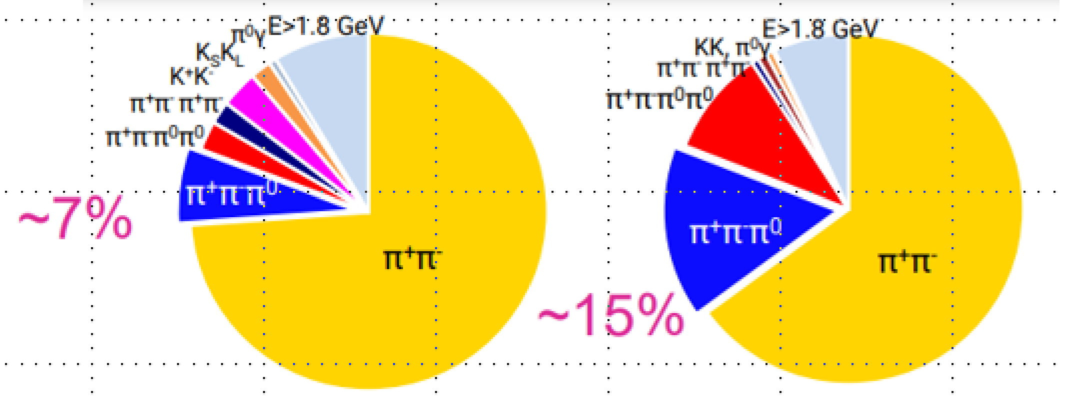
$$a_\mu^{\mathrm{QCD}} = a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}}$$

Leading-order HVP rerm

$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{ds}{s}R(s)K(s)$$

Hadronic R-ratio

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



2nd largest contribution to the hadronic vacuum polarization estimate as region below 1 GeV in c.m. energy dominates

$\boldsymbol{\sigma(e^+e^- \to \pi^+\pi^-\pi^0)}$

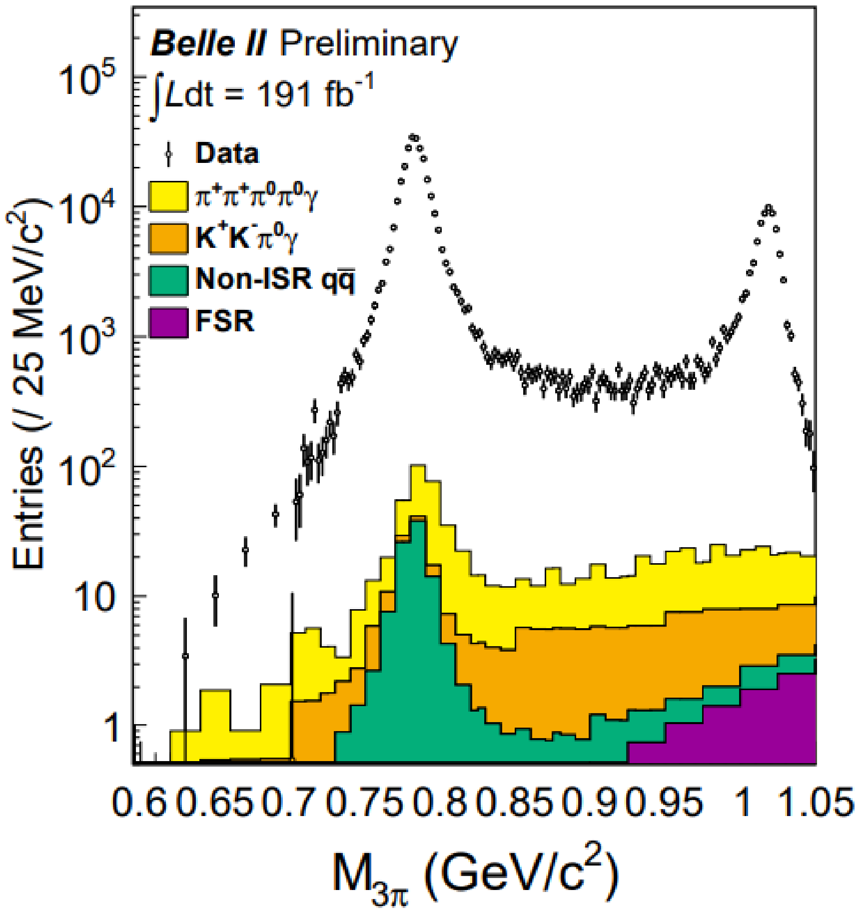
Signal process : $e^+e^- \to \gamma_{\mathrm{ISR}}\pi^+\pi^-\pi^0(\to \gamma\gamma)$

Signal spectrum **Efficiency**

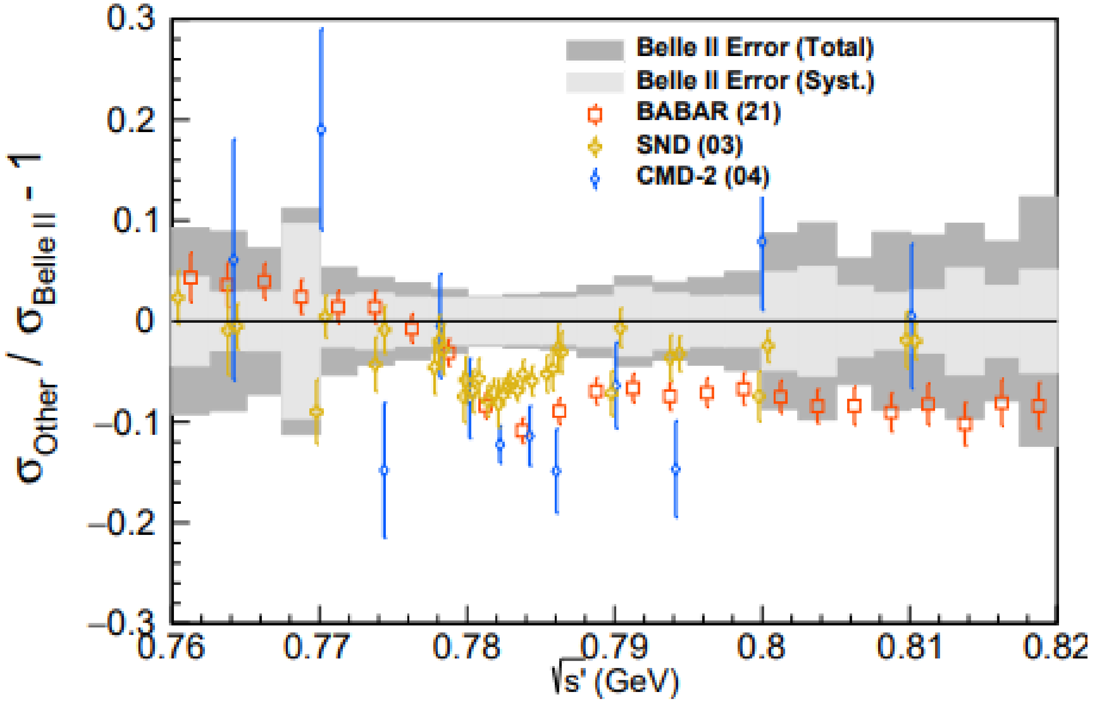
$$\frac{dN_{\mathrm{signal}}}{dm} = \sigma_{ee\to 3\pi} \cdot \varepsilon \cdot \frac{d\mathcal{L}_{\mathrm{eff}}}{dm}$$

3π mass **Cross section** **Effective luminosity**

- Initial-state radiation technique – wide invariant mass range
- Partial Run 1 data set – 191 fb^{-1}
- Selection via kinematic fits
- Key challenge is π^0 efficiency
  - Custom determination using ω decay
- Background control samples for $e^+e^- \to \pi^+\pi^-\pi^0\,\pi^0\gamma_{ISR}$, $e^+e^- \to q\bar{q}\gamma_{ISR}$ and $e^+e^- \to K^+K^-\pi^0\gamma_{ISR}$



$\sigma(e^+e^- \rightarrow \pi^+\pi^-\pi^0)$



Source	0.62–1.05 GeV/c^2	
Trigger	0.1	(−0.09)
ISR photon detection	0.7	(+0.15)
Tracking	0.8	(−1.35)
π^0 detection	1.0	(−1.43)
Kinematic fit (χ^2)	0.6	(+0.0)
Event selection	0.2	(−1.90)
Generator	1.2	
Integrated luminosity	0.6	
Radiative corrections	0.5	
MC statistics	0.2	
Background subtraction	0.3–0.5	
Unfolding	0.7–15	
Total uncertainty	2.2-15	
(Total correction $\varepsilon/\varepsilon_{MC} - 1$)		(−4.61)

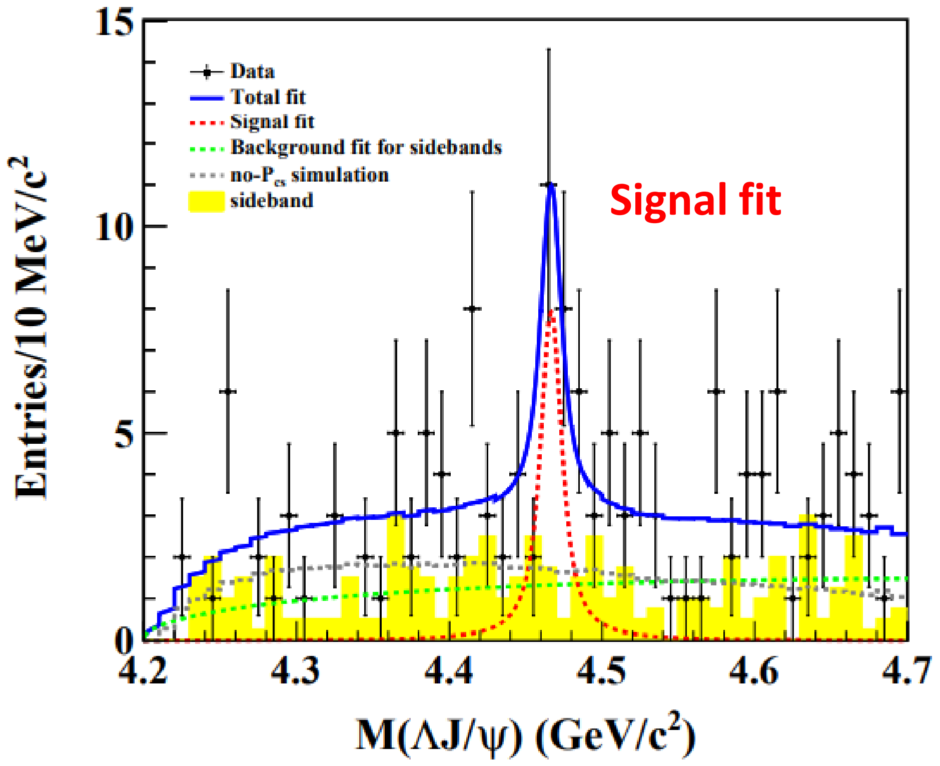
$$a_\mu^{3\pi} = (49.02 \pm 0.23 \pm 1.07) \times 10^{-10},$$

2.6σ tension with BaBar

Evidence for $P_{cs}(4459)$

Paper in preparation

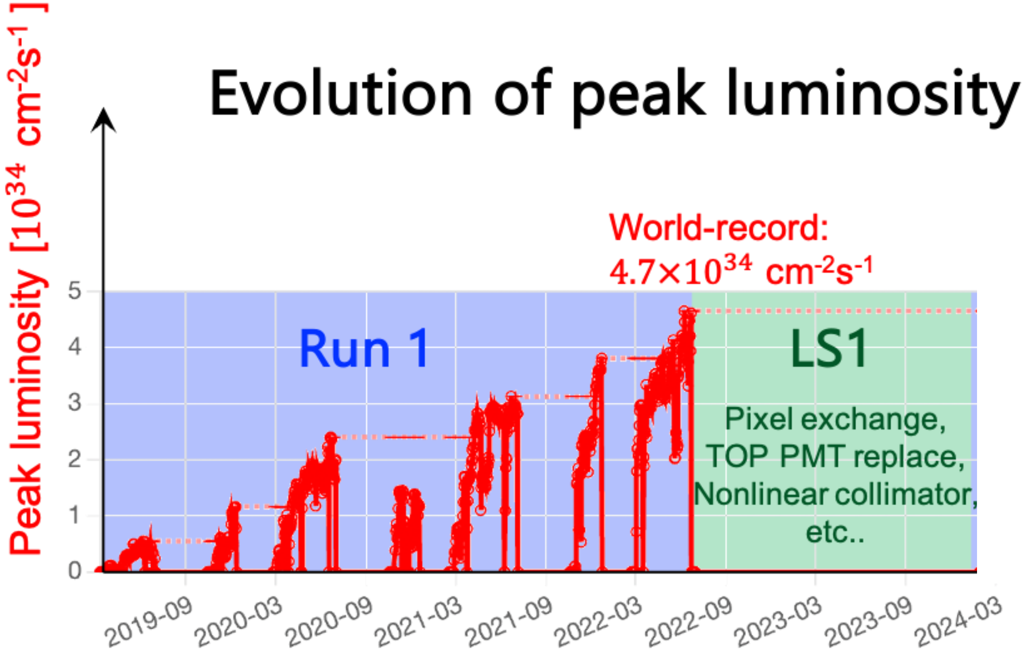
- OZI suppressed decays of Υ(1S) and Υ(2S) rich in gluons
  - enhanced baryon production
  - **pentaquark production?**
- Measure inclusive $\Upsilon(1S,2S)\rightarrow J/\psi\Lambda + X$ decays in the Belle sample
- Search $m(J/\psi\Lambda)$ for pentaquark signal
  - **background from sideband and off resonance**
- Use LHCb mass and width from their evidence in Ξ_b decay - [Sci. Bulletin **66**, 1278 (2021)]
  - **3.3 standard deviation significance**
  - free mass and width 4 standard deviation local significance

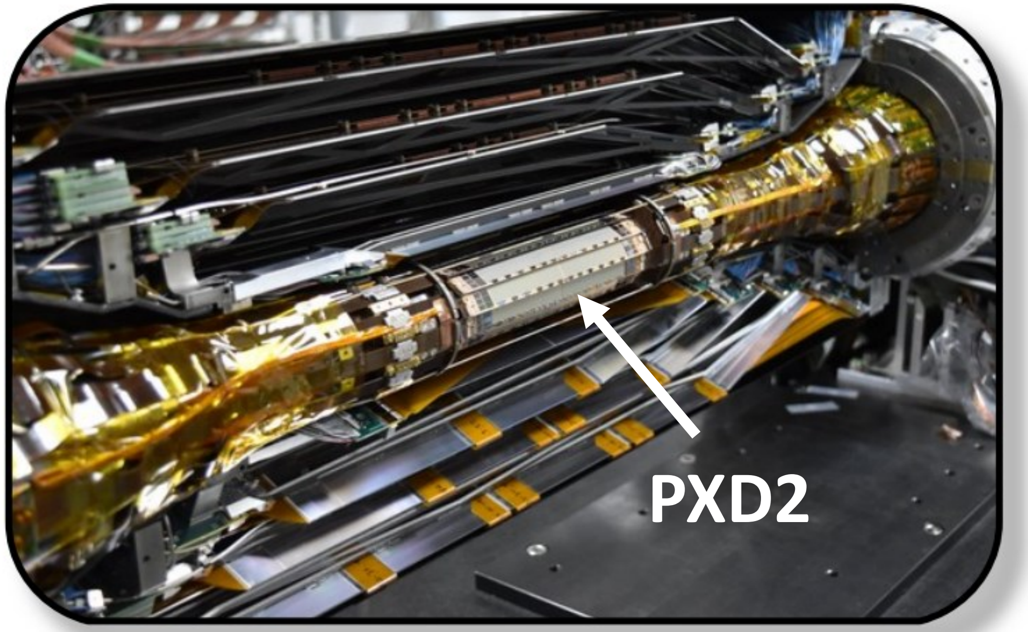


Part III: the future

Belle II and SuperKEKB prospects

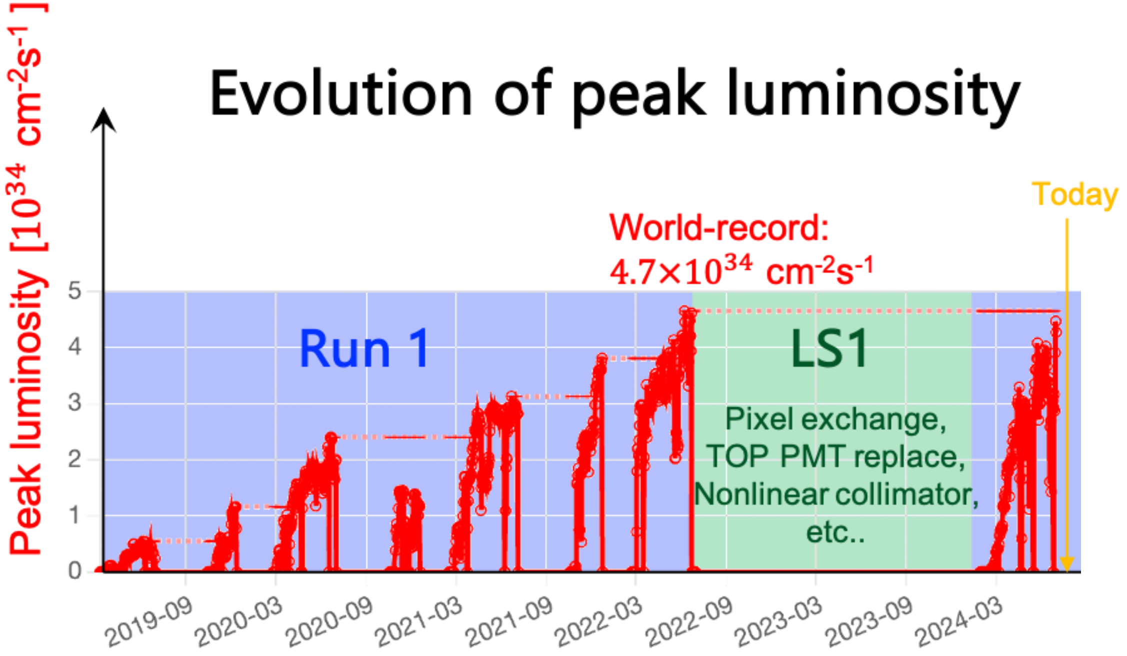
SuperKEKB/Belle II status and plans

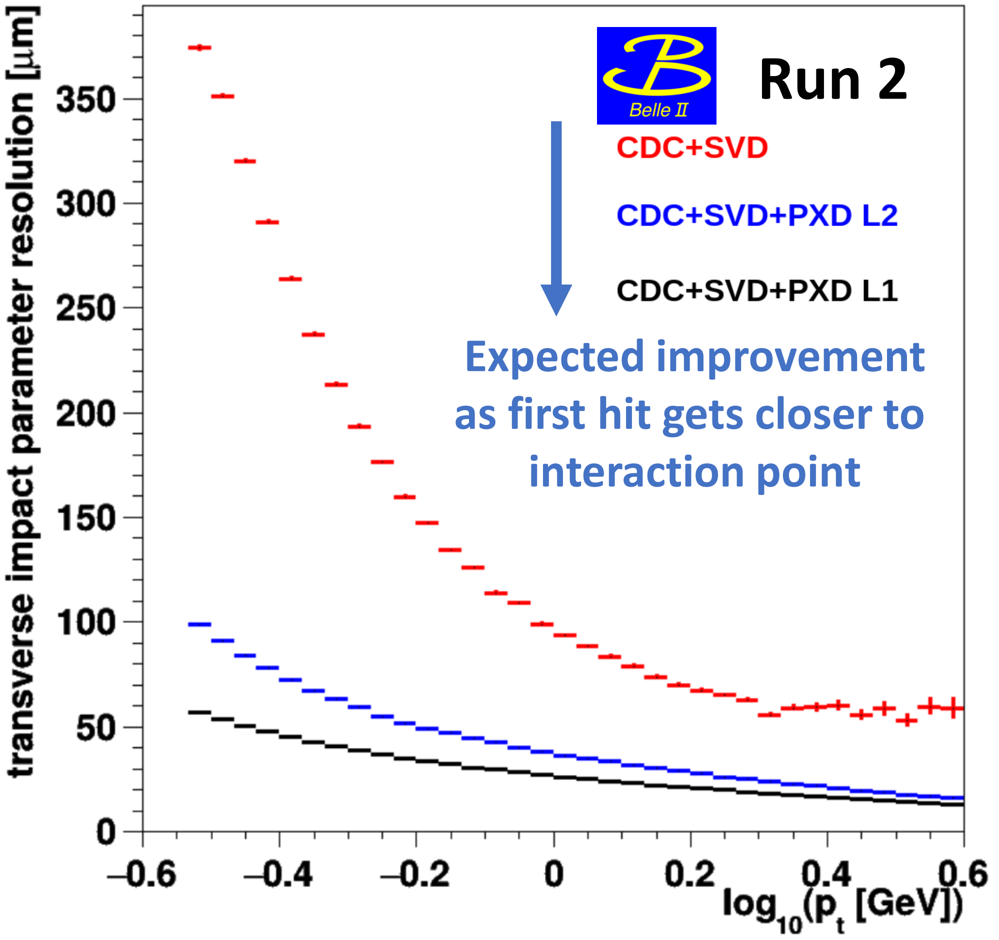




- Run 1 (2019-2022) – **similar data set to 1st generation B factory**
- Long shutdown 1 – LS1 (2022-2024)
  - detector improvements – mainly installation of full **two-layer pixel detector** (PXD2)
  - accelerator improvements, e.g., non-linear collimators to combat beam background

SuperKEKB/Belle II status and plans

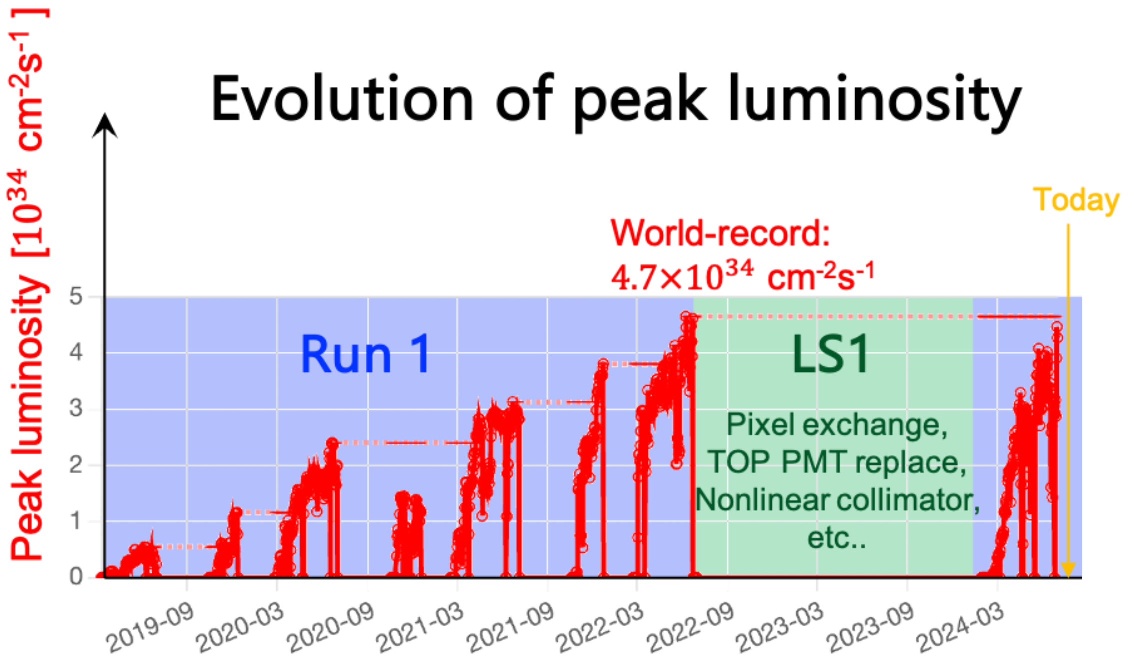




- Run 2 (2024 –)
  - back to operation at $4 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$
  - detector performance as before or better
  - ….but the goal in this run is luminosity of **$\sim 10^{35}\,\mathrm{cm^{-2}s^{-1}}$**

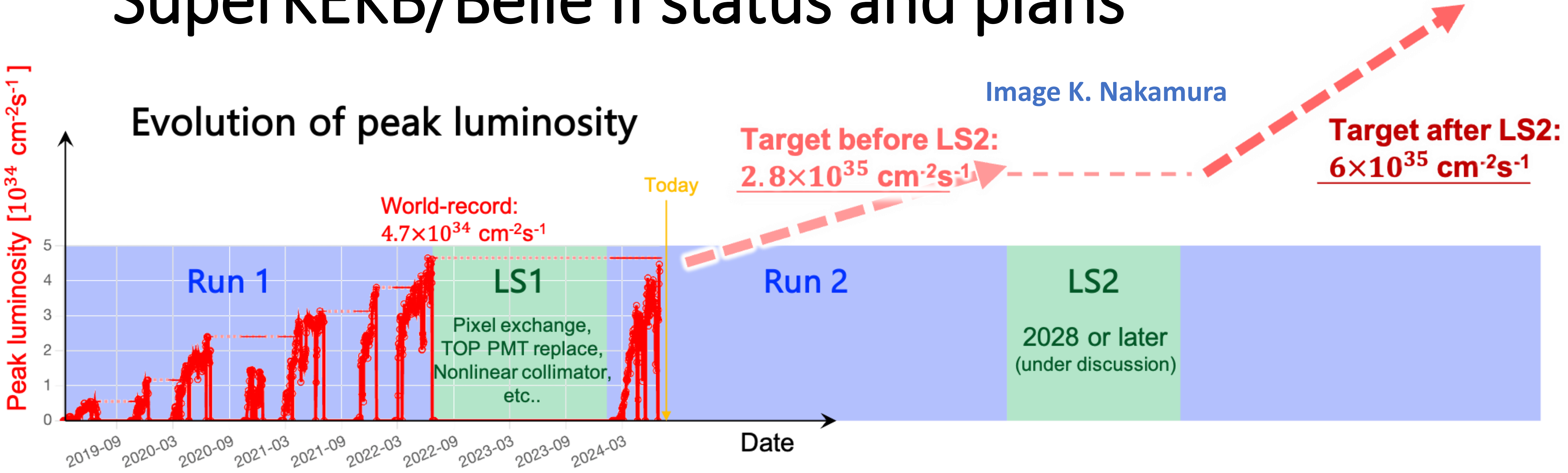
SuperKEKB/Belle II status and plans

ICHEP talk
by K. Shibata



- Run 2 (2024 –)
  - Sudden beam loss has happened frequently that can lead to v. large dose in the detector
    - Hampering increasing luminosity
  - Two such losses led to damage of 2% of PXD2 gates
    - **turned off PXD2 as a precautionary measure until beam losses mitigated**
  - So far Run 2 has been largely dedicated to machine studies
    - only ~100 fb^{-1} collected
  - **Some understanding of how the losses start**
    - remediation in summer shutdown

SuperKEKB/Belle II status and plans



- Run 2 is long – end 2028 or later
  - Steady accumulation at ~2 x 10^{35} $cm^{-2}s^{-1}$ for several ab^{-1} – 2nd generation
  - After Run 2 – upgrade proposal for reach design luminosity and tens of ab^{-1}
    - Framework CDR arXiv:2406.19421

Conclusion

- A brief tour of the why and current Belle II physics
  - Highlights: Kνν, K*ττ, CP violation and tau/low multiplicity physics

- Lot's more to be done with the Run 1 data + Belle

- Life at the intensity frontier is hard but hopefully we will enter the 10^{-35} $cm^{-2}s^{-1}$ era soon in Run 2

Backup

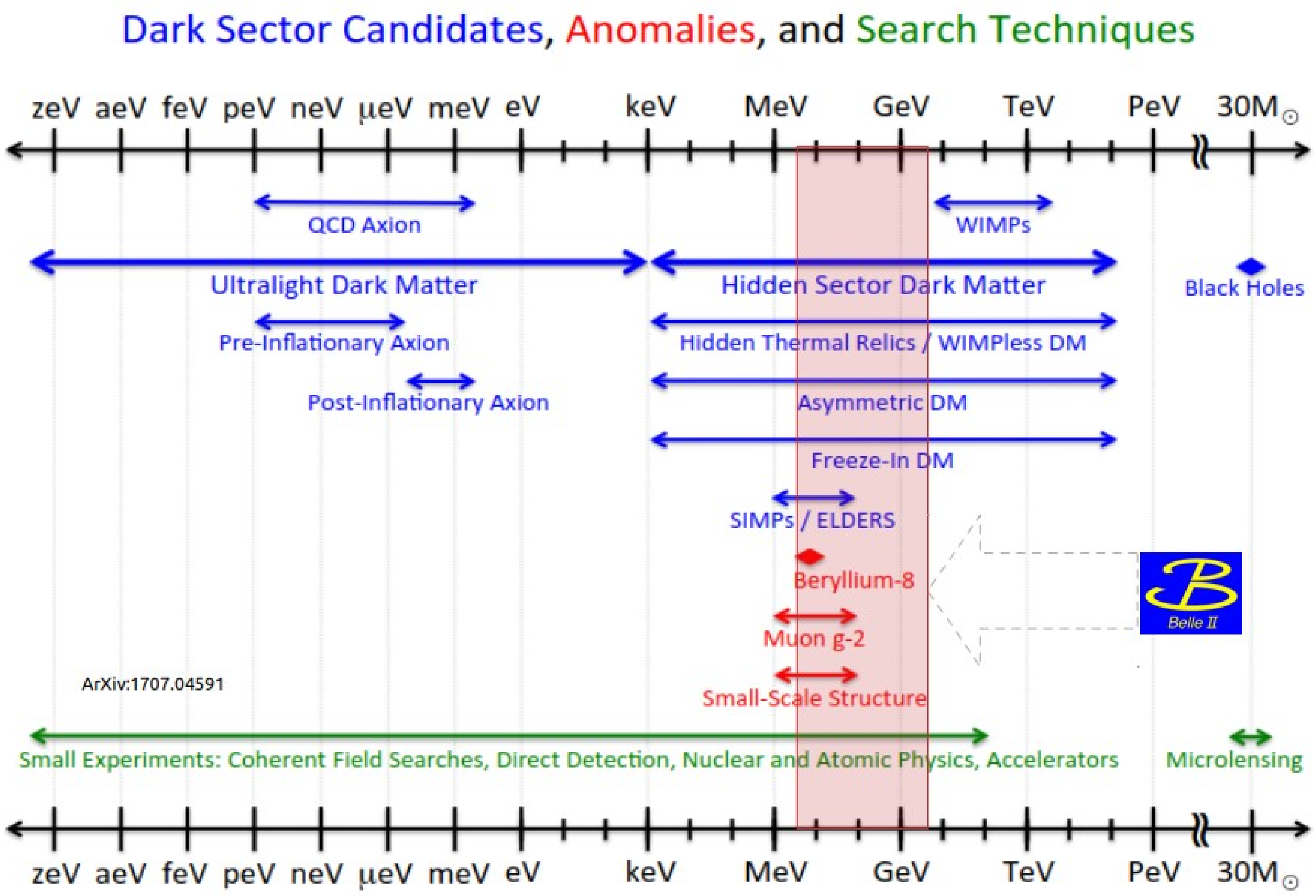
Belle II upgrade

Belle III + ChiralSuperKEKB > 2030+

- Many plans and possibilities
- Work on a Conceptual Design Report begun to be delivered in 2023
- Followed by a Technical Design Report in 2024
- Shutdown end of 2028 or later for installation
- Accumulate 10s of ab^{-1} into the 2030s

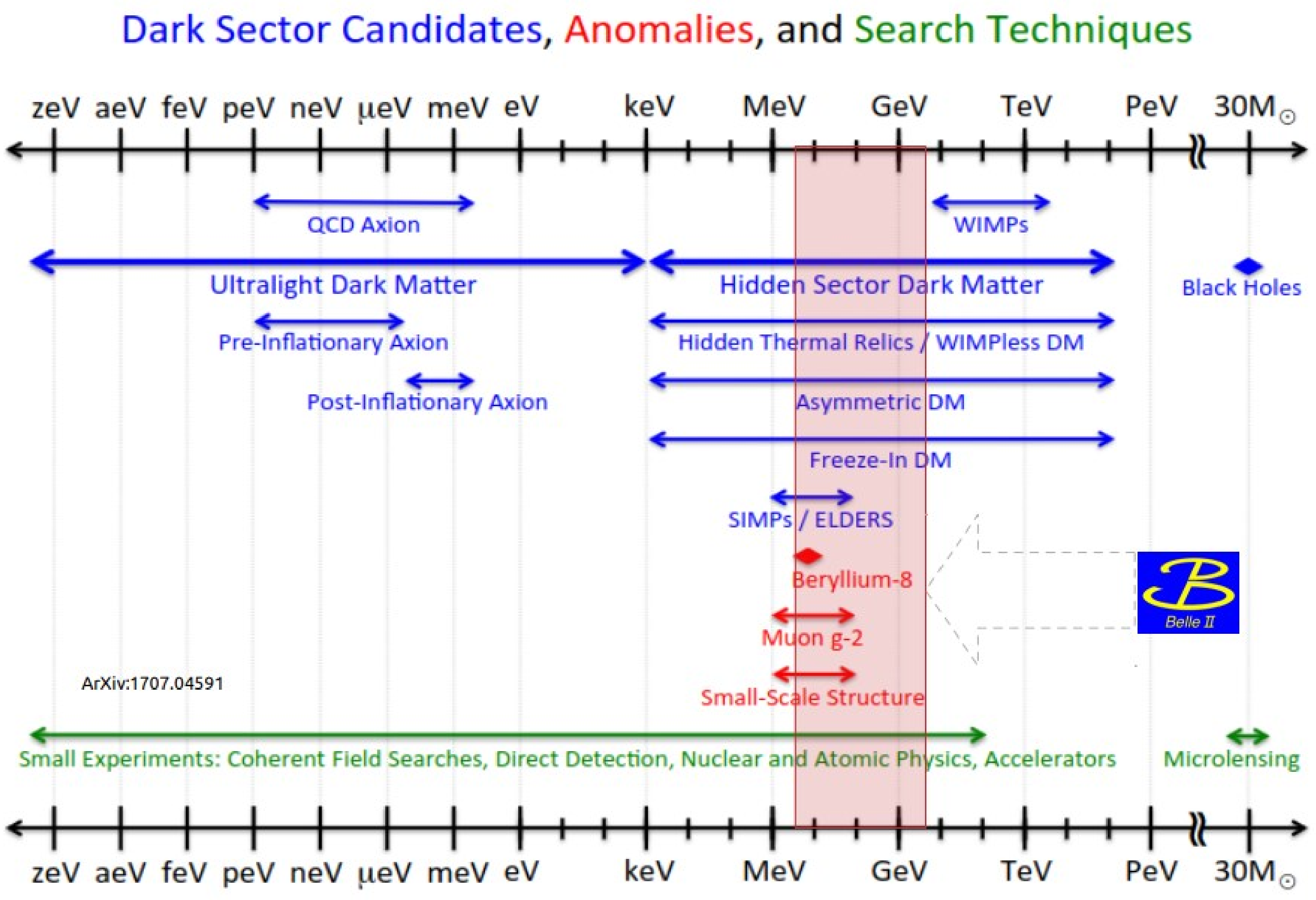
EOI	Upgrade ideas scope and technology	Time scale
DMAPS	Fully pixelated Depleted CMOS tracker, replacing the current VXD. Evolution from ALICE ITS developed for ATLAS ITK.	LS2
SOI-DUTIP	Fully pixelated system replacing the current VXD based on Dual Timer Pixel concept on SOI	LS2
Thin Strips	Thin and fine-pitch double-sided silicon strip detector system replacing the current SVD and potentially the inner part of the CDC	LS2
CDC	Replacement of the readout electronics (ASIC, FPGA) to improve radiation tolerance and x-talk	< LS2
TOP	Replace readout electronics to reduce size and power, replacement of MCP-PMT with extended lifetime ALD PMT, study of SiPM photosensor option	LS2 and later
ECL	Crystal replacement with pure CsI and APD; pre-shower; replace PIN-diodes with APD photosensors.	> LS2
KLM	Replacement of barrel RPC with scintillators, upgrade of readout electronics, possible use as TOF	LS2 and later
Trigger	Take advantage of electronics technology development. Increase bandwidth, open possibility of new trigger primitives	< LS2 and later
STOPGAP	Study of fast CMOS to close the TOP gaps and/or provide timing layers for track trigger	> LS2
TPC	TPC option under study for longer term upgrade	> LS2

Light dark sector searches



- Can access the mass range favored by light dark sector
  - Possible sub-GeV scenario

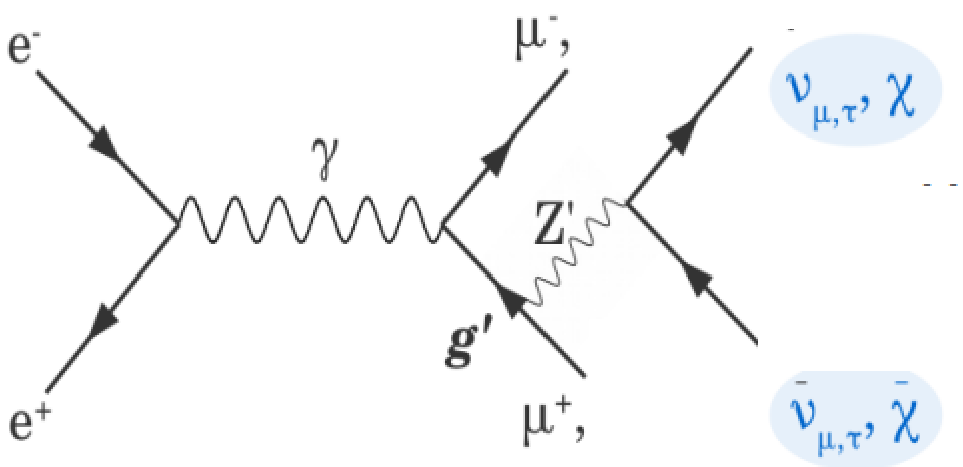
Light dark sector searches



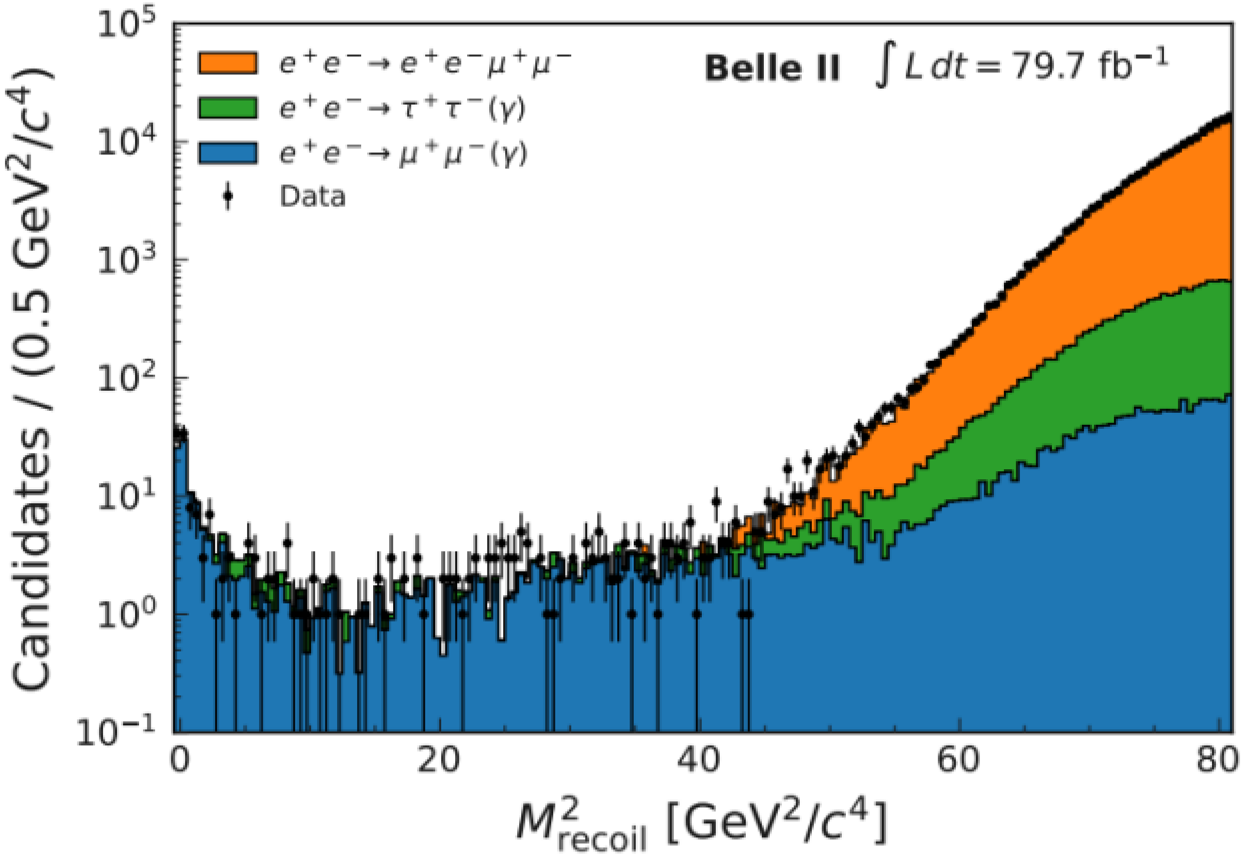
- Can access the mass range favored by light dark sector
  - Possible sub-GeV scenario
- DM weakly coupled to SM through a light mediator X:
  - vector (Z'/dark photon), axion like particles (ALPs), scalar (dark Higgs) or fermions (sterile ν)
- Some links to anomalies, e.g., g−2

Invisible decay of Z’ to dark matter

- Search for narrow peak in the recoil mass of dimuon pairs



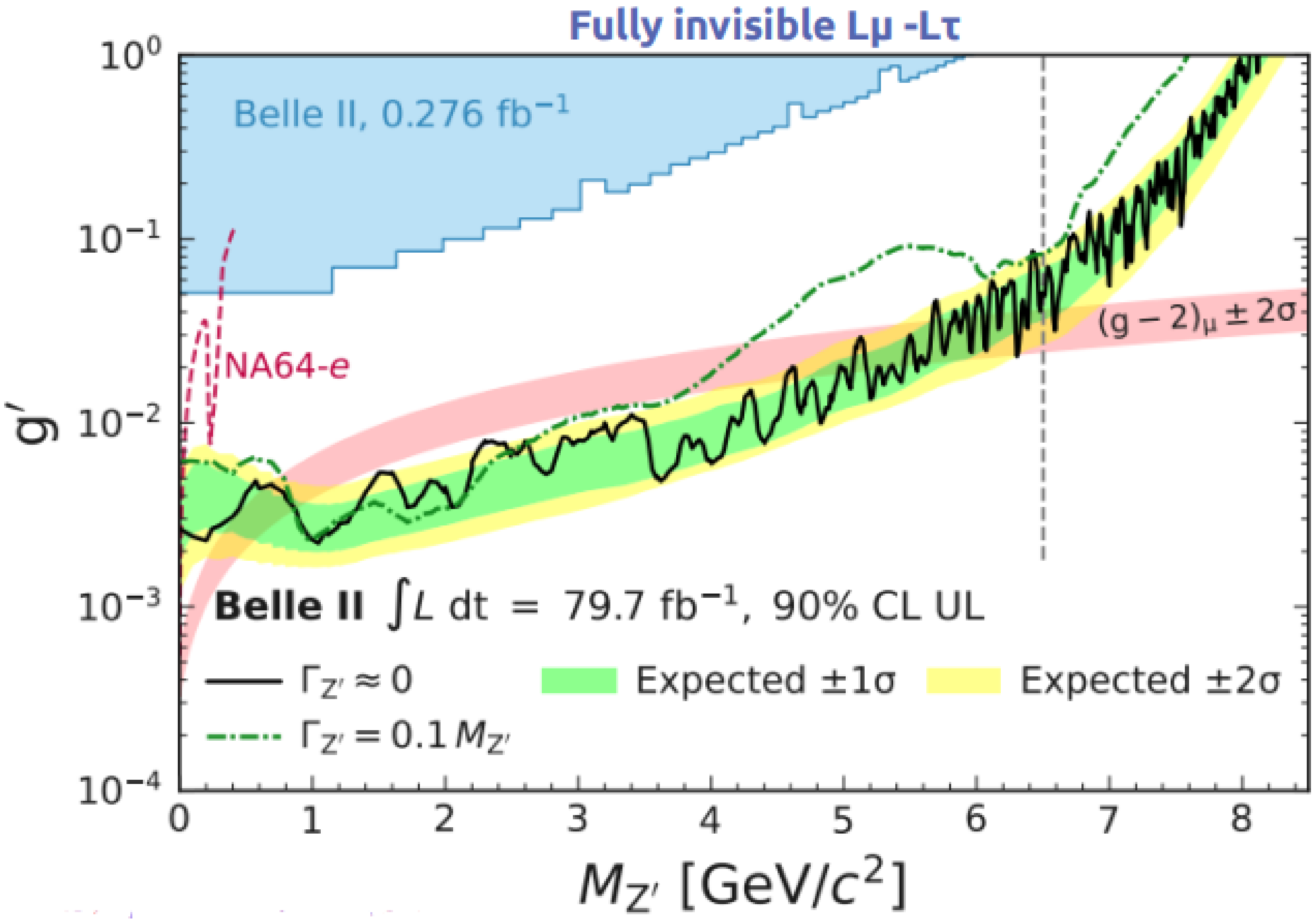
$e^+e^- \to \mu^+\mu^- Z'$; $Z' \to$ *invisible*



Invisible decay of Z’ to dark matter

- Limits on Z’ coupling g’ and mass
- g_μ-2 region ruled out for masses from 0.8 to 5 GeV

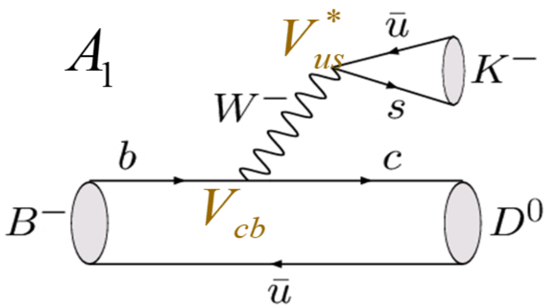
Phys. Rev. Lett. 130, 231801 (2023)

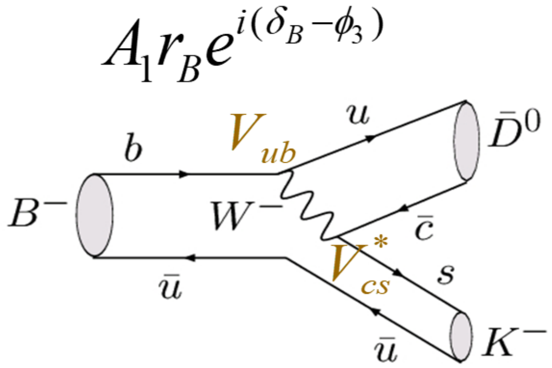


Paper in preparation

γ/ϕ_3: power of Belle + Belle II

- Standard candle in the SM
  - Tree-level only + no theory unc.
- LHCb leads the way: $\gamma=(63.8\pm3.6)°$
  - [LHCB-CONF-2022-003]()

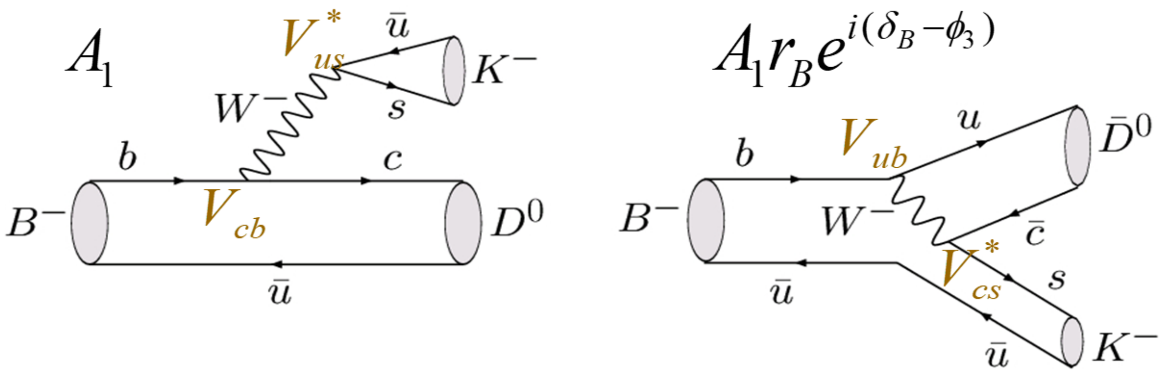


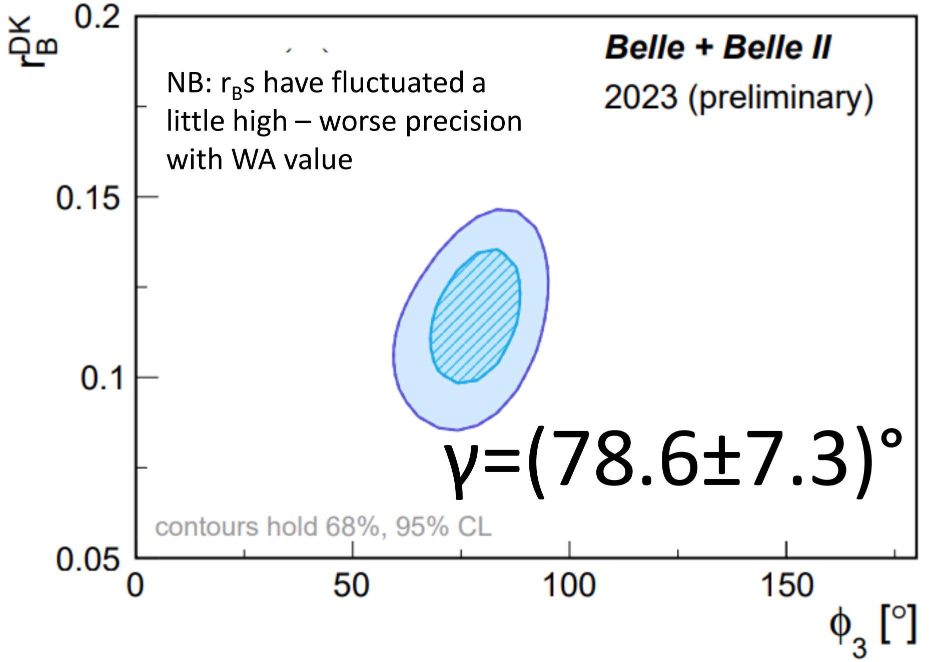


Paper accepted by JHEP

γ/ϕ_3: power of Belle + Belle II

- Standard candle in the SM
  - Tree-level only + no theory unc.
- LHCb leads the way: $\gamma=(63.8\pm3.6)°$
  - LHCB-CONF-2022-003
- Several Belle (711 fb^{-1}) + Belle II measurements (varying sample size) – total O(1 ab^{-1})
  - $D\to K^0_S hh$ - JHEP 02 (2022) 063
  - $D\to K^0_S K\pi$ - accepted by JHEP
  - $D\to K^0_S \pi^0$, KK - arXiv:2308.05048
  - + Belle-only $D\to K\pi$ and others
- A few ab^{-1} will give a good cross check of this SM parameter





Phys. Rev. D 109, 012001 (2024) **and** Phys. Rev. Lett. 131, 111803 (2023)

B→Kπ isospin sum rule

- Relates these various penguin modes to give a null test of the SM with O(1%) SM precision – PRD **59,** 113002 (1999)

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

- All inputs measured at Belle II including 'no vertex' time-dependent *CP* asymmetry for B→ $K^0_S\pi^0$ – 362 fb^{-1} sample

Belle II paper in preparation and PRL 131, 111803 (2023)

M. Dorigo's talk – WG5

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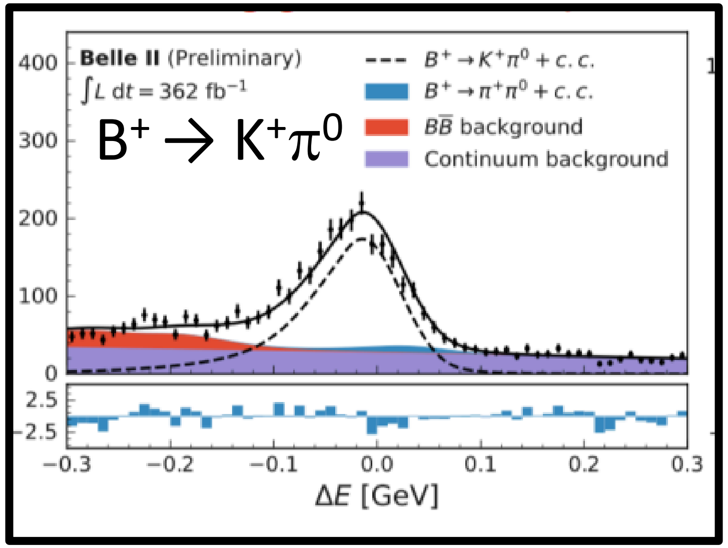
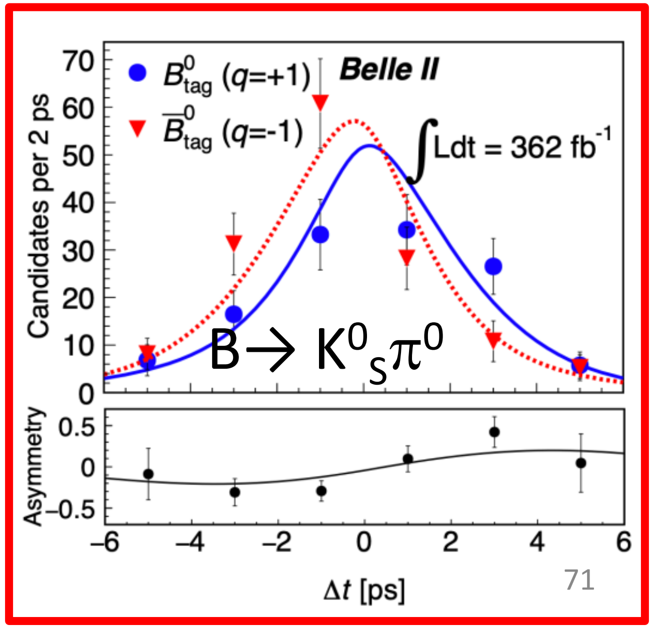


$B = (14.2 \pm 0.4 \pm 0.9) \times 10^{-6}$
Large π^0 efficiency syst.

$A_{K^0} = -0.01 \pm 0.12 \pm 0.05$
Combination of time-dependent and time-integrated analyses



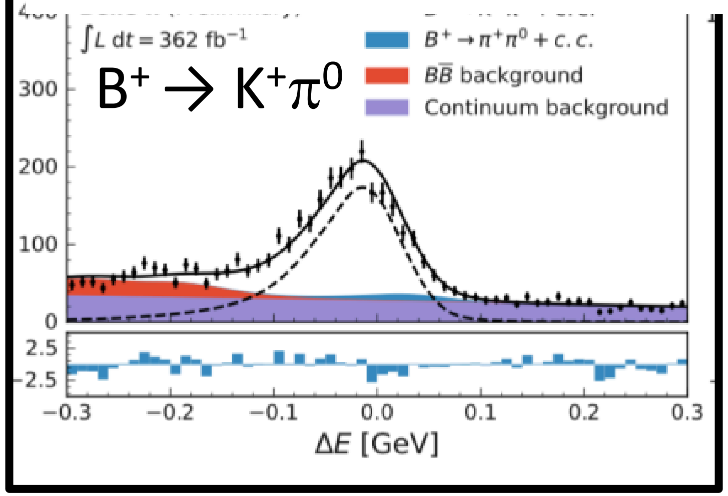
Belle II paper in preparation and arXiv:2305.07555 (accepted PRL)

B→Kπ isospin sum rule

- Relates these various penguin modes to give a null test of the SM with O(1%) SM precision – PRD **59**, 113002 (1999)

$$I_{K\pi} = (-3 \pm 13 \pm 5)\,\%$$

Agrees with SM. Competitive with WA: $(-13 \pm 11)\,\%$.



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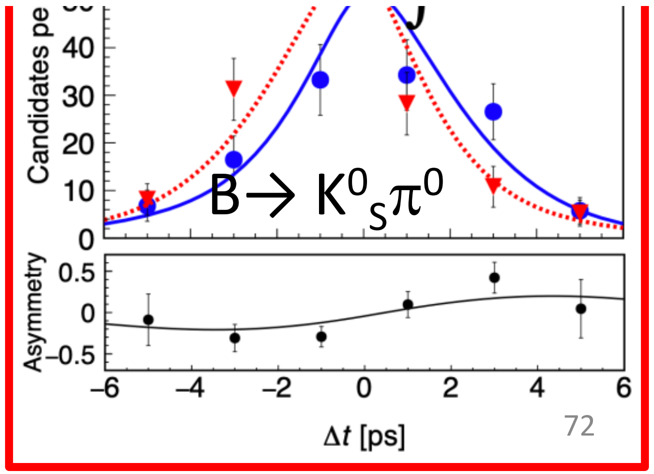
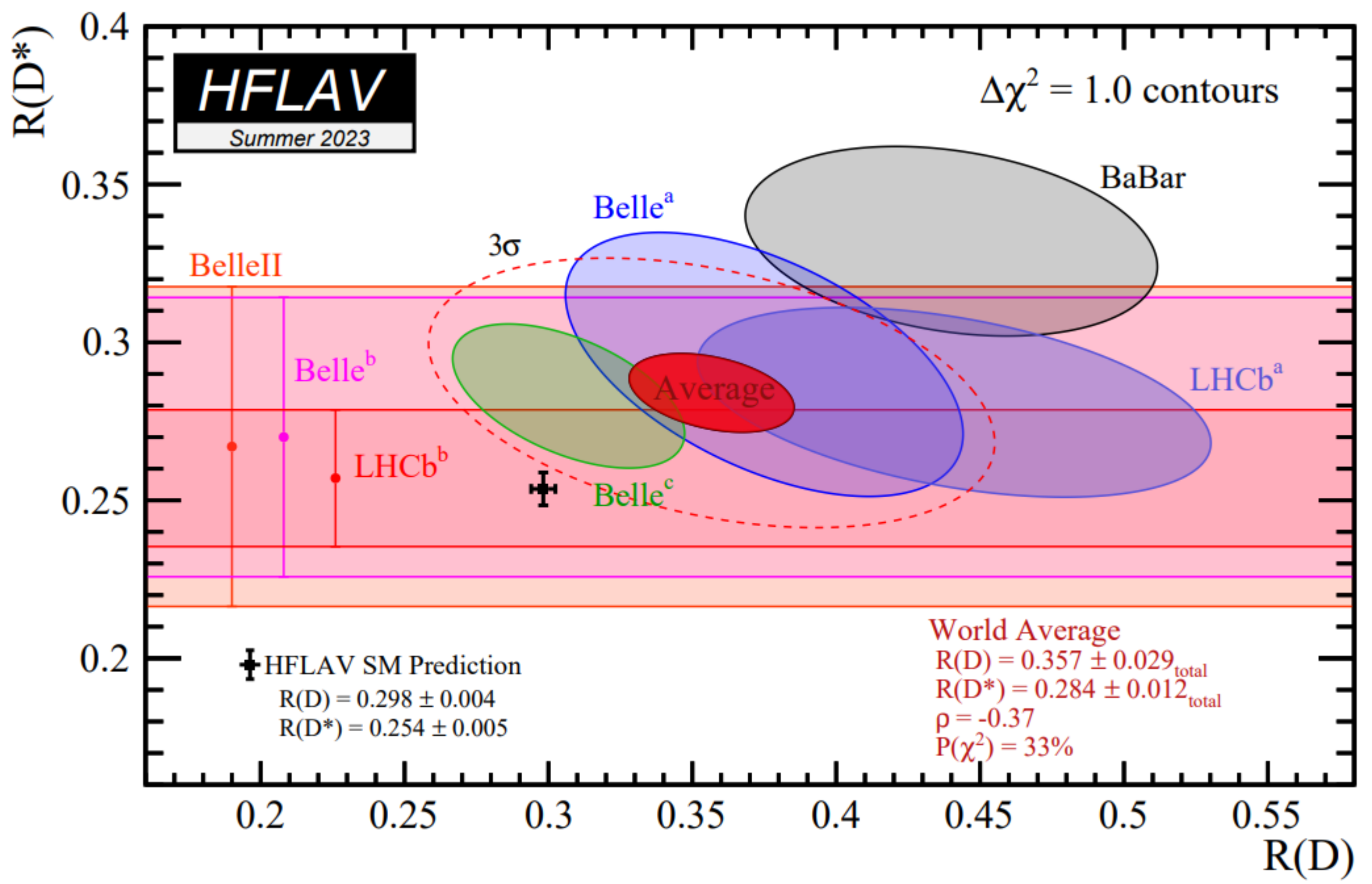


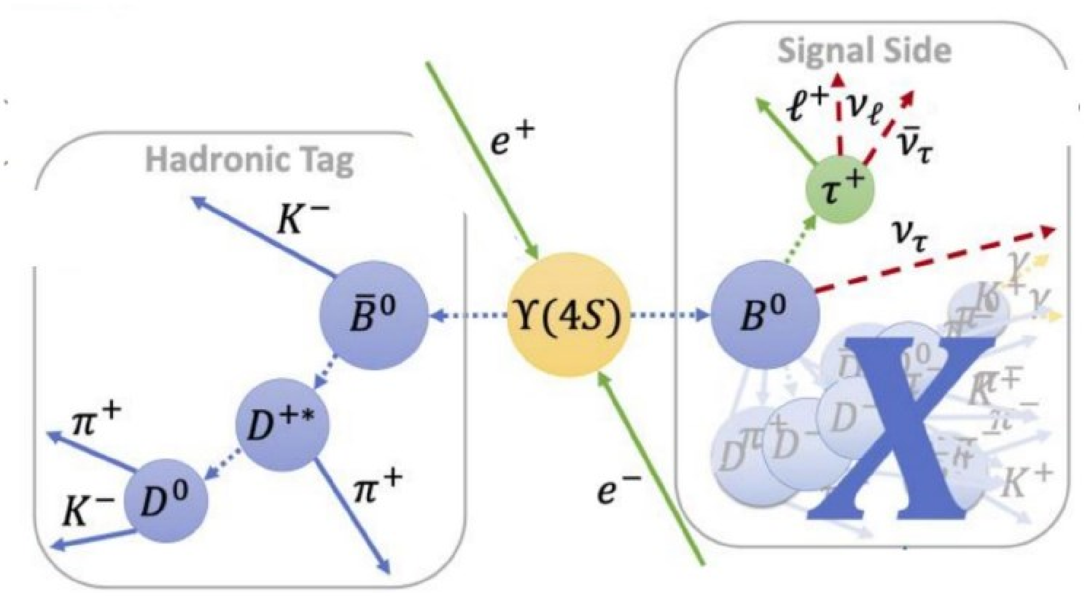


4) Lepton flavour/universality violation and rare decays

arXiv:2311.07248 [hep-ex]

Measurement of R(X)

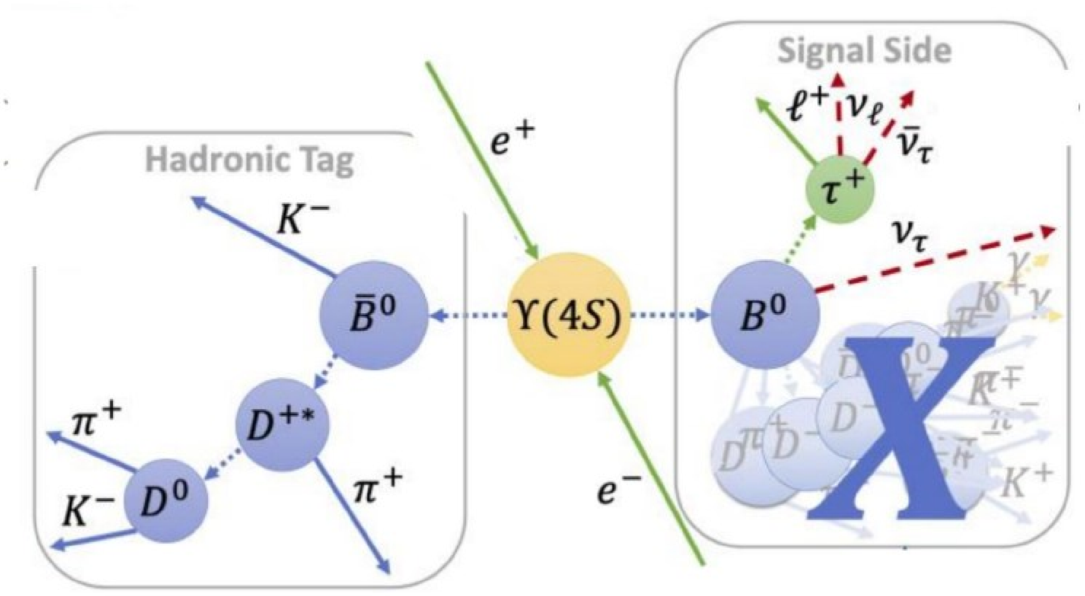
- Inclusive ratio $R(X) = \frac{BF(B \to X\tau\nu)}{BF(B \to Xl\nu)}$
    - A complementary alternative to $R(D^{(*)})$
- Hadronic-tagging method with a 189 fb^{-1} Belle II sample

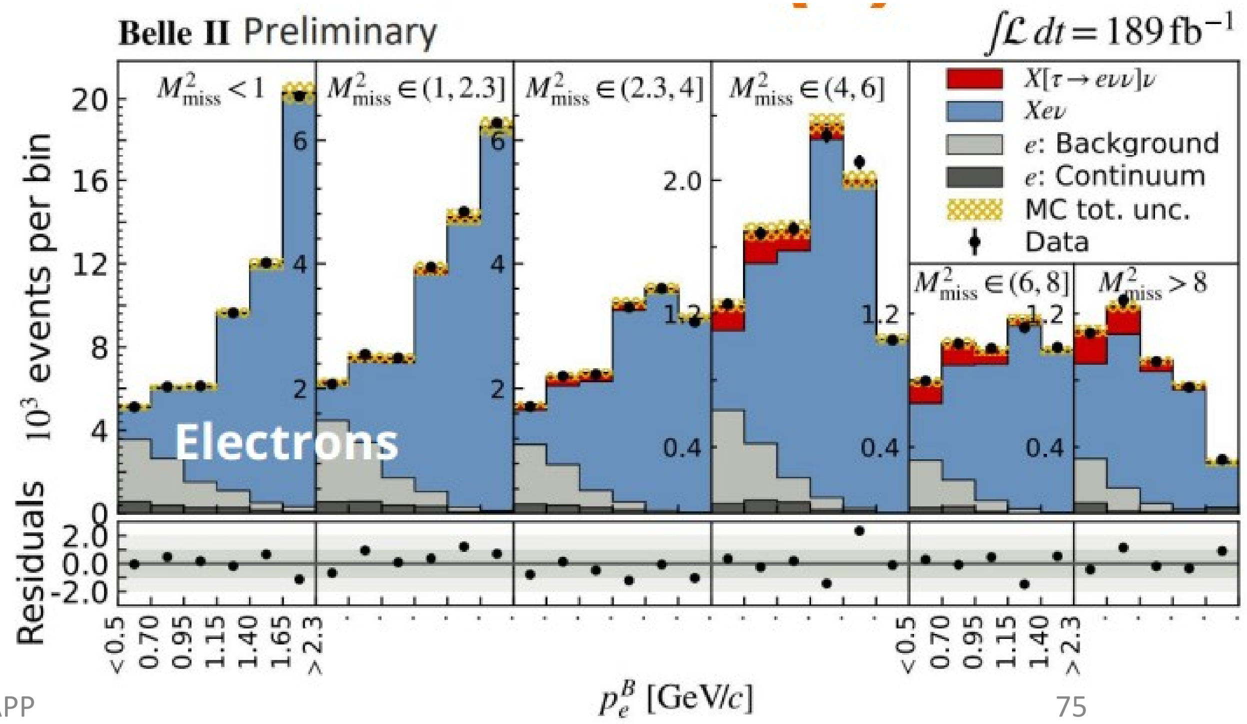


arXiv:2311.07248 [hep-ex]

Measurement of R(X)

- Inclusive ratio $R(X) = \frac{BF(B \to X\tau\nu)}{BF(B \to Xl\nu)}$
  - A complementary alternative to $R(D^{(*)})$
- Hadronic-tagging method with a 189 fb^{-1} Belle II sample
- Use missing-mass squared and lepton momentum to isolate signal above B→Xlν background
- Background templates calibrated to control samples and sidebands





arXiv:2311.07248 [hep-ex]

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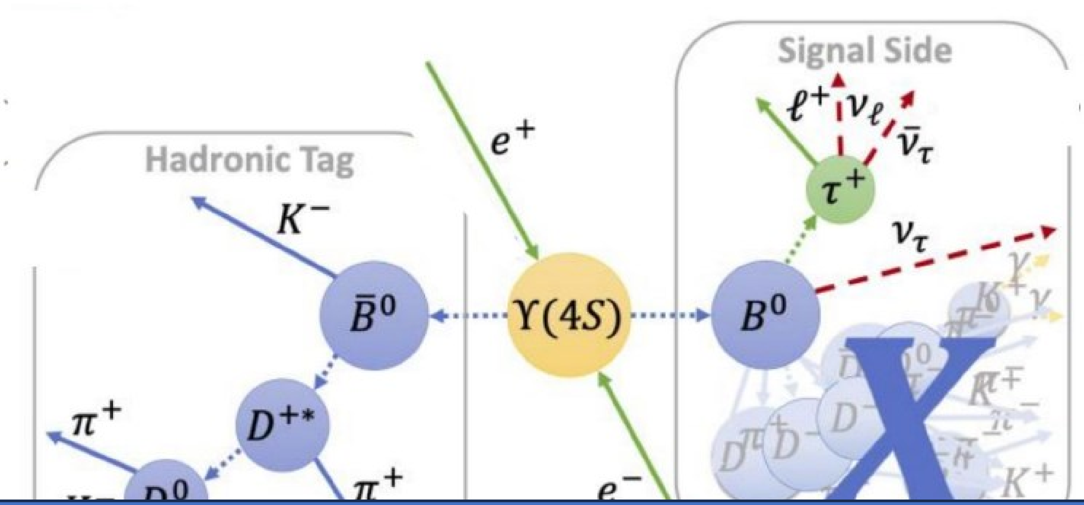


R(X)=0.228±0.016 (stat) ±0.036 (syst)

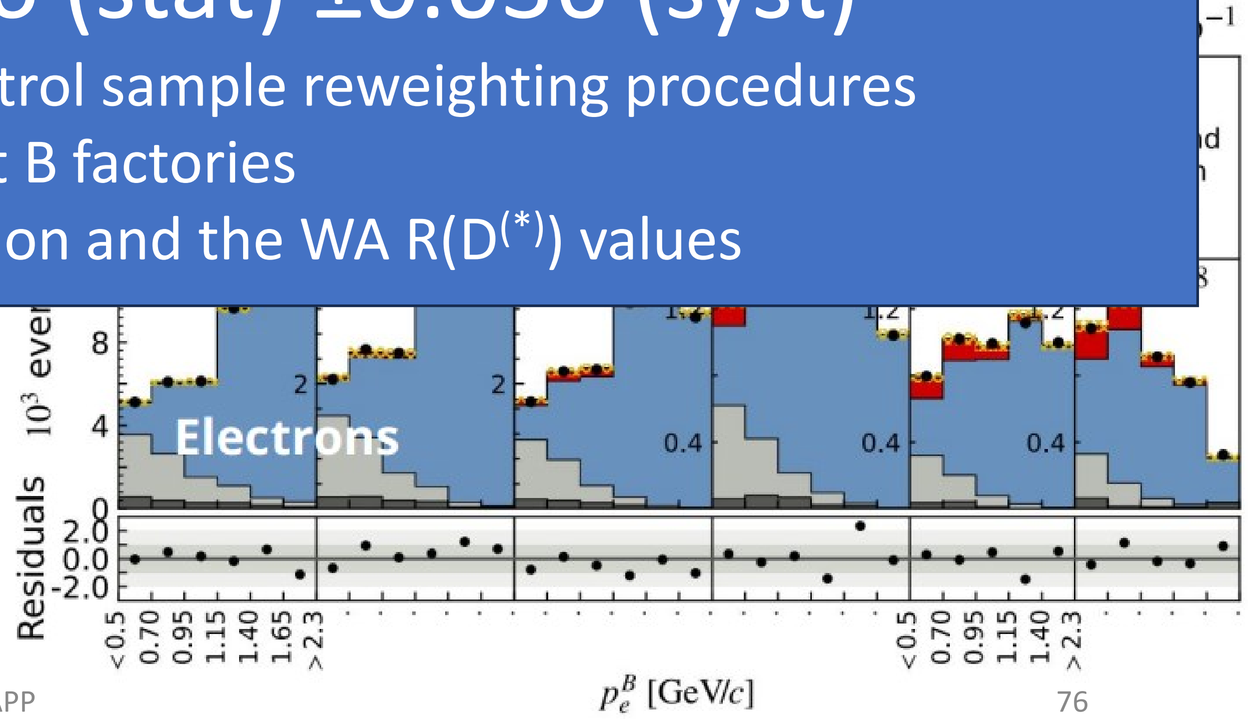
Systematics dominated by control sample reweighting procedures

First at B factories

Agrees with SM prediction and the WA R(D$^{(*)}$) values

signal above $B \to Xl\nu$ background

- Background templates calibrated to control samples and sidebands



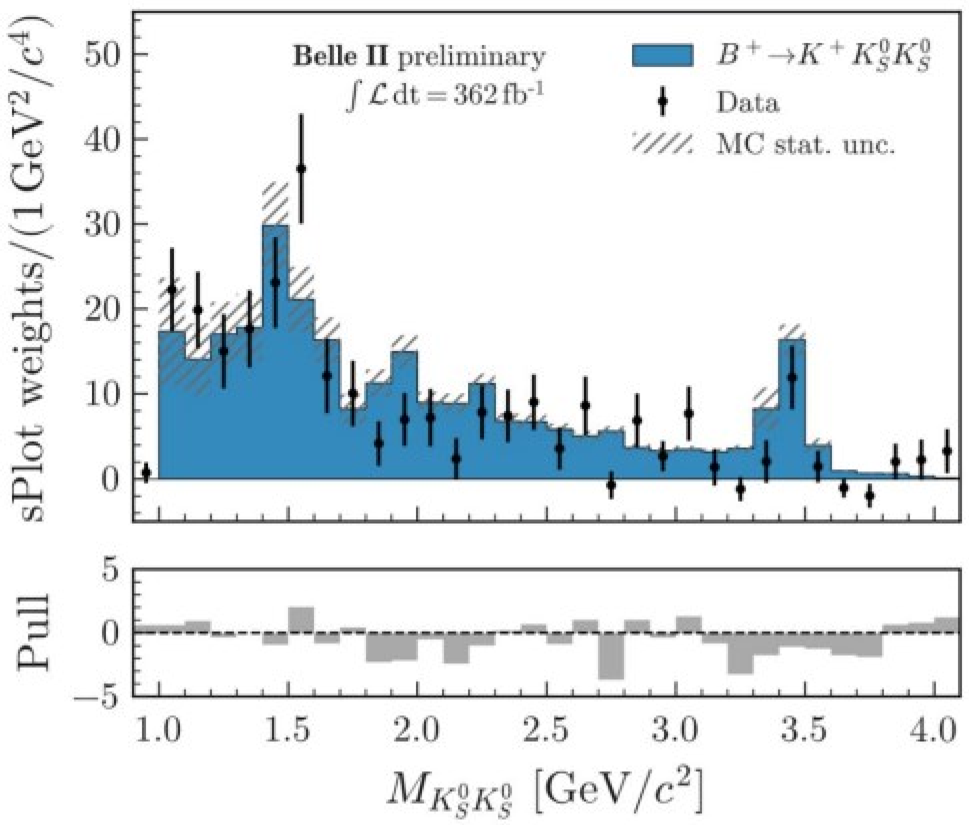
arXiv:2311.14647 [hep-ex]

$\boldsymbol{B^+ \to K^+ \nu \bar{\nu}}$: Background validation example

- An example of a difficult background is charmless $B^+ \to K^+ K_L^0 K_L^0$, where K_L^0 mesons escape detection
  - has an order of magnitude larger BF than signal

arXiv:2311.14647 [hep-ex]

$B^+ \to K^+\nu\bar{\nu}$: Background validation example



- An example of a difficult background is charmless $B^+ \to K^+K^0_L K^0_L$, where K^0_L mesons escape detection
  - has an order of magnitude larger BF than signal
- Dedicated studies $B^+ \to K^+K^0_S K^0_S$ show good modelling
  - generous systematics assigned
- Similar studies for $B^+ \to K^+ n\bar{n}$, $B^+ \to K^+K^0_L K^0_S$

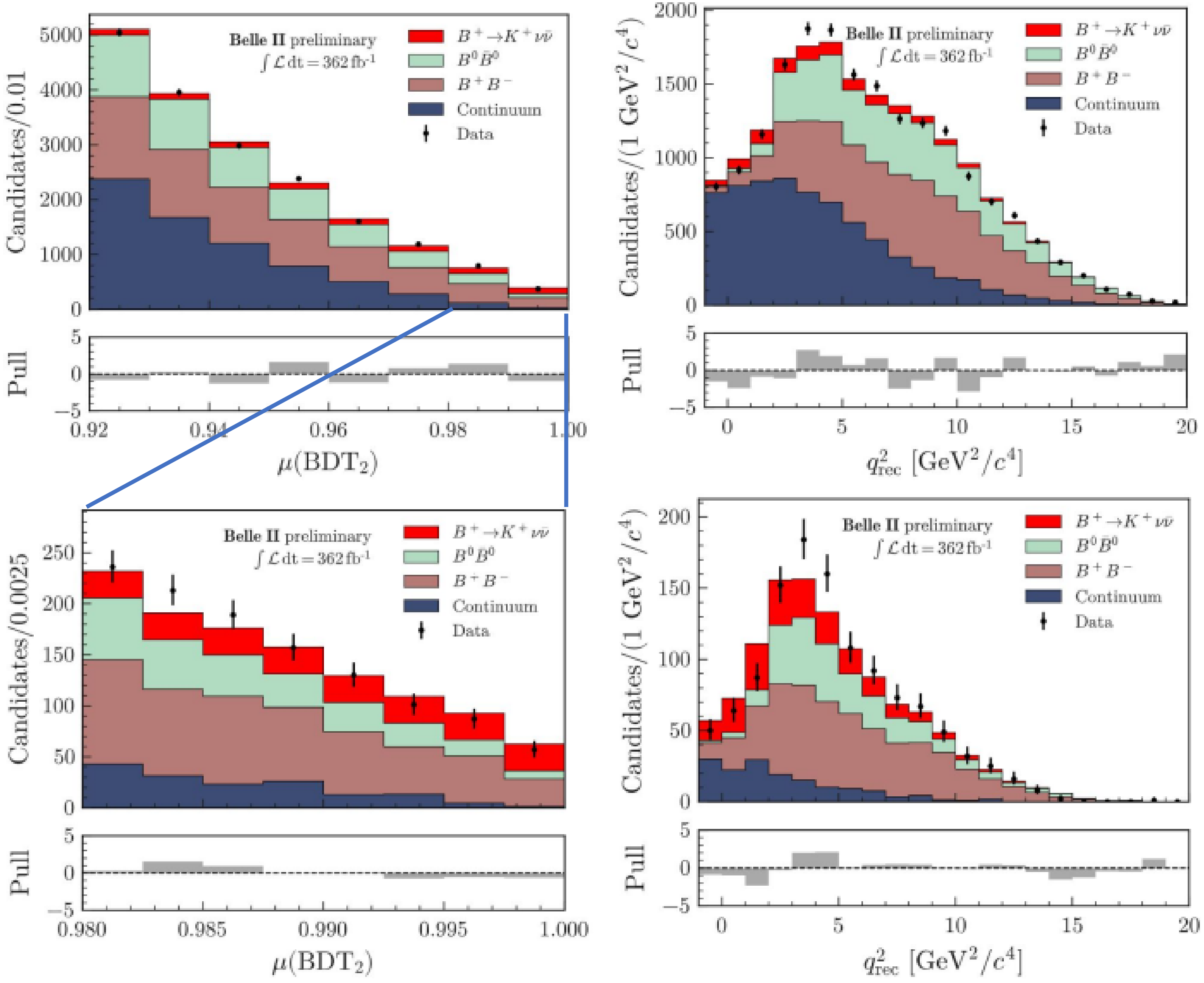
$B^+ \to K^+ \nu\bar{\nu}$: Systematic uncertainties

Source	Correction	Uncertainty type	Uncertainty size	Impact on σ_μ
Normalization of $B\bar{B}$ background	—	Global, 2 NP	50%	0.88
Normalization of continuum background	—	Global, 5 NP	50%	0.10
Leading B-decays branching fractions	—	Shape, 5 NP	$O(1\%)$	0.22
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	20%	0.49
p-wave component for $B^+ \to K^+ K^0_S K^0_L$	q^2 dependent $O(100\%)$	Shape, 1 NP	30%	0.02
Branching fraction for $B \to D^{(**)}$	—	Shape, 1 NP	50%	0.42
Branching fraction for $B^+ \to n\bar{n}K^+$	q^2 dependent $O(100\%)$	Shape, 1 NP	100%	0.20
Branching fraction for $D \to K_L X$	+30%	Shape, 1 NP	10%	0.14
Continuum background modeling, BDT$_c$	Multivariate $O(10\%)$	Shape, 1 NP	100% of correction	0.01
Integrated luminosity	—	Global, 1 NP	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1 NP	1.5%	0.02
Off-resonance sample normalization	—	Global, 1 NP	5%	0.05
Track finding efficiency	—	Shape, 1 NP	0.3%	0.20
Signal kaon PID	p, θ dependent $O(10-100\%)$	Shape, 7 NP	$O(1\%)$	0.07
Photon energy scale	—	Shape, 1 NP	0.5%	0.08
Hadronic energy scale	−10%	Shape, 1 NP	10%	0.36
K^0_L efficiency in ECL	−17%	Shape, 1 NP	8%	0.21
Signal SM form factors	q^2 dependent $O(1\%)$	Shape, 3 NP	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1 NP	3%	0.03
MC statistics	—	Shape, 156 NP	$O(1\%)$	0.52

Post-fit distributions

Upper: full fit region

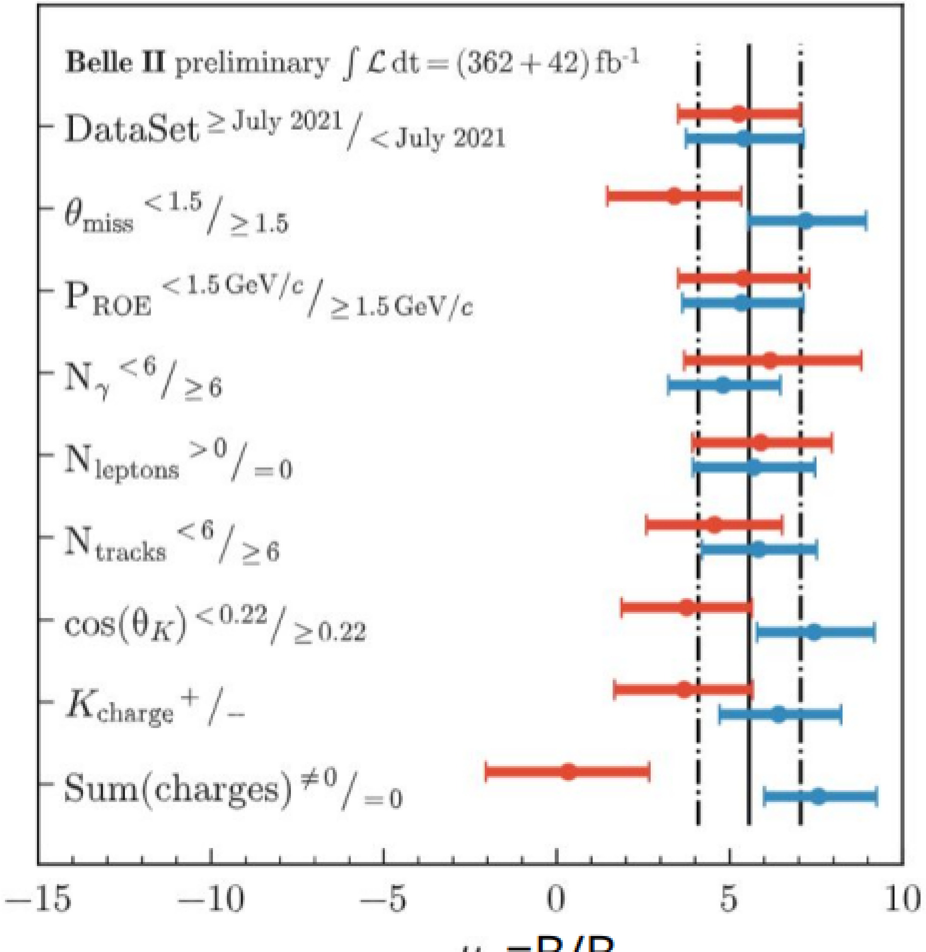
Lower: most sensitive region

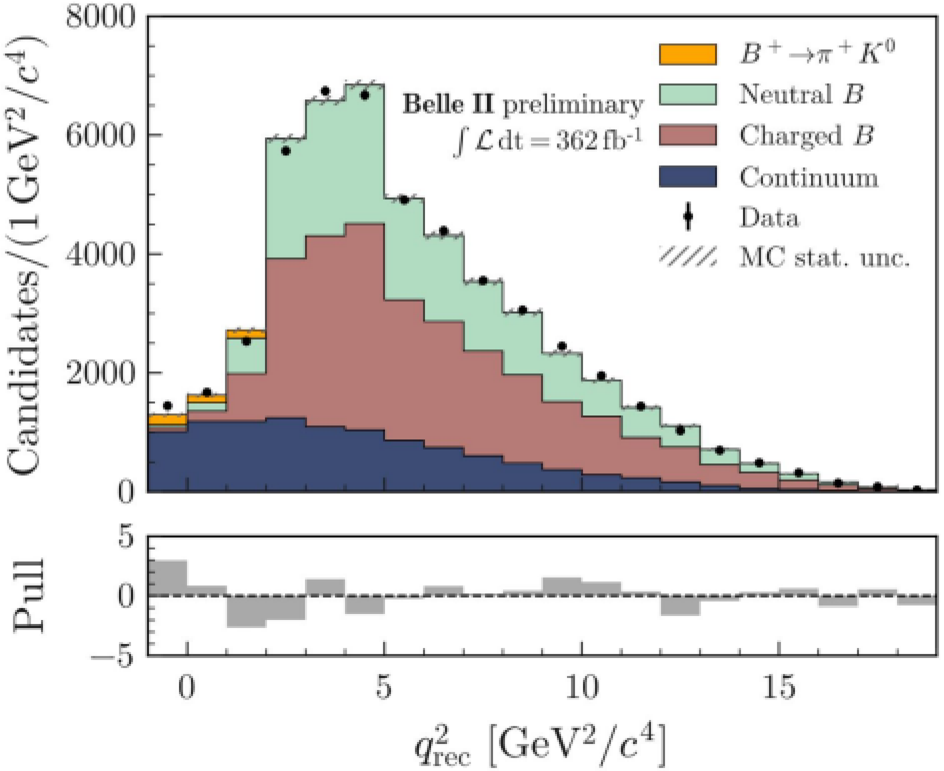


arXiv:2311.14647 [hep-ex]

Cross checks

arXiv:2311.14647 [hep-ex]





$\mathcal{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

PDG: $(2.38 \pm 0.08) \times 10^{-5}$

- Multiple checks of the analyses stability, including tests dividing data into approximately equal sub-samples. Reported here as measured branching fraction divided by SM expectation, μ=B/B$_{SM}$.
- Control measurement of $B^+ \to \pi^+ K^0$ decay

Slide from S. Glazov EPS