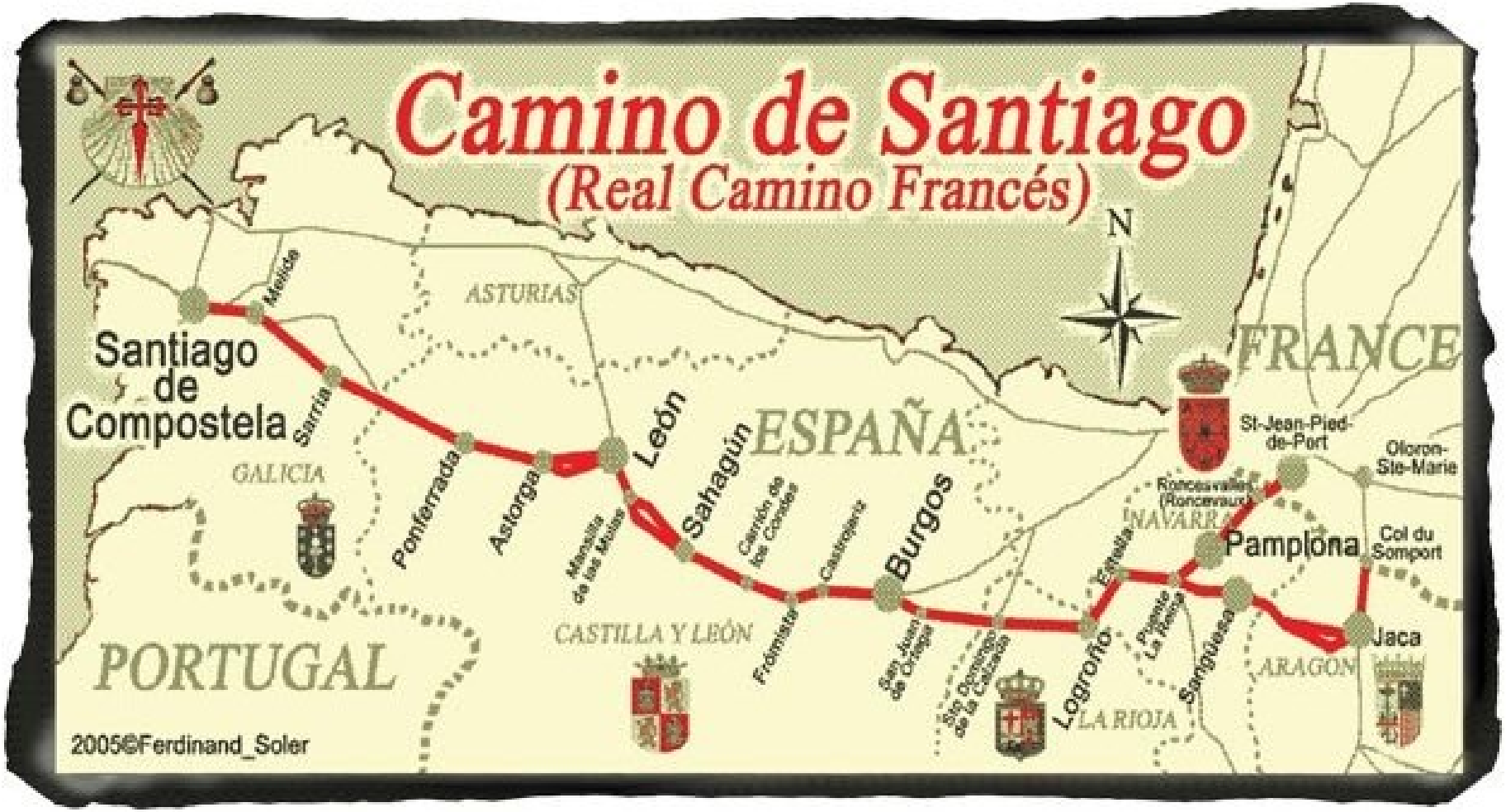
Status of and prospects for e^+e^- measurements

James (Jim) Libby on behalf of Belle and Belle II

Indian Institute of Technology Madras

Outline: The Way of St James



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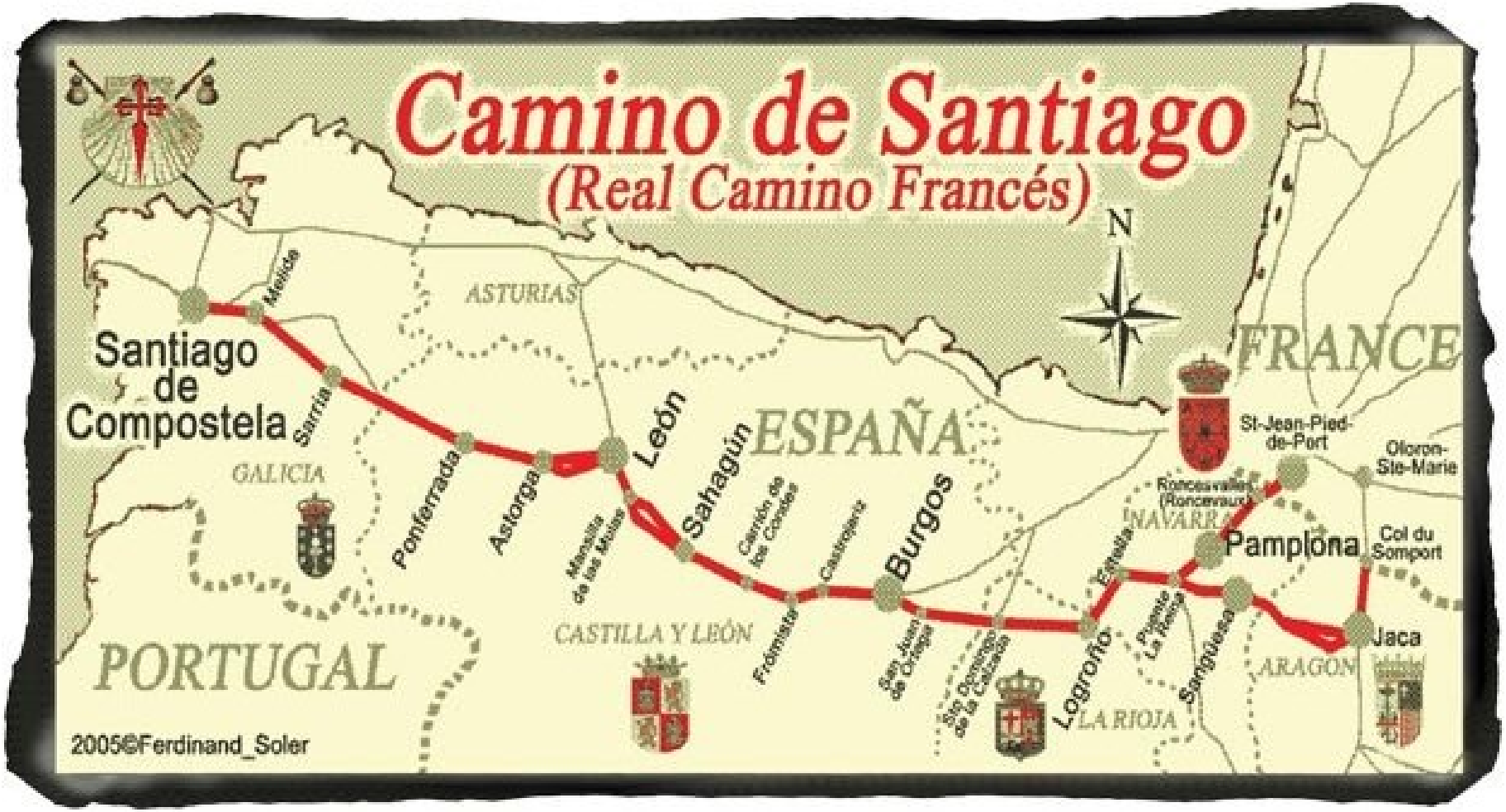

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0) Charm inc.
BESIII
(WG1 and 7)
Longke Li

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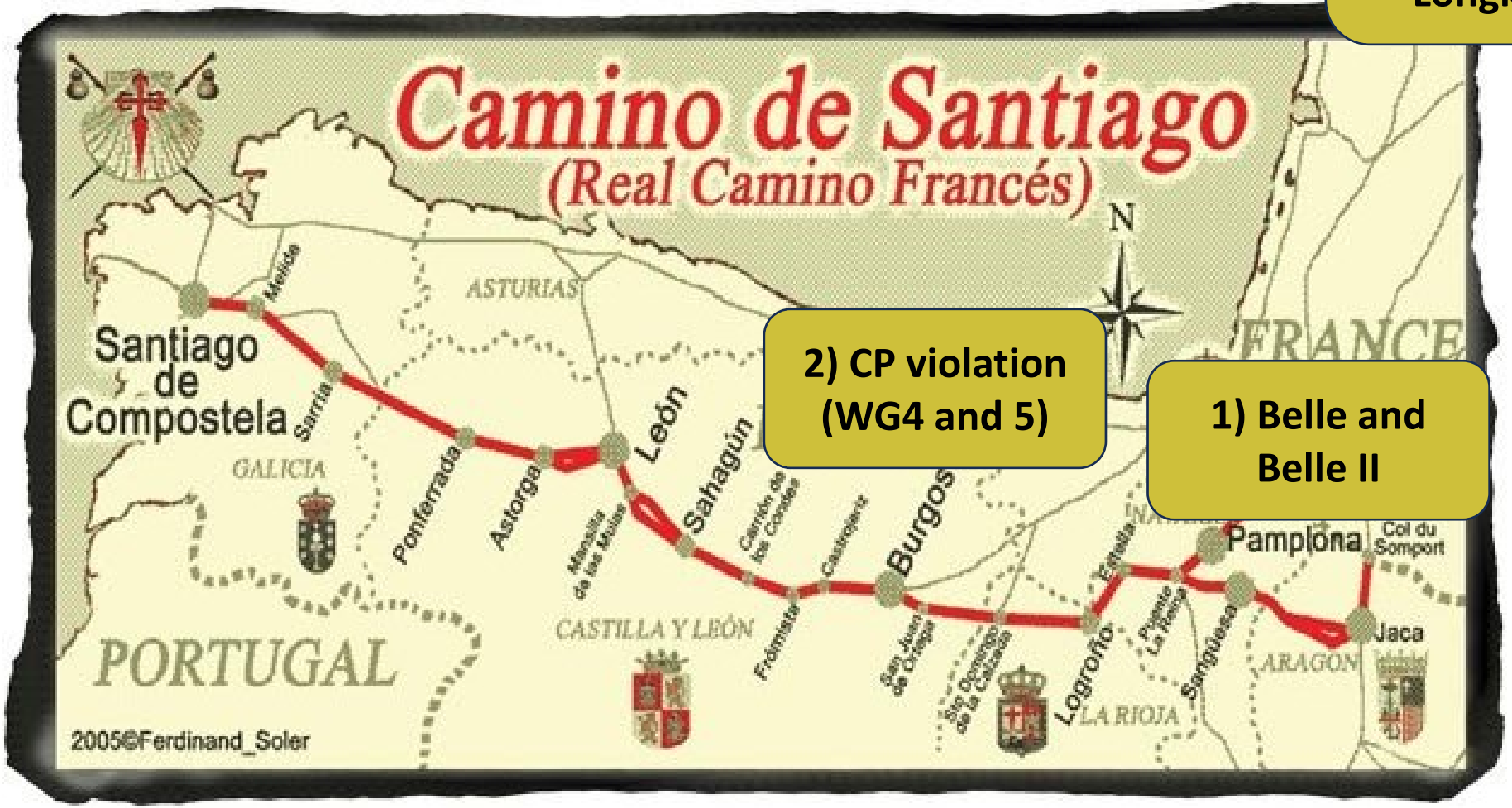

2) CP violation (WG4 and 5)

1) Belle and Belle II

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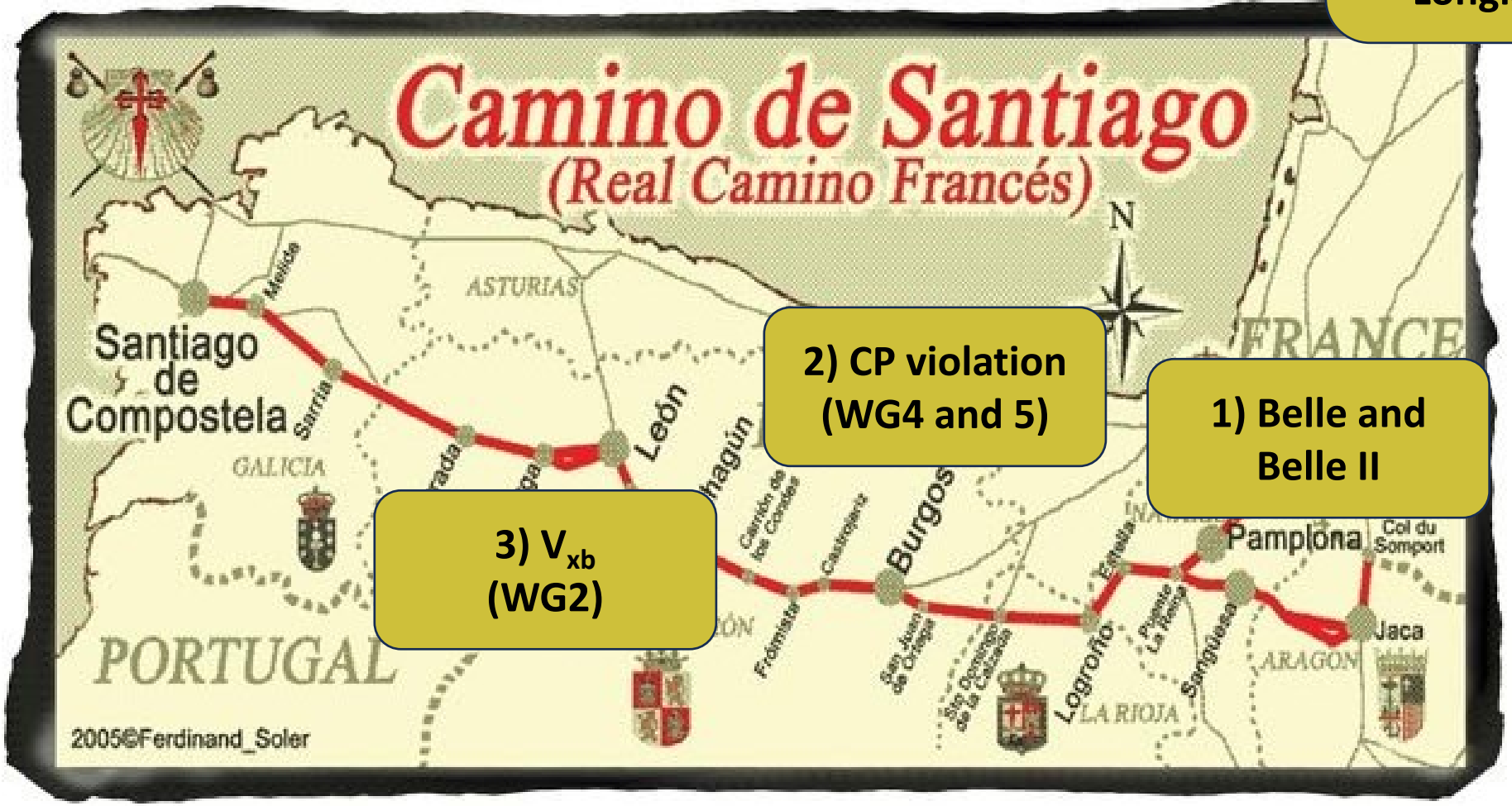

0) Charm inc. BESIII (WG1 and 7) Longke Li

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1) Belle and Belle II

3) V_{xb} (WG2)

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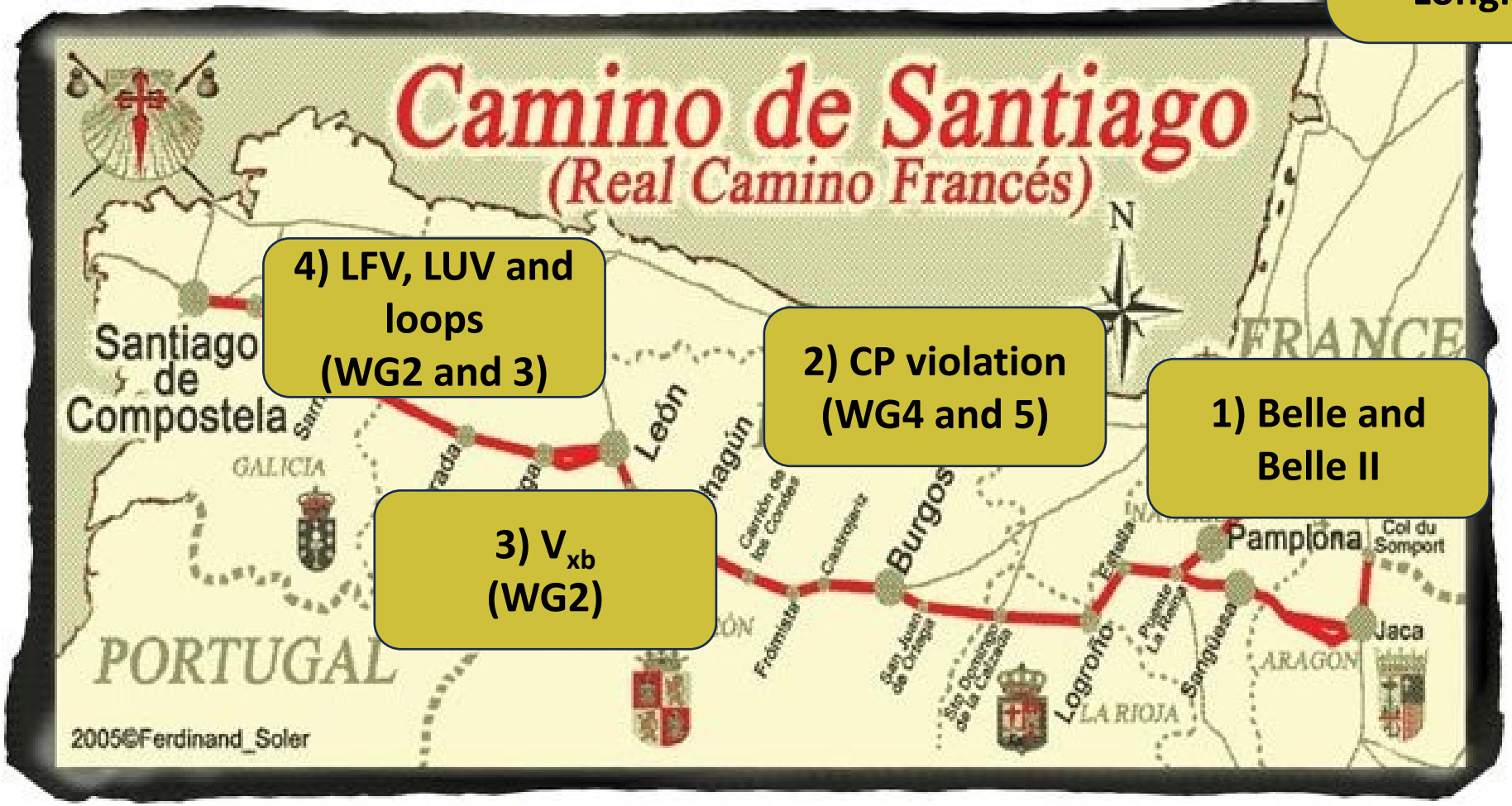

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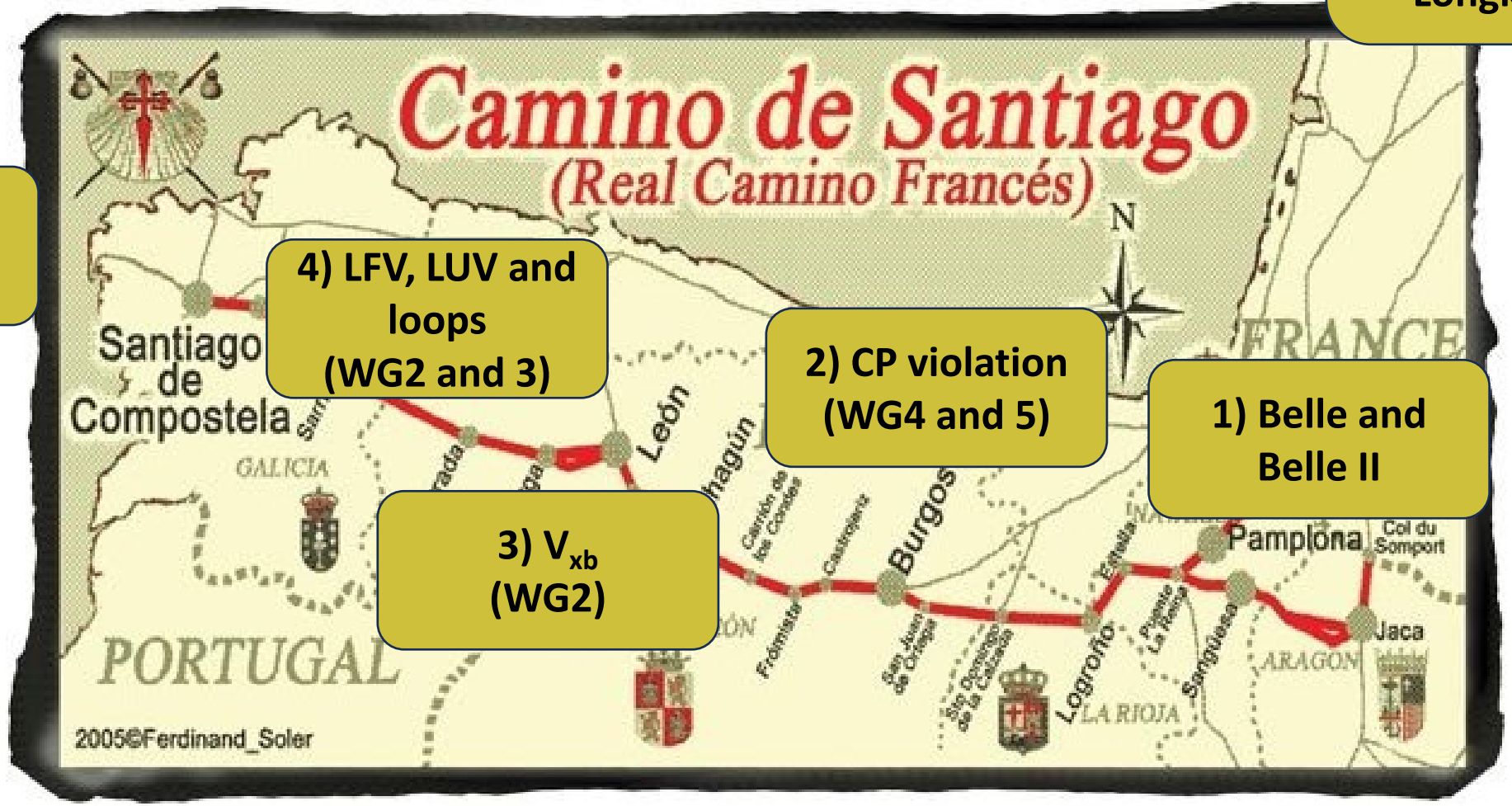

5) Prospects

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1) Belle and Belle II

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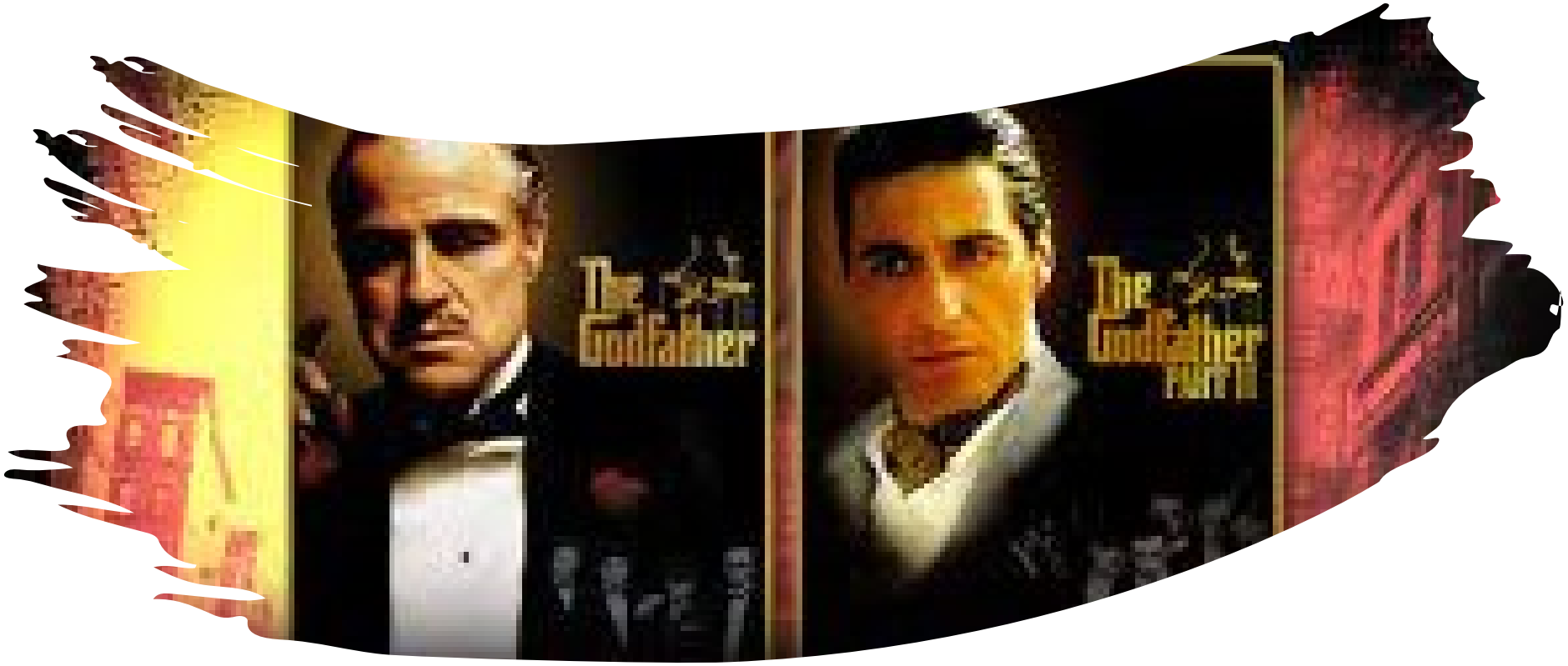

1) Belle and Belle II

Will the next generation perform as well as the first?

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

Why *B* physics at the Y(4S)?

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- **Advantages compared to proton-proton**
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  - 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
- **Disadvantages compared to proton-proton**
  - **Cross section – 150,000 times smaller**
  - No B_s, B_c, or Λ_b produced – can run at Y(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 ab^{-1} Y(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
  - nanobeam scheme to increase instantaneous luminosity by factor 30 to collect multi-ab^{-1} sample
  - **World record 4.7×10^{34} $cm^{-2}s^{-1}$**
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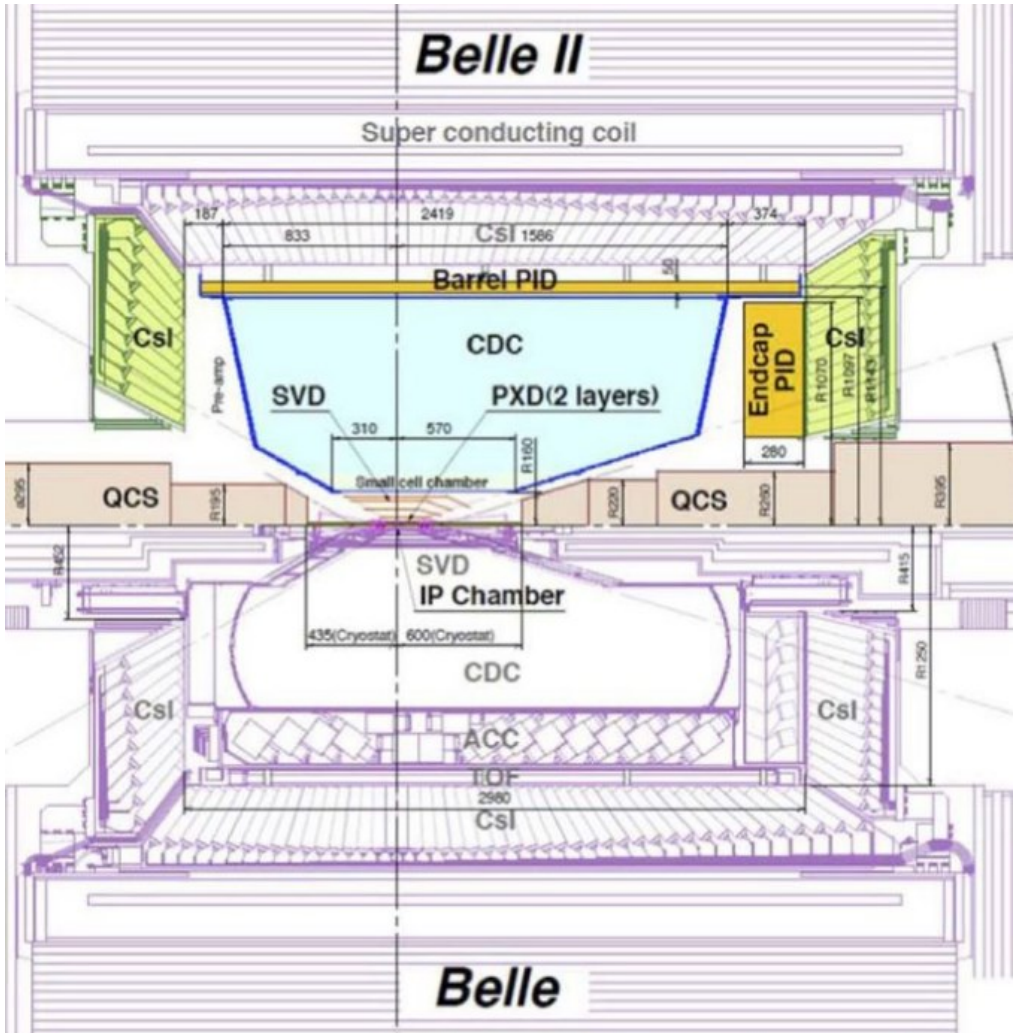
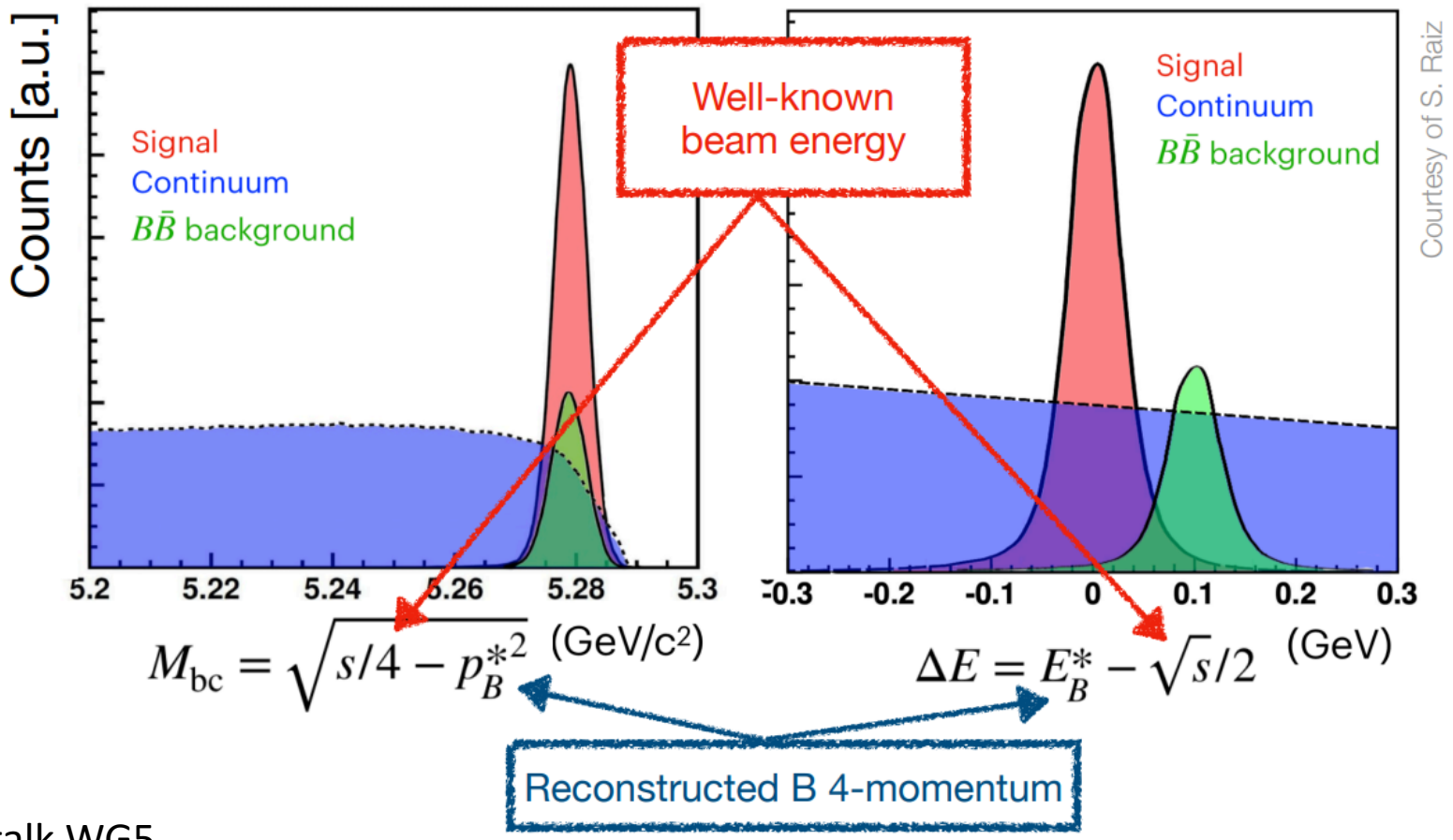


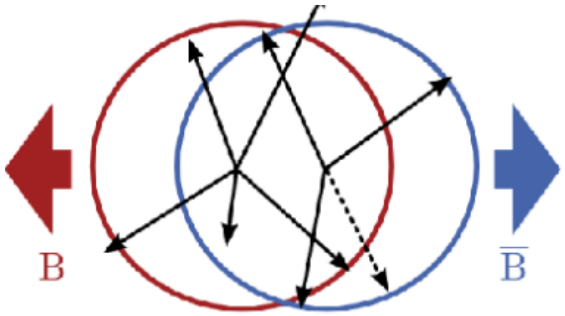
B-factory analysis essentials 1 – beam constrained kinematics



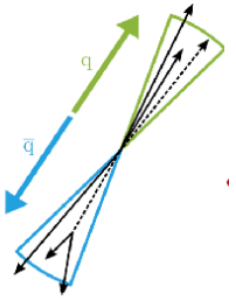
From Mirco Dorigo's talk WG5

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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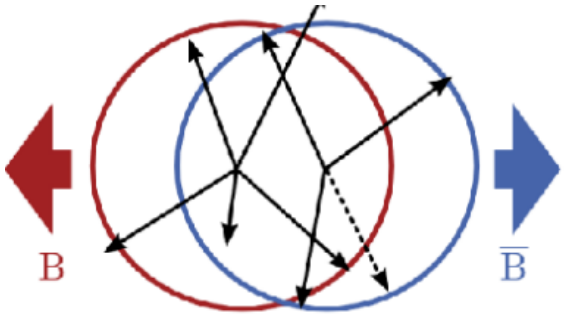
- In the c.m. frame B mesons almost at rest when they decay
  - isotropic distribution of particles
- In the c.m. frame continuum qq back-to-back
  - jetlike distribution of particles
- Shape variables, e.g., thrust and Fox-Wolfram moments, help distinguish topologies
- Ideal task for machine-learning
- Output oft used as a fit variable



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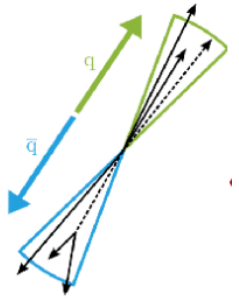
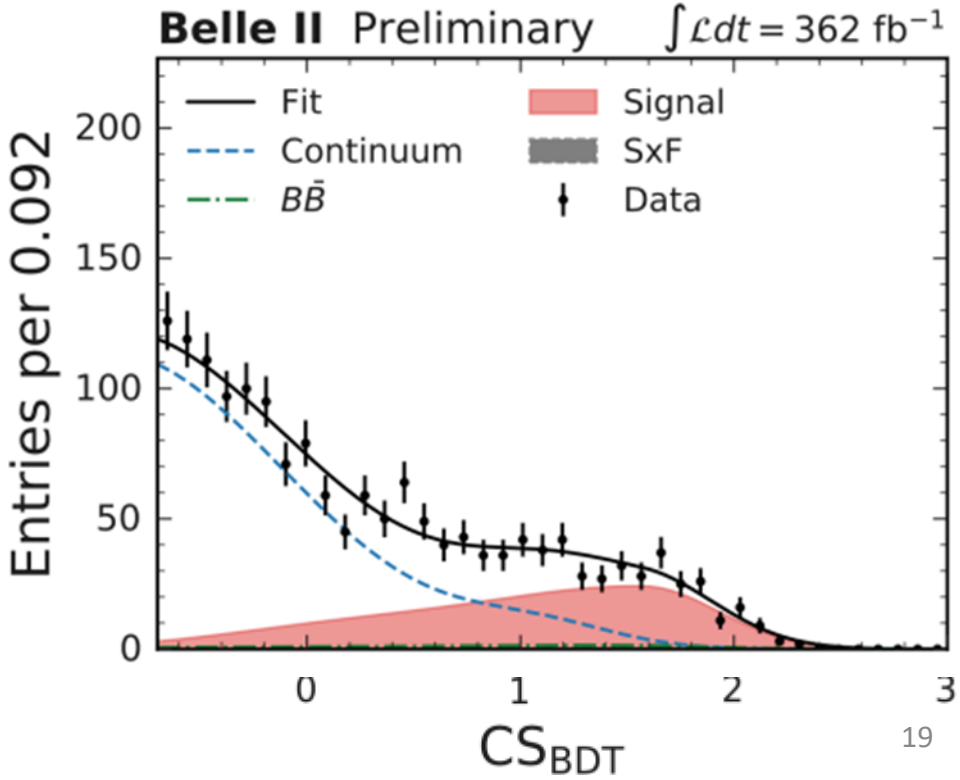
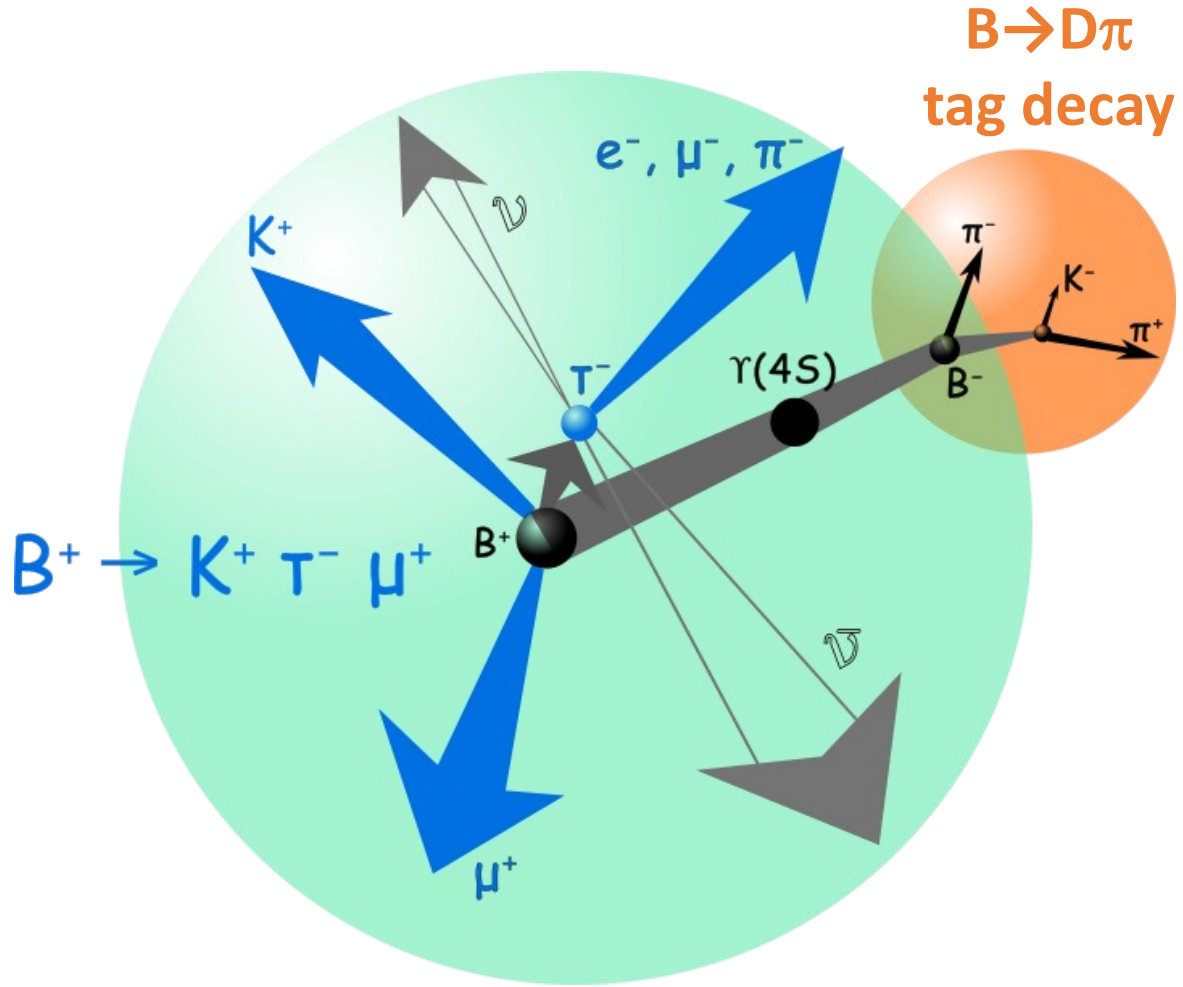




B-factory analysis essentials 3: hadronic tag

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



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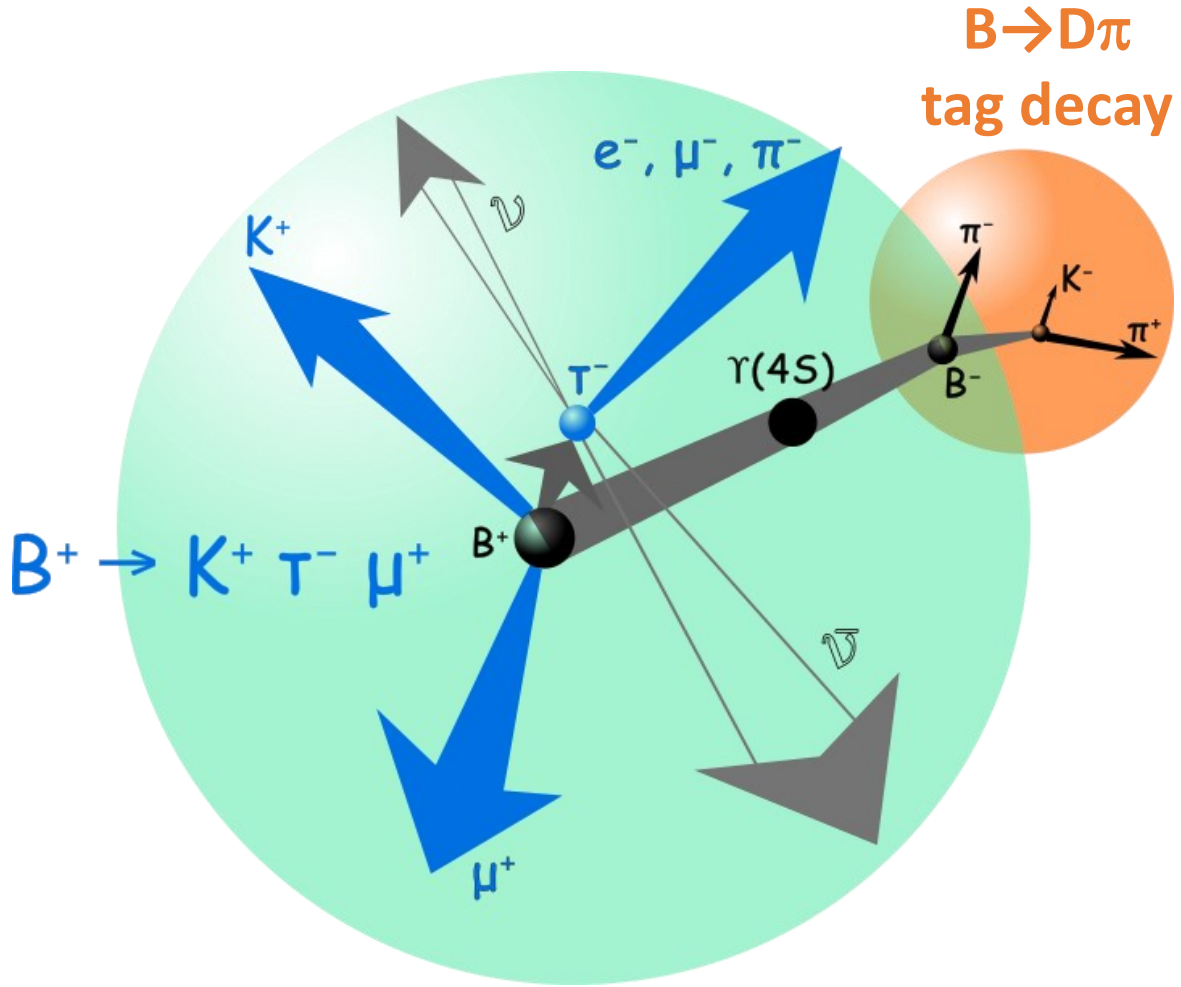
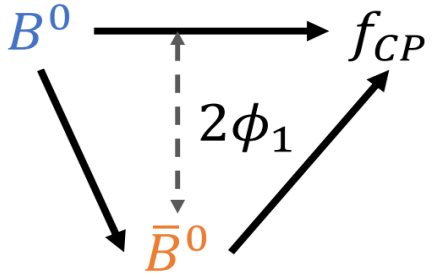
- Reconstruct other B as signal with missing energy
- Machine learning algorithm used to boost efficiency as much as possible
  - Comput. Softw. Big Sci. 3 (2019) 1, 6
- Total efficiency < 1% but a powerful tool
- Requires calibration



See Y. Uematsu's talk in WG4

B-factory analysis essentials 4 – vertexing and flavour tagging



$$\propto |V_{td}|^2 e^{2i\phi_1}$$

$\phi_1 \equiv \beta$

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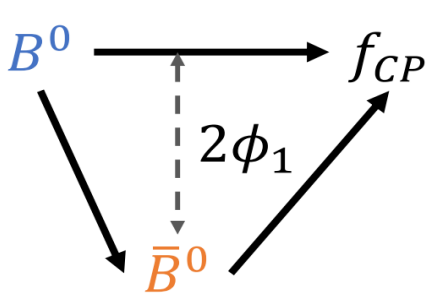

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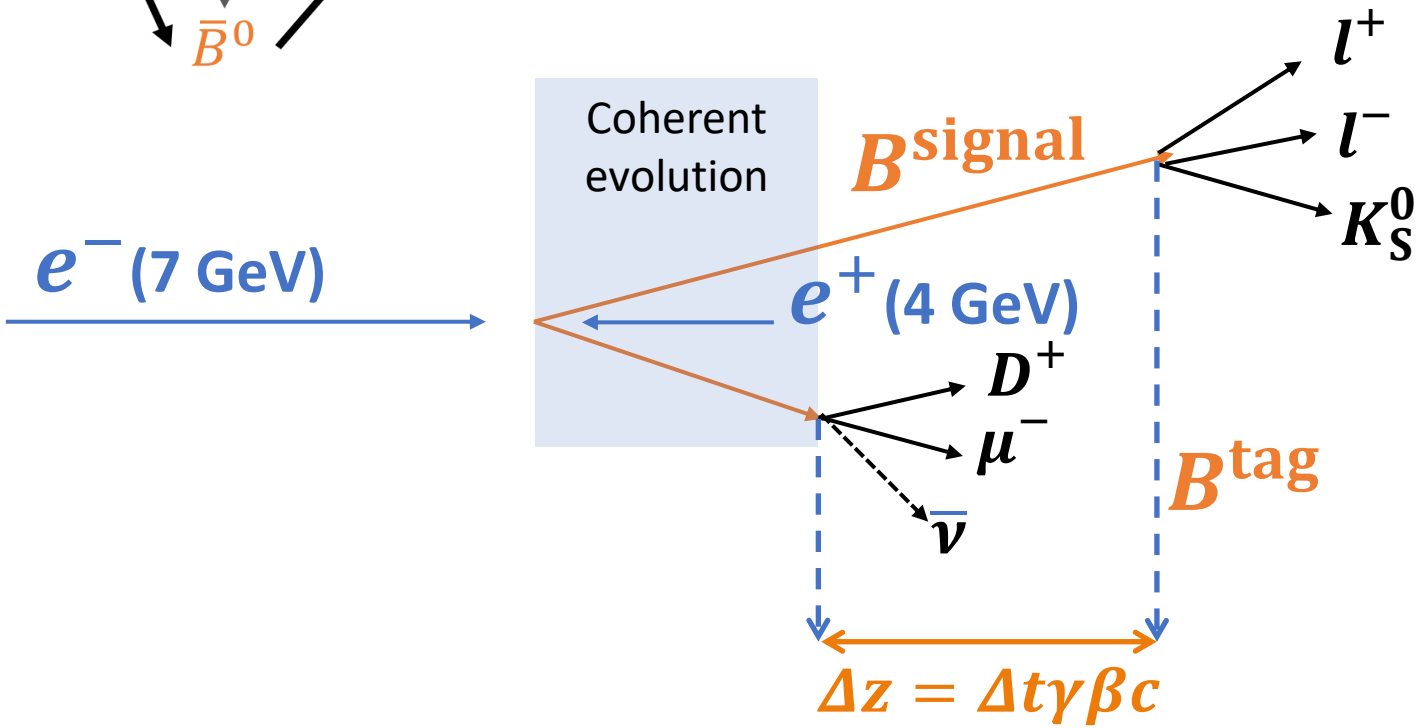

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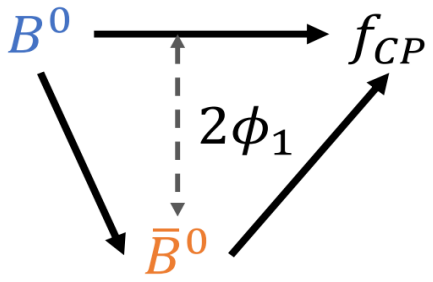

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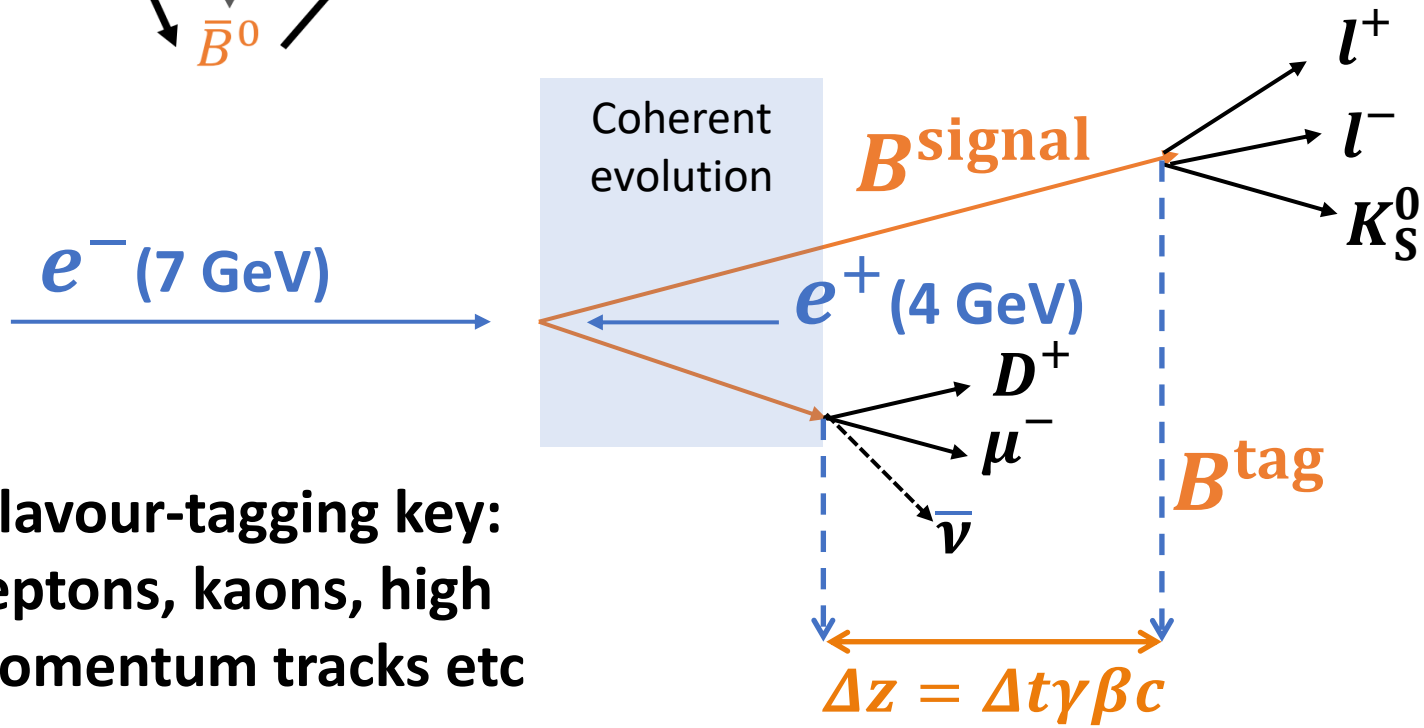
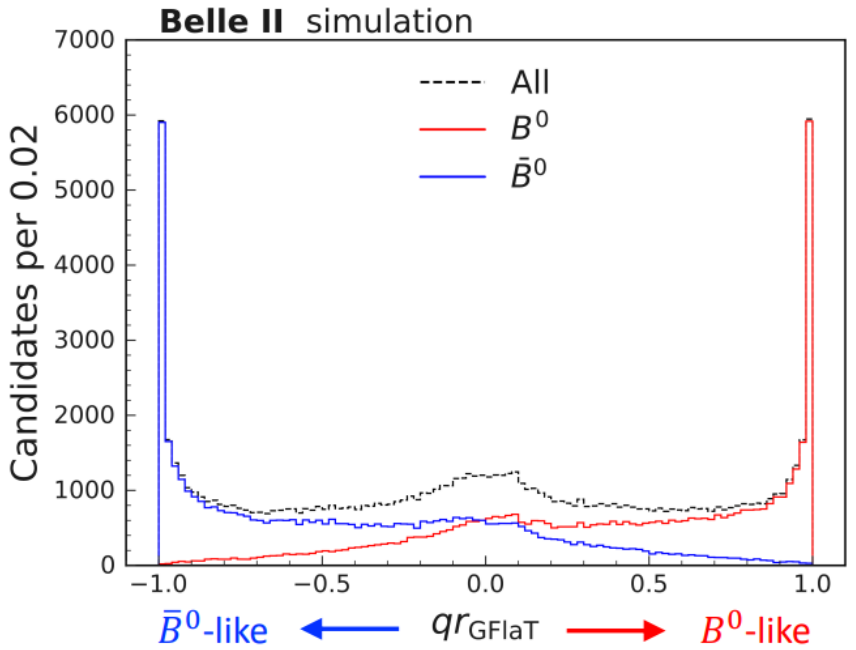


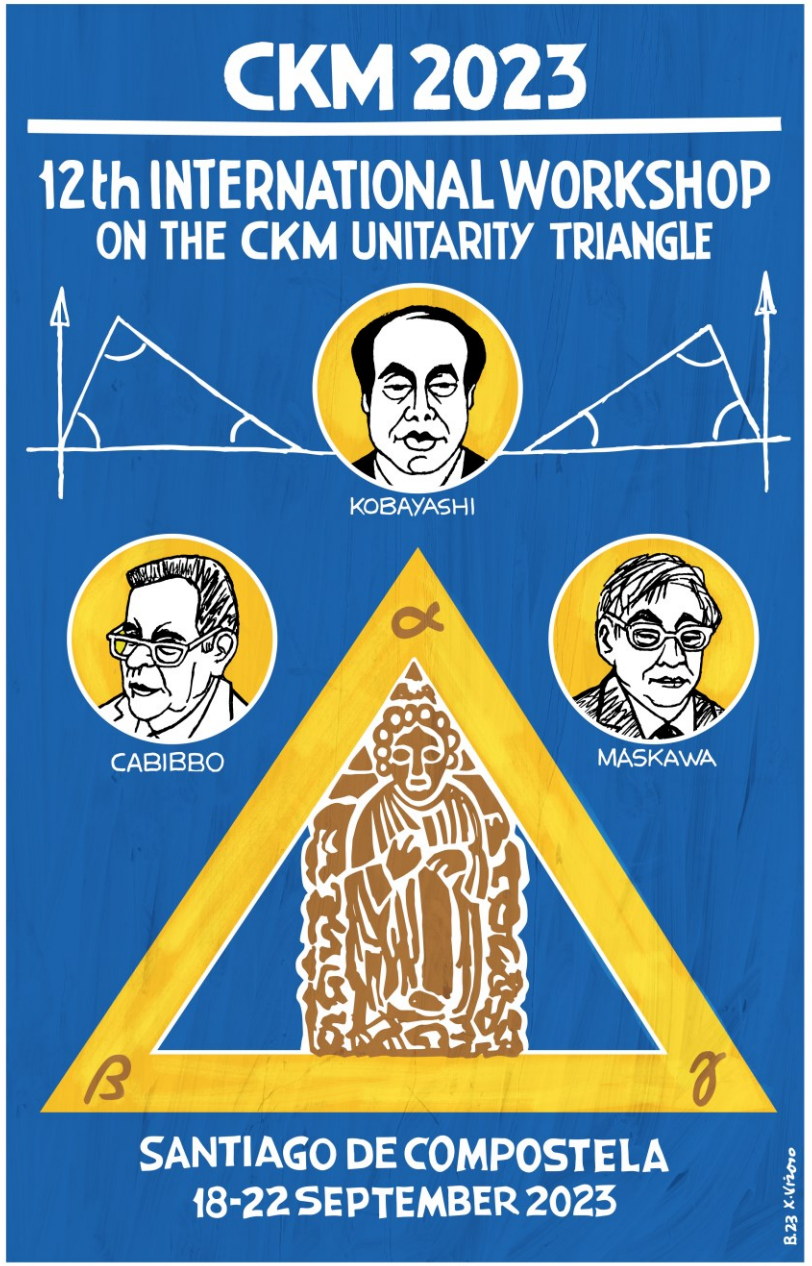
Flavour-tagging key: leptons, kaons, high momentum tracks etc



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

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

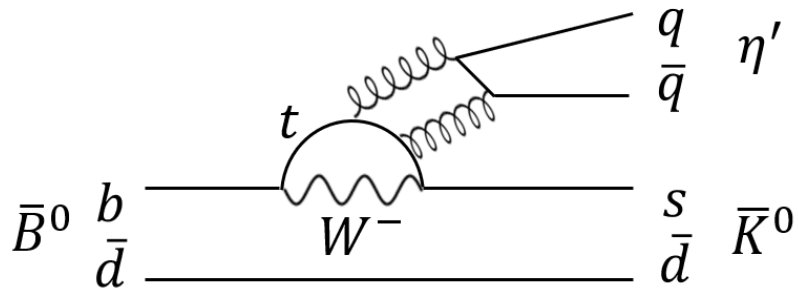
2) *CP* violation



Y. Uematsu's talk - WG4

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

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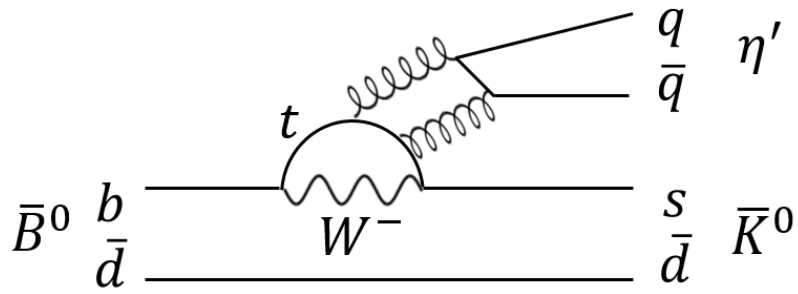
- Reconstructing $\eta' \to \eta(\gamma\gamma)\pi^+\pi^-$ and $\eta' \to \rho(\pi^+\pi^-)\gamma$ we select 829 ± 35 events in 362 fb^{-1} sample
  - 3D fit to ΔE, m_{BC} and continuum suppression output



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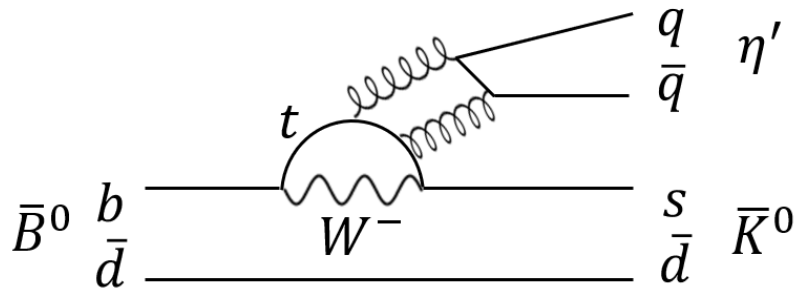
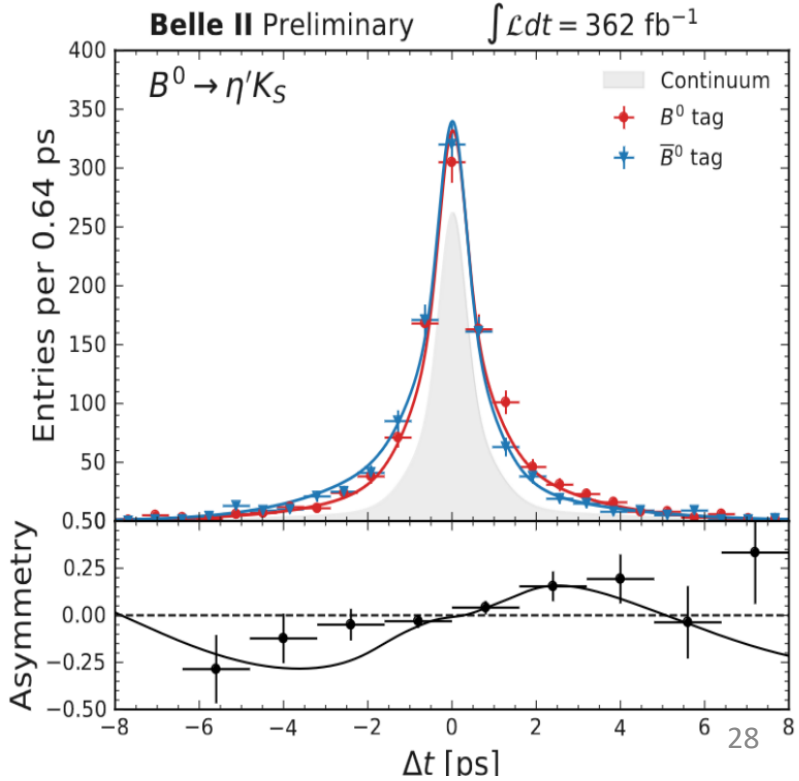
  - 3D fit to ΔE, m_{BC} and continuum suppression output
- **sin $2\phi_1$ = 0.67±0.10±0.04**
- Consistent with current HFLAV and that from $b \to c\bar{c}s$ result





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

M. Dorigo's talk – WG5

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)

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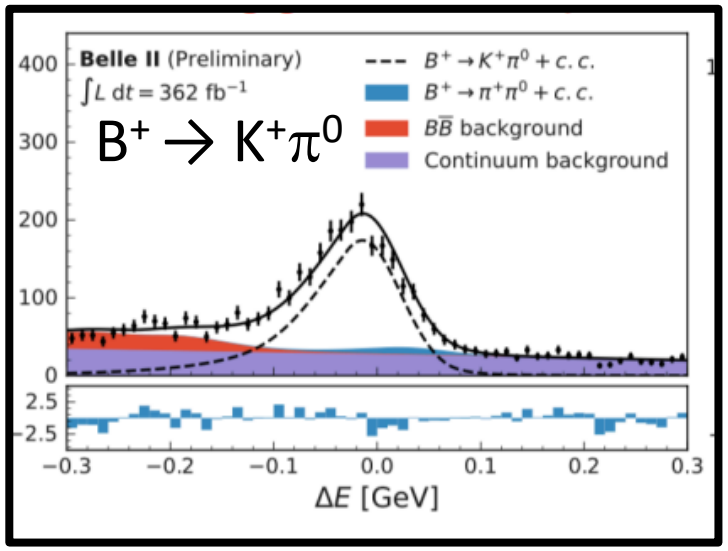
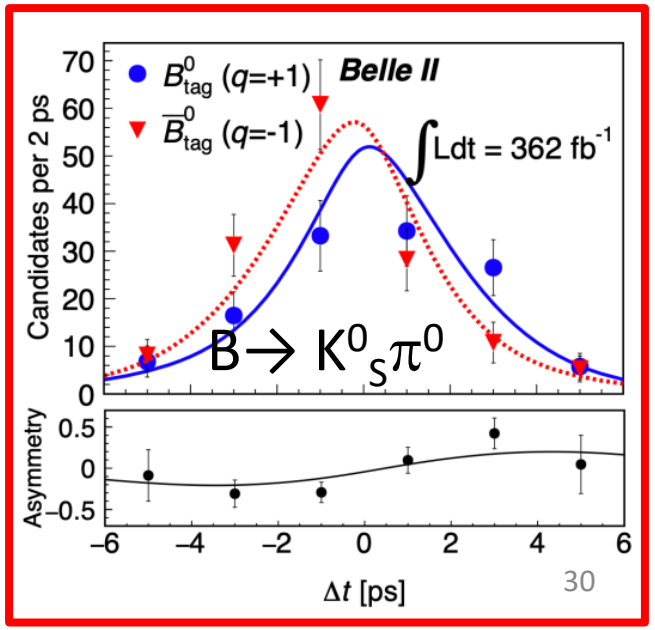


$B = (14.2 \pm 0.4 \pm 0.9) \times 10^{-6}$

Large π^0 efficiency syst.

$A_{K^0} = -0.01 \pm 0.12 \pm 0.05$

Combination of time-dependent and time-integrated analyses



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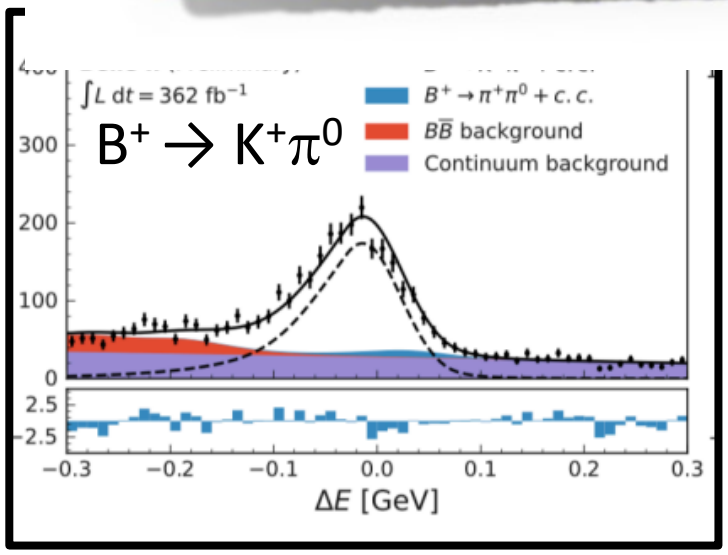
$$I_{K\pi} = (-3 \pm 13 \pm 5)\,\%$$

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



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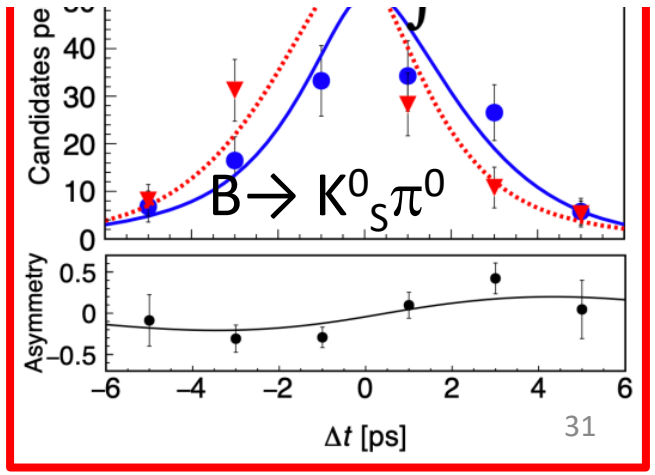
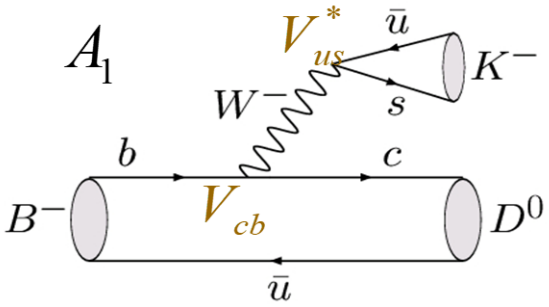


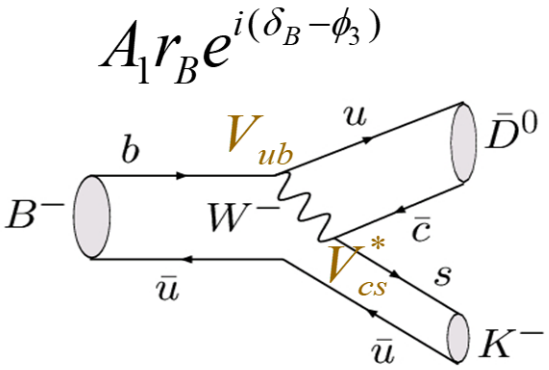
New for CKM – paper in preparation

γ/Φ_3: power of Belle + Belle II

K. Trabelsi's talk – WG5

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





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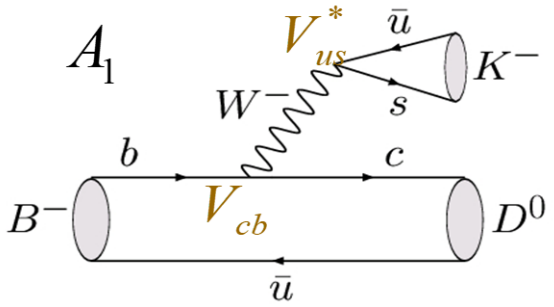
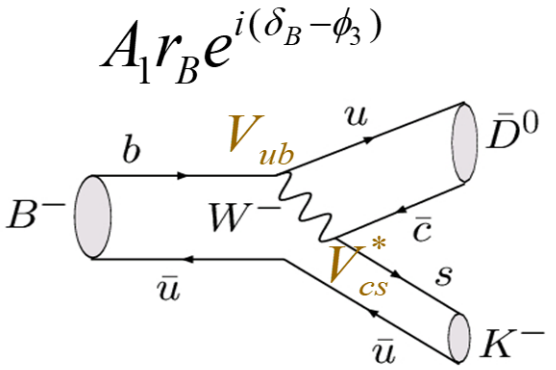
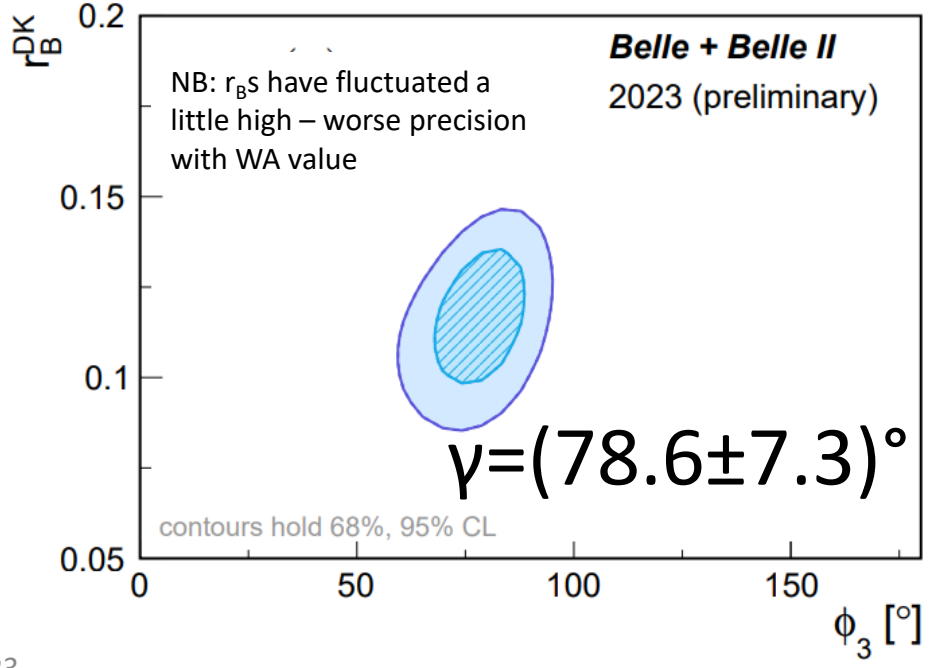
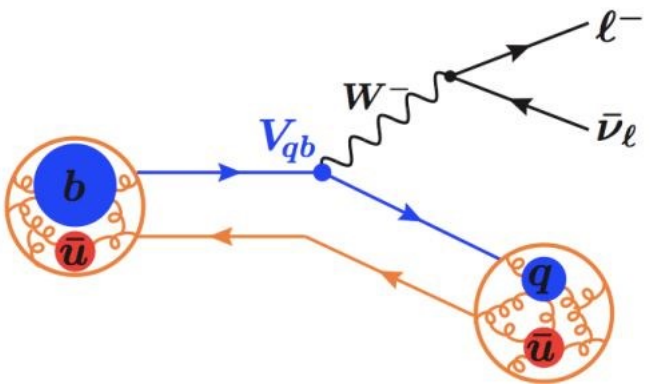
- LHCb leads the way: γ=(63.8±3.6)°
  - LHCB-CONF-2022-003
- Several Belle (711 fb^{-1}) + Belle II measurements (varying sample size) – total O(1 ab^{-1})
  - D→ K^0_S hh - JHEP 02 (2022) 063
  - D→ K^0_S Kπ - accepted by JHEP
  - D→ K^0_S π^0, KK - arXiv:2308.05048
  - + Belle-only D→Kπ and others
- A few ab^{-1} will give a good cross check of this SM parameter





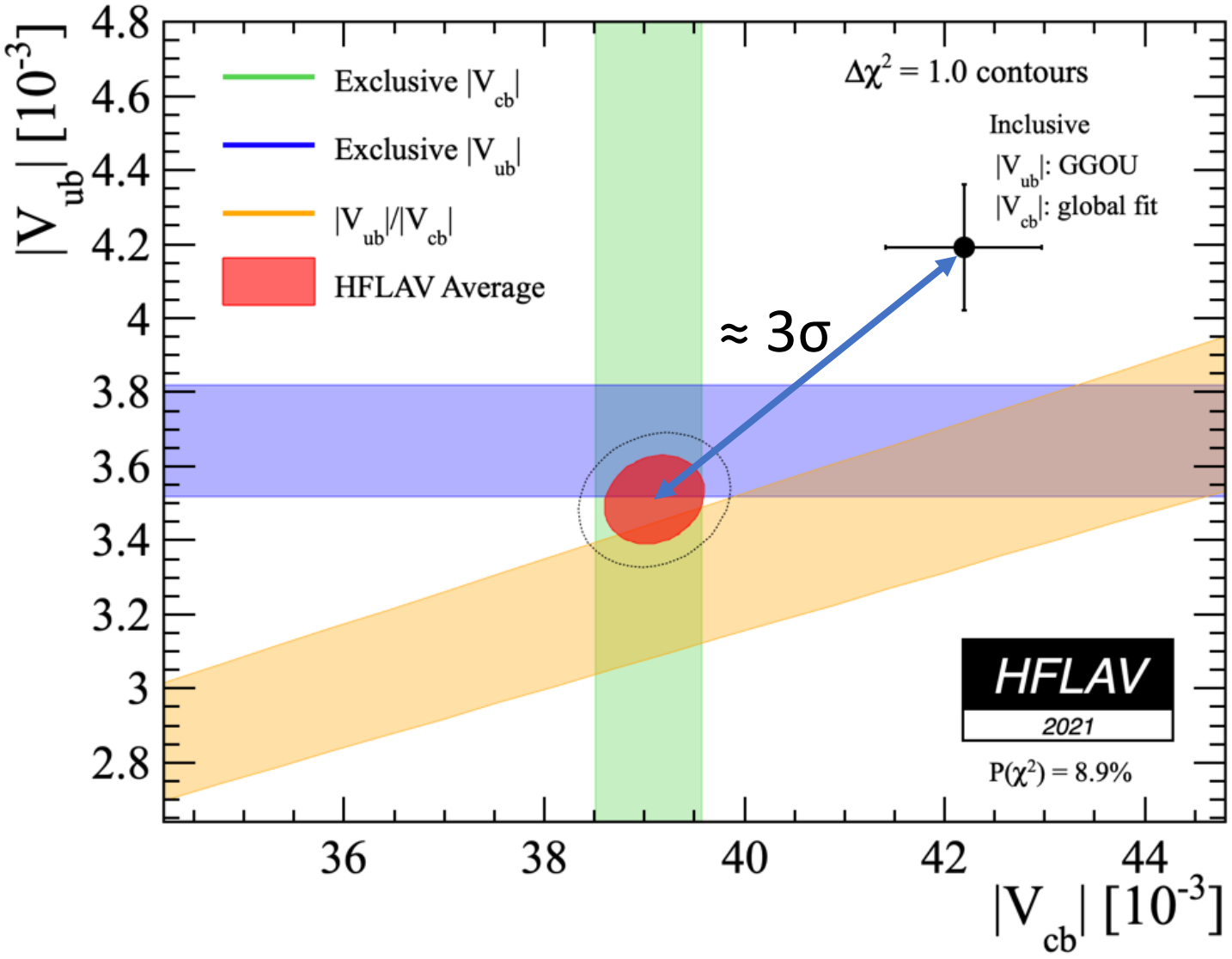




3) V_{xb}

Inclusive vs. exclusive

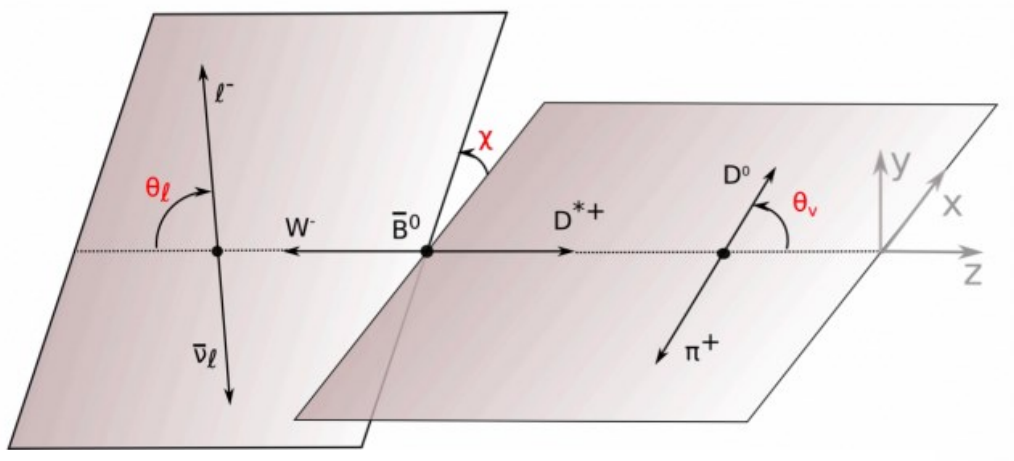
Theory + Experiment



Belle paper in preparation

Angular coefficients in B→D*lν and V_{cb}

- Measure 4D-differential distribution in terms of decay angles and w
  - overall proportionality to $|V_{cb}|^2$
  - $w \geq 1$ is the hadronic recoil parameter – relates to mom. transfer to the leptonic system



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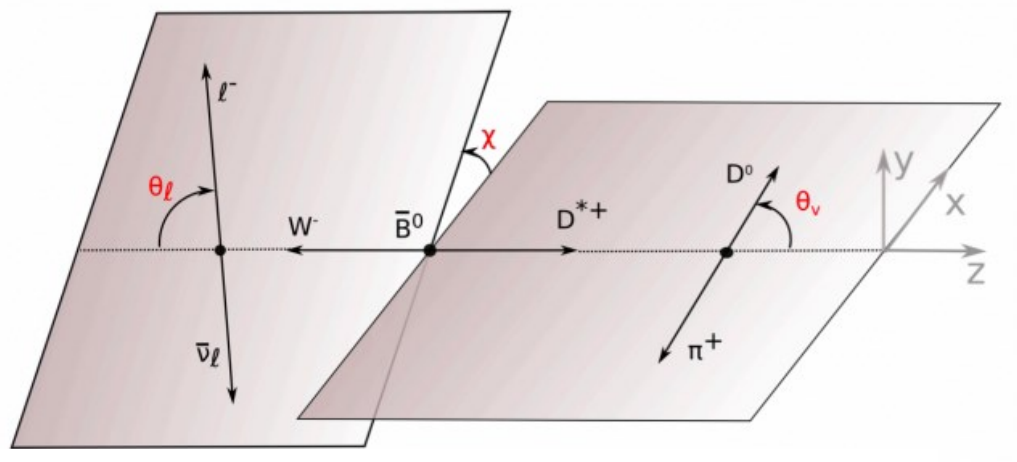

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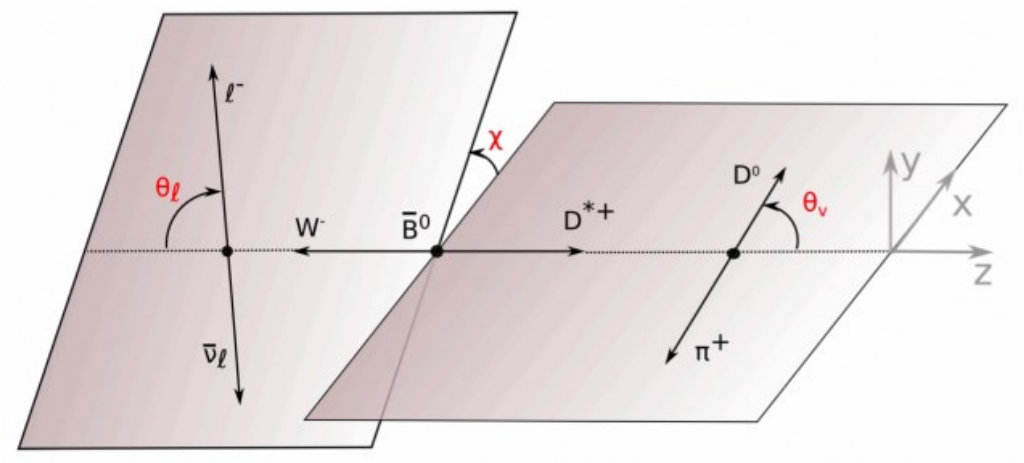
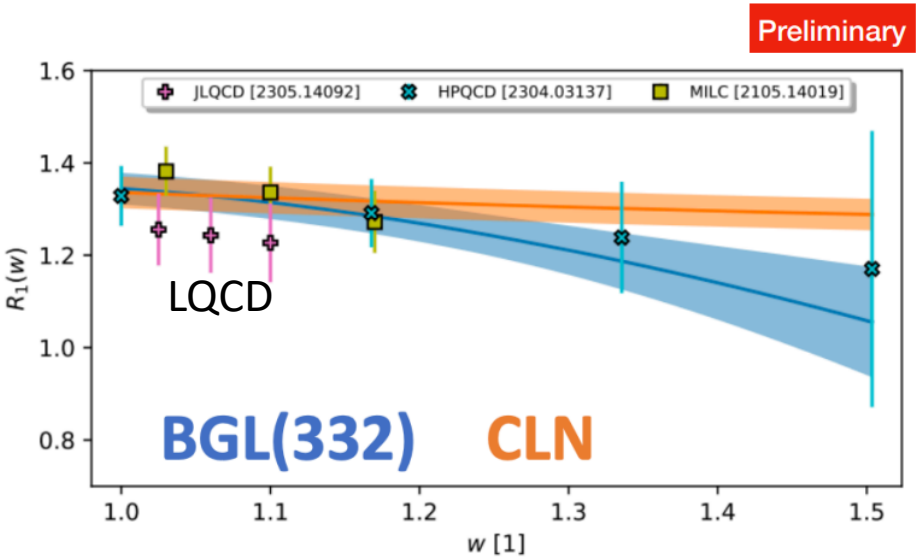
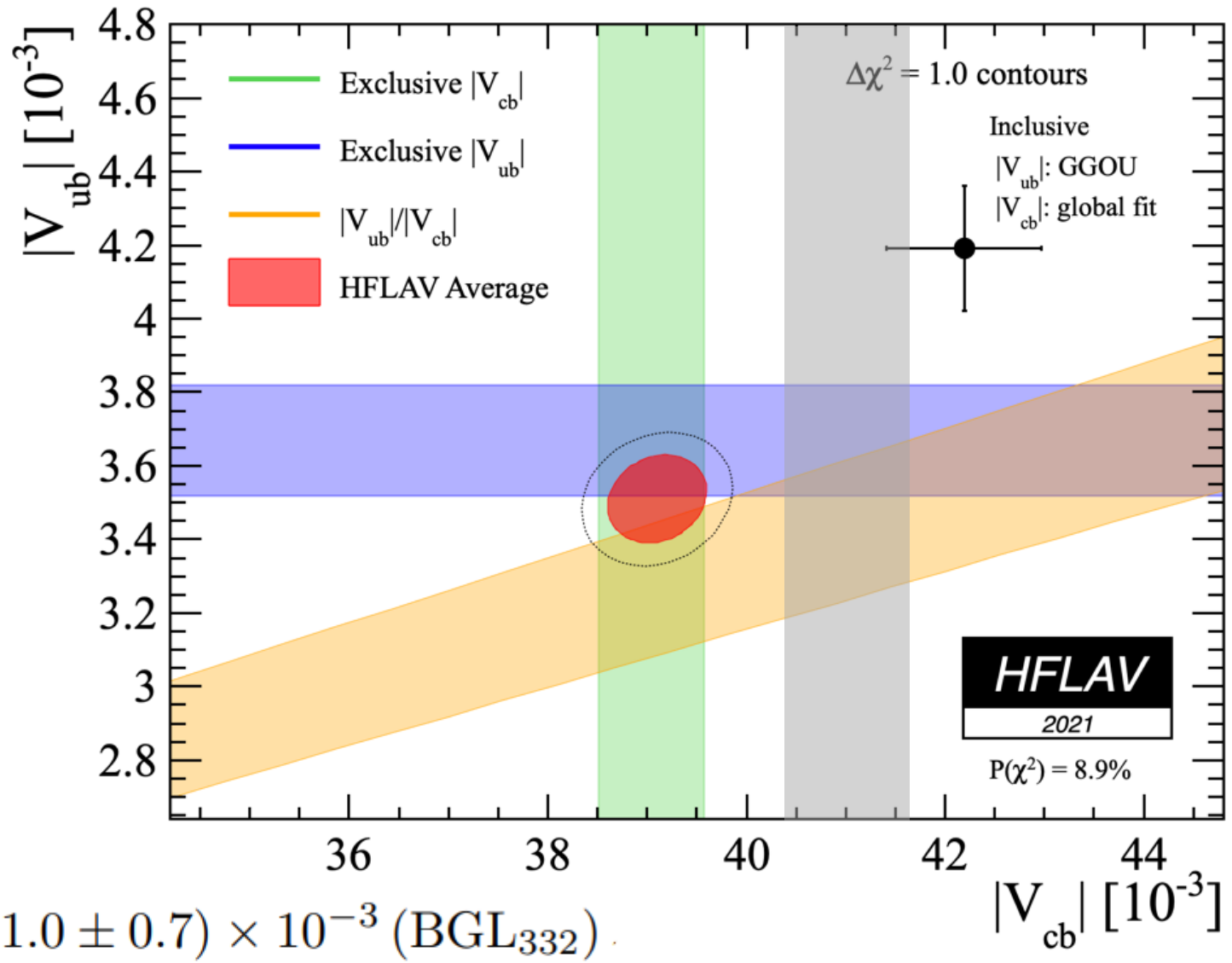
- Extract 12 angular coefficients of the distribution in bins of w for the first time using full Belle 711 fb^{-1} sample
  - hadronically tagged
- Fit performed to coefficients in different form-factor parameterizations and with LQCD inputs to extract V_{cb} as well as parameters of the form-factor model
  - WA BF also taken externally







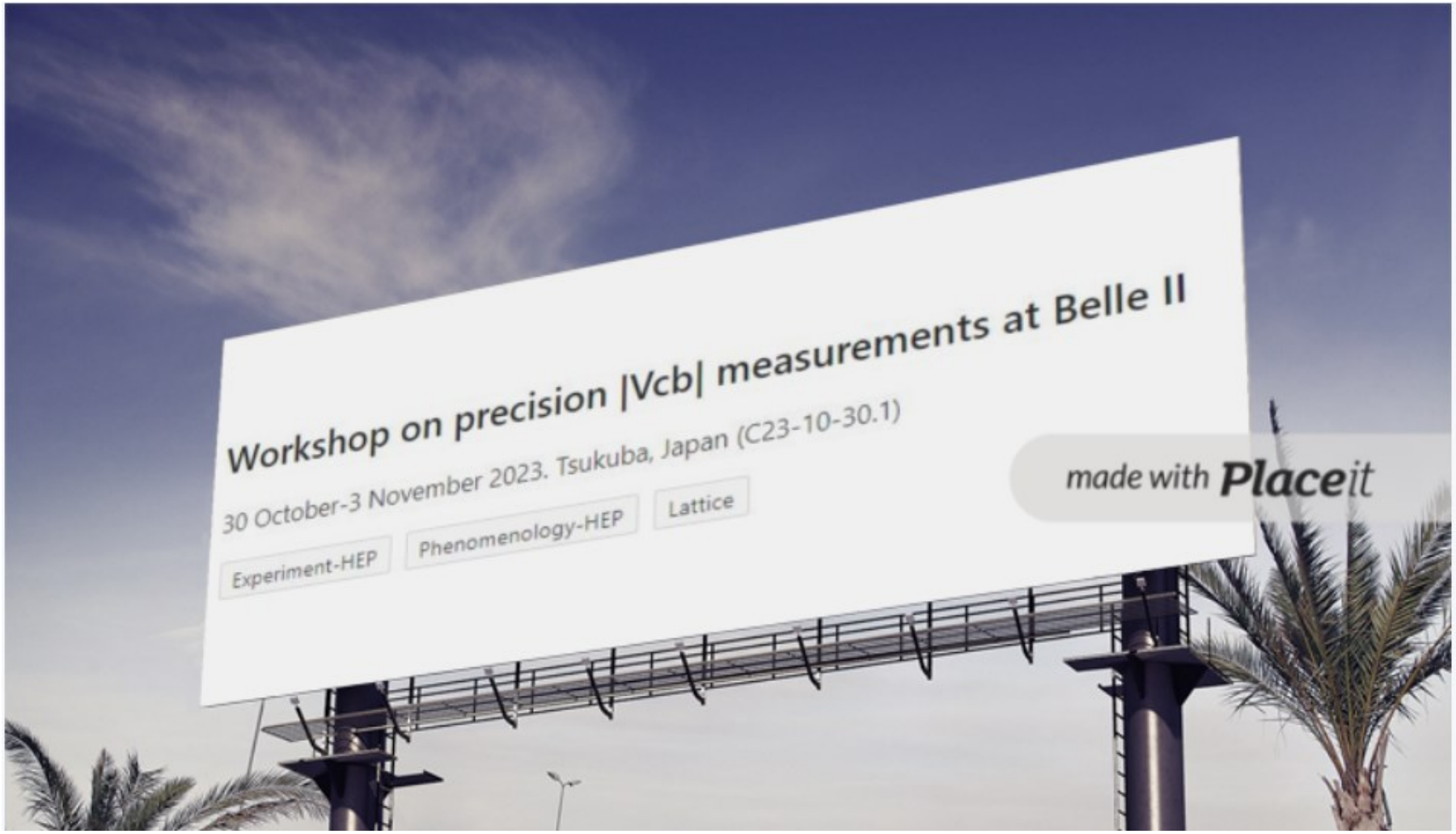
$$|V_{\mathrm{cb}}| = (41.0 \pm 0.7) \times 10^{-3}\,(\mathrm{BGL}_{332})$$

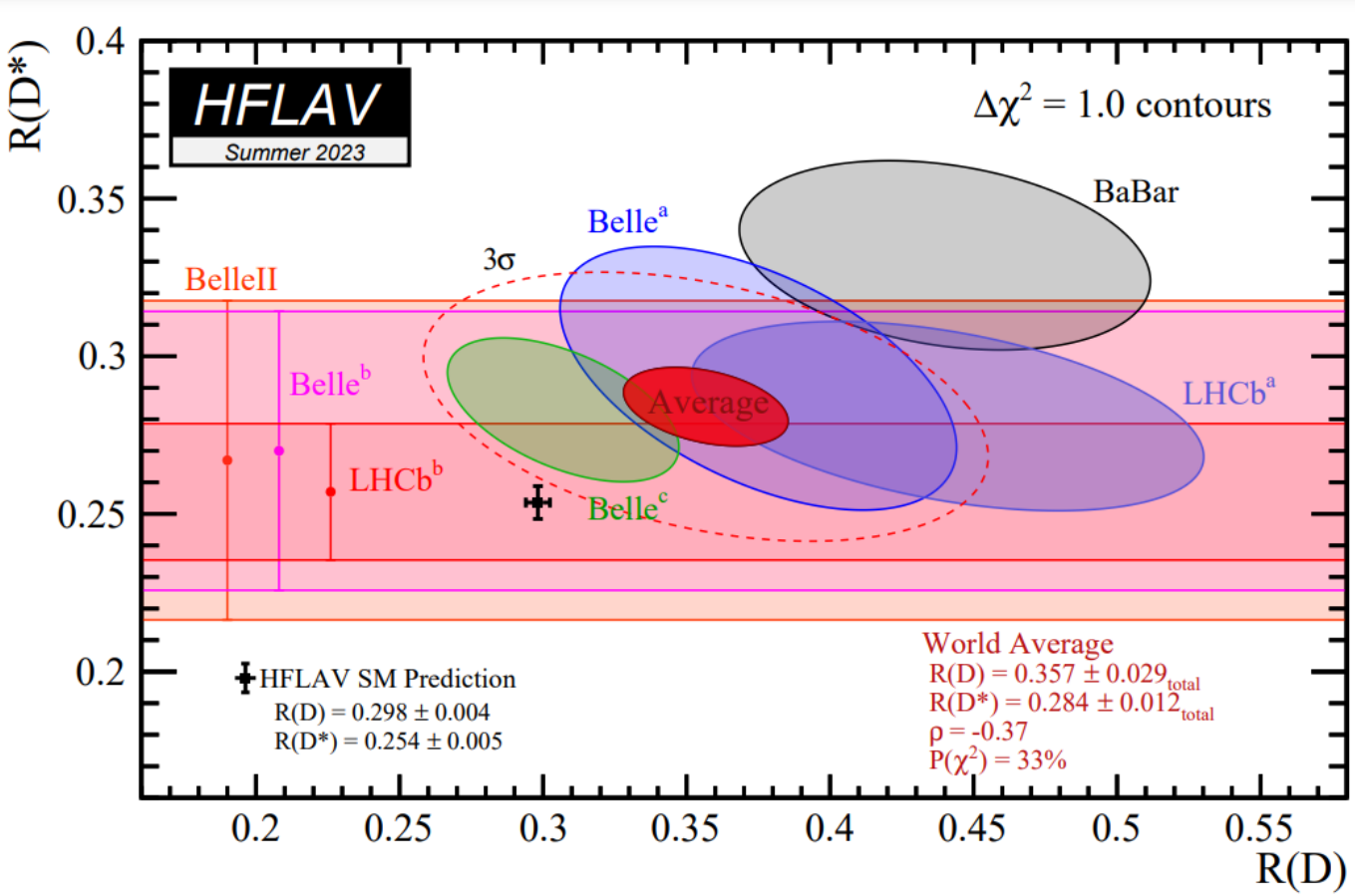
$$|V_{\mathrm{cb}}| = (40.9 \pm 0.7) \times 10^{-3}\,(\mathrm{CLN})$$

Commercial break

C. Schwanda (exclusive) WG2
M. Prim (inclusive) WG1+2

https://indico.belle2.org/event/9402/



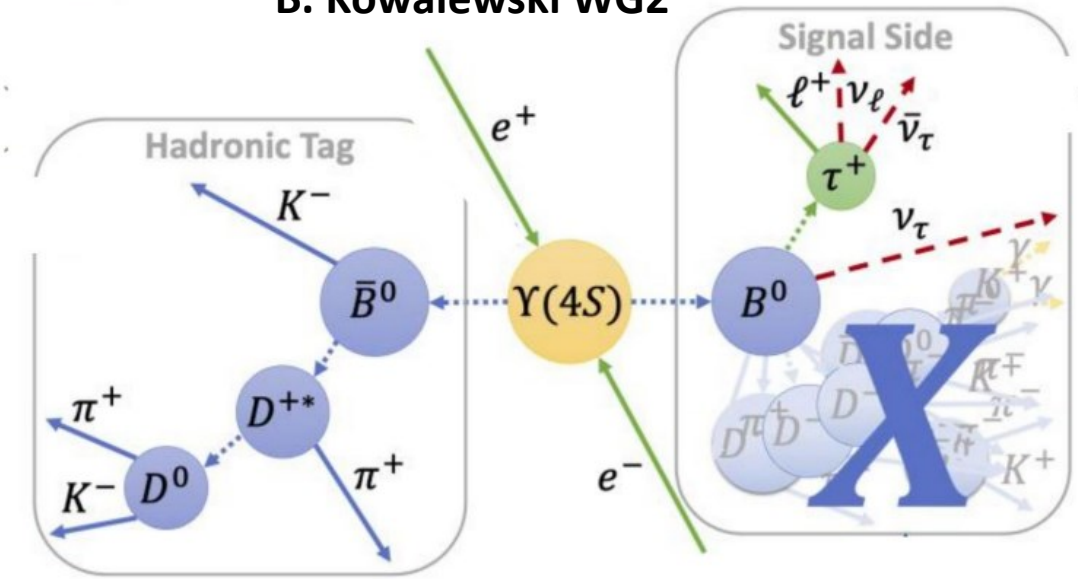


4) Lepton flavour/universality violation and rare decays

Beyond CKM

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



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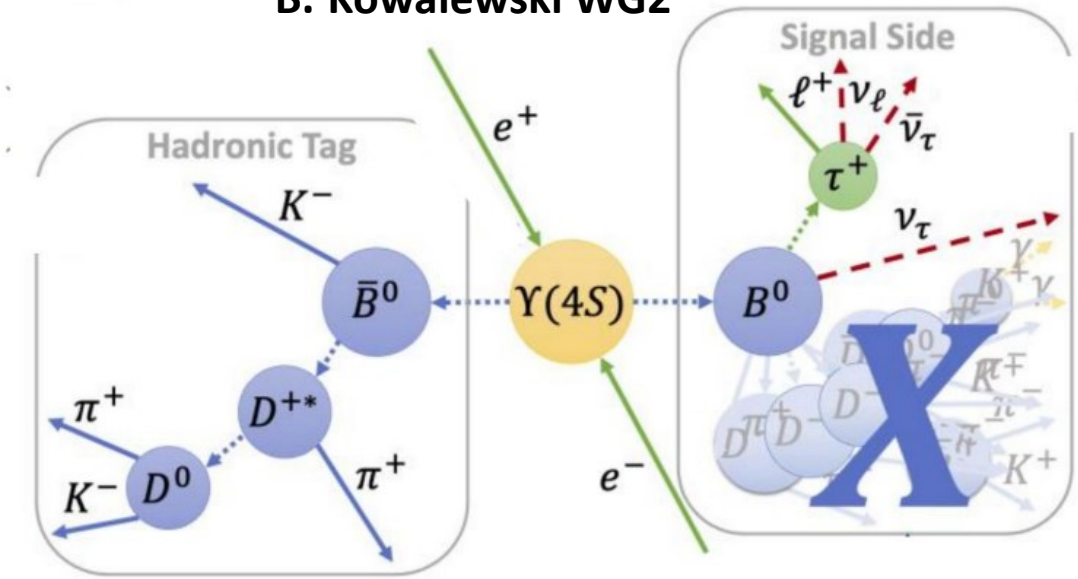
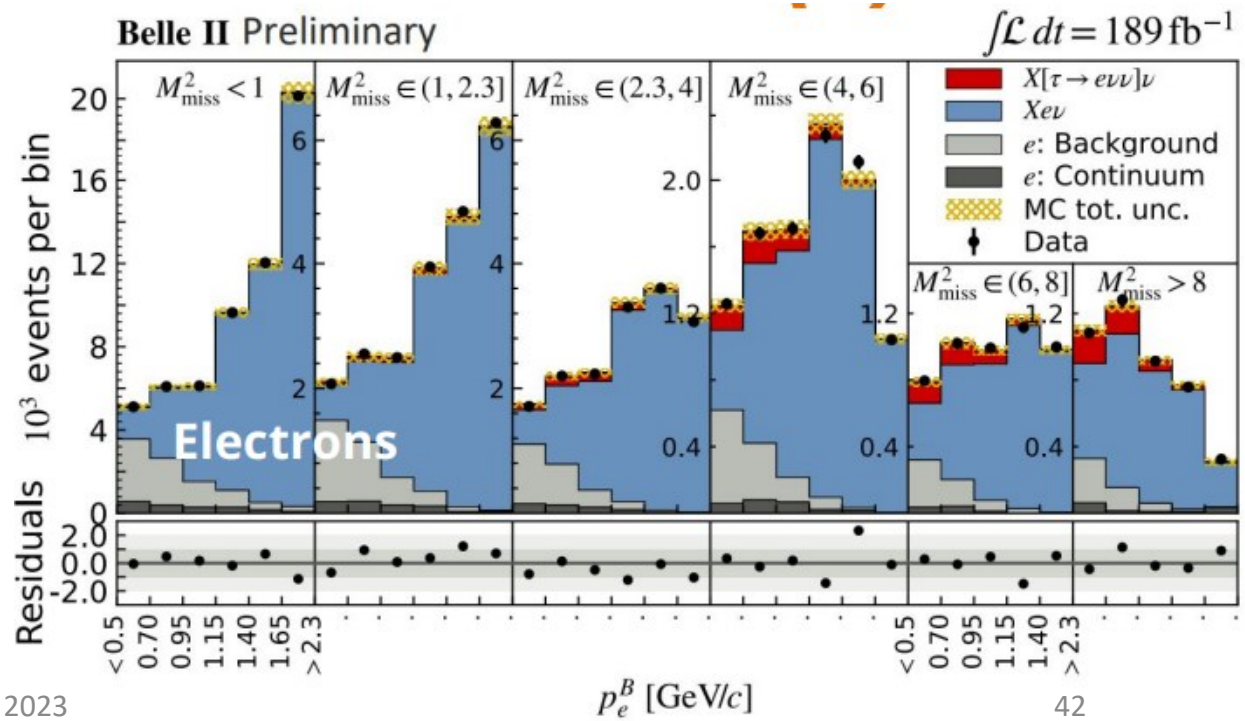
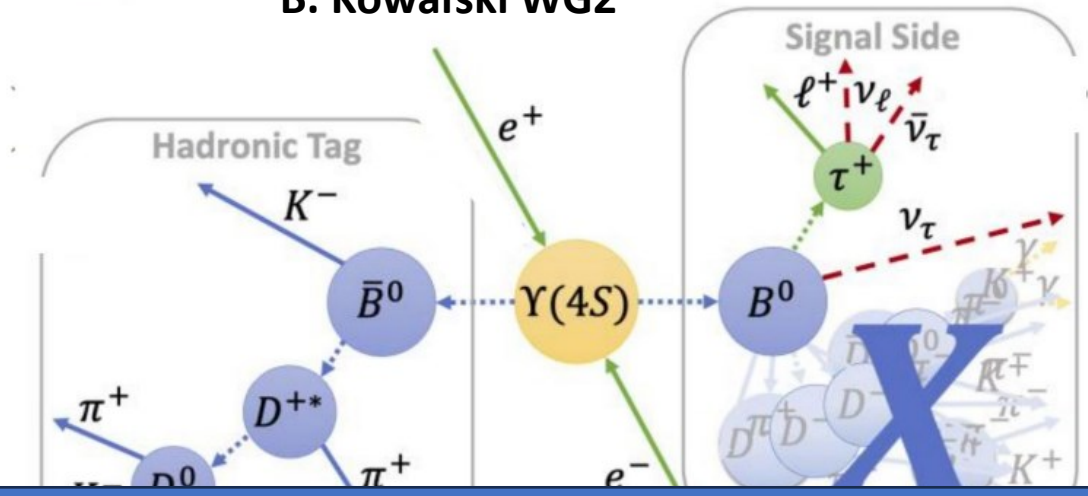
  - A complementary alternative to R($D^{(*)}$)
- Hadronic-tagging method with a 189 fb^{-1} Belle II sample
- Use missing-mass squared and lepton momentum to isolate signal above B→Xlv background
- Background templates calibrated to control samples and sidebands





Measurement of R(X)

- Inclusive ratio $R(X) = \frac{BF(B \to X\tau\nu)}{BF(B \to Xl\nu)}$
  - A unique alternative to R(D$^{(*)}$)
- Signal above B→Xlν background
- Background templates calibrated to control samples and sidebands

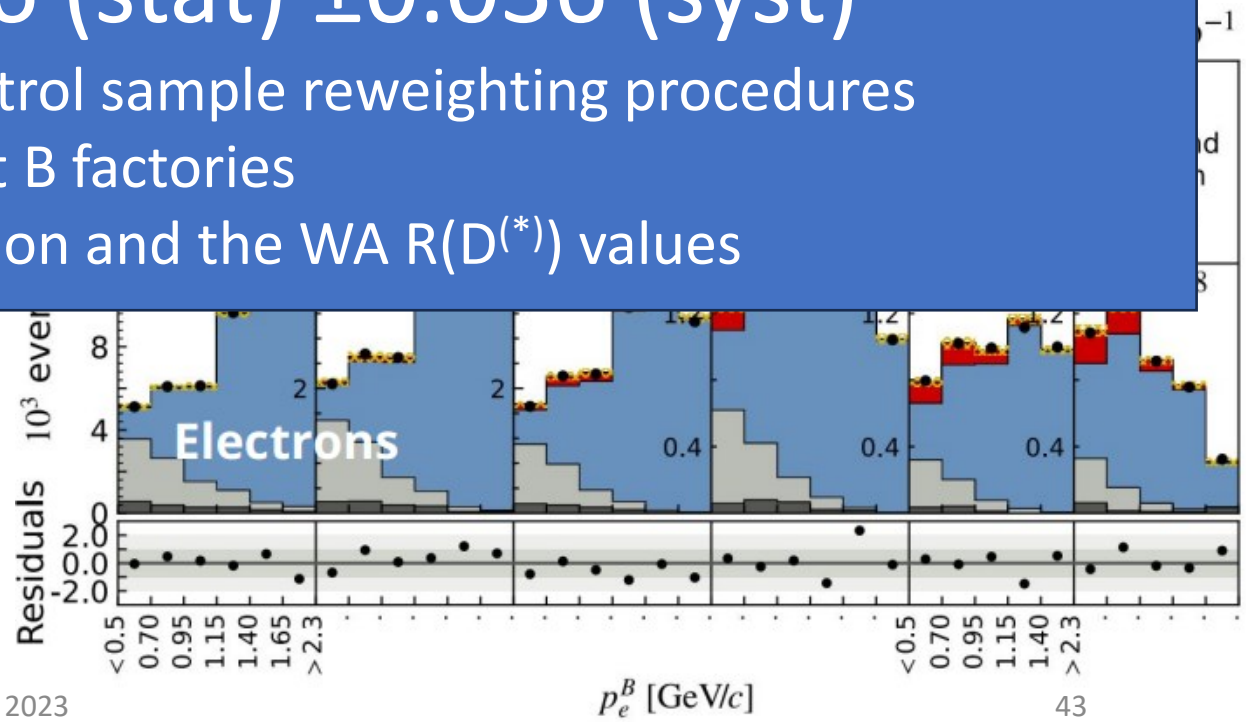


R(X)=0.228±0.016 (stat) ±0.036 (syst)

Systematics dominated by control sample reweighting procedures

First at B factories

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



PRL 130, 261802 (2023)

Belle search for $B^+ \to K^+ \tau^\pm l^\mp$

- Lower bounds on branching fractions in U(1) leptoquark models at O(10^{-7})
  - PRD 104, 055017 (2021)

PRL 130, 261802 (2023)

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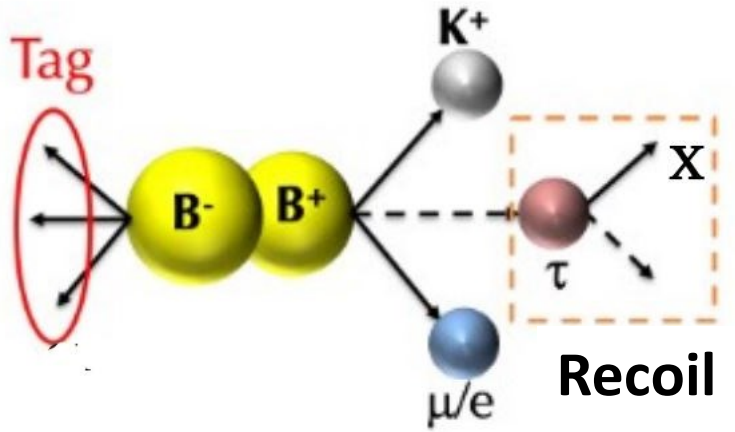
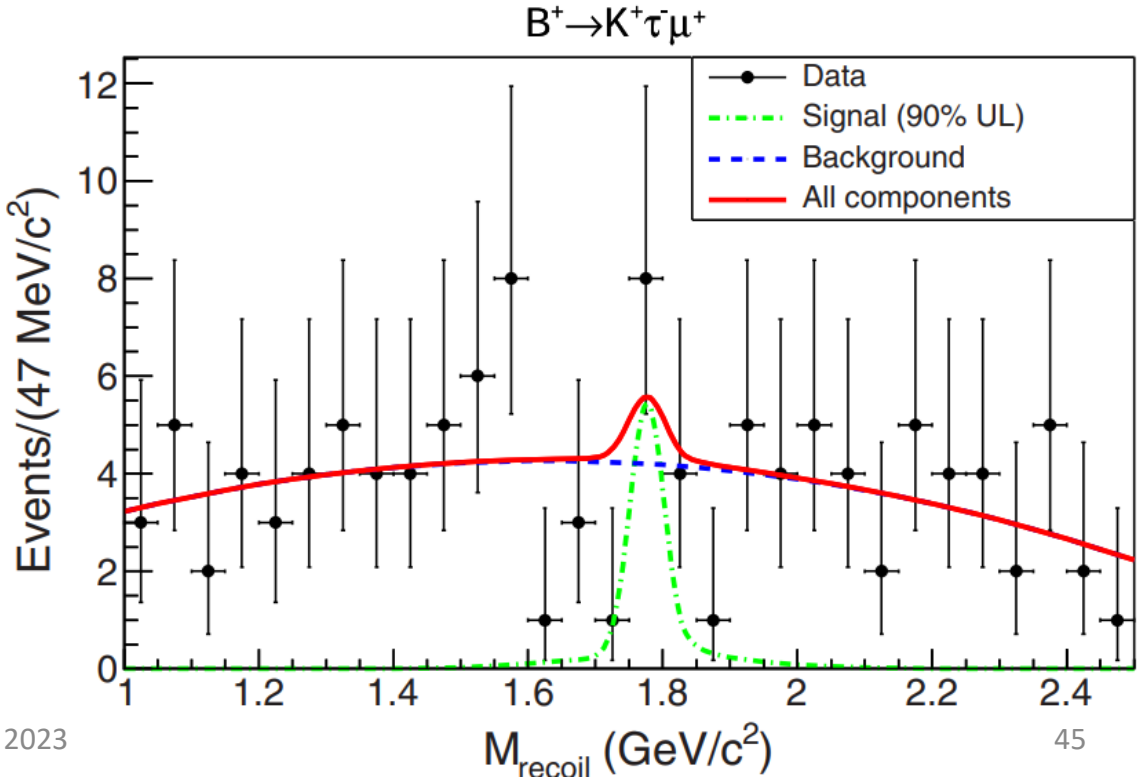
- Belle 711 fb^{-1} data sample
- Hadronic tagging – then use tag, kaon and lepton four momentum to workout recoil mass





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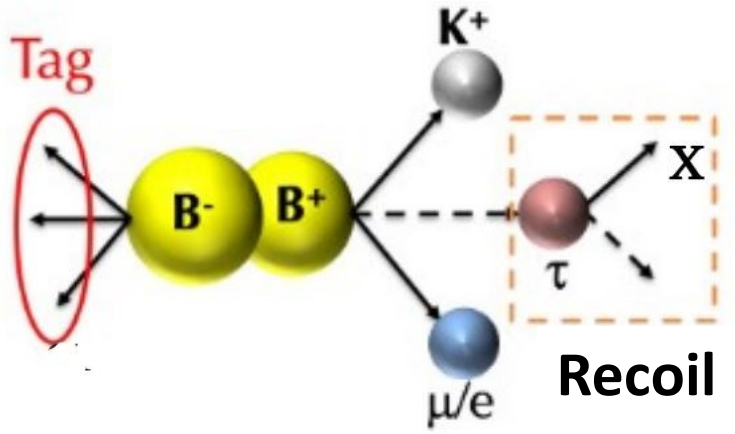

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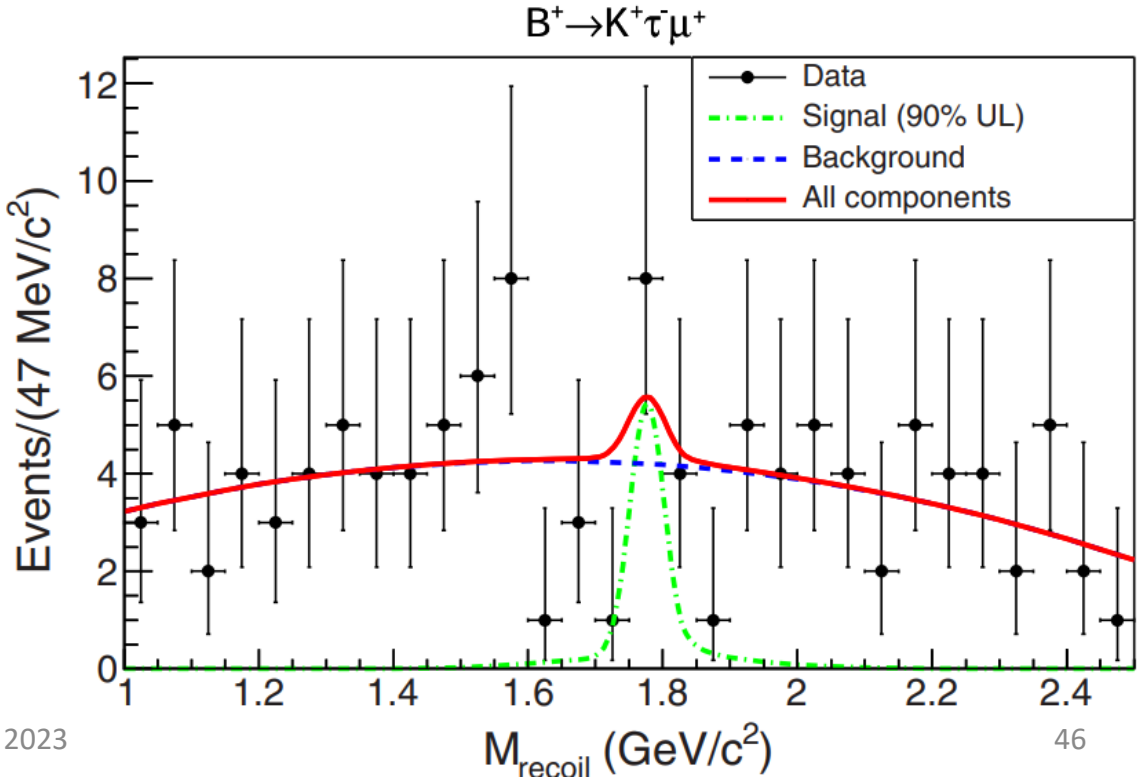
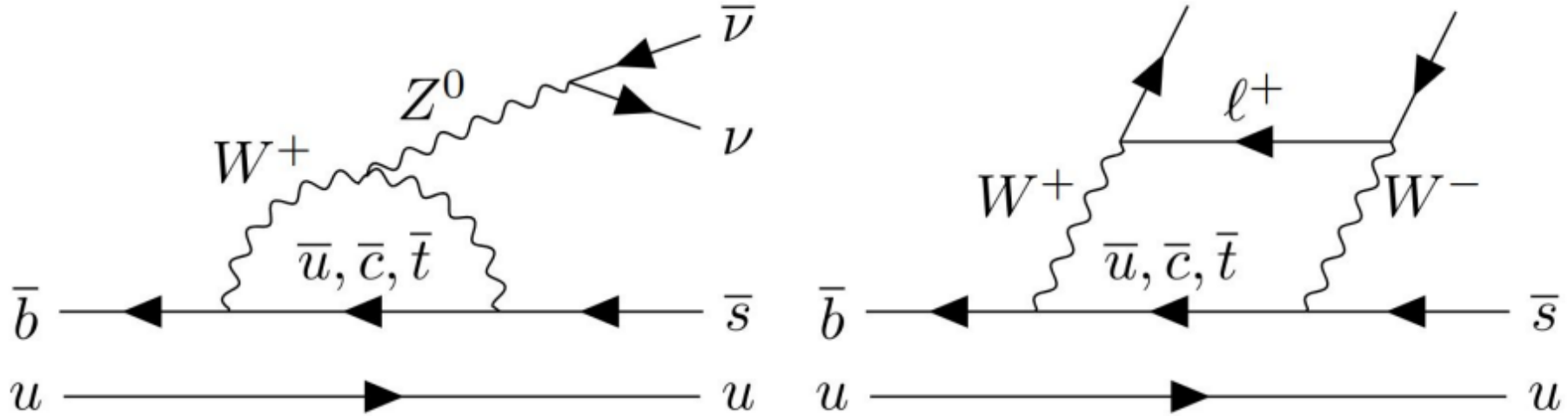
$$\mathcal{B}(B^+ \to K^+\tau^+\mu^-) < 0.59 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\tau^+e^-) < 1.51 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\tau^-\mu^+) < 2.45 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to K^+\tau^-e^+) < 1.53 \times 10^{-5}$$

World leading



S. Stefkova WG3
Belle II paper in preparation

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



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

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Belle II paper in preparation

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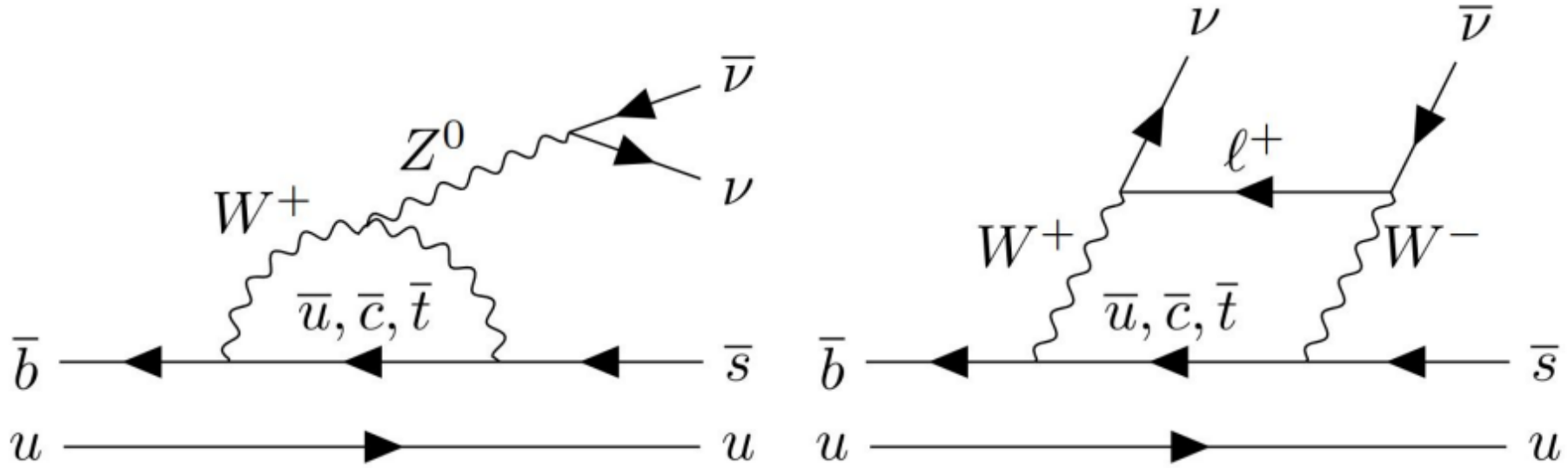
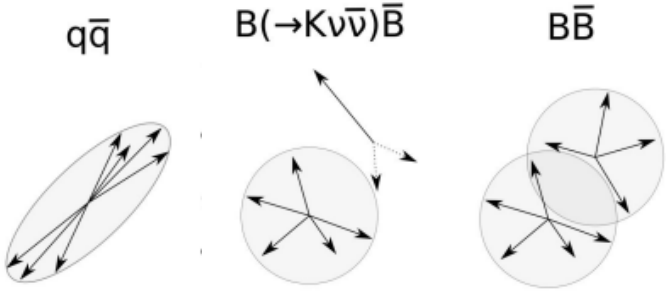


- Well known in SM but very sensitive to BSM enhancements
  - $B(B \to K^+ \nu\nu) = (5.6 \pm 0.4) \times 10^{-6}$ [arXiv:2207.13371]
- Challenging experimentally
  - Low branching fraction with large background
  - No peak – two neutrinos leads to no good kinematic constraint

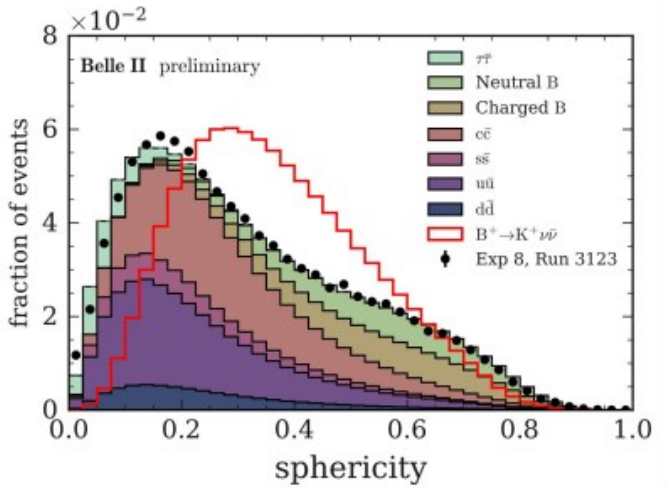
$B^+ \to K^+ \nu\bar{\nu}$: Analysis strategy

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

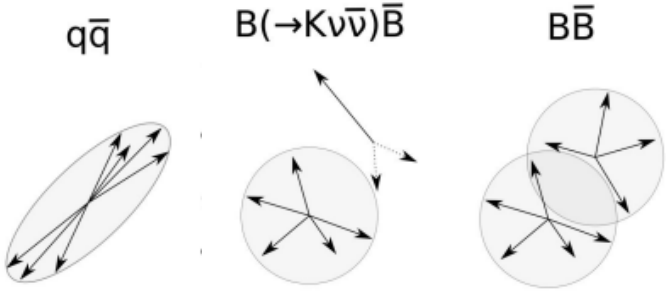
$B^+ \to K^+ \nu\bar{\nu}$: Analysis strategy



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



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



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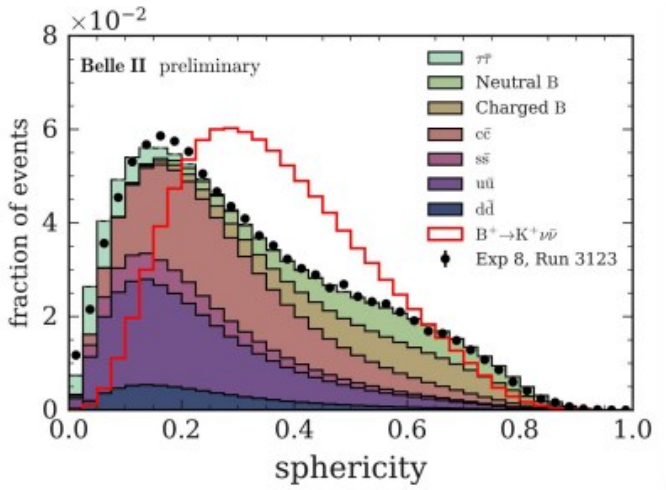
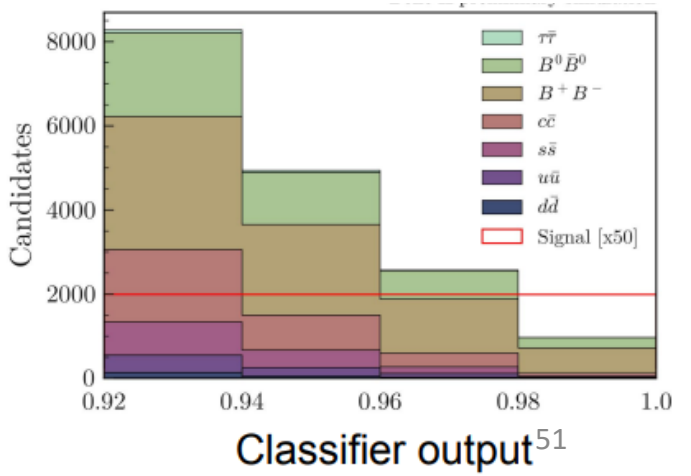
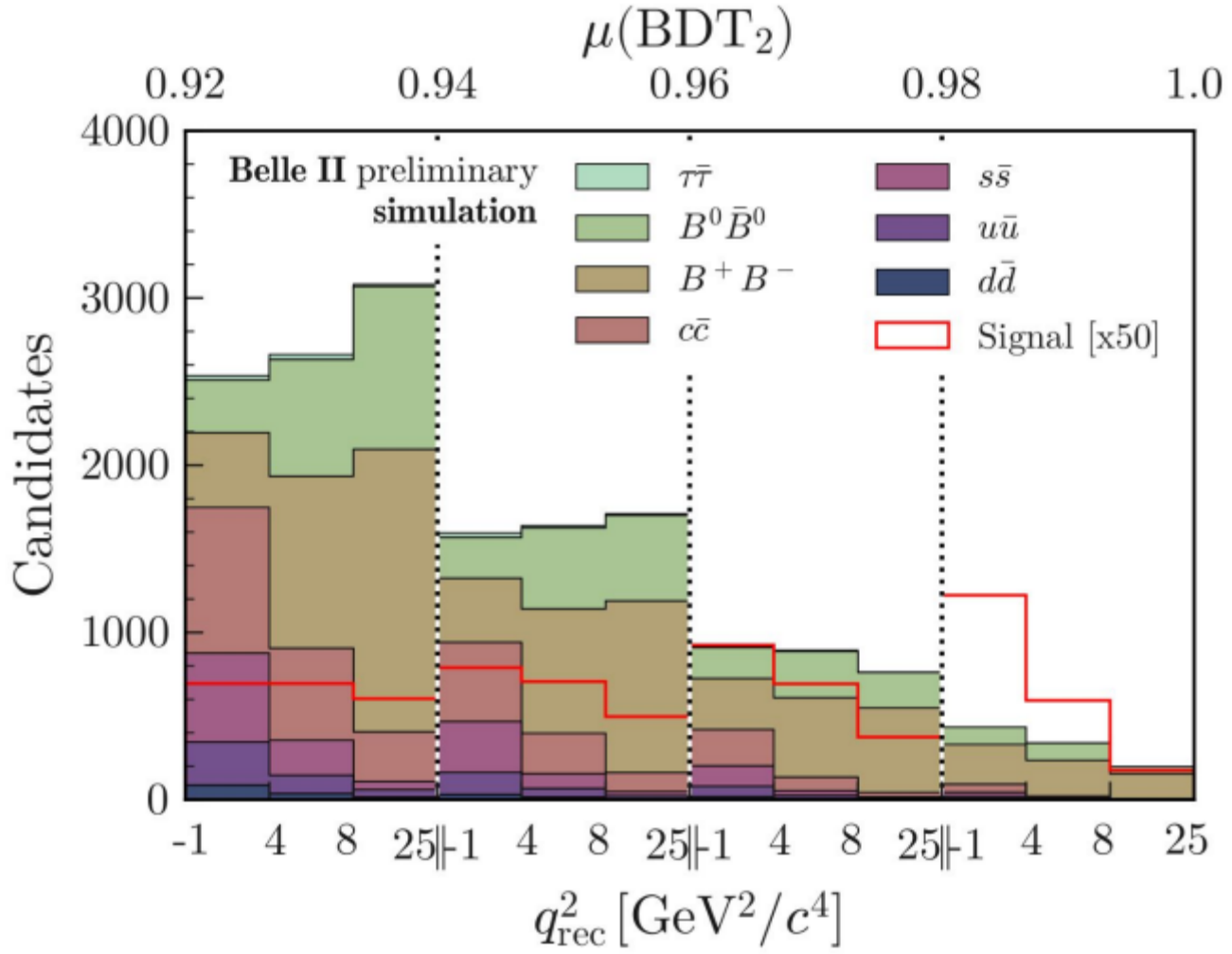
    2. First boosted decision tree (BDT1): 12 variables
    3. Second BDT2: 35 variables – 3 times sensitivity
    4. BDT2 fit extraction variable in bins of $\nu\bar{\nu}$ mass-squared – q^2
  - Hadronic tag: single BDT for fit
    - key variable any additional calorimeter energy other than K+tag





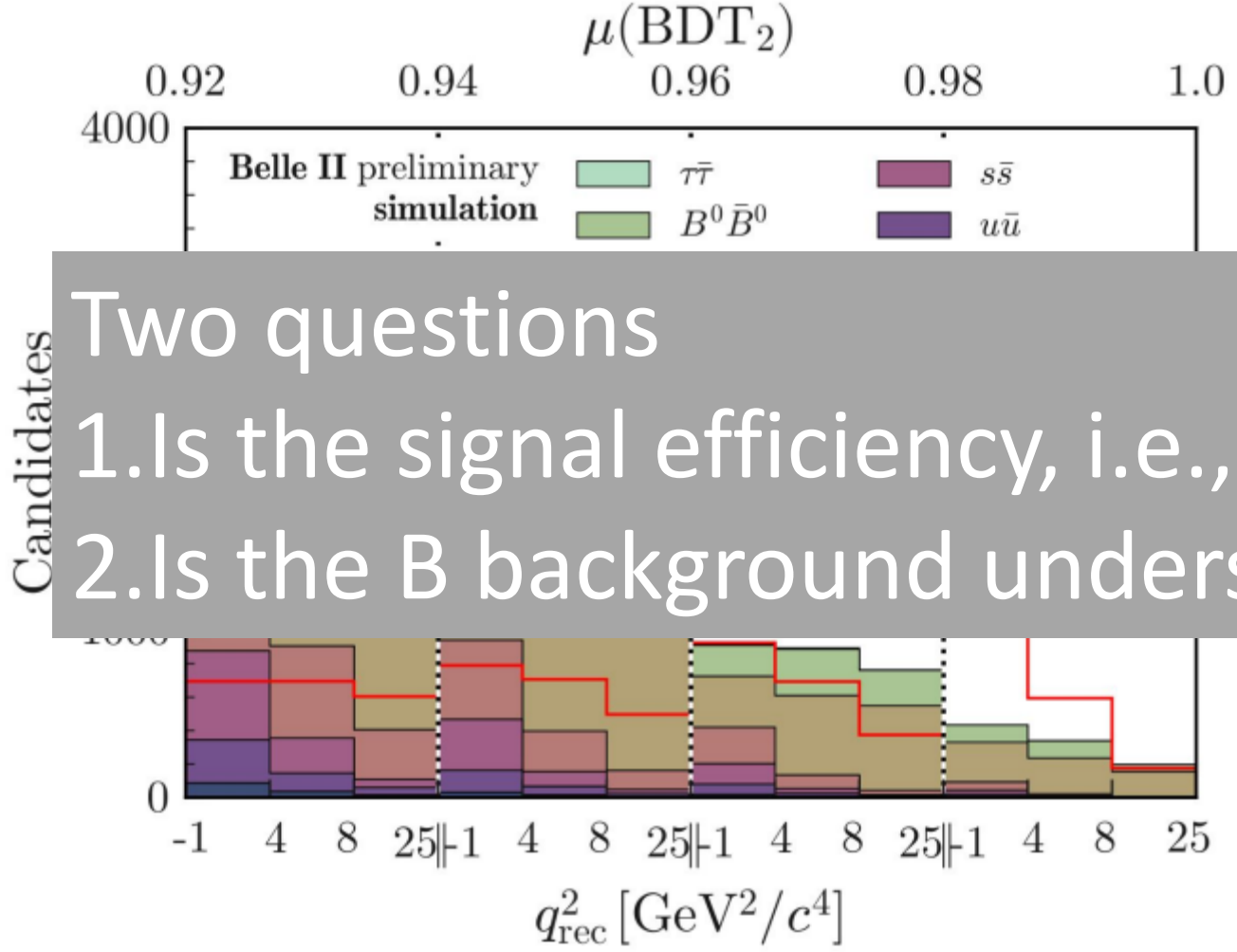
$B^+ \to K^+ \nu\bar{\nu}$: Inclusive signal extraction



(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

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

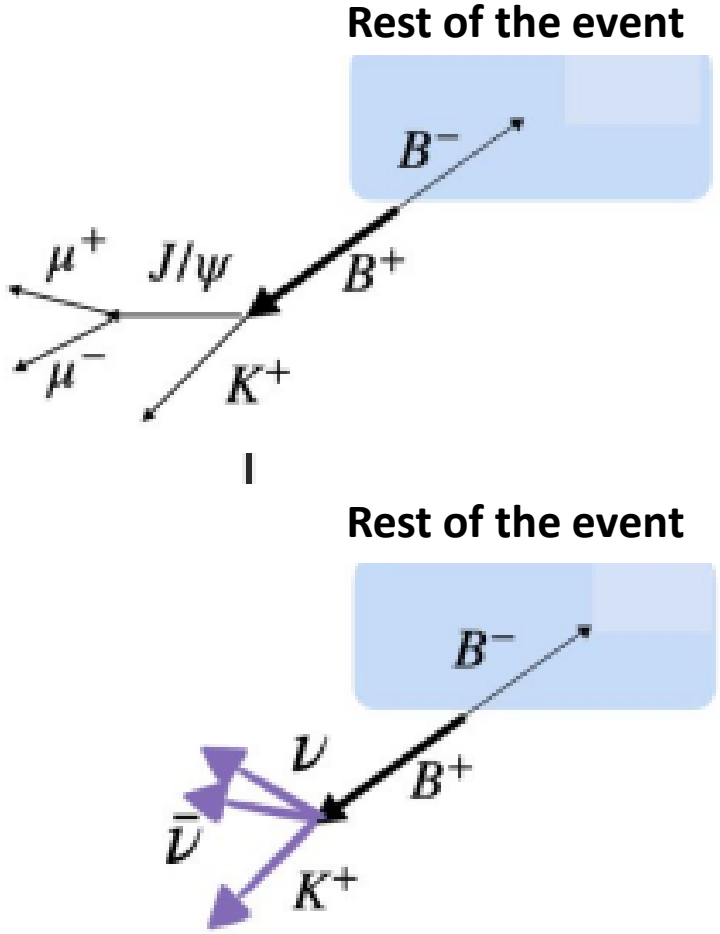


(3 bins in q^2_{rec}) x (4 bins in $\mu(\mathrm{BDT}_2)$)

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

- 1 signal and 7 background templates from simulation
- Continuum template constrained by off-resonance

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



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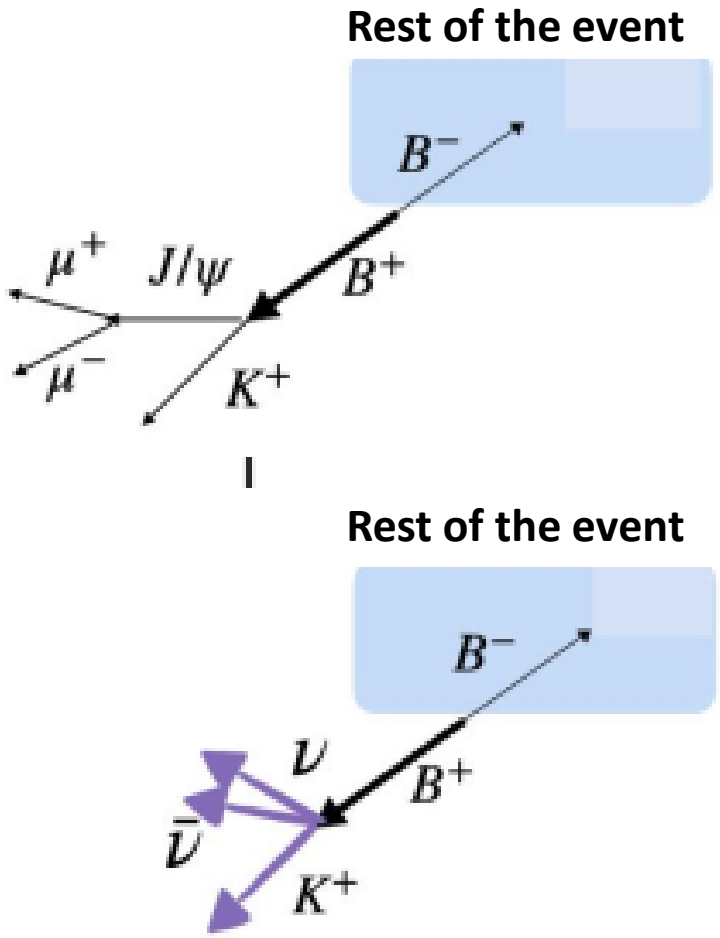
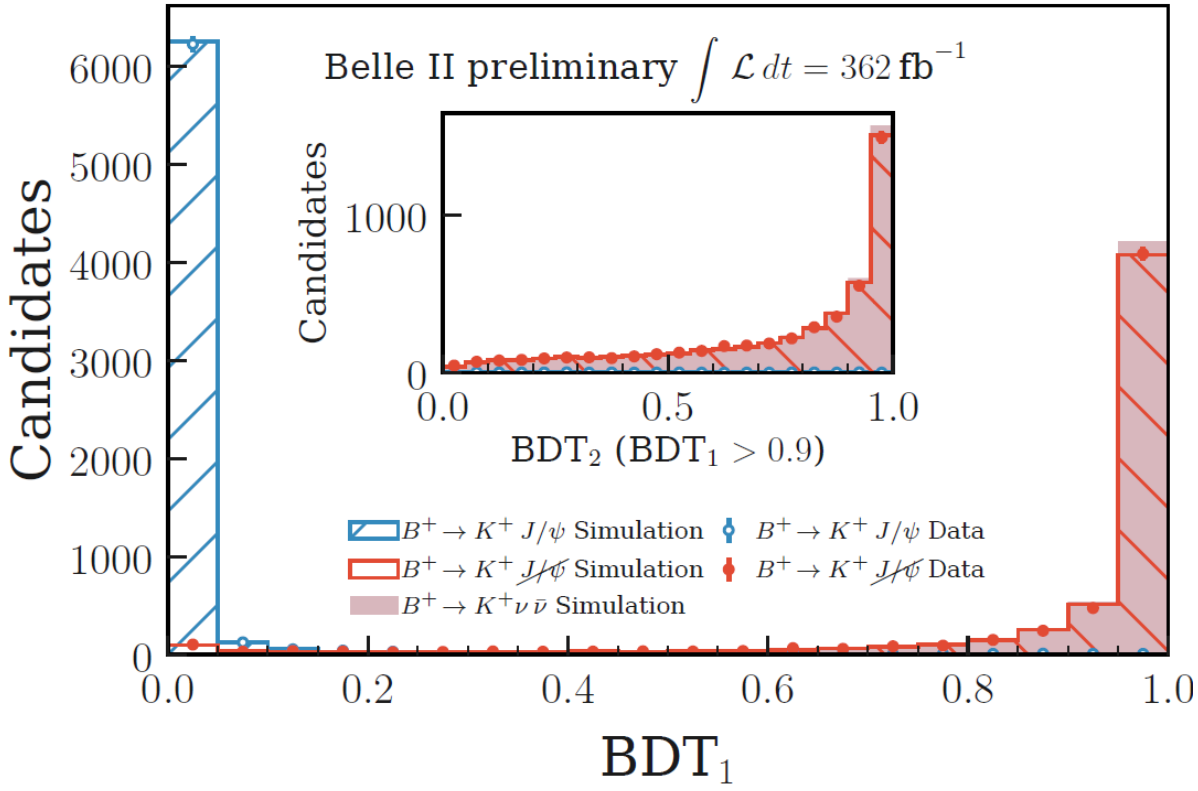


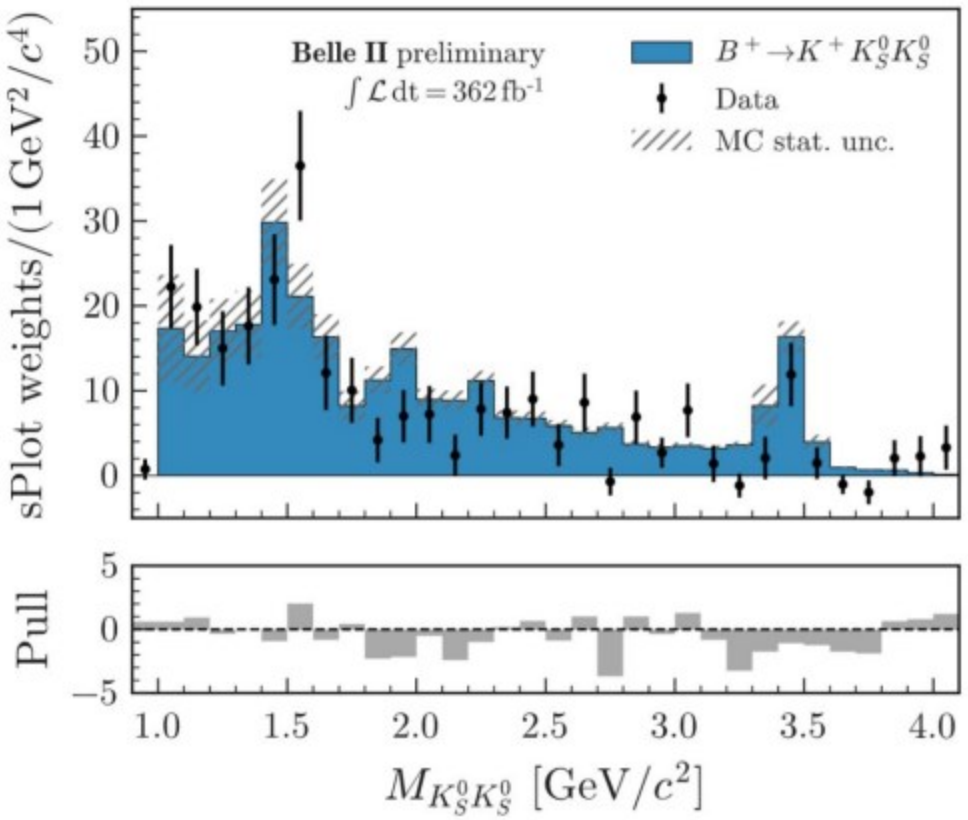


Ratio between selection on data and simulation for the control sample 1 with 3% uncertainty

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

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



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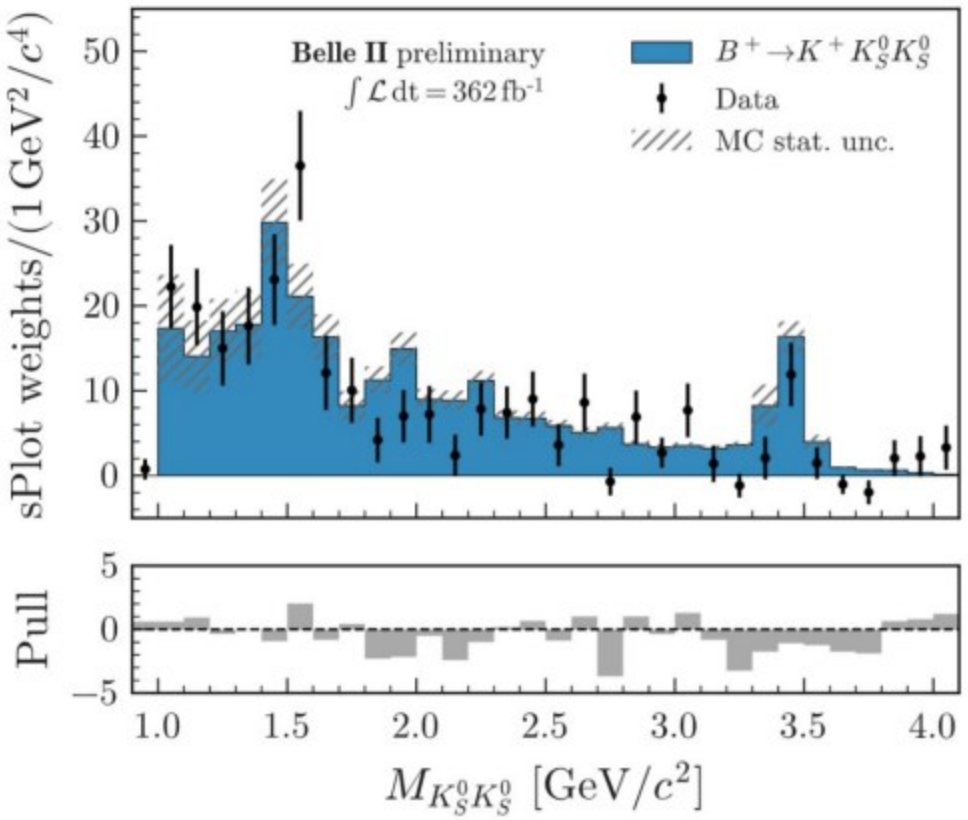

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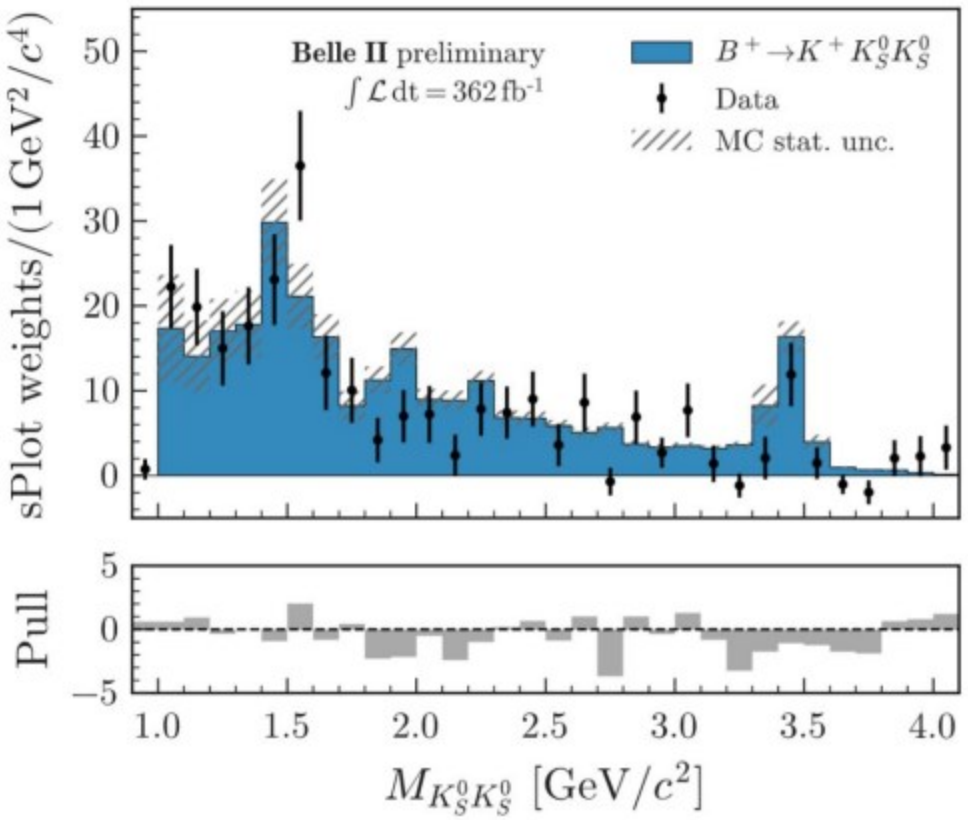

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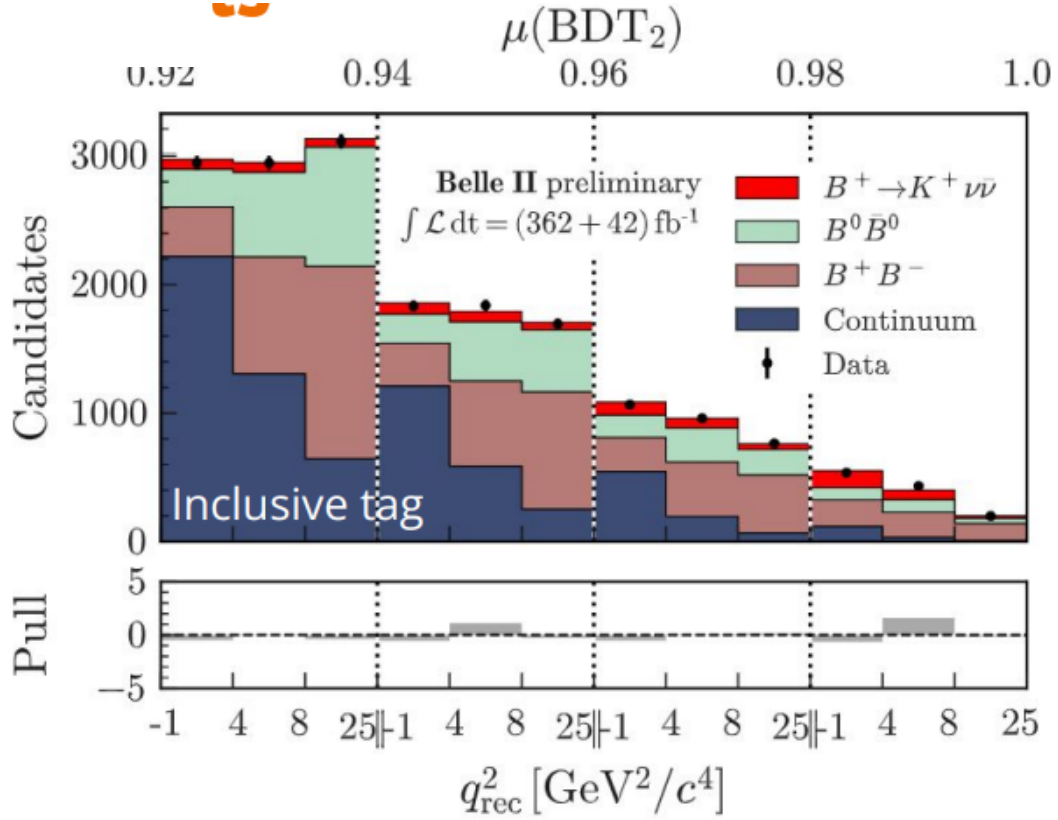
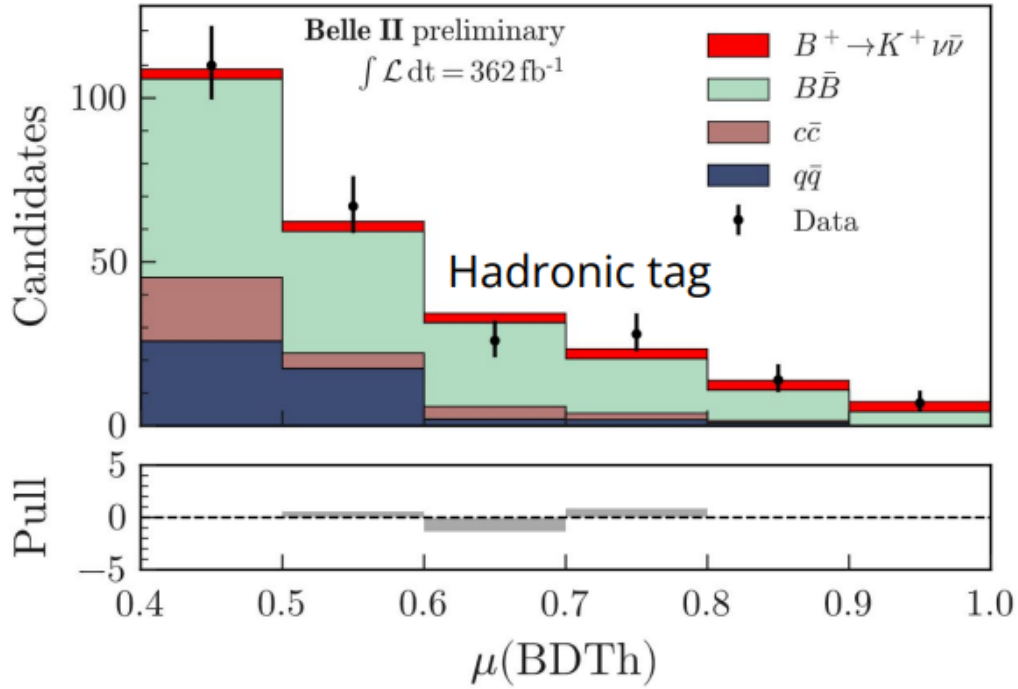
$B^+ \to K^+ \nu\bar{\nu}$: Results

S. Stefkova WG3
Belle II paper in preparation





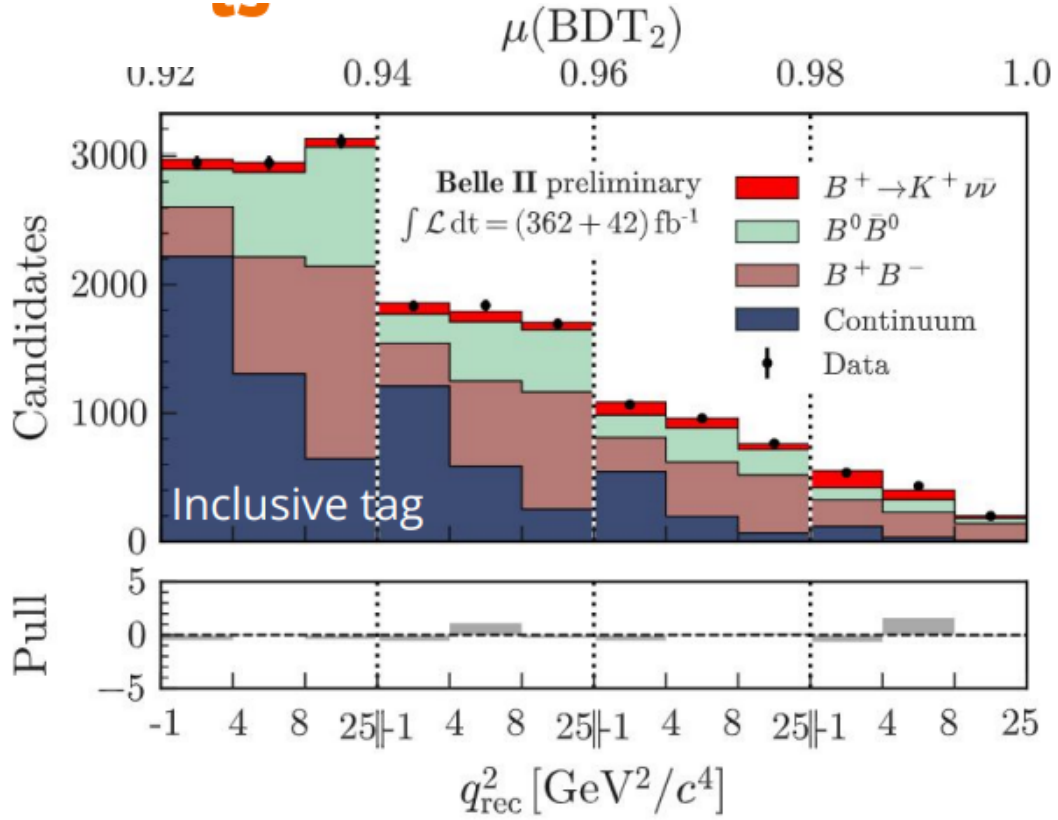
$$\mathrm{BF}_{\mathrm{inc}} = (2.8 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst})) \times 10^{-5}$$

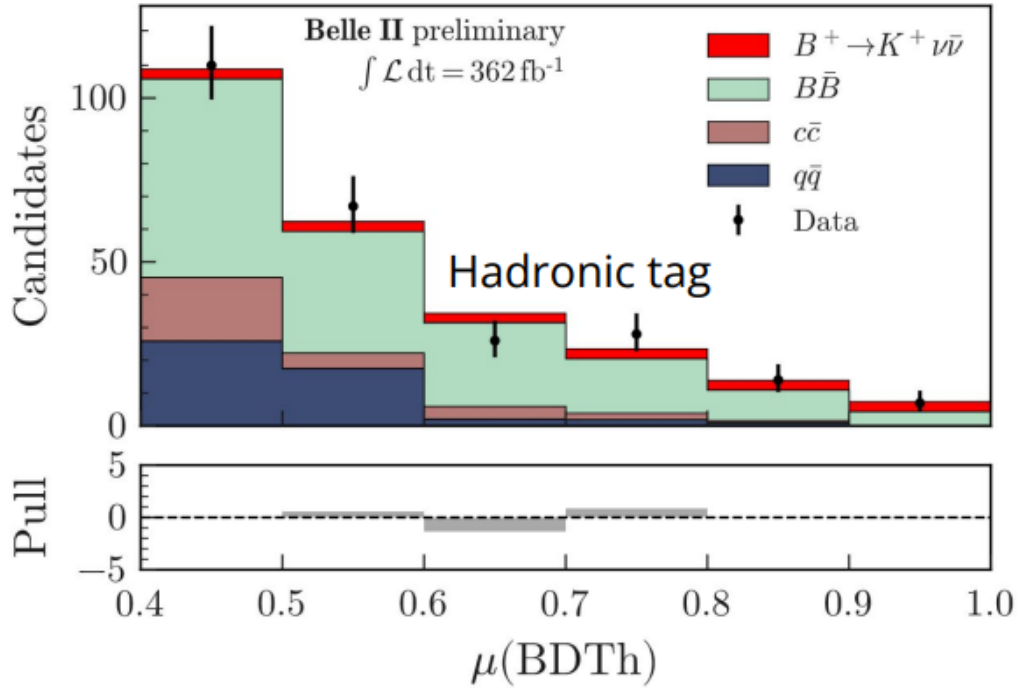
$$\mathrm{BF}_{\mathrm{had}} = \left(1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})\right) \times 10^{-5}$$

$$\mathrm{BF}_{\mathrm{comb}} = \left(2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$$

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

S. Stefkova WG3
Belle II paper in preparation





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Combined result

- **Evidence @ 3.6σ**
- **Tension with SM (0.6×10^{-5}) @ 2.8σ**

Team sheet

Just a snapshot:
Belle II 37 new results since CKM 2021 targeting journals
Belle: approximately 50 papers submitted since CKM 2021

- 13 parallel talks Belle/Belle II

1. **WG1: Charmed meson lifetimes and prospects for future determinations of V_{cs}, V_{cd} at Belle / Belle II: Alan Schwarz**
2. WG1+WG2: Recent measurements of inclusive SL decays at the beauty and charm factories (including BESIII): Markus Prim
3. WG2: Exclusive SL B-decays at Belle/Belle II: Christoph Schwanda
4. WG2: LFU tests at Belle / Belle II: Bob Kowalewski
5. **WG2+WG3: Recent results on leptonic/rare decays at Belle/Belle II: Justine Serrano**
6. **WG3: b → s/d γ at Belle/Belle II : Rahul Tiwary**
7. WG3: B → K + invisible at Belle/Belle II: Slavomira Stefkova
8. WG3: LFV B decays (inc. LHCb): Gagan Mohanty
9. WG4: Measurement of $\sin2\phi_1$ and $\sin2\phi_1$ effective at Belle/Belle IIYuma Uematsu
10. WG4+WG5: New results of the CKM angle γ/ϕ_3 at Belle/Belle II: Karim Trabelsi
11. WG5: Measurement of branching ratios in hadronic B to charm decays at Belle/Belle II: Vidya Sagar Vobbilisetti
12. WG5: Direct CP violation measurements with charmless B decays at Belle/Belle II: Mirco Dorigo
13. **WG7: CPV in D meson decays at Belle/Belle II: Michel Bertemes**

Not discussed in this summary

Team sheet

Just a snapshot:
Belle II 37 new results since CKM 2021 targeting journals
Belle: approximately 50 papers submitted since CKM 2021

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+2 plenary = 15!

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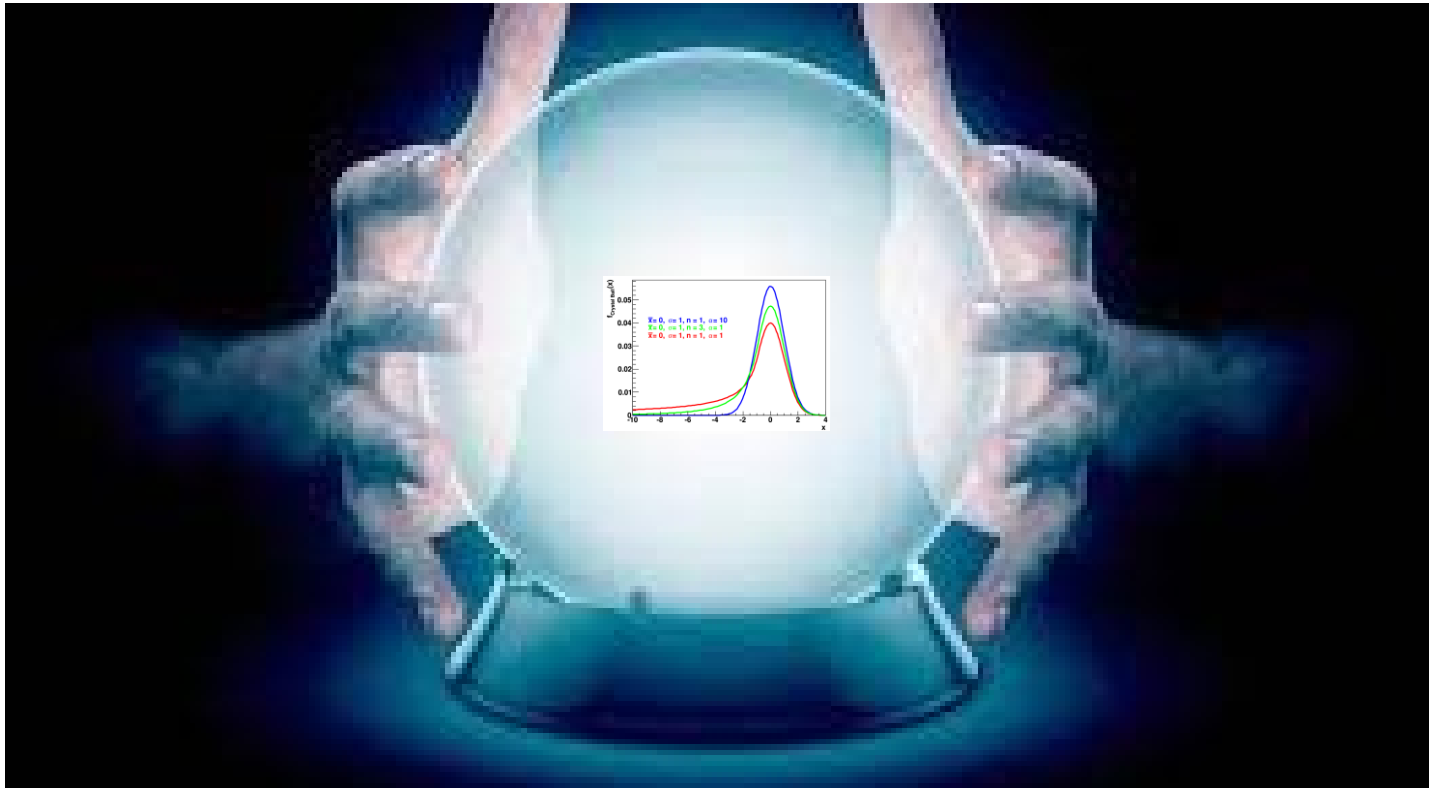
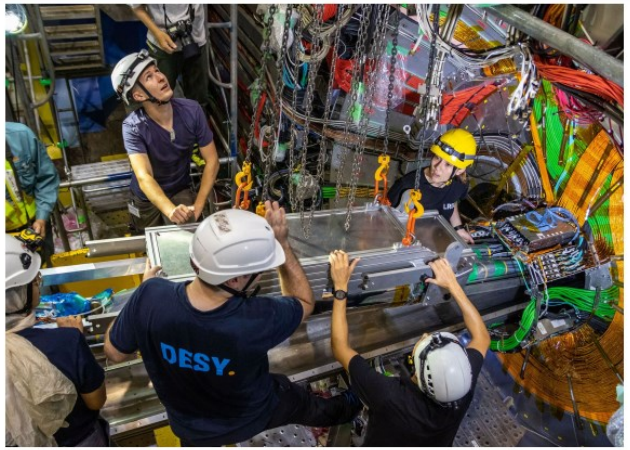
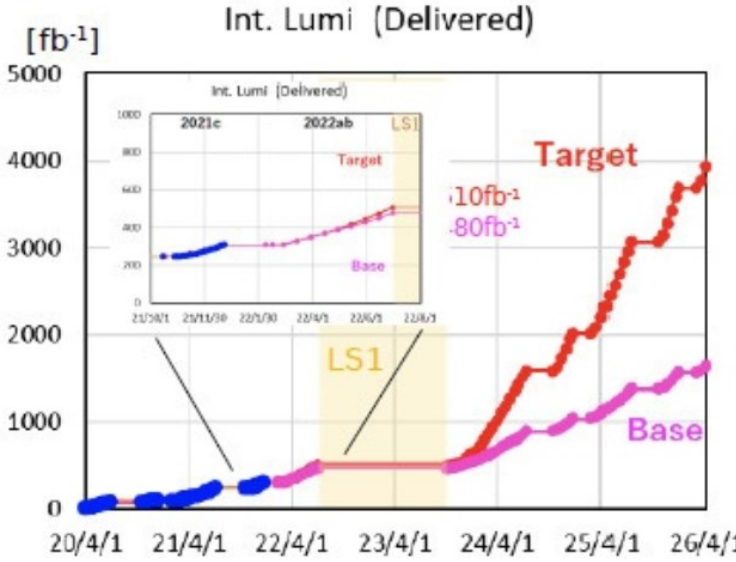


5) Prospects and conclusion

Belle II: after current shutdown

- We have not collected the sample size planned to date
  - Beam conditions
- Since summer 2022 shutdown for accelerator upgrades to mitigate background and increase luminosity
- Detector upgrades too
  - two-layer pixel detector installed
- On target to restart SuperKEKB in December
- **Path to 2 × 10^{35} cm $^{-2}$s^{-1} but new final focus to go beyond**
- **Proposed upgrade from 2027**
  - J. Baudot FPCP 2023





Far future: FCC-ee

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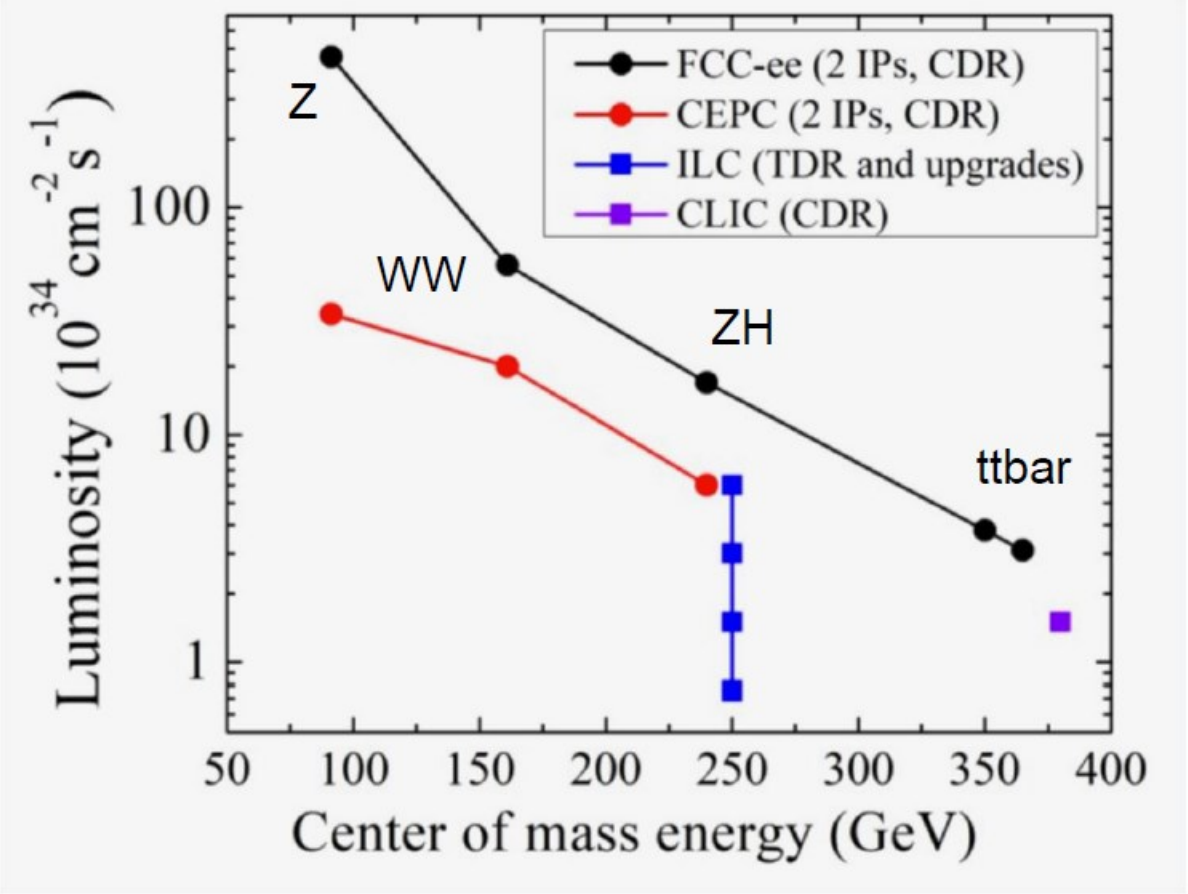

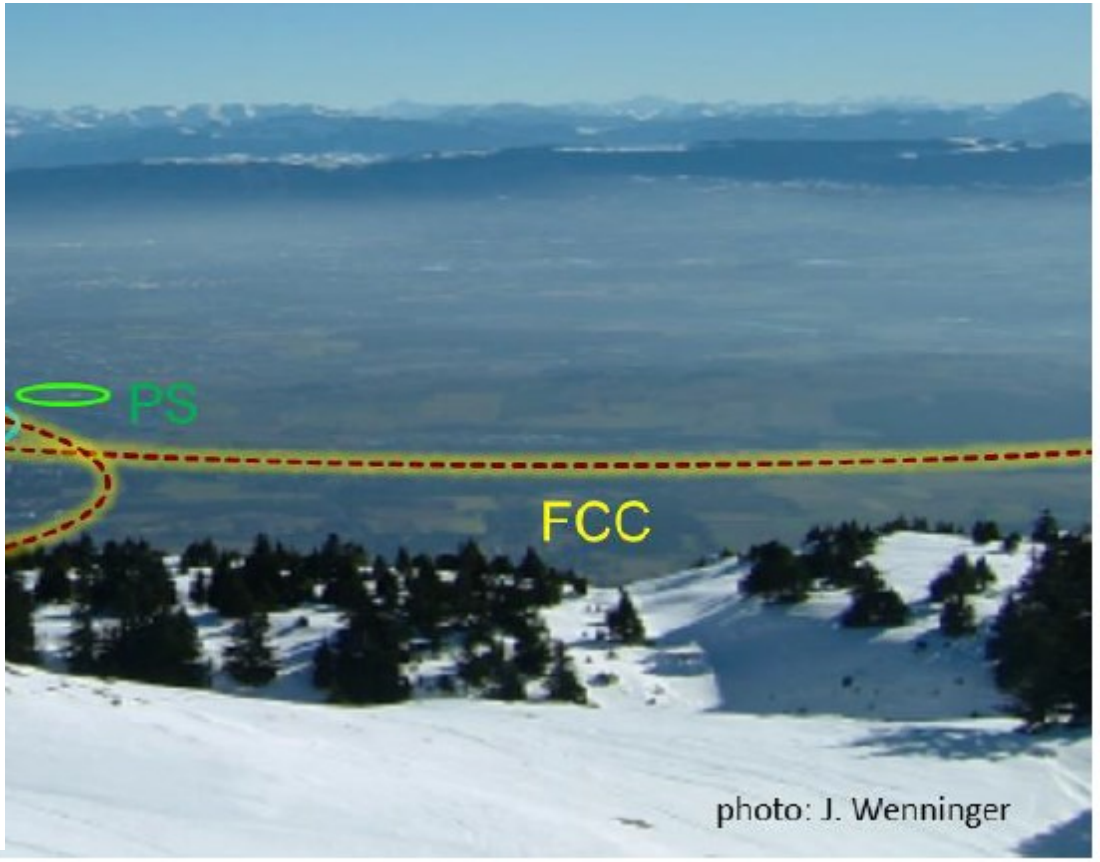

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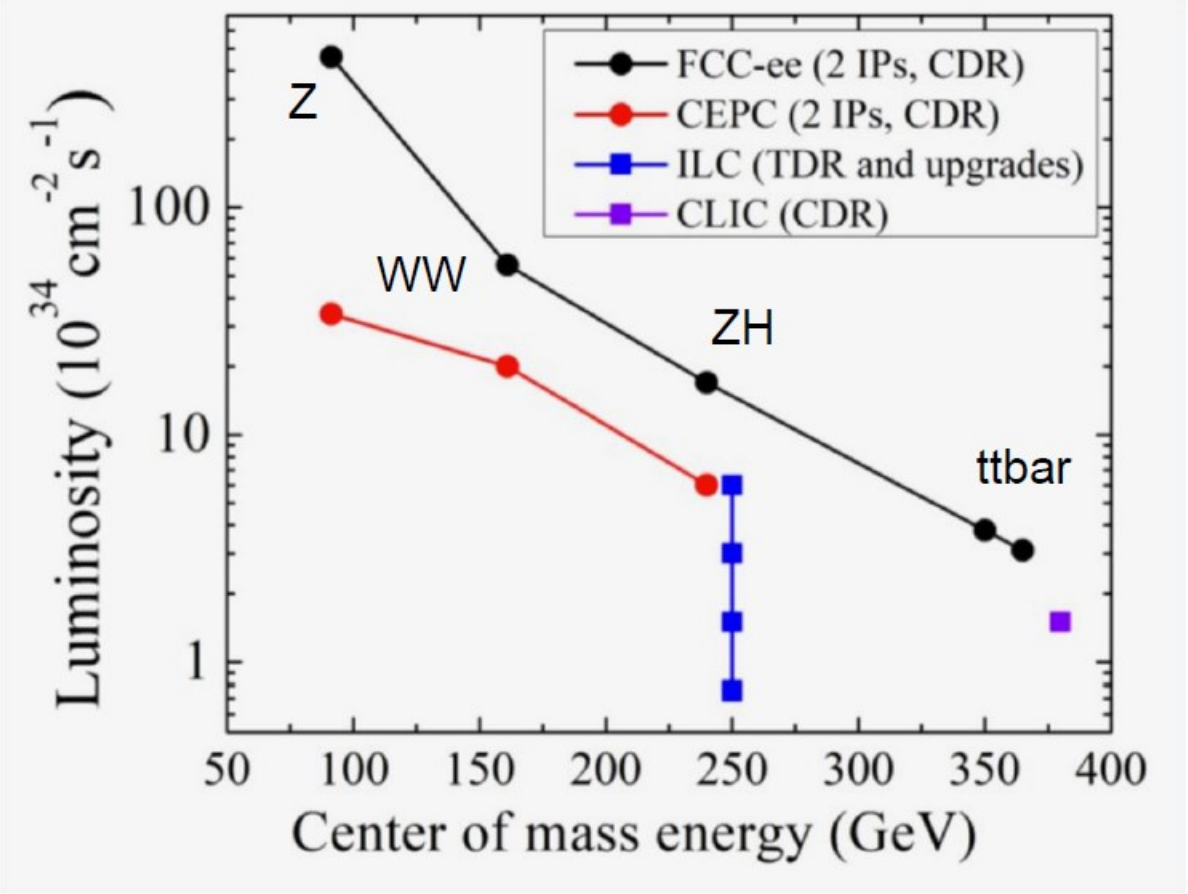
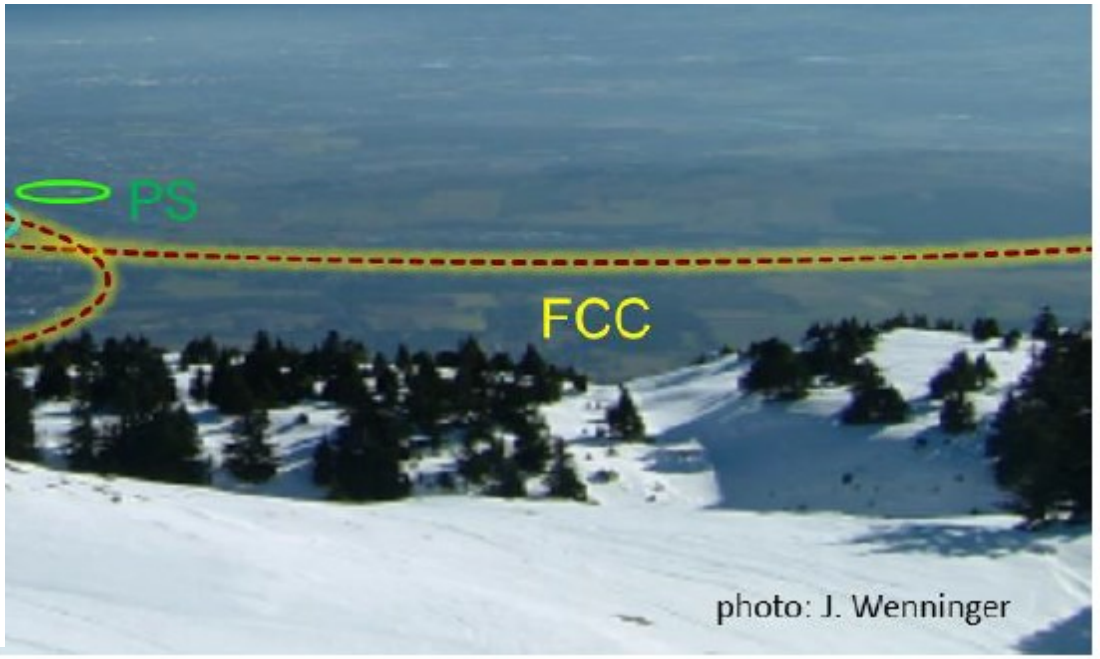


	Y(4S)	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production x-sec		✓	
Negligible trigger losses	✓		✓
Low background environment	✓		✓
Initial energy constraint	✓		(✓)



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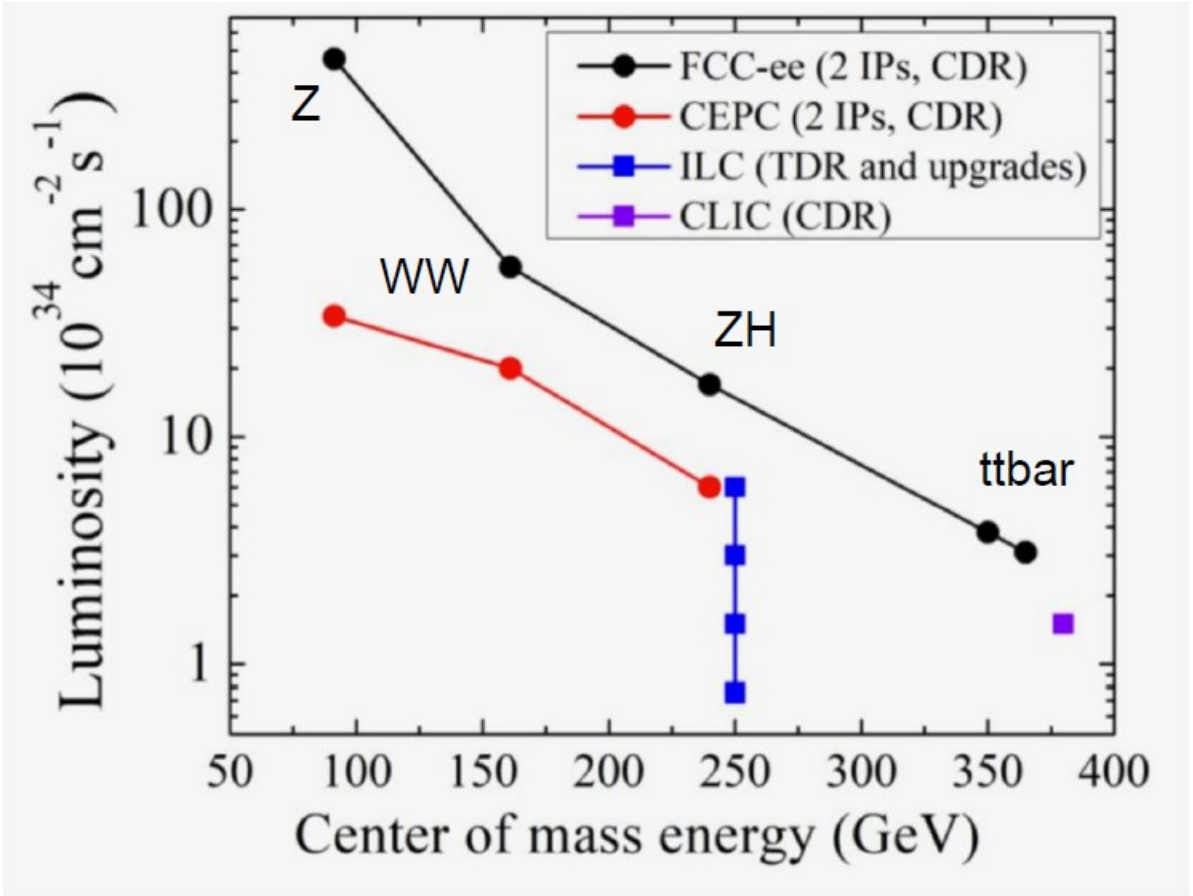

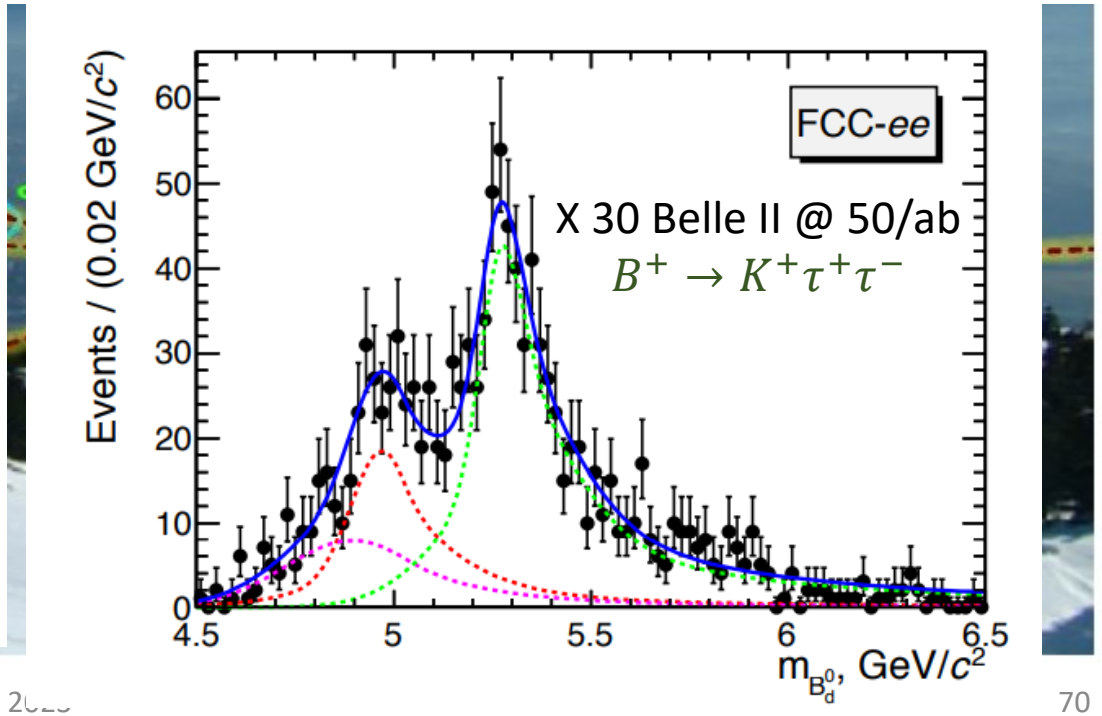

CKM 2023

Another use of ML in HEP

CKM 2045-if I'm lucky

Conclusion

- e^+e^- has an important role to play and a bright future
  - Belle legacy continues
  - Even while Belle II is catching up, we are producing competitive and exciting results
    - Sometimes world leading with less data
      - Time-dependent CP violation in $B \to K^0\pi^0\gamma$ – Y. Uematsu WG4
  - A lot more to come once we enter the "10^{35} era"
- Upgrade plans for reaching the 10s of ab^{-1}

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 2027 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

J. Baudot FPCP 2023