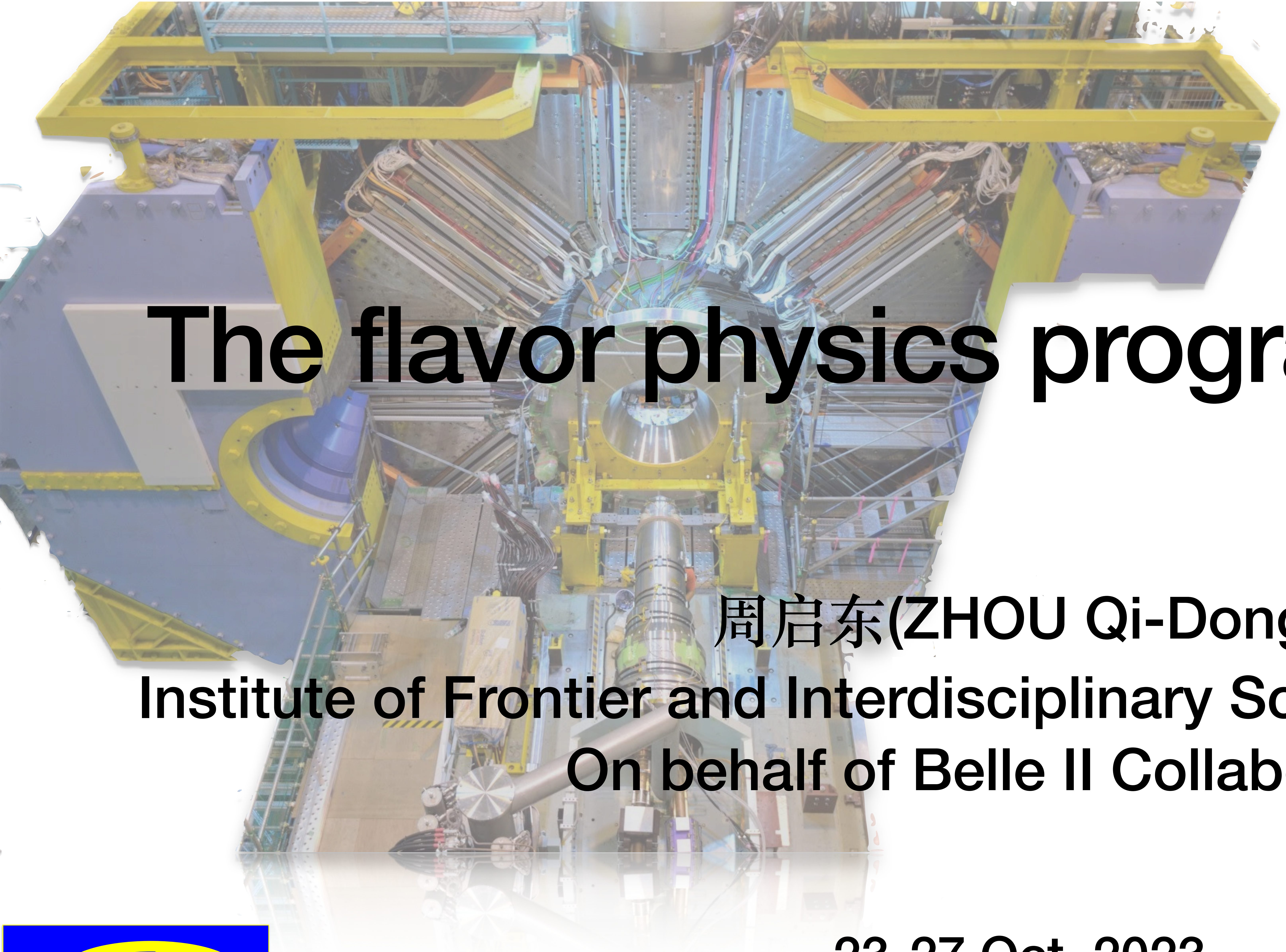

The flavor physics program of Belle II

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On behalf of Belle II Collaboration

23-27 Oct. 2023
The 2023 international Workshop on
the High Energy Circular Election Positron Collider

Belle II

SHANDONG UNIVERSITY 1901

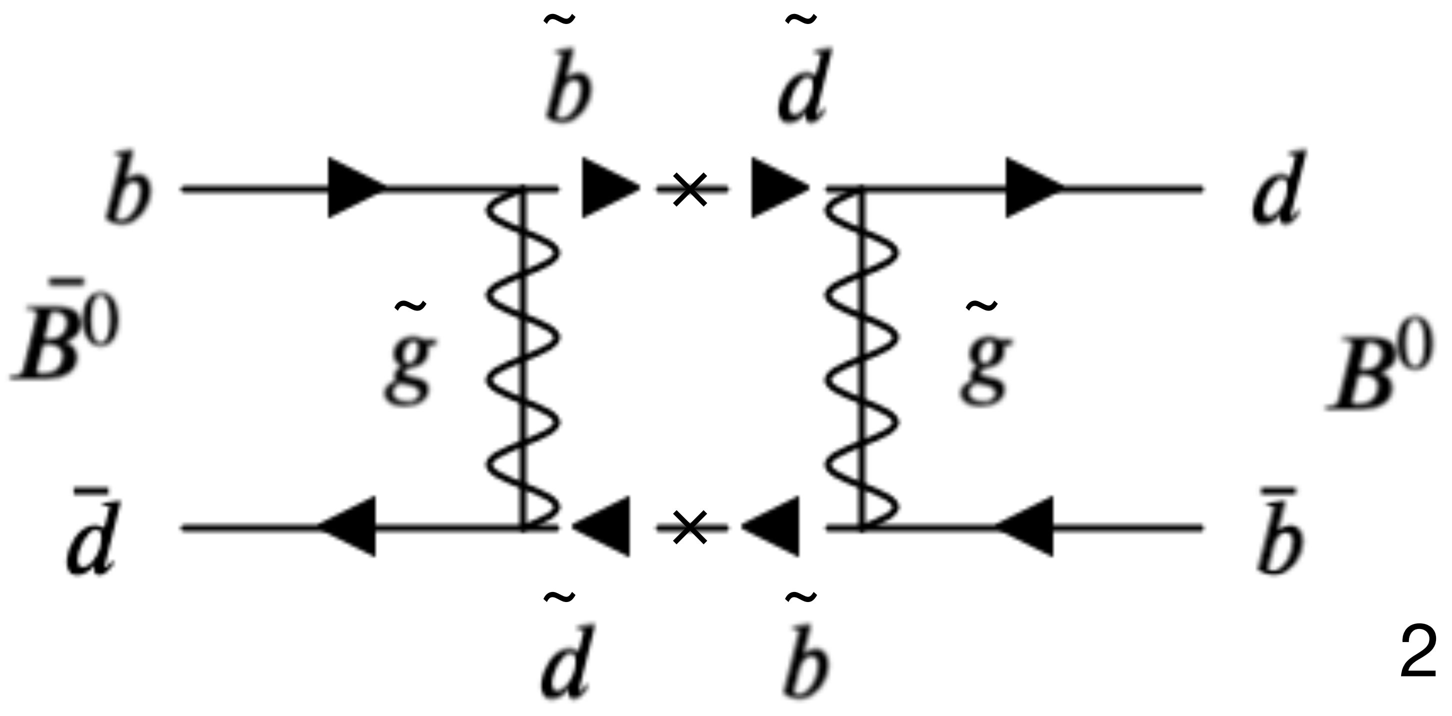
New physics search based on collider

- New physics (NP) beyond the Standard Model
  - What made the matter-antimatter asymmetry of the Universe?
  - What is dark matter?
  - …

Energy frontier : direct search

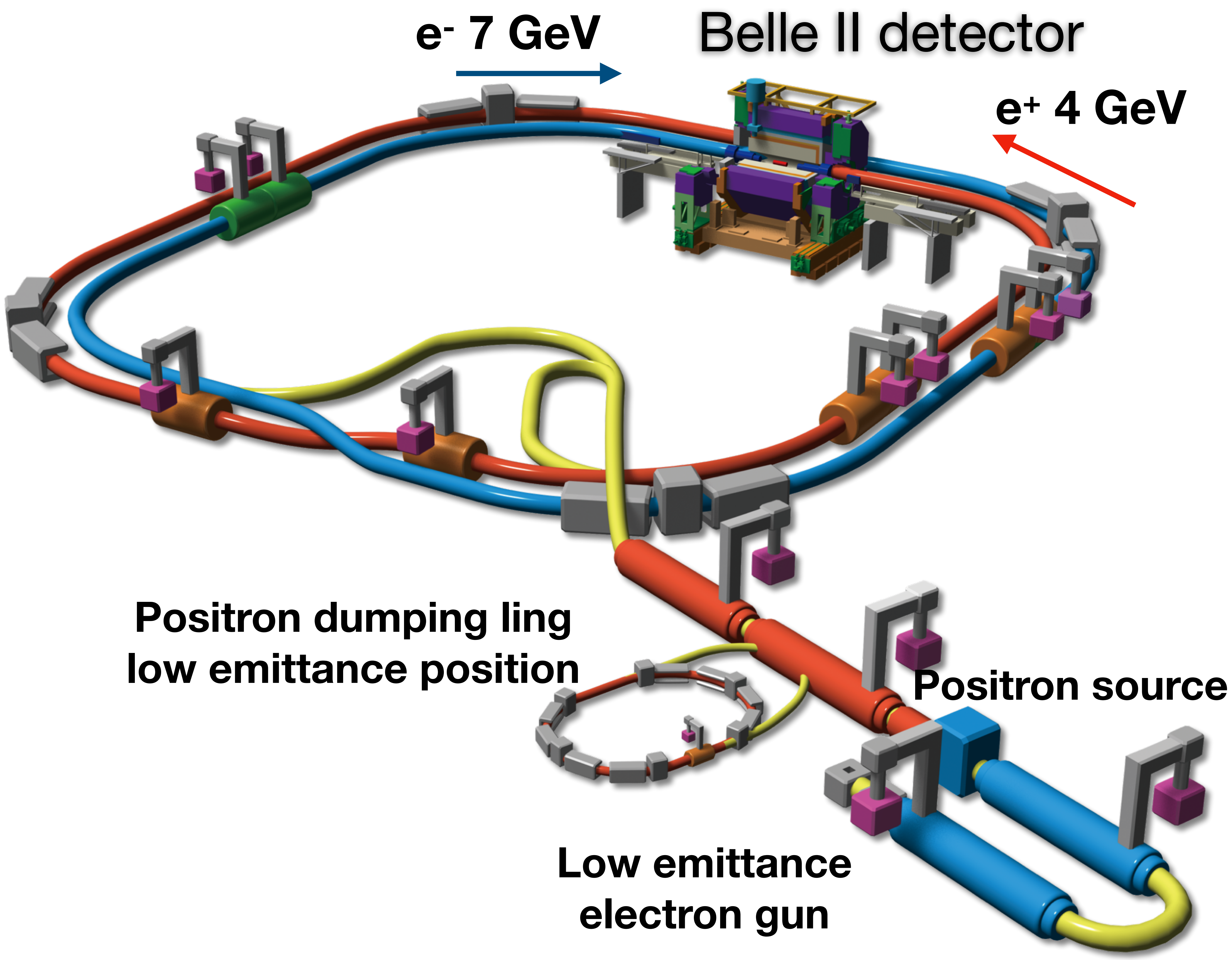
Luminosity frontier : indirect search

- Indirect search for NP in quantum effect
  - Sensitivity of NP detection up to 200 TeV for loop diagram (depending on the NP coupling constant) arXiv:1309.2293



Luminosity frontier: SuperKEKB

- Asymmetric e^+e^- collider
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
    - very clean and well-known initial state

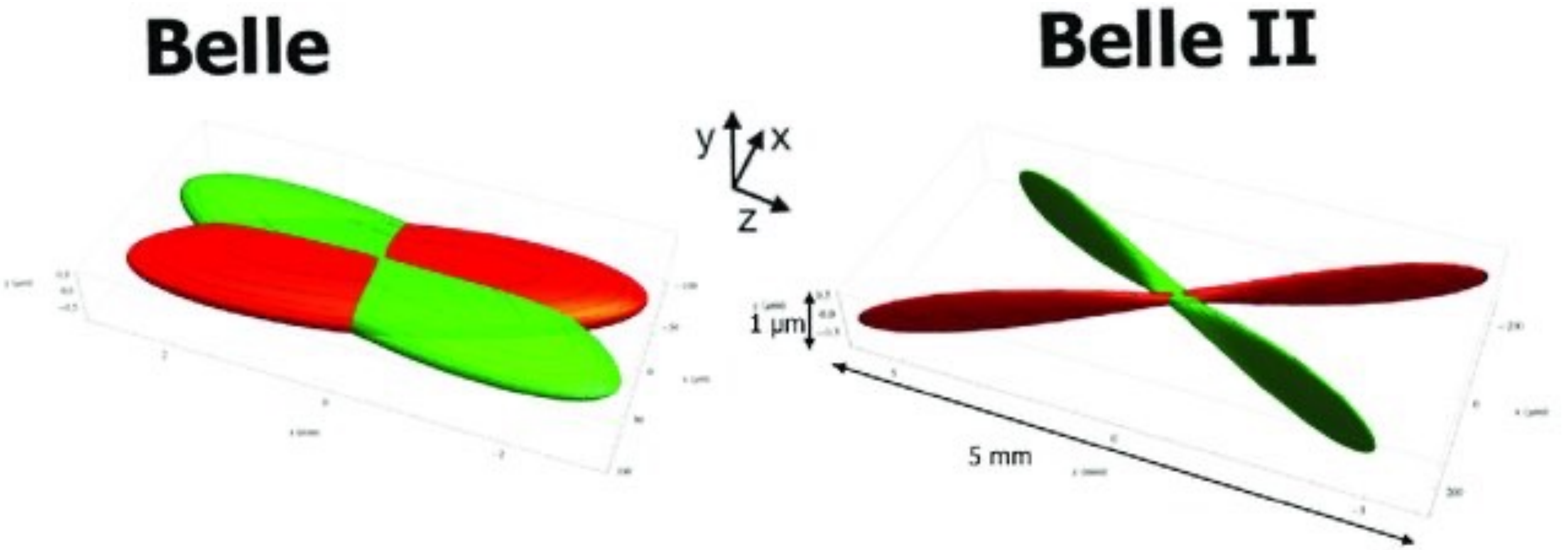


Beam current: KEKB x ~1.5

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

Beam squeeze: KEKB / ~20

Nano beam scheme

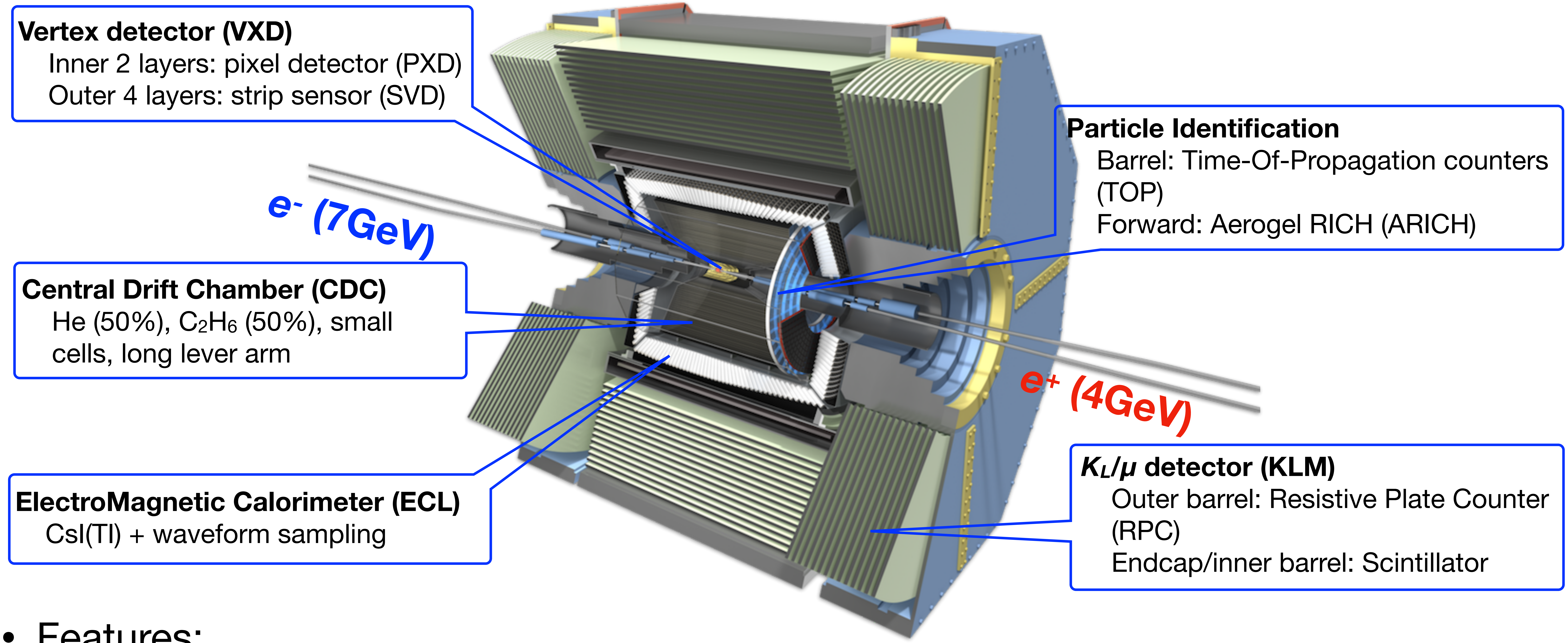


Target: L = 60 x 10^{34} cm^{-2} s^{-1}

Achieved : 4.7 x 10^{34} cm^{-2} s^{-1} (Record)

- Data at $\Upsilon(4S)$:
  - 362 fb^{-1} (Belle II) <-> 711 fb^{-1} (Belle)

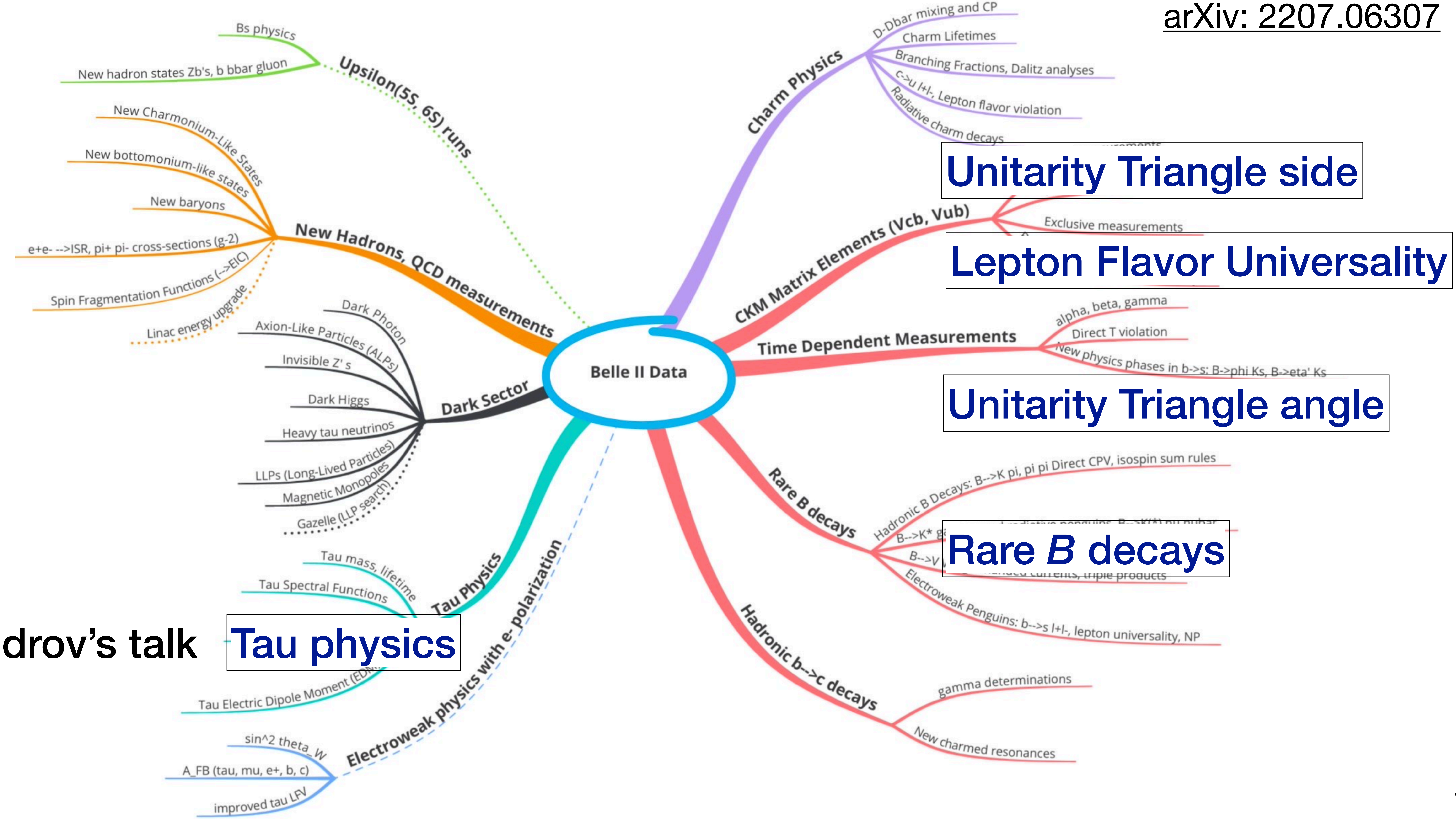
The Belle II detector



- Features:
  - Near-hermetic detector
  - Vertexing and tracking: σ vertex ~ 15μm, CDC spatial res. 100μm $\sigma(P_T)/P_T$ ~ 0.4%
  - Good at measuring neutrals, π^0, γ, K_L… $\sigma(E)/E$ ~ 2-4%

Belle II physics program

arXiv: 2207.06307



Denis Bodrov's talk

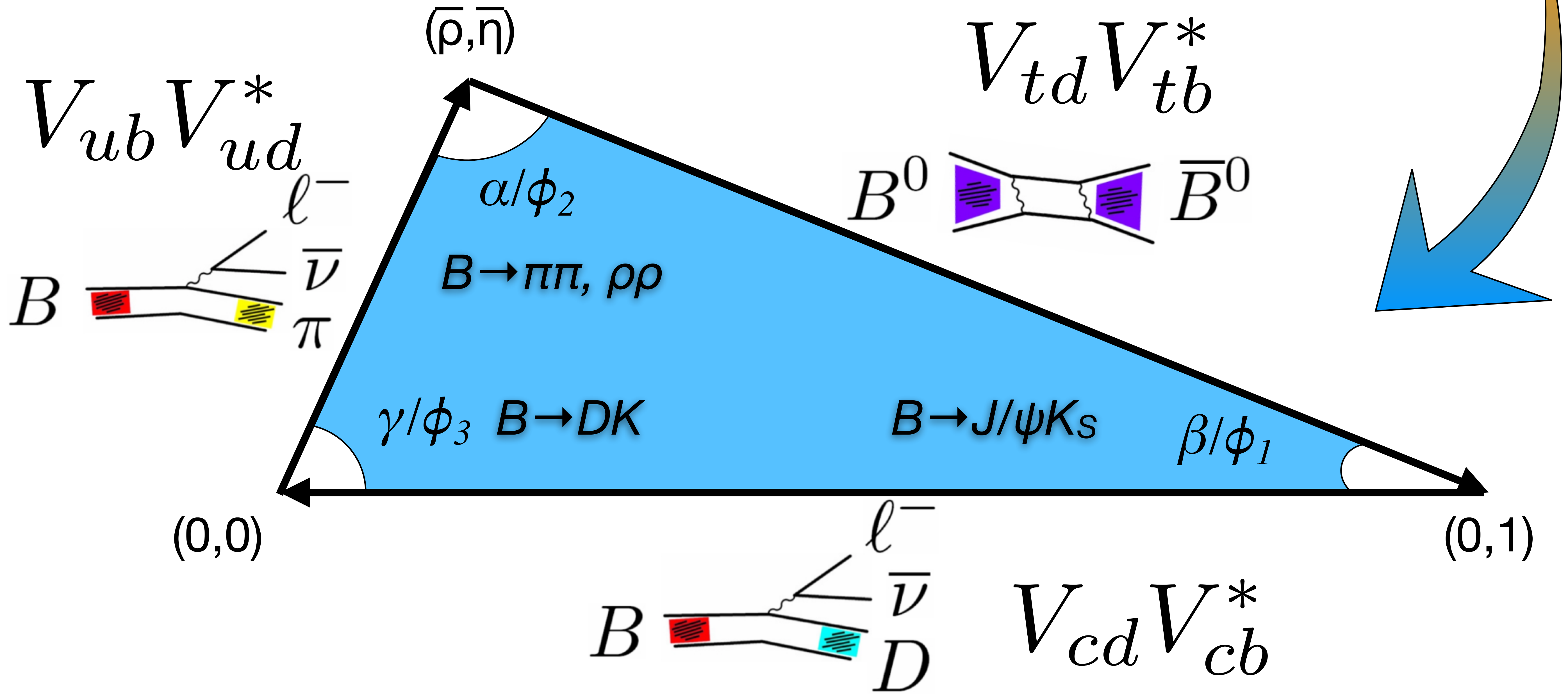
CKM matrix and unitarity triangle (UT)

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A^2\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Complex phase cause CP violation

$V^\dagger V = 1$ → (***b*** column)†(***d*** column) →

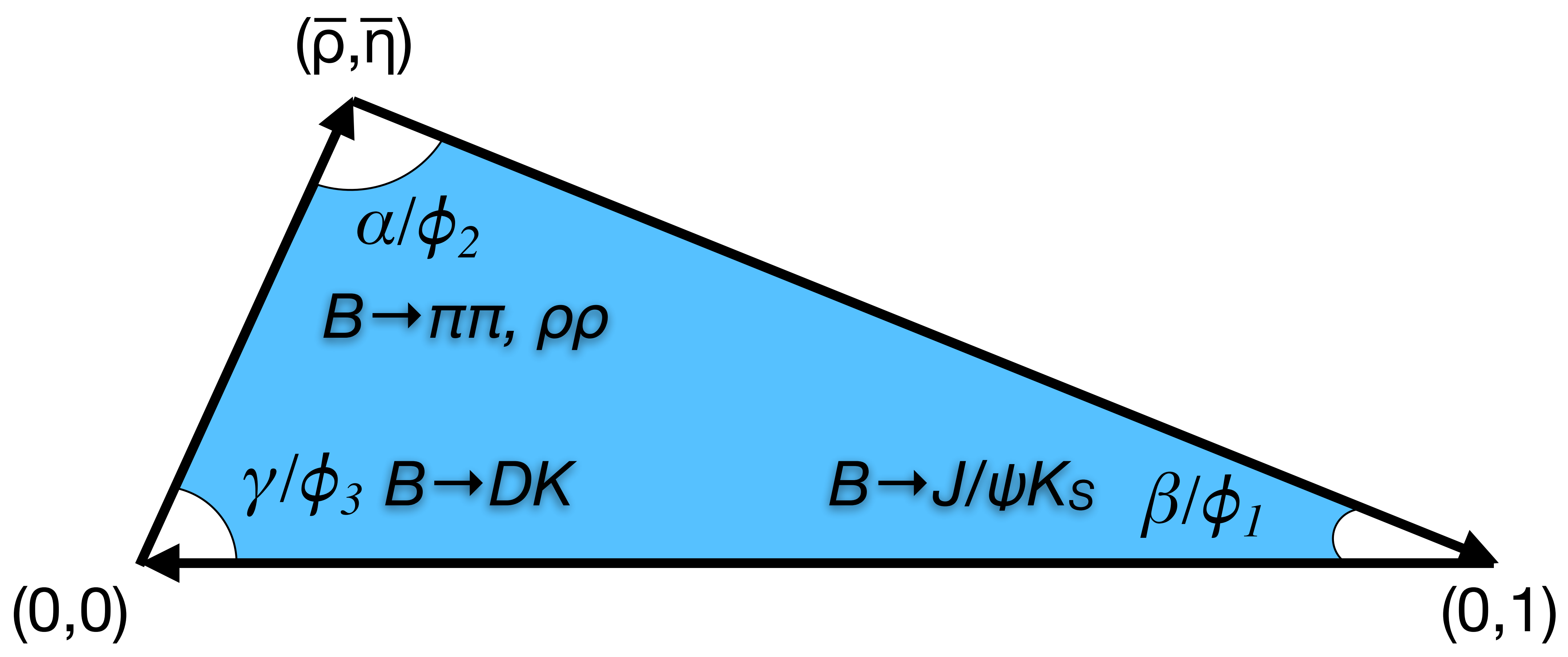
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$
$$\lambda^3 \cdot 1 \qquad \lambda^2 \cdot \lambda \qquad 1 \cdot \lambda^3$$



- A triangle on the complex plane
- Normalization by $\bar{\rho} = \rho(1 - \frac{\lambda^2}{2})$, $\bar{\eta} = \eta(1 - \frac{\lambda^2}{2})$

- Search NP in mixing (**tree**, **loop**) by precise measurement of UT
- Comprehensive test
  - Measure **all sides and angles**

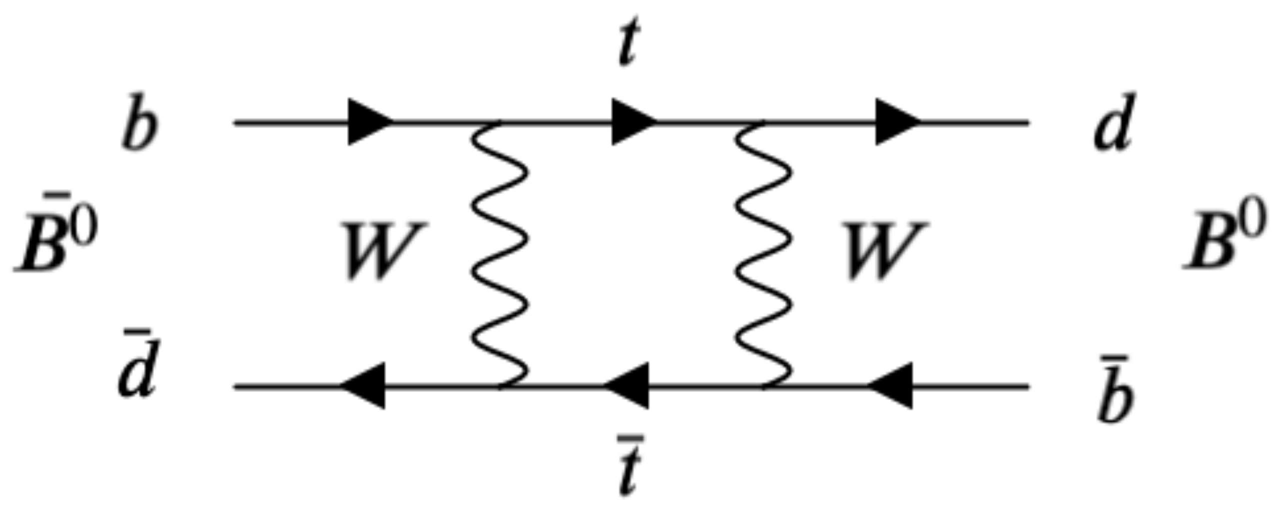
UT angle measurements

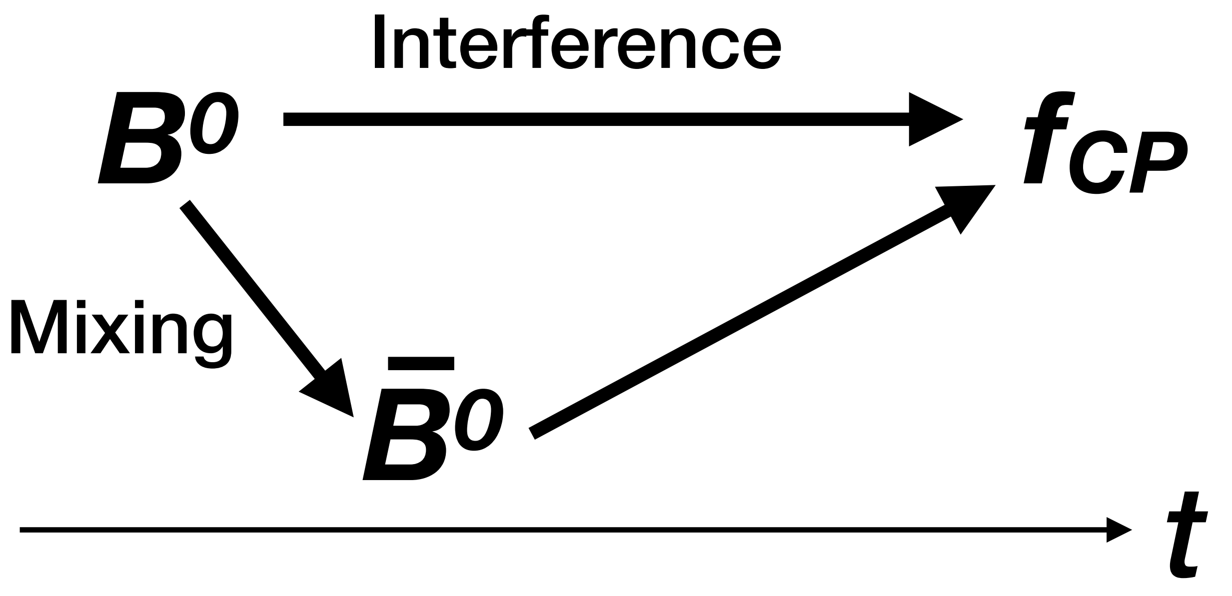


Time dependent CPV

TDCPV measurement:

- Precise measurement of Δt
- *B* flavor tagger



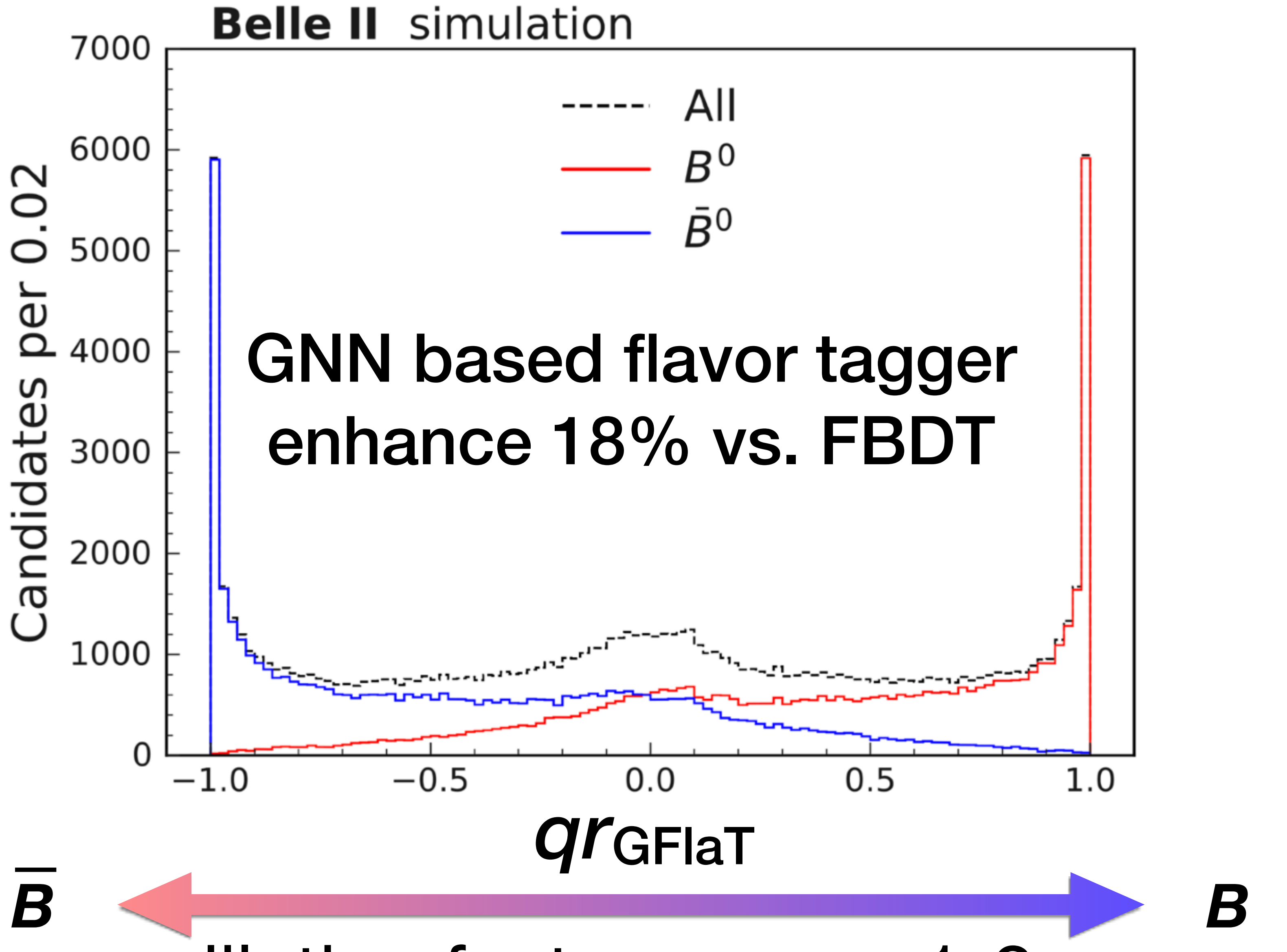


$$A_{CP} = \frac{\Gamma(\overline{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\overline{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})} = S\sin(\Delta m t) - C\cos(\Delta m t)$$

$C=-A$

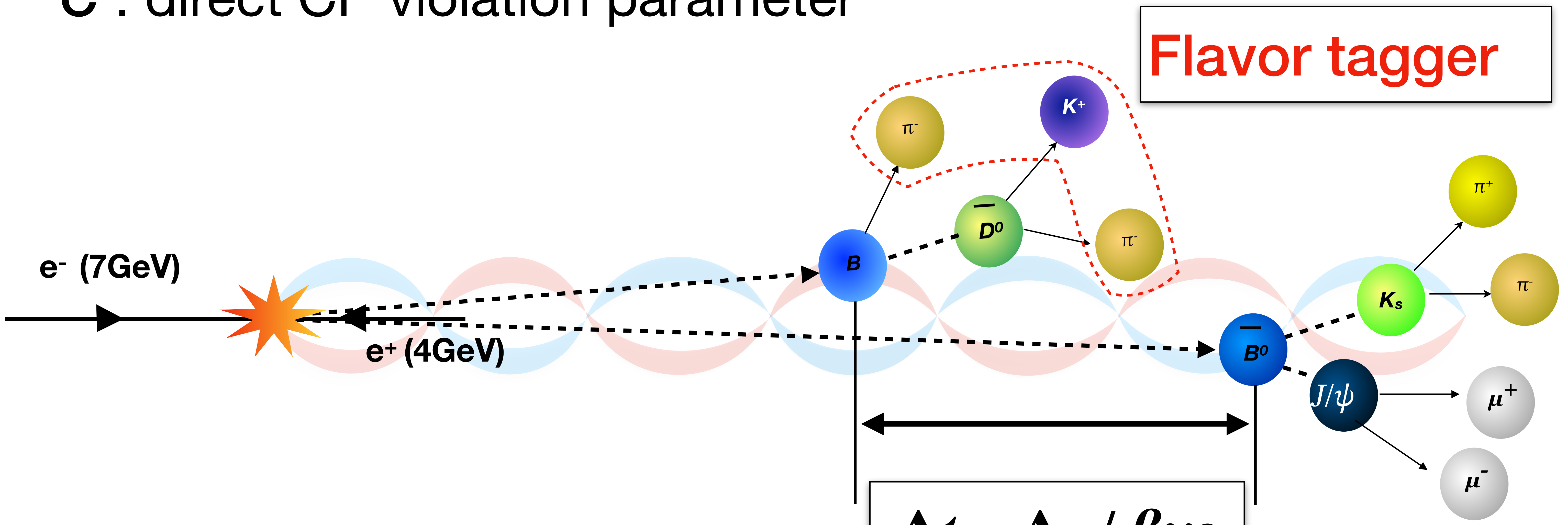
S : indirect CPV parameter

C : direct CP violation parameter



dilution factor r_{GFlaT} = 1-2w

w: wrong tagging fraction



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

$\Delta z \sim$ 130 um

Belle: $\beta\gamma$=0.43, Δz ~200um

Belle II: $\beta\gamma$=0.29, Δz ~130um

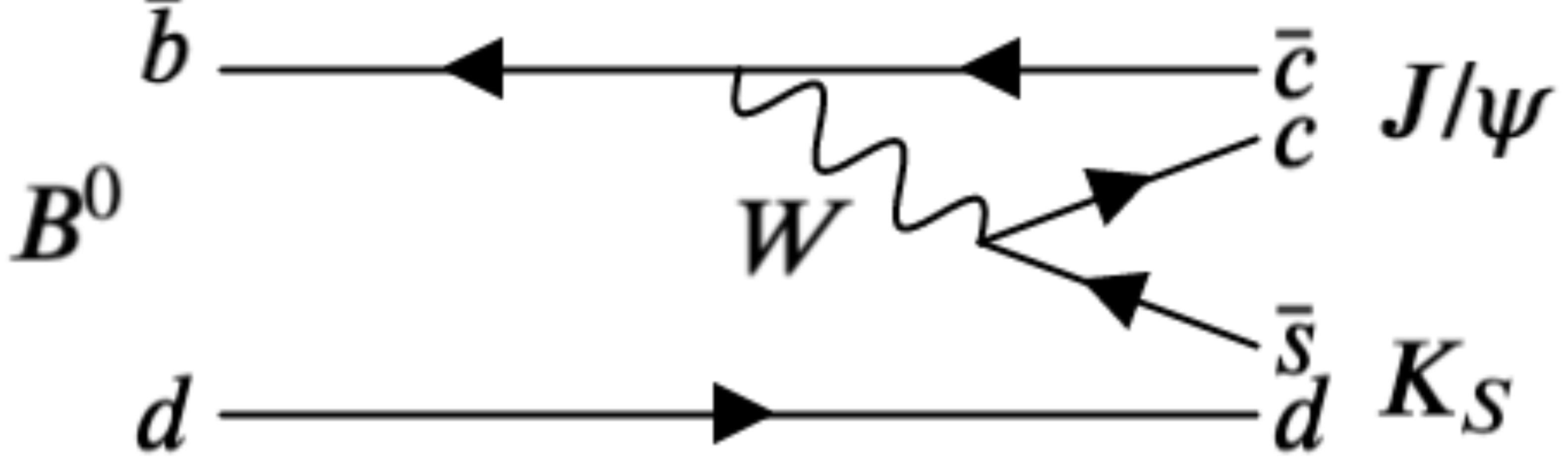
EPJC 82 (2022) 83

Effective flavor tagging efficiency:

- **Belle II : (37.40 ± 0.45 ± 0.41)%**
- Belle : (30.1 ± 0.4)%

Measurement of $\sin(2\phi_1)$

- ***b→c*** : **tree diagram** dominated golden modes $B^0 \to J/\psi K_s^0$, $B^0 \to \psi(2S) K_s^0$…
- Theoretical and experimental precise channel



$$P(\Delta t, q) = \frac{e^{-|\Delta t|\tau_{B^0}}}{4\tau_{B^0}}(1 + (1-2w)q[S\sin(\Delta m \Delta t) - C\cos(\Delta m \Delta t)])$$

C=-A

S : indirect CPV parameter, ~$\sin(2\phi_1)$

C : direct CP violation parameter, ~0 in SM for $B^0 \to J/\psi K_s^0$

$\sin(2\phi_1) \approx S =$ **0.724 ± 0.035 (stat.) ± 0.014 (syst.)**

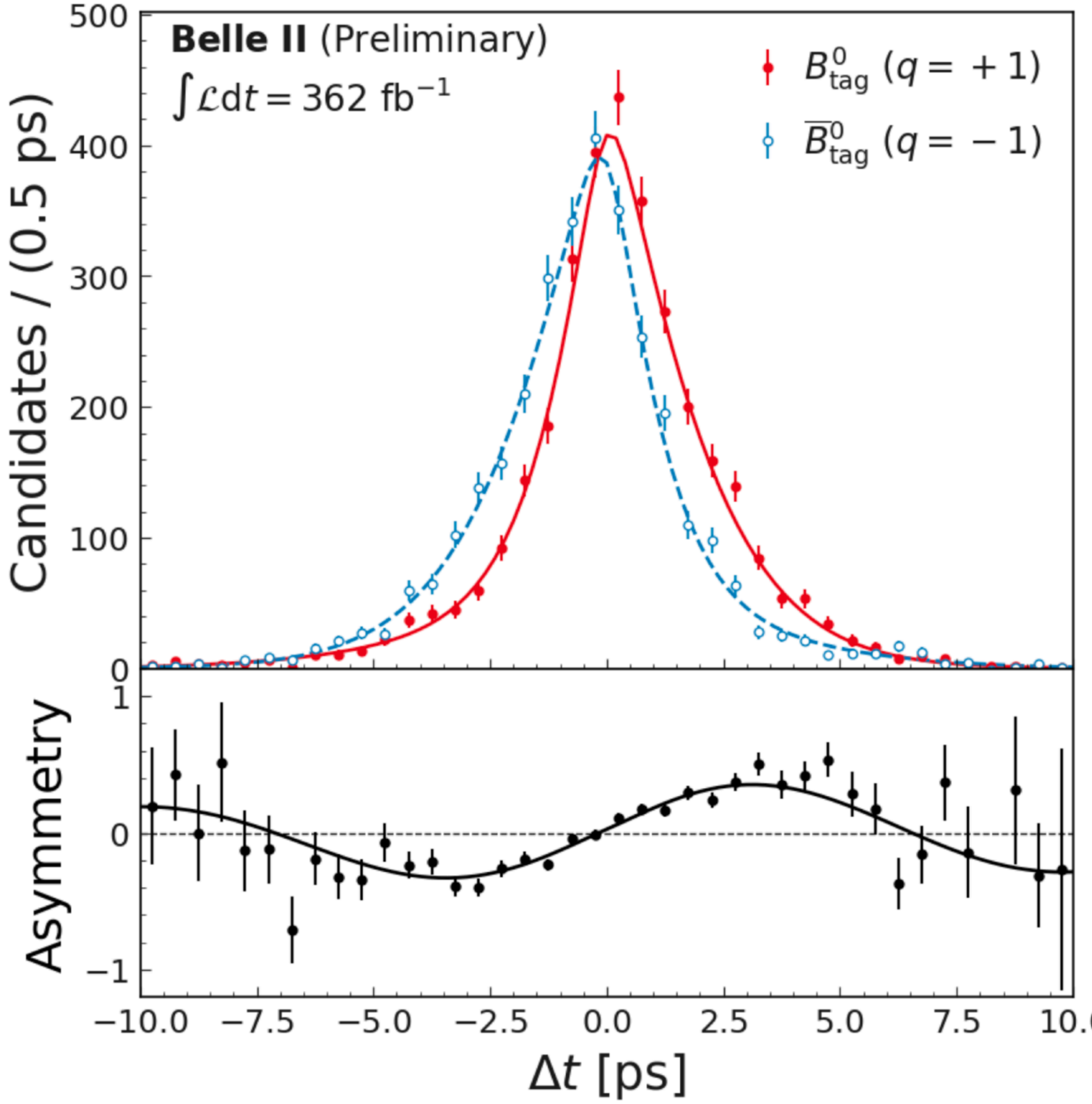
$C =$ **0.035 ± 0.026 (stat.) ± 0.012 (syst.)**

HFLAV: S = **0.695 ± 0.019**

C = **0.000 ± 0.020**

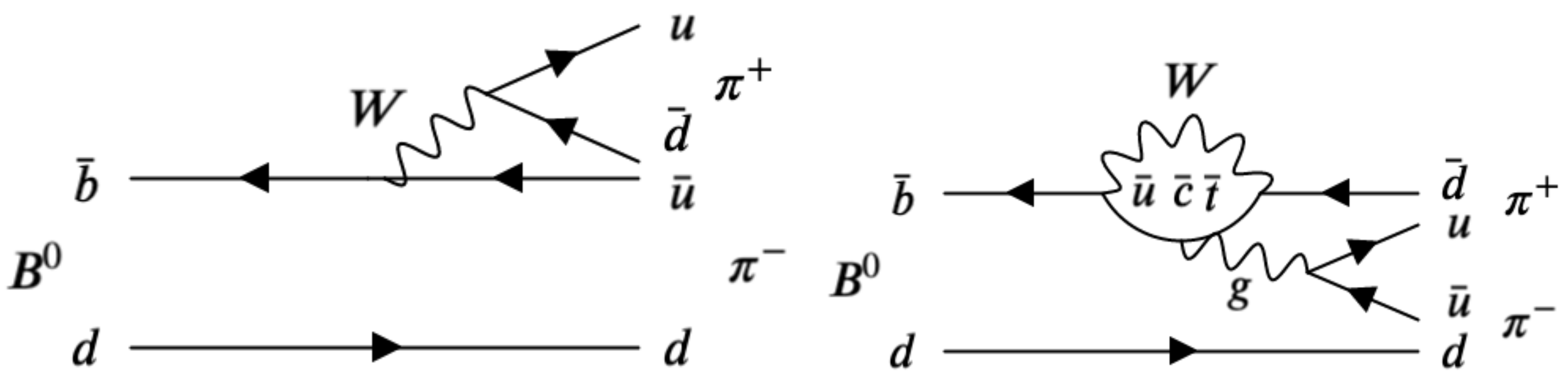
LHCb: S = **0.716 ± 0.015**

C = **0.012 ± 0.012** arXiv:2309.09728



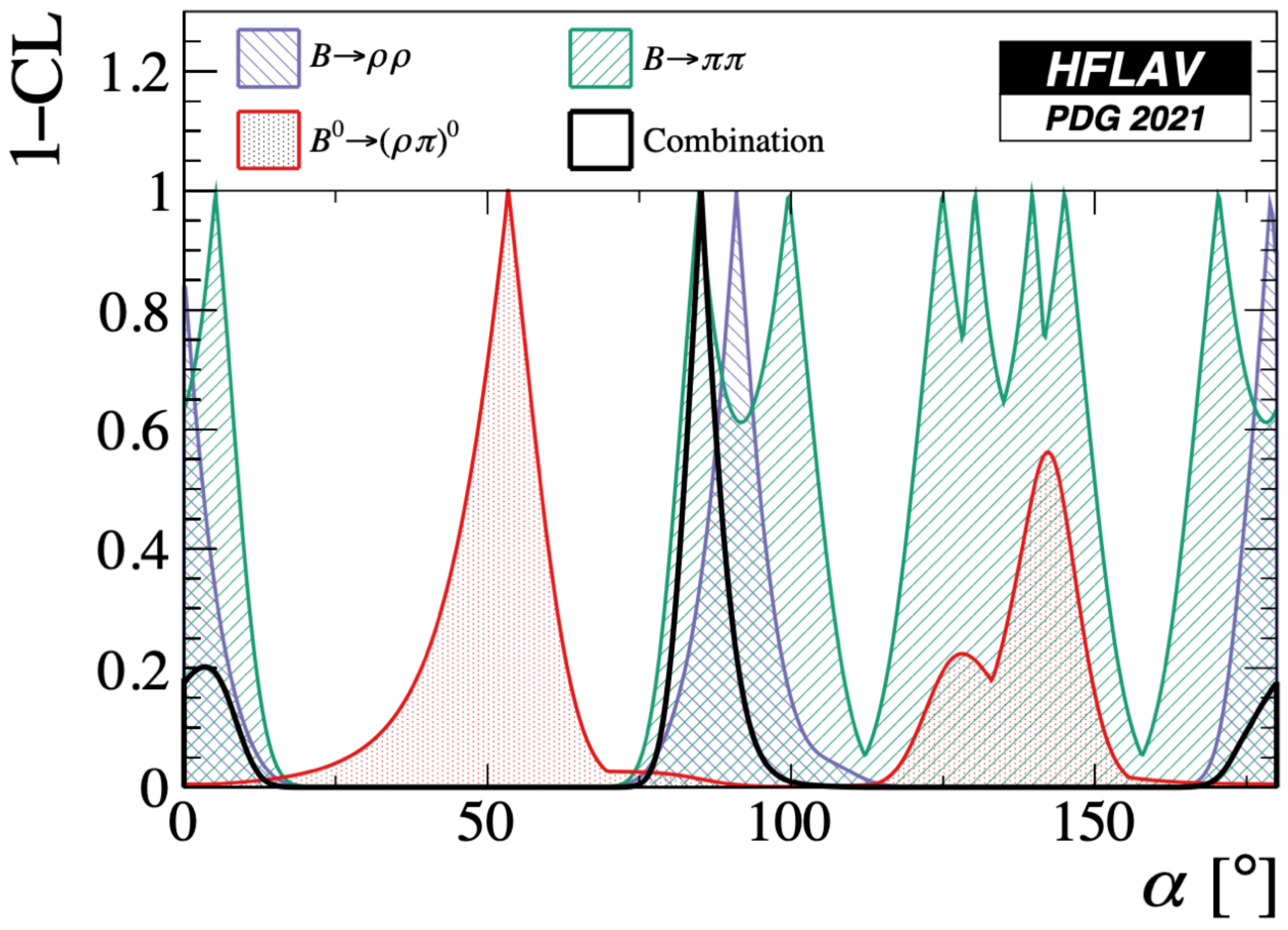
ϕ_2 measurement ($B\to\pi\pi$)

- ϕ_2 least known angle of UT, precision~4.5°, determined from an isospin analysis
  - Measure A_{CP} and branching fractions of all $B\to\pi\pi$ ($\pi^+\pi^-$, $\pi^\pm\pi^0$, $\pi^0\pi^0$),
  - ϕ_2 determination based on $B\to\pi\pi$ limited by $B\to\pi^0\pi^0$
    PRL 65(1991) 3381

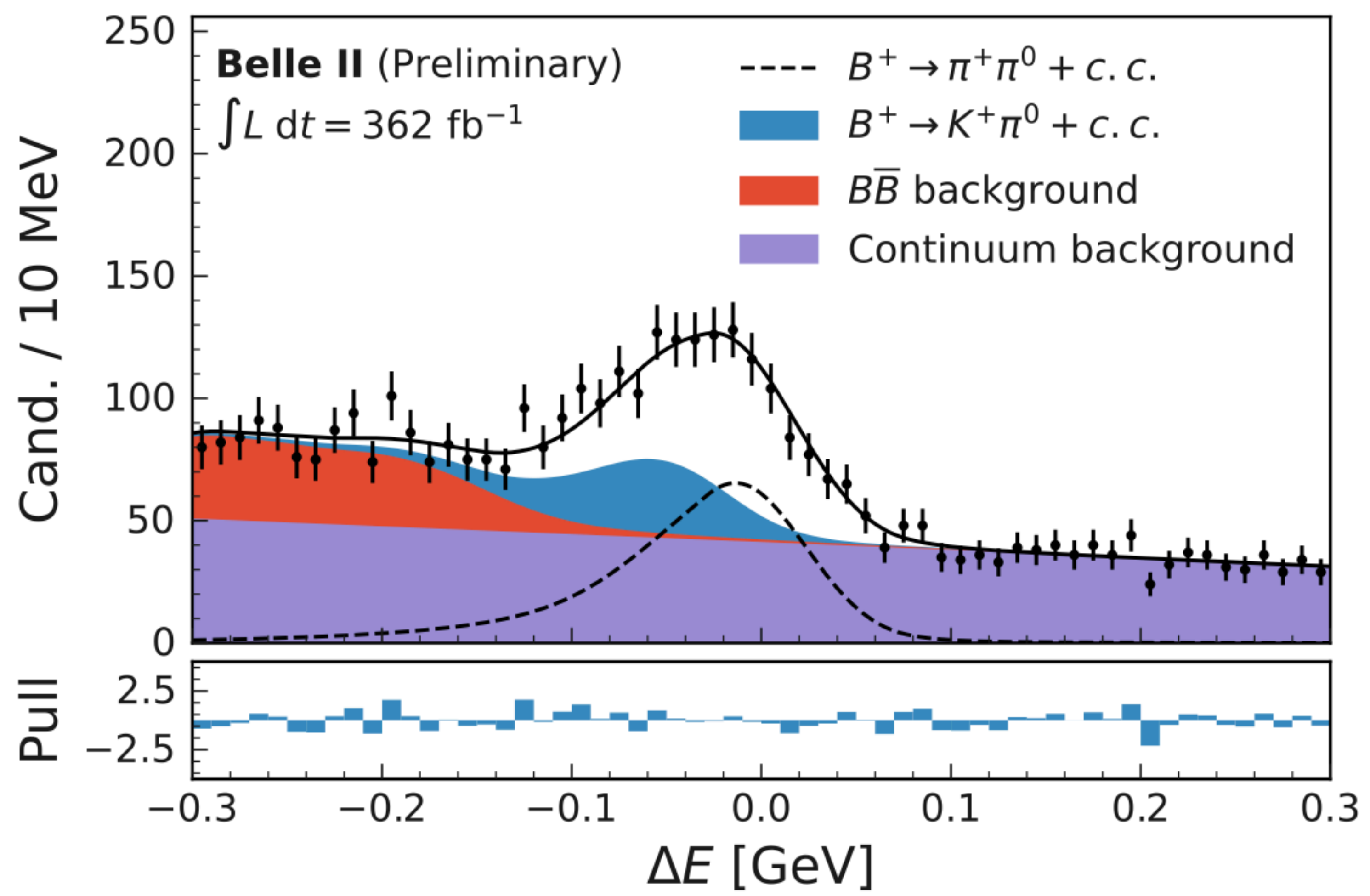


$$S_f = \sqrt{1 - A_f{}^2} sin(2\phi_2 + 2\Delta\phi_2)$$

Interference between tree and penguin

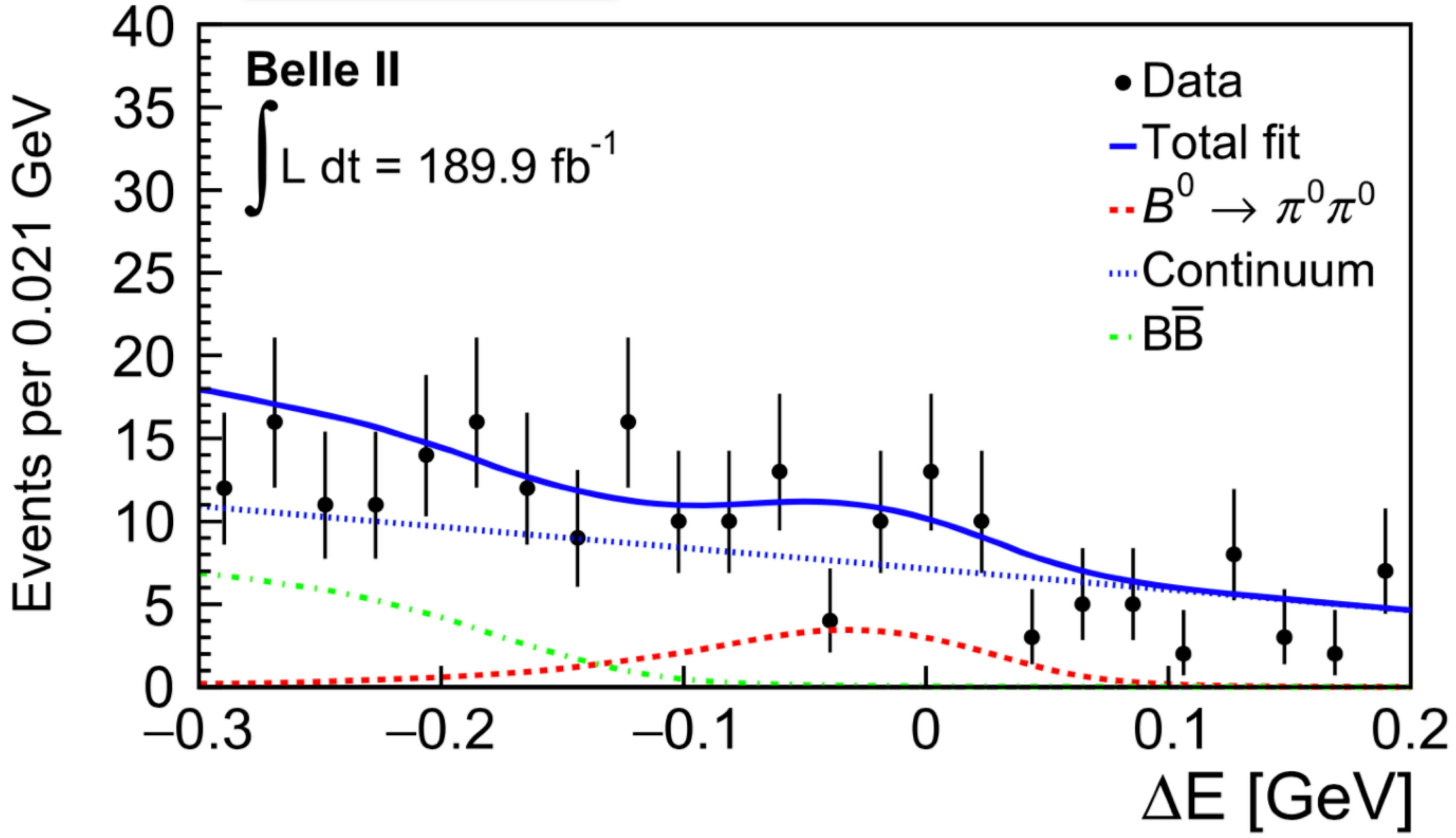


$B^+\to\pi^+\pi^0$ arXiv:2310.06381



$$\Delta E = E^*_B - E^*_{beam}$$

$B^0\to\pi^0\pi^0$ PRD107 (2023) 112009

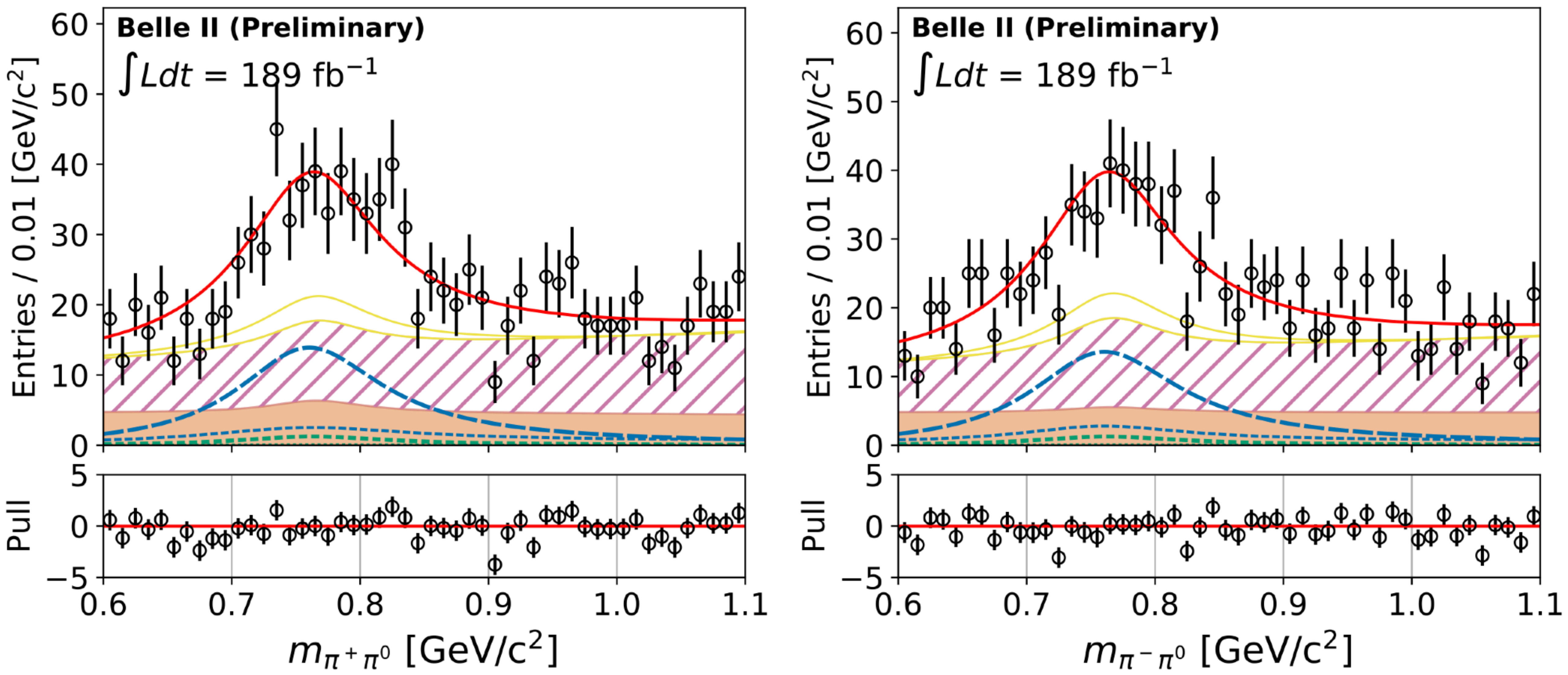


	$B^0\to\pi^+\pi^-$	$B^+\to\pi^+\pi^0$	$B^0\to\pi^0\pi^0$
$\mathcal{B}$ x 10^{-6}	5.83 ± 0.22 ± 0.17	5.10 ± 0.29 ± 0.32	1.38 ± 0.27 ± 0.22
A_{CP}		-0.081 ± 0.54 ± 0.008	0.14 ± 0.46 ± 0.07
A_{CP}(PDG)		0.03 ± 0.04	0.33 ± 0.22

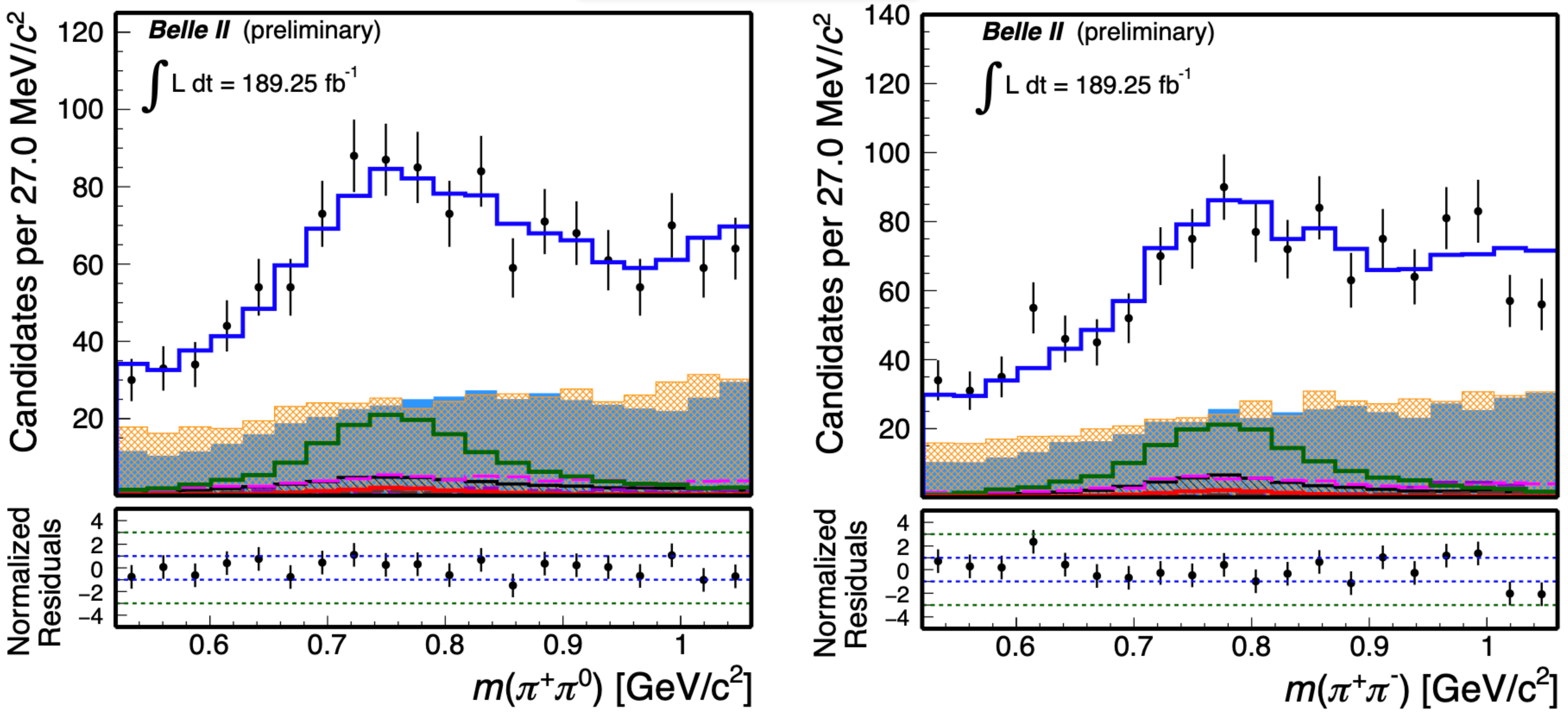
ϕ_2 measurement ($B \to \rho\rho$)

- $B \to \rho\rho$ isospin analysis and $B \to \rho(\pi\pi)\pi$ Dalitz analysis of 3 body decays
- Unique measurement at Belle II

$B^0 \to \rho^+\rho^-$ arXiv:2208.03554



$B^+ \to \rho^+\rho^0$ arXiv:2206.12362

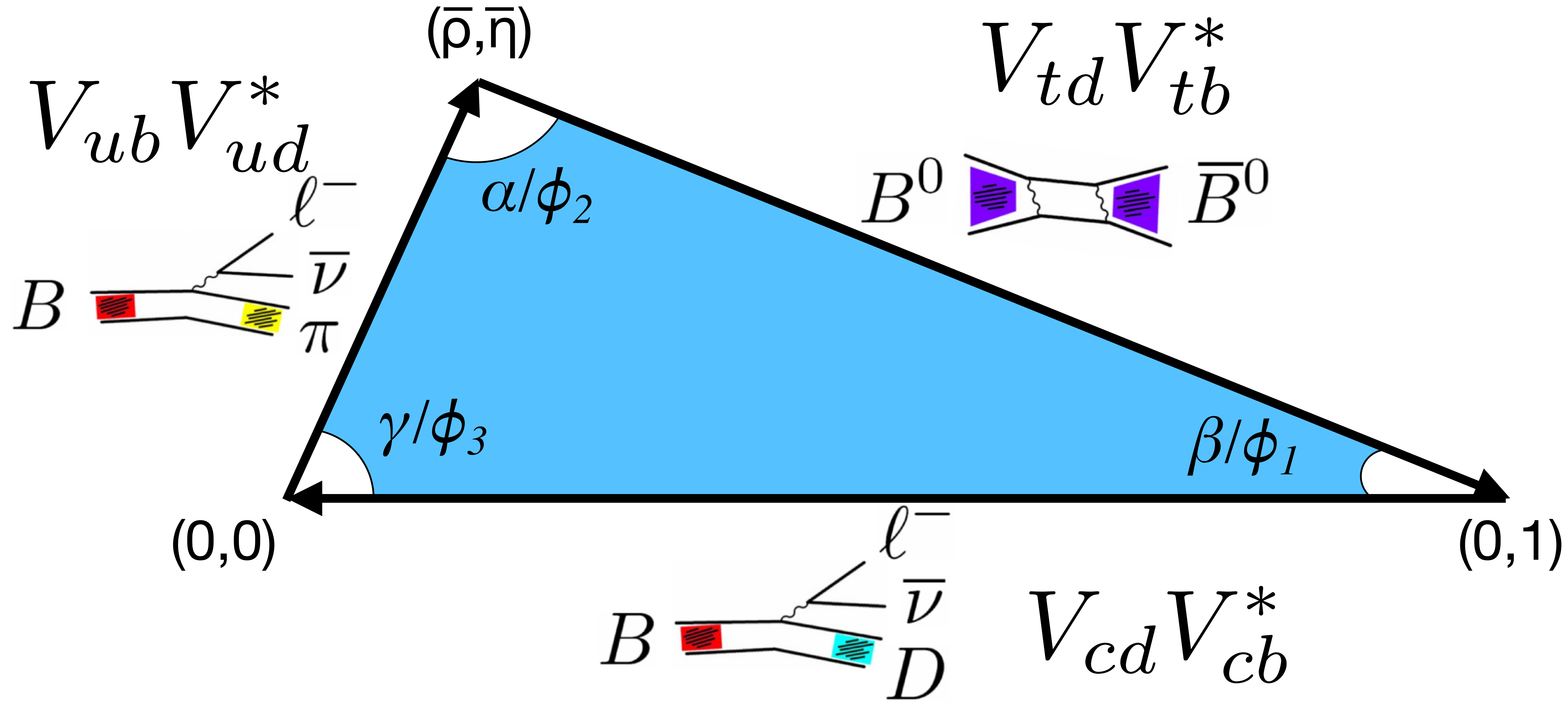


	$B^0 \to \rho^+\rho^-$	$B^+ \to \rho^+\rho^0$
$\mathcal{B} \times 10^{-6}$	$26.7 \pm 2.8 \pm 2.8$	$23.2^{+2.2}_{-2.1} \pm 2.7$
A_{CP}		$-0.069 \pm 0.069 \pm 0.060$
A_{CP}(PDG)		-0.05 ± 0.05

- Compatible with PDG value
- Performance superior to early Belle results
- **$\Delta\phi_2$~2.5°** with 10 ab^{-1} data

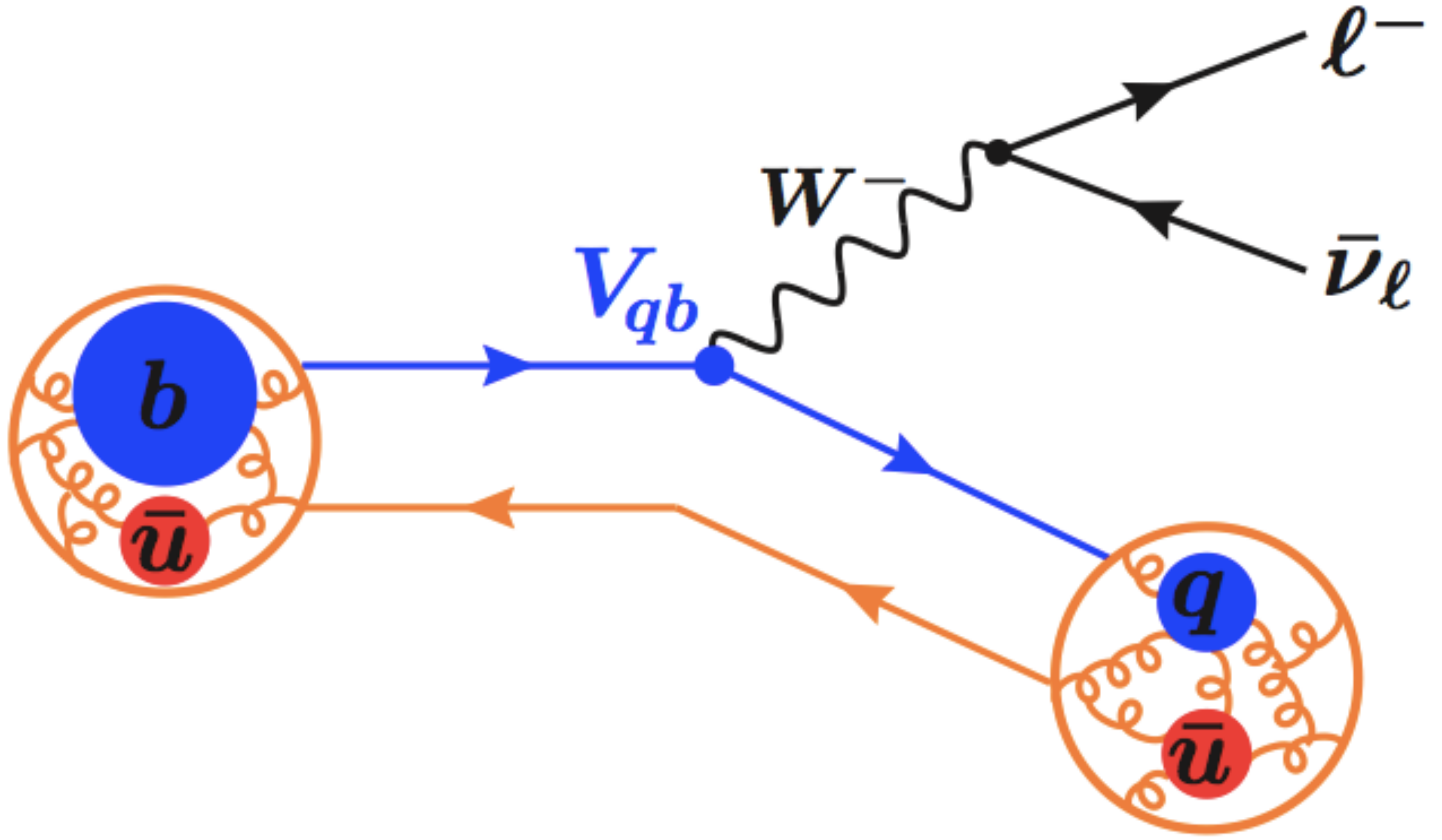
arXiv:2207.06307

$|V_{cb}|$, $|V_{ub}|$ measurement through semi-leptonic B decays

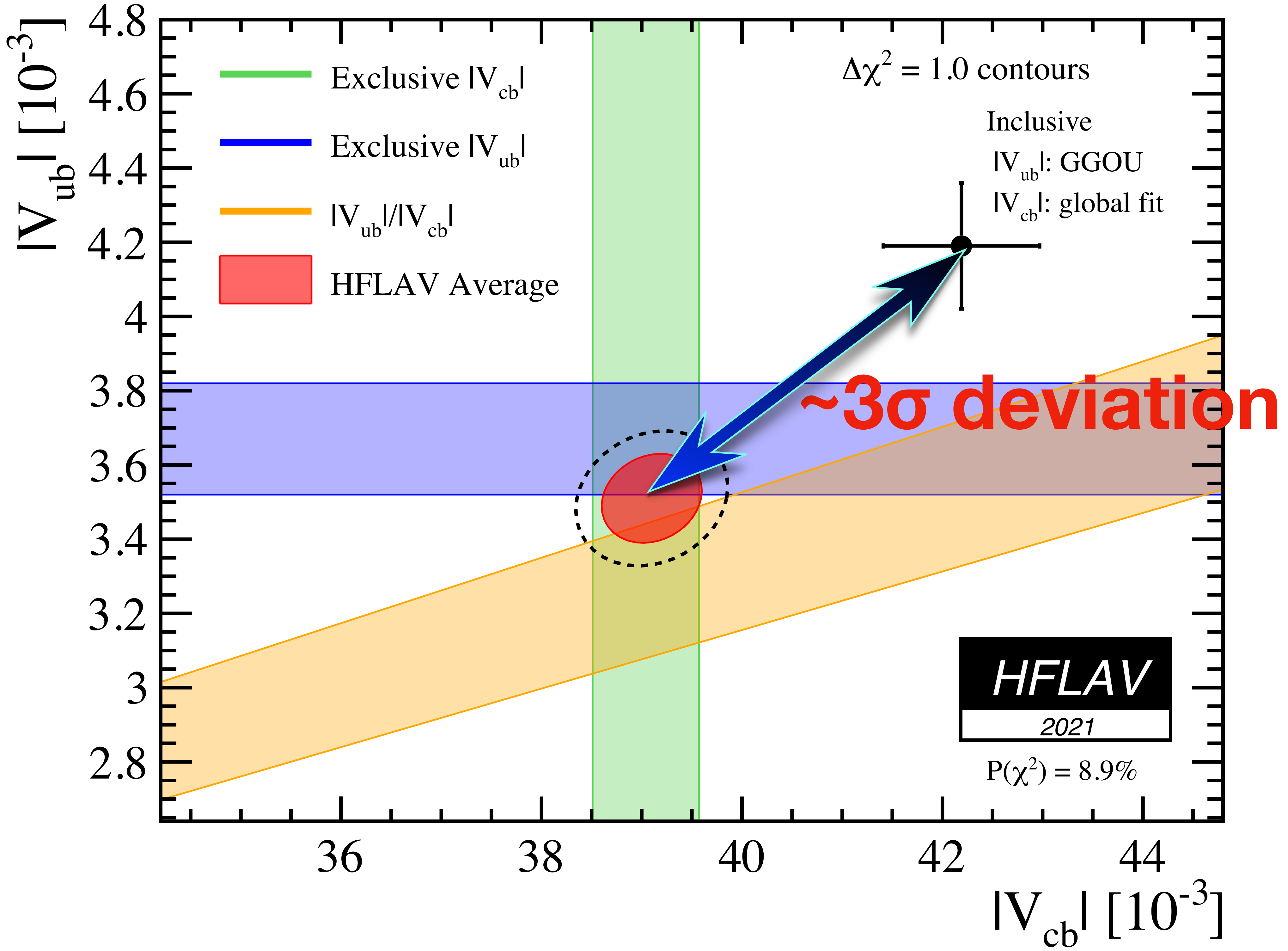


Status of $|V_{cb}|$ and $|V_{ub}|$

Side	Observable		Dominant uncertainties
$\|V_{cb}\|$	$Br(b \to cl\nu)$	$Br(B \to D^{(*)}l\nu)$	Exclusive: Lattice QCD Inclusive: experiment vs. phenomenology
		$Br(B \to X_c l\nu)$	
$\|V_{ub}\|$	$Br(b \to ul\nu)$	$Br(B \to \pi/\rho l\nu)$	
		$Br(B \to X_u l\nu)$	

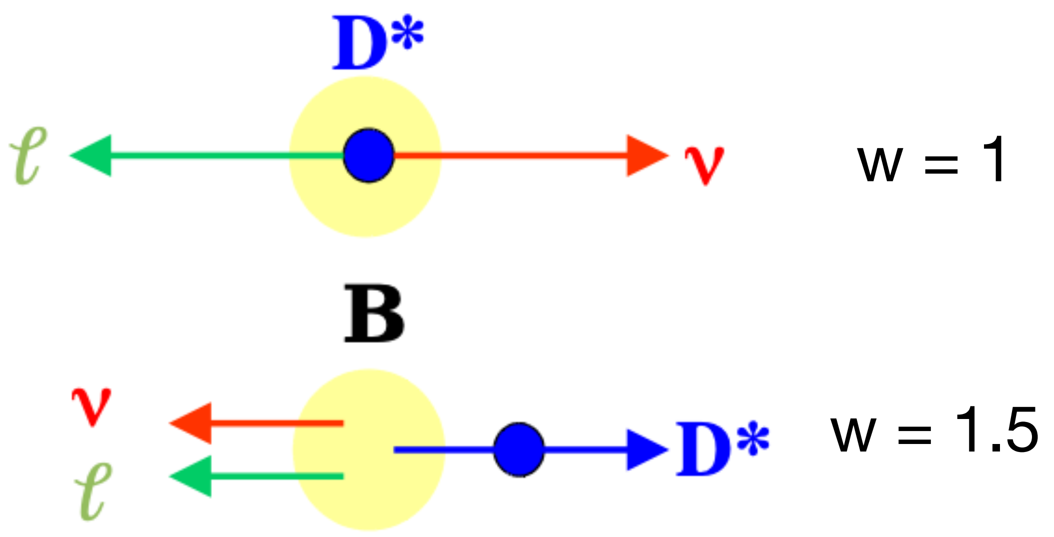


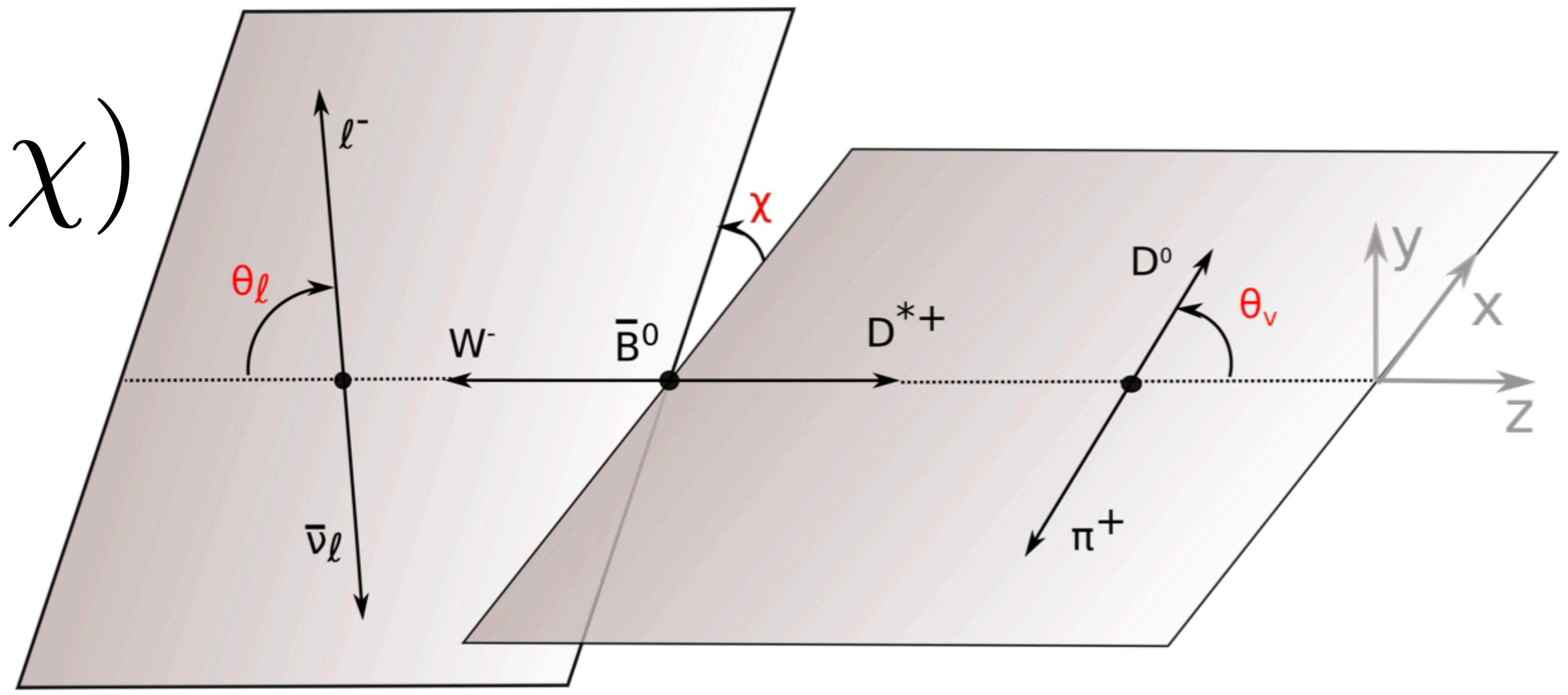
- $|V_{ub}|$ and $|V_{cb}|$ determinations based on inclusive and exclusive measurements differ by ~3σ
- Experimental focus is on understanding this discrepancy, as it limits the power of precision flavor physics



Measurement of $B \to D^* l \nu$ for $|V_{cb}|$

$$\frac{d^4\Gamma}{dw\, d\cos\theta_l\, d\cos\theta_V\, d\chi} \propto |V_{cb}|^2 A(w, \cos\theta_l, \cos\theta_V, \chi)$$

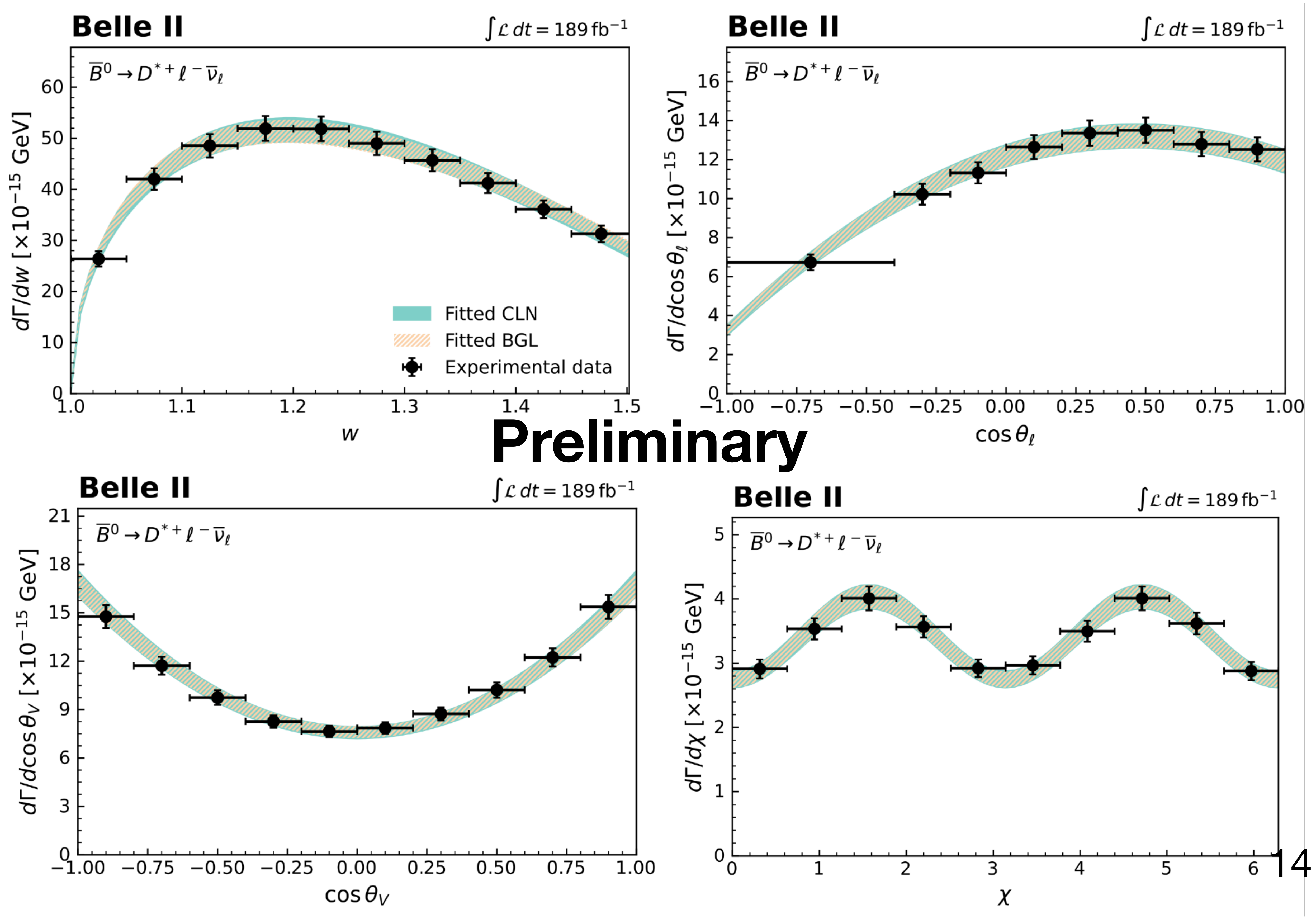




- Form factor parameterisations, BGL and CLN
  - Determination rely heavily on zero recoil w = 1
- LQCD used only for normalisation at zero recoil (w=1)
  - $\mathcal{F}(1)$ = 0.906 ± 0.013

$|V_{cb}|_{CLN}$ = (40.13 ± 0.47 ± 0.93 ± 0.58) x 10^{-3}
$|V_{cb}|_{BGL}$ = (40.57 ± 0.31 ± 0.95 ± 0.58) x 10^{-3}

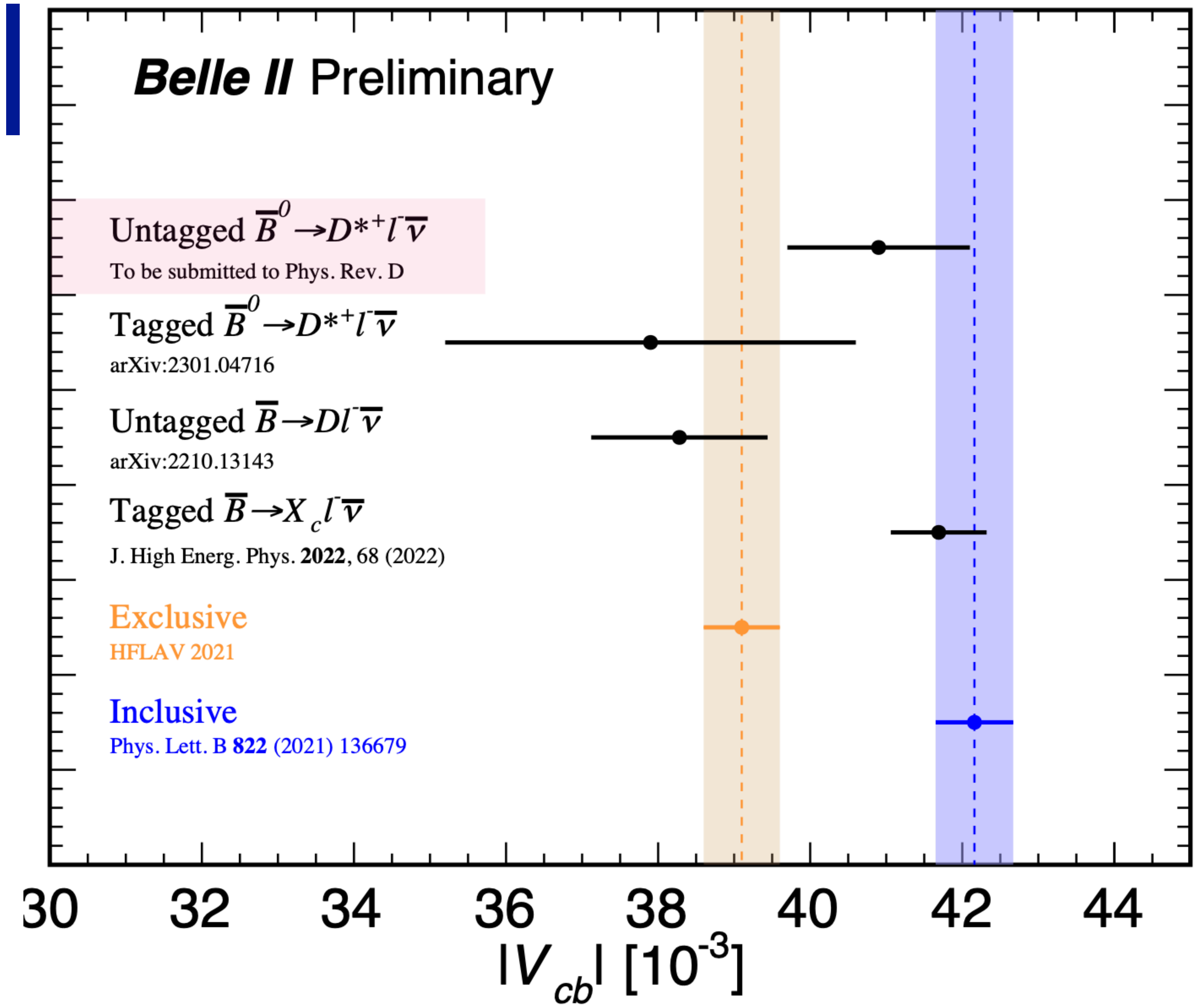
arXiv:2310.01170 Accepted by PRD

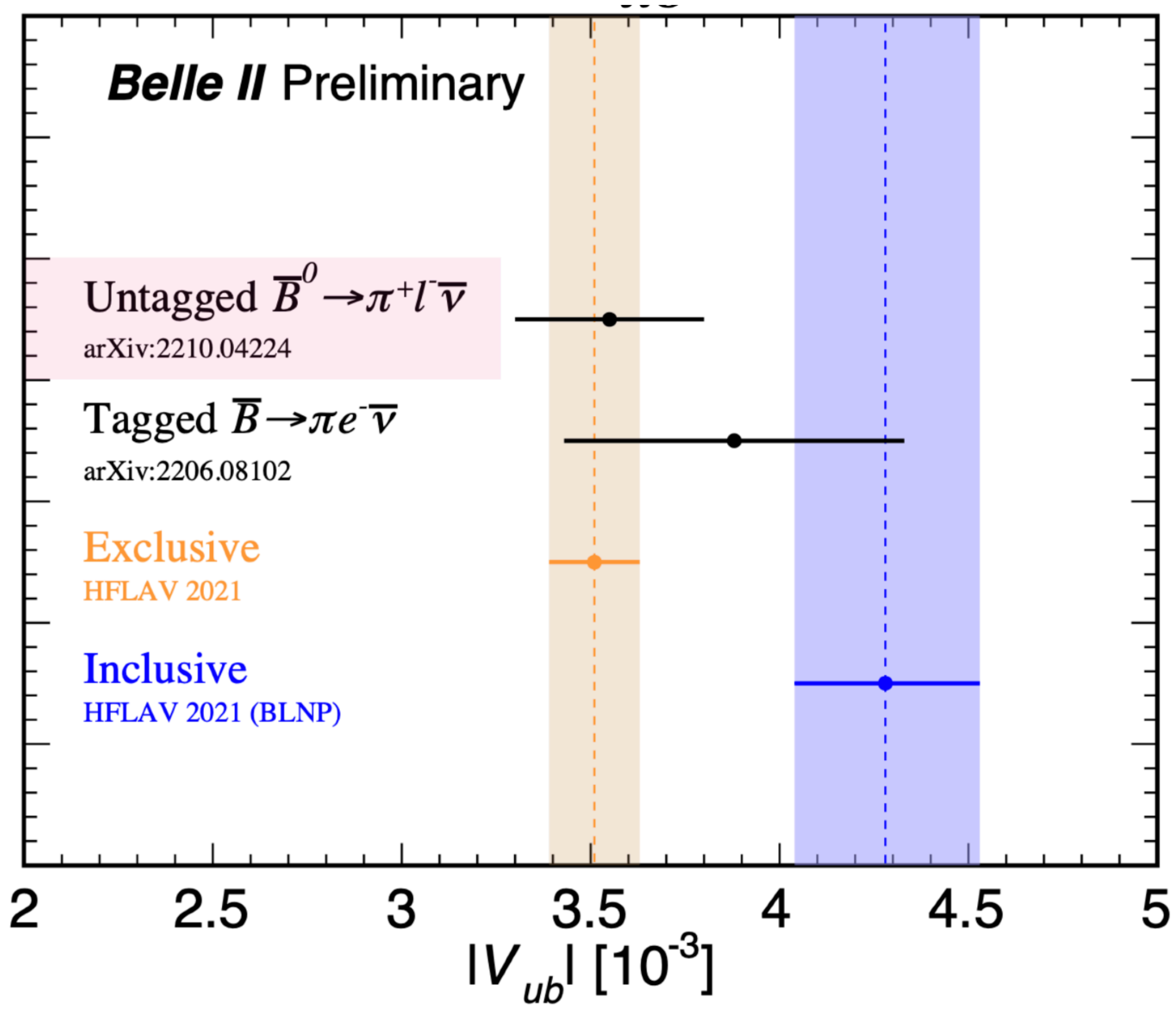


- BGL: Boyd, Grinstein, Lebed, PRD56(1997)6895
- CLN: Caprini, Lellouch, Neubert, Nucl. Phys. B530(1998) 153

$|V_{cb}|$ and $|V_{ub}|$ status from Belle II

$|V_{cb}|$





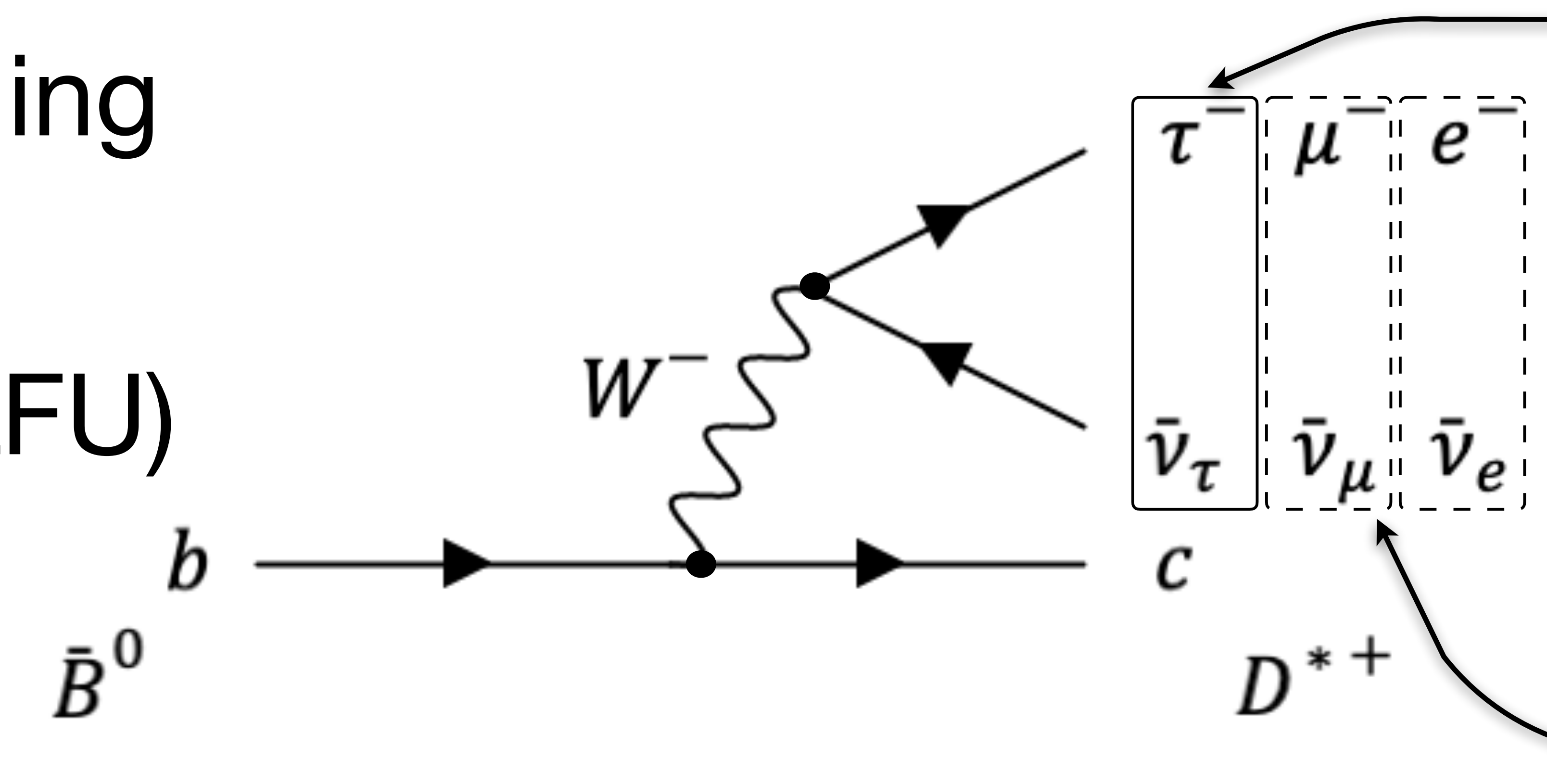
$|V_{ub}|$

- Consistent with world average
- Slightly reduced the tension between exclusive and inclusive $|V_{cb}|$ and $|V_{ub}|$
- Belle II experimental statistical and systematic uncertainty can be significantly reduced with more data

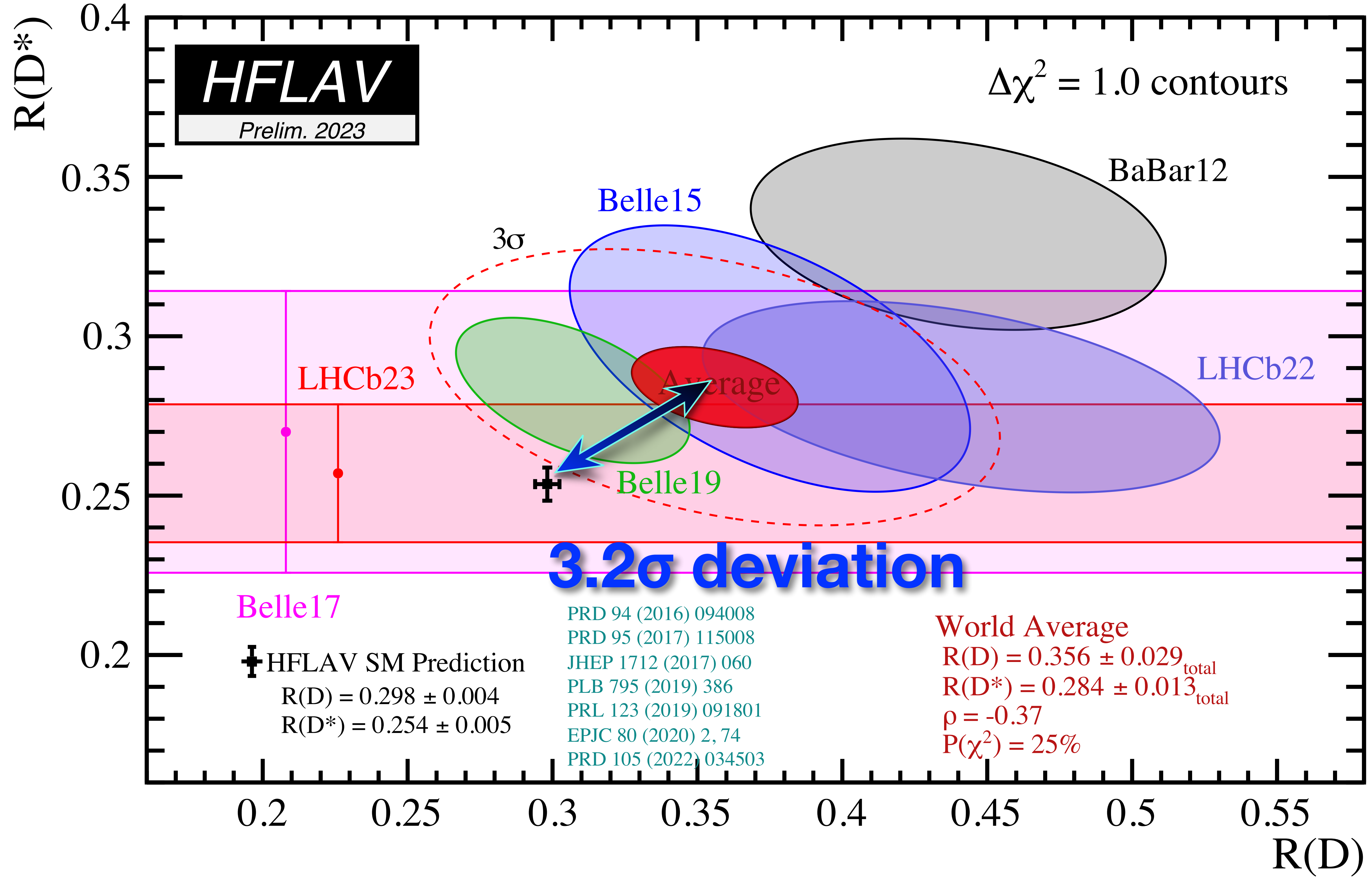
Test of Lepton Flavor Universality

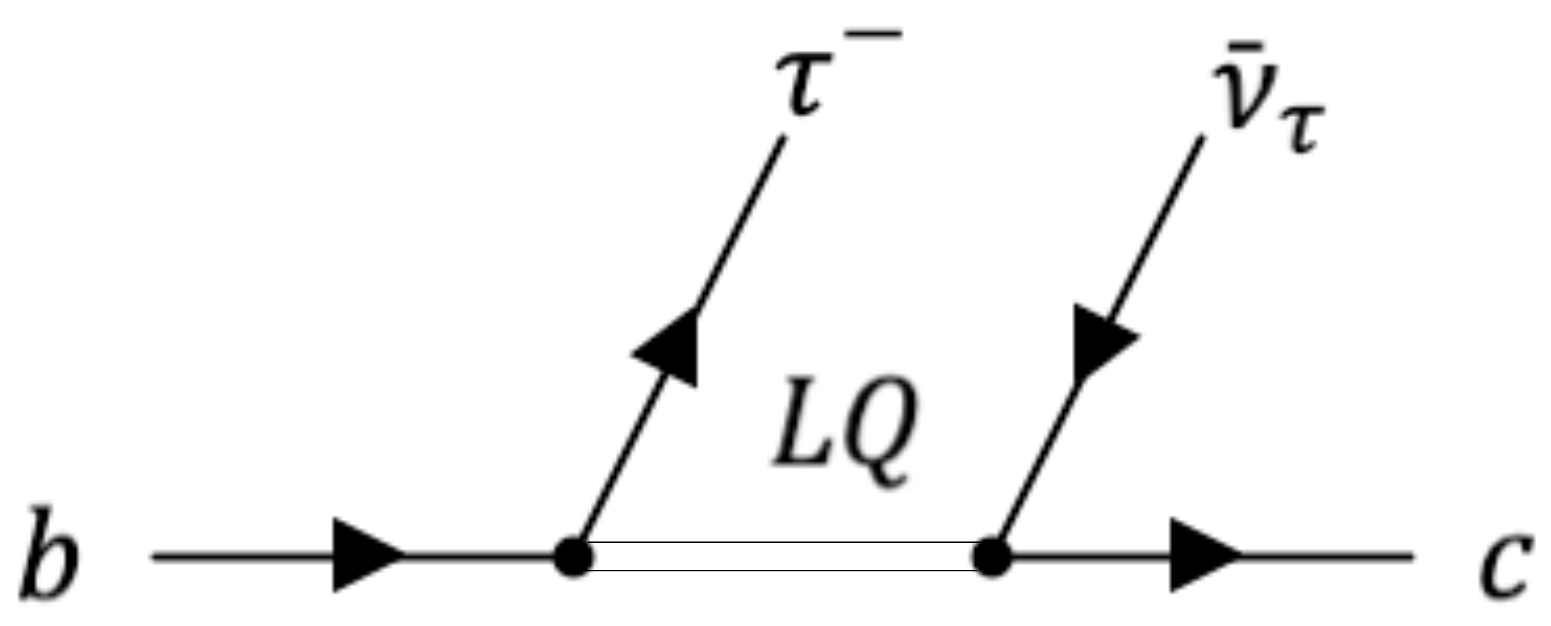
$R(D)$ and $R(D^*)$ anomaly

- Universality of the lepton coupling to the W gauge boson
  - Lepton Flavor Universality (LFU) is fundamental axiom of Standard Model (SM)
- Ratio of branch fractions cancel out most of the uncertainties on $|V_{cb}|$, form factors and the experimental systematics
- $B \to D^{(*)}\tau\nu$ sensitive to NP because the massive 3rd generation b quark and τ lepton are involved



$$R(D^{(*)}) = \frac{Br(\bar{B}^0 \to D^{(*)+}\tau^-\bar{\nu}_\tau)}{Br(\bar{B}^0 \to D^{(*)+}\ell^-\bar{\nu}_\ell)}$$





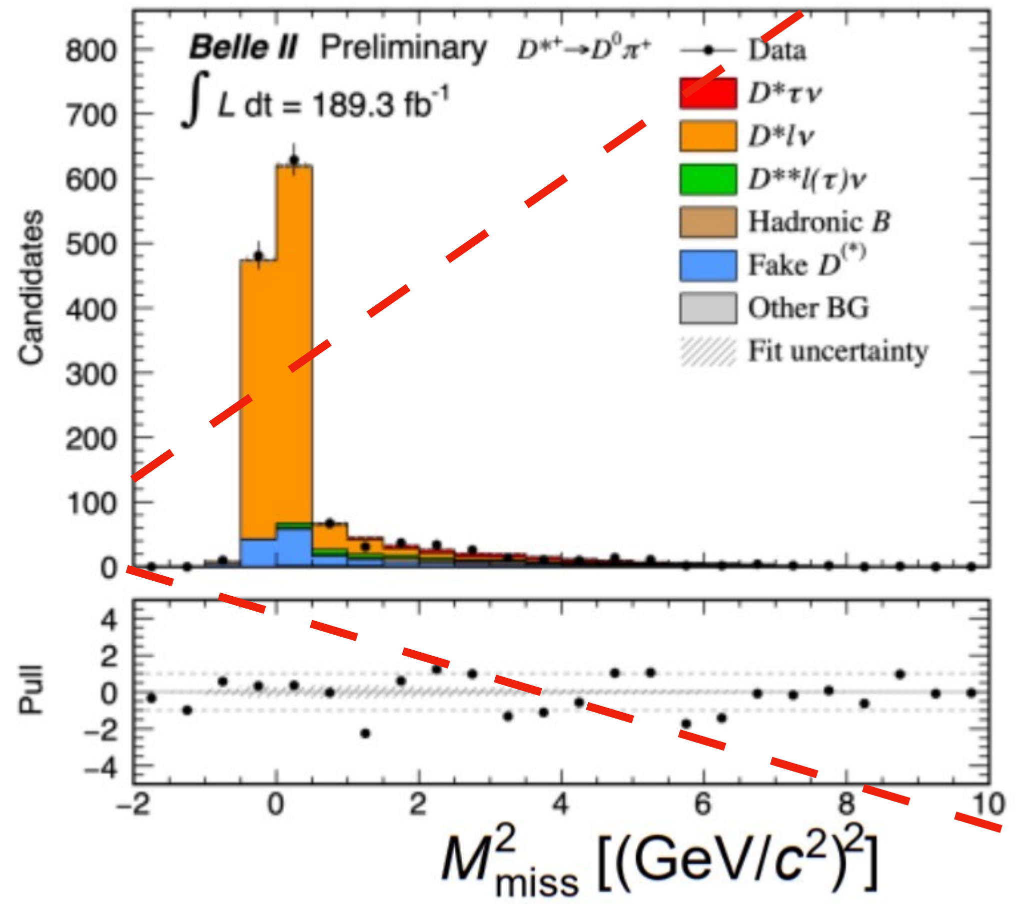
3.8σ —> 3.1σ —> 3.3σ —> 3.2σ —> 3.2σ
LHCb18 Belle19 2021 LHCb22 LHCb23

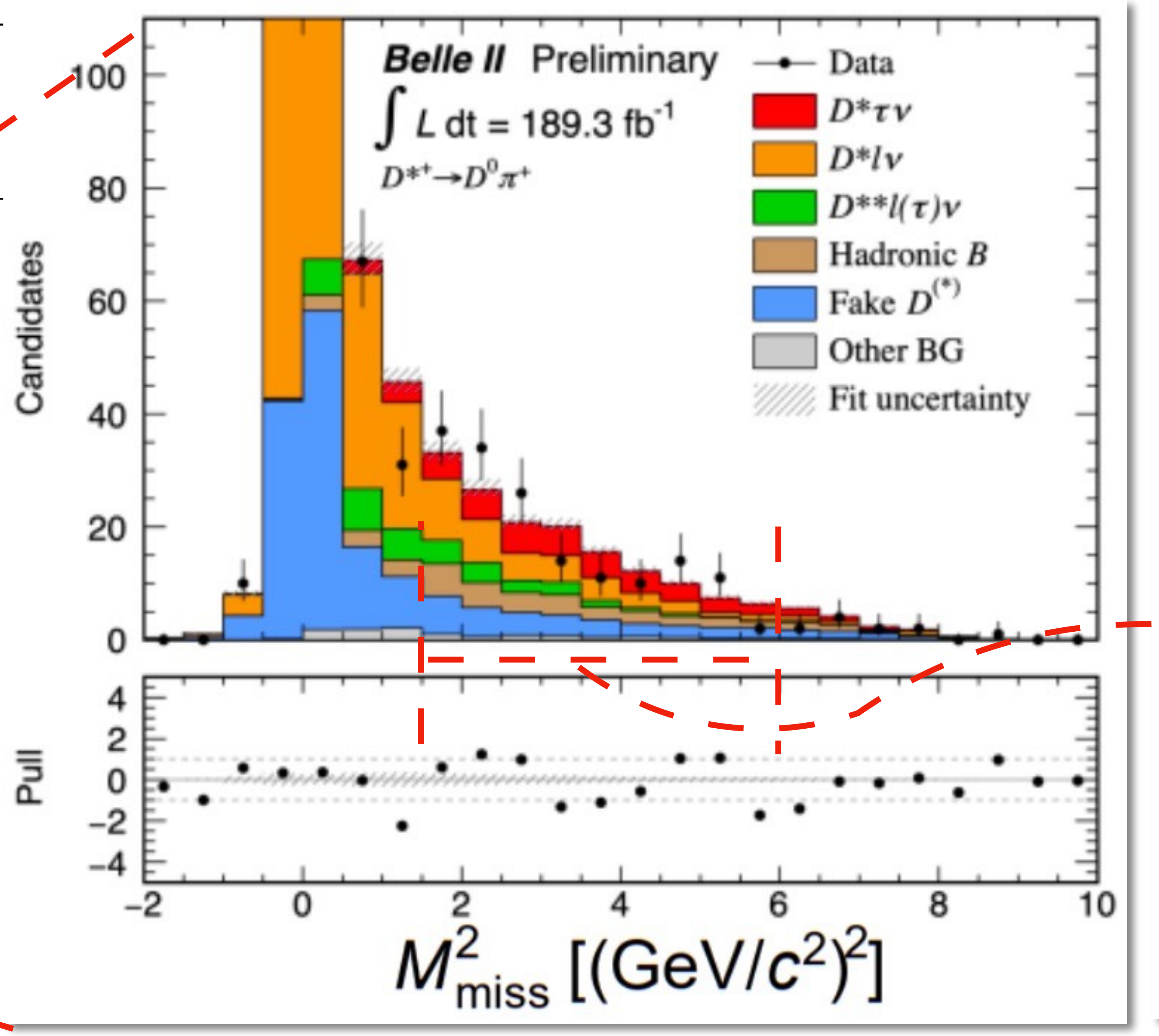
Signal extraction and uncertainties of Belle II $R(D^*)$

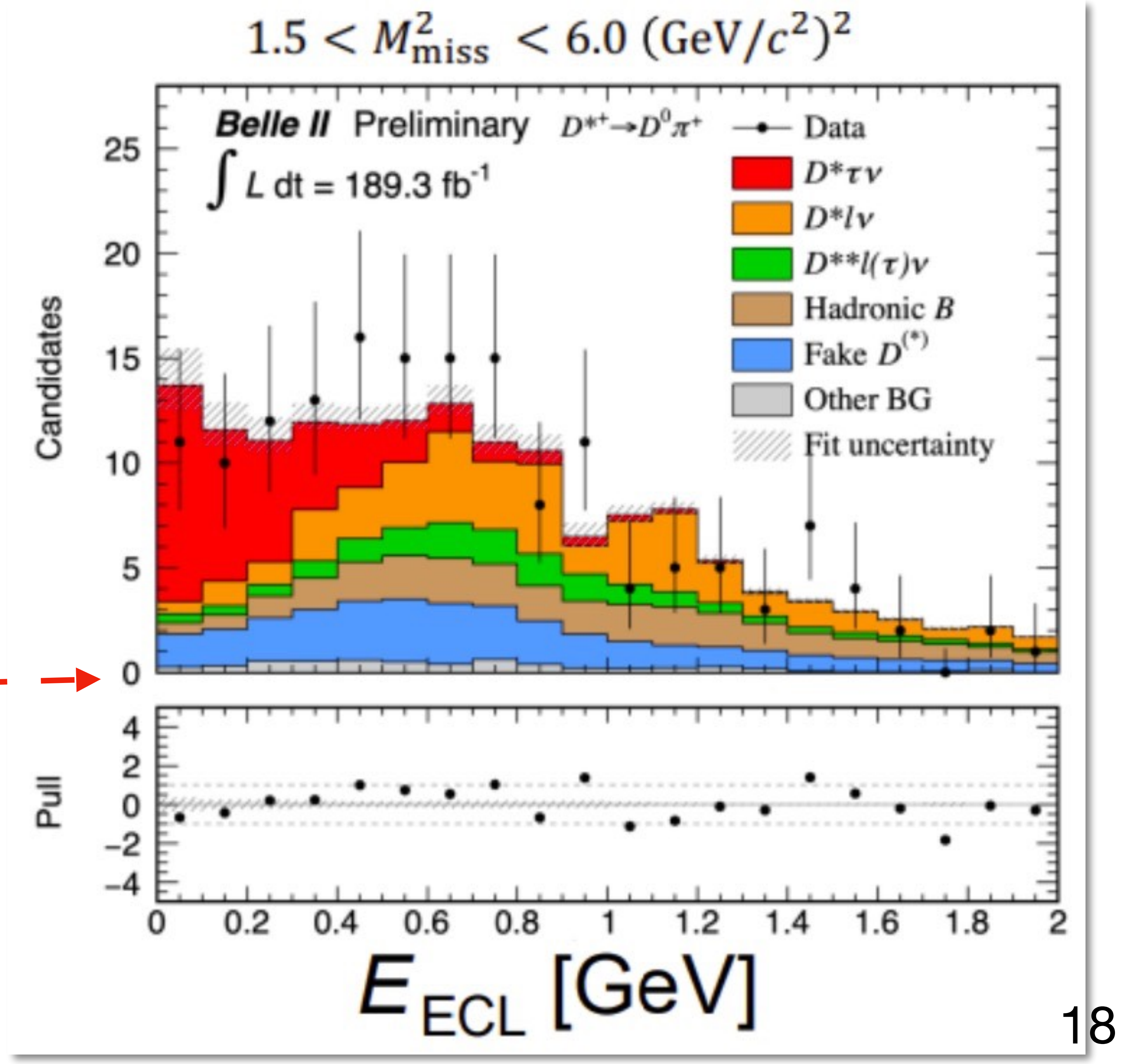
- Extracting $B \to D^*\tau\nu$, $B \to D^*l\nu$ yields by a two-dimensional simultaneously fit
- Similarly sensitivity as Belle 15' result @ 711 fb^{-1} with only 189 fb^{-1}

Source	Uncertainty
Statistical uncertainty	+15.4% -14.6%
E_{ECL} PDF shape	+5.5% -9.3%
MC statistics	±7.0%
$B \to D^{**}l\nu$ modeling	+4.7% -2.7%

- $M^2_{miss} = (p_{beam} - p_{Btag} - p_{D(*)} - p_l)^2$
- E_{ECL}: **extra** neutral energy in the calorimeter **NOT** associate with signal







Belle II *R*(*D**) result at 189 fb^{-1}

- Belle II first preliminary result for *R*(*D**)

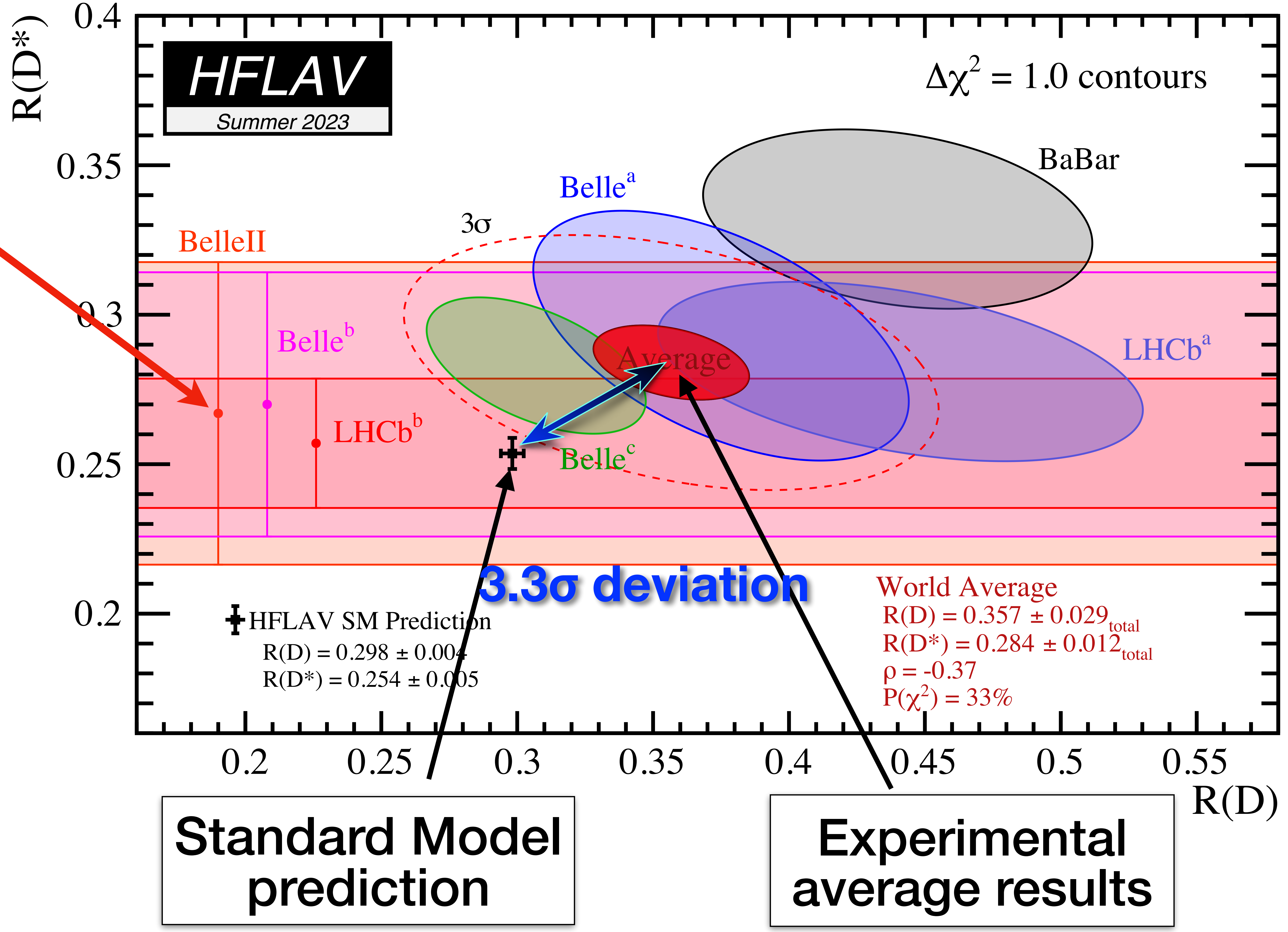
$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat})\ ^{+0.028}_{-0.033}(\text{sys})$$

- Consistent with

  SM: 0.254 ± 0.005,

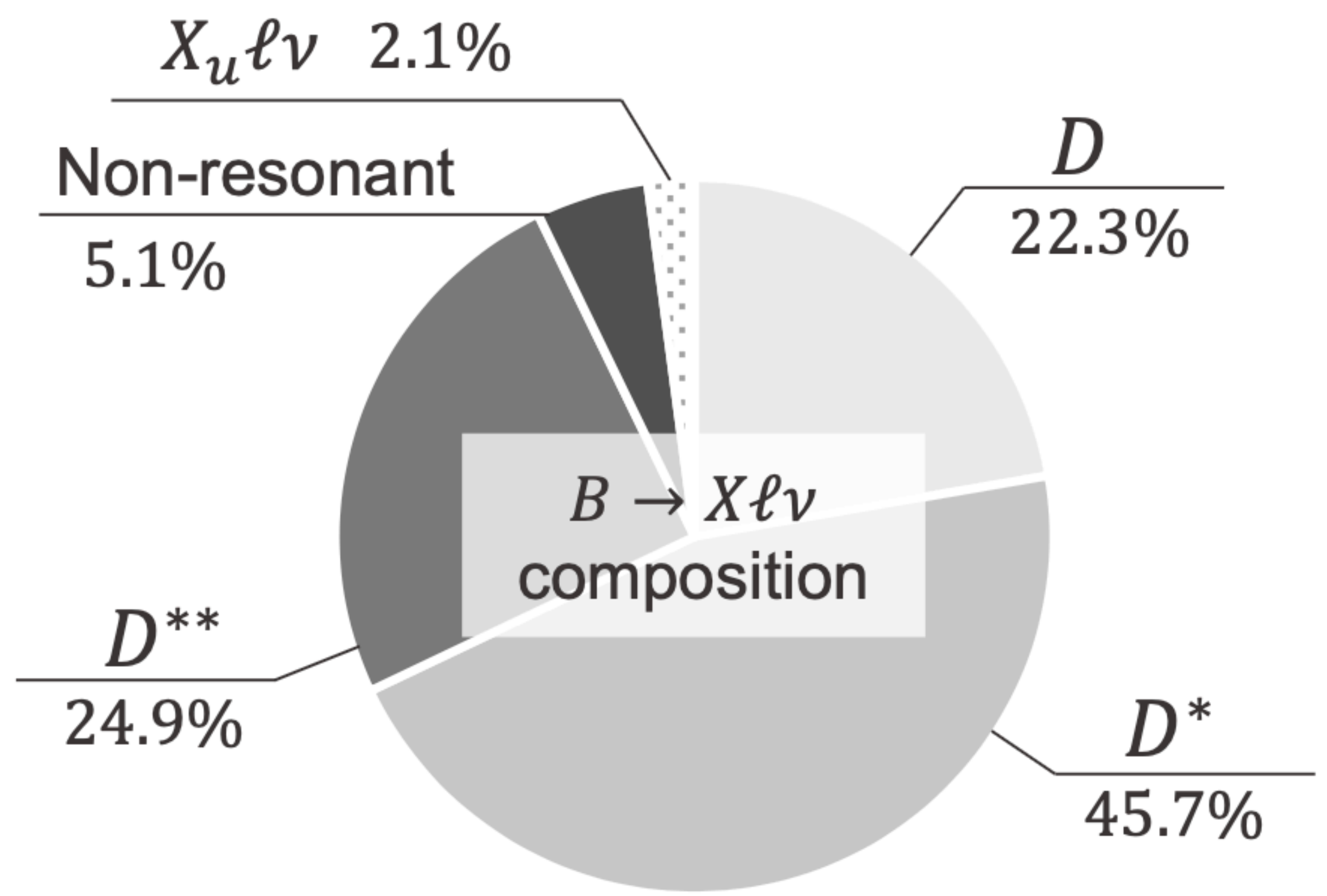
  HFLAV: 0.284 ± 0.013

- SM vs. experimental average deviation: 3.2σ → 3.3σ



LFU test by $R(X_{\tau/l})$ measurement

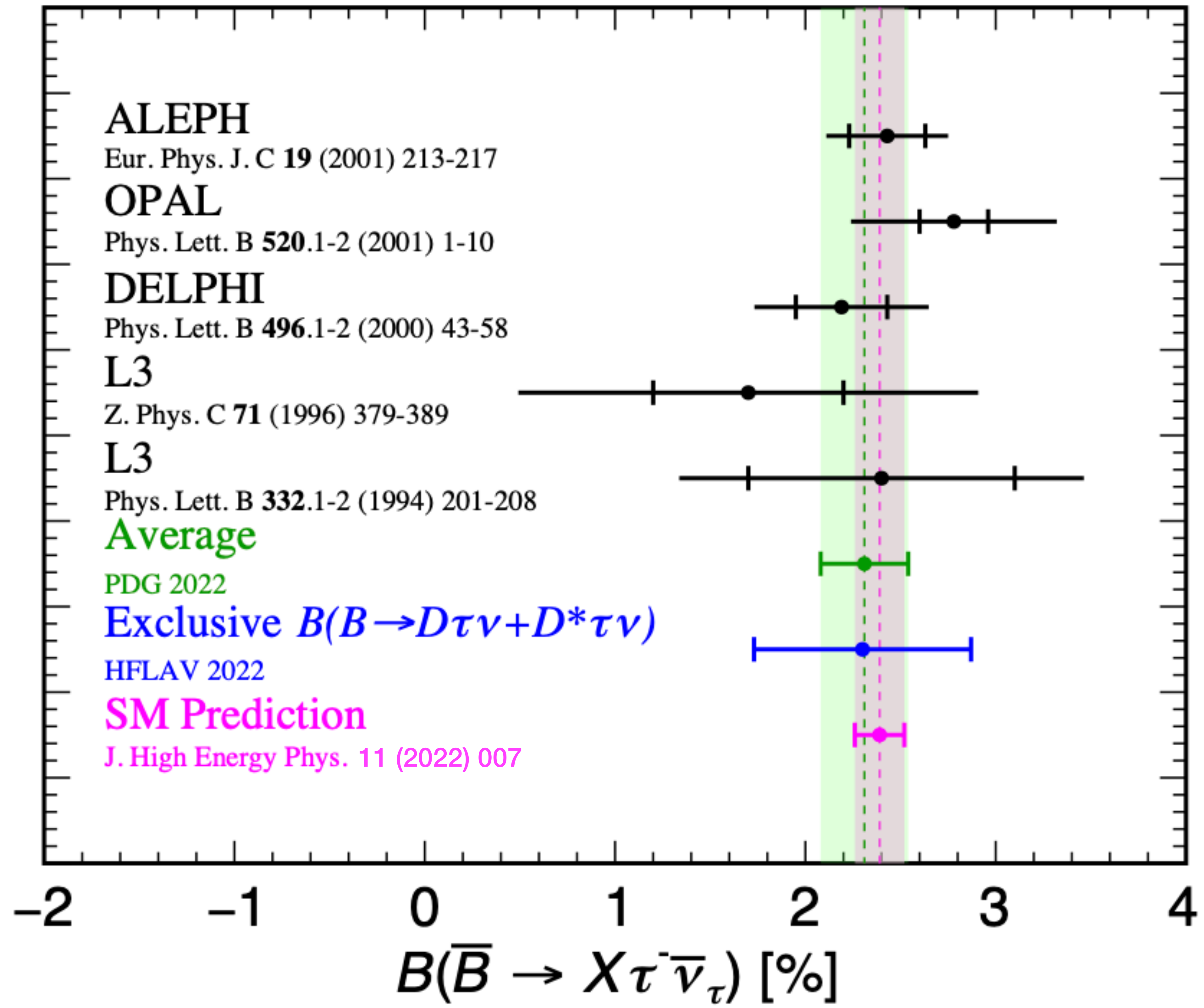
- Breakdown of $B \to Xl\nu$ branching fractions
  - ~ 2/3 overlap with D and D^*
    - ~ 3/4 D decay to ν, K_L^0, $n\pi$ …
  - ~ 1/3 contribution from D^{**} and nonresonant X_c
- Multiple LEP experiments measured Br($B \to X\tau\nu$)
  - Br($B \to X\tau\nu$) are completely saturated by D/D^* BFs
  - ➡ An update measurement is needed



- $R(X)$ is critical cross-check of $R(D^{(*)})$, largest contribution from $R(D^{(*)})$, a partially complementary test of LFU

$$R(X_{\tau/\ell}) = \frac{Br(\bar{B} \to X\tau^-\bar{\nu}_\tau)}{Br(\bar{B} \to X\ell^-\bar{\nu}_\ell)}$$

- $R(X)$ has never been measured



Results of $R(X_{\tau/\ell})$ for LFU test

- Signal yields are extracted by a binned maximum-likelihood simultaneous fit to lepton momentum
- Main systematics
  - Adjustment to MC (form factor, D and B branching factions)
  - Sample size in sideband for reweighting

- First Belle II preliminary $R(X_{\tau/\ell})$ result

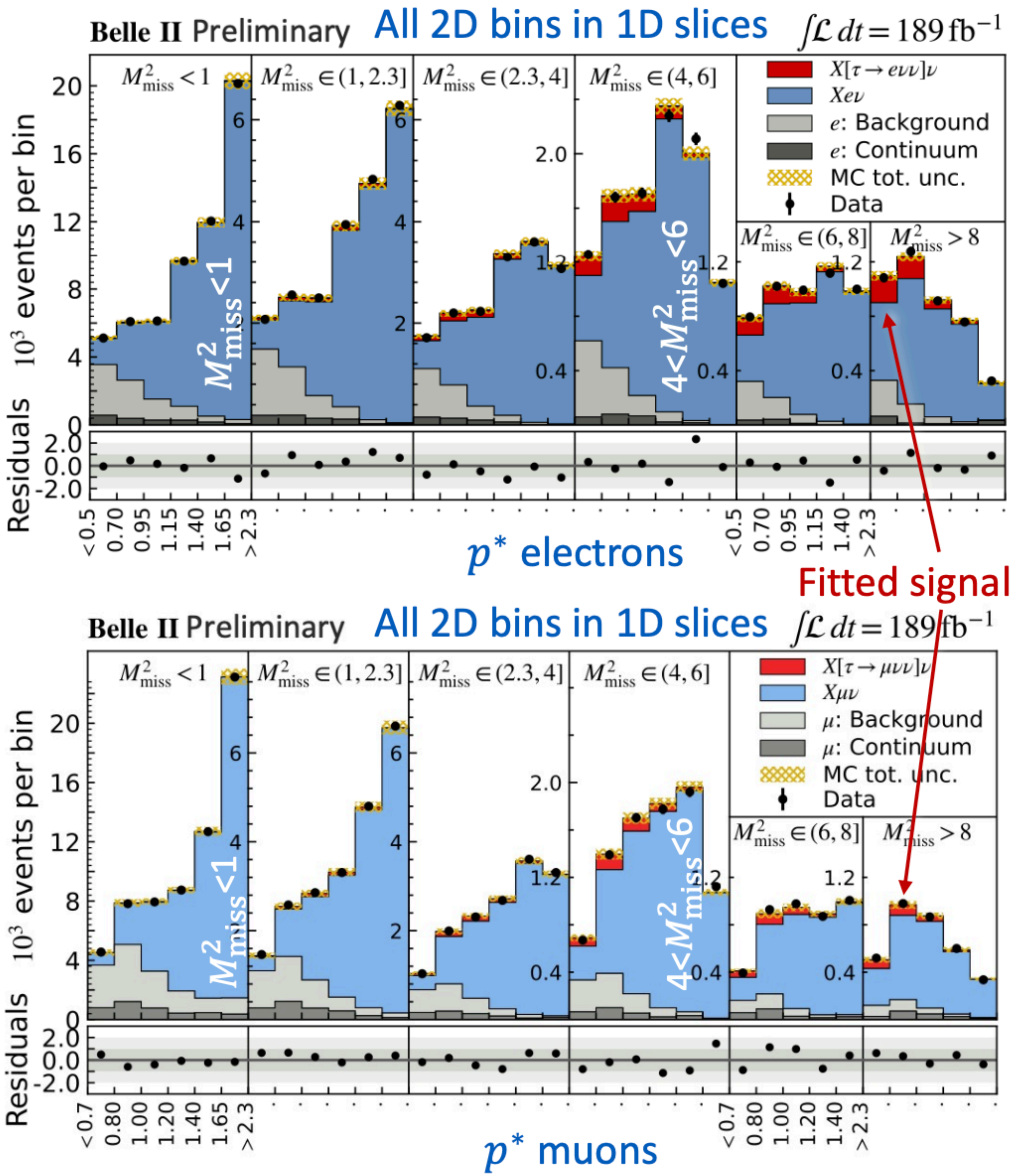
  $R(X_{\tau/\ell})$ = 0.228 ± 0.016 (stat) ± 0.036 (syst)

  $R(X_{\tau/e})$ = 0.232 ± 0.020 (stat) ± 0.037 (syst)

  $R(X_{\tau/\mu})$ = 0.222 ± 0.027 (stat) ± 0.050 (syst)

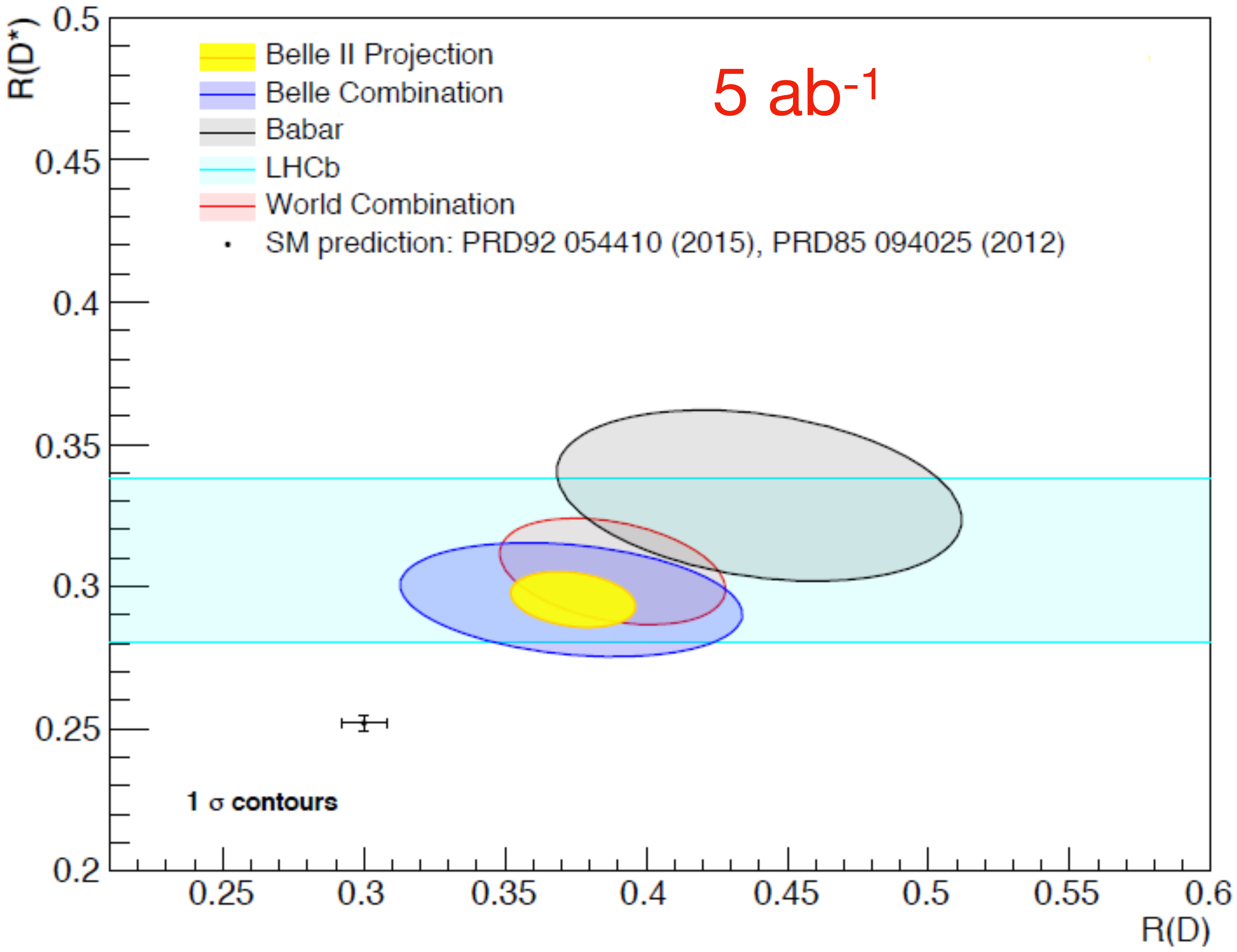
- Consistent with rough SM expectation

  $R(X_{\tau/l})_{SM} \approx 0.222$

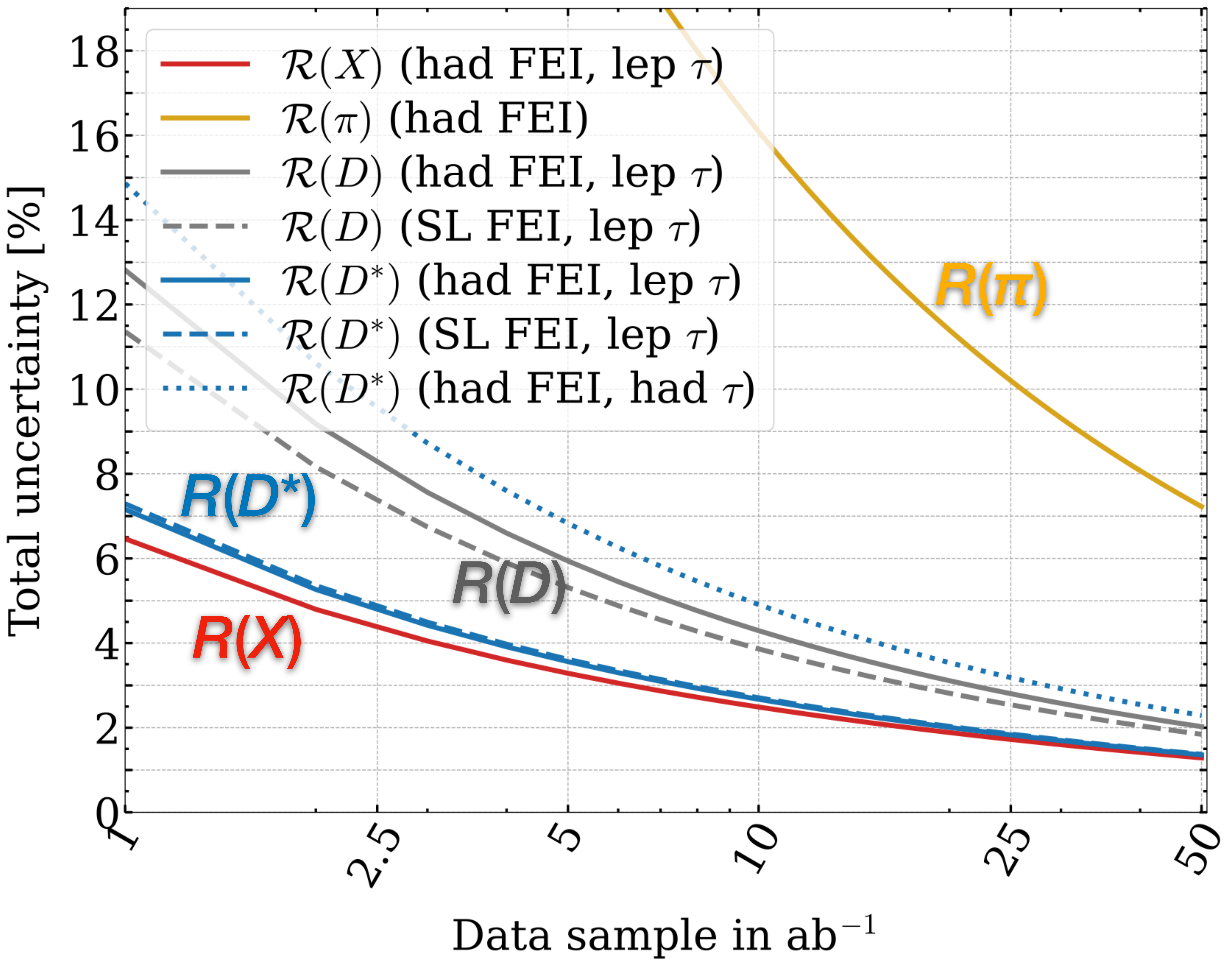


Expected sensitivity of LFU test at Belle II

The Belle II Physics Book, PTEP 2019, 123C01



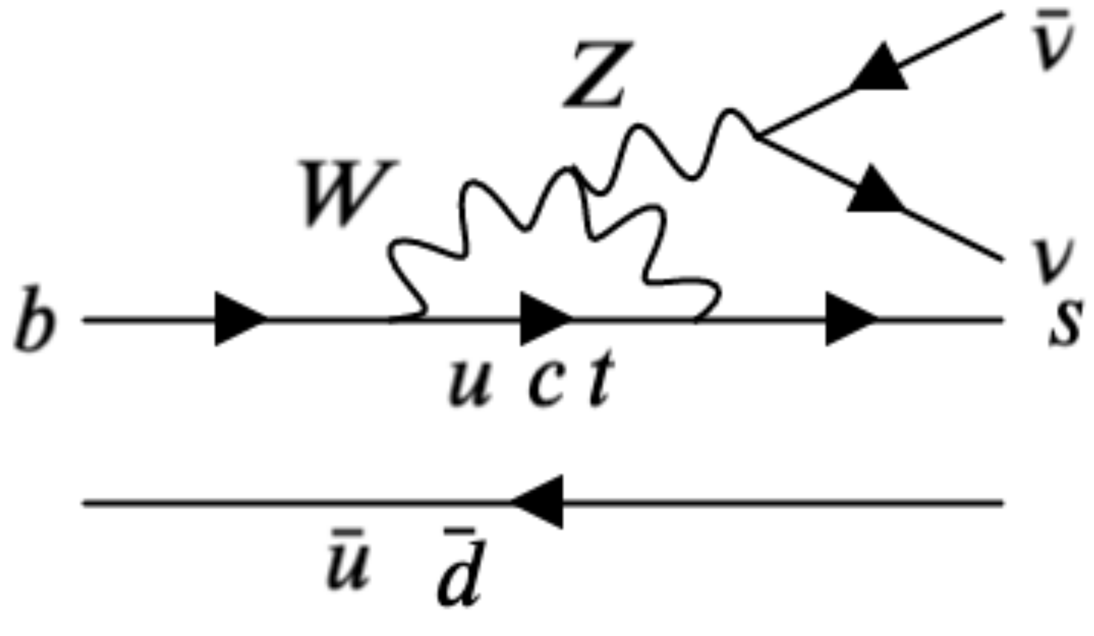
arXiv:2207.06307

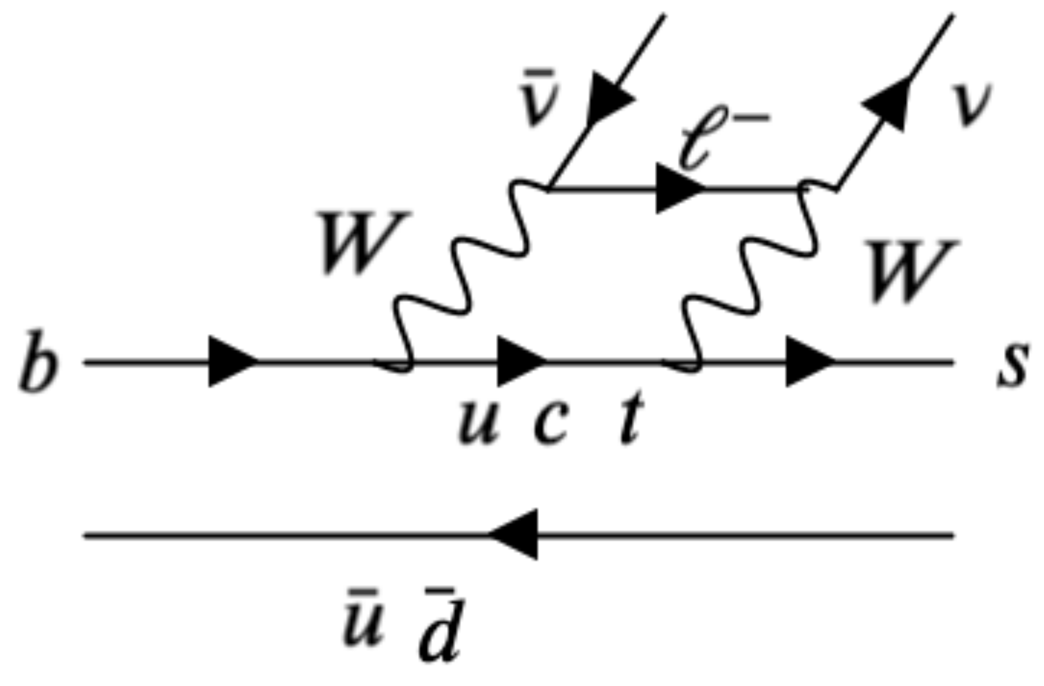


Rare *B* decays

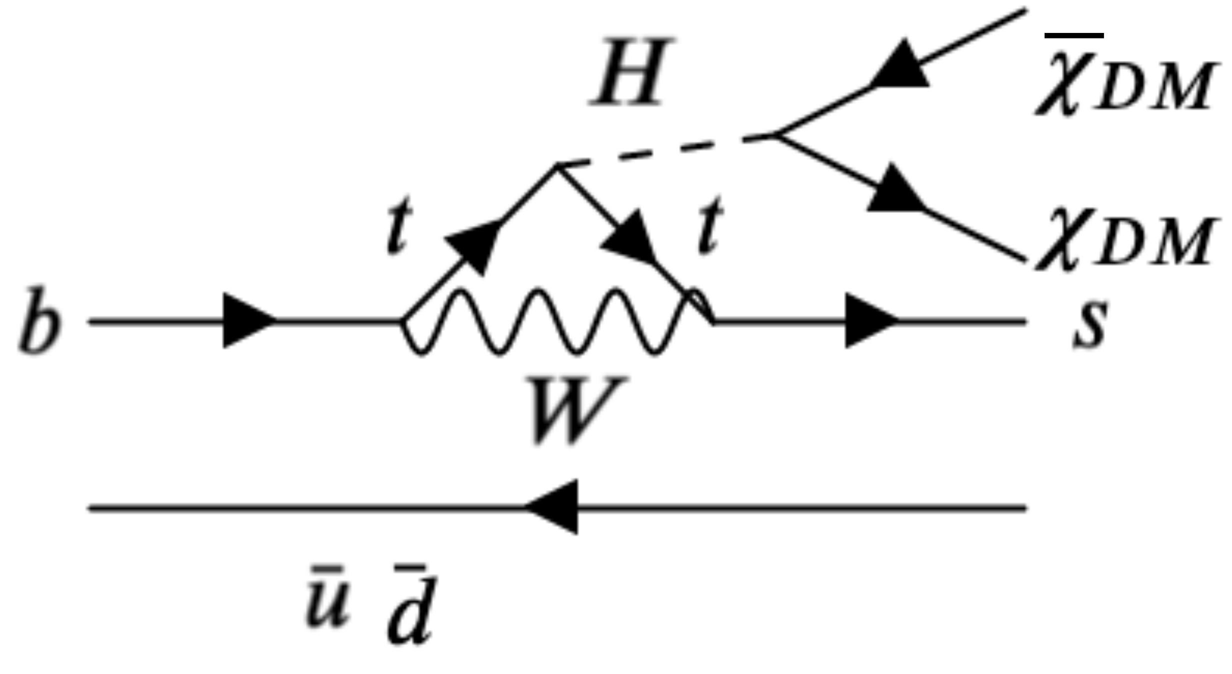
Measurement of $B^+ \to K^+ \nu\bar{\nu}$

- $b \to s\nu\bar{\nu}$ is theoretical clean and well known in SM (5.6±0.4)x10^{-6}, sensitive to NP





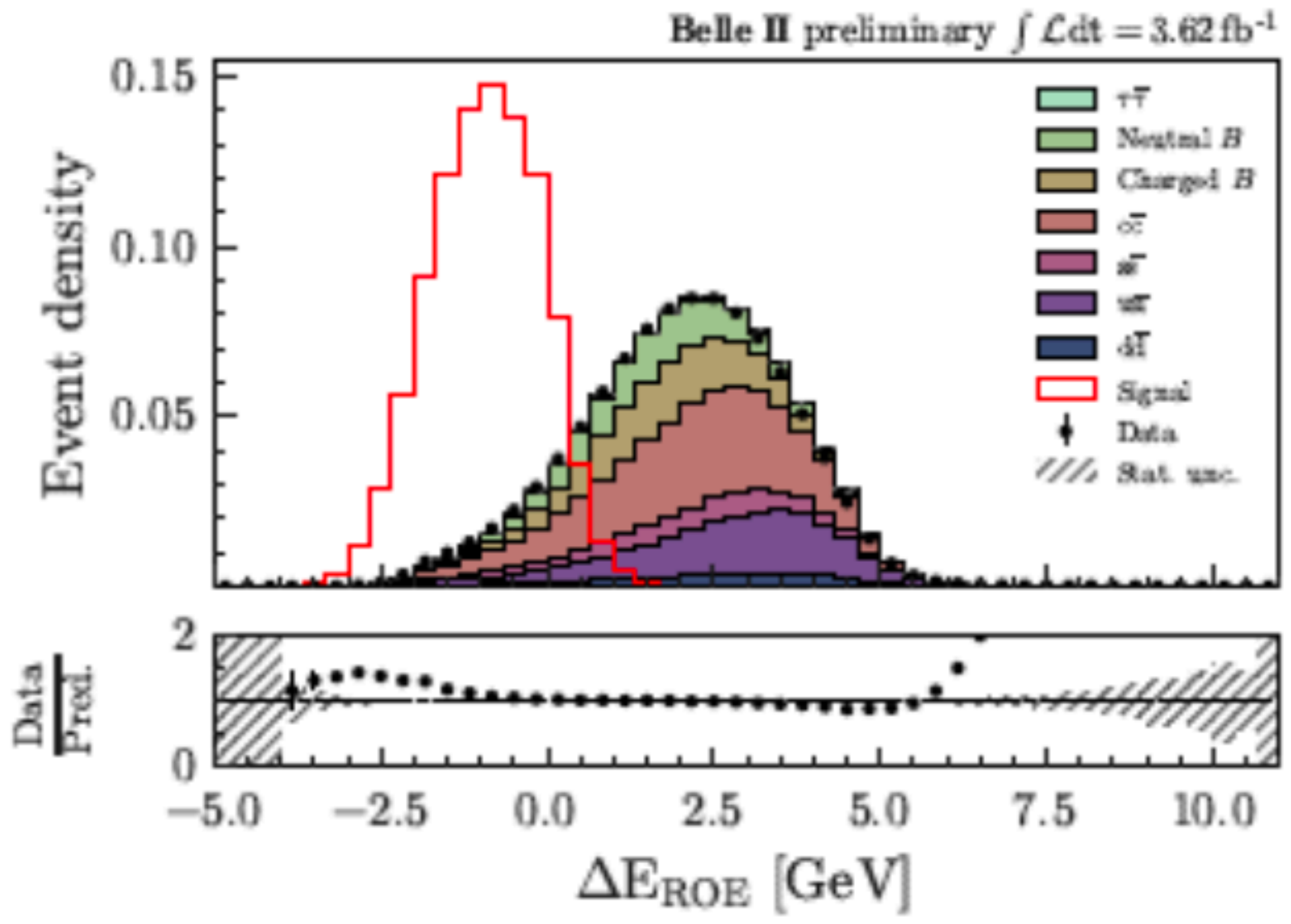
Light dark matter

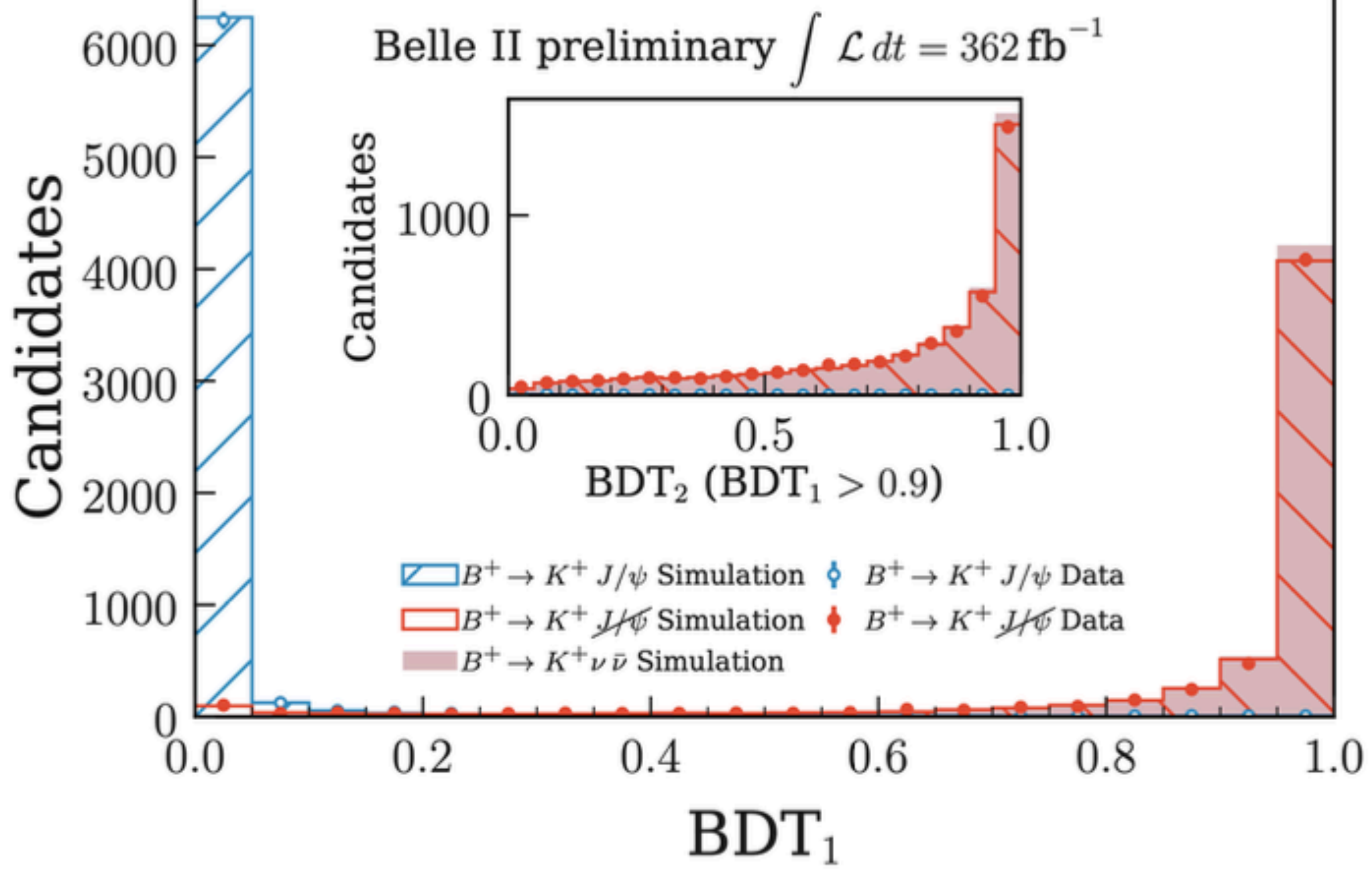


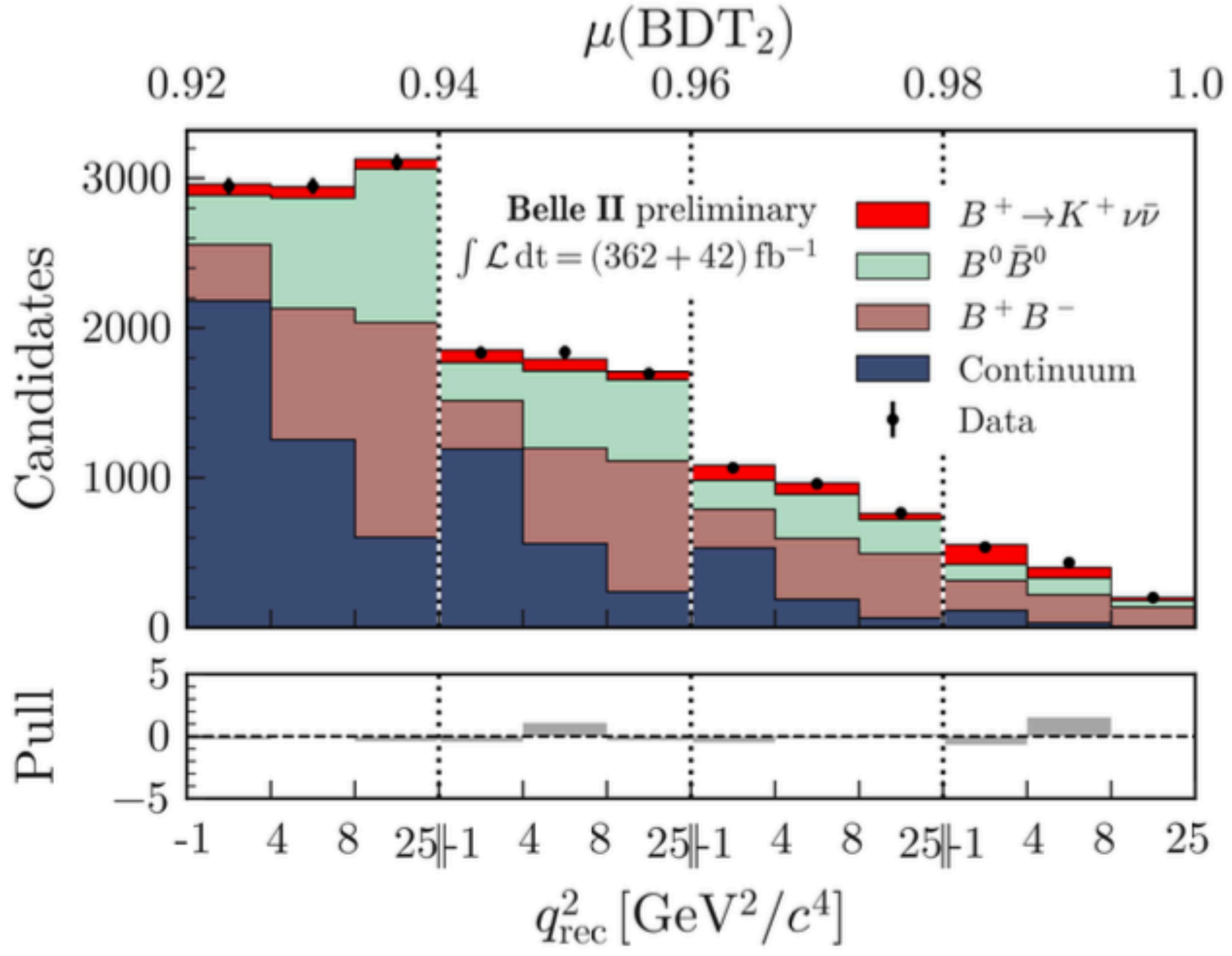
- Experimentally challenging due to two neutrinos in the final state
  - *B* tagging: typical method used by Belle and Babar
    - ε ~0.04% (HTA: Hadronic Tagging)
    - Purity: 8/211 ~3.8%
  - Untagging
    - ε ~8% (ITA: Inclusive Tagging, 2 step Fast BDT, 1st FBDT 12 variables, 2nd FBDT 35 variables)
    - Purity: 159/17529 ~0.9%

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

ITA





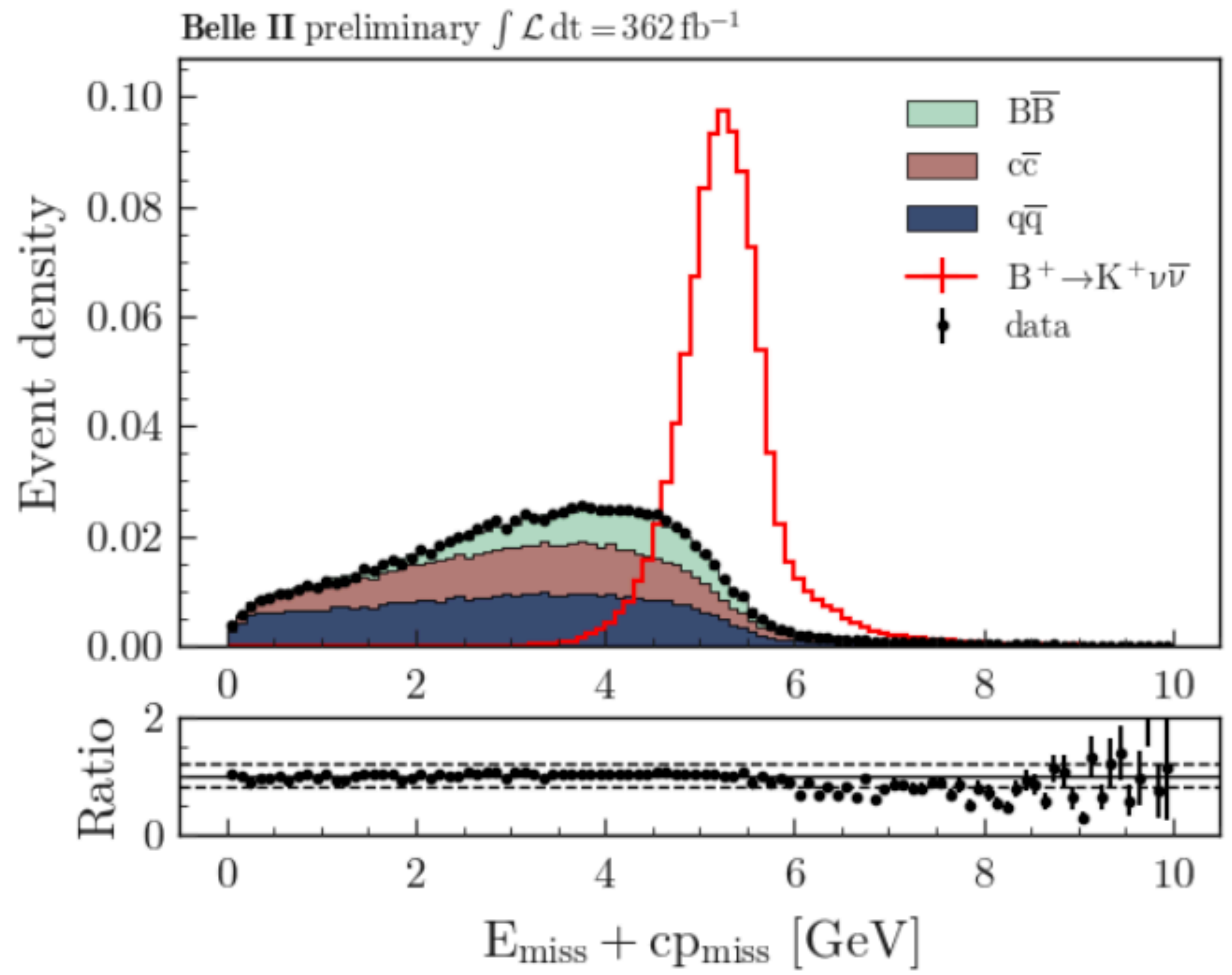


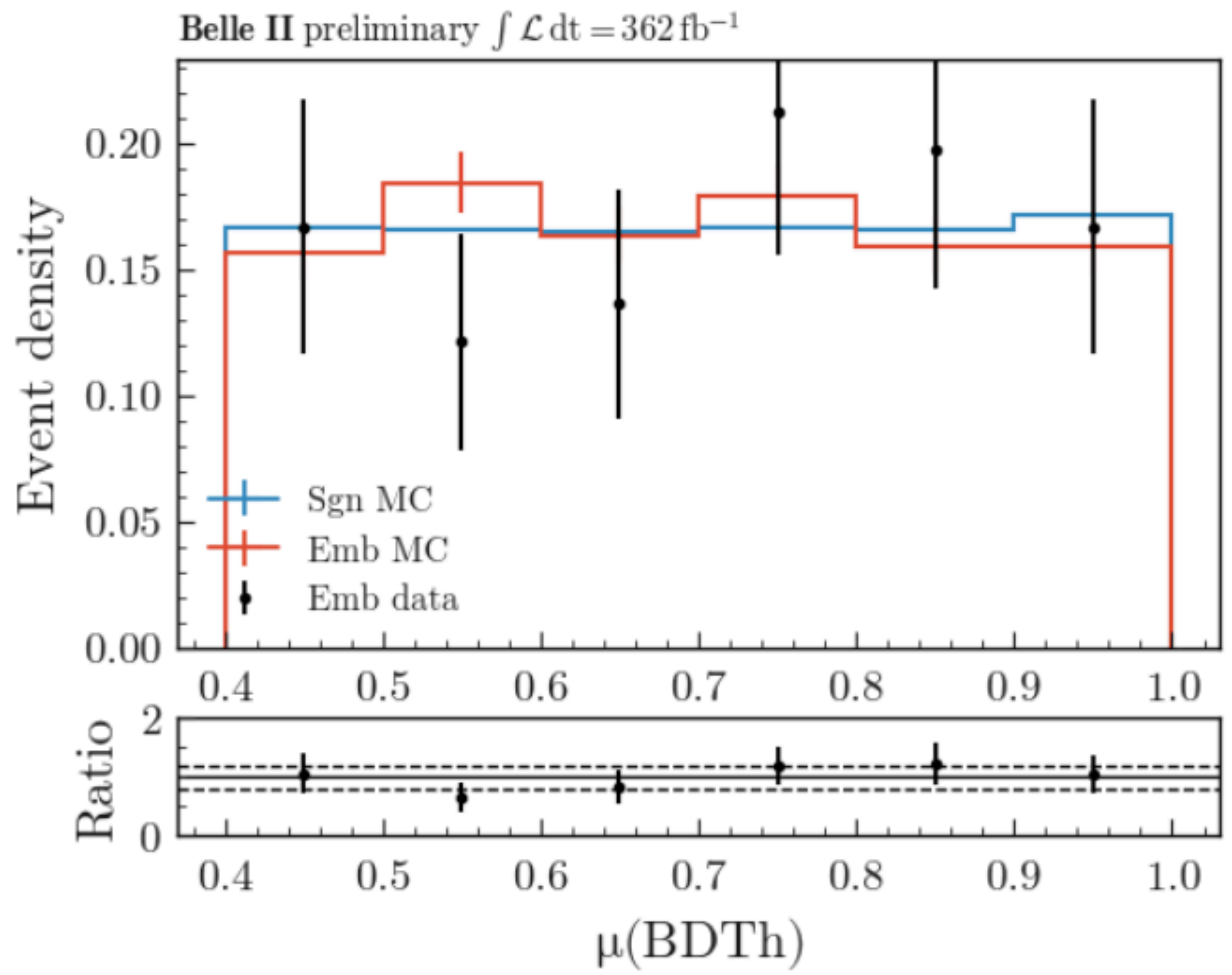
Background suppression

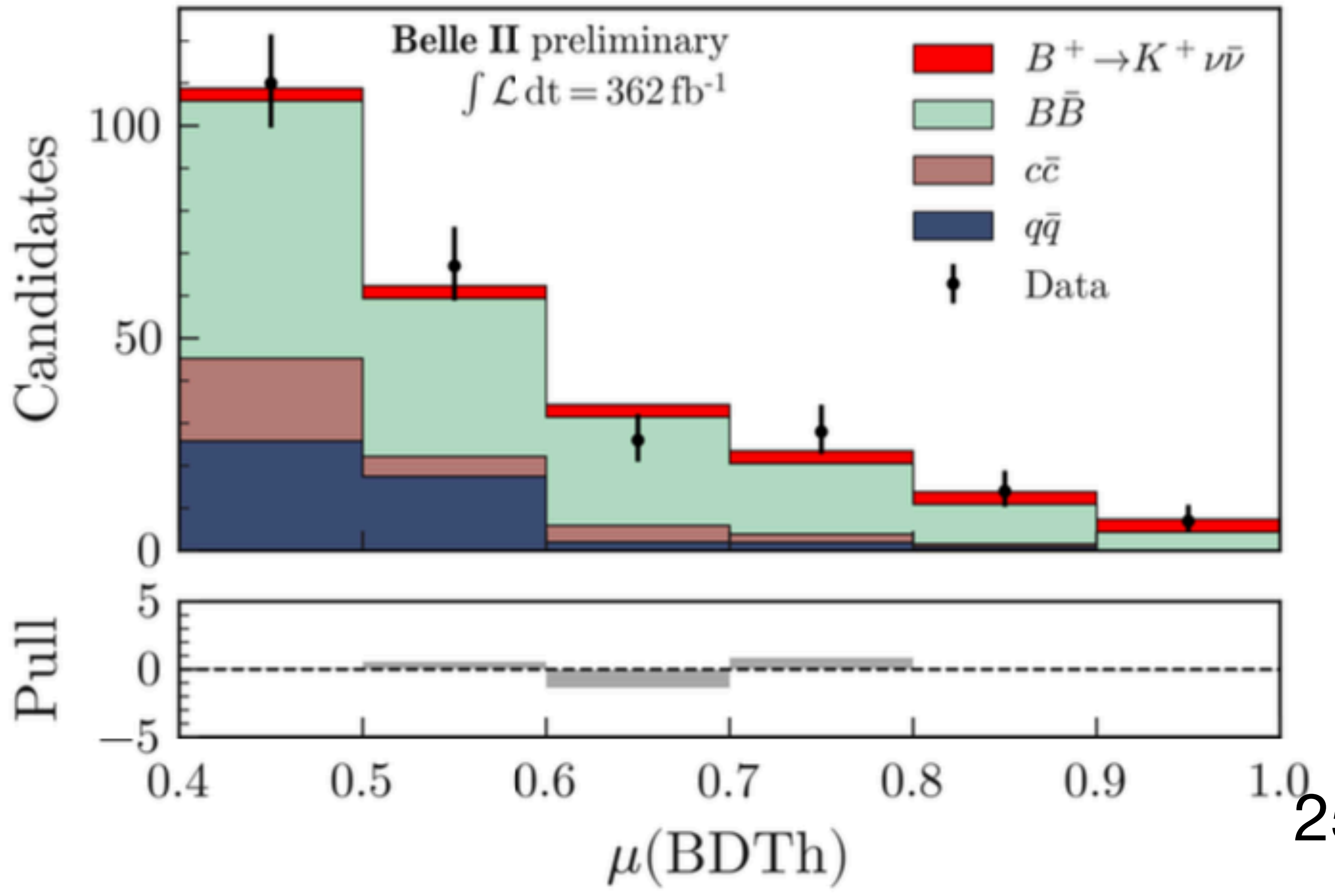
Validation

Signal extraction

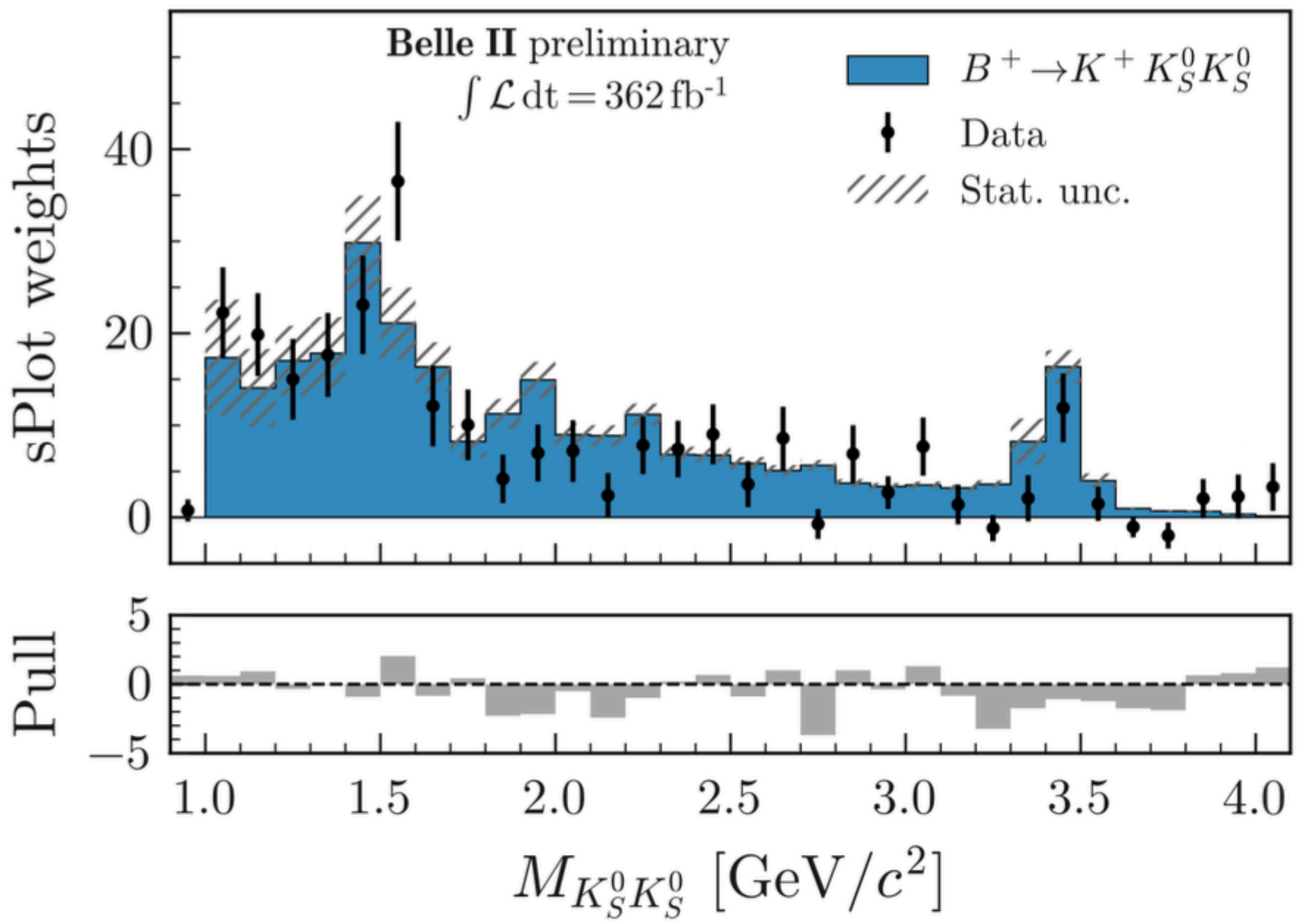
HTA

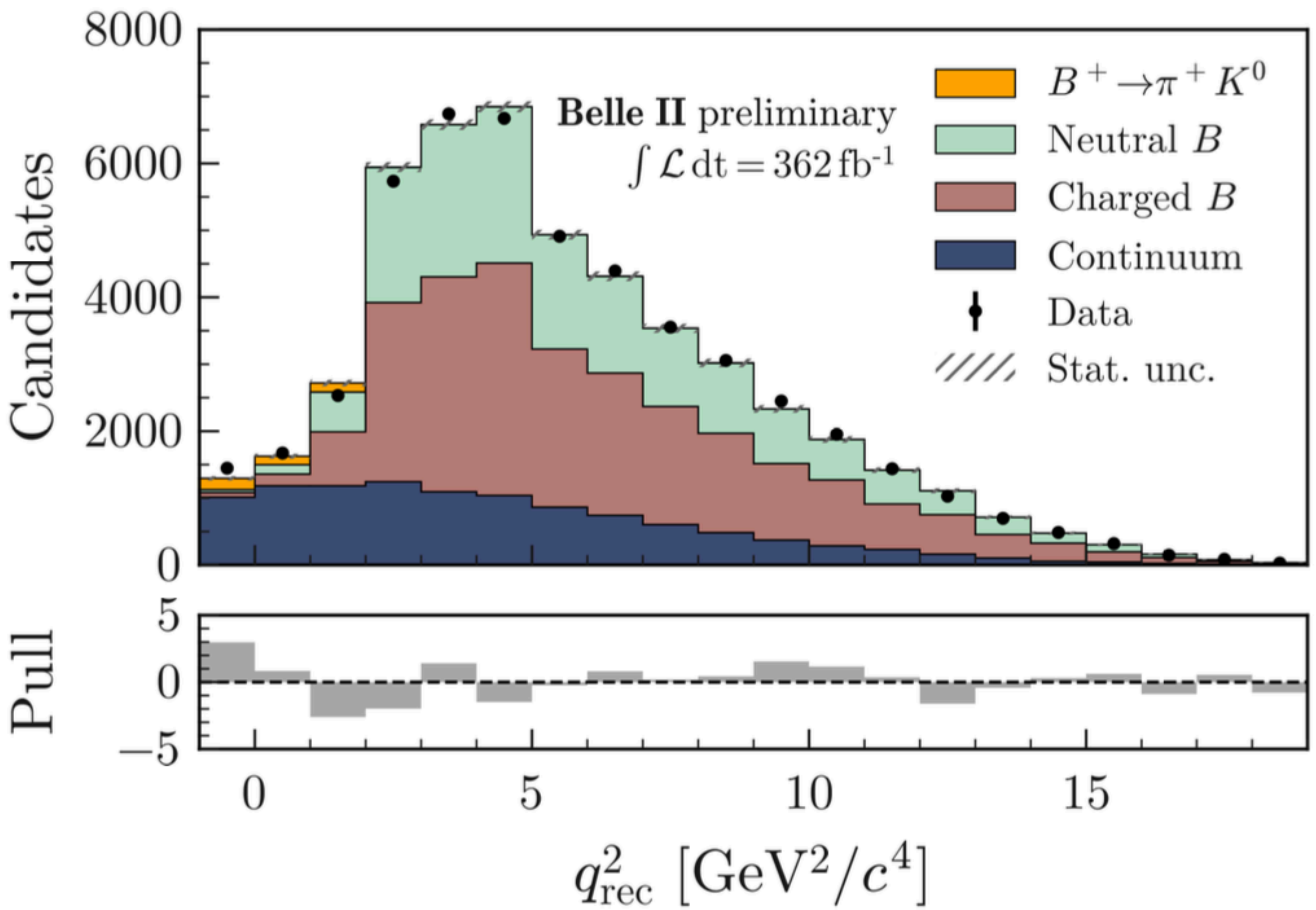






ITA validation of $B^+ \to K^+ \nu\bar{\nu}$ measurement





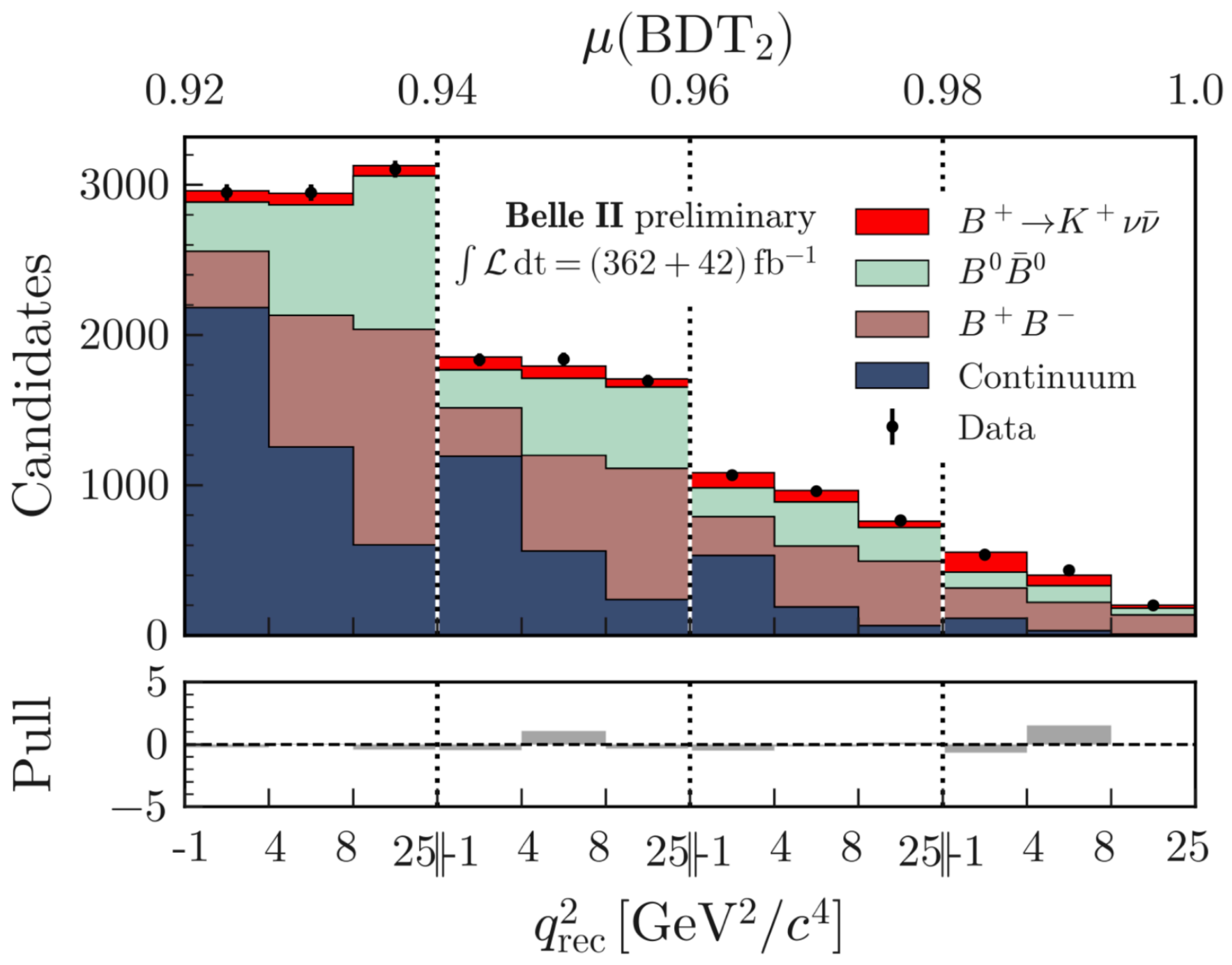
- A difficult background $B^+ \to K^+ K_L K_L$, where escape K_L detection
- Dedicate validation of $B^+ \to K^+ K_s^0 K_s^0$ shows a good modelling
- Similar studies for $B^+ \to K^+ n\bar{n}$, $B^+ \to K^+ K_L K_s^0$ …

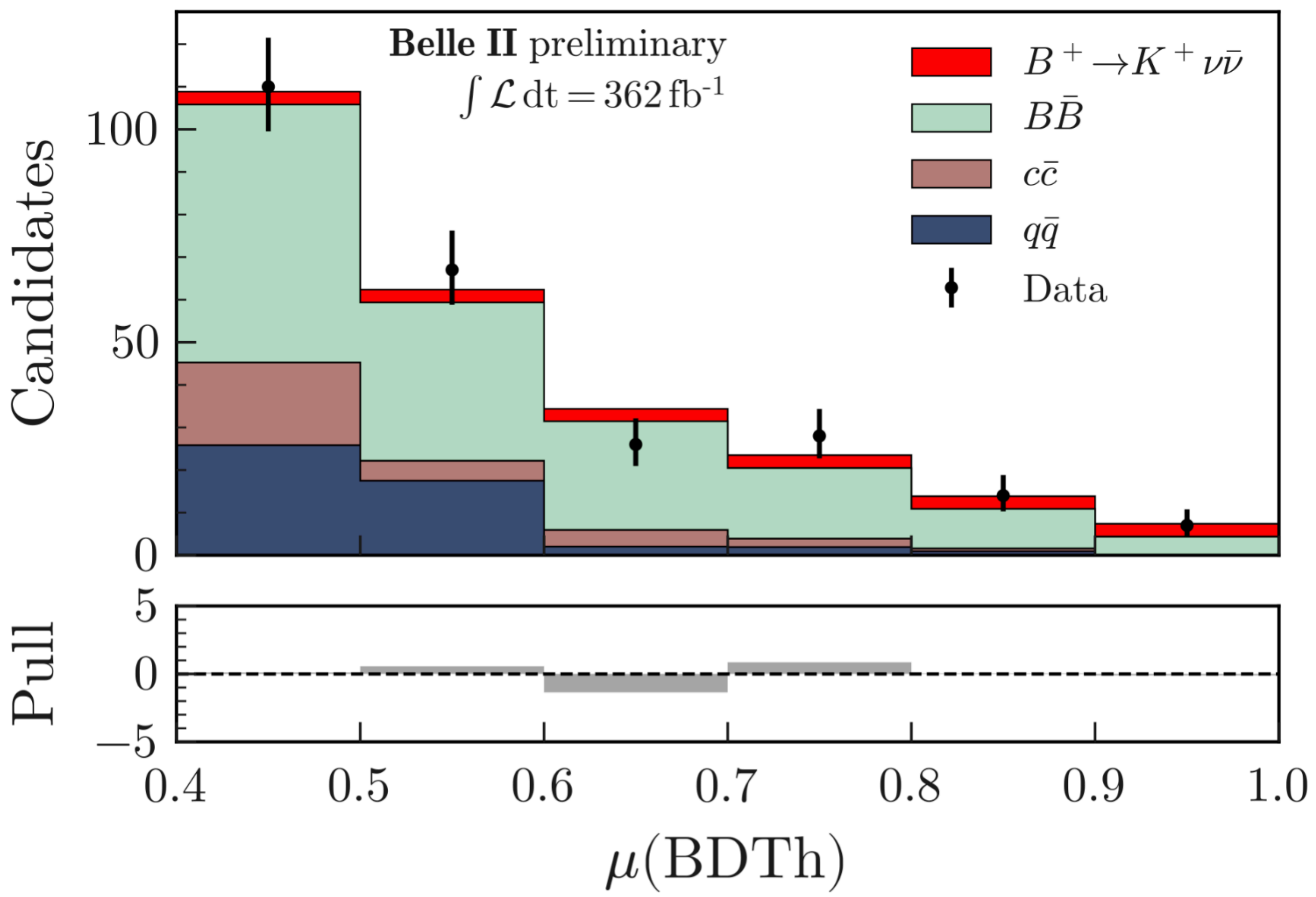
- Measure the known mode as the main background for validation

  Br($B^+ \to \pi^+ K_s^0$) = (2.5 ± 0.5) x 10^{-5}
  Br($B^+ \to \pi^+ K_s^0$)$_{PDG}$ = (2.3 ± 0.08) x 10^{-5}

- Consistent with PDG

First evidence of the $B^+ \to K^+ \nu\bar{\nu}$ precess





$Br(B^+ \to K^+\nu\bar{\nu})_{\mathrm{Inc.}} = (2.8 \pm 0.5(\mathrm{stat.}) \pm 0.5(\mathrm{syst.})) \times 10^{-5}$

$Br(B^+ \to K^+\nu\bar{\nu})_{\mathrm{Had.}} = (1.1^{+0.9}_{-0.8}(\mathrm{stat.})^{+0.8}_{-0.5}(\mathrm{syst.})) \times 10^{-5}$

The combined result: $Br(B^+ \to K^+\nu\bar{\nu})_{\mathrm{Comb.}} = (2.4 \pm 0.5(\mathrm{stat.})^{+0.5}_{-0.4}(\mathrm{syst.})) \times 10^{-5}$

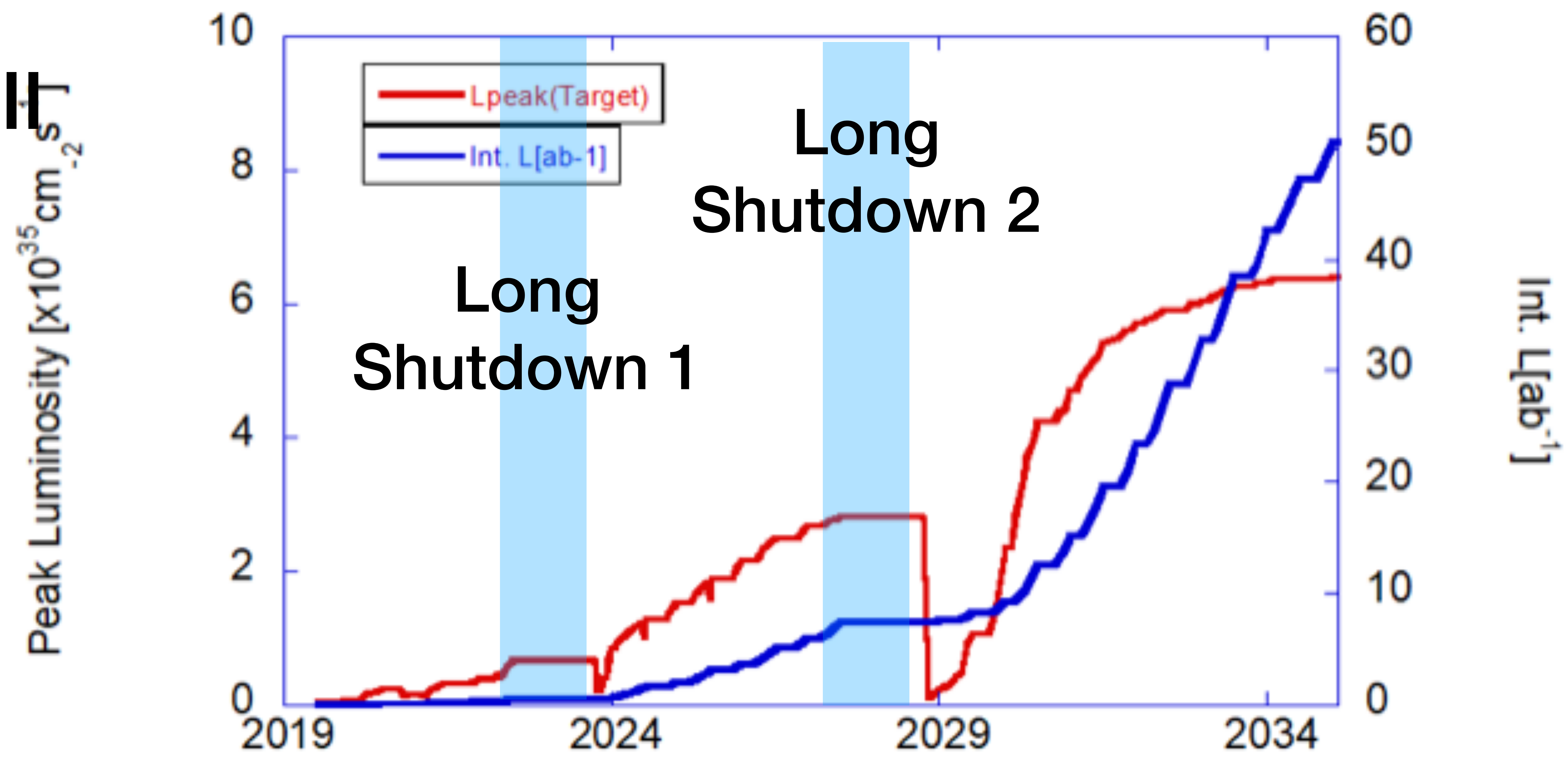
- First evidence (3.6σ) of the $B^+ \to K^+\nu\bar{\nu}$ process
- 2.8σ tension w.r.t SM prediction

Summary and prospects

- Belle II accumulated 362 fb^{-1} $\Upsilon(4S)$ data
- Unitarity triangle (angle, side) measurements already started providing world leading results
- $R(D^{(*)})$ shows 3.2σ tension, a hint of Lepton Flavor Universality Violation
  - Belle II performed $R(D^*)$ and $R(X_{\tau/\ell})$ measurement with hadronic tagging based on 189 fb^{-1} data
  - $R(D^{(*)})$ anomaly move to 3.3σ
  - $R(X_{\tau/\ell})$ consistent with SM expectation
- $B^+ \to K^+ \nu\bar{\nu}$ measured with 362 fb^{-1} data at Belle II
  - First evidence for $B^+ \to K^+ \nu\bar{\nu}$ decays

$$Br(B^+ \to K^+ \nu\bar{\nu}) = (2.4 \pm 0.5(\text{stat.})^{+0.5}_{-0.4}(\text{syst.})) \times 10^{-5}$$

- SuperKEKB/Belle II will resume operation at the beginning of 2024



Stay tuned !

Backup

HTA systematic uncertainties of $B^+ \to K^+ \nu\nu$

Source	Uncertainty size	Impact on σ_μ	
Normalization $B\bar{B}$ background	30%	0.91	1.
Normalization continuum background	50%	0.58	
Leading B-decays branching fractions	$O(1\%)$	0.10	
Branching fraction for $B^+ \to K^+ K^0_L K^0_L$	20%	0.20	
Branching fraction for $B \to D^{(**)}$	50%	< 0.01	
Branching fraction for $B^+ \to K^+ n\bar{n}$	100%	0.05	
Branching fraction for $D \to K_L X$	10%	0.03	
Continuum background modeling, BDT$_c$	100% of correction	0.29	
Number of $B\bar{B}$	1.5%	0.07	
Track finding efficiency	0.3%	0.01	
Signal kaon PID	$O(1\%)$	< 0.01	
Extra photon multiplicity	$O(20\%)$	0.61	2.
K^0_L efficiency	17%	0.31	
Signal SM form factors	$O(1\%)$	0.06	
Signal efficiency	16%	0.42	
Simulated sample size	$O(1\%)$	0.60	3.

statistical uncertainty on μ = 2.3

ITA systematic uncertainties of $B^+ \to K^+ \nu\nu$

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

statistical uncertainty on μ = 1.1

Results and global picture of $B^+ \to K^+ \nu\nu$

ITA fit results:

$$\mu = 5.6 \pm 1.1(\text{stat})^{+1.1}_{-0.9}(\text{syst})$$

$$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu}) = 2.8 \pm 0.5(\text{stat}) \pm 0.5(\text{syst}) \times 10^{-5}$$

- **Significance of the excess with respect to the background-only hypothesis ($\mu = 0$): 3.6 σ**
- **Significance of the excess with respect to the SM signal hypothesis ($\mu = 1$): 3.0 σ**

First evidence of the $B^+ \to K^+ \nu\bar{\nu}$ process

HTA fit results:

$$\mu = 2.2 \pm 2.3(\text{stat})^{+1.6}_{-0.7}(\text{syst})$$

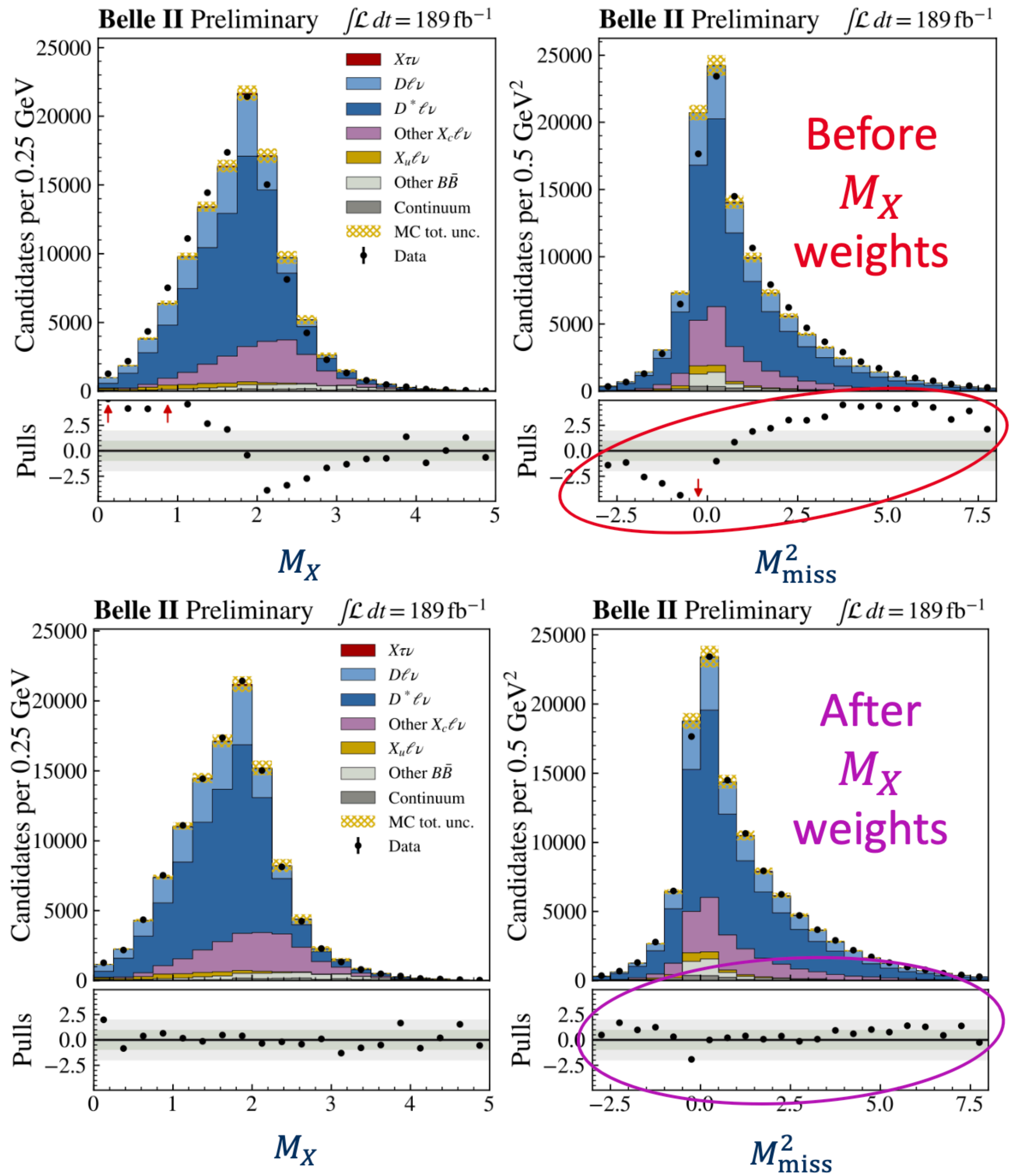
$$\mathscr{B}(B^+ \to K^+ \nu\bar{\nu}) = [1.1^{+0.9}_{-0.8}(\text{stat})^{+0.8}_{-0.5}(\text{syst})] \times 10^{-5}$$

- **Significance with respect to the background-only hypothesis ($\mu = 0$): 1.1 σ**
- **Significance with respect to the SM signal hypothesis ($\mu = 1$): 0.6 σ**

Light-lepton universality test $R(X)$

arXiv:2301.08266

- Test light-lepton universality by measuring $R(X_{\tau/\ell}) = \dfrac{Br(\bar{B} \to X\tau^-\bar{\nu_\tau})}{Br(\bar{B} \to X\ell^-\bar{\nu_\ell})}$
- Approach employed at Belle II: M_X reweighting
  - Events weights from data/MC ratio in M_X distribution, applied to all events
  - q^2, M^2_{miss} can be expressed by reliable parts and M_X part
- Signal yields are extracted by a binned maximum-likelihood simultaneous fit to lepton momentum



Light-lepton universality test $R(X_{e/\mu})$

arXiv:2301.08266

- First $R(X_{e/\mu})$ measurement

  $R(X_{e/\mu}) = 1.033 \pm 0.010\ \text{(stat)} \pm 0.019\ \text{(syst)}$

- Most precise BF based LFU test of e-μ universality with semileptonic B decays to date
- Consistent with SM value by 1.2σ

  $R(X_{e/\mu})_{SM} = 1.006 \pm 0.001$ JHEP 11 (2022) 007

- Compatible with exclusive Belle measurements

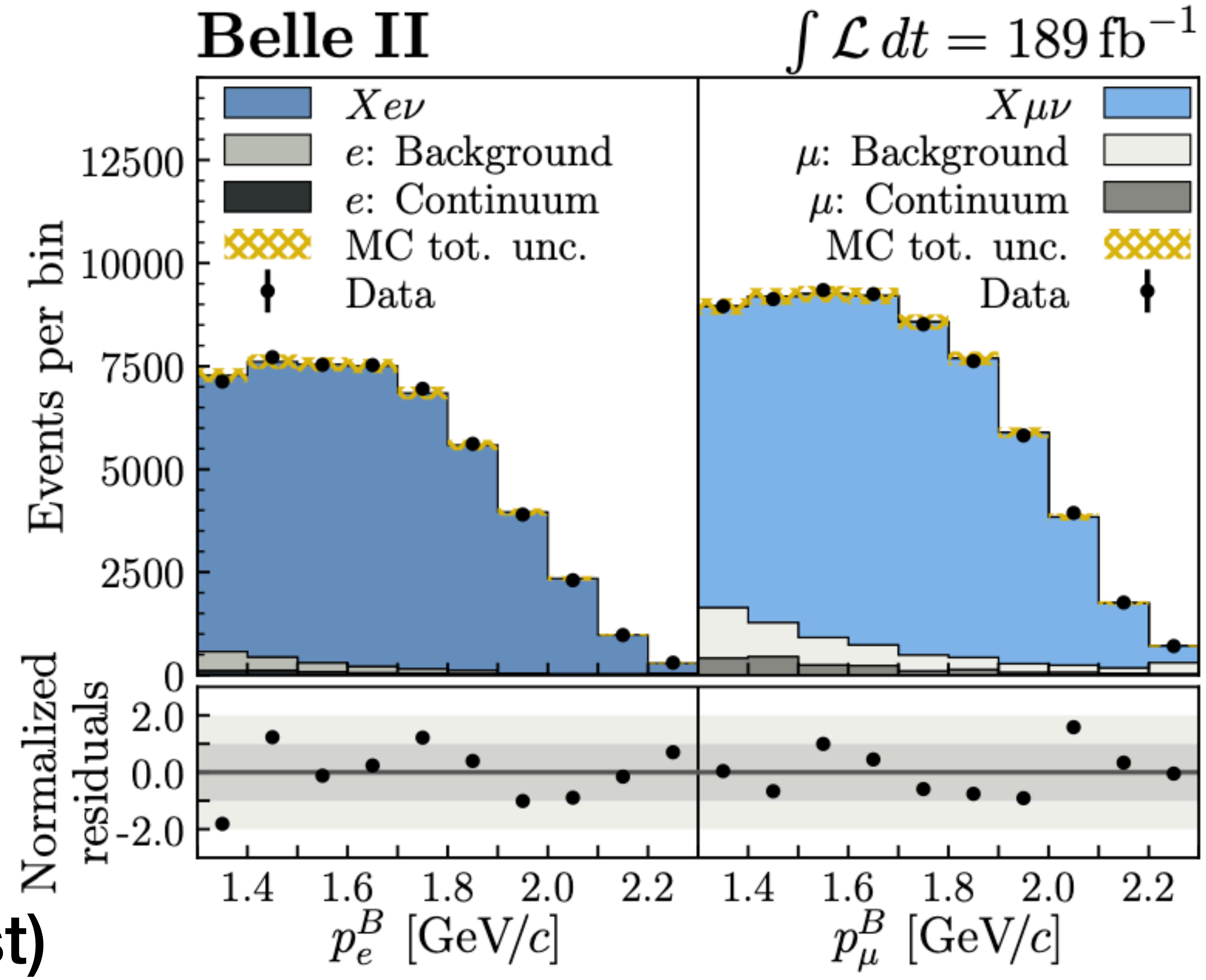
  PRD 100, 052007 (2019)

  $R(D^*_{e/\mu}) = 1.01 \pm 0.01\ \text{(stat)} \pm 0.03\ \text{(syst)}$

  $R(D^*_{e/\mu}) = 0.990 \pm 0.021\ \text{(stat)} \pm 0.023\ \text{(syst)}$

  arXiv:2301.07529

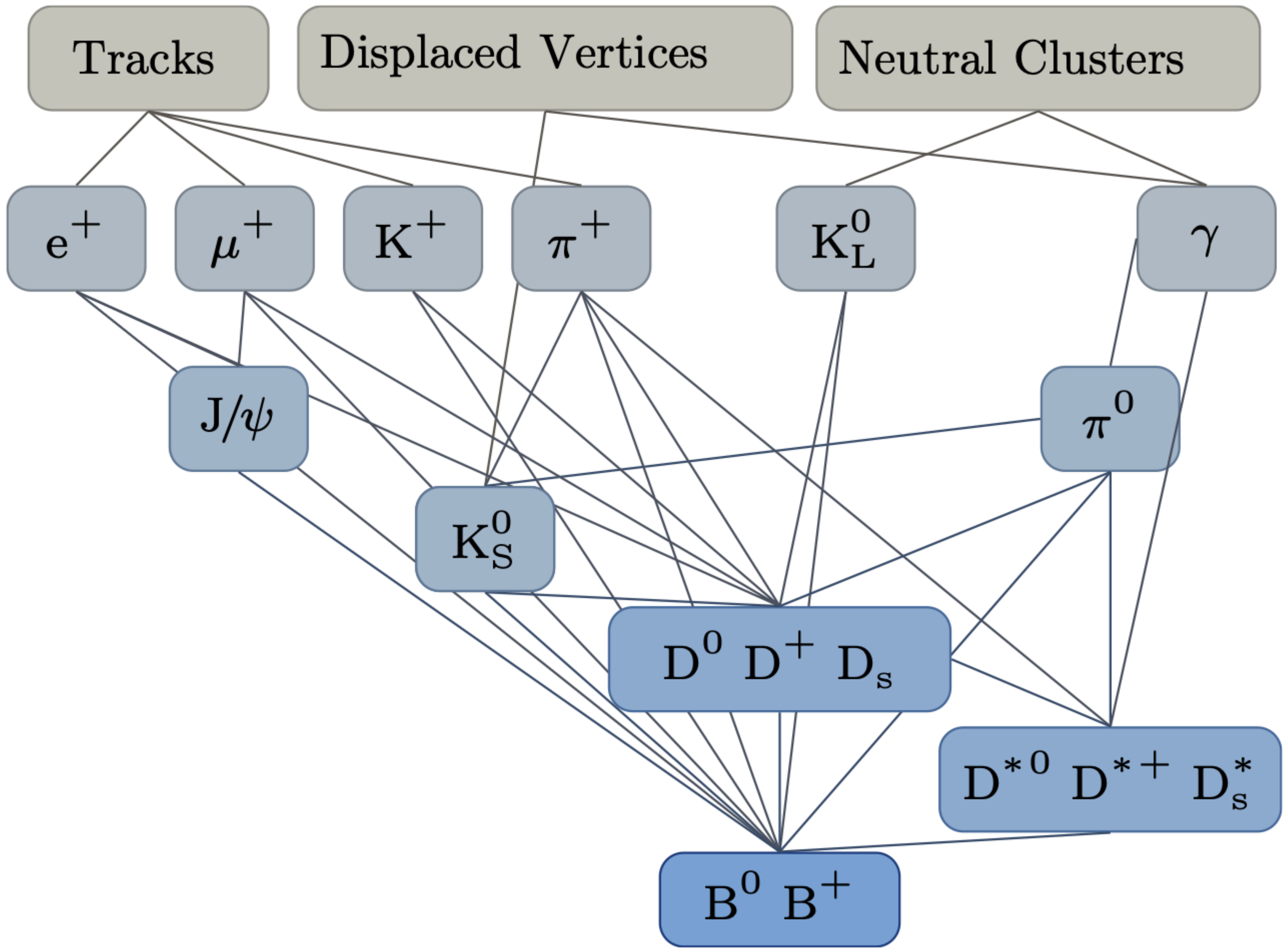
Signal channel ($B^0\bar{B}^0/B^+B^-$)



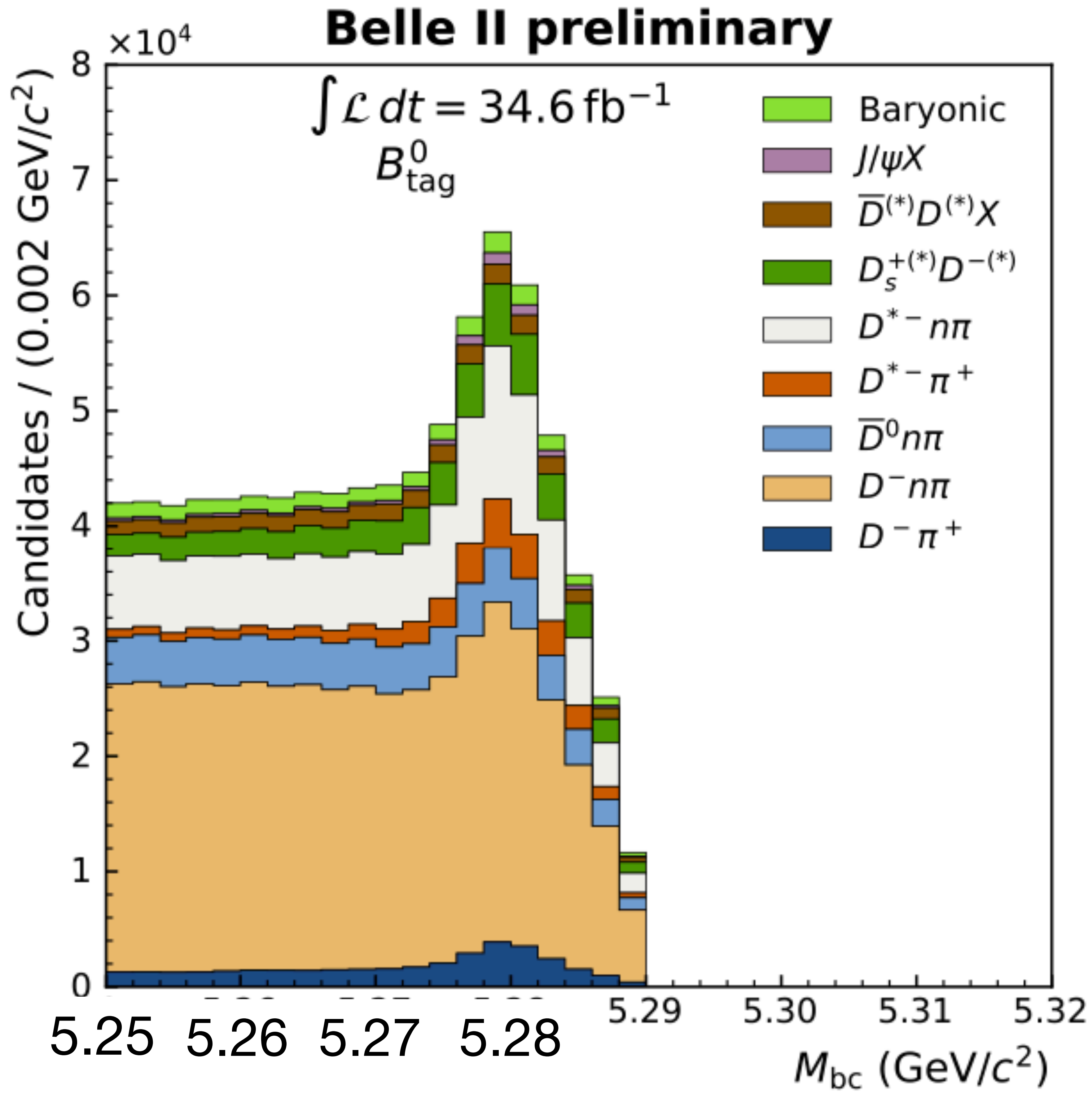
Hadronic tag reconstruction at Belle II

- Hadronic tagging reconstruction : Full Event Interpretation (FEI) trained 200 Boost Decision Tree (BDT) to reconstruct ~100 decay channels, ~10,000 B decay chains
  - ε=0.30% for $B^{\pm}$ 10-30% increased
  - ε=0.23% for B^0
  - ε=0.28% for $B^{\pm}$ @Belle
  - ε=0.18% for B^0 @Belle

Comp. and Soft. For Big Sci. 3, 6 (2019)



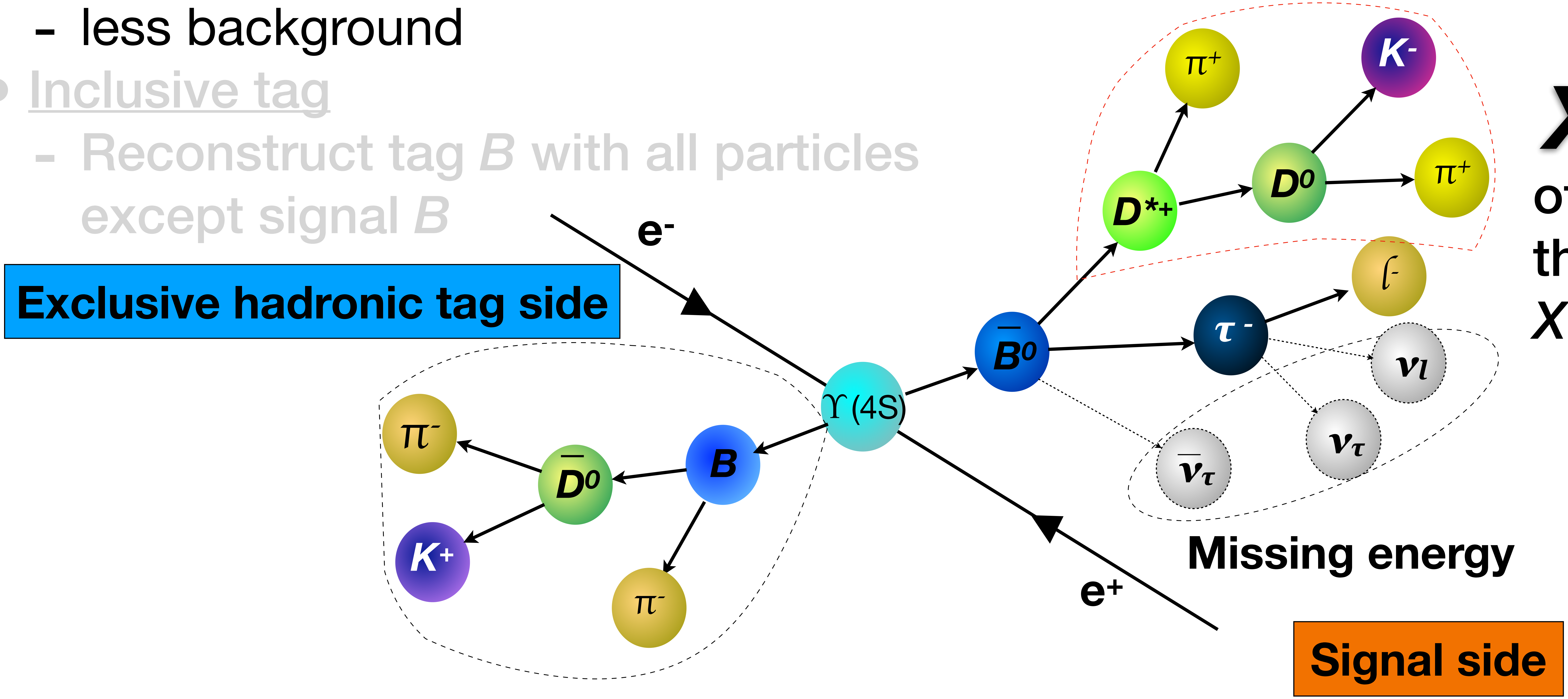
arXiv:2008.06096



$$m_{\rm bc} = \sqrt{(E^*_{\rm beam})^2 - (p^*_B)^2}$$

Tagging methods

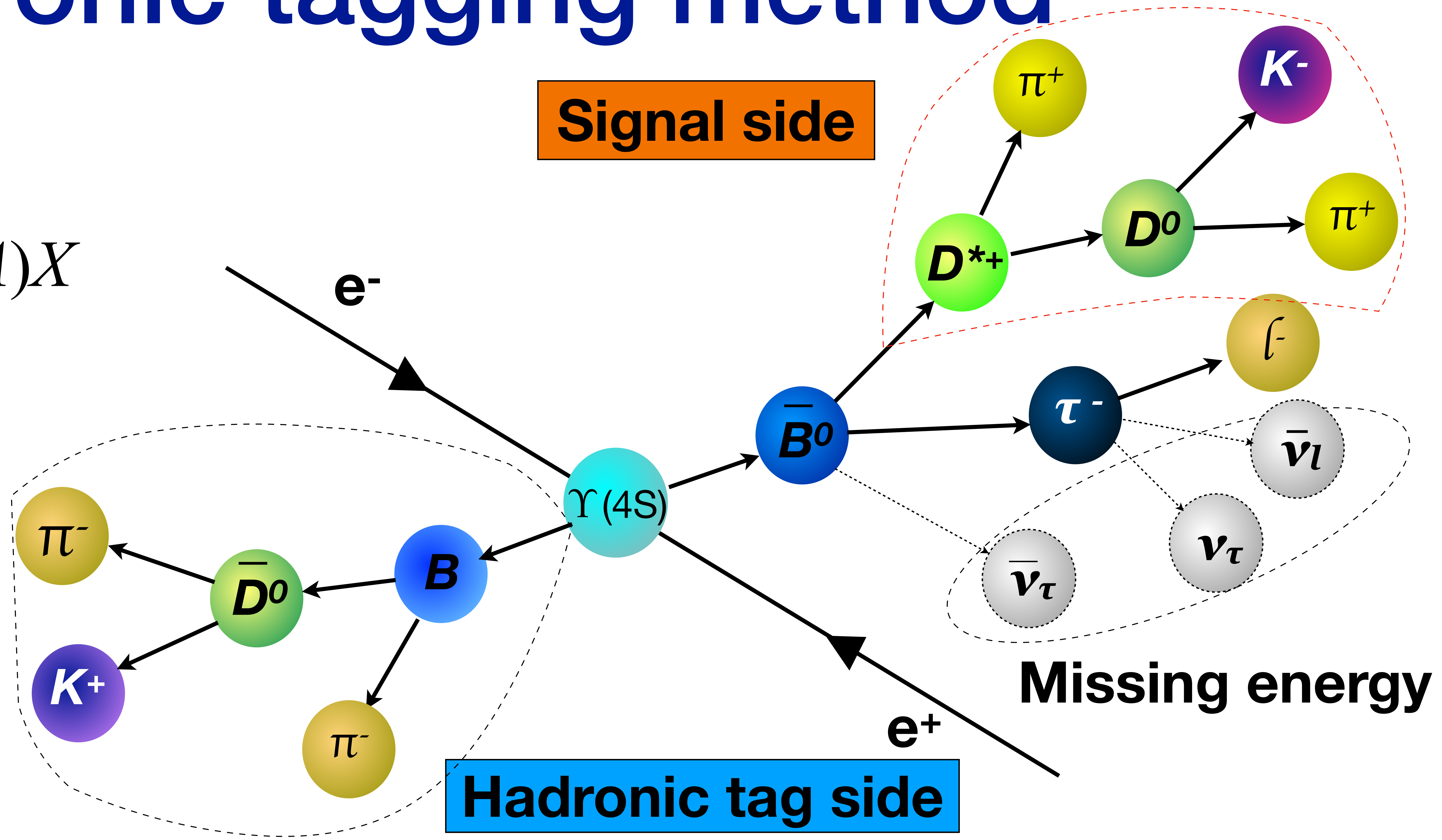
- B tagging is necessary to measure $B \to X / D^* \tau \nu$, $B \to X / D^* l \nu$ ($\nu \geq 2$) simultaneously
- Hadronic tag
  - Exclusive tag
    - Fully reconstruct $B \to D^{(*)}(/J/\psi/\Lambda)X$
    - Tagging efficiency 0.2~0.4%
    - less background
  - Inclusive tag
    - Reconstruct tag B with all particles except signal B
- Semileptonic tag
  - Reconstruct $B \to D^{(*)} l \nu$
  - Tagging efficiency ~0.5%
  - More background



X : reconstruct other particles than a lepton as *X* on signal side

Exclusive hadronic tagging method

- Hadronic tag
  - Exclusive tag
    - Fully reconstruct $B \to D^{(*)}(/J/\psi/\Lambda)X$
    - Tagging efficiency 0.2~0.4%
    - less background



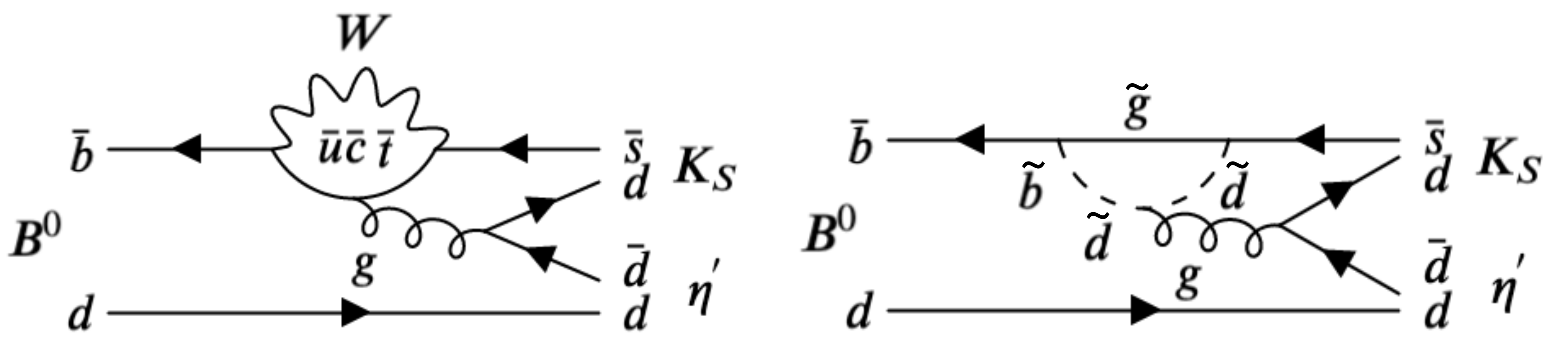
- Fully reconstruct one of the B mesons (B tag), possible to measure momentum of other B meson (B signal)
- Indirectly measure missing momentum of neutrinos in signal B decays
- $M^2_{\text{miss}} = (p_{\text{beam}} - p_{B\text{tag}} - p_{D^{(*)}} - p_{\ell})^2$
- E_{ECL} unassigned neutral energy in the calorimeter

$$E_{\text{ECL}} = \sum_i E_i^{\gamma}$$

} Fitting variables for yields determination

Effective ϕ_1 with QCD penguin

- $b \to s\bar{q}q$: QCD penguin dominated contribution, suppressed in SM, sensitive to New Physics
  - Deviation of $S_f = \sin(2\phi_1^{eff})$ from $\sin(2\phi_1)$ indicates NP



- Golden mode, e.g. $B \to \phi K$, $B \to \eta' K$ ...
  - Fully hadronic states with neutrals
    - Unique at Belle II

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

$S = 0.75^{+0.20}_{-0.23} \pm 0.04$

$C = -0.04^{+0.14}_{-0.15} \pm 0.04$

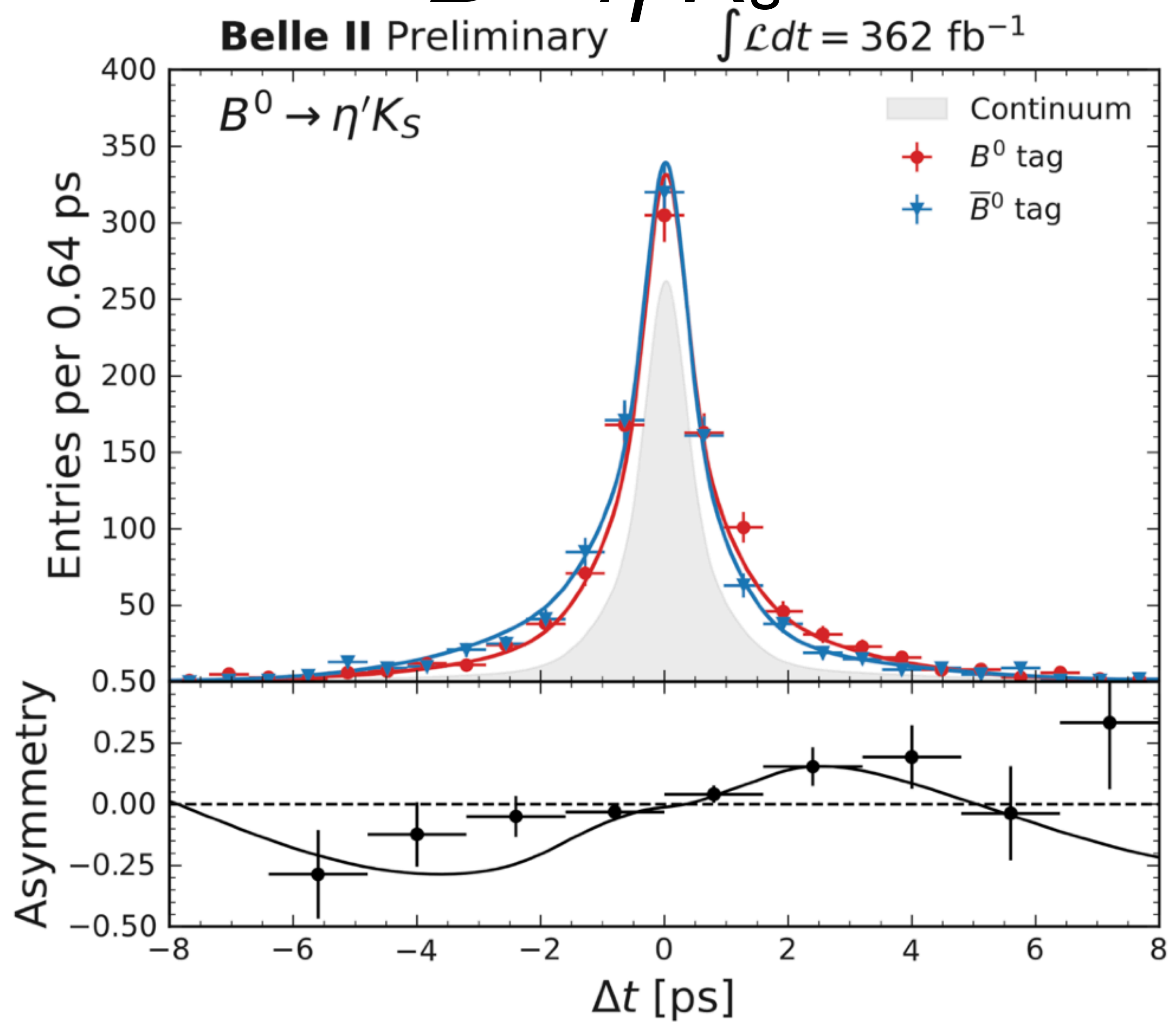
arXiv:2305.07555

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

$S = -1.37^{+0.35}_{-0.45} \pm 0.03$

$C = -0.07 \pm 0.20 \pm 0.02$

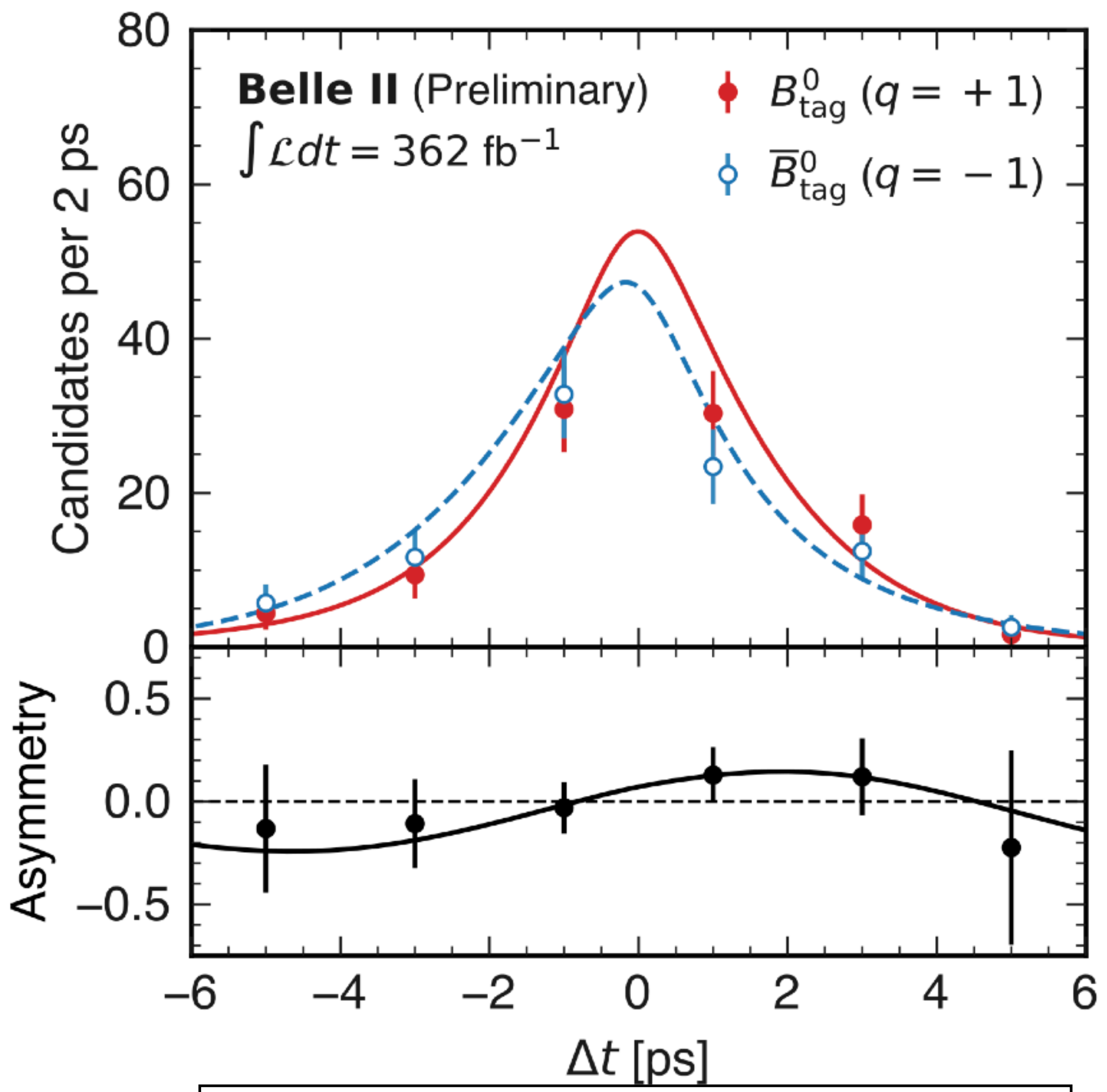
$B \to \eta' K_s^0$



$S = 0.67 \pm 0.10 \pm 0.04$

$A = -0.19 \pm 0.08 \pm 0.03$

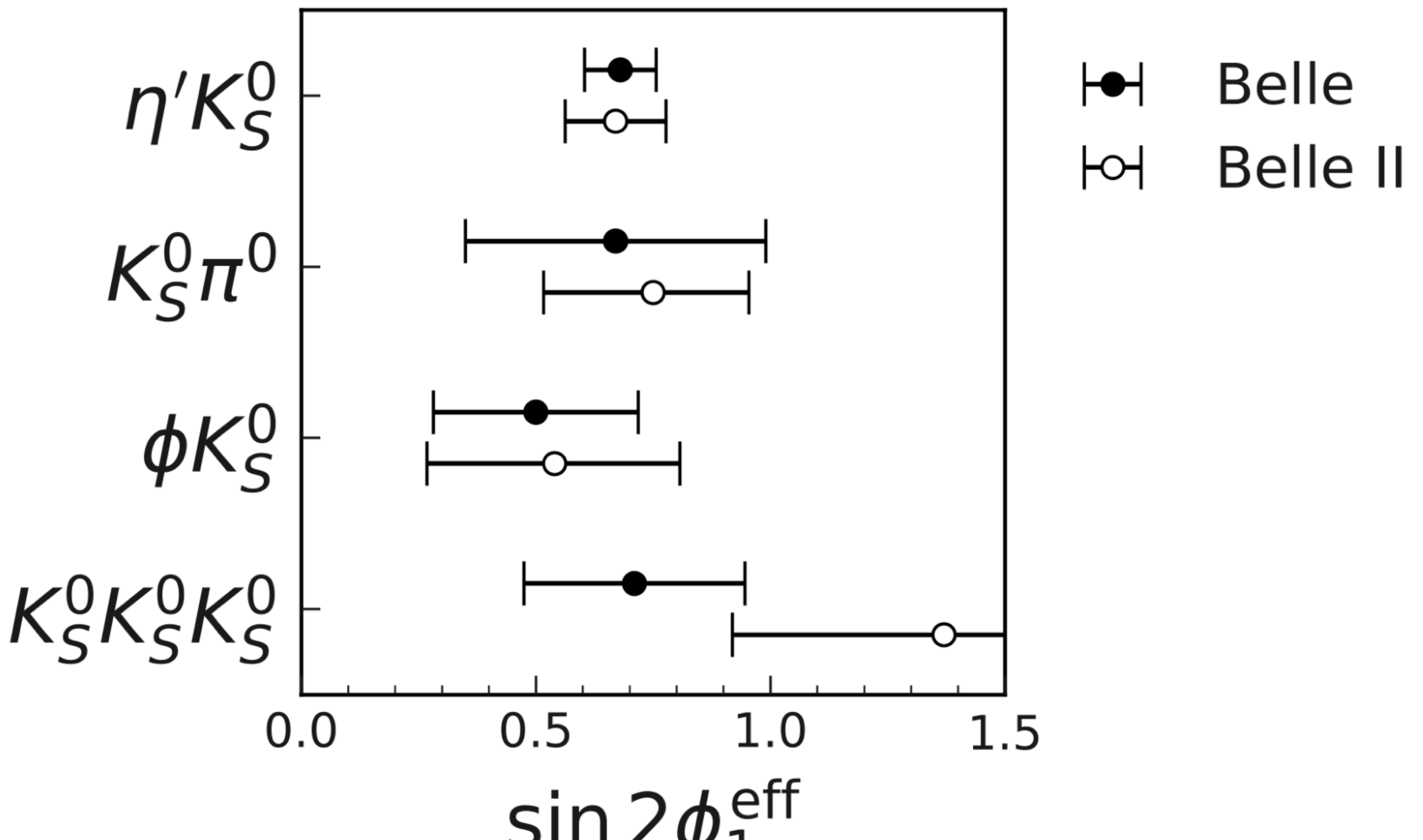
$B^0 \to \phi K_s^0$



$S = 0.54 \pm 0.26^{+0.06}_{-0.08}$

$C = -0.31 \pm 0.20 \pm 0.05$

arXiv:2307.02802

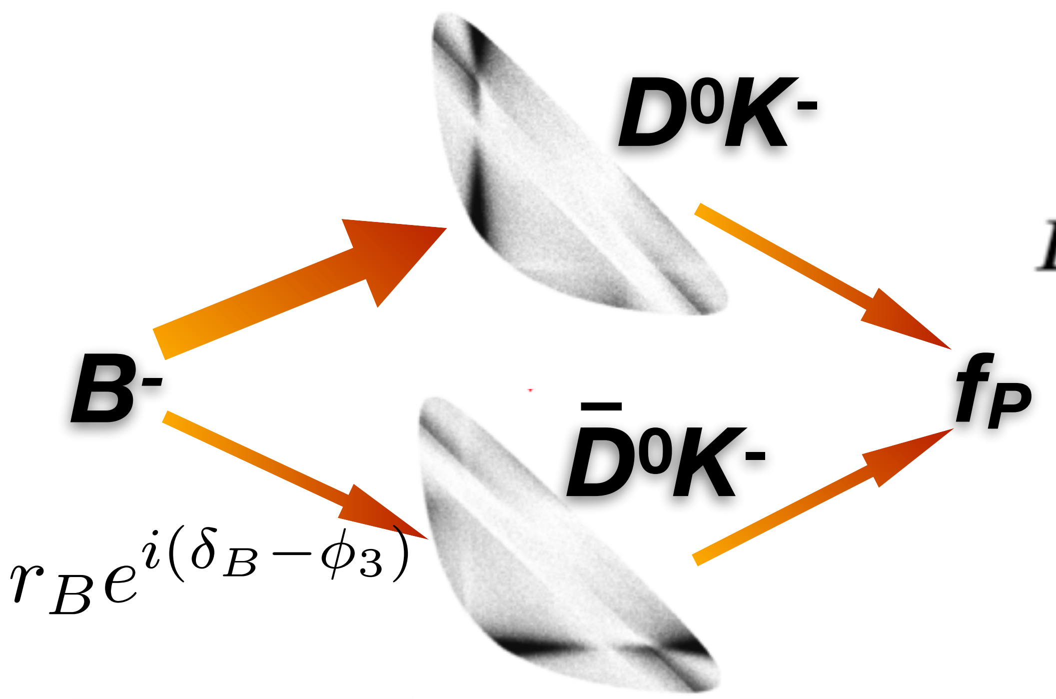


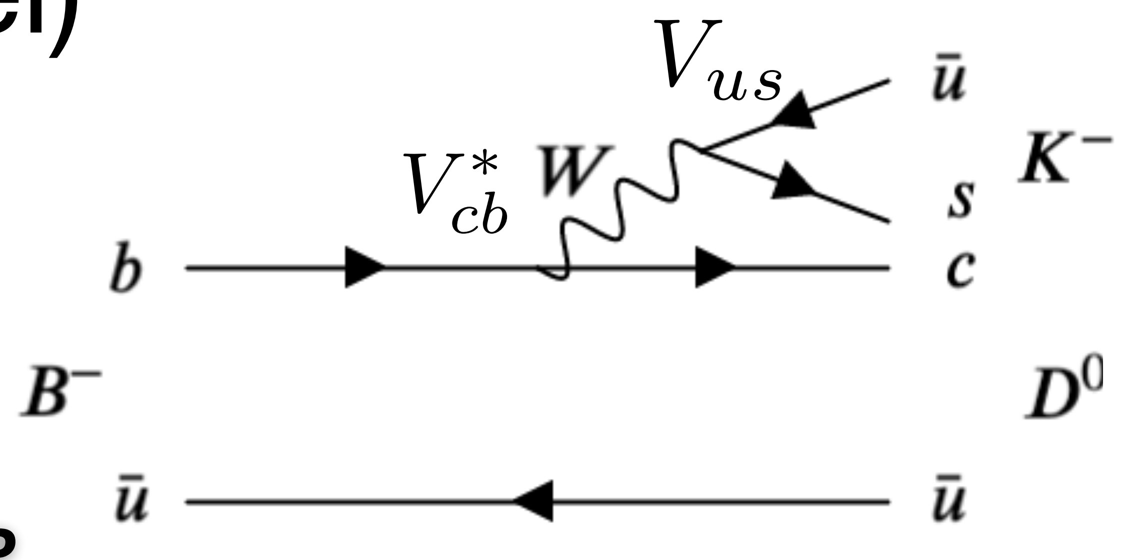
ϕ_3 measurement

- Interference between $b \to c$ and $b \to u$ (tree level)
- Current precision ~3.5°

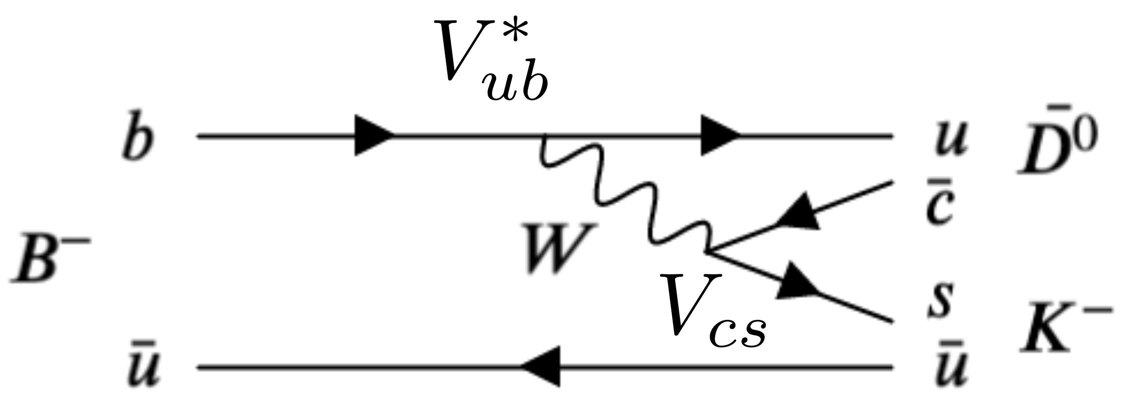
$$\frac{A^{suppr.}(B^- \to \bar{D}_0 K^-)}{A^{favor.}(B^- \to D_0 K^-)} = r_B e^{i(\delta_B - \phi_3)}$$

r_B : ratio of amplitude
δ_B : strong phase difference

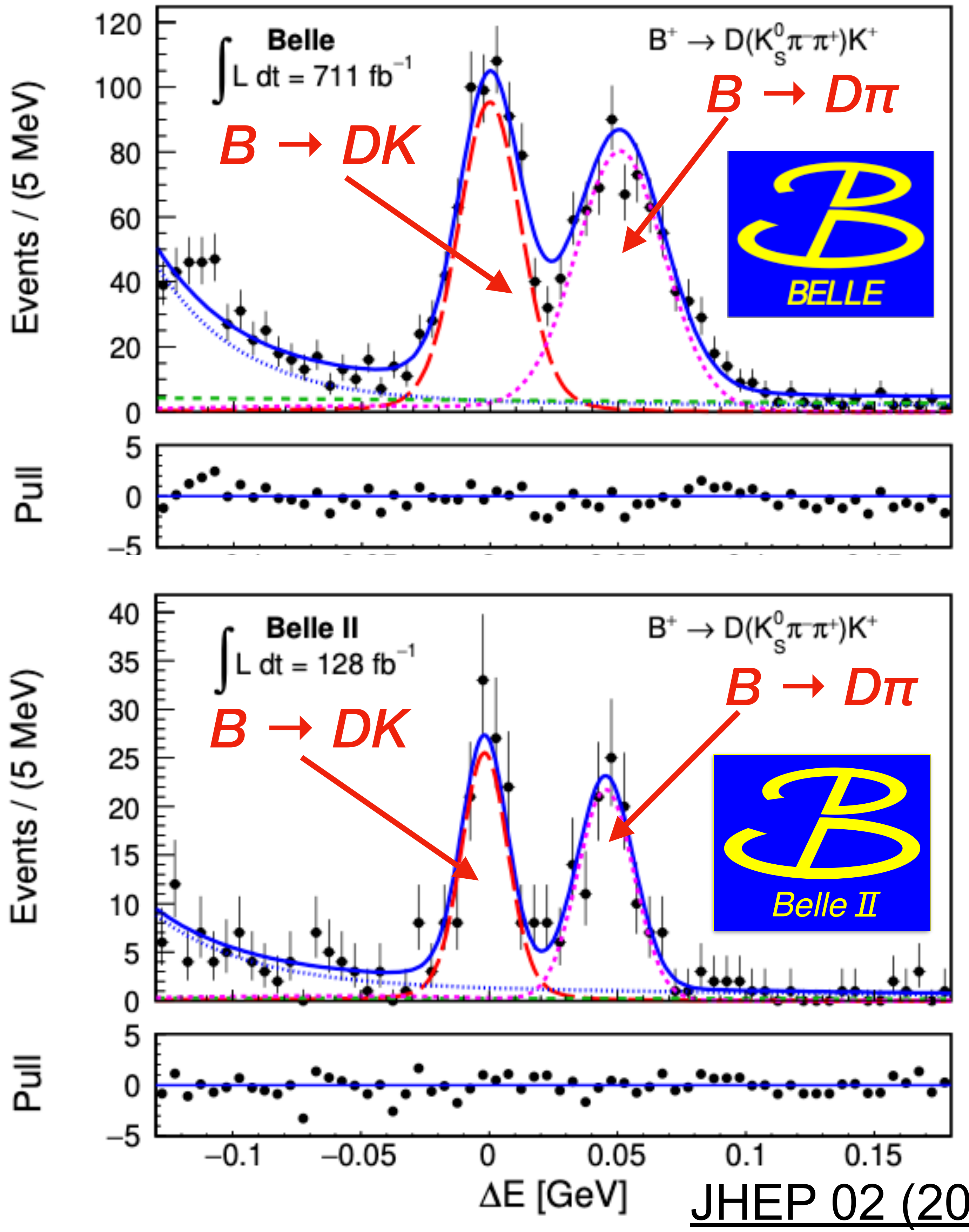




Favored



Color suppressed



JHEP 02 (2022) 063

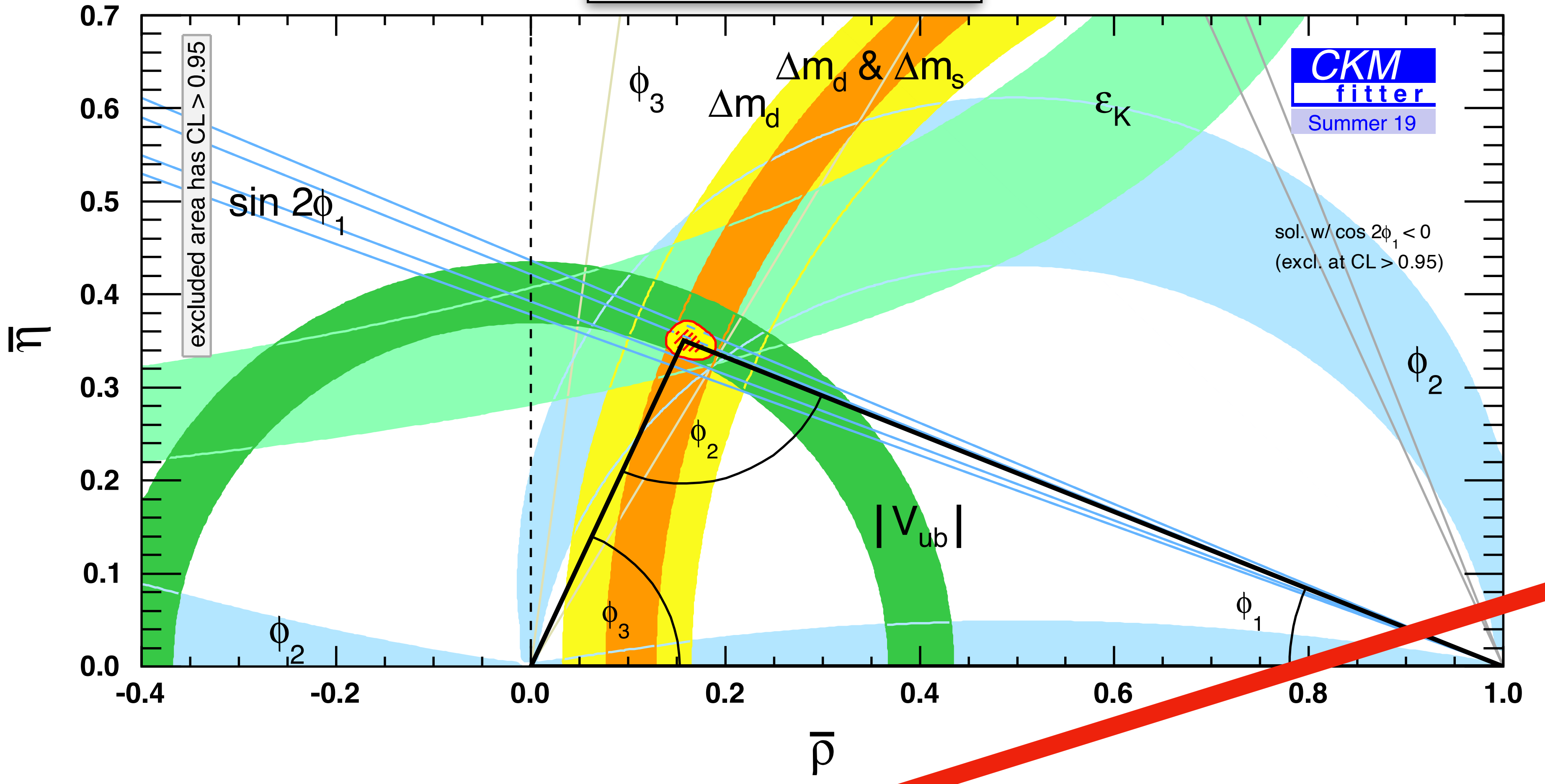
B decay	D decay	Method	Data set (Belle + Belle II) [fb^{-1}]	
$B^+ \to Dh^+$	$D \to K^0_S h^- h^+$	BPGGSZ	$711 + 128$	[JHEP 02 063 (2022)]
$B^+ \to Dh^+$	$D \to K^0_S \pi^- \pi^+ \pi^0$	BPGGSZ	$711 + 0$	[JHEP 10 178 (2019)]
$B^+ \to Dh^+$	$D \to K^0_S \pi^0, K^- K^+$	GLW	$711 + 189$	[arxiv:2308.05048]
$B^+ \to Dh^+$	$D \to K^+ \pi^-, K^+ \pi^- \pi^0$	ADS	$711 + 0$	[PRL 106 231803 (2011)]
$B^+ \to Dh^+$	$D \to K^0_S K^- \pi^+$	GLS	$711 + 362$	[arxiv:2306.02940]
$B^+ \to D^* K^+$	$D \to K^0_S \pi^- \pi^+$	BPGGSZ	$605 + 0$	[PRD 81 112002 (2010)]
$B^+ \to D^* K^+$	$D \to K^0_S \pi^0, K^0_S \phi, K^0_S \omega, K^- K^+, \pi^- \pi^+$	GLW	$210+0$	[PRD 73 051106 (2006)]

- Belle + Belle II combined results obtained for ϕ_3 determination
- First Belle + Belle II combination: ϕ_3 = (78.6±7.3), HFLAV:$66.2^{+3.4}_{-3.6}$

Unitarity Triangle fit extrapolation

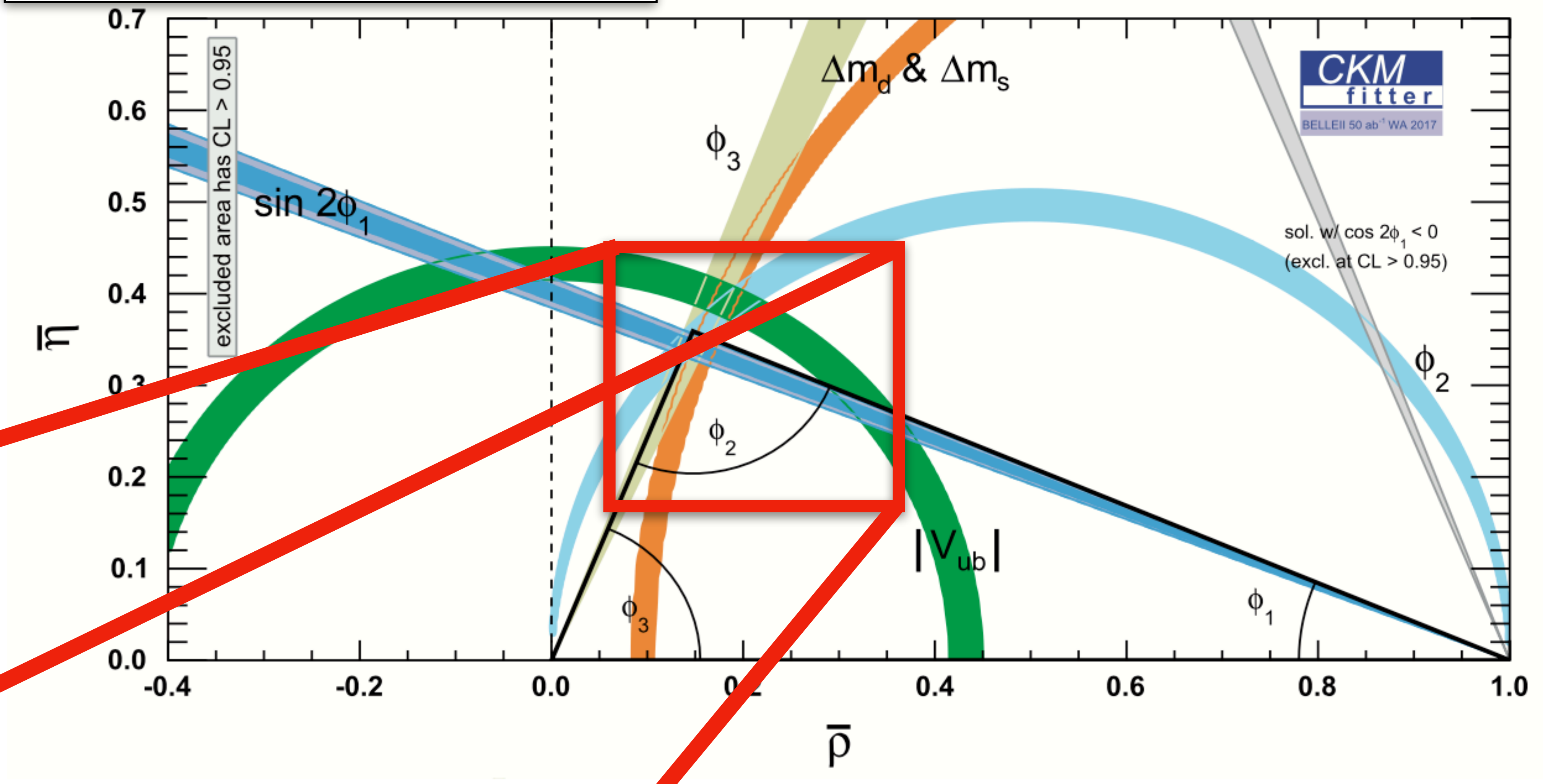
The Belle II Physics Book, PTEP 2019, 123C01

Current

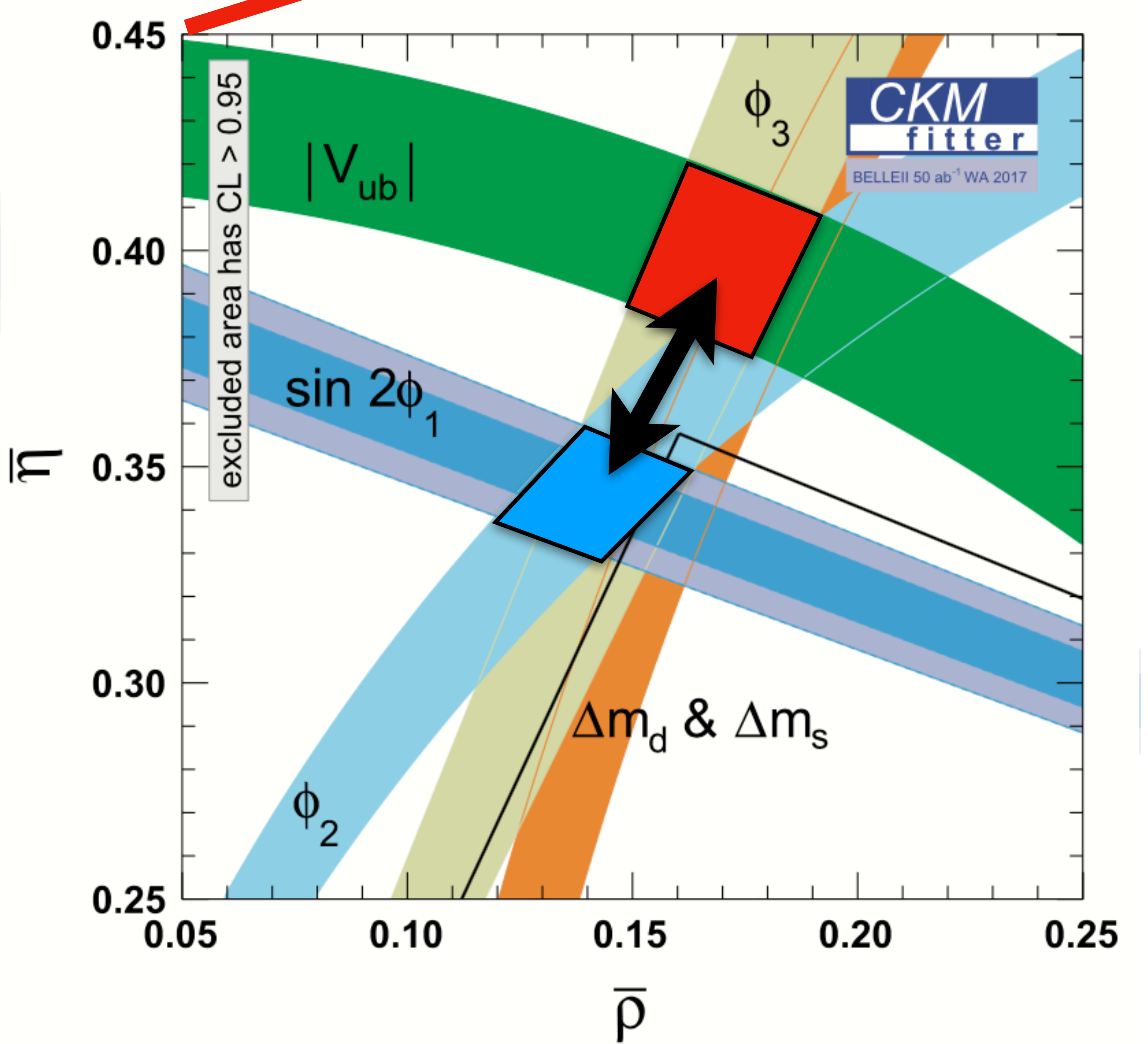


Belle II 50 ab^{-1}

If the current World Average hold



Zoom



- Tensions existed on V_{ub} and ϕ_1
  - UT can not close if keeping the central value for 50 ab^{-1}
- Differences between UT determined by **tree** (V_{ub}, ϕ_3) and **loop** (ϕ_1, ϕ_2) can be discriminated with 50 ab^{-1} data-set

Belle II - LHCb comparison

P. URQUIJO @ Beauty 2020

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. $B\to K\nu\nu$, $\mu\nu$), inclusive decays, time dependent CPV in B_d, τ physics.

LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).
LHCb scheduled major upgrades during LS3 and LS4.
Belle II formulating a 250 ab^{-1} upgrade program post 2028.

	Observable	Current Belle/ Babar	2019 LHCb	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})	LHCb (23 fb^{-1})	Belle II Upgrade (250 ab^{-1})	LHCb upgrade II (300 fb^{-1})
	CKM precision, new physics in CP Violation							
✸	$\sin 2\beta/\phi_1$ ($B\to J/\psi K_S$)	0.03	0.04	0.012	0.005	0.011	0.002	0.003
✸	γ/ϕ_3	13°	5.4°	4.7°	1.5°	1.5°	0.4°	0.4°
✸	α/ϕ_2	4°	–	2	0.6°	–	0.3°	–
✸	$\lvert V_{ub}\rvert$ (Belle) or $\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$ (LHCb)	4.5%	6%	2%	1%	3%	<1%	1%
	ϕ_s	–	49 mrad	–	–	14 mrad	–	4 mrad
✸	$S_{CP}(B\to\eta' K_S$, gluonic penguin)	0.08	○	0.03	0.015	○	0.007	○
✸	$A_{CP}(B\to K_S\pi^0)$	0.15	–	0.07	0.04	–	0.02	–
	New physics in radiative & EW Penguins, LFUV							
✸	$S_{CP}(B_d\to K^*\gamma)$	0.32	○	0.11	0.035	○	0.015	○
✸	$R(B\to K^* l^+ l^-)$ ($1<q^2<6$ GeV$^2/c^2$)	0.24	0.1	0.09	0.03	0.03	0.01	0.01
✸	$R(B\to D^*\tau\nu)$	6%	10%	3%	1.5%	3%	<1%	1%
	$Br(B\to\tau\nu)$, $Br(B\to K^*\nu\nu)$	24%, –	–	9%, 25%	4%, 9%	–	1.7%, 4%	–
	$Br(B_d\to\mu\mu)$	–	90%	–	–	34%	–	10%
	Charm and τ							
✸	$\Delta A_{CP}(KK-\pi\pi)$	–	8.5×10^{-4}	–	5.4×10^{-4}	1.7×10^{-4}	2×10^{-4}	0.3×10^{-4}
✸	$A_{CP}(D\to\pi^+\pi^0)$	1.2%	–	0.5%	0.2%	–	0.1%	–
	$Br(\tau\to e\gamma)$	$<120\times10^{-9}$	–	$<40\times10^{-9}$	$<12\times10^{-9}$	–	$<5\times10^{-9}$	–
	$Br(\tau\to\mu\mu\mu)$	$<21\times10^{-9}$	$<46\times10^{-9}$	$<3\times10^{-9}$	$<3\times10^{-9}$	$<16\times10^{-9}$	$<0.3\times10^{-9}$	$<5\times10^{-9}$

Results on other D & τ modes expected

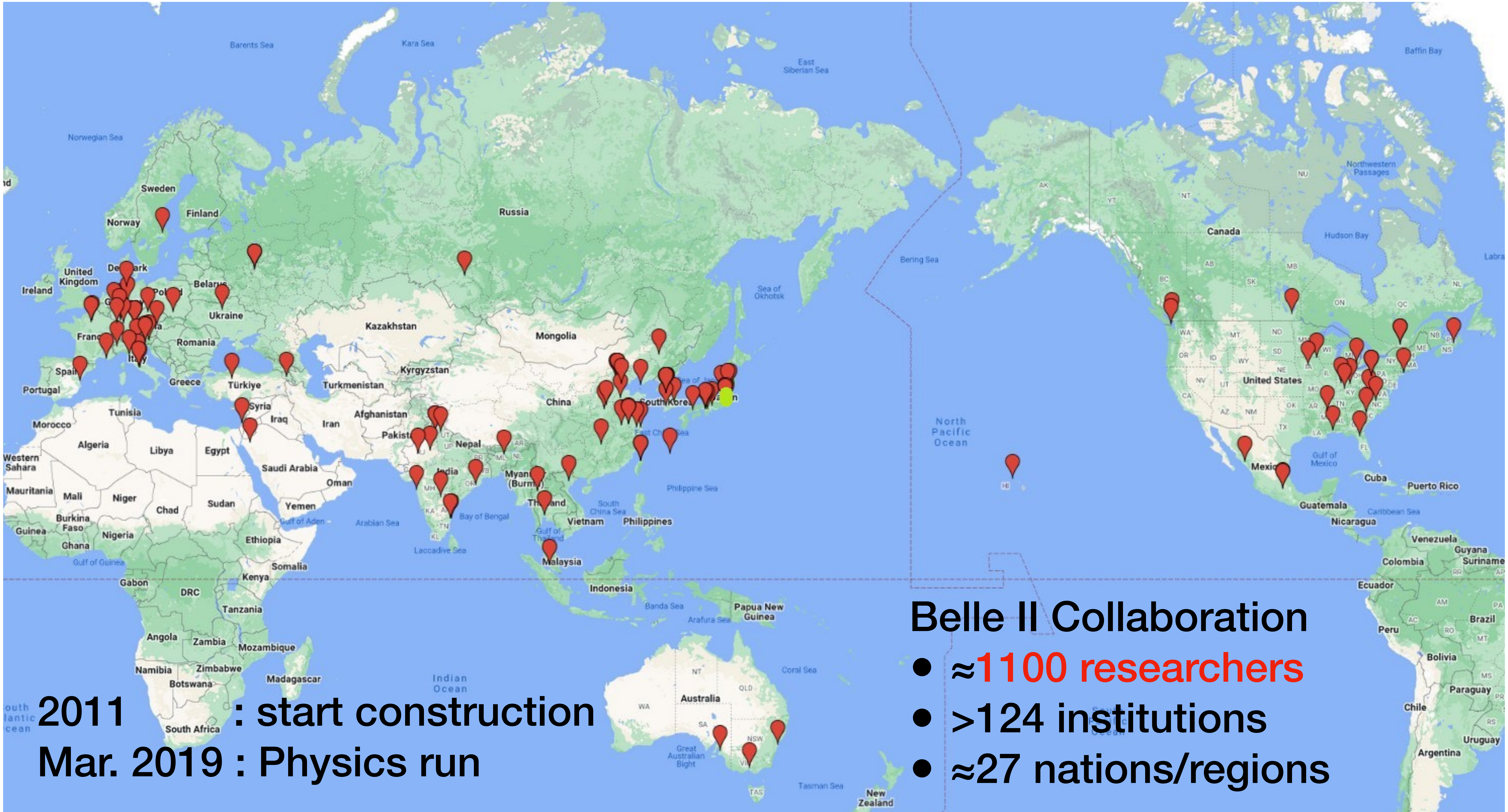
○ *Possible in similar channels, lower precision*
– *Not competitive.*

arXiv: 1808.08865 (Physics case for LHCb upgrade II), PTEP 2019 (2019) 12, 123C01 (Belle II Physics Book)

SuperKEKB

- High Energy Accelerator Organization (KEK@Tsukuba)
- SuperKEKB: asymmetric e+ (4GeV) e- (7GeV)collider, 3km
- Nano beam scheme, squeeze the beam σ_y^*~50nm

The Belle II Collaboration



2011 : start construction
Mar. 2019 : Physics run

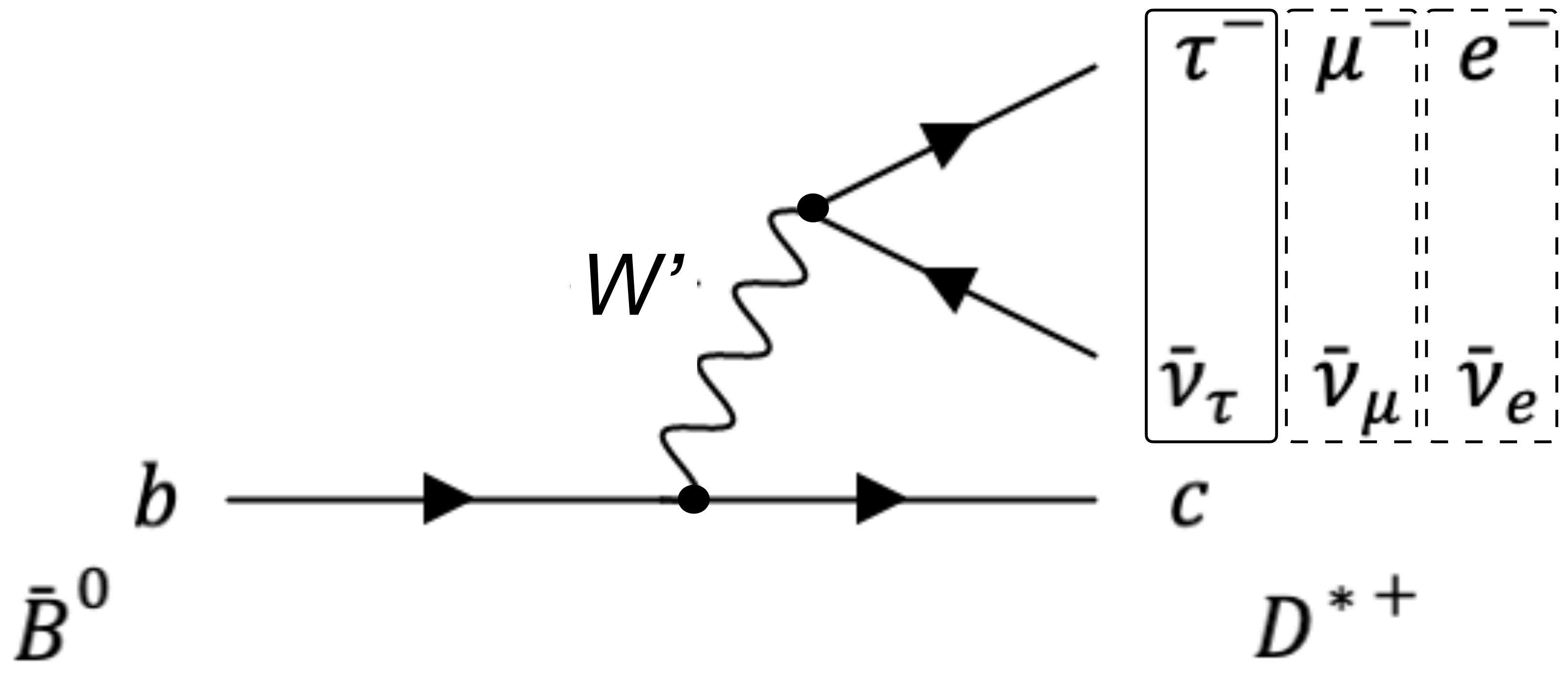
Belle II Collaboration

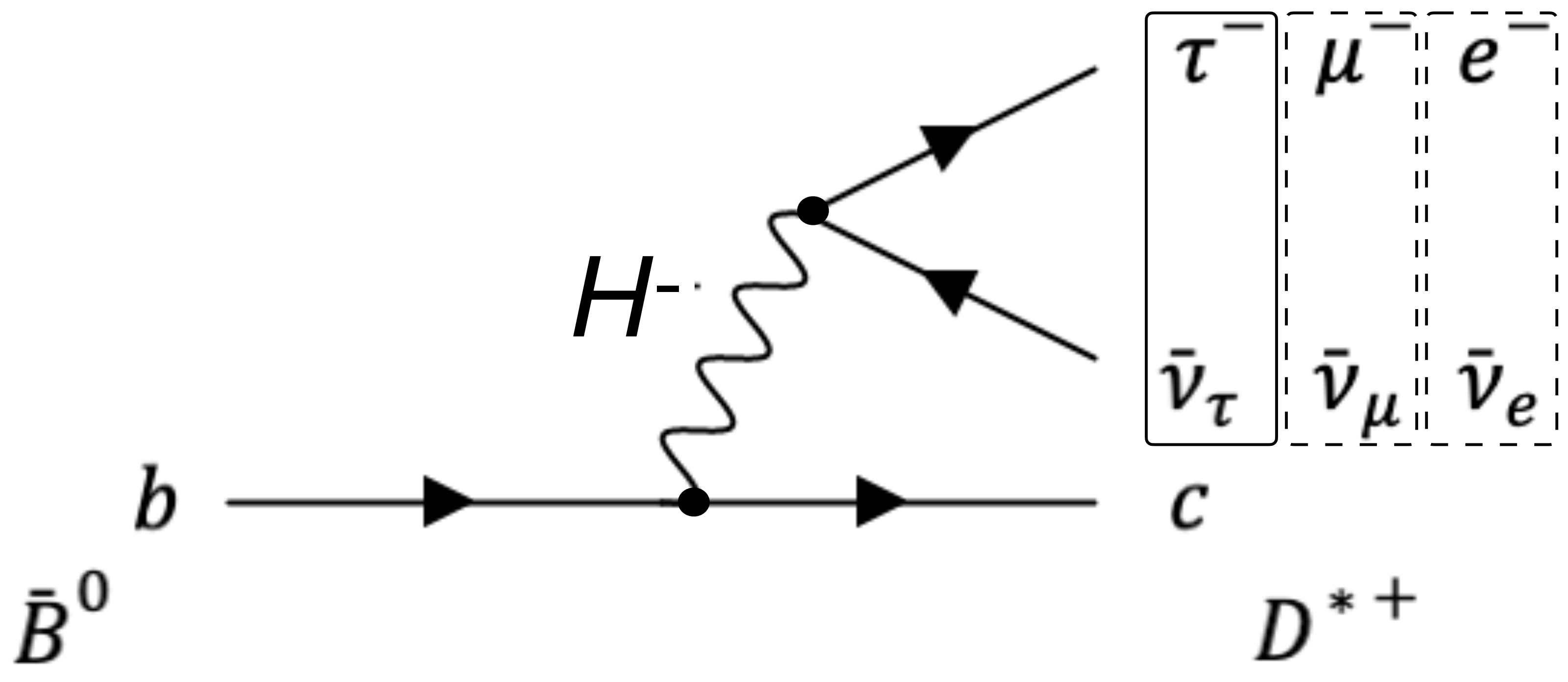
- ≈1100 researchers
- >124 institutions
- ≈27 nations/regions

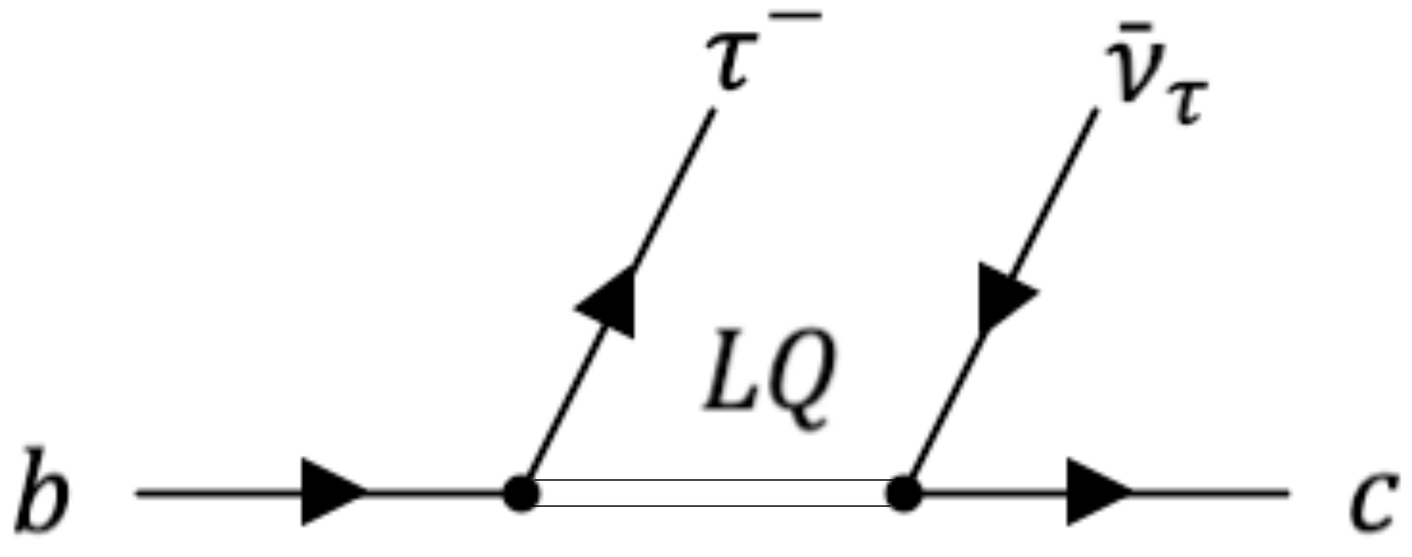
New physics scenarios

In general, there are three typical candidate scenarios to explain the anomaly observed in $R(D^{(*)})$

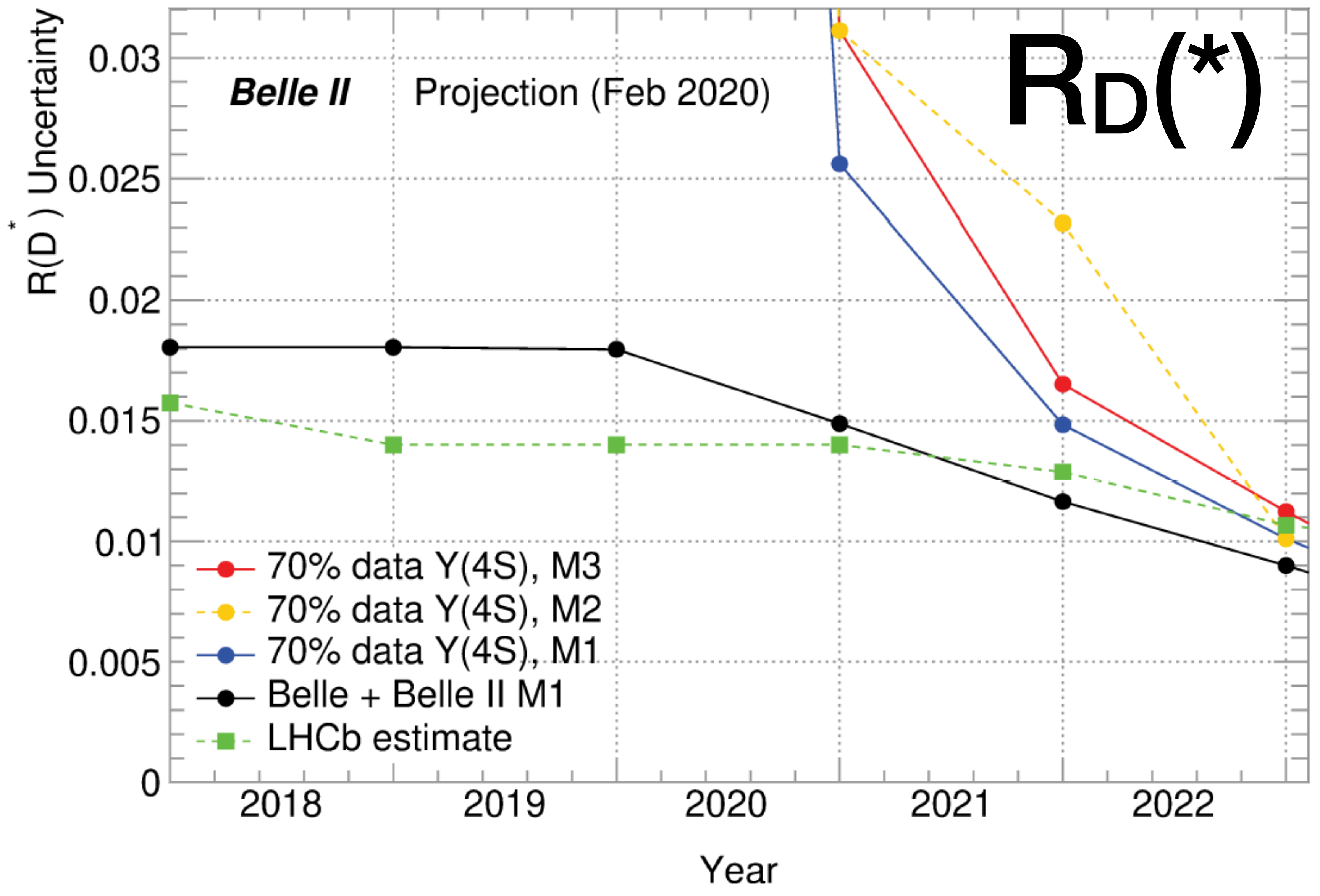
- Heavy vector bosons
  - Constrained from $W' \to \tau\nu$ and $Z' \to \tau\tau$ search
- Charged Higgs
  - Constrained from $B_c \to \tau\nu$ and $H^{\pm} \to \tau\nu$,still allowed
  - Previously, it was rejected by $B_c \to \tau\nu$ measurement, however, recovered by recalculating the B_c lifetime. arXiv:2201.06565
- Leptoquark
  - $gg \to LQ\ LQ^*$, still broad parameter regions are allowed

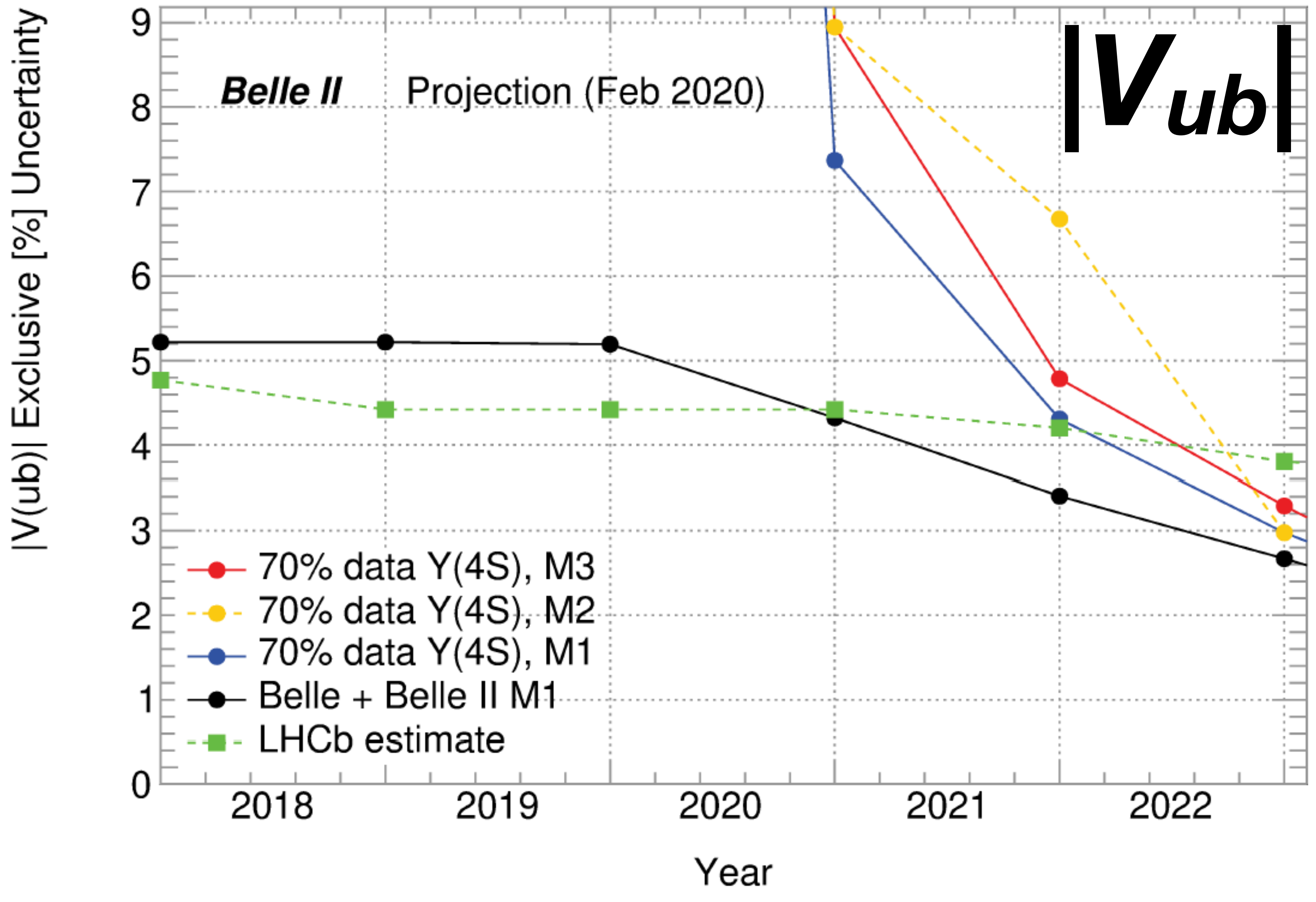


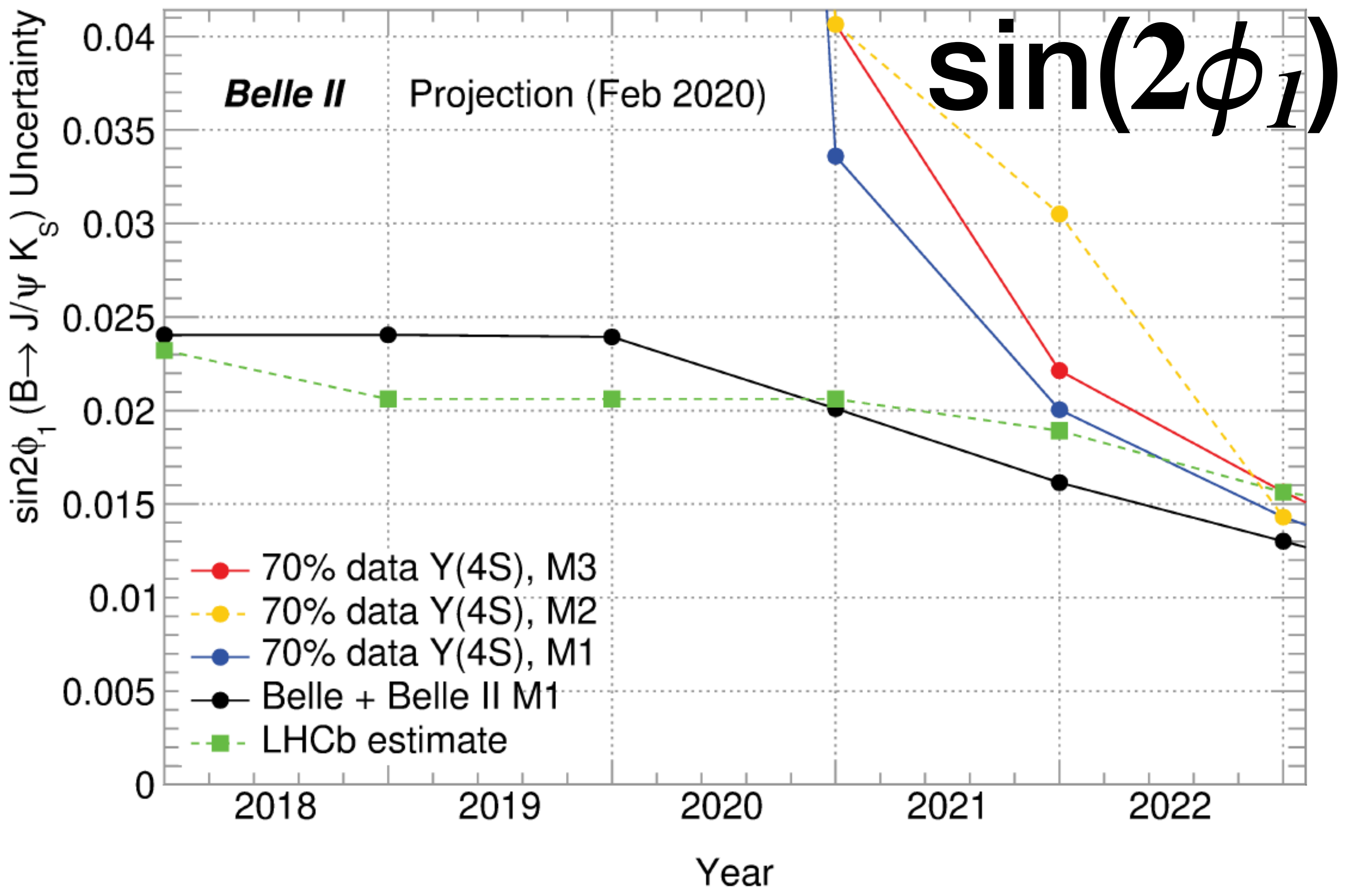


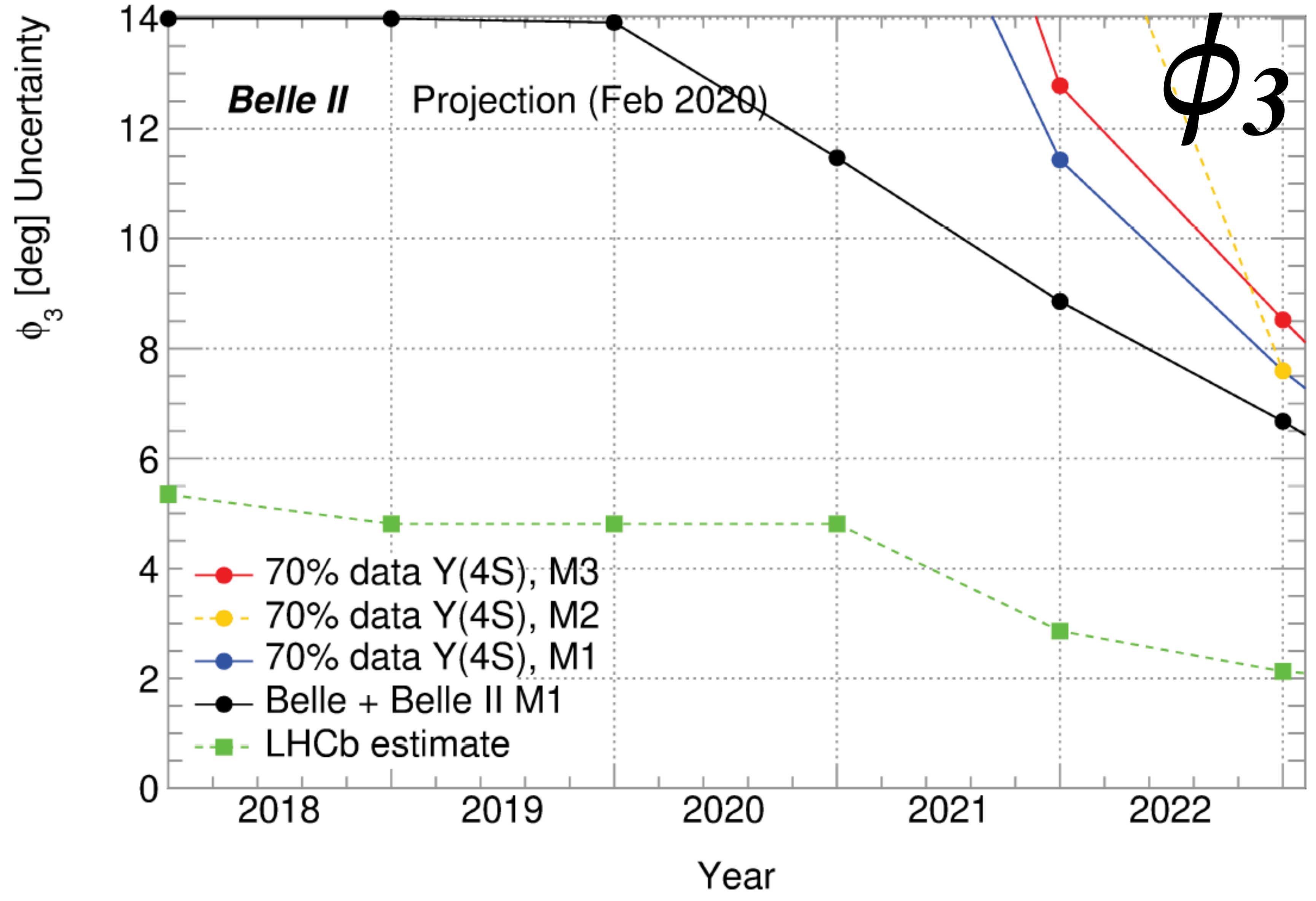


Belle II - LHCb comparison









Semi-leptonic *B* decays