Recent Results from Belle and Belle II

8th Workshop on Theory, Phenomenology and Experiments in Flavour Physics

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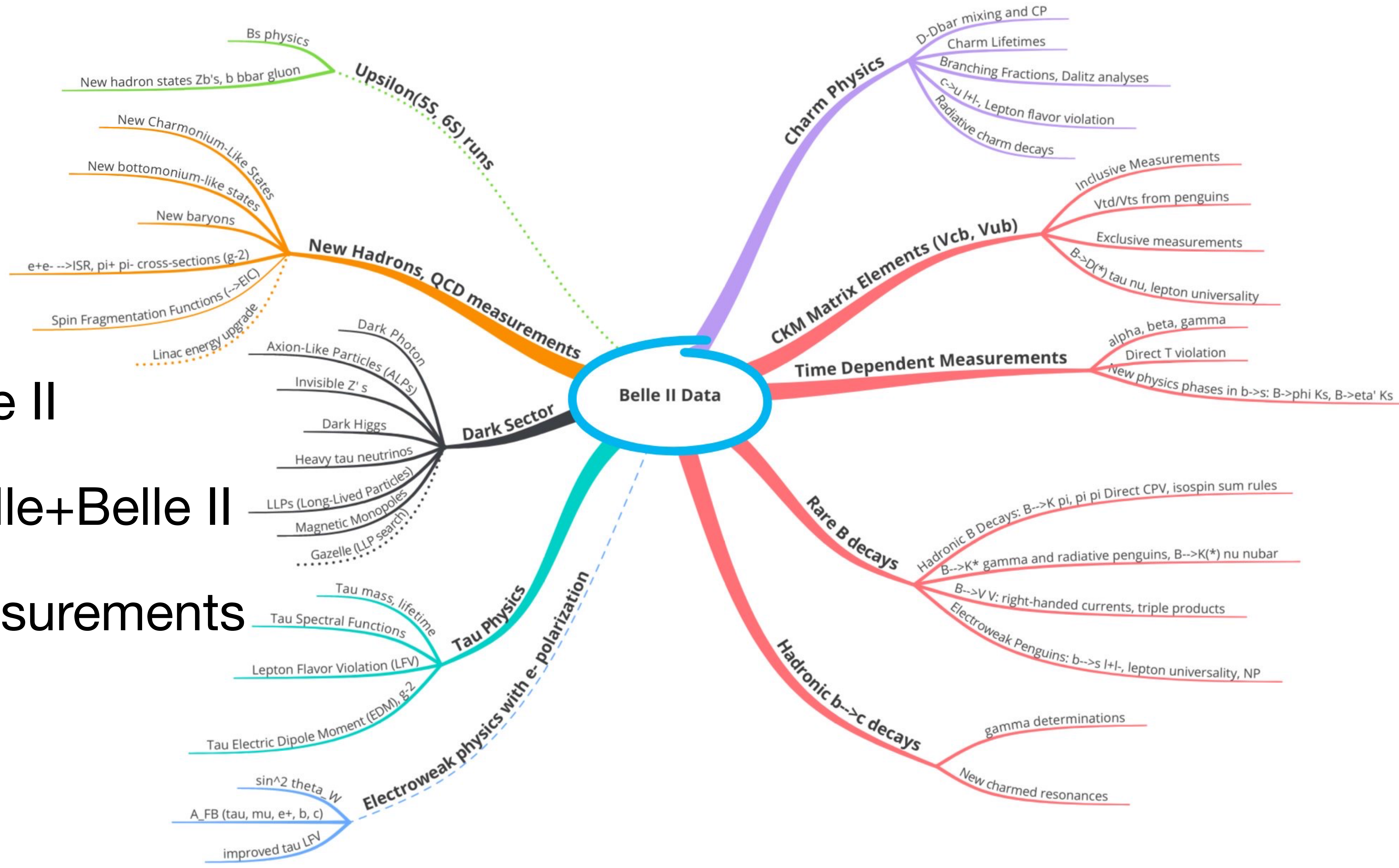
Outline

- Belle and Belle II
- Charm lifetimes at Belle II
- CKM ϕ_3: combined Belle+Belle II
- Other CPV related measurements
- Semileptonic B decays
- LFU/LFV at Belle

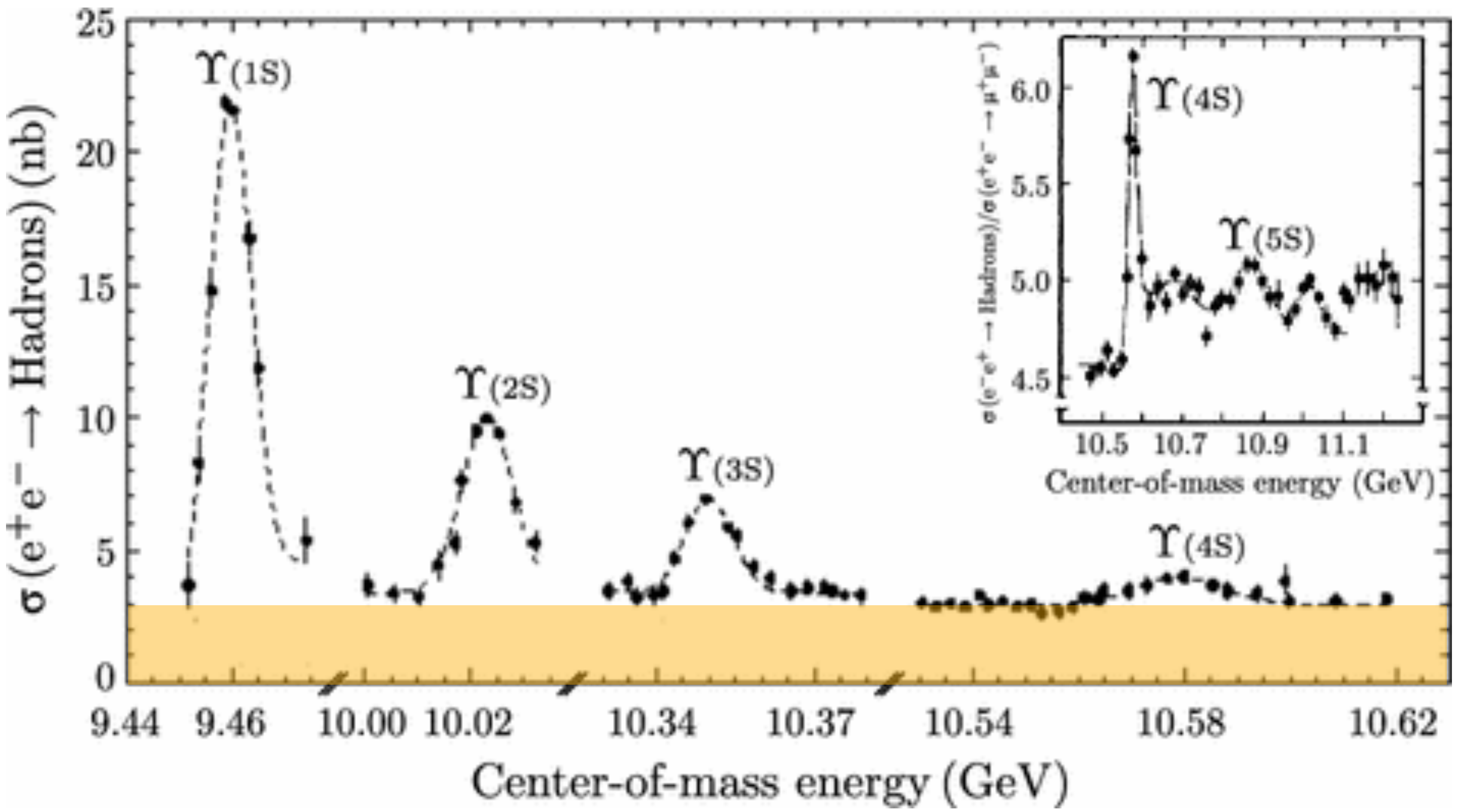


The Setup for a B-Factory

- Collide e^+e^- at center of mass energy slightly above **~2x B-meson mass**:

$$e^+ \longrightarrow \Upsilon(4S)\ \langle b\bar{b} \rangle \longleftarrow e^- \qquad \sqrt{s} = 10.58\ \text{GeV}$$

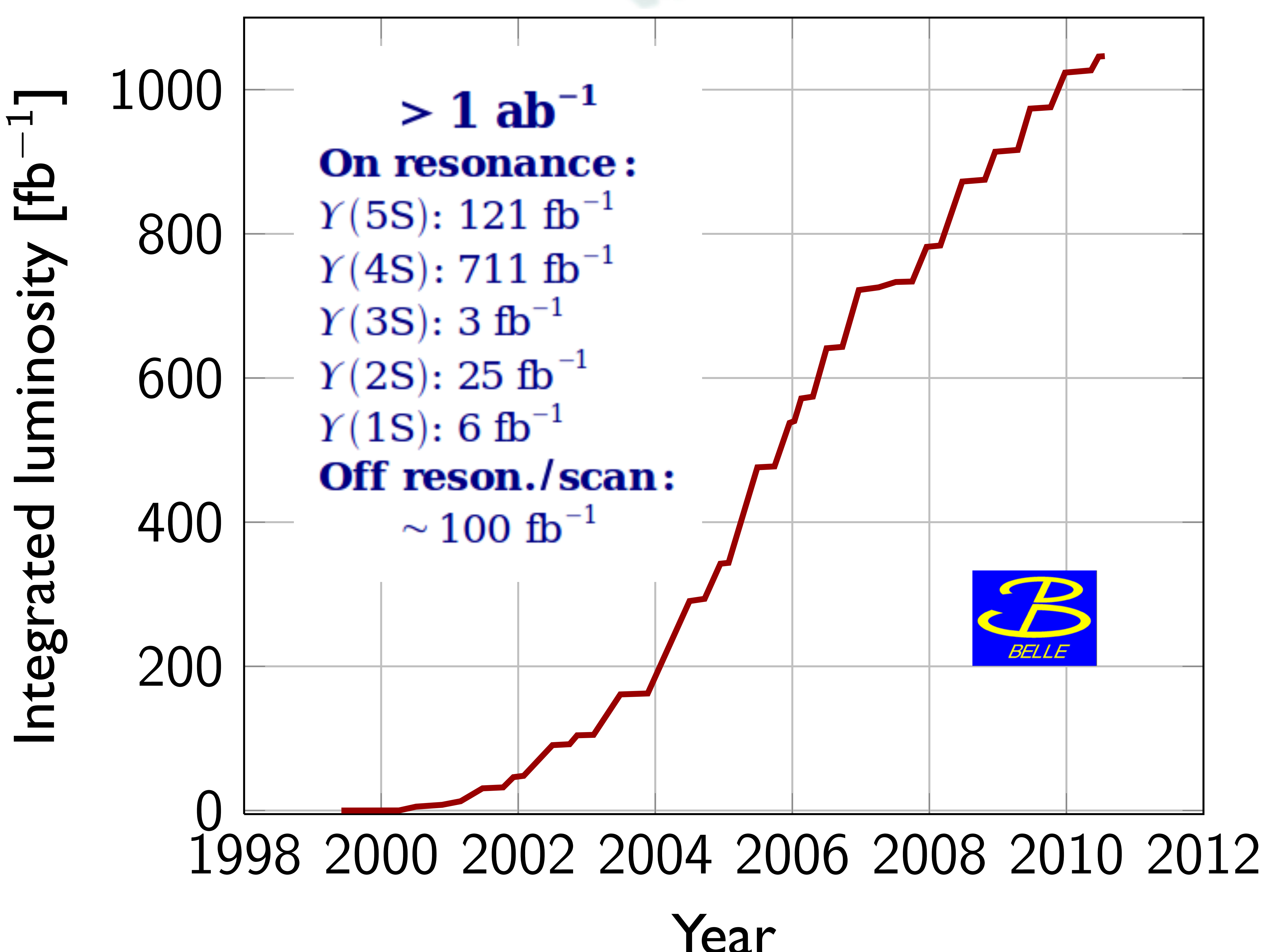
$\sigma(e^+e^- \to \Upsilon(4S))$	**1.05 nb**
$\sigma(e^+e^- \to \tau^+\tau^-)$	0.92 nb
$\sigma(e^+e^- \to c\bar{c})$	1.33 nb

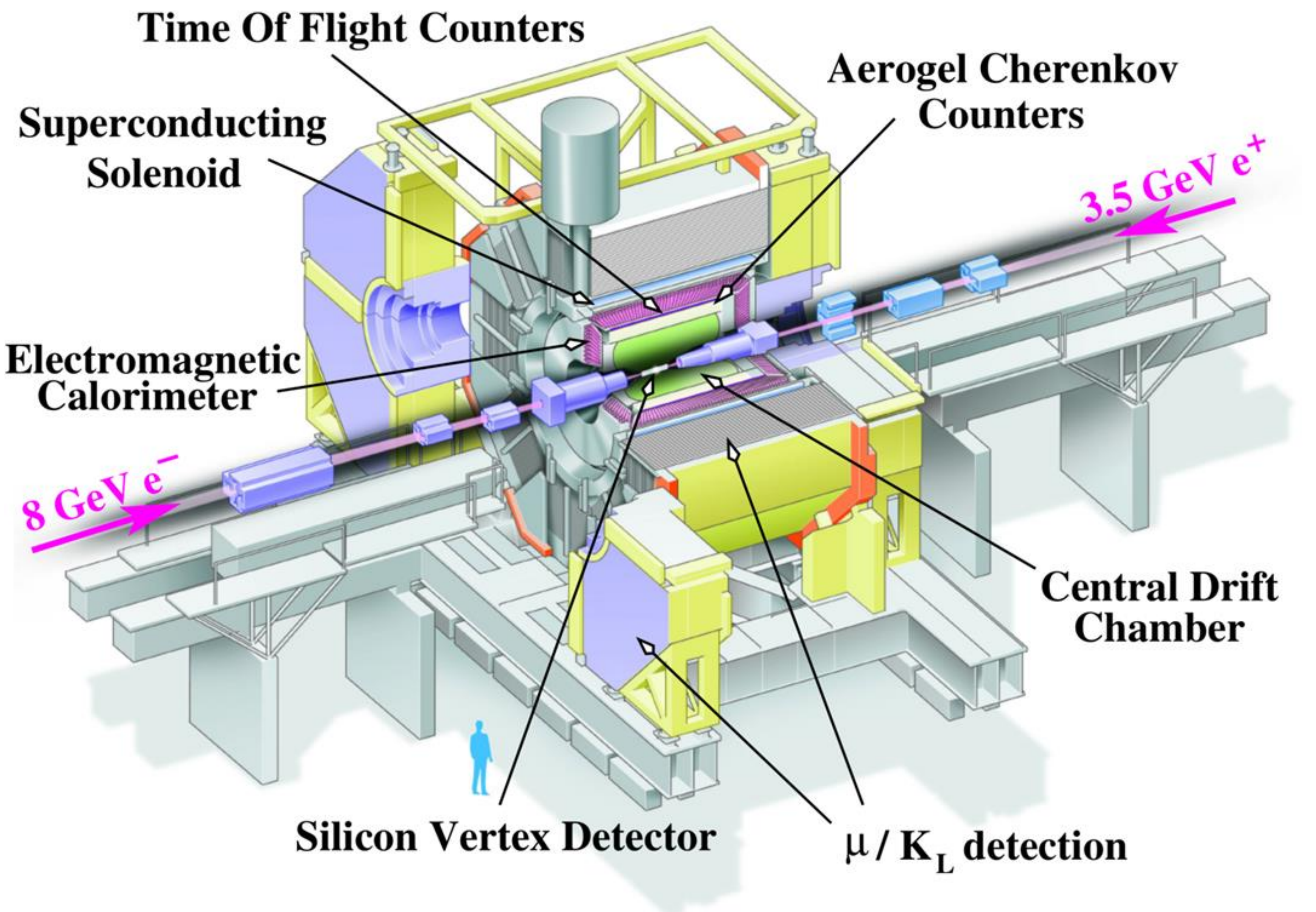


- Large, relatively clean samples of **B-mesons**, **D-mesons** and **τ-leptons**.
- Well known initial state + Large solid angle coverage (>90%) → **Well constrained decay kinematics**
- Advantage in studies with neutral or missing particles.

The Belle Experiment

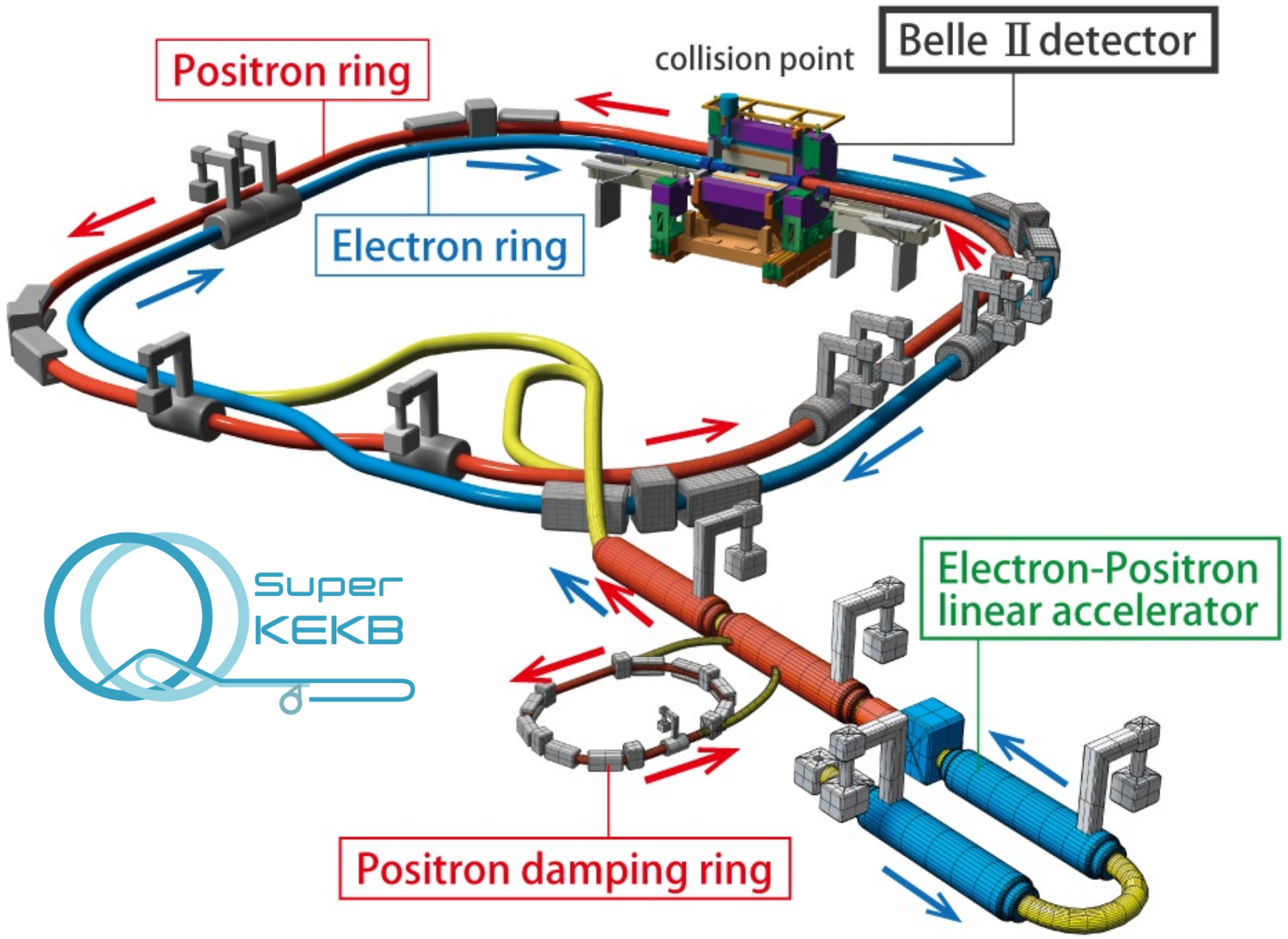
- Was located at the interaction region of **KEKB,** a *first generation* B-factory in Tsukuba, Japan.

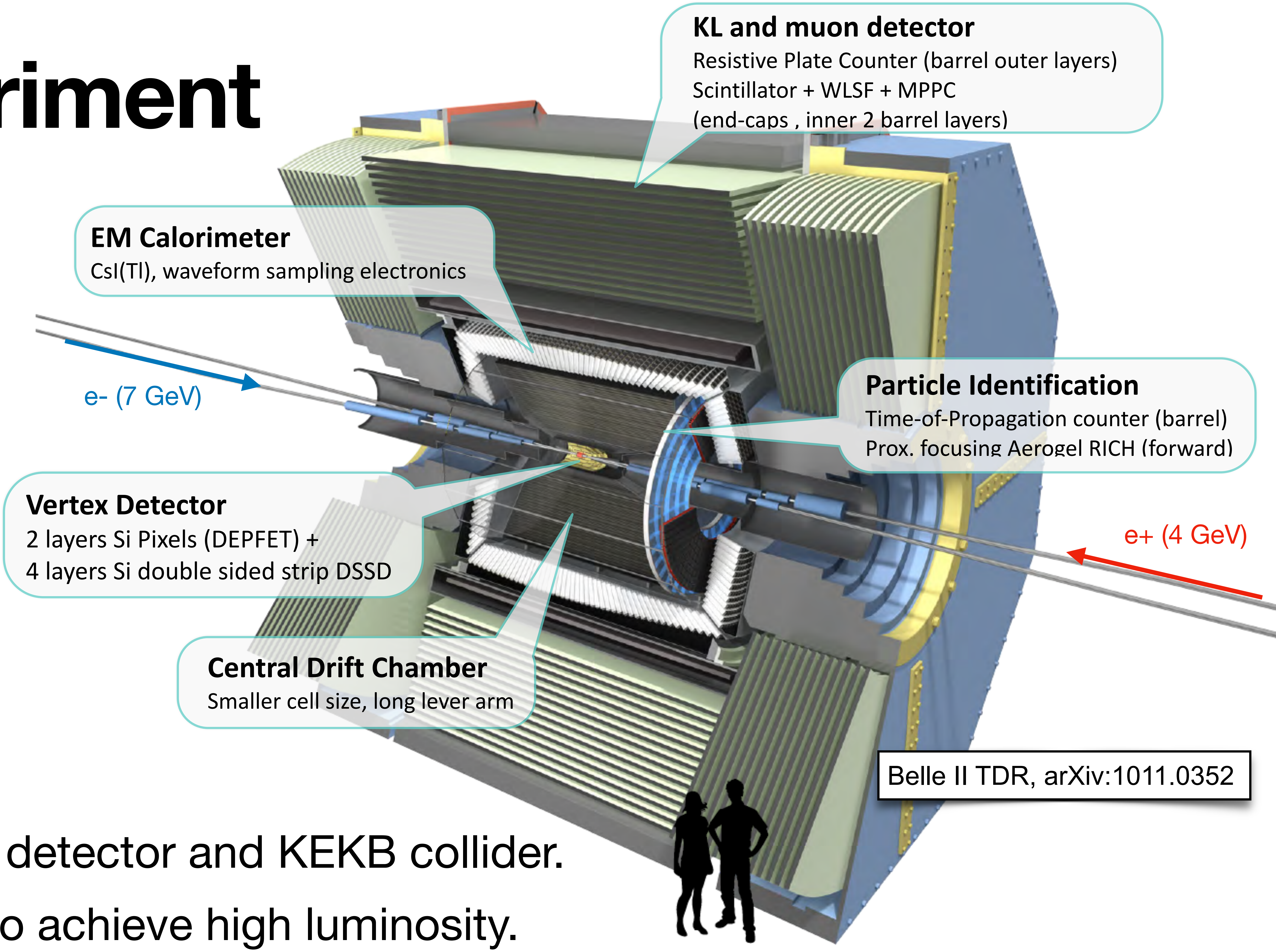




- General-purpose spectrometer operating between **1999** and **2010**
- Collected **~1 ab^{-1}**, or approximately:
  - 772 million $B\bar{B}$ pairs
  - 910 million $\tau^+\tau^-$ pairs

The Belle II Experiment

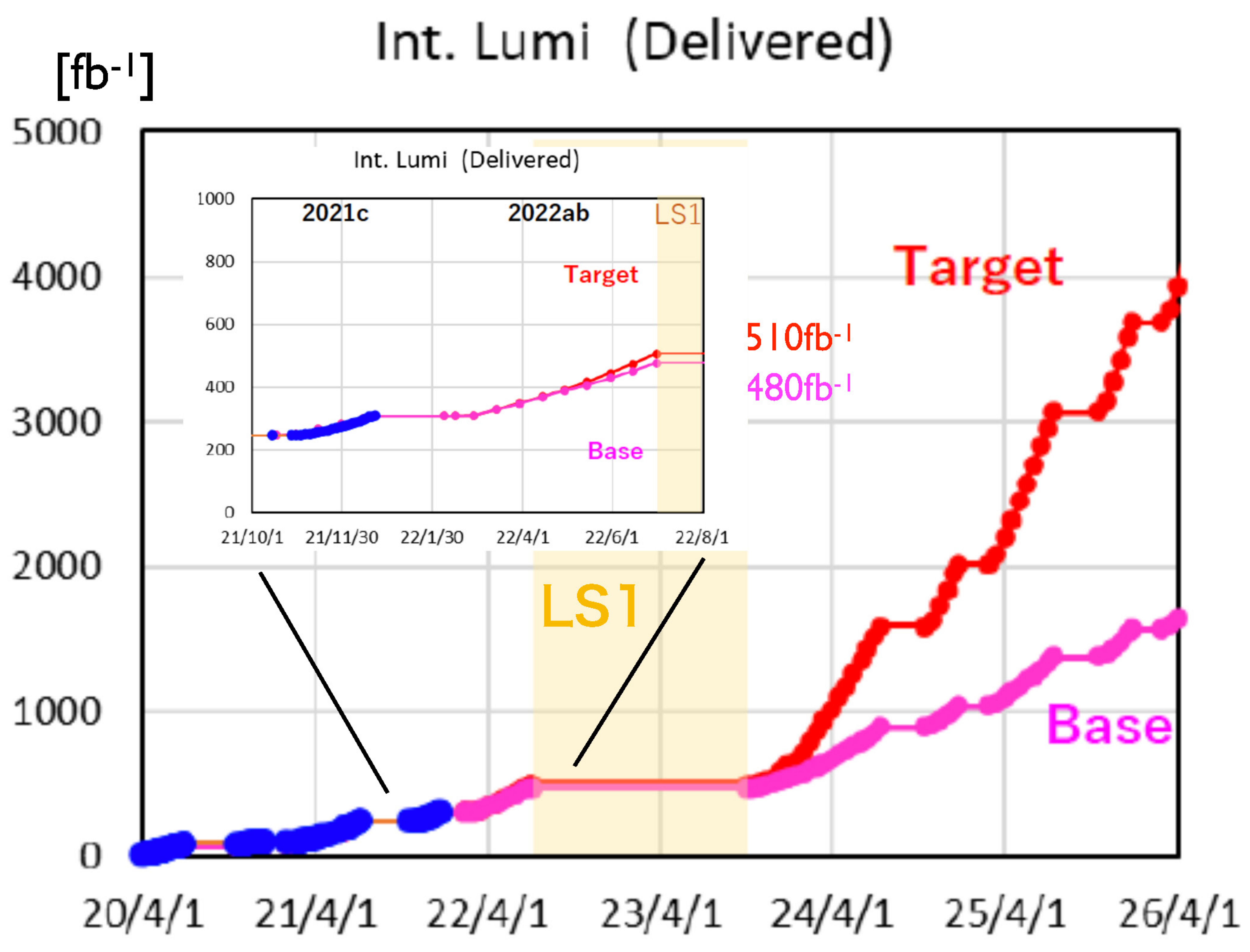




- **Belle II/SuperKEKB** succeed Belle detector and KEKB collider.
- **SuperKEKB:** Nano-beam scheme to achieve high luminosity.
- **Belle II:** all-new detector with improved vertex reconstruction and particle identification.

Belle II Timeline

- Roll-in in 2017 followed by commissioning.
- **Full detector operation started in 2019.**
- Achieved **world record** luminosity of **4.65×10^{34} cm^{-2} s^{-1}** (June 8th, 2022)
  - **x2** Belle instantaneous luminosity
  - **Aiming one order higher**
- Long Shutdown 1 (LS1) starts this summer to replace PXD + detector maintenance and improvement.



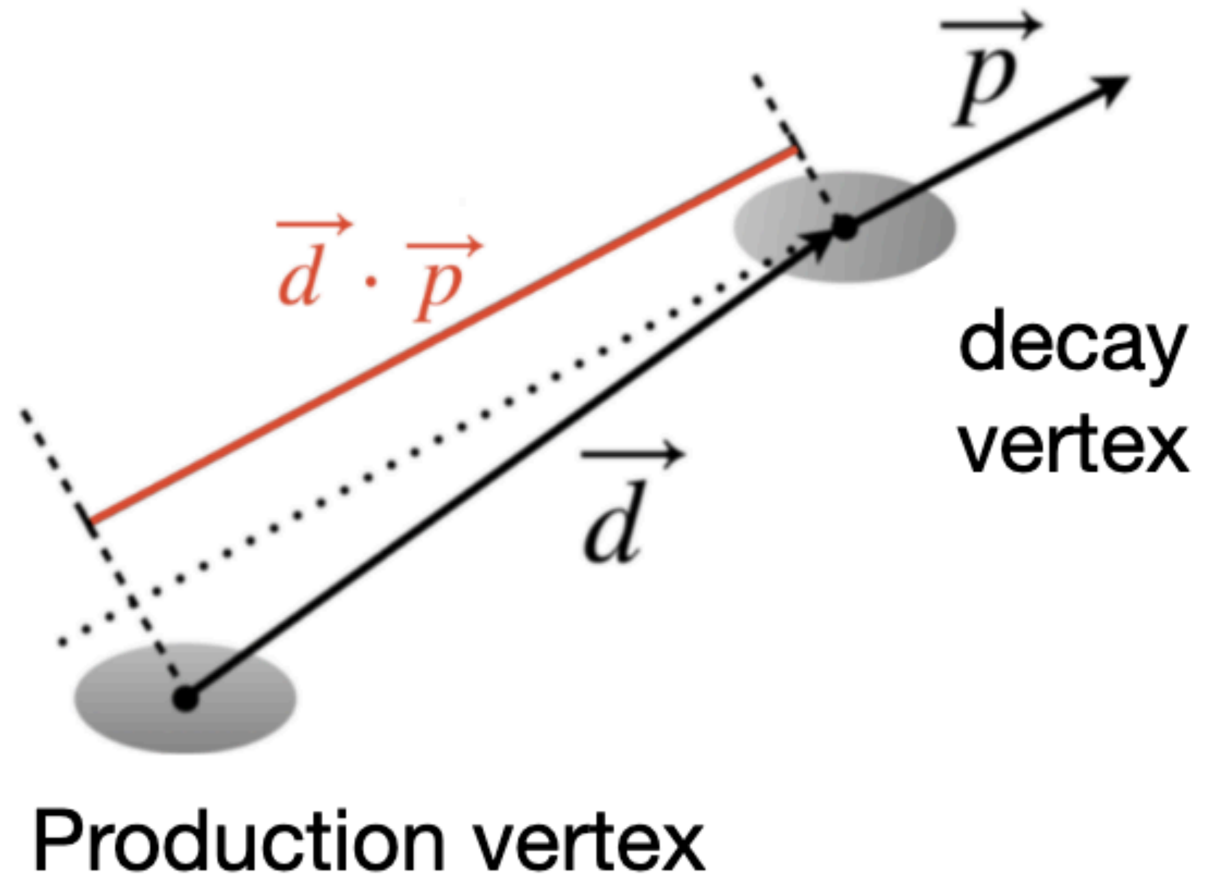
Base: Conservative extrapolation from 2021 run parameters

Target: Extrapolation from 2021 with expected improvements

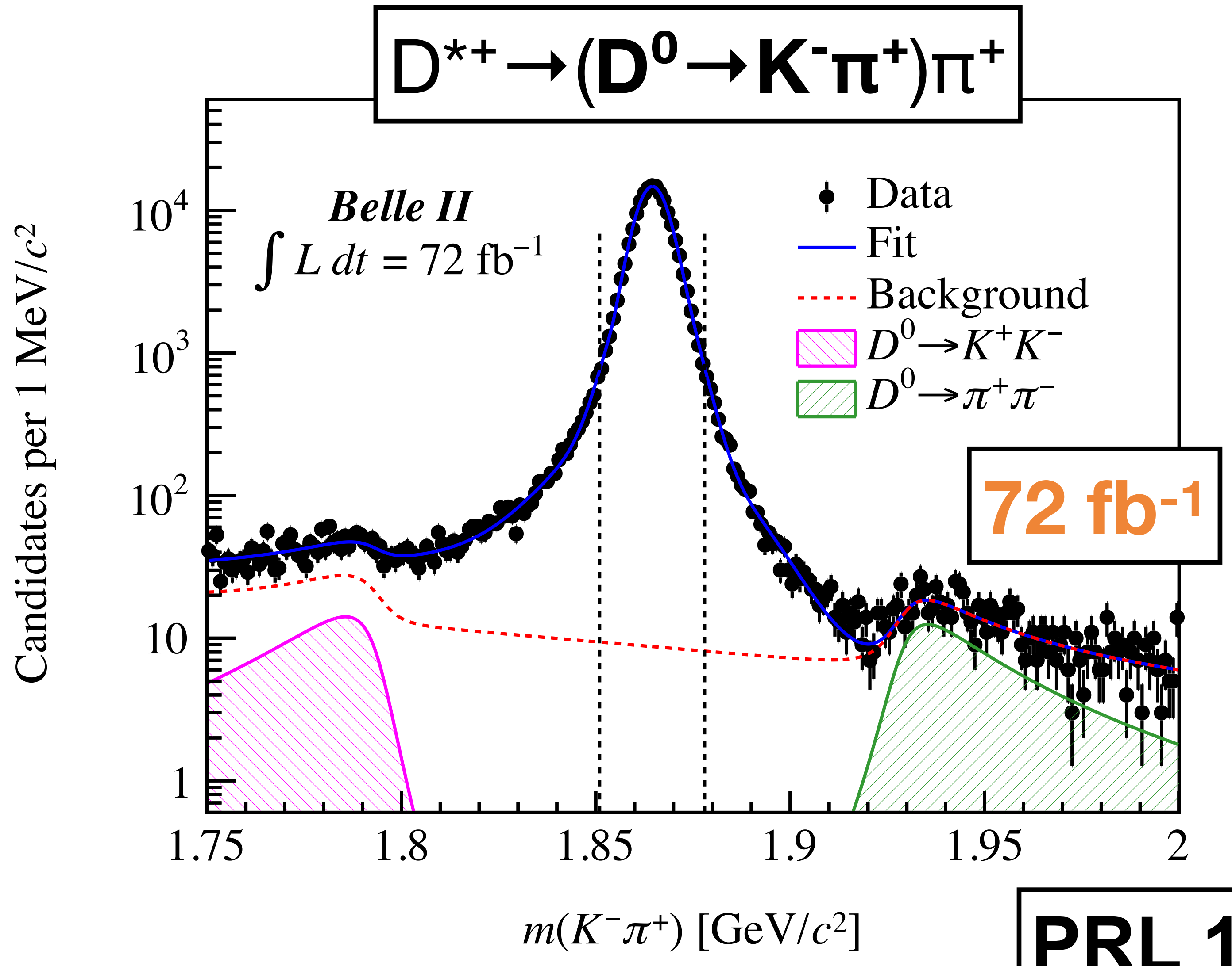
- **~400 fb^{-1} at LS1** can already match BaBar **(~550 fb^{-1})** and challenge Belle's results **(~1 ab^{-1})** thanks to improved reconstruction performance.

Don't believe me?
Here's an example...

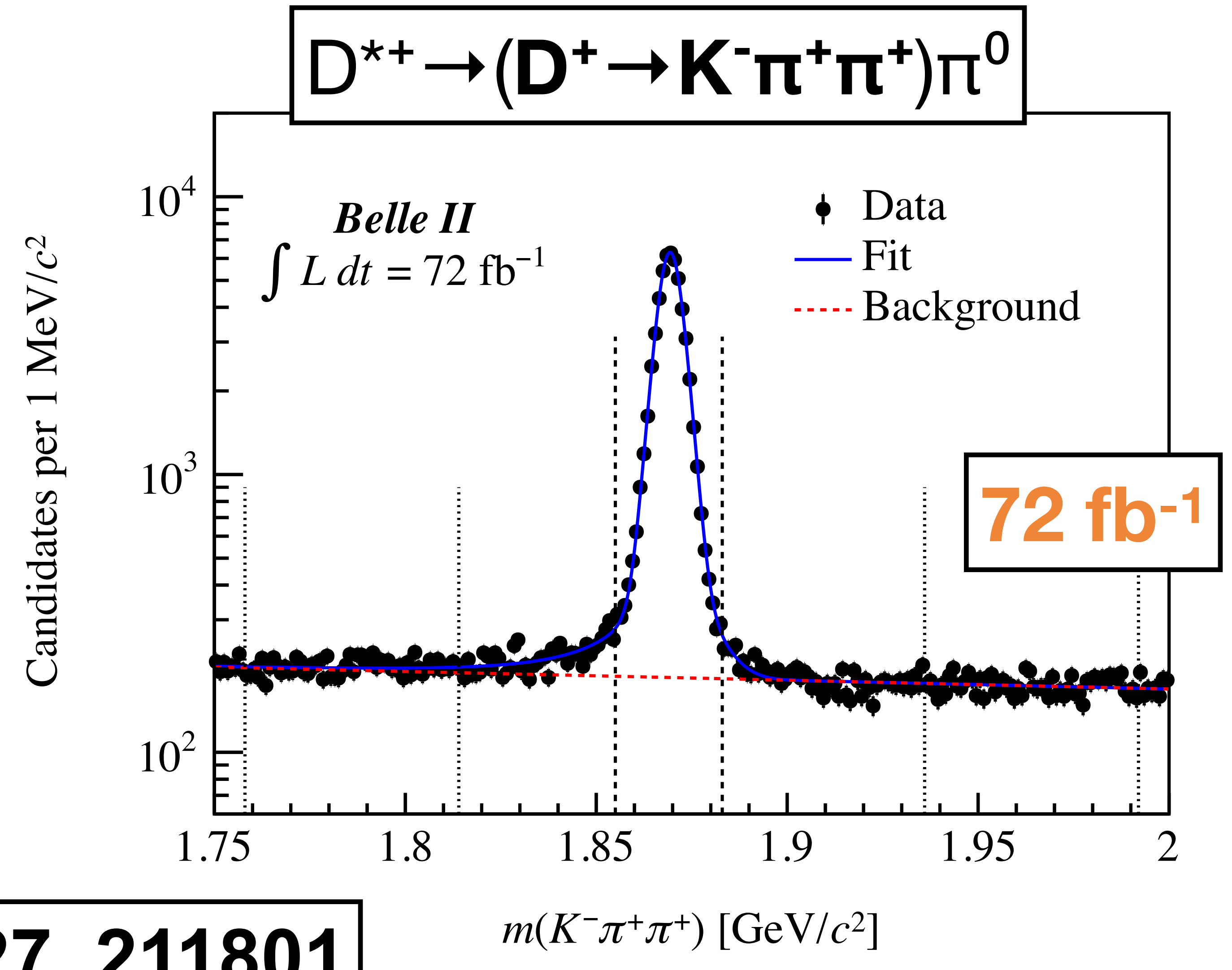
Charm Lifetime @Belle II

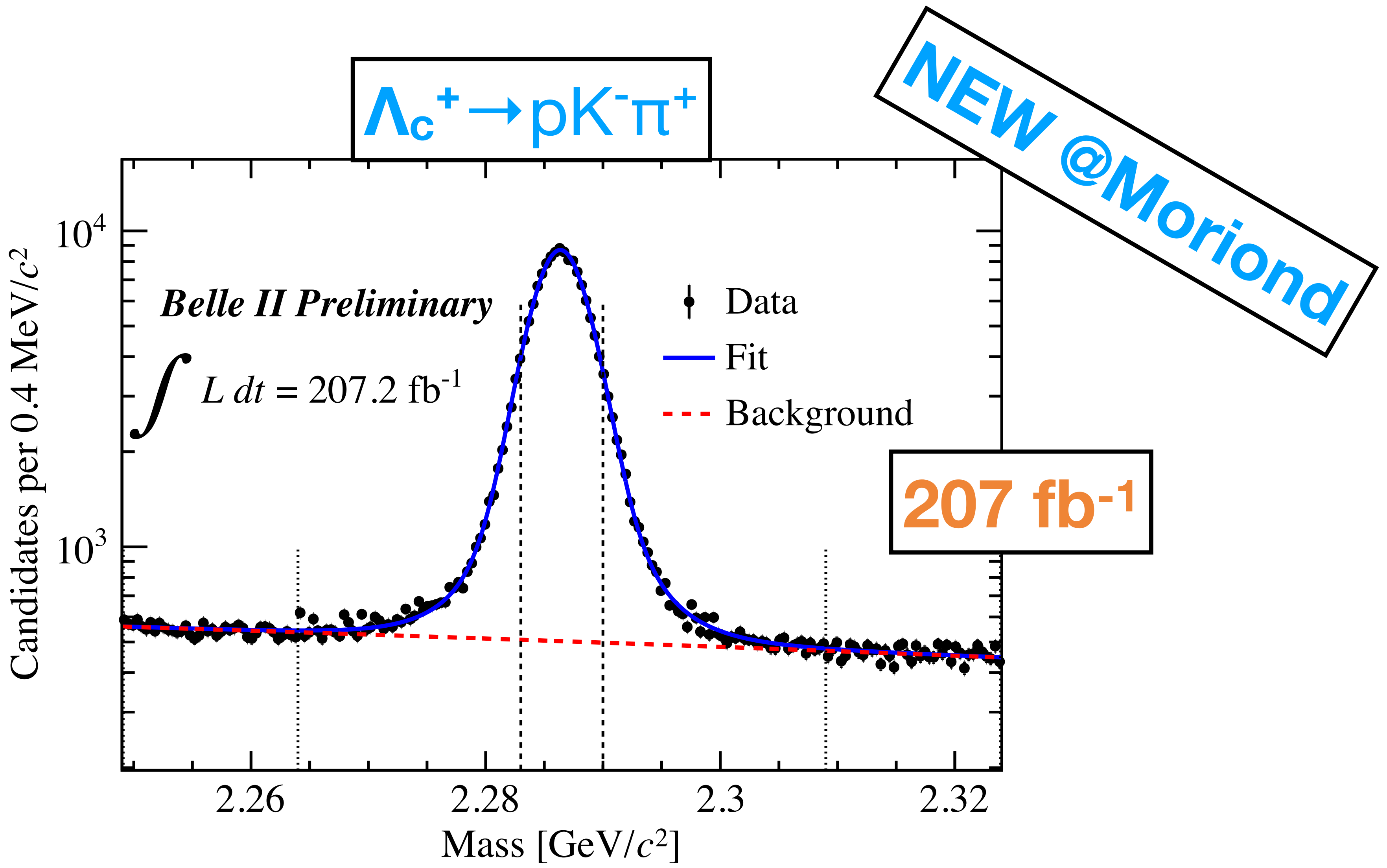


- Test of effective theory models e.g. strong corrections to weak decays at low energy
- Challenge: requires high resolution and carefully controlled systematics
    - New detector offers **2x decay time resolution of** Belle and BaBar thanks to smaller interaction region and vertex detector located closer to the IP.



PRL 127, 211801



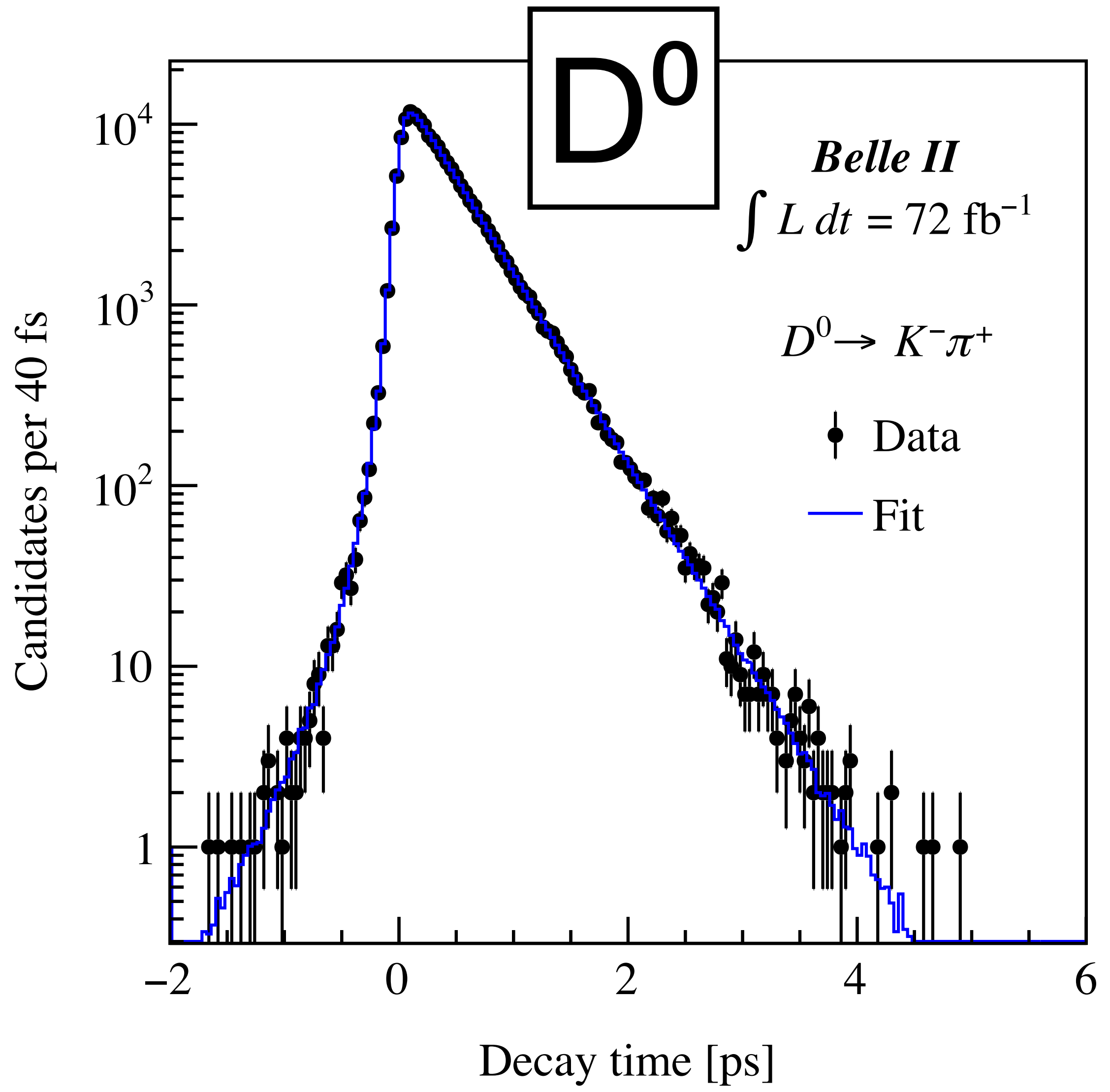


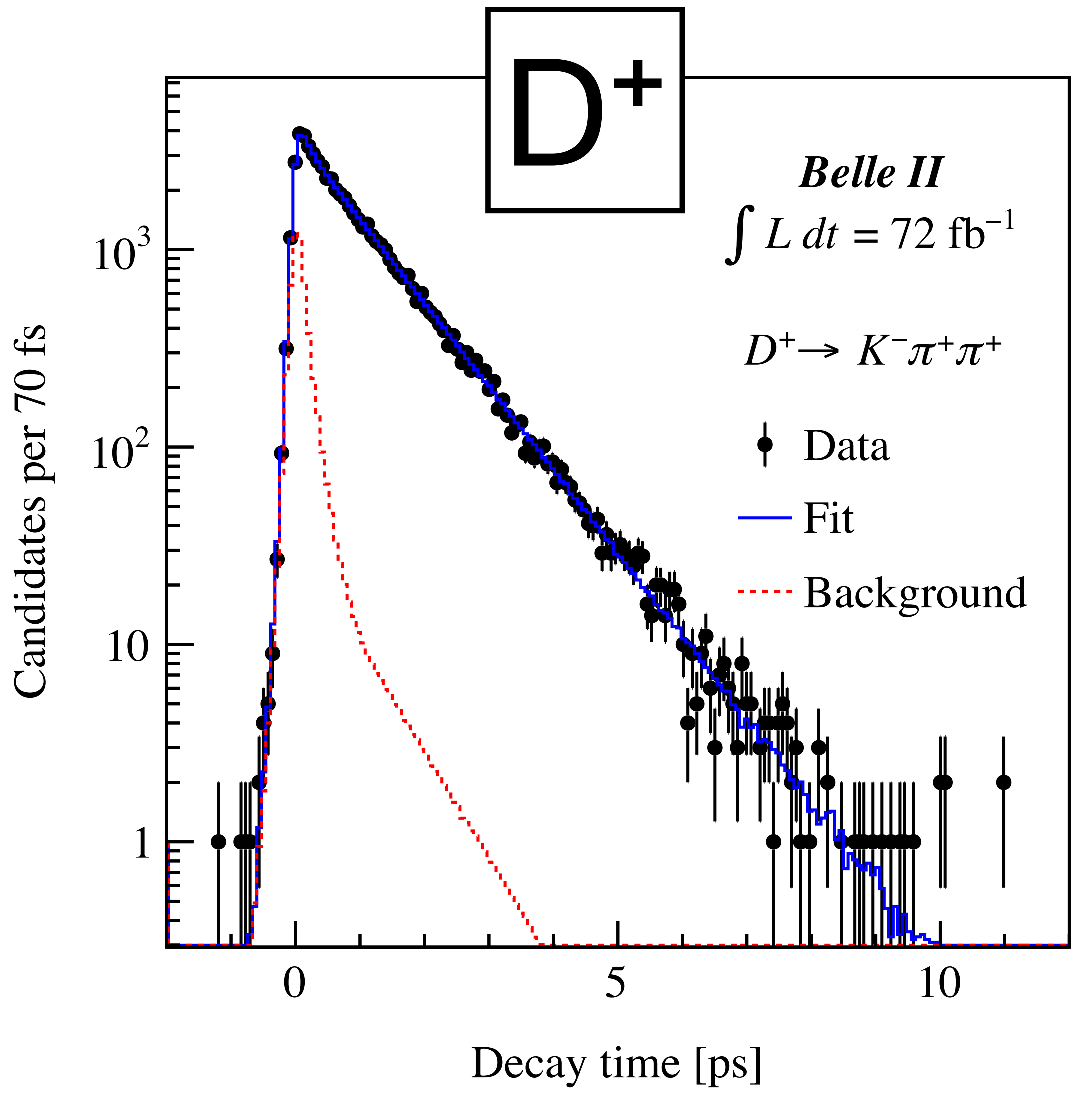
Charm Lifetime @Belle II

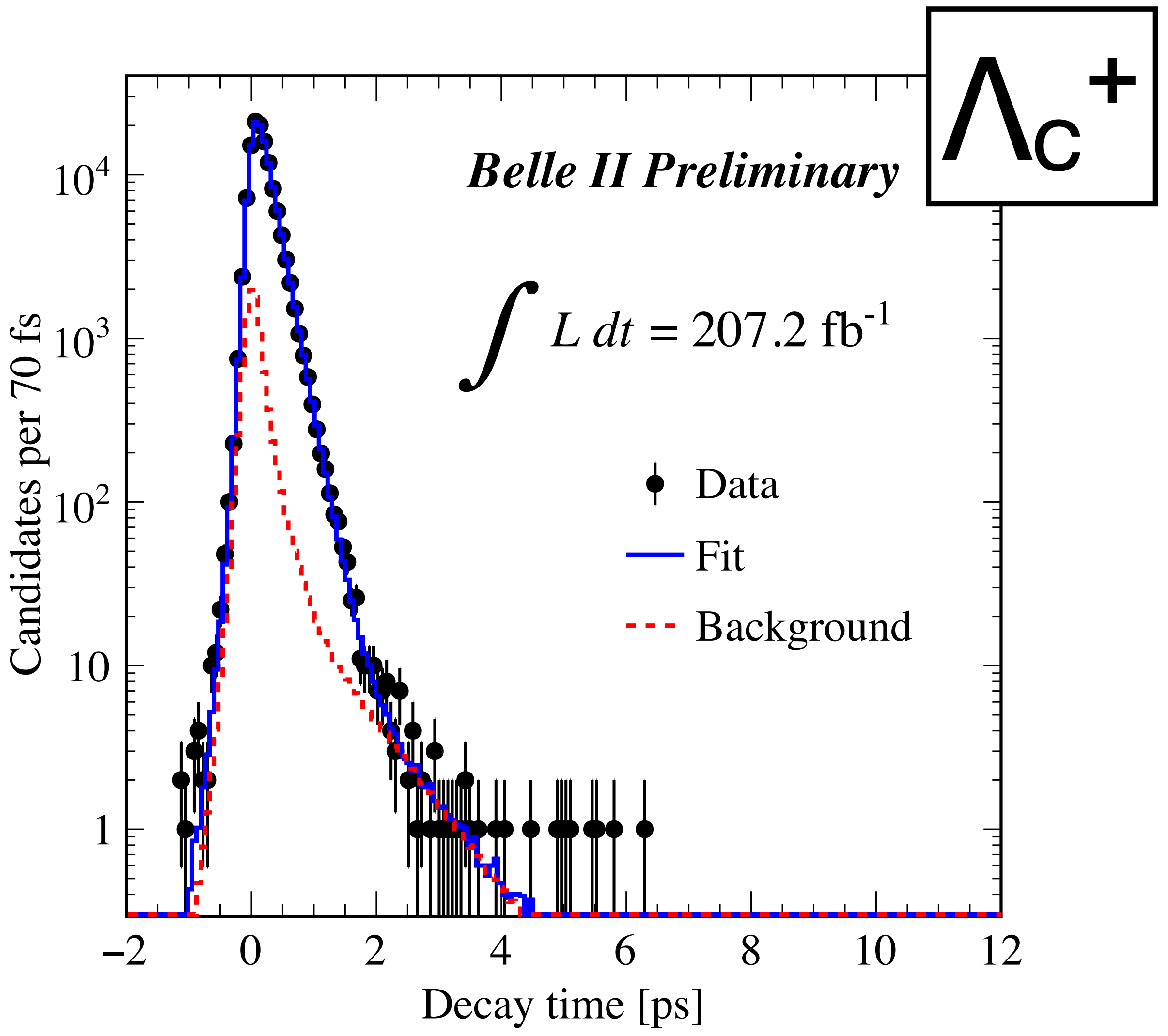
	Belle II	World average
$\tau(D^0)$ =	**(410.5 ± 1.1 ± 0.8) fs**	(410.1 ± 1.5) fs
$\tau(D^+)$ =	**(1030.4 ± 4.7 ± 3.1) fs**	(1040 ± 7) fs
$\tau(\Lambda_c^+)$ =	**(204.1 ± 0.8 ± 0.7 - 1.4) fs**	(202.4 ± 3.1) fs

extra syst from $\Xi_c \rightarrow \Lambda_c \pi$

- 2D fit of unbinned decay time distributions.
- Background from simultaneous fit of sidebands.
- Dominant uncertainties: physics background and detector alignment.
- **World's best** result, establishes the potential of the Belle II detector.

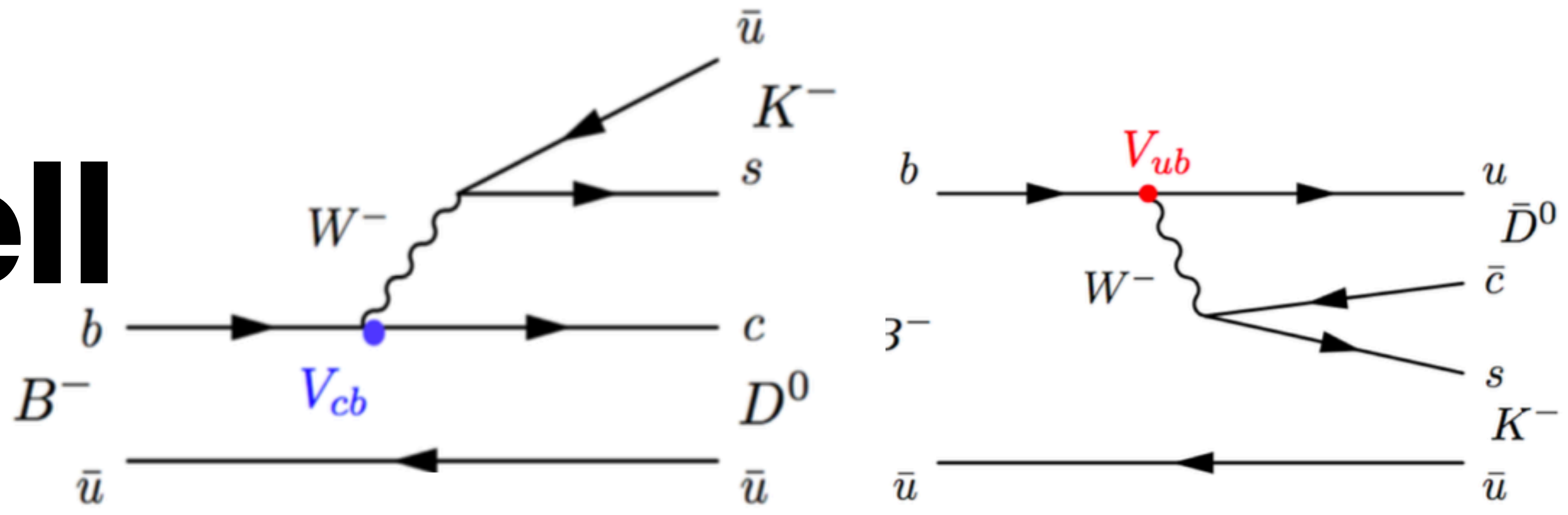






Hadronic B decays

CKM angle ϕ_3@Belle+BelleII



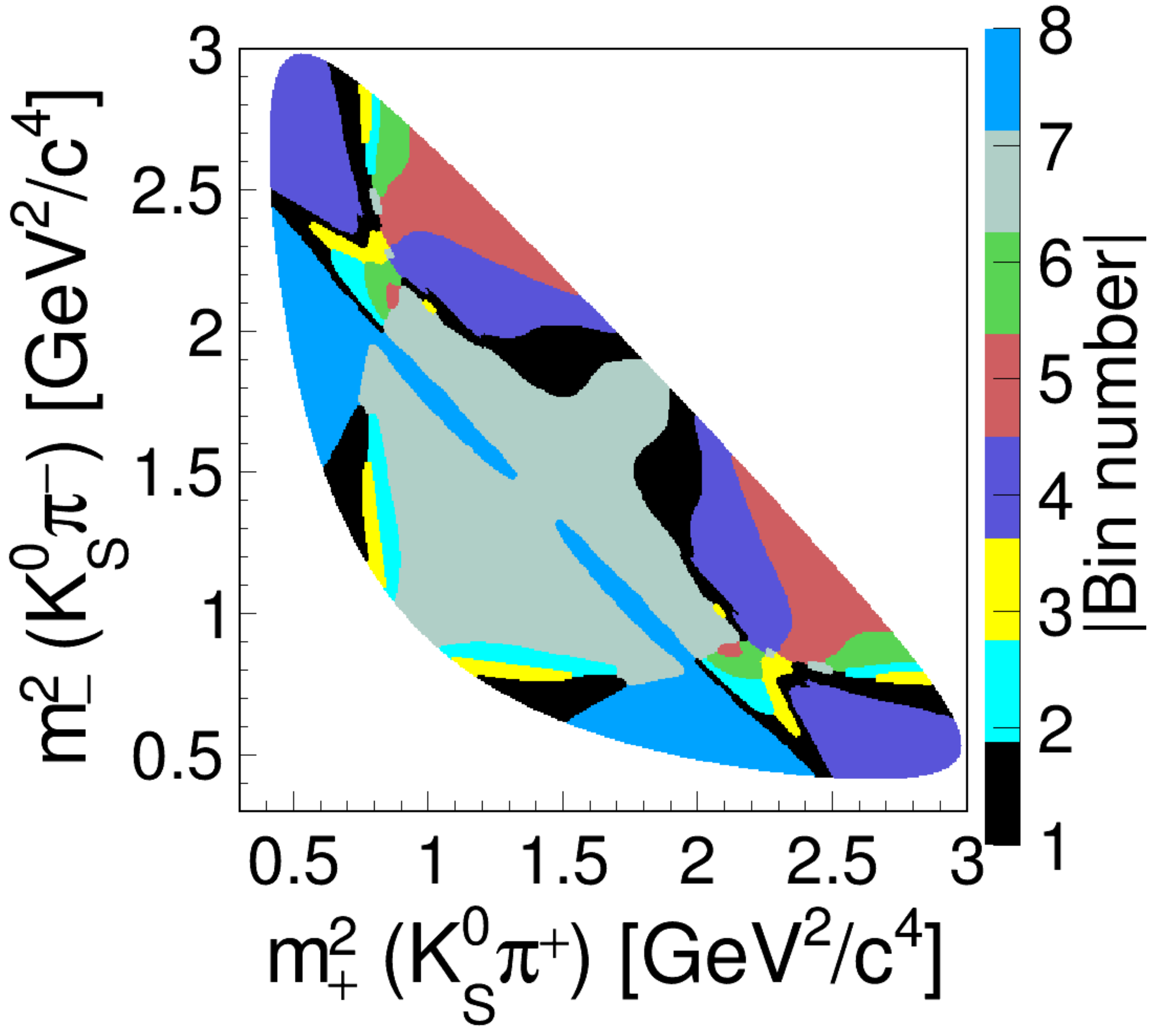
- ϕ_3 measured from interference of b→c$\bar{u}$s (**favored**) and b→u$\bar{c}$s (**suppressed**)
- Tree level process → SM benchmark mode, input for CKM fit. → *current status:* $(66.2^{+3.4}_{-3.6})°$
- **First combined Belle (711 fb^{-1}) and Belle II (128 fb^{-1}) analysis.**

$$\frac{A^{suppr.}[B^- \to \bar{D}^0 K^-]}{A^{favor.}[B^- \to D^0 K^-]} = r_b e^{i(\delta_B - \phi_3)}$$

- "Optimally binned" Dalitz plot analysis of D→Ks h$^+$h$^-$ using BPGGSZ method [PRD 68. 054018 (2003)] :

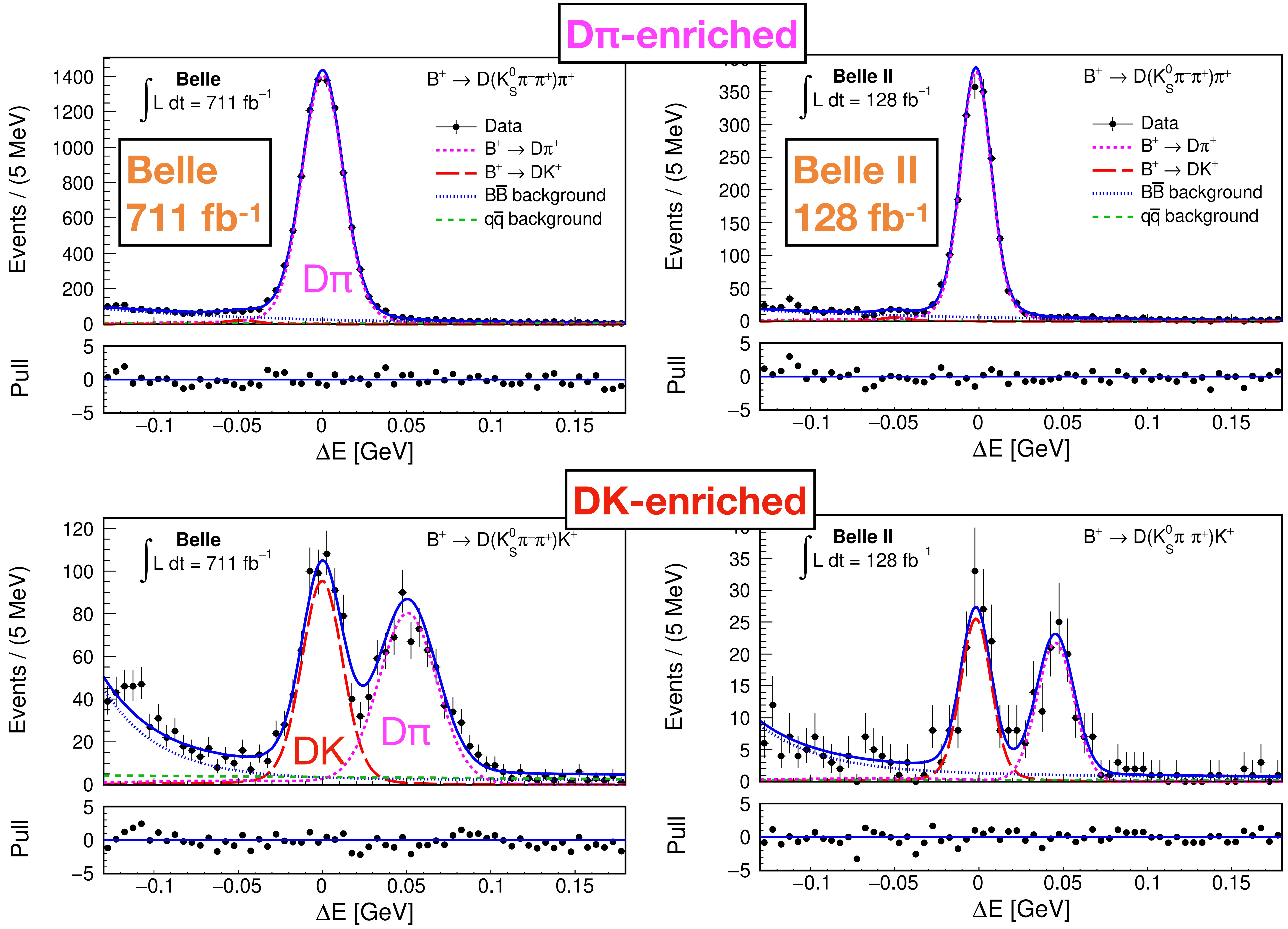
$$N_i^{\pm} = h_B^{\pm}\left[F_i + r_B^2 \bar{F}_i + 2\sqrt{F_i \bar{F}_i}(c_i x_{\pm} + s_i y_{\pm})\right]$$

$$(x_{\pm}, y_{\pm}) = r_b\left(cos(\phi_3 + \delta_B), sin(\phi_3 + \delta_B)\right)$$



- c_i, s_i: D^0-$\bar{D}^0$ strong phase input from BES III/CLEO
- F_i: fraction of decays to i-th bin

CKM angle ϕ_3@Belle+BelleII



- Simultaneous fit of B→Dπ, B→DK to extract K-π efficiencies and misidentification rates from data.

$$\Delta E = \sum_i E_i^* - E_{\text{beam}}^*$$ + BDT output

Belle:

$K_S{}^0\pi\pi$: 1467 ± 53

$K_S{}^0KK$: 194 ± 17

Belle II :

$K_S{}^0\pi\pi$: 280 ± 21

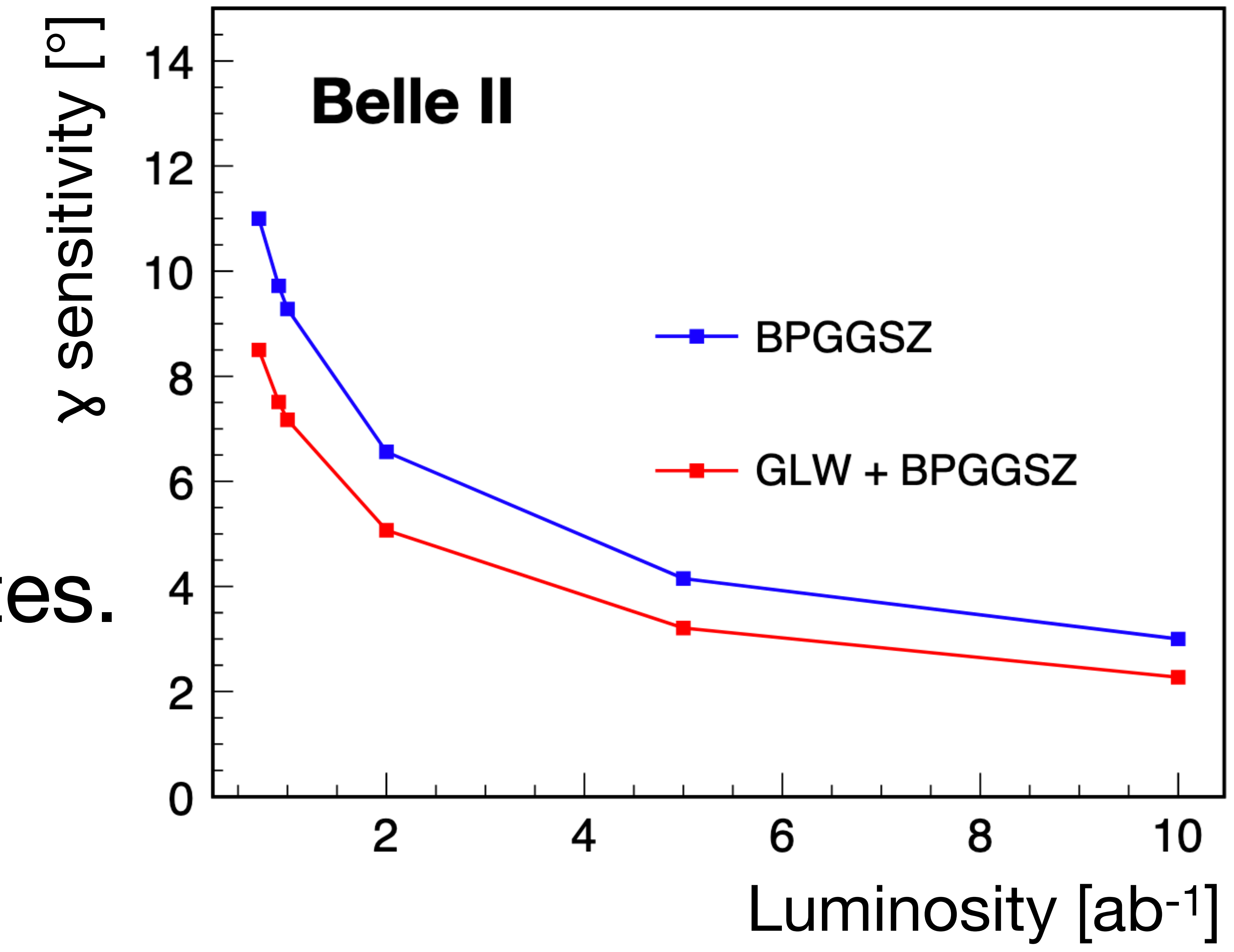
$K_S{}^0KK$: 34 ± 7

CKM angle ϕ_3@Belle+BelleII

- $\delta_B[°]$ = 124.8 ± 12.9 (stat) ± 0.5 (syst) ± 1.7 (ext)
  r_B = 0.129 ± 0.024 (stat) ± 0.001 (syst) ± 0.002 (ext)
  $\phi_3[°]$ = 78.4 ± 11.4 (stat) ± 0.5 (syst) ± 1.0 (ext)

JHEP 02, 063 (2022)

- Previous Belle (711 fb^{-1}) result: $\phi_3[°] = 77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3$ [Phys. Rev. D 85, 112014 (2012)]
- **Better** K_S selection, bkg suppression, analysis strategy.
- **Improved systematics** from BES III external input.
- Total improvements w.r.t. previous Belle result equivalent to **doubling statistics.**
- Expect <3° uncert. at 10 ab^{-1} by including more D final states.
- Measurement is still statistically dominated.



NEW @Moriond

$B \to K_S \pi^0$ @Belle II

- Rare decays, model independent test of new physics.
- Null sum in SM from isospin rule:

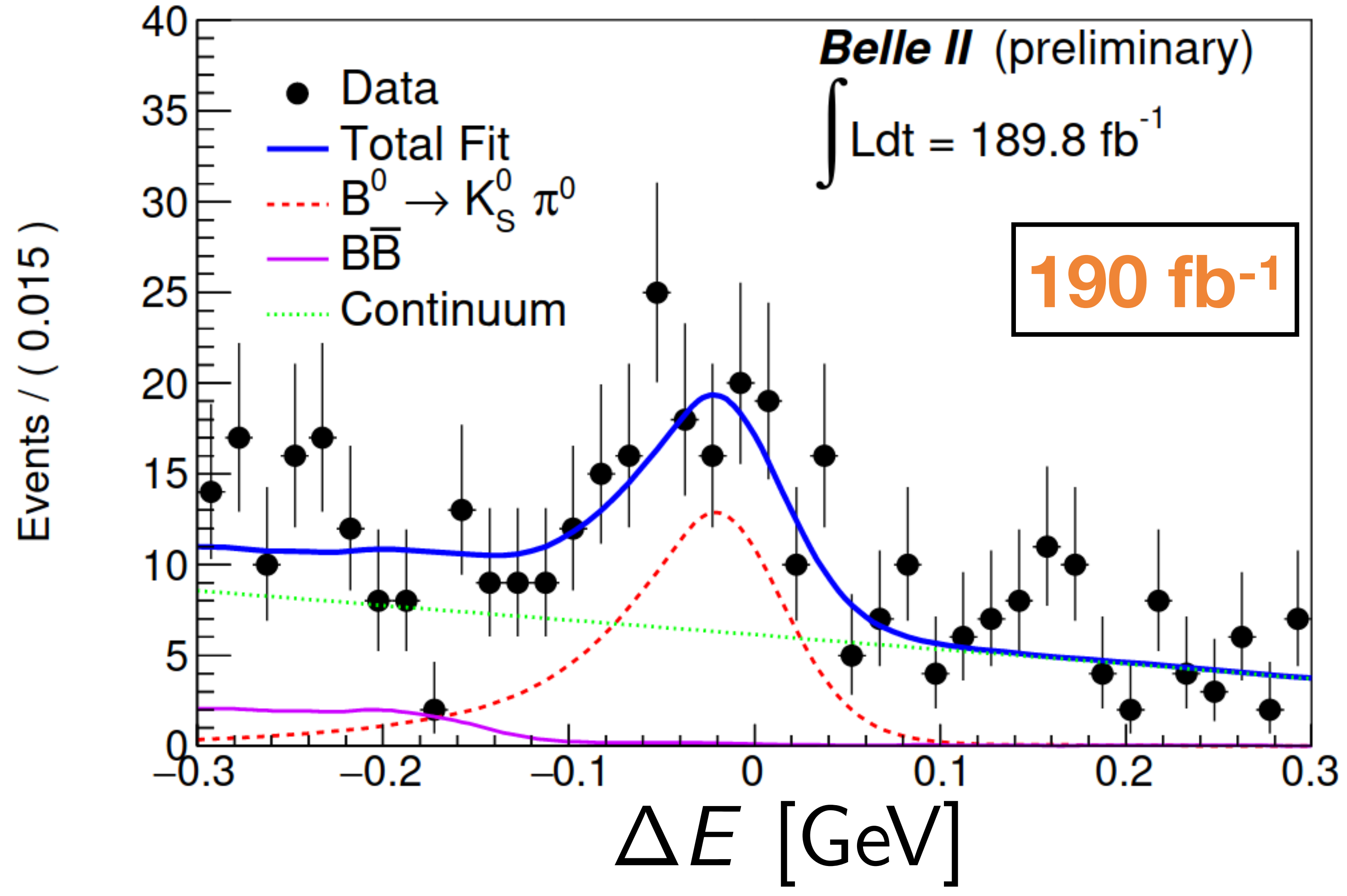
dominant uncertainty

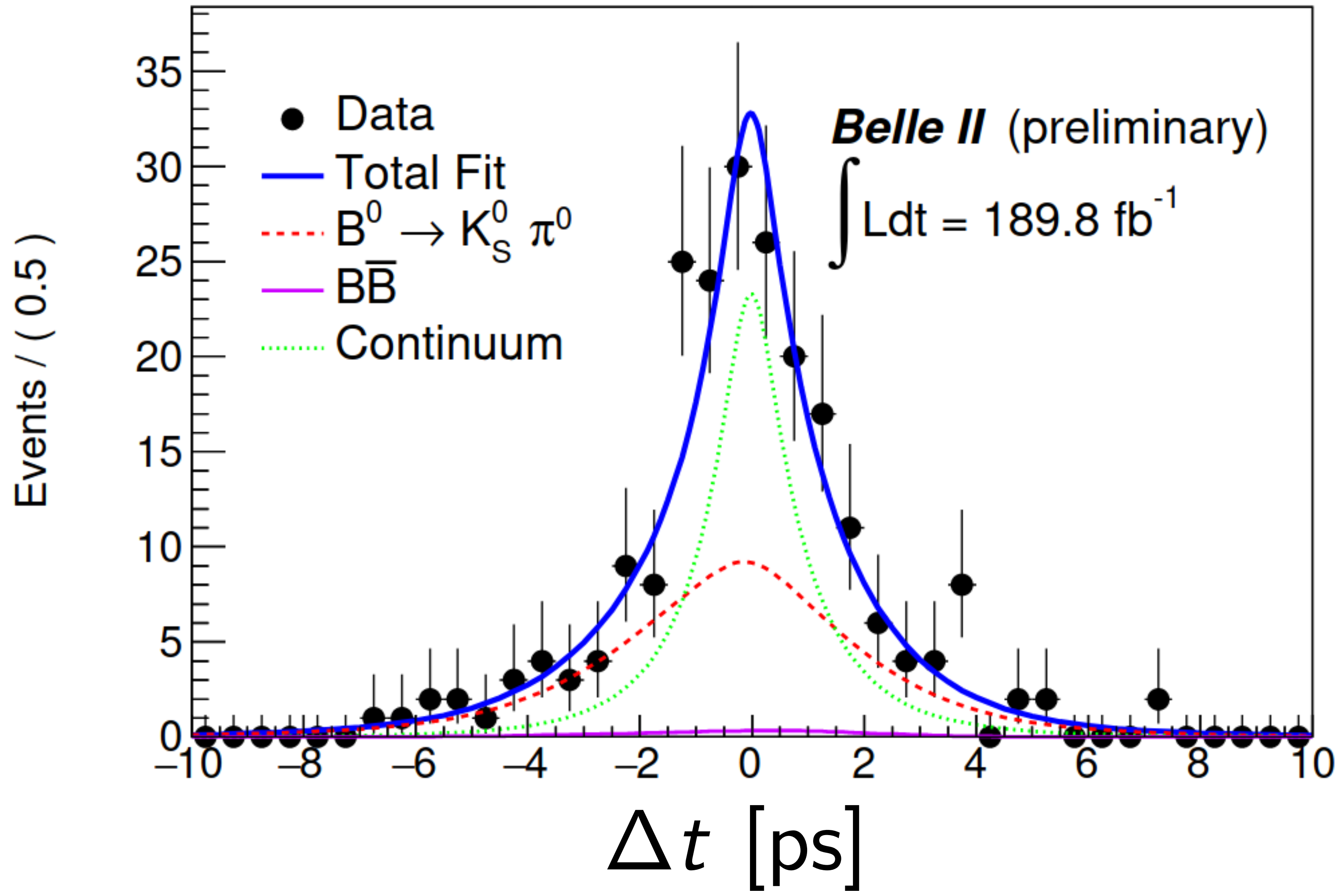
$$2A_{CP}(B^0 \to K^+\pi^-) + 1.3A_{CP}(B^+ \to K_S\pi^+) - 1.2A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K_S\pi^0) \approx 0$$

- Challenge: need good neutral reconstruction, precise beam spot knowledge to reconstruct Ks decay
  → **unique to B-Factories.**
- 4D unbinned maximum likelihood fit in ΔE, Δt, M_{bc}, BDT out

$$A_{CP} = -0.41^{+0.30}_{-0.32}\,(\text{stat.}) \pm 0.09\,(\text{syst.})$$
$$\mathcal{B} = (11.0 \pm 1.2\,(\text{stat.}) \pm 1.0\,(\text{syst.})) \times 10^{-6}$$

World average: $A_{CP} = 0.00 \pm 0.13.$

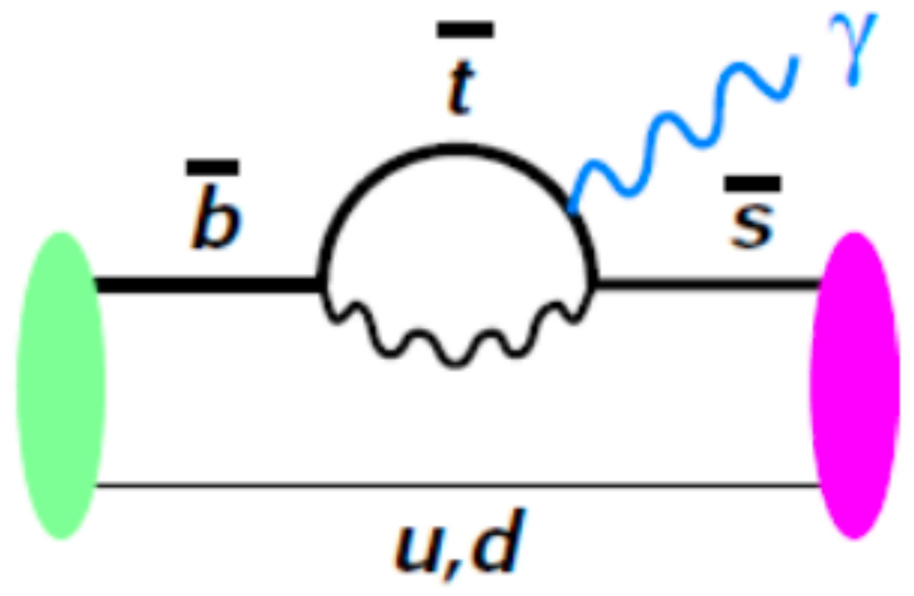




$$m_{bc} = c^{-2}\sqrt{E^{*2}_{\text{beam}} - \left|\sum_i \vec{\mathbf{p}}^*_i\right|^2 c^2},$$

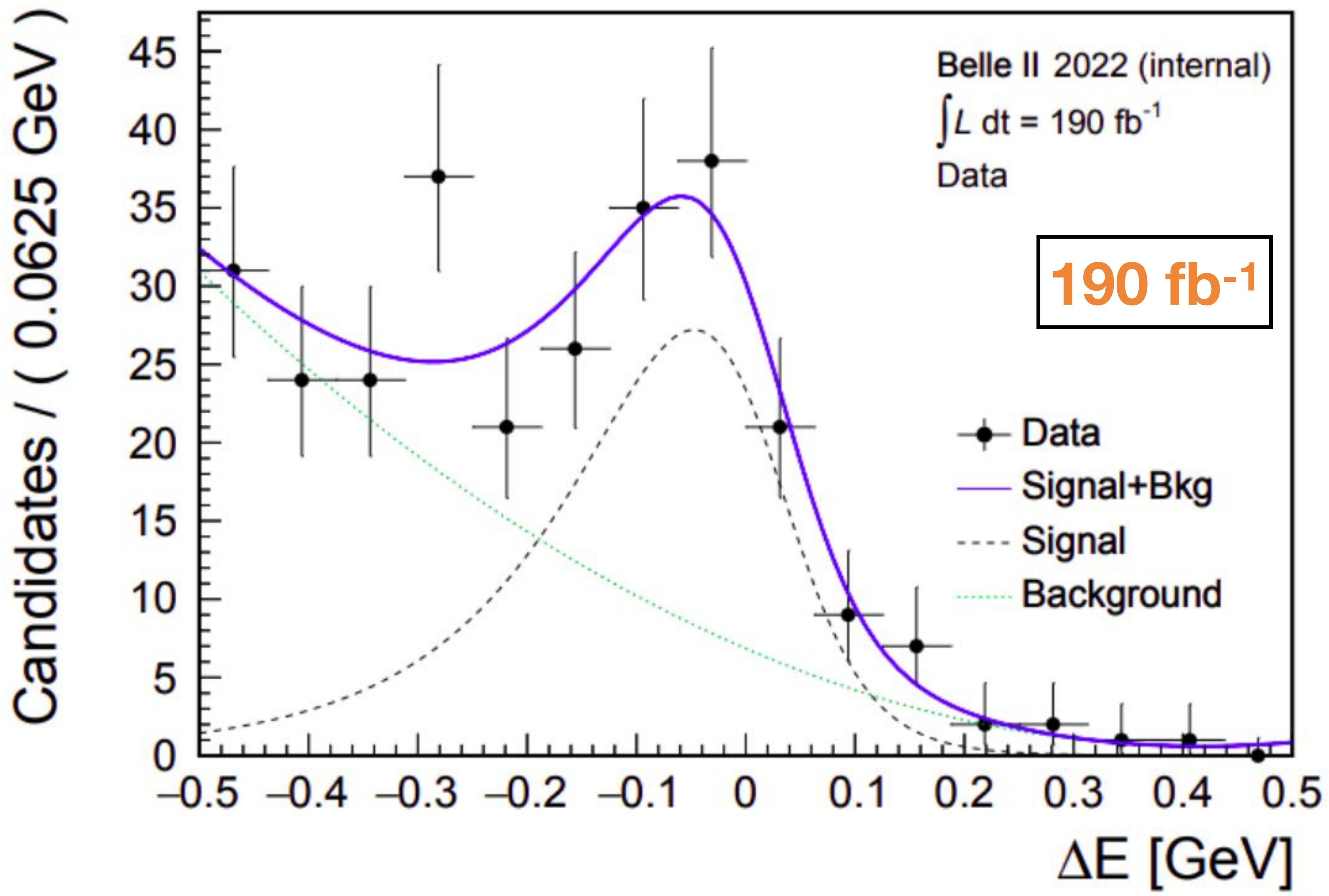
Branching Fraction of $B^0 \to K_S \pi^0 \gamma$ @Belle II

- $b \to s\gamma$ is only possible at loop level in SM.
- **Flavor-specific** polarization: $B^0 \to K_S \pi^0 \gamma$(RH) and $\bar{B}^0 \to K_S \pi^0 \gamma$(LH)
  - we do not expect time-dependent asymmetry in SM
  - possible in NP with different chiral structure
- **$B^0 \to K_S \pi^0 \gamma$ is only measurable at B-Factories**
- In preparation of a time-dependent analysis, we measure the BF:



$$\mathcal{B} = (7.3 \pm 1.8\ (\text{stat.}) \pm 1.0\ \text{syst}) \times 10^{-6}$$

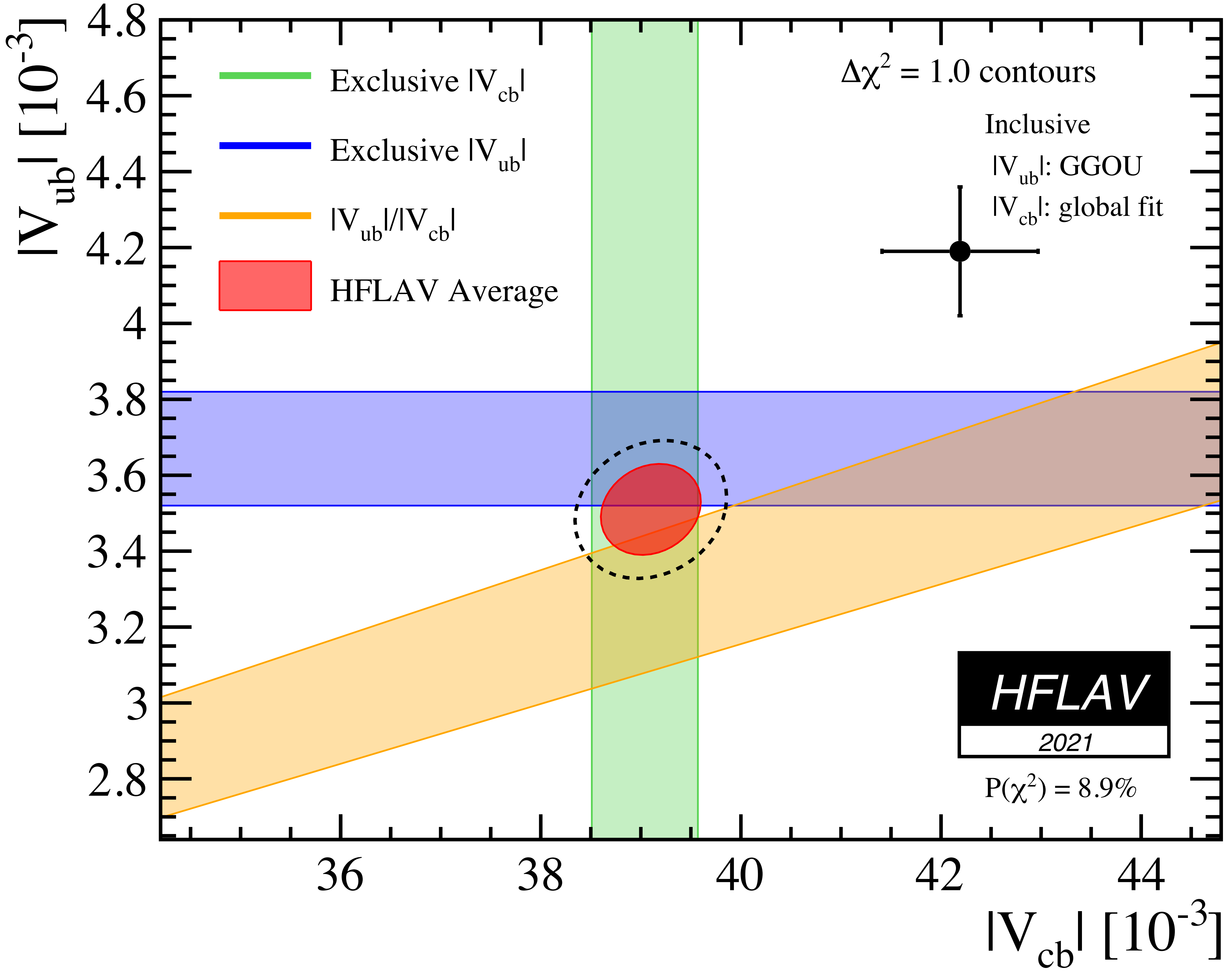
Compatible with world average
$\mathcal{B} = (7.0 \pm 0.4) \times 10^{-6}$

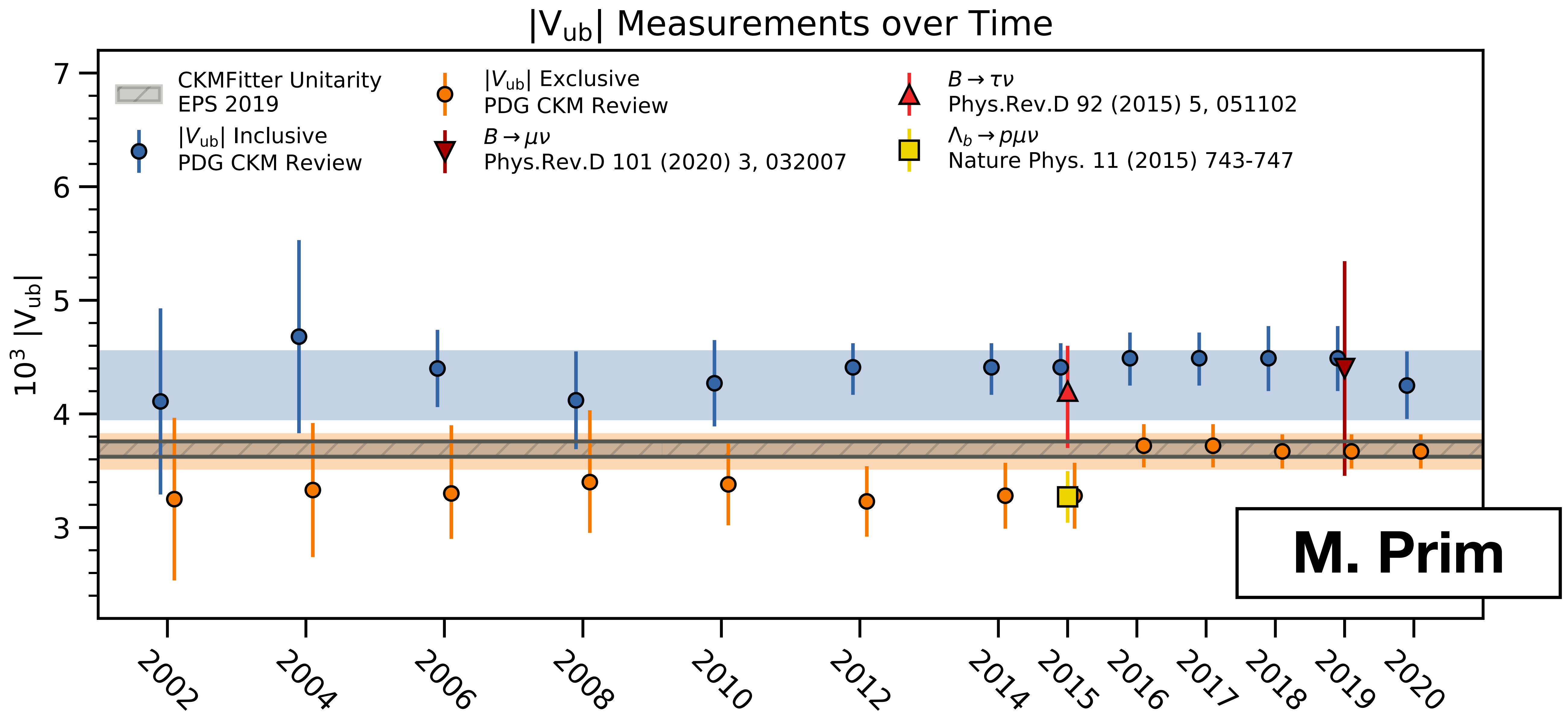


$|V_{ub}|$ and $|V_{cb}|$

|Vub| and |Vcb| Puzzles

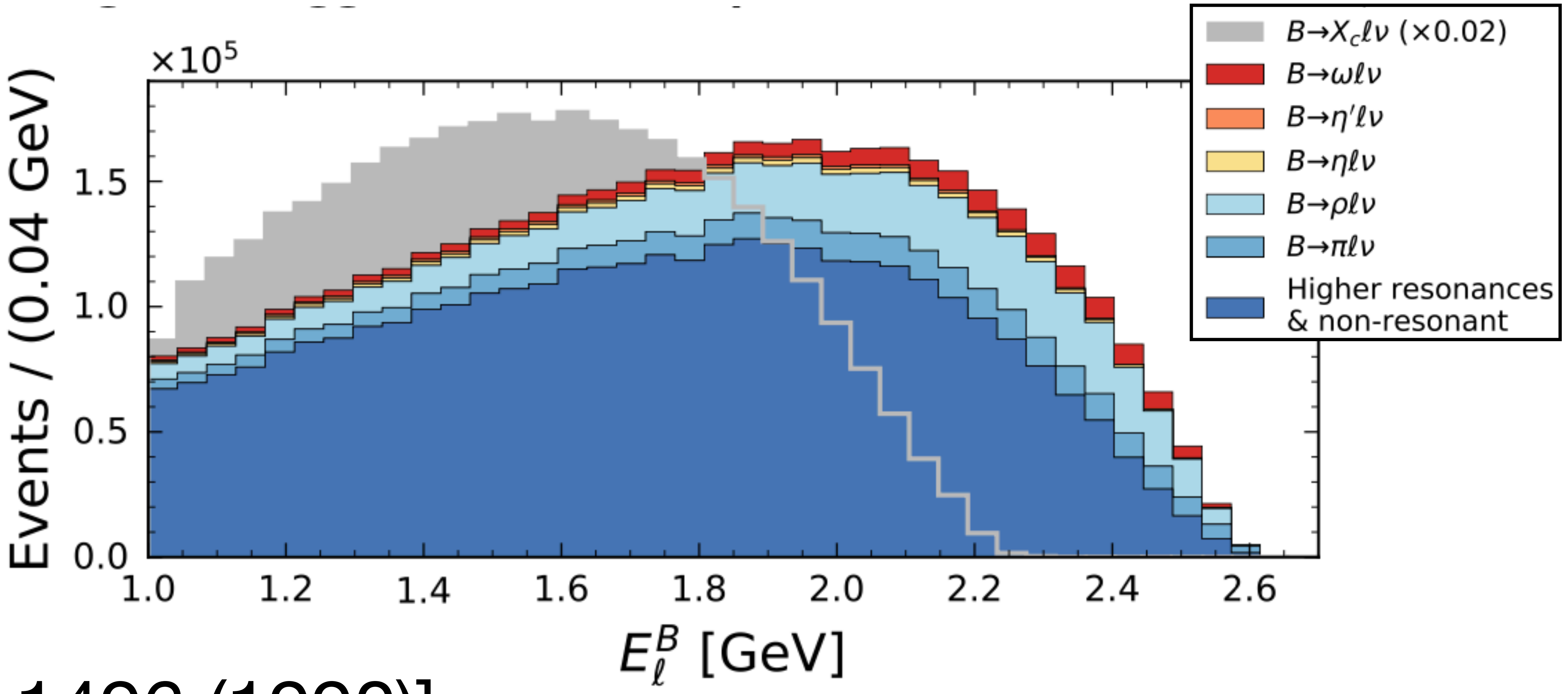
- Longstanding tension (~3σ) between inclusive and exclusive measurements
- Crucial input for SM rare decay BF, limits power of CKM unitarity tests





Partial B.F. of $B \to X_u \ell \nu$ @ Belle

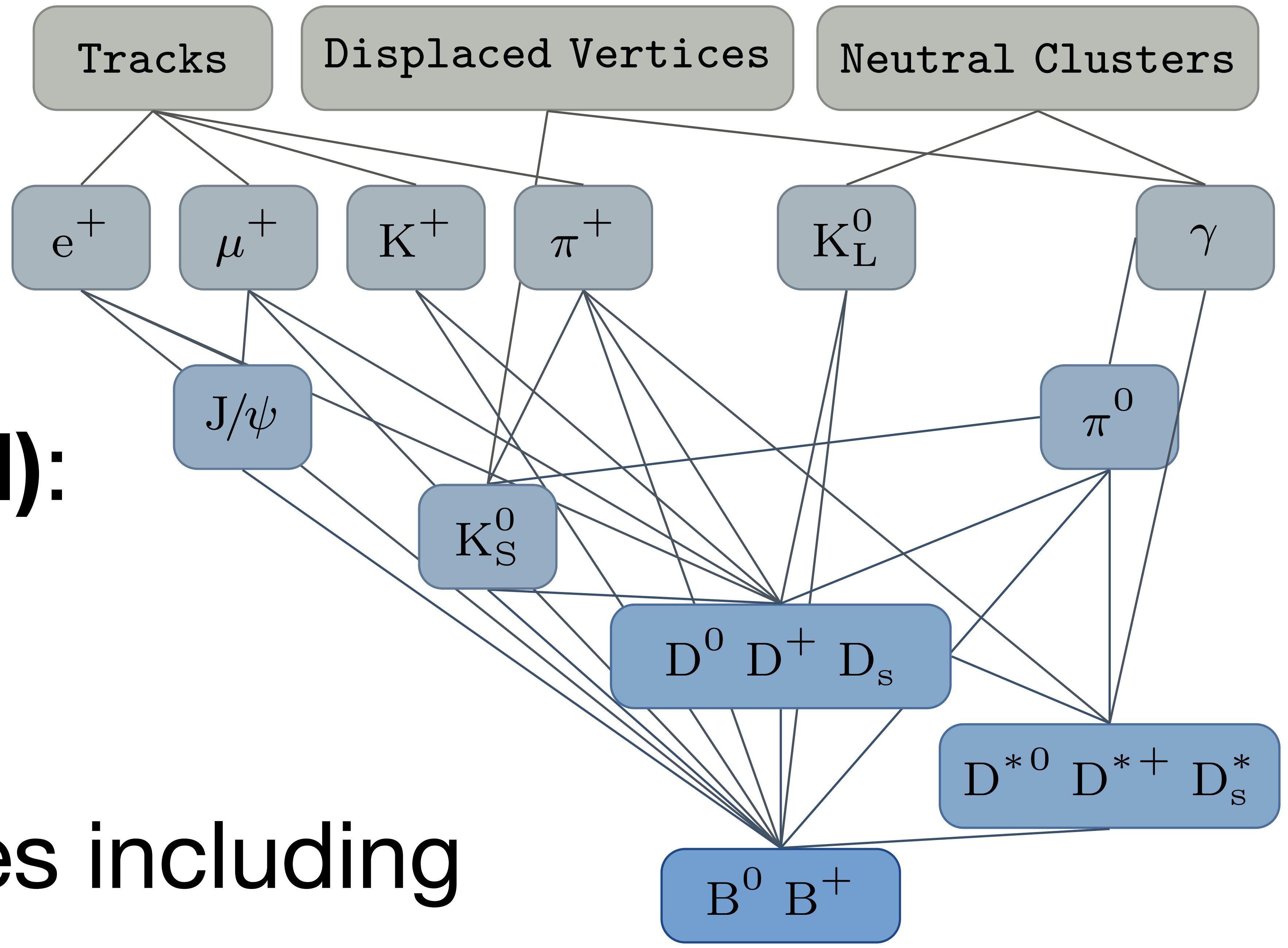
- Extremely challenging due to dominant $B \to X_c \ell \nu$ background (~50x $B \to X_u \ell \nu$)
- Clean sample at lepton endpoint
  ... but large theoretical errors to $|V_{ub}|$
- Extend as much as possible into the $B \to X_u \ell \nu$ dominated region
- Improve modeling of b→u and b→c
  - Hybrid MC model [Phys. Rev. D 41, 1496 (1990)]
  - **Recent idea** shown by Belle: Data-driven modeling of $B \to X_c \ell \nu$.
    Derive b→c template in X_c-enriched sample, use for fit of X_c-depleted sample.



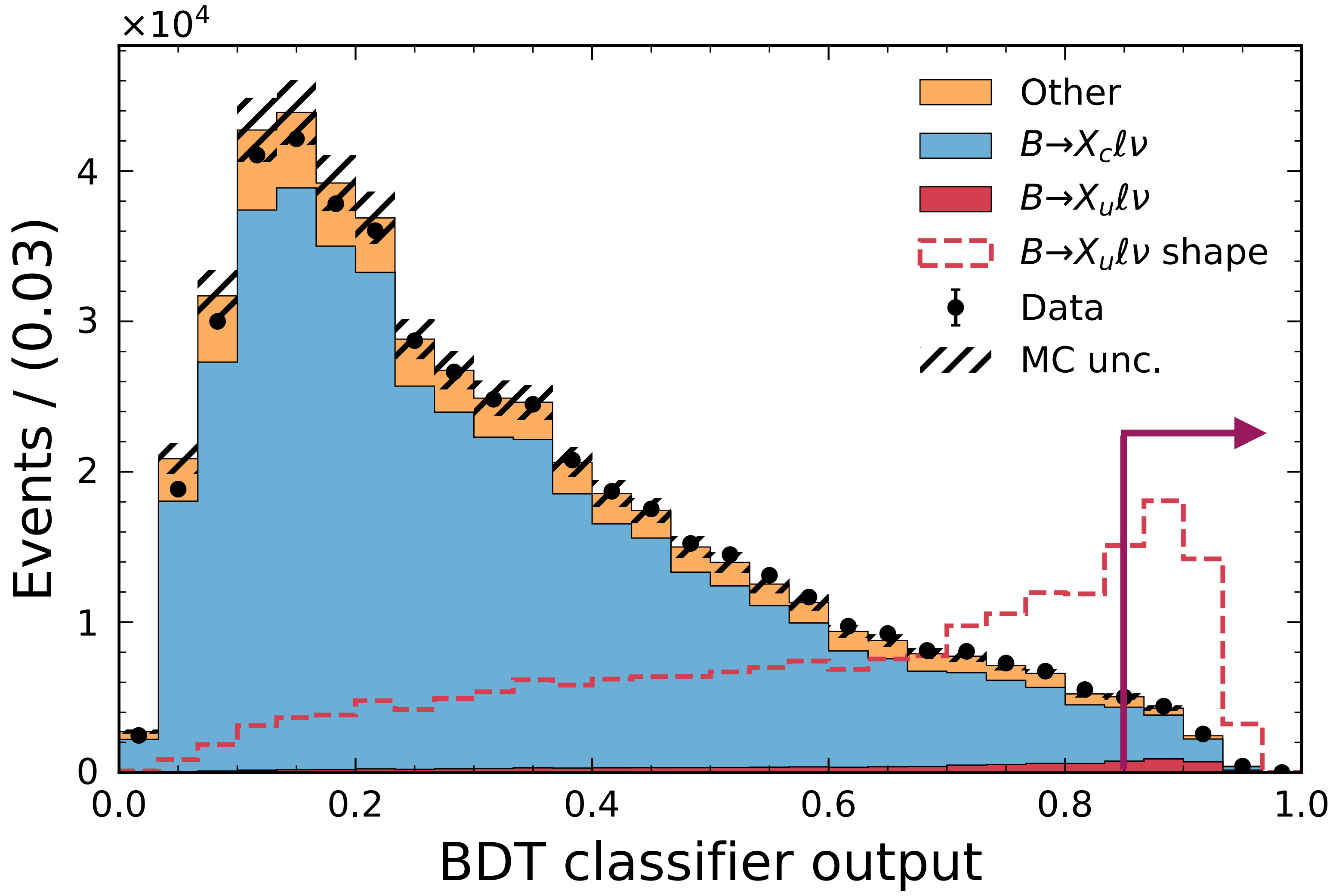
Not covered here - see M. Hohmann's talk @Barolo2022

PRD 104, 012008 (2021)

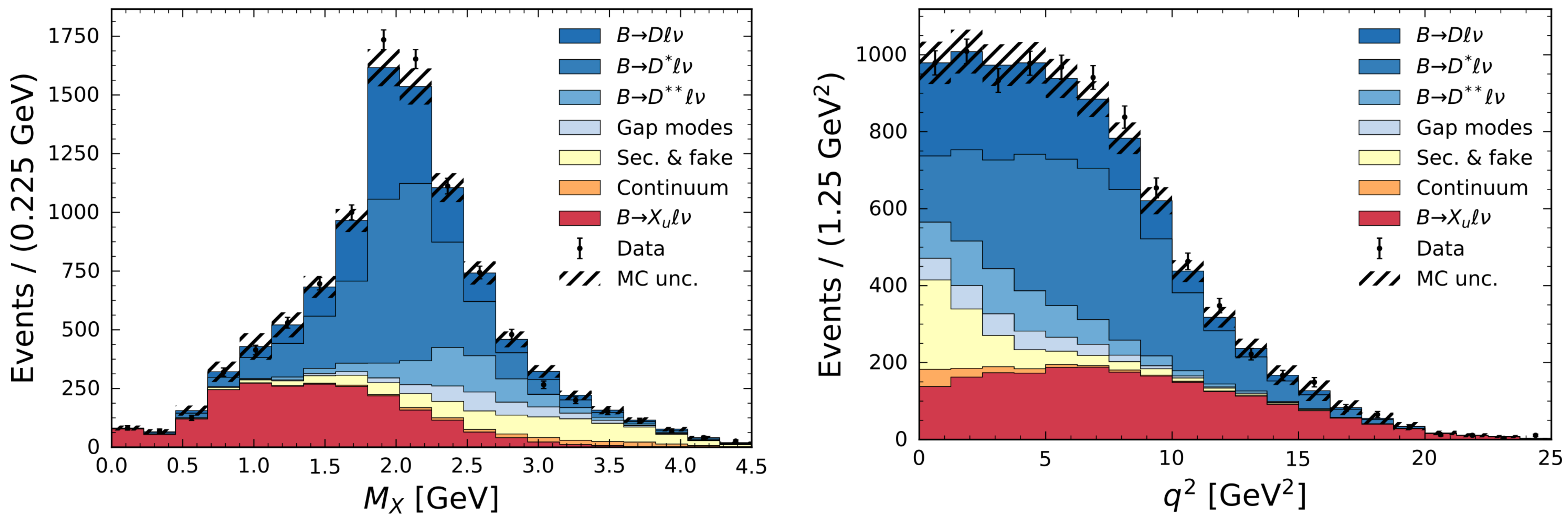
Analysis Strategy



- Hadronic tag with **Full Event Interpretation (FEI)**: Exclusive B-tagging with increased efficiency (0.5 (0.3)% for $B^+(B^0)$) using BDT.
- Use second BDT classifier trained on 11 variables including M_{miss}^2, #K, #Ks,... to suppress b→c background.



Signal and background after BDT cut



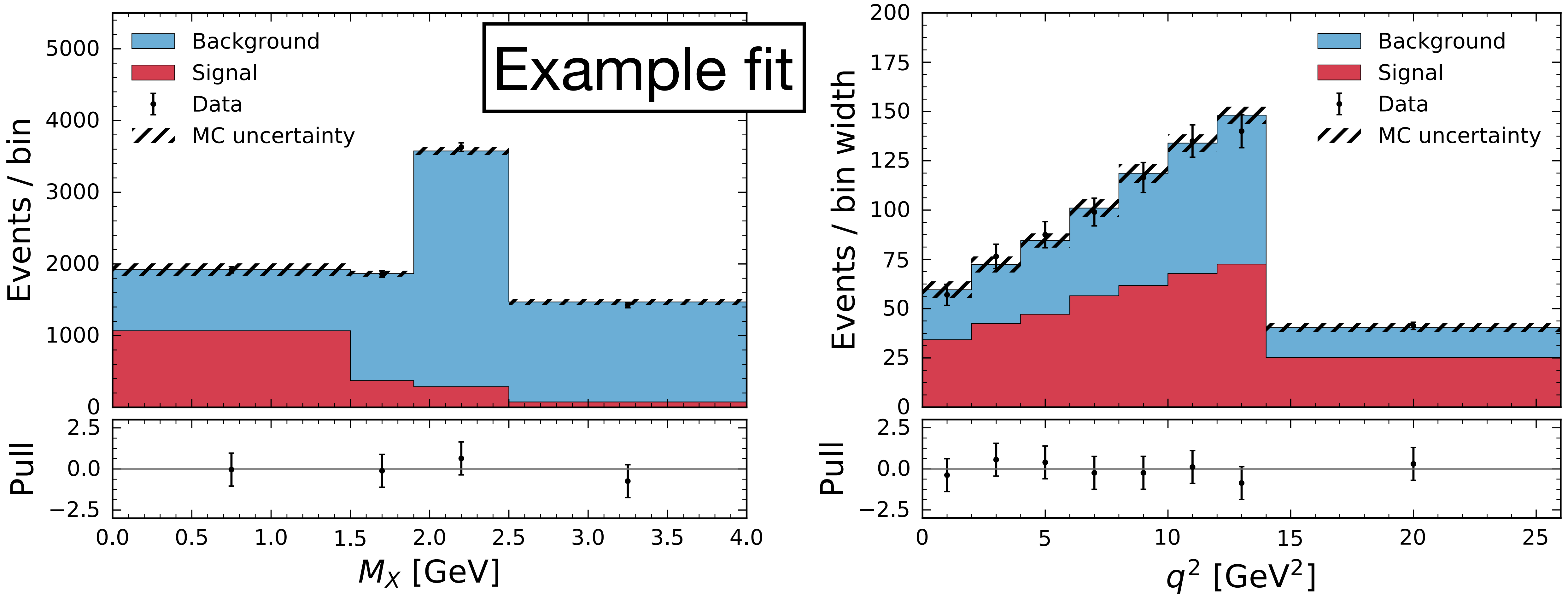
Results

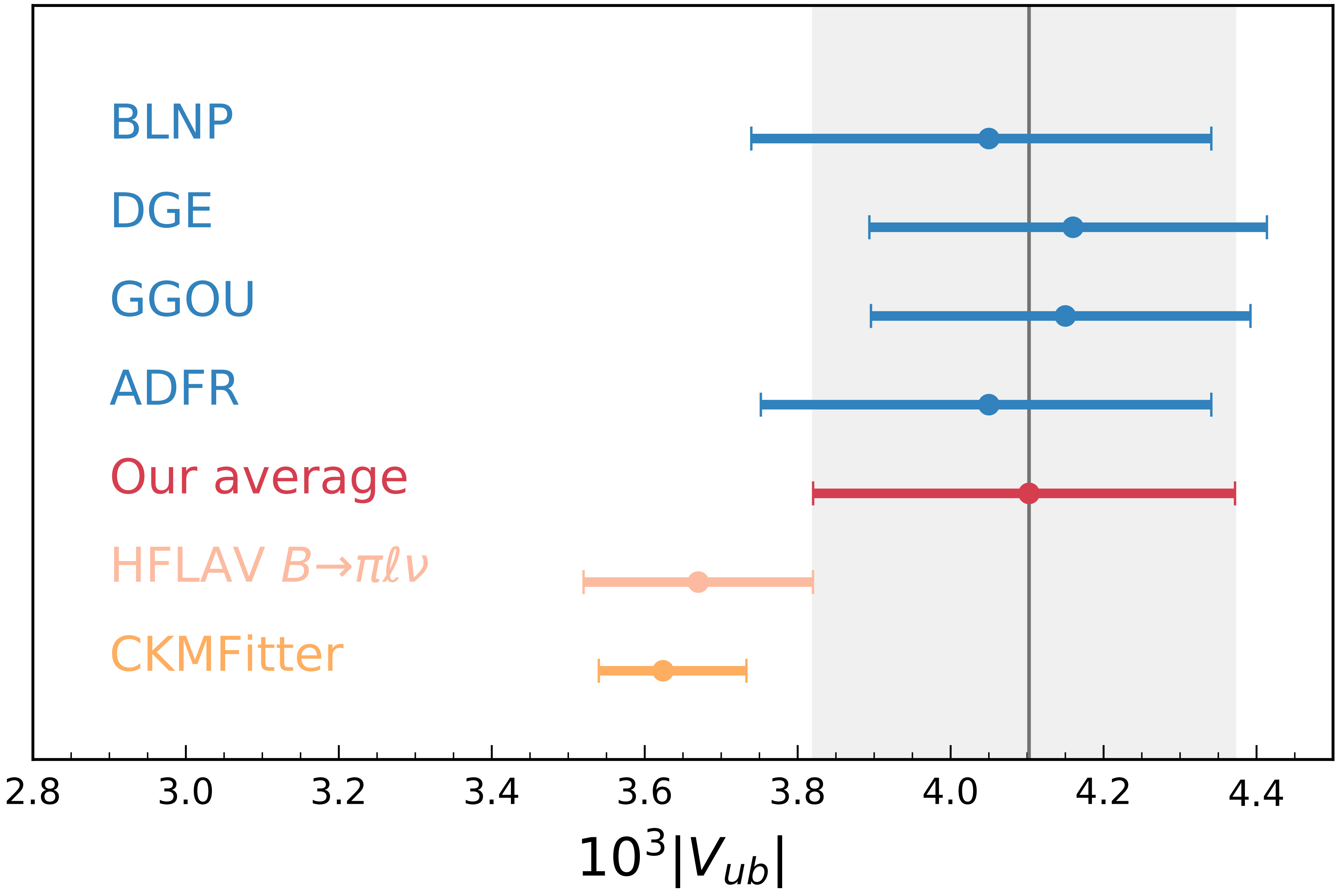
PRD 104, 012008 (2021)

- 2D fit on (M_X, q^2) with $E_\ell > 1.0\ GeV$
- **ΔB(B→X$_u$ℓν) =(1.59±0.07±0.17)x10^{-3}**
- Using theory predictions we calculate

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u\, \ell^+\, \nu_\ell)}{\tau_B \cdot \Delta\Gamma(B \to X_u\, \ell^+\, \nu_\ell)}}$$

- **$|V_{ub}|$ = (4.10 ± 0.09 ± 0.22 ± 0.15) × 10^{-3}**
- Consistent with other inclusive determinations.

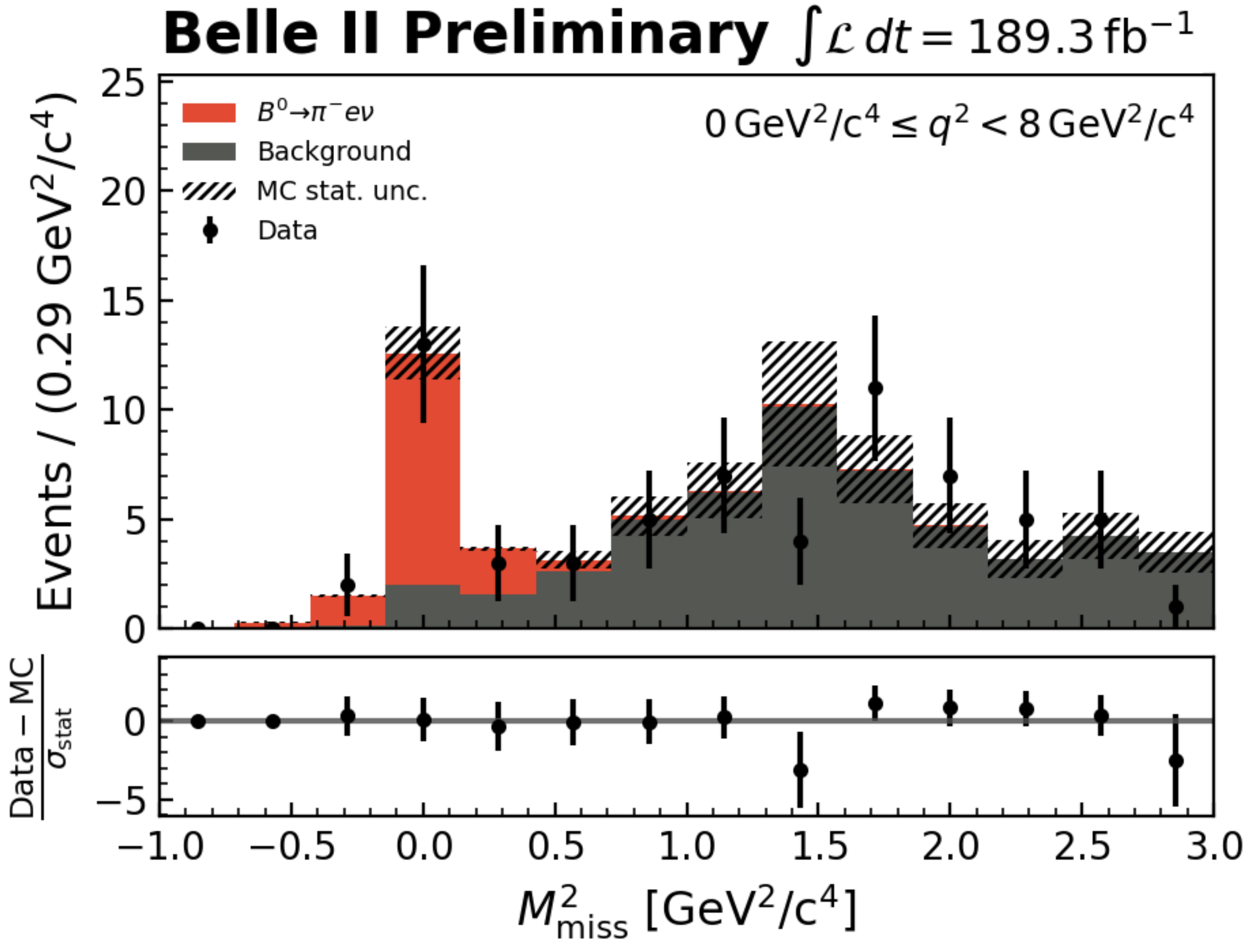


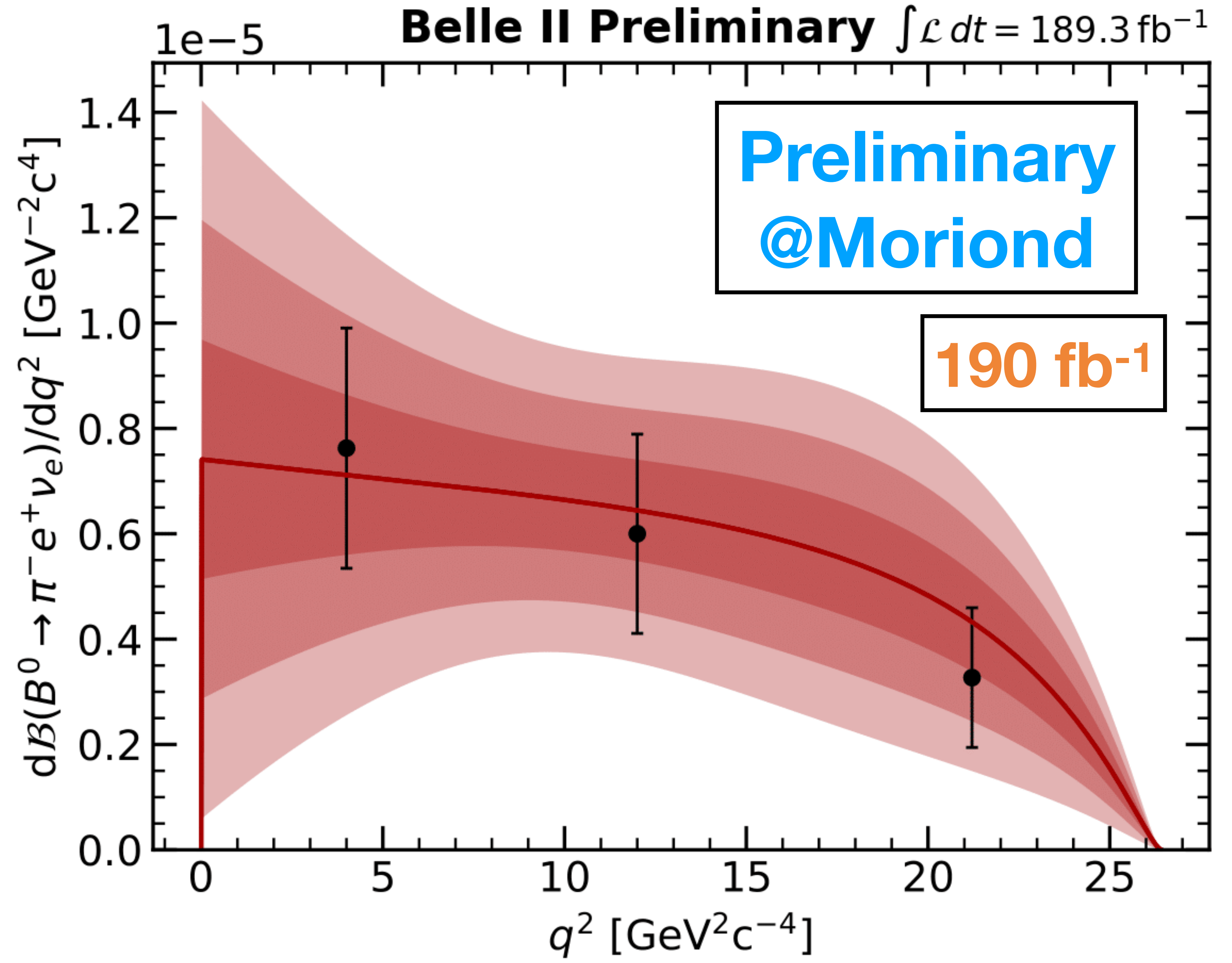


Meanwhile at Belle II…

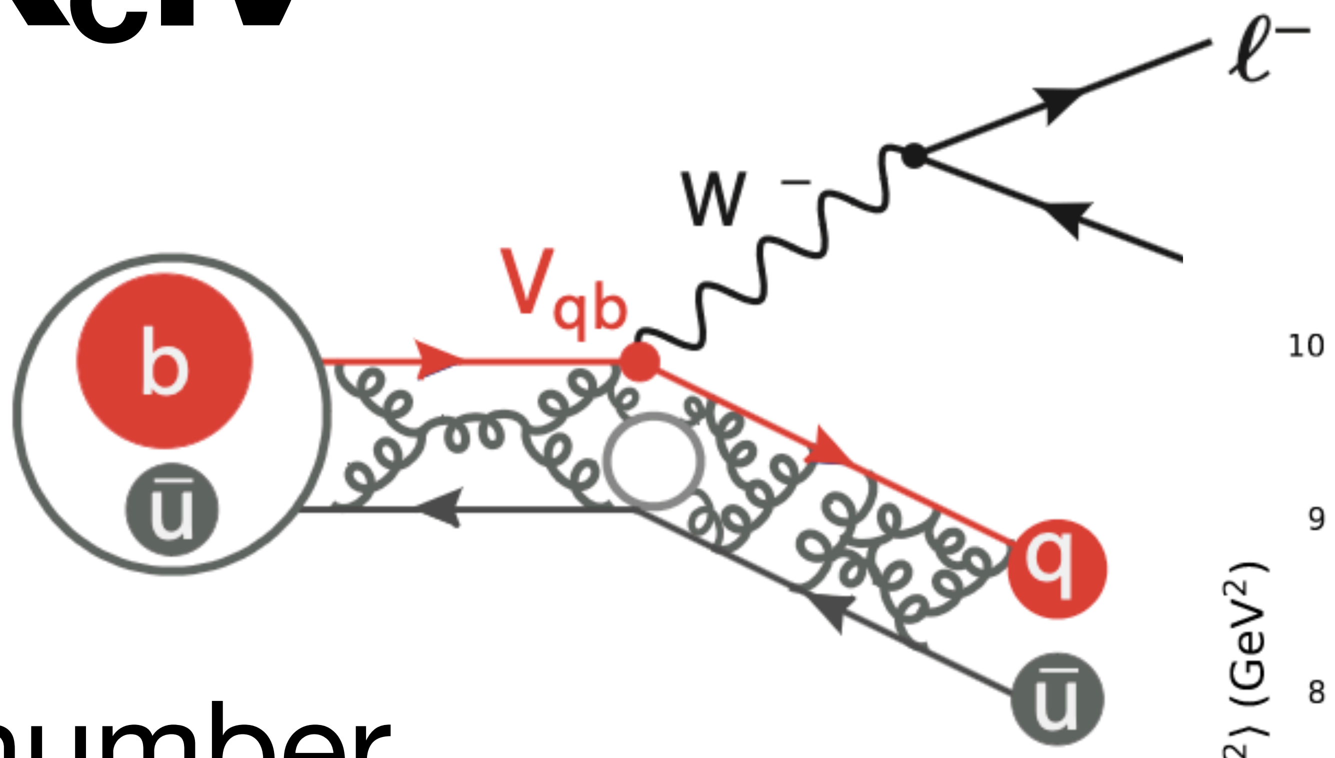
|Vub| from B→πeν @ Belle II

- Reconstruct **$B^0 \to \pi^- e^+ \nu$** and **$B^+ \to \pi^0 e^+ \nu$** with FEI hadronic tag.
- Fit missing mass in three $q^2 = (p_e + p_\nu)^2$ bins.
- **$\mathcal{B}(B^0 \to \pi^- e^+ \nu) = (1.43 \pm 0.27 \pm 0.07) \times 10^{-4}$**
  $\mathcal{B}(B^+ \to \pi^0 e^+ \nu) = (8.33 \pm 1.67 \pm 0.55) \times 10^{-5}$
- Fit $\mathrm{d}\mathcal{B}/\mathrm{d}q^2 \propto |V_{ub}|^2 f_+^2(q^2)$ using lattice QCD input (Fermilab/MILC) [arXiv:1503.07839]
- Combined fit: $|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$
- Consistent with PDG but still limited by statistics.

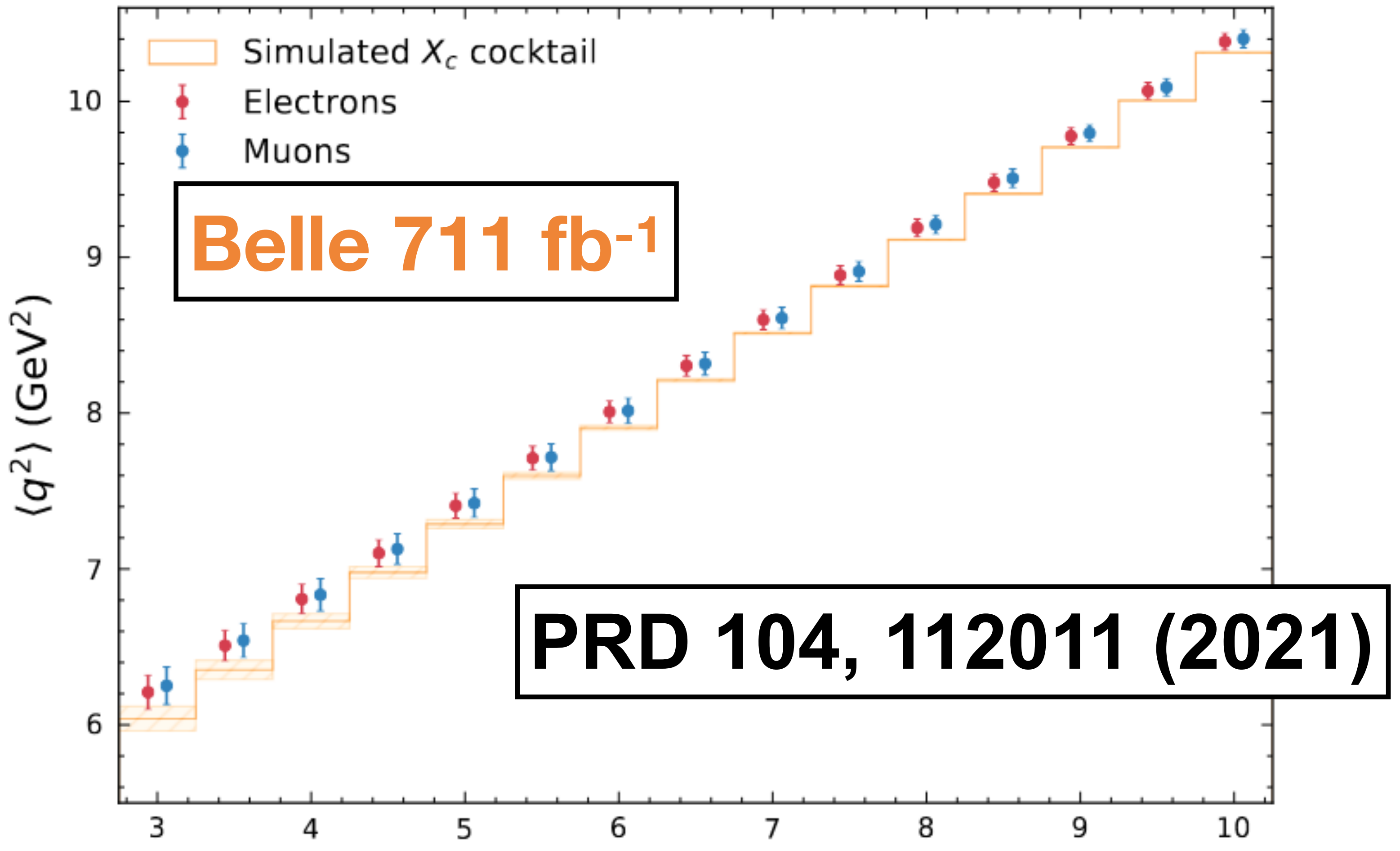


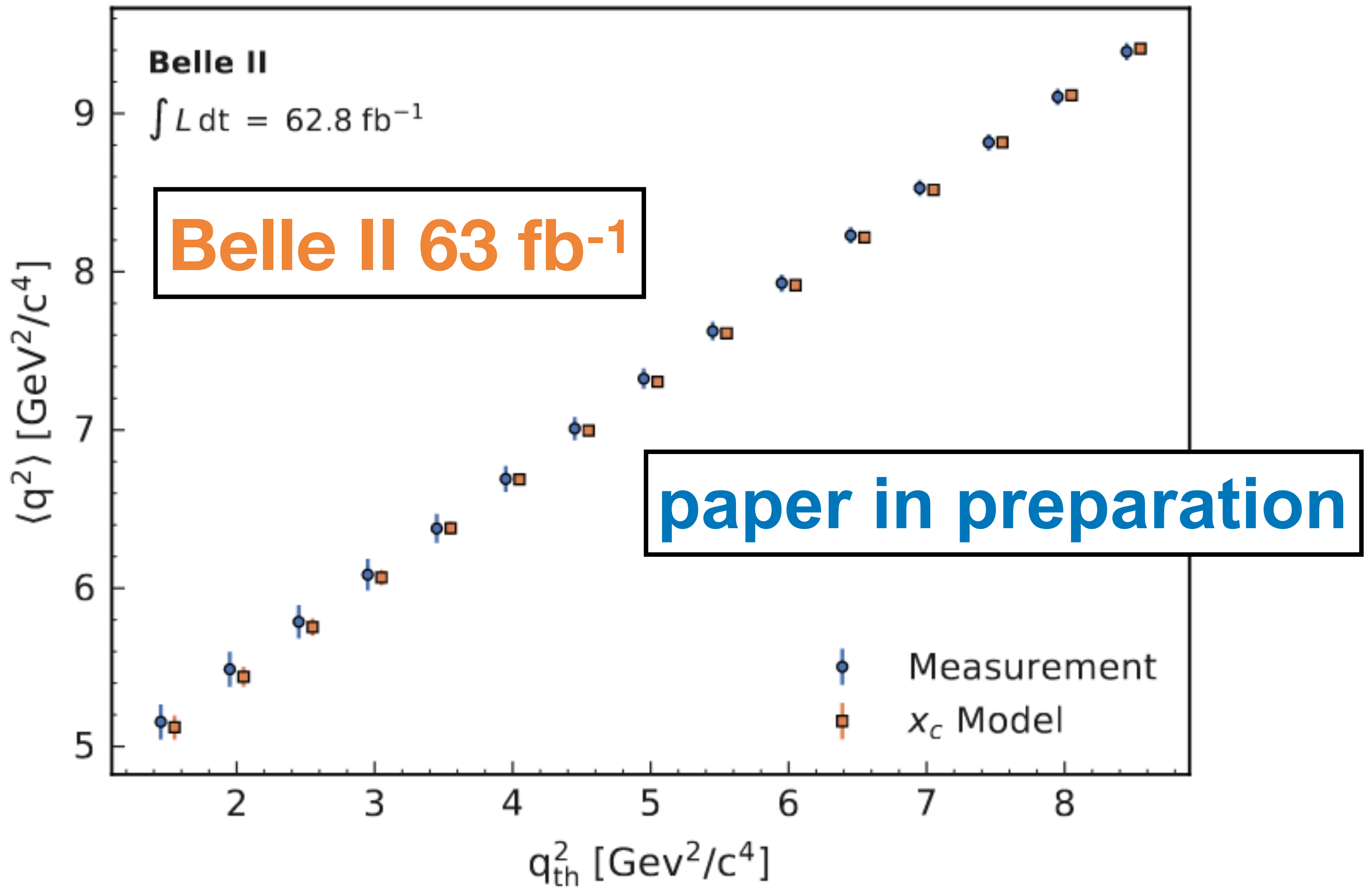


q^2 moments of $B \to X_c l \nu$



- Inclusive $|V_{cb}|$ measurement relies on Heavy Quark Expansion (HQE)
- Non perturbative matrix elements, number increases if one increases expansion in $(1/m_b)$
- Recent idea [JHEP 02 (2019) 177] to reparametrise:
  - Reduce number of M.E. for q^2, 13→8 at $O(1/m_b^4)$
  - Measured at both Belle (recent) and Belle II (new!) for $< (q^2)^n >$, n=1-4, using hadronic tag.
- **$|V_{cb}|$ global fits with this input in the near future.**





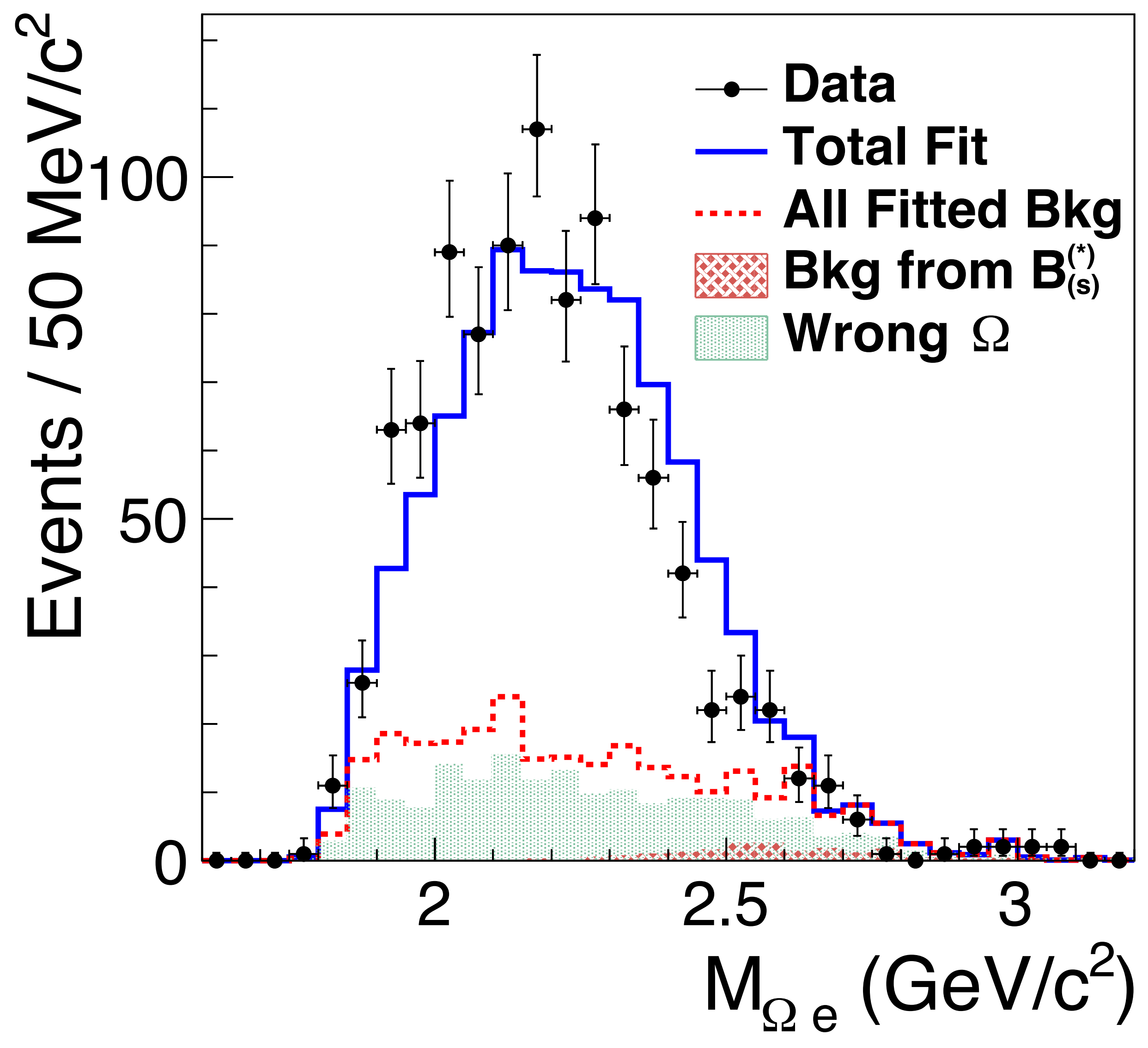
LFU/LFV

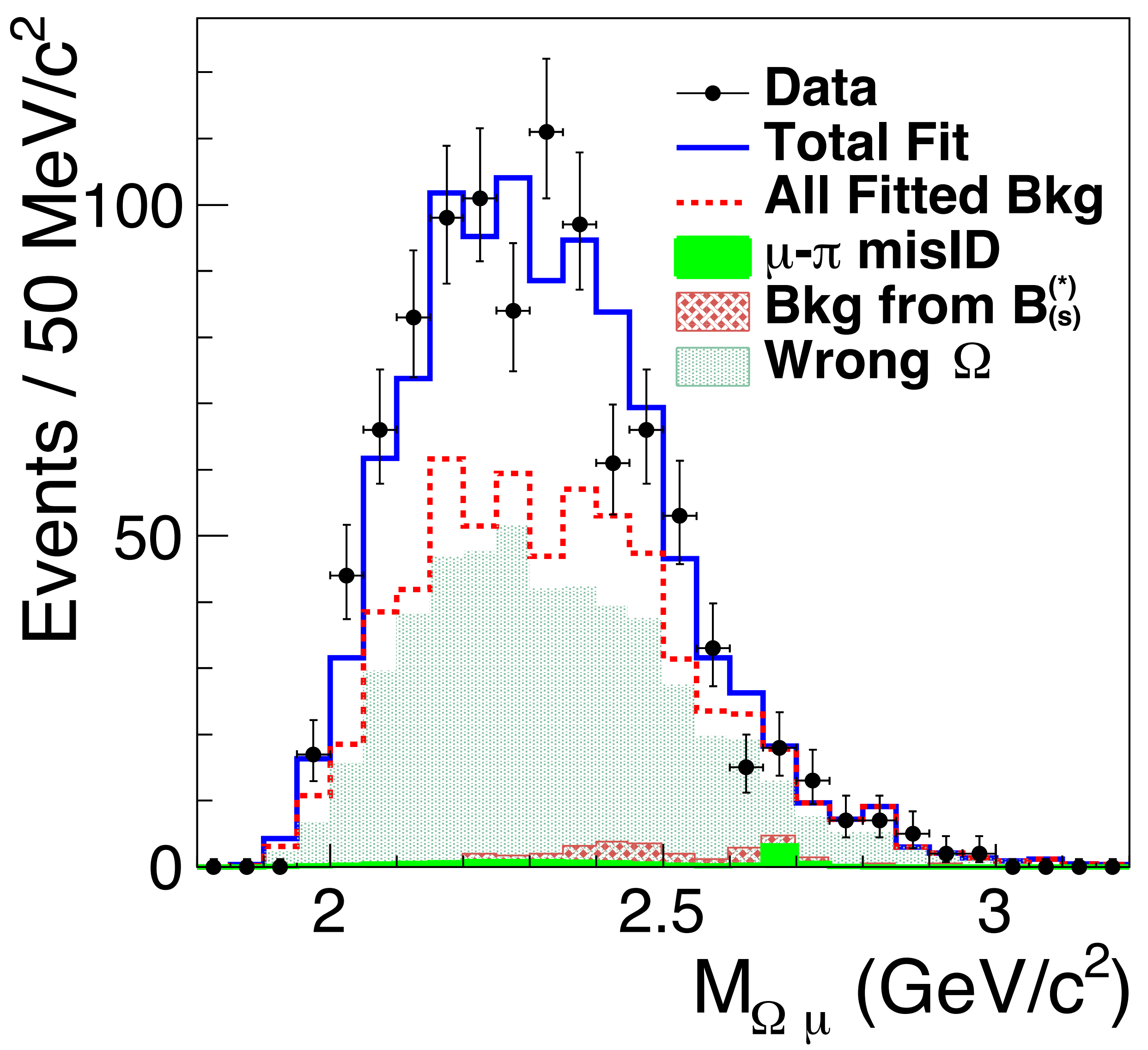
LFU Ratio in $\Omega_c^0 \to \Omega^- \ell^+ \nu_\ell$ @Belle

Phys. Rev. D 105, L091101 (2022)

- EW coupling of gauge bosons flavour-independent in SM.
- LFU tensions in e.g. $R(D^{(*)}) = \frac{BF(B \to D^{(*)}\tau\nu_\tau)}{BF(B \to D^{(*)}\ell\nu_\ell)}$ (~3.1σ WA).
- **NEW: First probe of LFU in Ω_c.**
- Full Belle data set of 89.5 fb^{-1}, 711 fb^{-1} and 121.1 fb^{-1} . (10.52, 10.58 and 10.86 GeV)
- Measured $\frac{BF(\Omega_c^0 \to \Omega^- e^+ \nu_e)}{BF(\Omega_c^0 \to \Omega^- \mu^+ \nu_\mu)}$ = 1.02 ± 0.10 ± 0.02
- **Consistent with LFU.**

Reference mode: $\Omega_c^0 \to \Omega^- \pi^+$

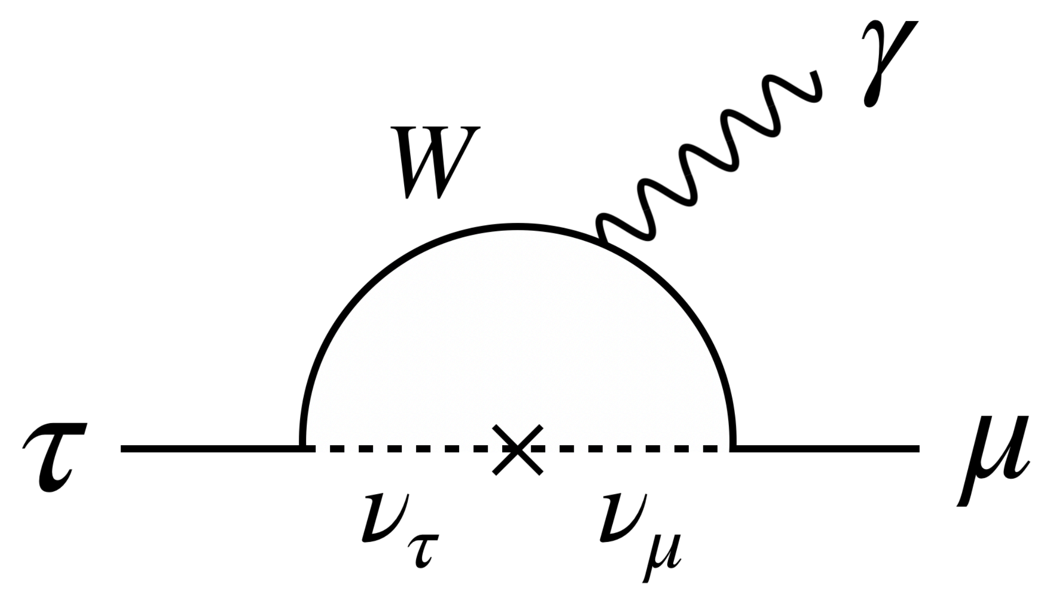




LFV in τ→ℓγ

- Within the SM lepton flavour and total lepton numbers are conserved.
- Lepton flavour violation observed the neutral sector (**ν** oscillation).
- Charged LFV can occur in SM through loops, e.g.

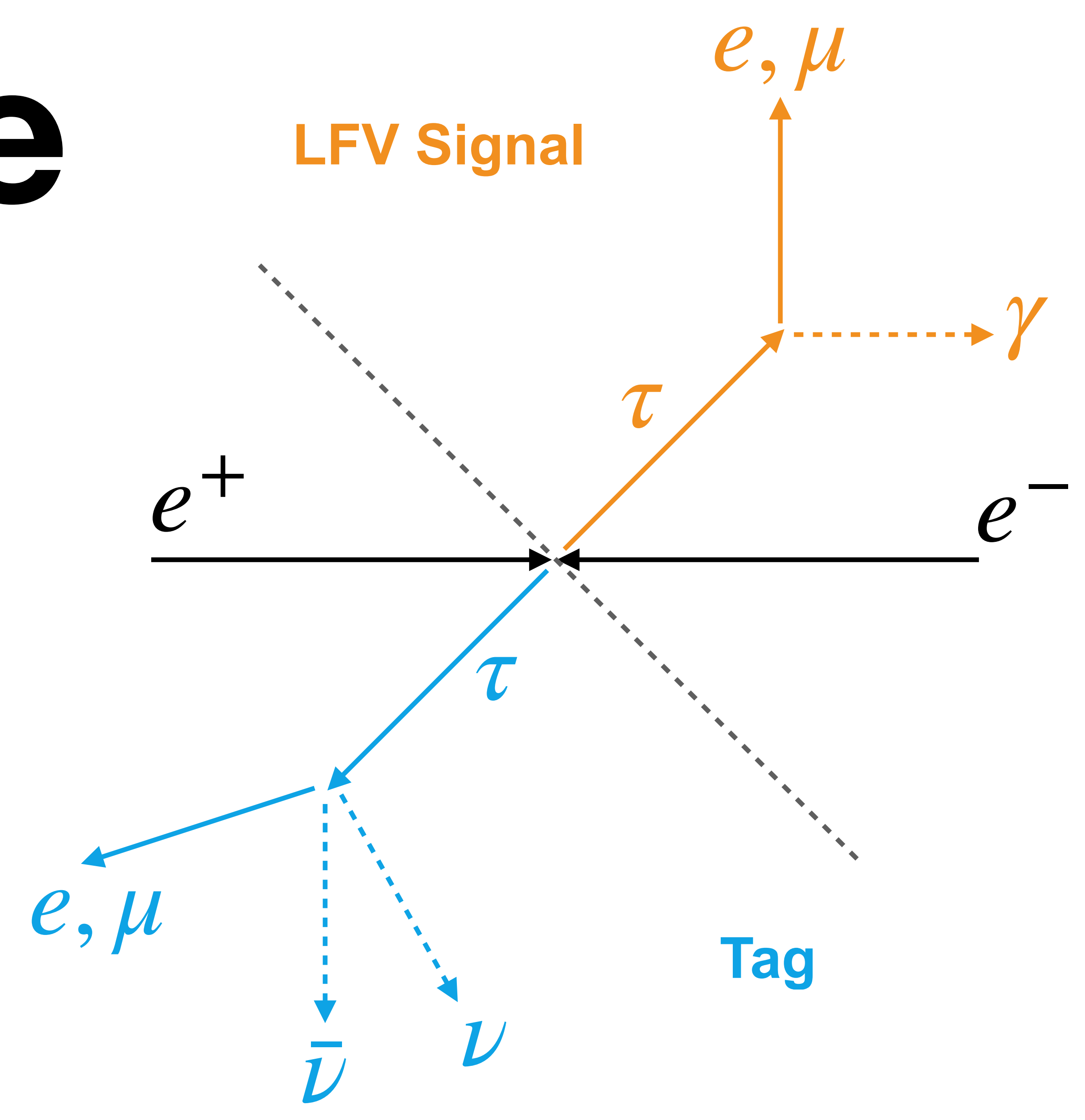
$$\mathcal{B}_{\nu SM}(\tau \to \mu\gamma) = \frac{3\alpha}{32\pi}\left|U^*_{\tau i}U_{\mu i}\frac{\Delta m^2_{3i}}{m^2_W}\right|^2 < 10^{-40}$$



- Enhanced to **~10^{-10}-10^{-7}** in several theories → unambiguous NP signature.

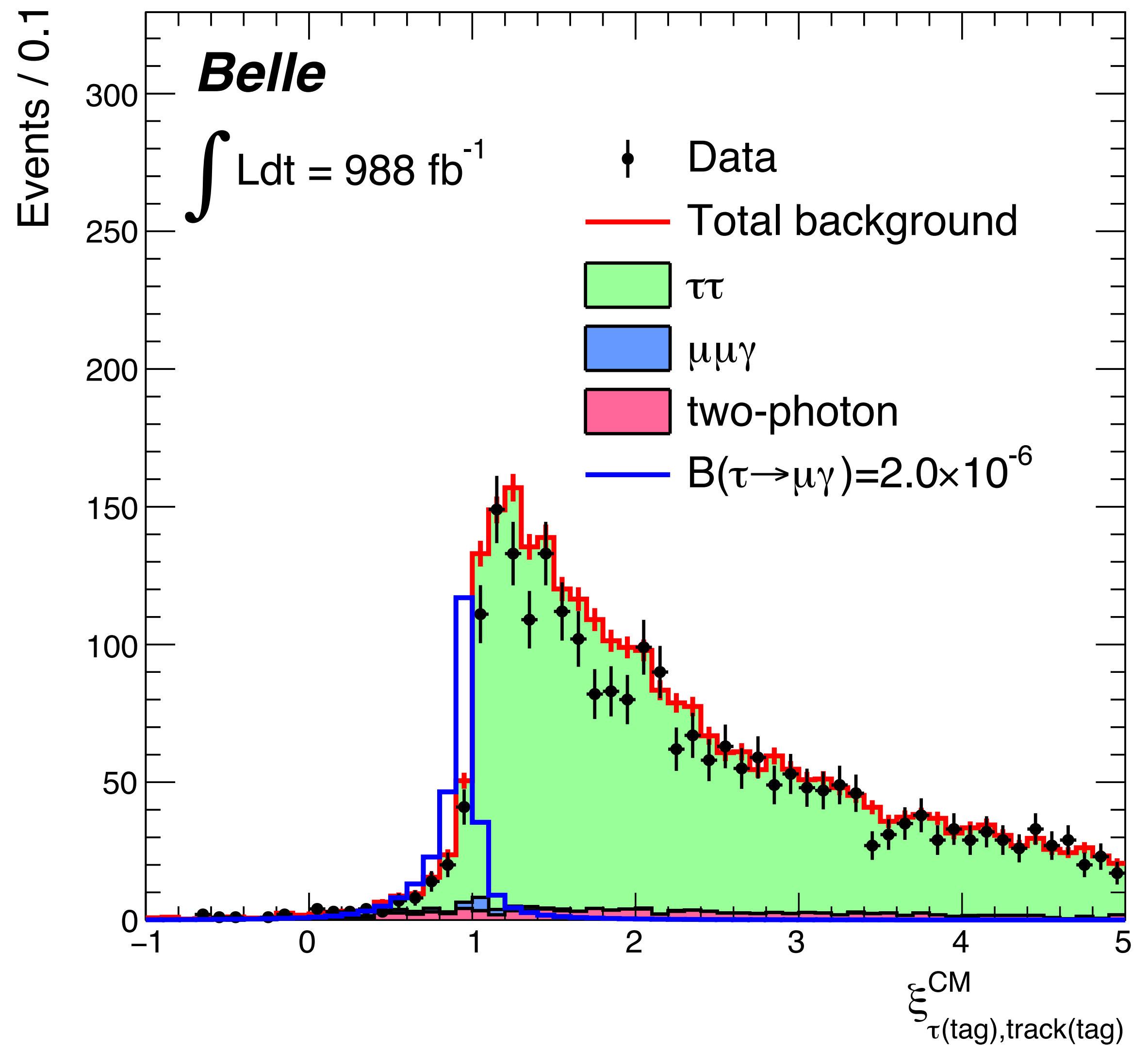
JHEP 2110, 019 (2021)

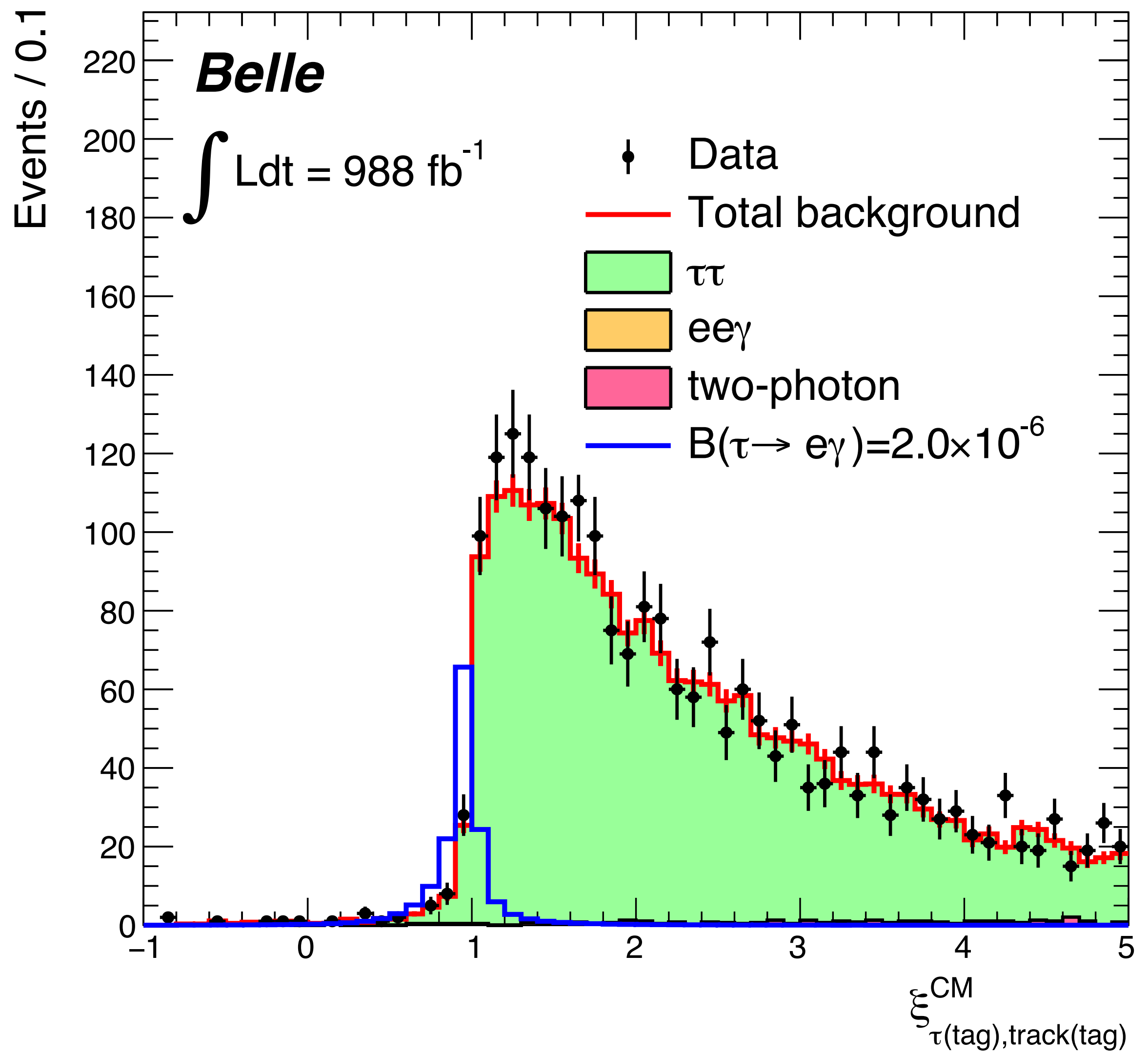
New Measurement of τ→ℓγ @Belle



- **Signal:** N_ℓ=1, N_γ=1 with 1-prong tag.
- **Dominant background** from accidental coincidences in **τ→ℓνν + γ** and **ee→ℓℓ + γ**, γ=(ISR or beam background)
- Increased luminosity (**535/fb→988/fb**)
- New selection on angular variable (angle between τ-tag and tag track) related to missing energy of system

$$\xi^{\mathrm{CM}}_{\tau(\mathrm{tag}),\mathrm{track}(\mathrm{tag})} = \frac{\vec{p}^{\,\mathrm{CM}}_{\tau(\mathrm{tag})} \cdot \vec{p}^{\,\mathrm{CM}}_{\mathrm{track}(\mathrm{tag})}}{|\vec{p}^{\,\mathrm{CM}}_{\tau(\mathrm{tag})}||\vec{p}^{\,\mathrm{CM}}_{\mathrm{track}(\mathrm{tag})}|} \quad \in [0,1]$$





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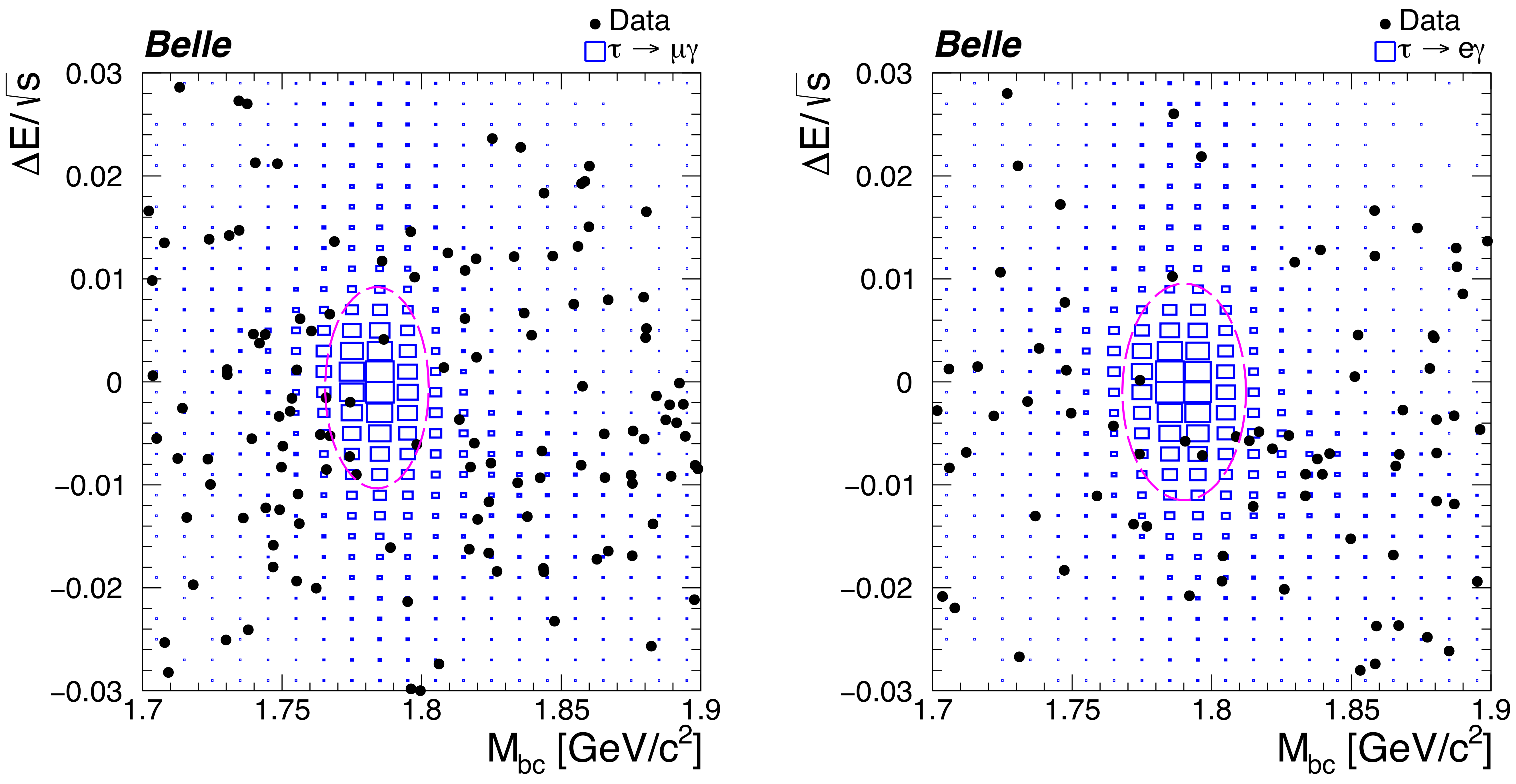
New Measurement of τ→ℓγ @Belle



- Unbinned maximum likelihood fit in 2D signal region centered in:

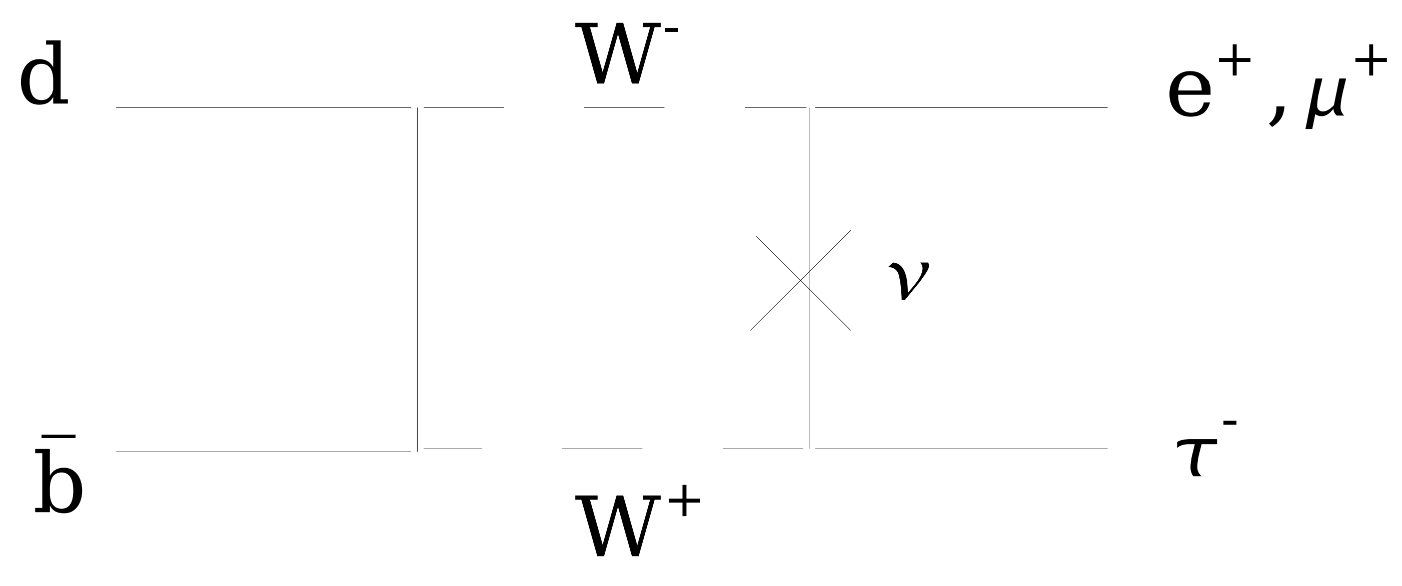
$$M^{inv}_{\ell\gamma}\left(=\sqrt{E^2_{\ell\gamma}-P^2_{\ell\gamma}}\right)\sim M_\tau$$

$$\Delta E\left(=E^{CM}_{\ell\gamma}-E^{CM}_{beam}\right)\sim 0$$

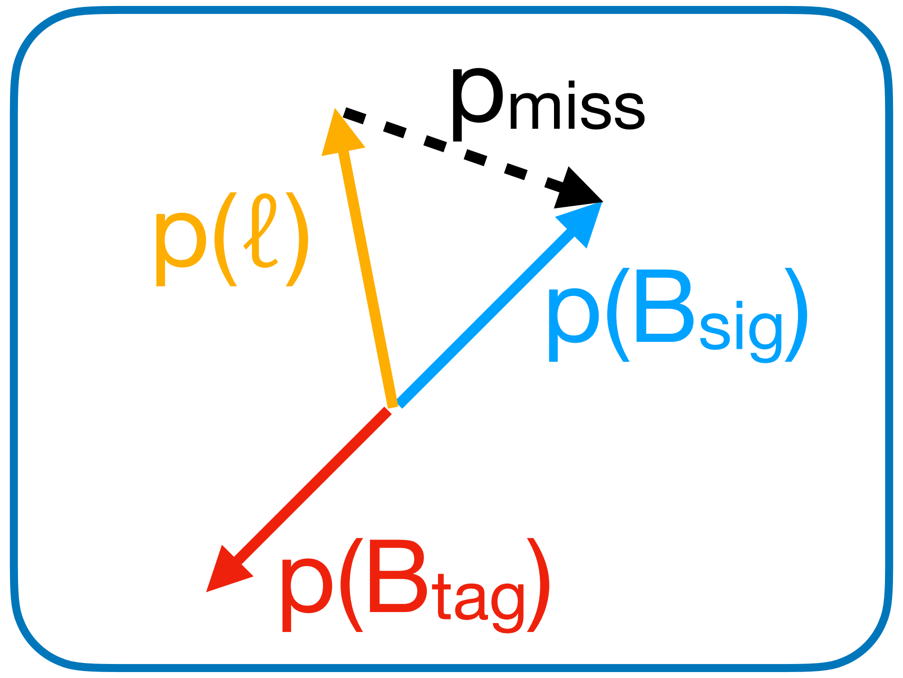
- Mu-channel improves previous limit set by BaBar.
- Could Belle II be competitive at LS1 luminosities?

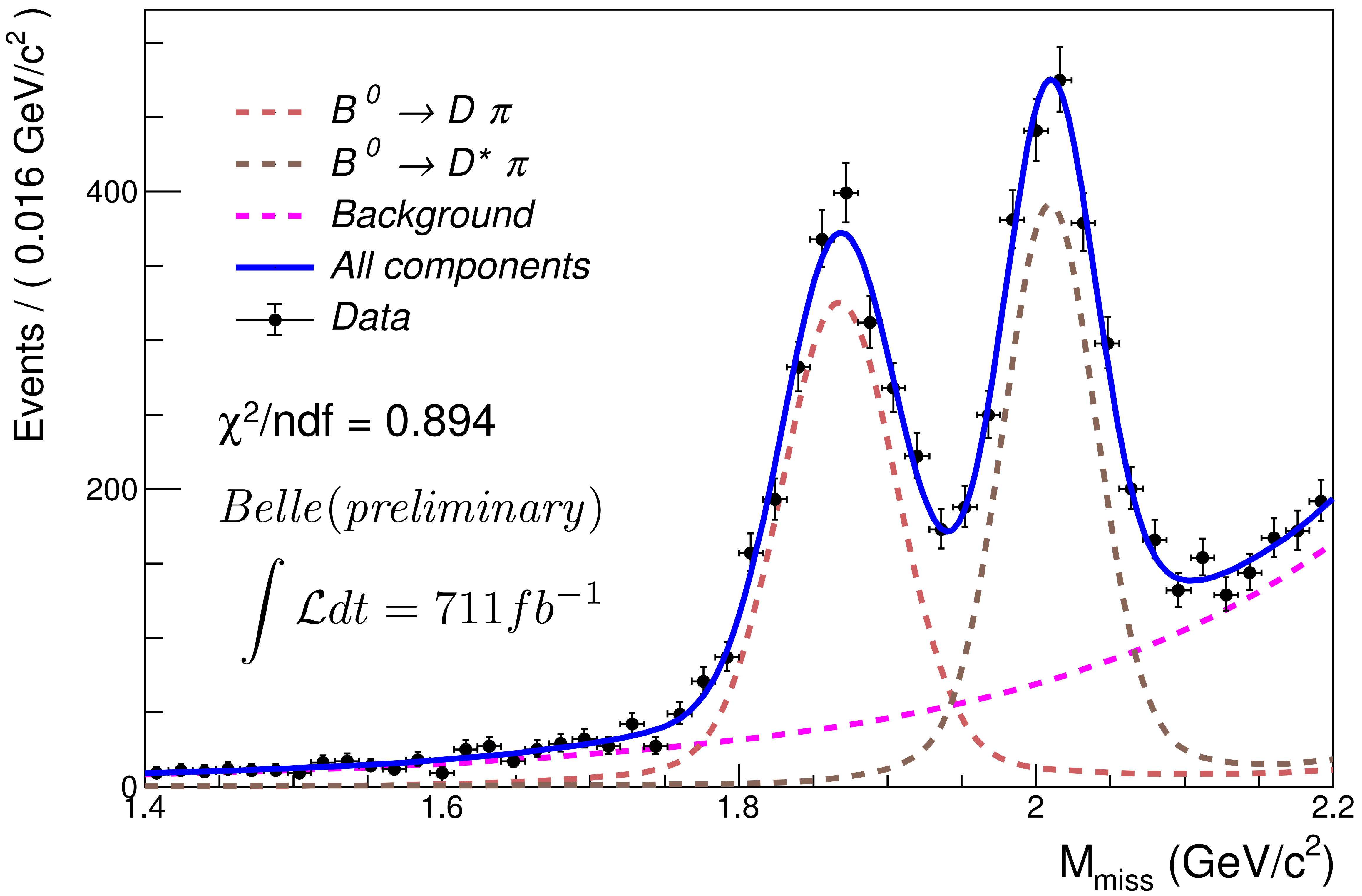
95% CL	τ→eγ	τ→μγ	Luminosity
Belle (2021)	<5.6x10^{-8}	<4.2x10^{-8}	988 fb^{-1}
BaBar	<3.3x10^{-8}	<4.4x10^{-8}	516 fb^{-1}

LFV $B^0 \to \tau\ell$ @Belle



- Can similarly occur at loop level in SM, but is enhanced in NP (e.g. leptoquarks)
- B_{tag} reconstructed hadronically, $\Upsilon(4S) \to B_{tag}B_{sig}(\to \tau\ell)$.



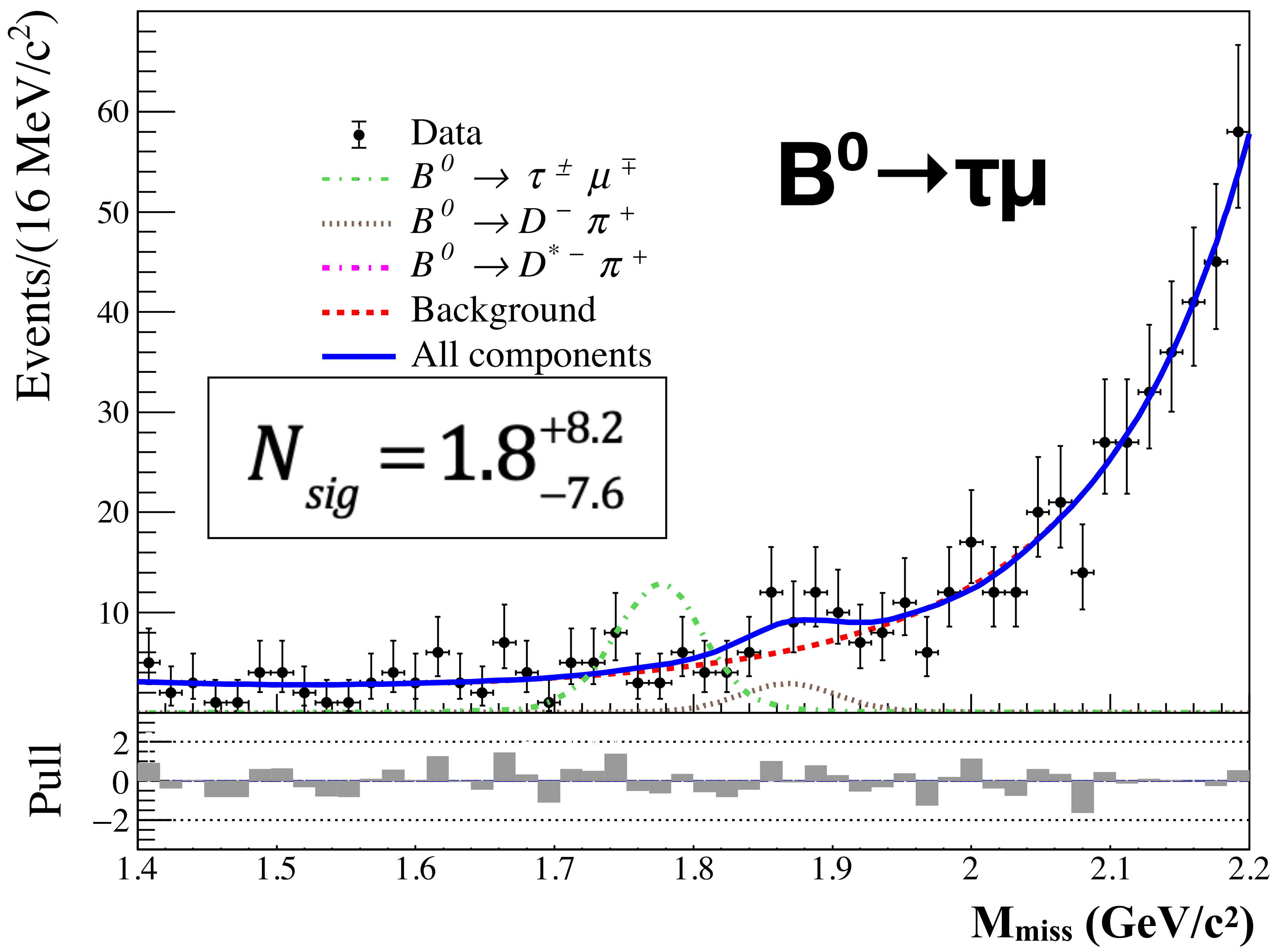


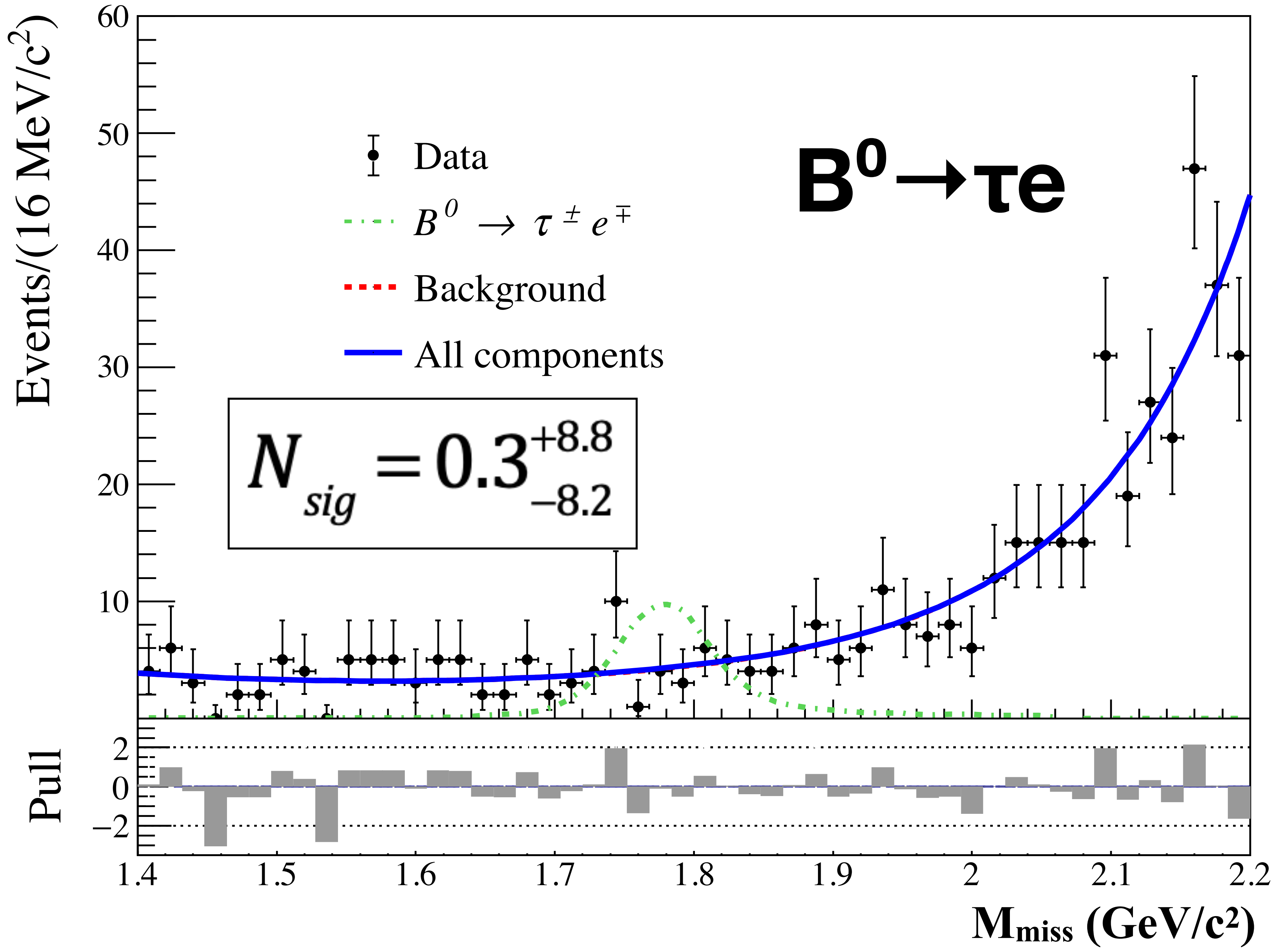
- Use 4-momentum conservation to reconstruct τ kinematics → M_{miss}
- No τ reconstruction required.
- Validate by reconstructing $B \to D^{(*)}\pi$ using the $B \to \tau\mu$ selection. → Good agreement with PDG.

LFV $B^0 \to \tau\ell$ @Belle

PRD 104, L091105 (2021)

- Unbinned extended maximum likelihood fit of M_{miss} in **711 fb^{-1}** of data.





- Upper limits of **BF($B^0 \to \tau\mu$)<1.5x10^{-5}** and **BF($B^0 \to \tau e$)<1.6x10^{-5}** at 90%C.L.

LHCb **BF($B^0 \to \tau\mu$)<1.2x10^{-5}**

world best

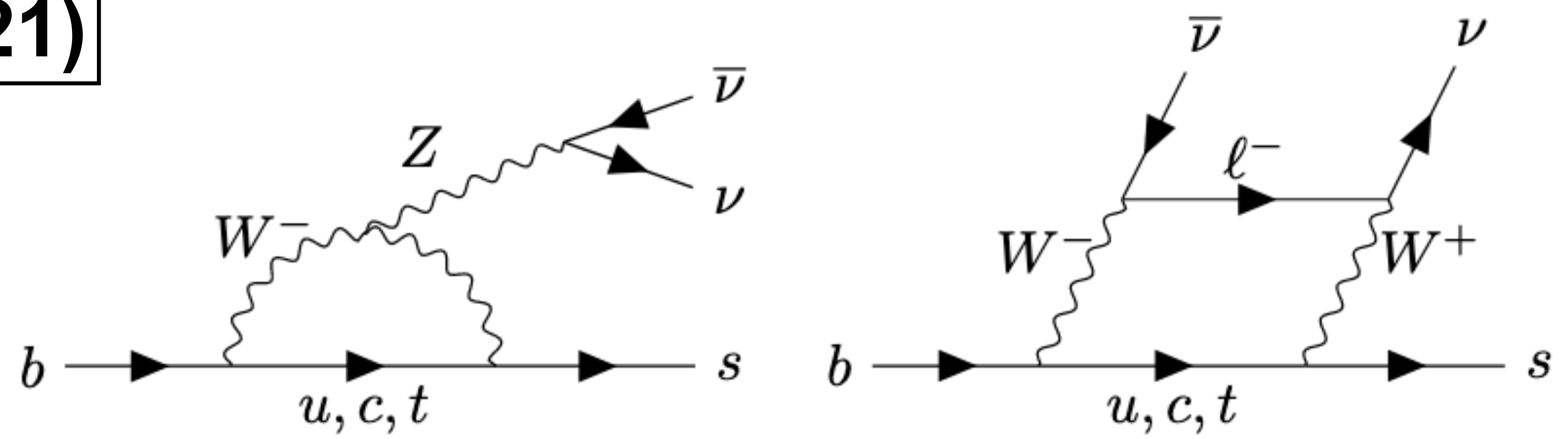
Summary

- Belle and Belle II offer a unique and fertile physics environment.
- Belle II with ~400 fb^{-1} LS1 data can already provide physics output on the level of its predecessors.
- **Many more topics** I wasn't able to cover: (in backup)
  - Electroweak penguin B decays ($B \to K^* \ell\ell$, $B \to K\nu\nu$, ...);
  - Dark sector (e.g. Dark Higgsstrahlung, shown by Belle II at Moriond);
  - Hadron spectroscopy at energies above Υ(4S);
  - B^0 lifetime and mixing measurements; and more.
- **Expect more results to come soon.**

BACKUP

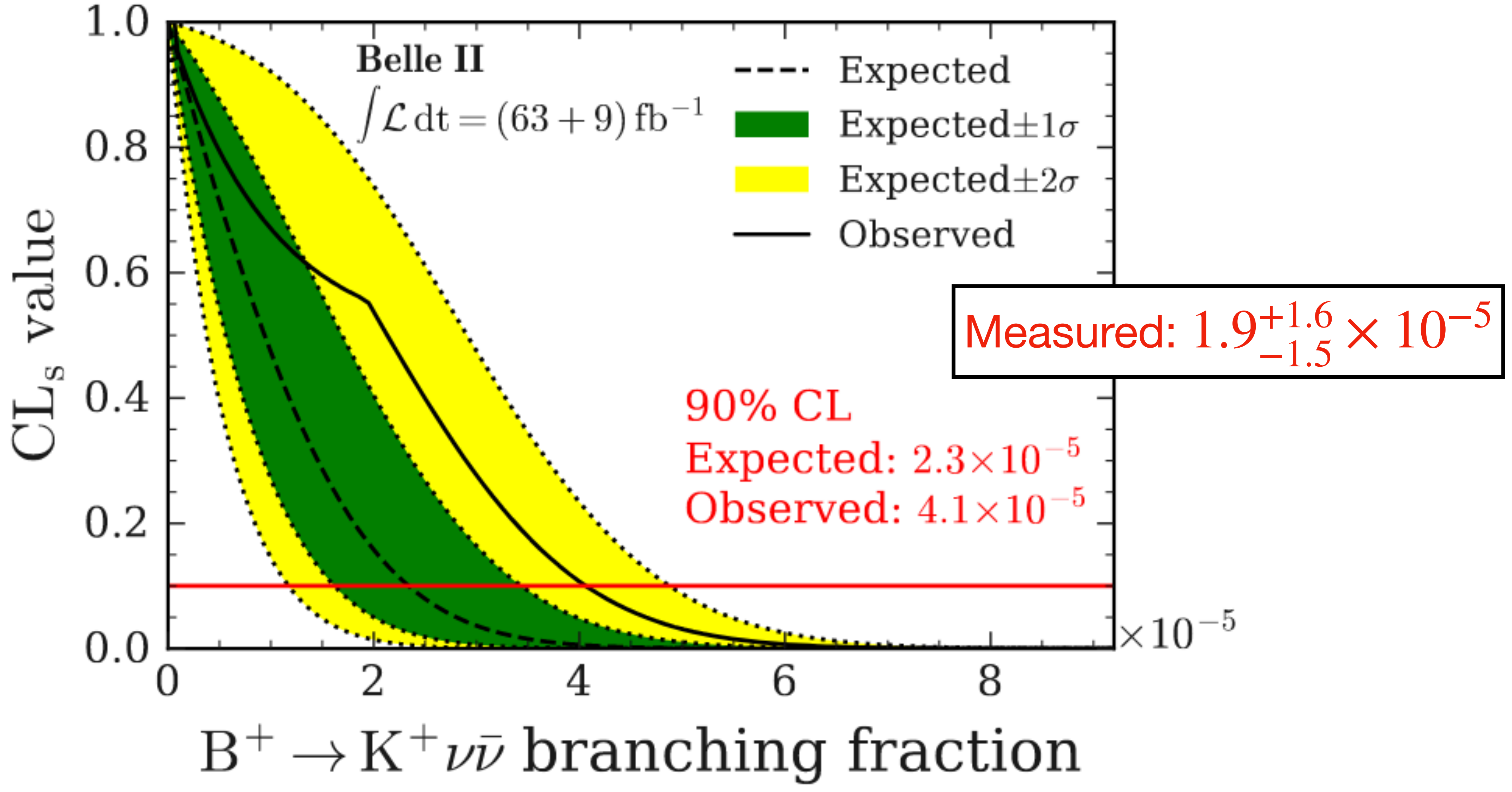
PRL 127, 181802 (2021)

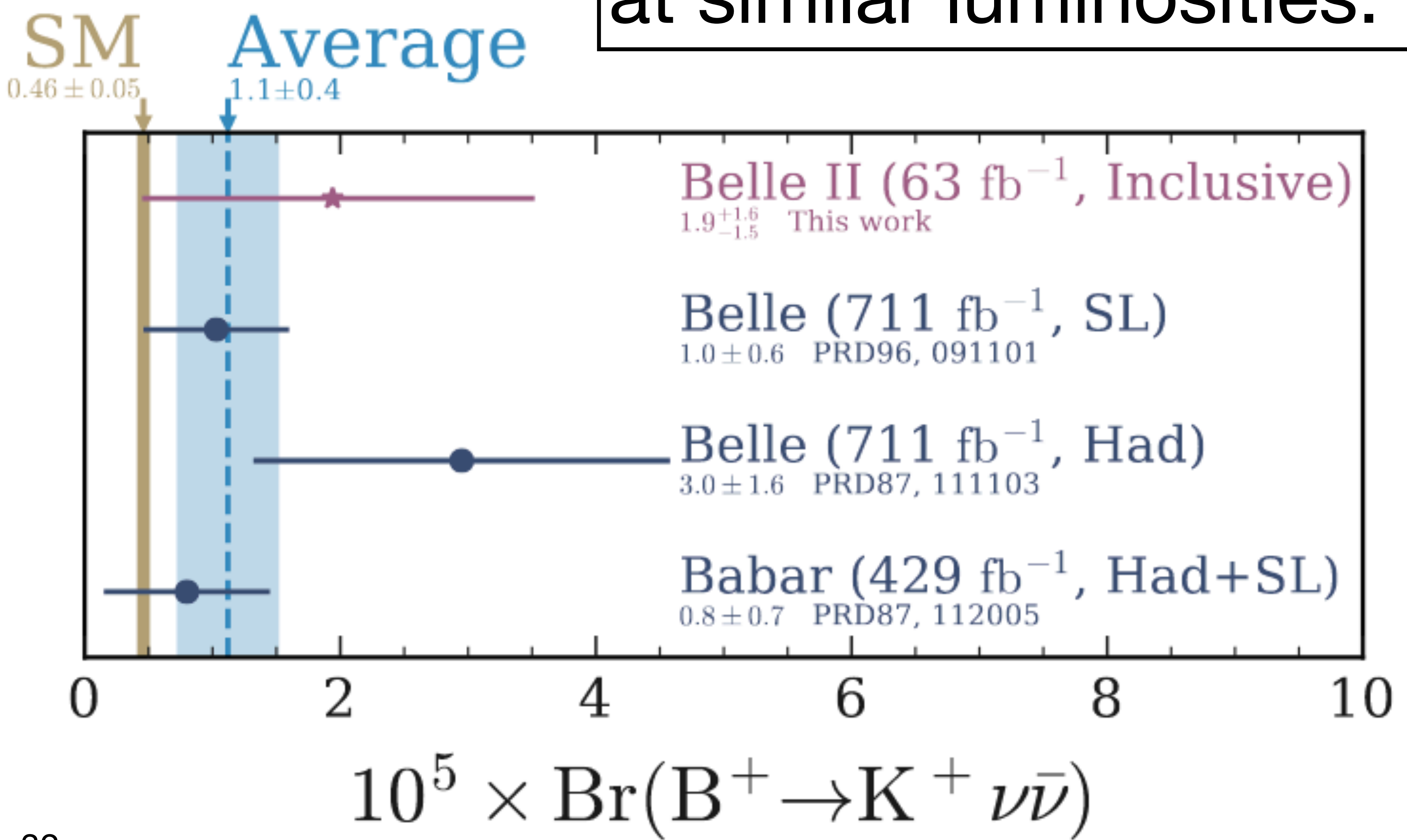
B→Kνν @Belle II



- Hermetic detector offers unique opportunity to study this channel
- FCNC strongly suppressed - SM expectation: **(4.6±0.5)x10^{-6}**
- New inclusive tagging approach.
- Validated using $B^+ \to J/\psi(\to \mu\mu)K^+$

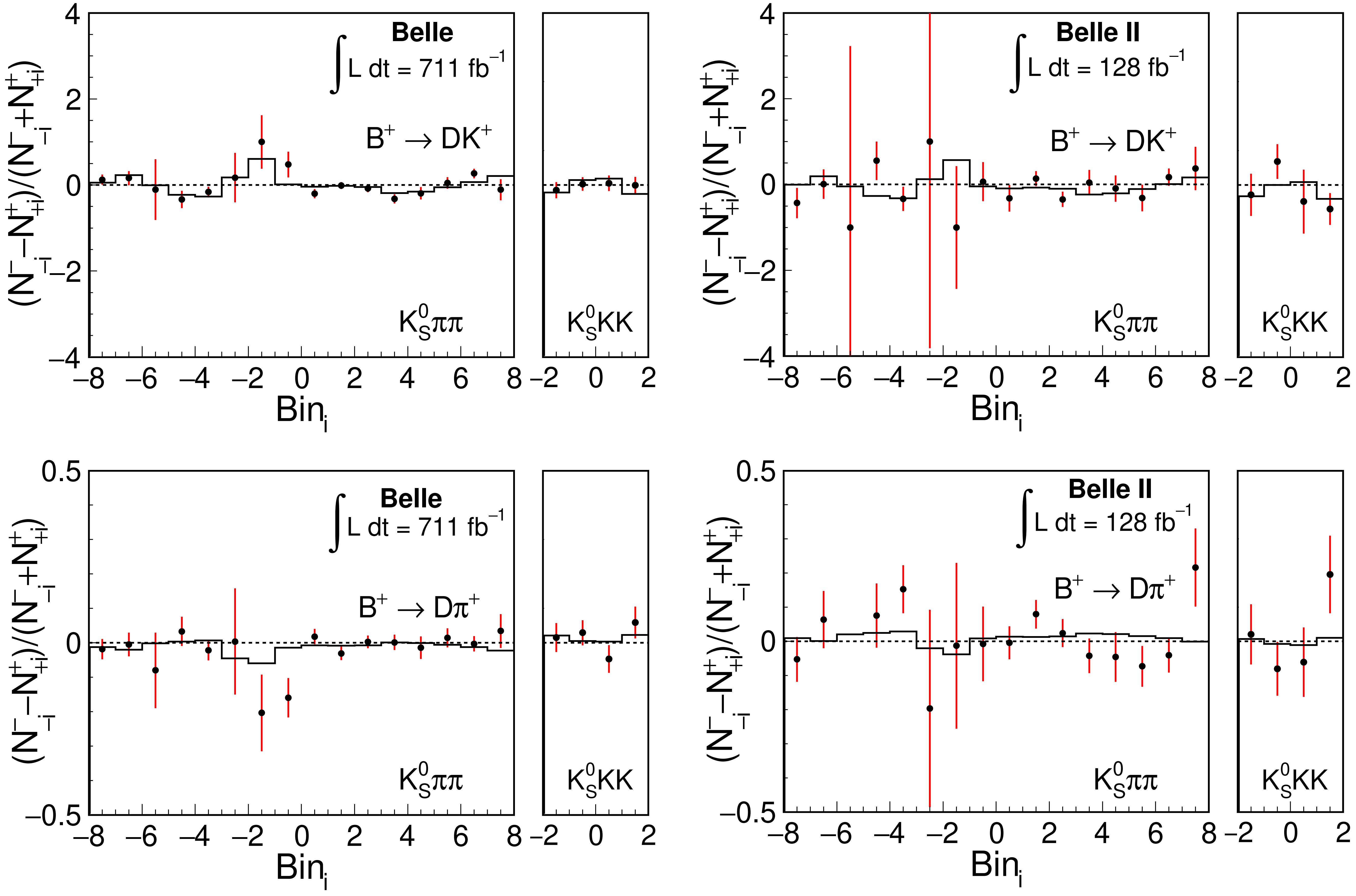
>3.5x better than hadronic tag, ~20% better than semileptonic tag at similar luminosities.





ϕ_3 (γ) @Belle+BelleII

- Simultaneous fit in each Dalitz bin to extract CP observables $(x_\pm, y_\pm)$



- Misidentification rates fixed from previous fit.
- F_i extracted directly in data → less reliant on simulation

$$x_+^{DK} = -0.113 \pm 0.032$$
$$y_+^{DK} = -0.046 \pm 0.042$$
$$x_-^{DK} = +0.092 \pm 0.033$$
$$y_-^{DK} = +0.100 \pm 0.042$$

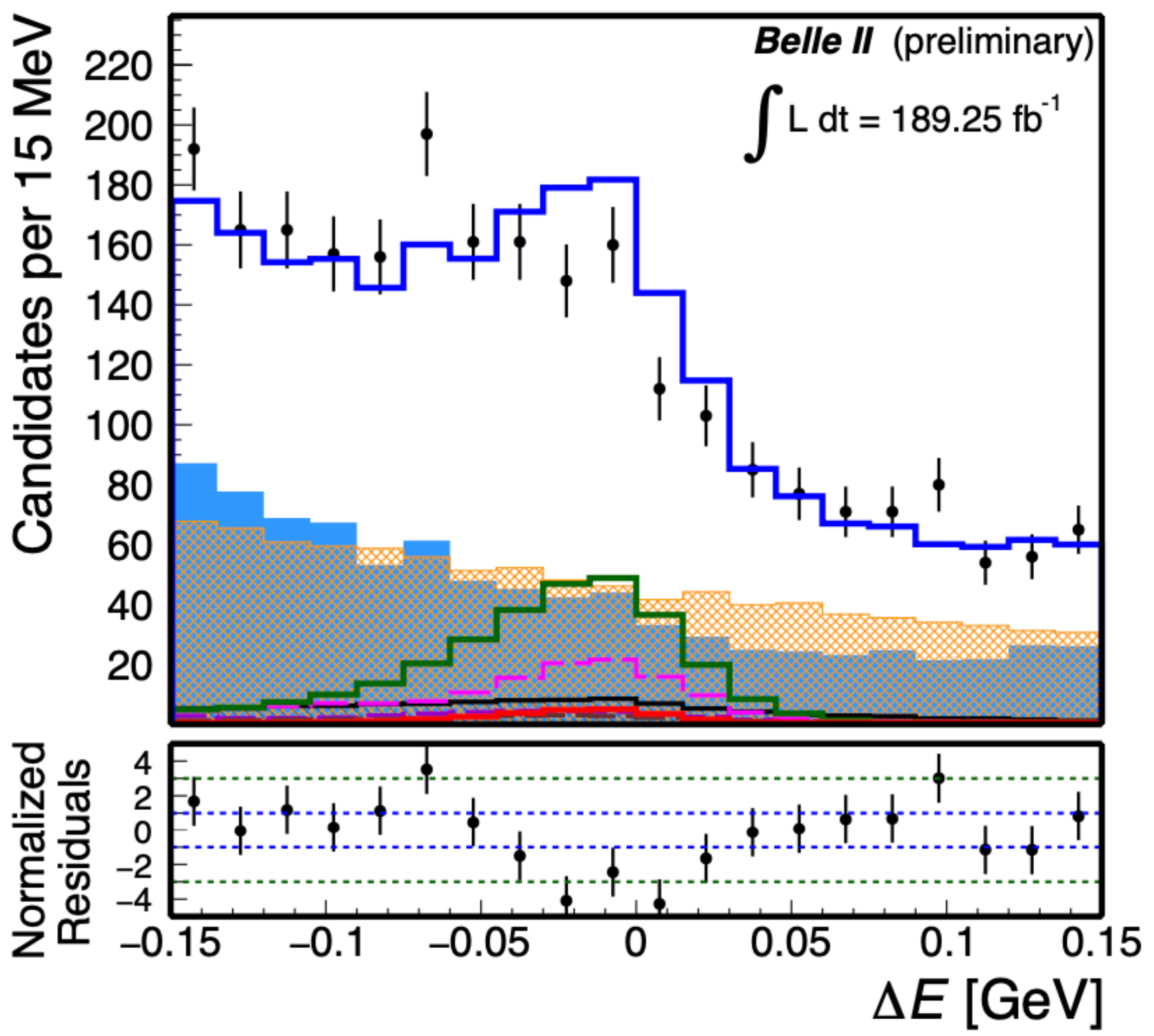
$B^+ \to \rho^+\rho^0$ @ Belle II

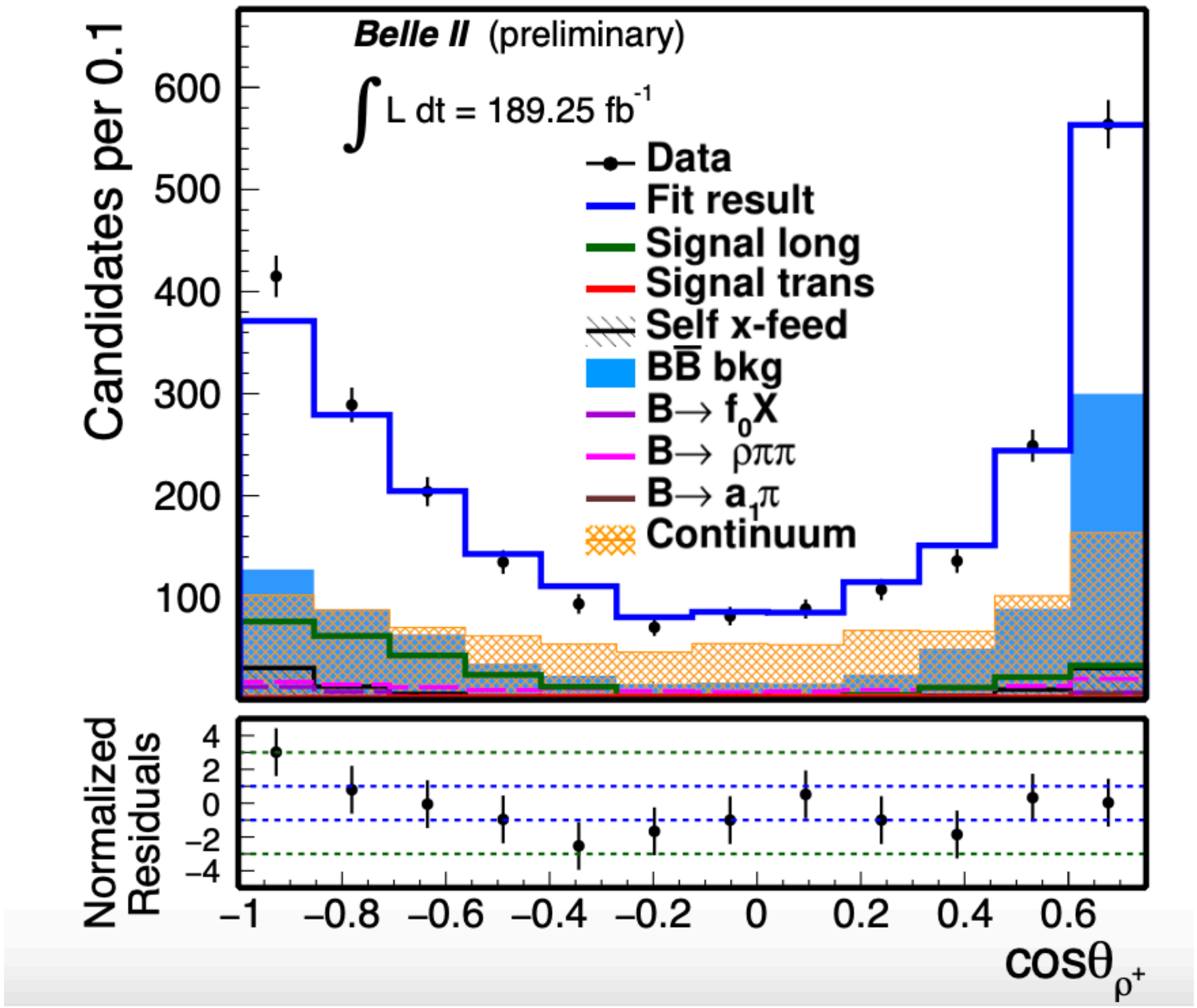
Preliminary @Moriond

- Can access CKM angle ϕ_2 by combining measurements of **$B^+ \to \rho^+\rho^0$**, $B^0 \to \rho^0\rho^0$, $B^0 \to \rho^+\rho^-$
- Direct CPV measurement only possible at B-factories

$$A_{CP} = -0.069 \pm 0.068\,(\text{stat.}) \pm 0.060\,(\text{syst.})$$
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = \left(23.2^{+2.2}_{-2.1}\,(\text{stat.}) \pm 2.7\,(\text{syst.})\right) \times 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033}\,(\text{stat.}) \pm 0.027\,(\text{syst.})$$

World average: $A_{CP} = -0.05 \pm 0.05$





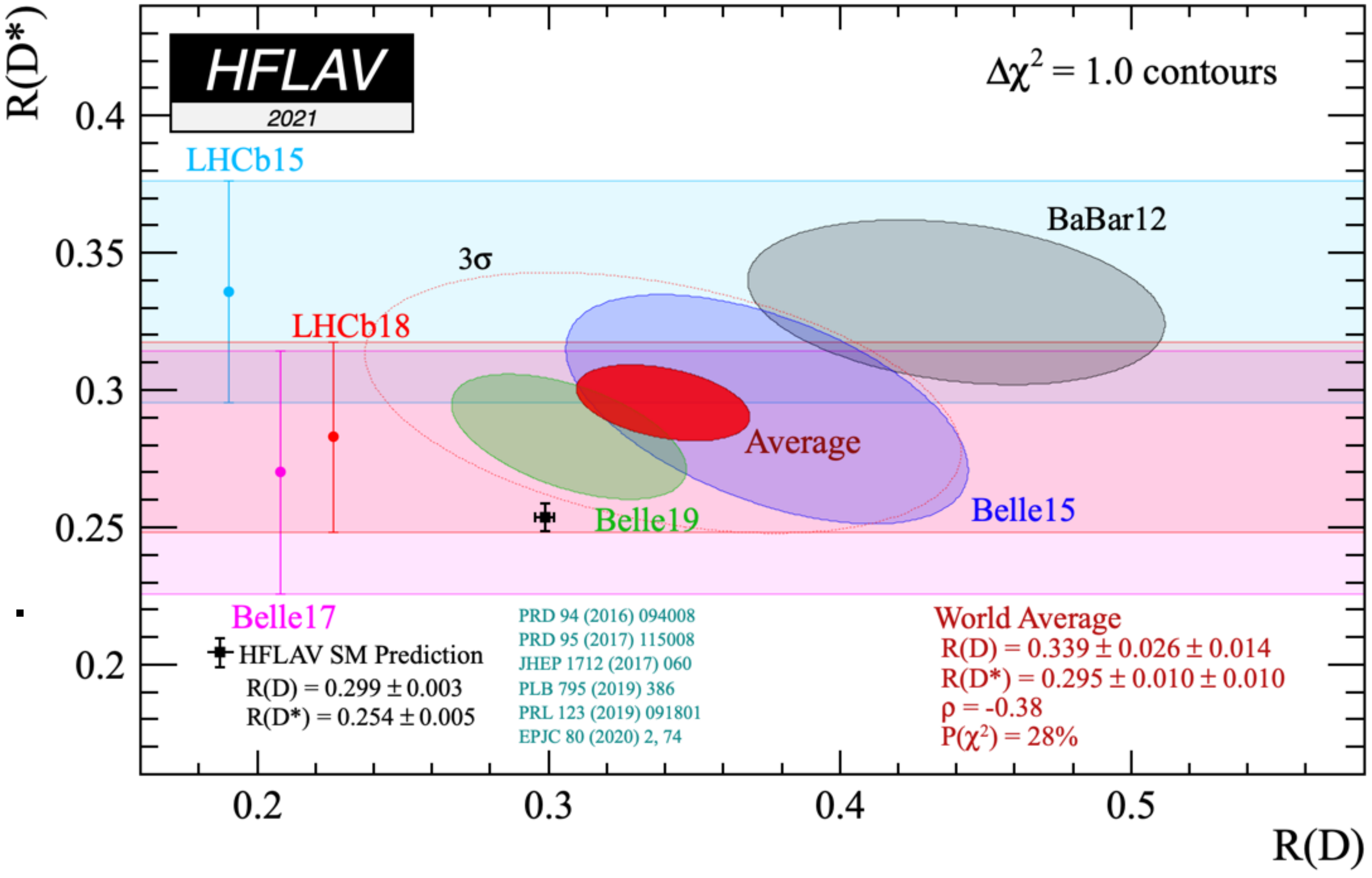
Lepton Flavor Universality

- EW coupling of gauge bosons is expected to be flavour-independent.

- Hints of LFU violation in charged current decays, e.g.:

$$R(D^{(*)}) = \frac{BF(B \to D^{(*)}\tau\nu_\tau)}{BF(B \to D^{(*)}\ell\nu_\ell)}$$

- World averaged tension of ~3.1σ .



τ LFV Theory Predictions

Model	Reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z’	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}