Recent results from Belle II

QCD22 25th HIGH-ENERGY PHYSICS INTERNATIONAL CONFERENCE IN QUANTUM CHROMODYNAMICS

MONTPELLIER 4-7 july 2022

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on behalf of Belle II collaboration

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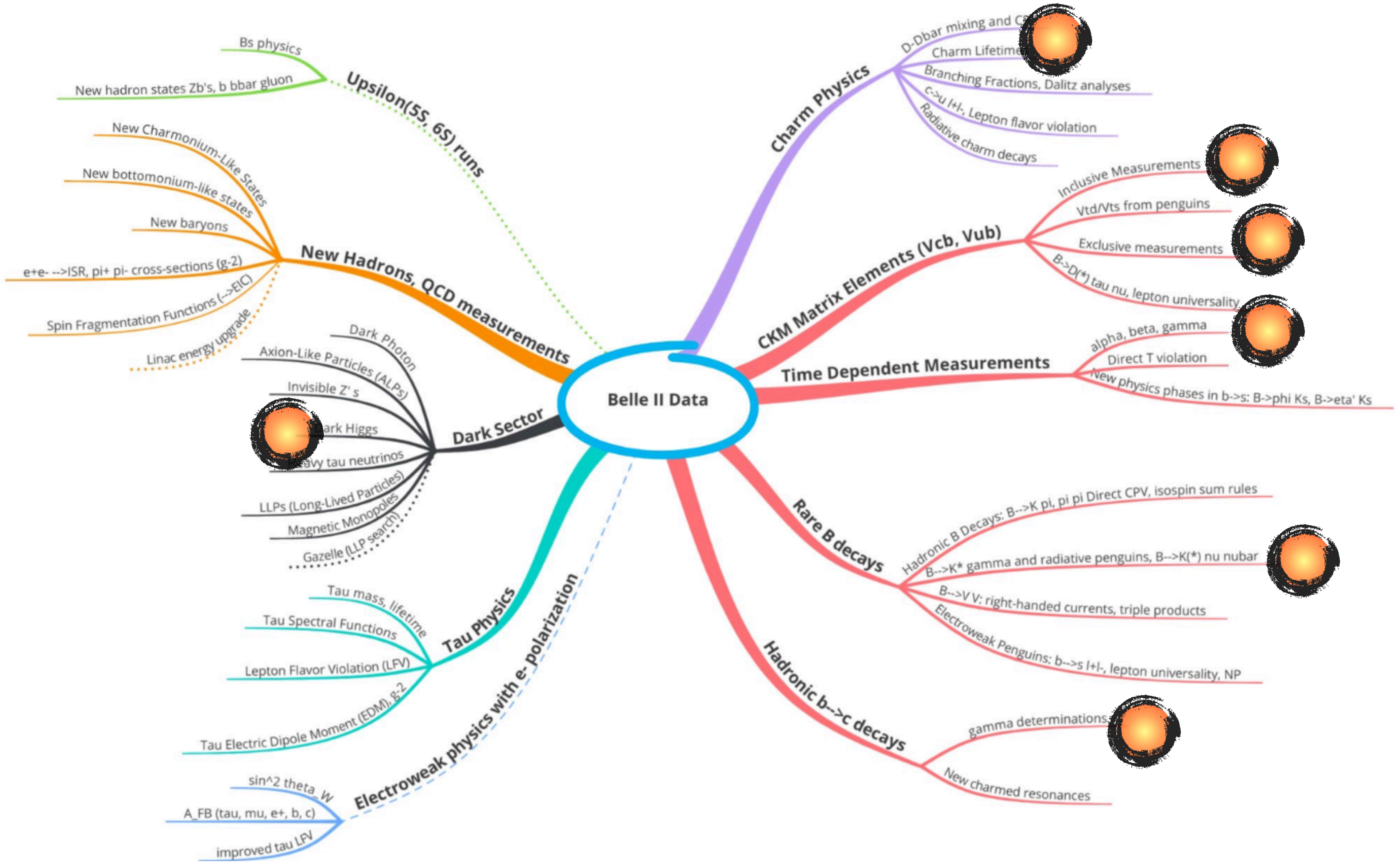
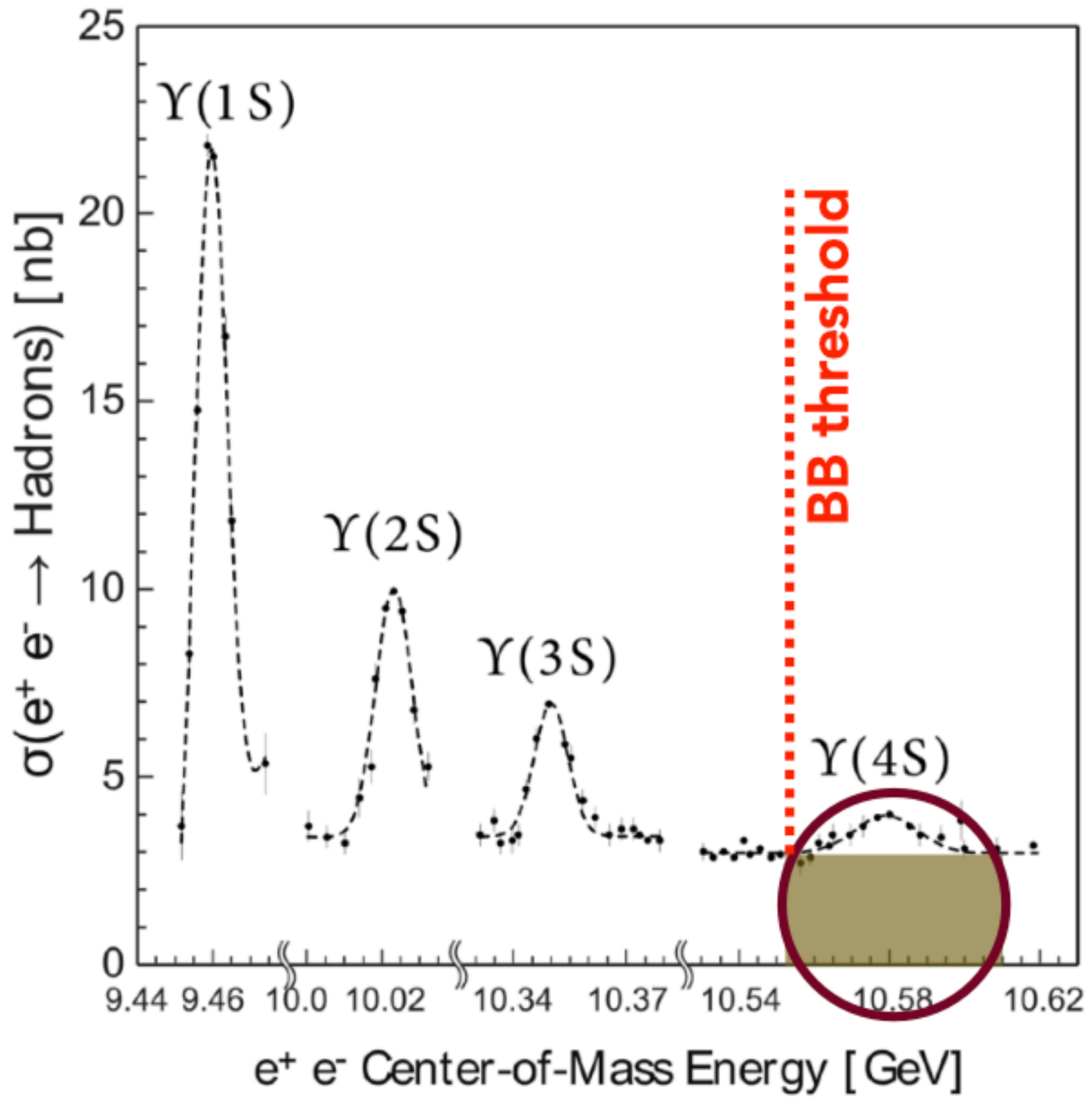
Outline

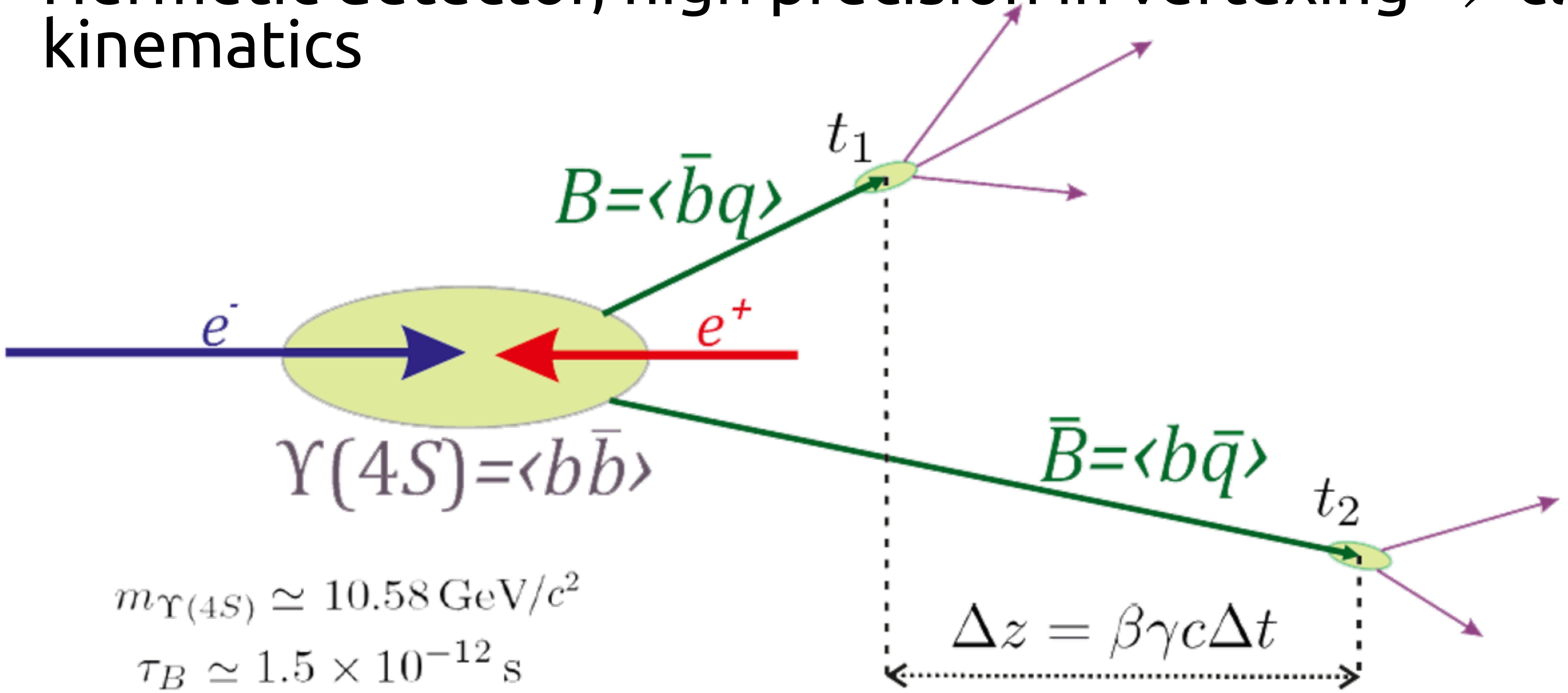
- SuperKEKB and Belle II detector
- **Charm** physics
- SM precision: **CKM Matrix**
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CP violation)
  - Time dependent CP Violation
- Portals for **new physics**:
  - Rare B decays
  - Dark Sector



B-Factory idea

- Asymmetric collider e^+e^-, $E_{cm} = m(\Upsilon(4S)) = 10.58\ \text{GeV}$ $\Rightarrow$ coherent $B\overline{B}$ pairs
- Boost of center-of-mass ($\beta\gamma = 0.28$)$\Rightarrow$ measure of Δz
- High luminosity $\Rightarrow$ precision measurements
- Hermetic detector, high precision in vertexing $\Rightarrow$ closed kinematics





$m_{\Upsilon(4S)} \simeq 10.58\,\text{GeV}/c^2$

$\tau_B \simeq 1.5\times 10^{-12}\,\text{s}$

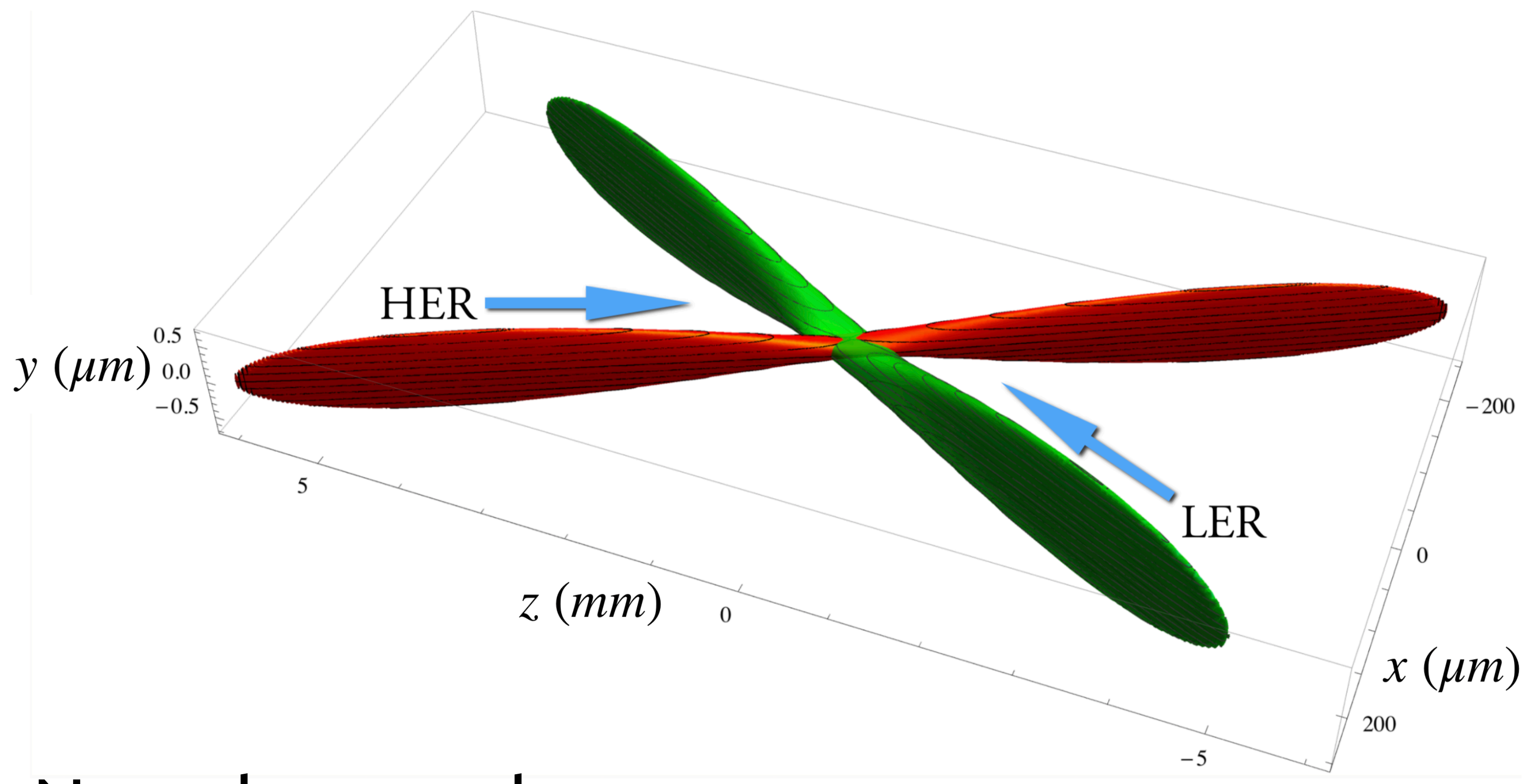
$m_B \simeq 5.279\ \text{GeV}/c^2$

$e^+e^- \to$	Cross section [nb]
$\Upsilon(4S)$	1.05 ± 0.10
$c\bar{c}$	1.30
$s\bar{s}$	0.38
$u\bar{u}$	1.61
$d\bar{d}$	0.40
$\tau^+\tau^-(\gamma)$	0.919
$\mu^+\mu^-(\gamma)$	1.148
$e^+e^-(\gamma)$	300 ± 3

Belle II experiment at SuperKEKB collider

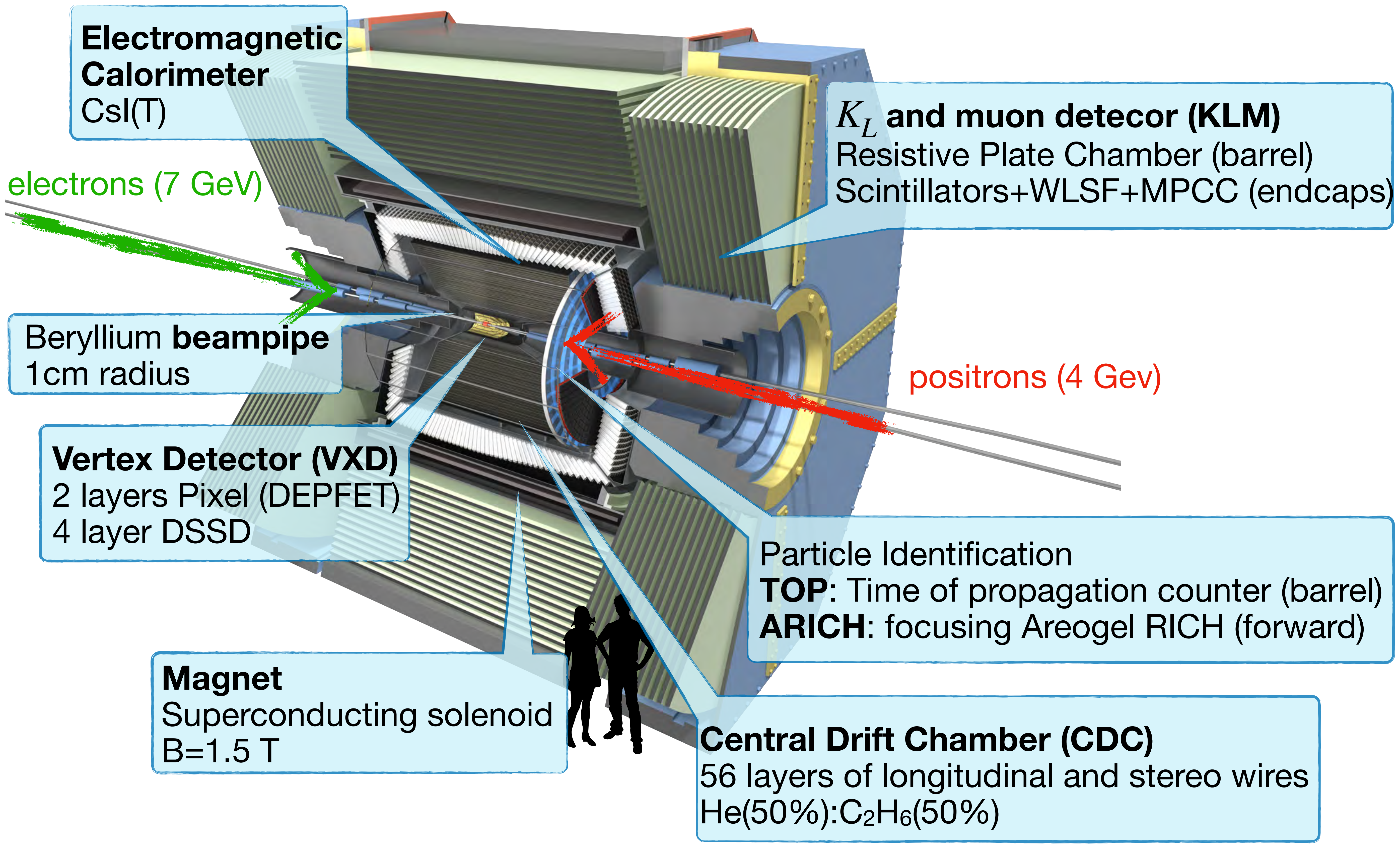
SuperKEKB

- Successor of KEKB (1999-2010, KEK, Japan)
- Target peak luminosity: $6 \cdot 10^{35}\ \mathrm{cm^{-2}s^{-1}}$ (x 30 of KEKB)
- Target integrated luminosity: $50\ \mathrm{ab}^{-1}$ (x 70 Belle at $\Upsilon(4S)$)



Nano-beam scheme:
250 μm (Z) × 10 μm (X) × 50 nm (Y)

Belle II



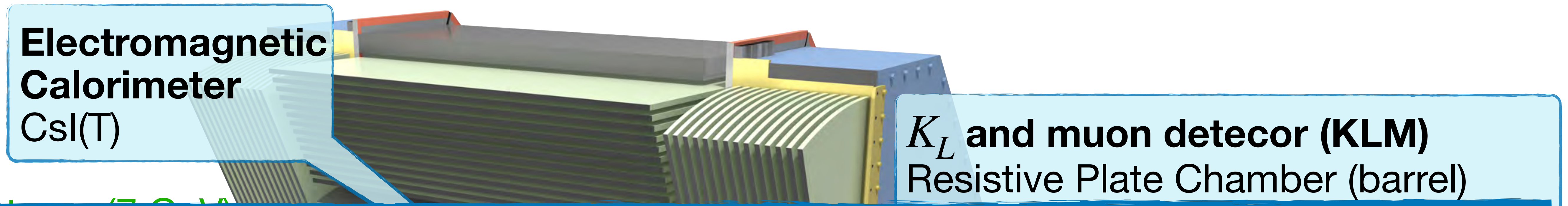
[Belle II Technical Design Report, arXiv:1011.0352]

Belle II experiment at SuperKEKB collider

SuperKEKB

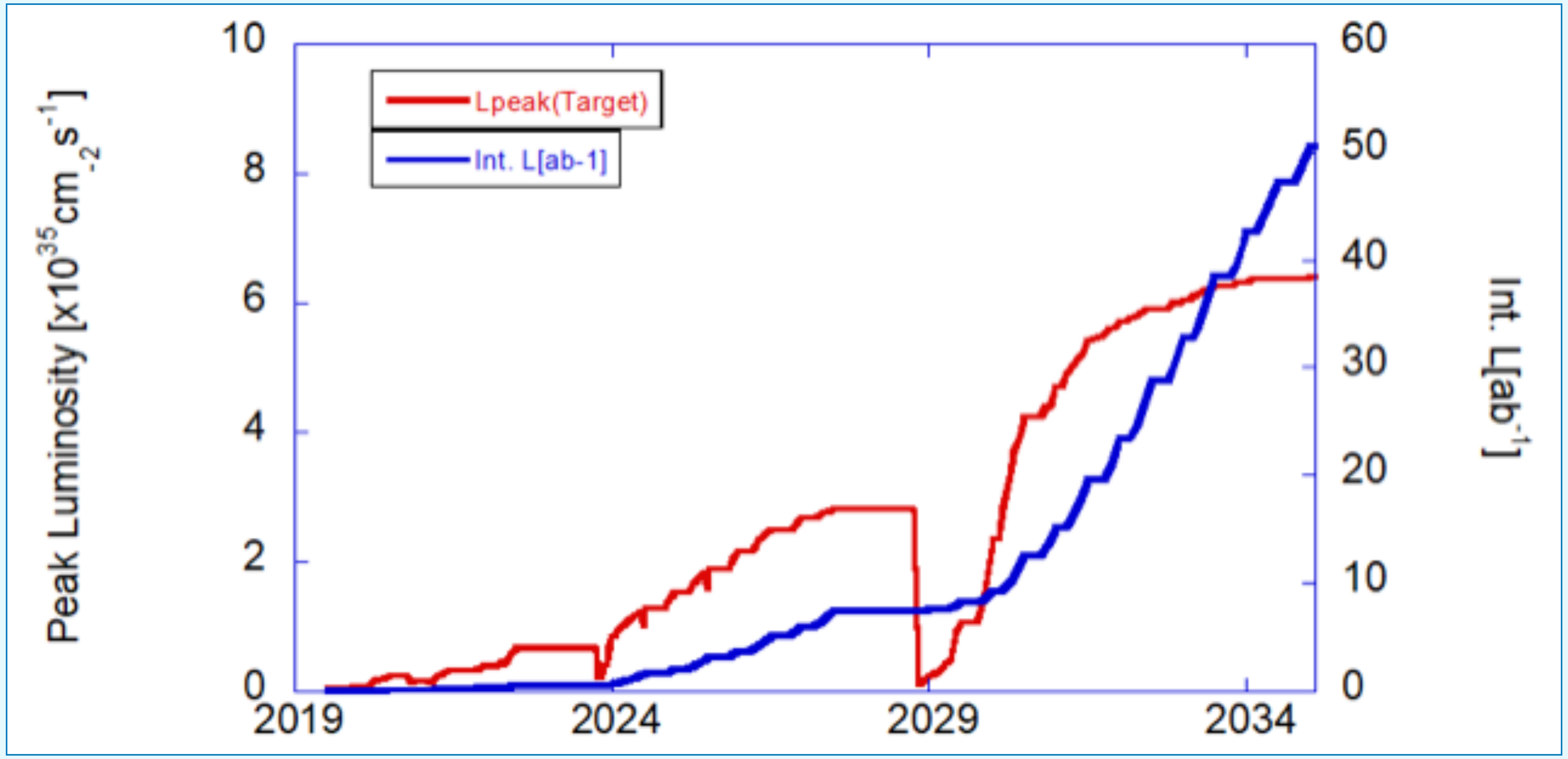
- Successor of KEKB (1999-2010, KEK, Japan)

Belle II



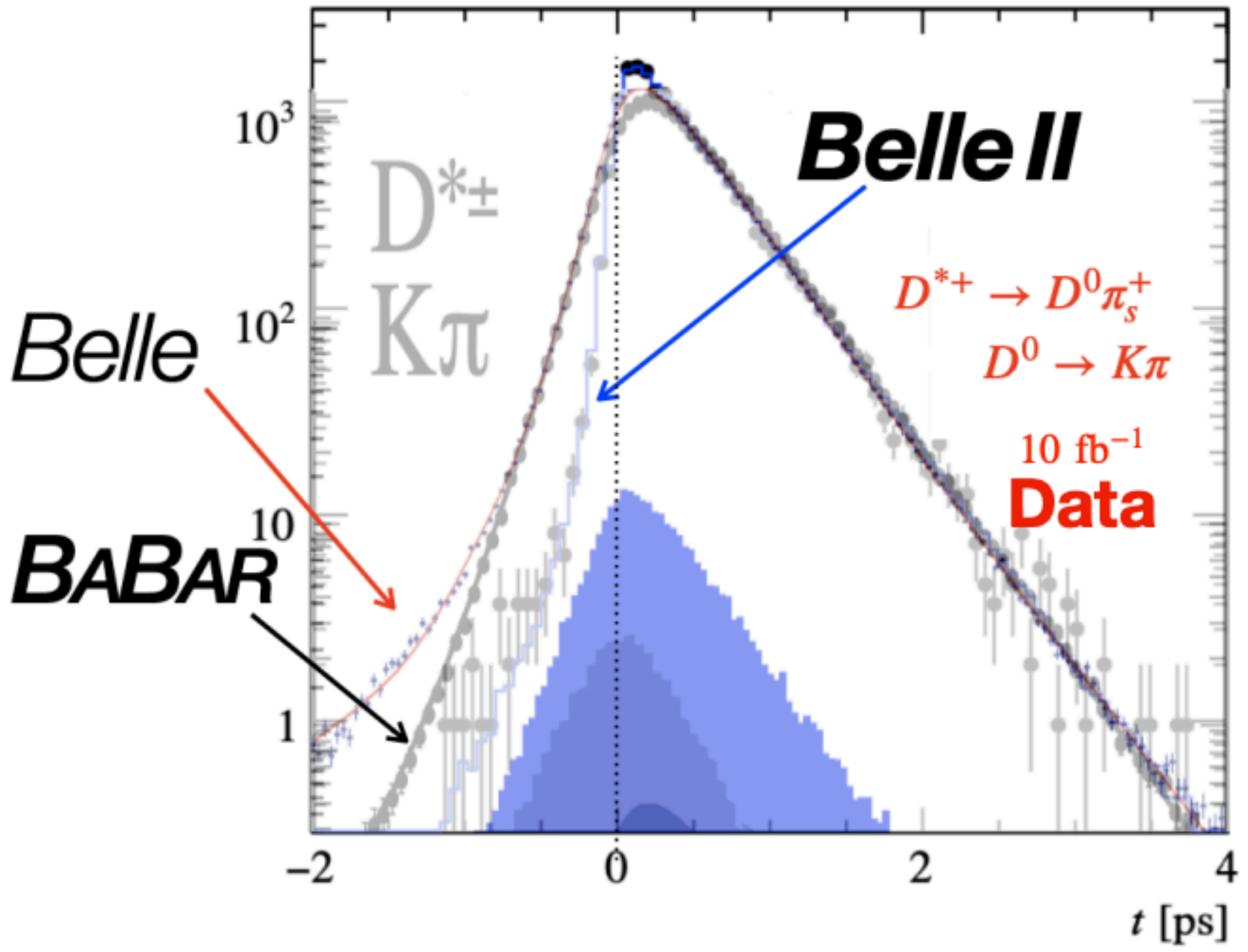
Current Status

- complete detector data taking started in 2019
- Current peak luminosity $4.7 \cdot 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (reached the 22/06/2022)
- current integrated luminosity: $\sim 424\ \mathrm{fb}^{-1}$ (~Babar~0.5 Belle)
- Long Shutdown 1 (LS1) is starting now for several upgrades (beam pipe, pixel, TOP PMT)



Charm physics: lifetimes

- Motivation:
  - charm physics ⇒ low-energy QCD (nonperturbative/higher order correction) ⇒ effective models uncertainties
  - measurement of lifetimes tests these model
- Opportunity:
  - $\sigma_{c\bar{c}} \simeq \sigma_{b\bar{b}} \Rightarrow$ high statistics
  - B-factory environment allow absolute (un-biased selection) **lifetime measurements**
  - SuperKEKB **small interaction region** and **Belle II vertex detector** provide strong constraints and improved resolutions
  - current sample is not sufficient for charm CPV measurements, but can produce world best lifetime measurements (constraints for the future)



Charm physics: D^0, D^+ and Λ_c^+ lifetimes

$72\ ,\ 207\ \mathrm{fb}^{-1}$

[Phys. Rev. Lett. 127 (2021), 211801]

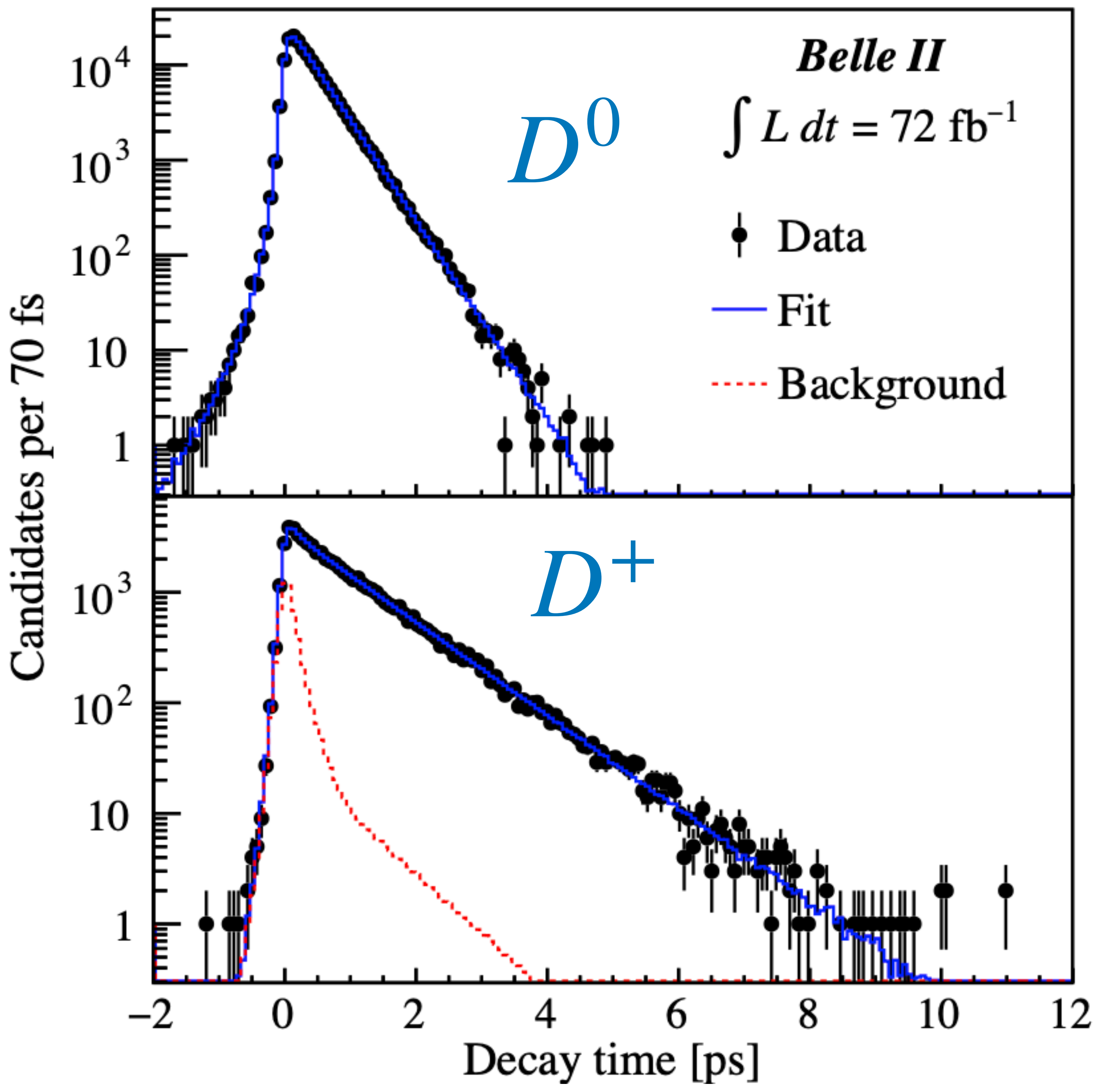
[arXiv:2206.15227v1]

- $t = m_{D/\Lambda}\vec{L}\cdot\vec{p}/|\vec{p}|^2$ $(\vec{L}\sim 10^2\ \mu\mathrm{m})$
- **2D ML fit to $t\times\sigma_t$** distribution
- bkg: estimated from **sideband** in $m_{D/\Lambda}$

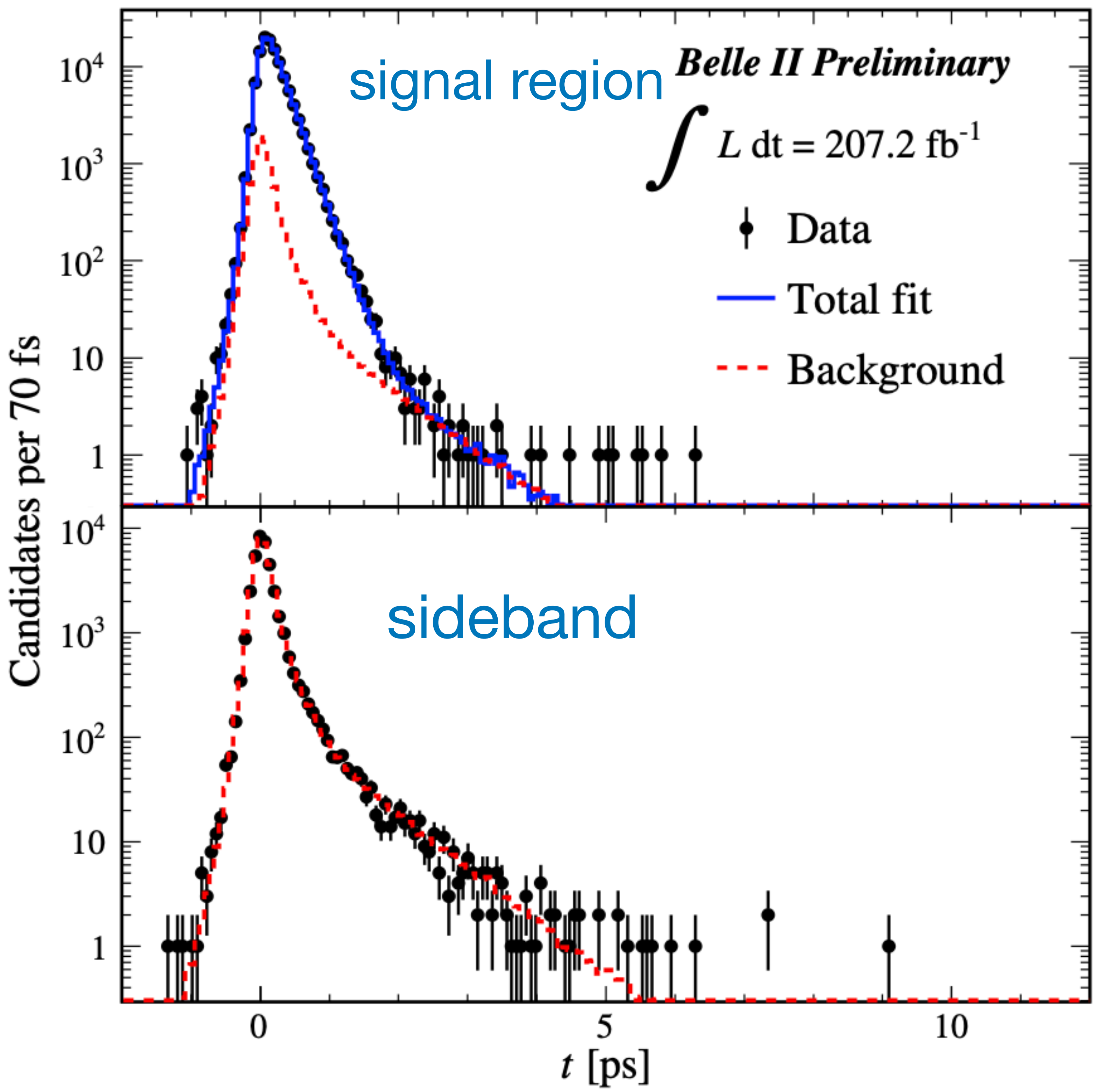
Belle II	World average
$\tau(D^0)$ = **(410.5 ± 1.1 ± 0.8) fs**	(410.1 ± 1.5) fs
$\tau(D^+)$ = **(1030.4 ± 4.7 ± 3.1) fs**	(1040 ± 7) fs
$\tau(\Lambda_c^+)$ = **(204.1 ± 0.8 ± 0.7 - 1.4) fs**	(202.4 ± 3.1) fs

$D^{*+}\to D^0(\to K^-\pi^+)\pi^+$

$D^{*+}\to D^+(\to K^-\pi^+\pi^+)\pi^0$



$\Lambda_c^+\to pK^-\pi^+$

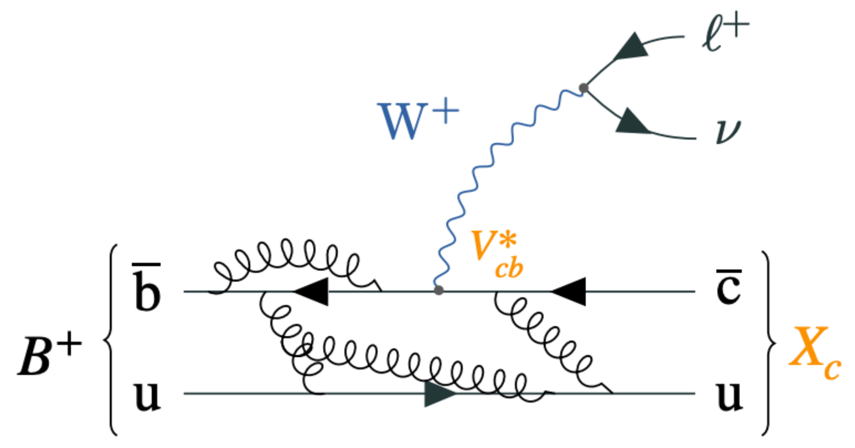


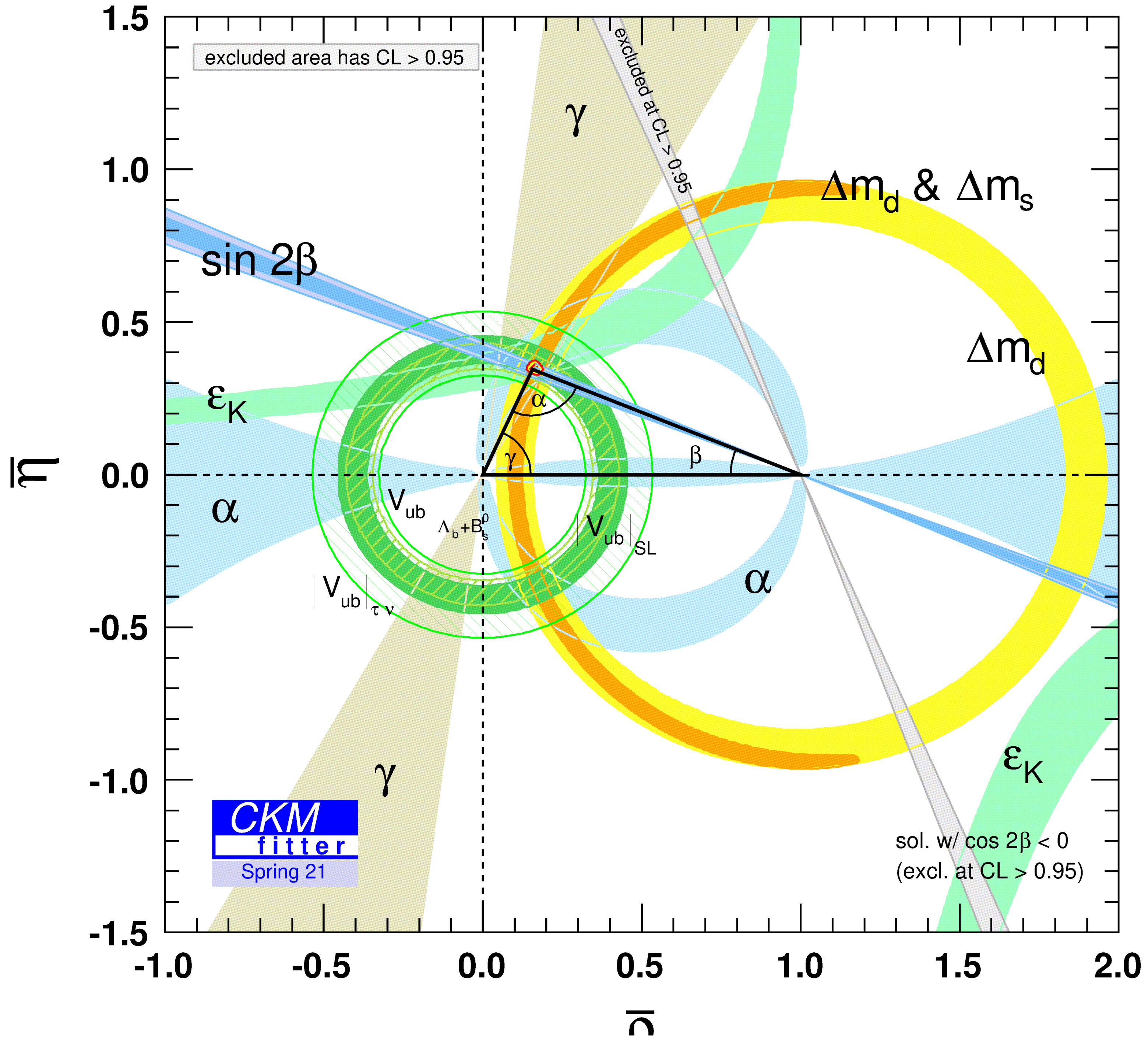
Next steps:

- **Additional lifetime** measurements are coming
- Belle II is starting to enter in the **charm mixing/CPV** phase

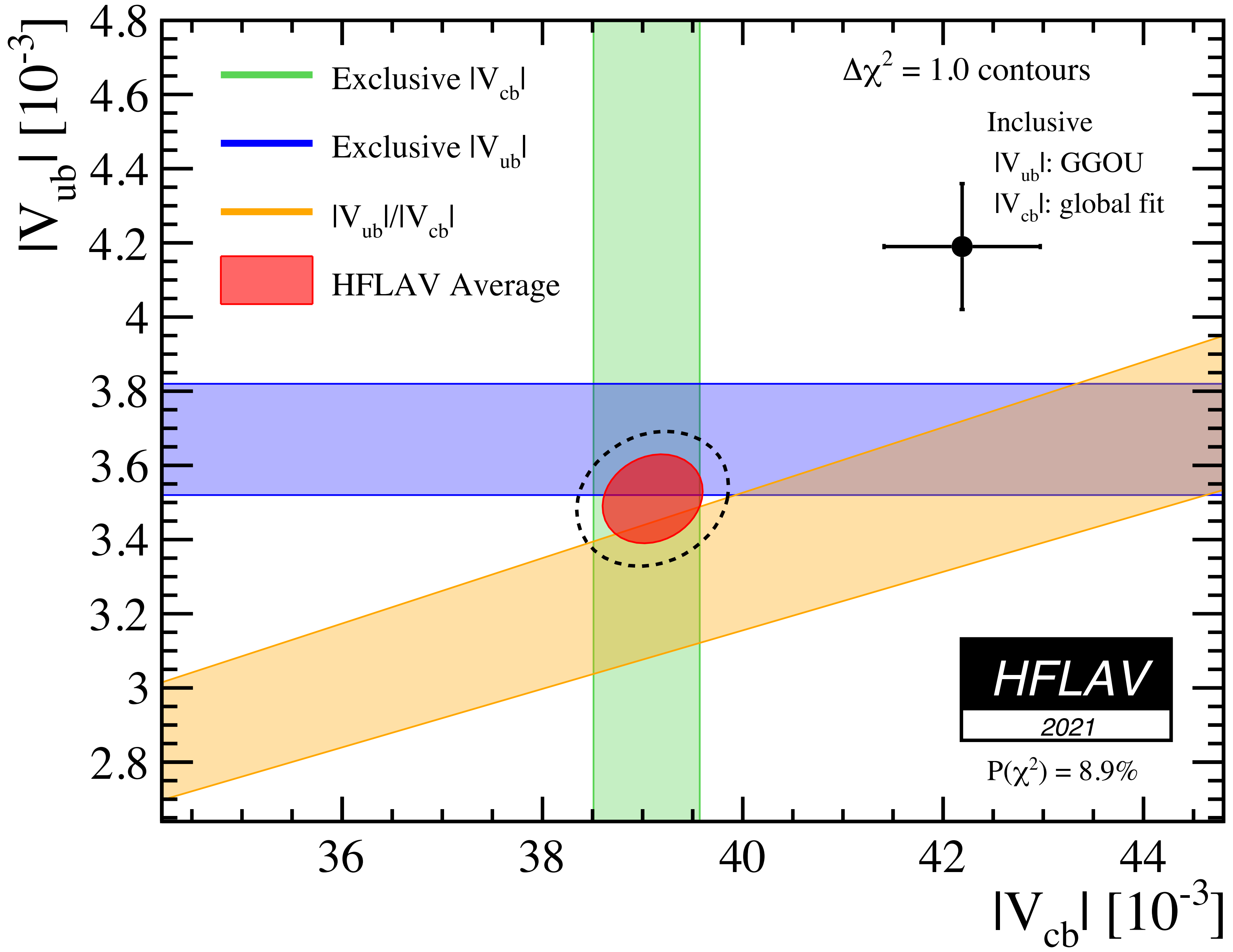
CKM Matrix elements

- Unitarity triangle ⇒ Powerful test of the SM
- $V_{qq'}$ required for rare decays prediction ⇒NP searches
- Focus: Longstanding **tension** (3σ) between **inclusive** and **exclusive** determination of $|V_{cb}|$ and $|V_{ub}|$
- **Semileptonic B decays** ⇒ natural channels
- Several efforts in Belle II:
  - inclusive $B \to X_c \ell \nu$
  - $|V_{cb}|$ from $B \to D^* \ell \nu$ with hadronic tagging
  - $|V_{ub}|$ from $B \to \pi e \nu$ with hadronic tagging



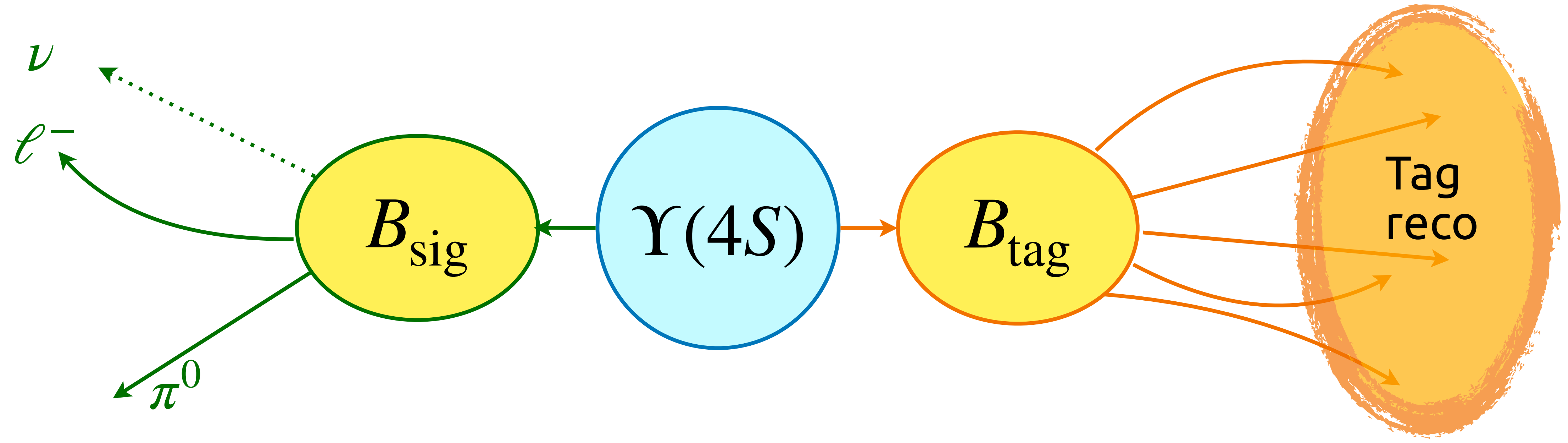


[CKM Fitter, 2021]



[HFLAV, 2021]

B-tagging at Belle II



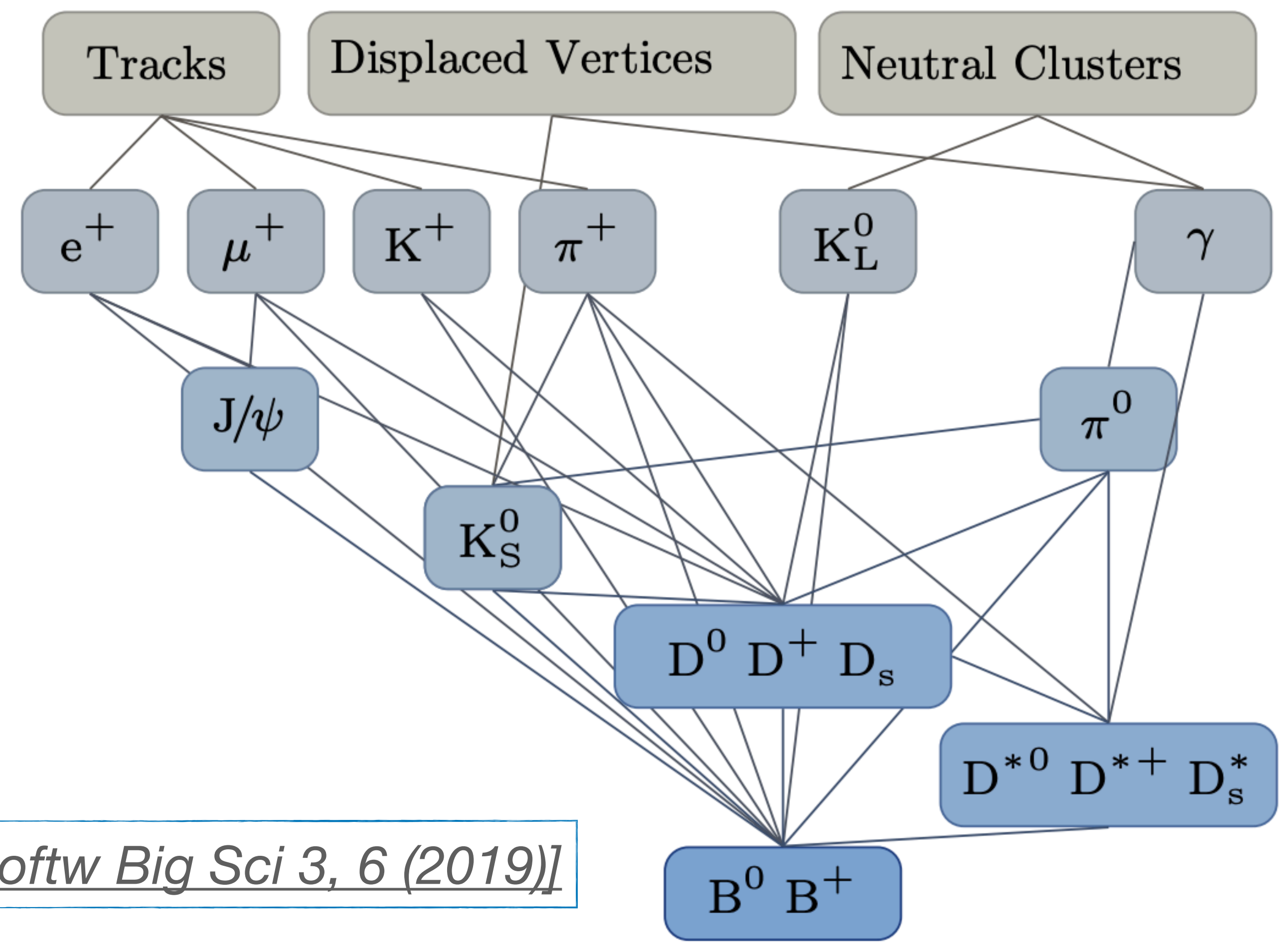
In channels with missing energy ⇒ use of the the **Rest of the Event (ROE)** information:

1. Reconstruction of one B (B_{tag}) using **well-known channels**
2. Using the $\Upsilon(4S)$ constraint, infer the information on the second B (B_{sig}): **flavour**, **charge** and **kinematic** constraints

- **Hadronic tagging:** lower efficiency, but full tag reconstruction
- **Semileptonic Tagging:** higher efficiency, but lower purity
- **Inclusive Tagging:** signal reconstruction first, and then use of the ROE to add information to the signal

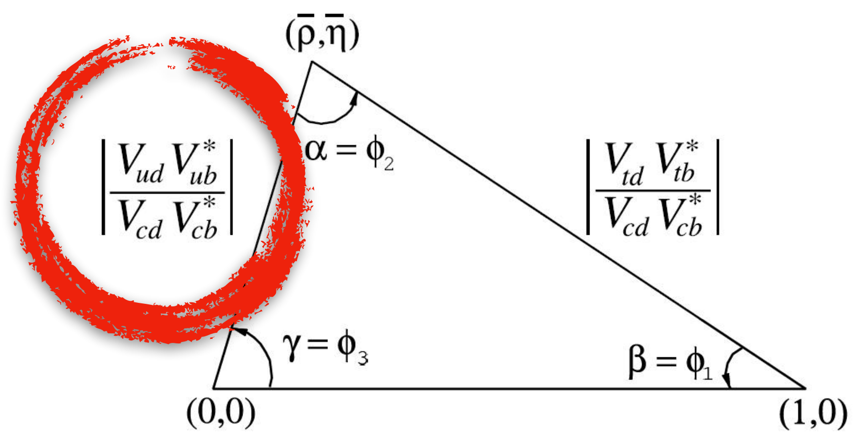
Full Event Interpretation (FEI)

- MVA based B-tagging algorithm
- hierarchical approach to reconstruct $\mathcal{O}(10^4)$ decay chains
- $\varepsilon_{had} \simeq 0.5\,\%\,,\quad \varepsilon_{SL} \simeq 2\,\%$



[T. Keck et al, Comput Softw Big Sci 3, 6 (2019)]

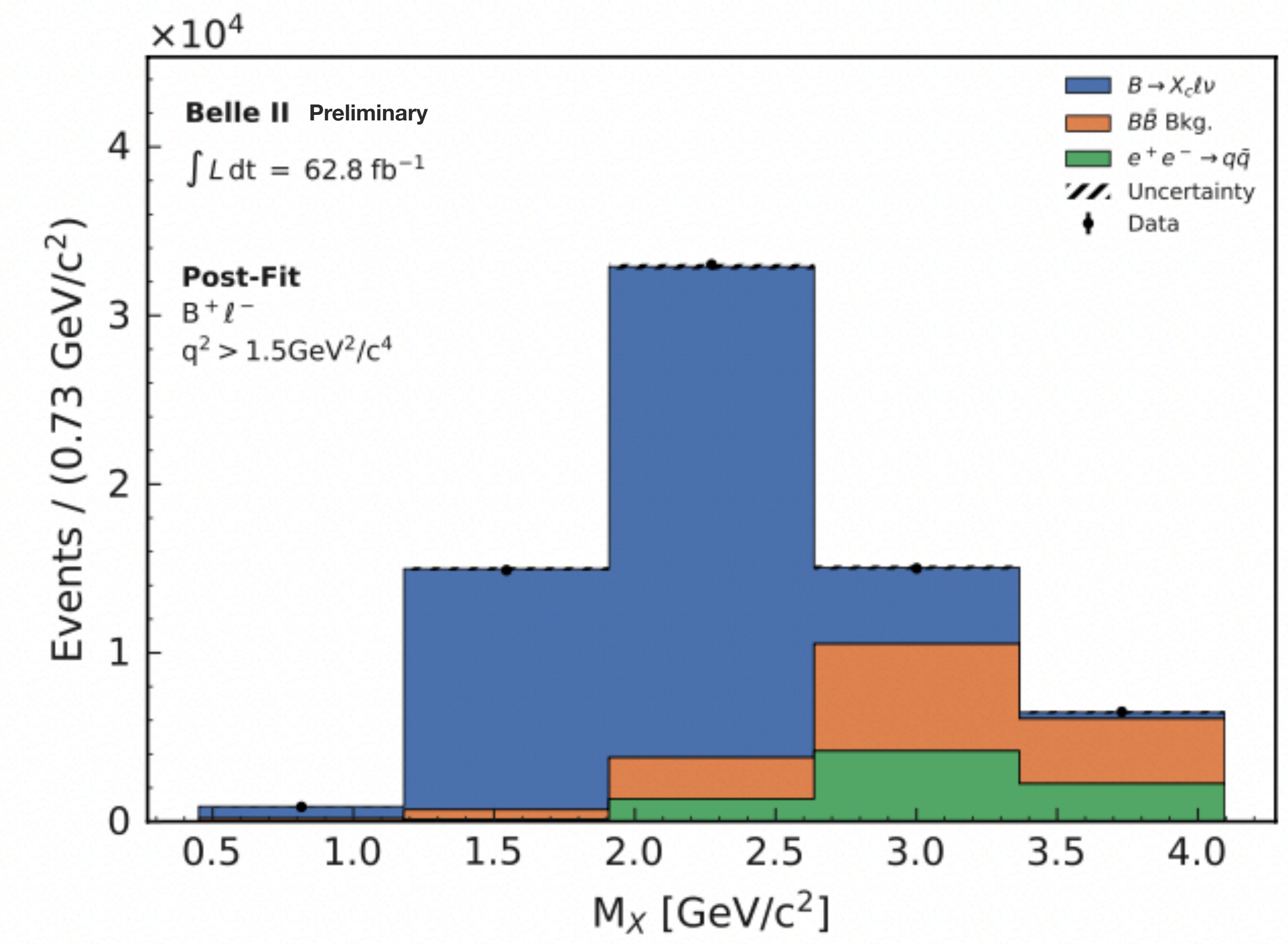
CKM Matrix: q^2 moments from $B \to X_c \ell \nu$

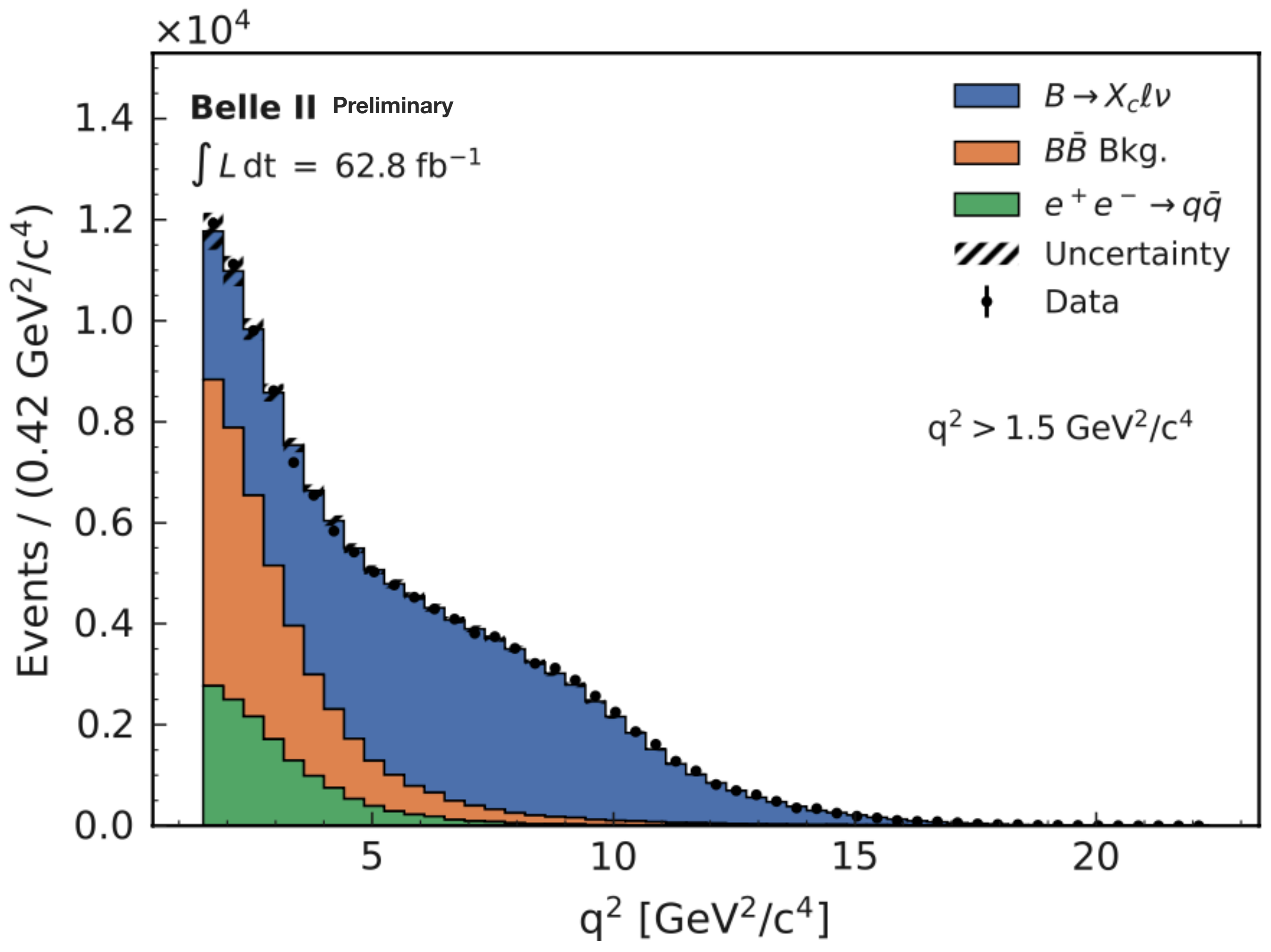


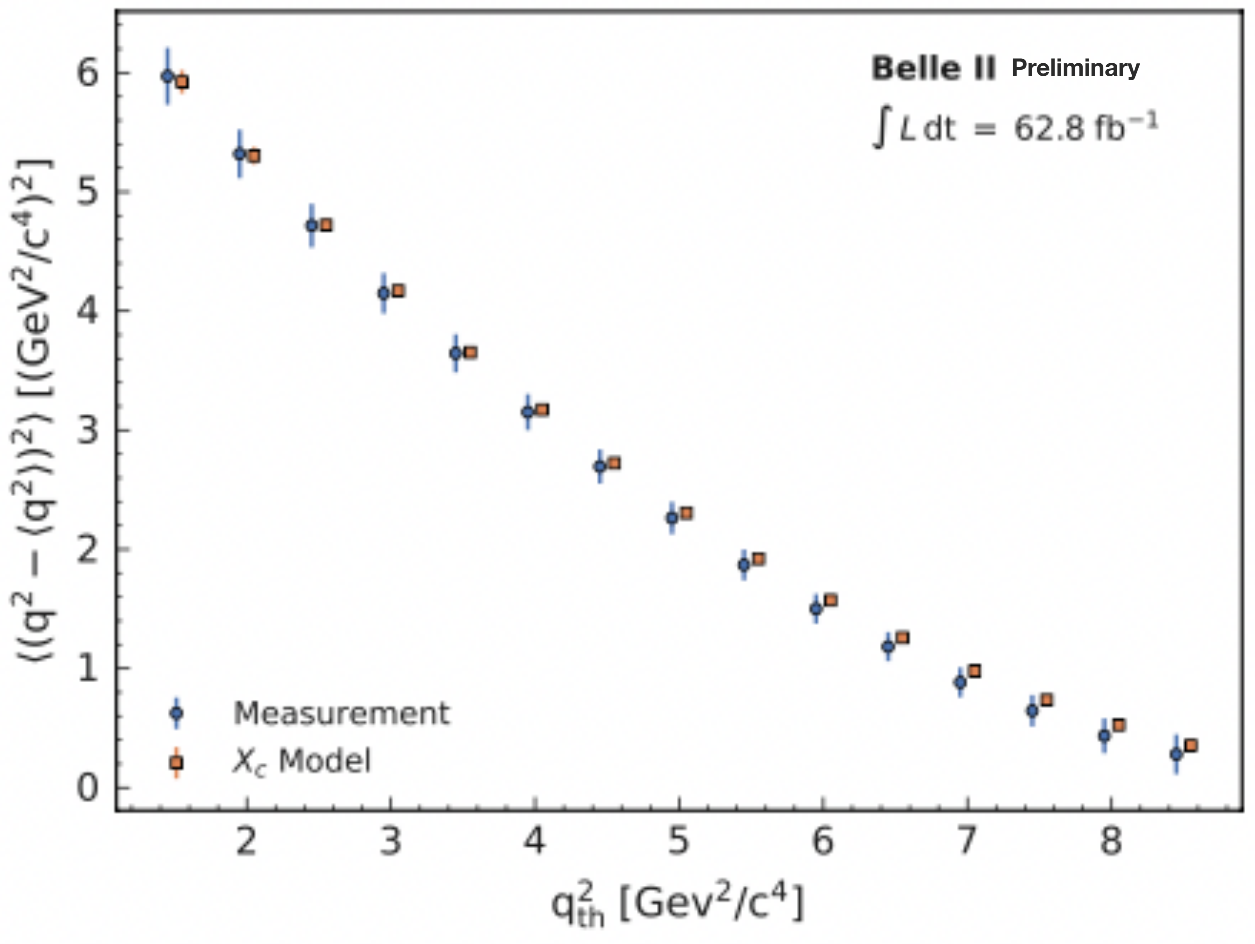
63 fb^{-1}

[arxiv:2205.06372]

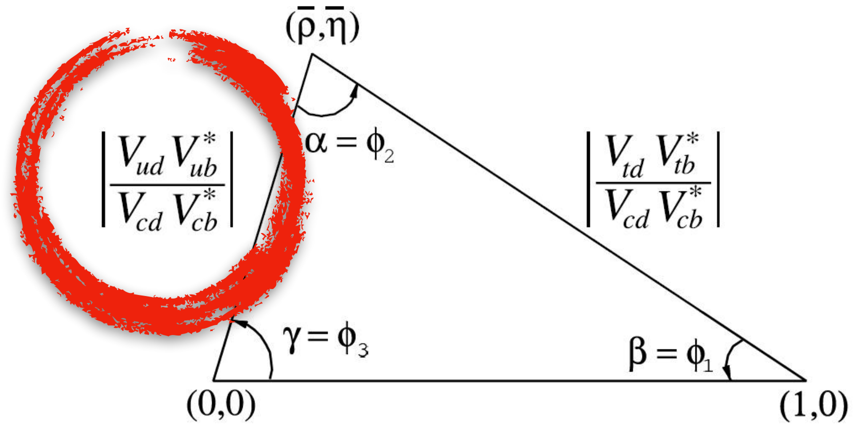
- Motivation:
  - Heavy Quark Expansion (**HQE**) $\Rightarrow$ extract $|V_{cb}|$ from $\Gamma_{B\to X_c\ell\nu}$
  - **Reparametrization invariance** to reduce 13 $\to$ 8 matrix elements (up to $1/m_b^4$)
  - Required the spectral moments of $q^2 = (p_\ell + p_\nu)^2 = (p_b - p_{X_c})^2$ [arXiv:1812.07472]
- **Hadronic B-tagging**, X_c as ROE of $B_{\text{tag}}\ell$ + kinematic fit + $\boldsymbol{M_X}$ **template fit** for bkg suppression
- $\langle q^{2n} \rangle = \dfrac{\sum_i w_i(q^2) q^{2n}_{\text{cal},i}}{\sum_i w_i(q^2)} C_{\text{cal}} C_{\text{gen}}$ $\Rightarrow$ q^{2n} moments ($n = 1-4$) as function of q^2_{thr} (range: 1.5-8.5 GeV² i.e. 77% of phase-space)
- input for the **fit** (eg. [arXiv:2205.10274]) $\Rightarrow$ $|V_{cb}| = (41.69 \pm 0.63)\cdot 10^{-3}$ (w.a. $42.19 \pm 0.78 \cdot 10^{-3}$)







CKM Matrix: exclusive $|V_{cb}|$ and $|V_{ub}|$



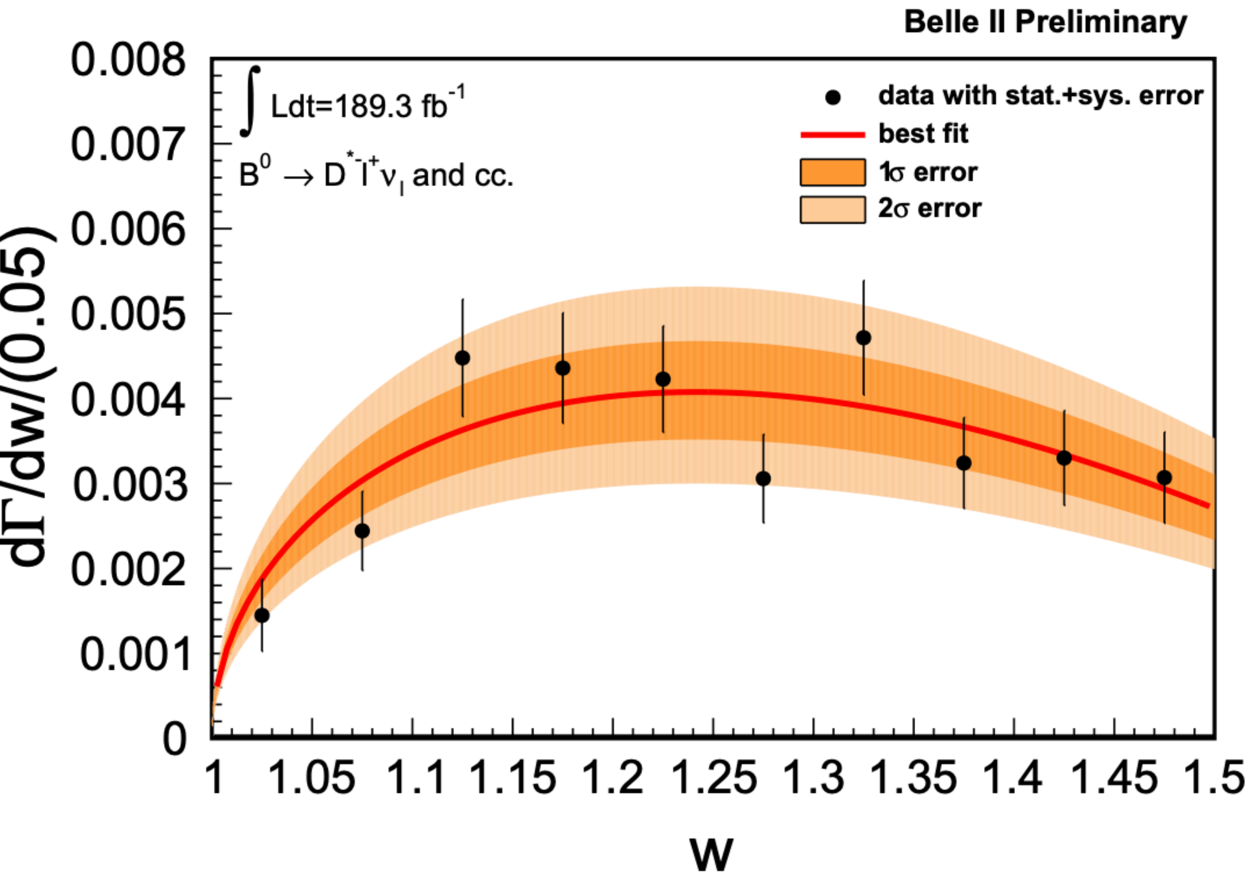
$190\ \text{fb}^{-1}$

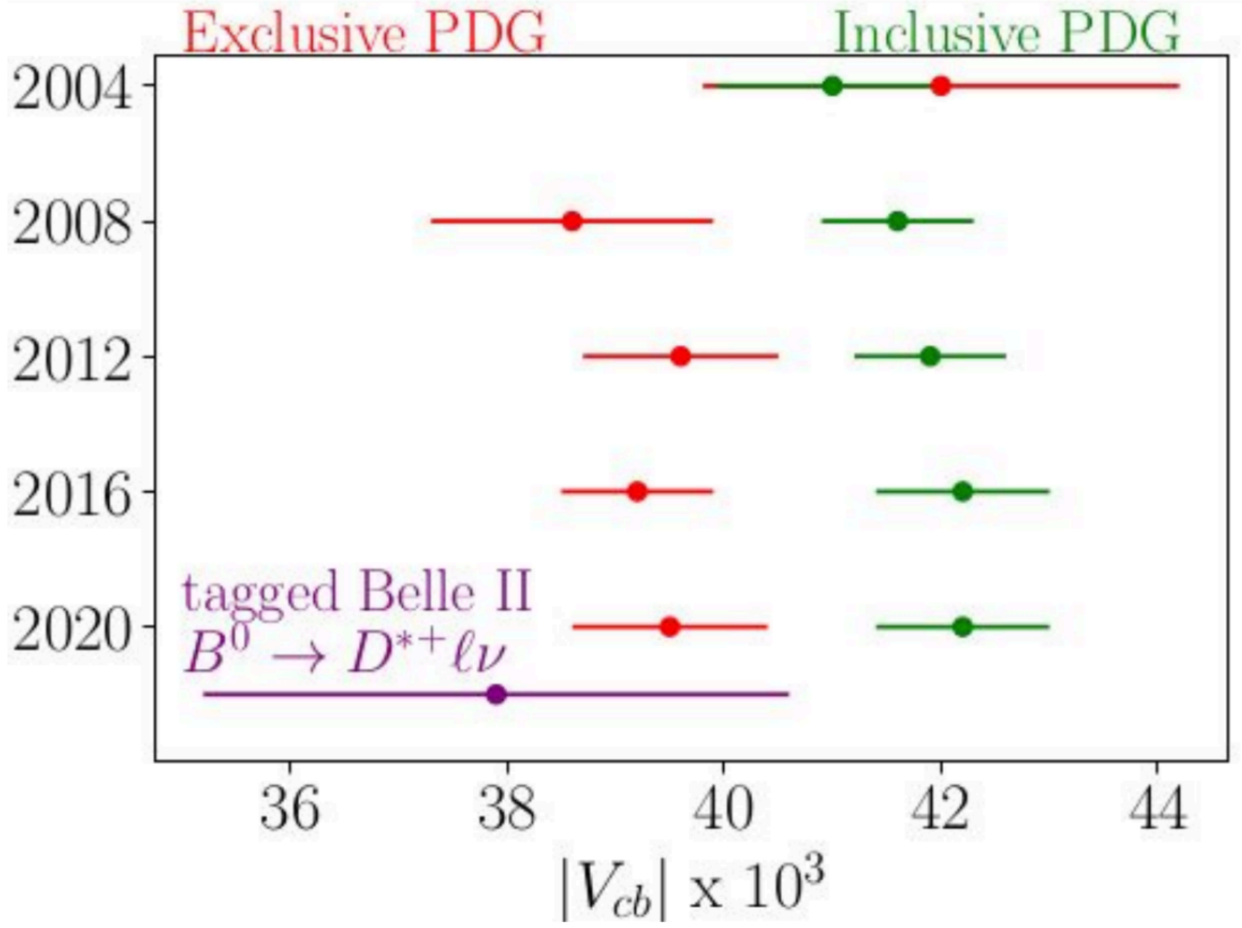
[BELLE2-TALK-CONF-2022-032]

$B \to D^*\ell\nu$

- **Hadronic B-tagging,** $B^0 \to D^{*-}(\to \overline{D}^0(\to K^+\pi^-))\ell^+\nu$
- $w = \dfrac{m_B^2 + m_{D^*} - q^2_{\ell+\nu}}{2m_B mD^*}$ ⇒Fit to: $\dfrac{d\Gamma}{dw} \propto \eta^2_{EW} g(w)F^2(w)|V_{cb}|^2$
- **CLN parametrization** $g(w)F^2(w) \to \rho^2, R_1(1), R_2(1)$ and $F(1)$ from lattice QCD [Nucl. Phys. B530, 153 (1998)]
- $\text{BR}(B \to D^*\ell\nu) = (5.27 \pm 0.22 \pm 0.38)\ \%$

$\eta_{EW}F(1)|V_{cb}| = (3.54 \pm 0.4)\cdot 10^{-3},\ \ \rho^2 = 0.94 \pm 0.21$



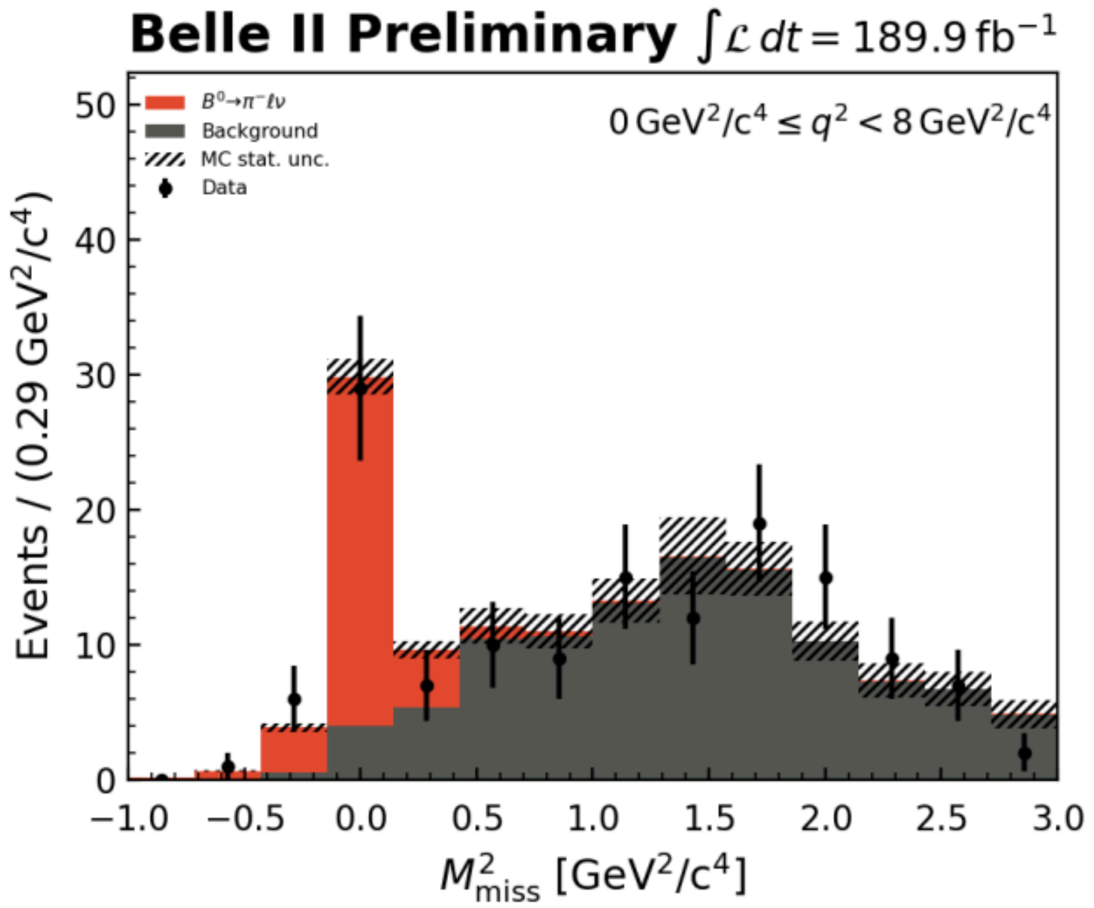


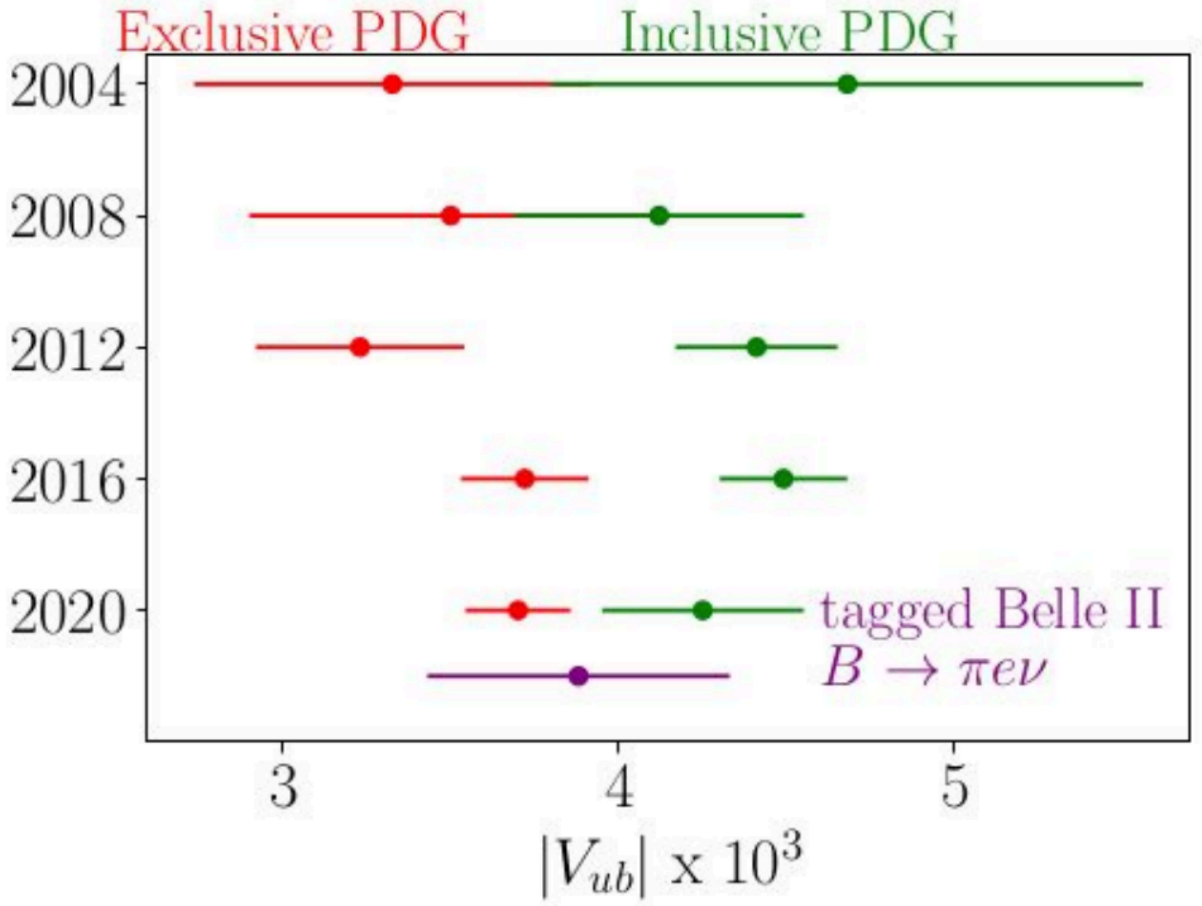
$|V_{cb}| = (37.9 \pm 2.7)\cdot 10^{-3}$ (stat+syst)

$B \to \pi e\nu$

[arXiv:2206.08102]

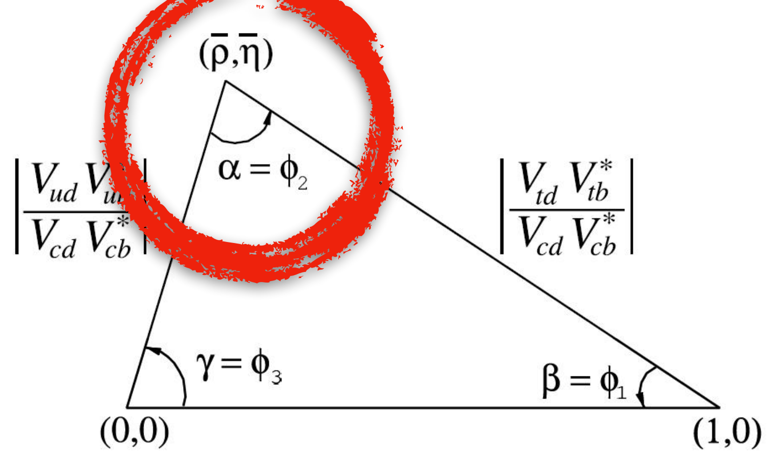
- **Hadronic B-tagging,** neutral and charged π
- Fit to M^2_{miss} in 3 bins of $q^2_{\ell\nu}$
- Unfolding $q^2 \Rightarrow \dfrac{d\text{BR}(B \to \pi\ell\nu)}{dq^2} \propto |V_{ub}|^2 f_+^2(q^2)$
- Lattice QCD inputs: [Phys. Rev. D 92, 014024 (2015)] [Phys. Rev. D 79, 013008 (2009)]





$|V_{ub}| = (3.88 \pm 0.45)\cdot 10^{-3}$ (stat+syst)

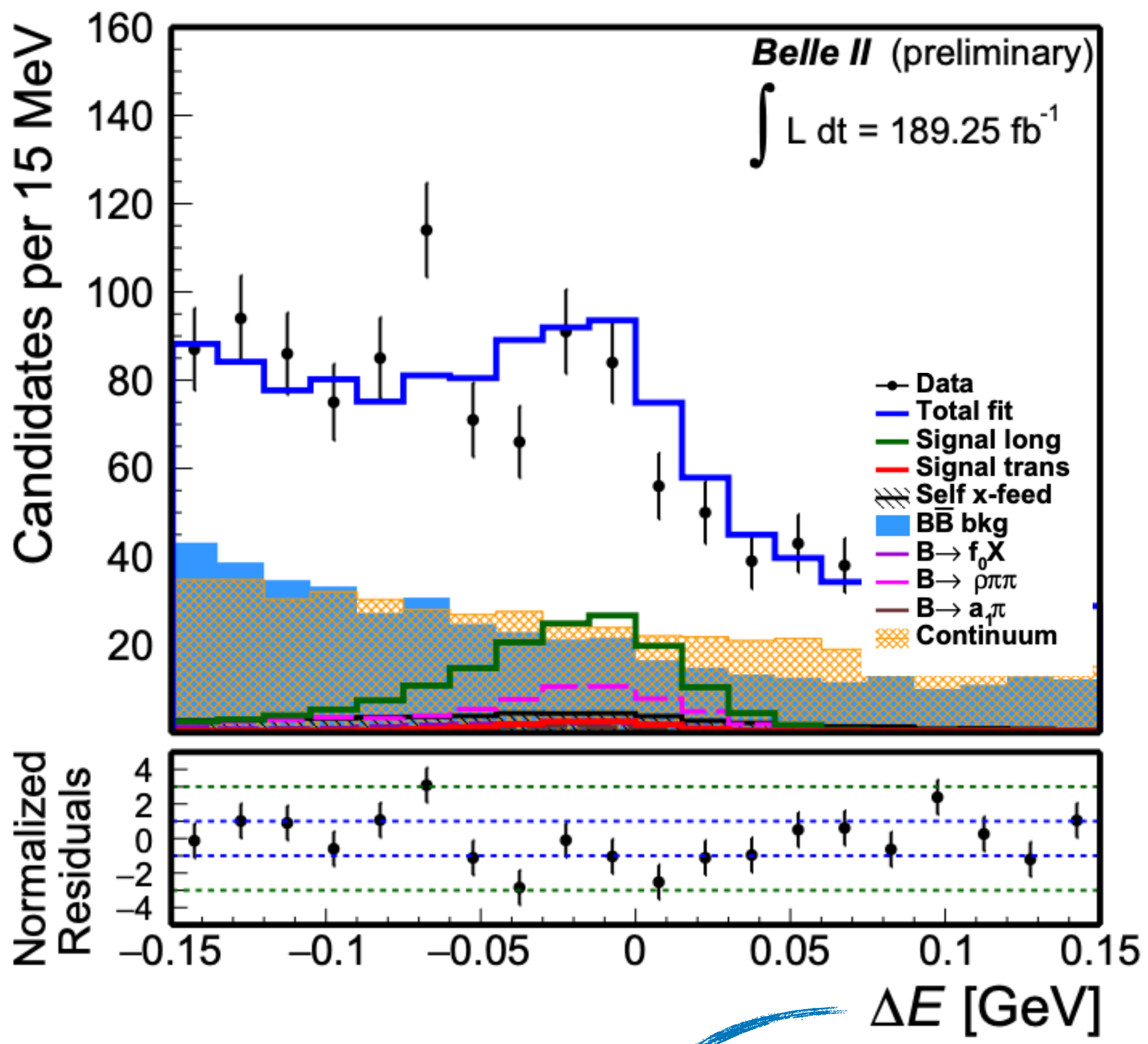
CP Violation: $B^+ \to \rho^0\rho^+$



190 fb^{-1}

[arXiv:2206.12362]

- Motivation:
  - access **direct CP violation** (A_{CP} between $B^+ \to \rho^0\rho^+$ and $B^- \to \rho^0\rho^-$ in the interference between tree and penguins)
  - **measurement α angle** (time dependent CPV)
- Reconstruction: $\rho^0(\to \pi^+\pi^-)\rho^+(\to \pi^+\pi^0)$
- Bkg: $ee \to q\bar{q}$ suppressed with BDT
- Fit: **6D fit** (ΔE, bkg sup., $m_{\pi^+\pi^0}$, $m_{\pi^+\pi^-}$, $\theta^{\text{helicity}}_{\rho^{0,+}}$)
- Results: similar to luminosity-scaled Belle result (w.a. $A_{CP} = -0.05 \pm 0.05$)



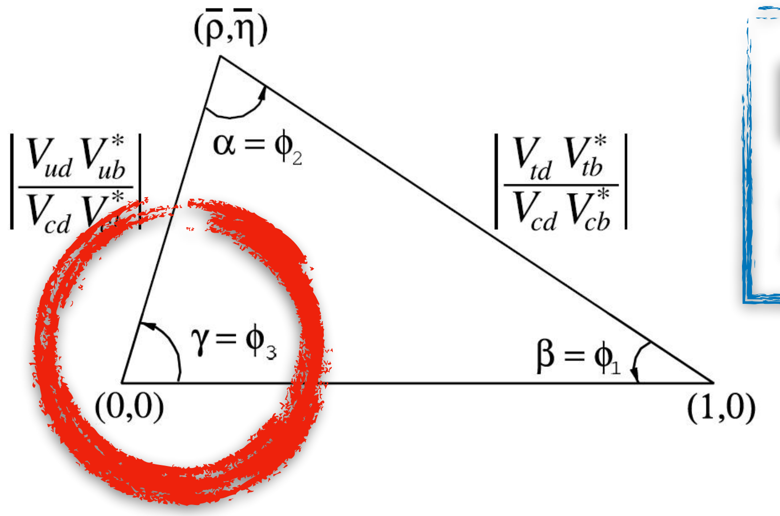
$$\Delta E = E^*_B - E^*_{\text{beam}}$$

$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [23.2^{+\,2.2}_{-\,2.1}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6},$$

$$f_L = 0.943^{+\,0.035}_{-\,0.033}(\text{stat}) \pm 0.027(\text{syst}),$$

$$\mathcal{A}_{CP} = -0.069 \pm 0.068(\text{stat}) \pm 0.039(\text{syst}).$$

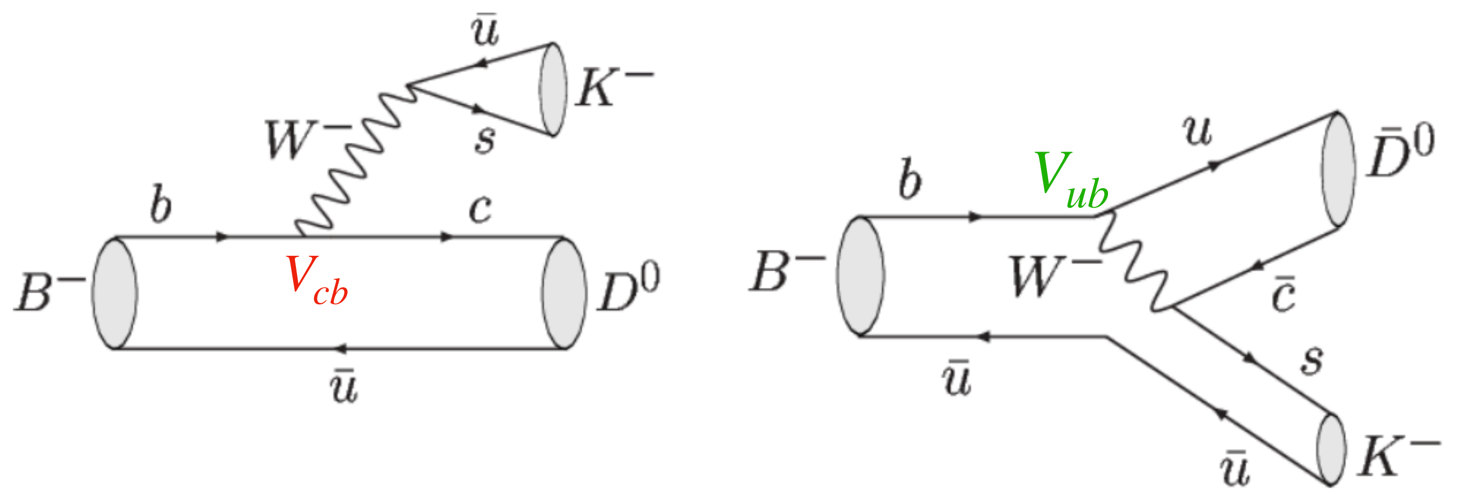
CP Violation: $B^+ \to D(\to K_S h^- h^+) h^+$

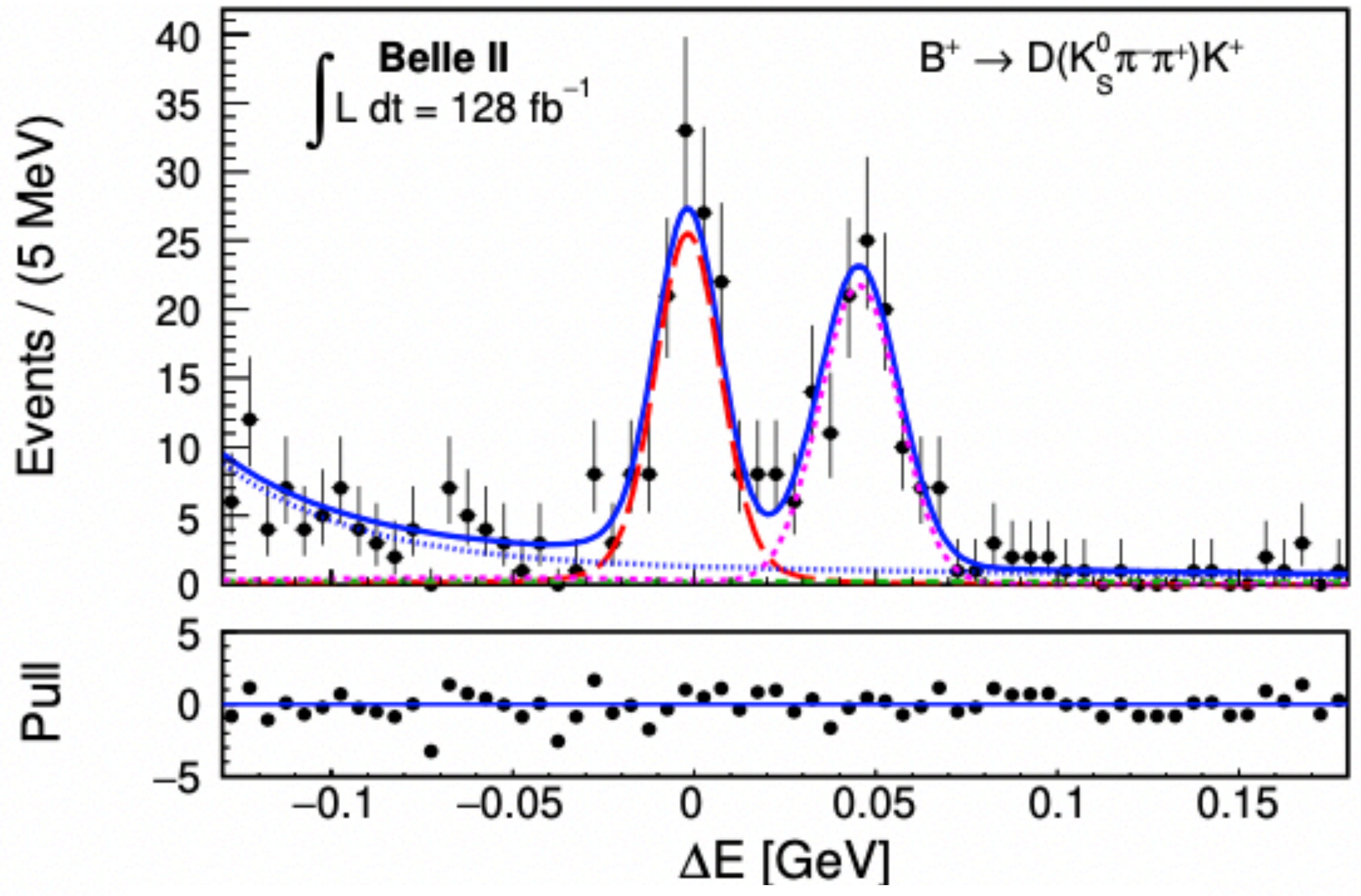


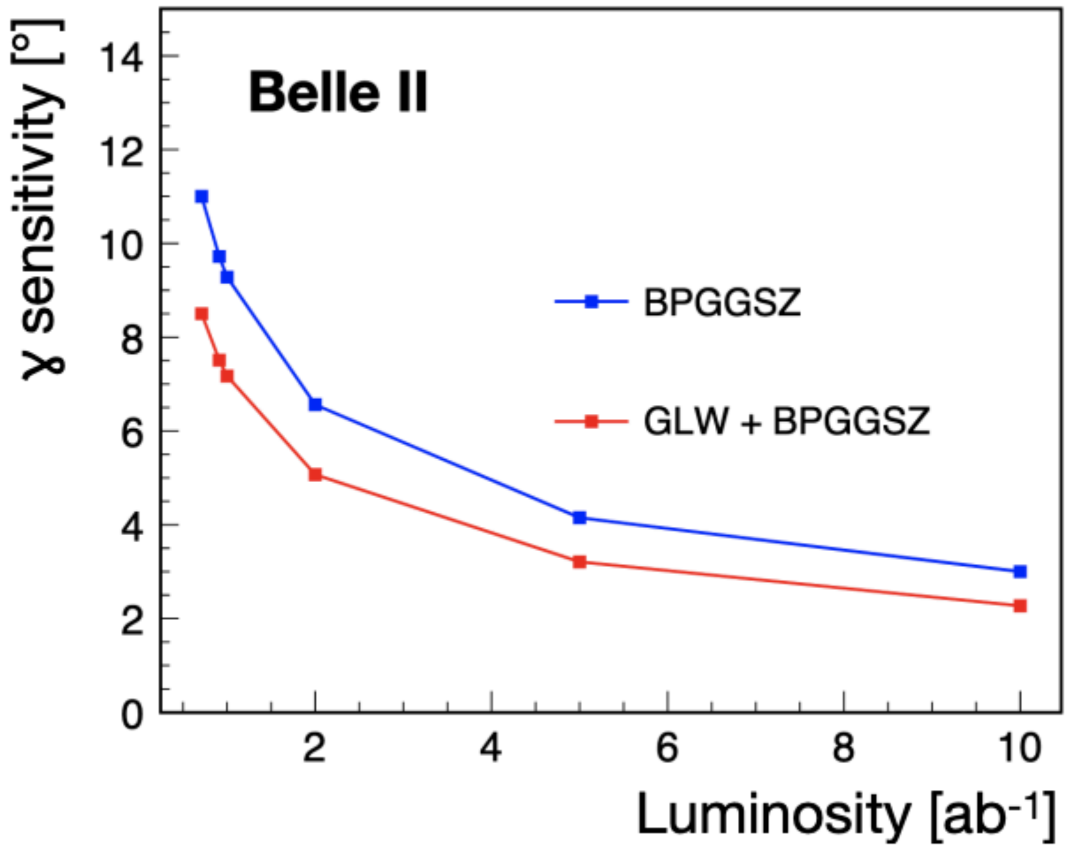
Belle II + Belle: $128\ \mathrm{fb}^{-1} + 711\ \mathrm{fb}^{-1}$

[JHEP 02 2022, 063 (2022)]

- Motivation:
  - CPV in the interference $b \to c\bar{u}s$ and $b \to u\bar{c}s \Rightarrow \frac{A_{\rm sup}(B^- \to \overline{D^0}K^-)}{A_{\rm fav}(B^- \to D^0K^-)} = r_B e^{i(\delta_B - \phi_3)} \Rightarrow \gamma\ (\phi_3)$
  - Tree-dominated $\Rightarrow \Delta\gamma_{\rm theory}/\gamma \sim 10^{-7}$
- self-conjugate D^0 decays: $D \to K_S^0\pi^+\pi^-, K_S^0K^+K^-$
- binning in Dalitz space $\Rightarrow$ **model independence**
- Use of strong phases from **external input** (CLEO, BES III)
- simultaneous fit of $B^+ \to D(\to K_S hh)K^+$ and control sample $B^+ \to D(\to K_S hh)\pi^+$ to constrain the fraction of event in each dalitz bin
- **Fit to $\Delta E \times C'_{\rm BDT}$**
- Results: $\gamma[^\circ] = 78.4 \pm 11.4({\rm stat}) \pm 0.5({\rm syst}) \pm 1.0 \pm ({\rm ext})$ (W.A=$65.9^{+3.3}_{-3.5}$)







TDCPV: B^0 lifetime and mixing frequency

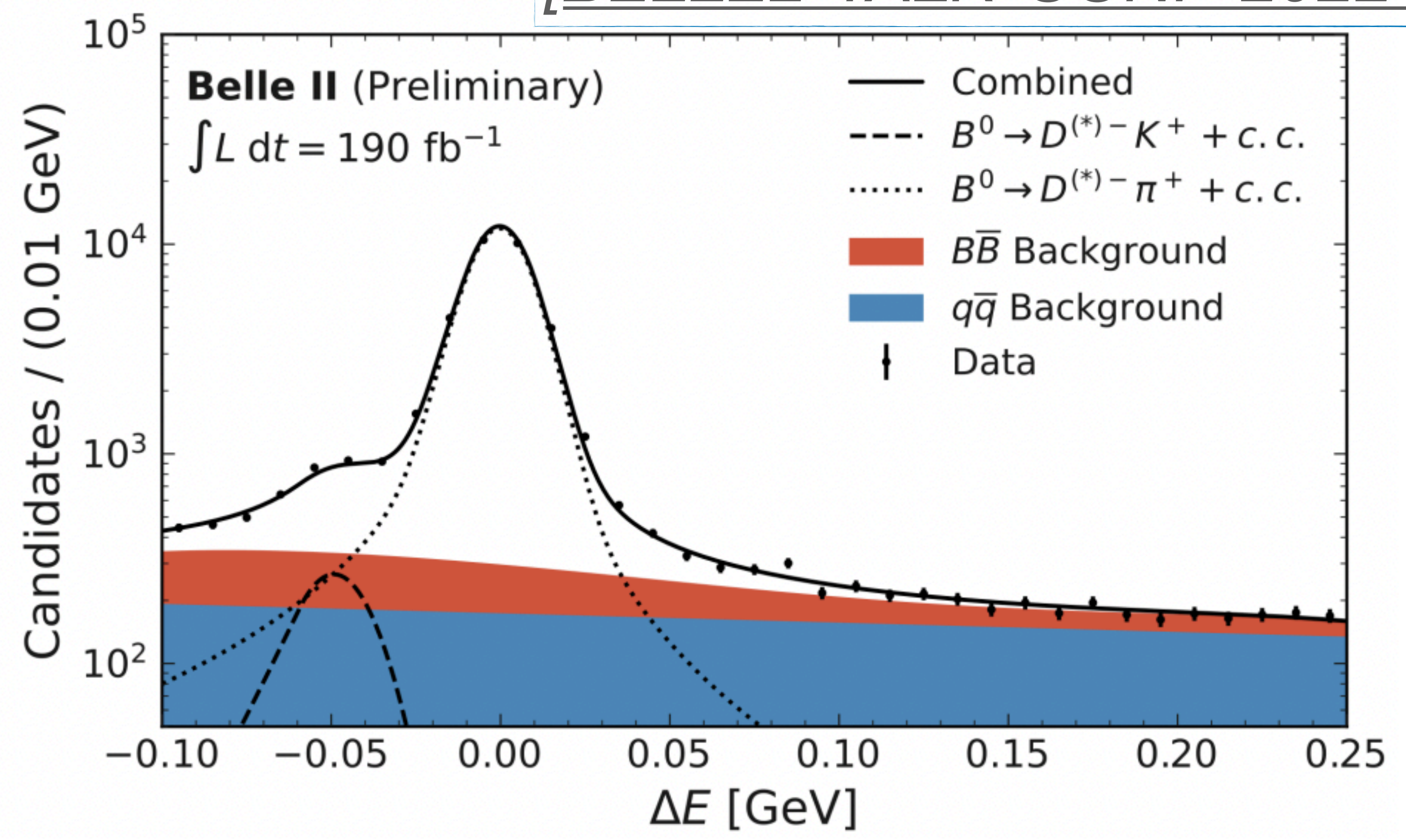
$190\ \text{fb}^{-1}$

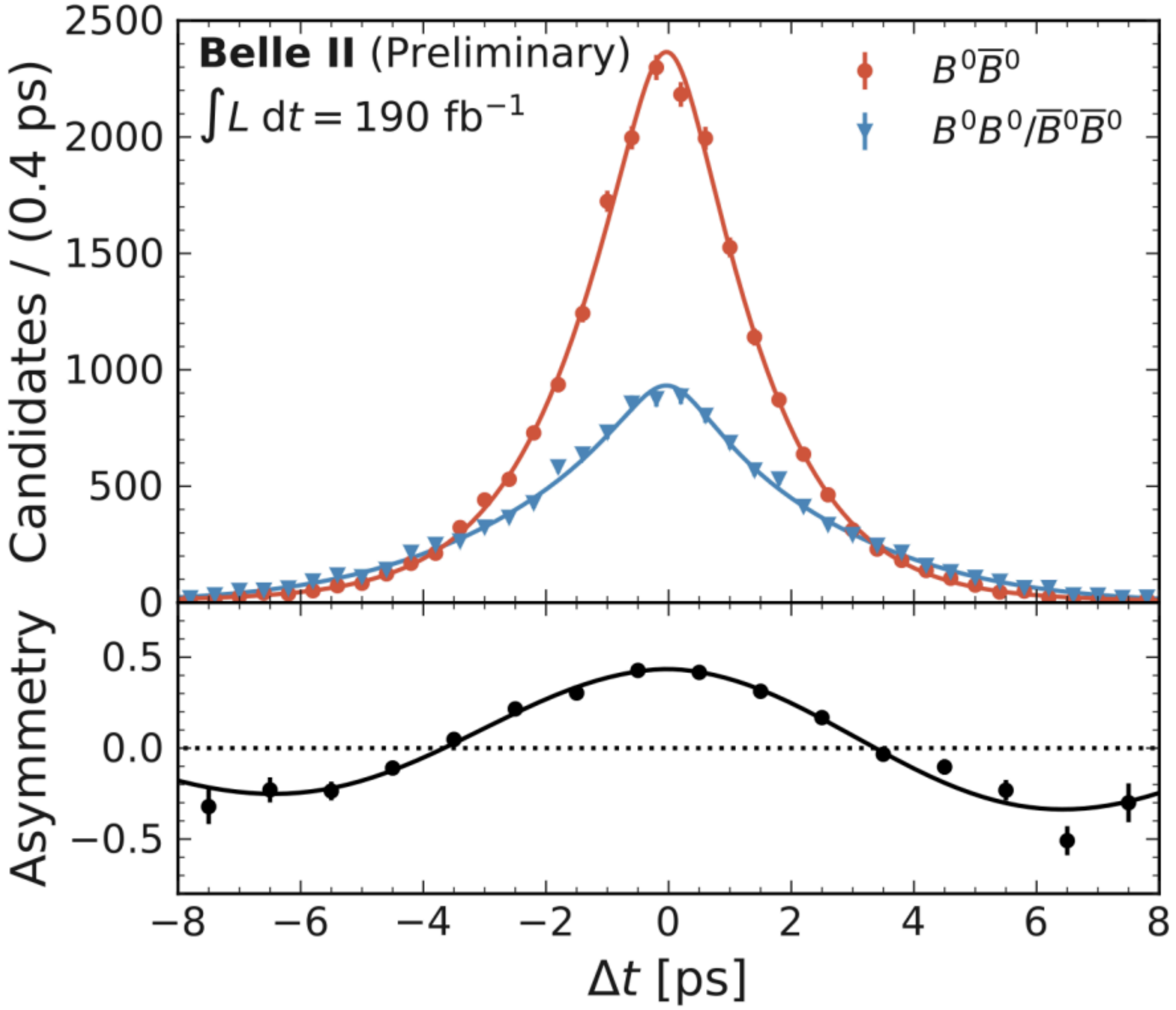
[BELLE2-TALK-CONF-2022-031]

- Motivations: Δt and Δm_d are central ingredients for **TDCPV** analysis
- Reconstruction:
  - B^0_{sig} reconstruction in specific $D^{(*)}\pi^+/K^+$ modes
  - B_{tag} reconstruction from the Rest Of the Event tracks
  - Flavour tagging ⇒ Same Flavour / Opposite Flavour categories
- Bkg: $ee \to q\bar{q}, B\bar{B}$ suppressed with ΔE+BDT
- Fit: Δt using a model including **wrong-tagging** and **vertex resolution** effects
- Results: Not competitive, but syst. reduced compared to Belle

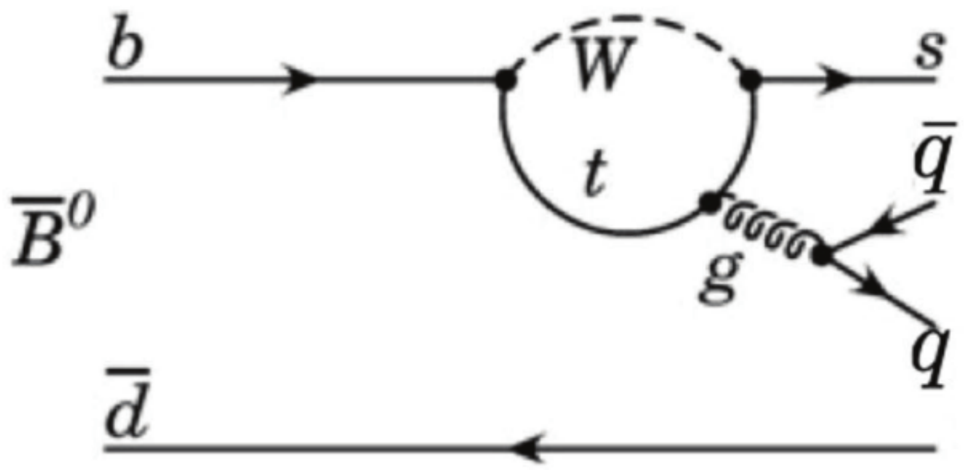
$\tau_{B^0} = 1.499 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})\ \text{ps}$	w.a. $1.510 \pm 0.004\,\text{ps}$
$\Delta m_d = 0.516 \pm 0.008\,(\text{stat}) \pm 0.005\,(\text{syst})\ \text{ps}^{-1}$	w.a. $0.50665 \pm 0.0019\,\text{ps}^{-1}$

- Next steps: add **semileptonic**, $\mathbf{\sin 2\beta}$, increase **statistic** (Belle measurement is only 150 fb^{-1}, but included semileptonic)





TDCPV: $B^0 \to K^0_S \pi^0$



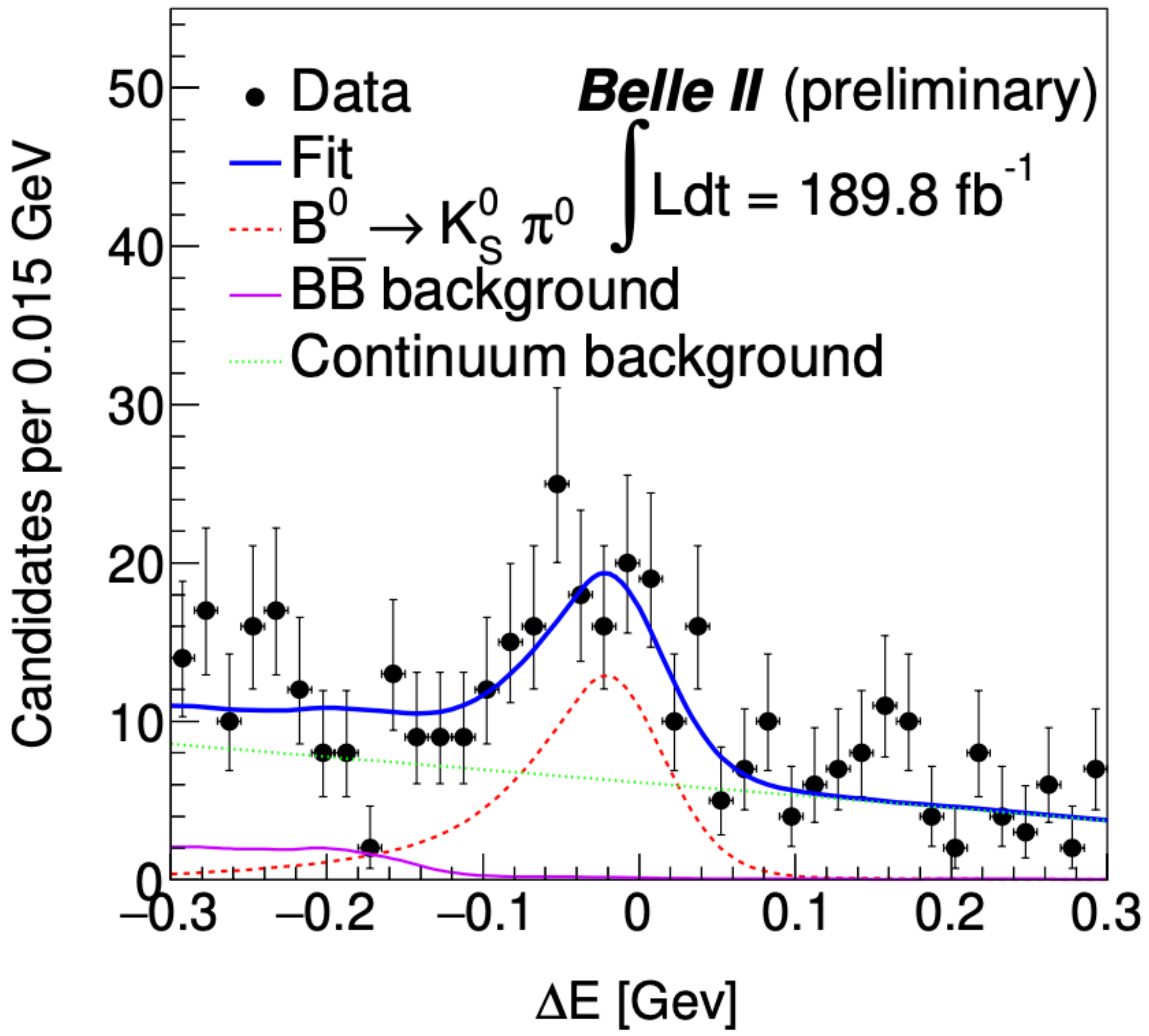
190 fb^{-1}

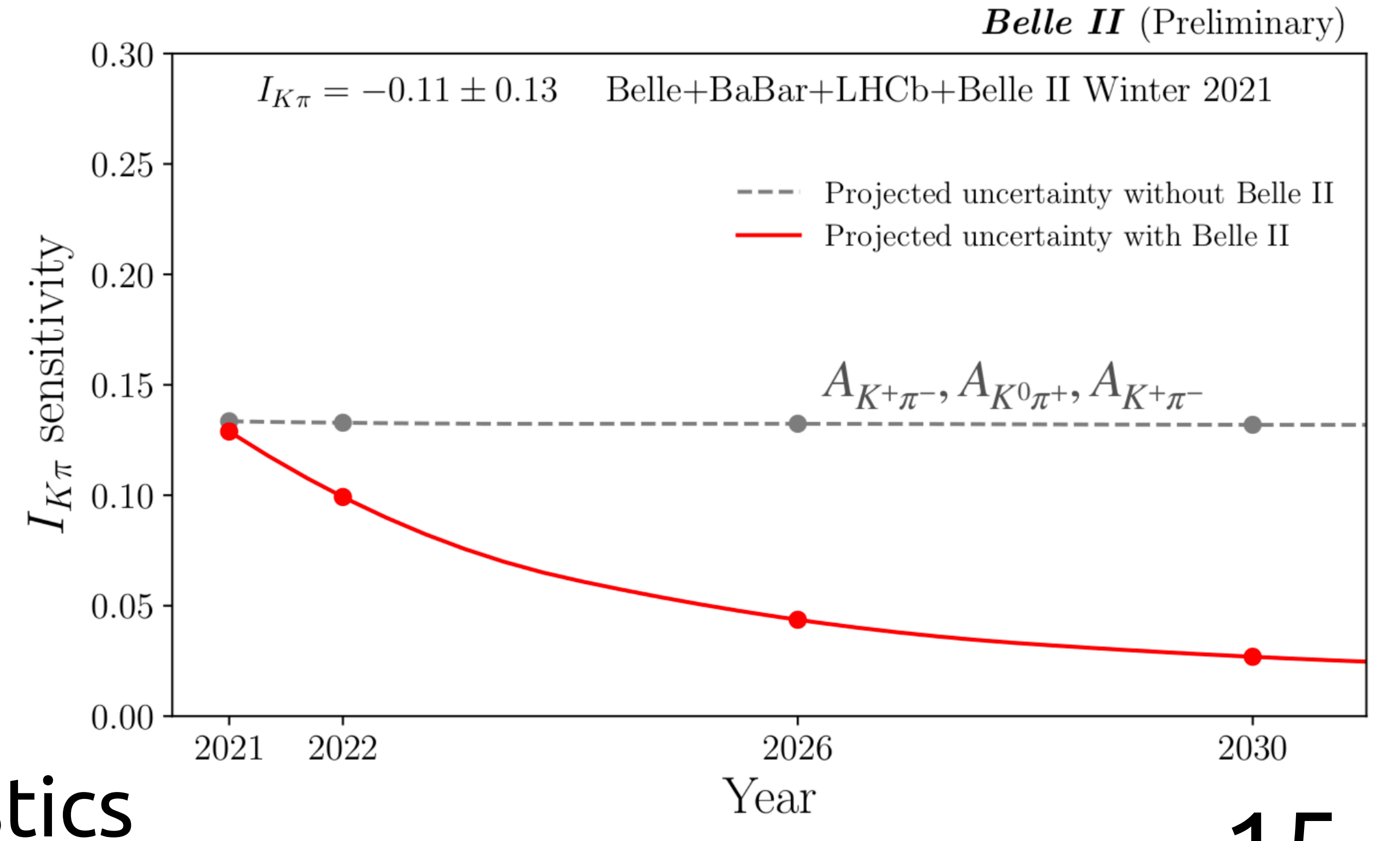
[arXiv:2206.07453]

- Motivation:
  - **Suppressed in SM** ($b \to s d\bar{d}$ loop)
  - **CPV direct** (A_{CP}) or in **mixing** (S_{CP}), SM predict $A_{CP} \simeq 0,\ S_{CP} \simeq \sin 2\beta$
  - ***Kπ*-puzzle**: $I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$

    Current measured value $I_{K\pi} = -0.11 \pm 0.13$, main unc. from $A_{K^0\pi^0}$ [Phys.Lett. B627 (2005) 82-88]
- Reconstruction: $K^0_S \to \pi^+\pi^-$, $\pi^0 \to \gamma\gamma$ + **use of K^0_S vertex** + flavour tag
- **4D ML fit** to $\Delta E, M'_{bc}, C'_{out}, \Delta t$
- Results: equivalent of full Belle precision

Observable	Fitted value	WA[1] value
$\mathscr{B}(B^0 \to K^0\pi^0) \times 10^{+6}$	$11.0 \pm 1.2(stat) \pm 1.0(syst)$	9.9 ± 0.5
$\mathcal{A}_{CP}$	$-0.41^{+0.30}_{-0.32}(stat) \pm 0.09(syst)$	-0.01 ± 0.10





- Next steps:
  - perform a full TDCPV analysis: $\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q\{\mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)\}]$
    (S_{CP}, Δm kept fixed in current fit)
  - In the same fashion $\boldsymbol{B^0 \to K^0_S \pi^0 \gamma}$ **analysis**: currently only BR, but TDCPV with more statistics
    [more details in the backup]

Rare B decays

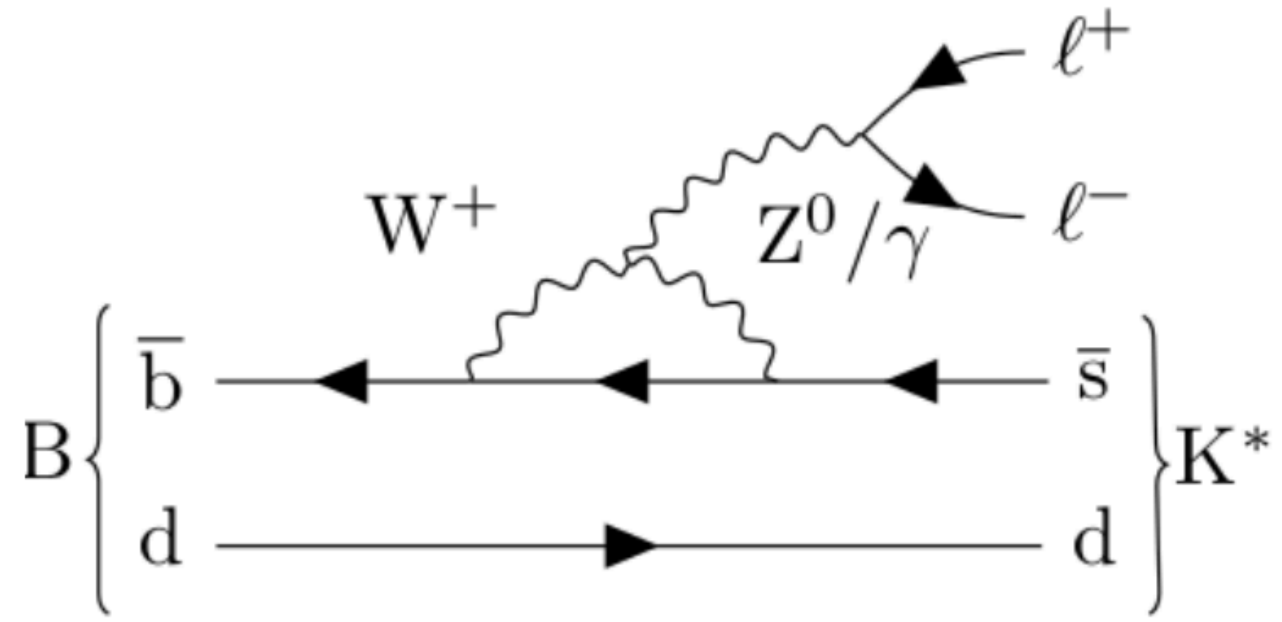
- $b \to s$ transitions are **FCNC** ⇒SM suppressed (forbidden at tree level) ⇒ sensitive to NP
- SM BR $\mathcal{O}(10^{-5} - 10^{-7})$ with 10-30% uncertainty, but ratios, asymmetries, angular distributions can be used
- Opportunity to test LFU and LFV (eg. $R_{K^{(*)}}$, $B \to K\ell\ell'$)
  - NB: Belle II has similar (and good) performance **both in electron and muons**
- Most of the channels in Belle II will become **competitive with few ab**$^{-1}$, now Belle II is statistically limited
- Several unique opportunities in Belle II (radiative, multiple neutrinos)

Rare B decays: $B \to K^*\ell\ell$

190 fb^{-1}

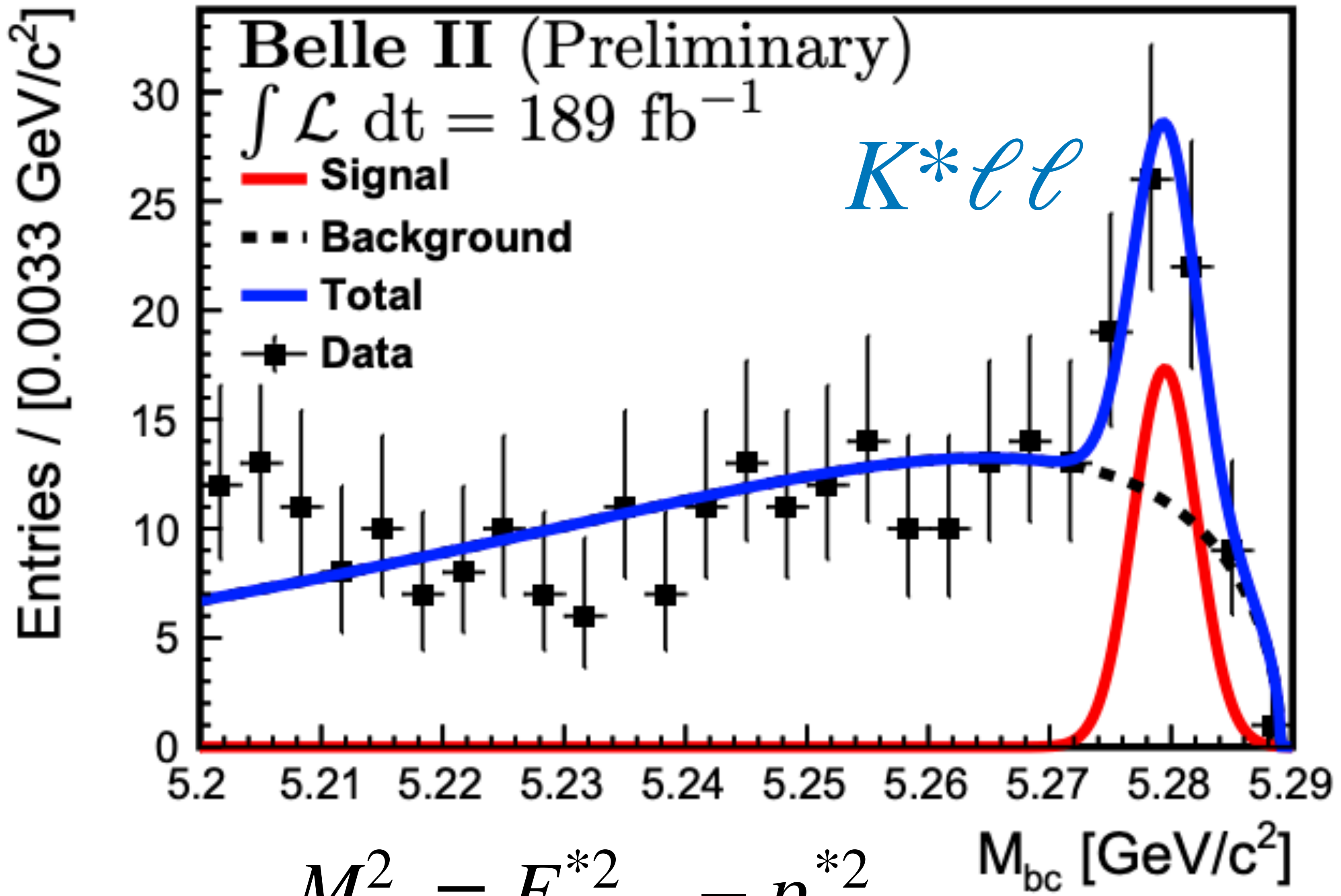
[arXiv:2206.05946]

- First step towards R_{K^*} (currently 2-3σ discrepancy with SM)
- Bkg: BDT (for $ee \to q\bar{q}, B\overline{B}$...) + veto on $M(J/\psi, \psi(2S) \to \ell\ell)$
- **2D Fit to $M_{bc} \times \Delta E$** distribution
- Results **statistically limited:**

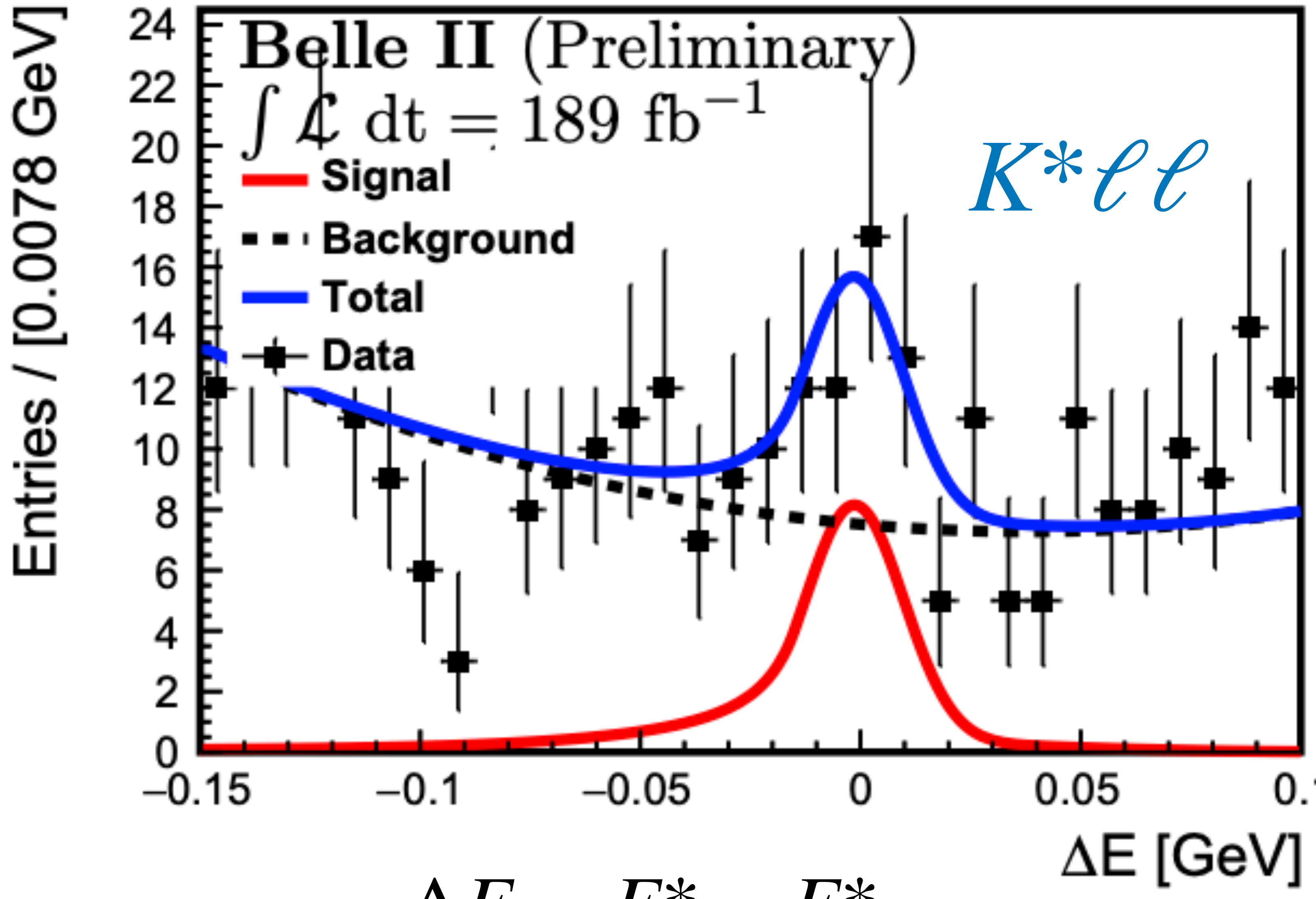


$$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30 \pm^{+0.08}_{-0.07}) \times 10^{-6}.$$

w.a.
$(1.06 \pm 0.09) \times 10^{-6}$
$(1.19 \pm 0.20) \times 10^{-6}$
$(1.05 \pm 0.10) \times 10^{-6}$



$M_{bc}^2 = E_{\mathrm{beam}}^{*2} - p_B^{*2}$

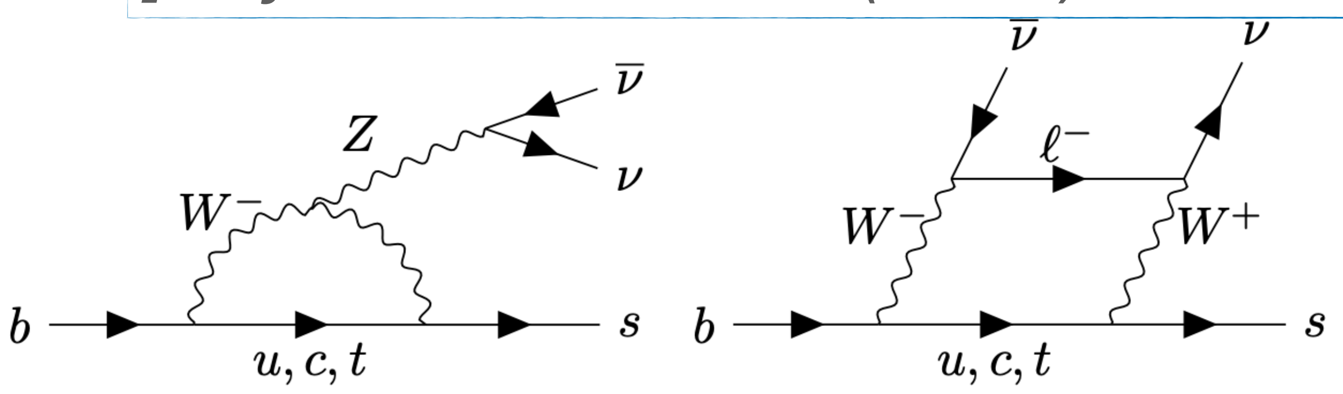


$\Delta E = E_B^* - E_{\mathrm{beam}}^*$

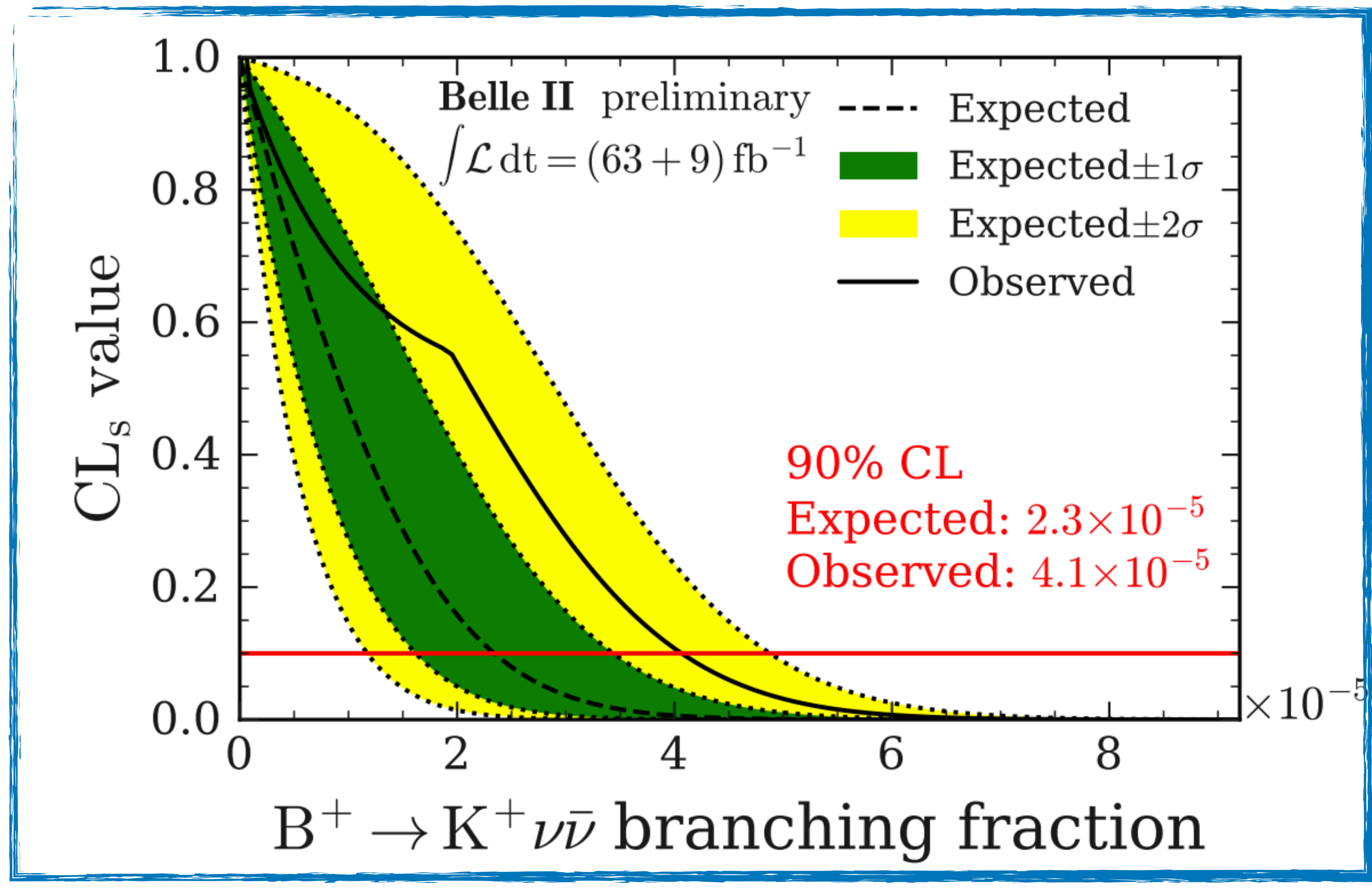
Rare B decays: $B^+ \to K^+ \nu\bar{\nu}$

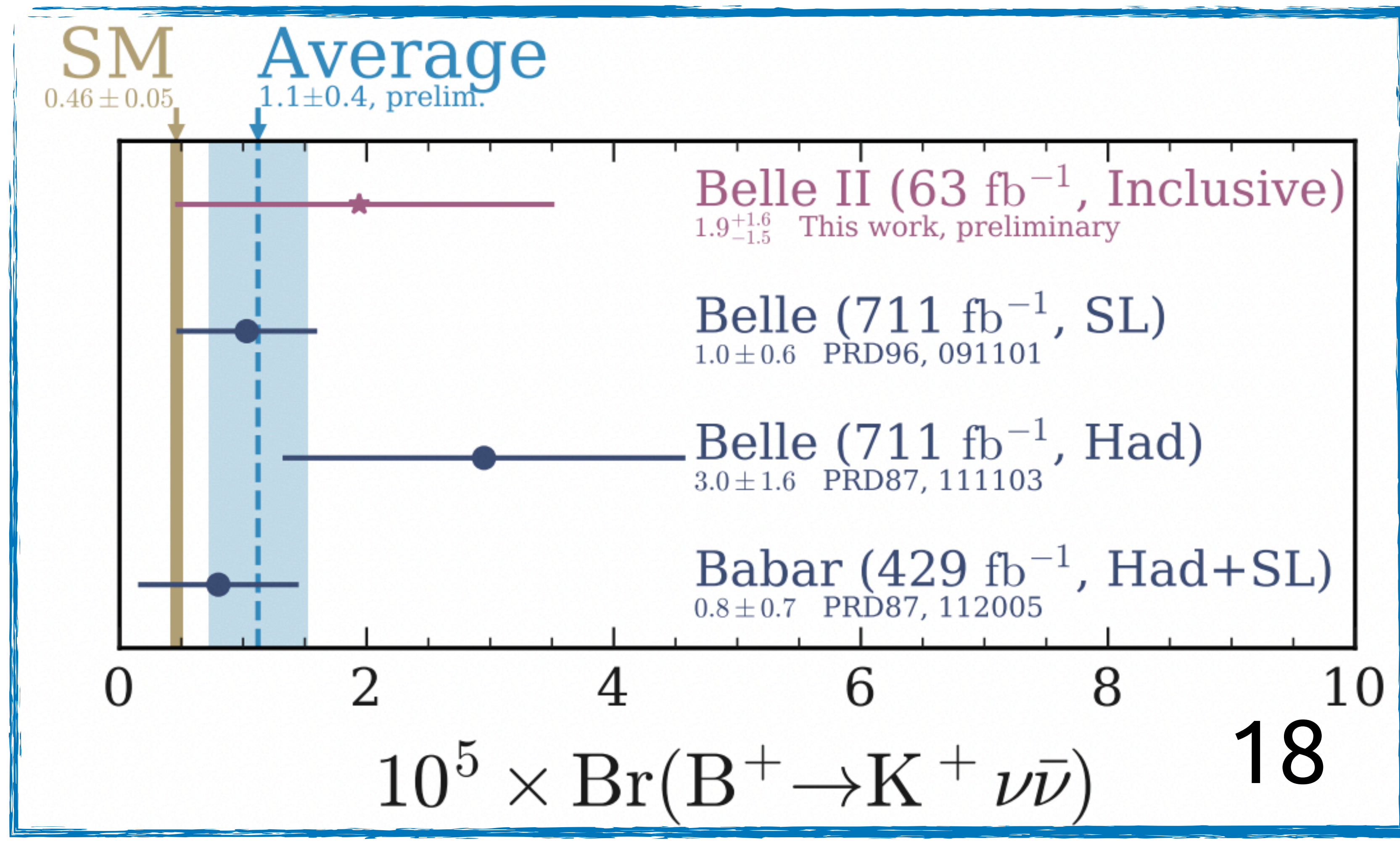
$63 \ \ \text{fb}^{-1}$

[Phys.Rev.Lett. 127 (2021) 18, 181802]



- Unique opportunity in Belle II
- Reconstruction: **inclusive tagging,** K^+ = highest p_T track, ROE information, validated with $B^+ \to J/\psi(\to \mu\mu)K^+$
- Bkg: **2 BDT in cascade** to exploit the event information and suppress the bkg
- Results:
  - No signal observed $\Rightarrow$ **Upper limit**
  - signal strenght compatible with SM prediction at 1σ or bkg-only at 1.3σ
  - Inclusive tagging ($\varepsilon = 4.3\ \%$)$\Rightarrow$ x3.5 better of hadronic tag, 20% better of SL tag
- Next steps: results with the **new sample (190 fb^{-1}) and extra channels** (K^*, K_S) are coming



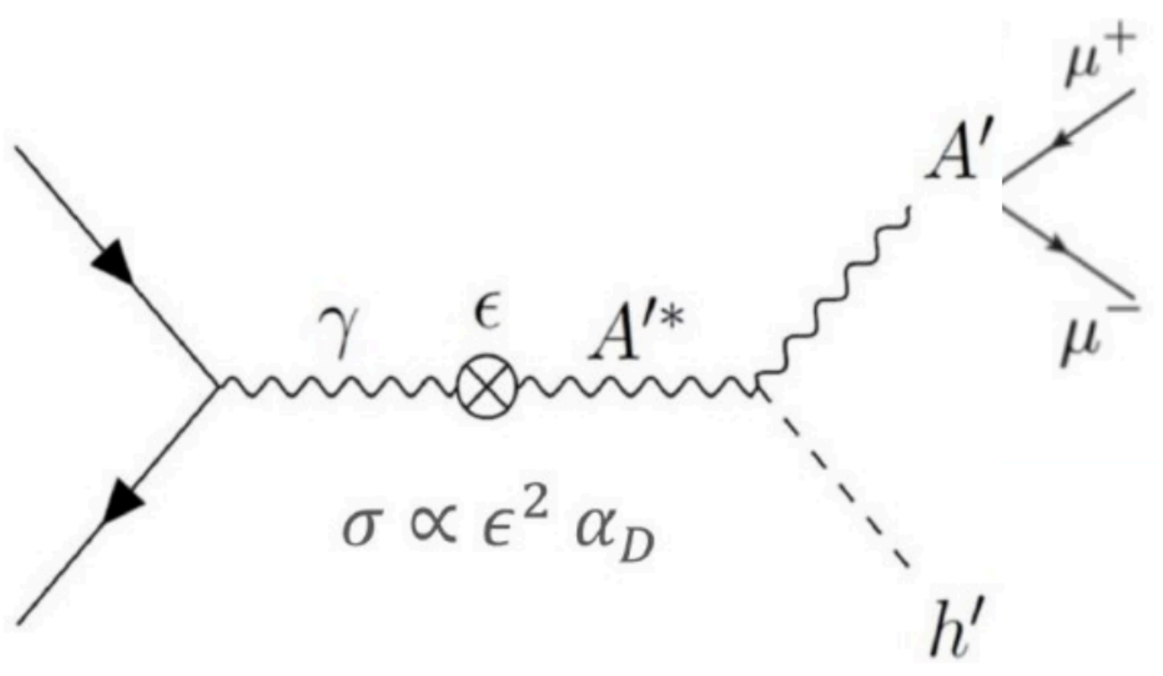


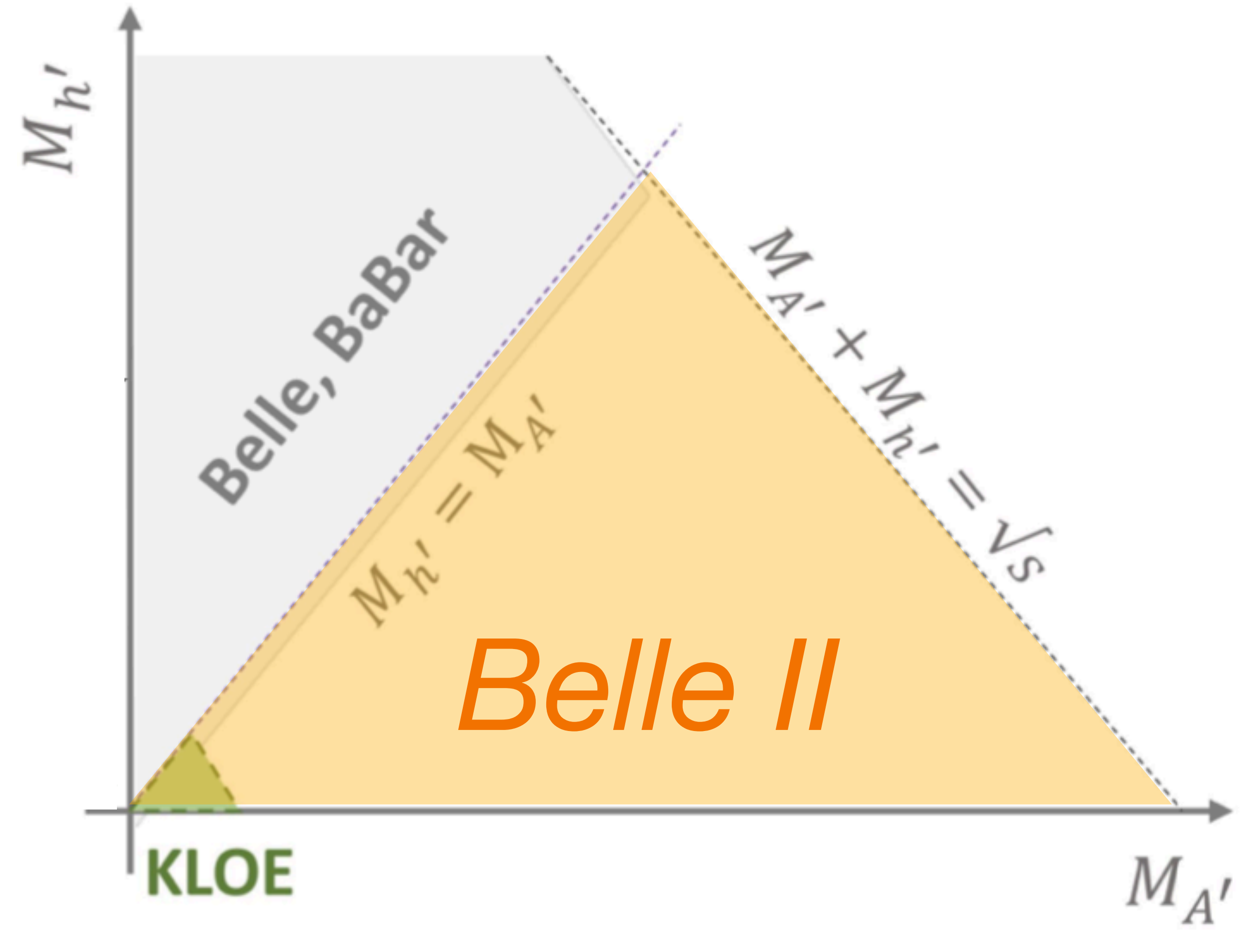
Dark sector: Dark Higgsstrahlung

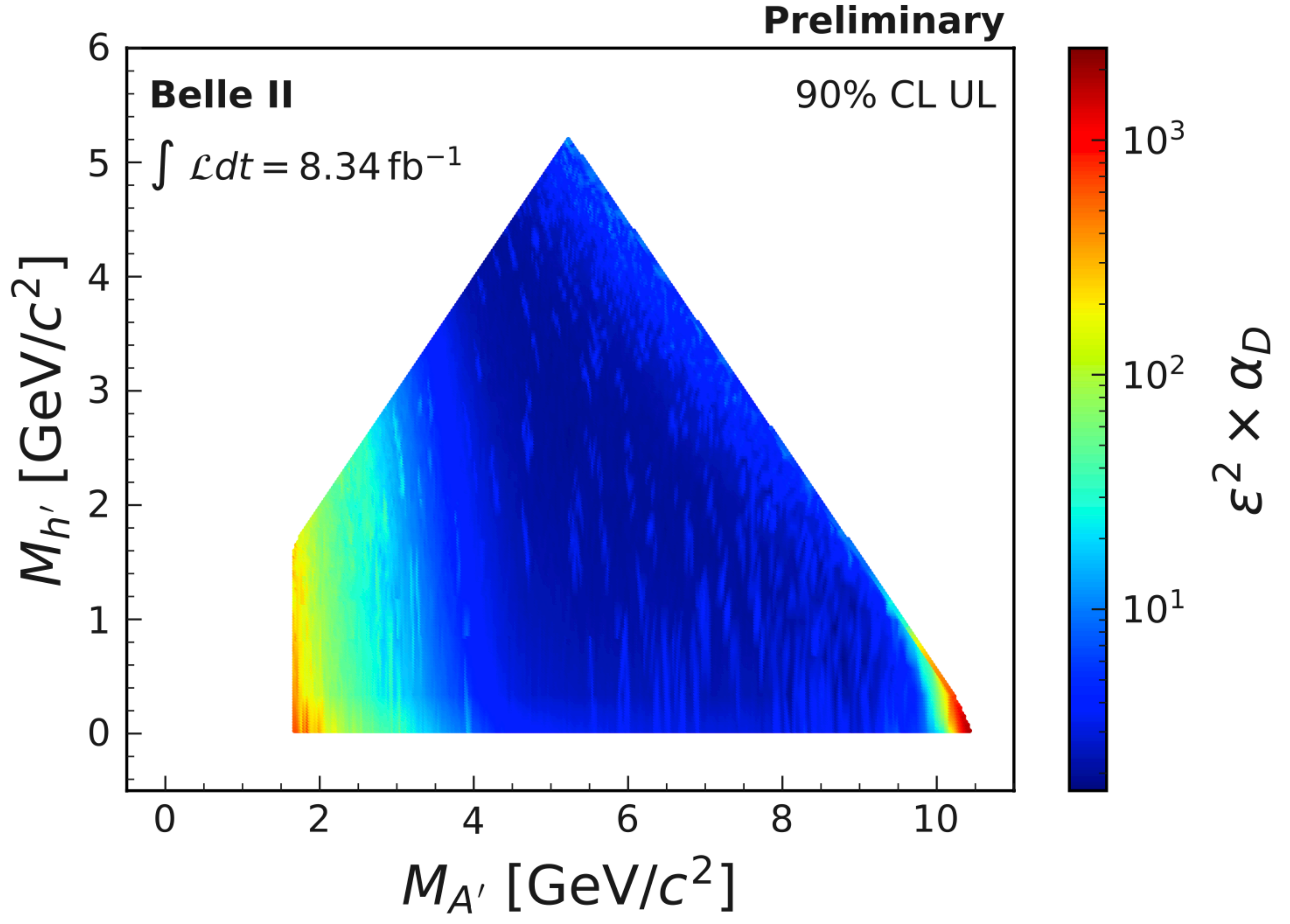
$8\ \text{fb}^{-1}$

[arxiv:2207.00509]

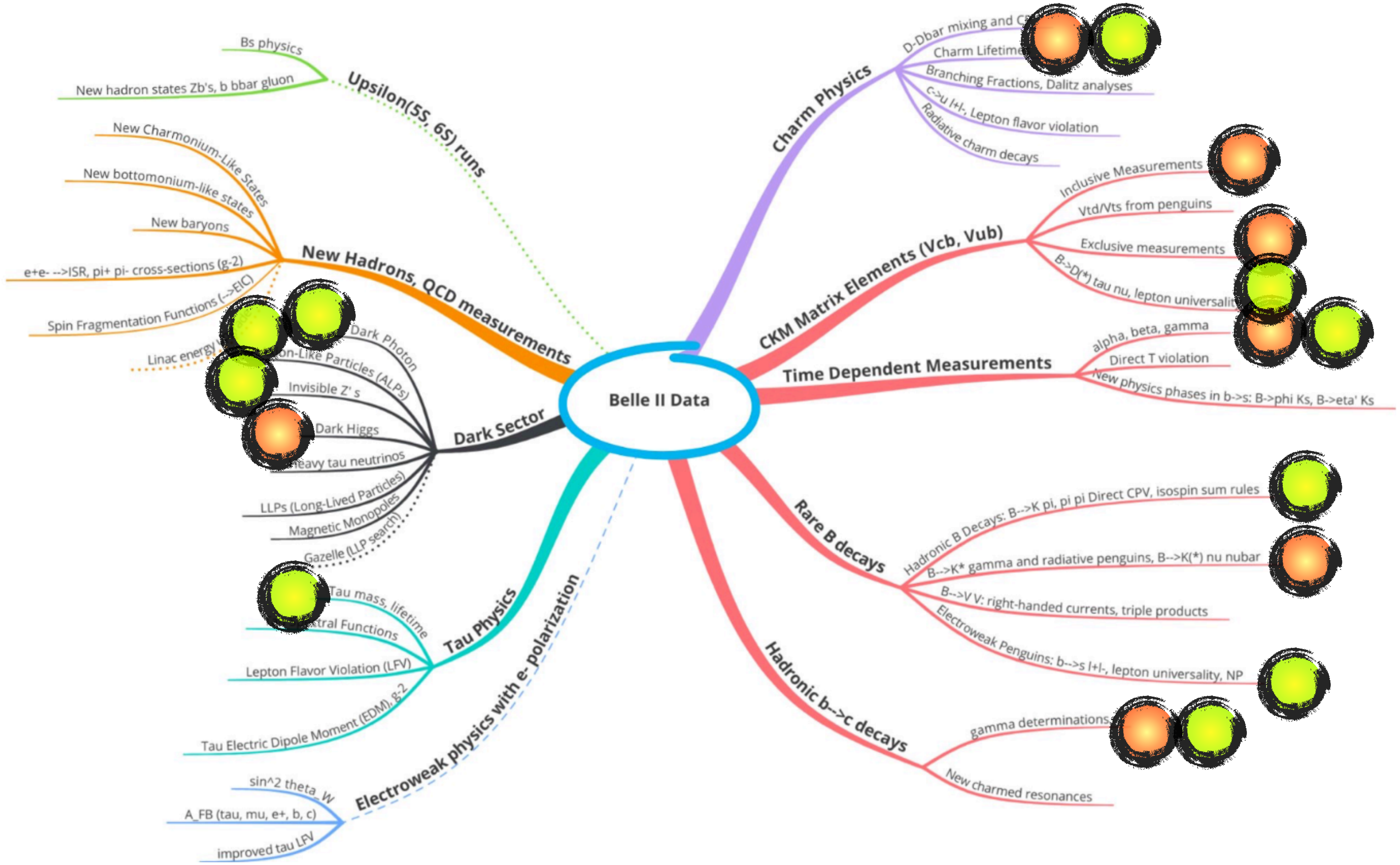
- Opportunity:
  - Unique reach in light DM (MeV-GeV) scale
  - Hermetic detector, clean events
  - Dedicated low-multiplicity trigger
  - Large statistics
- **Next-to-Minimal dark photon Model**:
  - dark photon (A') mixed with γ_{SM}
  - A' mass via SSB$\Rightarrow$ dark higgs (h') with no SM coupling
  - **mass hierarchy**: $m_{h'} < m_{A'} \Rightarrow h'$ emitted via higgstrahlung and long-lived, $A' \to \mu\mu$
- Analysis Strategy: **Scan of $M_{\mu\mu} \times M_{\text{rec}}$** (rec= recoil against dimuon)
- Results: **no excess found** but world **best UL** for 1.65 GeV $< m_{A'} < 10.51$ GeV

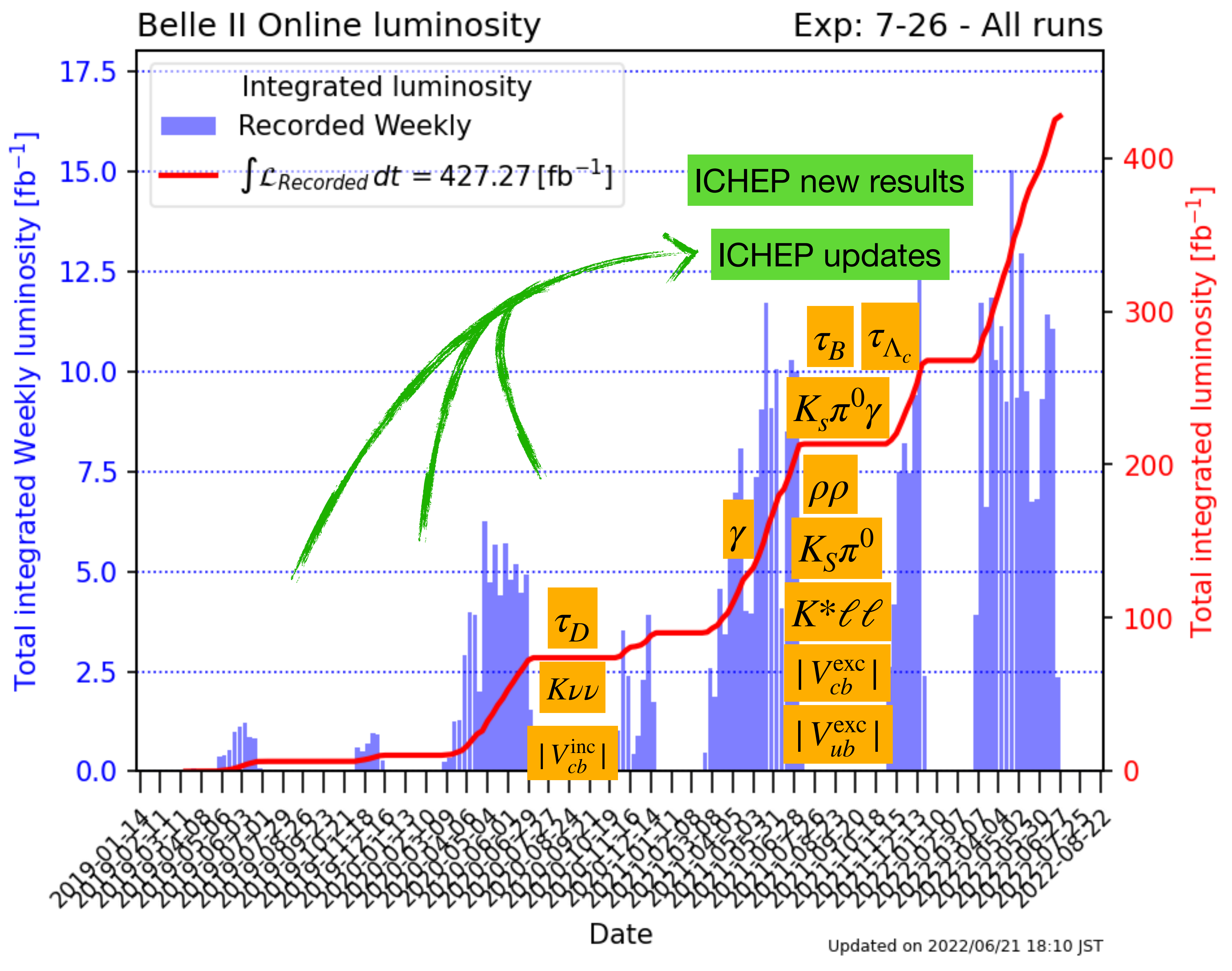






The Belle II physics program - coming soon





Not covered sector:

- Quarkonium *[see S. Jia's talk]*

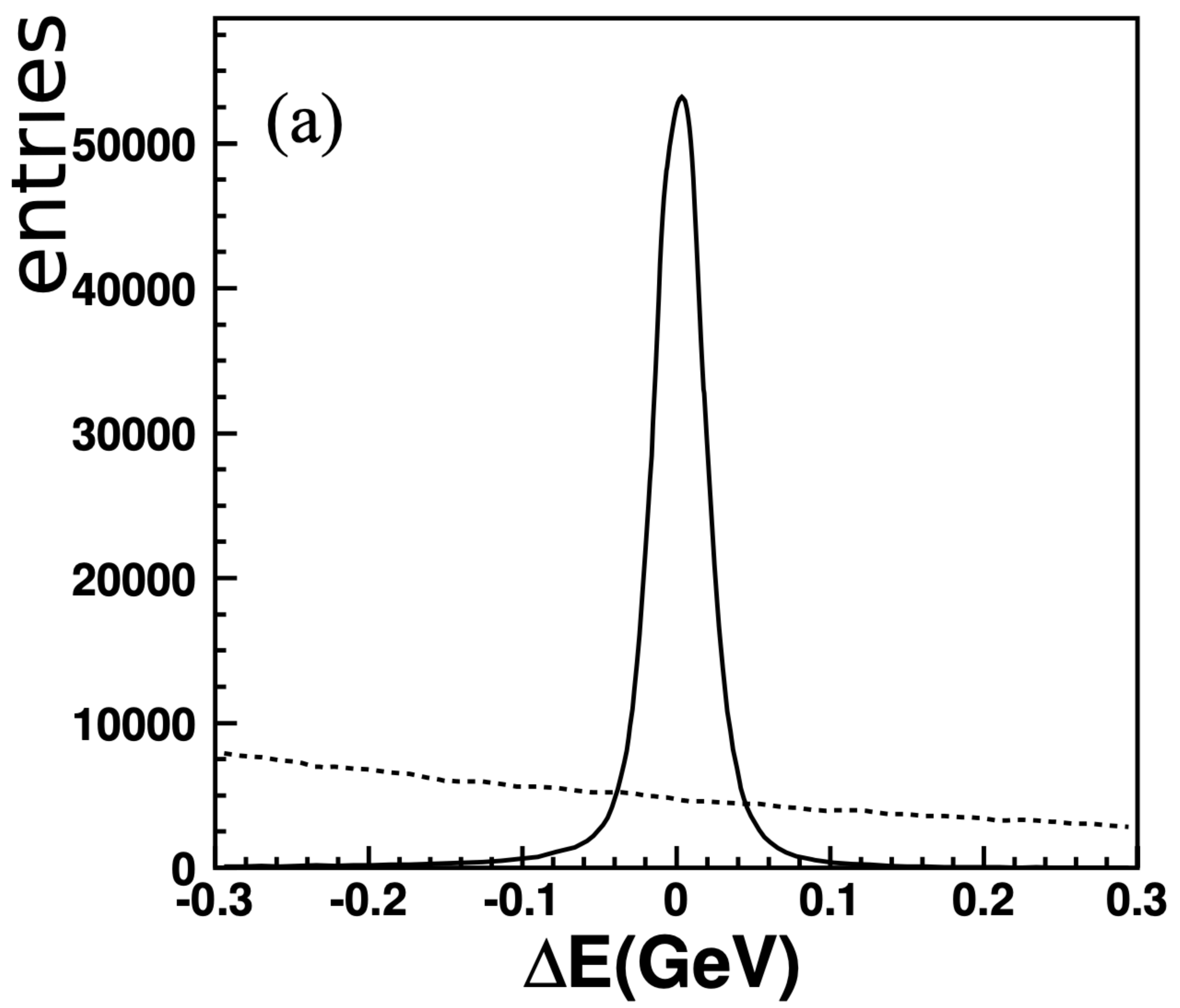
BACKUP SLIDES

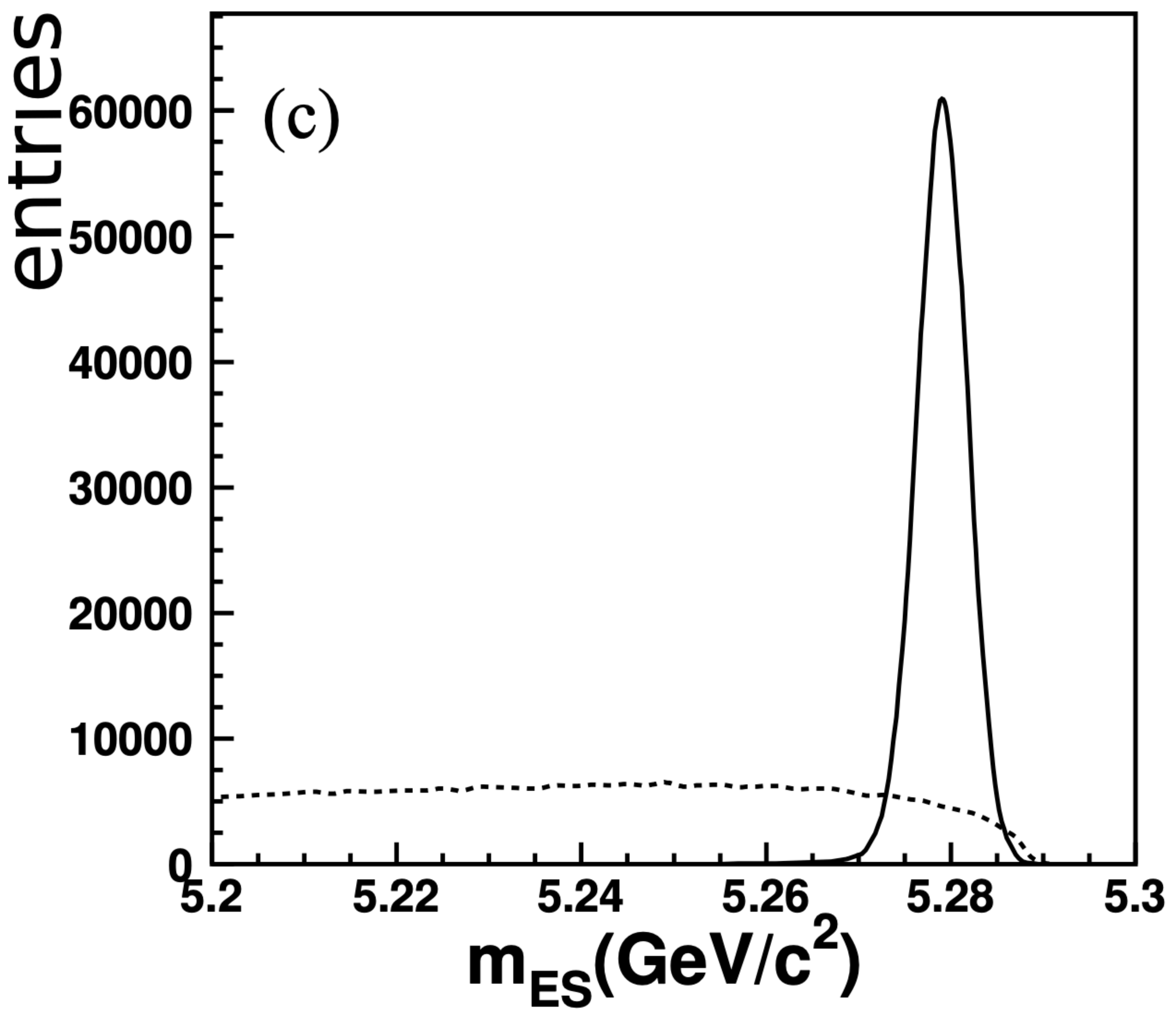
B factory variables

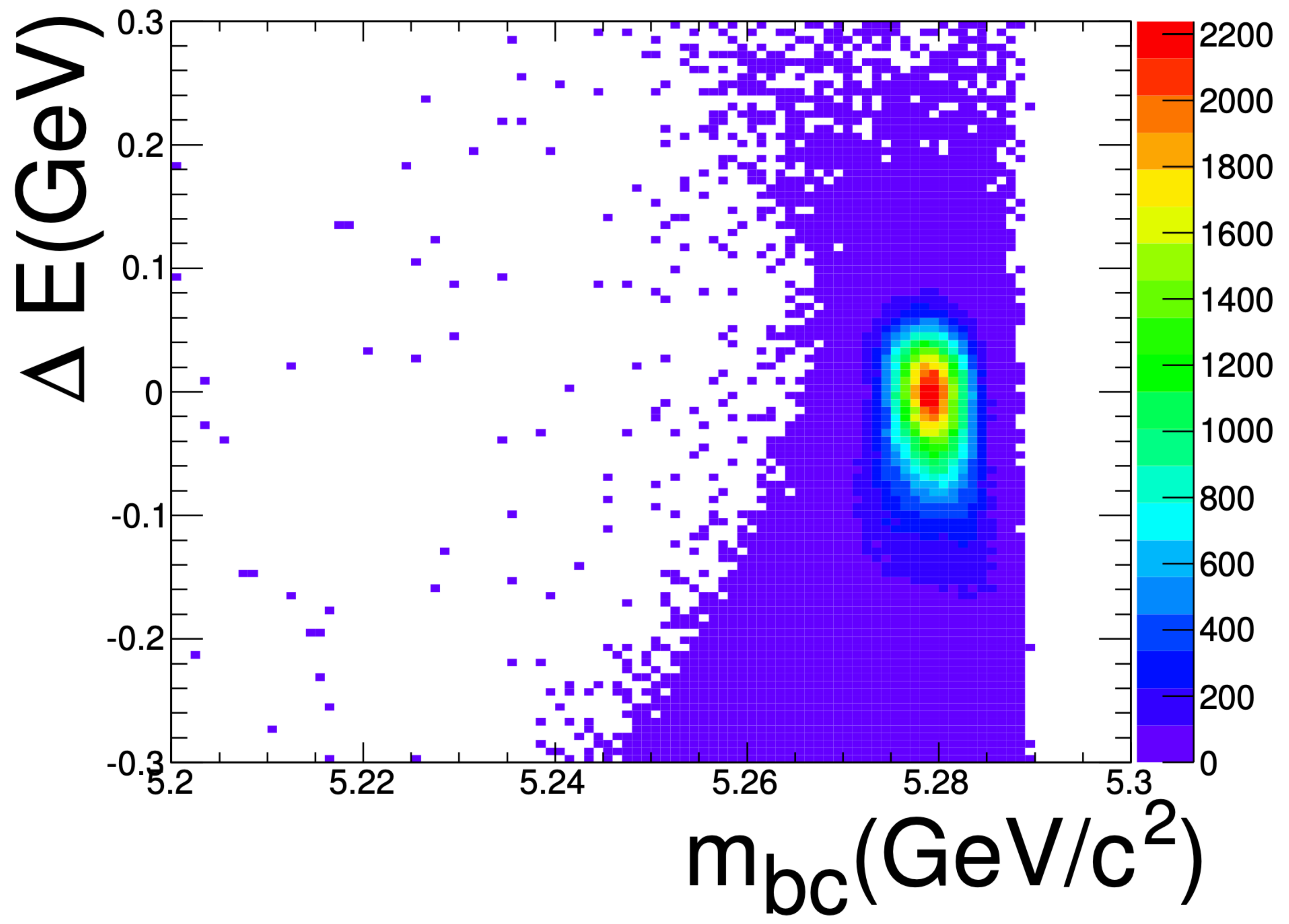
- $\Delta E = E^*_B - E^*_{\rm beam}$
- Expected $\Delta E \simeq 0$ for properly reconstructed signal

- $m_{ES} = m_{bc} = \sqrt{E^{*2}_{\rm beam} - \overrightarrow{p}^2_B}$
- Expected $m_{bc} \simeq m_B$ for properly reconstructed signal

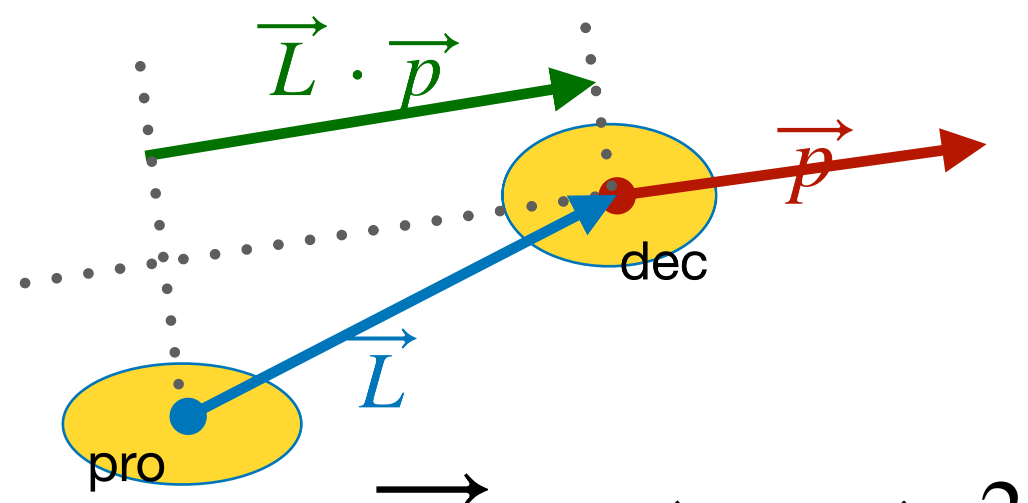
- 2 variable mostly uncorrelated
- tag-signal relation:
  - $E^*_{B_{\rm tag}} = E^*_{B_{\rm sig}} = \sqrt{s}/2,$
  - $\overrightarrow{p}^*_{B_{\rm tag}} = -\overrightarrow{p}^*_{B_{\rm sig}}$





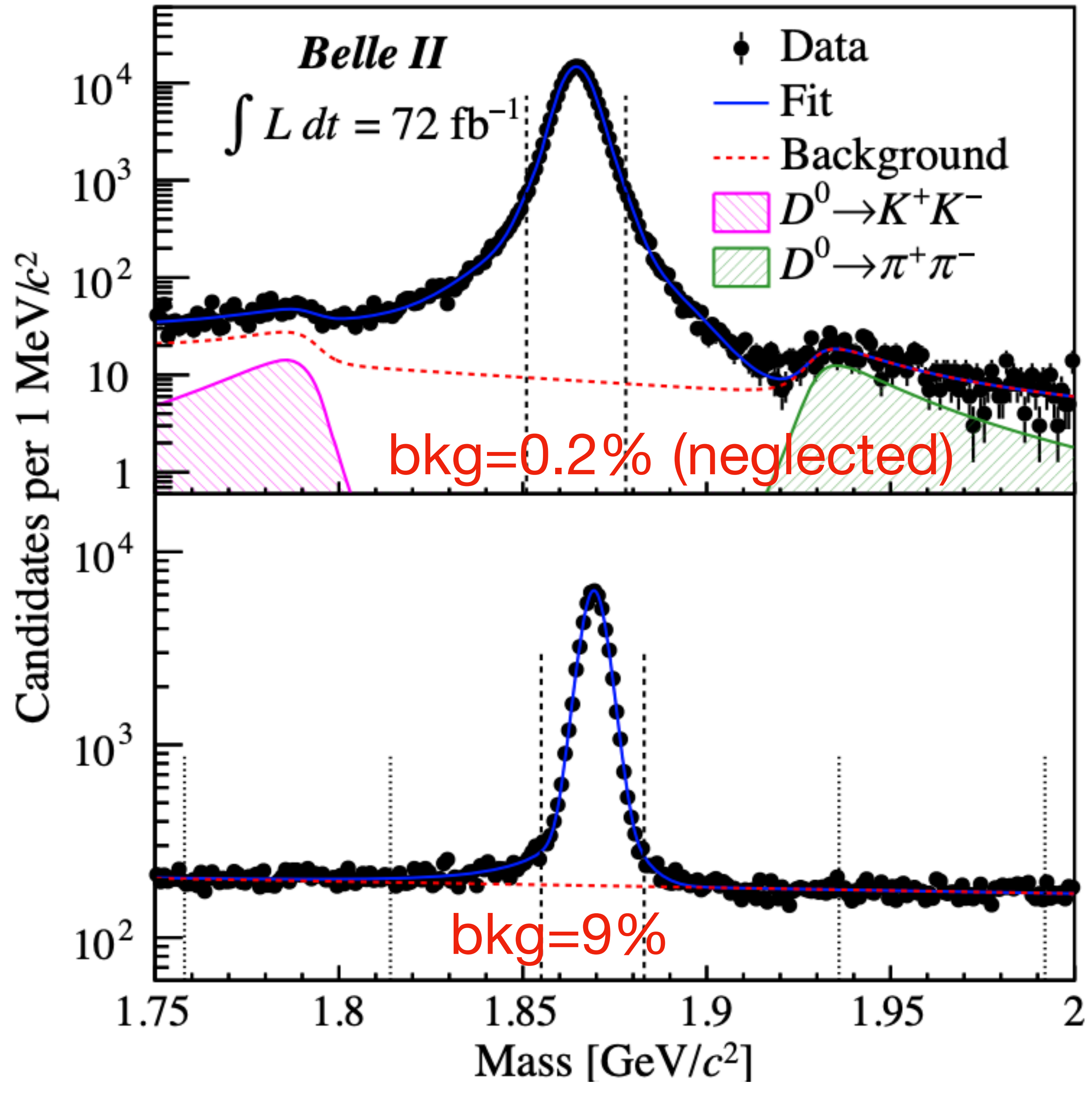


Charm sector lifetimes extra information



$D^{*+} \to D^0(\to K^-\pi^+)\pi^+$

$D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$

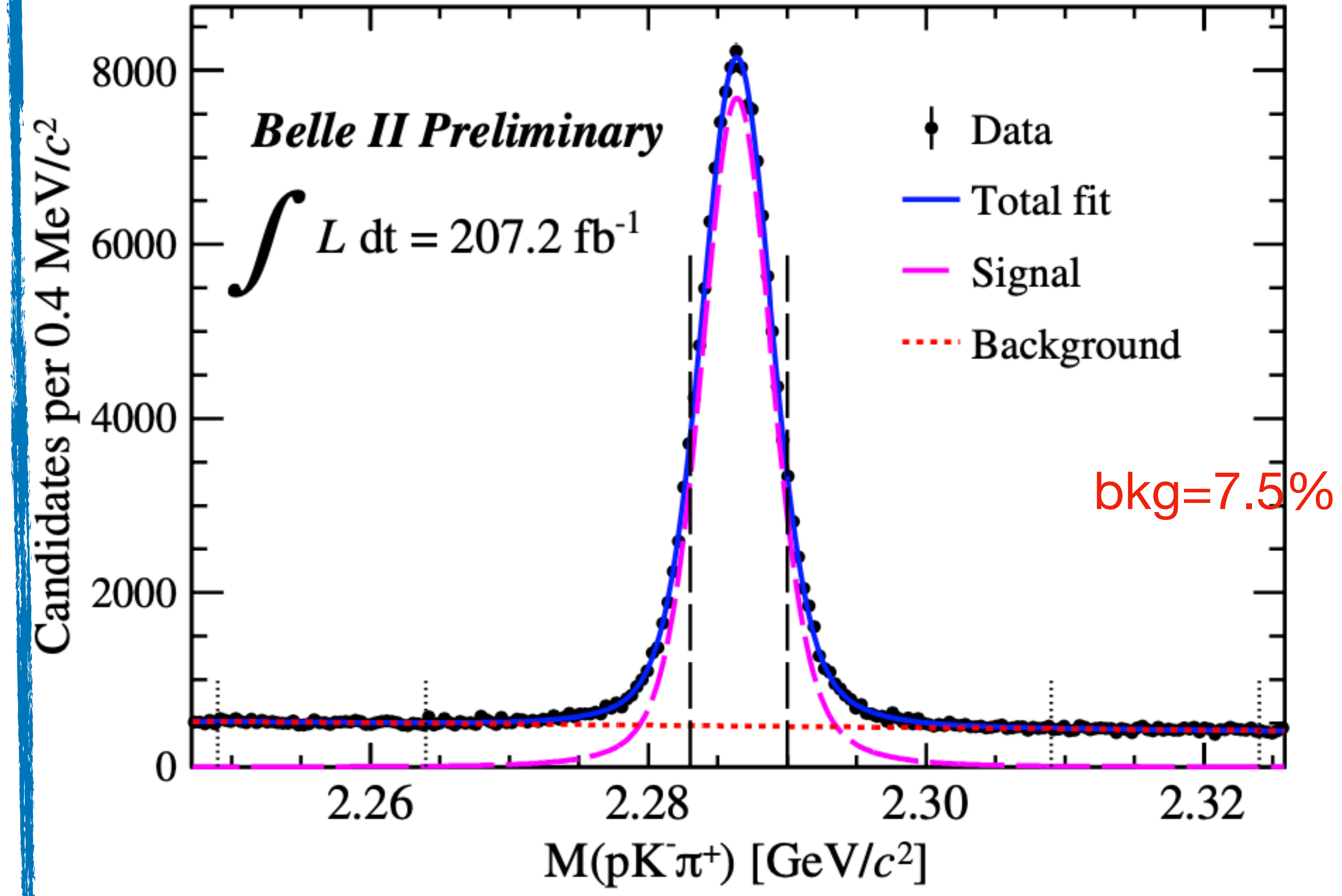


- Fit function:
- signal: exp convoluted with double/ single gauss (resolution)
- σ_t data driven template
- bkg: sideband fit

Source	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10

$\Lambda_c^+ \to pK^-\pi^+$

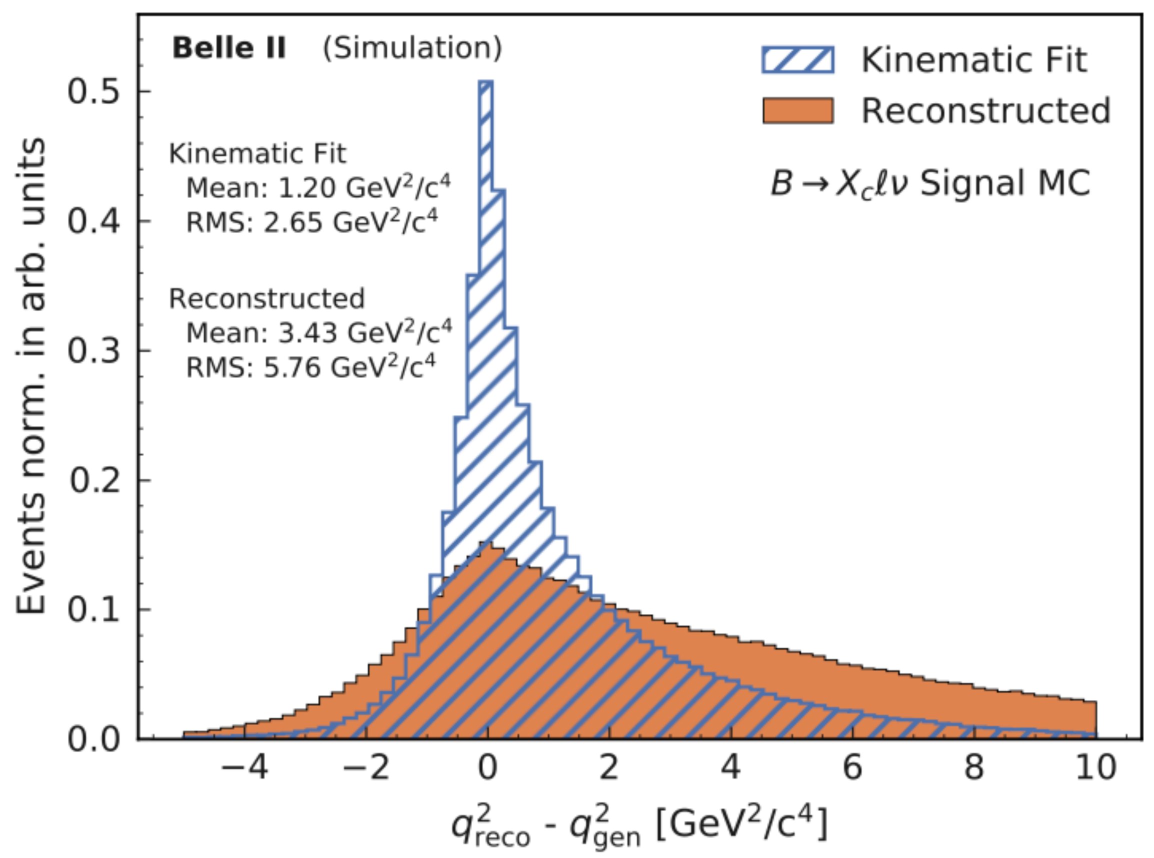
$t = m_{D/\Lambda}\vec{L}\cdot\vec{p}/|\vec{p}|^2$



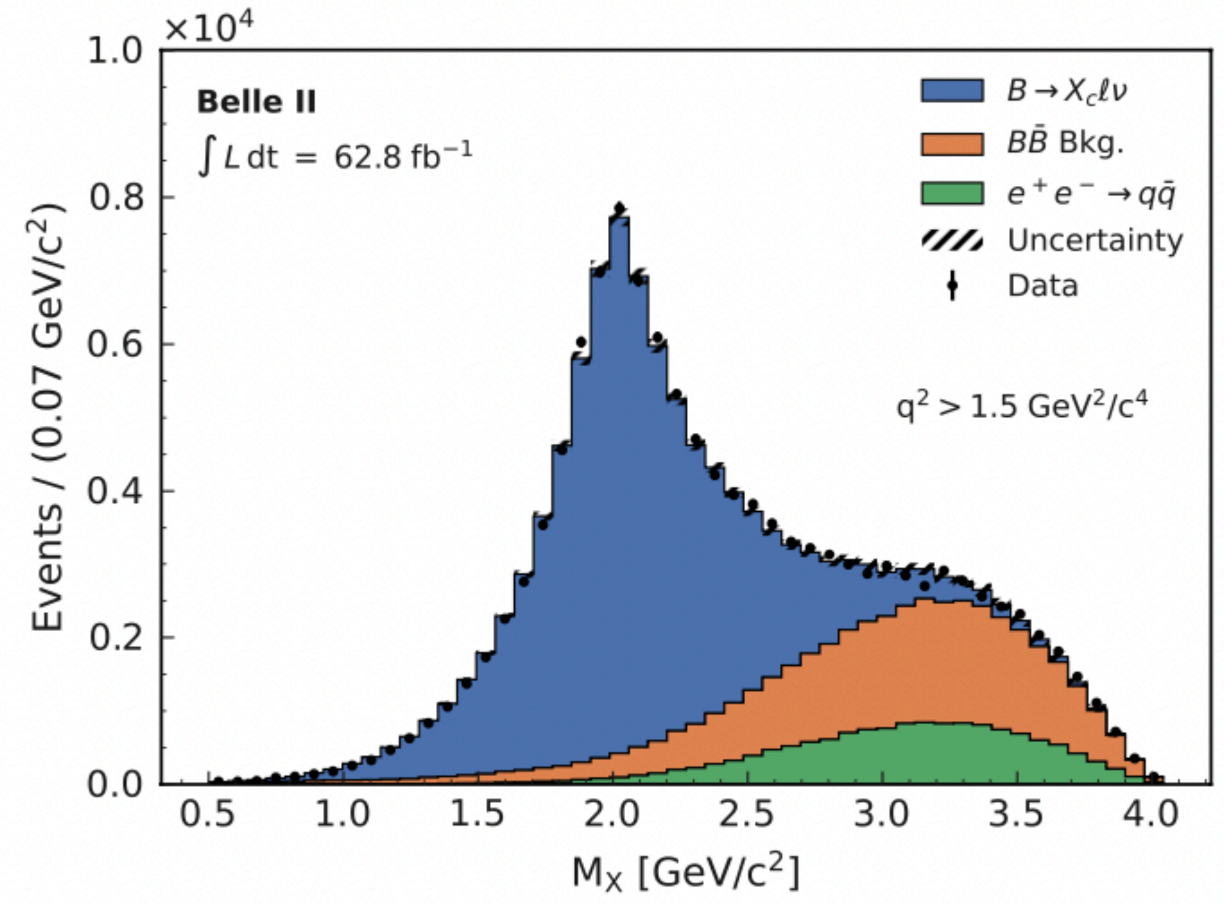
Source	Uncertainty [fs]
Ξ_c contamination	0.34
Resolution model	0.46
Non-Ξ_c backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Total	0.77

q^2 moments from $B \to X_c \ell \nu$ extra information

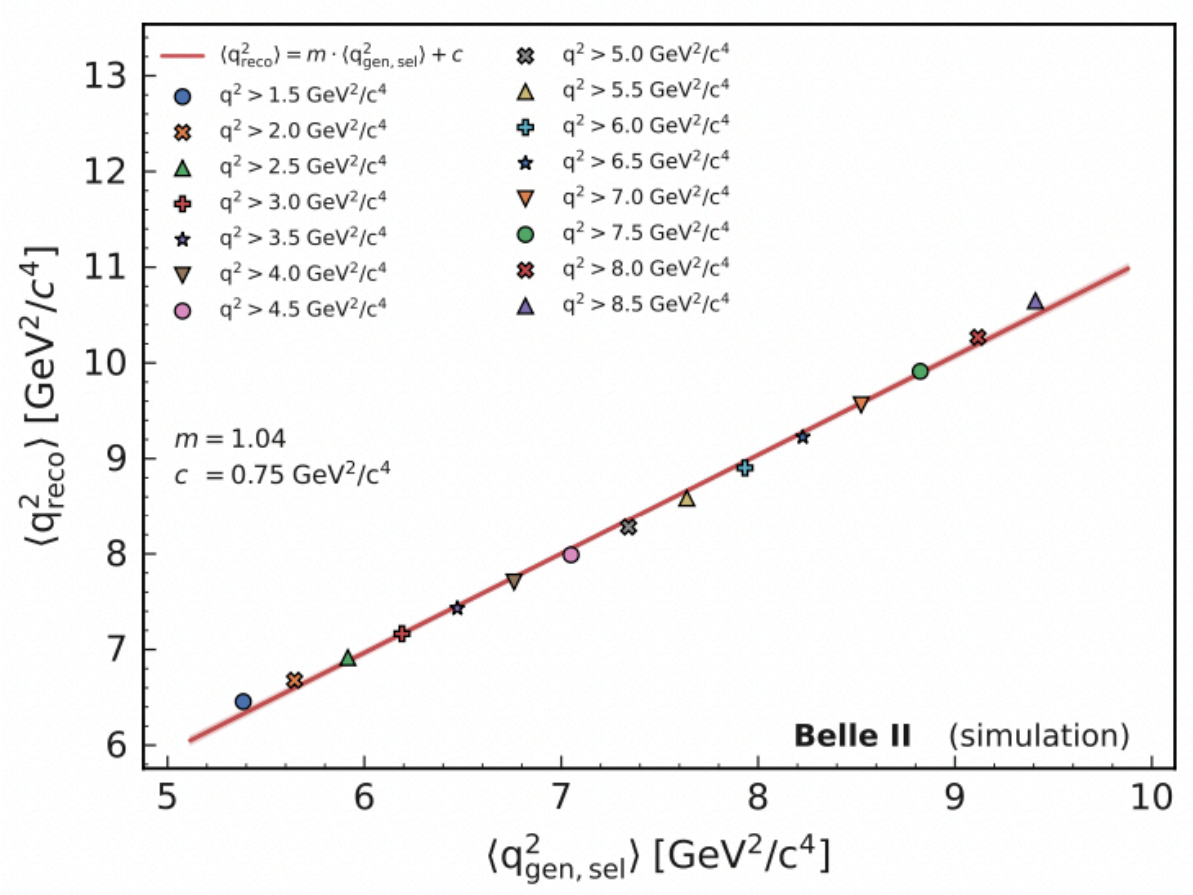
kinematic fit



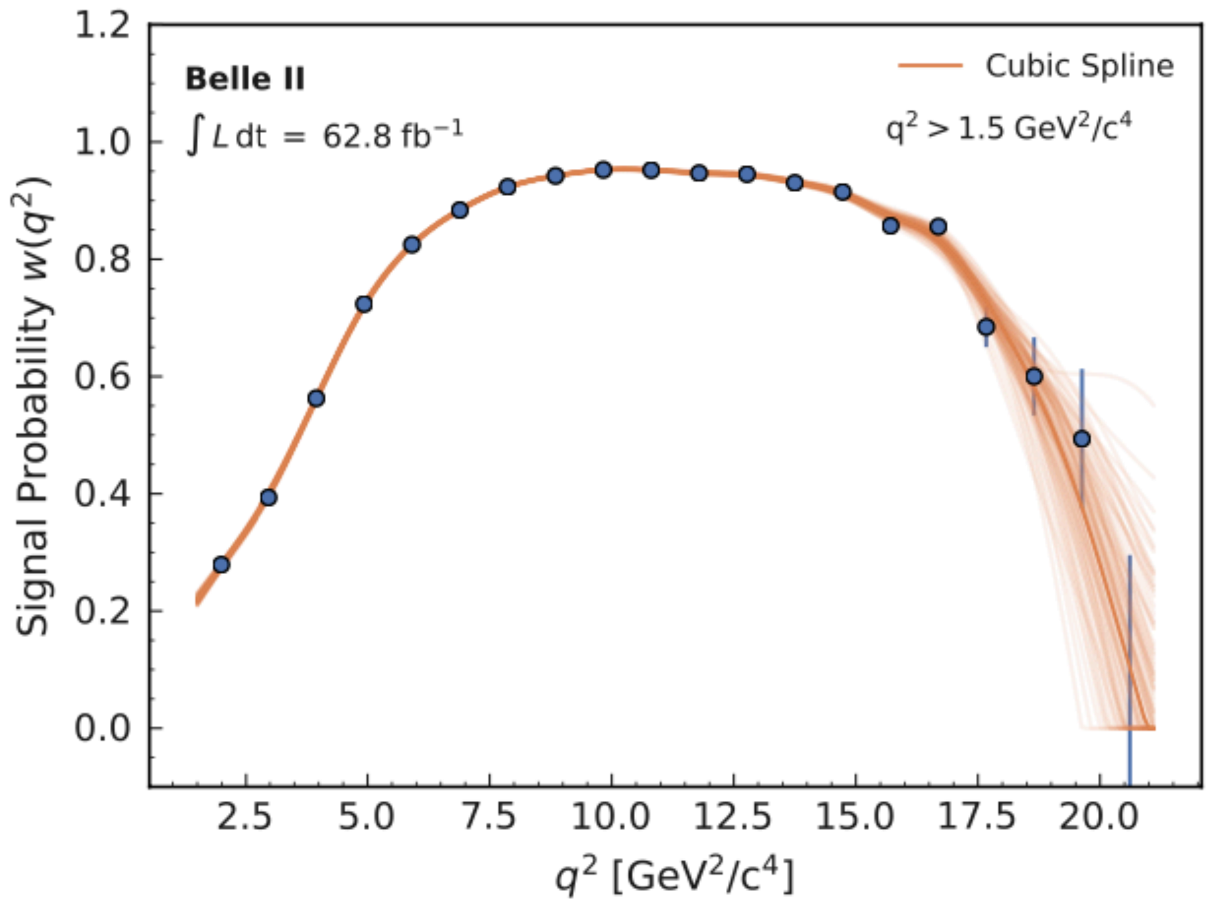
M_X distribution



linear calibration curve



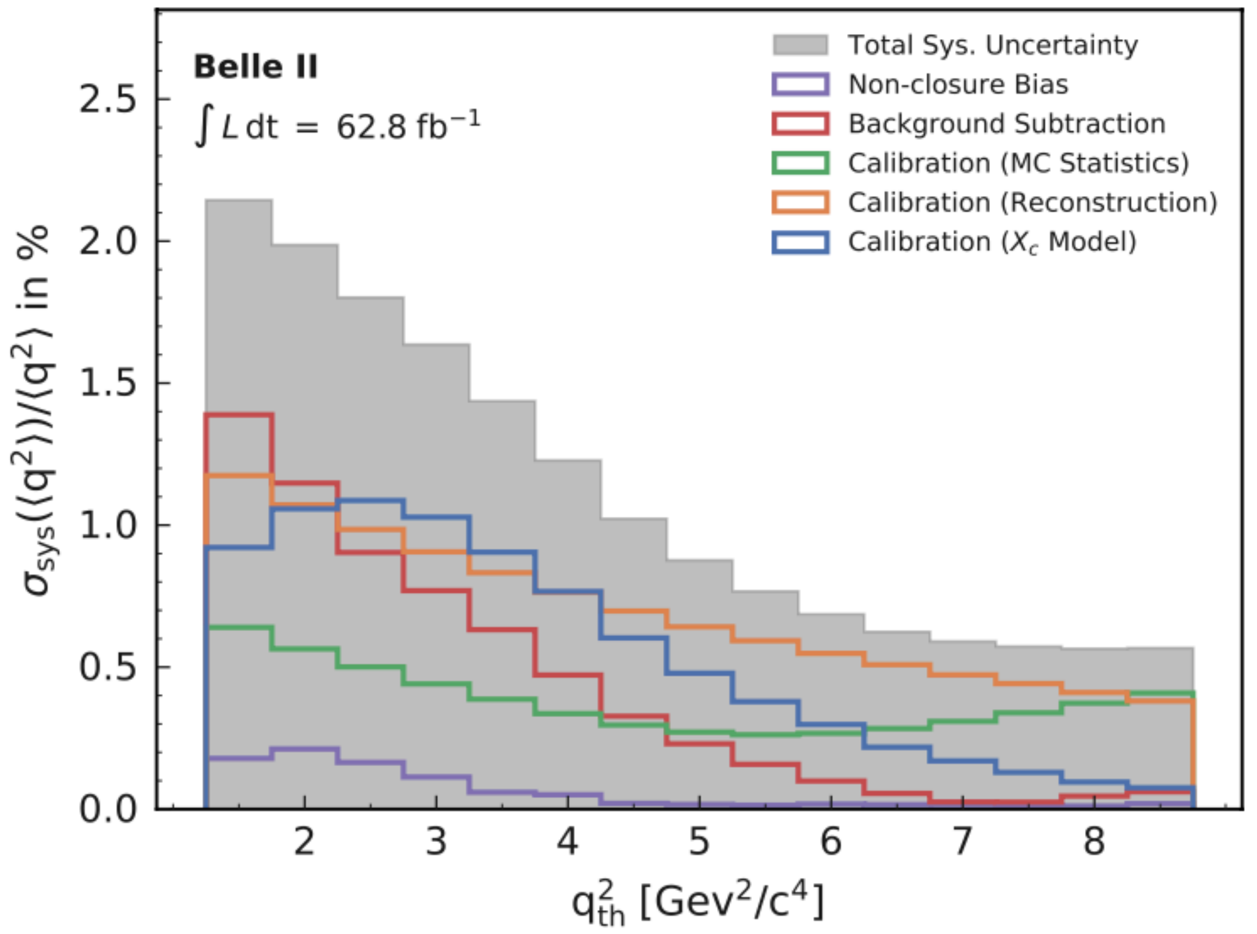
interpolation of $w_i(q^2)$



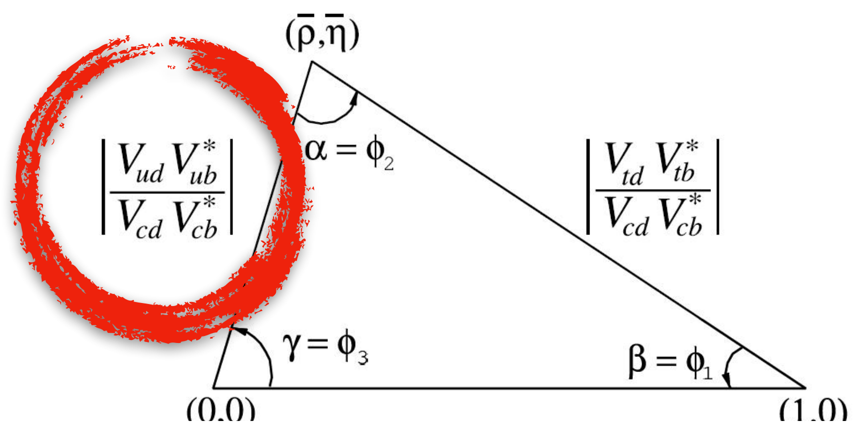
- $\Gamma_{B\to X_c\ell\nu}$ expanded in power of Λ_{QCD}/m_b
- Bkg suppression: **Template fit** to M_X with 3 components (signal, $ee \to q\bar{q}$, $B\overline{B}_{\text{bkg}}$), $q^2 > 1.5$ GeV
- $\langle q^{2n} \rangle = \dfrac{\sum_i w_i(q^2) q^{2n}_{\text{cal},i}}{\sum_i w_i(q^2)} C_{\text{cal}} C_{\text{gen}}$, with: $w_i = \dfrac{N_i^{\text{data}} - N_i^{\text{bkg}}}{N^{\text{data}}}$
- **central moments**: $\langle (q^2 - \langle q^2 \rangle)^n \rangle$ --> less correlation with q^2_{thr}
- Most recent Belle measurement: 58%

systematic uncertainties

2 categories: bkg subtraction, calibration

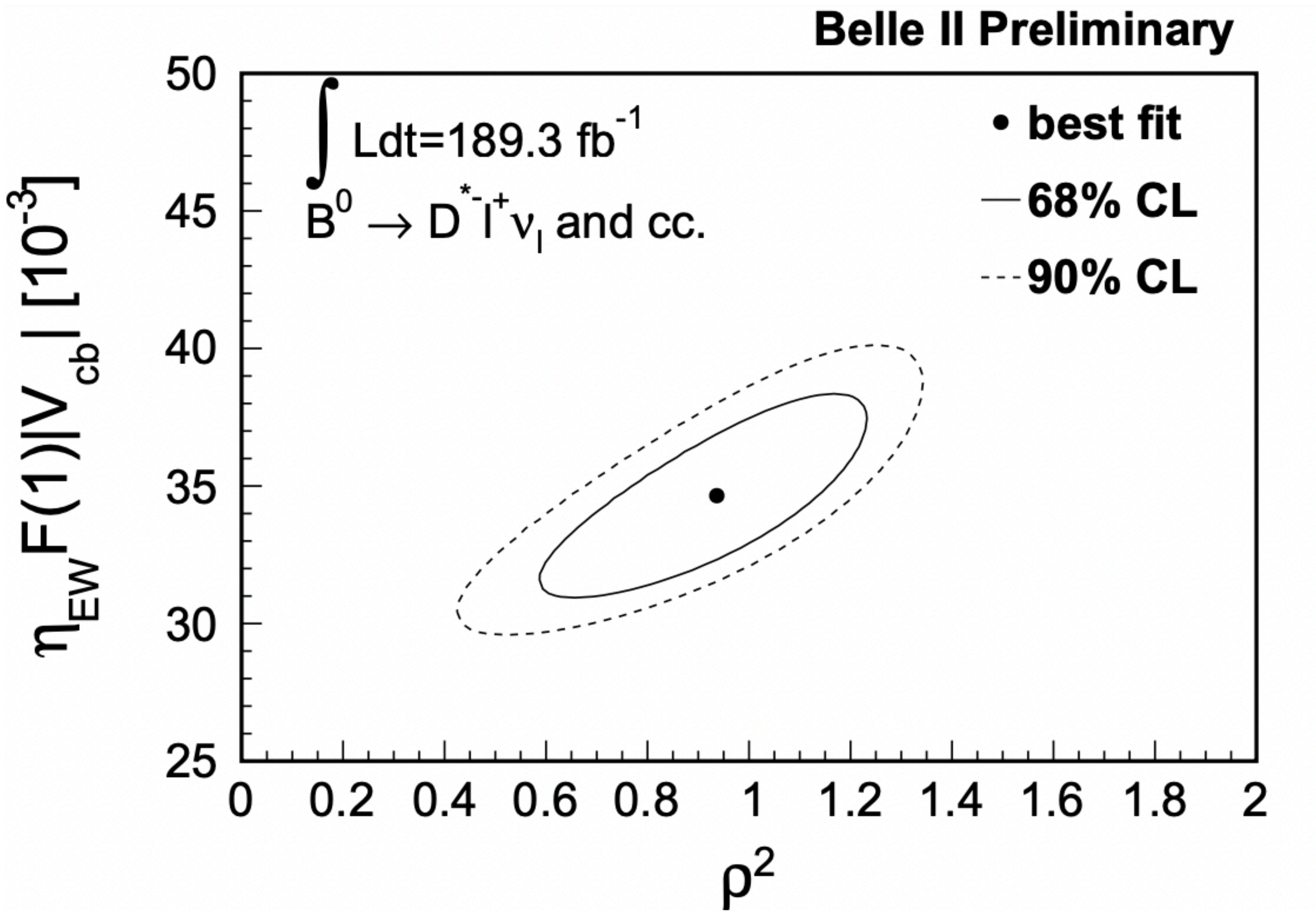


$|V_{cb}|$ from $B \to D^*\ell\nu$ extra information



$190\ \text{fb}^{-1}$

- $\text{BR}(B \to D^*\ell\nu) = (5.27 \pm 0.22 \pm 0.38)\ \%$
- $\eta_{EW}F(1)\,|V_{cb}| = (3.54 \pm 0.4)\cdot 10^{-3},\ \ \rho^2 = 0.94 \pm 0.21$
- $|V_{cb}| = (37.9 \pm 2.7)\cdot 10^{-3}$
- binned ML fit:



- $g(w)$ = phase space
- $F(w)$ = form factor
- $R_1(1), R(2), \rho$ combination of form factors

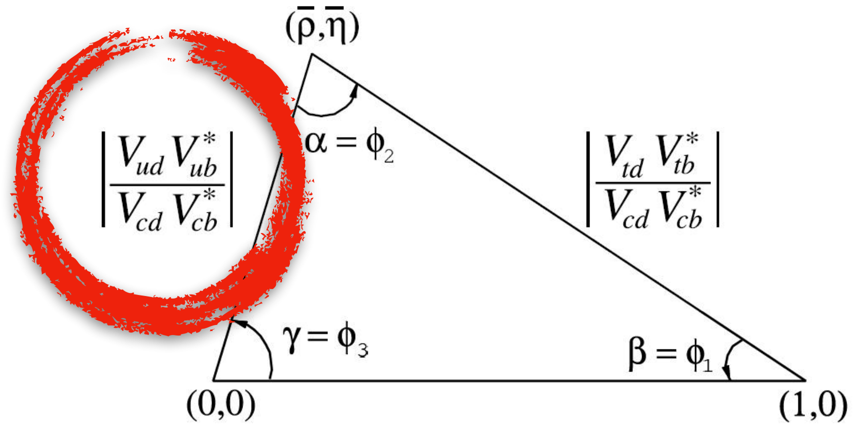
TABLE II. Input of $R_1(1)$ and $R_2(1)$ [10].

$R_1(1)$	1.270 ± 0.026
$R_2(1)$	0.852 ± 0.018
Correlation coefficient of $R_1(1)$ and $R_2(1)$	-0.715

systematic uncertainties

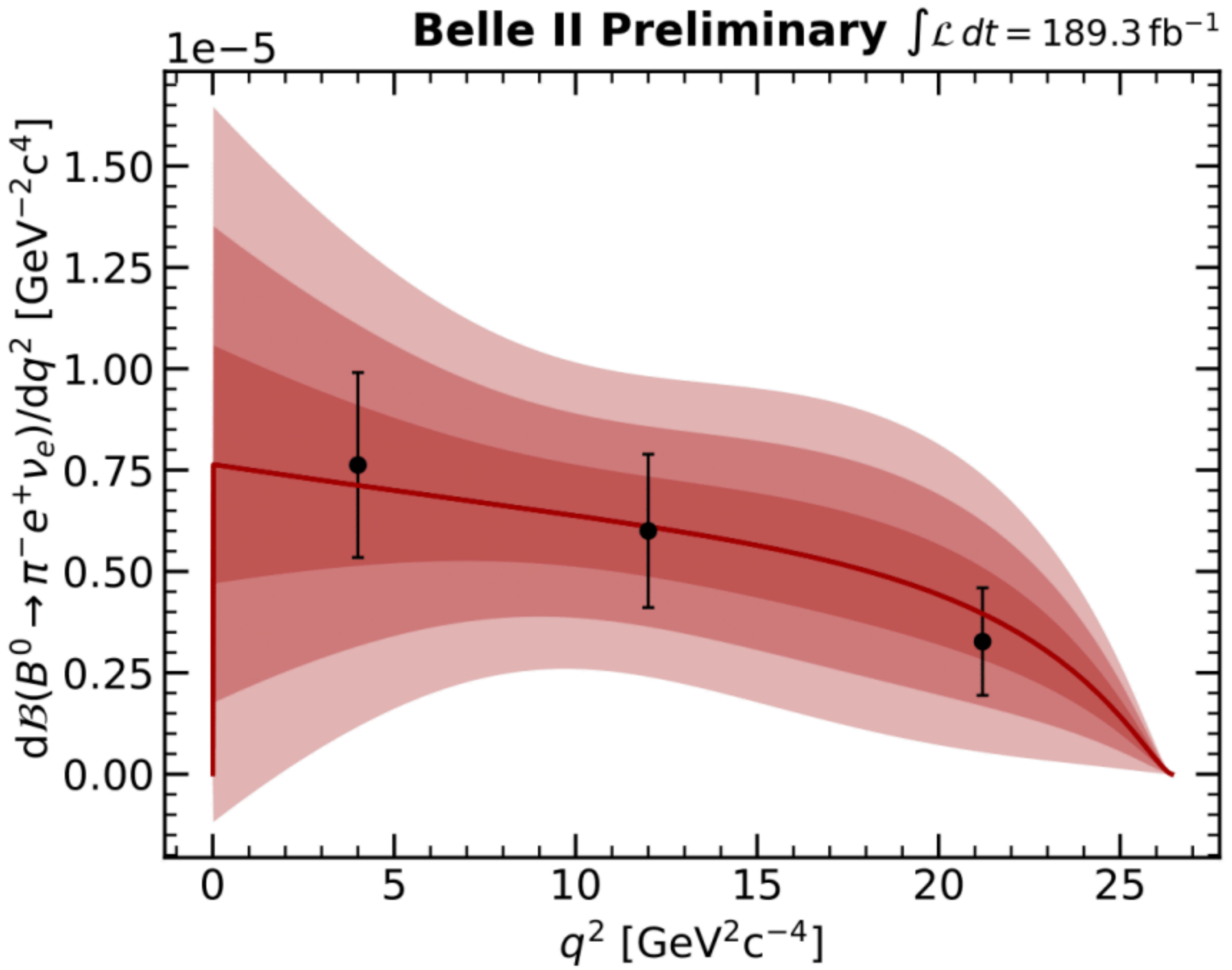
Systematic sources	Relative uncertainty (%)
FEI efficiency	3.9
Low momentum π efficiency	4.1
Tracking efficiency	0.9
Lepton particle identification	2.0
Background	1.2
$N_{B\bar{B}}$	2.9
f_{+0}	1.2
$\mathcal{B}\left(D^{*-} \to \pi^- \bar{D}^0\right)$	0.7
$\mathcal{B}\left(\bar{D}^0 \to K^+\pi^-\right)$	0.8
ECL energy	1.0
Form factor	0.1
MC statistics	1.8
Total	7.3

$|V_{ub}|$ from $B \to \pi e \nu$ extra information



$190\ \mathrm{fb}^{-1}$

$$|V_{ub}| = (3.88 \pm 0.45) \cdot 10^{-3}$$



systematic uncertainties

Source	% of $\Delta\mathcal{B}_i(B^0 \to \pi^-\ell^+\nu)$		
	$0\ \mathrm{GeV}^2 \le q^2 < 8\ \mathrm{GeV}^2$	$8\ \mathrm{GeV}^2 \le q^2 < 16\ \mathrm{GeV}^2$	$16\ \mathrm{GeV}^2 \le q^2 \le 26.4\ \mathrm{GeV}^2$
f_{+0}	1.17		
FEI calibration	3.68		
$N_{B\bar{B}}$	2.31		
Tracking	1.38		
Reconstruction efficiency ϵ_i	0.90	0.81	0.99
Lepton ID	0.60	0.40	0.87
Pion ID	0.35	0.30	0.30
Total	4.84	4.80	4.90

$B^+ \to \rho^0\rho^+$ extra information

<u>α measurement information</u>

- α measured from TDCPV analysis of $b \to u\bar{u}d$ transition
- $b \to u$ tree transition $\Rightarrow \alpha$ phase
- $b \to d$ penguin transition $\Rightarrow \Delta\phi_2$ penguin pollution
- Penguin pollution estimated from isospin analysis BR($\rho^+\rho^-, \rho^0\rho^0, \rho^+\rho^0$) and direct CP violation parameter A_{CP}
- $B \to \rho\rho$ is the (set of) channel **with the lowest penguin pollution**
- Only the **longitudinal-polarized** component can be used for the measurement

systematic uncertainties

source	$\mathcal{B}$ [%]	f_L [%]
Tracking	0.6	-
π^0 and PMVA	7.7	-
PID	0.8	-
Continuum suppression	2.1	-
$N_{B\bar{B}}$	2.9	-
Single candidate selection	1.5	0.8
Signal model	2.4	2.0
Self cross-feed model	$^{+2.7}_{-0.9}$	< 0.1
Continuum model	1.3	0.7
$B\bar{B}$ model	2.0	2.2
peaking background model	0.4	0.7
$\cos\theta_{\rho^\pm}$ mismodel	4.4	0.3
Fit bias	0.9	1.0
MC stat.	1.0	0.2
Total	$^{+10.9}_{-10.6}$	± 3.4

$B^+ \to D(K_S h^- h^+)h^+$ extra information

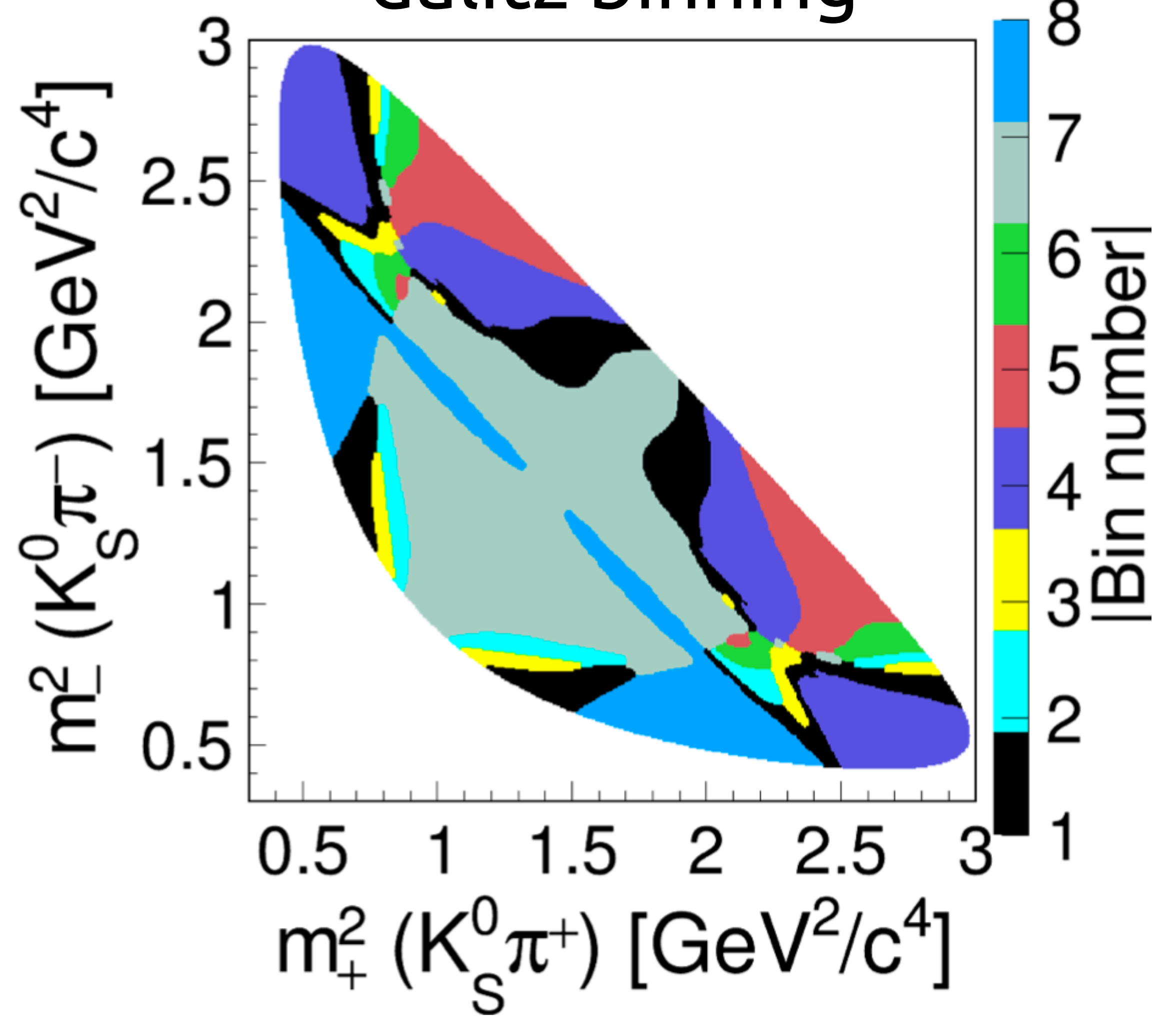
Improvement compared to Belle

- added $K_S K^+ K^-$
- Better K_S selector (lowered stat. unc.)
- improved bkg suppression
- new BES III input (lowered syst. unc.)
- better signal description
- Conclusion: **equivalent to a factor 2 in the luminosity**

Bkg suppression

- Bkg: BDT suppressed $\Rightarrow C'_{BDT}$
- **Fit to $\Delta E \times C'_{\mathbf{BDT}}$** with signal+$ee \to q\overline{q}, B\overline{B}$ +peaking misID bkg

dalitz binning

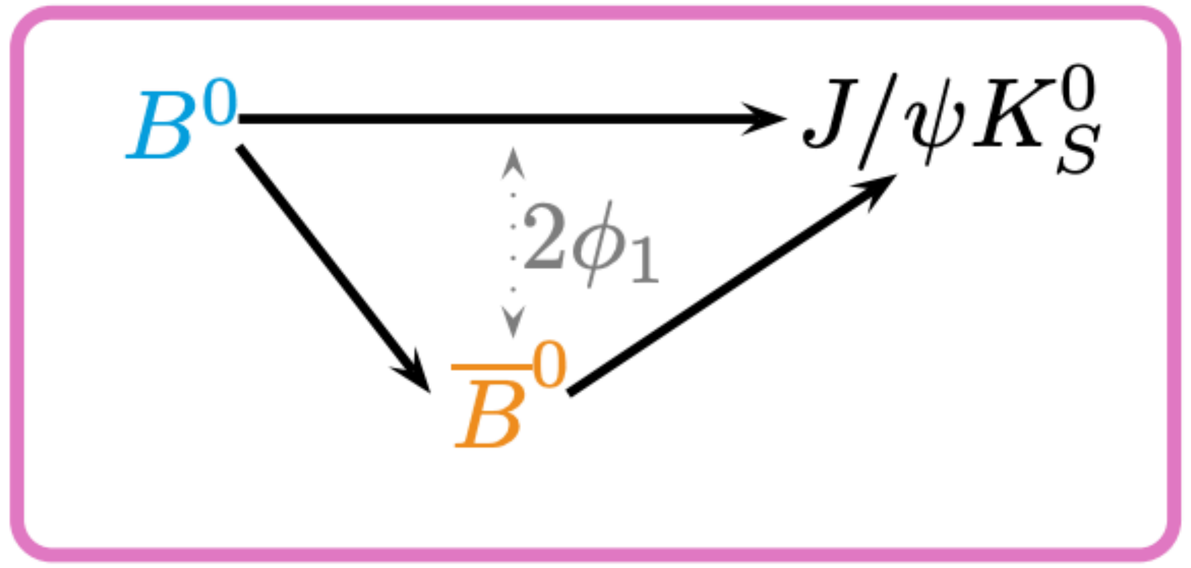


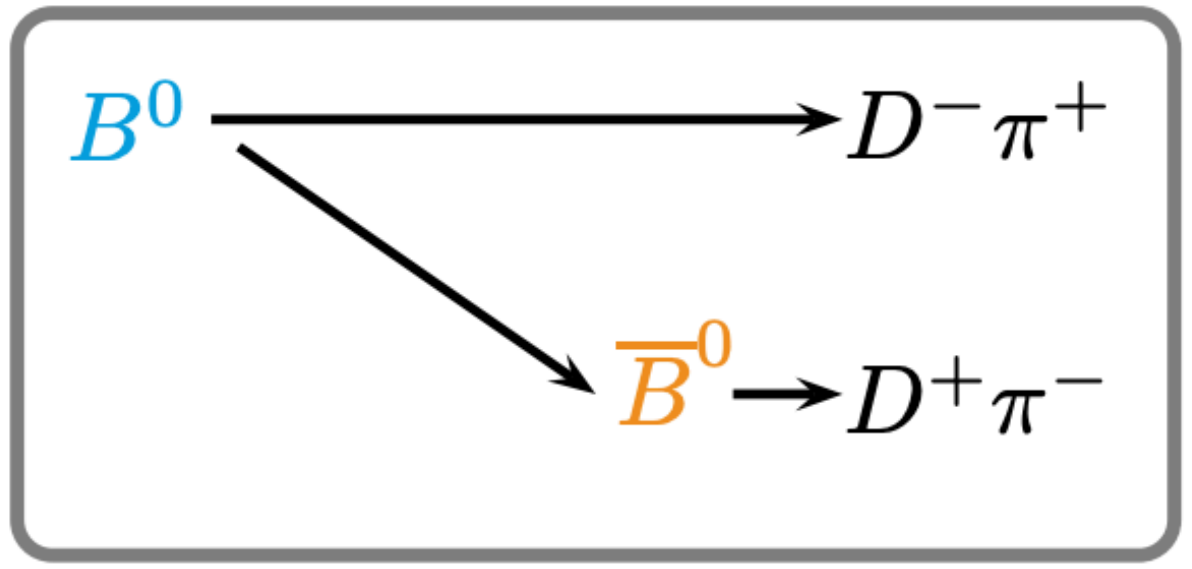
systematic uncertainties

Source	$\sigma_{x_+^{DK}}$	$\sigma_{y_+^{DK}}$	$\sigma_{x_-^{DK}}$	$\sigma_{y_-^{DK}}$	$\sigma_{x_\xi^{D\pi}}$	$\sigma_{y_\xi^{D\pi}}$
Input c_i, s_i	0.22	0.55	0.23	0.67	0.73	0.82
PDF parametrisation	0.07	0.08	0.12	0.16	0.12	0.12
PID	< 0.01	< 0.01	< 0.01	0.01	< 0.01	< 0.01
Peaking background	0.03	0.05	0.03	0.04	0.02	0.10
Fit bias	0.16	0.06	0.12	0.16	0.49	0.10
Bin migration	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.03
Total	0.18	0.11	0.17	0.23	0.51	0.19
Statistical	3.15	4.20	3.27	4.20	4.75	5.44

Table 3. Systematic uncertainty summary. All values are quoted in units of 10^{-2}.

Time-Dependent CPV analysis scheme





CP-asymmetry in interference between mixing and decay:

$$\mathcal{A}_{\mathrm{CP}}(t) = \frac{N(B^0 \to f_{CP}) - N(\overline{B}^0 \to f_{CP})}{N(B^0 \to f_{CP}) + N(\overline{B}^0 \to f_{CP})}(t) = (S_{CP}\sin(\Delta m_d t) + A_{CP}\cos(\Delta m_d t))$$

with S_{CP}: time-dependent asymmetry and A_{CP}: direct CP-asymmetry.

B^0-$\overline{B}^0$ mixing:

$$\mathrm{mix}(t) = \frac{N(B^0 \to B^0) - N(B^0 \to \overline{B}^0)}{N(B^0 \to B^0) + N(B^0 \to \overline{B}^0)}(t) = \cos(\Delta m_d t)$$

with Δm_d the oscillation frequency.

[From Thibaud Humair, Moriond EW 22]

B^0 lifetime extra information

- Δt obtained projecting the two vertices in the direction of $\Upsilon(4S)$ momentum:

$$\Delta t^{\mathrm{MC}} = \frac{\Delta \ell^{\mathrm{MC}}}{\beta\gamma\gamma^*}. \qquad \Delta t = \frac{\Delta \ell}{\beta\gamma\gamma^*}.$$

$$f^i_{\mathrm{phys}}(\Delta\tau, q) = n_i \frac{1}{4\tau} \exp\left(\frac{-|\Delta t^{\mathrm{MC}}|}{\tau}\right) \cdot (1 + q(1-2w_i)\cos(\Delta m_d \Delta t^{\mathrm{MC}})).$$

- Previous measurements:

Collaboration+year	τ_B [ps]	Δm_d [ps^{-1}]
BaBar 2005 [3]	$1.504 \pm 0.013 \pm 0.016$	$0.511 \pm 0.007 \pm 0.007$
Belle 2005 [2]	$1.534 \pm 0.008 \pm 0.010$	$0.511 \pm 0.005 \pm 0.006$
LHCb 2016 [5]	-	$0.505 \pm 0.002 \pm 0.001$
LHCb 2014 [6]	$1.524 \pm 0.006 \pm 0.004$	-
Belle II 2020 [1]	-	$0.531 \pm 0.046 \pm 0.013$
PDG [4]	1.519 ± 0.004	0.5065 ± 0.0019

systematic uncertainties

Uncertainty	τ[ps]	Δm_d[ps^{-1}]
Statistical	**0.0130**	**0.0079**
Analysis bias	0.0003	0.0011
Alignment	0.0027	0.0024
Resolution function	0.0063	0.0028
Momentum scale	0.0002	0.0008
Multiple candidates	0.0024	0.0009
Binning of $\sigma_{\Delta t}$	0.0005	0.0010
$B^0 \to D^{(*)+}\pi^-$ fraction	0.0007	0.0003
ΔE; LTBDT shapes		
$\to b\bar{b}$ ΔE shapes	0.0004	0.0001
$\to q\bar{q}$ ΔE shapes	0.0006	0.0000
$\to$ LTBDT shapes	0.0004	0.0014
Beam		
$\to$ Beam spot	0.0021	0.0014
$\to$ Boost vector	0.0003	0.0001
$\to$ CoM energy	0.0007	0.0002
Total systematic	**0.0077**	**0.0046**

$B \to K\pi$ puzzle

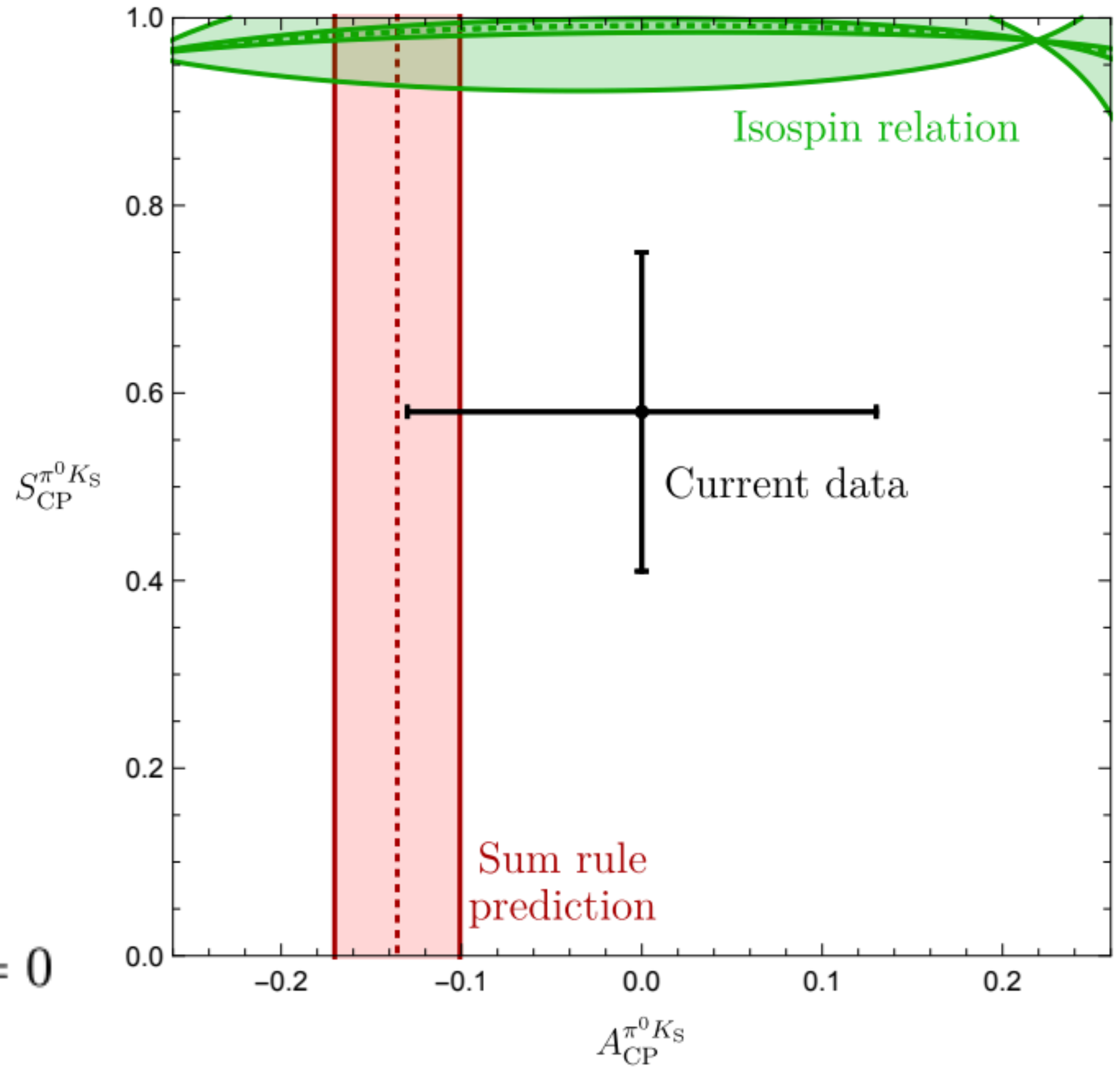
$$\frac{\Gamma(\overline{B}^0_d(t) \to \pi^0 K_S) - \Gamma(B^0_d(t) \to \pi^0 K_S)}{\Gamma(\overline{B}^0_d(t) \to \pi^0 K_S) + \Gamma(B^0_d(t) \to \pi^0 K_S)} = A_{\rm CP}^{\pi^0 K_S} \cos(\Delta M_d t) + S_{\rm CP}^{\pi^0 K_S} \sin(\Delta M_d t),$$

- where $$A_{\rm CP}(B \to f) \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}.$$
- Expected **equal asymmetries** between $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ at LO
- Isospin sum rule:

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

in the limit or isospin symmetry and no EW penguins

- if EWP are considered, **still precision below 1%** with largest uncertainties from $B \to K^0\pi^0$
- Deviation can be NP or enhancement of color suppressed tree



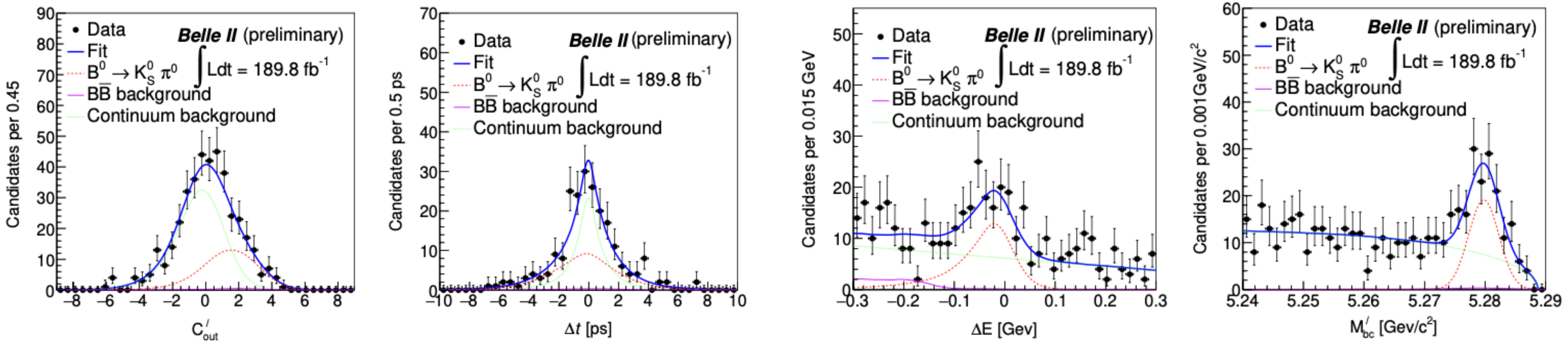
[Eur. Phys. J. C 78, 943 (2018)]

$B^0 \to K_S^0 \pi^0$ extra information

- Δt fit PDF (w=wrong tag, μ=difference in tag eff., $R_{\rm sig}$=resolution)

$$\mathcal{P}_{\rm sig}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[\{1 - q\Delta w_r + q\mu_r(1-2w_r)\} + \{q(1-2w_r) + \mu_r(1 - q\Delta w_r)\}$$
$$\{\mathcal{A}_{CP}\cos(\Delta m_d \Delta t) + \mathcal{S}_{CP}\sin(\Delta m_d \Delta t)\}] \otimes \mathcal{R}_{\rm sig},$$

Source	$\delta\mathcal{B}$ (%)	$\delta\mathcal{A}_{CP}$
Tracking efficiency	0.6	–
K_S^0 reconstruction efficiency	4.2	–
π^0 reconstruction efficiency	7.5	–
Continuum suppression efficiency	1.6	–
Number of $B\bar{B}$ pairs	3.2	–
Flavor tagging	–	0.040
Resolution function	–	0.050
External inputs	0.4	0.021
$B\bar{B}$ background asymmetry	–	0.002
Signal modelling	1.0	0.015
Background modelling	0.9	0.004
Possible fit bias	2.0	0.010
Tag-side interference	–	0.038
Total	9.6	0.086

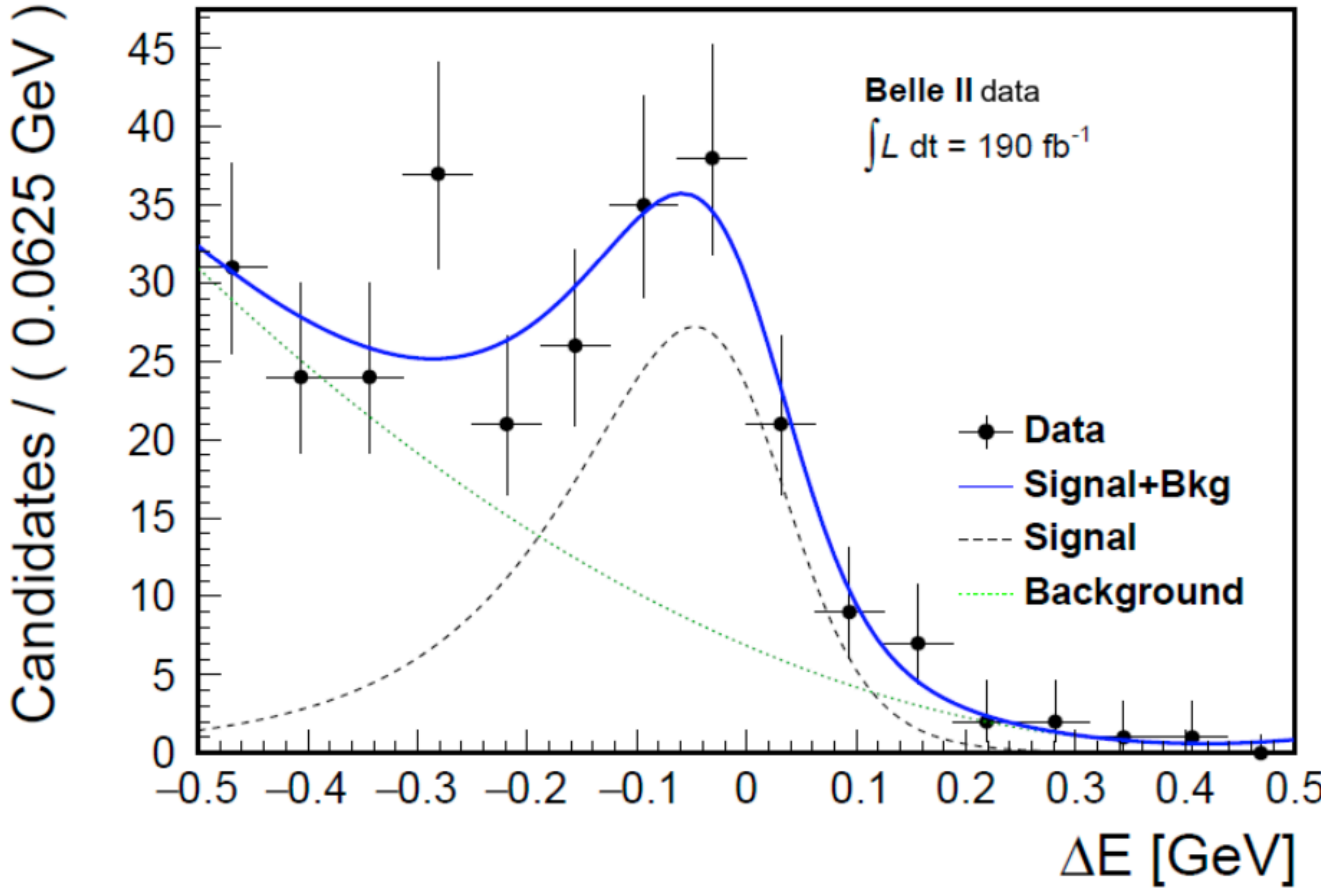


TDCPV: $B^0 \to K_S^0 \pi^0 \gamma$

190 fb^{-1}

[BELLE2-TALK-CONF-2022-031]

- Motivation: $b \to s\gamma$ suppressed in SM and chiral ⇒ $B^0\overline{B}^0$ interference suppressed ⇒ time dependent CP-violation sensitive to NP
- Fit: ML fit to ΔE
- Result:
  - **forerunner of complete TDCPV analysis**
  - compatible with world average



systematic uncertainties

MC sample size	0.2%
MC generation	2.0%
π^0 reconstruction	5.5%
K_S^0 reconstruction	3.5%
π^0-η veto	1.9%
γ selection	0.3%
Continuum suppression	3.0%
Total efficiency	7.7%
Fit bias	11.5%
Number of $B^0\overline{B}^0$ pairs	2.9%
f^{00} systematic	1.2%
Total systematic on $\mathcal{B}$	14.2%

$\mathrm{BR}(B^0 \to K_S^0 \pi^0 \gamma) = (7.3 \pm 1.8\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst})) \cdot 10^{-6}$ w.a. $(7.0 \pm 0.4) \cdot 10^{-6}$

R_{K*} extra information

- $R_{K^{(*)}} = \dfrac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$
- decay chain: $K* \to K^+\pi^-, K^0_S\pi^+, K^+\pi^0$
- Belle II measurement

$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.28 \pm 0.29^{+0.08}_{-0.07}) \times 10^{-6}$ (PDG: $(1.06 \pm 0.09) \times 10^{-6}$)

$\mathcal{B}(B \to K^*e^+e^-) = (1.04 \pm 0.48^{+0.09}_{-0.09}) \times 10^{-6}$ (PDG: $(1.19 \pm 0.20) \times 10^{-6}$)

$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.22 \pm 0.28^{+0.08}_{-0.07}) \times 10^{-6}$ (PDG: $(1.06 \pm 0.10) \times 10^{-6}$)

- LHCb [https://doi.org/10.1007/JHEP04(2017)142]

$$\mathcal{B}(B^0 \to K^*(892)^0\mu^+\mu^-) = (0.904\,^{+0.016}_{-0.015} \pm 0.010 \pm 0.006 \pm 0.061) \times 10^{-6},$$

- LHCb R_{K*} [https://doi.org/10.1007/JHEP08(2017)055]

$$R_{K^{*0}} = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4\,, \\ 0.69\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2/c^4\,. \end{cases}$$

$B \to K^* \ell\ell$ extra information

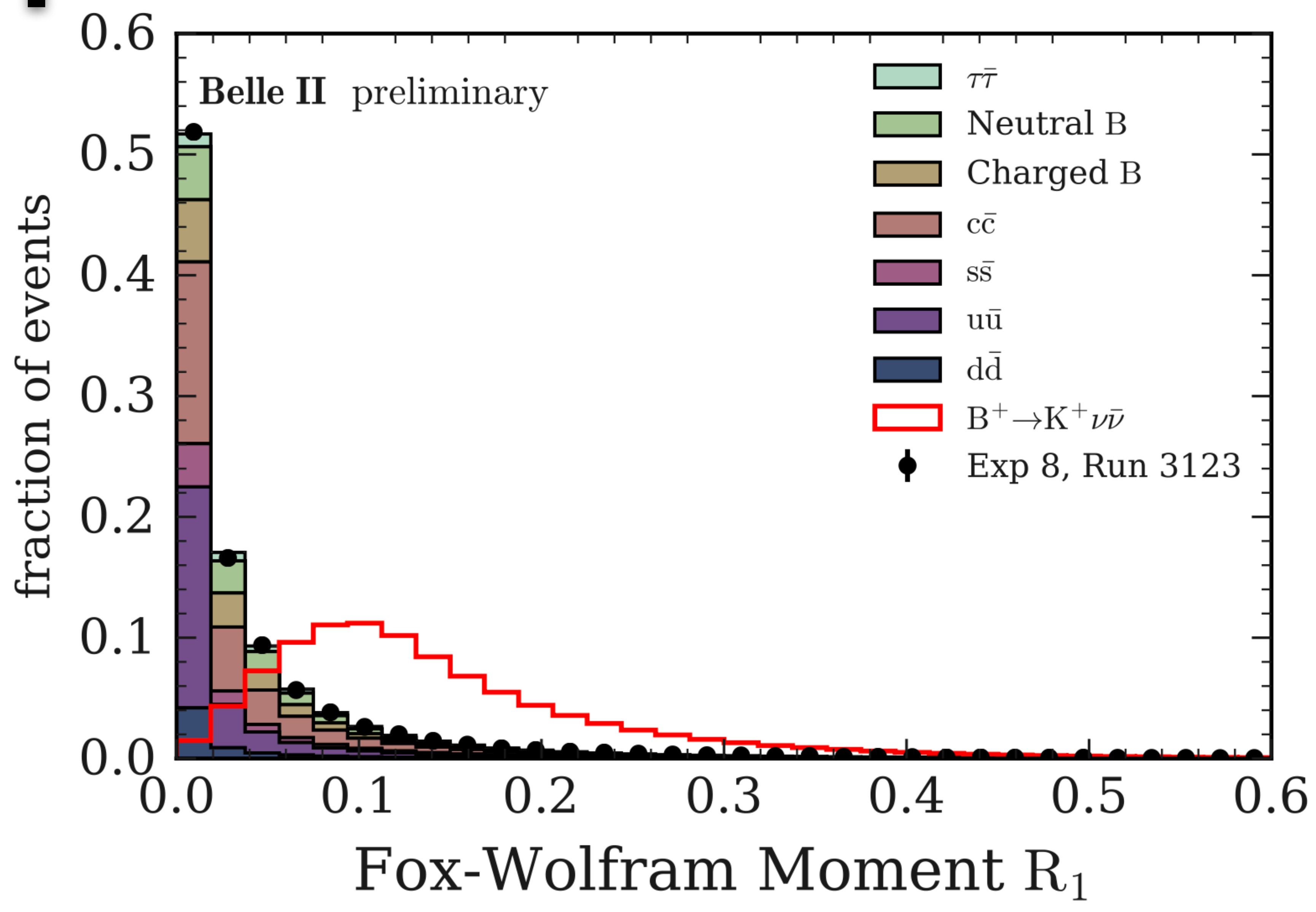
systematic uncertainties

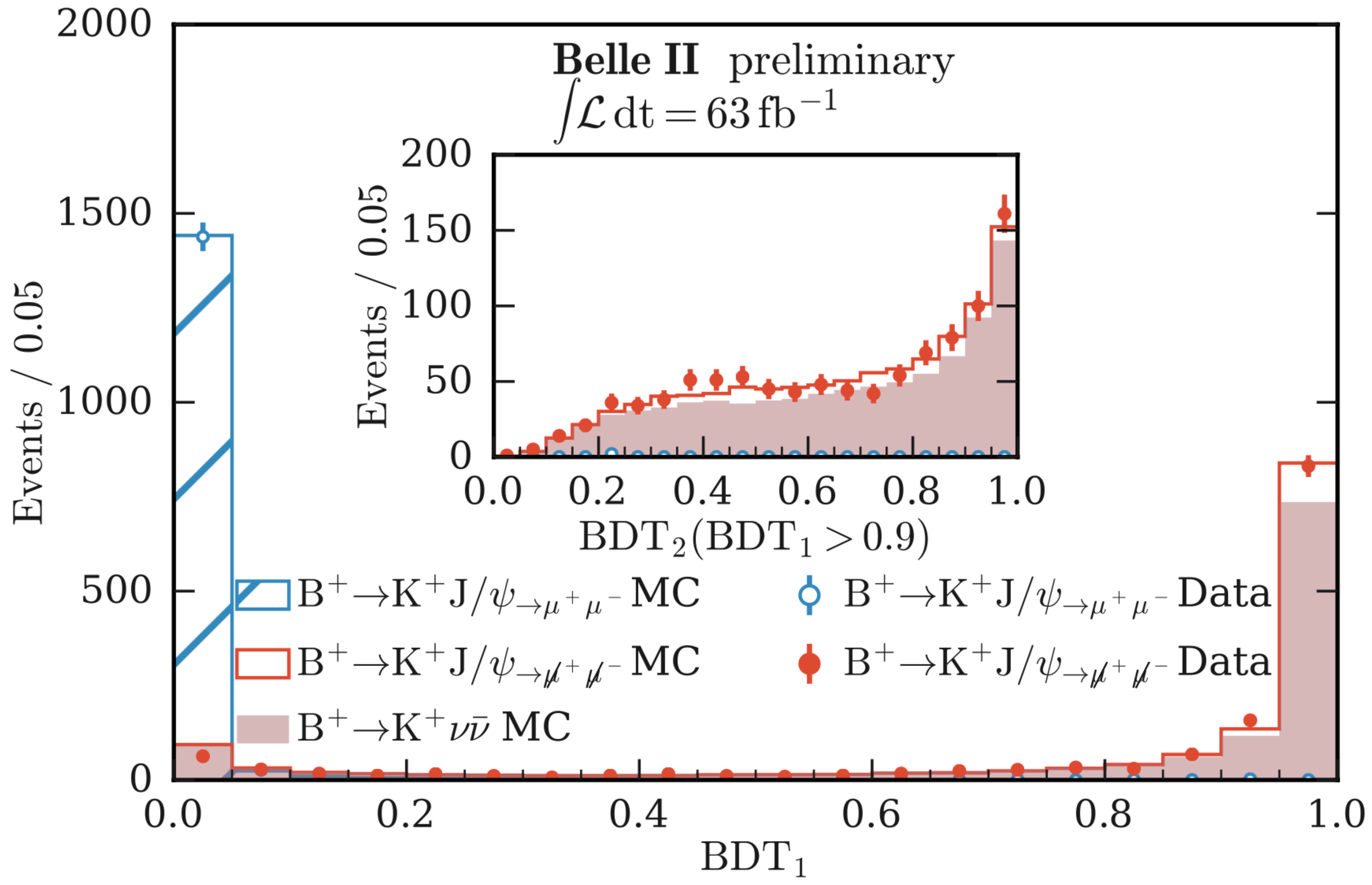
Source	Systematic (%)
Kaon identification	0.4
Pion identification	2.5
Muon identification	$^{+1.9}_{-0.8}$
Electron identification	$^{+0.9}_{-0.5}$
K_S^0 identification	2.0
π^0 identification	3.4
Tracking	1.2 – 1.5
MVA selection	1.3 – 1.7
Simulated sample size	< 0.5
Signal cross feed	$< 1\%$
Signal PDF shape	0.5 – 1.0%
$\mathcal{B}(\Upsilon(4S) \to B^+B^-)[(\mathcal{B}(\Upsilon(4S) \to B^0\overline{B^0}))$	1.2
Number of $B\overline{B}$ pairs	2.9
Total	$^{+6.7}_{-6.0}$

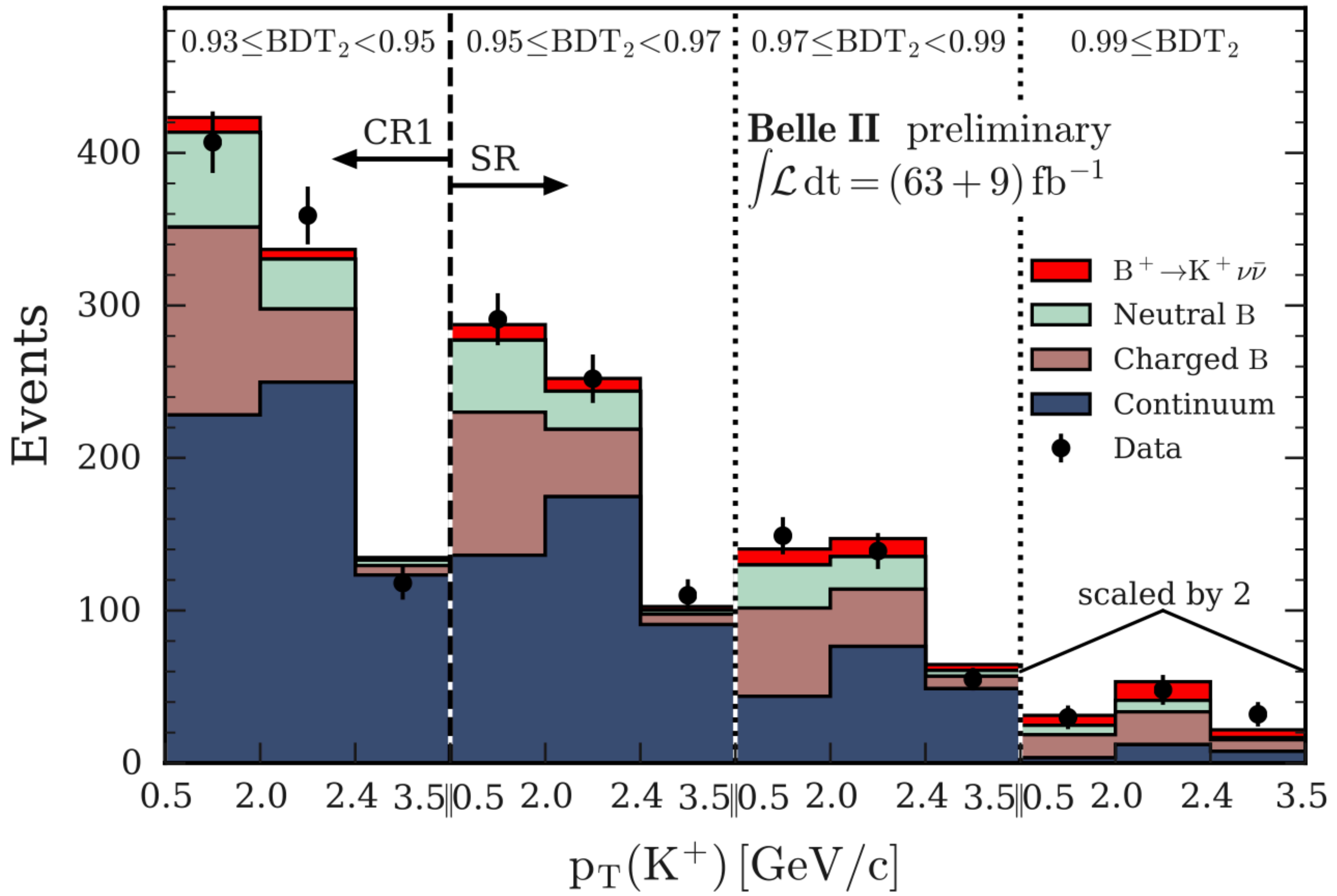
$B^+ \to K^+ \nu \bar{\nu}$ extra information

- Leading systematic uncertainty: background normalization
- Calibration: $B^+ \to K^+ J/\psi(\to \mu\mu)$ without reconstructing the 2 muons
- Fit: performed in $p_T \times C_{BDT2}$ in signal region and 3 control regions (lower BDT values)

example of discrimination variable

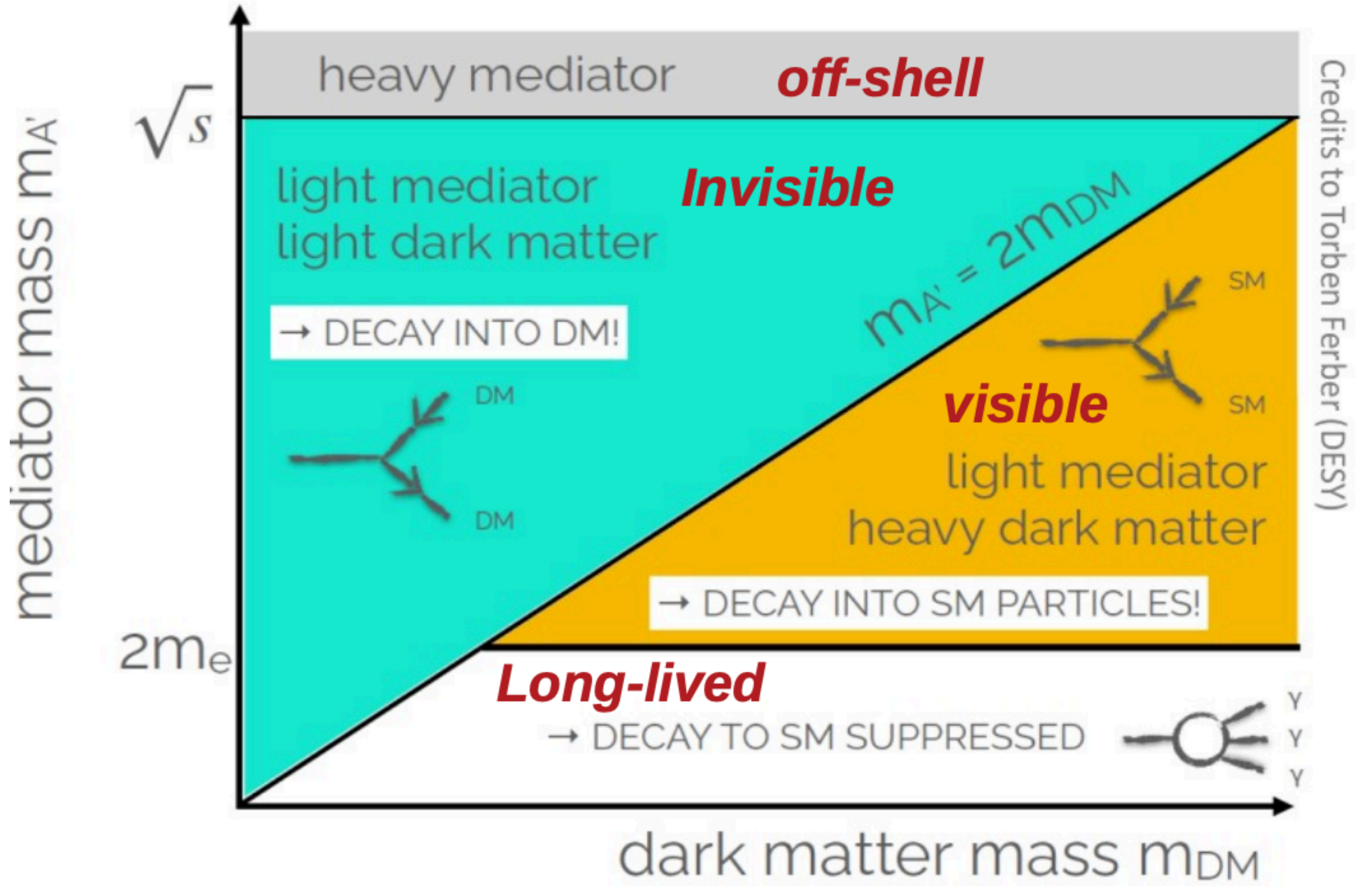


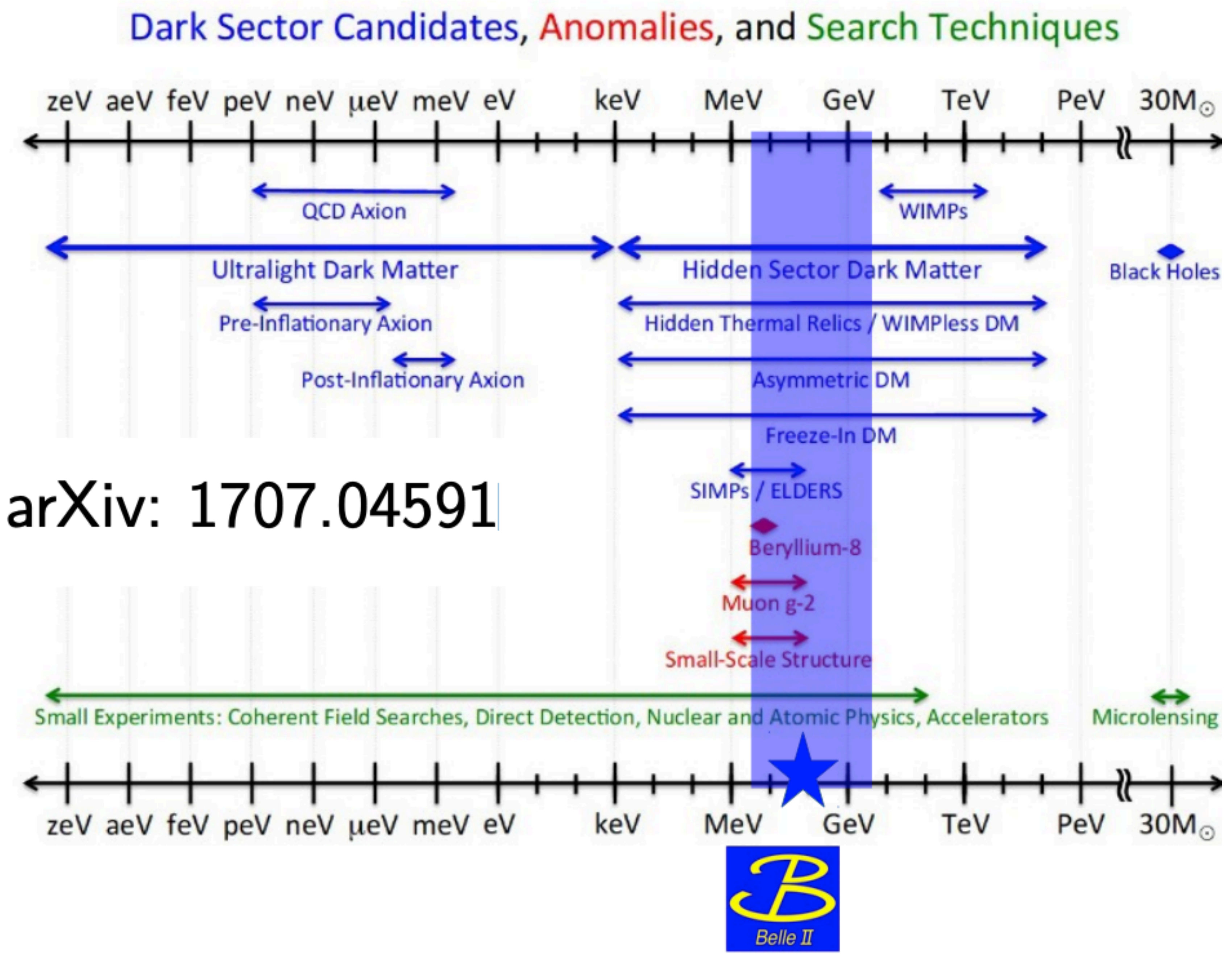




Dark sector (1/3)

- B-Factory opportunity:
  - Unique reach in light DM (MeV-GeV) scale
  - Hermetic detector, clean events
  - Dedicated low-multiplicity trigger (suppress QED)
  - Large statistics





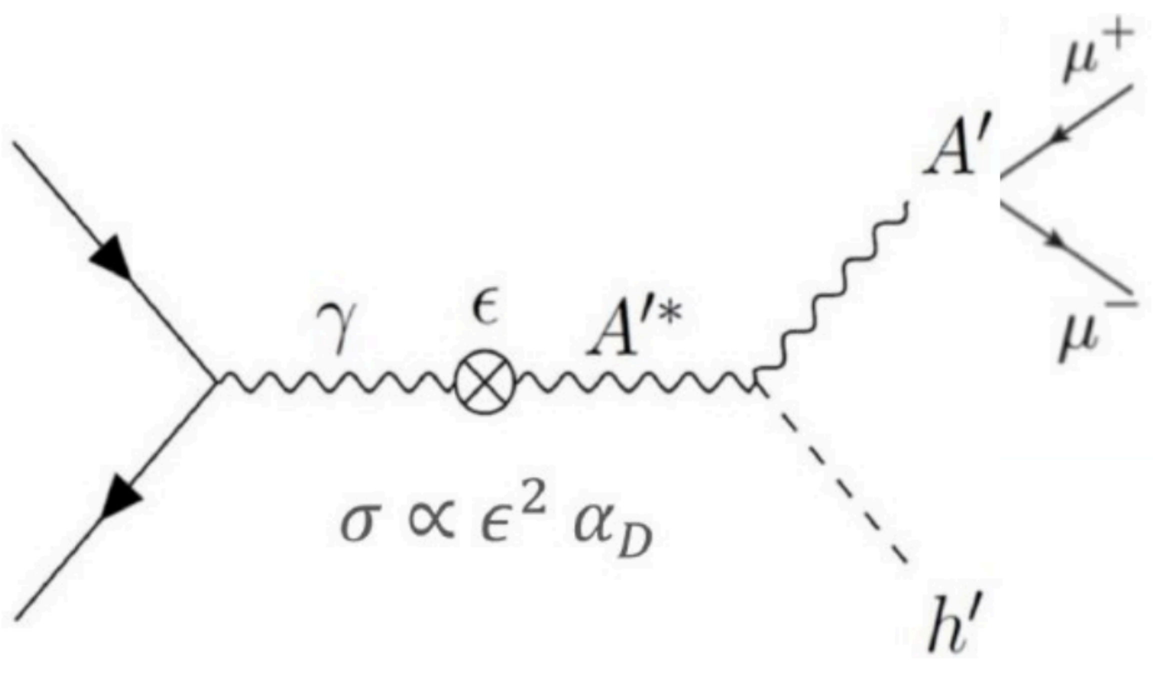
arXiv: 1707.04591

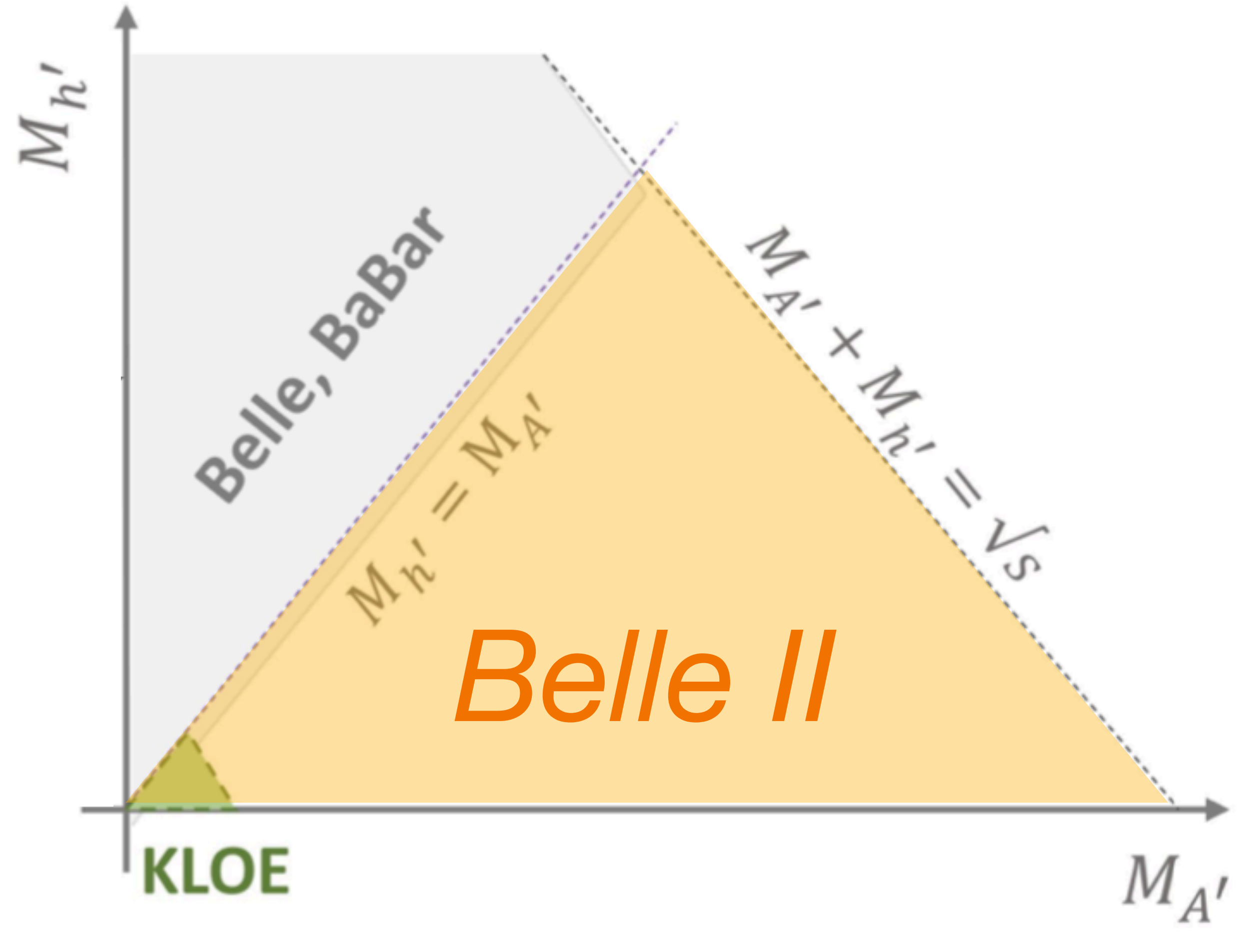
Dark sector (2/3): Dark Higgsstrahlung

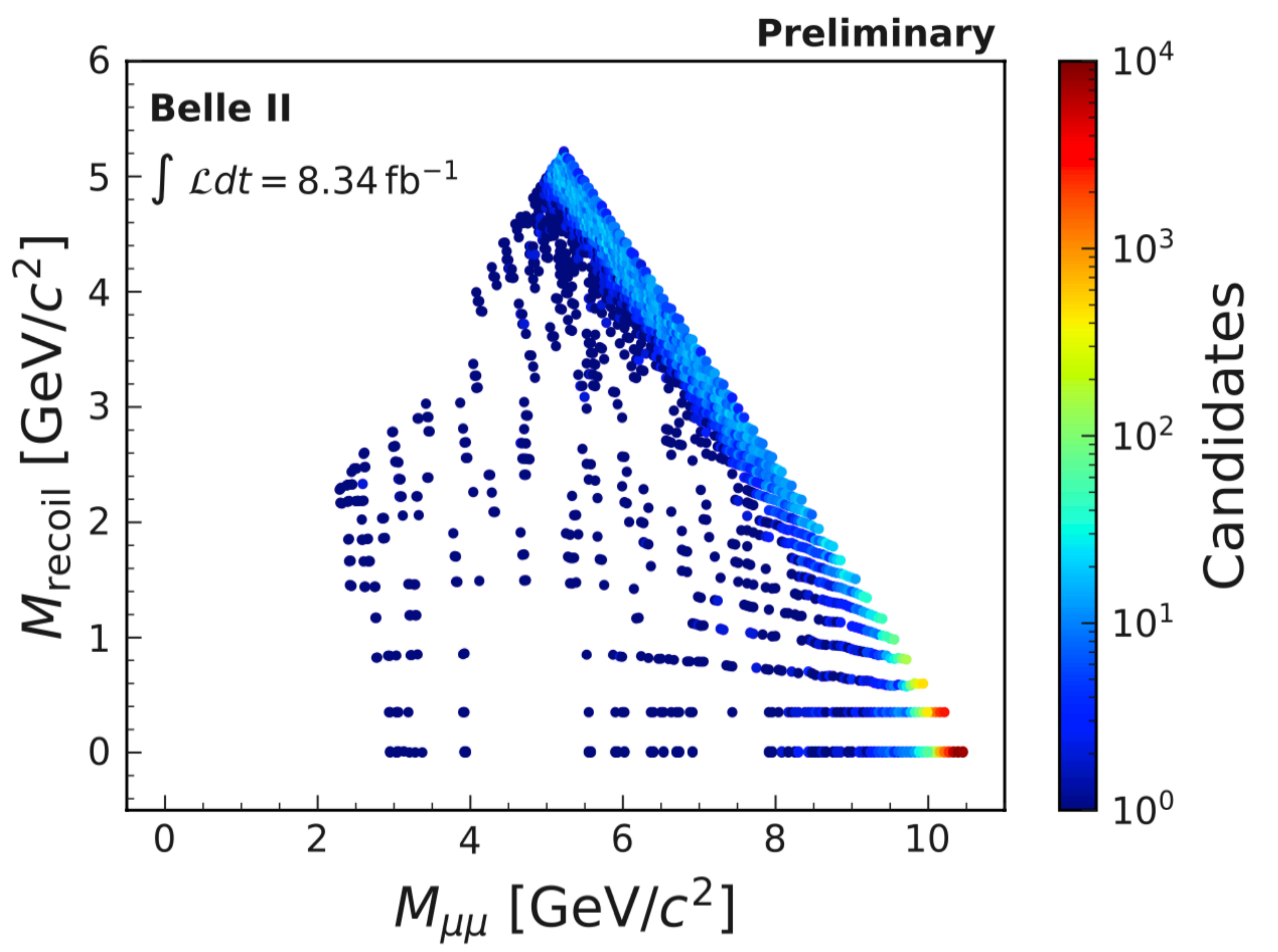
8 fb^{-1}

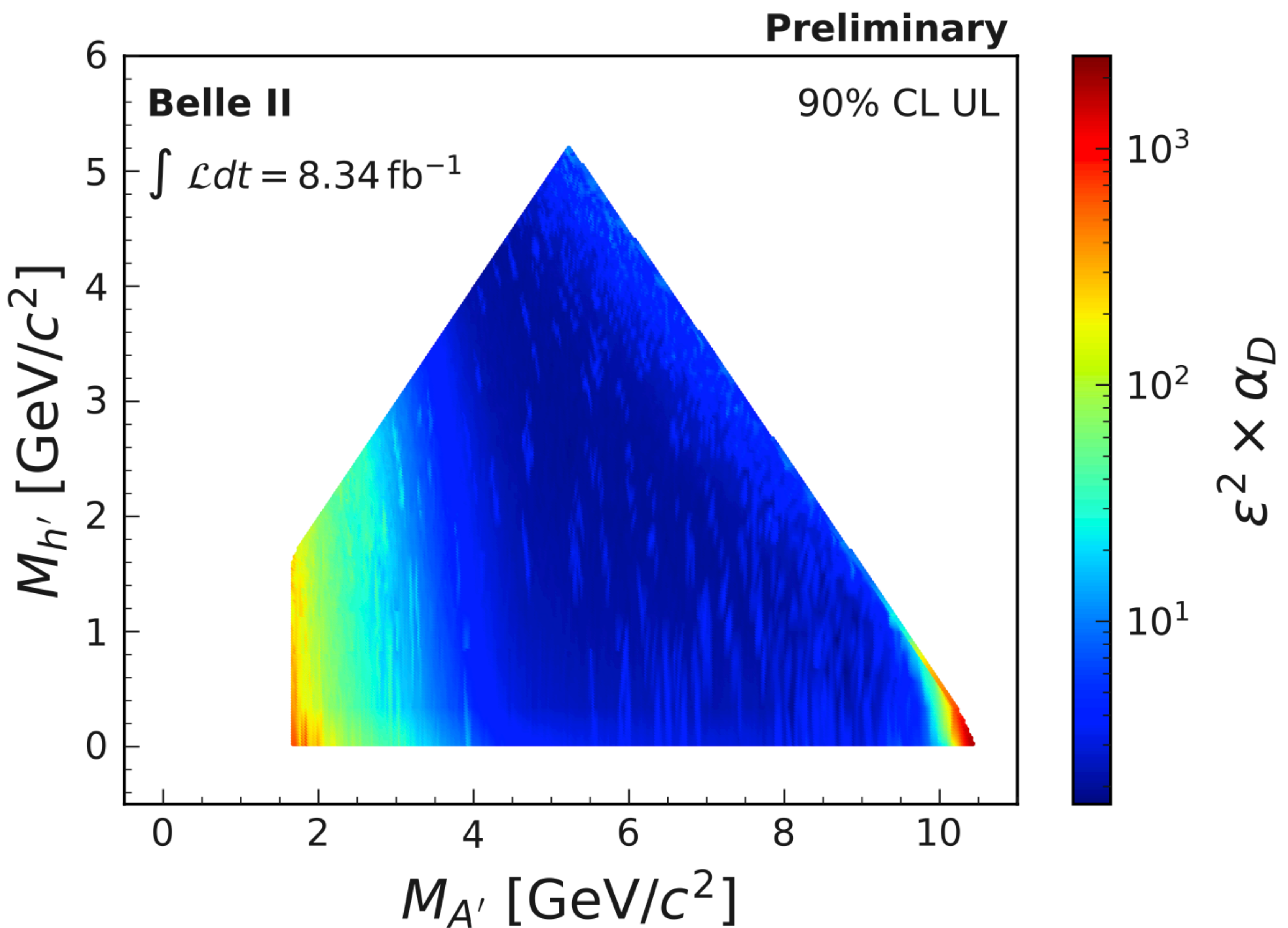
[arxiv:2207.00509]

- Next-to-Minimal dark photon Model:
  - dark photon (A') mixed with γ_{SM}
  - A' mass via SSB$\Rightarrow$ dark higgs (h') with no SM coupling
  - mass hierarchy: $m_{h'} < m_{A'} \Rightarrow h'$ emitted via higgstrahlung and long-lived, $A' \rightarrow \mu\mu$
- Analysis Strategy: **Scan of** $M_{\mu\mu} \times M_{\rm rec}$ (rec= recoil against dimuon)
- Results: **no excess found** but world **best UL** for 1.65 GeV $< m_{A'} < 10.51$ GeV









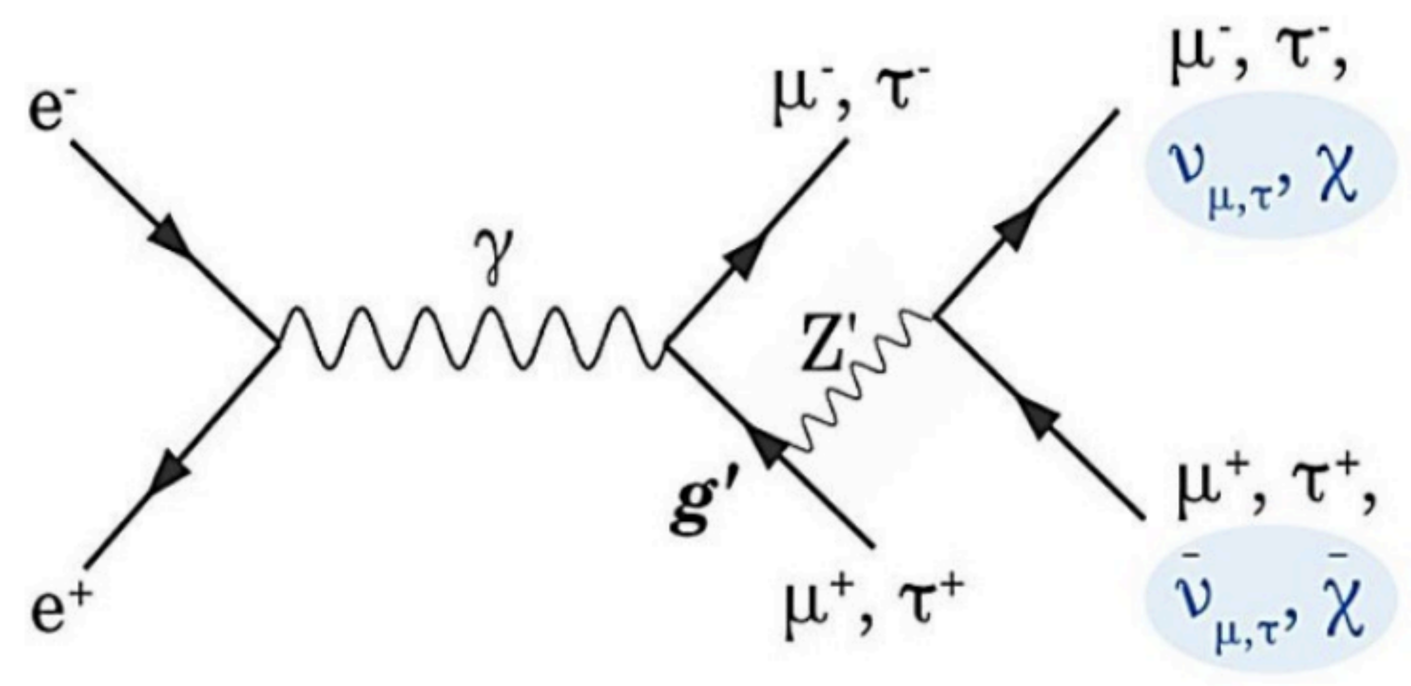
Dark sector (3/3): invisible Z' decay

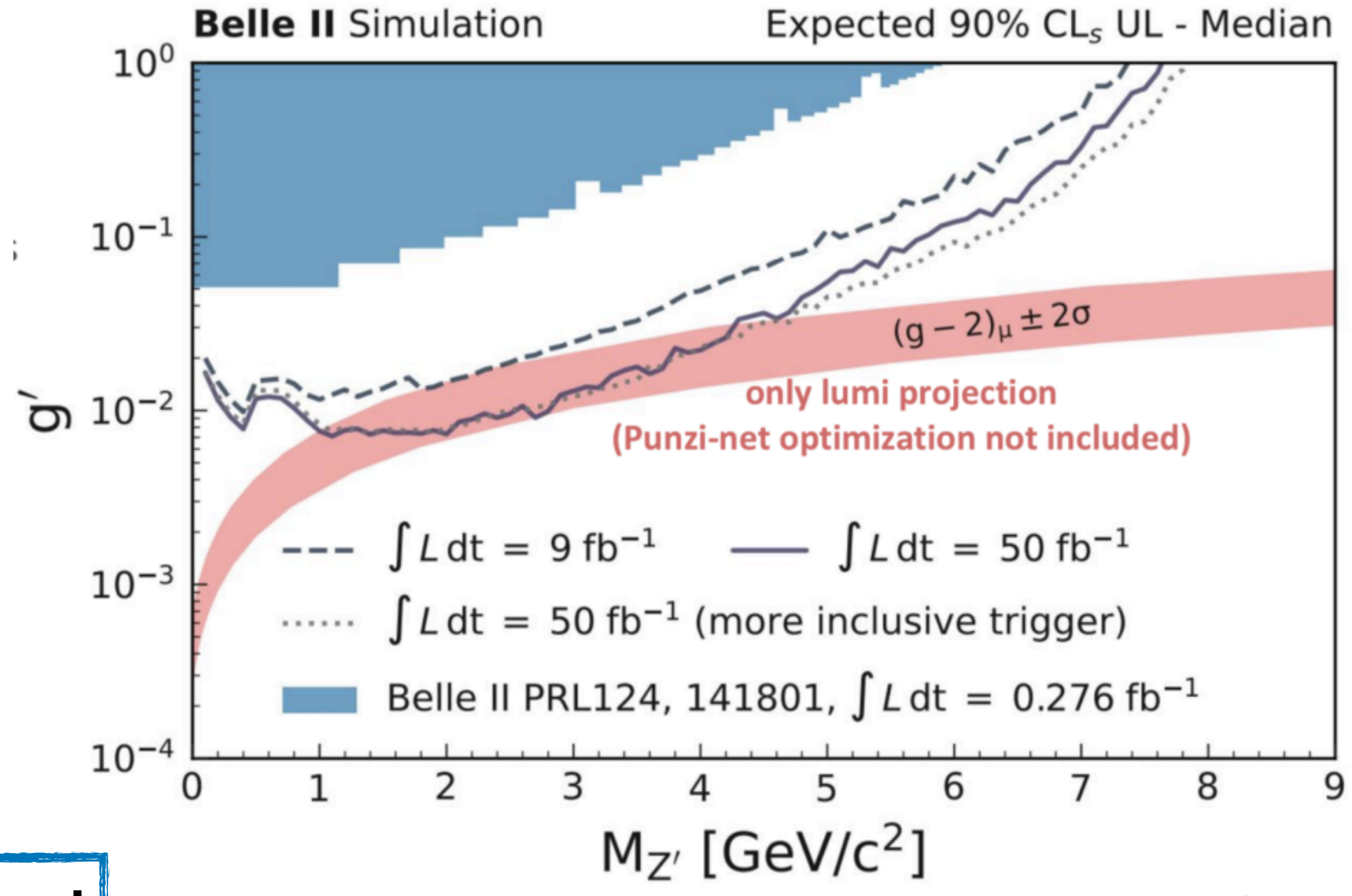
$0.3\ (80)\ \ \mathrm{fb}^{-1}$

[Phys Rev Lett 124, 141801 (2020)]

[BELLE2-TALK-CONF-2022-056]

- Model:
  - new massive gauge boson, coupling with μ and τ: $(L_\mu - L_\tau)$
  - Consequences: **solution of DM,** $(g-2)_\mu$ **anomaly,** $b \to s\ell\ell$ **anomalies** [JHEP, 1612 (2016), 106], [Phys. Rev. D 89, 13004 (2014)]
  - Can decay in $\nu\nu, \chi\bar{\chi}$ or $\mu\mu, \tau\tau$ depending on $m_{Z'}$
- Strategy:
  - $e^+e^- \to \mu^+\mu^- Z' \Rightarrow$ 2 tracks and missing energy
  - look for peak in M_{rec}
  - Bkg: radiative QED processes $(\ell\ell\gamma)$ ⇒NN-based Punzi-loss selection [EPJC 82 (2022) 121]





Result out soon!

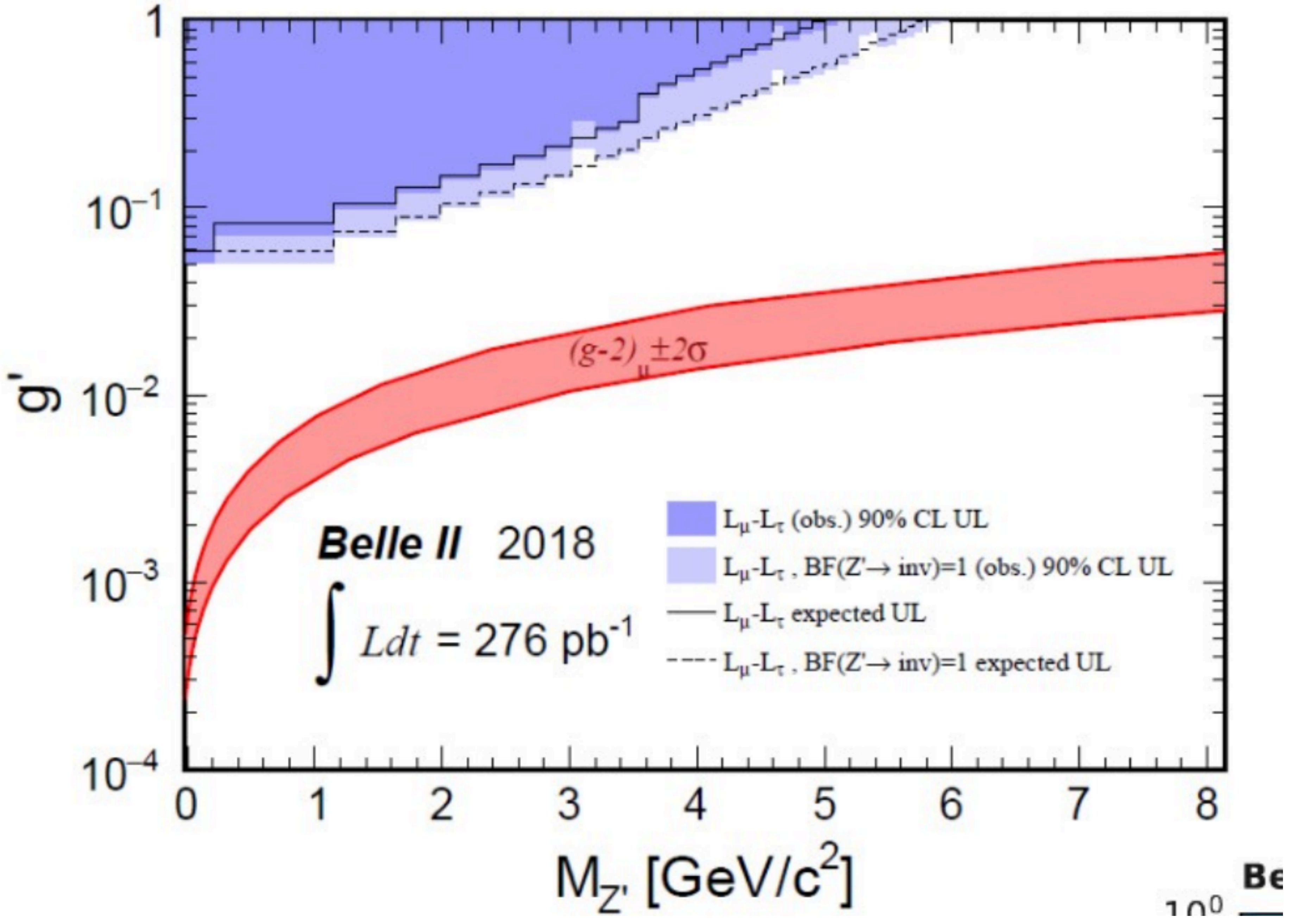
Invisible Z' decay extra information

- Mass hierarchy:

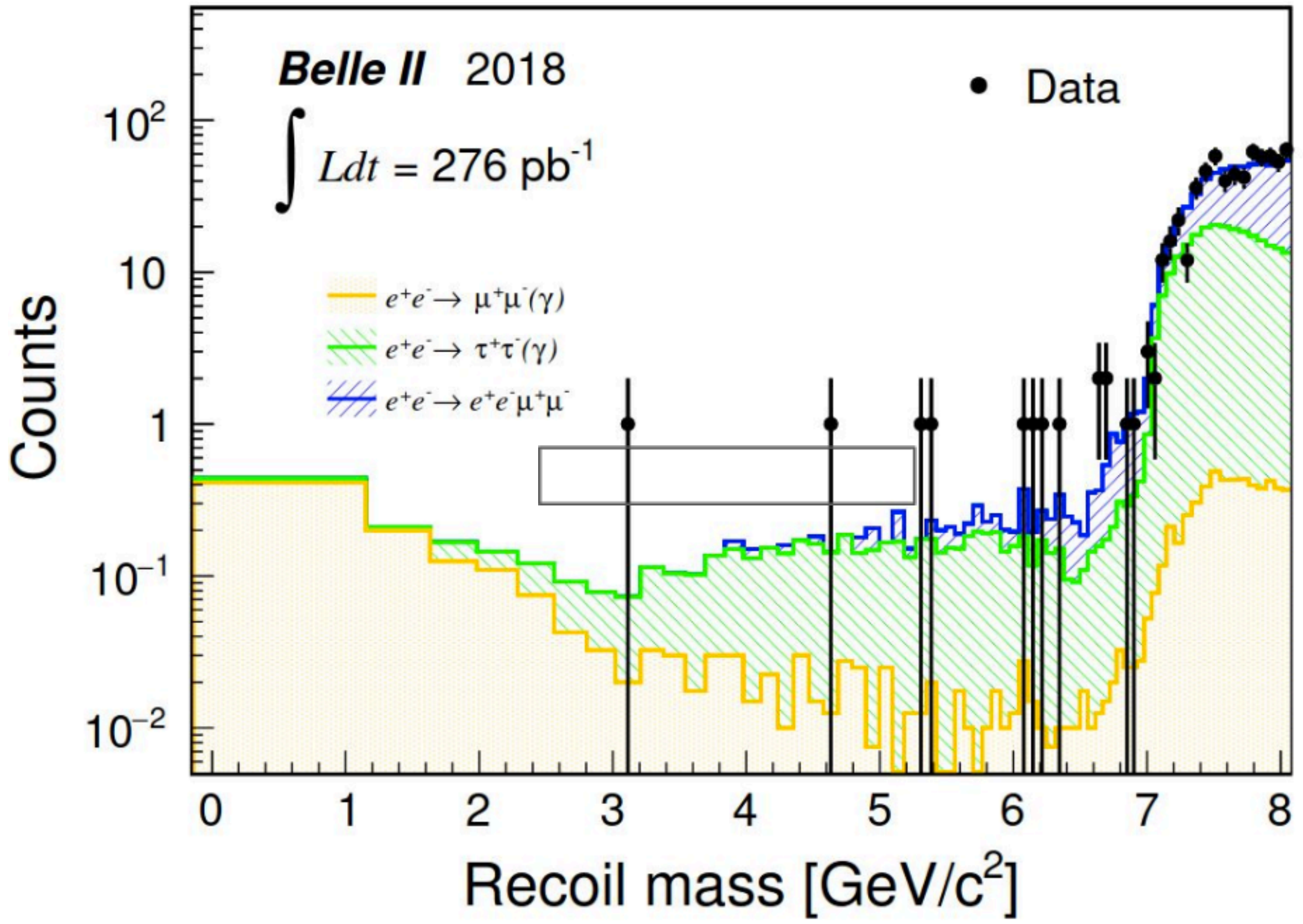
$$
\begin{aligned}
M_{Z'} < 2M_\mu \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] = 1, \\
2M_\mu < M_{Z'} < 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/2, \\
M_{Z'} > 2M_\tau \quad &\Longrightarrow \quad BF[Z' \to \text{invisible}] \simeq 1/3.
\end{aligned}
$$

$$
\text{if } M_{Z'} > 2M_\chi
$$
$$
BF(Z' \to \chi\bar{\chi}) = 1
$$

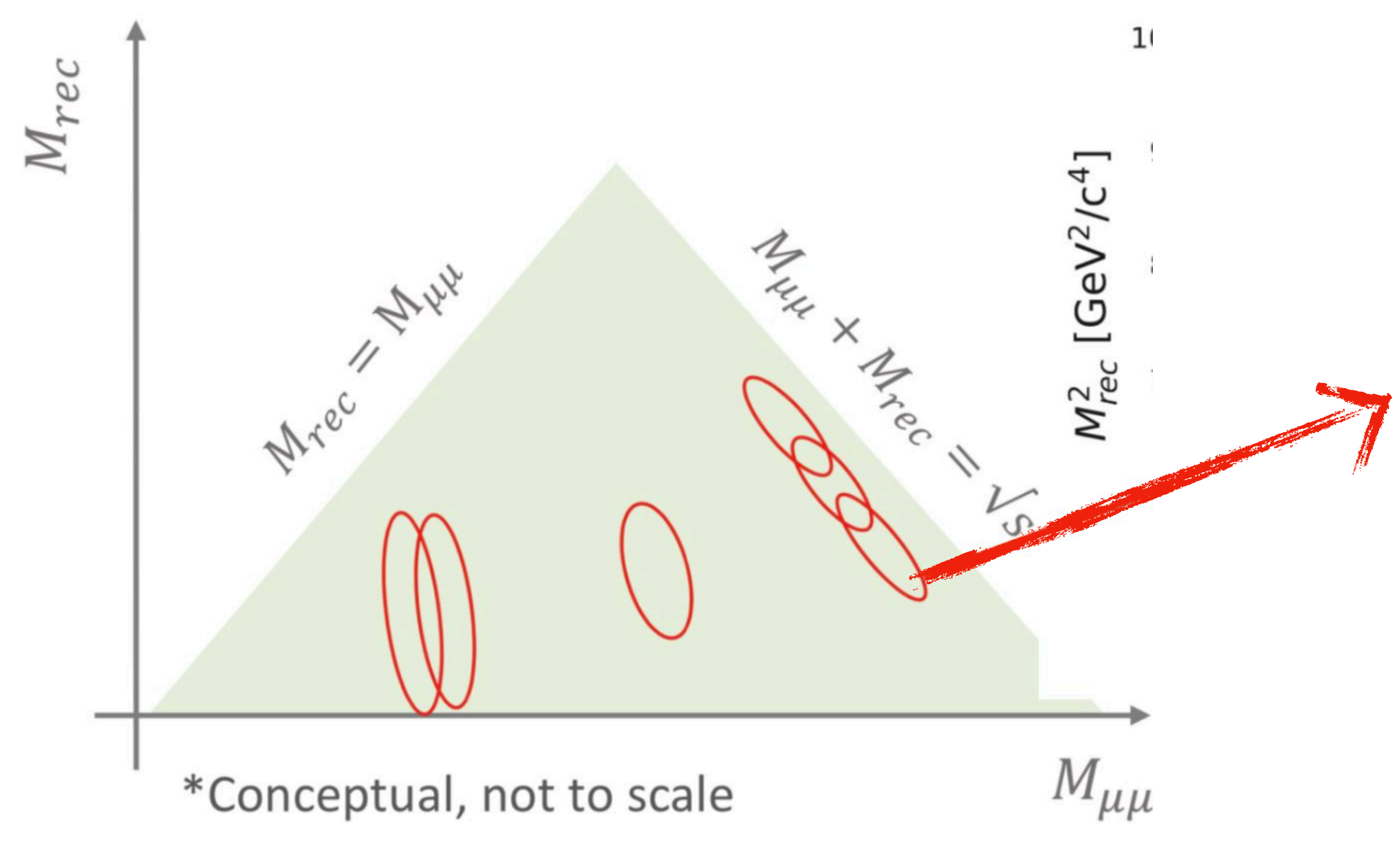
- Old result

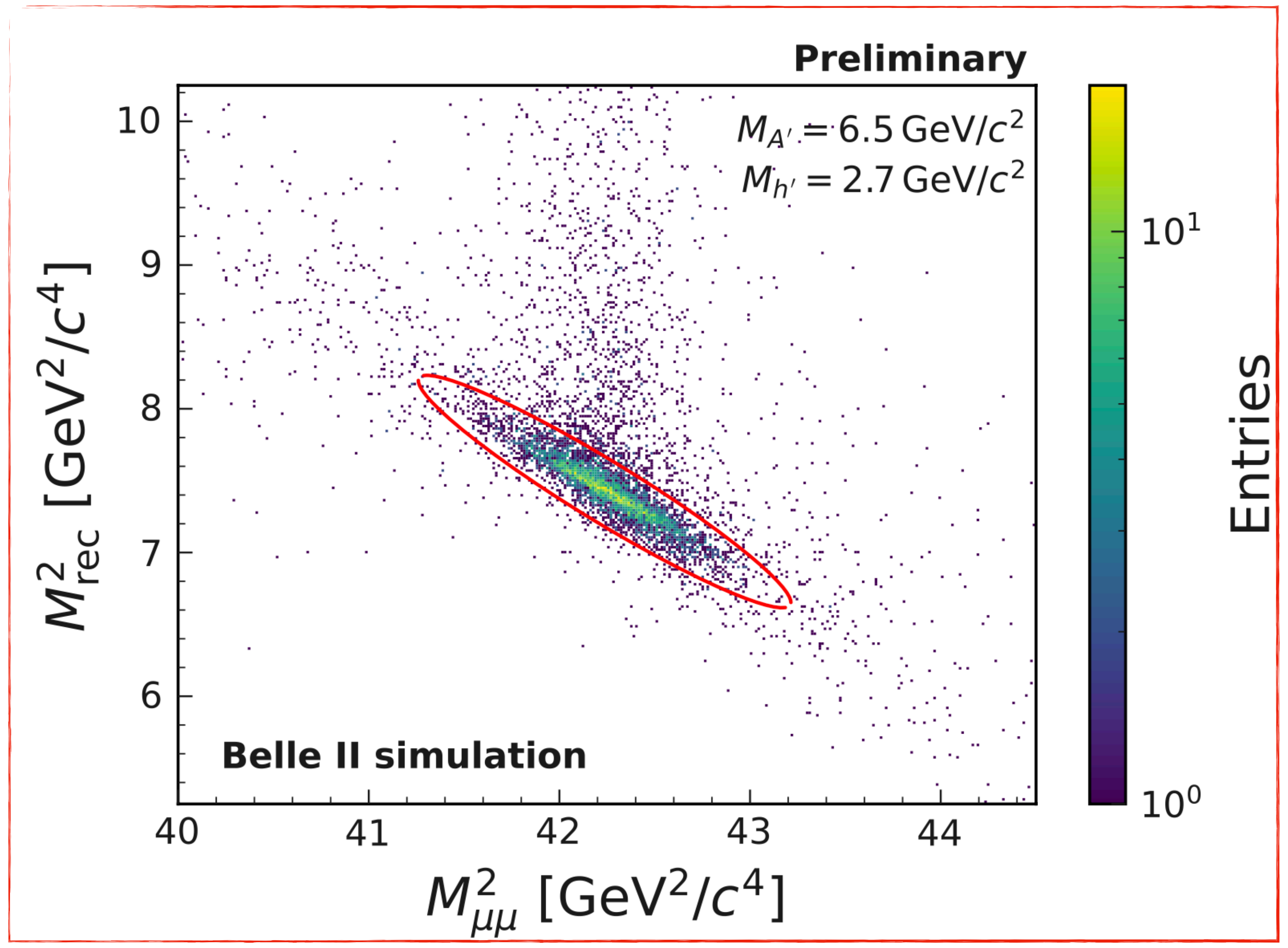


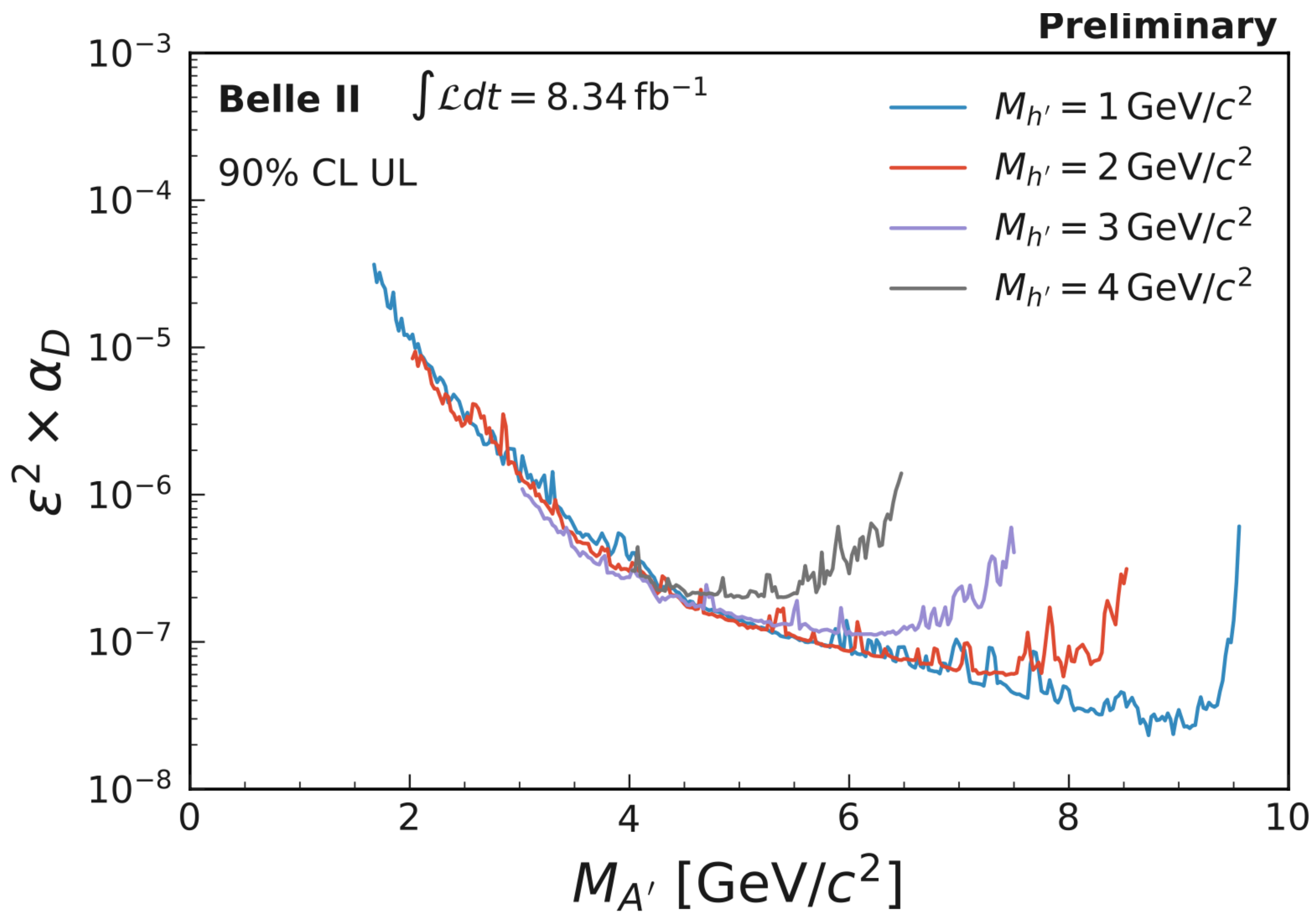
[Phys. Rev. Lett. 124, (2020) 141801]

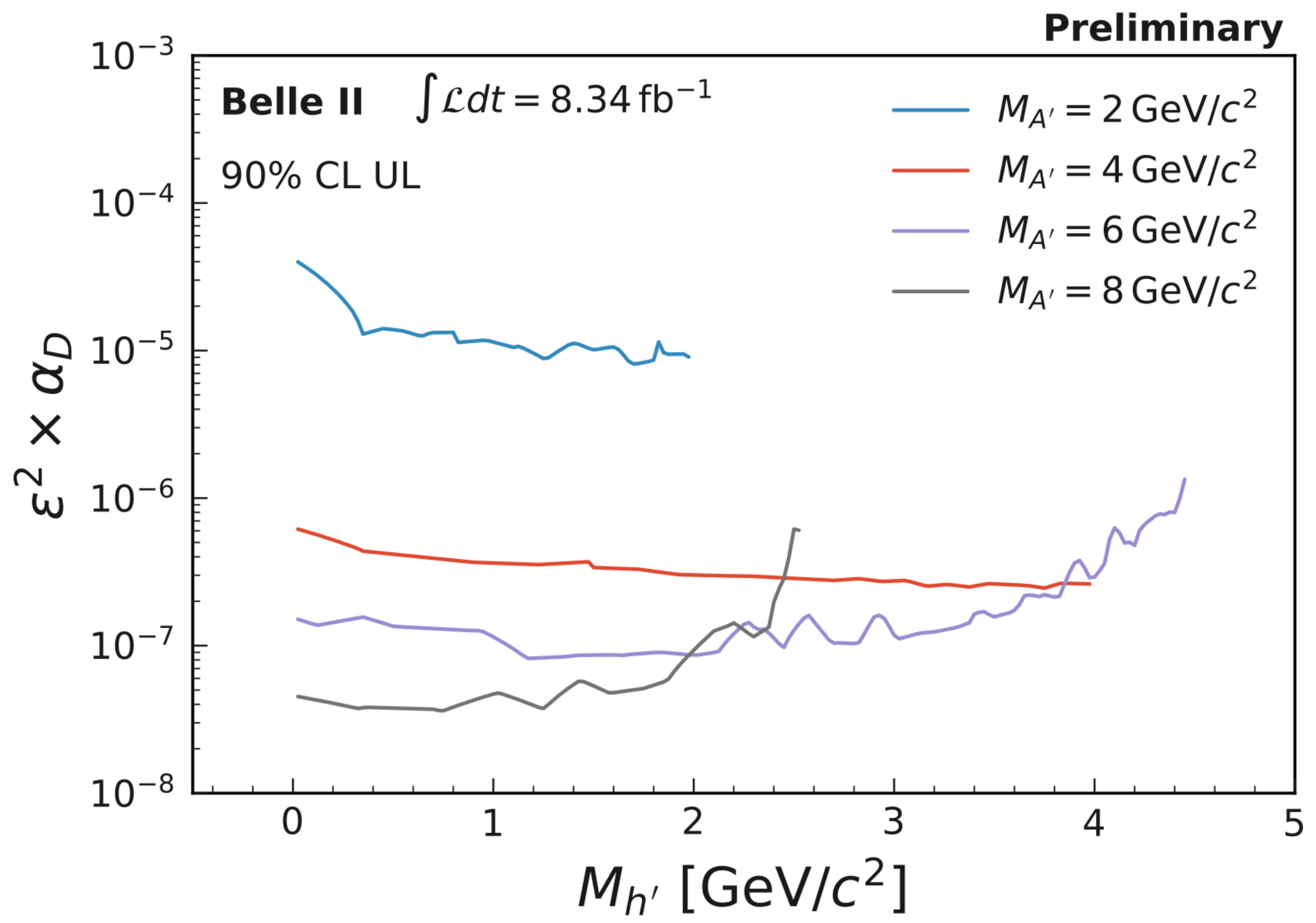


Dark higgssralhung extra information







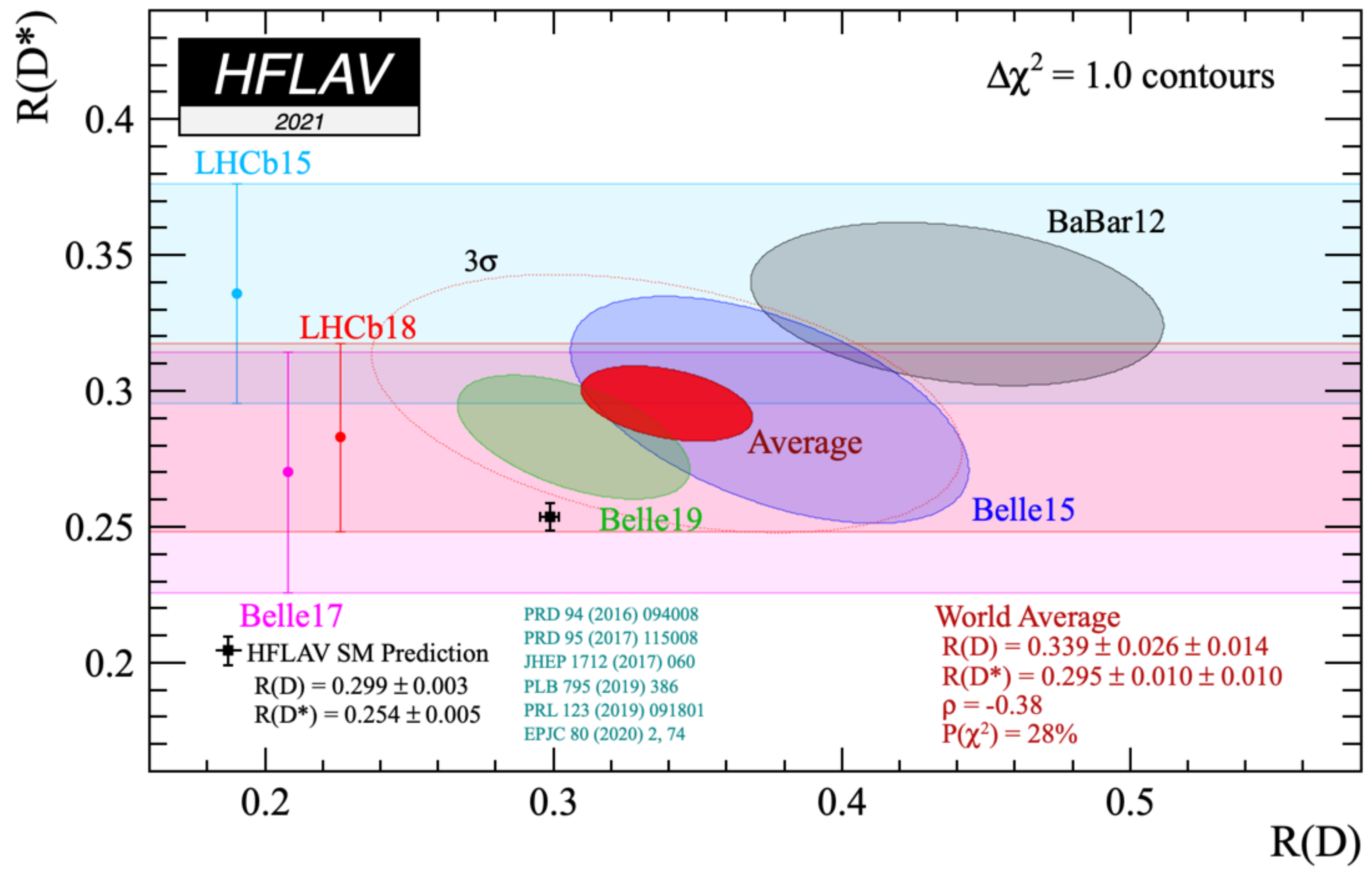


References

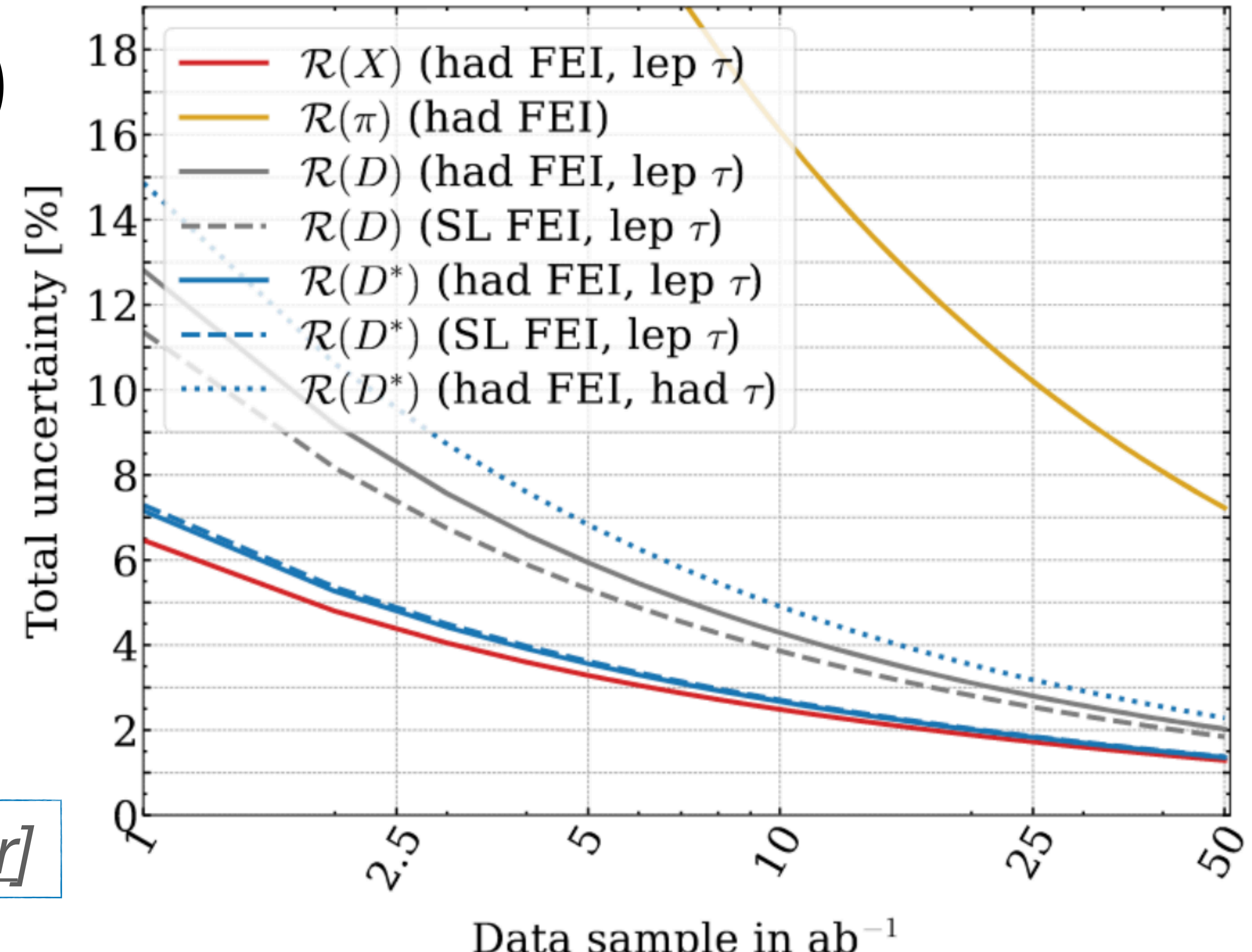
- Model: [Phys. Rev. D 79, 115008 (2009)]
- Babar: [Phys. Rev. Lett. 108, 211801(2012)]
- Belle: [Phys. Rev. Lett. 114, 211801 (2015)]
- KLOE-2: [Phys.Lett.B, 747 (2015)]

Lepton Flavour Universality $R_{D^{(*)}}$

- $R_{D^{(*)}} = \dfrac{BR(B \to D^{(*)}\tau\nu_\tau)}{BR(B \to D^{(*)}\ell\nu_\ell)}$
- 3.1σ deviation from SM
- Pro: Theory uncertainties in $|V_{cb}|$ and form factor mostly cancel out
- Cons: Large Background (multiple neutrinos, low p_T)
- Belle II projection:

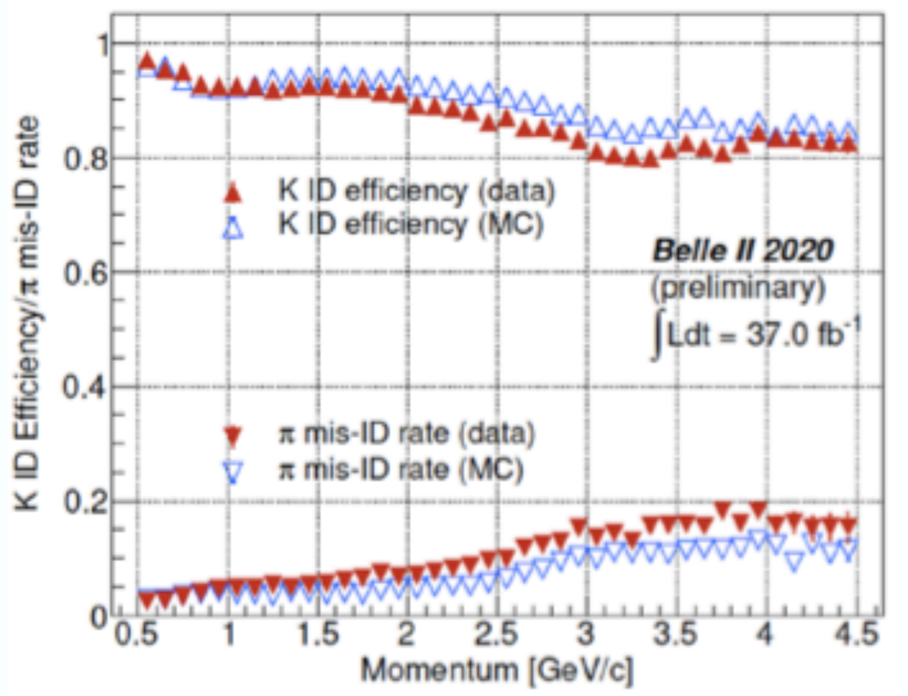


[HFLAV,2021]

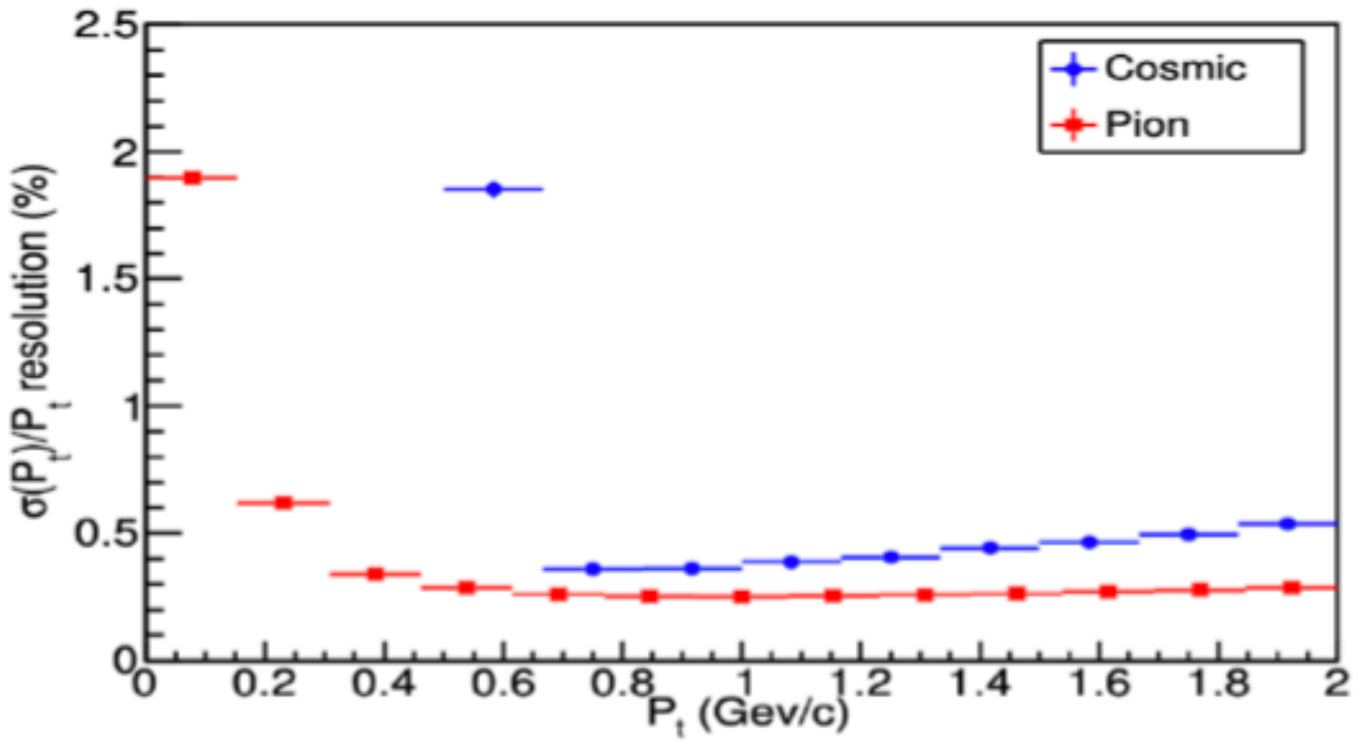


[Snowmass white paper]

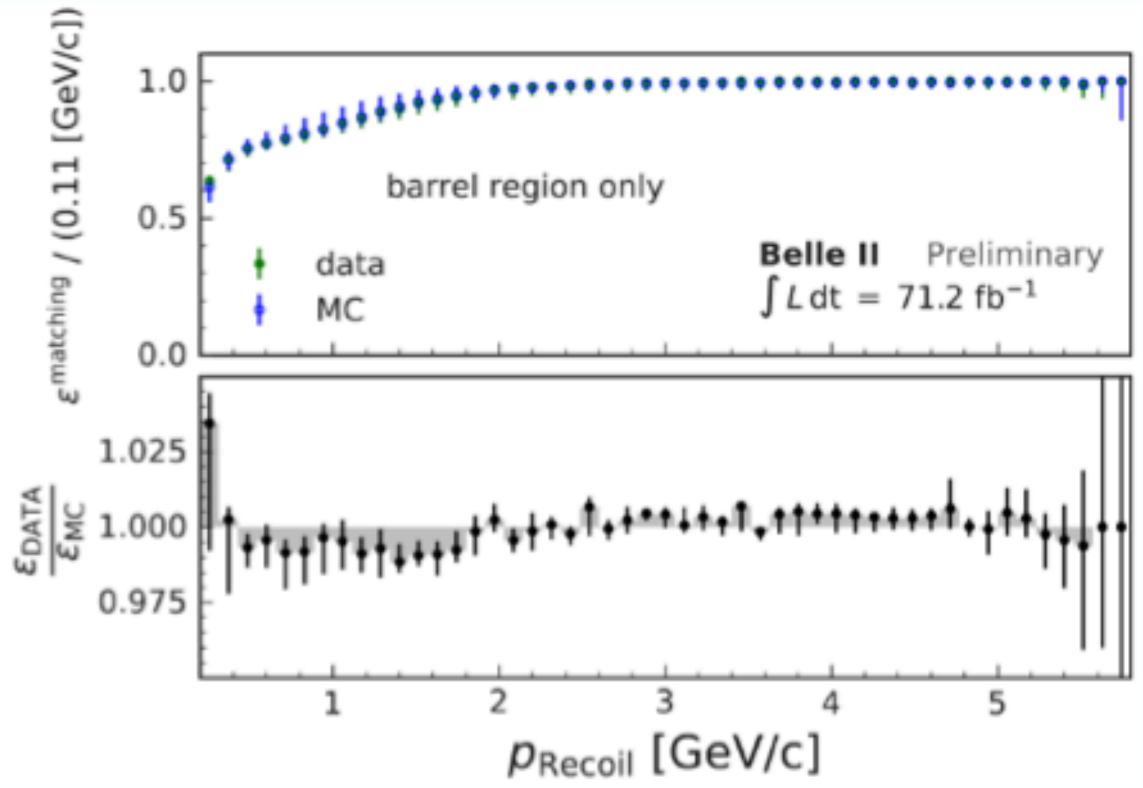
Belle II performance



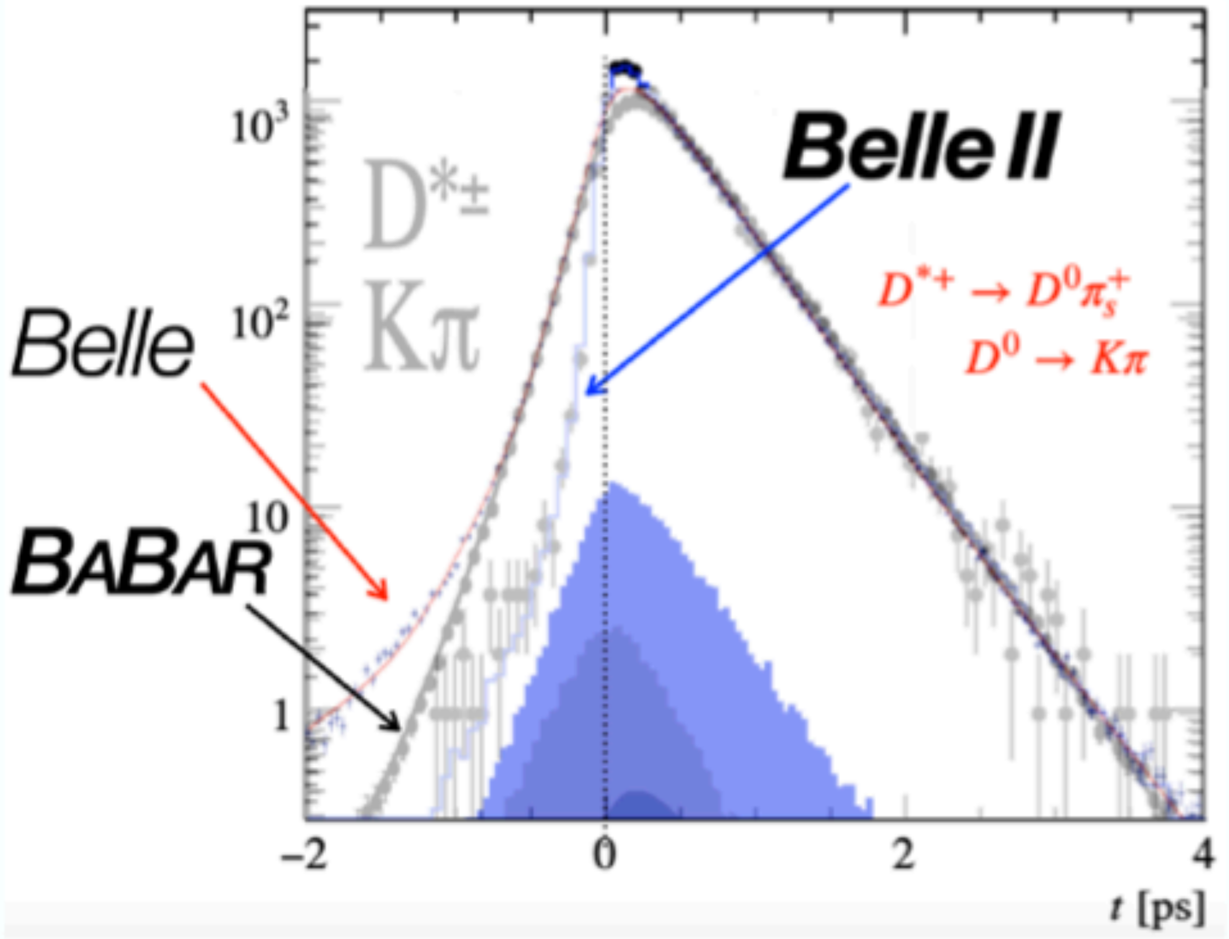
PID still 20% worse than Belle but improving



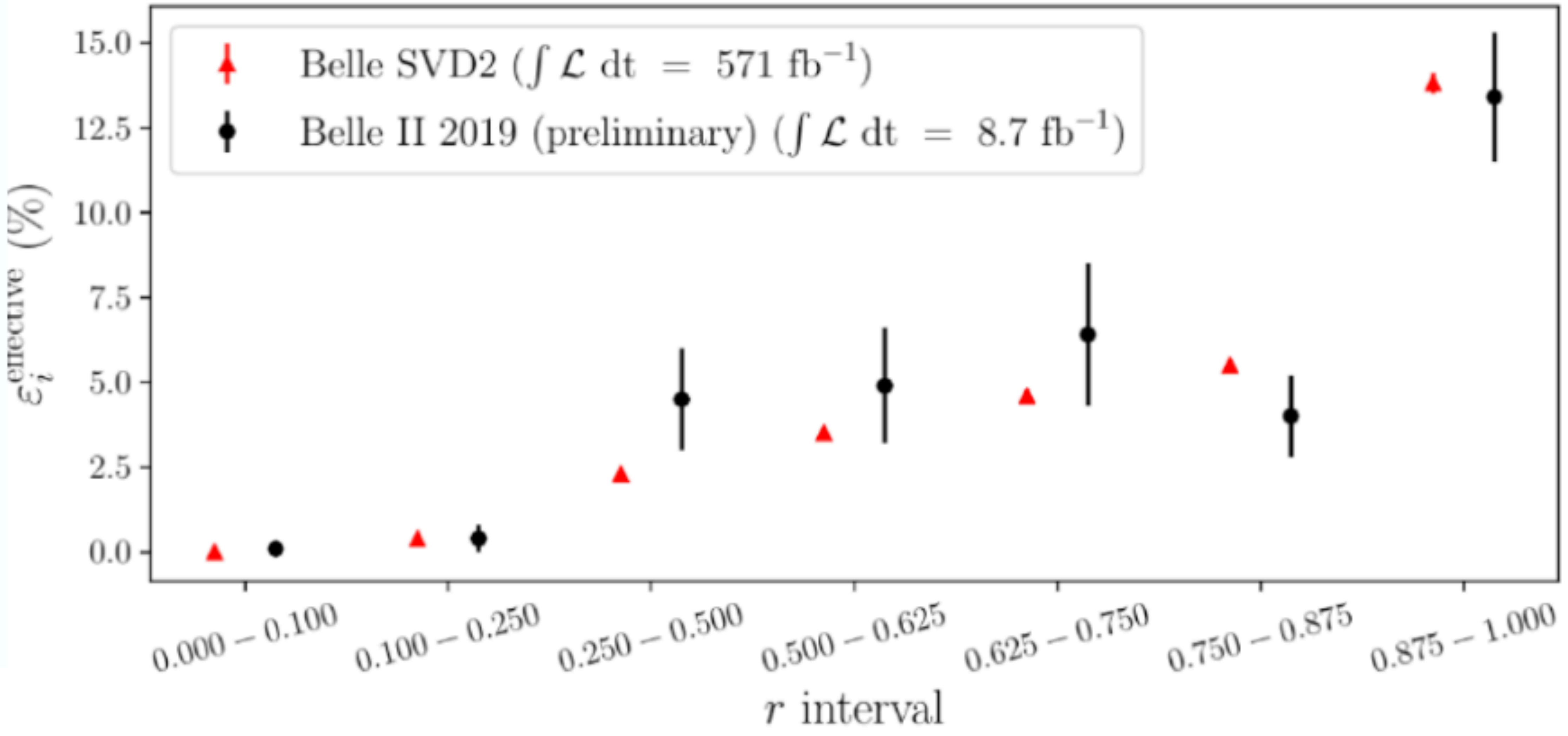
Momentum resolution 20% better than Belle



High photon efficiency,



Nearly 2x better decay-time resolution than Belle



Tagging performance similar to Belle and improving

[From D. Tonelli]