Measurements of EW Penguin and LFV *B* Decays at Belle & Belle II

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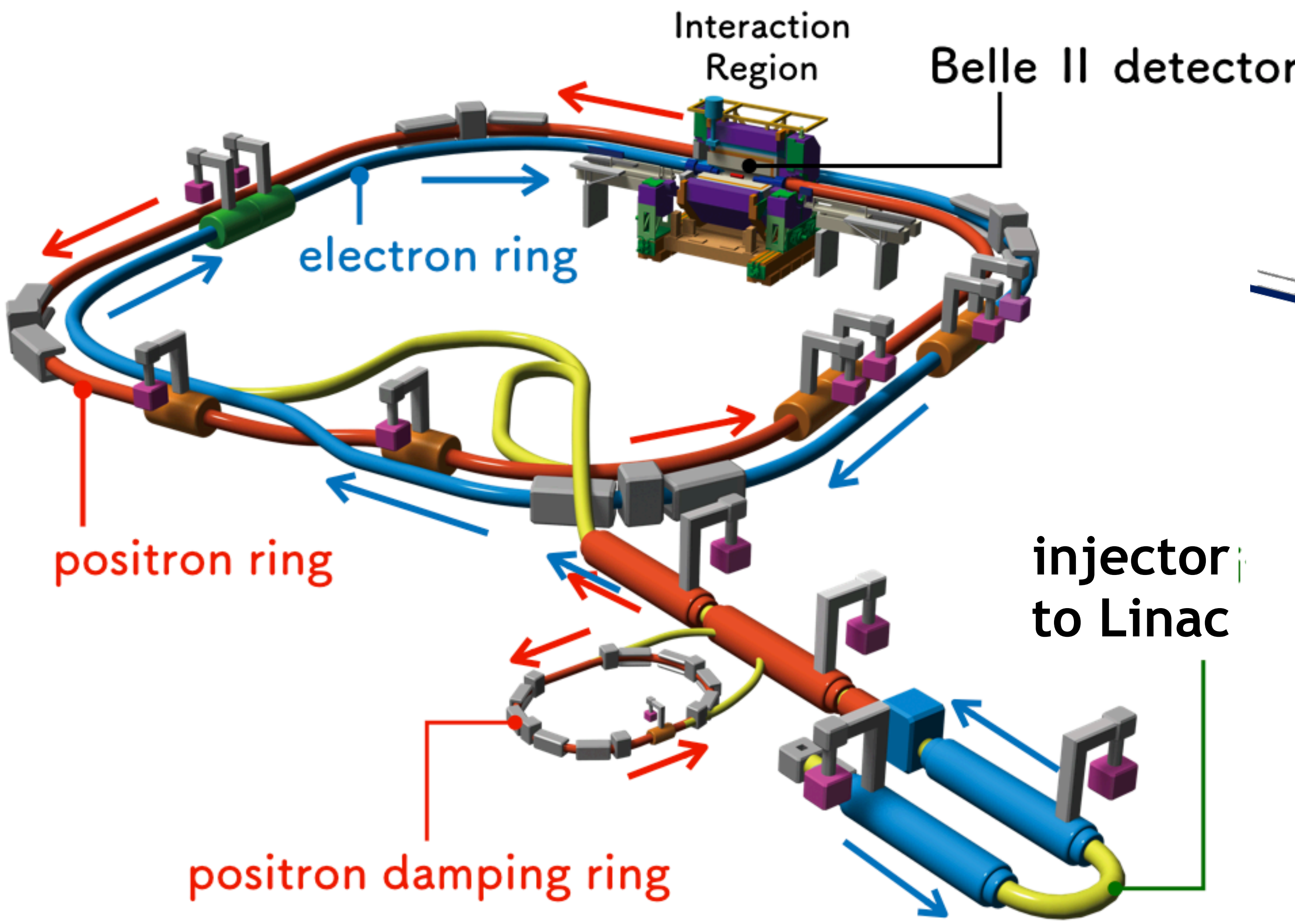
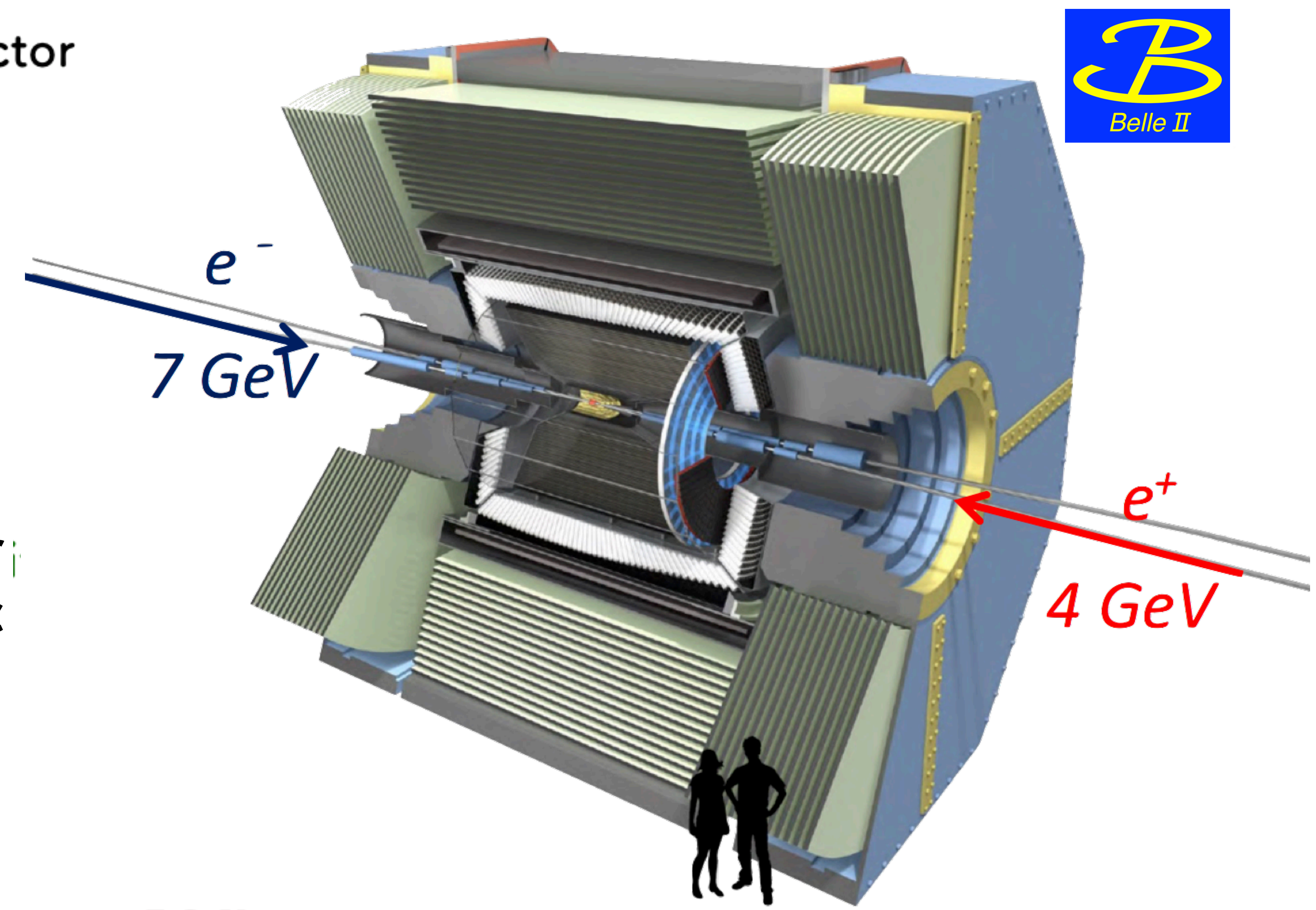
Overview

- Quick intro. to Belle & Belle II
- Some physics highlights
  - ✓ Evidence for $B^+ \to \tau^+\nu$ (Belle II) — Neither EWP, nor LFV, but very sensitive to LFU, and irreducible bkgd. to $B^+ \to K^+\nu\bar{\nu}$
  - ✓ $B^0 \to K^{*0}\tau^+\tau^-$ (Belle II) — EWP, and very crucial for LFU
  - ✓ $B^0 \to K_S^0\tau^\pm\ell^\mp$ (Belle + Belle II) — EWP and LFV
  - ✓ $B \to K^{(*)}\gamma\gamma$ for ALP search (Belle) — EWP, and relevant for dark sector
- Closing remarks

SuperKEKB

Belle II





$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

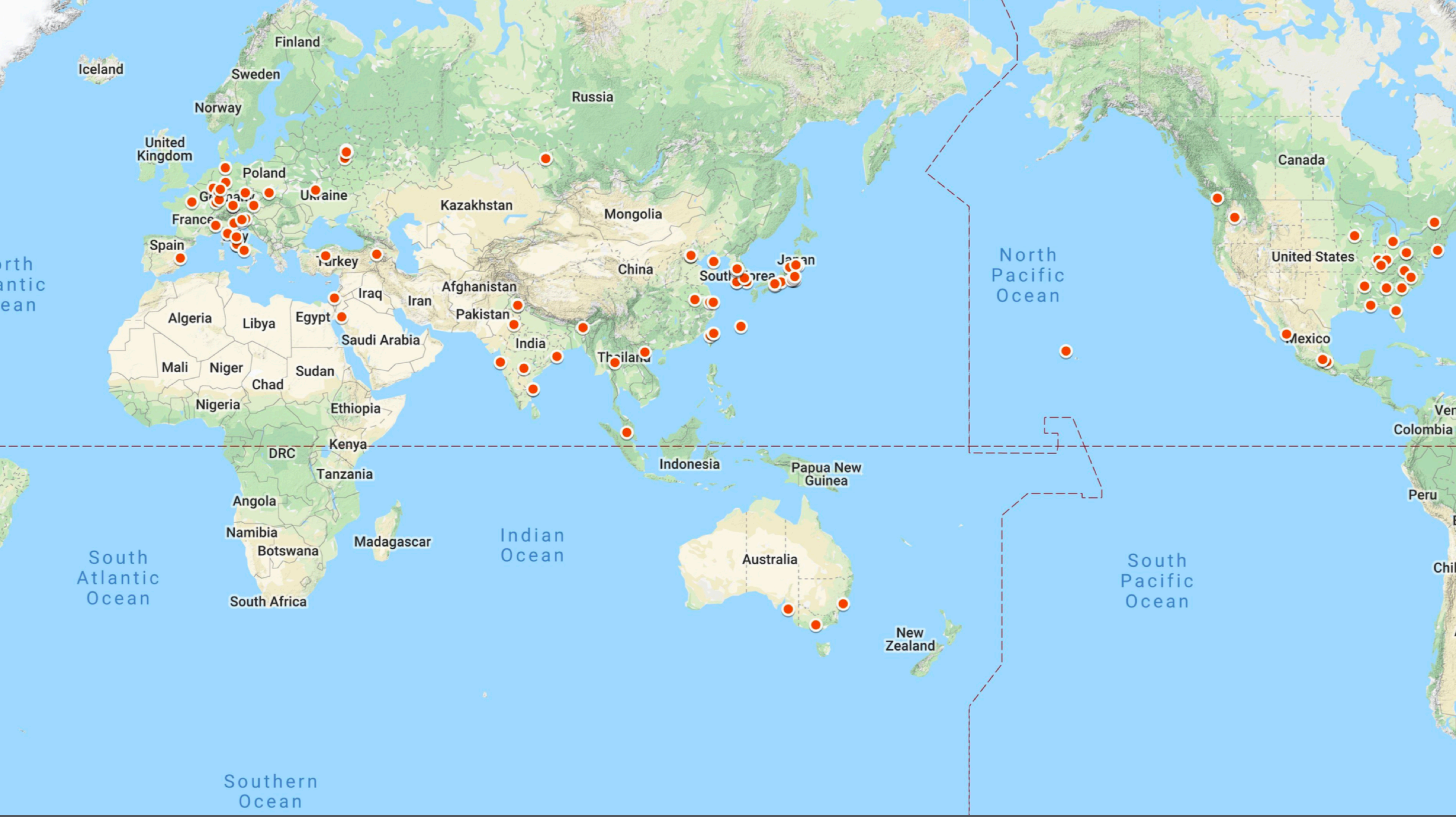
$$\sqrt{s} = 10.58\text{ GeV} = m_{\Upsilon(4S)}c^2$$

We also have data taken off-resonance as well as energy scan around $\Upsilon(5S)$

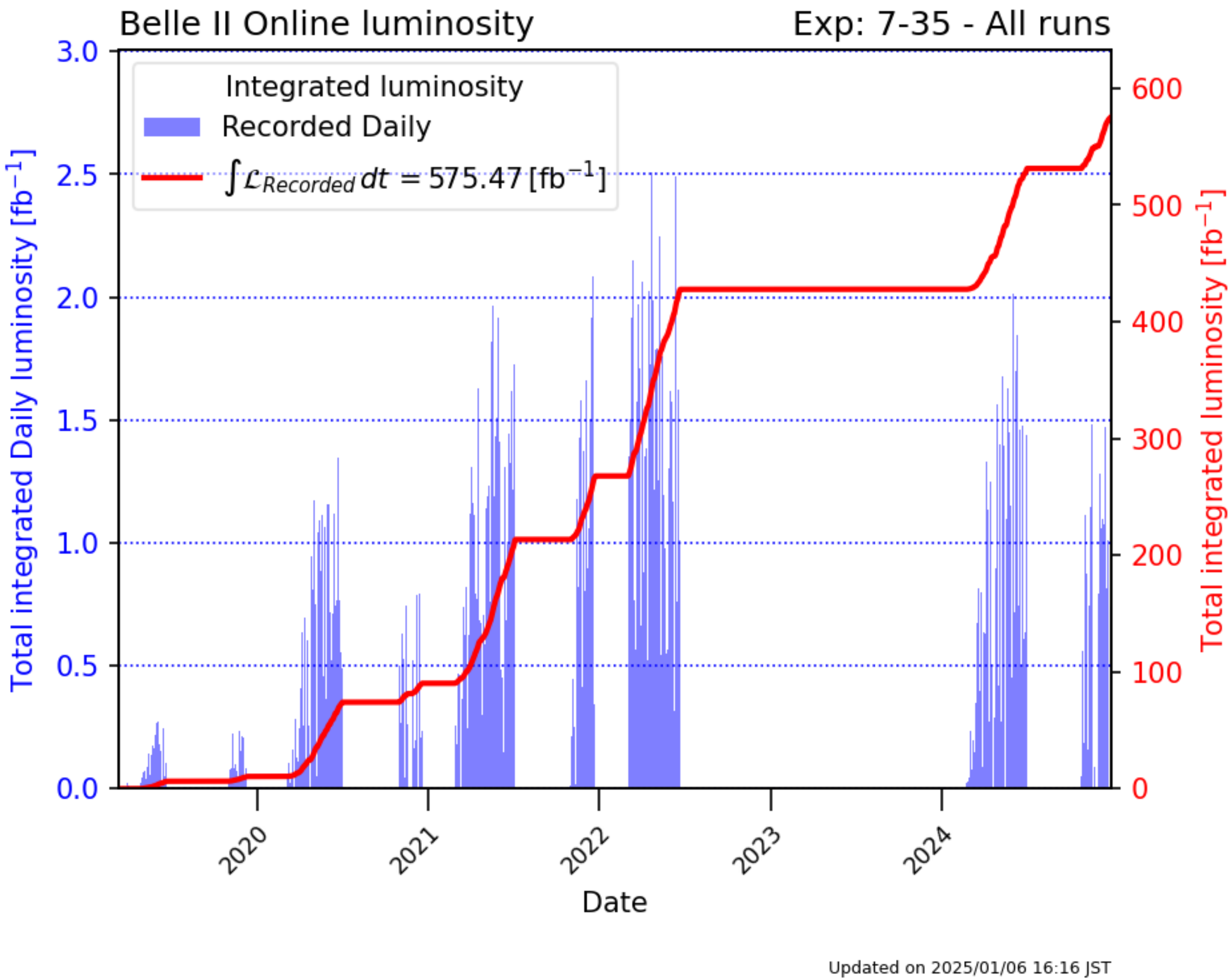
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state

$\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained "B-tagging" *unique to e^+e^- B-factory*

See Appendix, p.28-32.



28 countries/regions, 124 institutions, ~1200 collaborators


Belle II Online luminosity
Exp: 7-35 - All runs
Integrated luminosity
Recorded Daily
$\int \mathcal{L}_{Recorded}\, dt = 575.47\ [\mathrm{fb}^{-1}]$
Total integrated Daily luminosity [fb^{-1}]
Total integrated luminosity [fb^{-1}]
Date
3.0
2.5
2.0
1.5
1.0
0.5
0.0
600
500
400
300
200
100
0
2020
2021
2022
2023
2024
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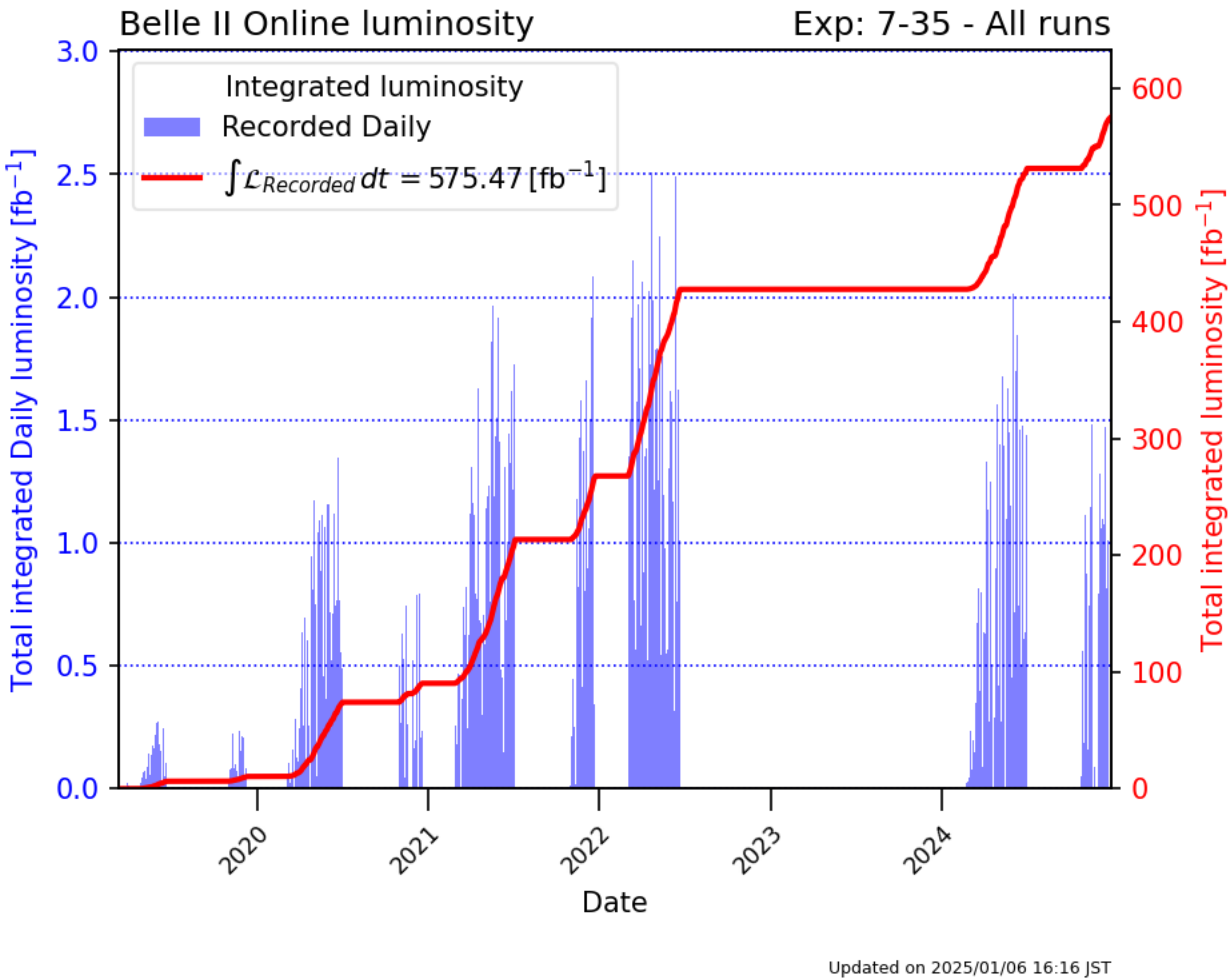


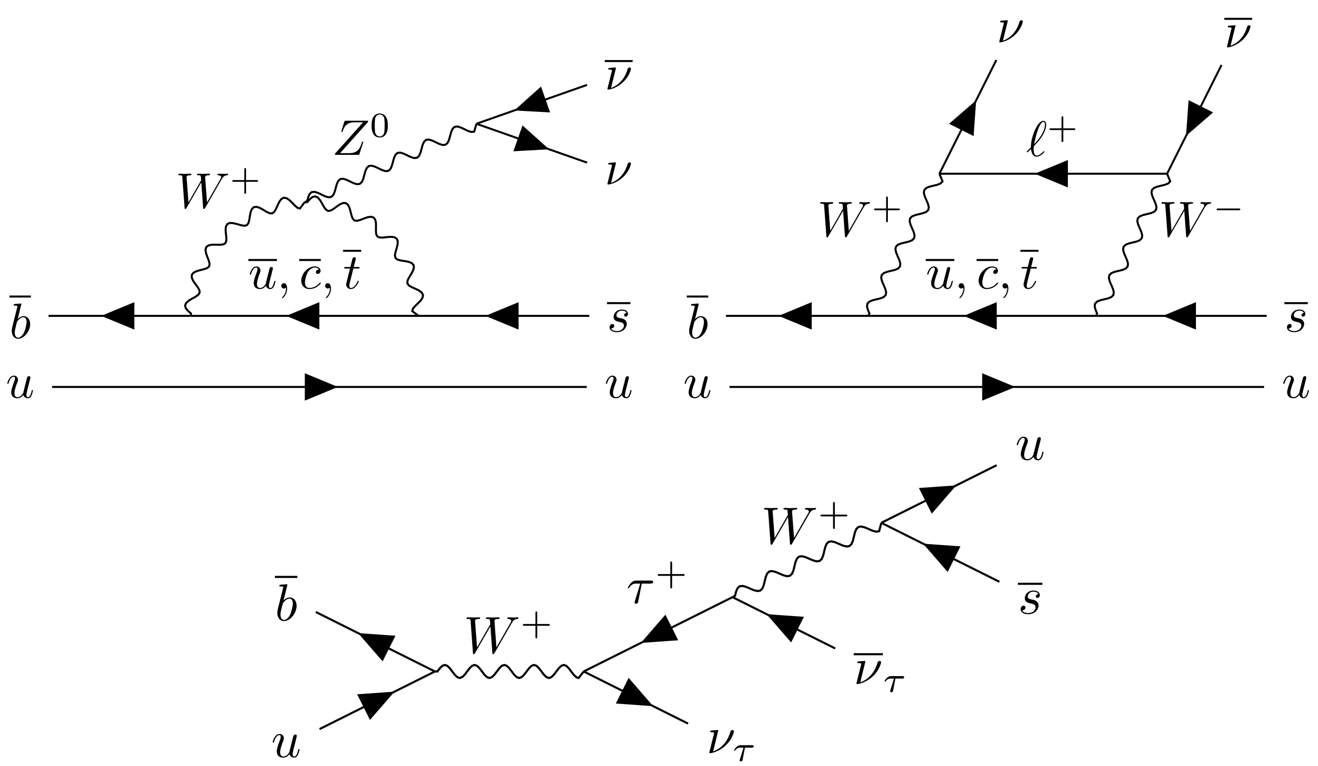
Belle (1999-2010) Luminosity

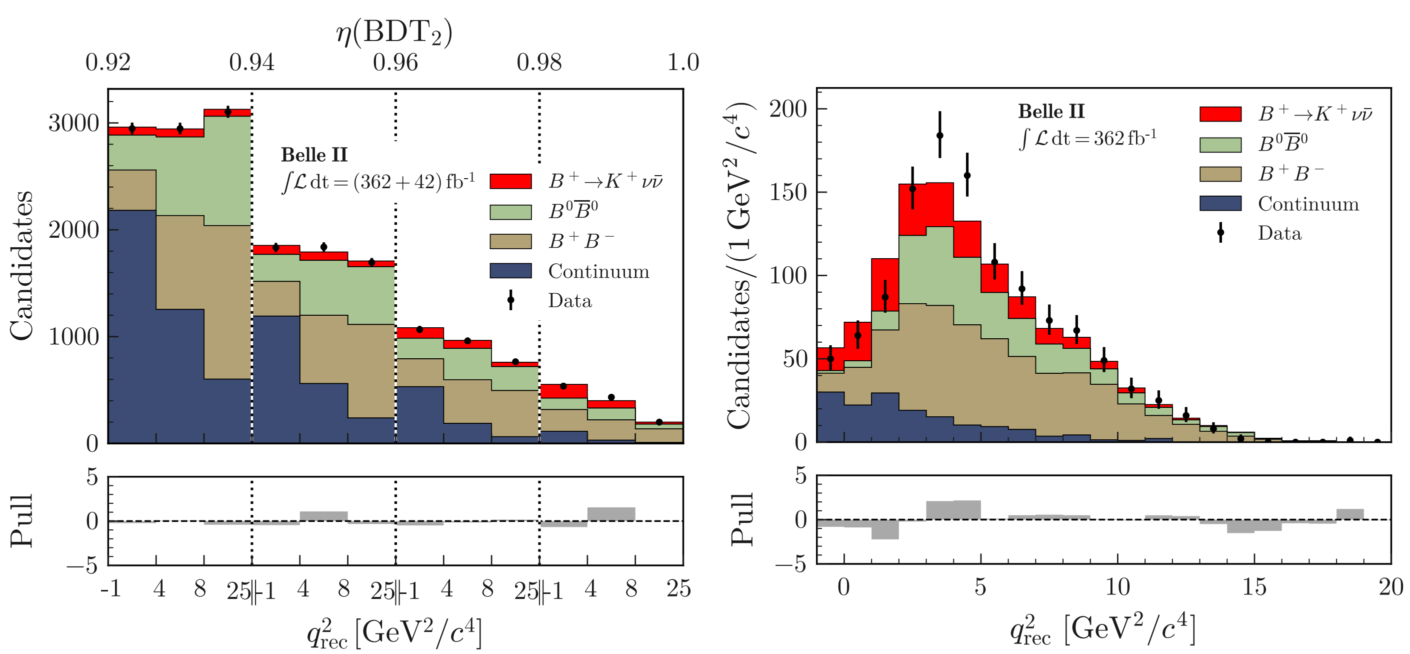
- $\int \mathscr{L}_{\text{total}} = 1039\ \text{fb}^{-1}$

  $980\ \text{fb}^{-1}$ for charm
- $\int \mathscr{L}_{\Upsilon(4S)} = 711\ \text{fb}^{-1}$

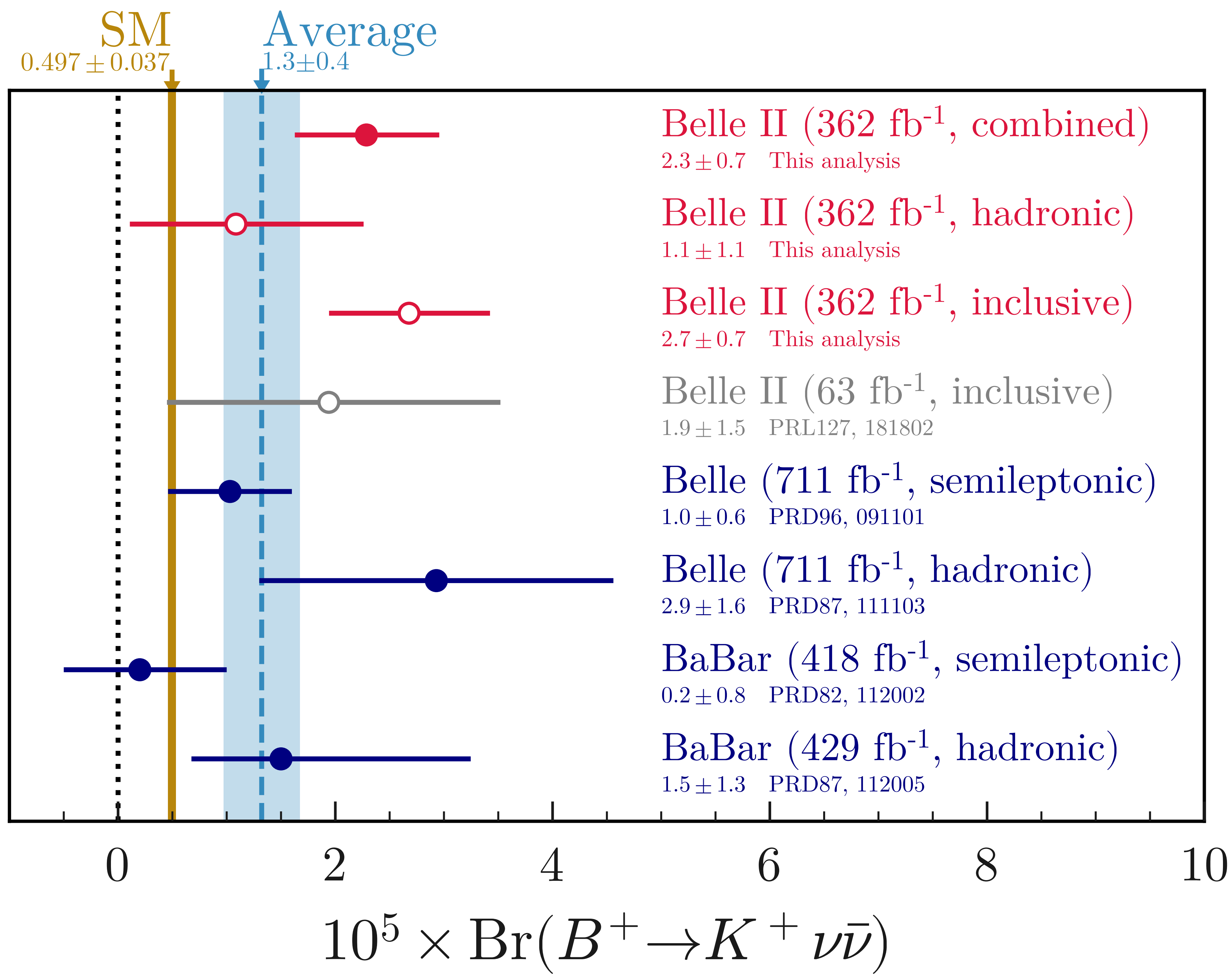
$$B^+ \rightarrow \tau^+ \nu$$

$B^+ \to K^+ \nu\bar{\nu}$ from Belle II @ DIS 2024



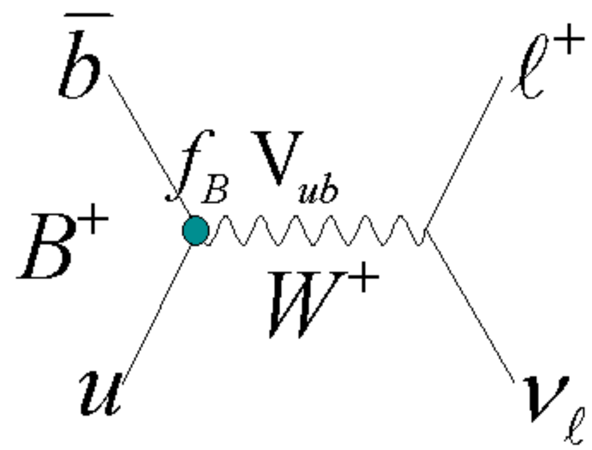


$$q^2_{\mathrm{rec}} = s/4 + M^2_{K^+} - \sqrt{s}E^*_{K^+}$$



$B^+ \to \tau^+\nu$ Intro

$B^+ \to \tau^+\nu$ in SM



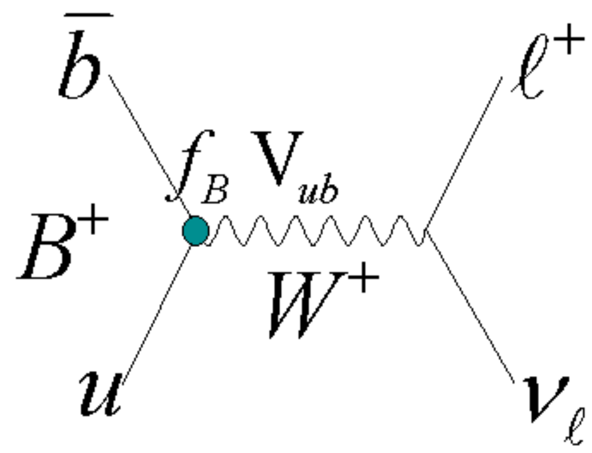
$$\Gamma(B^+ \to \ell^+\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

- $\mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu) \sim 10^{-4}$
- $\mathcal{B}_{\rm SM}(B^+ \to \mu^+\nu) \sim \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu)/300$
- $\mathcal{B}_{\rm SM}(B^+ \to e^+\nu) \sim \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu)/10^7$

► very clean place to measure $f_B|V_{ub}|$
and/or search for new physics (e.g. H^+, LQ)

$B^+ \to \tau^+\nu$ Intro

$B^+ \to \tau^+\nu$ in SM



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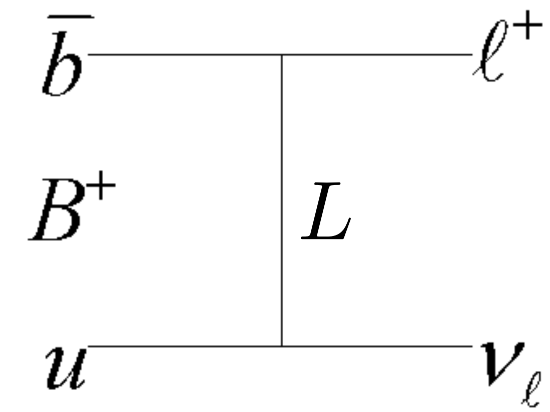
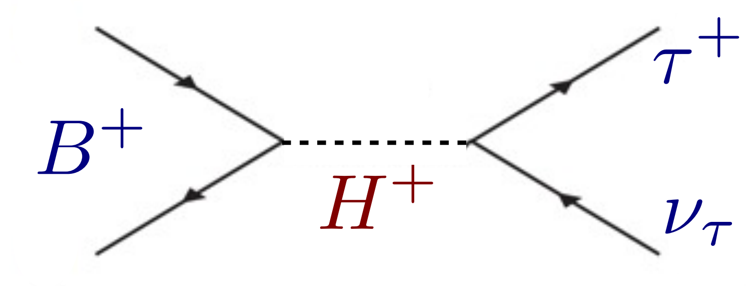




▶ $B^+ \to \tau^+\nu$ can be affected by new physics effects
For instance, H^+ of 2-Higgs doublet model (type II)

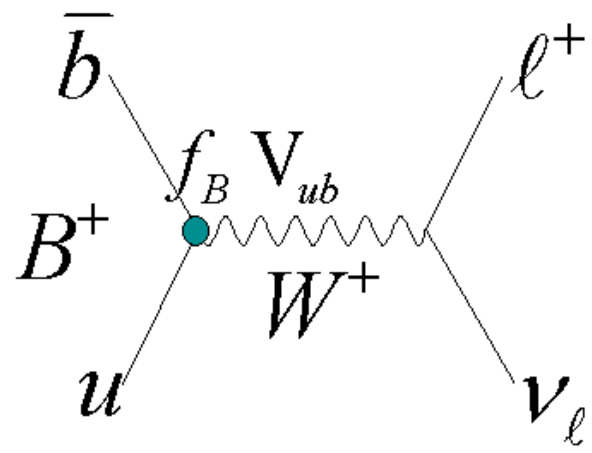
$$\mathcal{B}(B^+ \to \tau^+\nu) = \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu) \times r_H$$

where $r_H = \left[1 - (m_B^2/m_H^2)\tan^2\beta\right]^2$

W.-S. Hou, PRD 48, 2342 (1998)

$B^+ \to \tau^+\nu$ Intro

$B^+ \to \tau^+\nu$ in SM



$$\Gamma(B^+ \to \ell^+\nu) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2$$

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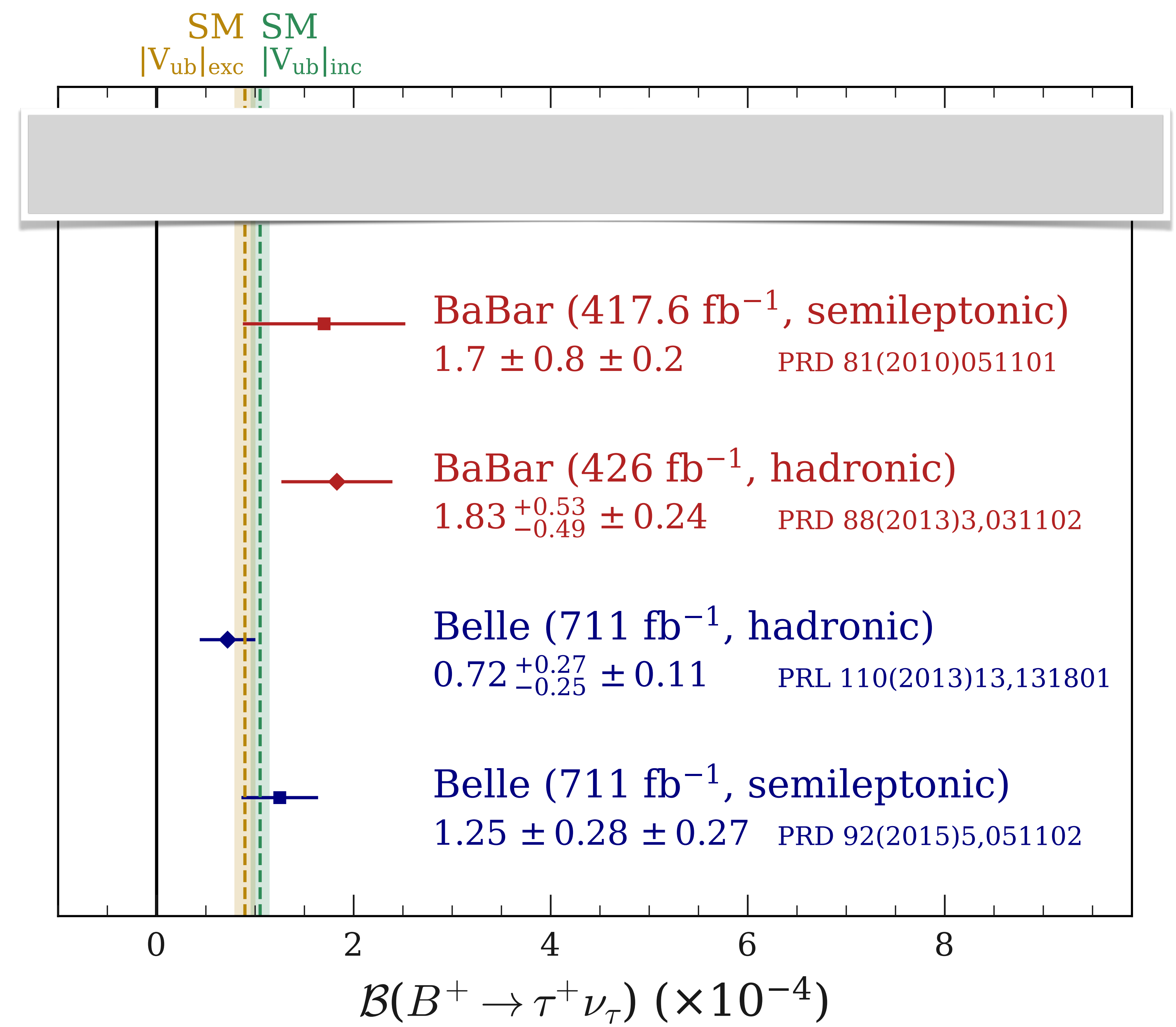
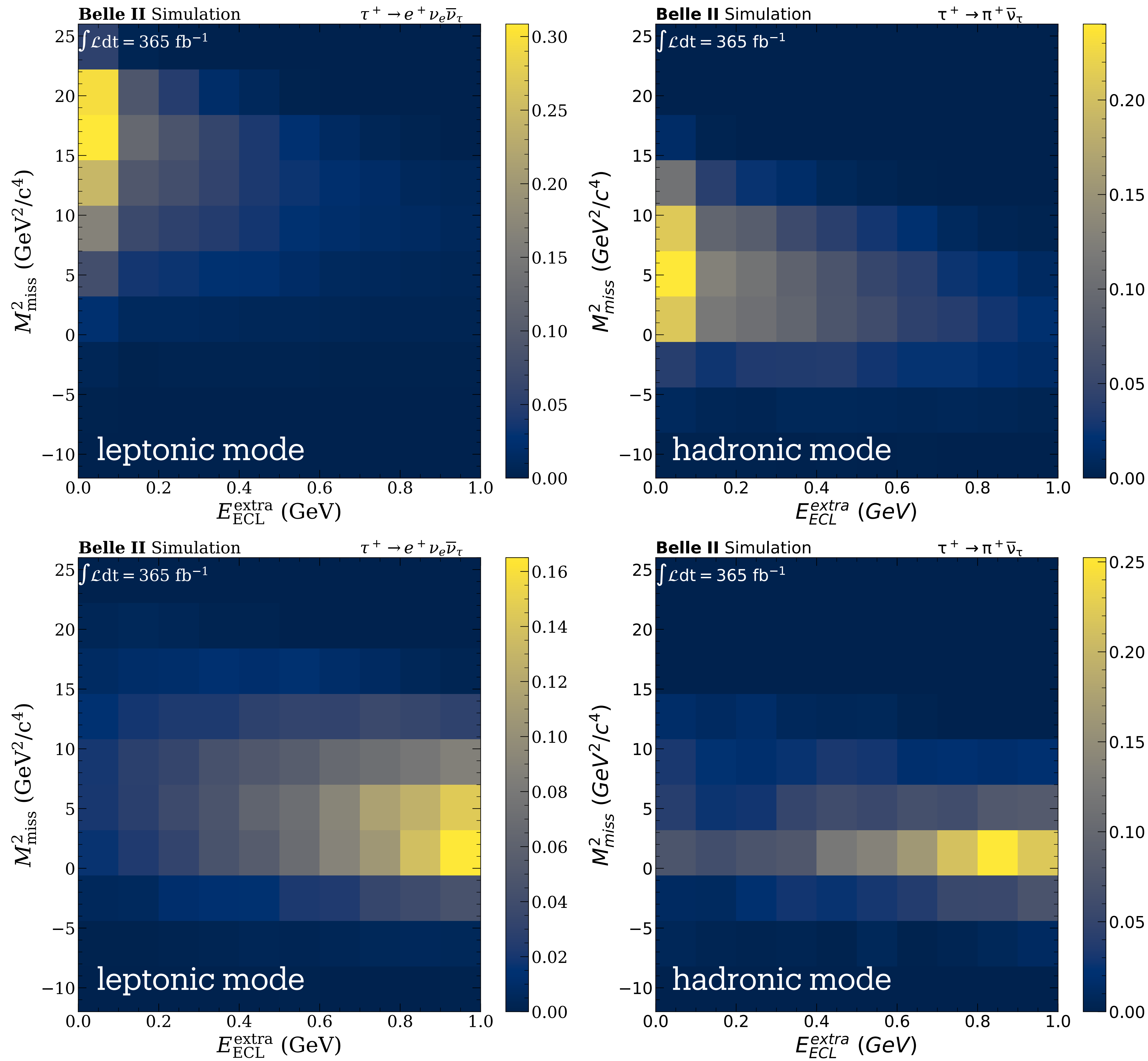
- $\mathcal{B}_{\rm SM}(B^+ \to e^+\nu) \sim \mathcal{B}_{\rm SM}(B^+ \to \tau^+\nu)/10^7$

► very clean place to measure $f_B|V_{ub}|$
and/or search for new physics (e.g. H^+, LQ)



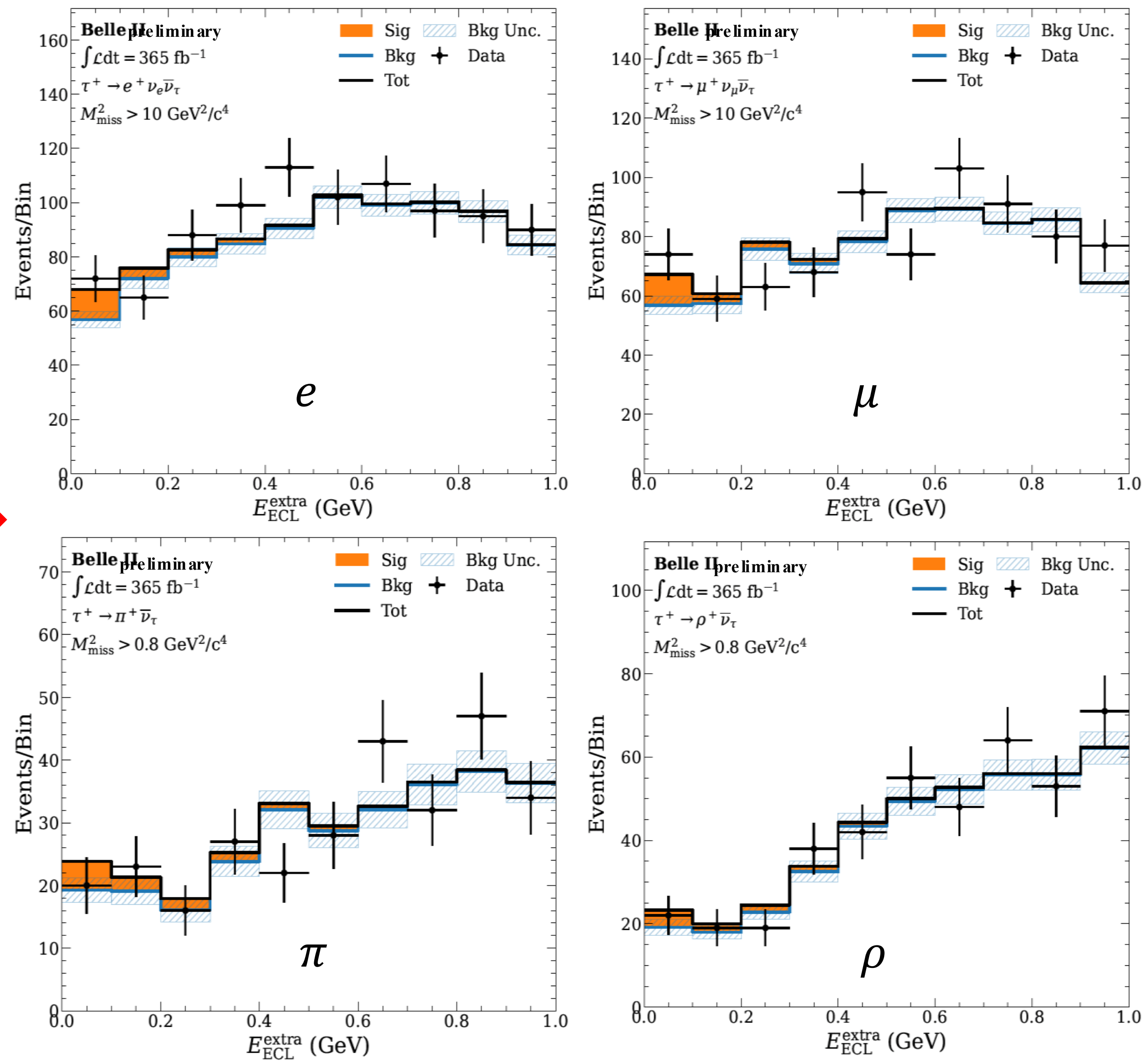
$B^+ \to \tau^+ \nu$

- Use hadronic B-tagging (FEI)
- $E_{\mathrm{ECL}}^{\mathrm{extra}}$ as a key variable
- Match $n_{\gamma\mathrm{extra}}$ b/w data & MC
  - $E_{\mathrm{ECL}}^{\mathrm{extra}}$ matches well in given $n_{\gamma\mathrm{extra}}$ bin (Appendix pp.33-34)
- Signal extraction by 2D fit on M_{miss}^2 vs. $E_{\mathrm{ECL}}^{\mathrm{extra}}$
- 2D histogram PDFs
  - (top) for signal
  - (bottom) for background



arXiv:2502.04885
submitted to PRD

$B^+ \to \tau^+\nu$, Results



13

$E^{\mathrm{extra}}_{\mathrm{ECL}}$

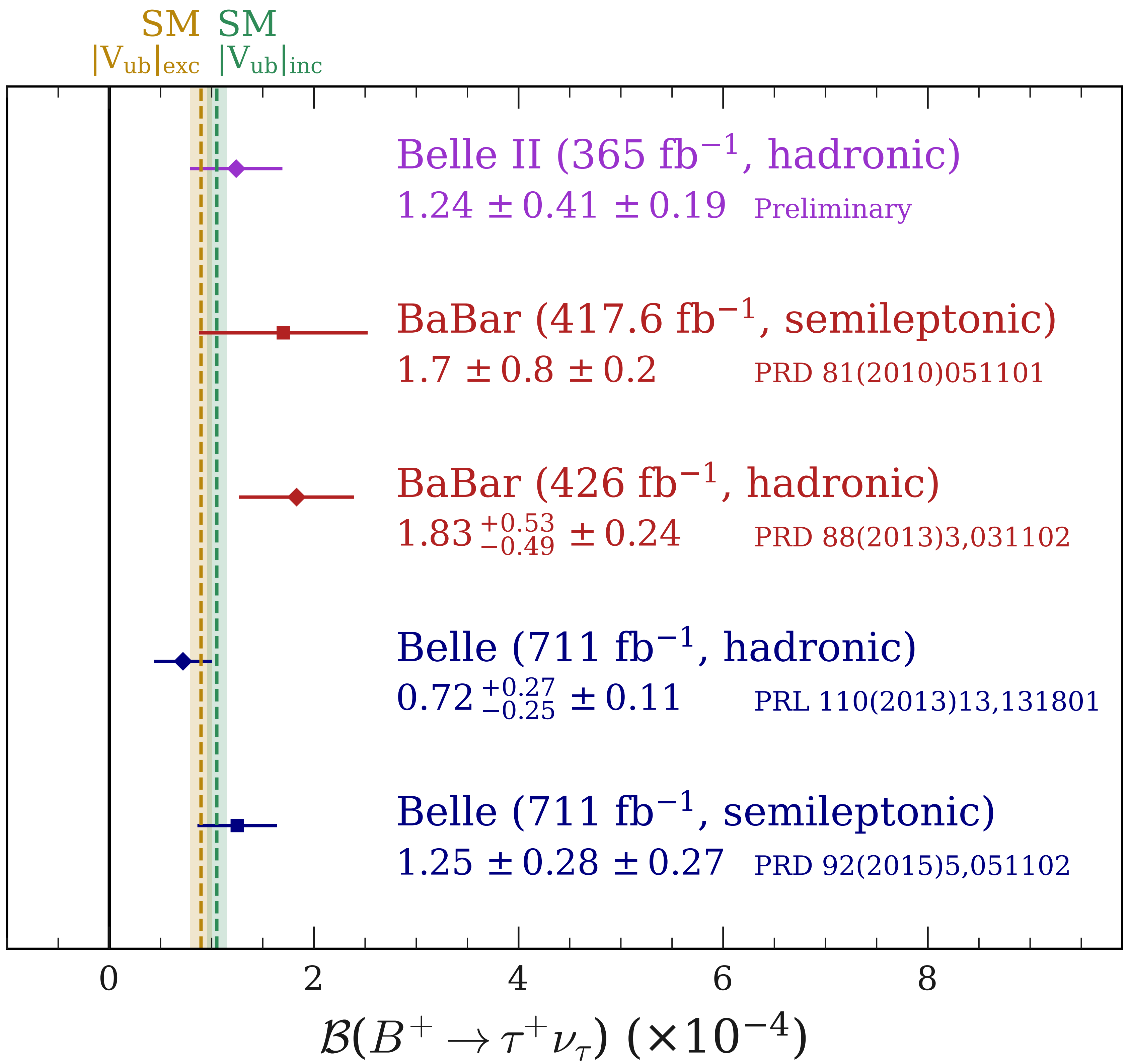
Decay mode	n_s	$\mathcal{B}(10^{-4})$
Simultaneous	94 ± 31	1.24 ± 0.41
$e^+\ \nu_e\ \overline{\nu}_\tau$	13 ± 16	0.51 ± 0.63
$\mu^+\ \nu_\mu\ \overline{\nu}_\tau$	40 ± 20	1.67 ± 0.83
$\pi^+\ \overline{\nu}_\tau$	31 ± 13	2.28 ± 0.93
$\rho^+\ \overline{\nu}_\tau$	6 ± 25	0.42 ± 1.82

$$\mathcal{B}(B^+ \to \tau^+\nu_\tau) = [1.24 \pm 0.41(\mathrm{stat.}) \pm 0.19(\mathrm{syst.})] \times 10^{-4}$$

- Check signal efficiency by using $B^+ \to K^+ J/\psi$ as control sample (see Appendix p.35) prepared by signal embedding technique

For signal-enhanced projection onto $E^{\mathrm{extra}}_{\mathrm{ECL}}$, require $M^2_{\mathrm{miss}} > 10\ (0.8)\ \mathrm{GeV}^2$ for leptonic (hadronic) channels

$B^+ \to \tau^+\nu$ Summary



- BR world average goes

  from $(1.09 \pm 0.24) \times 10^{-4}$

  to $(1.12 \pm 0.21) \times 10^{-4}$

- $|V_{ub}|$ by $B^+ \to \tau^+\nu$ becomes

  $$|V_{ub}^{\tau\nu}| = \left(4.19^{+0.38}_{-0.41}\right) \times 10^{-3}$$

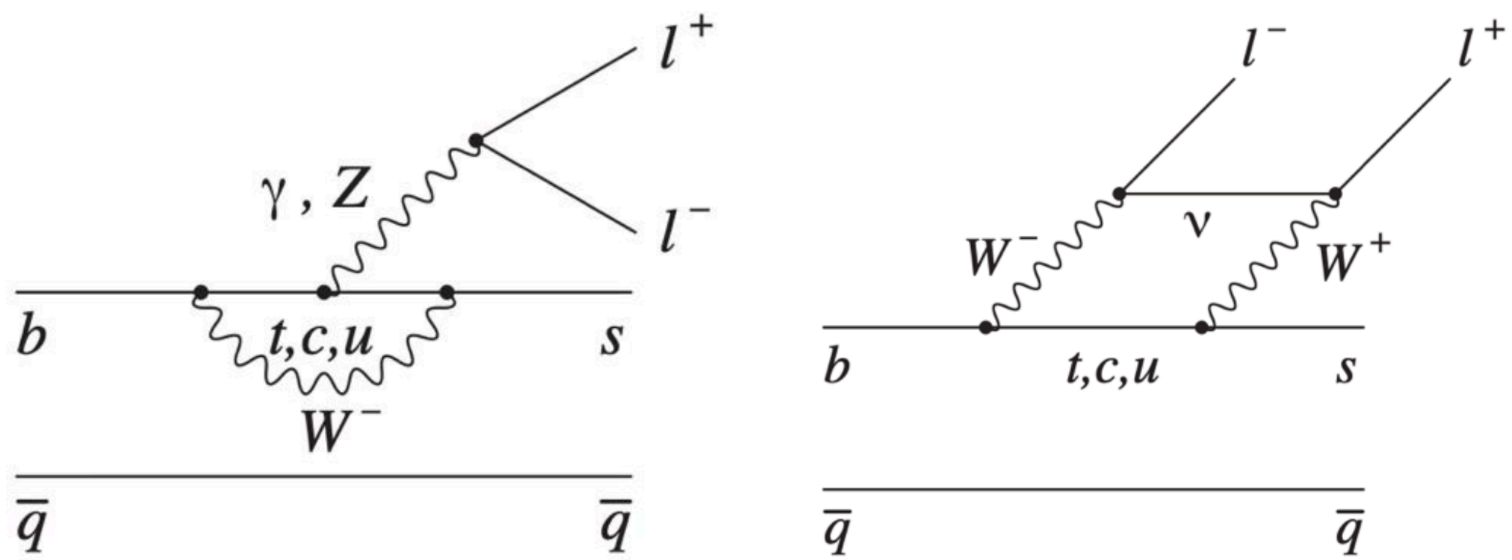
- compare with $|V_{ub}|$ from semileptonic B decays

  $$|V_{ub}^{incl}| = \left(4.06 \pm 0.12 \pm 0.11\right) \times 10^{-3}$$

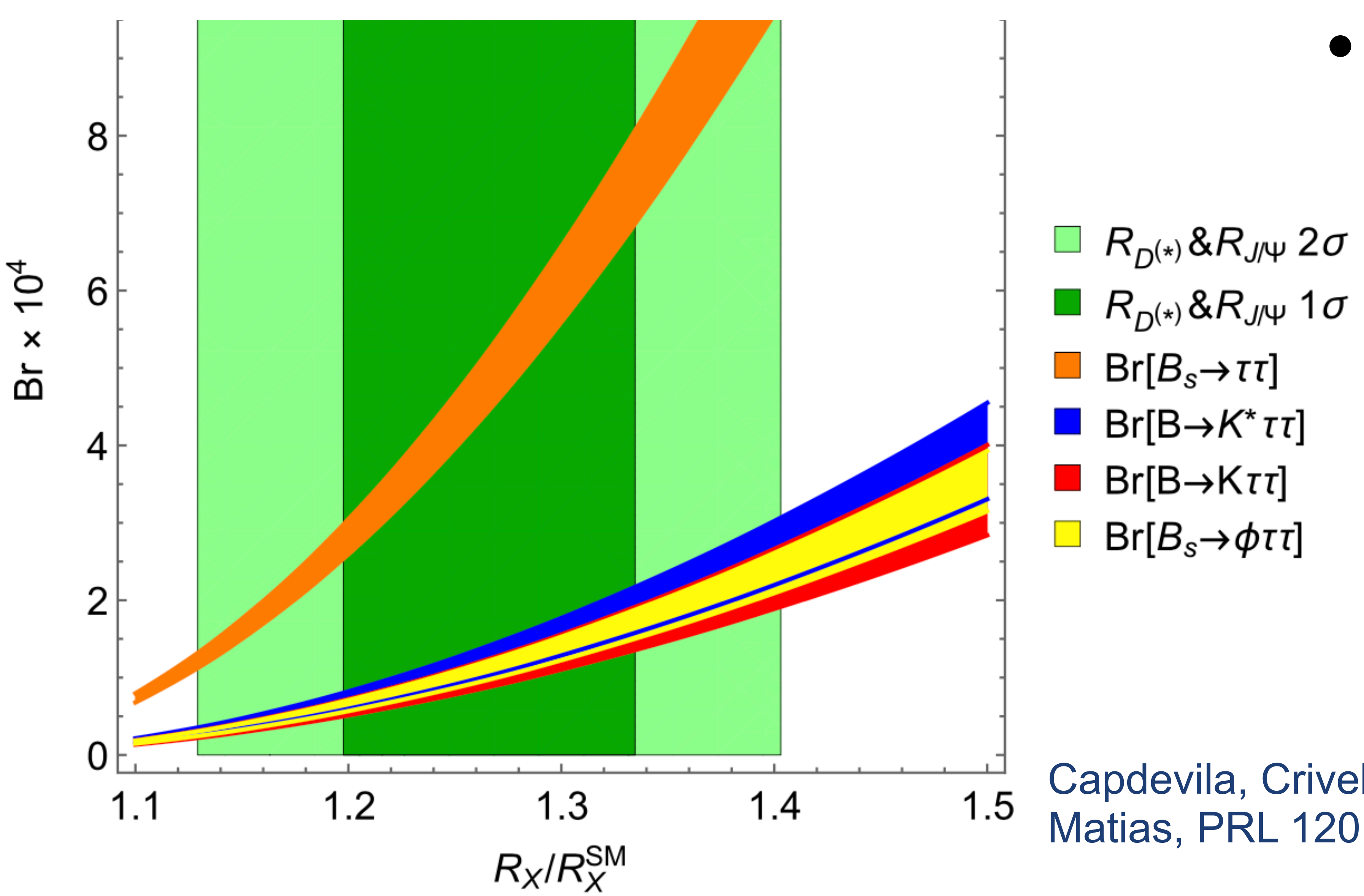
  $$|V_{ub}^{excl}| = \left(3.76 \pm 0.06 \pm 0.19\right) \times 10^{-3}$$

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

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

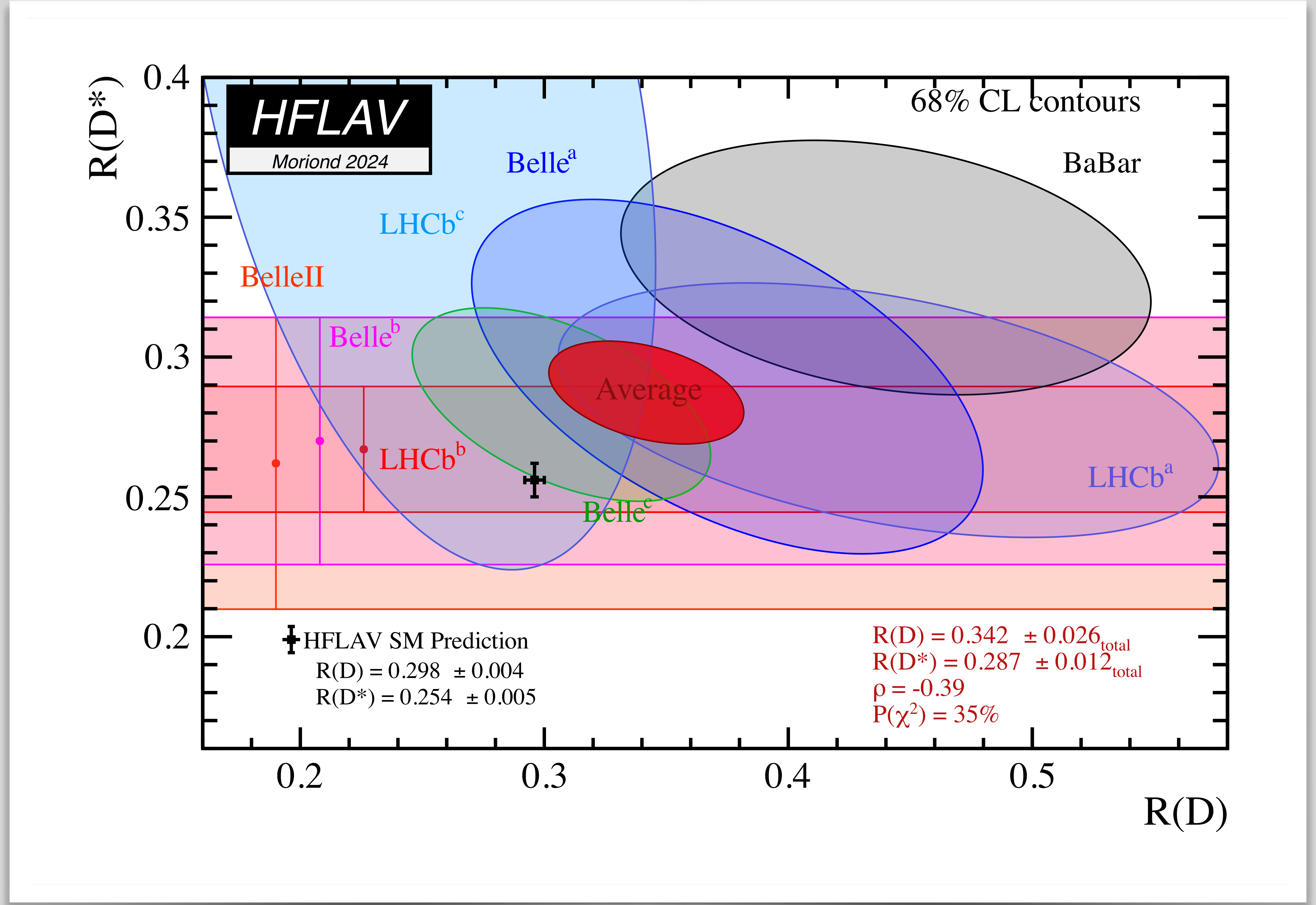


- FCNC — suppressed & sensitive to NP
- $K^{*0}\tau^+\tau^-$ involve 3rd gen. fermions
  - ✓ 3.1σ tension in $B \to D^{(*)}\tau\nu$
  - ✓ 2.7σ tension in $B^+ \to K^+\nu\bar{\nu}$
- SM prediction
  - ✓ $\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) = (0.98 \pm 0.10) \times 10^{-7}$
  - Potential enhancement in BF ($\sim 10^{-4}$), given $B \to D^{(*)}\tau\nu$ 'anomaly'



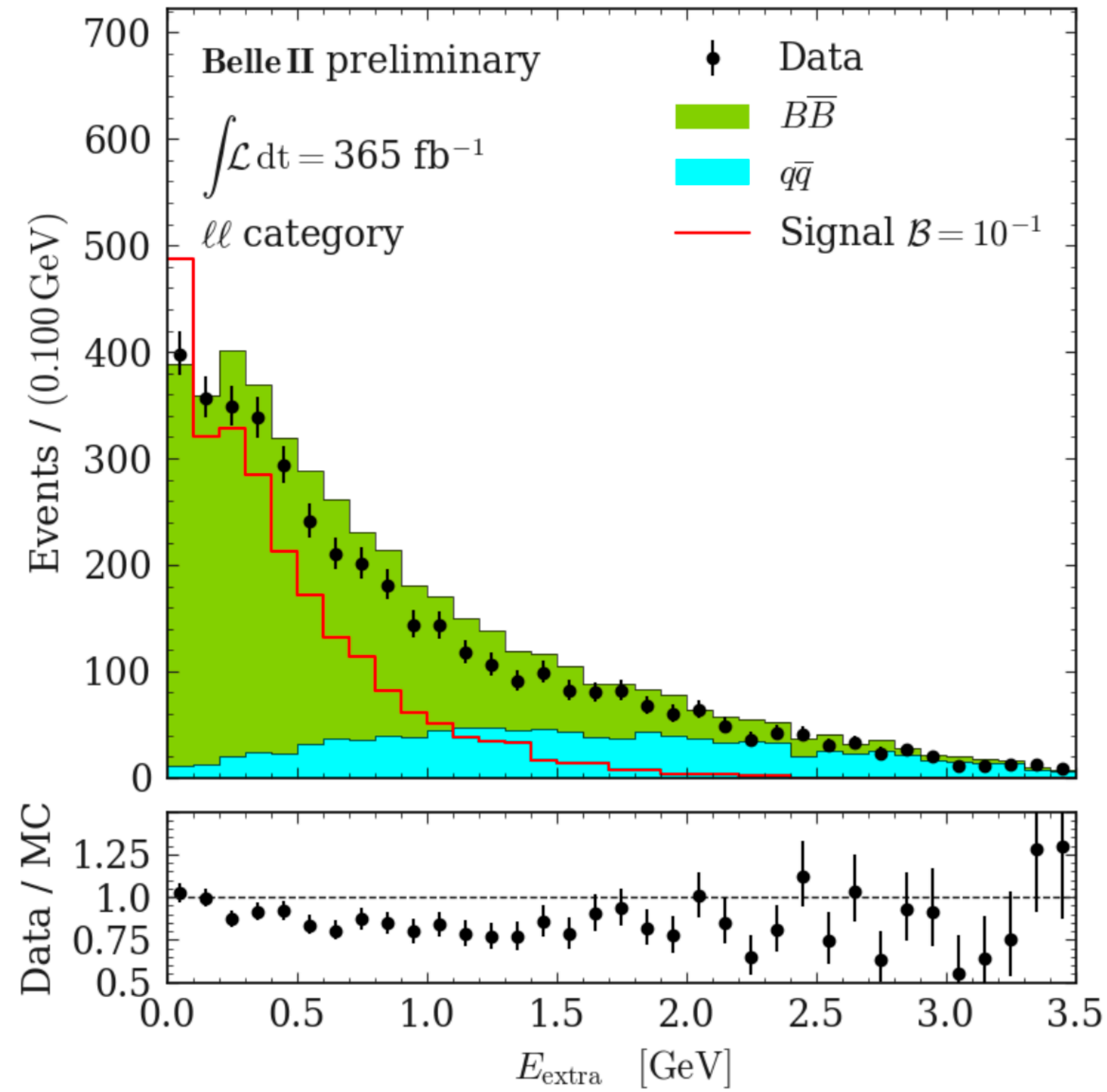
Capdevila, Crivellin, Descotes-Genon, Hofer, Matias, PRL 120, 181802 (2018)

$R(D)$ vs. $R(D^*)$, updated

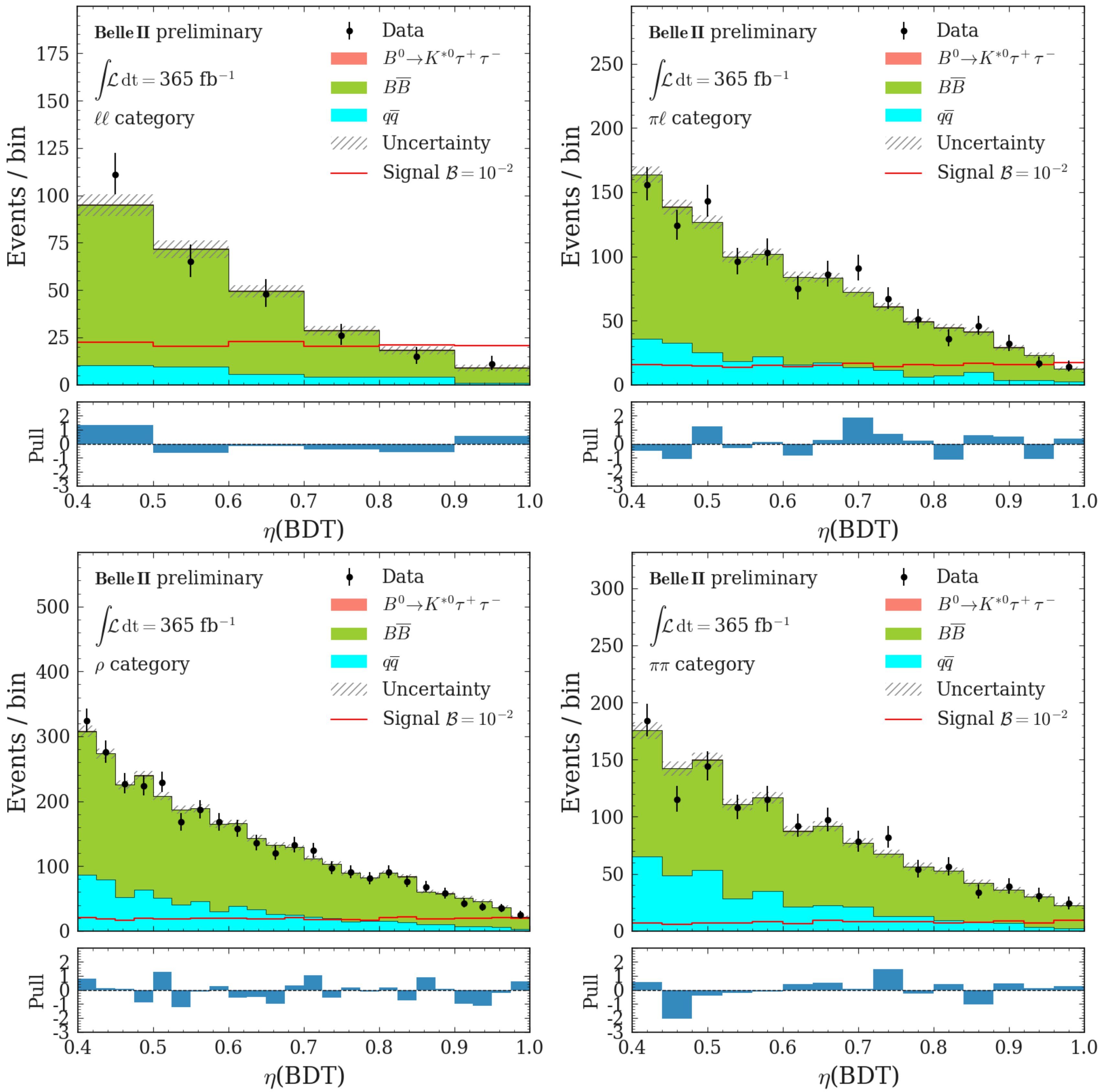


$B^0 \to K^{*0}\tau^+\tau^-$, Event selection

- FEI for B_{tag} recon. — ∃ multiple neutrinos
- For the B_{sig}
  - ✓ use τ decays to $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi^+\nu$, $\rho^+\nu$
  - ✓ $K^{*0} \to K^+\pi^-$
  - ✓ and require no additional tracks
- BDT for further selection, using
  - ✓ event shape variables, kinematics
  - ✓ p_{miss}, E_{extra}
  - ✓ $q^2 = (p_{\tau^+} + p_{\tau^-})^2 = (p_{ee} - p_{\text{tag}} - p_{K^*})^2$
  - ✓ $M(K^*\tau)$



$B^0 \to K^{*0}\tau^+\tau^-$, Fit & Result



- Fit BDT output for $\eta(\text{BDT}) > 0.5$
  - ✓ in 4 groups
  - ✓ for Signal + qq + BB
- Fit results

  $$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 1.8 \times 10^{-3}$$

  (90% CL with CLs method)
- Compare w/ Belle (711 fb^{-1})

  $$\mathscr{B}(B^0 \to K^{*0}\tau^+\tau^-) < 3.1 \times 10^{-3}$$

$$B^0 \to K_S^0 \tau^{\pm} \ell^{\mp}$$

$B^0 \to K_S^0 \tau^\pm \ell^\mp$, Intro.

- FCNC with LFV, forbidden in SM

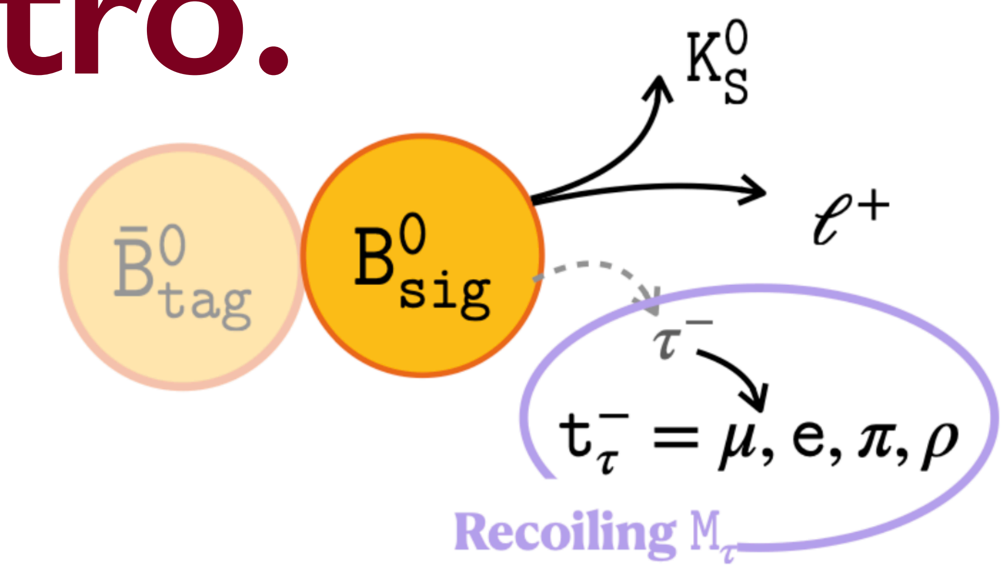
- Motivated by $B^+ \to K^+ \nu \bar{\nu}$ excess (Belle II),
  ∃ BSM model[*] that predicts
  - ✓ $\mathscr{B}(B \to K \tau^\pm \ell^\mp) \sim \mathcal{O}(10^{-6})$

- Existing results
  - ✓ $B^+ \to K^+ \tau^\pm \ell^\mp$ (BaBar, Belle, LHCb)
  - ✓ $B^0 \to K^{*0} \tau^\pm \mu^\mp$ (LHCb)
  - ✓ but nothing on modes with K_S^0

- This analysis
  - ✓ search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ using combined data of Belle & Belle II

[*] L. Allwicher *et al.*, Phys. Lett. B **848**, 138411 (2024).

$B^0 \to K_S^0 \tau^\pm \ell^\mp$, Intro.



- FCNC with LFV, forbidden in SM
- Motivated by $B^+ \to K^+ \nu \bar{\nu}$ excess (Belle II), $\exists$ BSM model[*] that predicts
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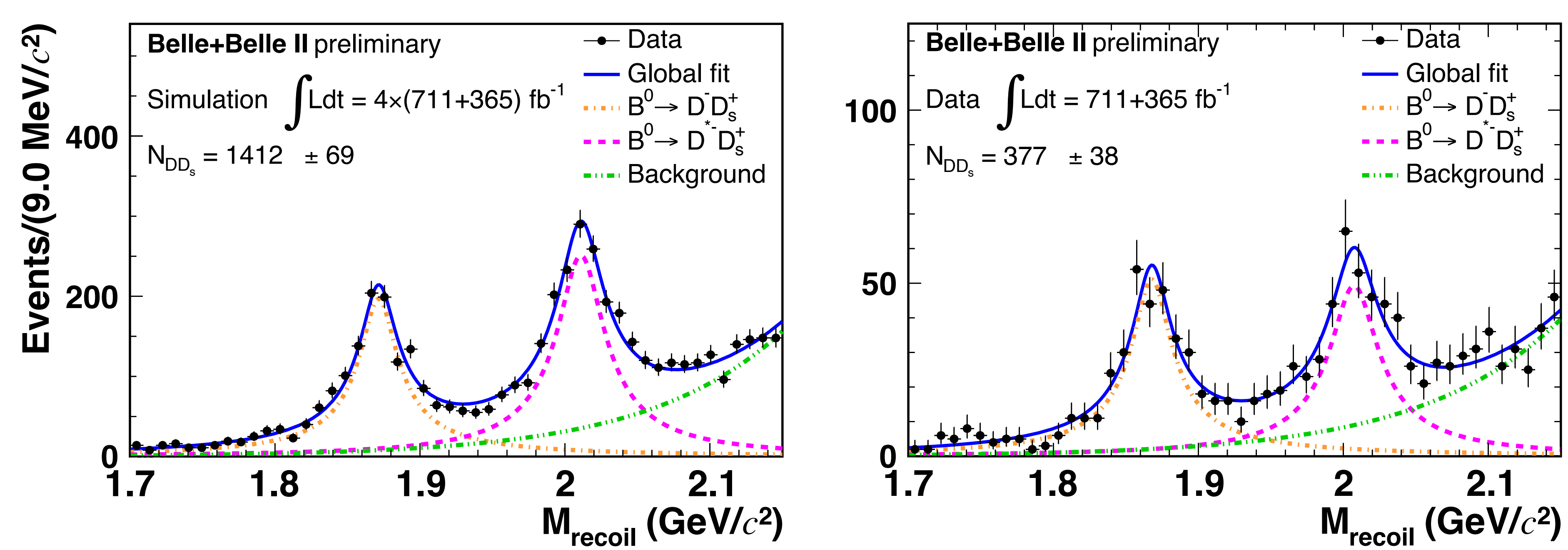
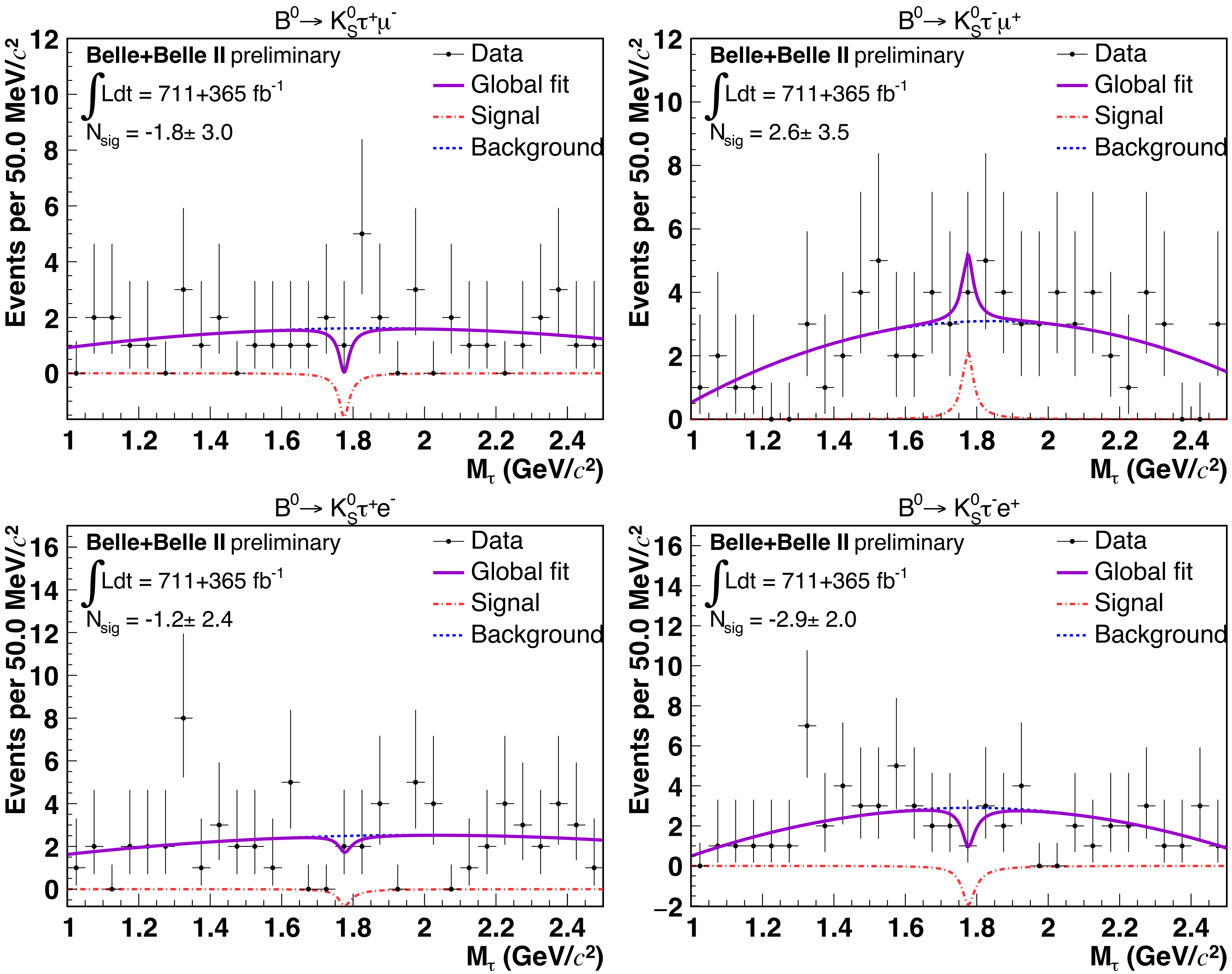
  - ✓ but nothing on modes with K_S^0
- This analysis
  - ✓ search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ using combined data of Belle & Belle II

- Hadronic B-tag and missing mass
  - ✓ recoiling against $K_S^0 \ell^\mp$ to look for $M(\tau)$
- calibration using $B^0 \to D_s^+ X$
  - ✓ to look for $D^{(*)-}$ in the recoil mass



[*] L. Allwicher *et al.*, Phys. Lett. B **848**, 138411 (2024).

$B^0 \to K_S^0 \tau^\pm \ell^\mp$, Results

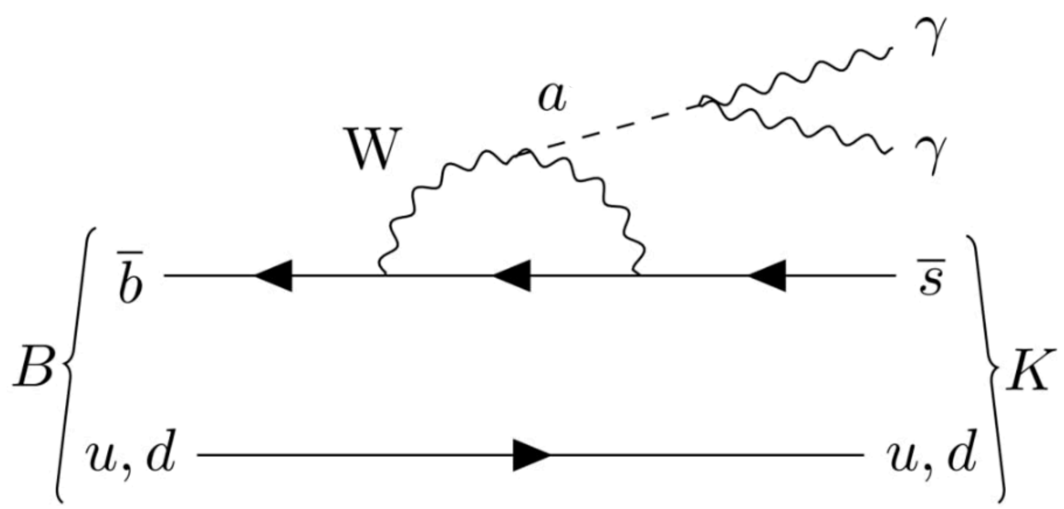


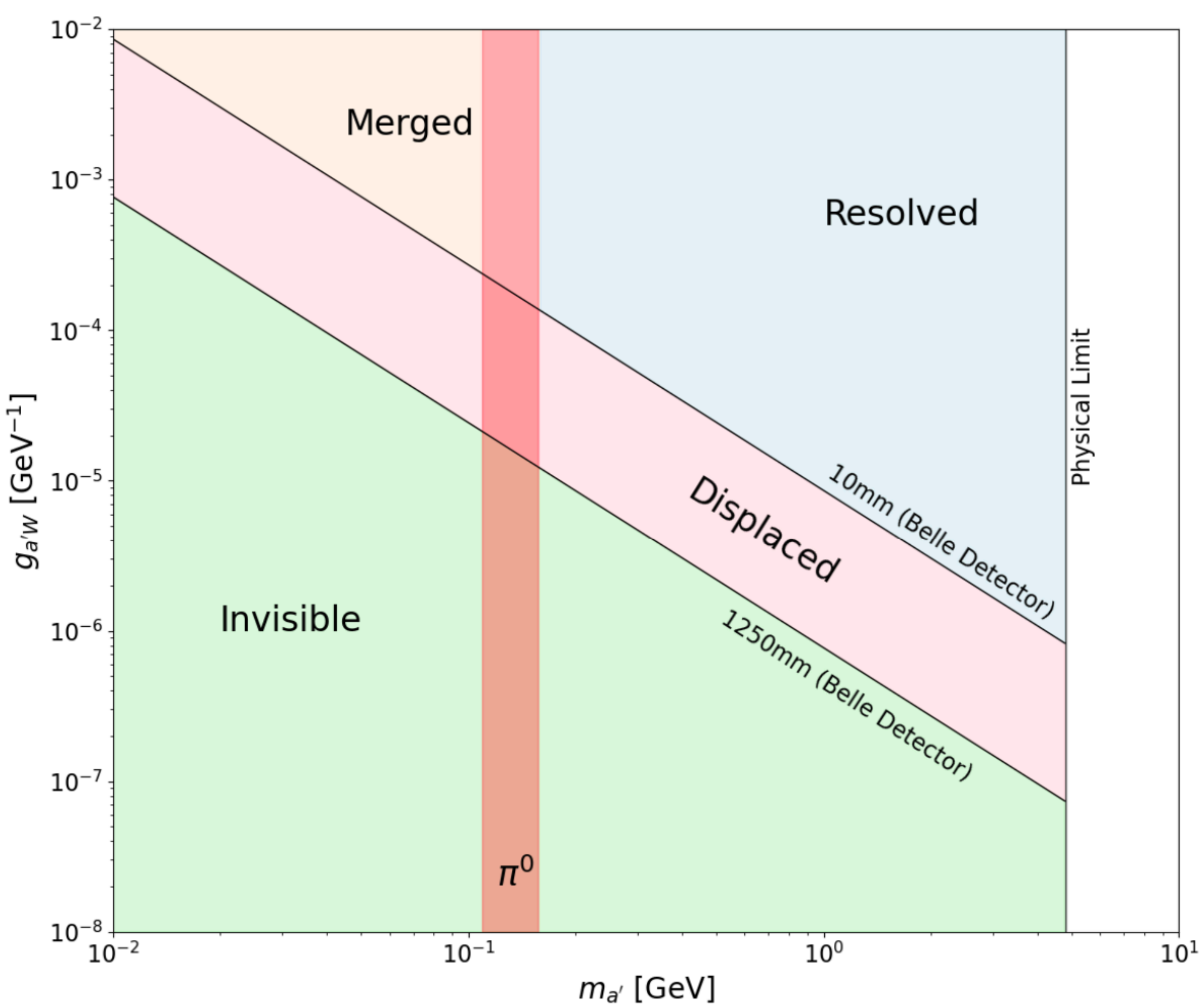
Channels	$\epsilon(10^{-4})$	$N_{\rm sig}$
$B^0 \to K_S^0 \tau^+ \mu^-$	1.7	-1.8 ± 3.0
$B^0 \to K_S^0 \tau^- \mu^+$	2.1	2.6 ± 3.5
$B^0 \to K_S^0 \tau^+ e^-$	2.0	-1.2 ± 2.4
$B^0 \to K_S^0 \tau^- e^+$	2.1	-2.9 ± 2.0

$$\mathcal{B}(B^0 \to K_S^0 \tau^+ \mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- \mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^+ e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0 \tau^- e^+) < 0.8 \times 10^{-5}$$

$B \to K^{(*)}\gamma\gamma$ for ALP

$B \to K^{(*)}\gamma\gamma$ for ALP, Intro.





- Search for axion-like particle (ALP)
  - $a \to \gamma\gamma$ (assume dominant)
  - also assume (mostly) prompt decay, but non-zero lifetime is considered for efficiency loss
  - if no signal, set upper limits on ALP-W coupling, g_{aW}[#]
  - search region:

    $0.16 < m_a < 4.20\ (4.50)$ GeV
  - no sensitivity for π^0, η, η' regions

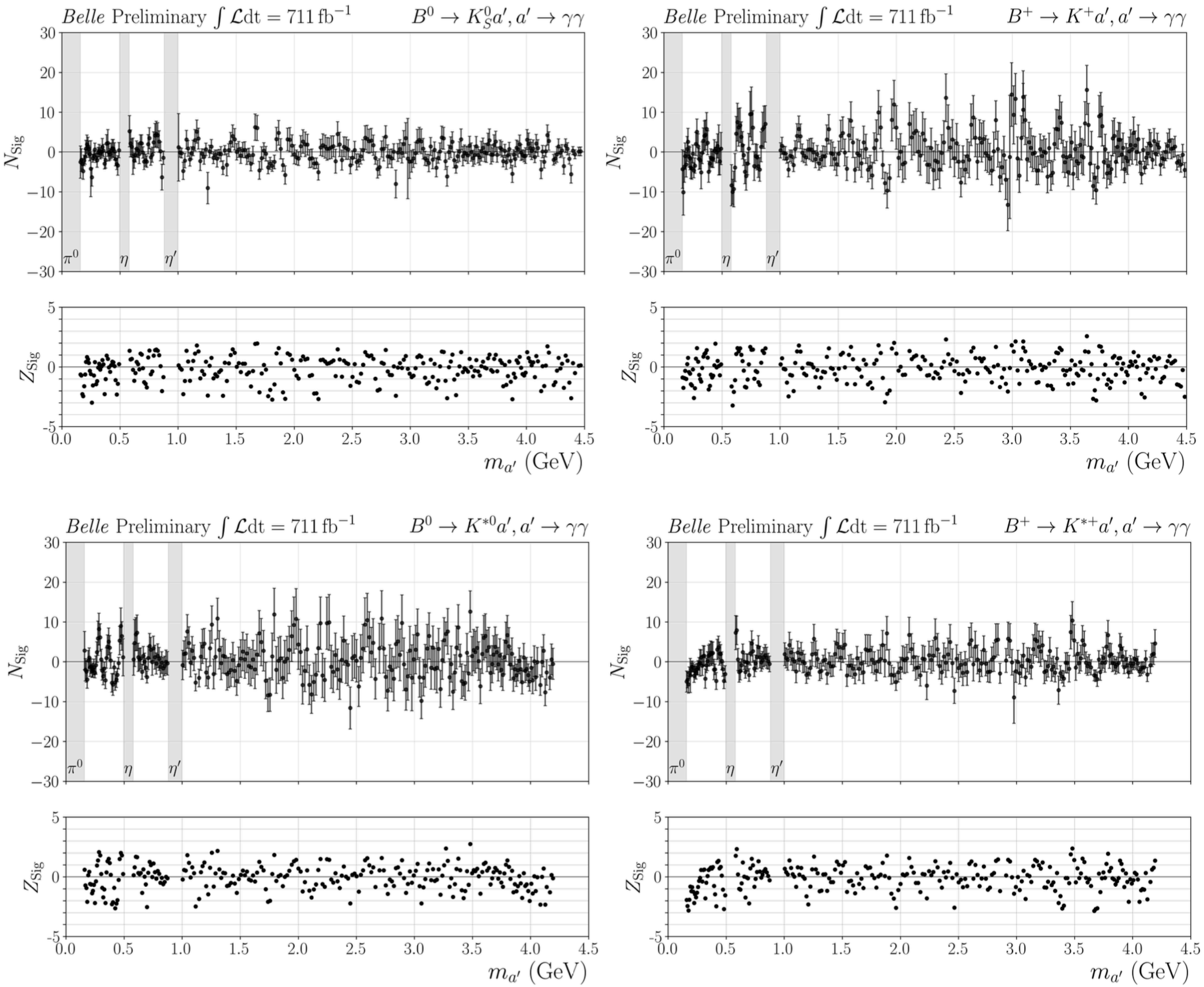
[#] PRL 118, 111802 (2017)

h' veto region

Type	3σ $M_{\gamma\gamma}$ region
π^0	0.109 ~ 0.158
η	0.497 ~ 0.578
η'	0.882 ~ 0.997

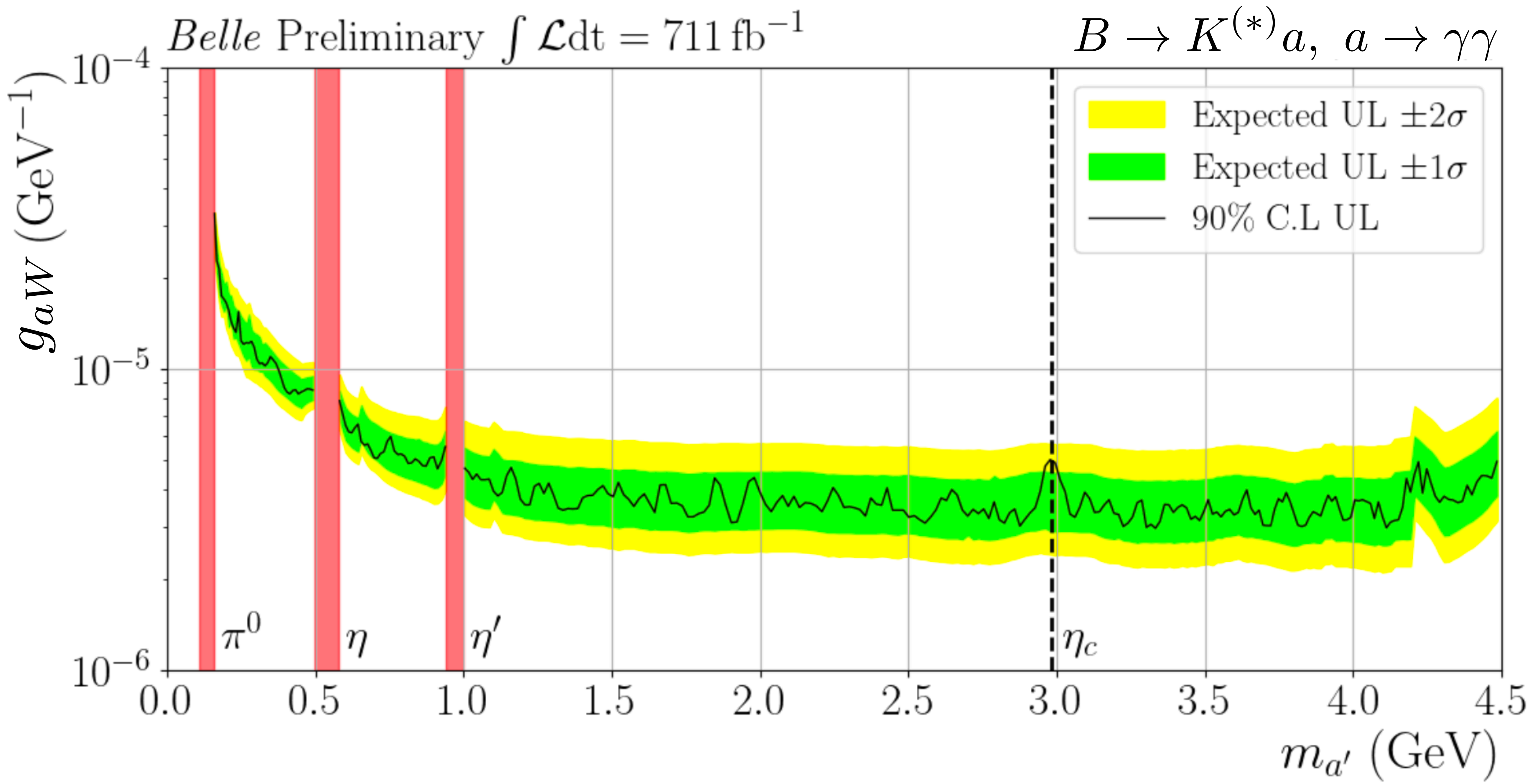
- Procedure
  - continuum suppression and $\pi^0 \to \gamma$ with separate Fast-BDT's (T. Keck, Comp Softw Big Sci 1, 2 (2017))
  - then apply $B \to X_s\gamma$ veto for remaining bkg.

$B \to K^{(*)}\gamma\gamma$ for ALP, Results w/ Belle data



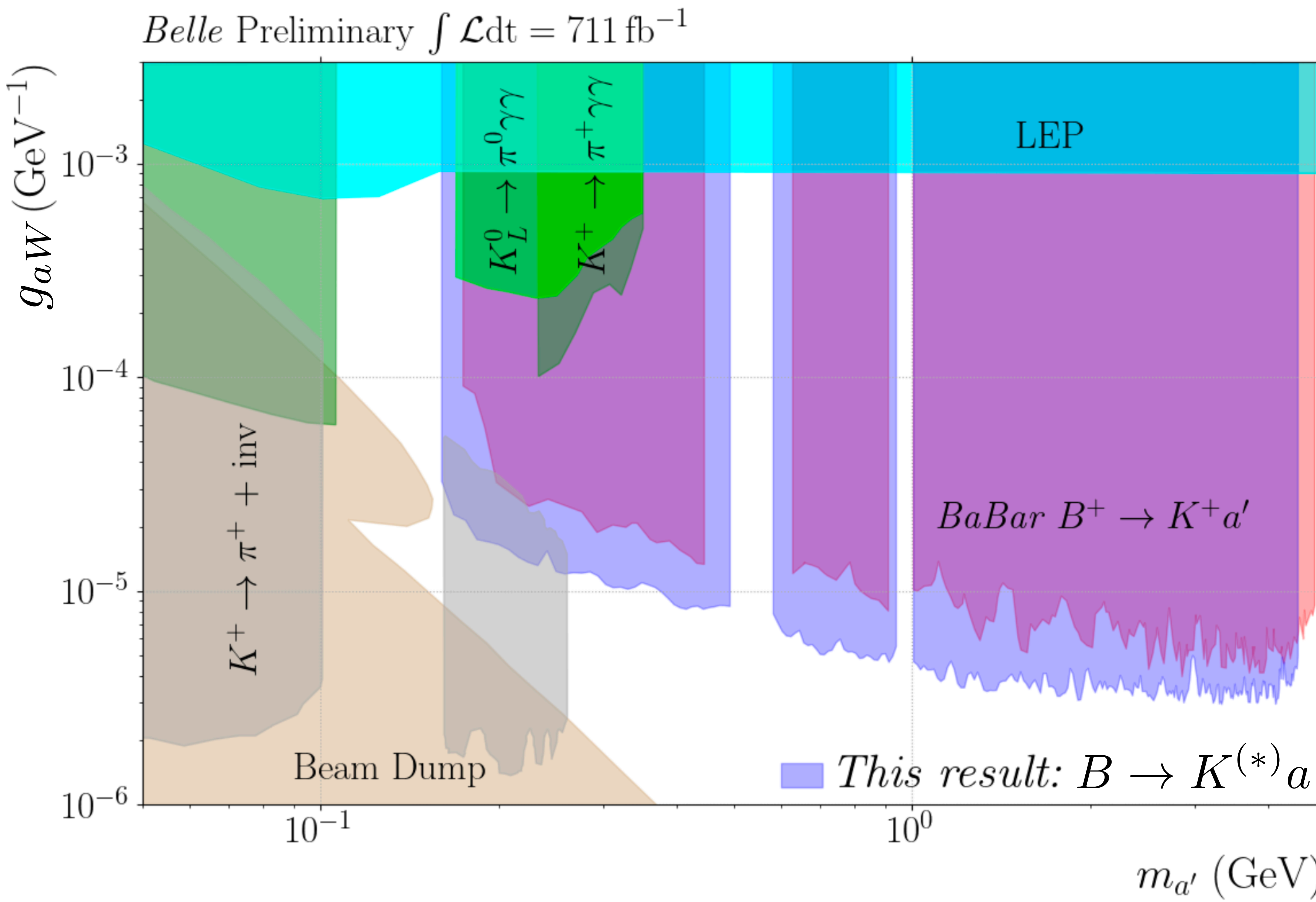
- Fitted results
  - for each $K^{(*)}$ mode
  - (top) signal yield
  - (bottom) in significance level
  - the gray vertical bands correspond to π^0, η, and η' regions

$B \to K^{(*)}\gamma\gamma$ for ALP, Upper limits on g_{aW}



90% CL upper limits on g_{aW} as a function of m_a

$B \to K^{(*)}\gamma\gamma$ for ALP, Upper limits on g_{aW}



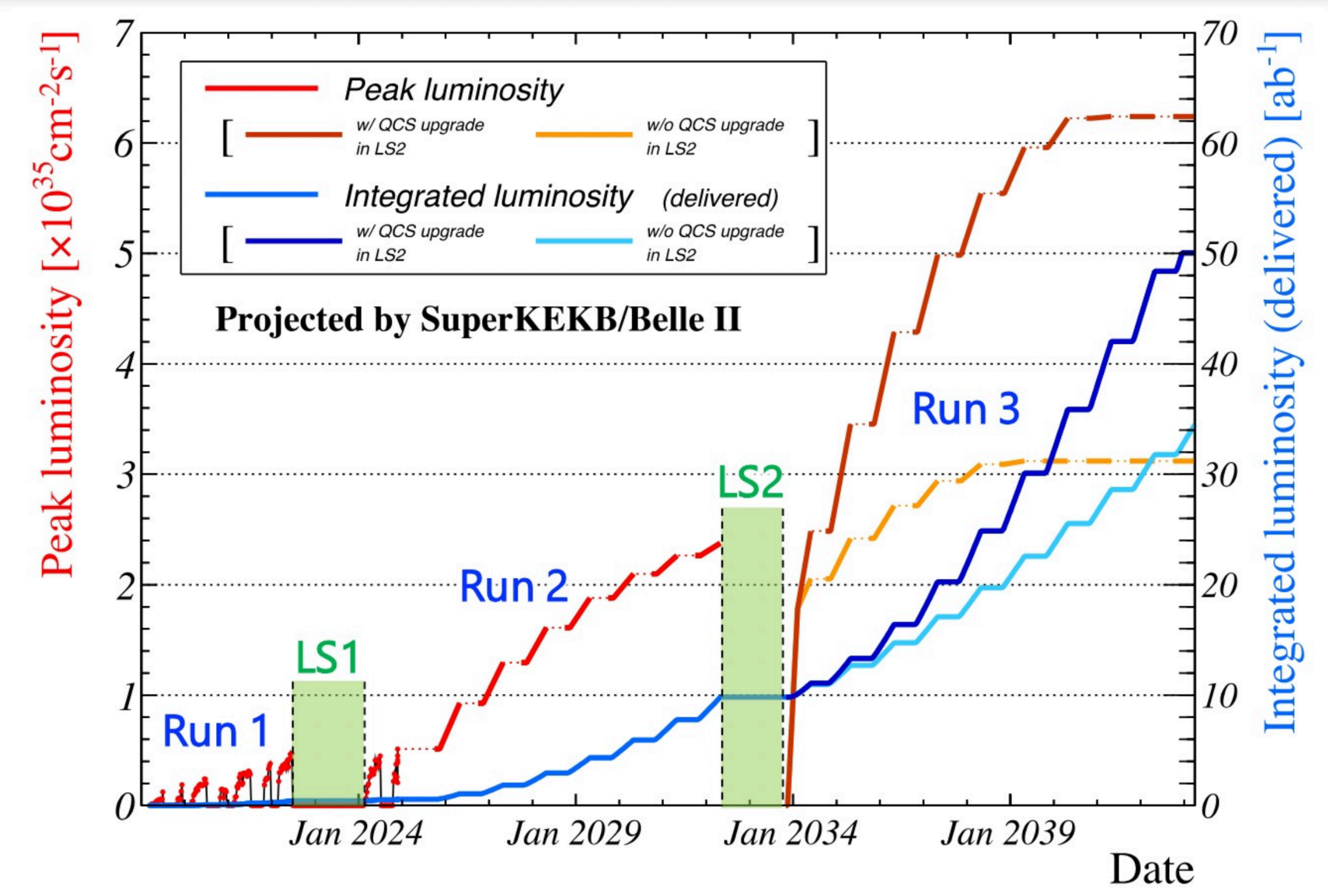
90% confidence level upper limits on g_{aW} as a function of m_a in comparison with other existing results

Closing remarks

- In this talk, we have presented just a few recent physics highlights from Belle II mostly on rare B decays, e.g. $B^+ \to \tau^+\nu$ (evidence!) and $B^0 \to K^{*0}\tau^+\tau^-$ (search).

- In addition, we showed Belle search for ALP in B decays, whereby setting the most stringent limit in ALP-W coupling.

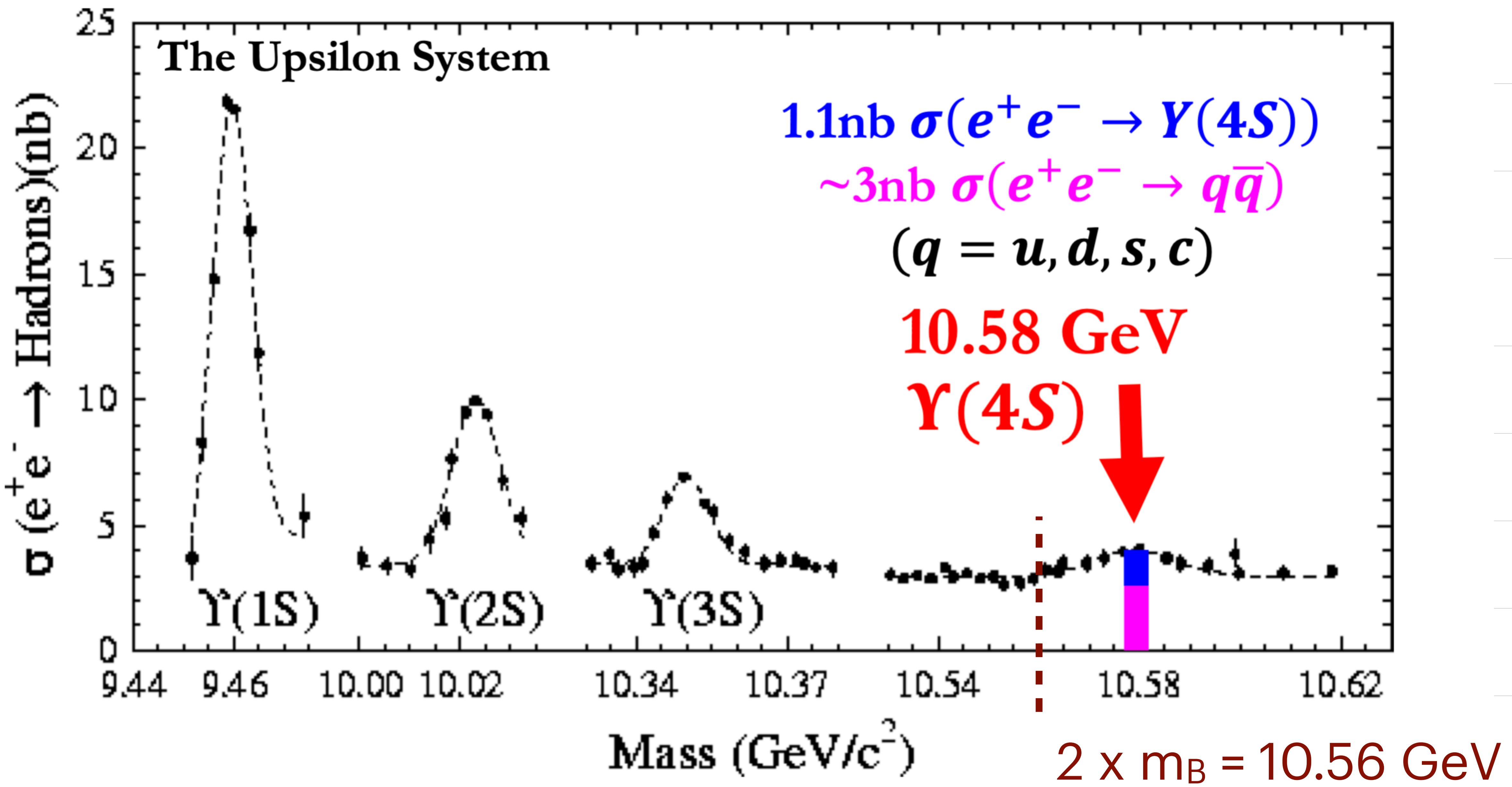
- Run 2 will resume in this year (currently in a short break) with goal of collecting several ab^{-1} data in the next few years. Please stay tuned!



Thank you!

Appendix

$e^+e^- \to \Upsilon(4S)$ as a B-factory

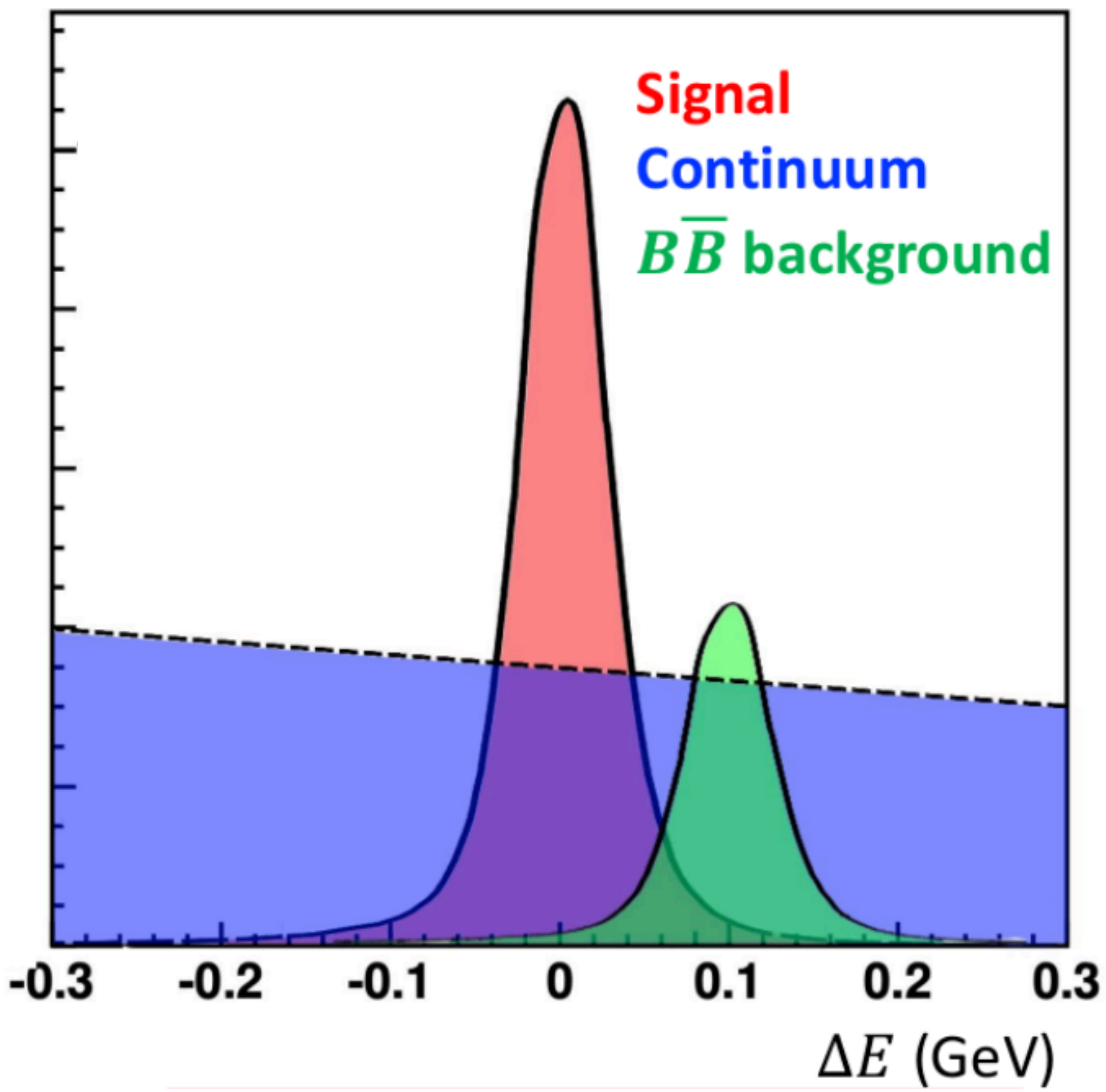


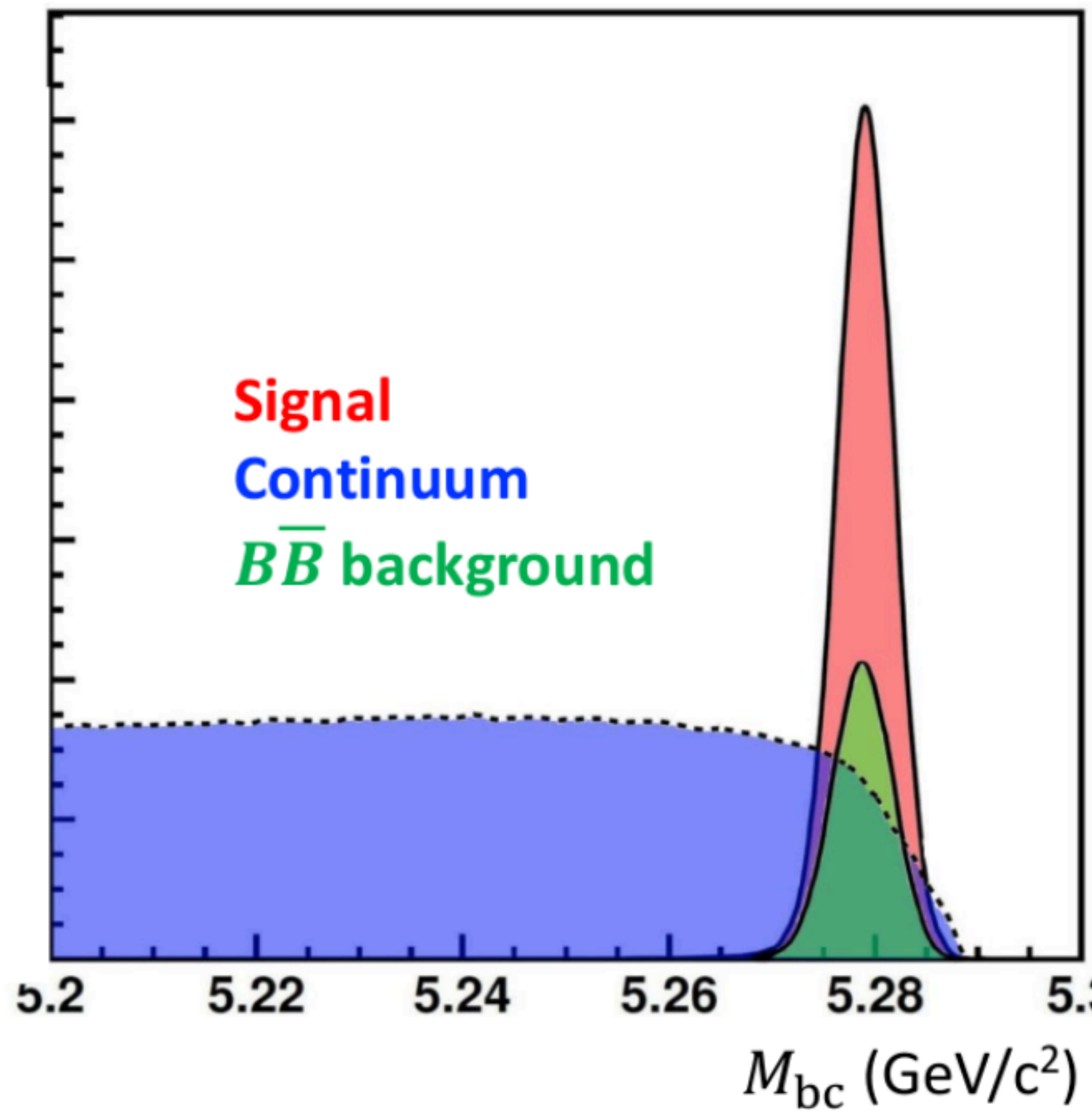
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained

Key variables of *B* decays

$$\Delta E = E_B^* - \sqrt{s}/2$$

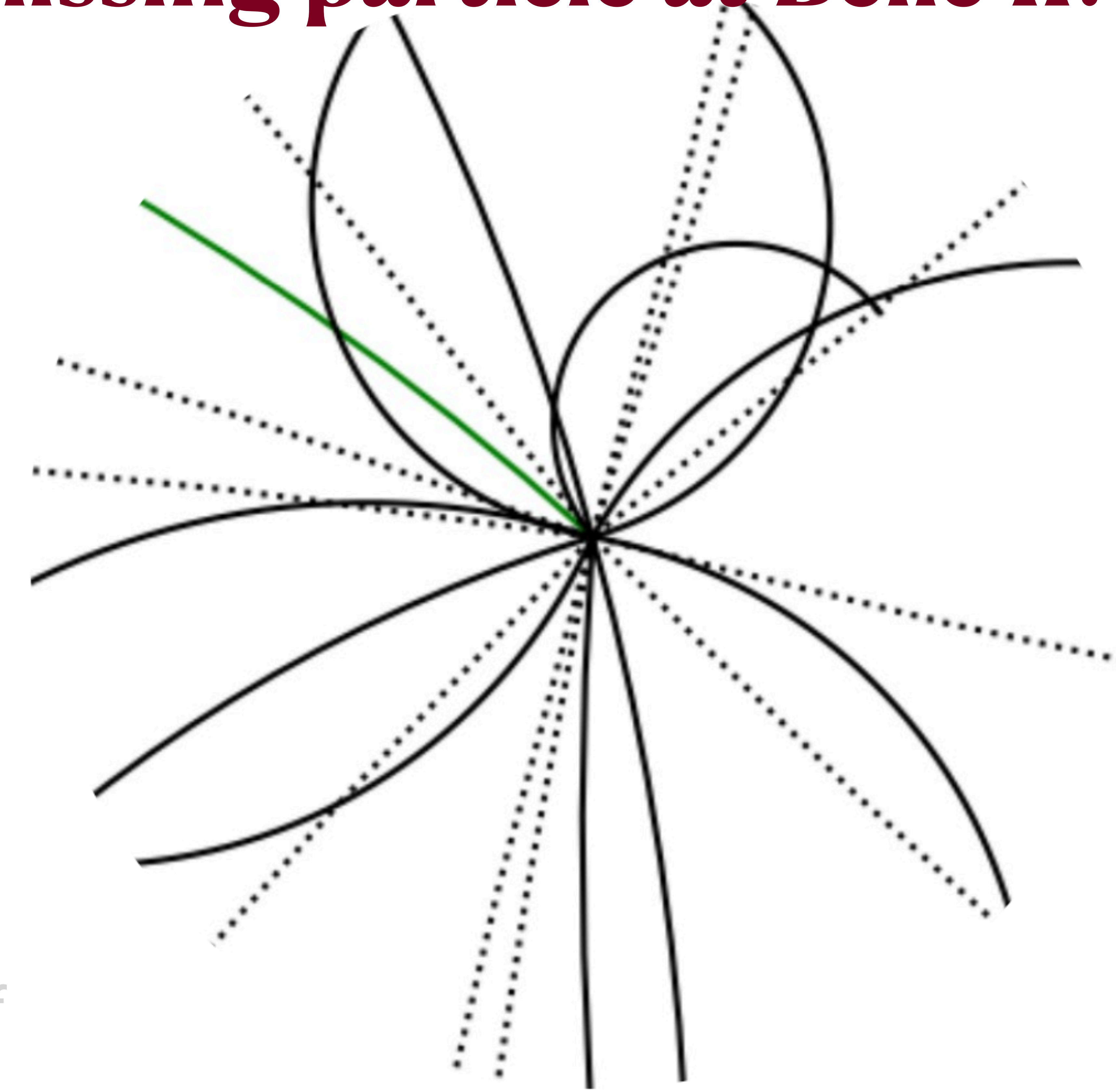
$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - \vec{p}_B^{*2}}$$





How to handle a missing particle at Belle II?

- $e^+e^- \to \Upsilon(4S) \to B\overline{B}$
  - only two B mesons in the final state
  - Since the initial state is clearly determined, fully accounting one B (B_{tag}) makes it possible to constrain the accompanying B (B_{sig})
  - Having a single missing particle (e.g. ν) is usually as clean as getting all particles measured
  - The price to pay is a big drop of efficiency ($< \mathcal{O}(1\%)$)



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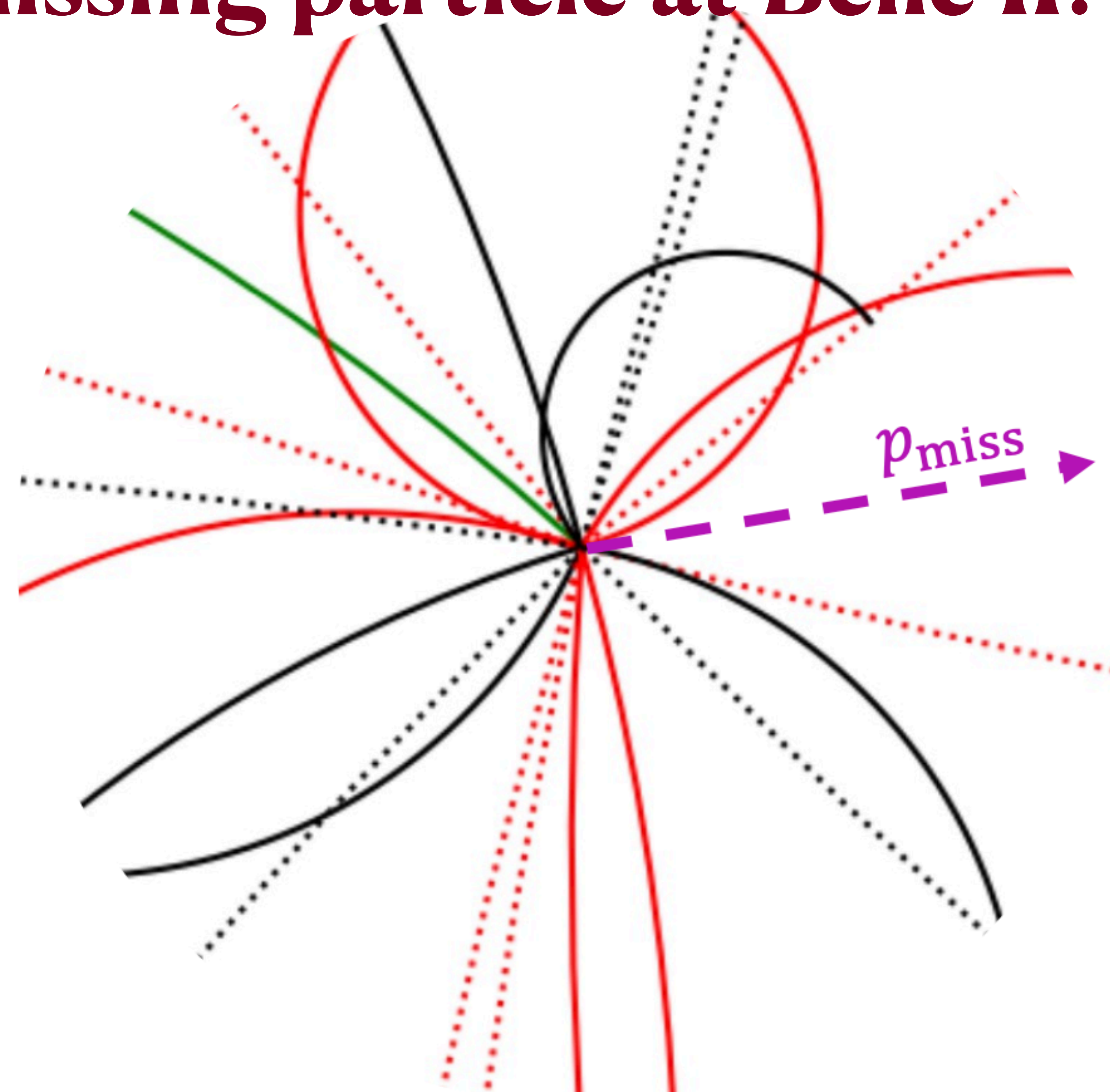
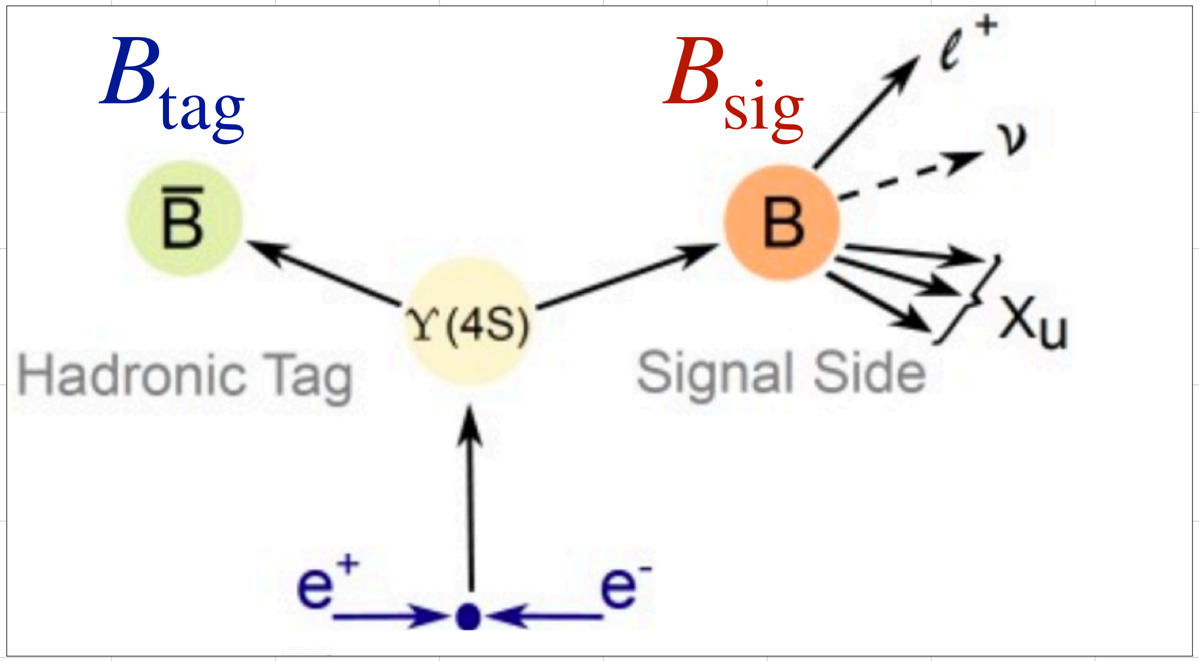
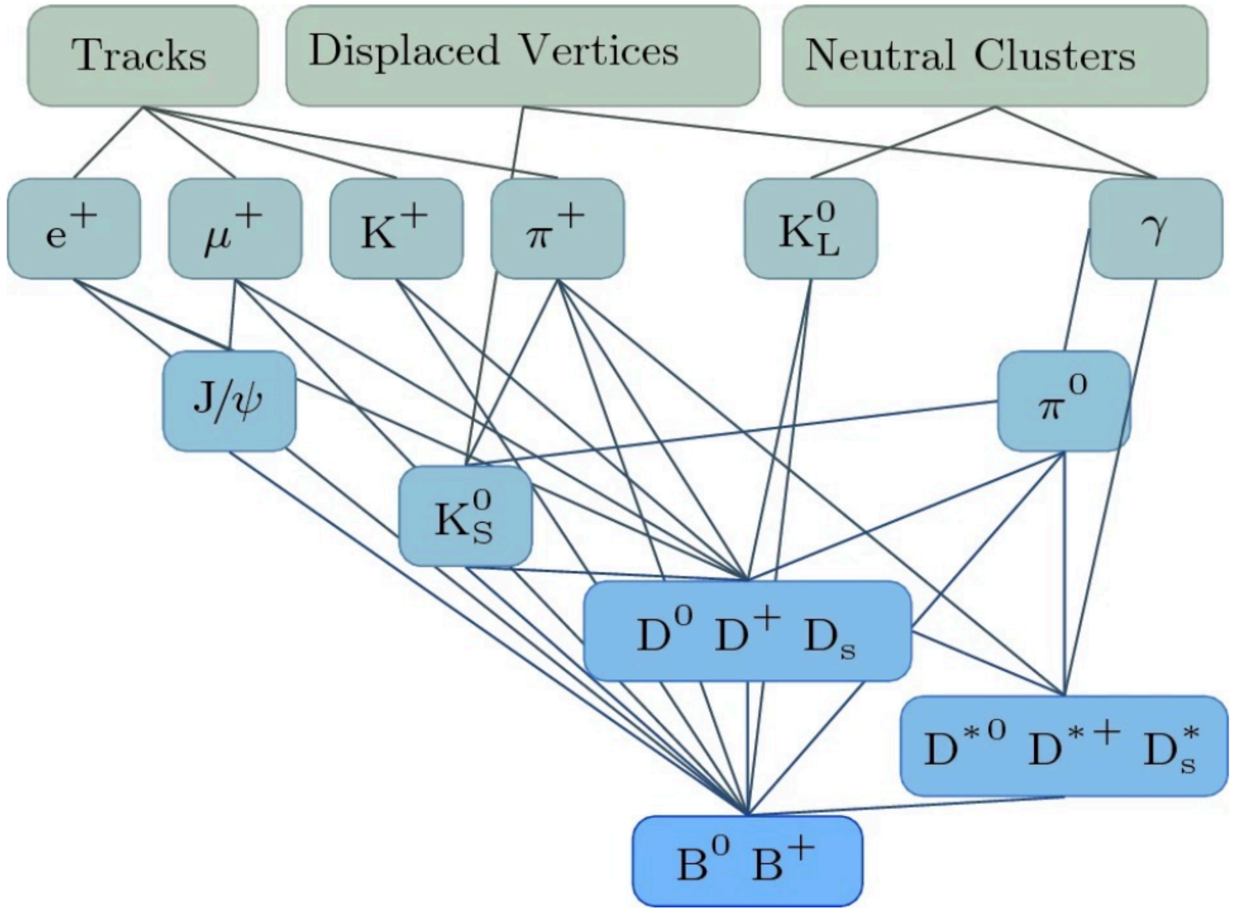


Full Event Interpretation (FEI)

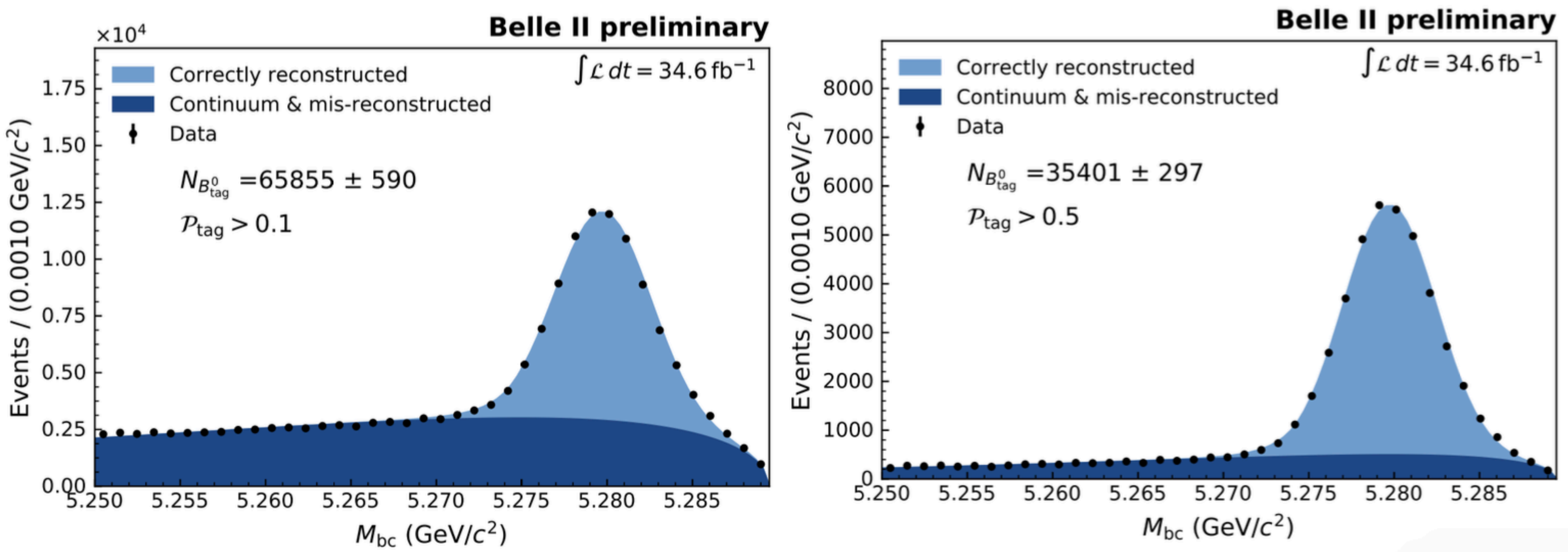
- FEI algorithm to reconstruct B_{tag}
  - uses ~200 BDT's to reconstruct $\mathcal{O}(10^4)$ different B decay chains
  - assign signal probability of being correct B_{tag}



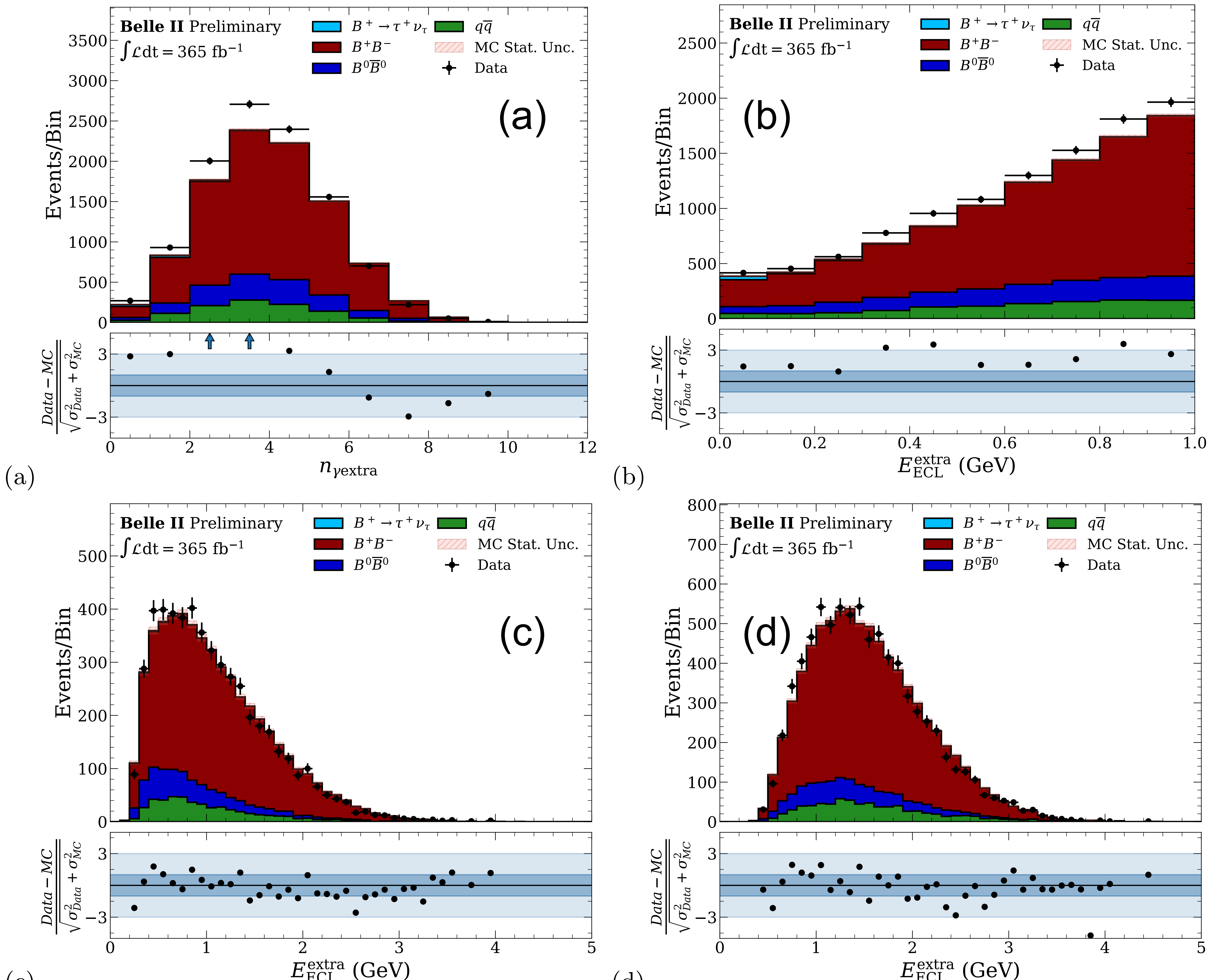
Comput Softw Big Sci 3, 6 (2019)



arXiv:2008.060965



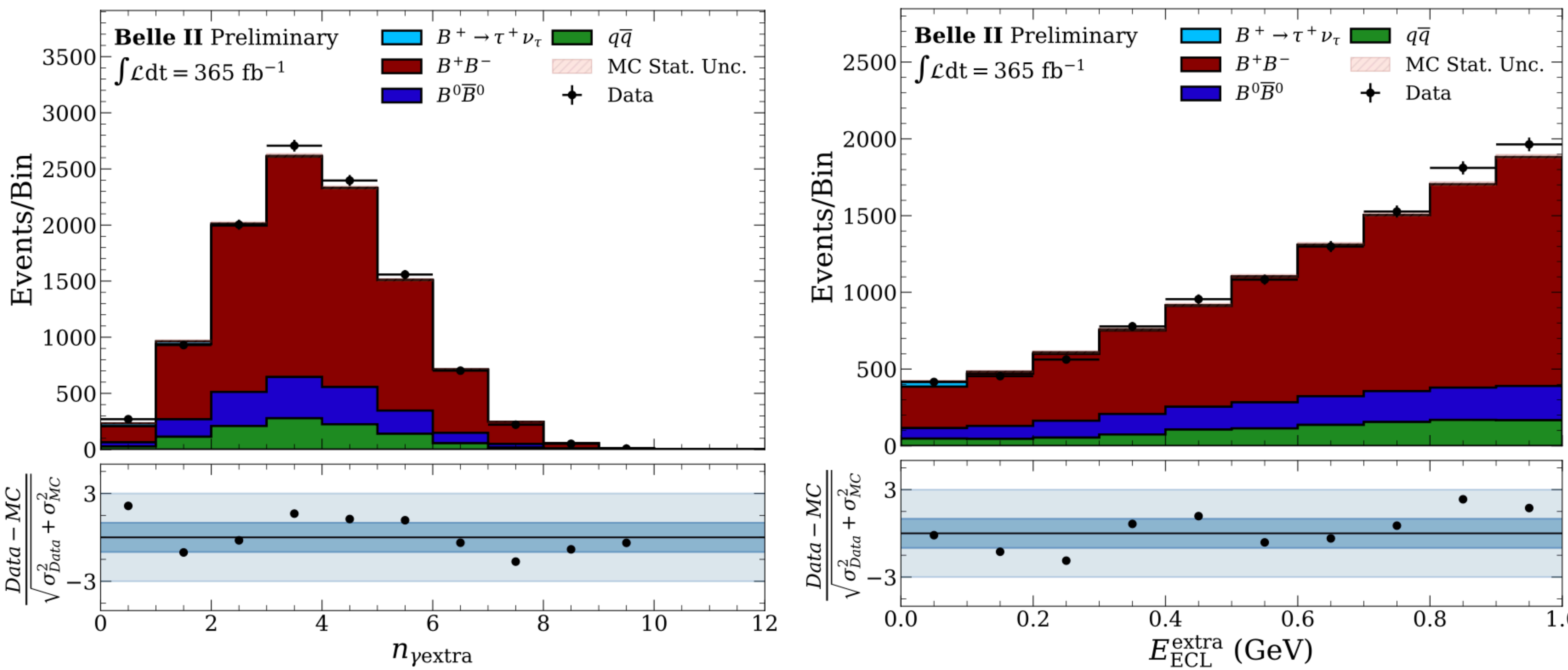
$B^+ \to \tau^+ \nu$



- $E_{\rm ECL}^{\rm extra}$ as a key variable
  - (a) $n_{\gamma\rm extra}$ for $E_{\rm ECL}^{\rm extra} < 1.0$
  - (b) $E_{\rm ECL}^{\rm extra}$
  - (c) $E_{\rm ECL}^{\rm extra}$ for $n_{\gamma\rm extra}$= 3
  - (d) $E_{\rm ECL}^{\rm extra}$ for $n_{\gamma\rm extra}$= 5
- Note: $E_{\rm ECL}^{\rm extra}$ matches well in a given $n_{\gamma\rm extra}$ bin

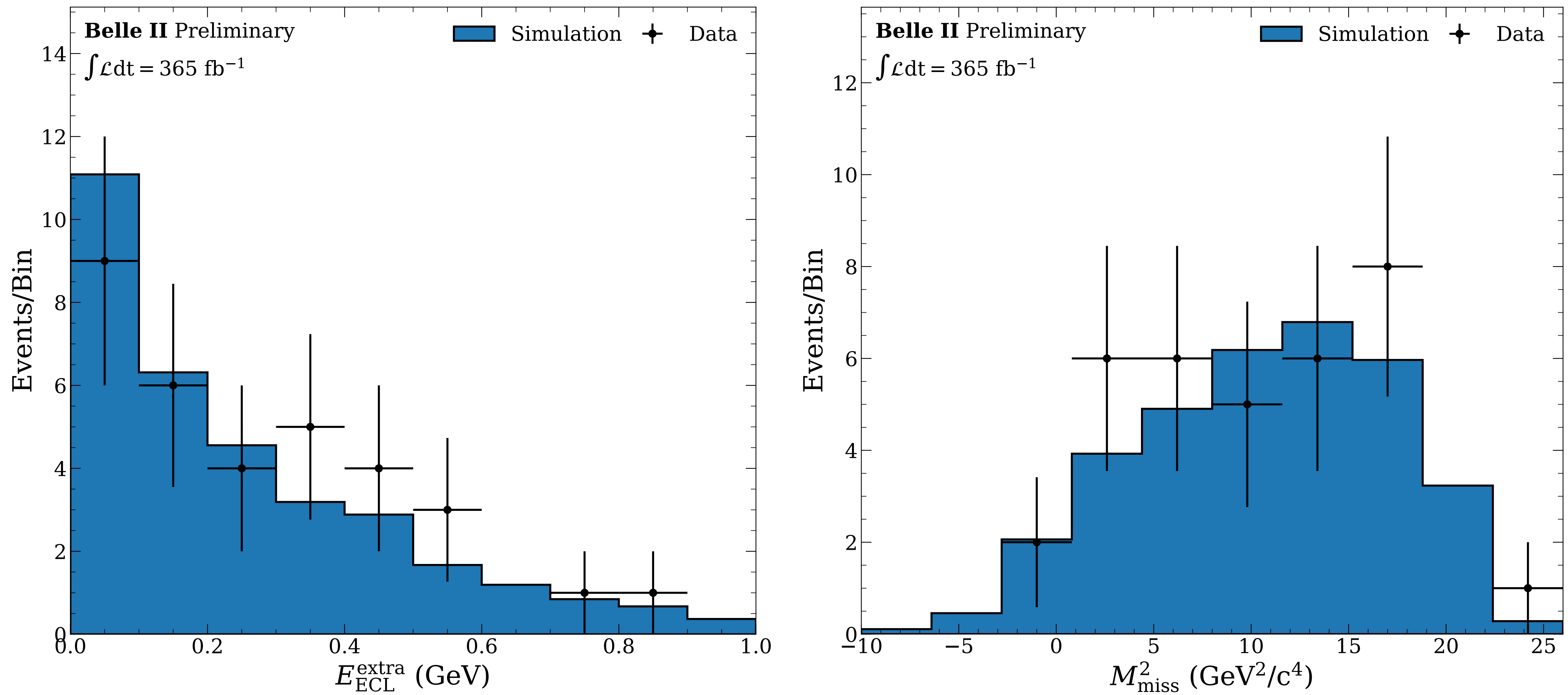
  ➔ match $n_{\gamma\rm extra}$ first!

$B^+ \to \tau^+\nu$



$n_{\gamma\text{extra}}$ and $E_{\text{ECL}}^{\text{extra}}$ after matching $n_{\gamma\text{extra}}$ with calibration sample

$B^+ \to \tau^+\nu$, Control sample check



- Check signal efficiency by using control sample,
- prepared by signal embedding technique
  - use $B^+ \to K^+ J/\psi$, cleanly reconstructed sample
  - throw the $K^+ J/\psi$ part away, to be replaced by MC-generated $B^+ \to \tau^+\nu$
  - the check gives 1.02 ± 0.18 for the efficiency ratio (good!)