Dark sector studies with Belle II & Belle

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Outline

- a quick intro.
  - Belle and Belle II
  - the dark sector
- recent highlights from Belle (II)
  - inelastic dark matter — PRL 135, 131801 (2025)
  - ALP search in ISR — PRL 125, 161806 (2020)
  - results in B decays
    - ALP search (Belle data) — JHEP 2025, 109 (2025)
    - FIP search (Belle data) — arXiv:2601.07104 to PRL
    - more news in $b \to s\nu\bar{\nu}$ — PRD 112, 092016 (2025); arXiv:2511.10980 to PRL
- closing remarks

(Super)KEKB & Belle (II)

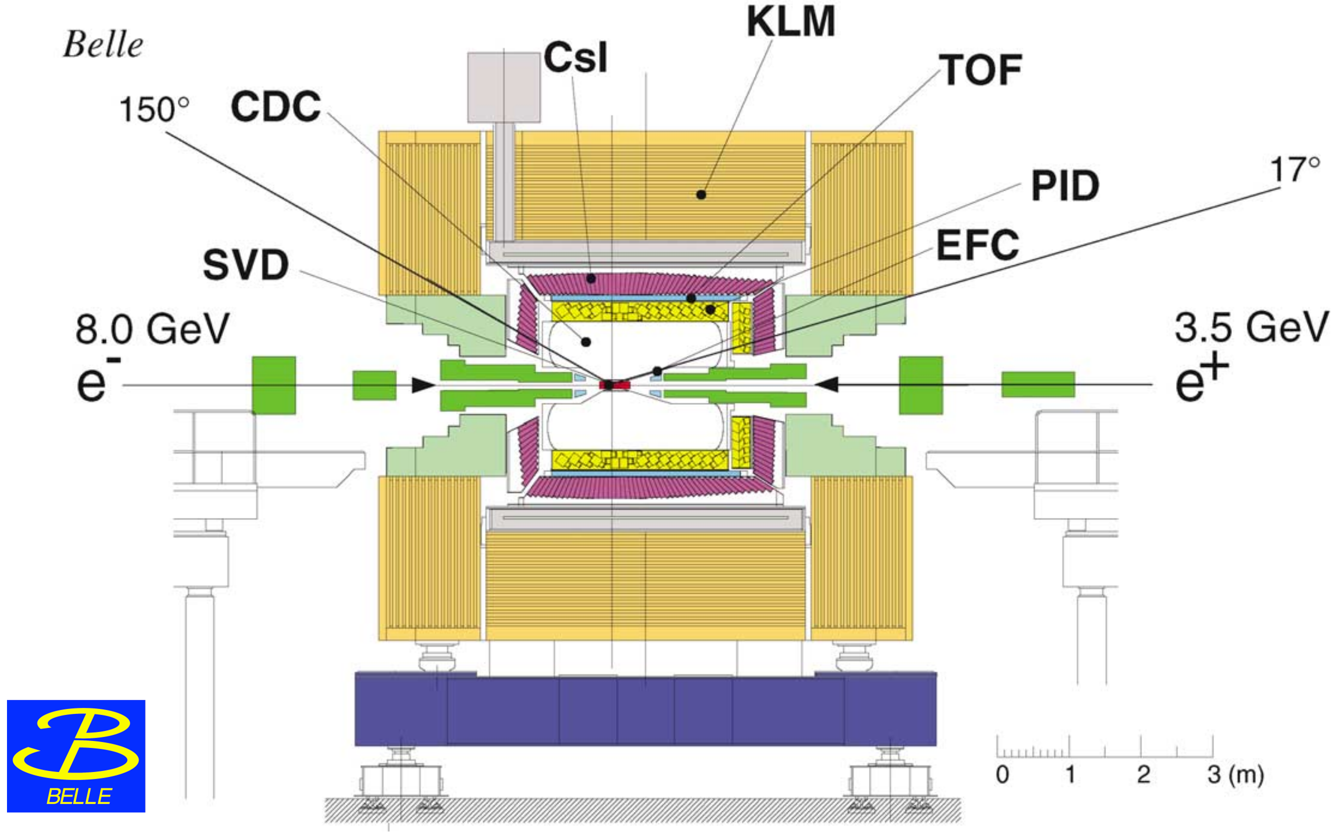
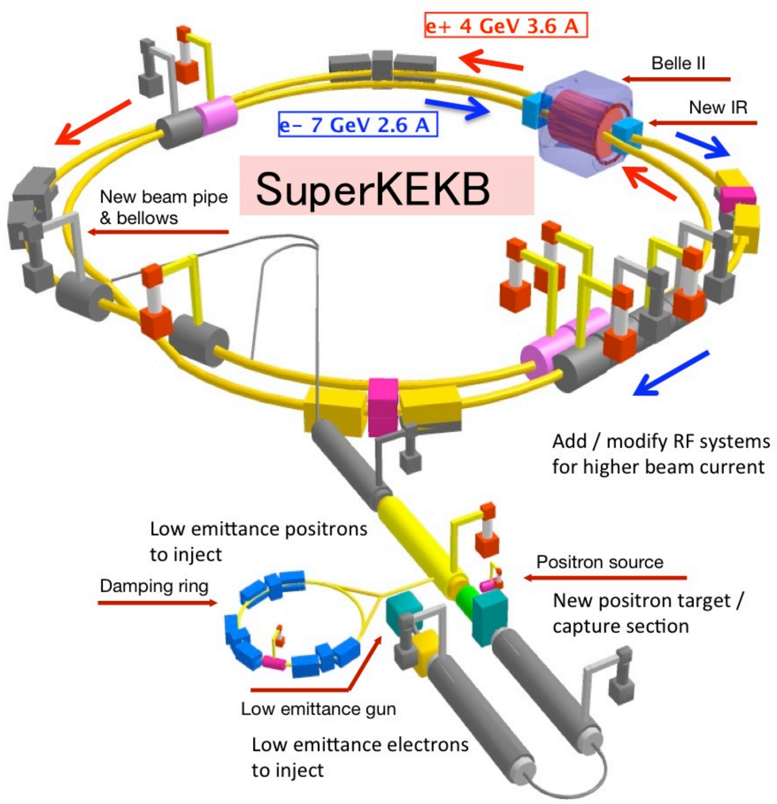
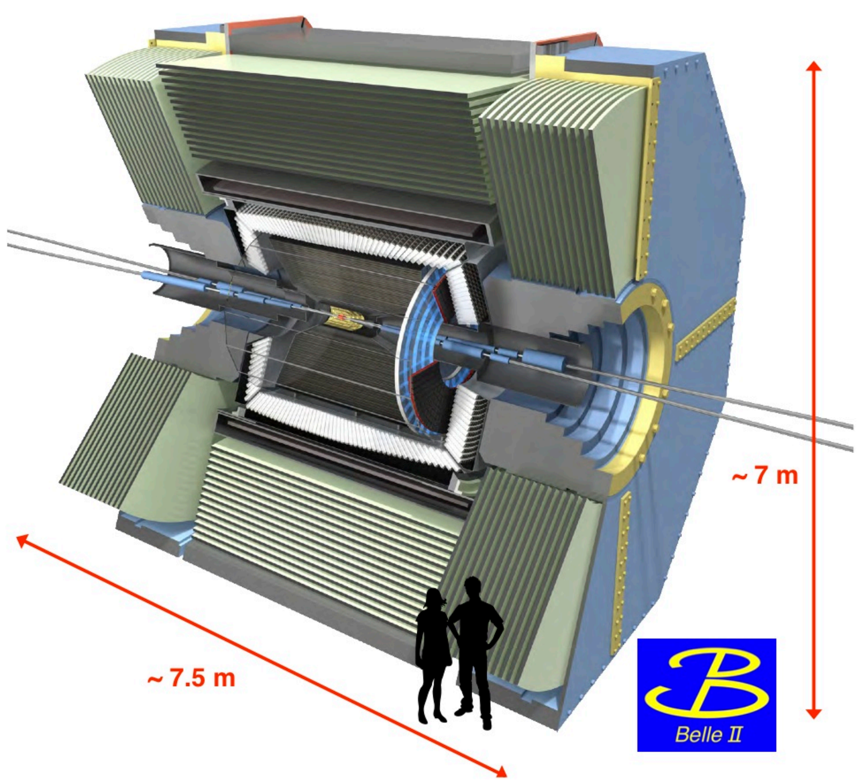


Fig. 1. Side view of the Belle detector.





Belle & Belle II

e^+e^- collision experiment

- conceived and constructed, mainly for **CP violation in B-meson** system
- **CP violation** — a necessary condition for baryon asymmetry in our Universe (i.e. extreme dominance of matter over anti-matter)

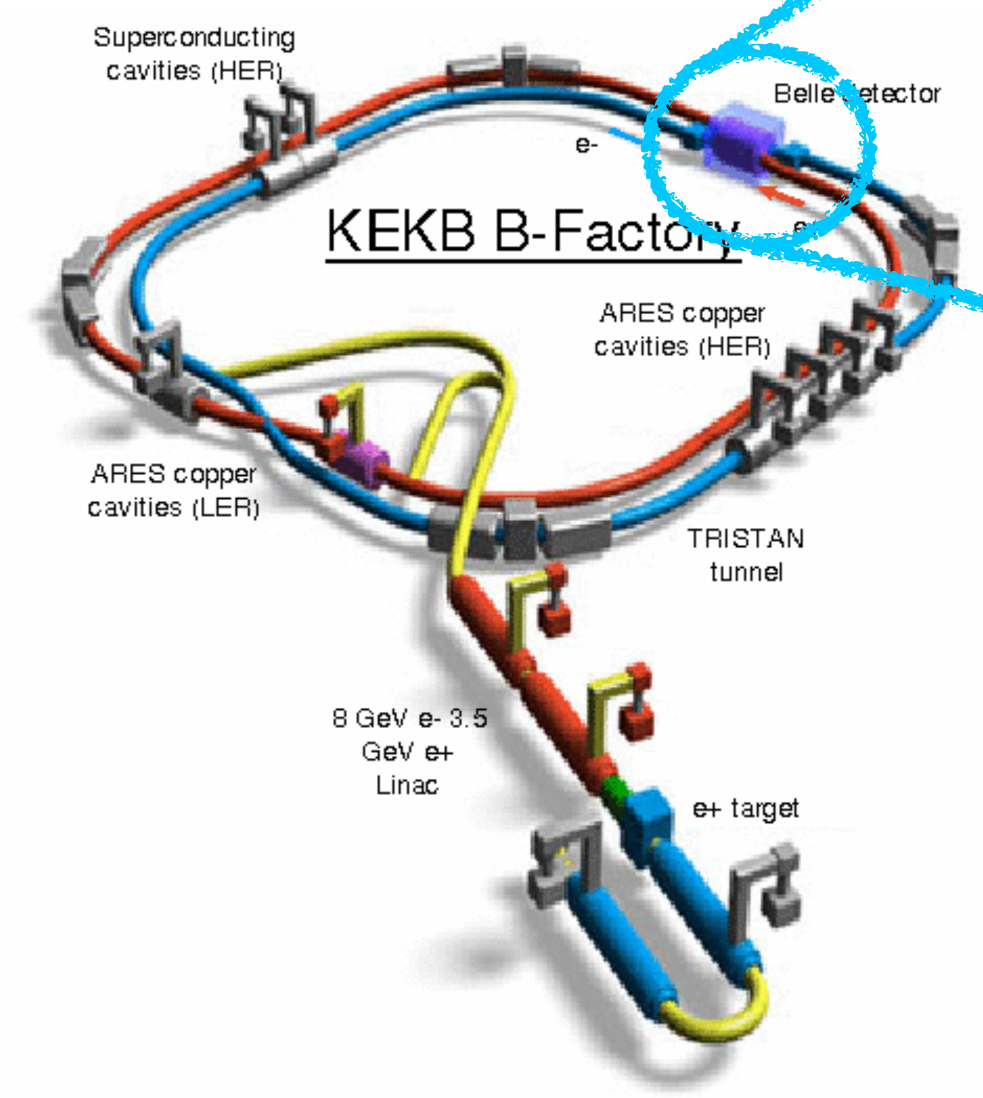
Belle & KEKB

- operated during 1999-2010 using KEKB e^+e^- collider at KEK, Japan
- produced more than 600 physics papers
- observed CP violation in the B-meson system (for the first time, along with BaBar) & confirmed Kobayashi-Maskawa hypothesis ➔ 2008 Nobel Physics prize
- $\sim$450 physicists from 22 countries

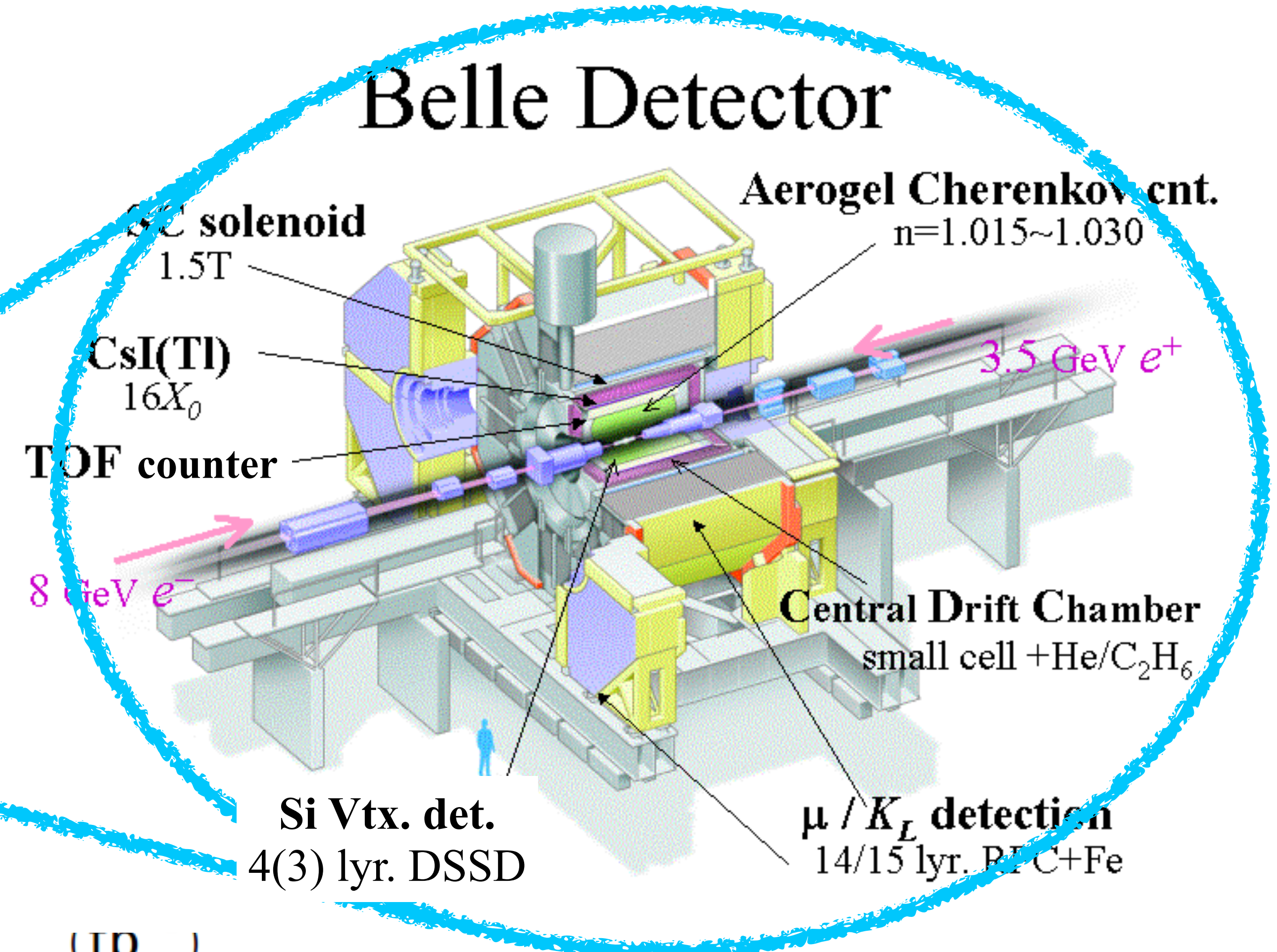

Mt. Tsukuba
BELLE II
~ 1 km
~ 1.5 km
KEKB Ring
Damping
Ring
Linac
KEK Tsukuba
Campus

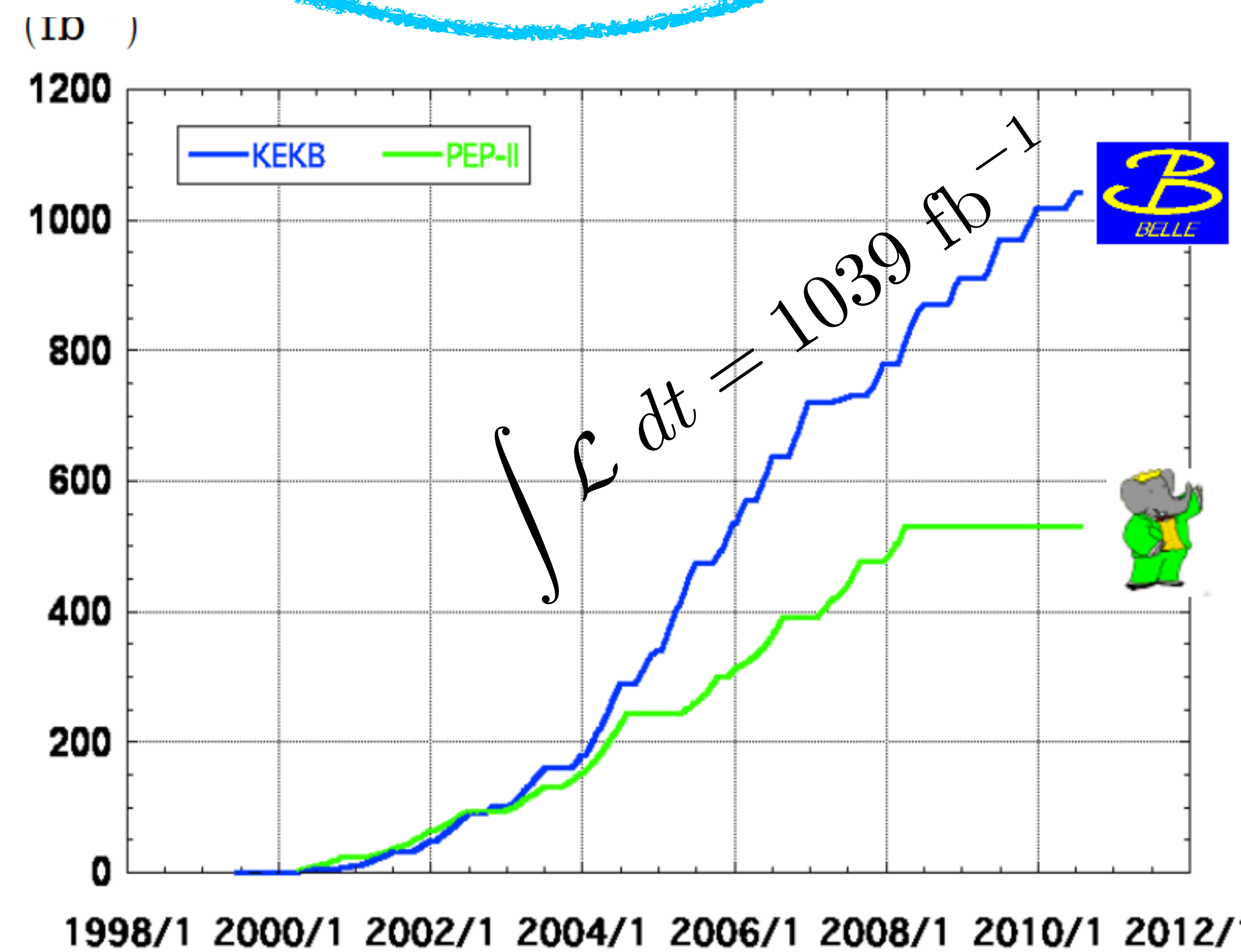
22 countries
100 institutions
~450 members

$$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$$



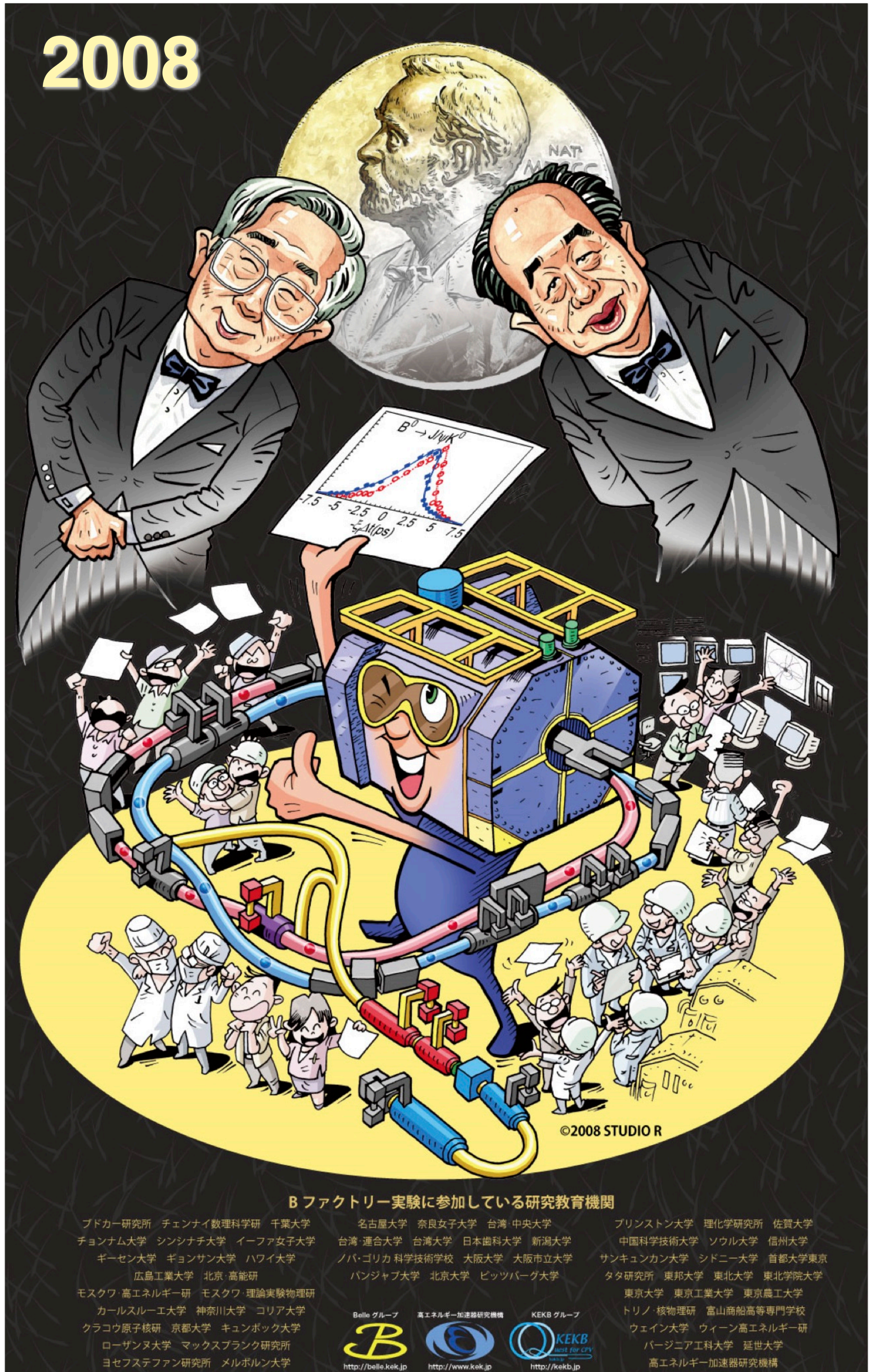
$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$





> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}



Belle (and BaBar, too) achievements include:

- CPV, CKM, and rare decays of B mesons (and B_s, too)
- Mixing, CP, and spectroscopy of charmed hadrons
- Quarkonium spectroscopy and discovery of (*many*) exotic states, e.g. $X(3872)$, $Z_c(4430)^+$
- Studies of τ and 2γ

Belle → Belle II

still not solved

- CP violation in the Standard Model (i.e. KM mechanism) is not large enough to explain the matter-antimatter asymmetry in our Universe

  ➔ *We need New Physics!*

- The origin of the Flavor structure of the SM is totally unknown

upgrade Belle → Belle II

- KEKB is upgraded to SuperKEKB,

  aiming at $\times 50$ total data size

- Belle detector is also upgraded to Belle II

Belle → Belle II

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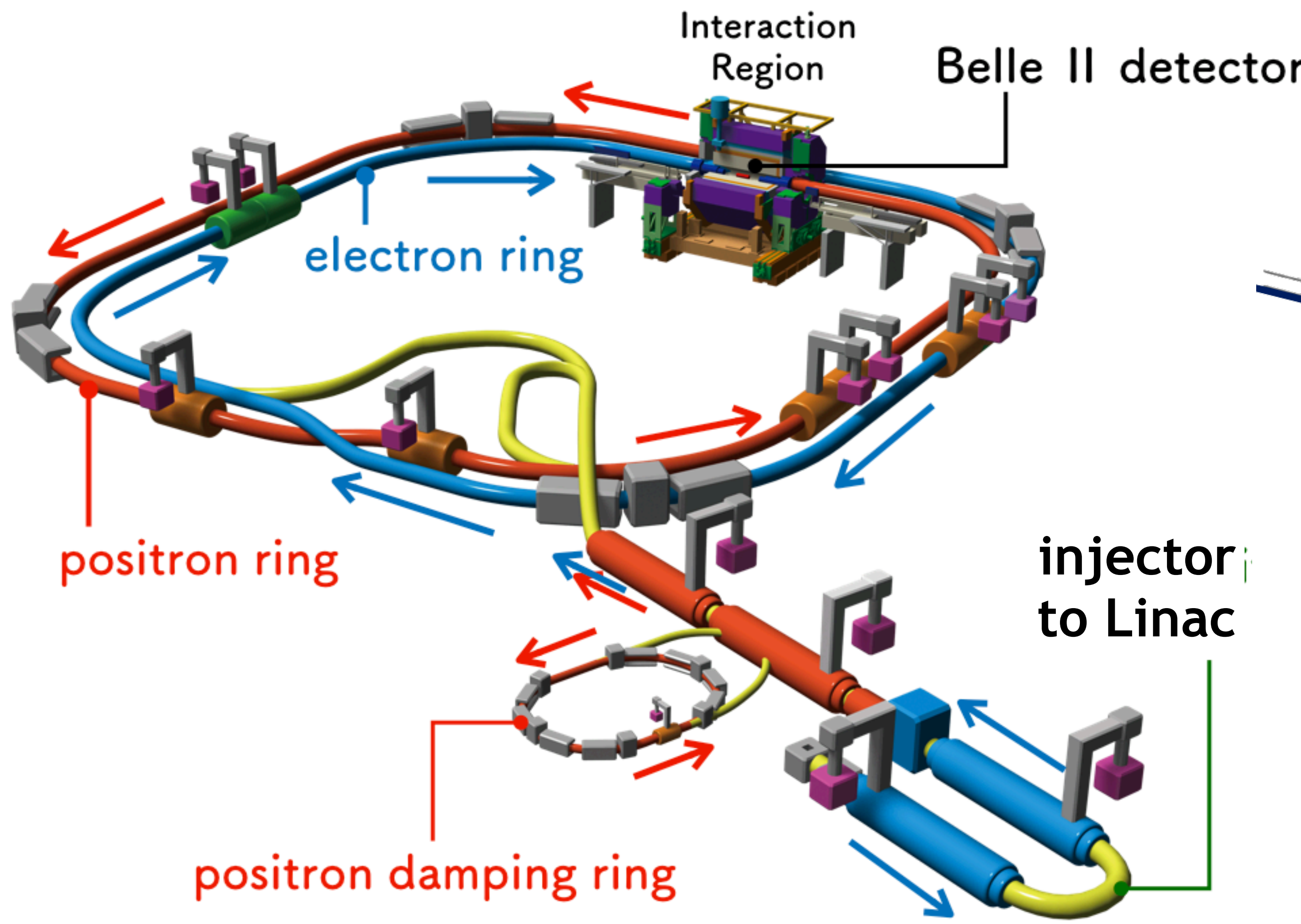
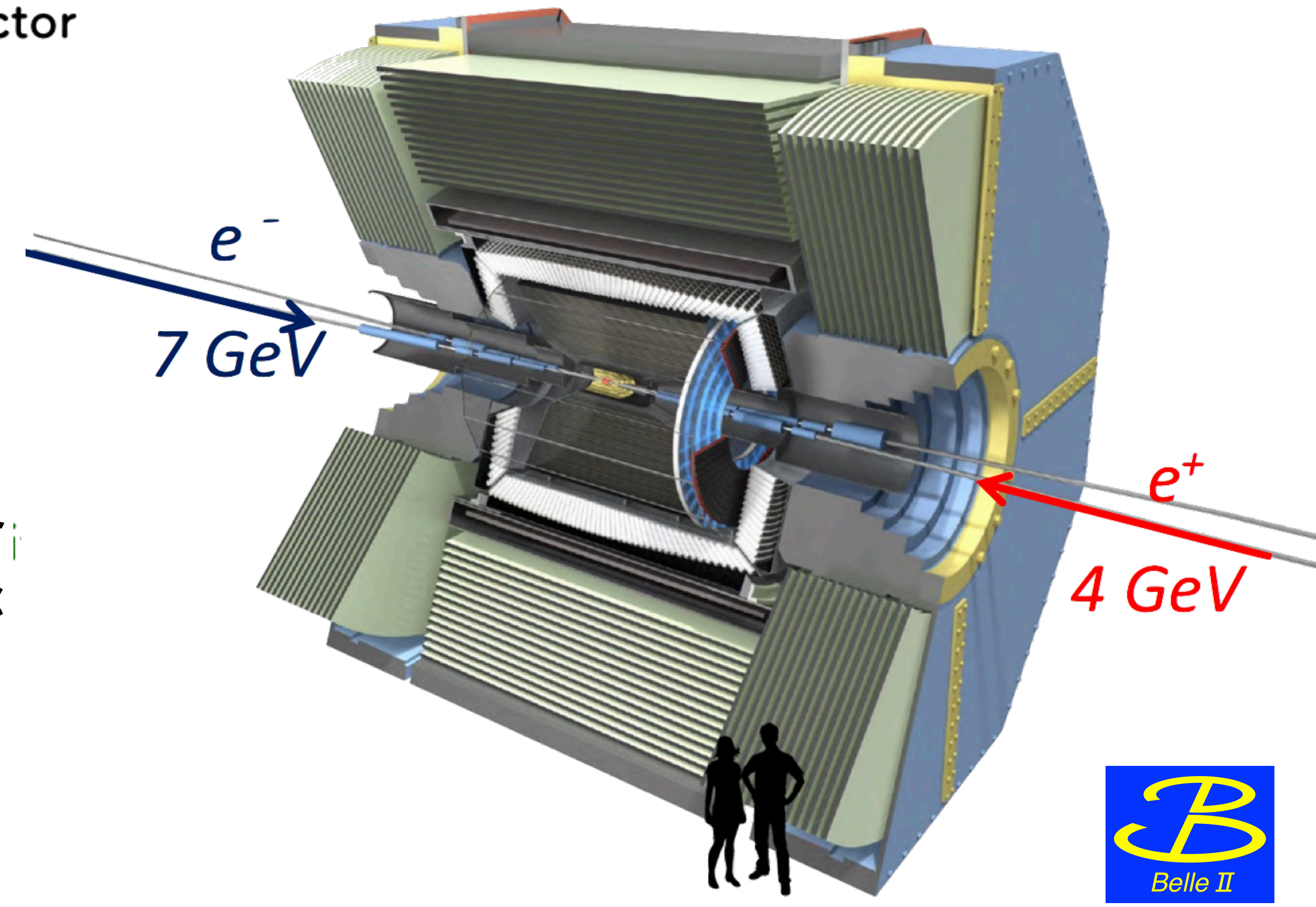
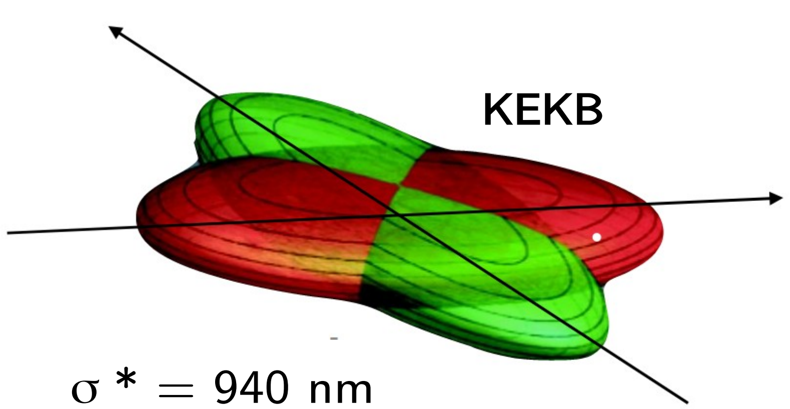
$$\int^{\text{goal}} \mathcal{L}\, dt = 50\ \text{ab}^{-1}$$

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



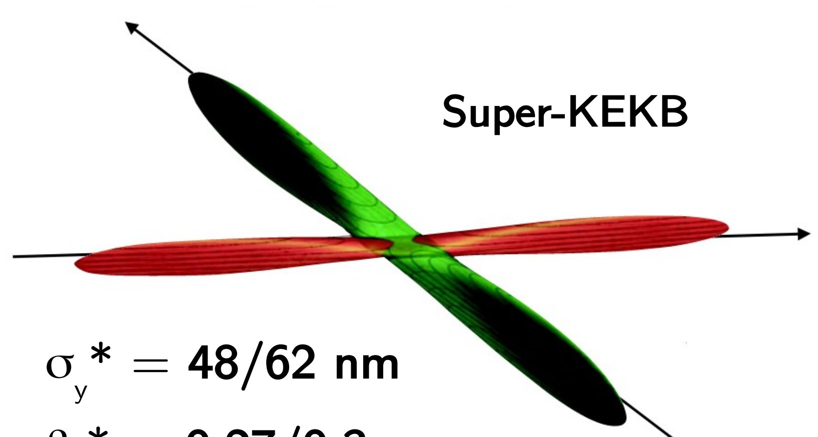




$\sigma_y^* = 940$ nm

$\beta_y^* = 5.9$ mm

$\sigma_x^* = 147/170$ μm



$\sigma_y^* = 48/62$ nm

$\beta_y^* = 0.27/0.3$ mm

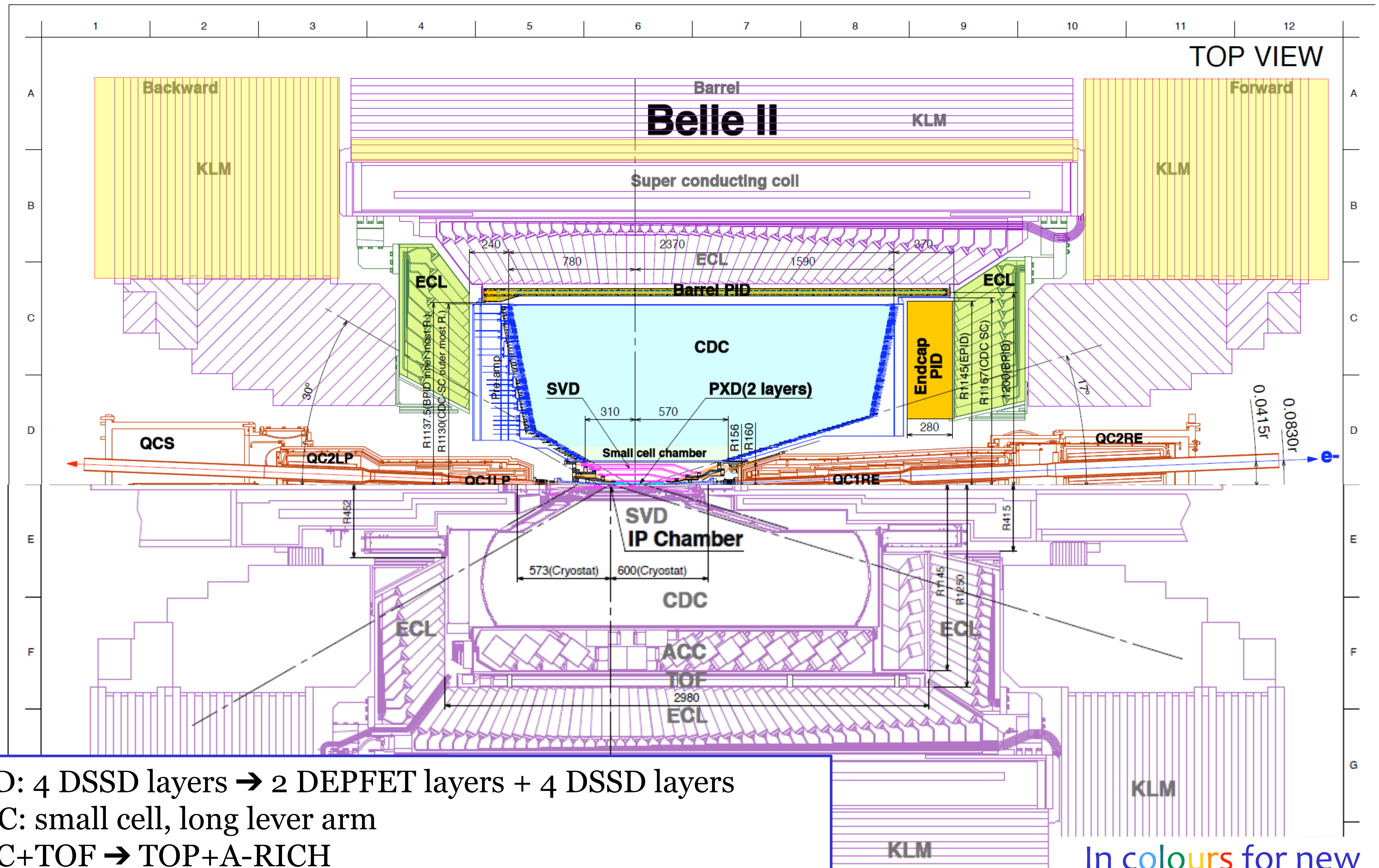
$\sigma_x^* = 10.1/10.7$ μm

$$\mathcal{L}_{\mathrm{II}}^{\mathrm{peak}} \approx 30 \times \mathcal{L}_{\mathrm{I}}^{\mathrm{peak}}$$

$$\int^{\mathrm{goal}} \mathcal{L}_{\mathrm{II}}\, dt = 50\ \mathrm{ab}^{-1} \approx 50 \int \mathcal{L}_{\mathrm{I}}\, dt$$

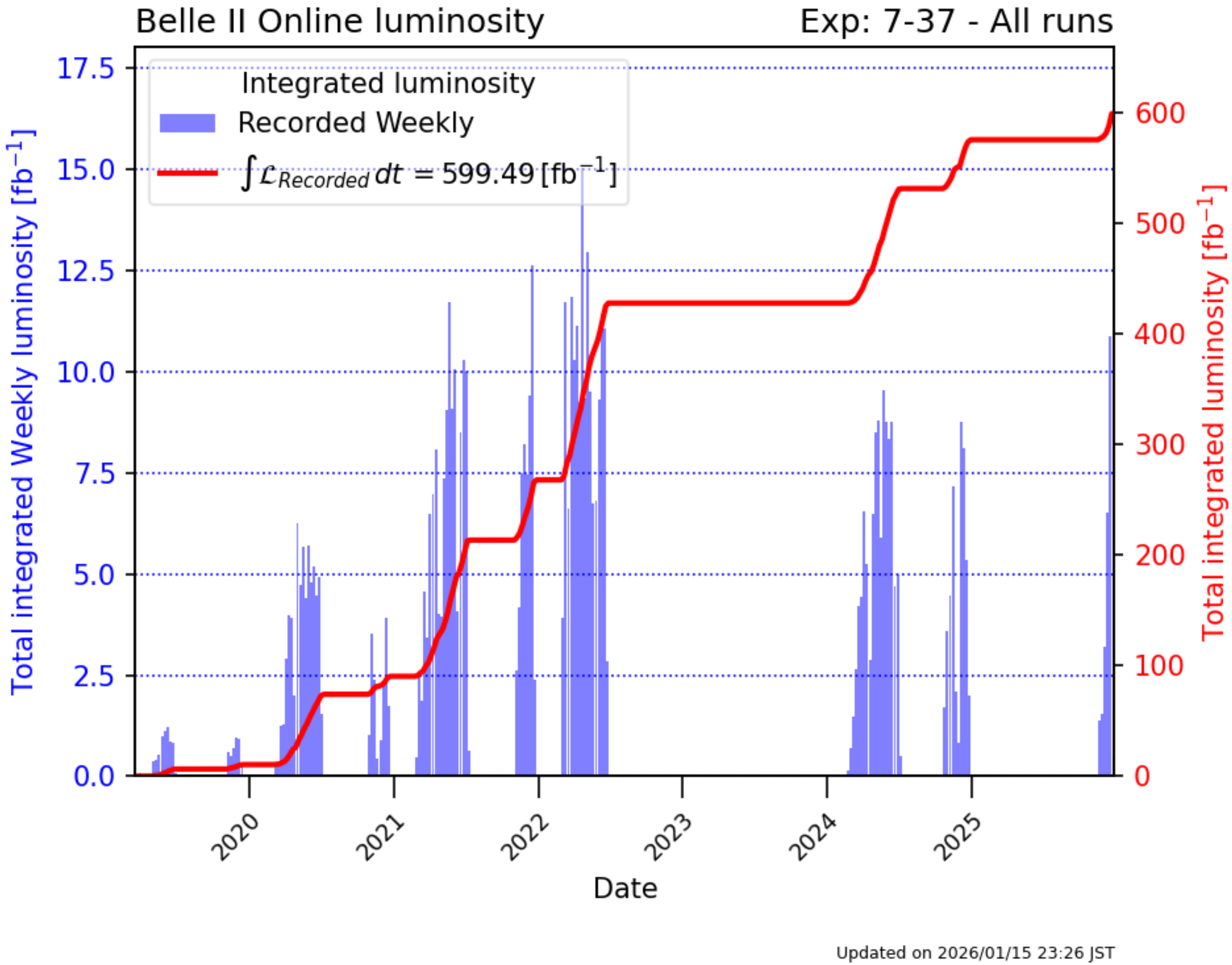
The Belle II Collaboration

26 countries/regions, ~120 institutions, ~1000 collaborators



SVD: 4 DSSD layers ➔ 2 DEPFET layers + 4 DSSD layers
CDC: small cell, long lever arm
ACC+TOF ➔ TOP+A-RICH
ECL: waveform sampling
KLM: RPC ➔ Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

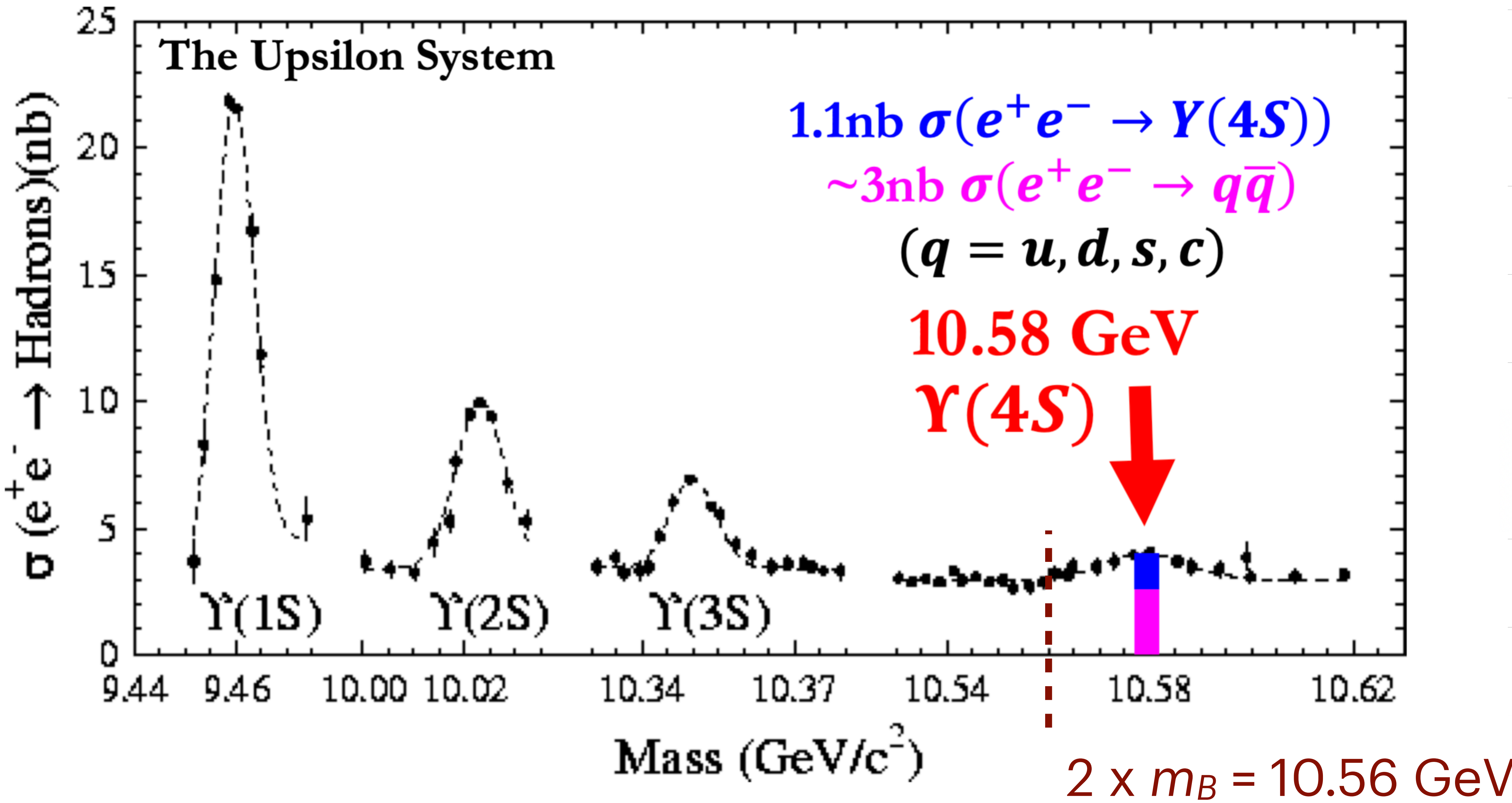
In colours for new components



Belle (1999-2010) Luminosity

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

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



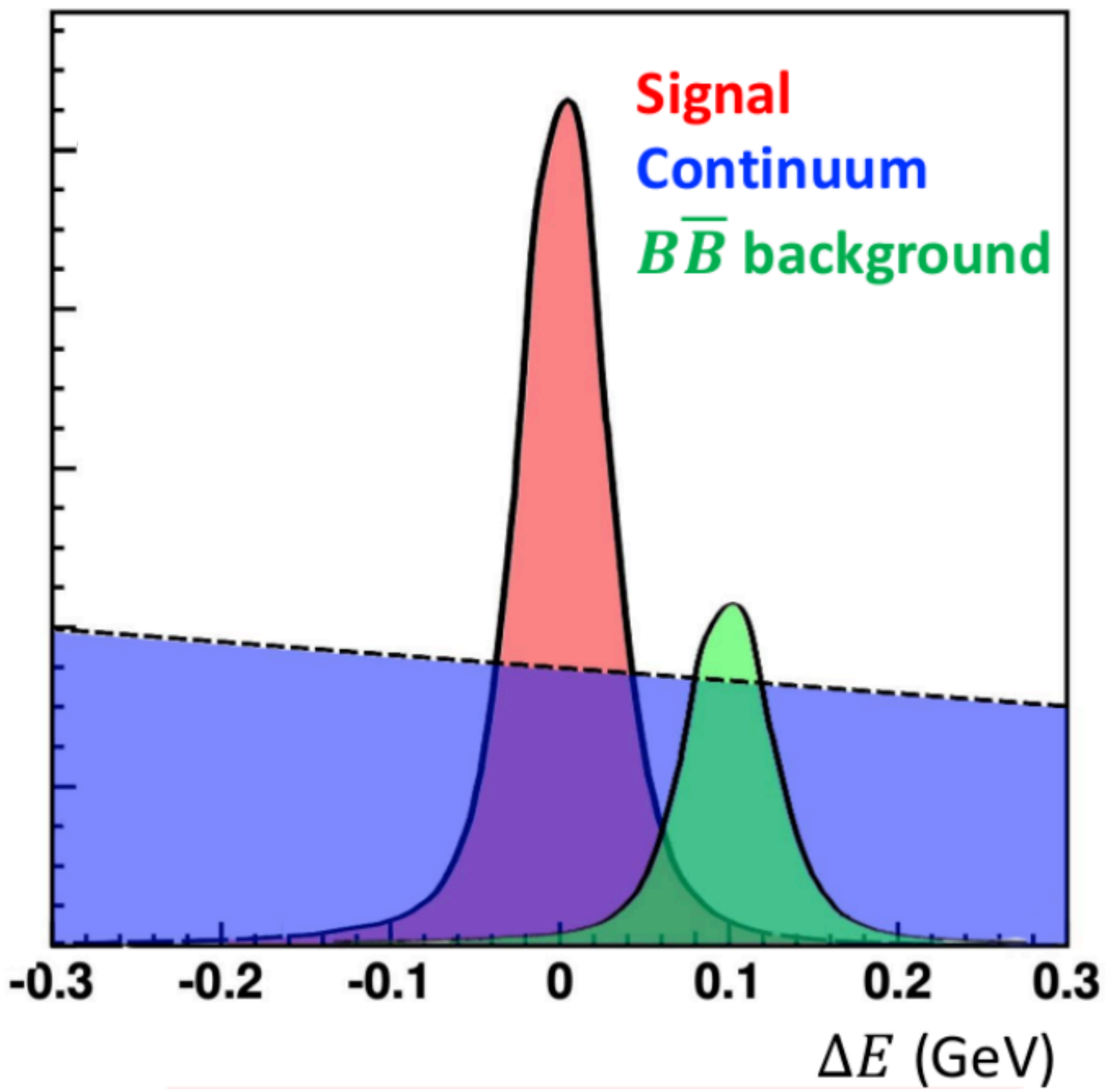
$$e^- \xrightarrow{\text{8 GeV}} (\star) \xleftarrow{\text{3.5 GeV}} e^+$$

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

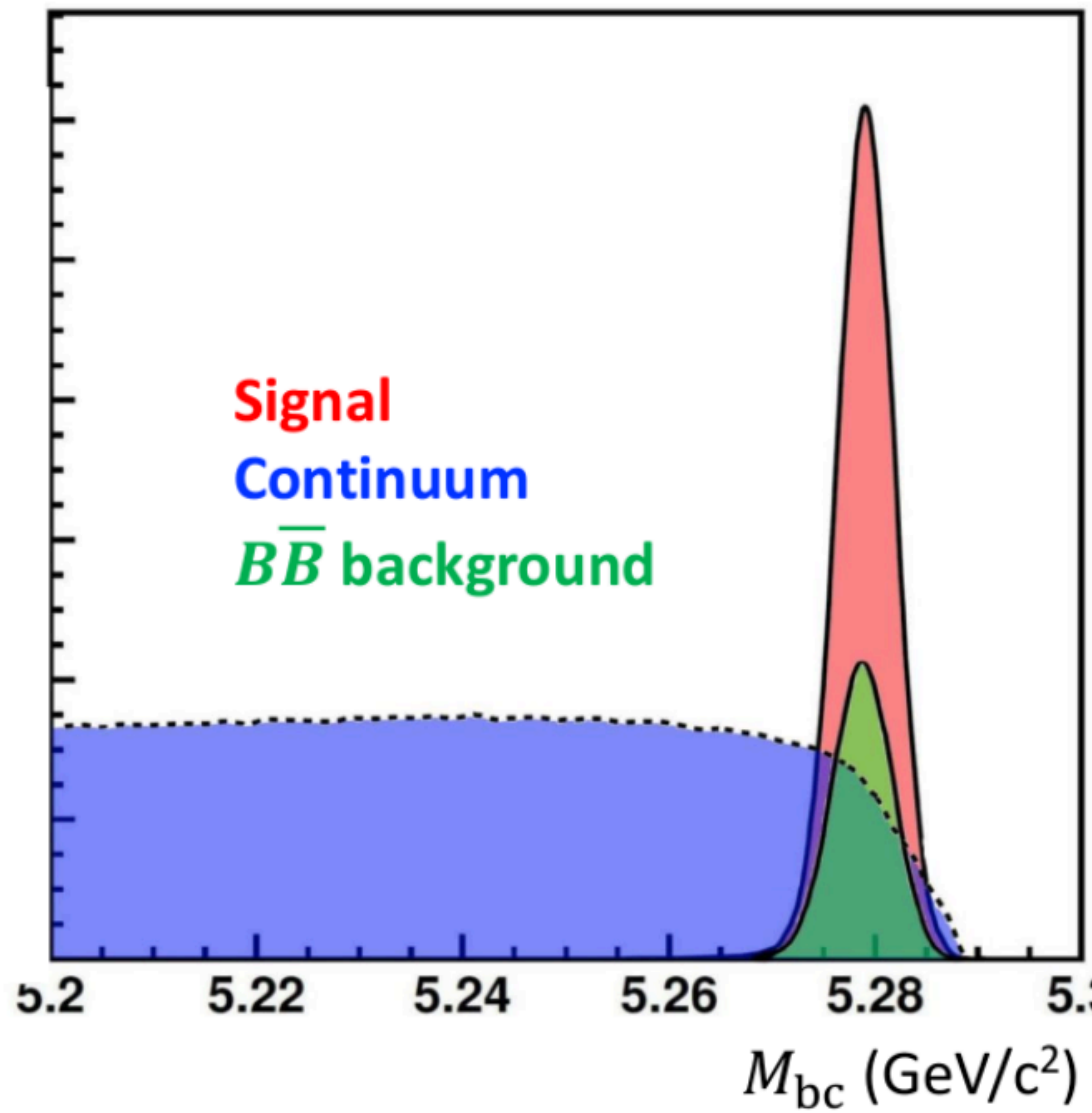
- $\mathcal{B}(\Upsilon(4S) \rightarrow B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained

Key variables of *B* decays

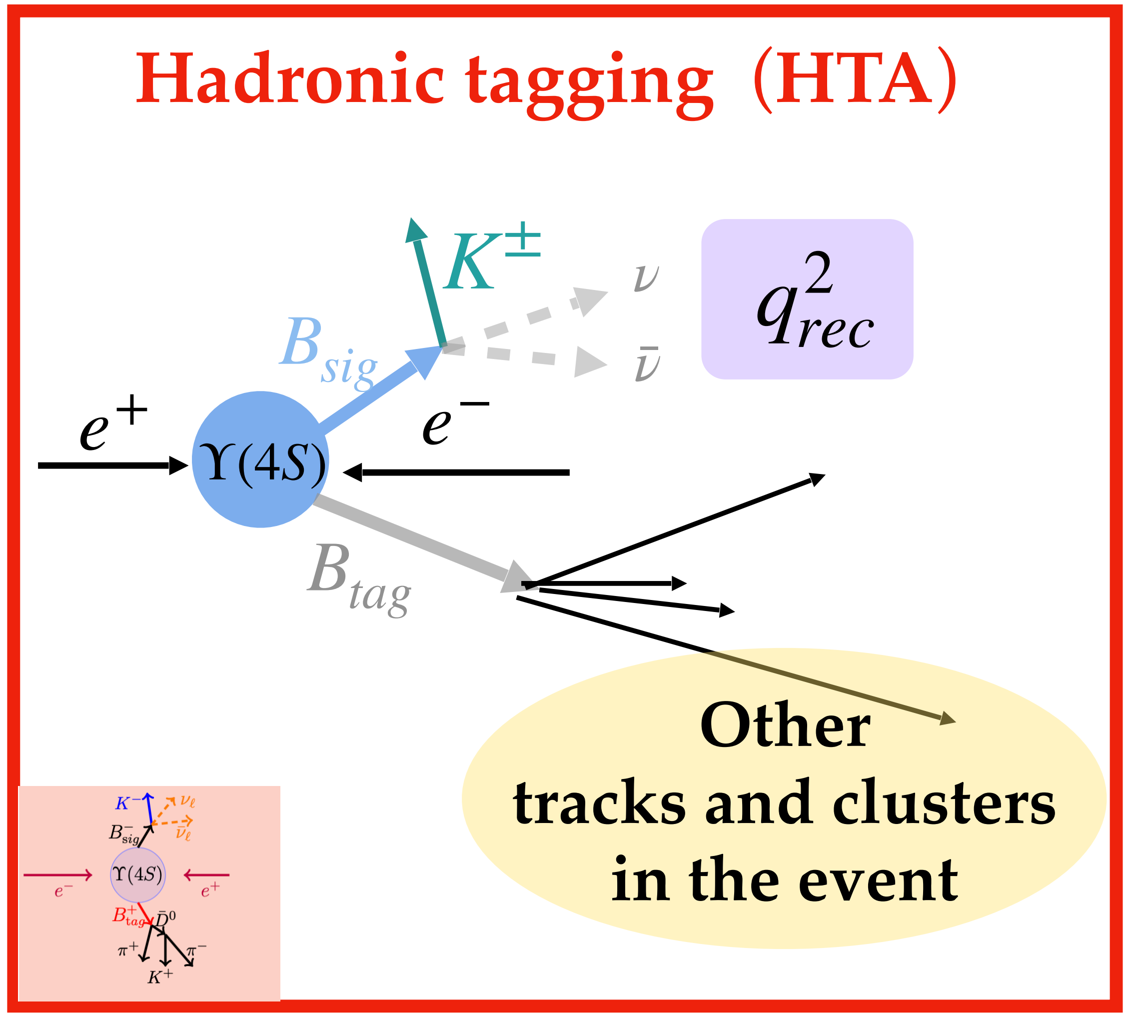
$$\Delta E = E_B^* - \sqrt{s}/2$$



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



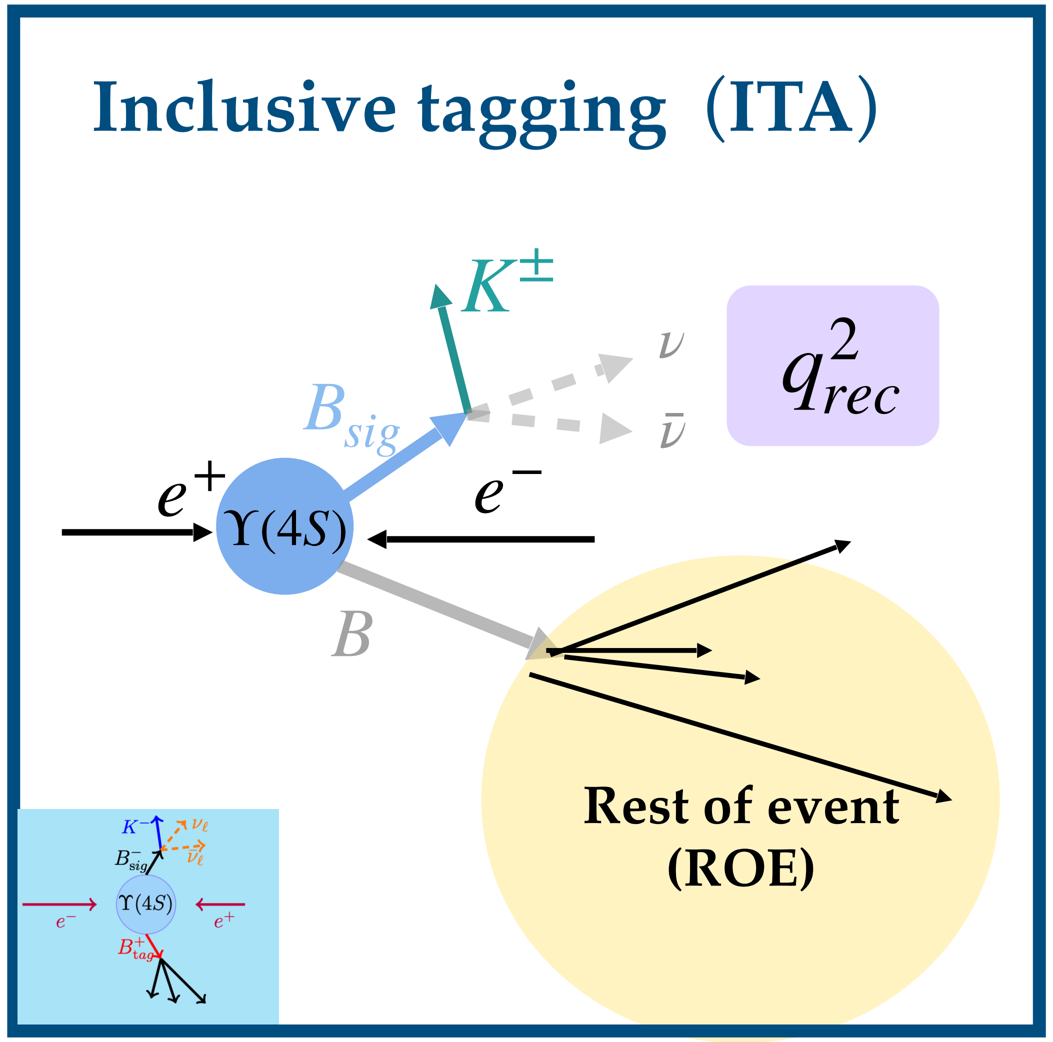
"A Tale of Two Taggings"



Efficiency →

q^2_{rec} : mass squared of the neutrino pair

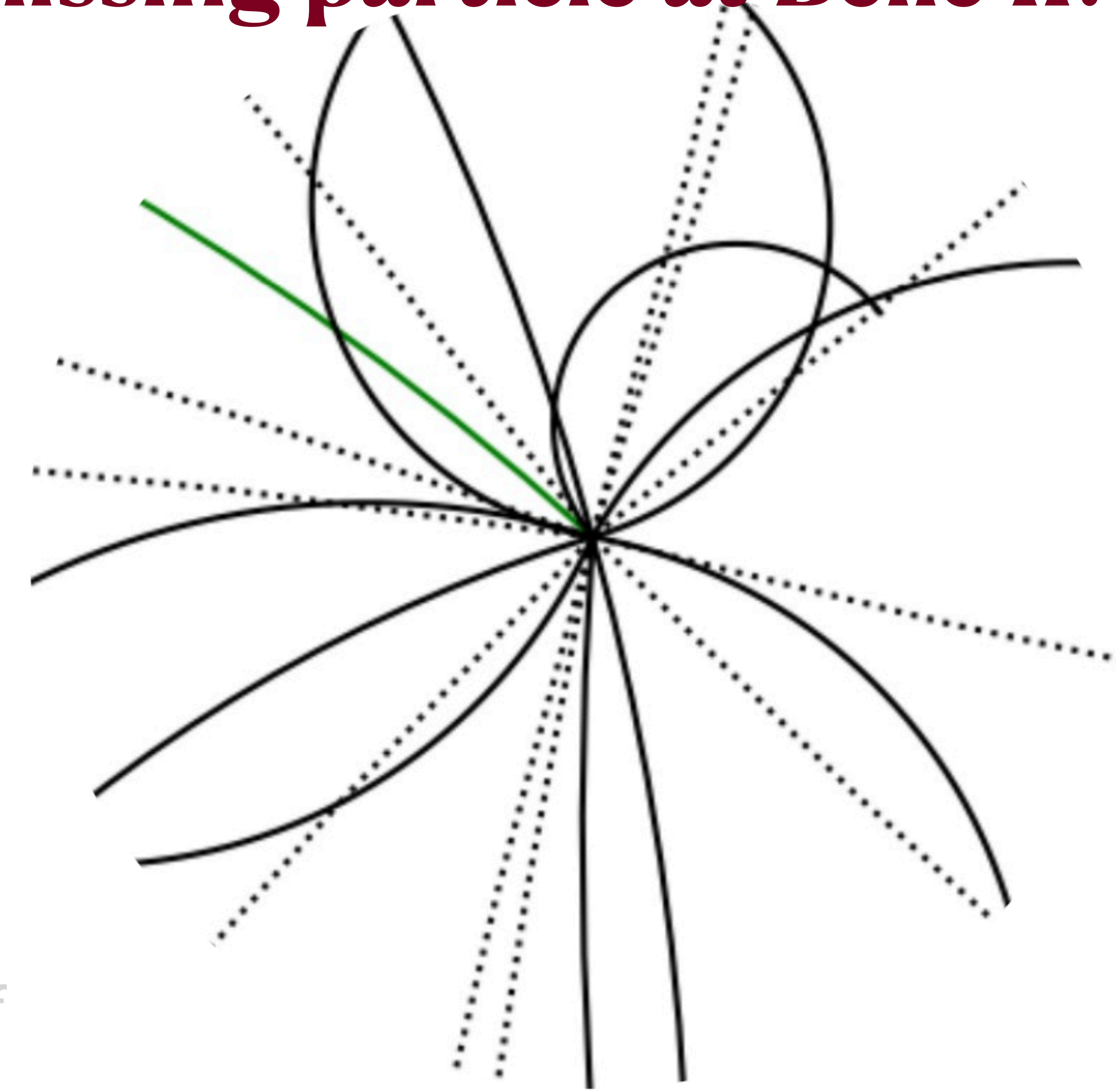
← Purity, Resolution



- Features of HTA
  - uses full decay chain information of of B_{tag}
  - high high purity, very low efficiency
  - uses BDT for signal extraction (BDT_h)
- Features of ITA
  - exploits inclusive properties of B_{tag}
  - high efficiency, low purity
  - BDTs in two stages (BDT_1 mostly for $q\bar{q}$; BDT_2 for final signal extraction)

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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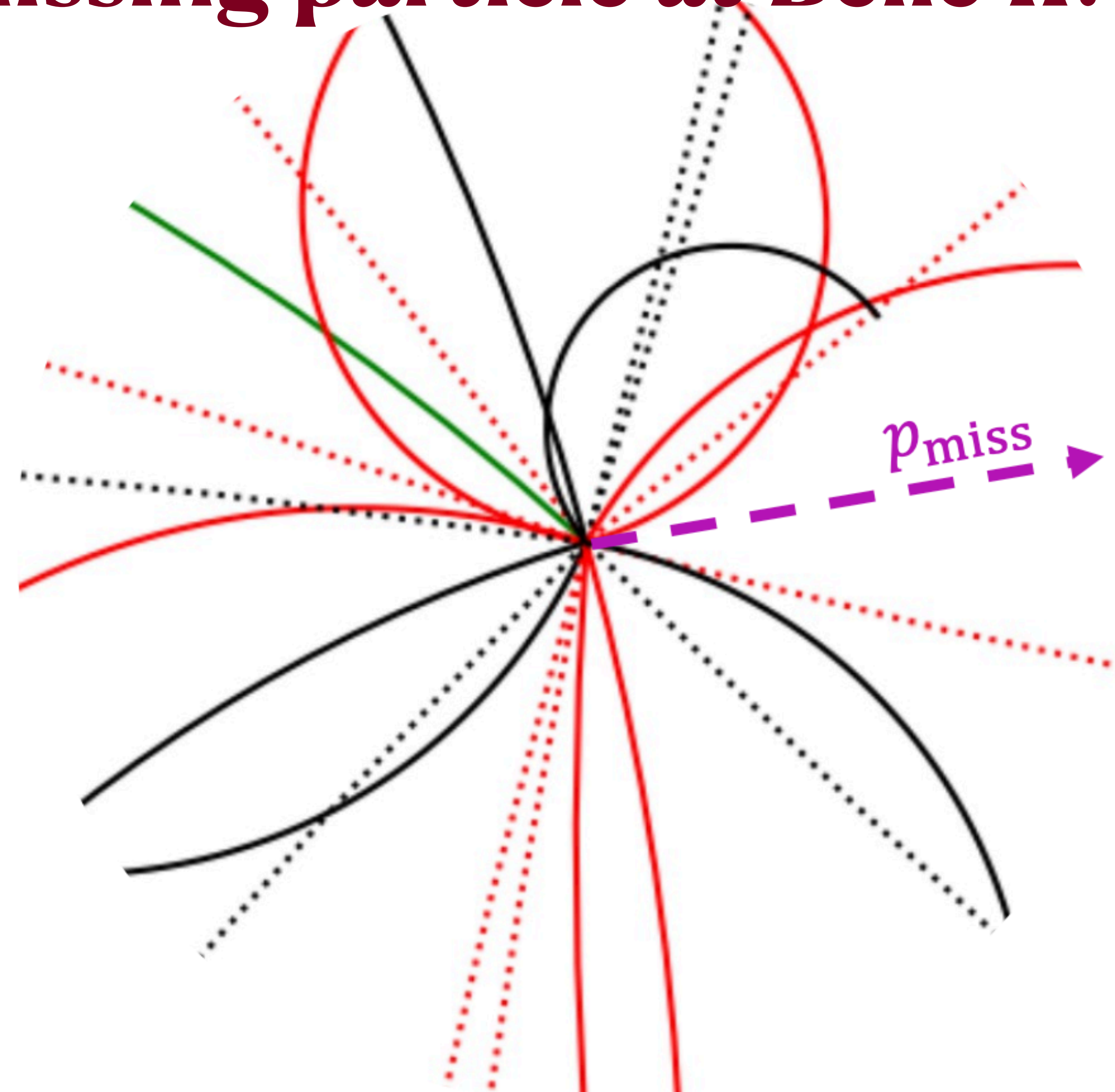
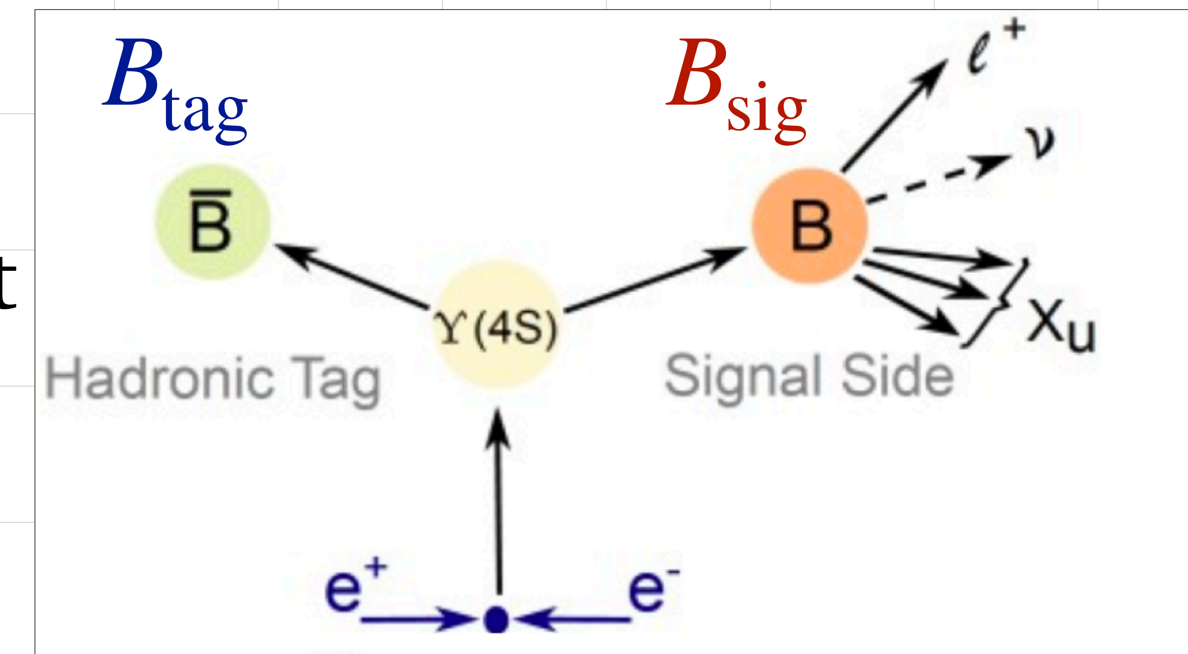
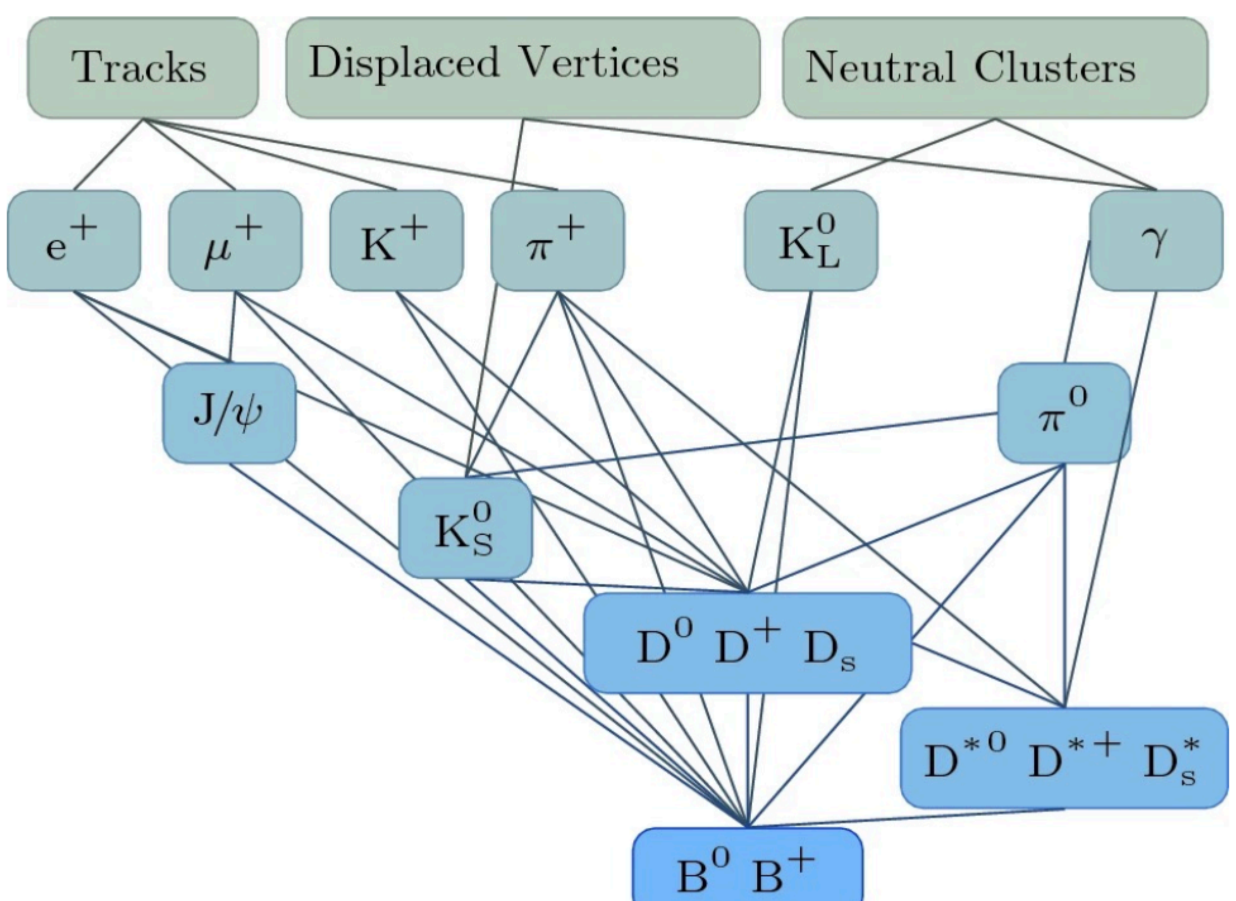


Full Event Interpretation (FEI)

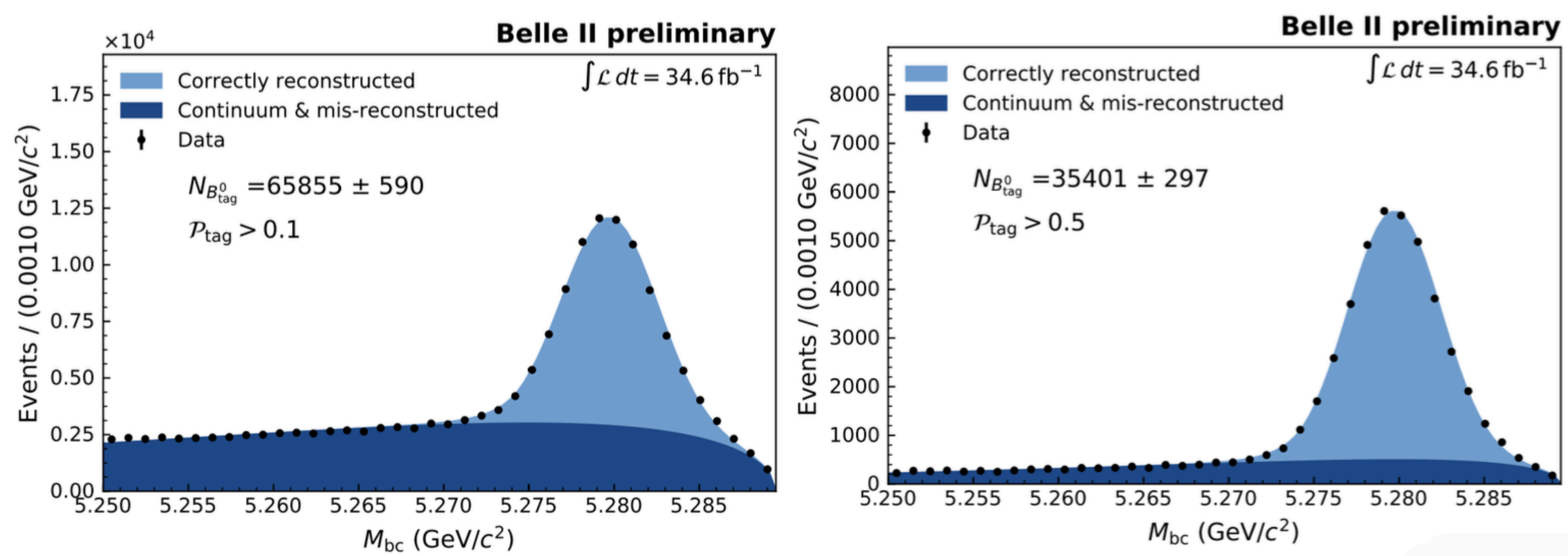
- FEI algorithm to reconstruct B_{tag}
  - uses ~200 BDT's to reconstruct $\mathcal{O}(10^4)$ different B decay chains
  - assign signal probability of being correct B_{tag}



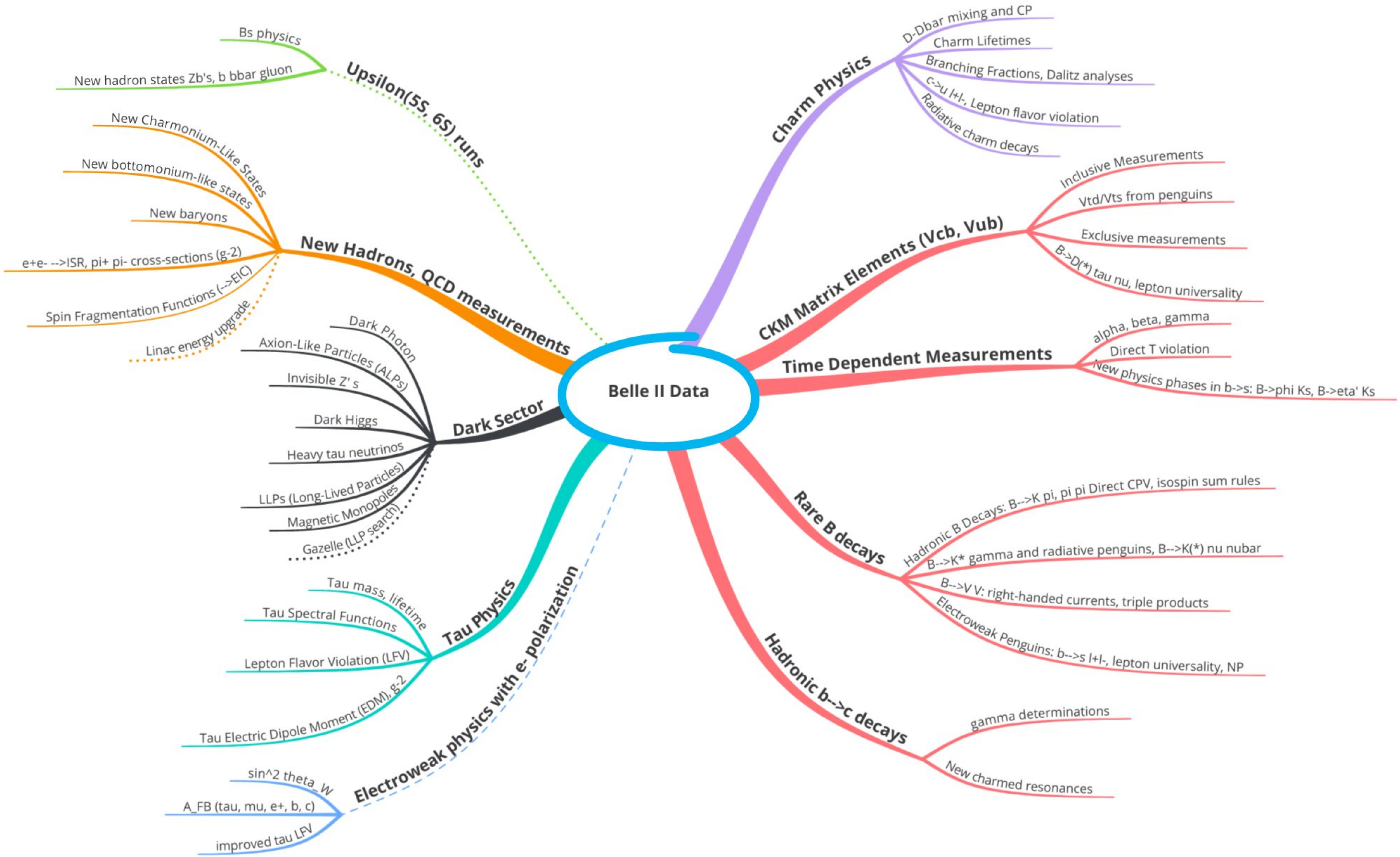
Comput Softw Big Sci 3, 6 (2019)



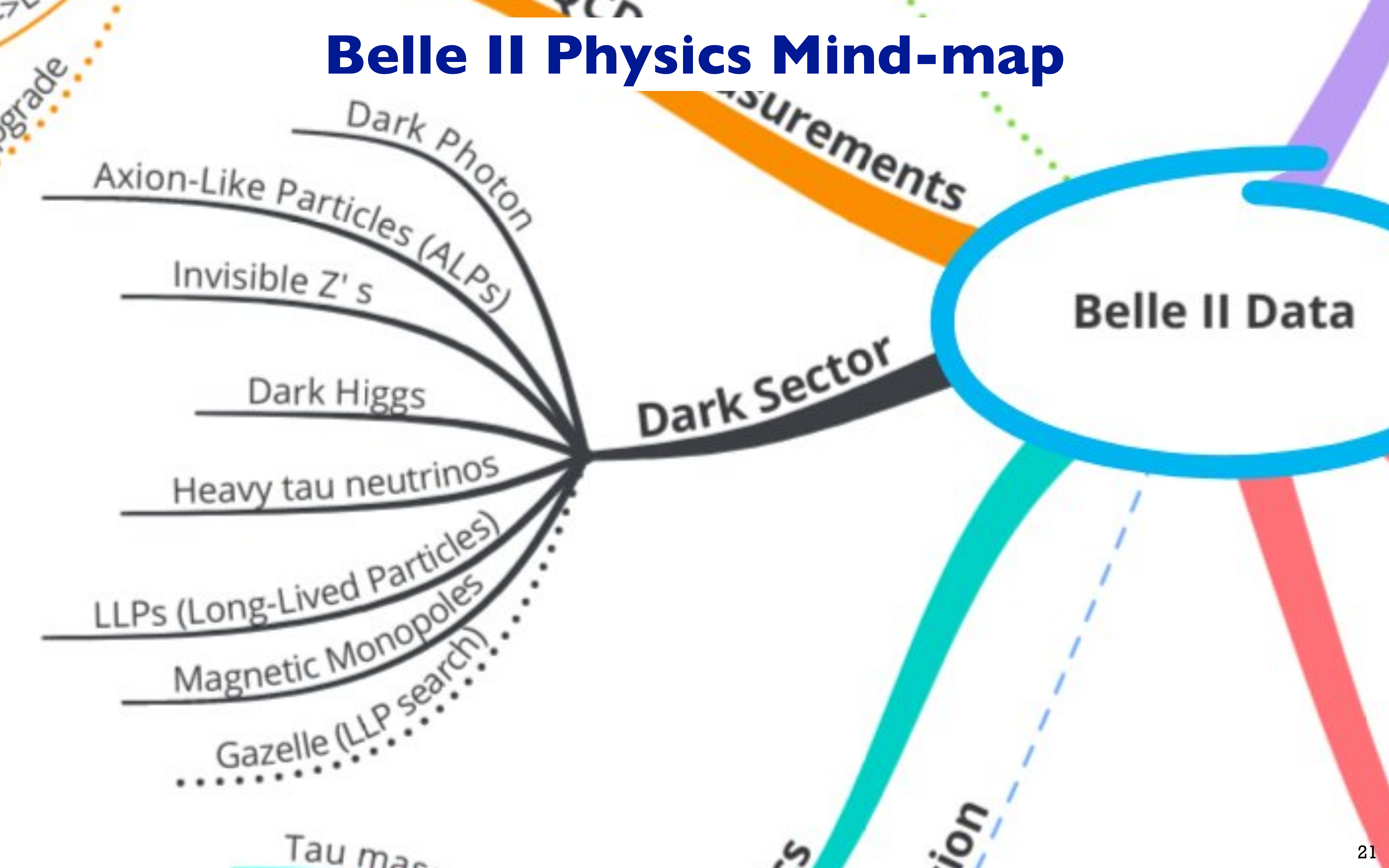
arXiv:2008.060965



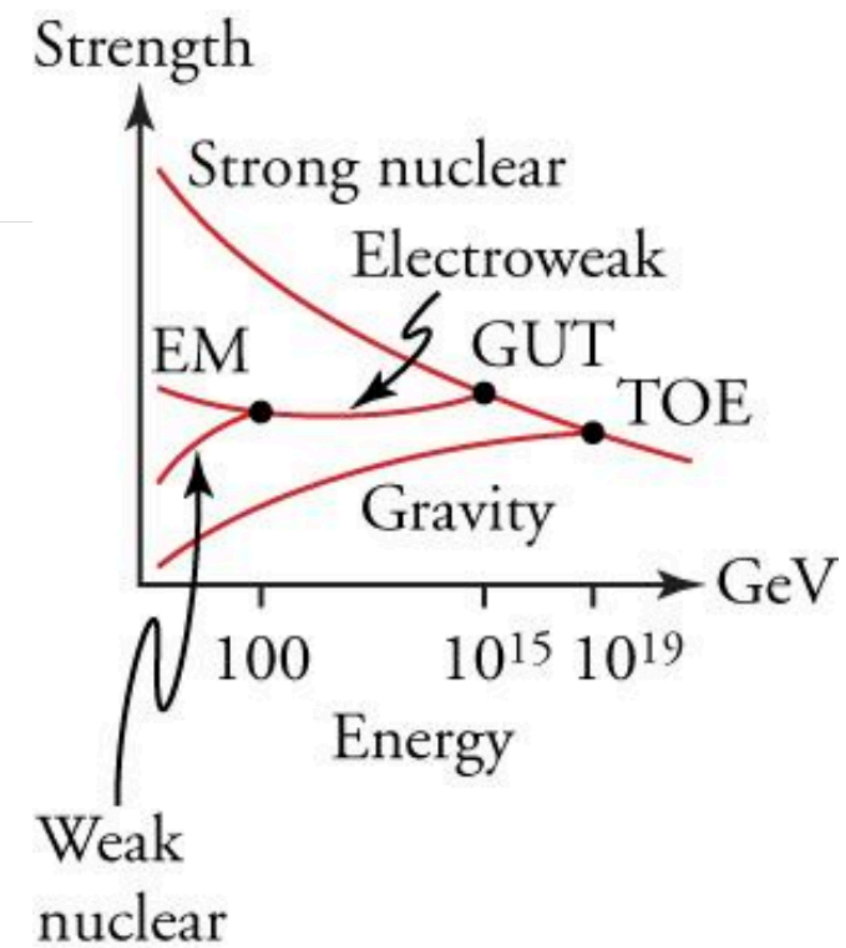
Belle II Physics Mind-map



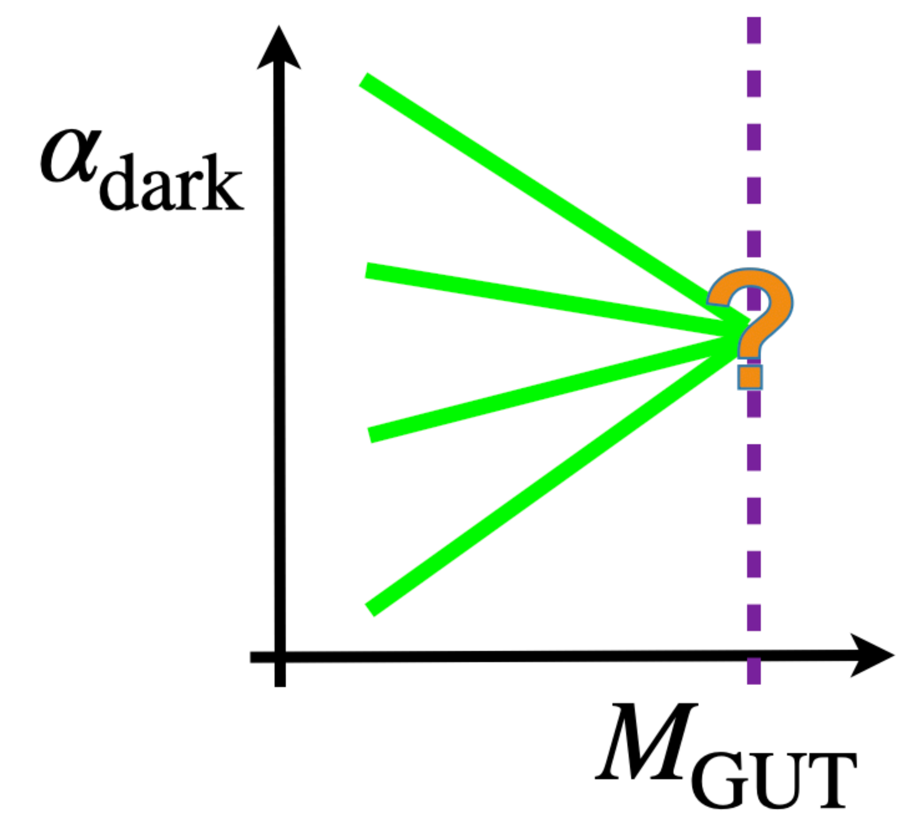
Belle II Physics Mind-map



why Dark World?

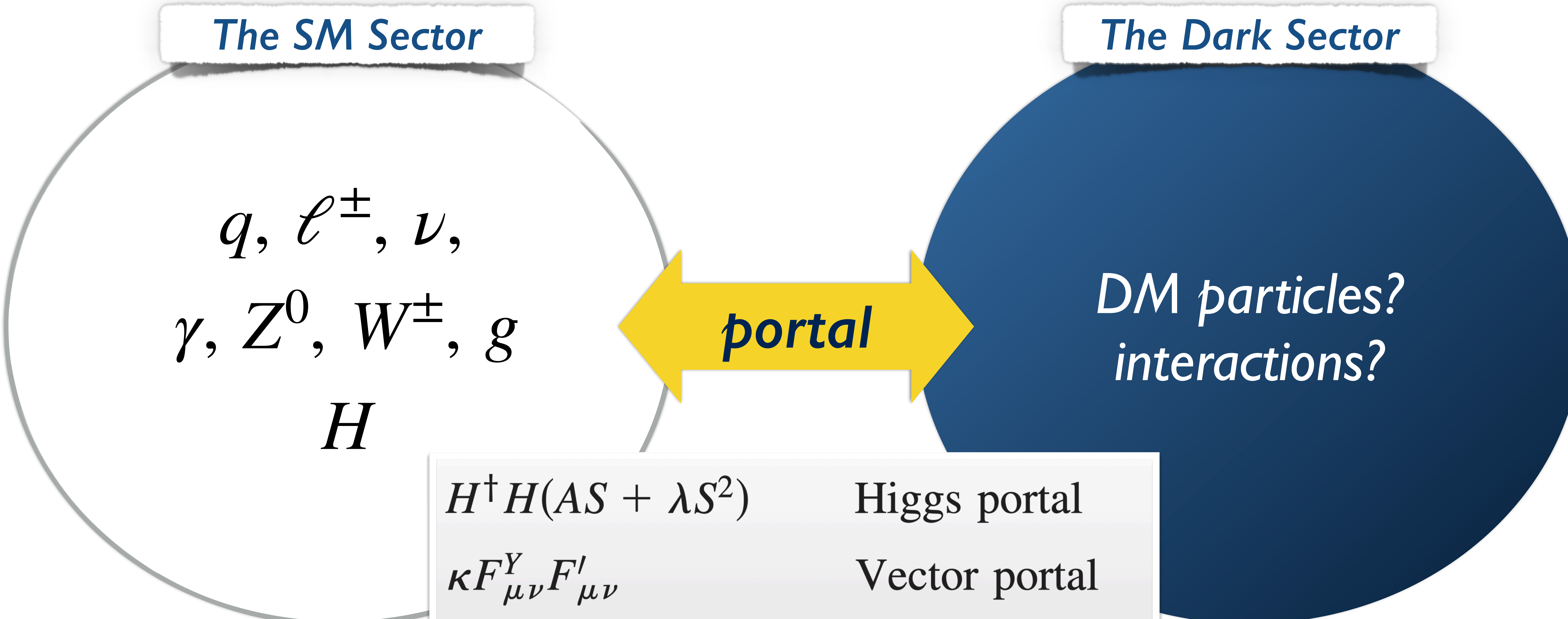


- We don't know anything about the identity/property of dark matter particle(s)
  - Is it just a single particle, or a collection of particles?
- If there are several dark matter particles, wouldn't they interact among themselves via "dark force"?
- Then, this dark force might be mediated (just like EM) by a vector gauge boson, which we may call a "dark photon"?
- Indeed, there might be several kinds of dark gauge bosons (and dark force interactions) just as in the SM sector



The dark sector and connection to SM

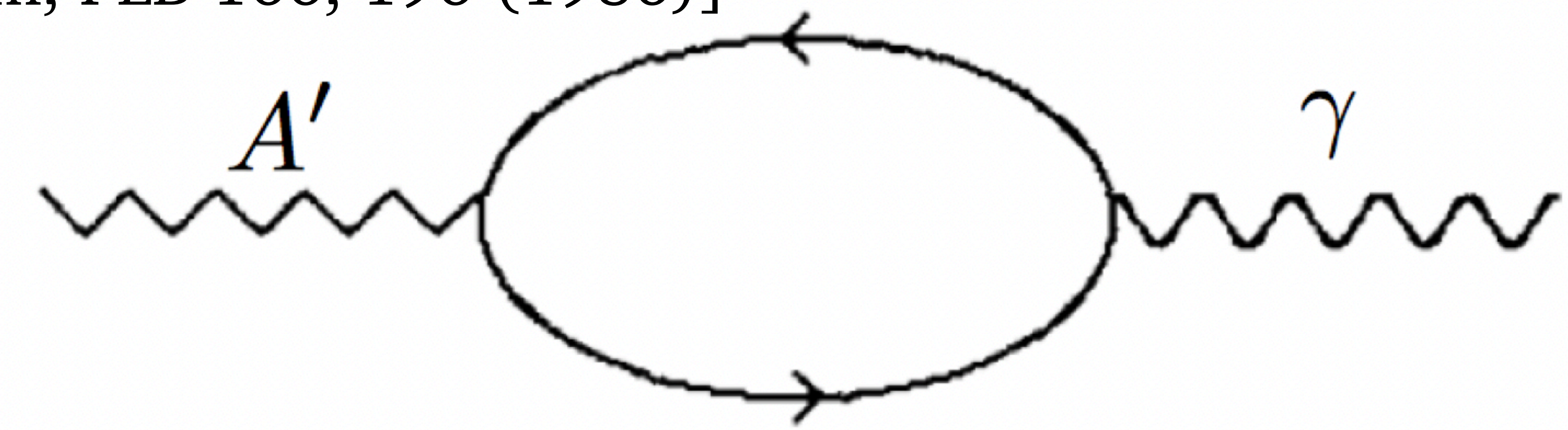
- The dark sector can be connected to SM via the so-called "**portals**".



$H^\dagger H(AS + \lambda S^2)$	Higgs portal
$\kappa F^Y_{\mu\nu} F'_{\mu\nu}$	Vector portal
$Y_N \bar{L} H N$	Neutrino portal
$f_a^{-1} \bar{\psi} \gamma_\mu \gamma_5 \psi \partial_\mu a$	Axion portal

Dark photon & kinetic mixing *- as a portal*

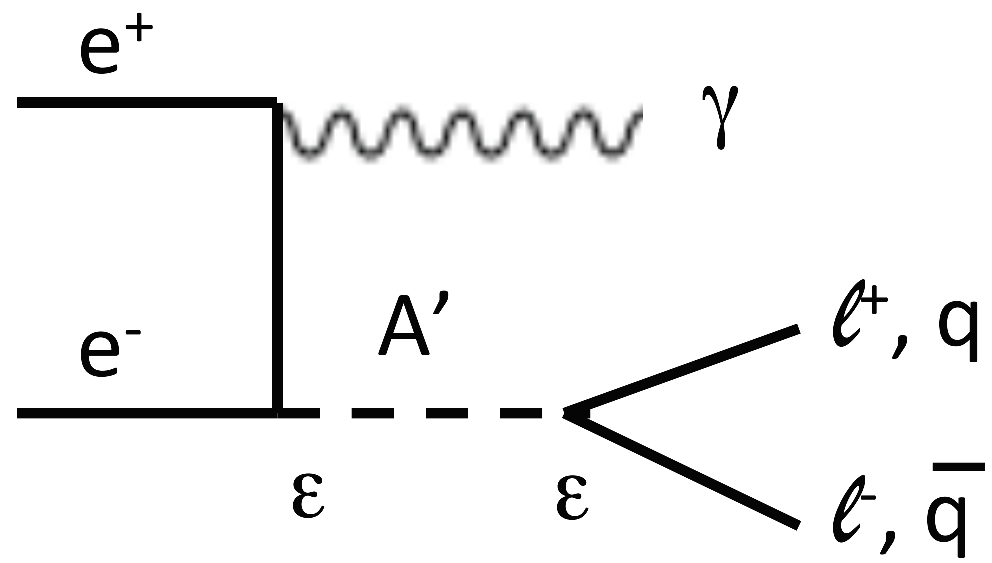
- Dark photon, first proposed in [P. Fayet, PLB 95, 285 (1980)]
- A boson A' belonging to an additional $U(1)'$ would mix kinetically with γ [B. Holdom, PLB 166, 196 (1986)]

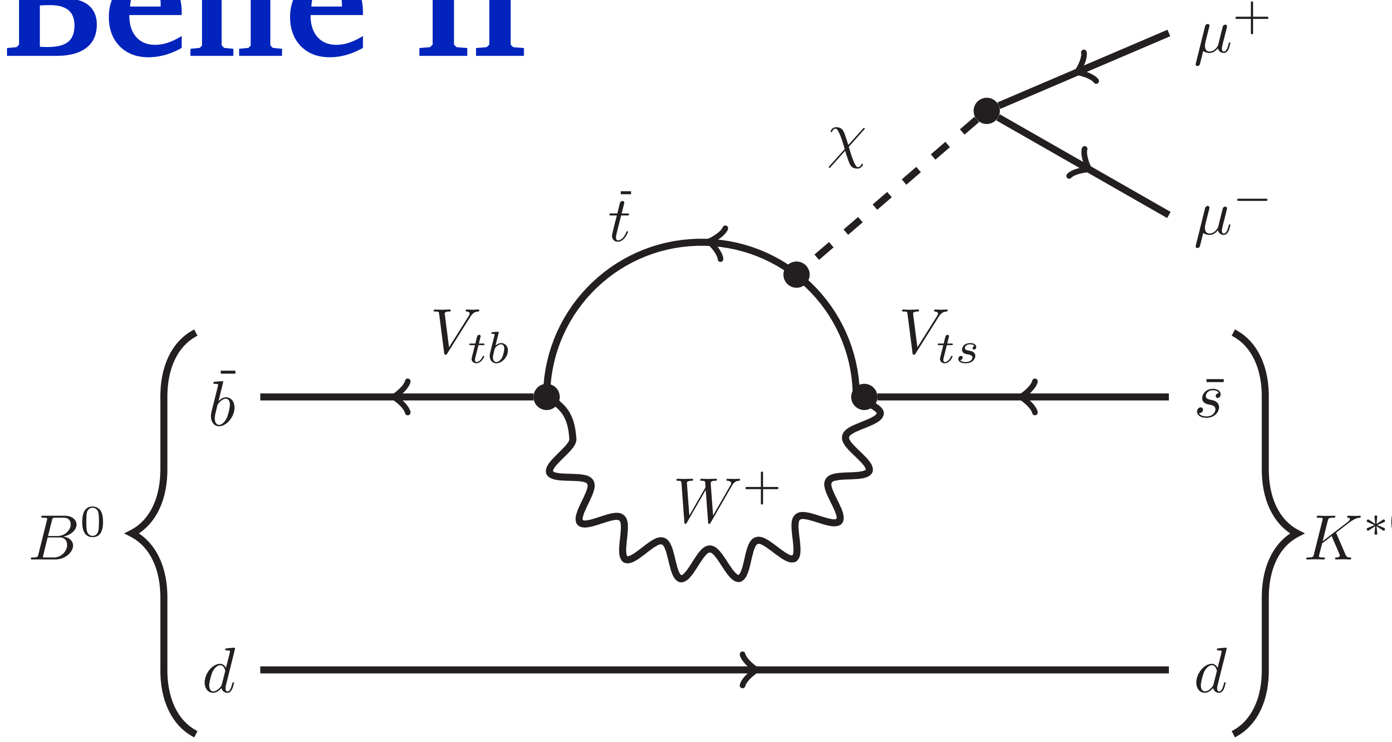


  - in general, one can express kinetic mixing as $(1/2)\epsilon F_{\mu\nu}F'^{\mu\nu}$
  - ϵ, the strength of the kinetic mixing, is supposed to be small

- For A' to acquire mass, an extended Higgs sector is required to spontaneously break this $U(1)'$

Where to look for DS in Belle II

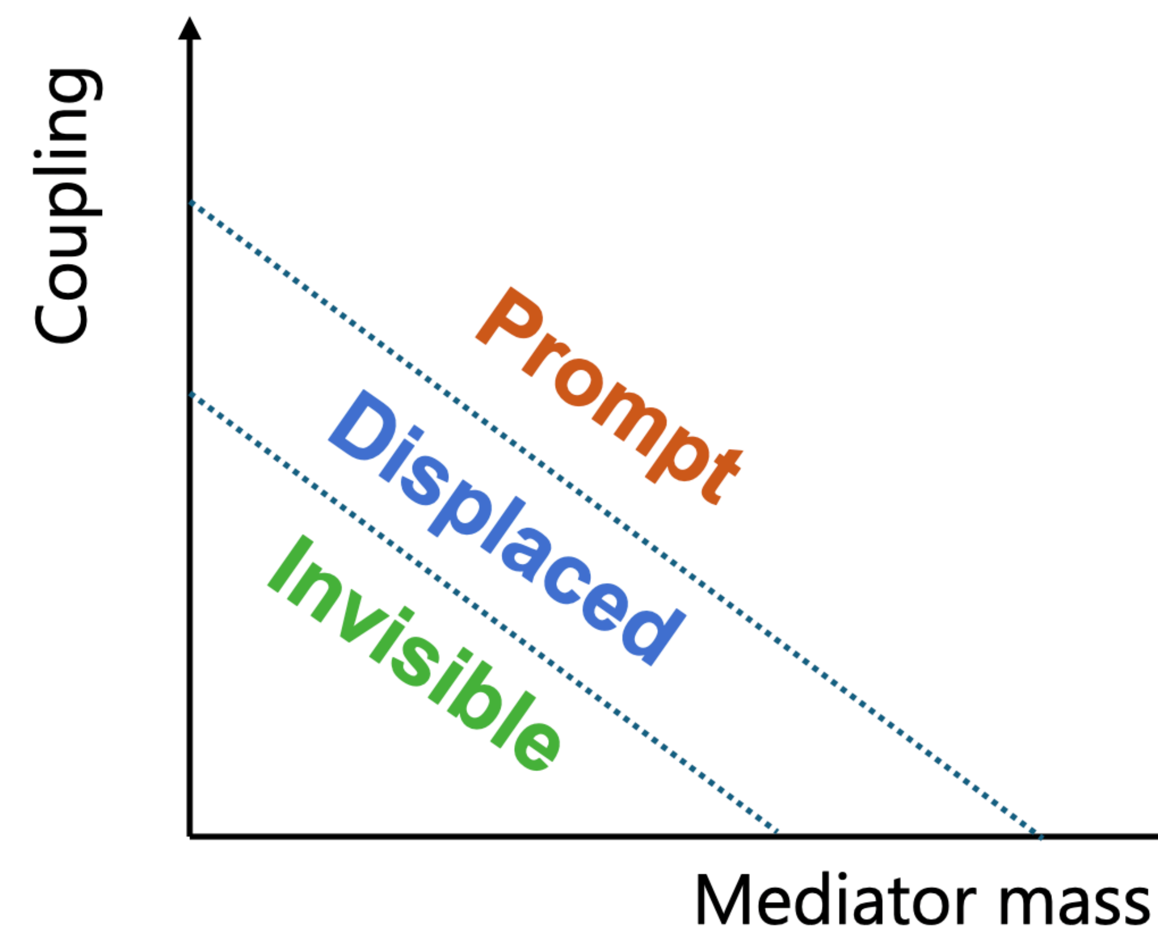




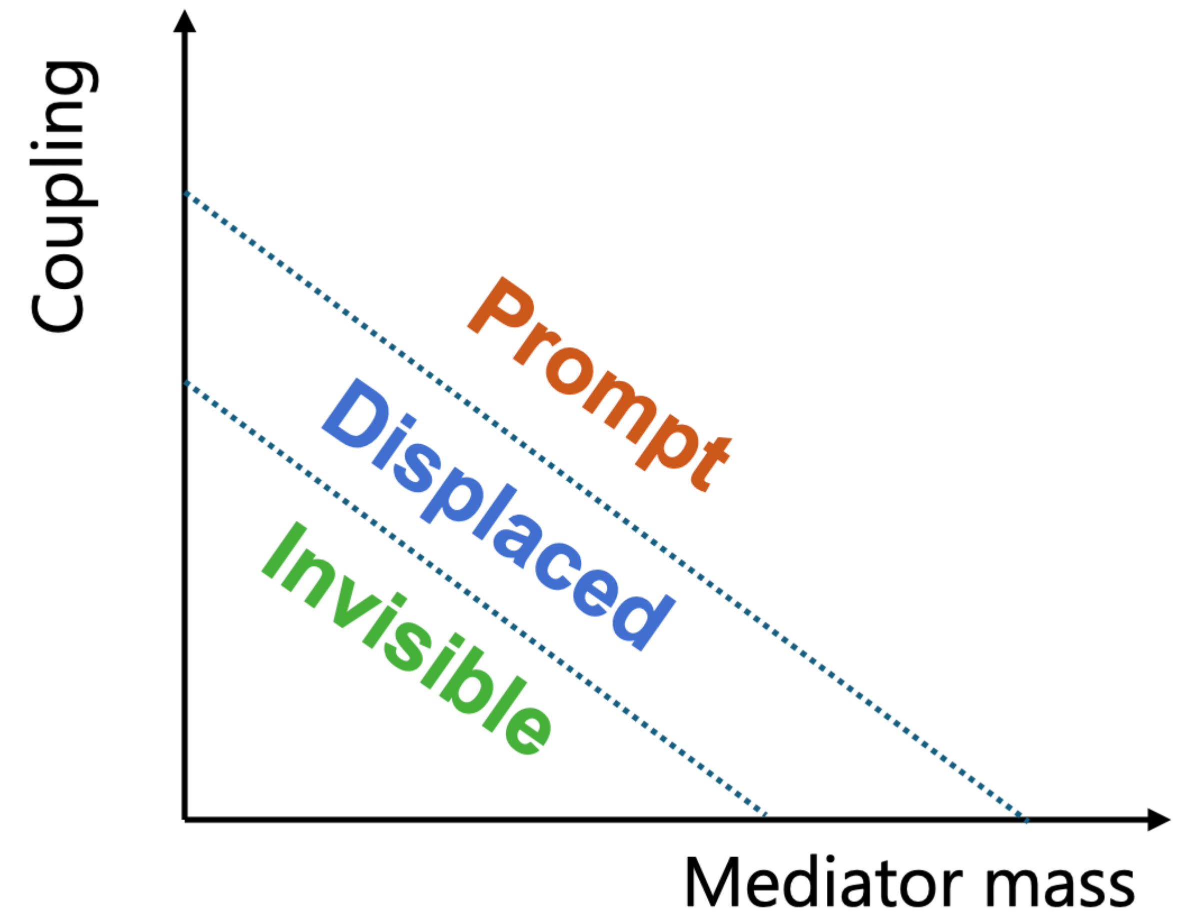
ISR

B decays

- Final-state features
  - depend on many model parameters
  - visible prompt decays to SM particles
  - invisible decays shown as missing $(E, \vec{p})$
    - decays to DM particles or very weak couplings
  - displaced vertices
    - long lifetime, weaker couplings



how to look for DS in Belle II

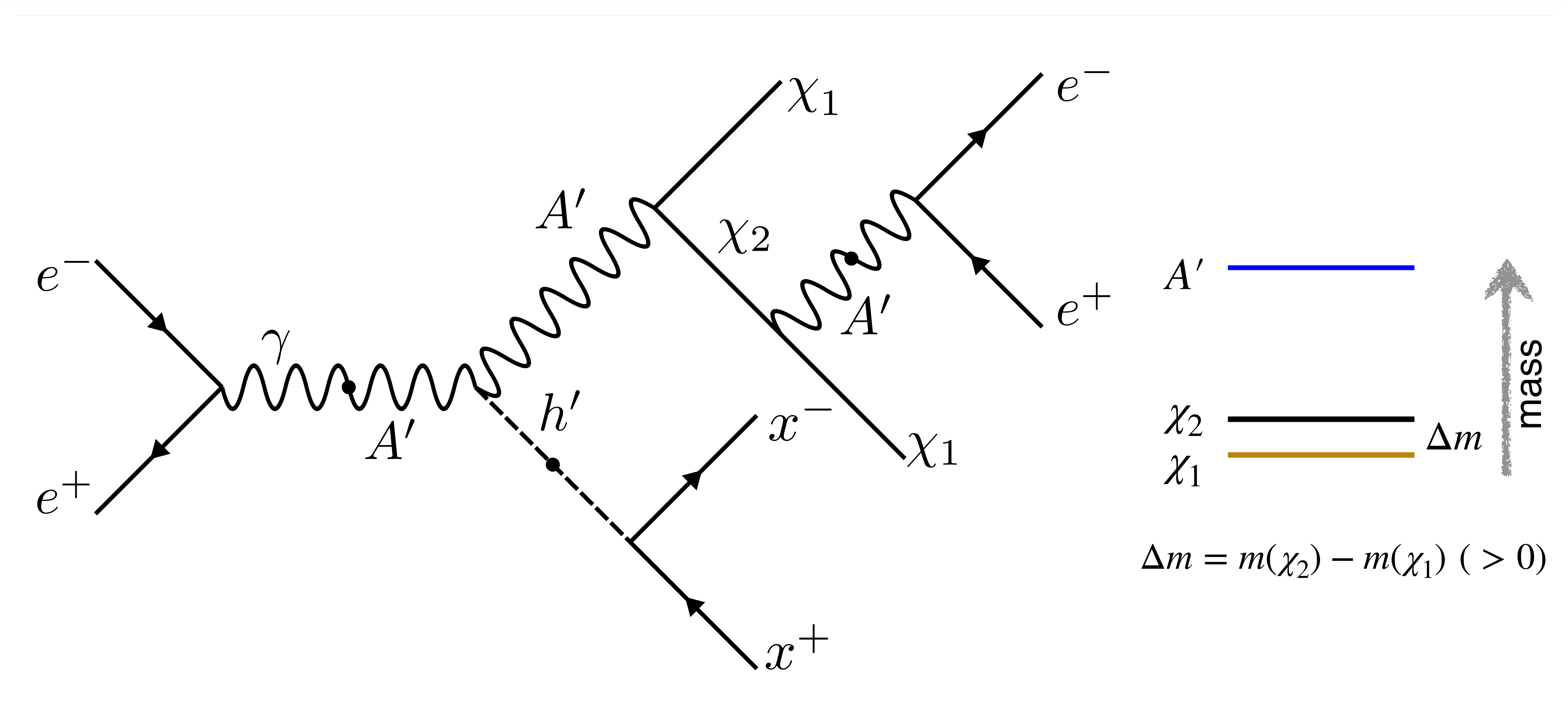


- For invisible final states
  - use missing $(E, \vec{p})$ — we are NOT testing the energy-momentum conservation
- For visible final states

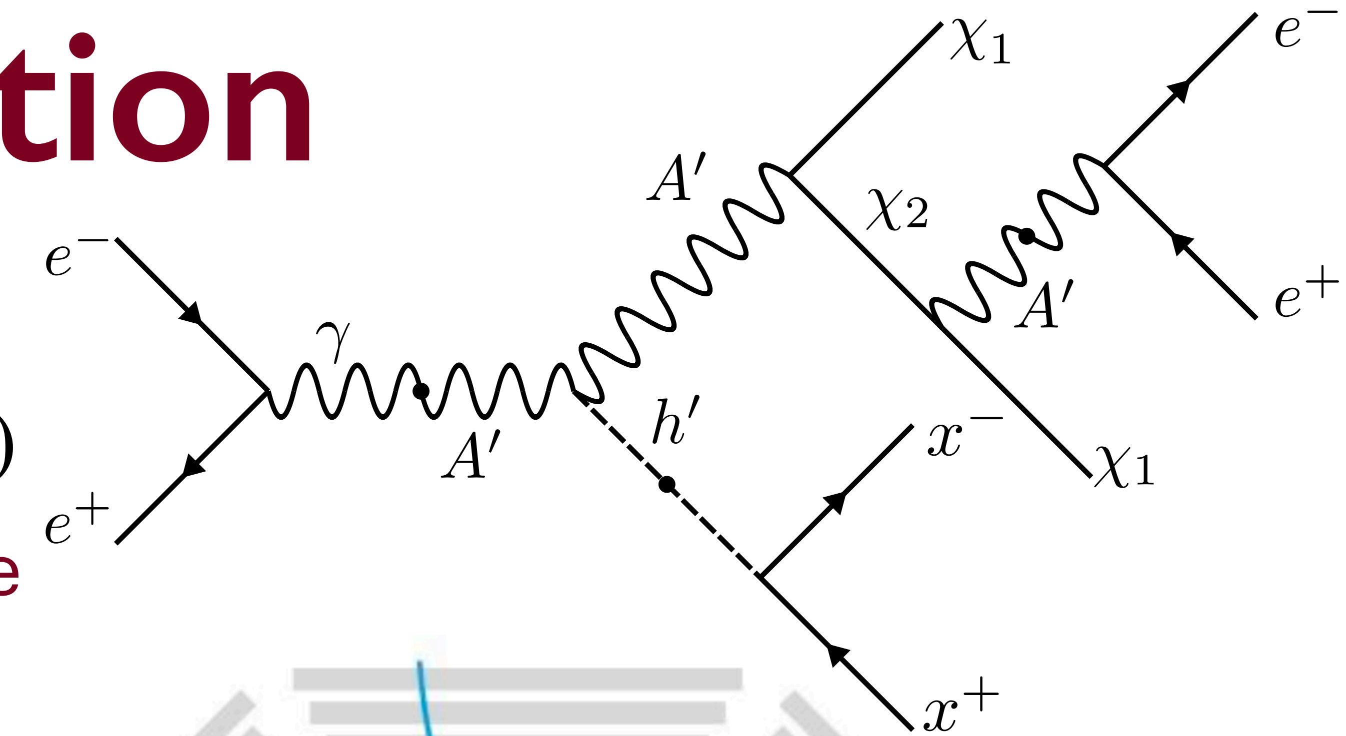
  (Q) how to distinguish it from SM particles?

  - search for resonant and/or kinematic features (e.g. displaced vertex) unknown in the SM

Dark Higgs in association with Inelastic DM

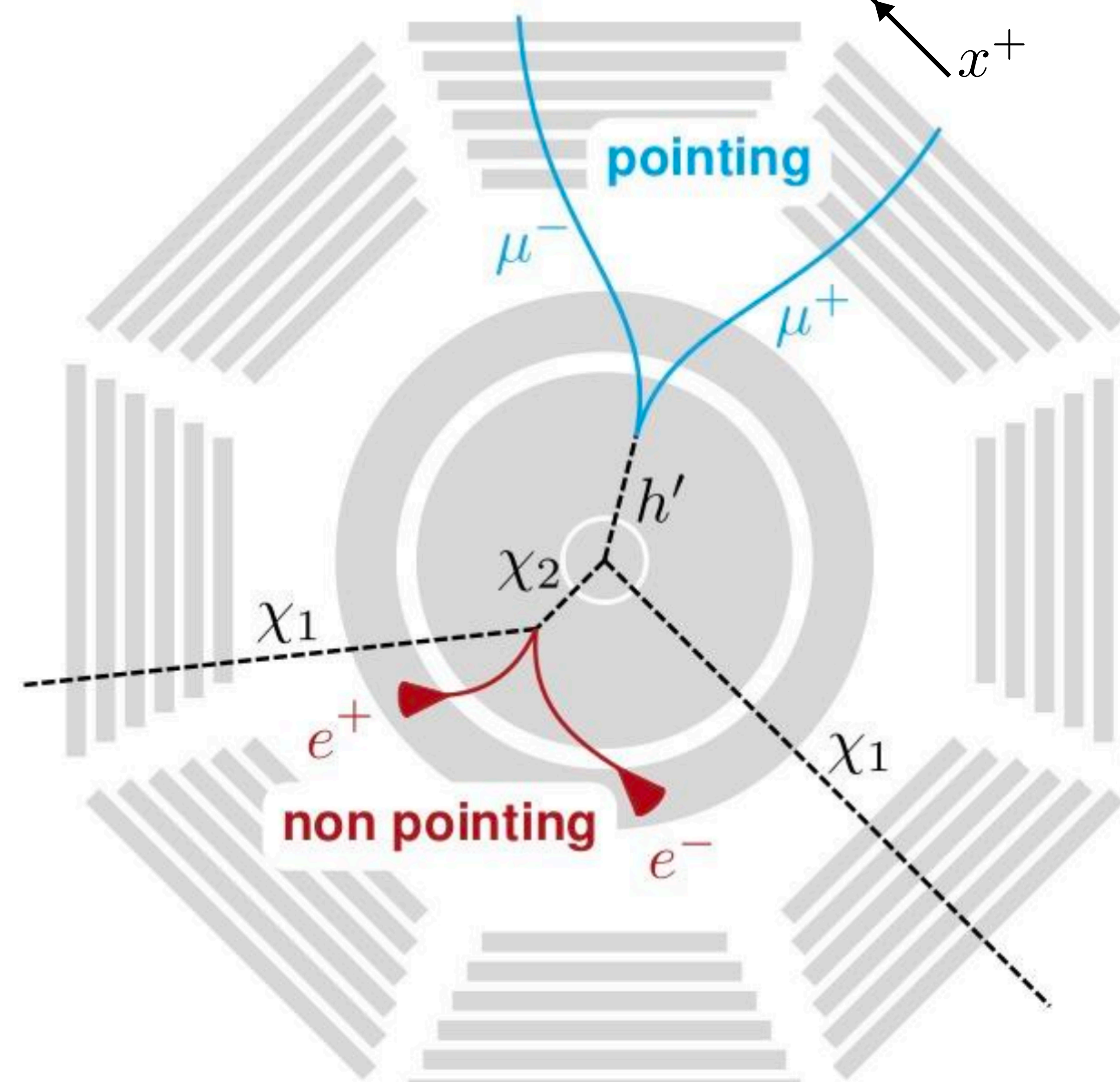


Inelastic DM, Introduction



- Dark sector with dark higgs h', dark photon A'
  - DM particles χ_2, χ_1 with $\Delta m = m(\chi_2) - m(\chi_1)$ (> 0)
  - χ_1 (lightest DS particle) — stable & relic DM candidate
  - Focus on $m(A') > m(\chi_2) + m(\chi_1)$ for $A' \to \chi_1\chi_2$

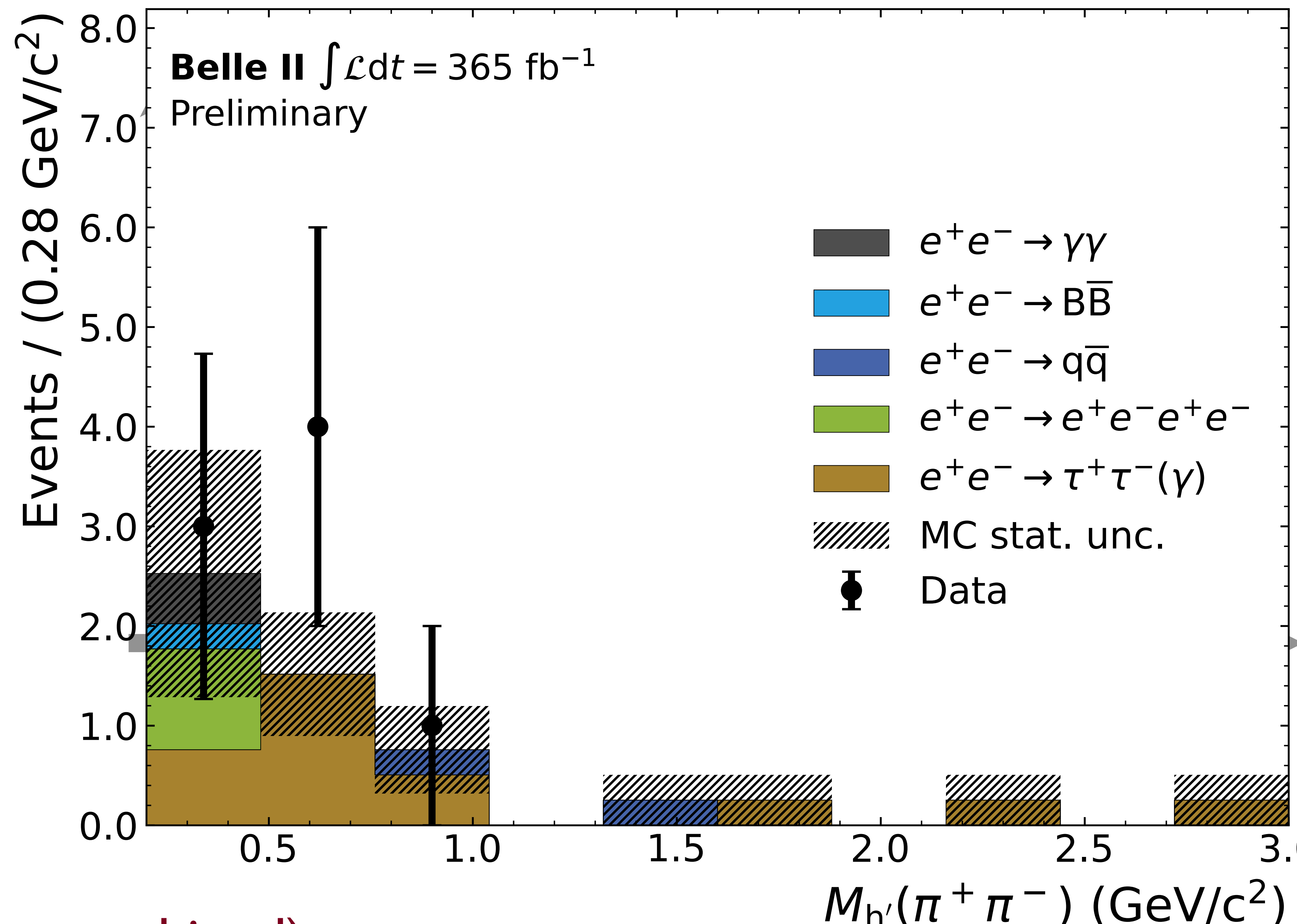
- Experimental Signature
  - challenging for tracking (displaced), trigger
  - Four tracks in the final state
  - (up to) two displaced vertices
    - ✓ $h' \to x^+x^-$ $(x = \mu, \pi, K)$ **"pointing"**
    - ✓ $\chi_2 \to \chi_1 A'(\to e^+e^-)$ **"non-pointing"**
  - missing energy due to stable χ_1
  - very small SM background ("smoking gun")



adapted from Duerr, Ferber et al, JHEP04 (2021) 146

Dark higgs, Results

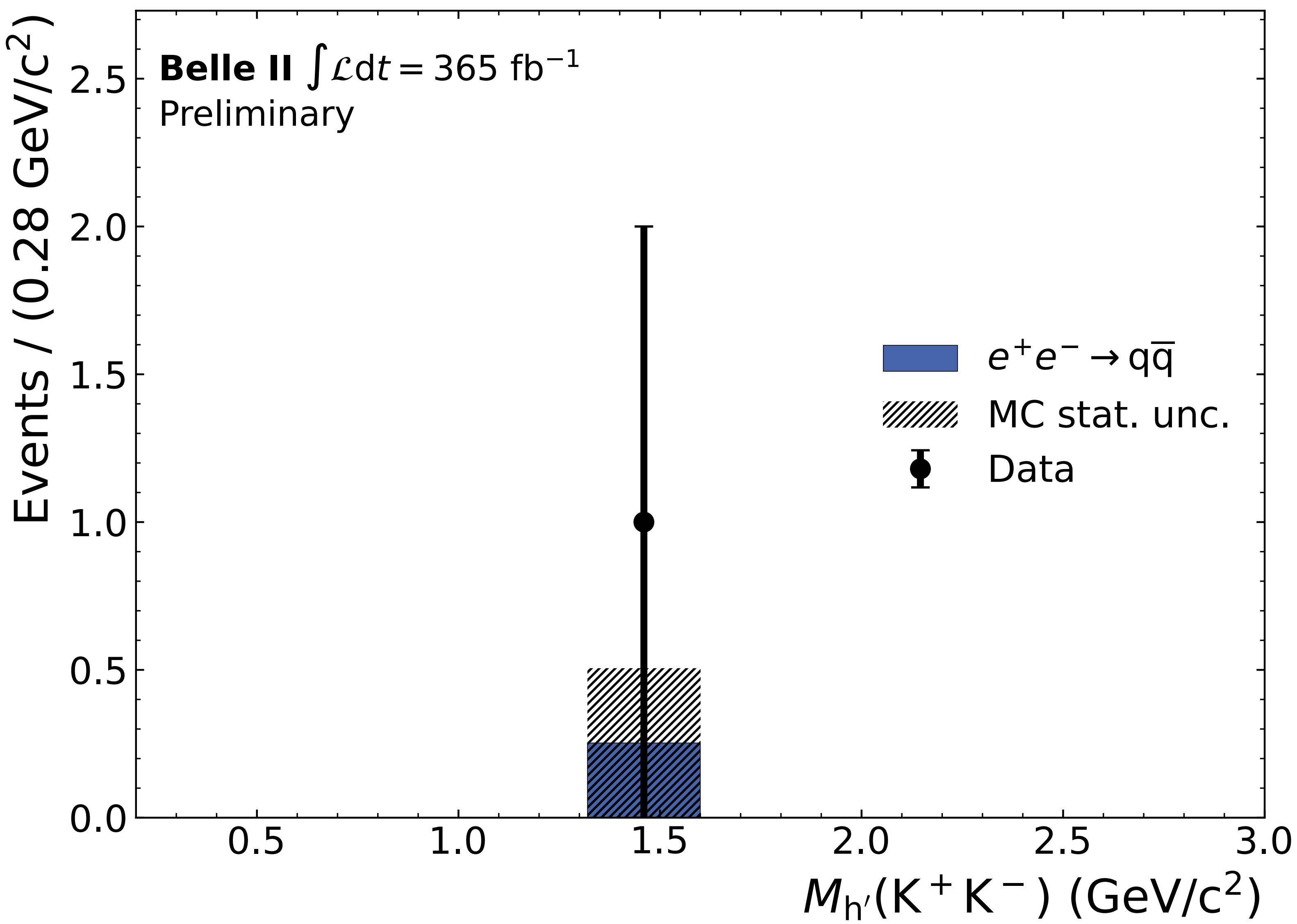
- Signal extraction procedure
  - cut-and-count for signal extraction
    - ✓ count events in narrow window of $M(x^+x^-)$
  - Background estimation using data sideband in $M(x^+x^-)$, not to rely on MC
    - ✓ full mass range for $\mu^+\mu^-$ and K^+K^-
    - ✓ for $\pi^+\pi^-$, split the mass region at 1 GeV

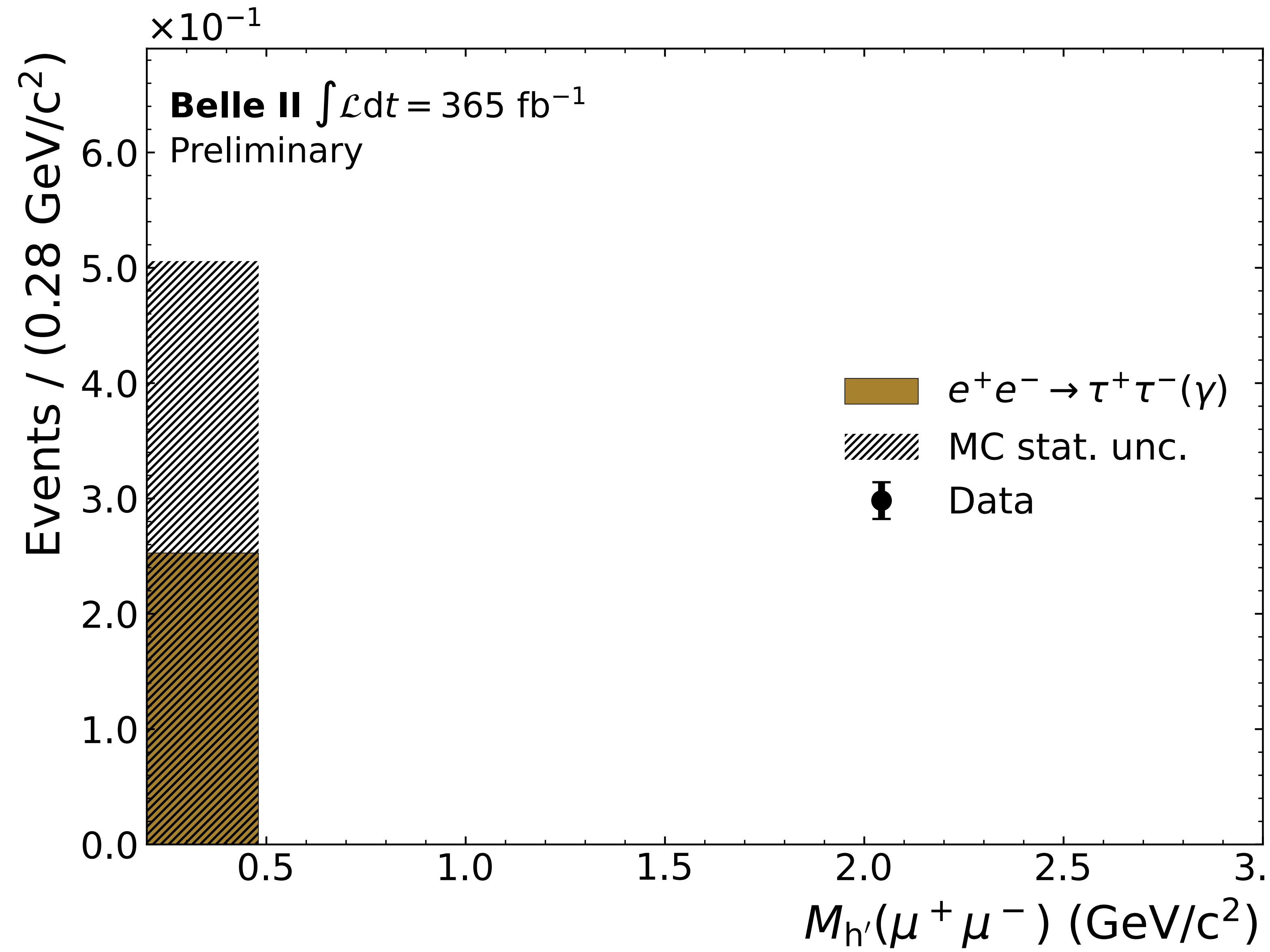


- No significant excess in any mode (or combined)
  - 8 event in $\pi^+\pi^-$ (consistent with background)
    - ✓ largest local significance of 2.9σ (1.1σ global) at $m(h') = 0.531$ GeV

Dark higgs, Results

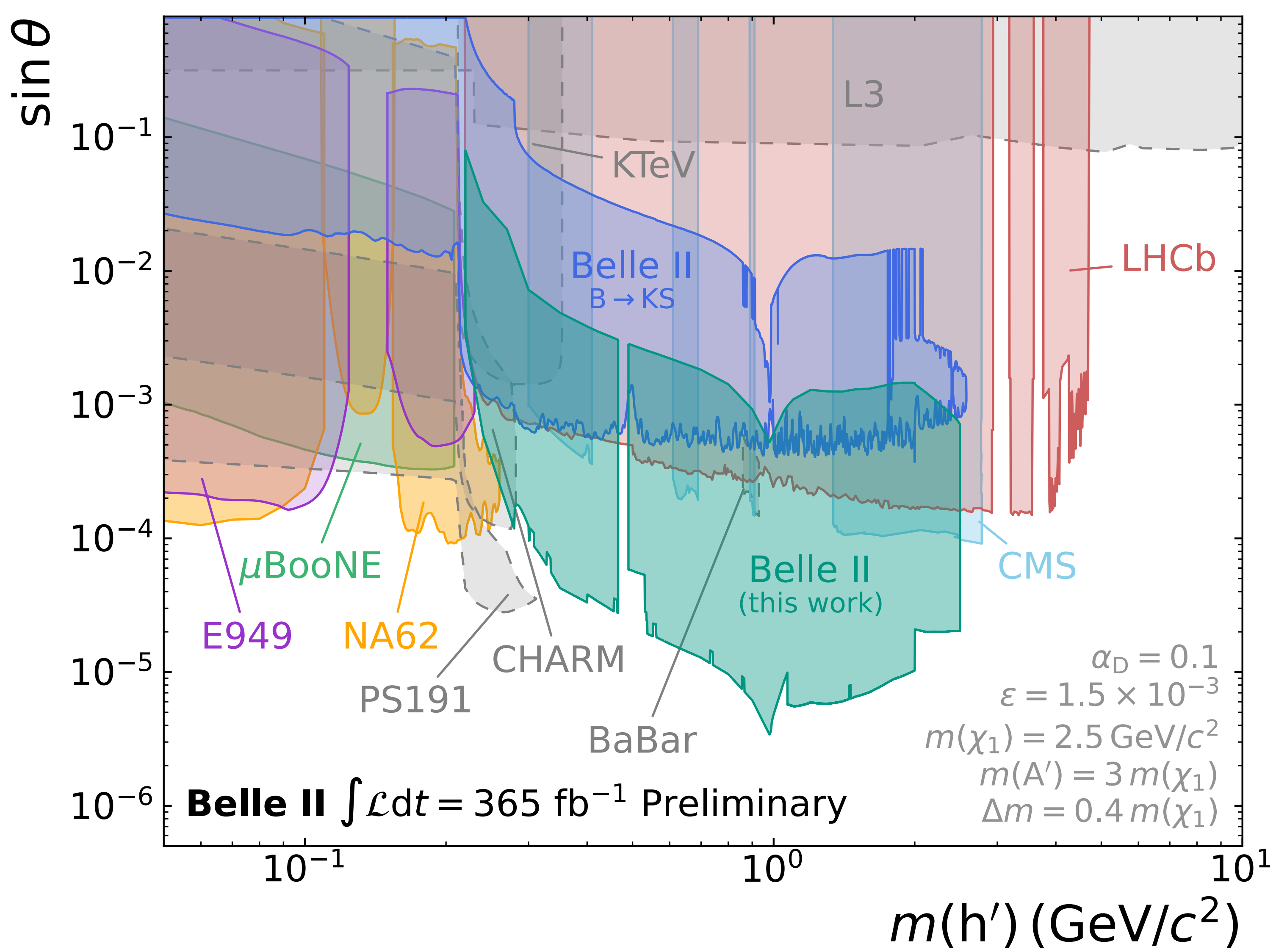
- No significant excess in any mode (or combined)
  - 8 event in $\pi^+\pi^-$ (consistent with background)
  - 1 event in K^+K^-, 0 event in $\mu^+\mu^-$

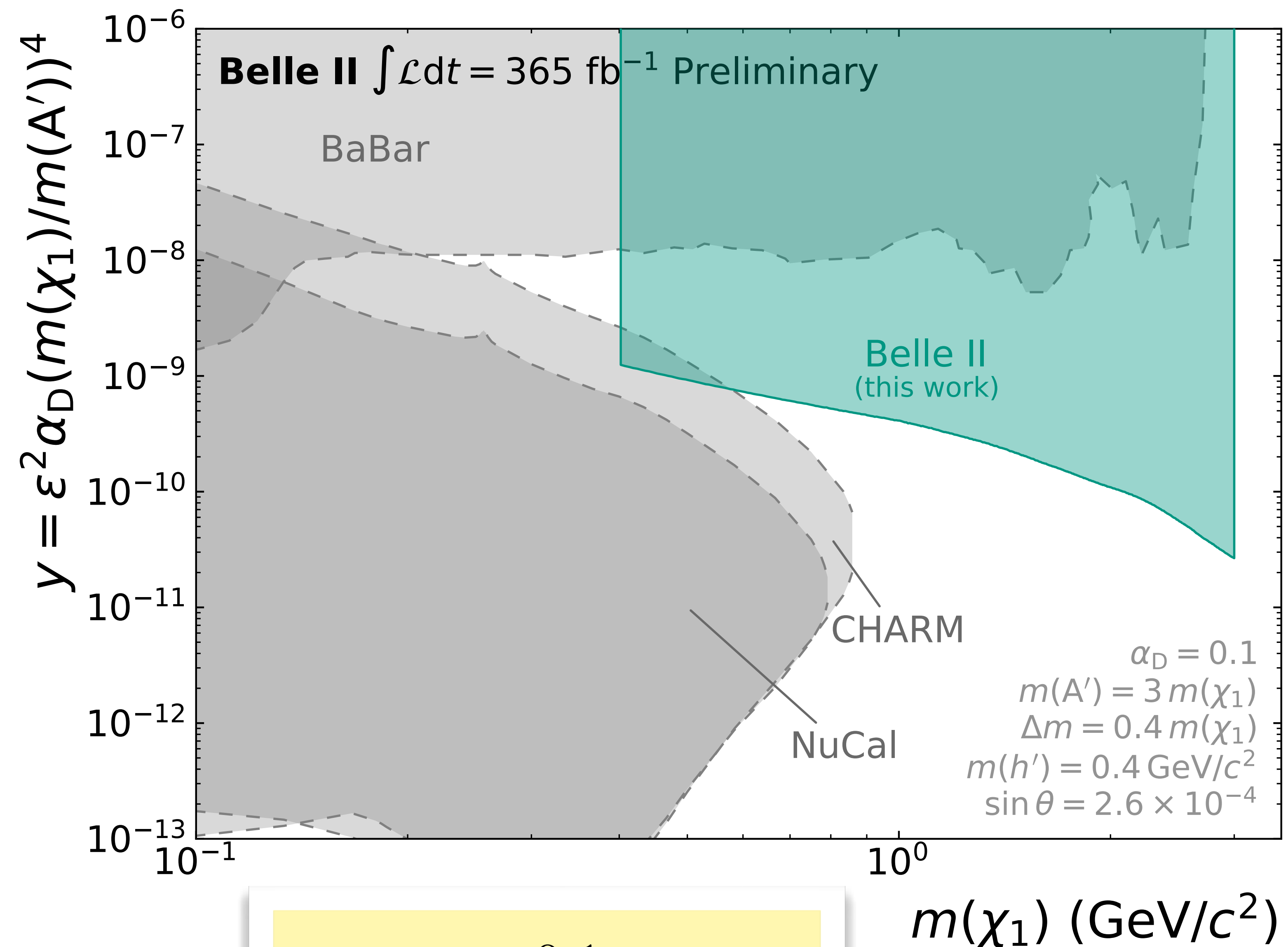




Editors' Suggestion PRL 135, 131801 (2025)

Inelastic DM, Results





- Model-dependent limits on the coupling strengths and parameters
  - shown here for a specific choice
  - many more plots (~30), for different parameter sets
  - (Right plot) non-Belle II limits do not assume h', so less model-dependent

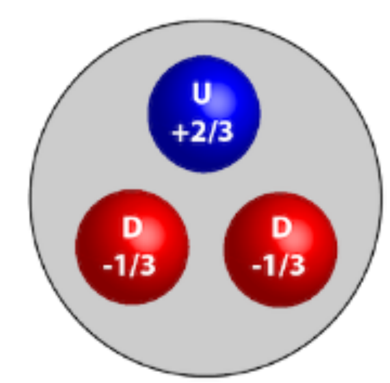
$$\alpha_D = 0.1$$
$$\varepsilon = 1.5 \times 10^{-3}$$
$$m(\chi_1) = 2.5\ \mathrm{GeV}$$
$$m(A') = 3m(\chi_1)$$
$$\Delta m = 0.4m(\chi_1)$$
$$\sin\theta = 2.6 \times 10^{-4}$$

See Appendix for meaning of the parameters

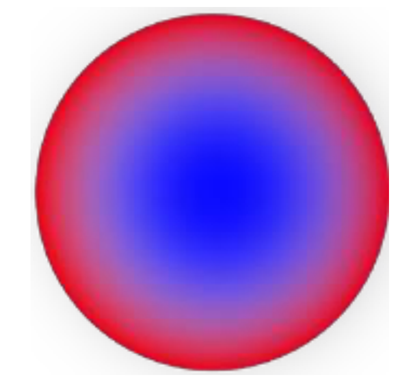
Axion-like particle (ALP)

- **Axion as solution to Strong CP problem**
  - Peccei-Quinn mechanism (1977)
  - QCD axion: $m_a^2 f_a^2 \sim m_\pi^2 f_\pi^2$ (cf. ALP)
- **Cosmological implication**
  - Accounting for dark matter (1983)
  - or, can be a portal to dark sector
- **Detection principle**
  - Sikivie effect (1983)

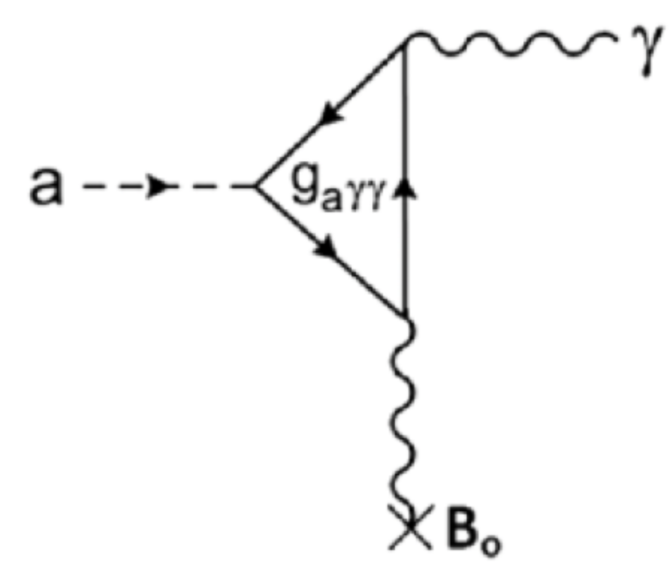
Absence of n-EDM

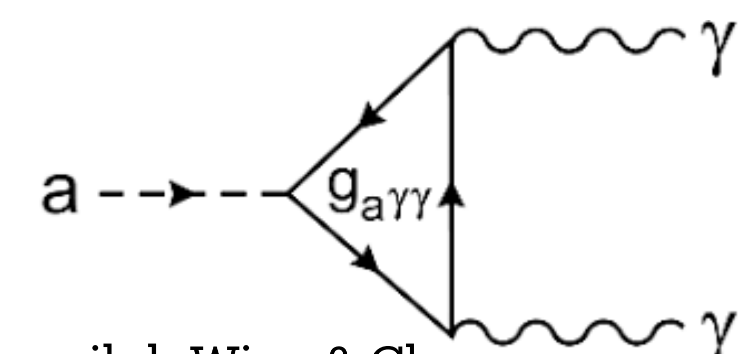


vs.



$$L_{QCD} \ni \theta \frac{\alpha_s}{32\pi} G\tilde{G} \Rightarrow \left[\theta - \frac{a(x)}{f_a}\right] \frac{\alpha_s}{32\pi} G\tilde{G}$$

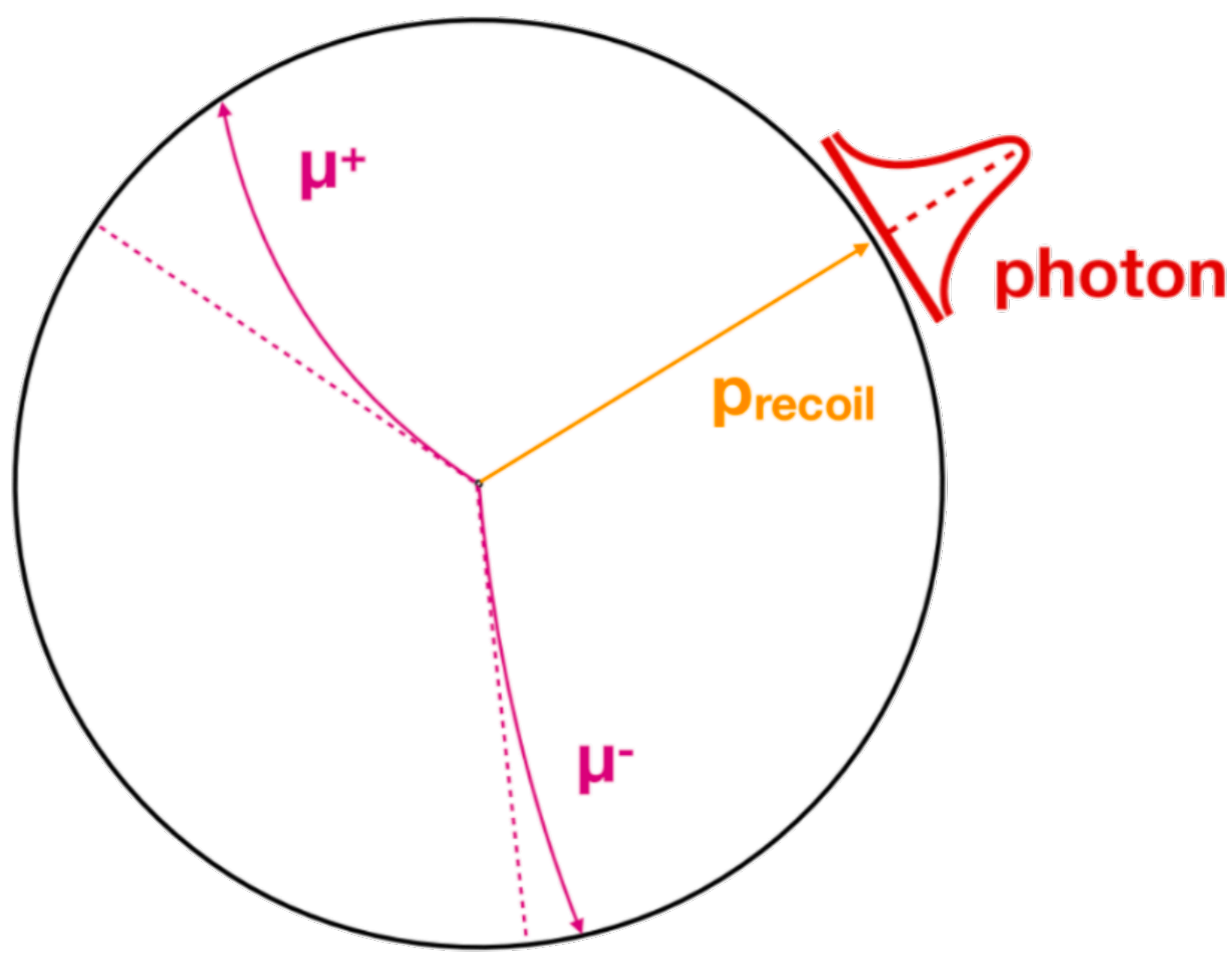


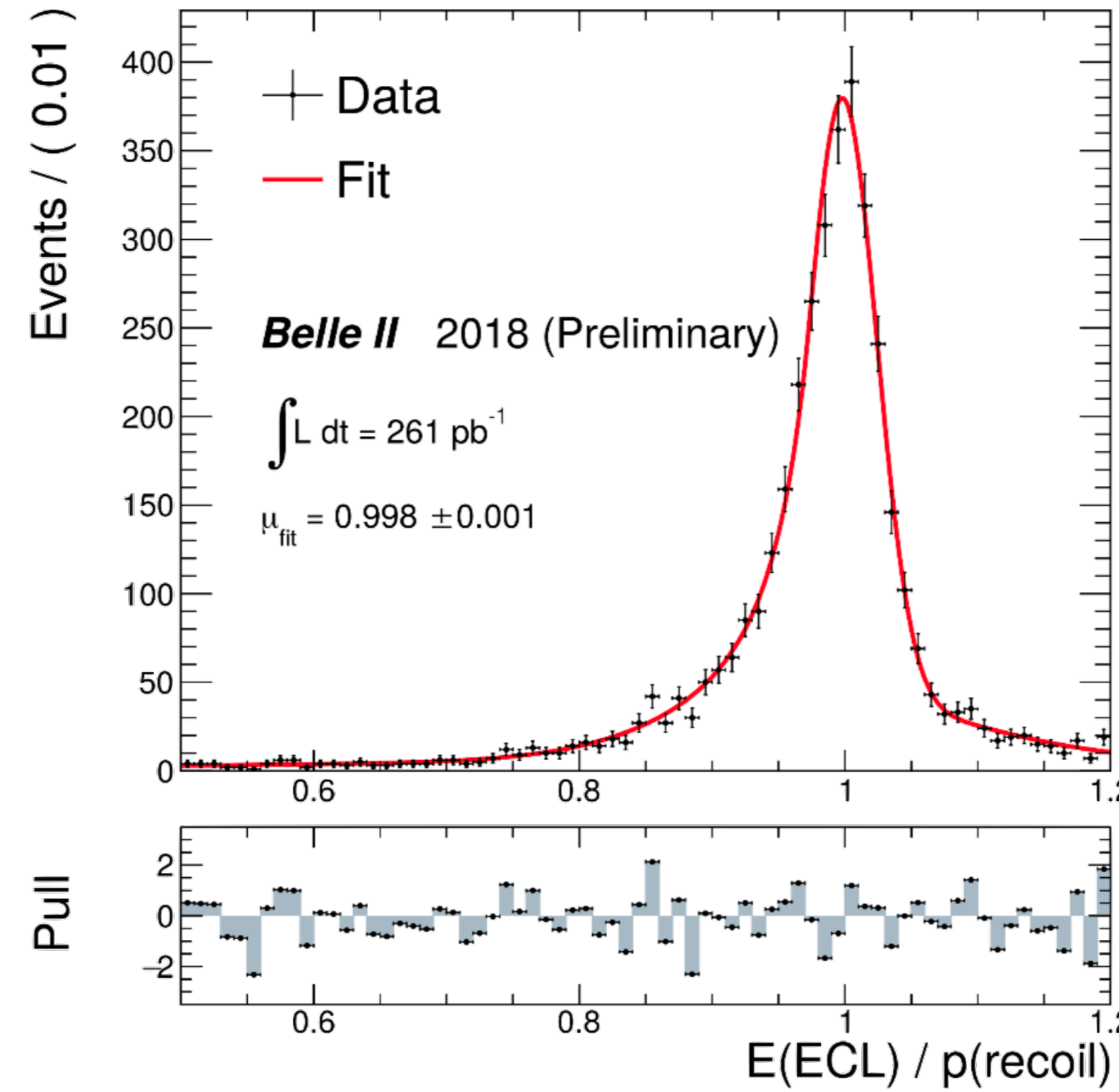


Photon measurement at Belle II

- to search for axion-like particles in $e^+e^- \to \gamma a$ for $a \to \gamma\gamma$ (i.e. 3γ final state) and $a \to$ invisible (i.e. γ + missing $(E, \vec{p})$)

$$e^+e^- \to \mu^+\mu^-\gamma$$



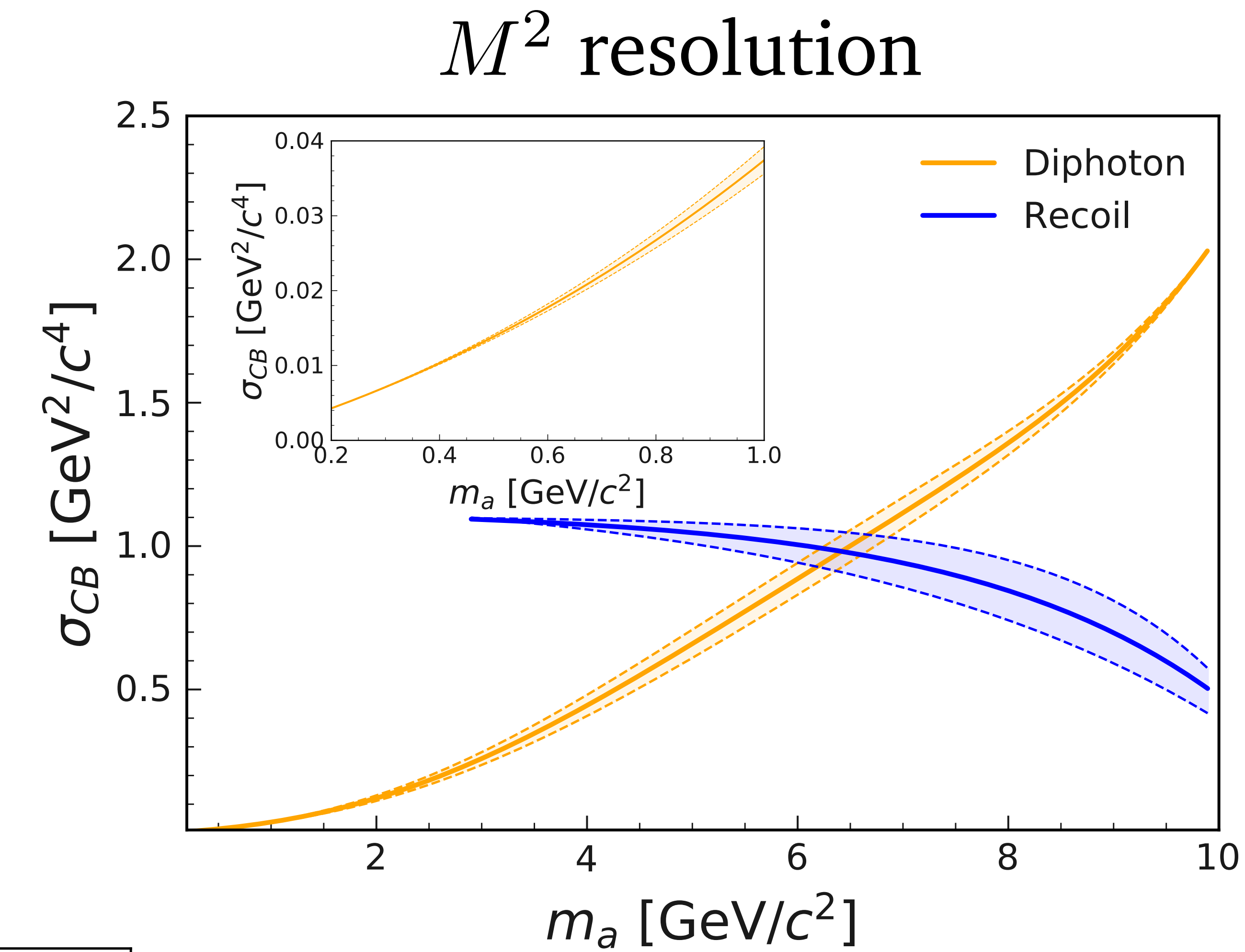


⇒ Ready for dark matter searches (single or triple γ triggers)

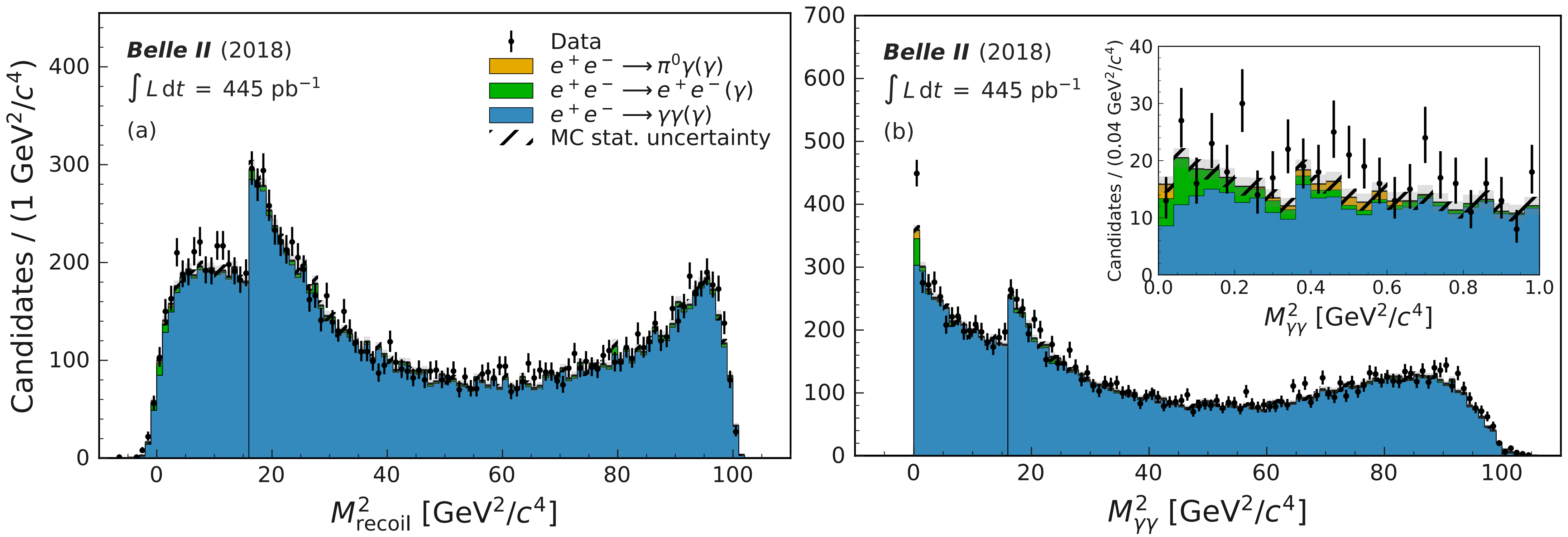
$$e^+e^- \to \gamma X \to \gamma(\gamma\gamma)$$

ALP search (1) in $e^+e^- \to \gamma a$

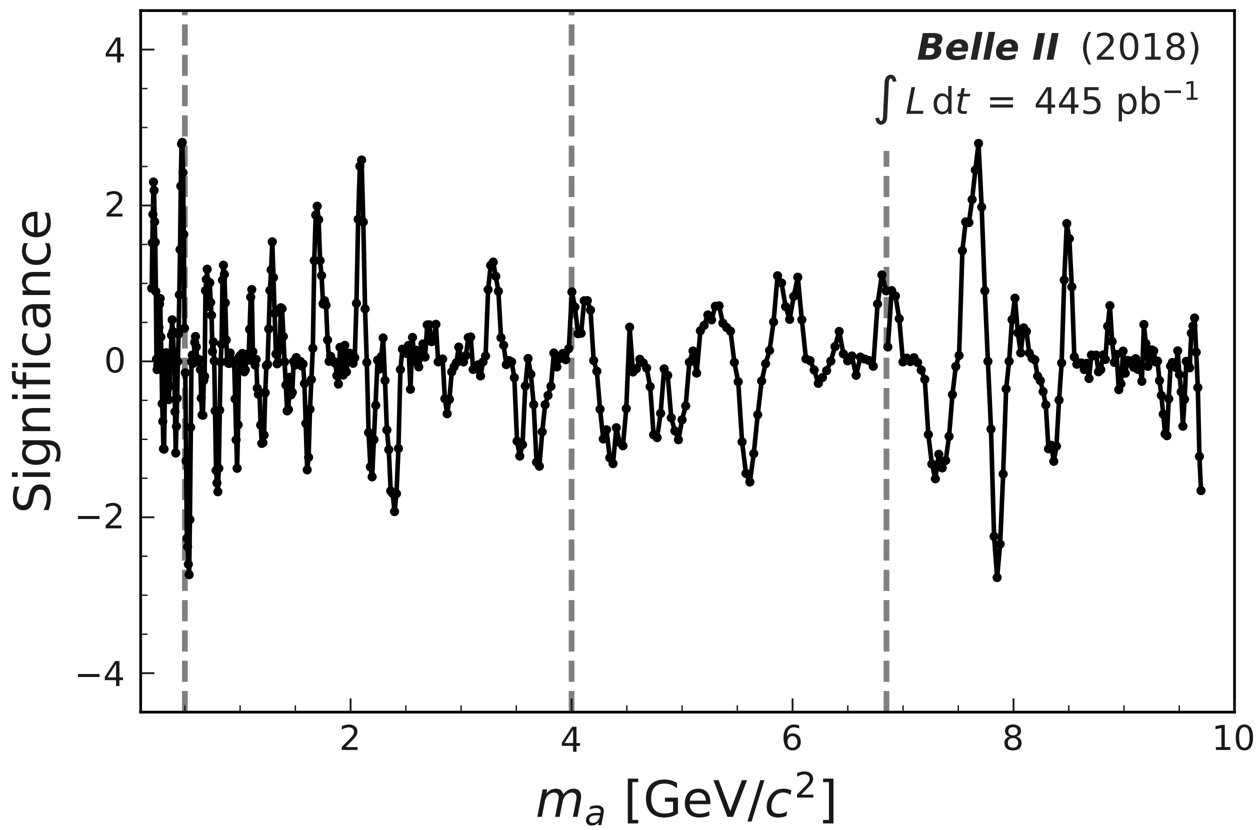
- Search for ALP in $e^+e^- \to \gamma a$ for $a \to \gamma\gamma$ (i.e. 3γ final state) and $a \to$ invisible (i.e. $\gamma + \not{h}$)



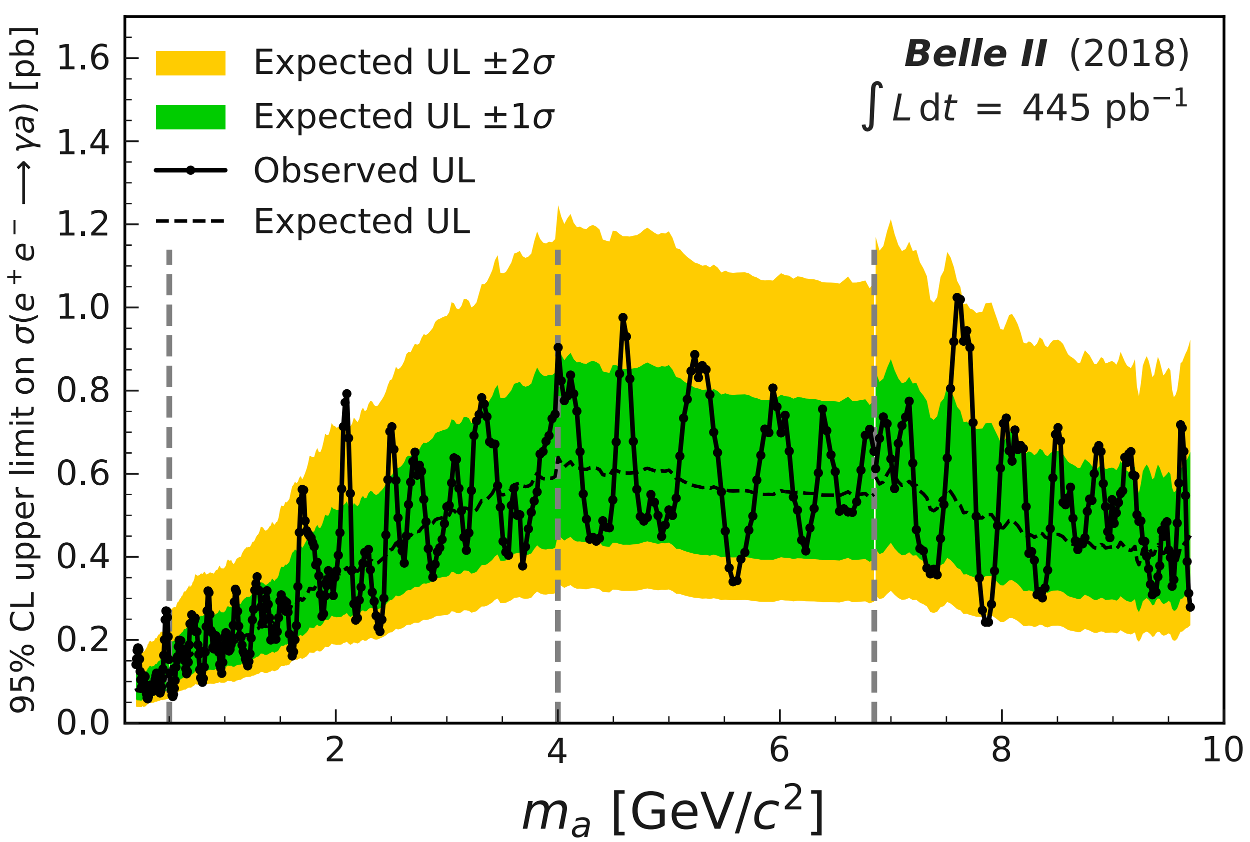
  - fit $M^2_{\gamma\gamma}$ for $0.2 < m_a < 6.85$ GeV
  - fit $M^2_{\rm rec}$ for $m_a > 6.85$ GeV,
  - Look for resonance in the fit

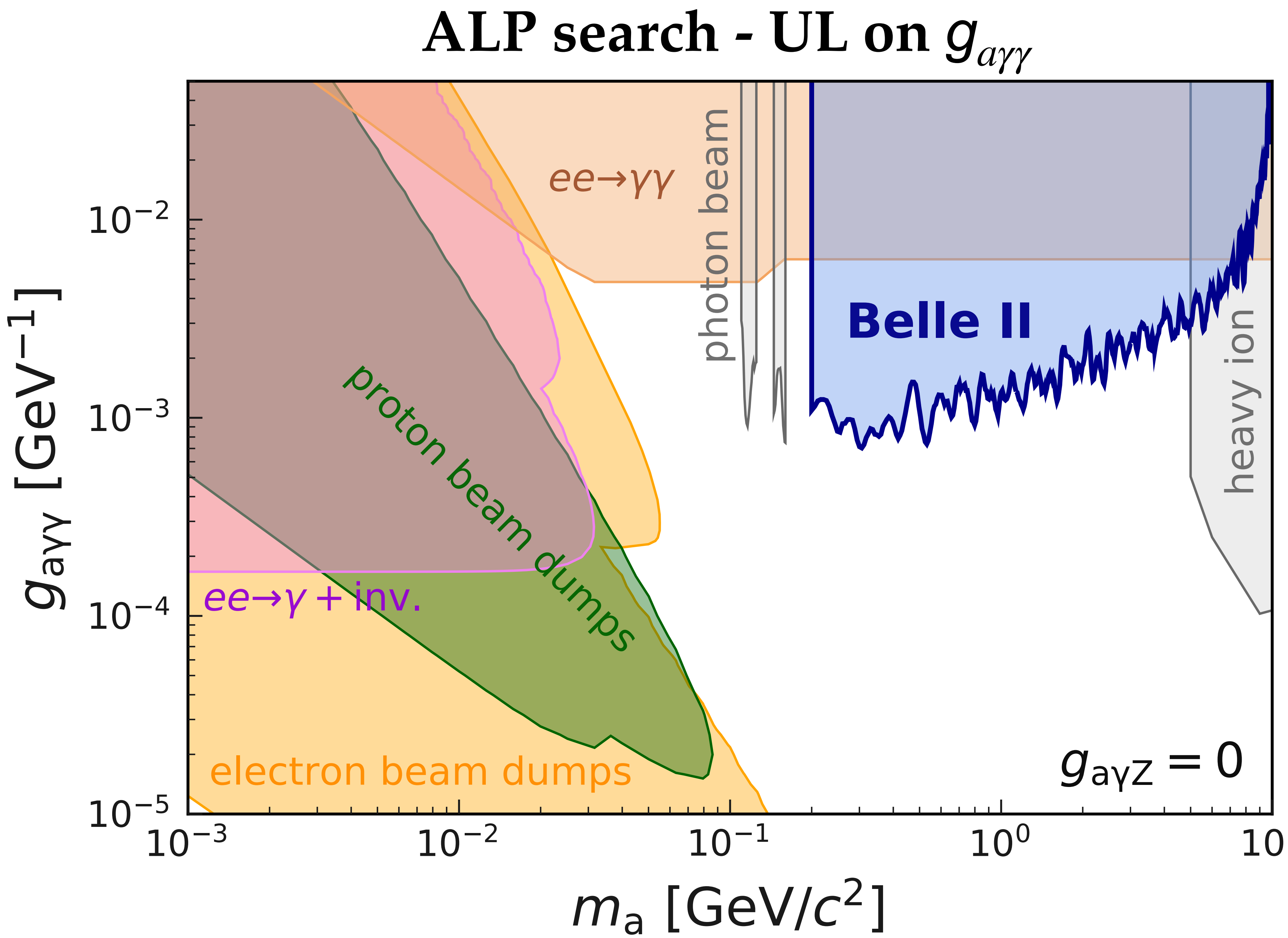


ALP search (1) in $e^+e^- \to \gamma a$



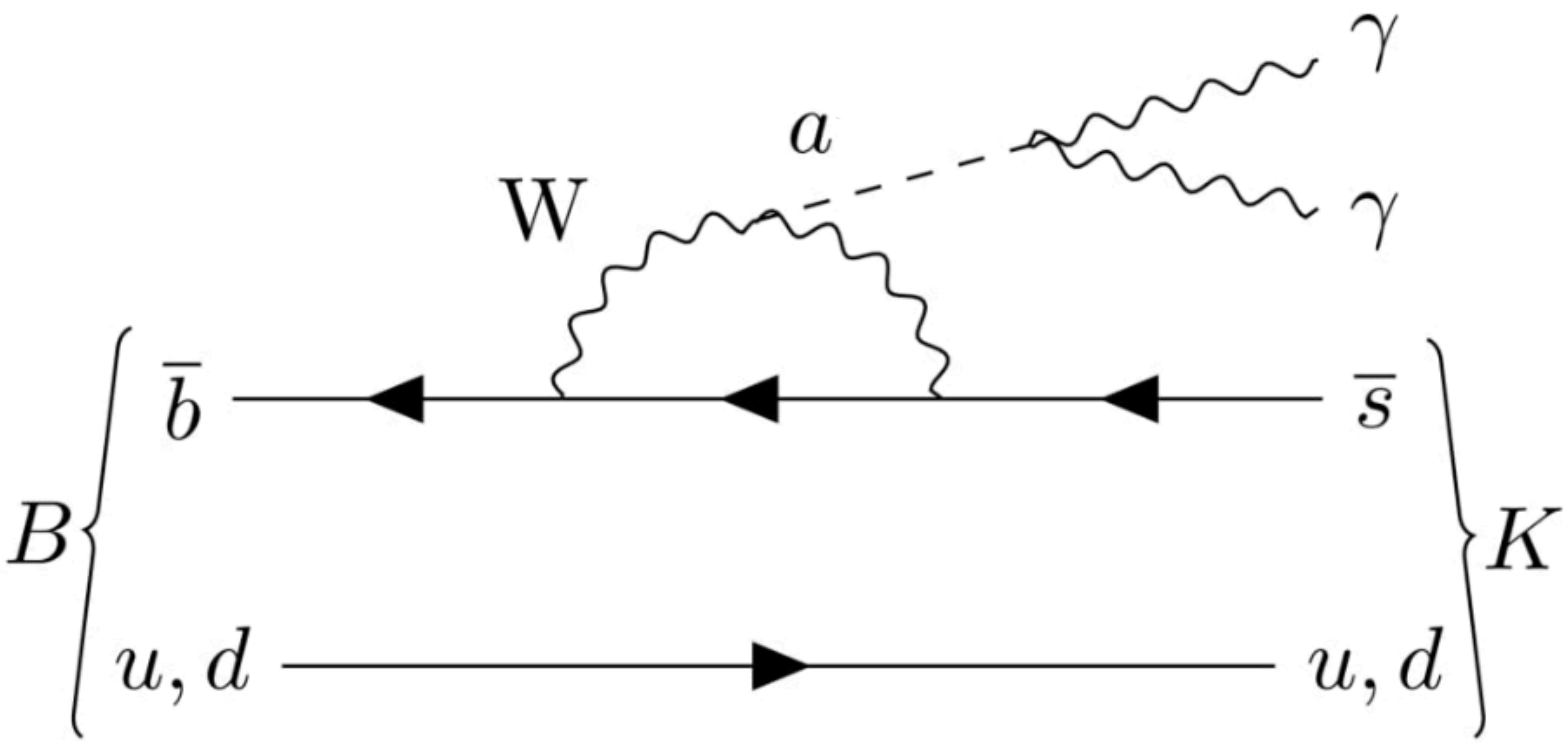
max. local significance of
$\mathcal{S} = 2.8$ at $m_a = 0.477$ GeV





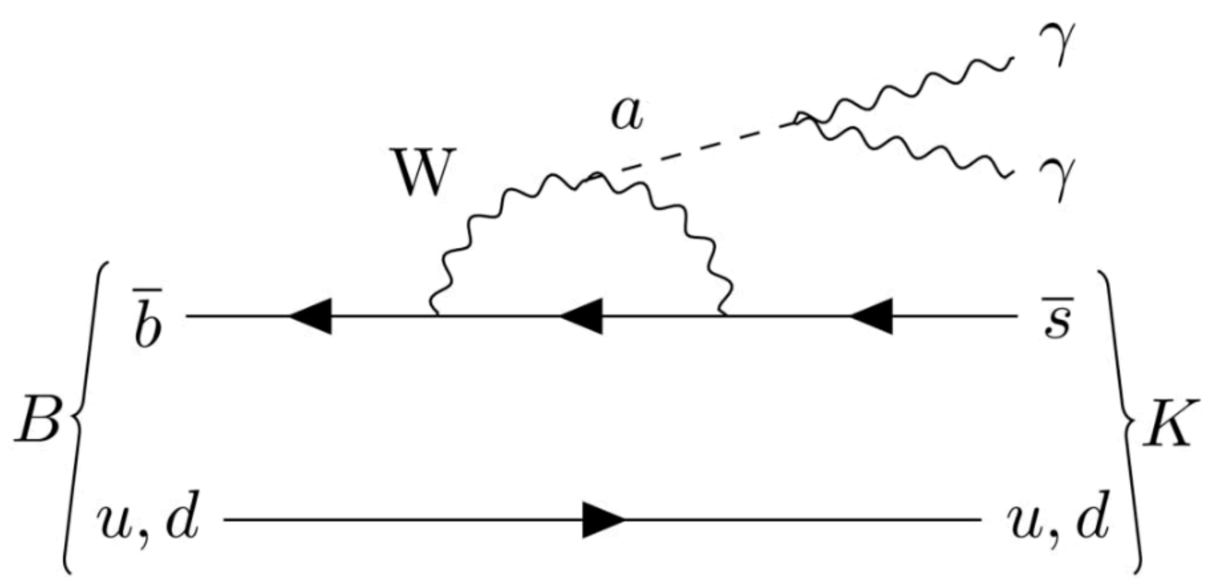
ALP search (2) in $B \to K^{(*)} a(\to \gamma\gamma)$

Dr. Sungjin Cho
(IBS/CUP)



to study one-loop impact of aWW coupling (g_{aW}) on rare B-meson decays

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



h' veto region

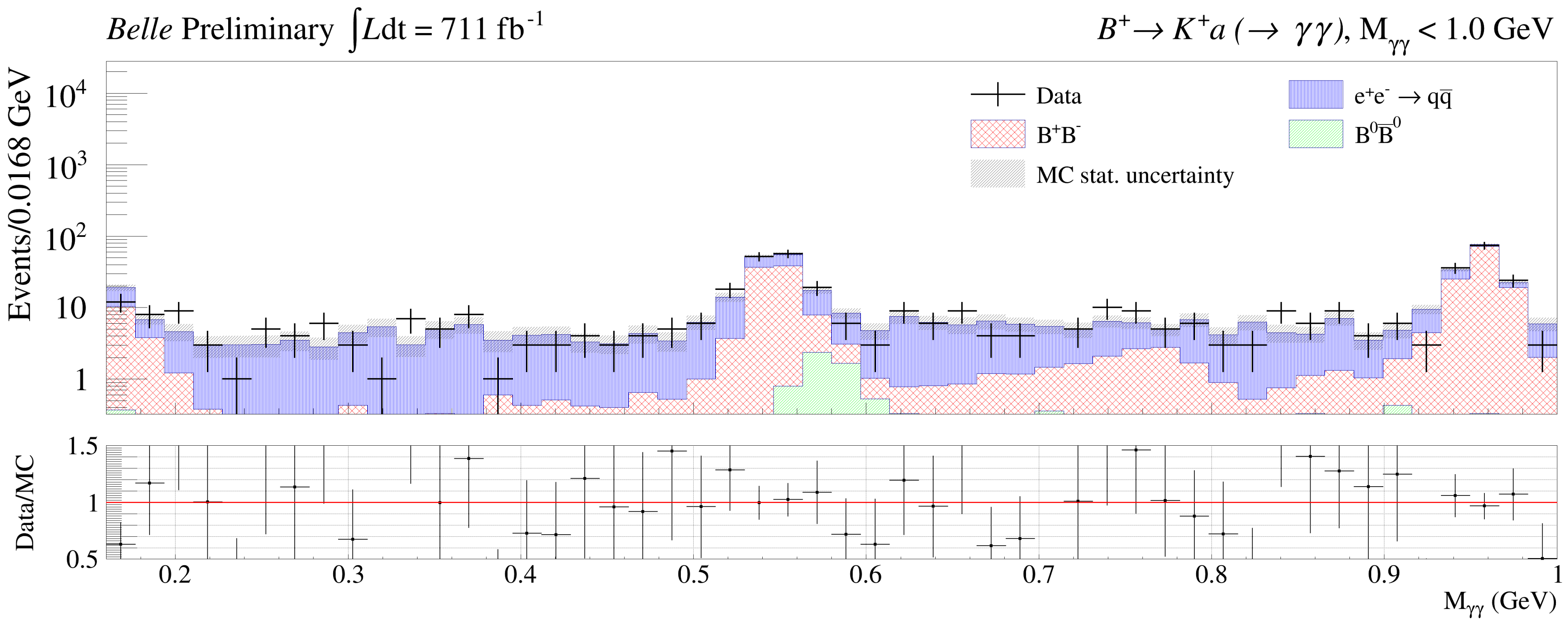
Type	3σ $M_{\gamma\gamma}$ region (GeV/
π^0	0.109 ~ 0.158
η	0.497 ~ 0.578
η'	0.882 ~ 0.997

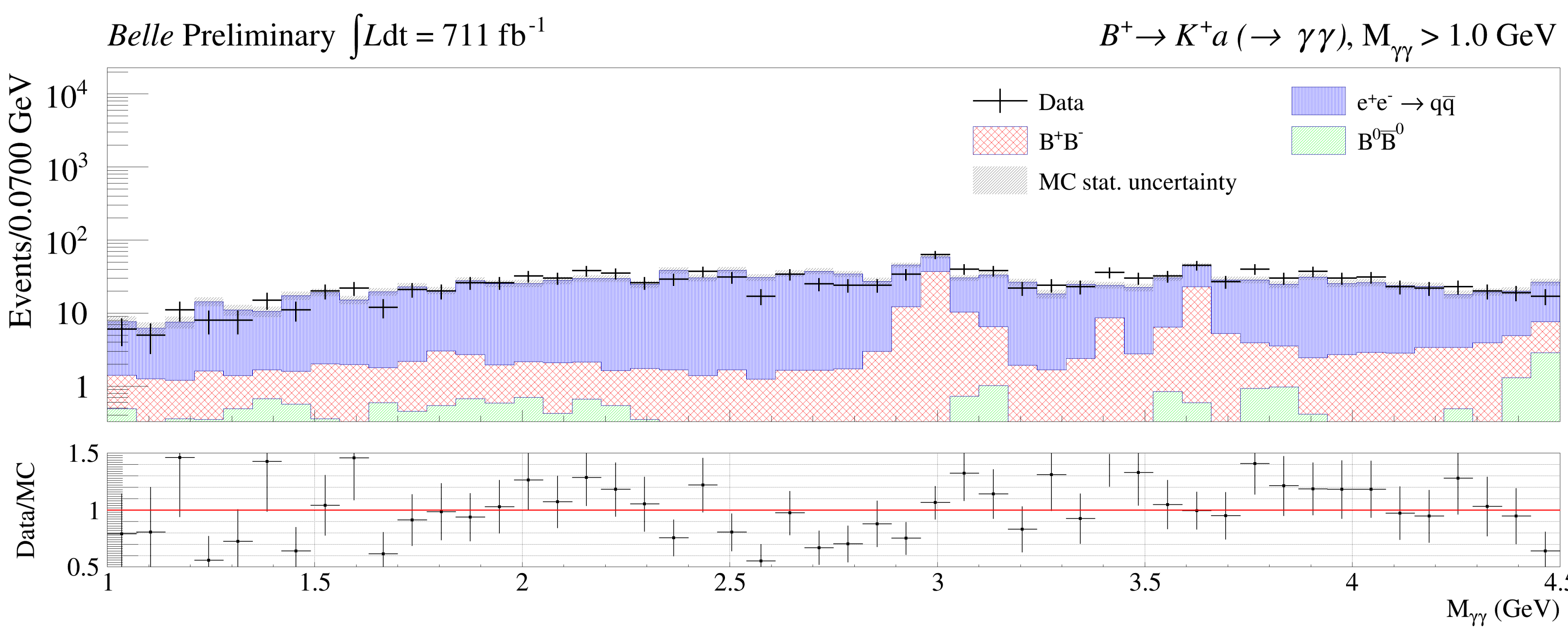
- Search for axion-like particle (ALP)
  - $a \to \gamma\gamma$ (assume dominant)
  - also assume (mostly) prompt decay, but non-zero lifetime is considered for efficiency loss
  - if no signal, set upper limits on ALP-W coupling, g_{aW} [#]
  - search region: $0.16 < m_a < 4.20\ (4.50)$ GeV
  - no sensitivity for π^0, η, η' regions

[#] PRL 118, 111802 (2017)

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

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

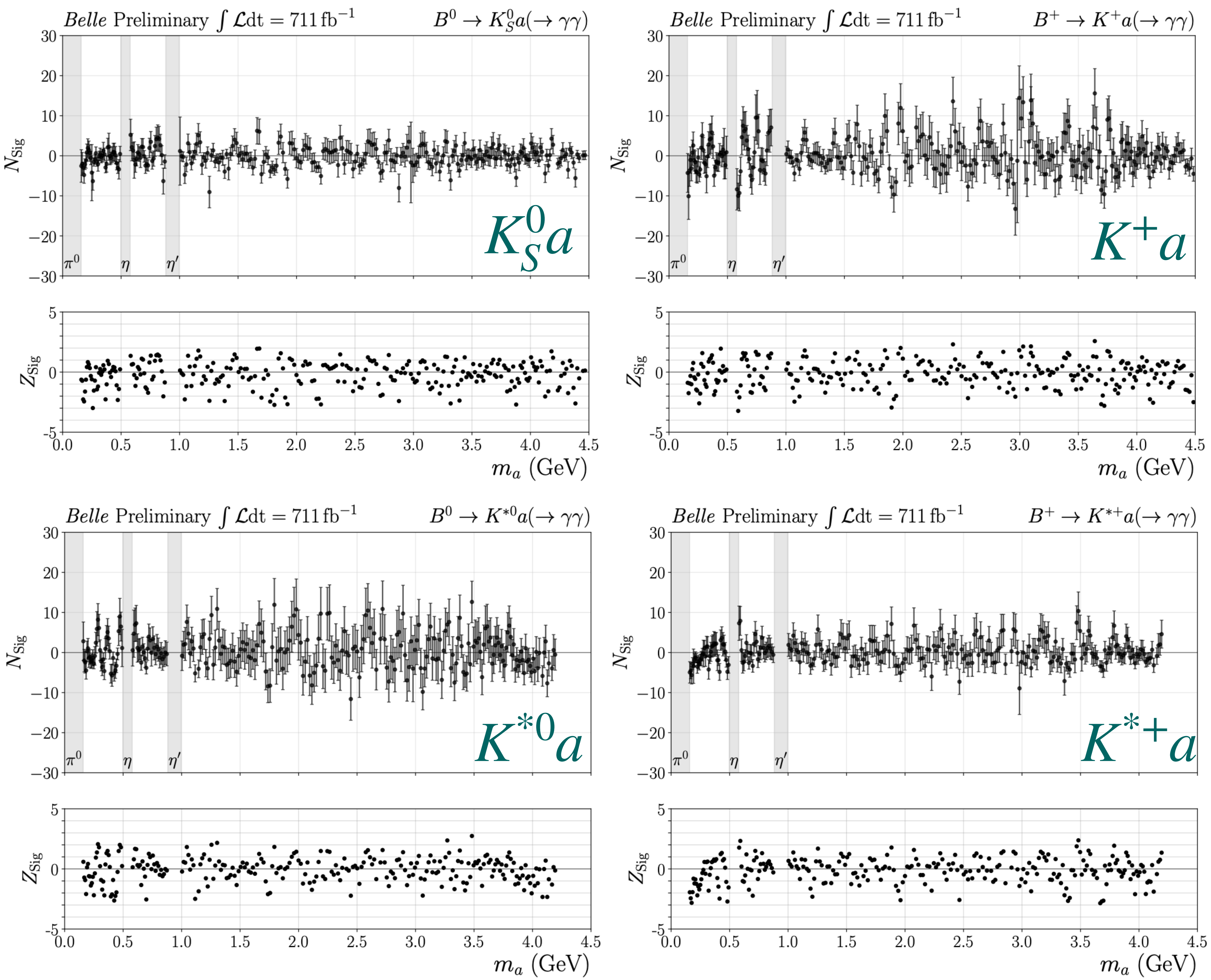




$M_{\gamma\gamma}$ (GeV)

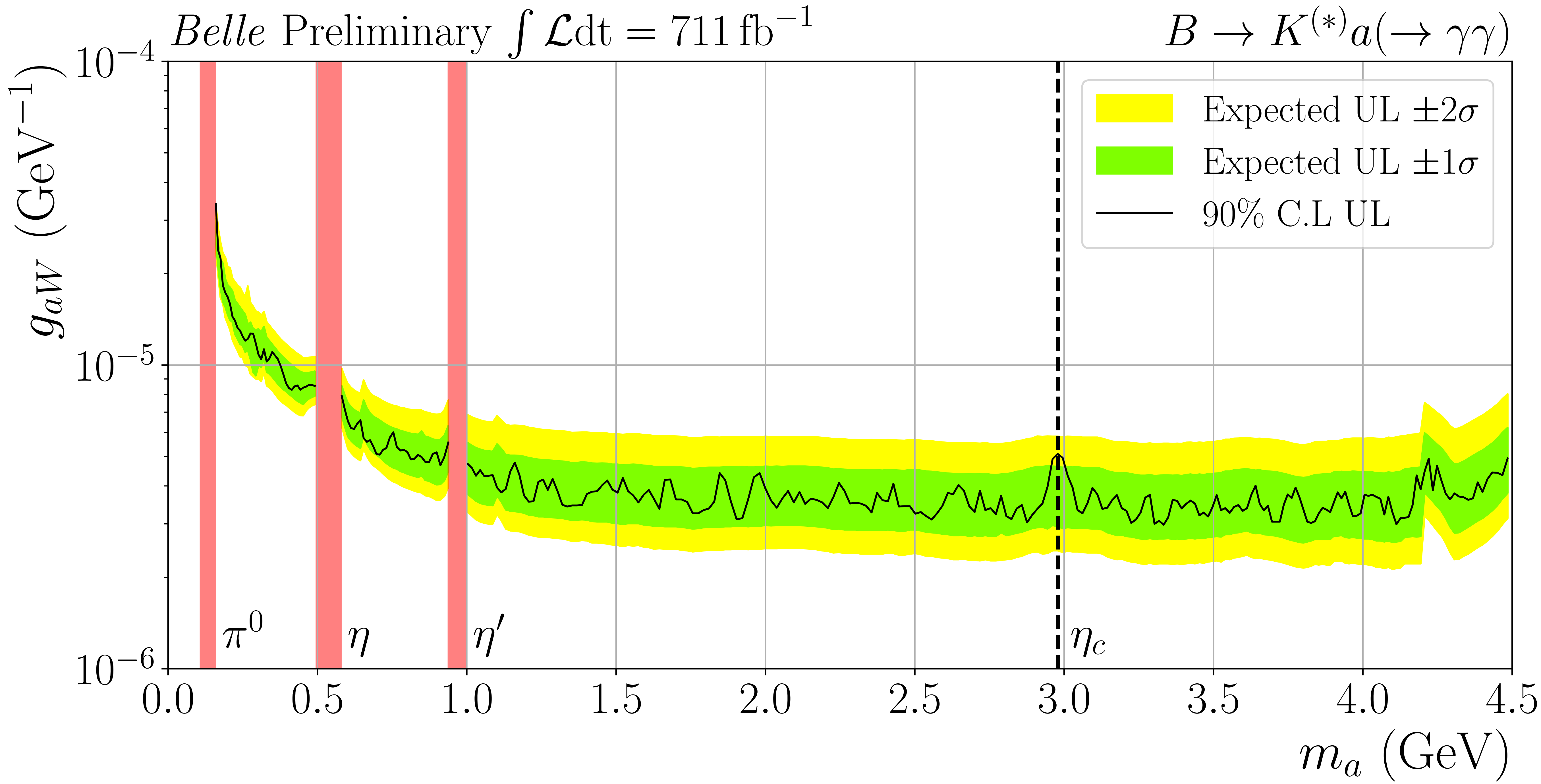
- Signal extraction by 1D max. likelihood fit to $M_{\gamma\gamma}$
- Data vs. MC compared
  - for K^+a mode, after MVA
  - (top) 0.1 < $M_{\gamma\gamma}$ < 1.0 GeV
  - (bottom) 1.0 < $M_{\gamma\gamma}$ < 4.5 GeV

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



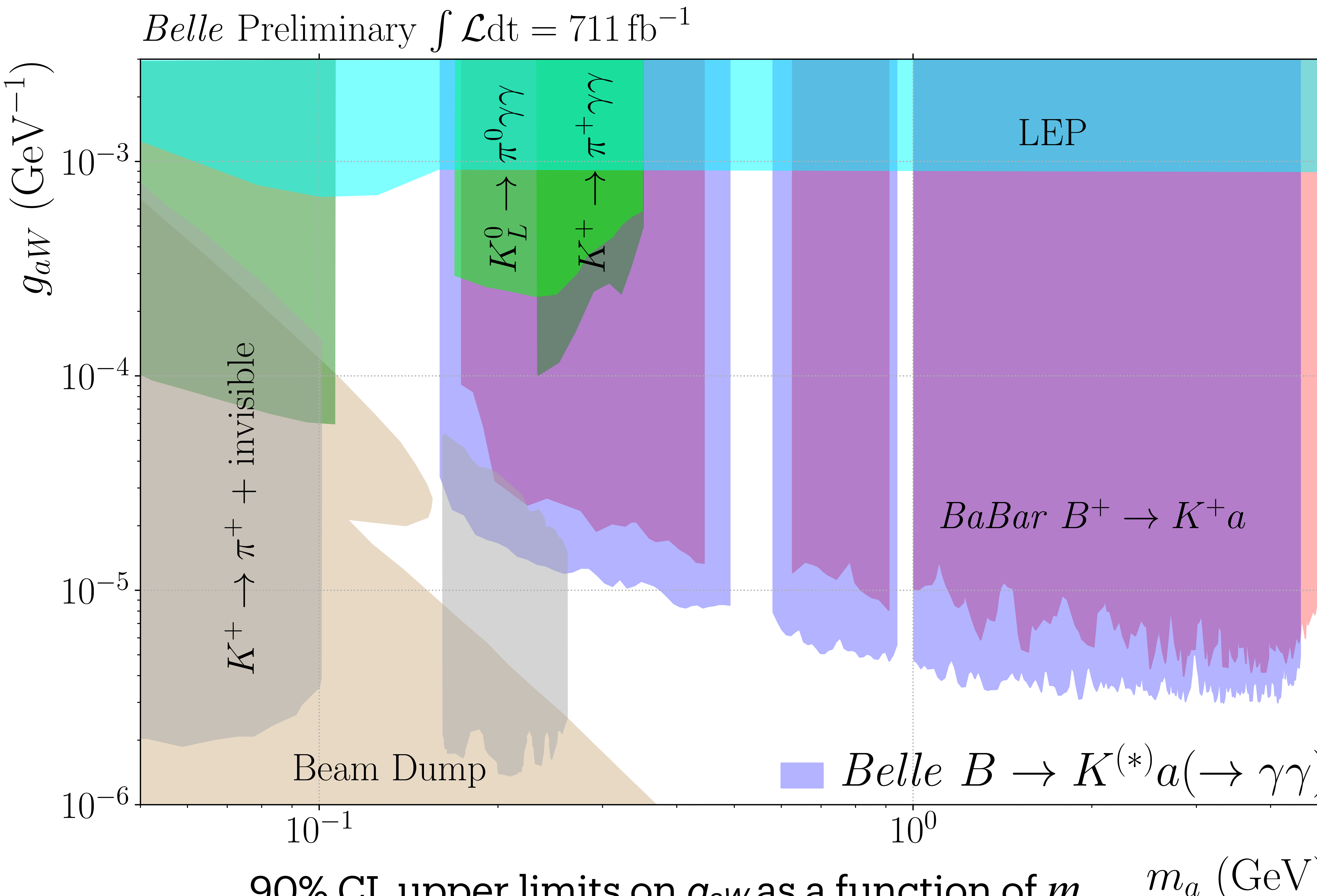
- Fitted results
  - for each $K^{(*)}$ mode
    - ✓ (top) signal yield
    - ✓ (bottom) significance level
  - the gray vertical bands correspond to π^0, η, and η' veto regions

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



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

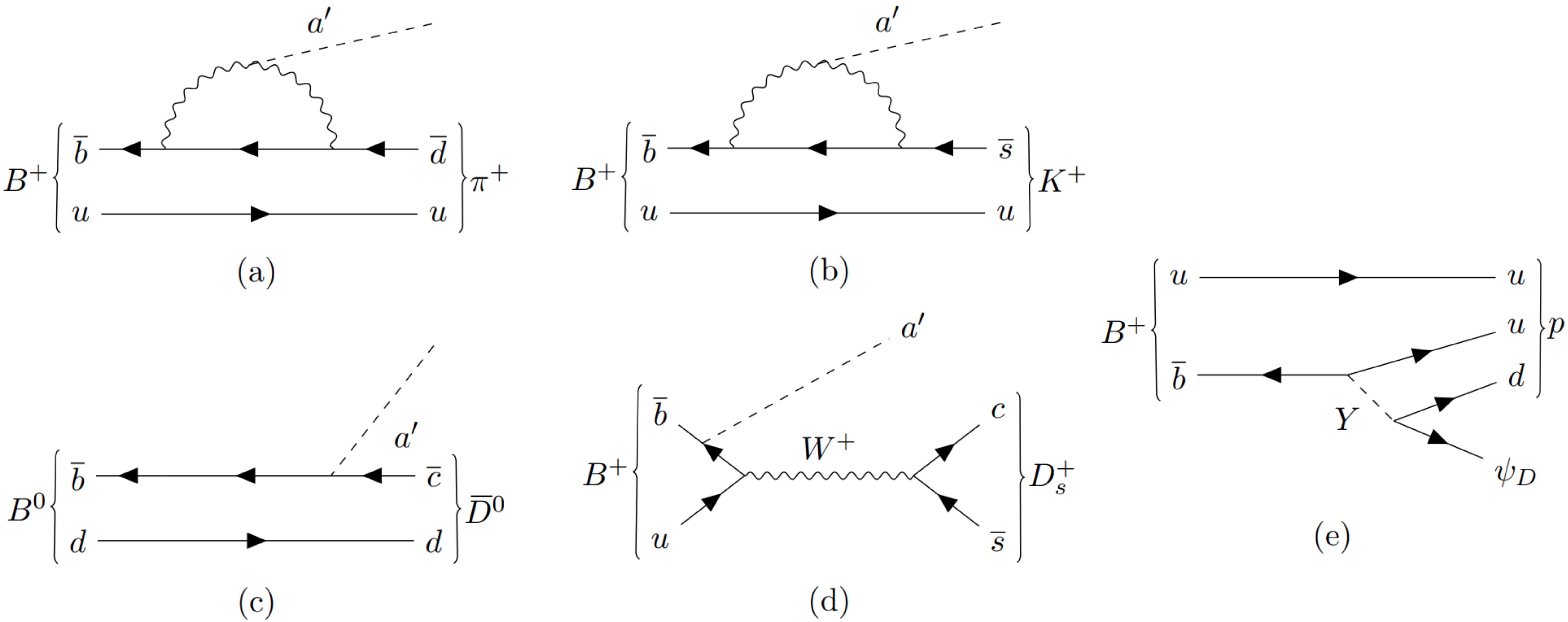
$B \to K^{(*)}\gamma\gamma$ for ALP, Upper limits on g_{aW}



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

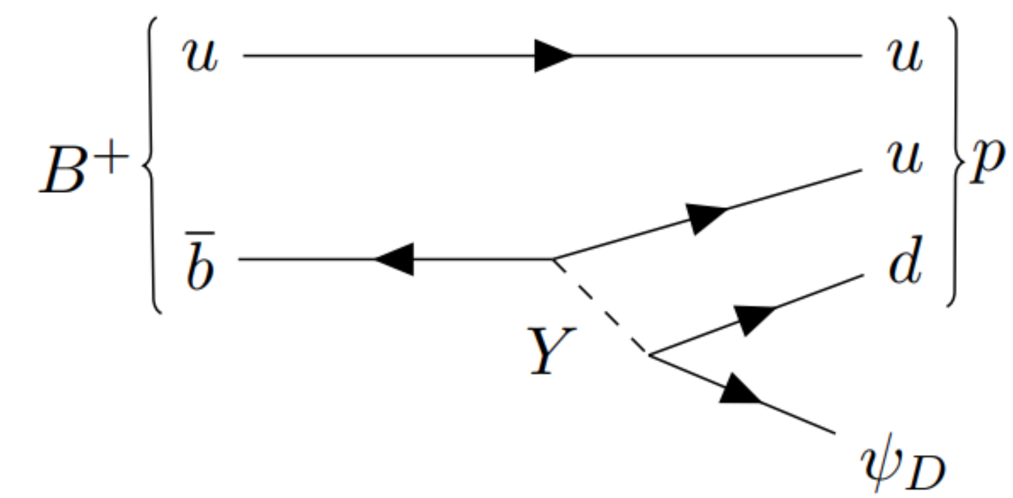
FIP search in $B \to hX_{\text{inv}}$

FIP = feably-interacting particle $\quad h = \pi^+,\ K^+,\ \overline{D}^0,\ D_s^+,\ p$



Motivation for FIP

- $\exists$ many new physics models for X_{inv}, with $B \to hX_{\mathrm{inv}}$
  - axion-like particle (1)
  - dark scalars (2)
  - dark photon, Z' (3)
  - dark baryons (B-mesogenesis) (4)



(e)

- Belle (II) can search for X_{inv} in mass region up to a few GeV

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(1) Izaguirre, Lin, Shuve, PRL 118, 111802 (2017); Zhang, Ishikawa, Kou, Marcantonio, Urquijo, PRD 109, 016008 (2024)

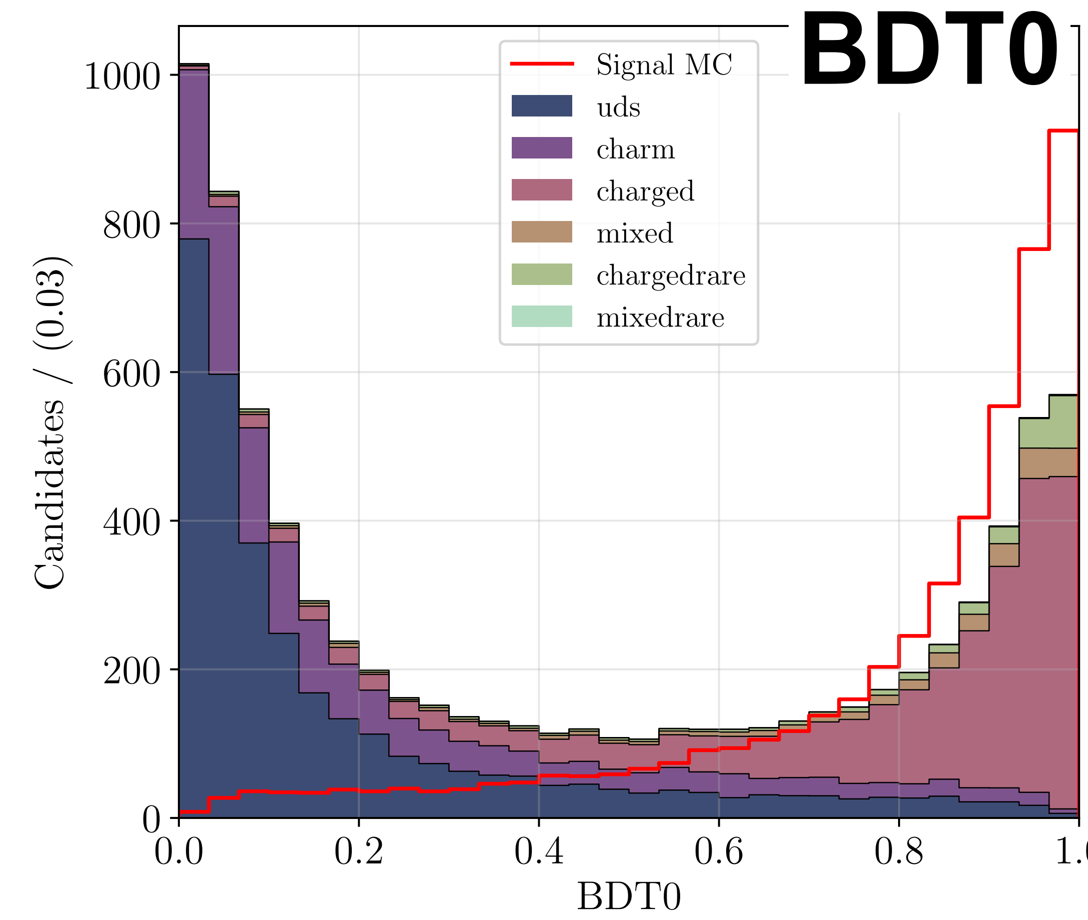
(2) Filimonova, Schäfer, Westhoff, PRD 101, 095006 (2020)

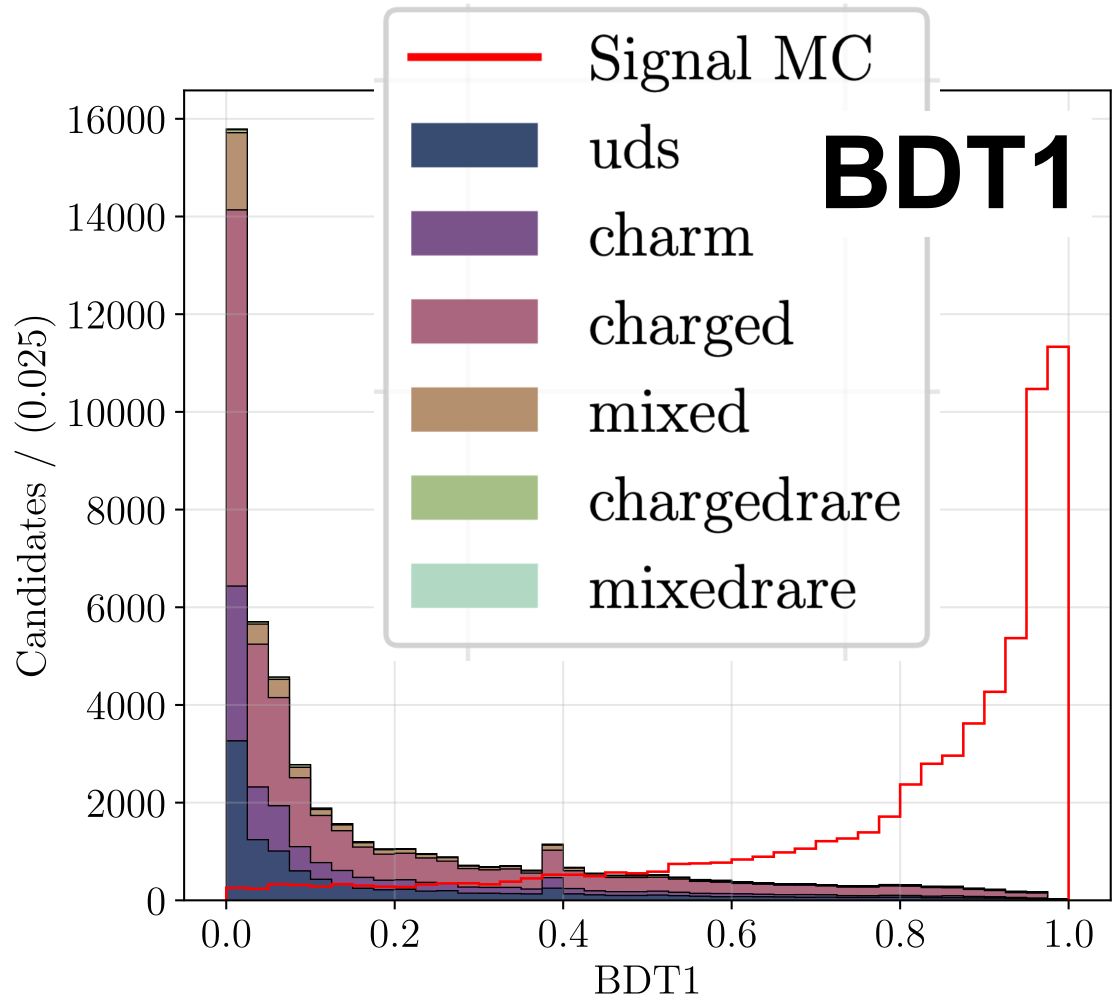
(3) Datta, Hammad, Marfatia, Mukherjee, Rashed, JHEP 2023, 108 (2023)

(4) Elor, Escudero, Nelson, PRD 99, 035031 (2019); Alonso-Álvarez, Elor, Escudero, PRD 104, 035028 (2021)

$B \to hX_{\text{inv}}$ search

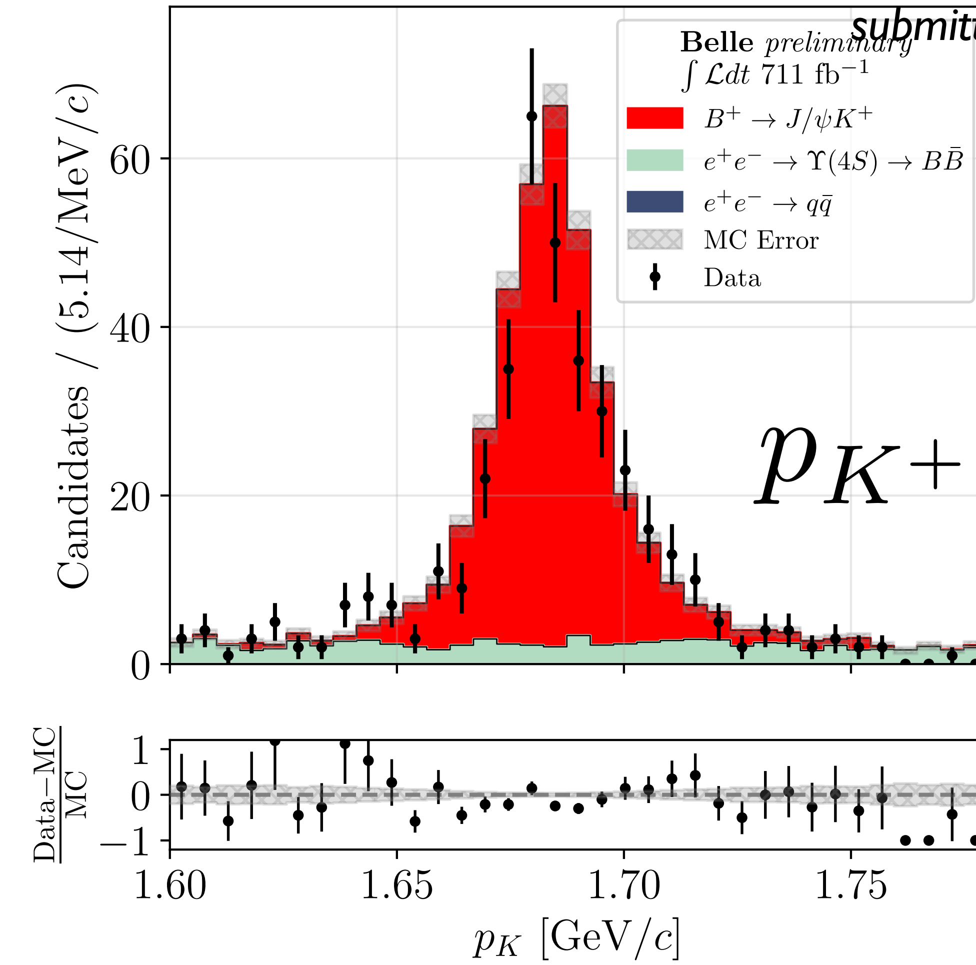
- model-agnostic approach as to why X_{inv} is invisible
  - a dark matter candidate
  - decays to a DM pair
  - long-lived, decays outside the detector
- analysis procedure
  - tag-side reconstruction using FEI
  - identify h in the signal side
- background suppression using BDT in 2 stages
  - to suppress qq continuum bkg
  - for remaining bkg.
    $\cos\theta_T$, $\cos\theta_{T,z}$, $\hat{T}(O)$, $\hat{T}(B)$, CLEO cones, ΔE_{tag}, flight distance, E^2_{miss}, E_{ECL}

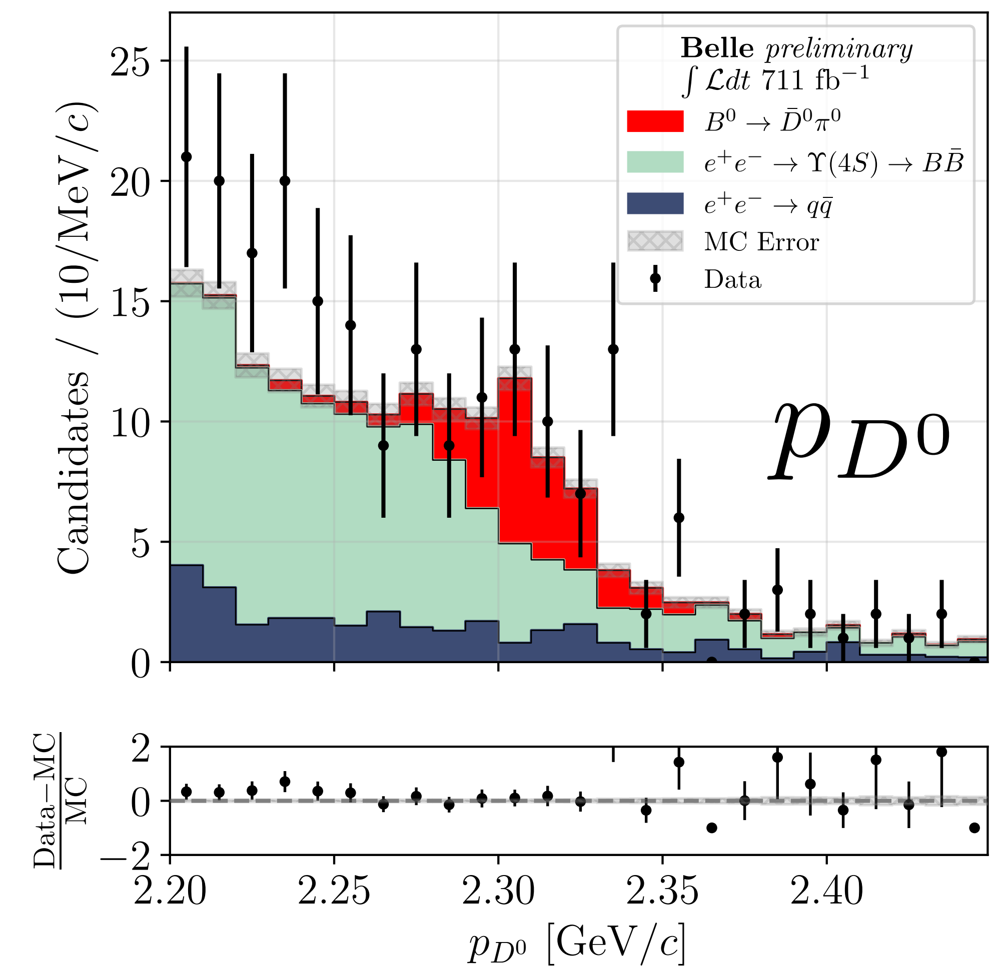




$B \to hX_{\rm inv}$ calibration

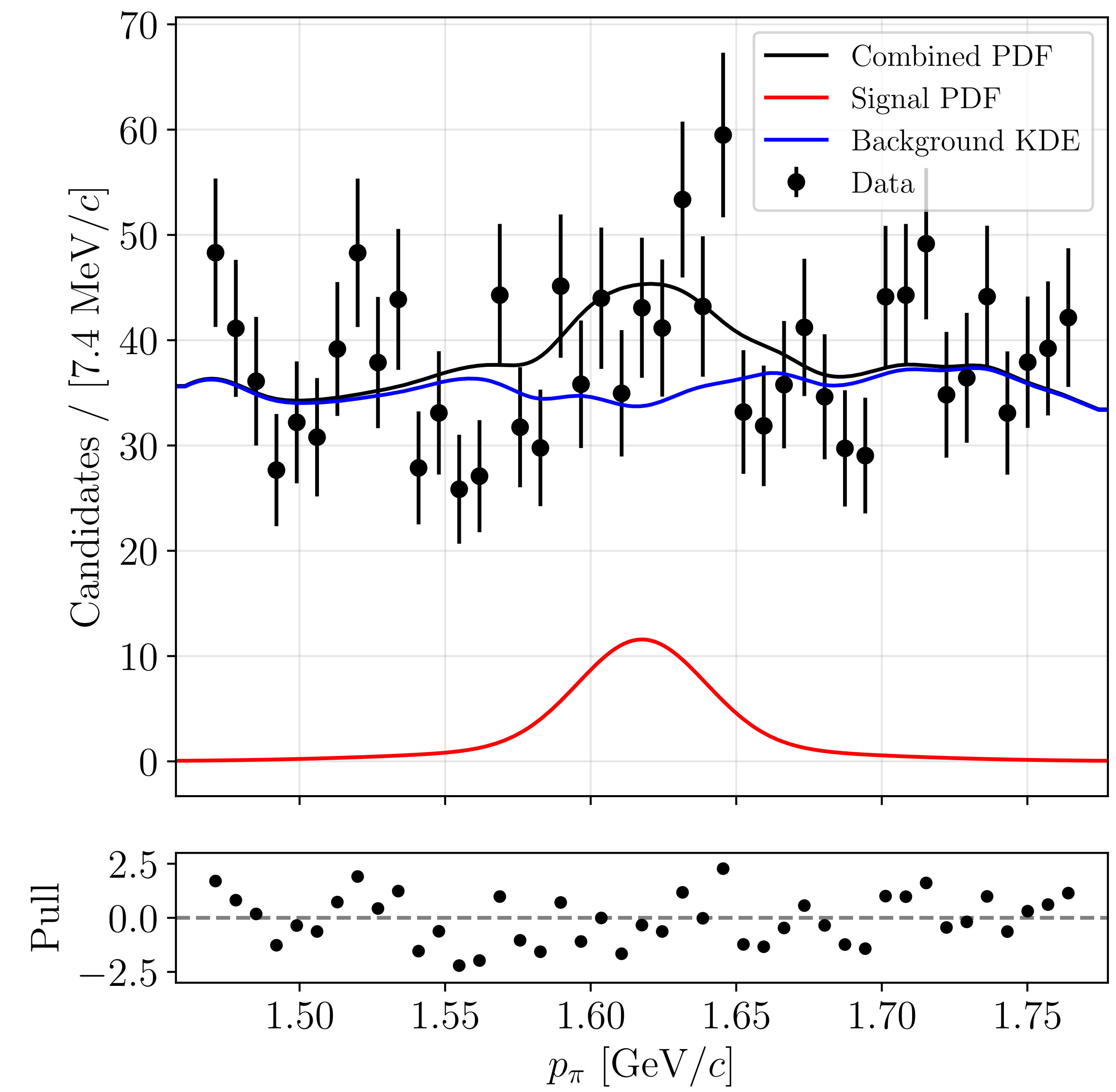
- BDT calibration, by using 2-body B decays
  - $B^+ \to J/\psi K^+$ (for $h = K^+$)
  - $B^0 \to \overline{D}^0\pi^0$ (for $h = D^0$) with $E_{\rm ECL}$ sideband
- FEI efficiency calibration
  - using $B \to D^{(*)}\ell\nu$
    - ✓ r(data/MC) = 0.79 ± 0.02 (B^+), and 0.78 ± 0.02 (B^0)
  - verified with 2-body B decay modes
- Figure (left) — p_h for control modes



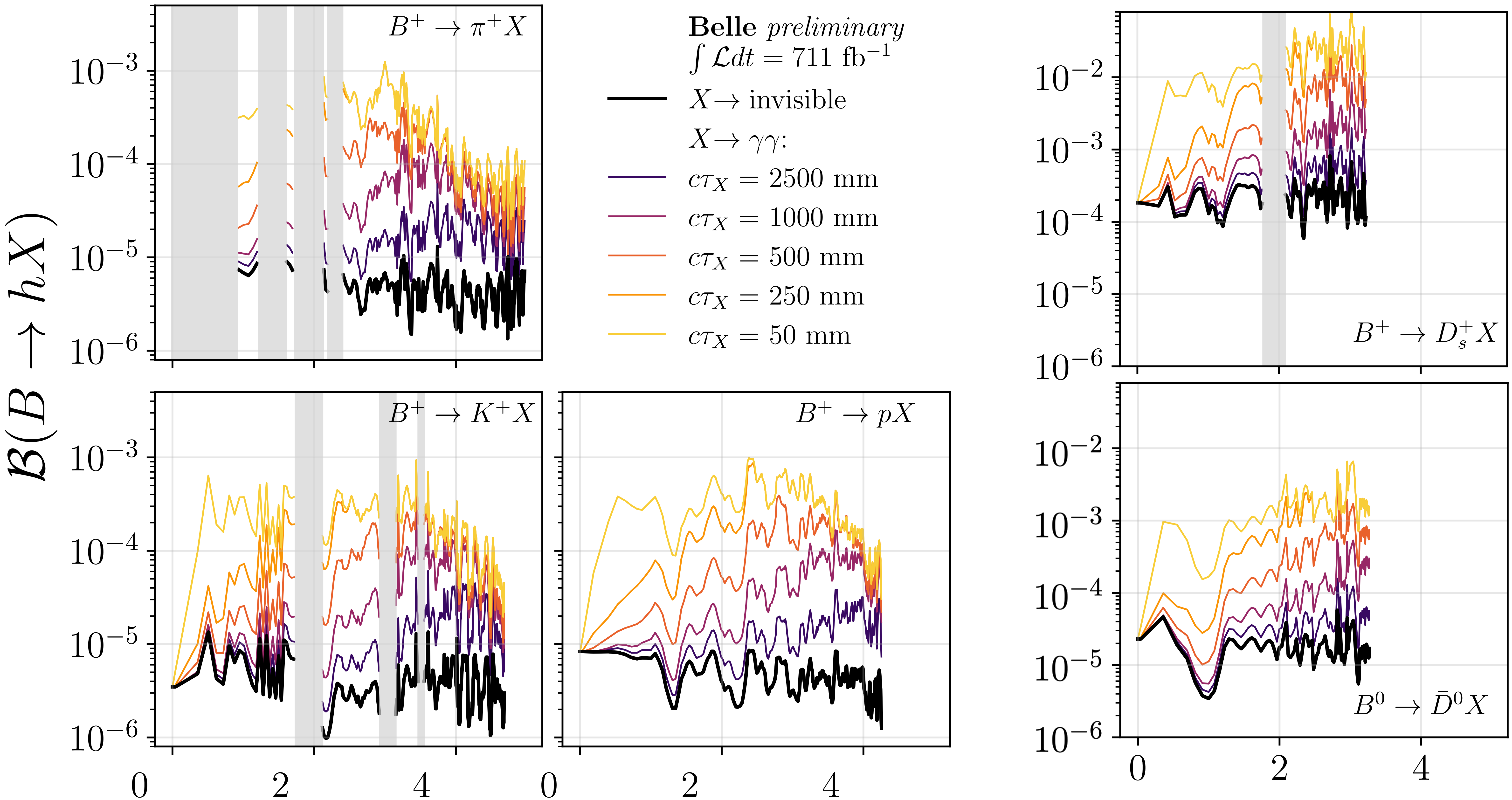


$B \to hX_{\rm inv}$ signal extraction

- Signal extraction
  - 1D fit to p_h
  - by scanning $m_{X_{\rm inv}}$
  - scan step = 1/2 of the signal mass resolution
- No signal in any mode, any bin
  - max local significance $S_{\rm local}$=2.95σ for $h = \pi^+$ at 3.28 GeV ($S_{\rm global}$=0.65σ with LEE)
  - set 90% UL, using $\rm CL_s$ method, on $\mathscr{B}(B \to hX_{\rm inv})$
  - also set UL on $\mathscr{B}[B \to hX(\to \gamma\gamma)]$ where X decay particles are missing due to long lifetime

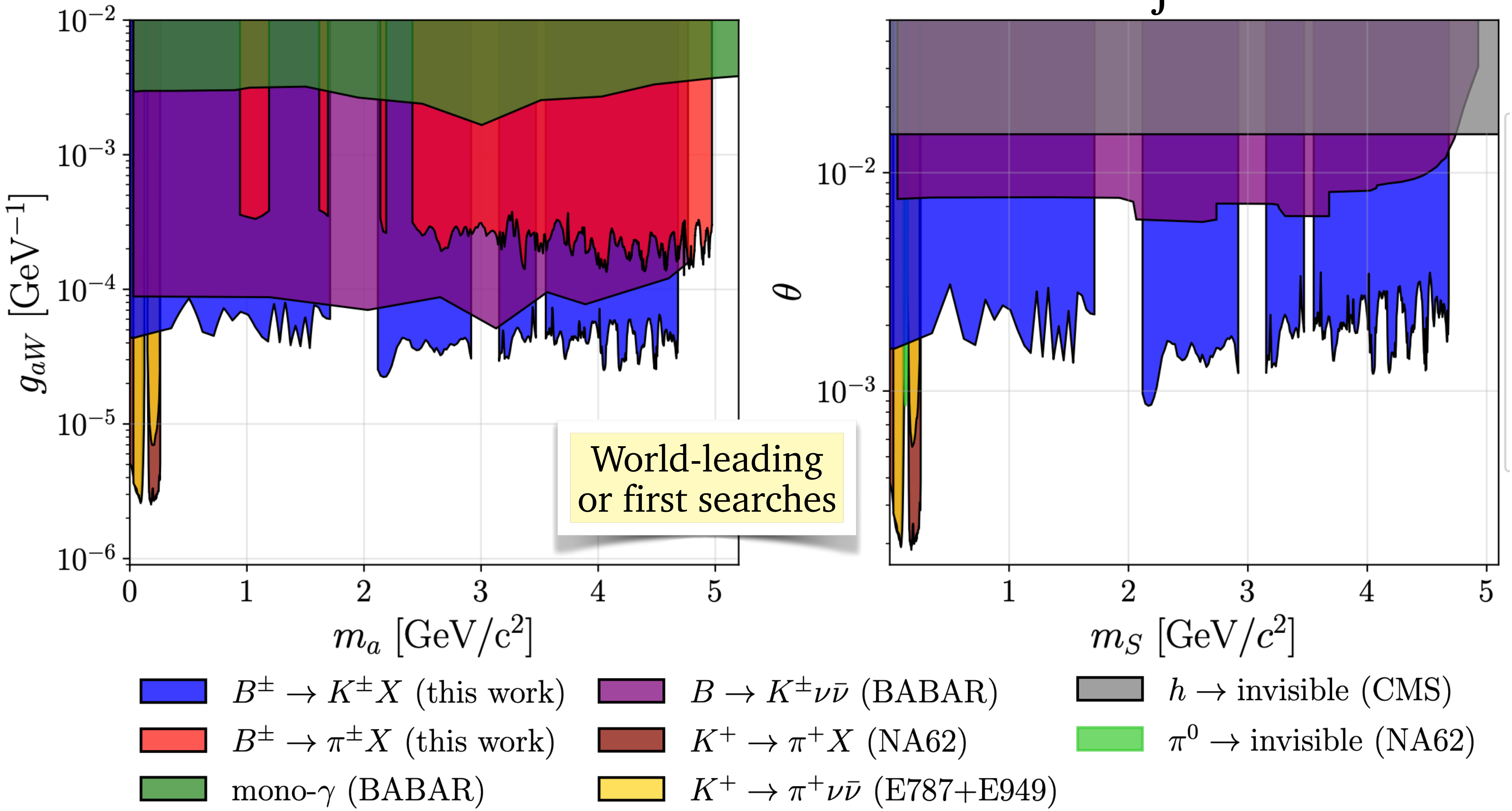


$\mathcal{B}(B \to hX_{\text{inv}})$ upper limits



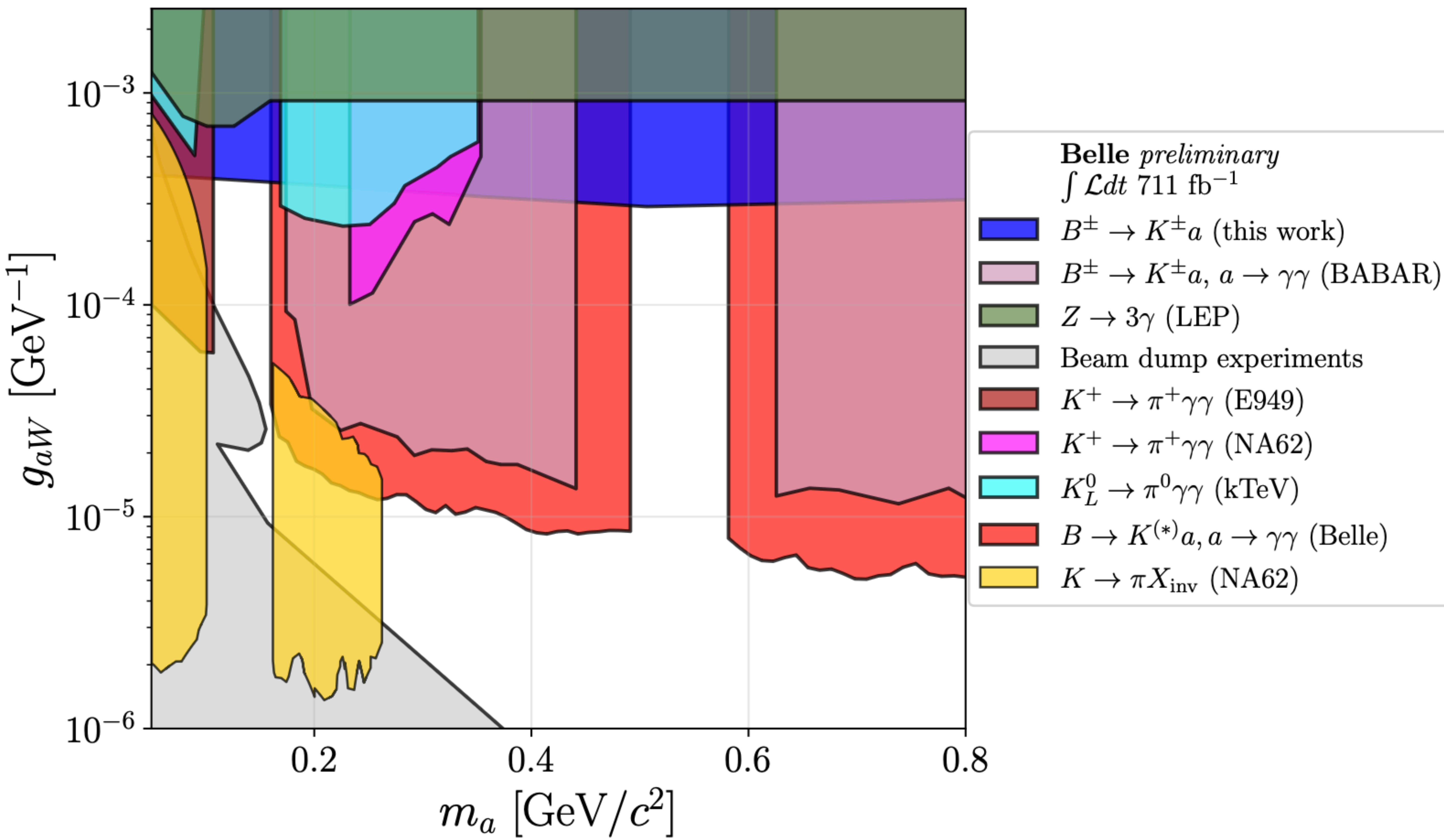
$B \to hX_{\text{inv}}$ results w/ others

Belle preliminary $\int \mathscr{L} dt = 711\ \text{fb}^{-1}$

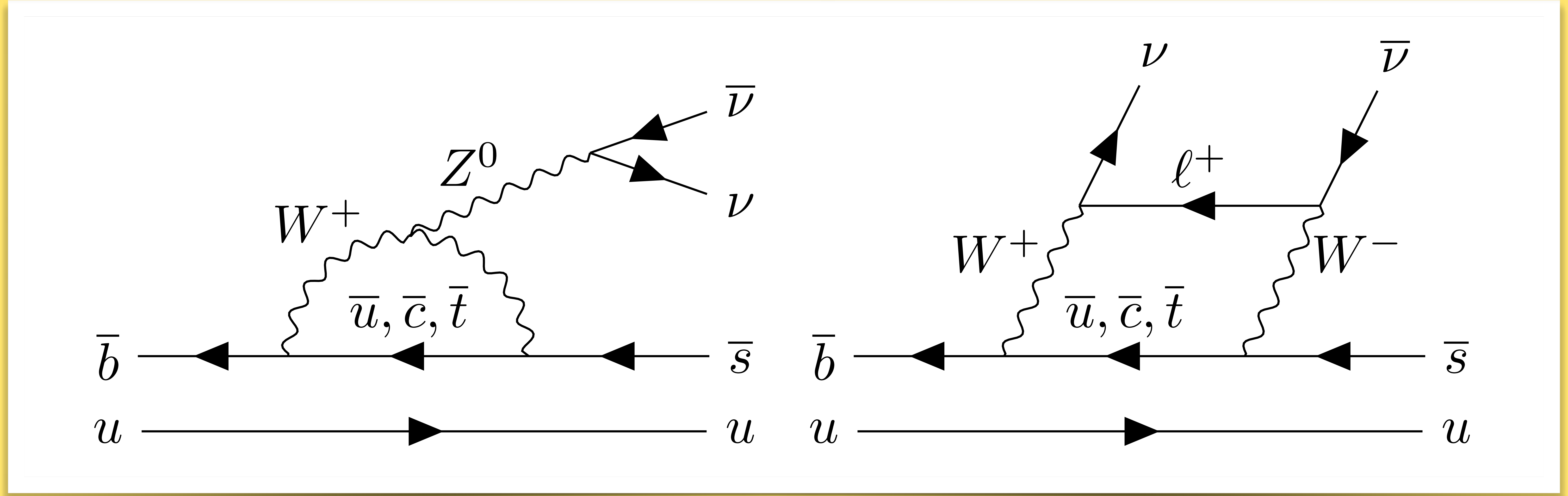


$B \to hX_{\text{inv}}$ results w/ others

arXiv:2601.07104
submitted to PRL

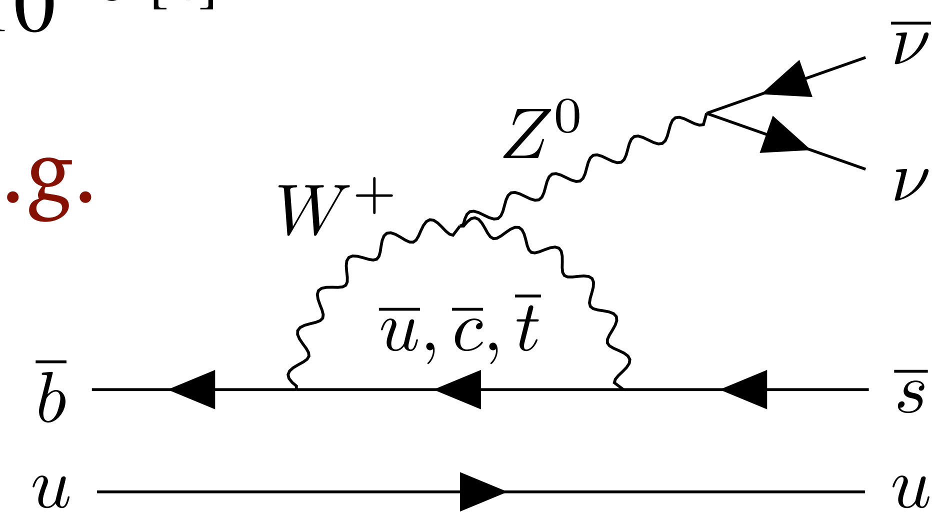


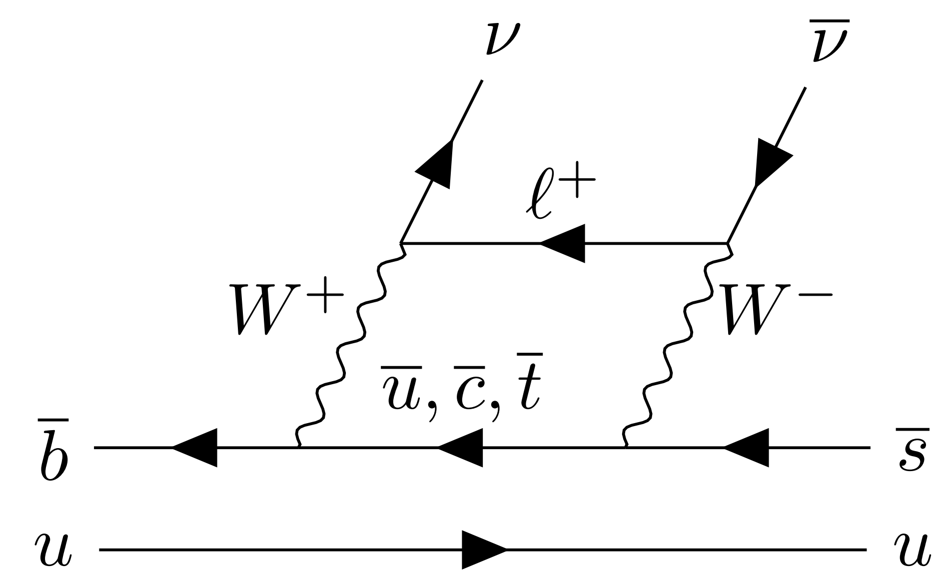
$B^+ \to K^+ \nu\bar{\nu}$ and $B \to X_s \nu\bar{\nu}$ (inclusive)

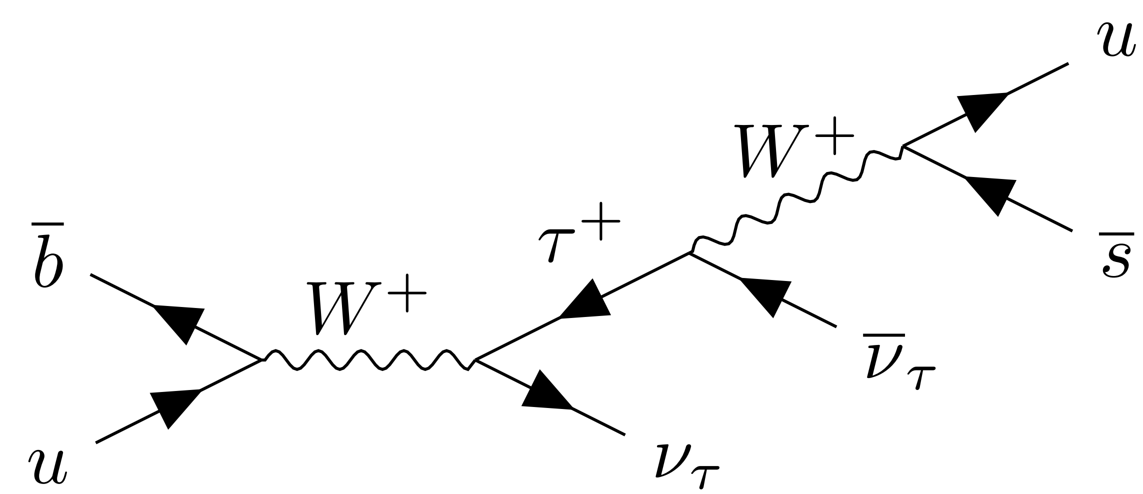


$B^+ \to K^+ \nu\overline{\nu}$

- In the SM,
  - suppressed (∵ FCNC loop)
  - $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$ [4]
- sensitive to new physics BSM, e.g.
  - leptoquarks,
  - axions,
  - DM particles, etc.
- Very challenging, experimentally
  - to exploit very clean initial & final states, along with energy-momentum conservation





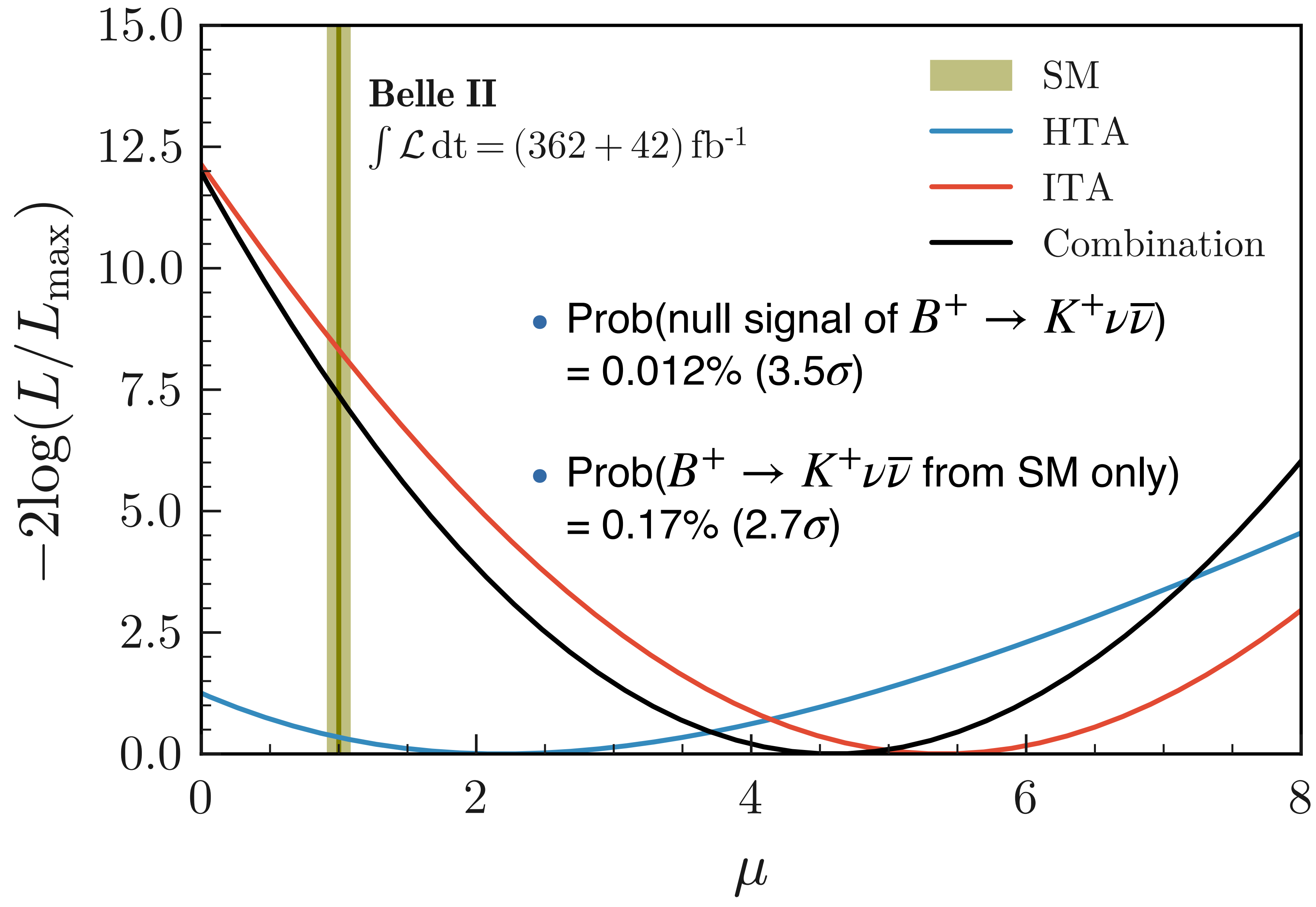


[4] W. G. Parrott et al. PRD 107, 014511 (2023)

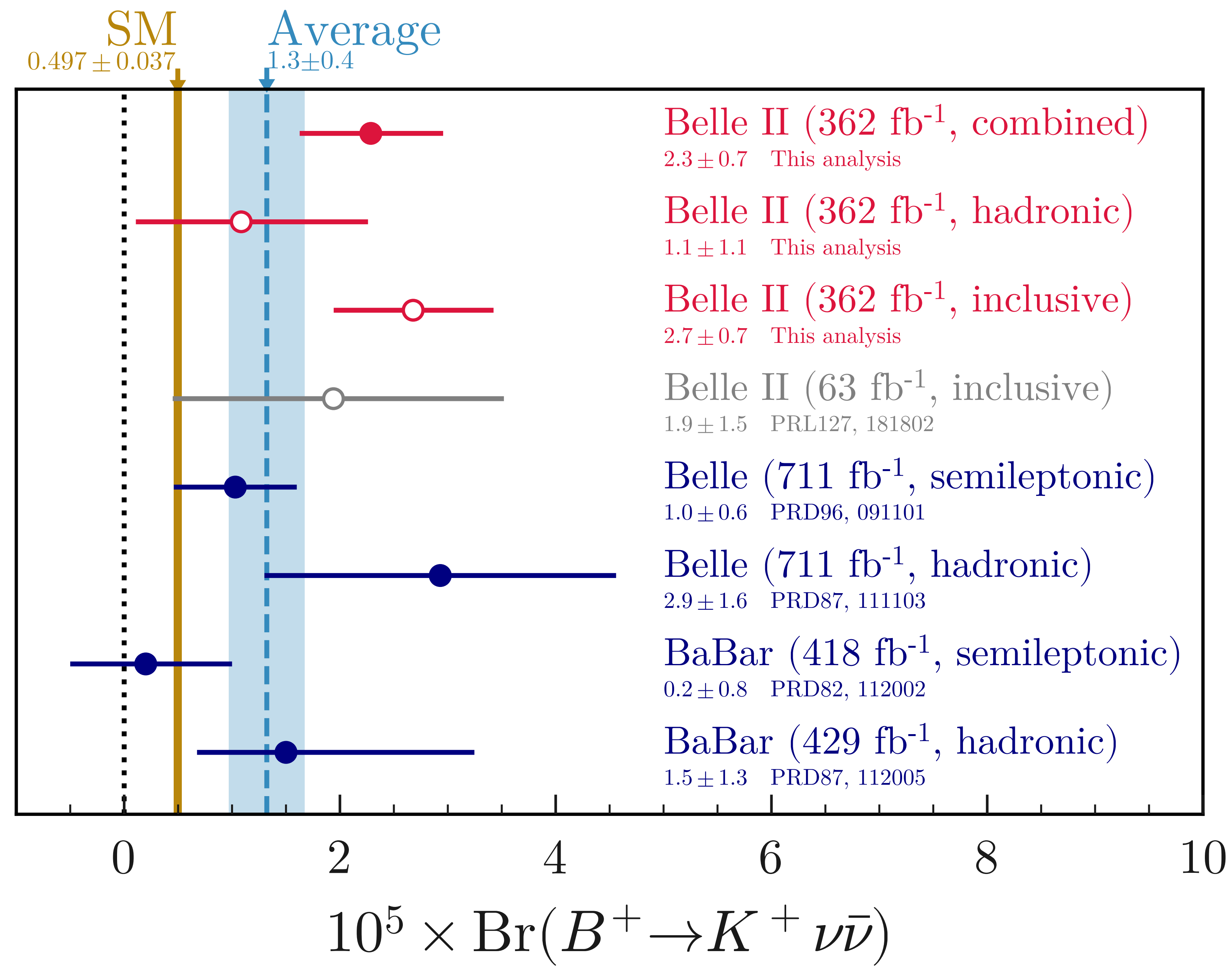
incl. long-distance contribution from $B \to \tau\nu$)

Editors' Suggestion PRD 109, 112006 (2024)

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



- Prob(null signal of $B^+ \to K^+\nu\bar{\nu}$) = 0.012% (3.5σ)
- Prob($B^+ \to K^+\nu\bar{\nu}$ from SM only) = 0.17% (2.7σ)



[Note] $\mu = 1 \Leftrightarrow \mathscr{B} = 4.97 \times 10^{-6}$
(SM value, not including $B \to \tau\nu$)

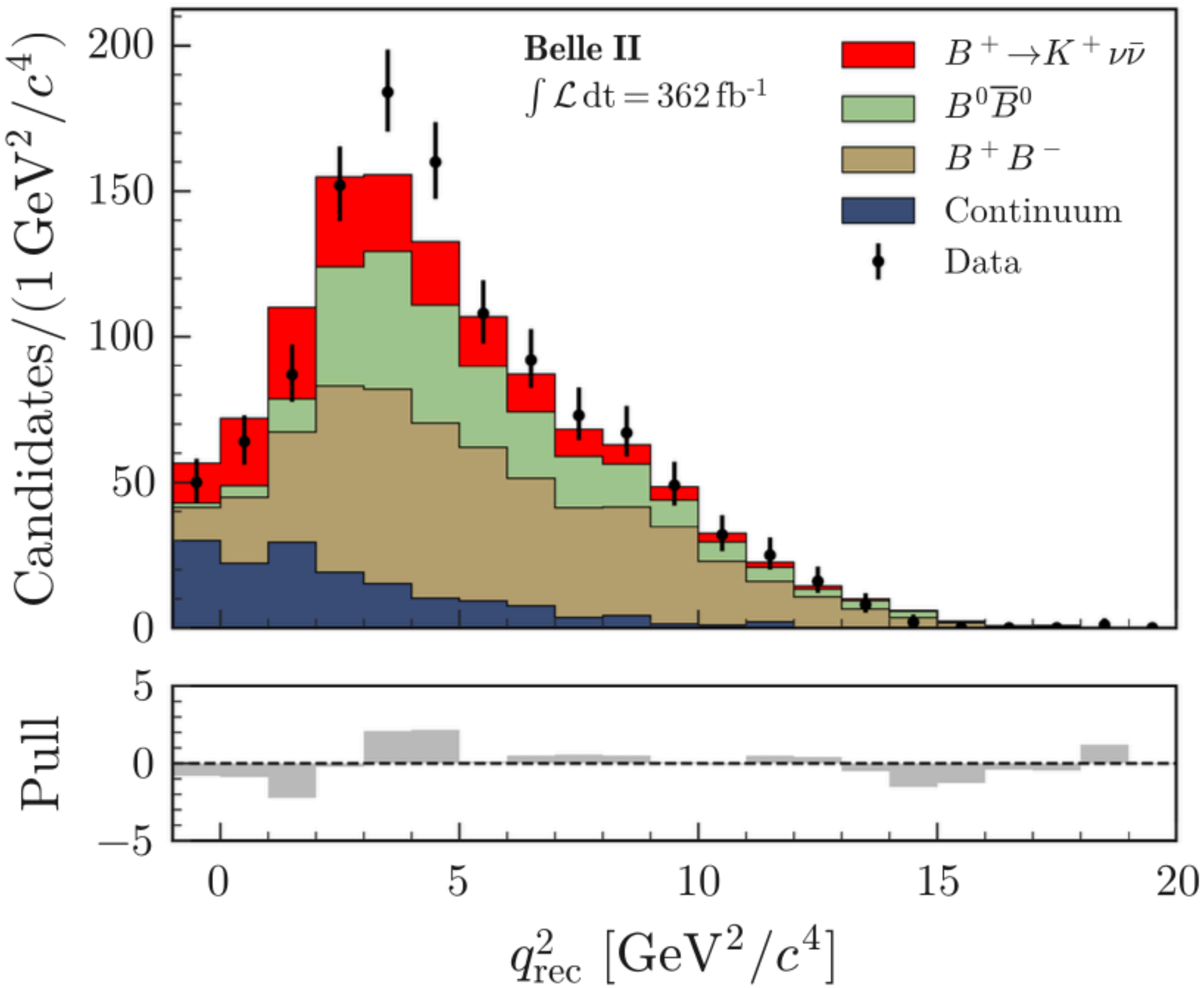
$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{HTA}} = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{ITA}} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{comb}} = (2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$$

Editors' Suggestion
PRD 109, 112006 (2024)

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



- Post-fit distribution
  - signal-enhanced region for inclusive-tag analysis
  - Data vs. MC discrepancy — analysis was done under SM scenario
  - ∃ a paper on *re-interpretation* method (EPJC 84(2024)693)
    ✓ why not apply it to $B^+ \to K^+\nu\bar{\nu}$?

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\rm ITA} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$$

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https://doi.org/10.1140/epjc/s10052-024-13038-4

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Constructing model-agnostic likelihoods, a method for the reinterpretation of particle physics results

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Abstract Experimental High Energy Physics has entered an era of precision measurements. However, measurements of many of the accessible processes assume that the final

terpretable. We showcase that publishing such likelihoods is crucial for a full exploitation of experimental results.

$B^+ \to K^+\nu\bar{\nu}$, Re-interpretation

- Things to note
  - The Belle II $B^+ \to K^+\nu\bar{\nu}$ [PRD (2024)] measurement — performed under SM scenario
  - ∃ a paper on ***re-interpretation*** method (EPJC 84(2024)693)
    ✓ why not apply it to $B^+ \to K^+\nu\bar{\nu}$?

$$q^2 = M(\nu\bar{\nu})^2$$

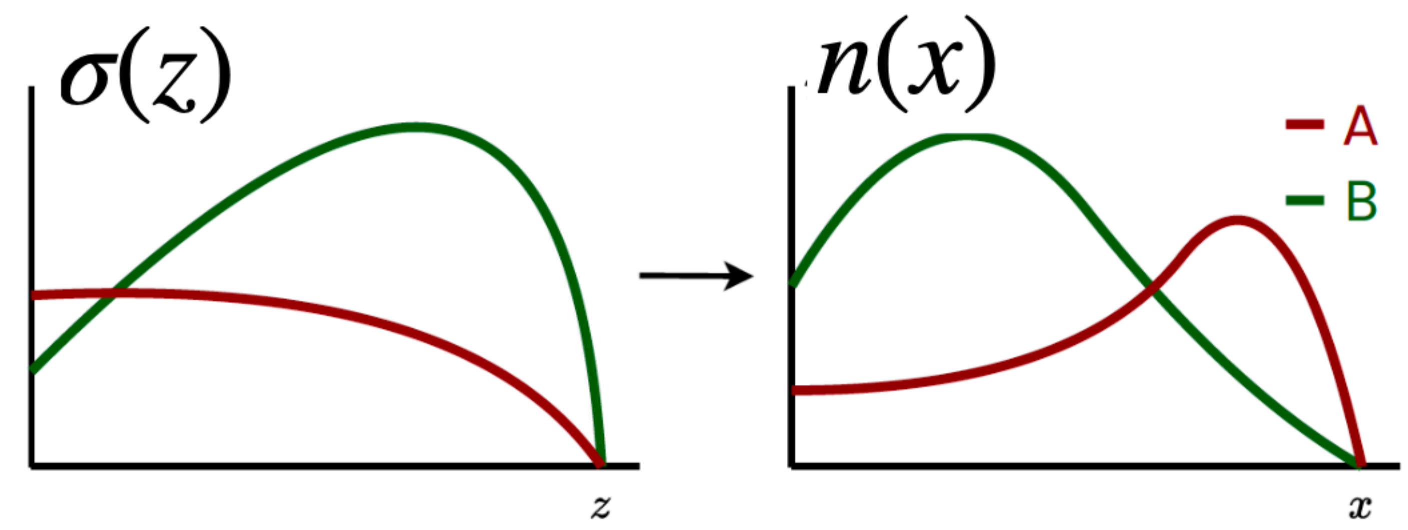
- Method
  - Number density & Joint number density
    ✓ σ = theory, ε = efficiency, x = fit variable
  - Null model (e.g. SM) vs. Alternative model

$$n(x) = L \int dq^2\ \varepsilon(x|q^2)\ \sigma(q^2)$$

$$n(x, q^2) \equiv L\ \varepsilon(x|q^2)\ \sigma(q^2)$$

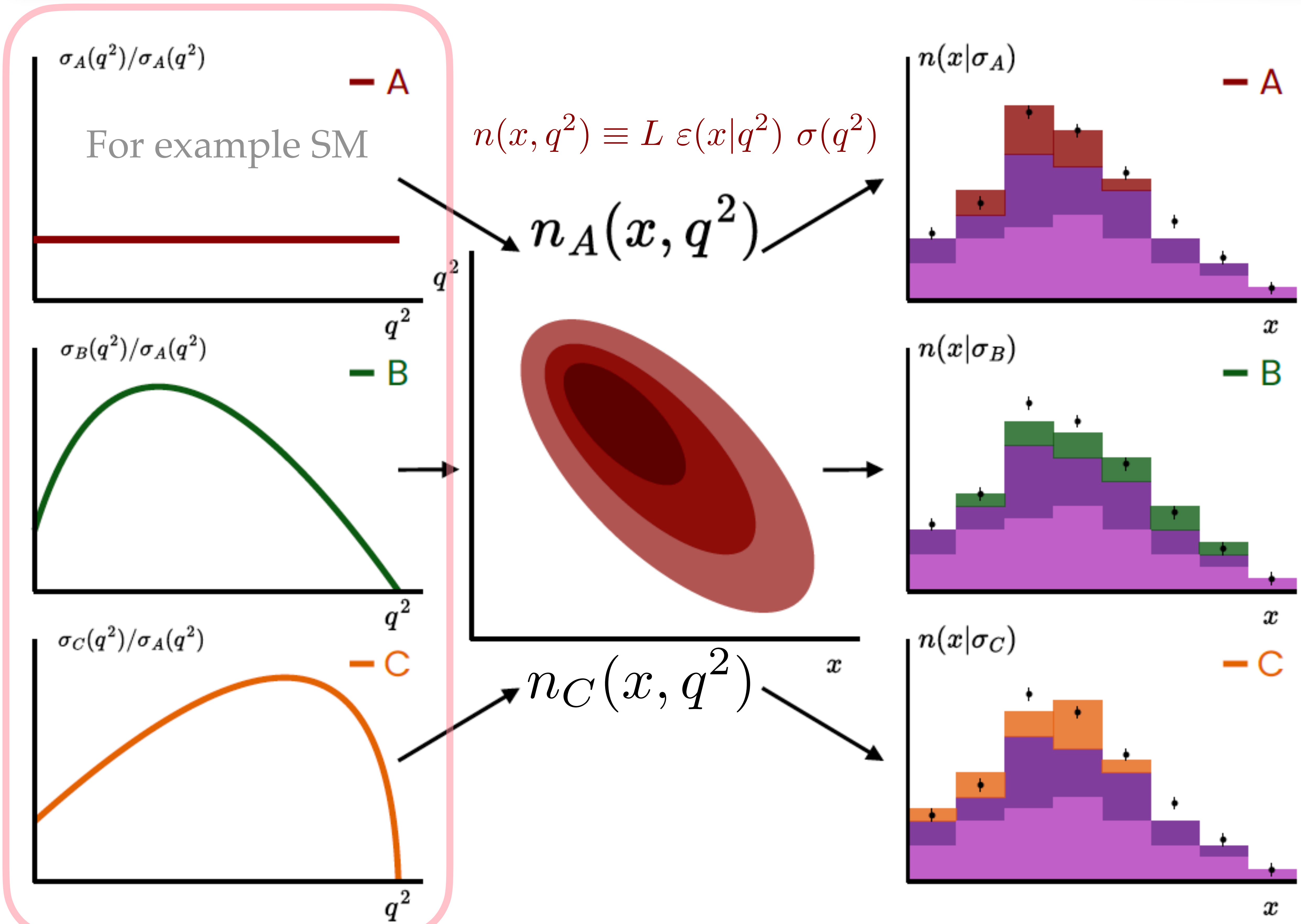
$$n_1(x) = L \int dq^2\ n_0(x, q^2)\ w(q^2)$$

$$w(q^2) = \frac{\sigma_1(q^2)}{\sigma_0(q^2)}$$



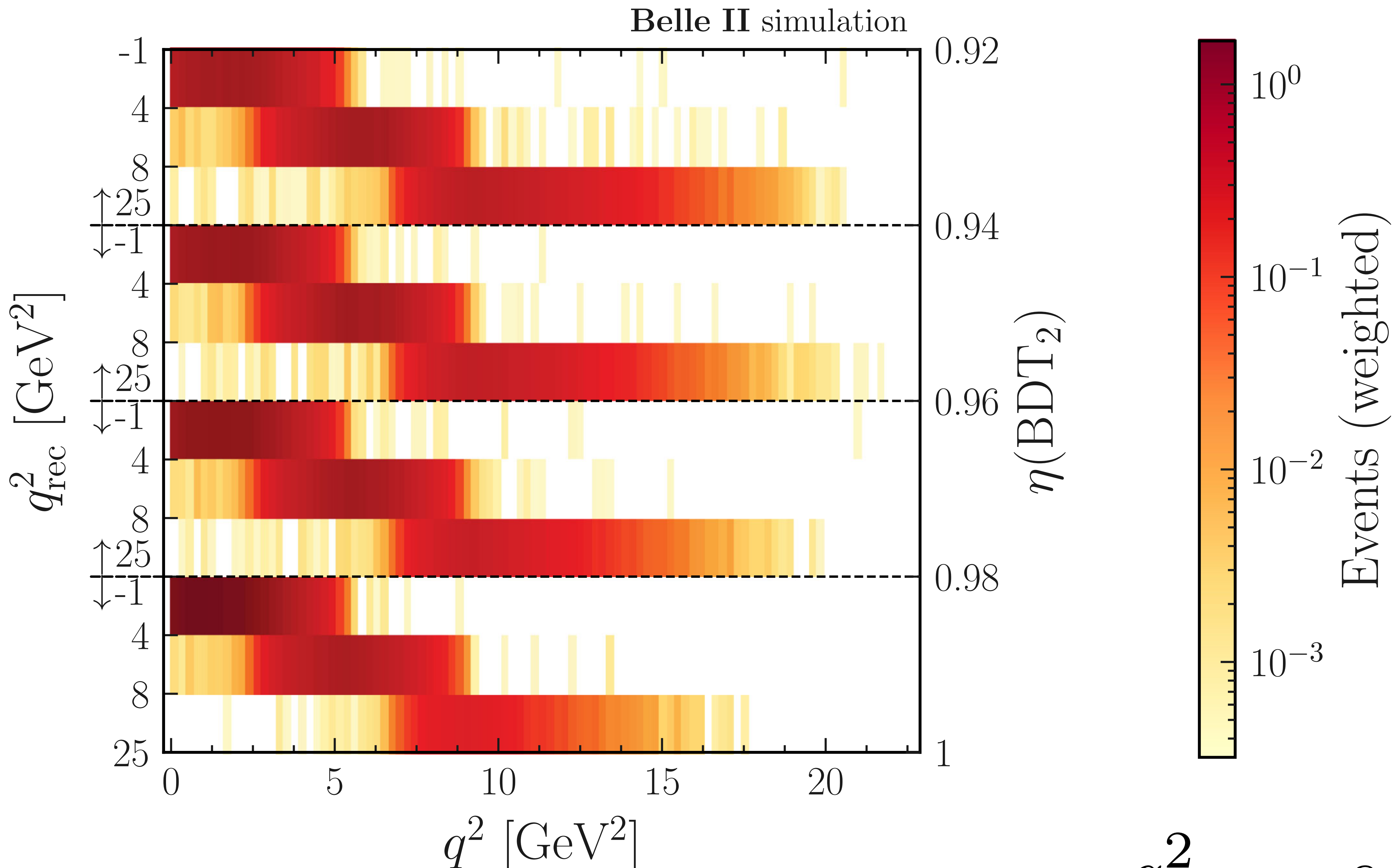
$B^+ \to K^+\nu\bar{\nu}$, Re-interpretation

$$w(q^2) = \frac{\sigma_1(q^2)}{\sigma_0(q^2)}$$



$B^+ \to K^+\nu\bar{\nu}$, Re-interpretation

Plot for x vs. q^2

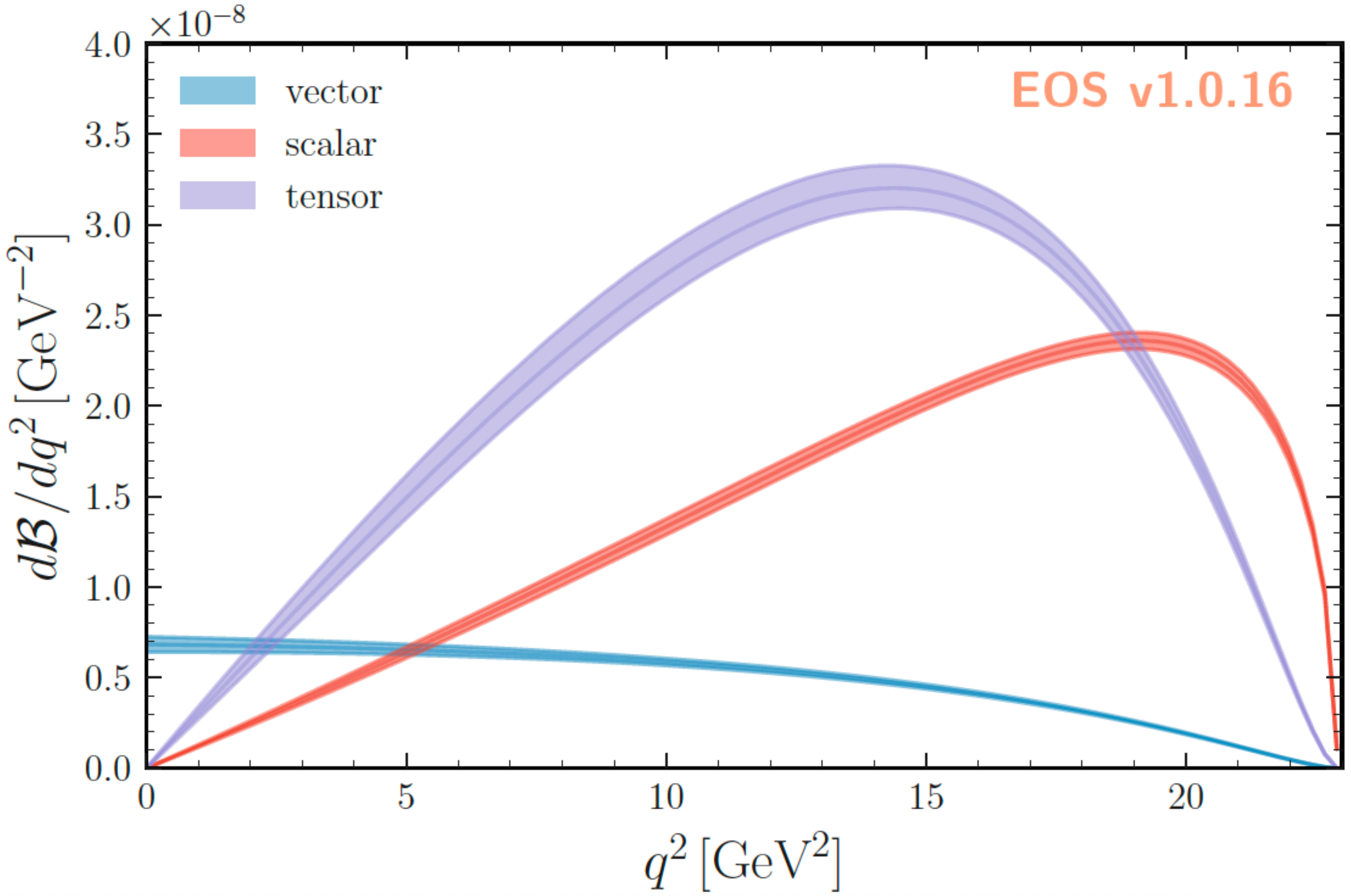


Reconstruction (fit) variable: $x = (\eta_{\mathrm{BDT}}, q^2_{\mathrm{rec}})$

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

$B^+ \to K^+\nu\bar{\nu}$, Re-interpretation

various models (here, shown for $d\mathscr{B}/dq^2$)



Parameters of interest

for re-interpretation in the weak effective theory (WET),

$$\boldsymbol{\eta} = [C_{\mathrm{VL}} + C_{\mathrm{VR}}, C_{\mathrm{SL}} + C_{\mathrm{SR}}, C_{\mathrm{TL}}]$$

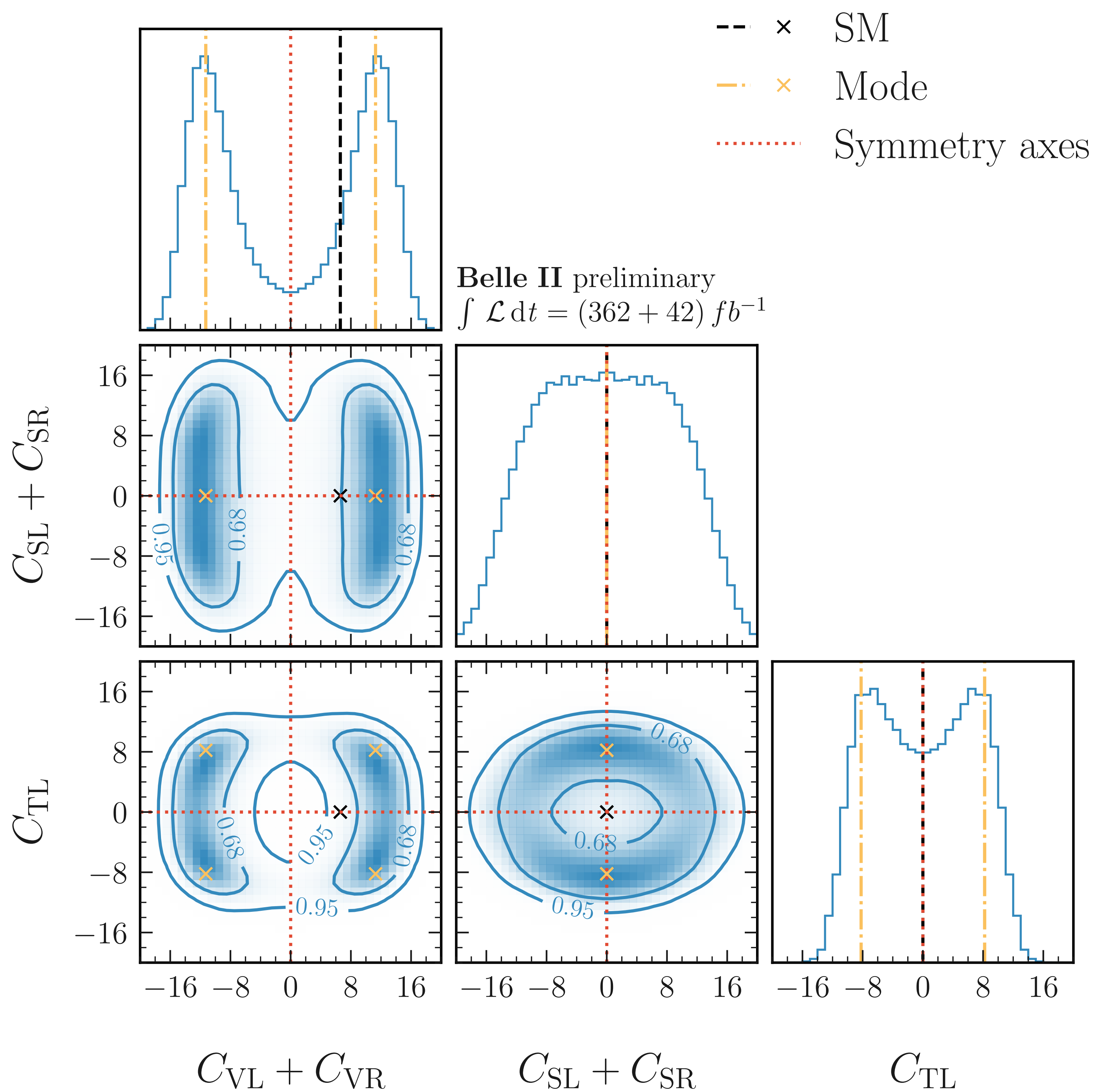
In the SM, only $C_{\mathrm{VL}} \neq 0$

$$\frac{d\mathcal{B}}{dq^2} = 3\tau_B \left(\frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi}\right)^2 |V_{ts}^* V_{tb}|^2 \frac{\sqrt{\lambda_{BK}}q^2}{(4\pi)^3 M_B^3} \cdot \left[\frac{\lambda_{BK}}{24q^2}|f_+(q^2)|^2|C_{\mathrm{VL}} + C_{\mathrm{VR}}|^2 + \frac{(M_B^2 - M_K^2)^2}{8(m_b - m_s)^2}|f_0(q^2)|^2|C_{\mathrm{SL}} + C_{\mathrm{SR}}|^2 + \frac{2\lambda_{BK}}{3(M_B + M_K)^2}|f_T(q^2)|^2|C_{\mathrm{TL}}|^2\right]$$

$$\mathcal{O}_{\mathrm{VL}} = (\overline{\nu_L}\gamma_\mu\nu_L)(\overline{s_L}\gamma^\mu b_L),$$
$$\mathcal{O}_{\mathrm{VR}} = (\overline{\nu_L}\gamma_\mu\nu_L)(\overline{s_R}\gamma^\mu b_R),$$
$$\mathcal{O}_{\mathrm{SL}} = (\overline{\nu_L^c}\nu_L)(\overline{s_R}b_L),$$
$$\mathcal{O}_{\mathrm{SR}} = (\overline{\nu_L^c}\nu_L)(\overline{s_L}b_R),$$
$$\mathcal{O}_{\mathrm{TL}} = (\overline{\nu_L^c}\sigma_{\mu\nu}\nu_L)(\overline{s_R}\sigma^{\mu\nu}b_L).$$

PRD 112, 092016 (2025)

$B^+ \to K^+ \nu\bar{\nu}$, Re-interpretation results

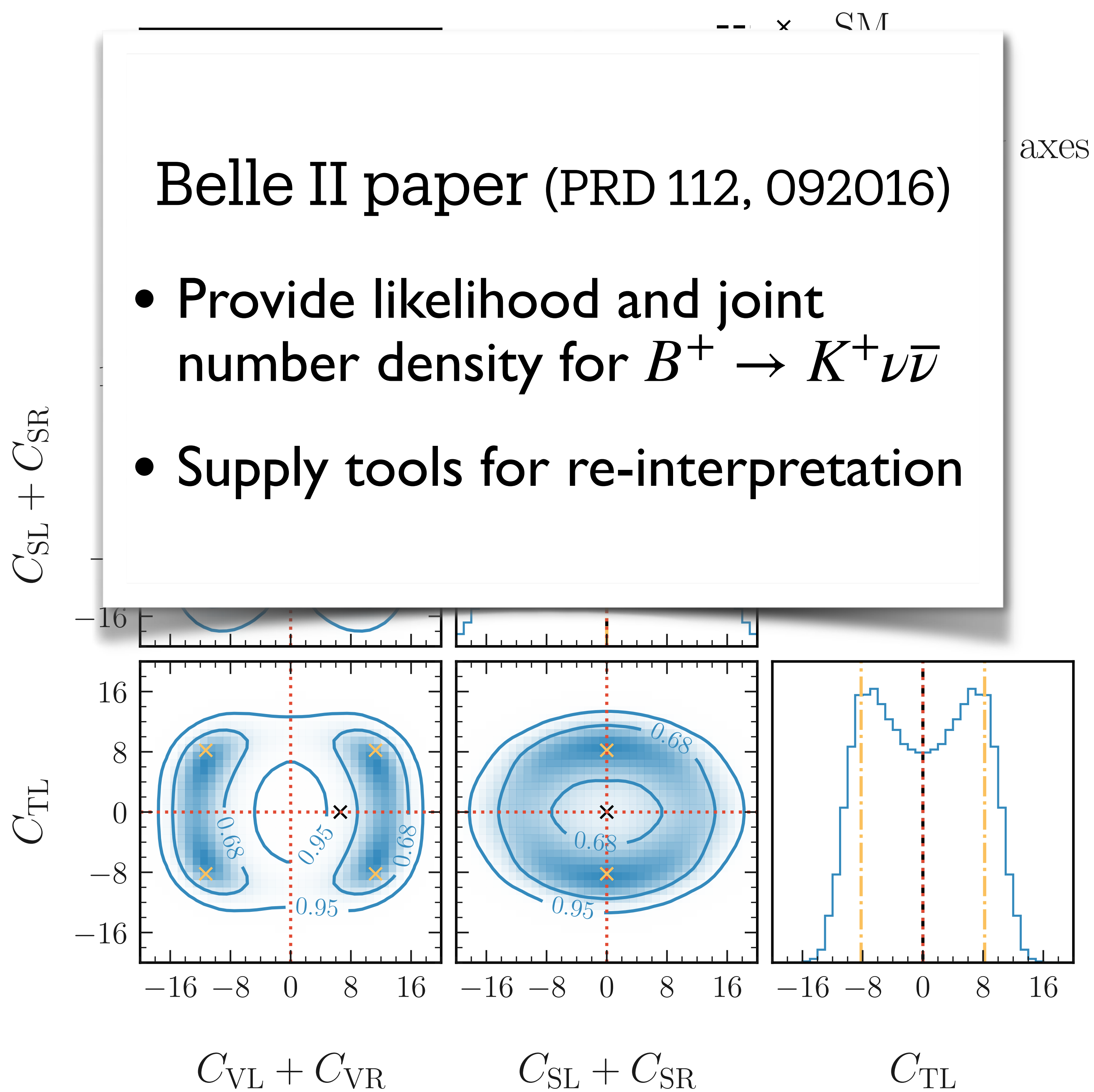


Marginal posterior for the Wilson coeffs. (Bayesian)

Parameters	Mode	68% HDI	95% HDI
$\lvert C_{VL}+C_{VR}\rvert$	11.3	[7.82, 14.6]	[1.86, 16.2]
$\lvert C_{SL}+C_{SR}\rvert$	0.00	[0.00, 9.58]	[0.00, 15.4]
$\lvert C_{TL}\rvert$	8.21	[2.29, 9.62]	[0.00, 11.2]

PRD 112, 092016 (2025)

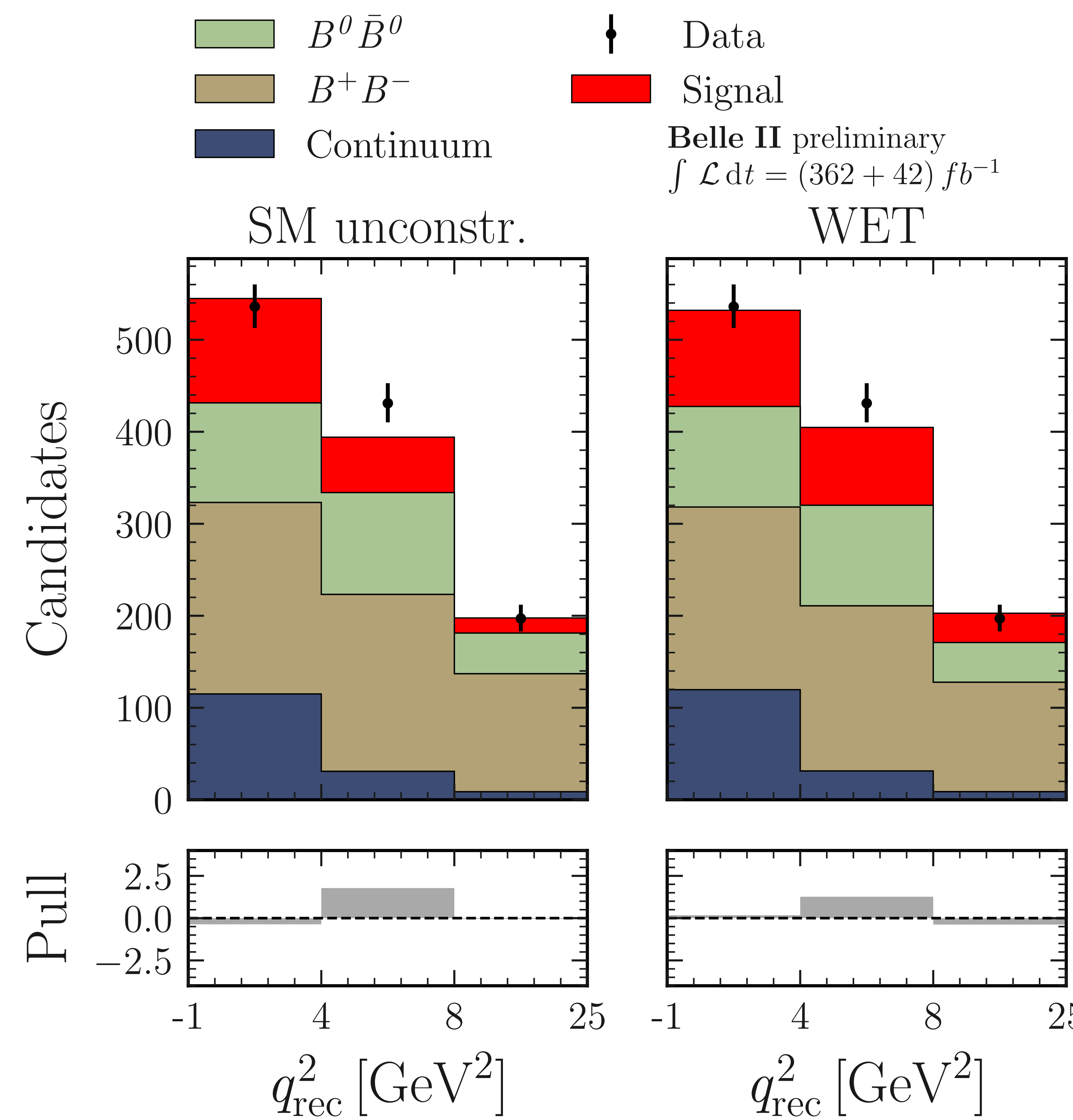
$B^+ \to K^+ \nu\bar{\nu}$, Re-interpretation results



Belle II paper (PRD 112, 092016)

- Provide likelihood and joint number density for $B^+ \to K^+ \nu\bar{\nu}$
- Supply tools for re-interpretation

Marginal posterior for the Wilson coeffs. (Bayesian)

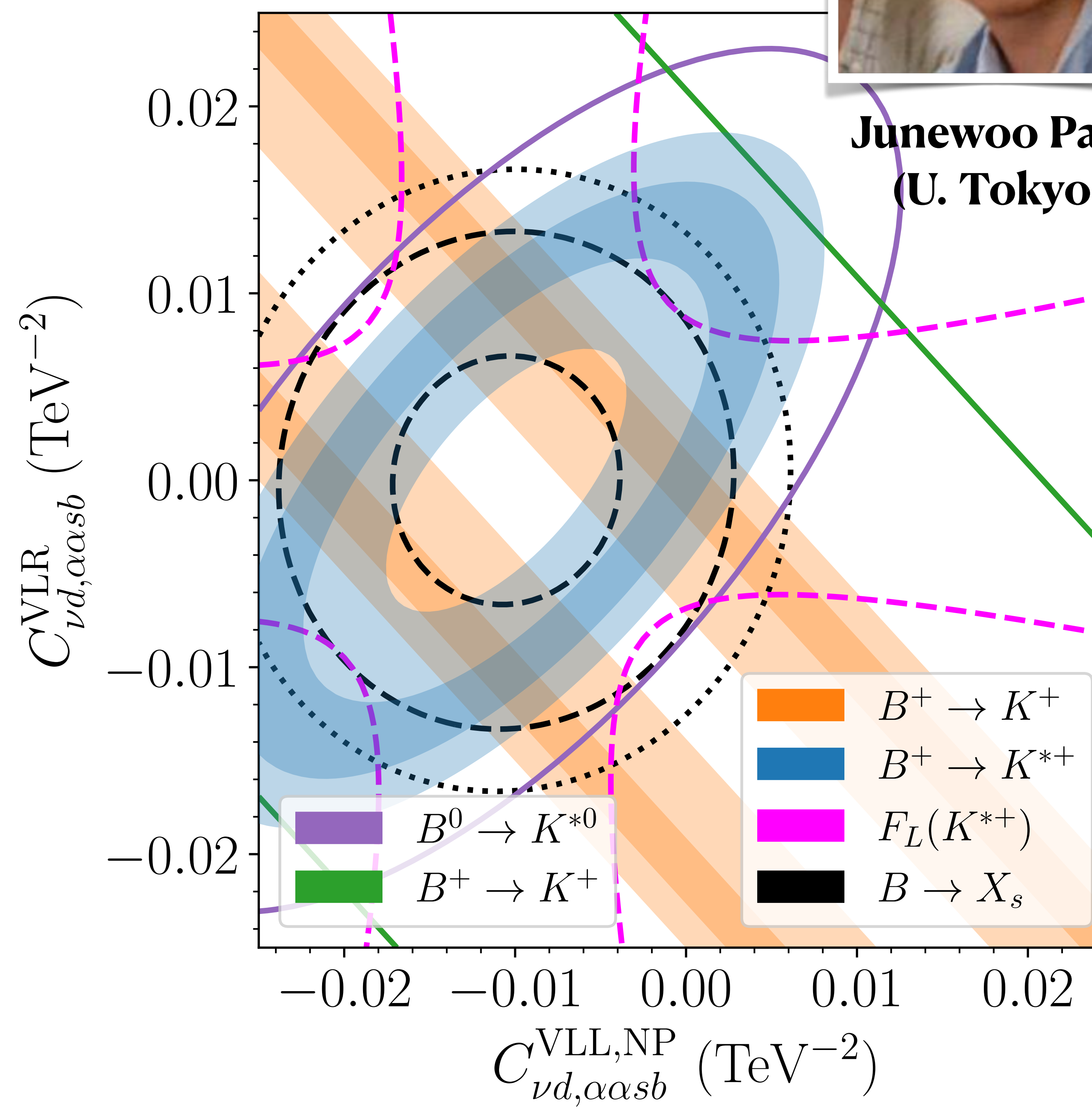


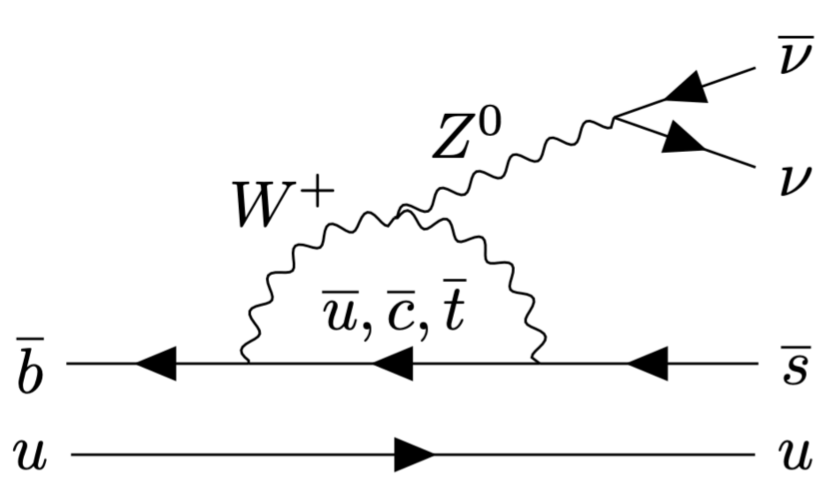
- SM vs. WET (V+T, preferred over SM)
- 3.3σ for WET vs. (Bkgd. only)

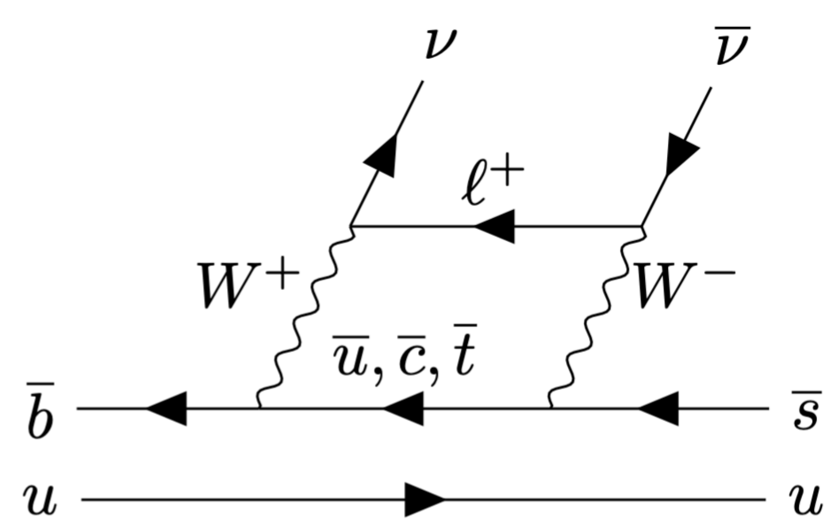
$B \to X_s \nu\bar{\nu}$ Inclusive, *why bother?*

Junewoo Park (U. Tokyo)

- Things to note
  - Inclusive measurement for X_s (= hadronic system with $S = \pm 1$) final states
  - sensitive to different (compared to $B^+ \to K^+ \nu\bar{\nu}$) aspects of SM & NP
    e.g. not depending on hadronic FF
  - not very well-measured
    only by ALEPH (BF < 6.4×10^{-4} @ 90% CL)
    no separate measurement for 'B mesons'

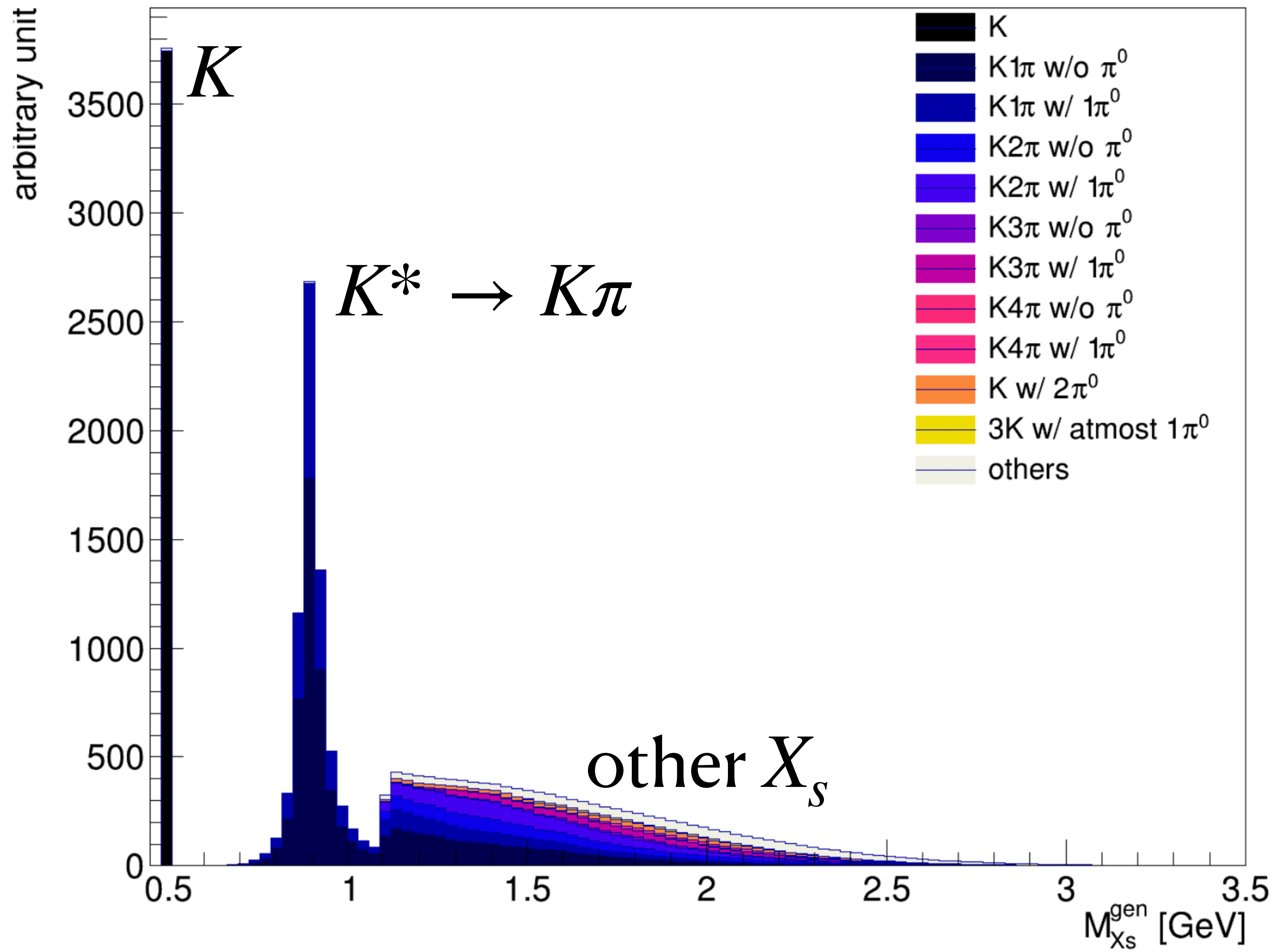






from Felkl, T., Li, S.L. & Schmidt, M.A. "A tale of invisibility: constraints on new physics in $b \to s\nu\nu$". *J. High Energ. Phys.* **2021**, 118 (2021)

breakdown of X_s states in $M_{X_s}^{\text{gen}}$

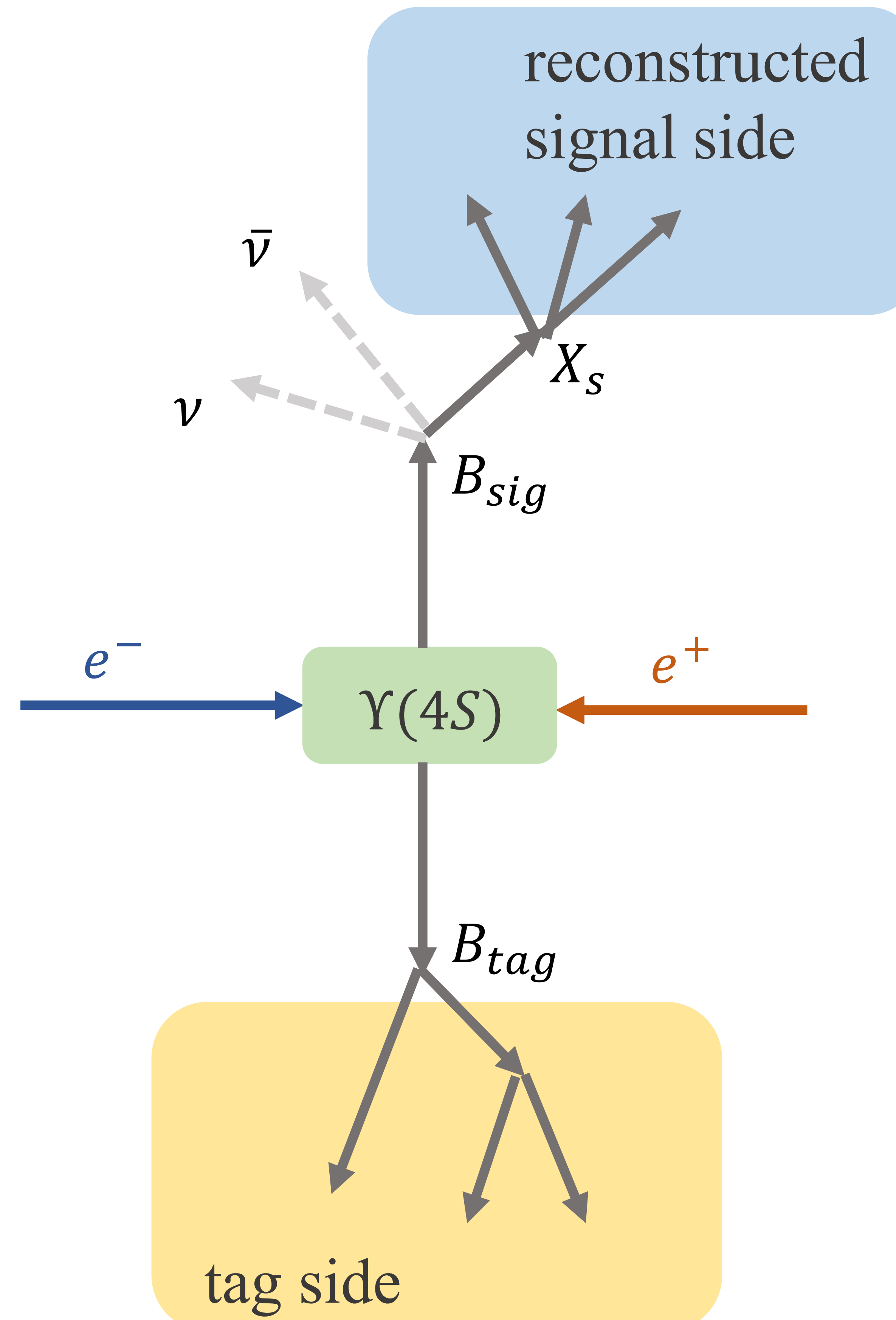


$B \to X_s \nu\bar{\nu}$ Inclusive, *how-to*

- Main features of analysis
  - Hadronic B-tagging via FEI
  - *Inclusive* measurement of X_s final states by using "sum of exclusive" method

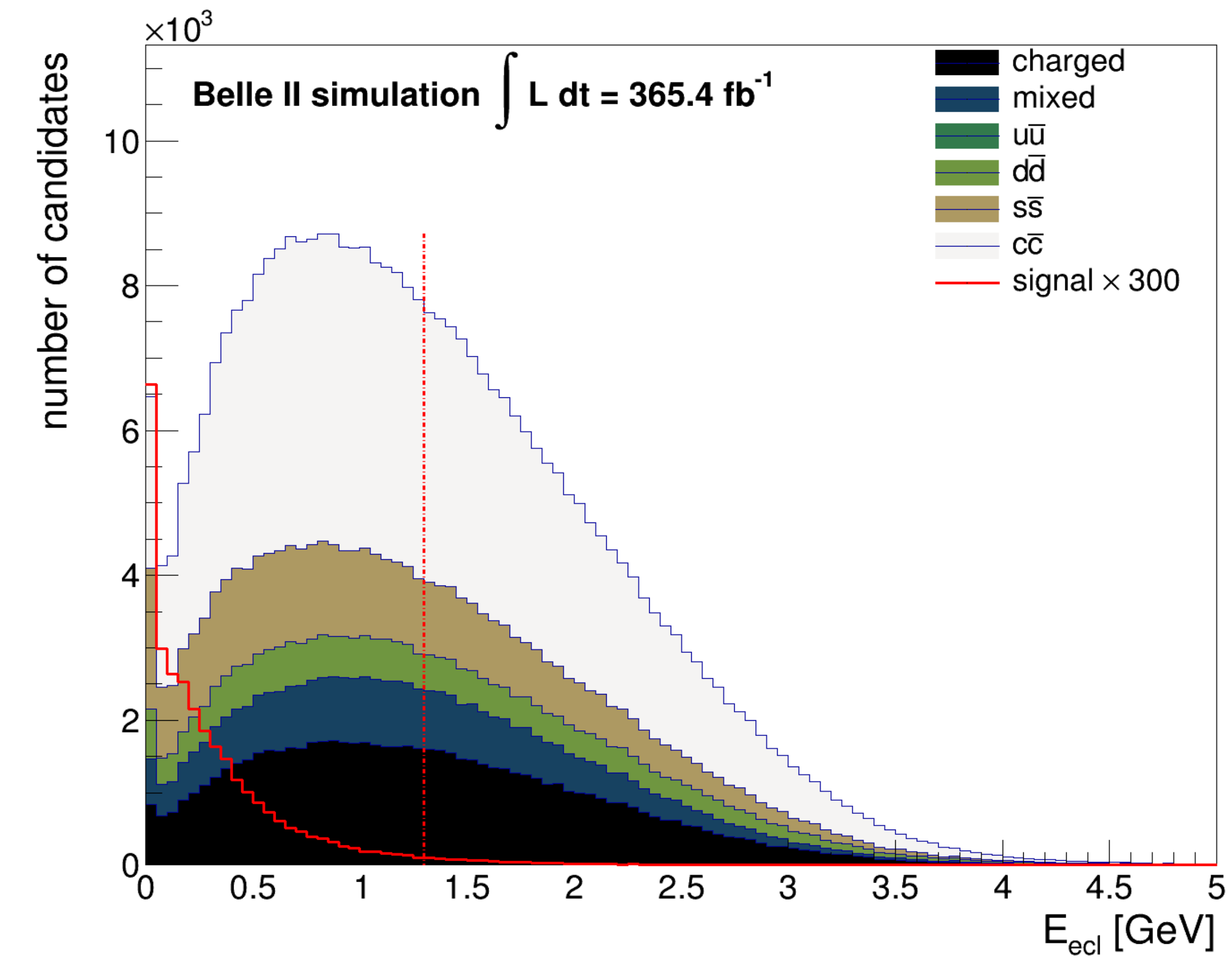
	$B^0\bar{B}^0$			$B^\pm$		
K	K_S^0			$K^\pm$		
$K\pi$	$K^\pm\pi^\mp$	$K_S^0\pi^0$		$K^\pm\pi^0$	$K_S^0\pi^\pm$	
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp$	$K_S^0\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0$	$K^\pm\pi^0\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0\pi^0$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0\pi^0$
$3K$	$K^\pm K^\mp K_S^0$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm\pi^\mp$	$K^\pm K^\mp K_S^0\pi^0$		$K^\pm K^\mp K^\pm\pi^0$	$K_S^0 K^\pm K^\mp\pi^\pm$	

The summed modes cover ~93% of the entire $X_s\nu\bar{\nu}$ decays, estimated from MC (assume K_S^0 is half of K^0)

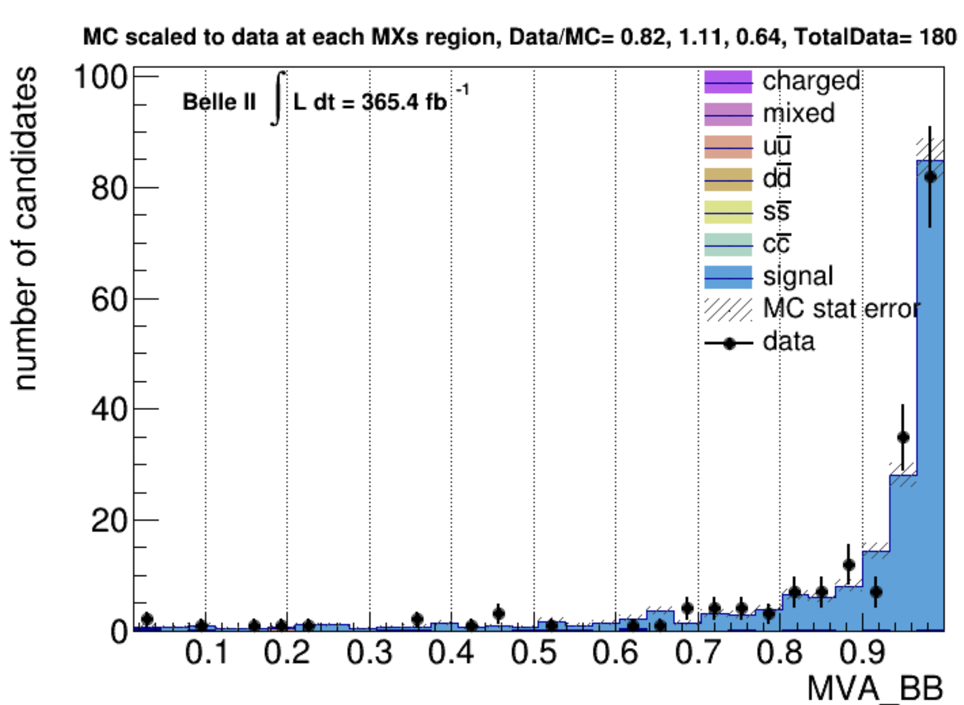


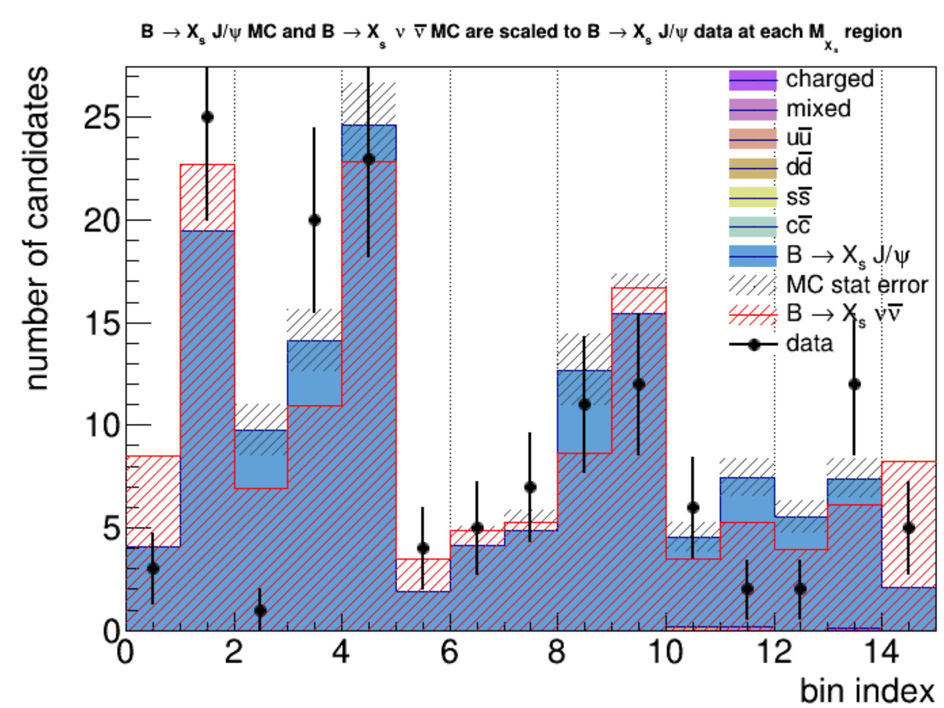
arXiv:2511.10980

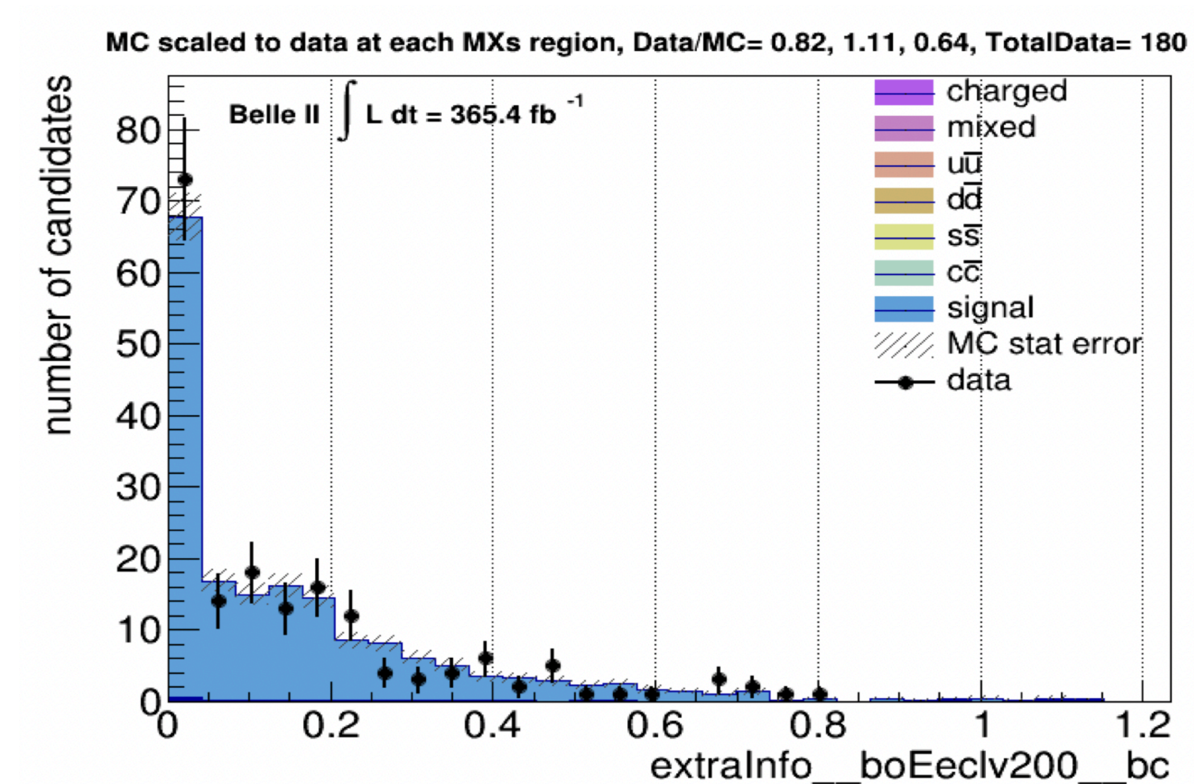
$B \to X_s \nu\bar{\nu}$ Inclusive



- Procedure after X_s reconstruction
  - use BDT for background suppression
  - validation & correction using control samples
    - ✓ off-resonance data
    - ✓ BDT side-band
    - ✓ $B \to X_s J/\psi$

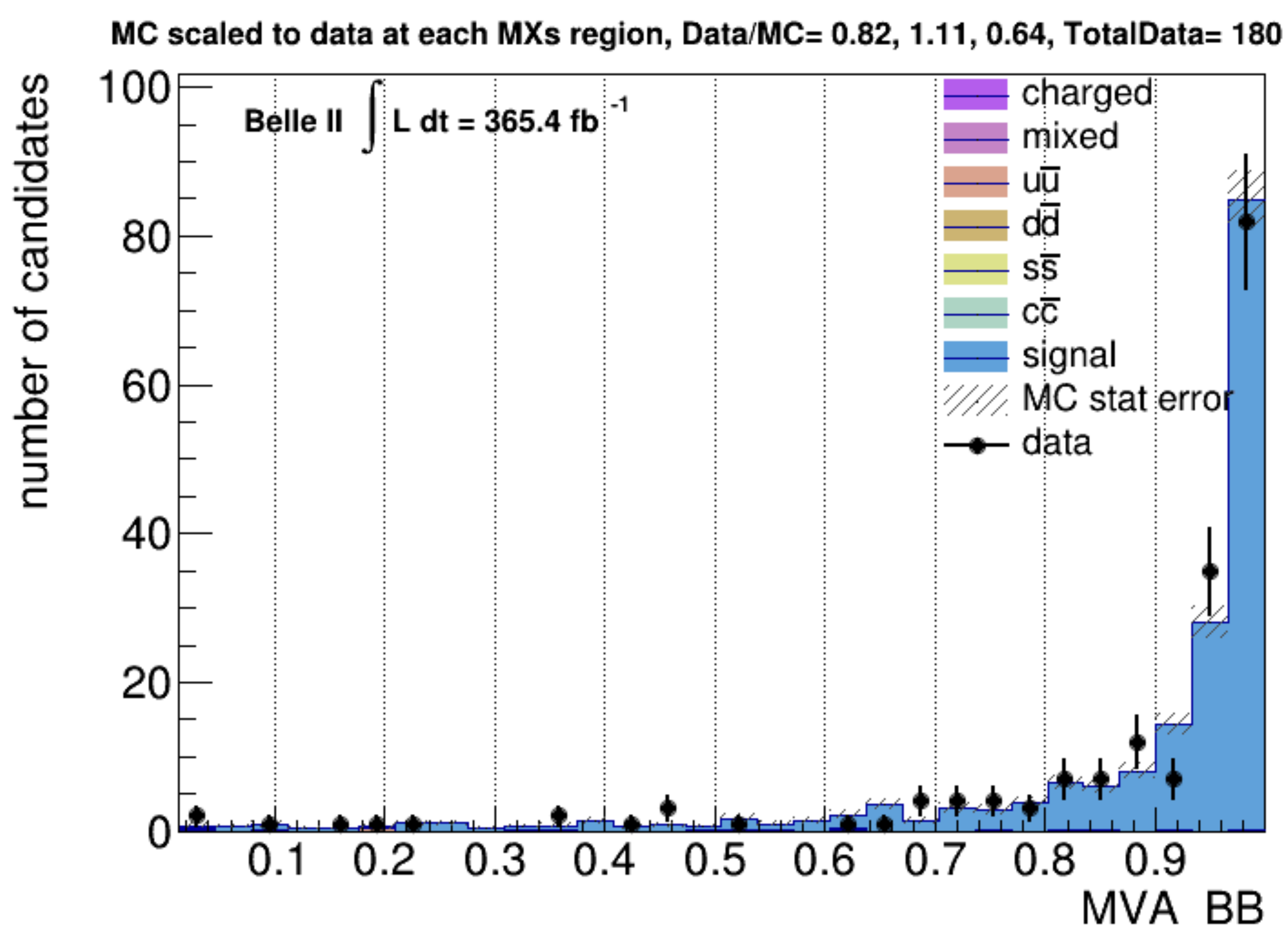


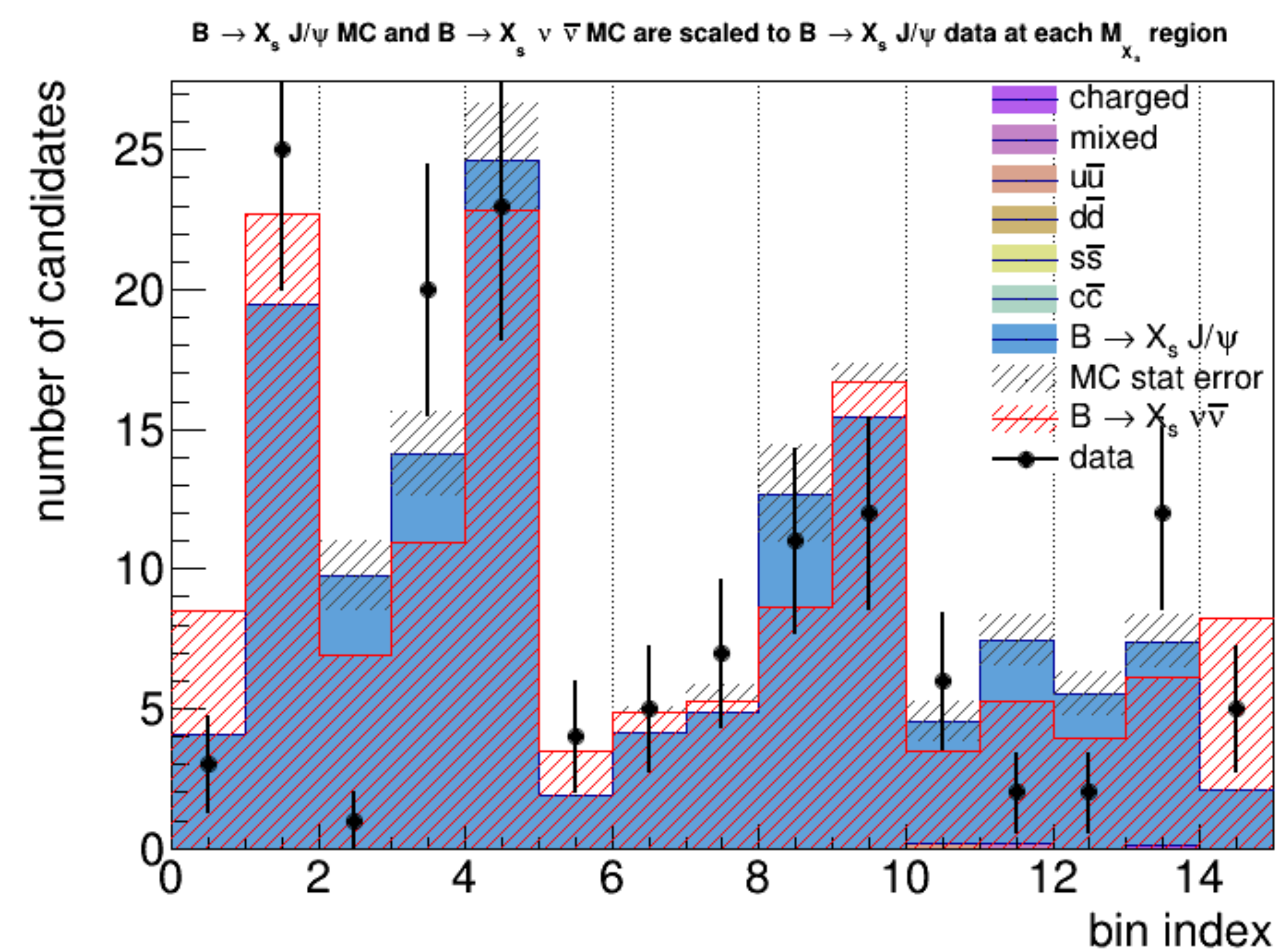




correction factor from $B \to X_s J/\psi$ control sample

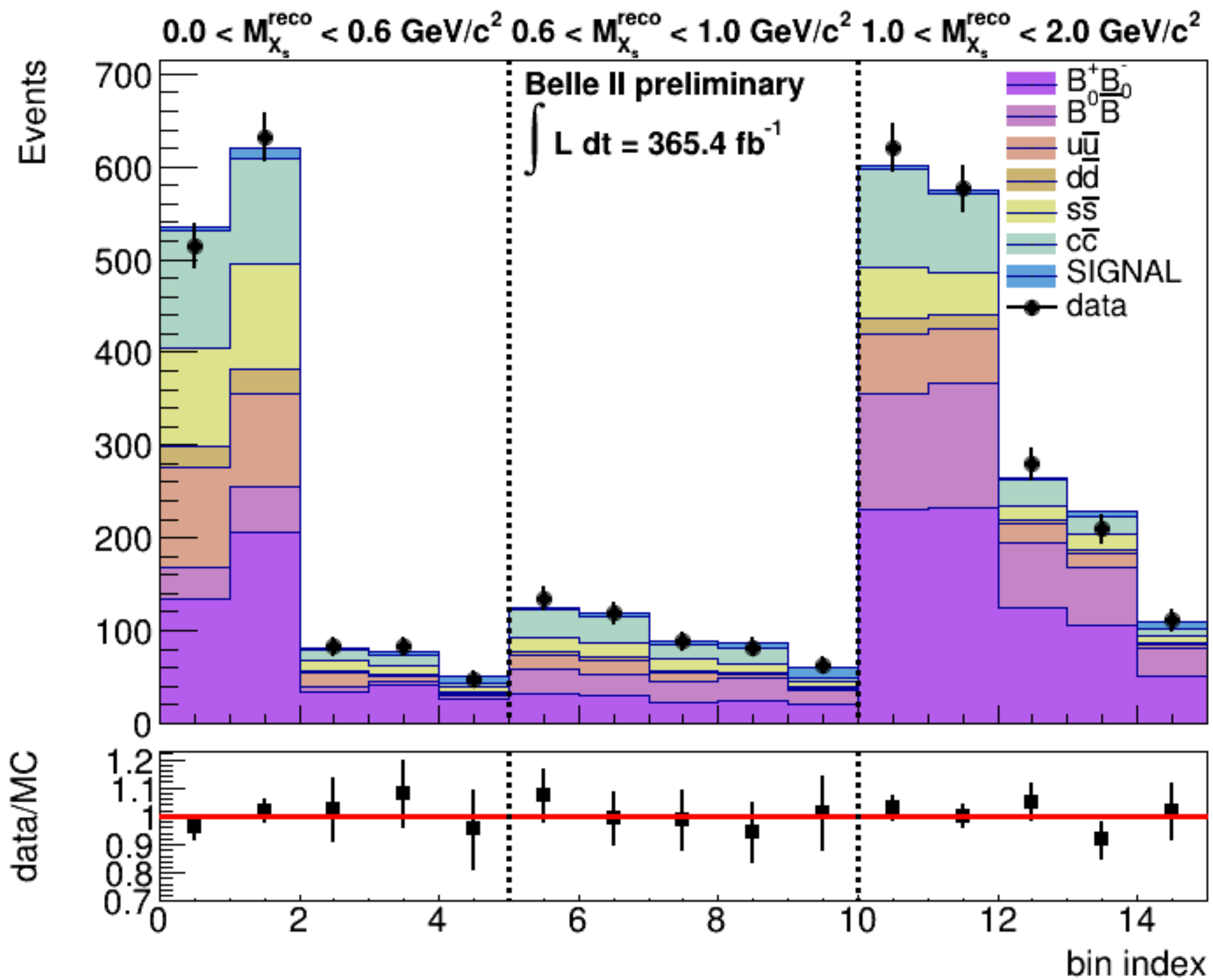
$$\frac{\epsilon^{\rm FBDT}_{\rm Data}}{\epsilon^{\rm FBDT}_{\rm MC}} = \begin{cases} 1.00 \pm 0.04 & (0.0 < M^{\rm reco}_{X_s} < 0.6\ {\rm GeV}), \\ 1.05 \pm 0.08 & (0.6 \leq M^{\rm reco}_{X_s} < 1.0\ {\rm GeV}), \\ 0.97 \pm 0.14 & (1.0 \leq M^{\rm reco}_{X_s} < 2.0\ {\rm GeV}), \end{cases}$$





$B \to X_s \nu\bar{\nu}$ Inclusive, *Results*

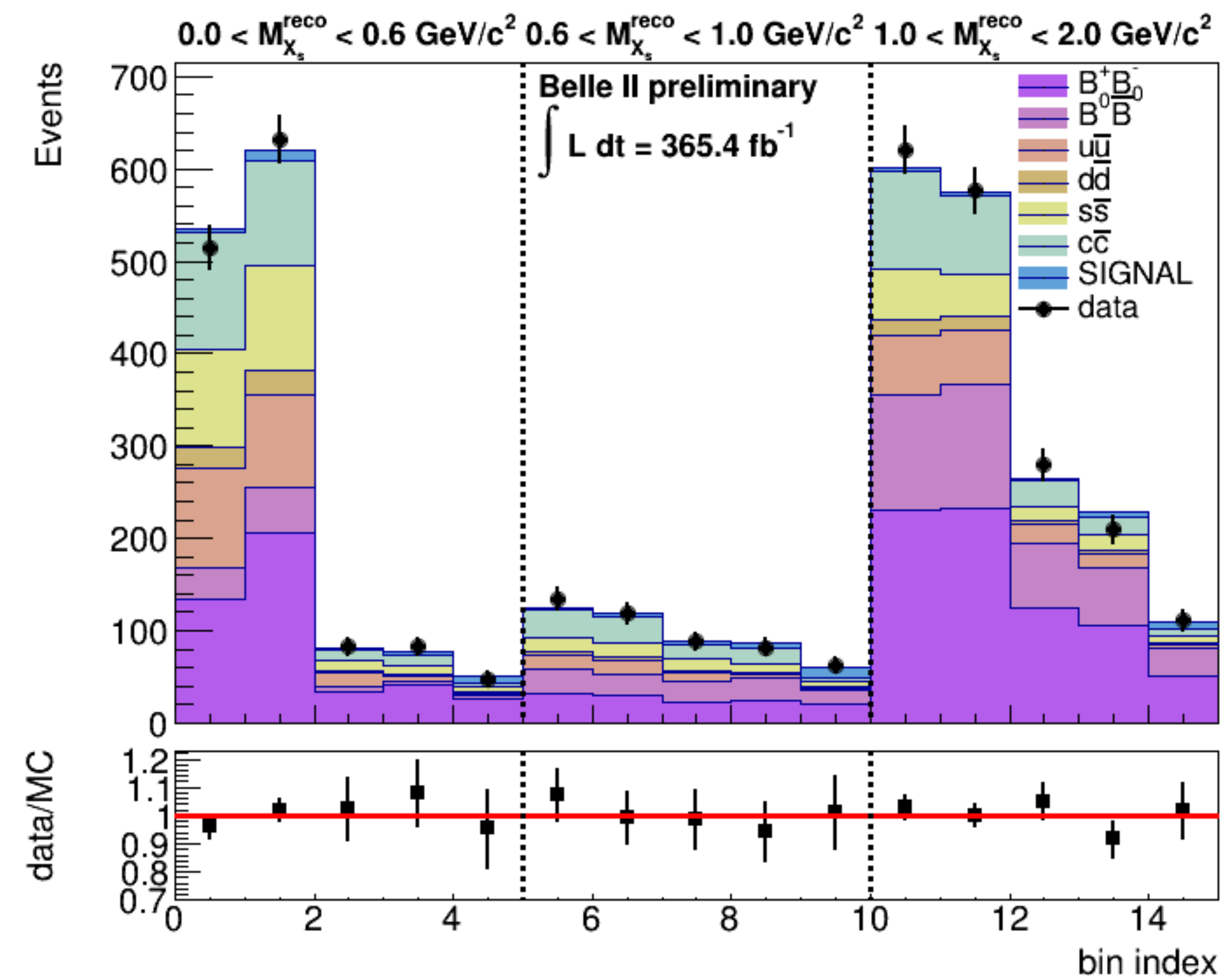
- signal extraction by 2D binned max. likelihood fit to ($M_{X_s}^{\mathrm{reco}}$, BDT output)



arXiv:2511.10980
submitted to PRL

$B \to X_s \nu \bar{\nu}$ Inclusive, *Results*

- No excess ➔ set upper limits (90% CL, by CLs method)
  - $\mathscr{B}(B \to X_s \nu \bar{\nu}) < 2.5 \times 10^{-5}$ ($M_{X_s} < 0.6$)
  - $\mathscr{B}(B \to X_s \nu \bar{\nu}) < 1.0 \times 10^{-4}$ $(0.6 < M_{X_s} < 1.0)$
  - $\mathscr{B}(B \to X_s \nu \bar{\nu}) < 3.5 \times 10^{-4}$ $(1.0 < M_{X_s}$)
  - $\mathscr{B}(B \to X_s \nu \bar{\nu}) < 3.6 \times 10^{-4}$ (all M_{X_s} region)



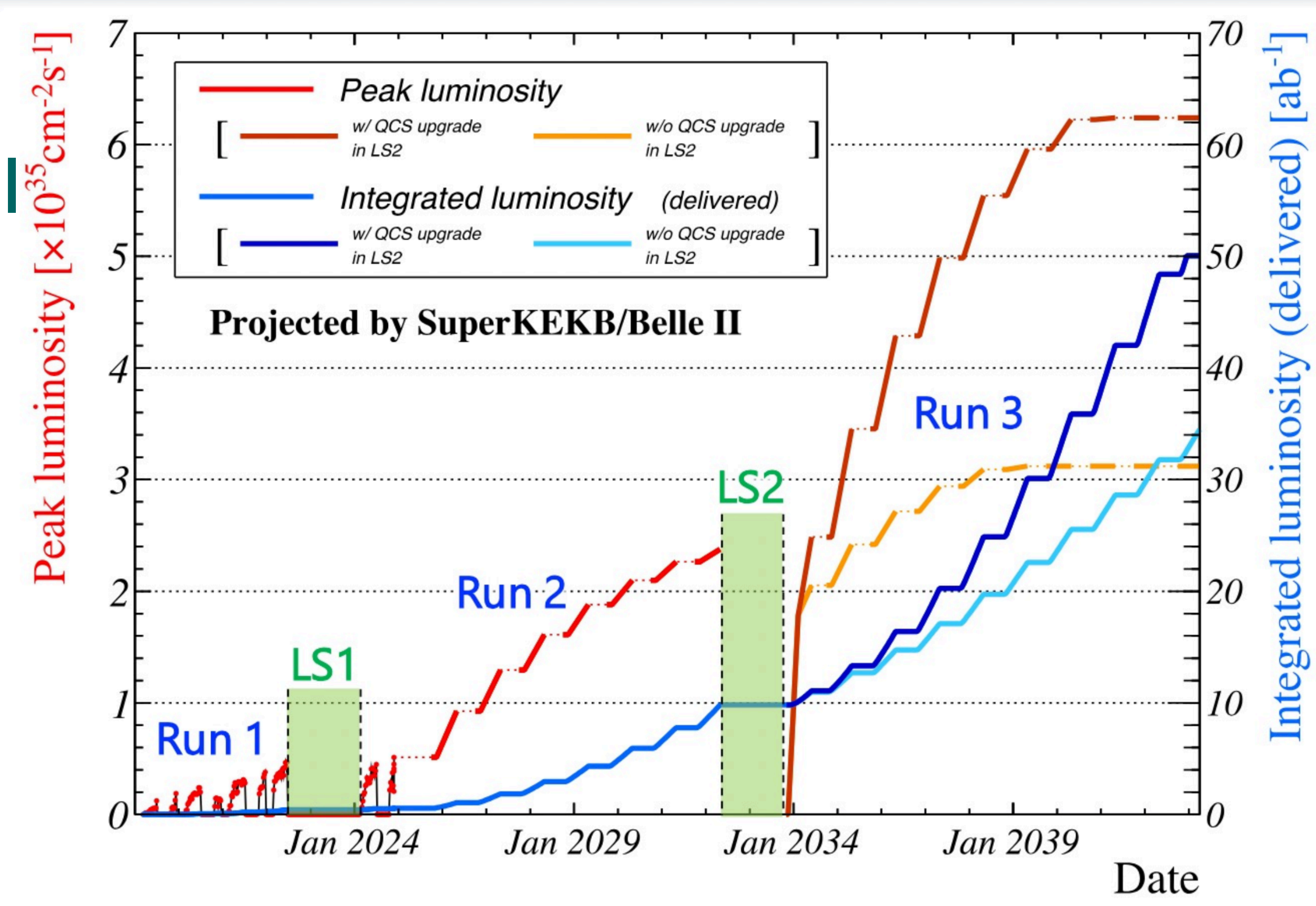
The most stringent limit for inclusive $B \to X_s \nu \bar{\nu}$
(the first for B-meson)

Closing remarks

- Although Belle II (and Belle) has been conceived and constructed mainly for studies of CP violation and heavy-flavor physics, it also provides an excellent probe for dark sector physics in $\mathcal{O}(1 \sim 10\ \mathrm{GeV})$ range.

- In this talk, we showed a few recent dark sector search results from Belle II and Belle.

- Belle II Run 2 resumed (*after a short break*) with a goal of collecting several ab^{-1} data in the next few years. Please stay tuned!



Thank you!

Appendix

Other dark sector results from Belle II

- Invisible Z' in $e^+e^- \to \mu^+\mu^- + (\text{missing})$ PRL 124, 141801 (2020)
- Invisible Z' in $e^+e^- \to \mu^+\mu^- + (\text{missing})$ PRL 130, 231801 (2023)
- A' and invisible h' in $e^+e^- \to \mu^+\mu^- + (\text{missing})$ PRL 130, 071804 (2023)
- $\tau^+\tau^-$ resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ PRL 131, 121802 (2023)
- Long-lived spin-0 mediator in $b \to sX$ PRD 108, L111104 (2023)

Honorable mentions

- Invisible boson α in $\tau^+ \to \ell^+\alpha$ PRL 130, 181803 (2023)

Parameters of dark sector with inelastic DM

- α_{D} = strength of dark-sector U(1) gauge interaction
- ε = mixing parameter between γ and A'
- θ = mixing angle between SM higgs h and dark higgs h'

$$\begin{aligned} \alpha_{\mathrm{D}} &= 0.1 \\ \varepsilon &= 1.5 \times 10^{-3} \\ m(\chi_1) &= 2.5\ \mathrm{GeV} \\ m(A') &= 3m(\chi_1) \\ \Delta m &= 0.4m(\chi_1) \\ \sin\theta &= 2.6 \times 10^{-4} \end{aligned}$$

a typical choice (p.31)