Dark sector studies with Belle & Belle II

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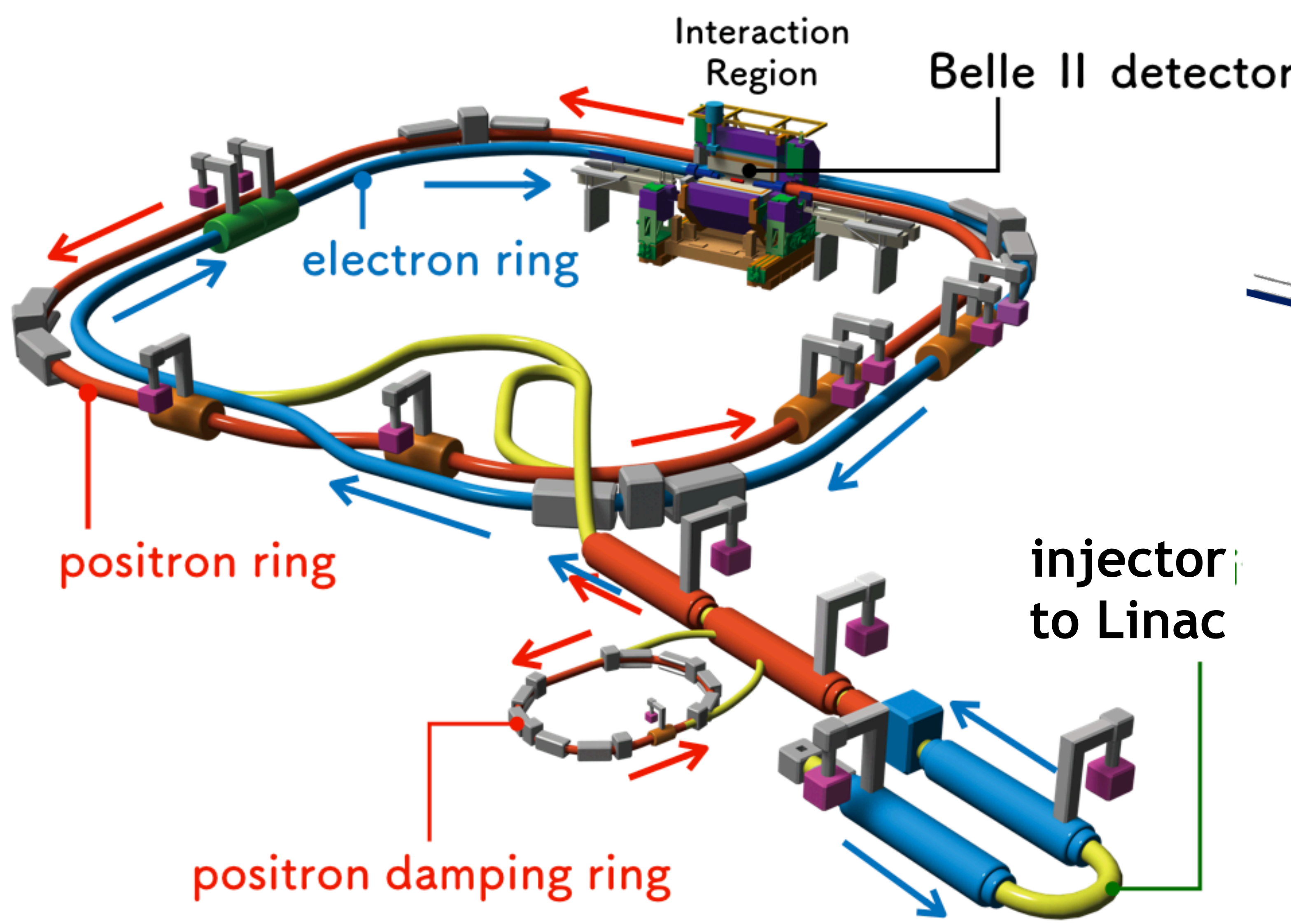
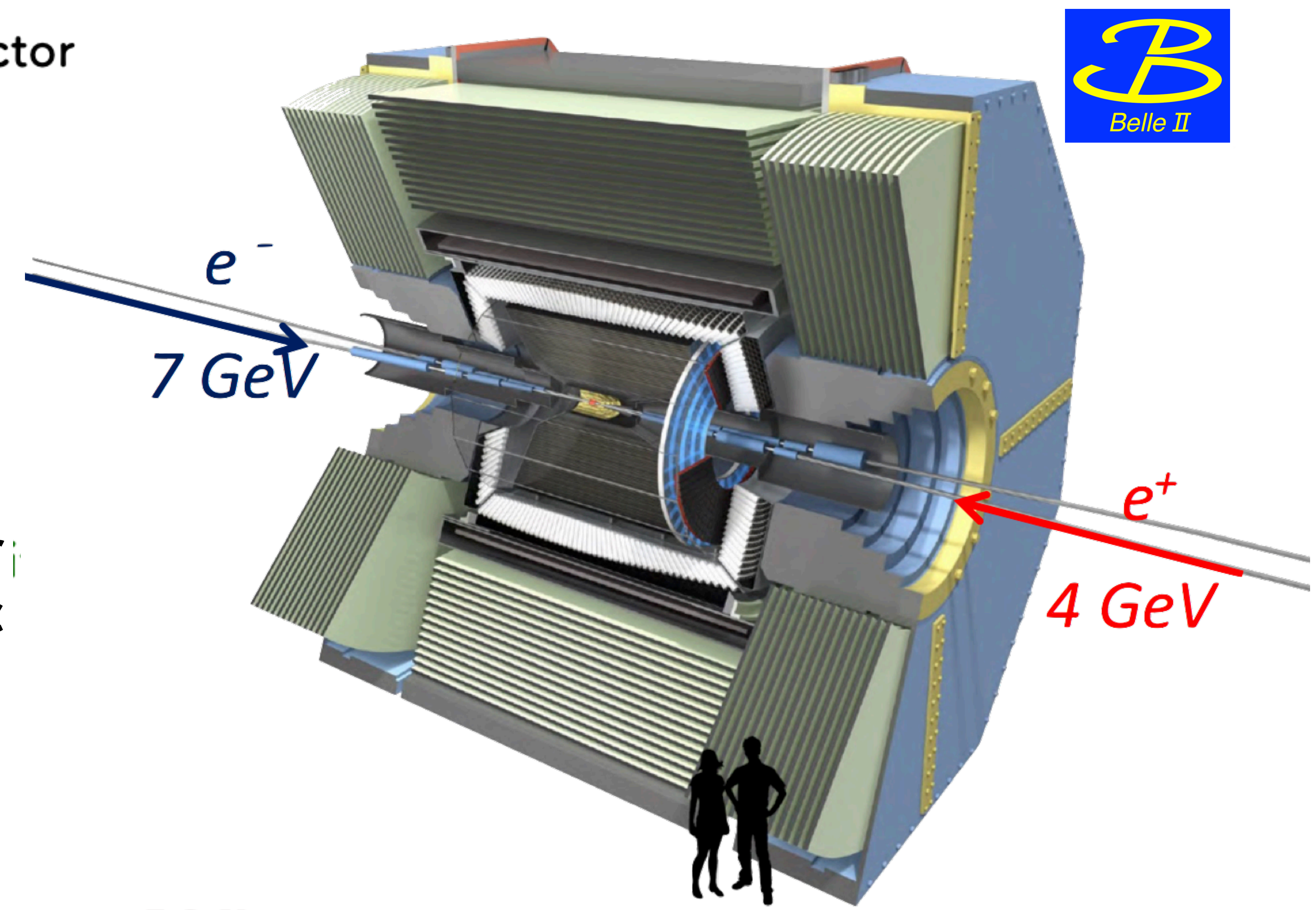
CPNR 2025 Workshop @ Chonnam NU., Gwangju, Sep. 4, 2025

Supported by National Research Foundation, Republic of Korea

SuperKEKB



Belle II



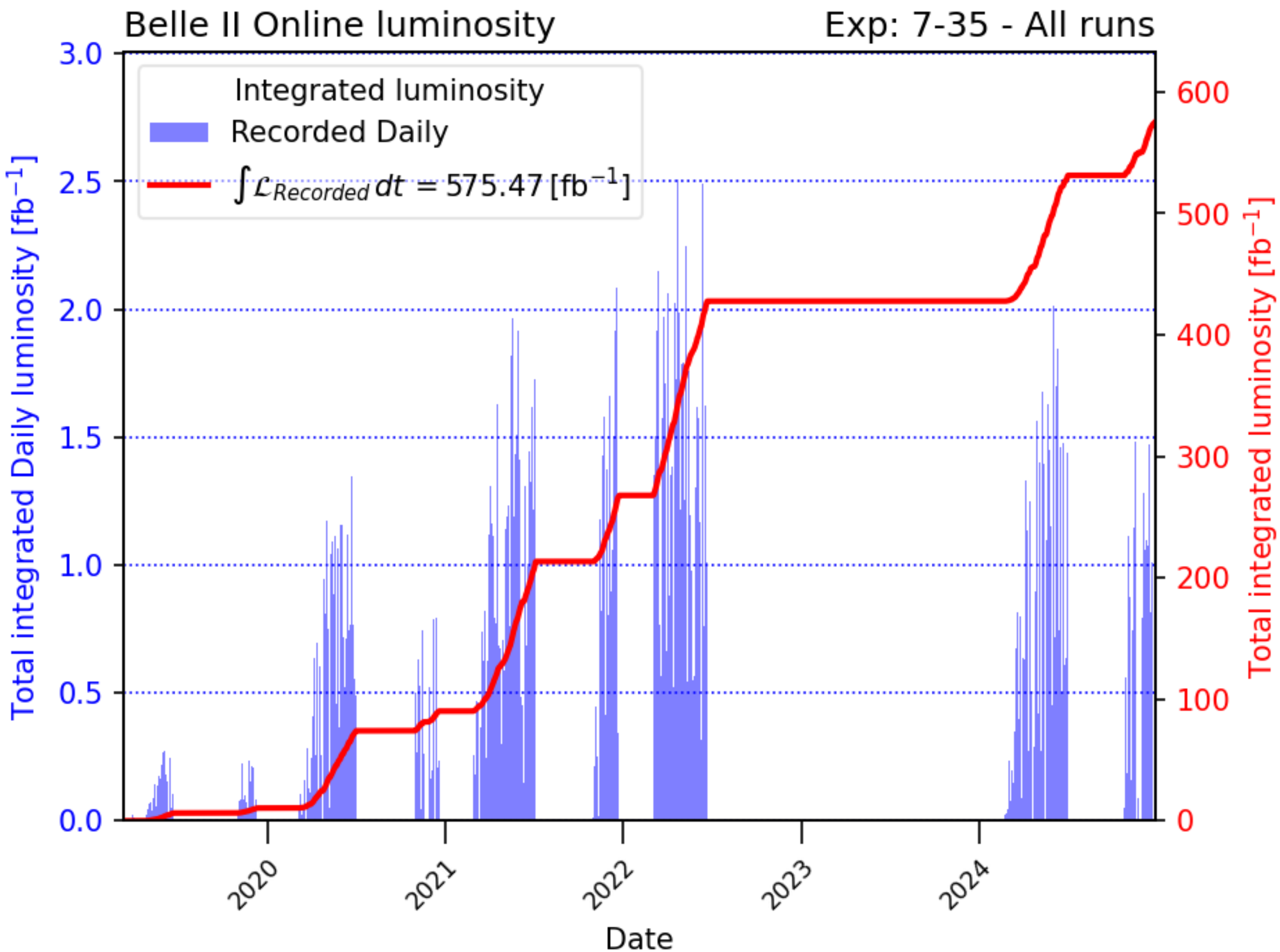
$$e^- \xrightarrow{7\text{ GeV}} (\star) \xleftarrow{4\text{ GeV}} e^+$$

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

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 $p_B^{CM} \sim 0.35\ \text{GeV}/c$
- 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*

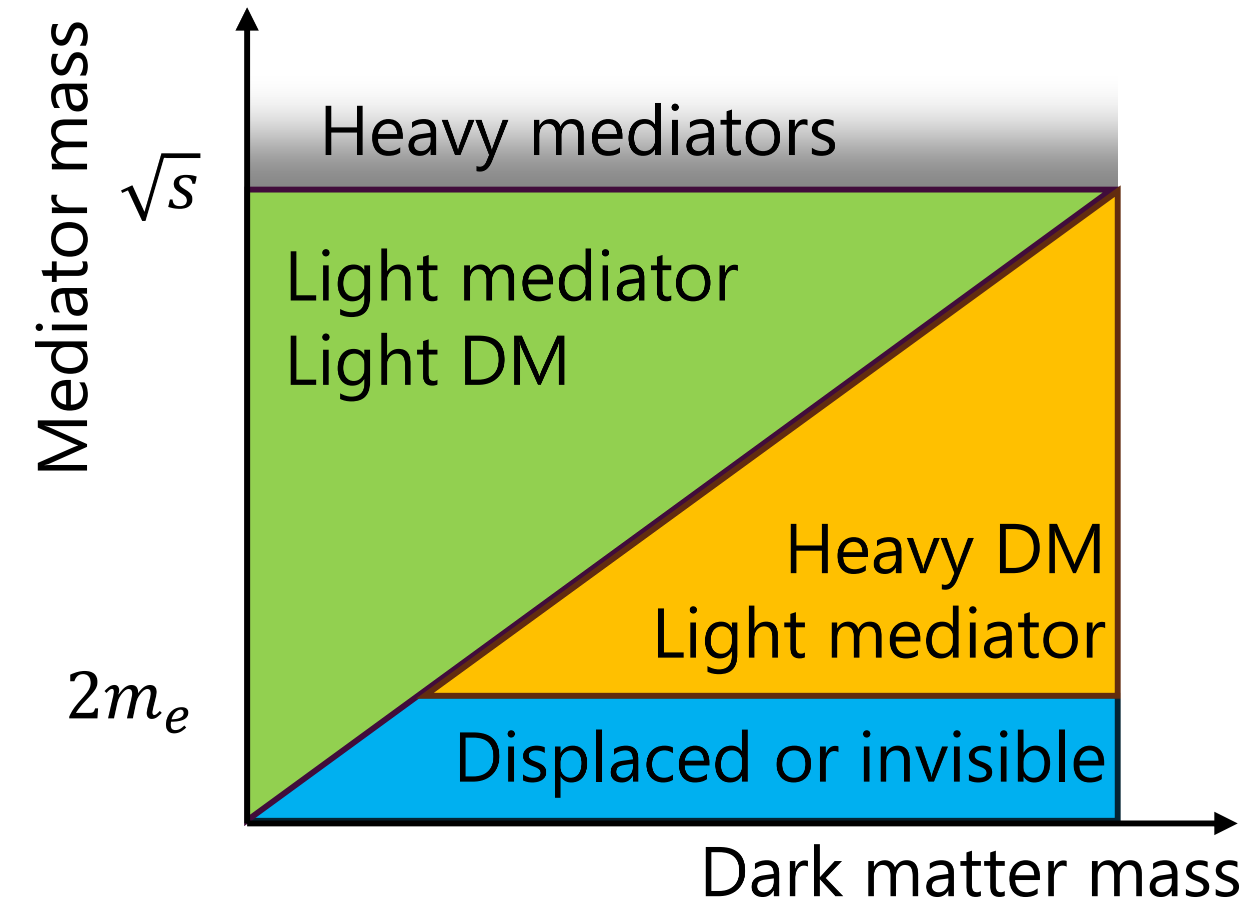


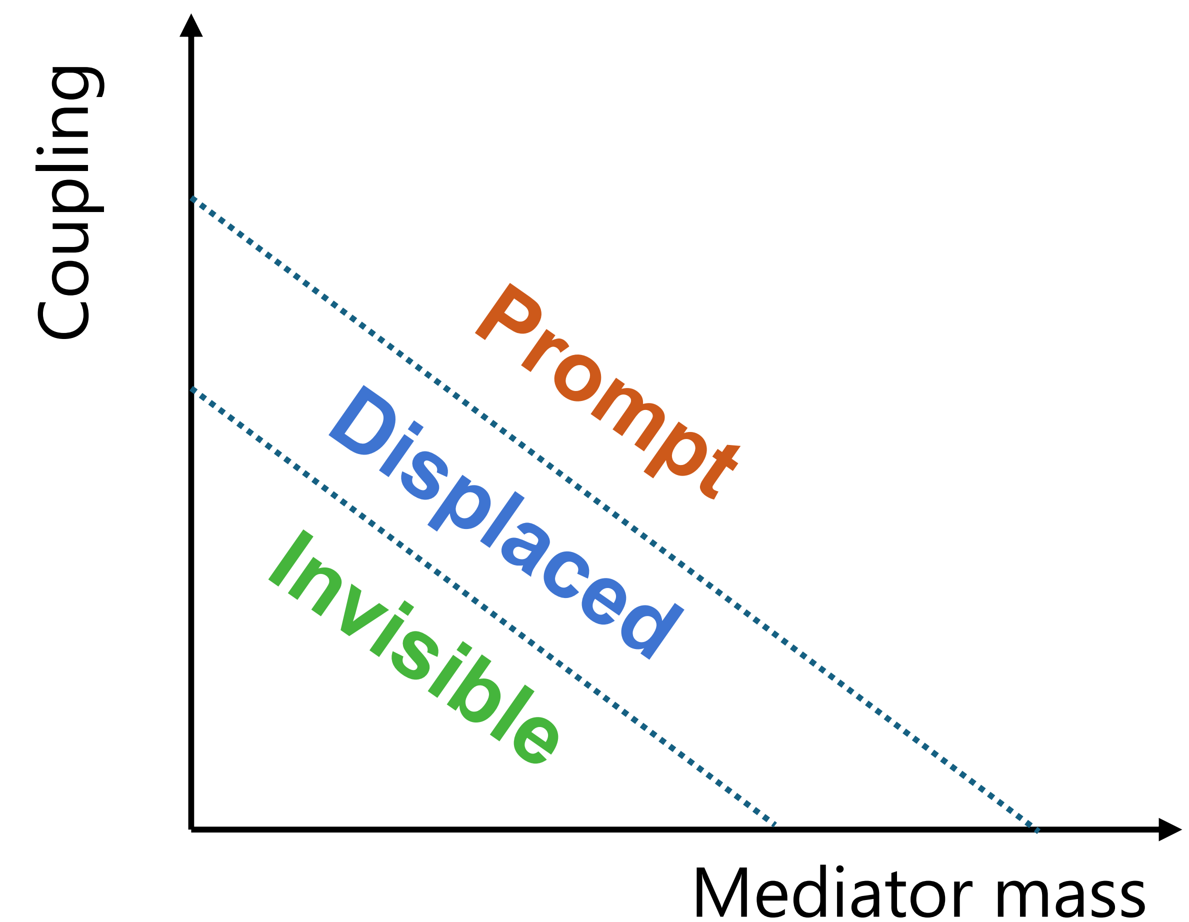
Belle (1999-2010) Luminosity

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

Dark sector @ Belle II

- Production mechanisms
  - Directly in e^+e^- collisions
  - In meson decays (B)
- 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





Outline

- A quick intro. to Belle II
- Recent results of dark sector particle search
  - ✓ Dark higgs with inelastic DM — arXiv:2505.09705 PRL (*accepted*)
  - ✓ Axion-like particle (ALP) search
    - $e^+e^- \to \gamma a$ — PRL 125, 161806 (2020)
    - $B \to K^{(*)}a$ (Belle) — arXiv:2507.01249 *submitted to JHEP*
  - ✓ B, D meson decays to a pair of neutrinos
    - $B^+ \to K^+\nu\bar{\nu}$ (exclusive) — PRD 109, 112006 (2024)
    - $B \to X_s\nu\bar{\nu}$ (inclusive) — *paper in preparation*
    - $D^0 \to \nu\bar{\nu}$ (Belle) — PRD 95, 011102(R) (2017) *Belle II analysis on-going*
- Closing remarks

Other dark sector results from Belle II

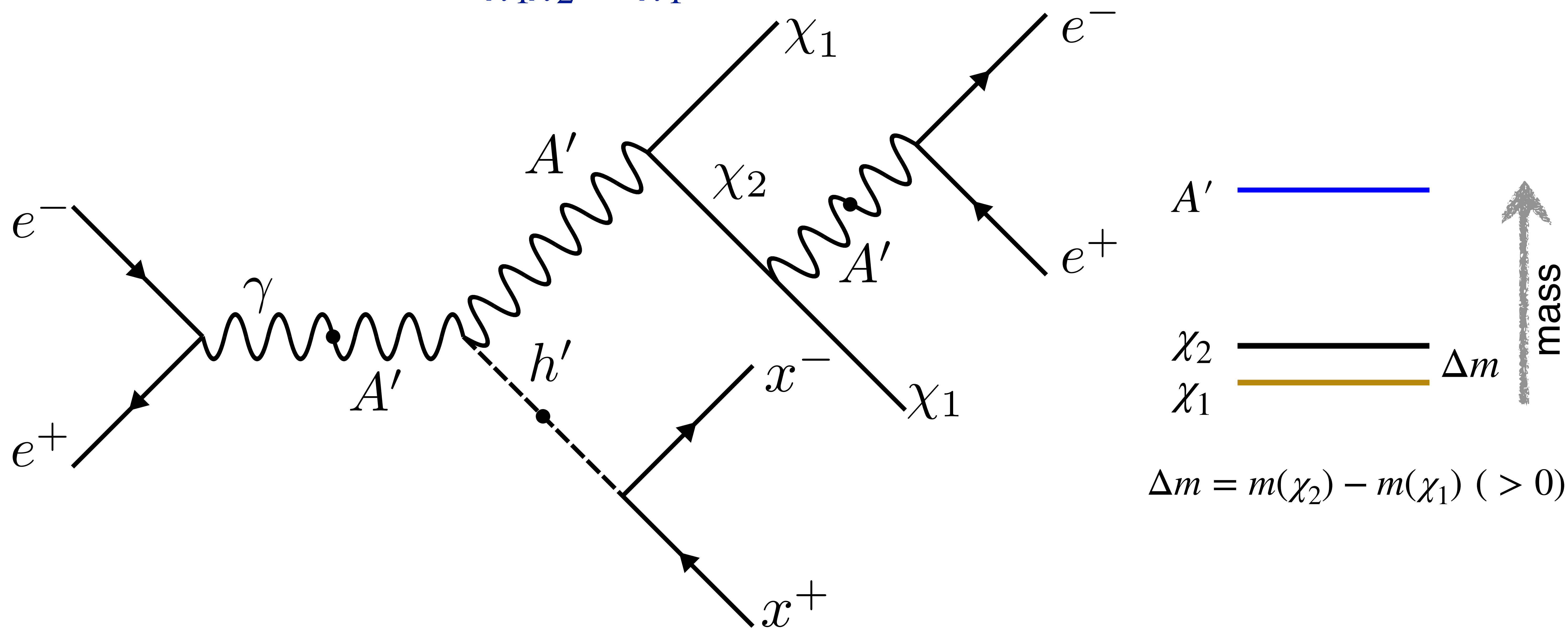
- Invisible Z' in $e^+e^- \to \mu^+\mu^- + (\text{missing})$ — PRL 124, 141801 (2020)
- Invisible Z' in $e^+e^- \to \mu^+\mu^- + (\text{missing})$ — PRL 130, 231801 (2023)
- A' and invisible h' in $e^+e^- \to \mu^+\mu^- + (\text{missing})$ — PRL 130, 071804 (2023)
- $\tau^+\tau^-$ resonance in $e^+e^-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

Honorable mentions

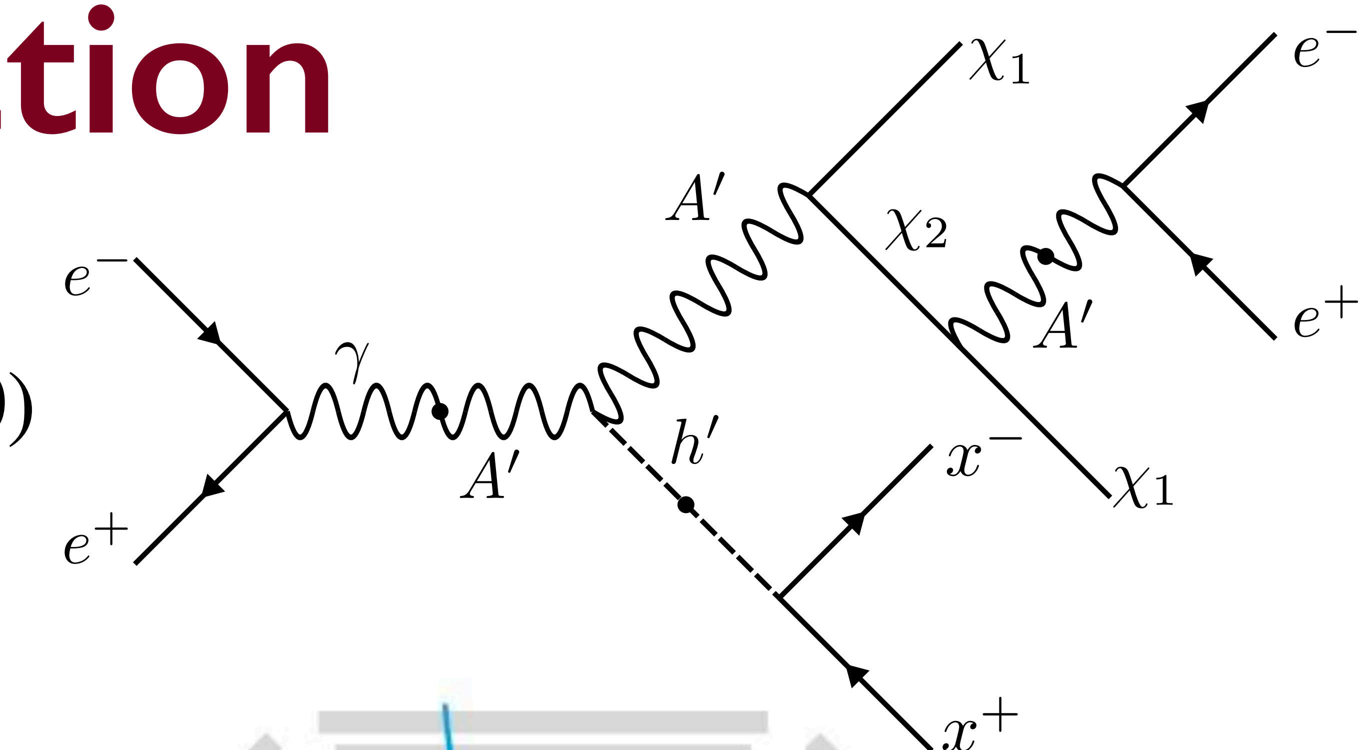
- Invisible boson α in $\tau^+ \to \ell^+\alpha$ — PRL 130, 181803 (2023)

Dark Higgs in association with Inelastic DM

$e^+e^- \rightarrow h'(\rightarrow x^+x^-)\ A'(\chi_1\chi_2(\rightarrow \chi_1 e^+e^-))$

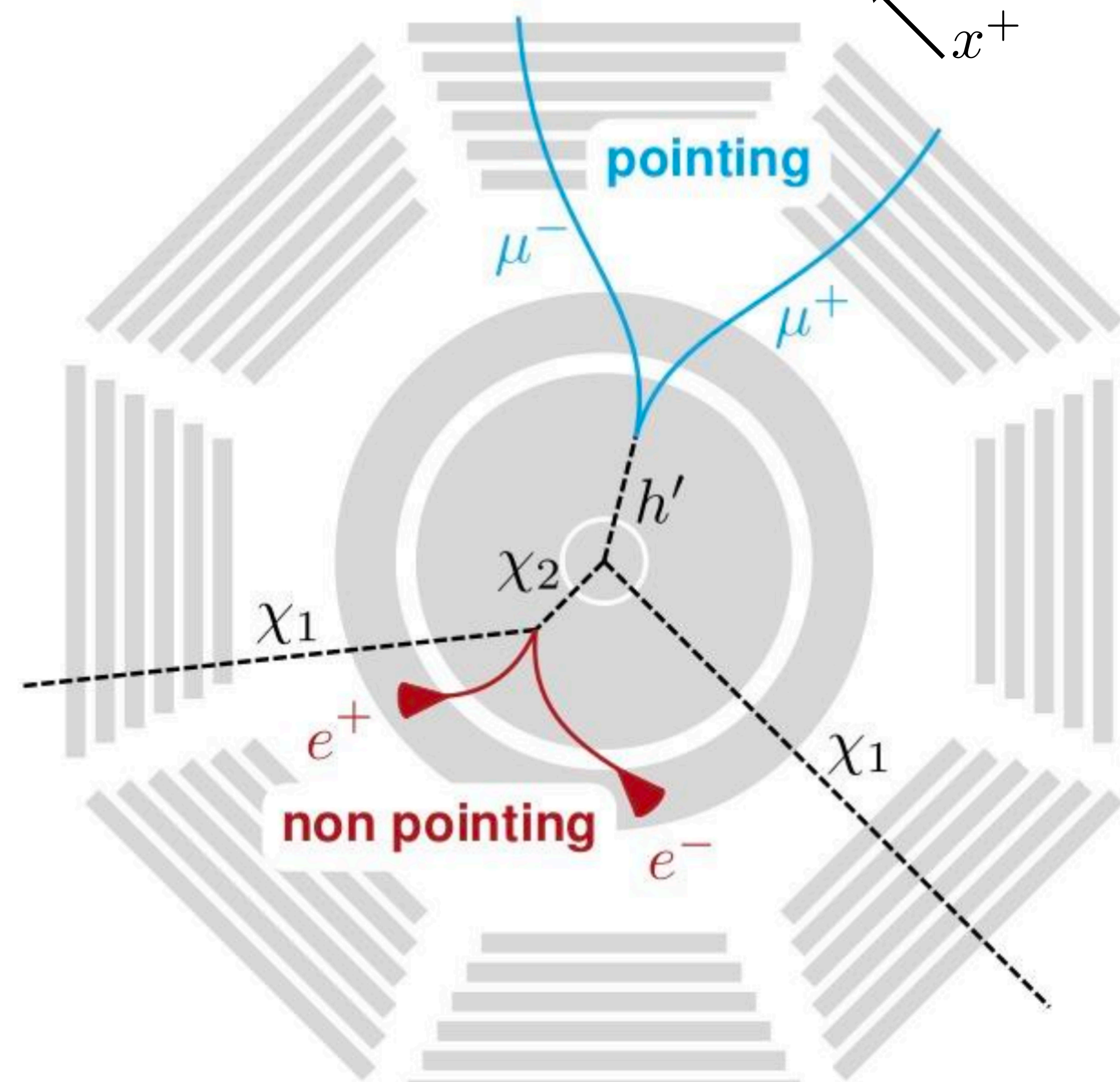


Inelastic DM, Introduction



- 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 — stable & relic DM candidate
  - consider small Δm for long-lived χ_2
  - 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

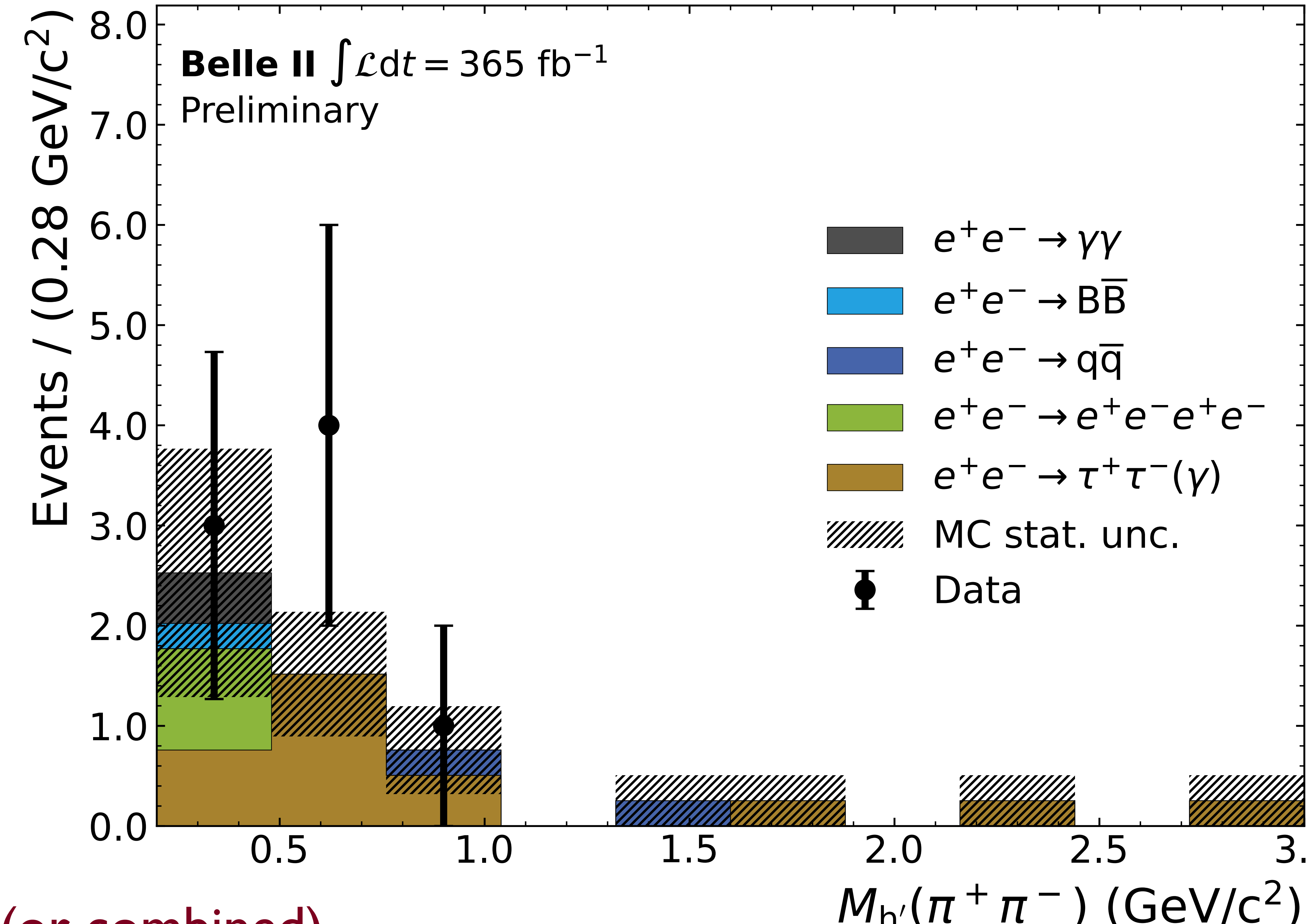


adapted from Duerr, Ferber et al, JHEP04 (2021) 146

Inelastic DM, Results

arXiv:2505.09705
PRL (*accepted*)

- 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

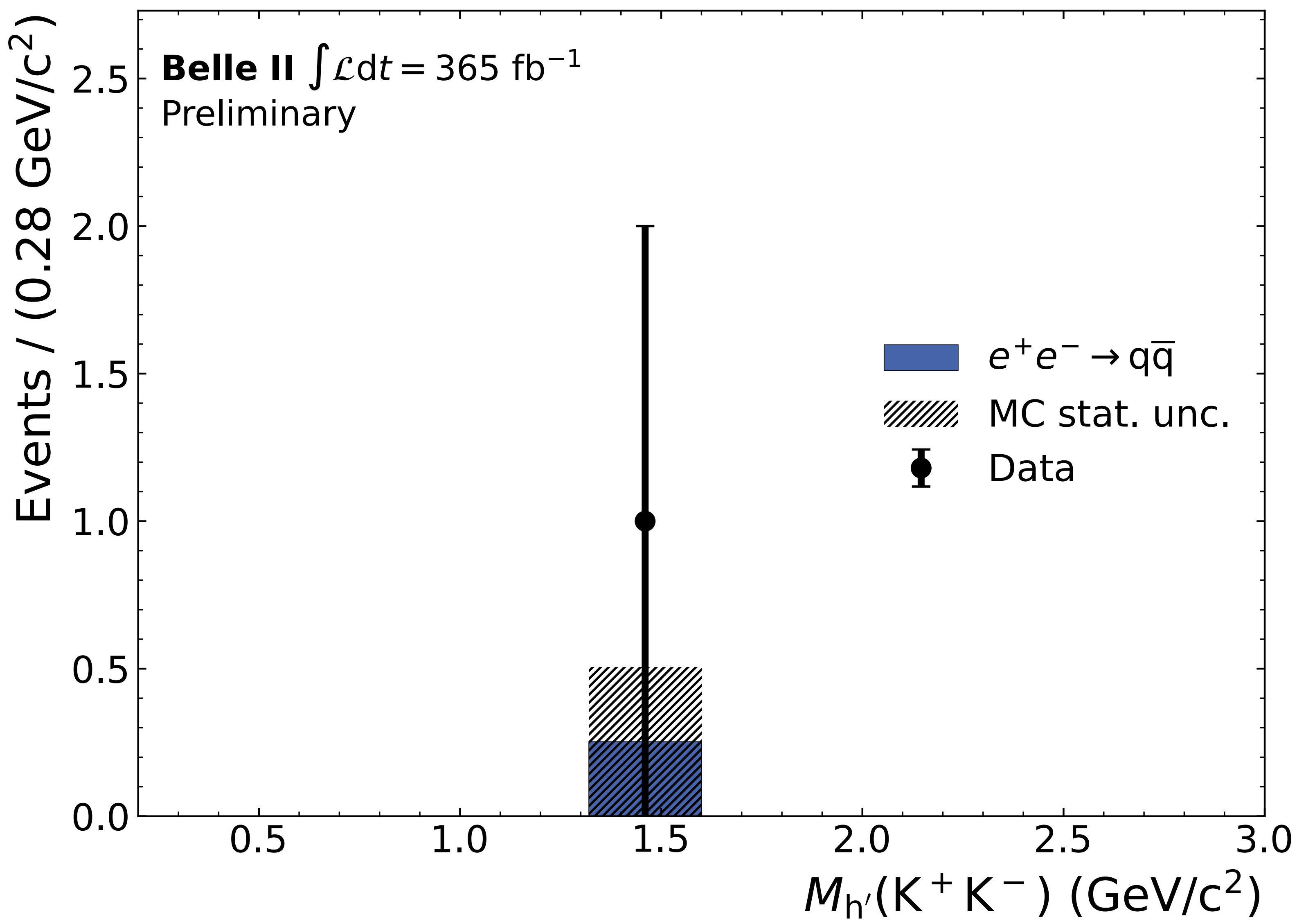


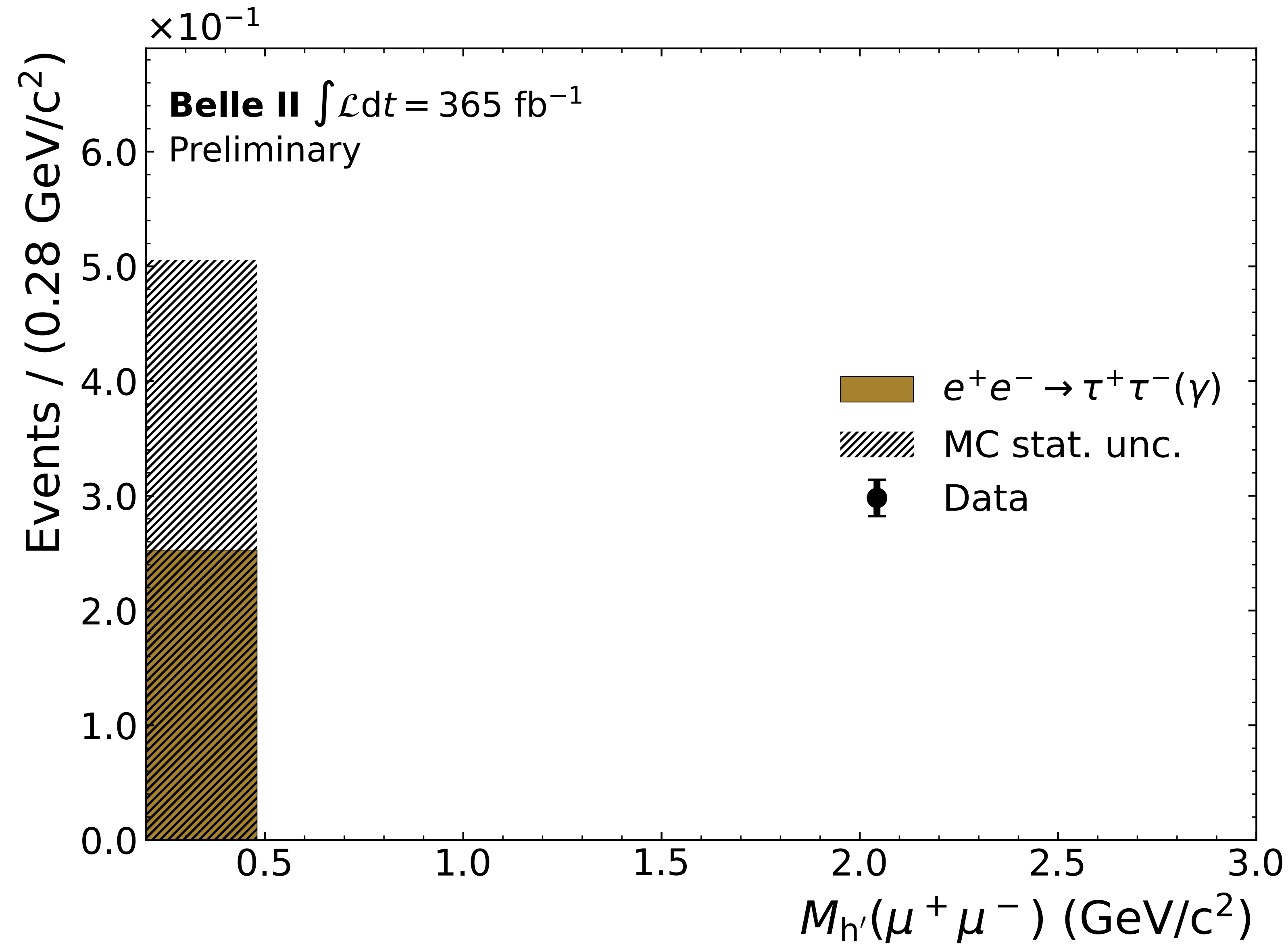
- No significant excess in any mode (or combined)
  - 8 event in $\pi^+\pi^-$ (consistent with background)
    - ✓ largest local significance of 2.9σ (1.1σ global) at $m(h') = 0.531$ GeV

arXiv:2505.09705
PRL (*accepted*)

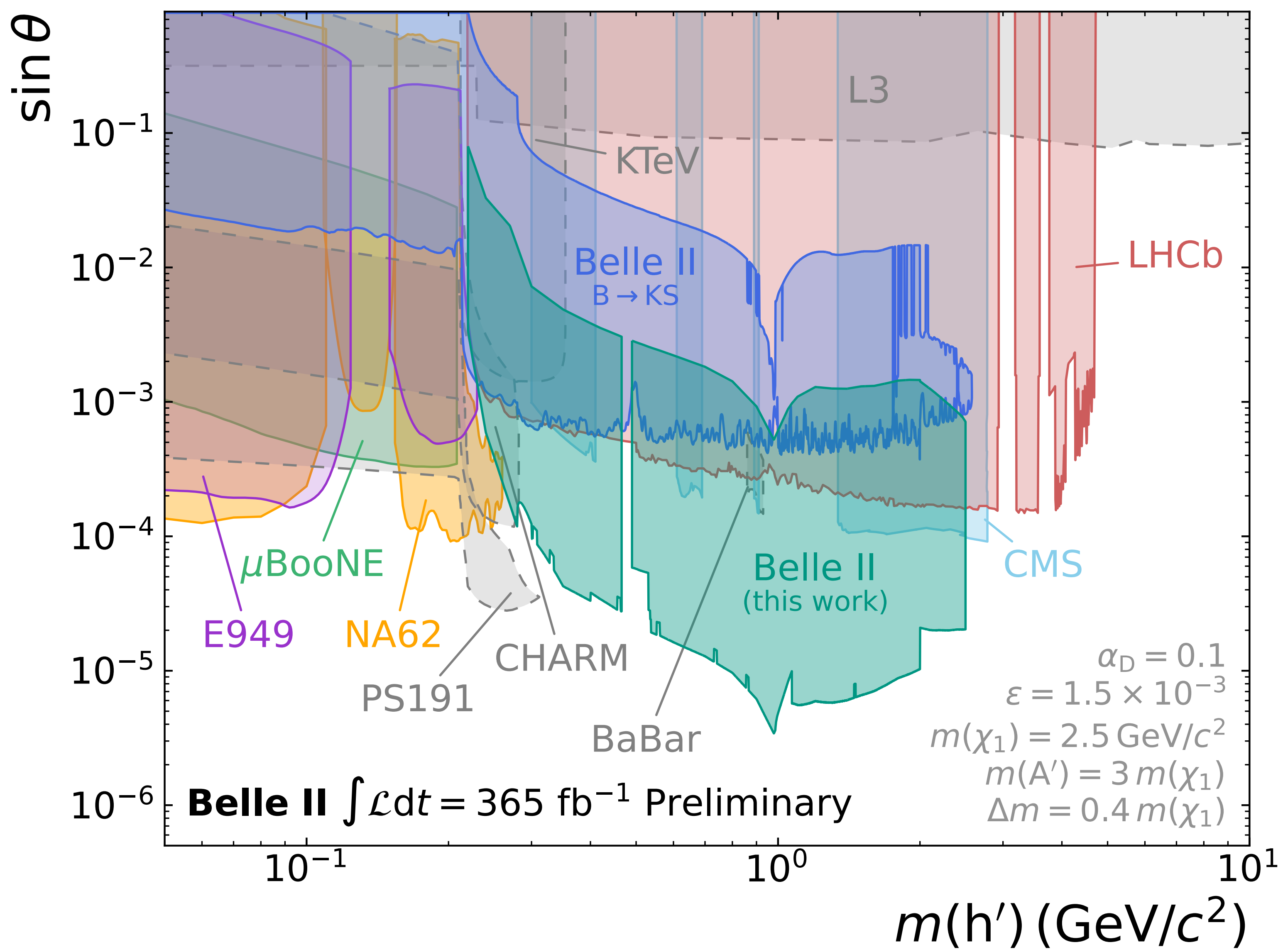
Inelastic DM, Results

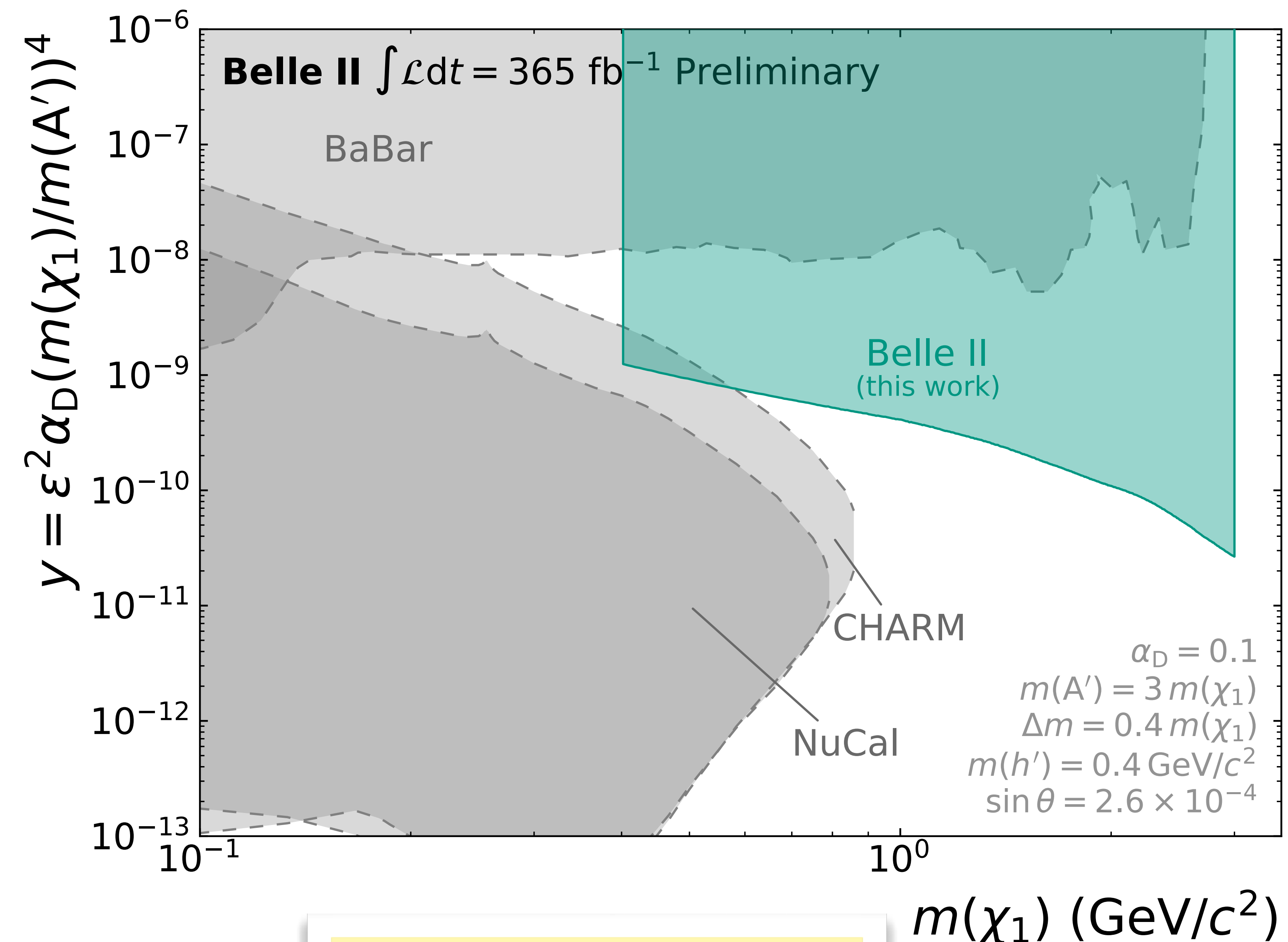
- No significant excess in any mode (or combined)
  - 8 event in $\pi^+\pi^-$ (consistent with background)
  - 1 event in K^+K^-, 0 event in $\mu^+\mu^-$





Inelastic DM, Results



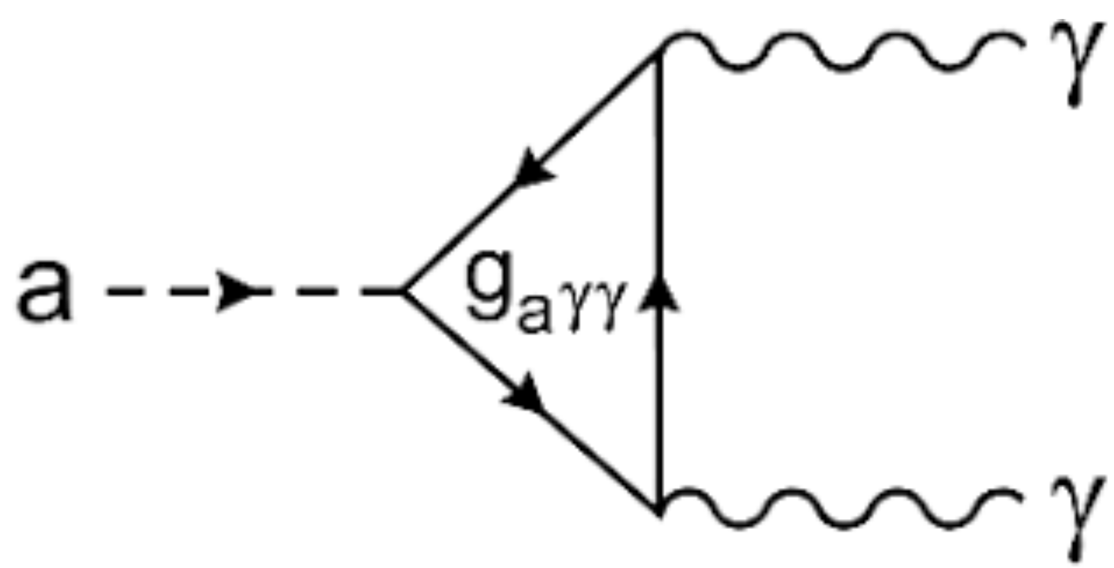


- Model-dependent limits on the coupling strengths and parameters
  - shown here for a specific choice
  - many more plots (~30), for different parameter sets
  - (Right plot) non-Belle II limits do not assume h', so less model-dependent

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

See Appendix for meaning of the parameters

ALP search

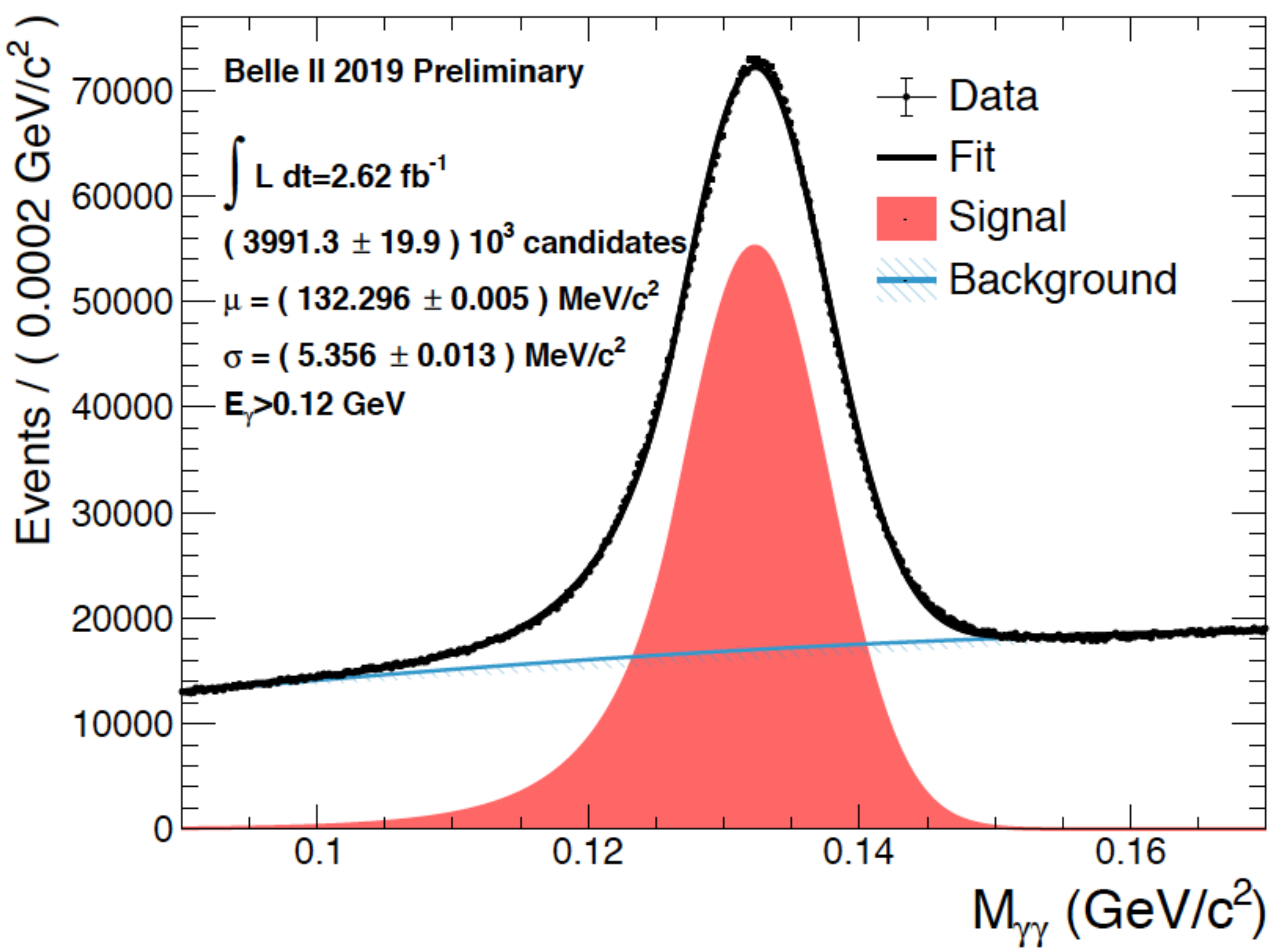


$$\mathcal{L} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

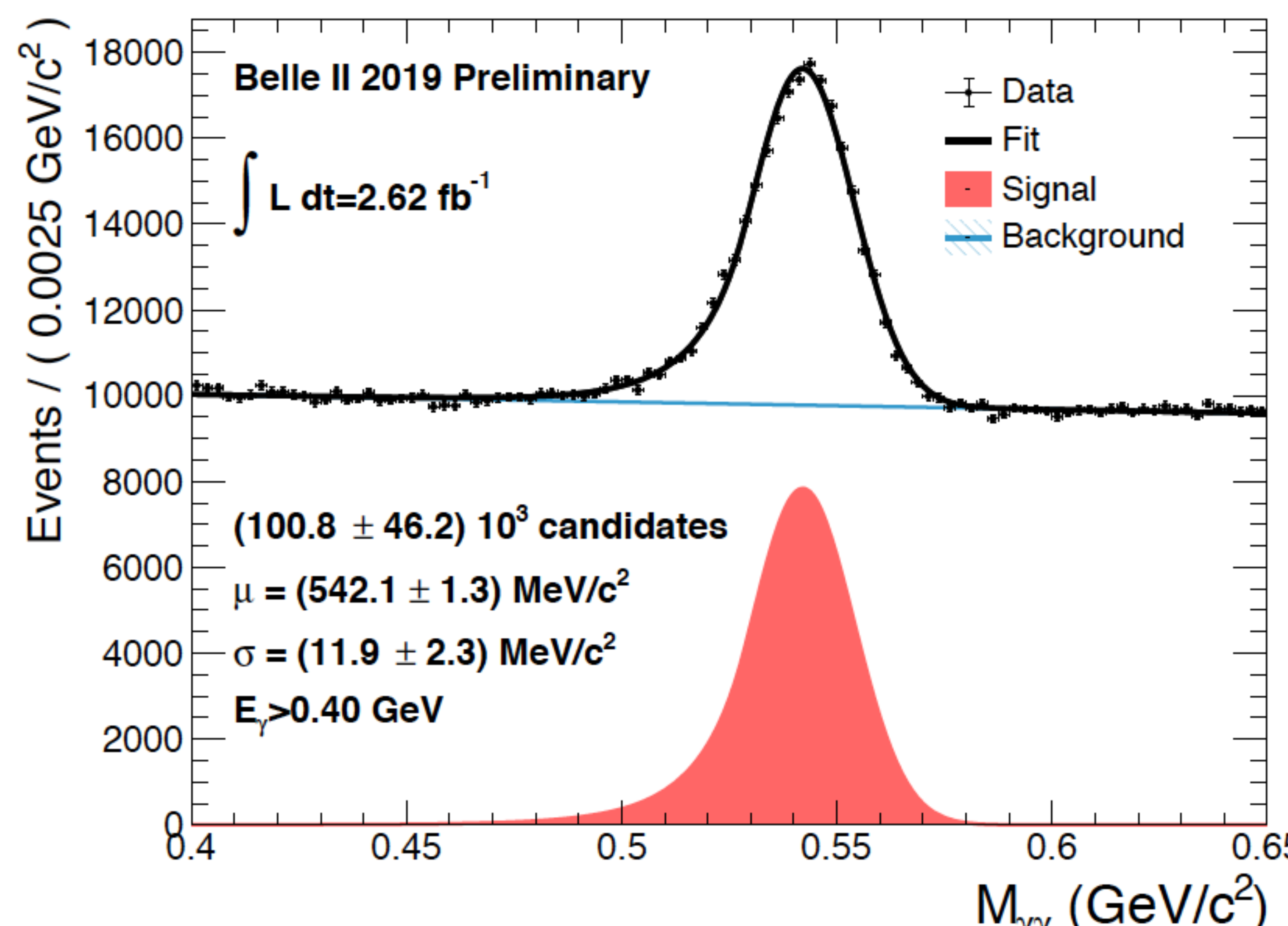
ALP search (1) in $e^+e^- \to \gamma a$

- 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 $(E, \vec{p})$)

$\pi^0 \to \gamma\gamma$



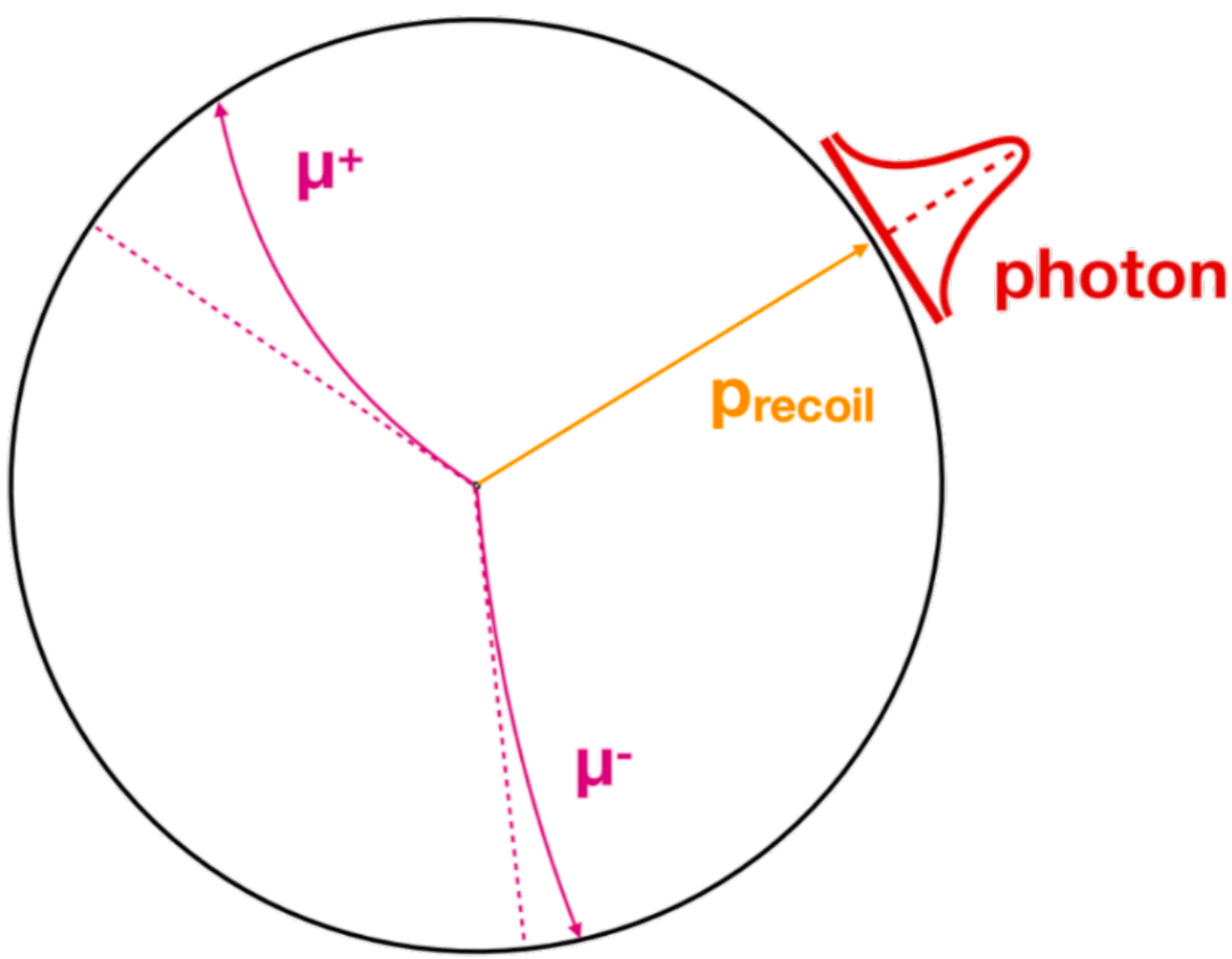
$\eta \to \gamma\gamma$

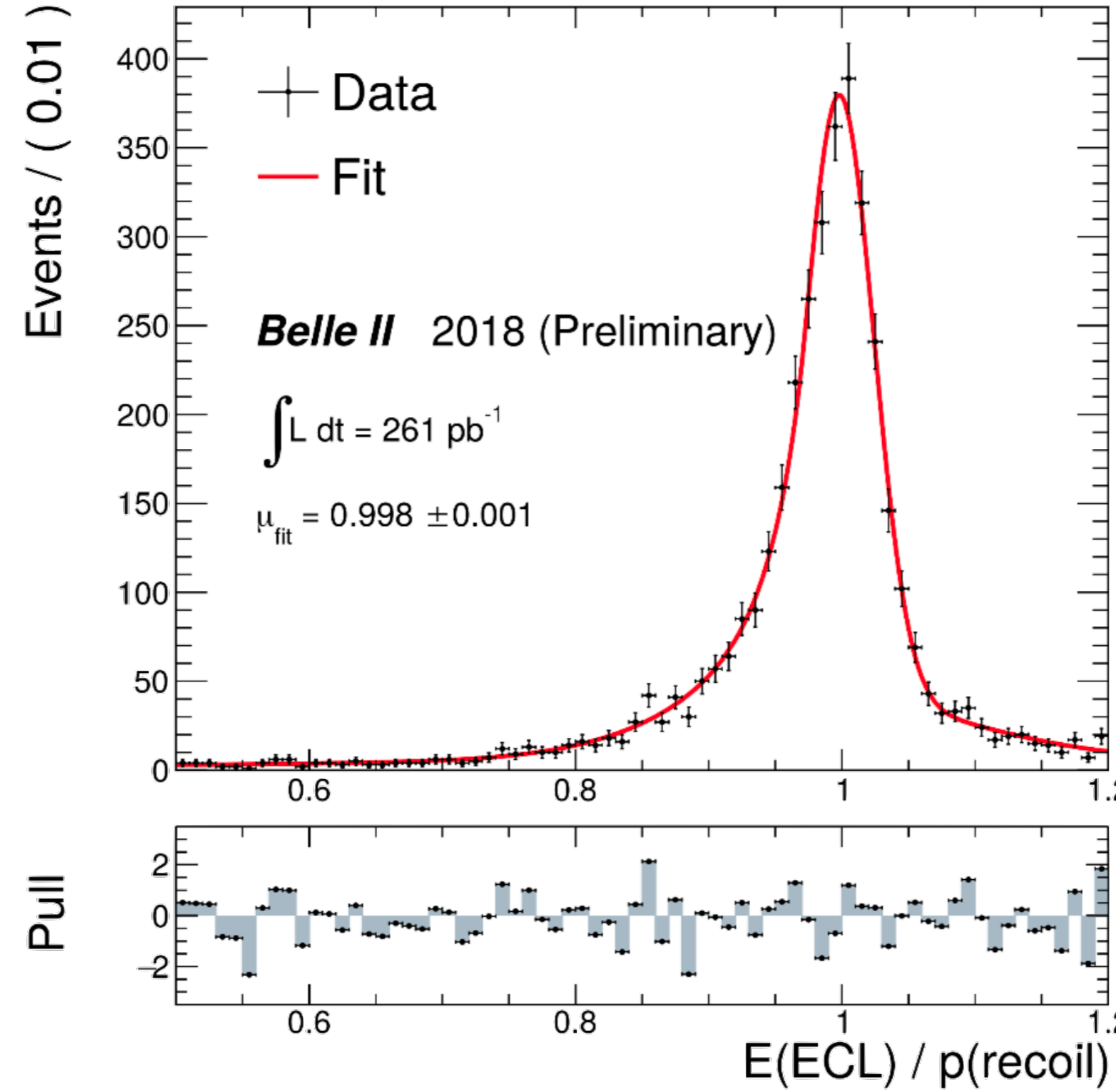


photon reconstruction at Belle II

Photon reconstruction at Belle II

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



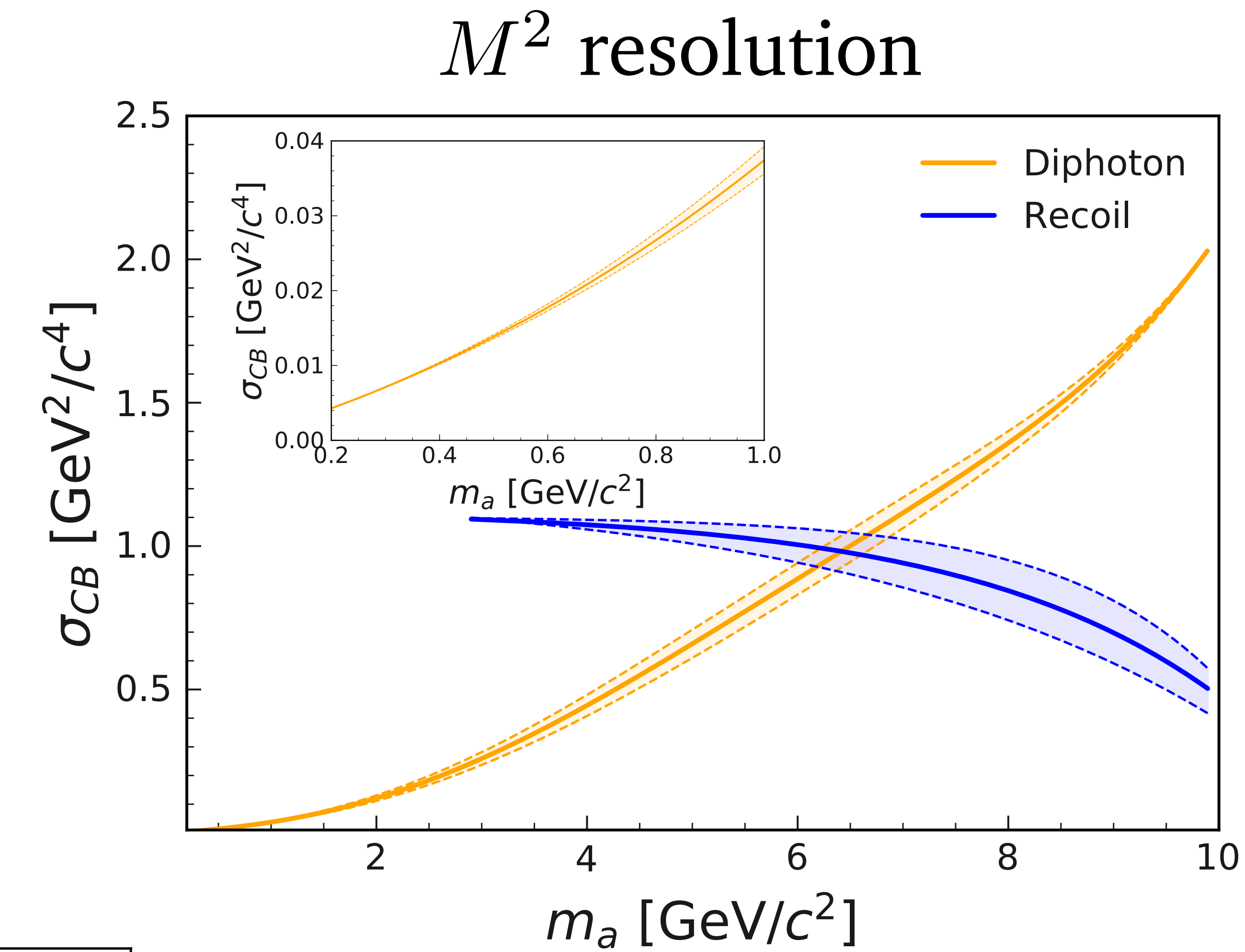


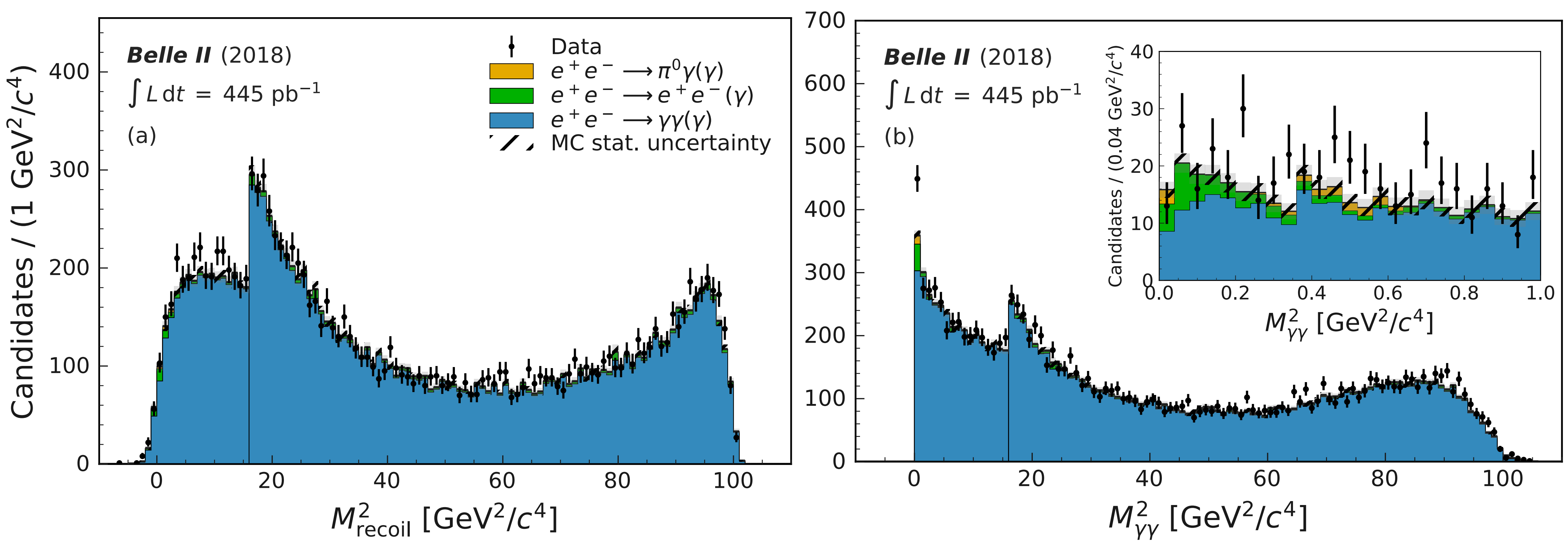
⇒ Ready for dark matter searches (single or triple γ triggers)

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

Search for ALPs at Belle II

- 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. $\gamma + \not{h}$)
- m_a-dependent E_γ threshold
  - ✓ 1.0 GeV for $m_a \leq 4$ GeV, and 0.65 GeV for $m_a > 4$ GeV,

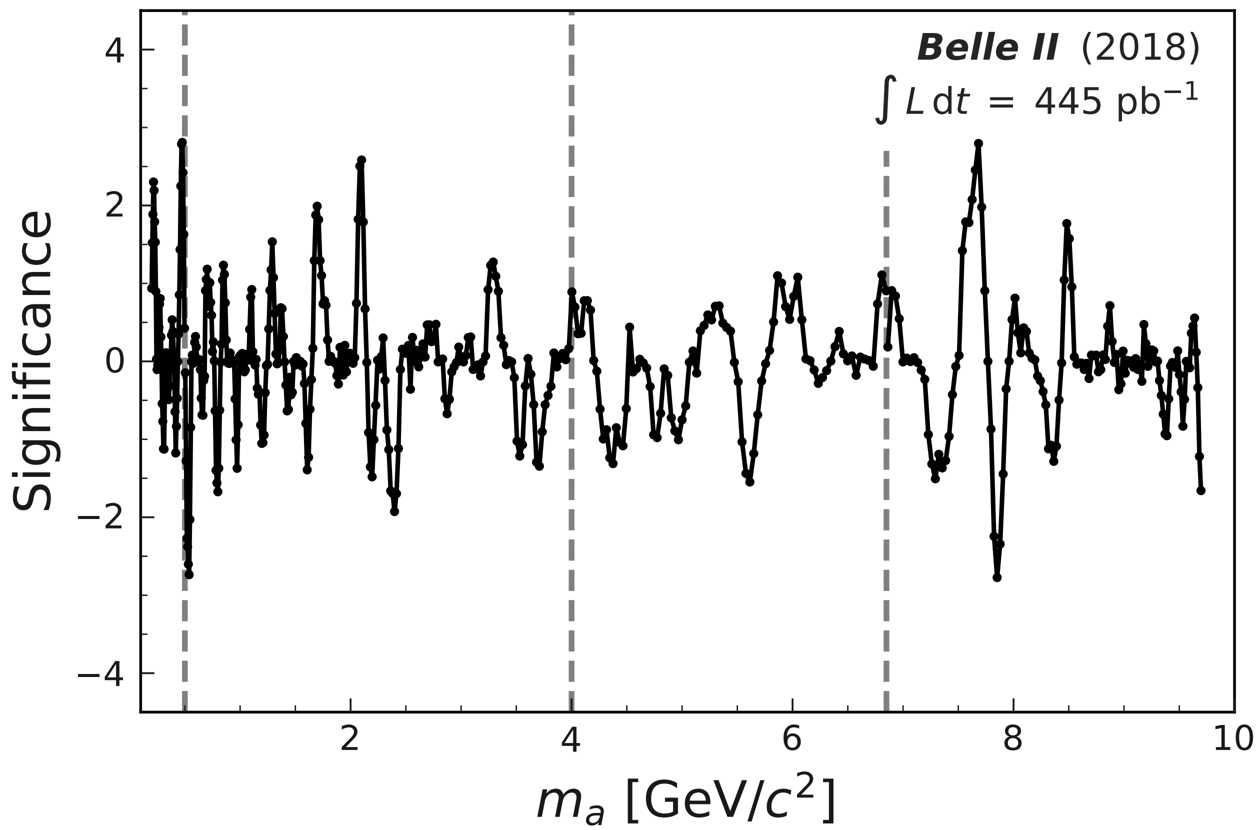




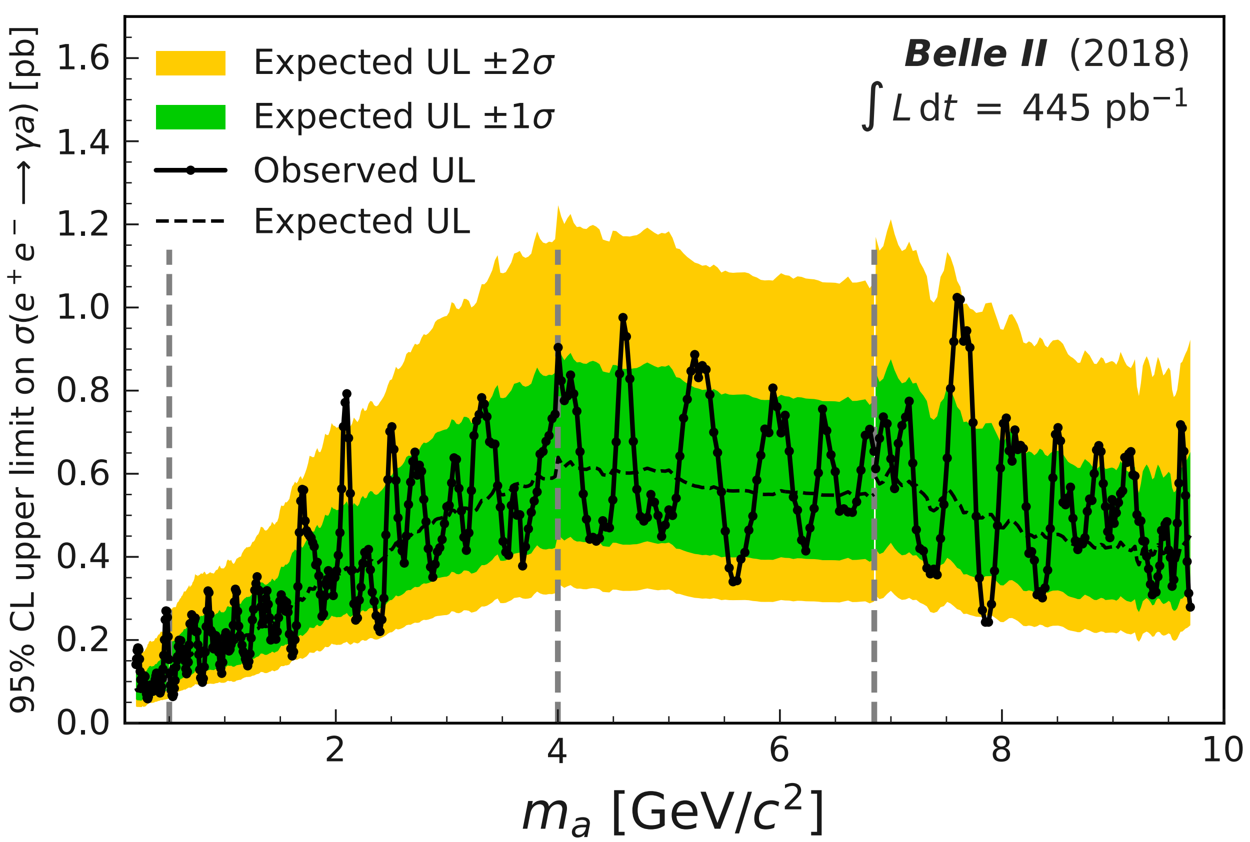
- fit $M^2_{\gamma\gamma}$ for $0.2 < m_a < 6.85$ GeV
- fit M^2_{rec} for $m_a > 6.85$ GeV,
- Look for resonance in the fit

PRL 125, 161806 (2020)

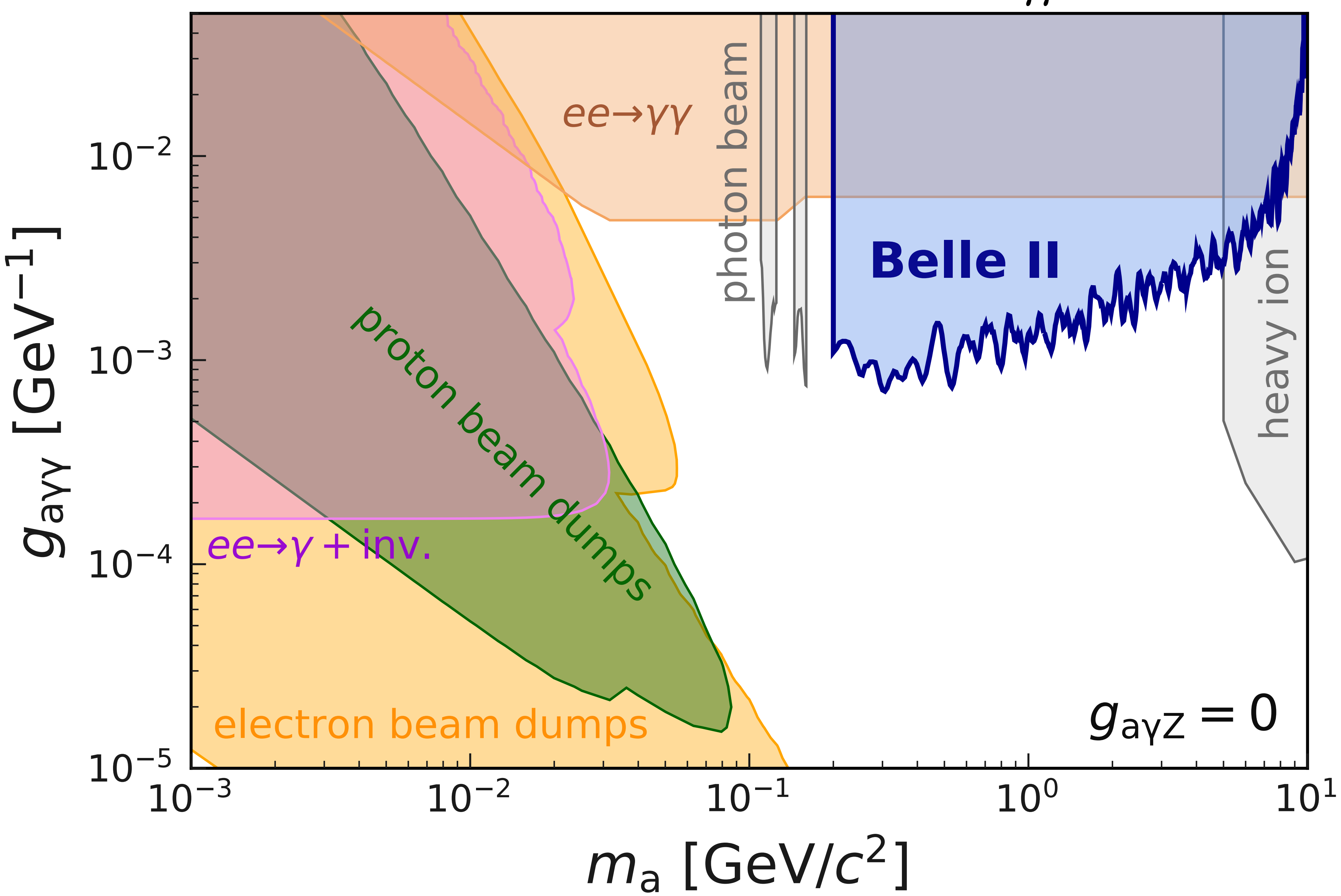
ALP search - significance & limits



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

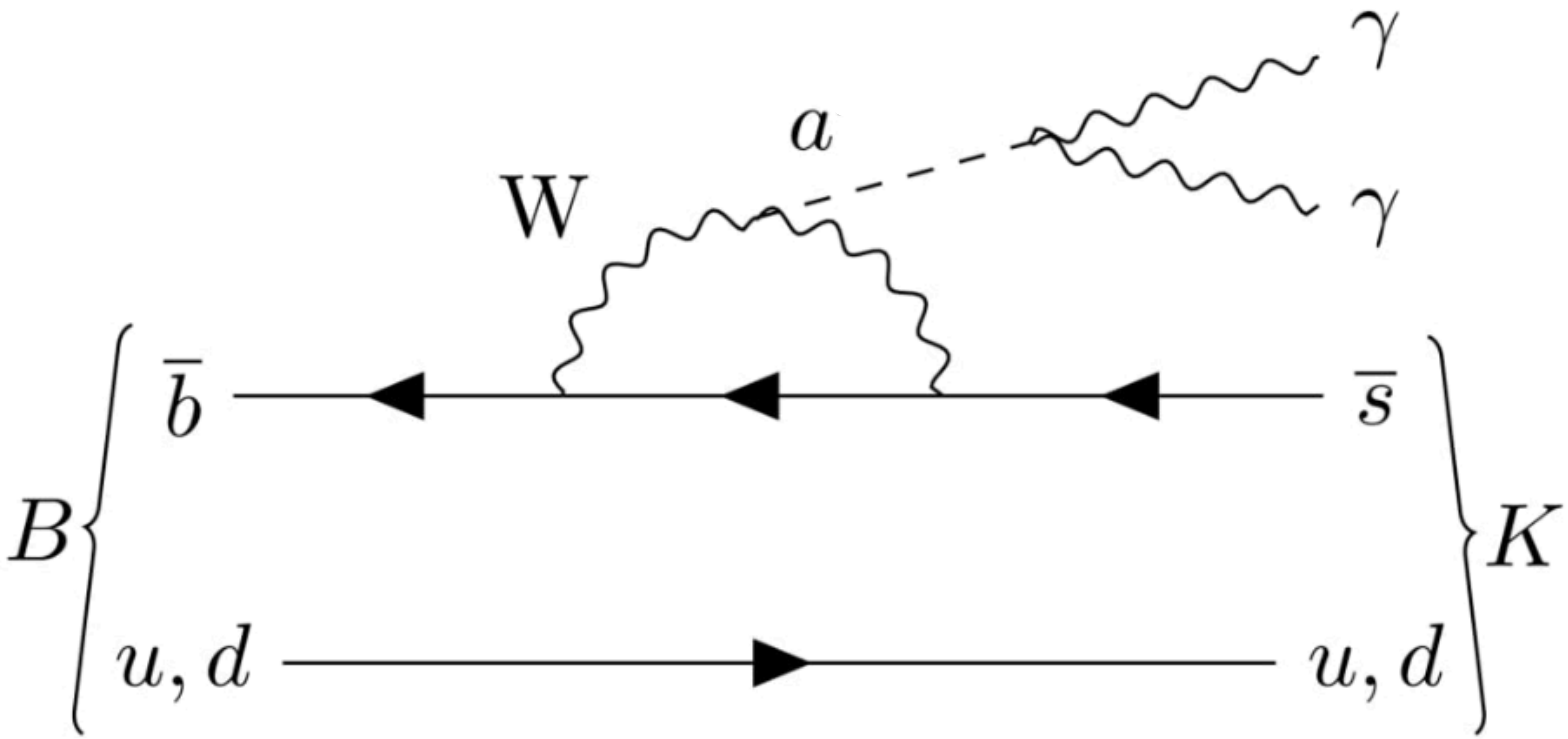


ALP search - UL on $g_{a\gamma\gamma}$



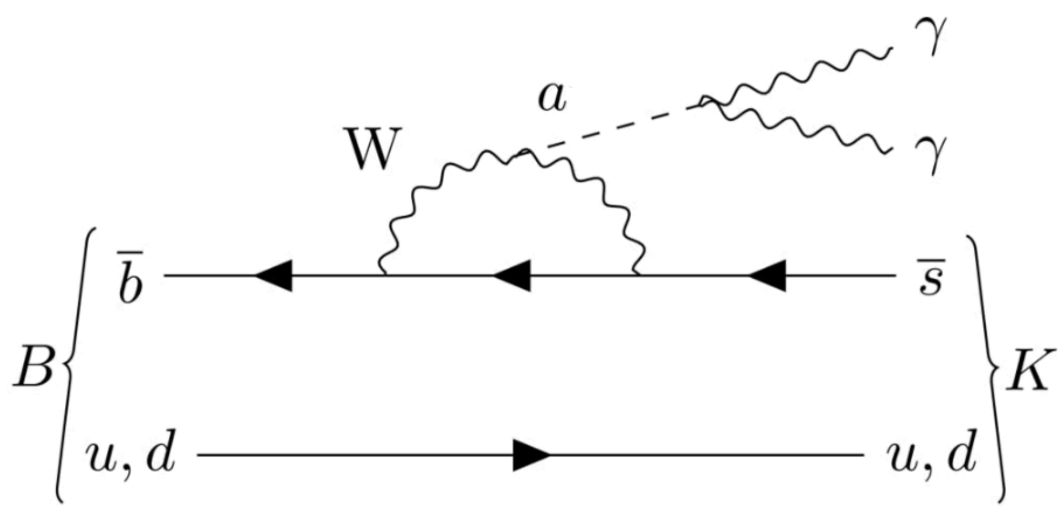
ALP search (2)
in $B \to K^{(*)} a(\to \gamma\gamma)$

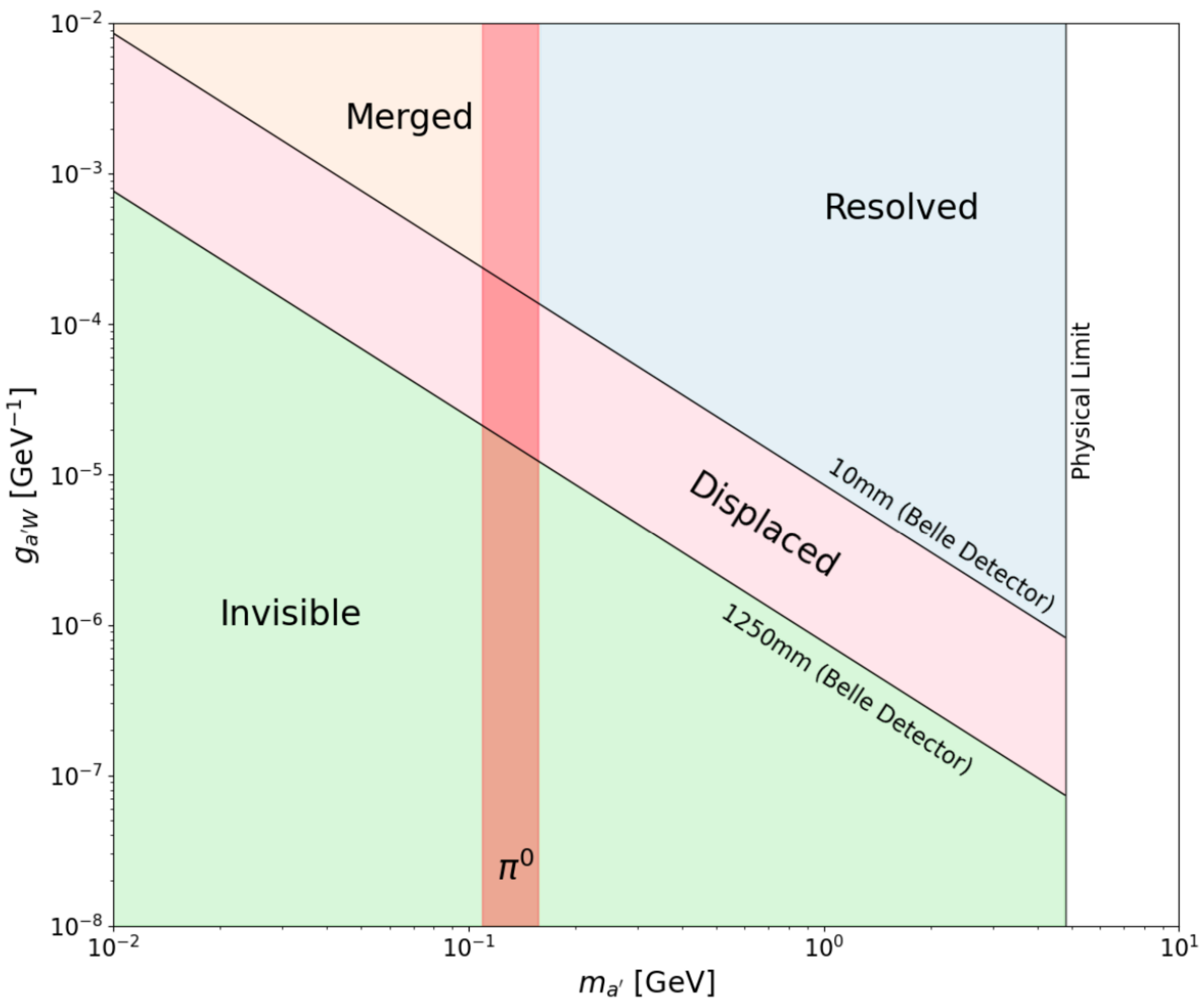
Dr. Sungjin Cho
(IBS/CUP)



arXiv:2507.01249
submitted to JHEP

$B \to K^{(*)}\gamma\gamma$ 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:
    $$0.16 < m_a < 4.20\ (4.50)\ \text{GeV}$$
  - no sensitivity for π^0, η, η' regions
- 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

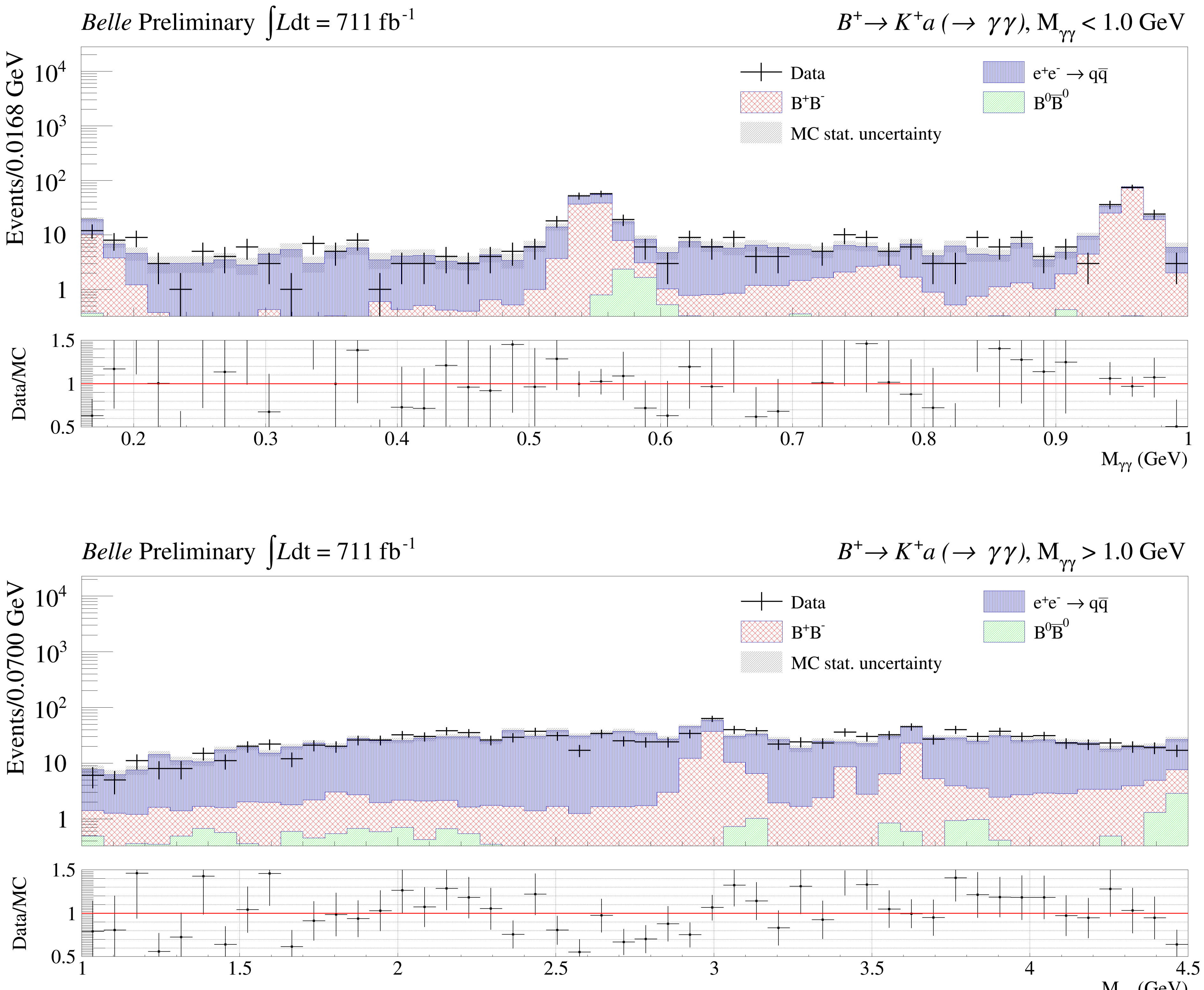
[#] PRL 118, 111802 (2017)

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

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

arXiv:2507.01249
submitted to JHEP



$M_{\gamma\gamma}$ (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

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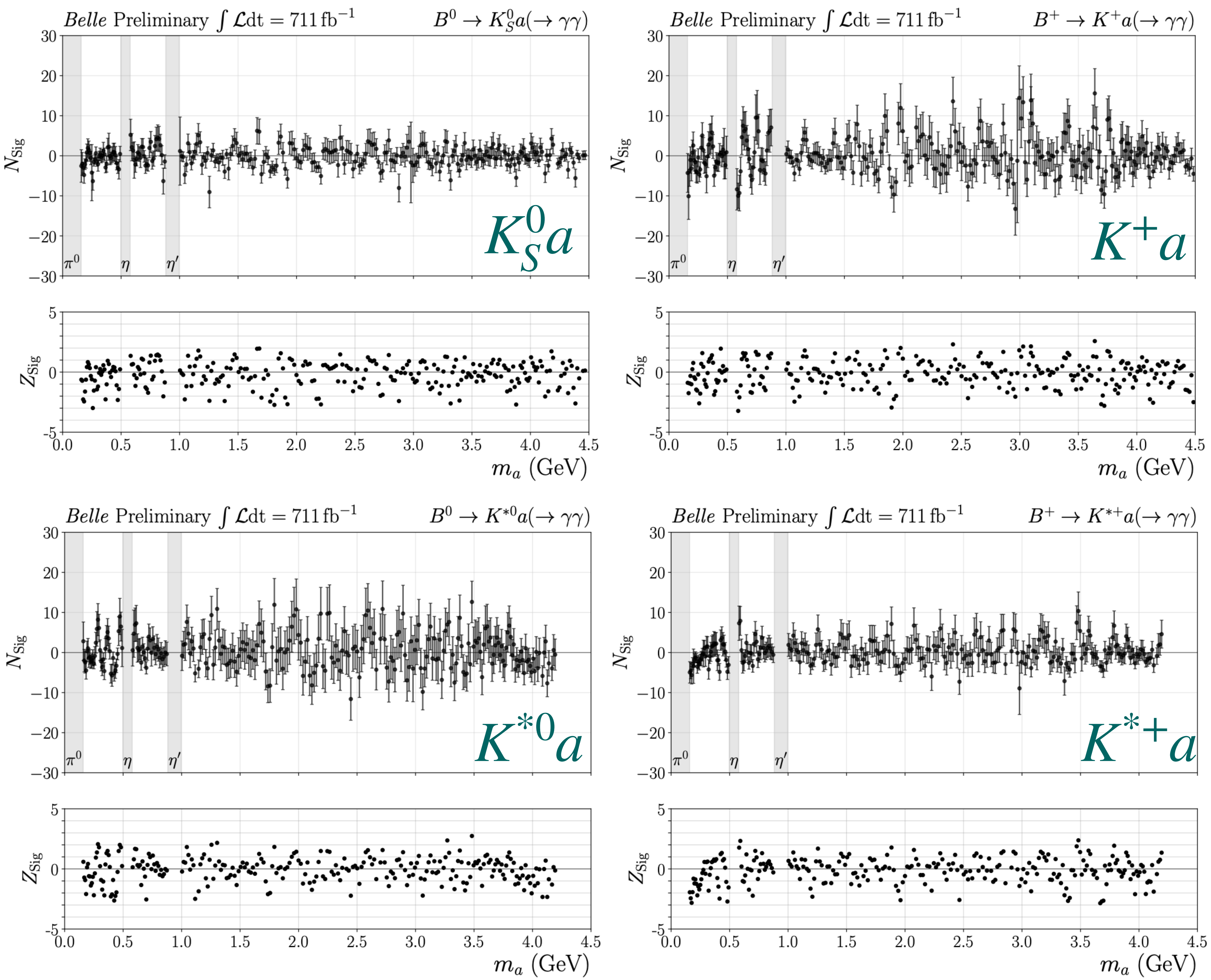
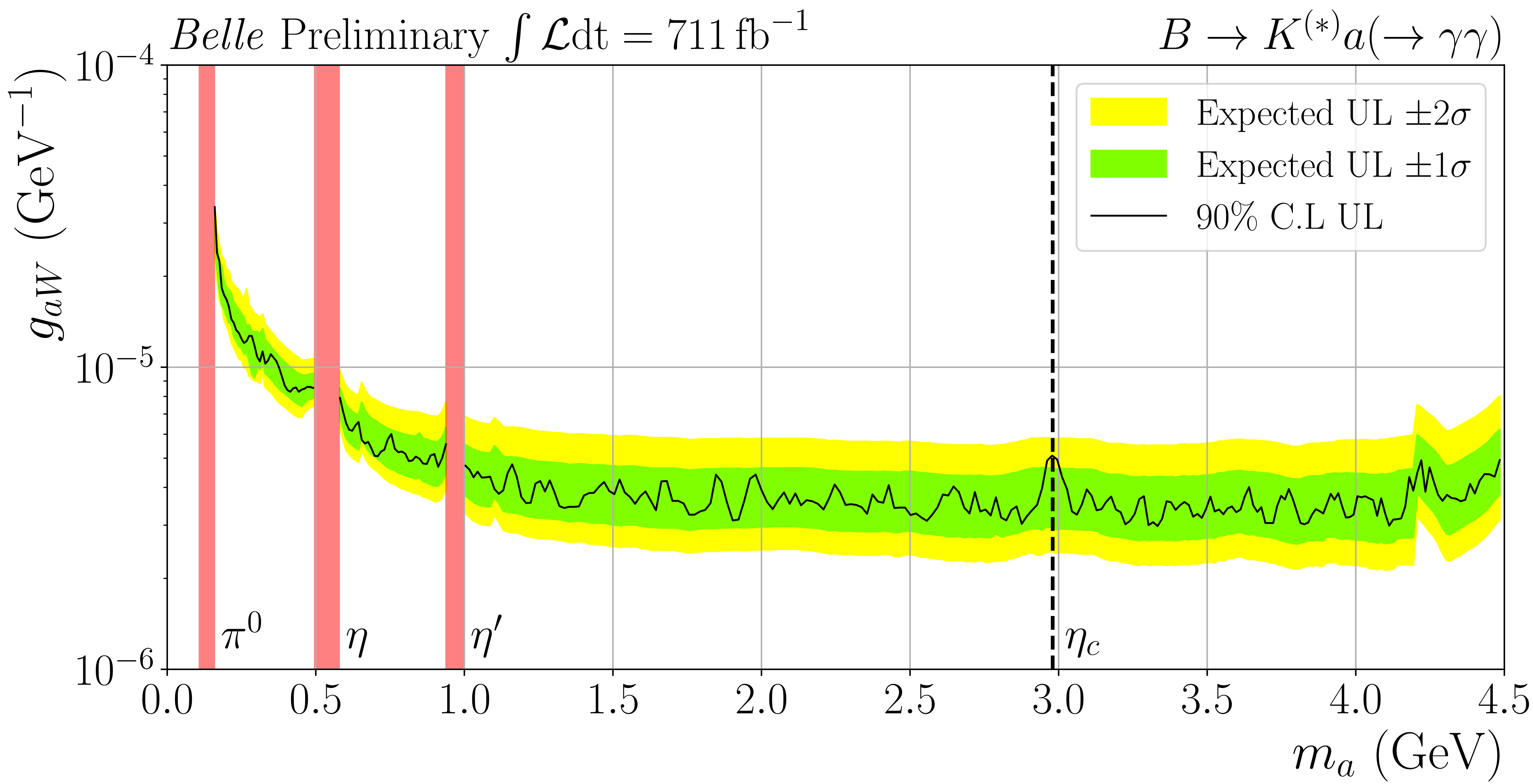


- Fitted results
  - for each $K^{(*)}$ mode
    - ✓ (top) signal yield
    - ✓ (bottom) significance level
  - the gray vertical bands correspond to π^0, η, and η' veto regions

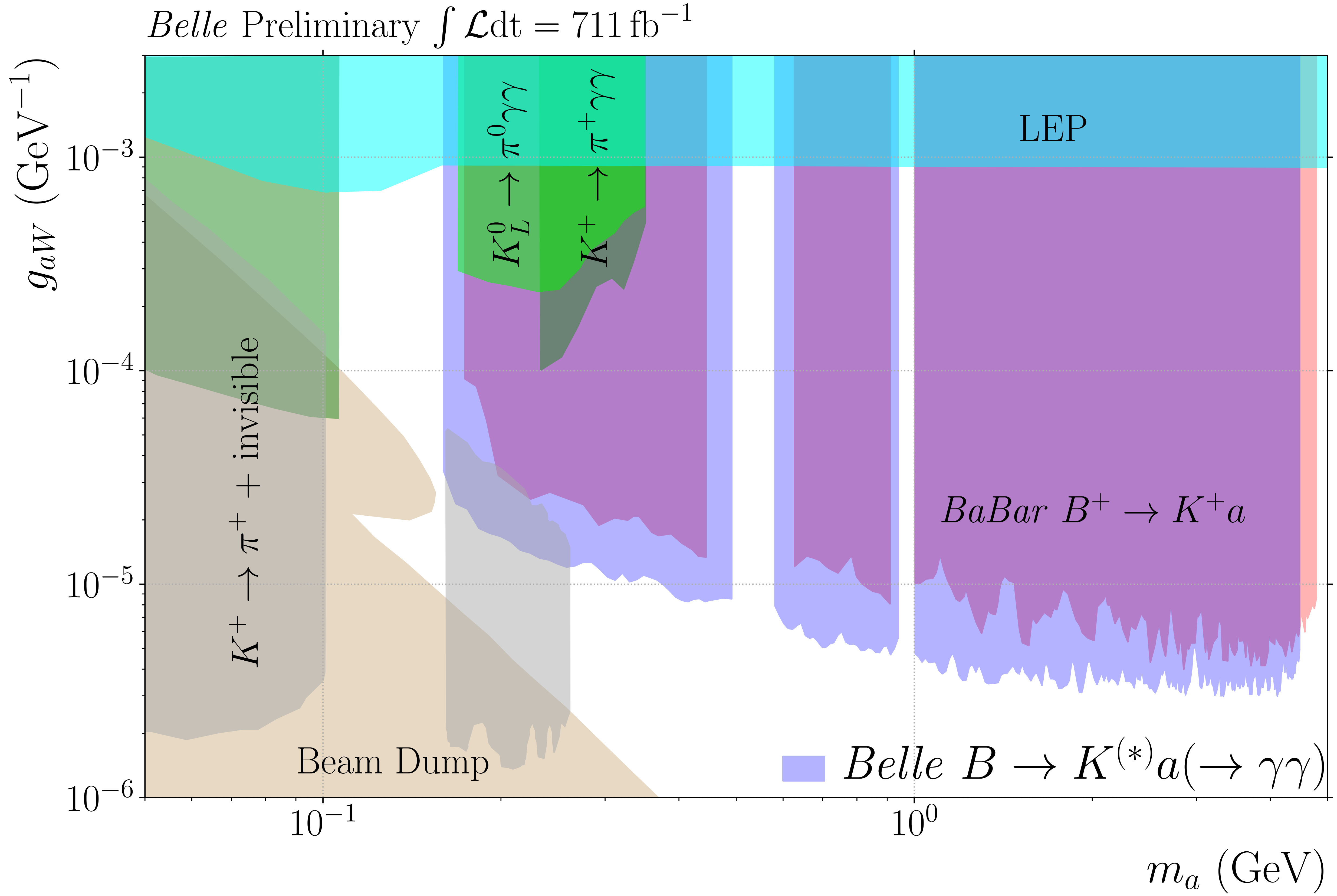
$B \to K^{(*)}\gamma\gamma$ for ALP, Upper limits on g_{aW}

arXiv:2507.01249
submitted to JHEP



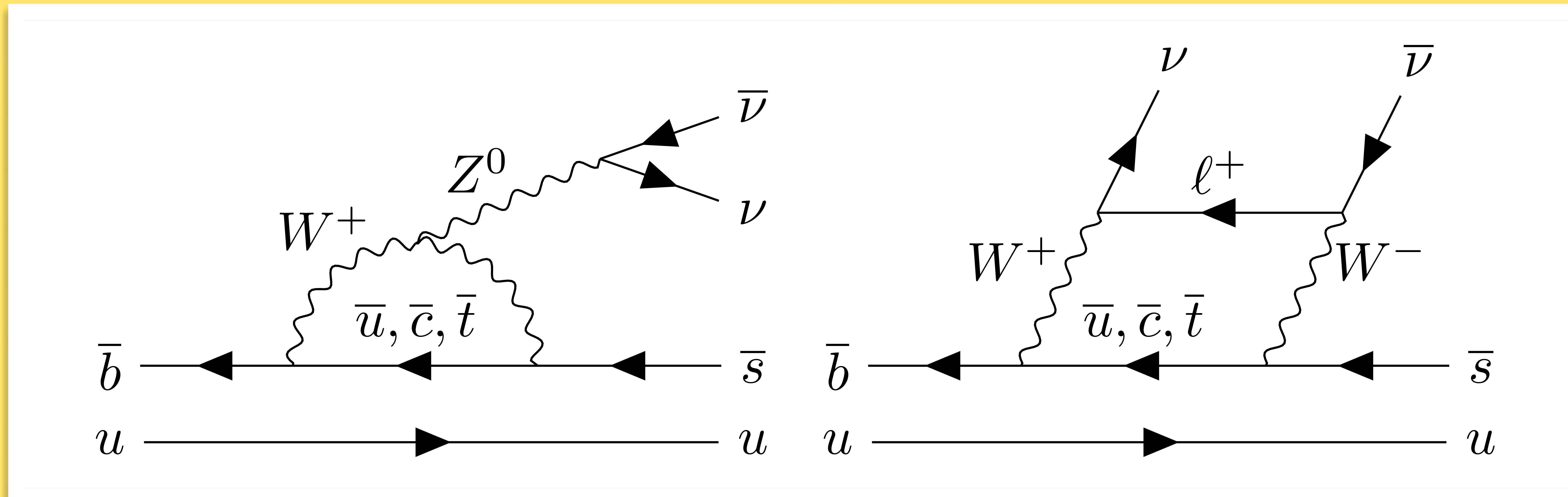
90% CL upper limits on g_{aW} as a function of m_a

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

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

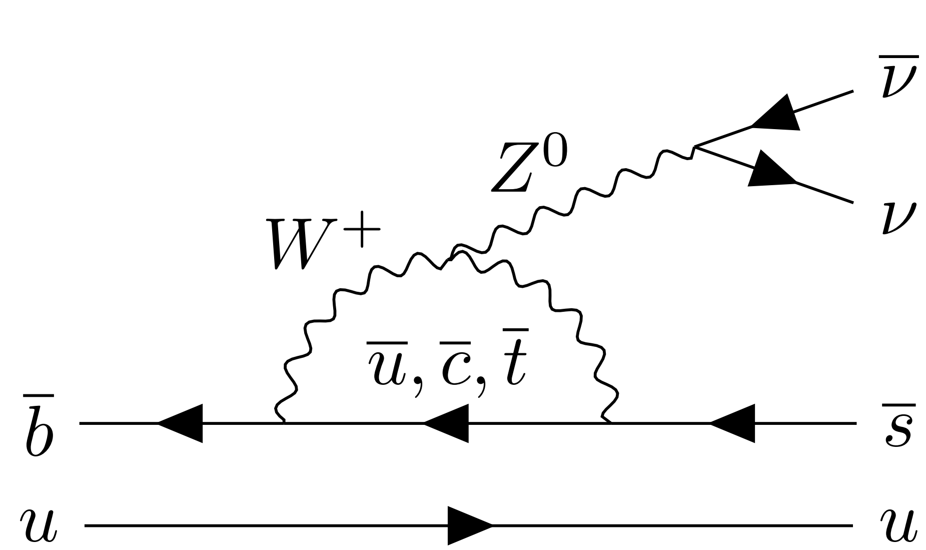


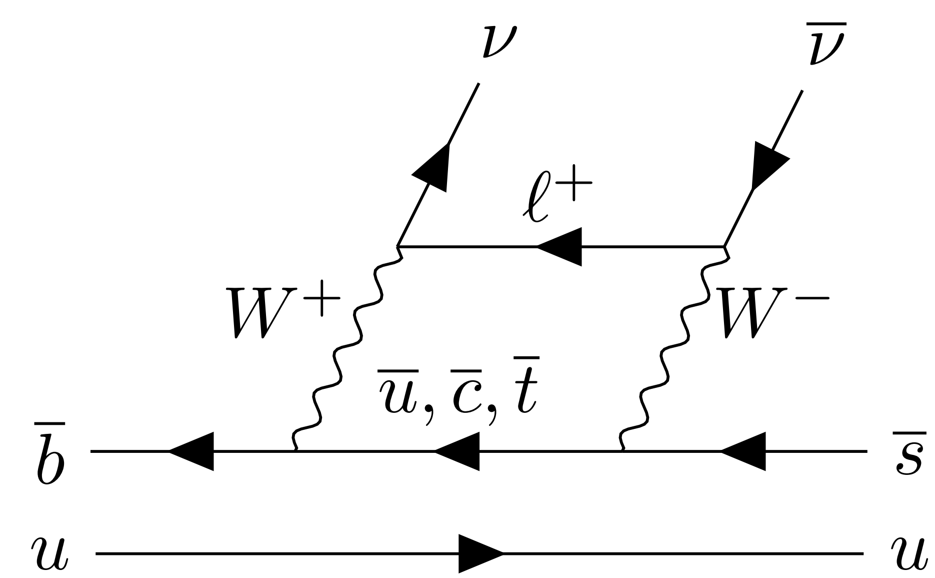
$B^+ \to K^+\nu\overline{\nu}$

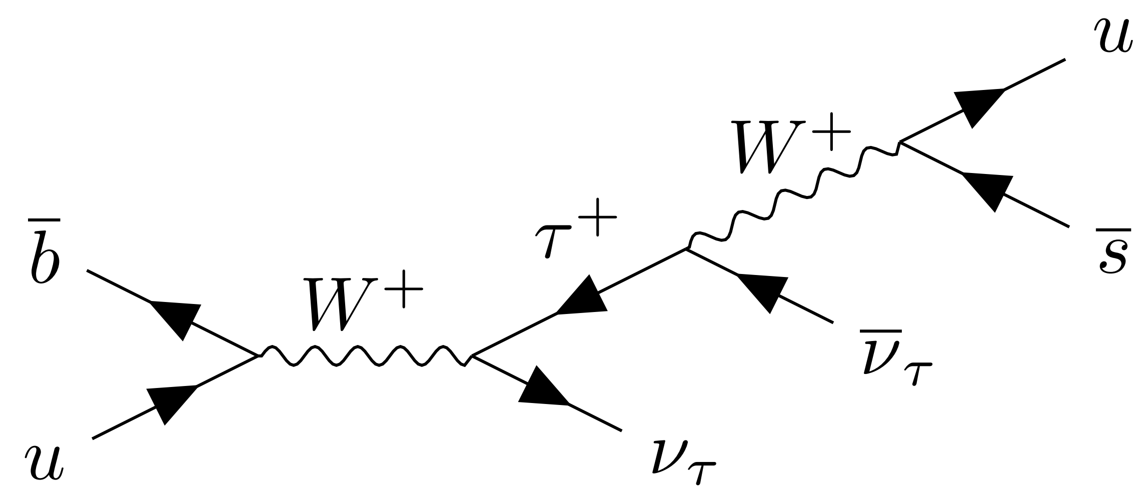
- In the SM,
  - $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$ [4]

[4] W. G. Parrott et al. PRD 107, 014511 (2023)
incl. long-distance contribution from $B \to \tau\nu$)

- sensitive to new physics BSM, e.g.
  - leptoquarks,
  - axions,
  - DM particles, etc.





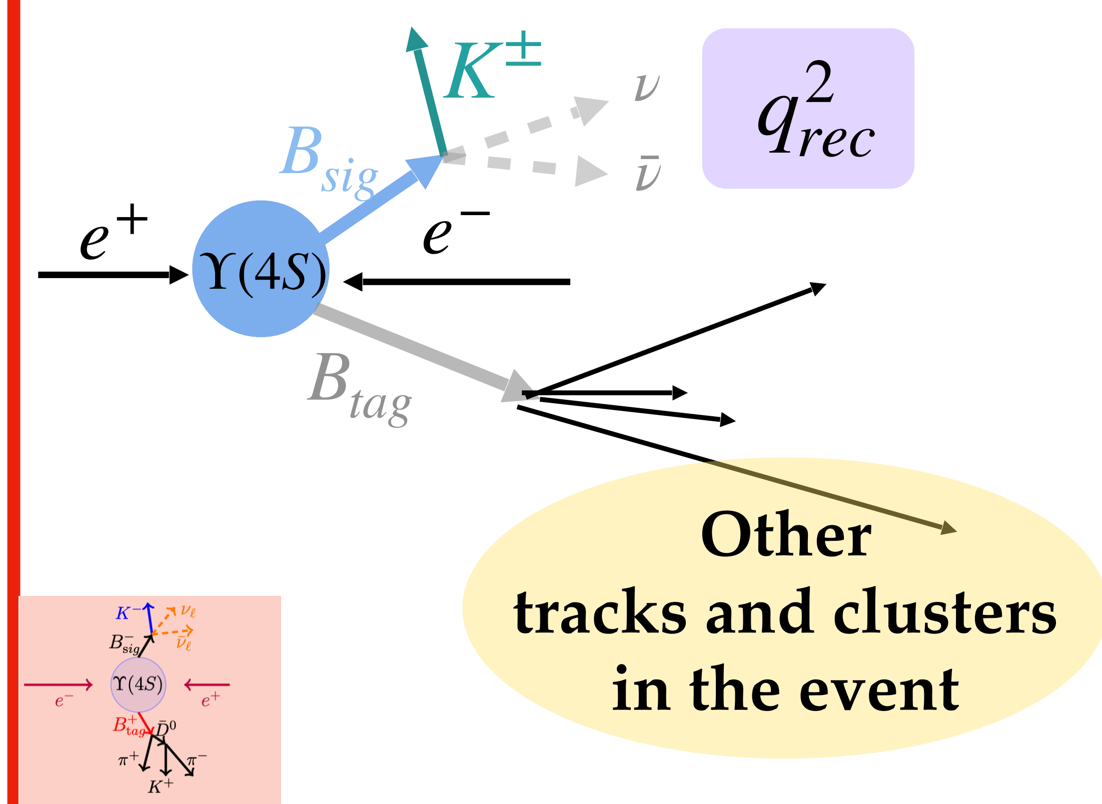


PRL 127, 181802 (2021)

$$\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) = (1.9^{+1.3+0.8}_{-1.3-0.7}) \times 10^{-5}$$
$$< 4.1 \times 10^{-5} \quad \text{@ 90\% CL}$$

"A Tale of Two Taggings"

Hadronic tagging (HTA)

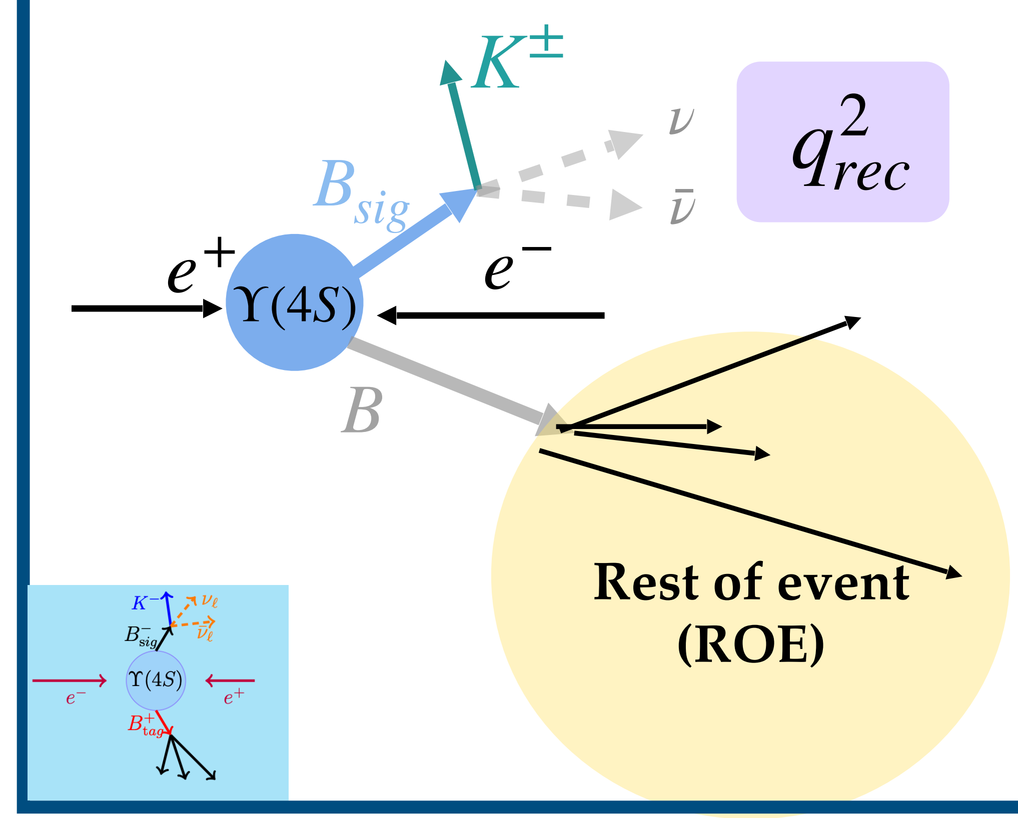


Efficiency →

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

← Purity, Resolution

Inclusive tagging (ITA)

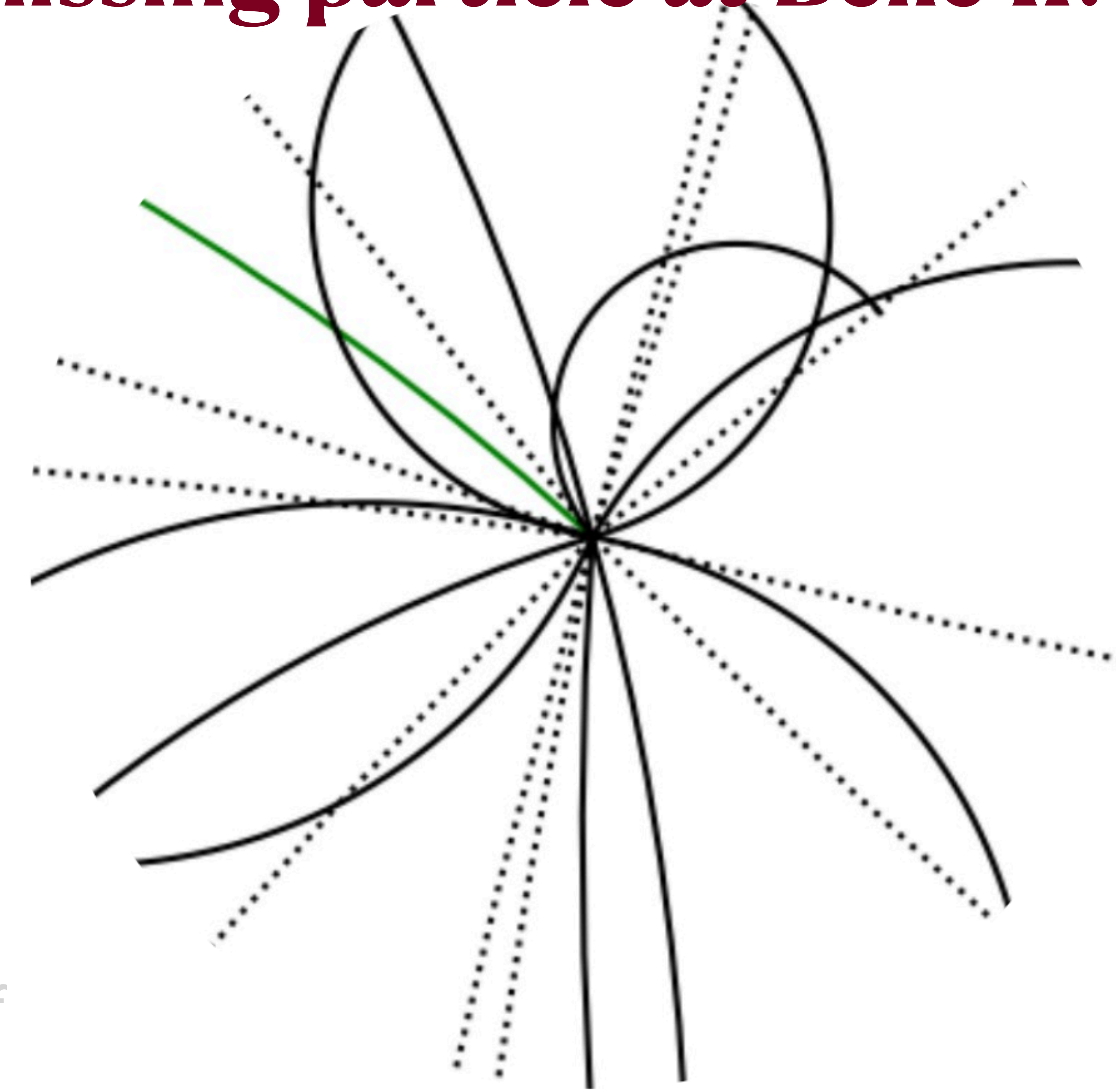


- Features of HTA
  - uses full decay chain information of of $B_{\rm tag}$
  - high high purity, very low efficiency
  - uses BDT for signal extraction ($\mathrm{BDT_h}$)

- Features of ITA
  - exploits inclusive properties of $B_{\rm tag}$
  - high efficiency, low purity
  - BDTs in two stages ($\mathrm{BDT_1}$ mostly for $q\bar{q}$; $\mathrm{BDT_2}$ 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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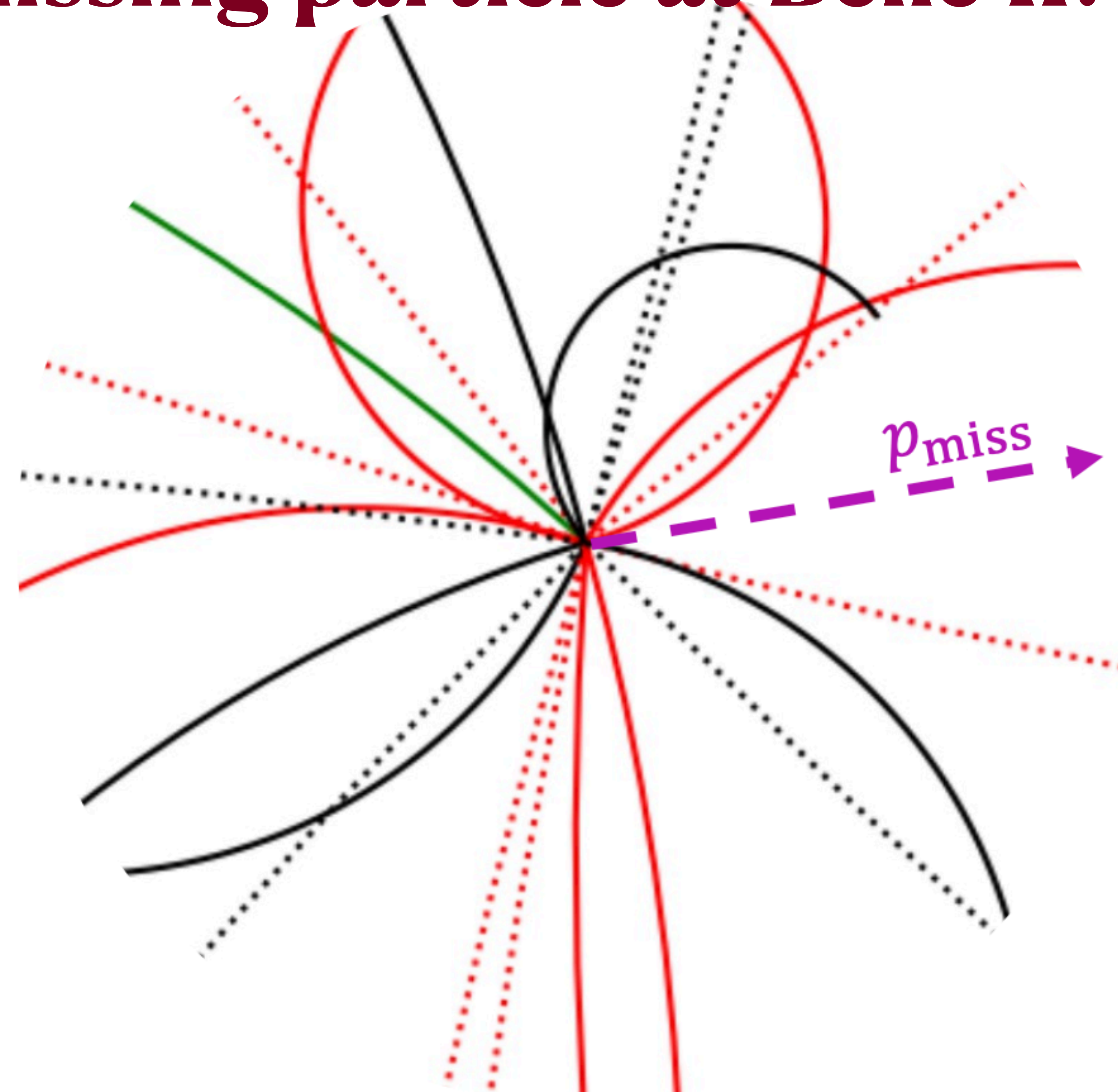
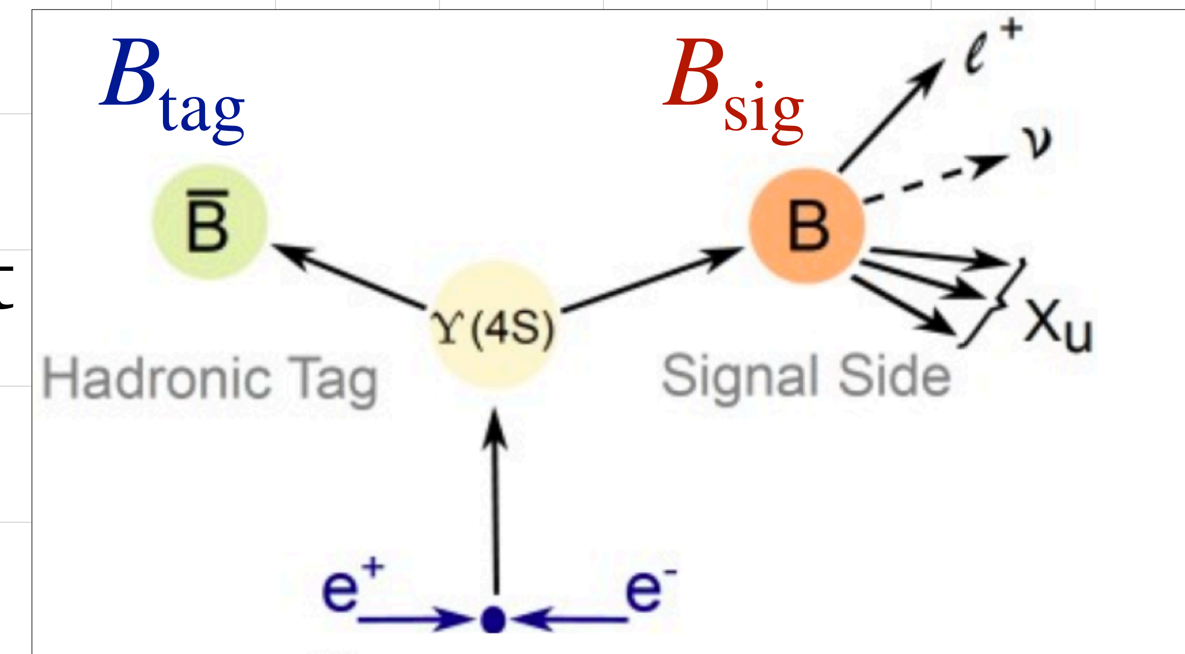


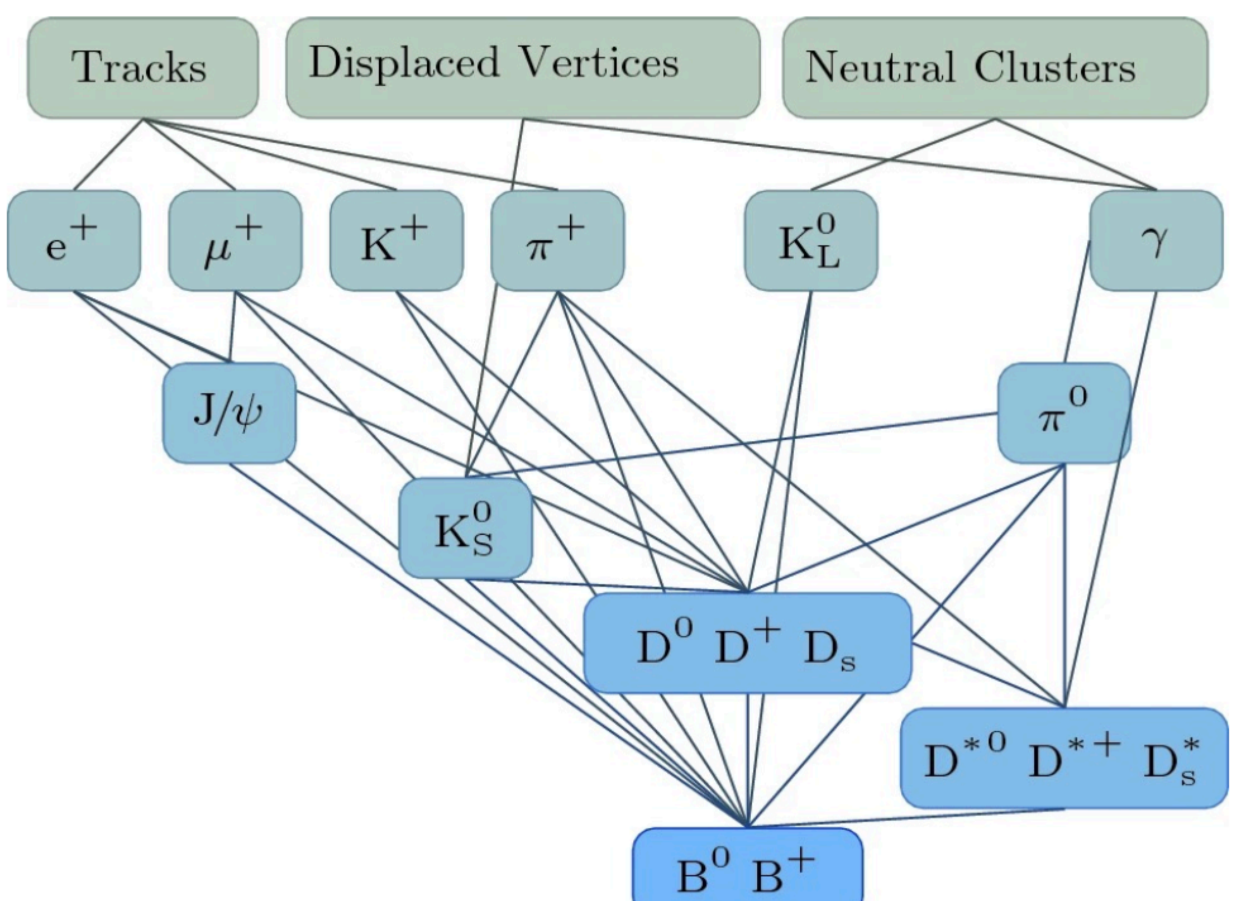
Full Event Interpretation (FEI)

FEI algorithm to reconstruct B_{tag}

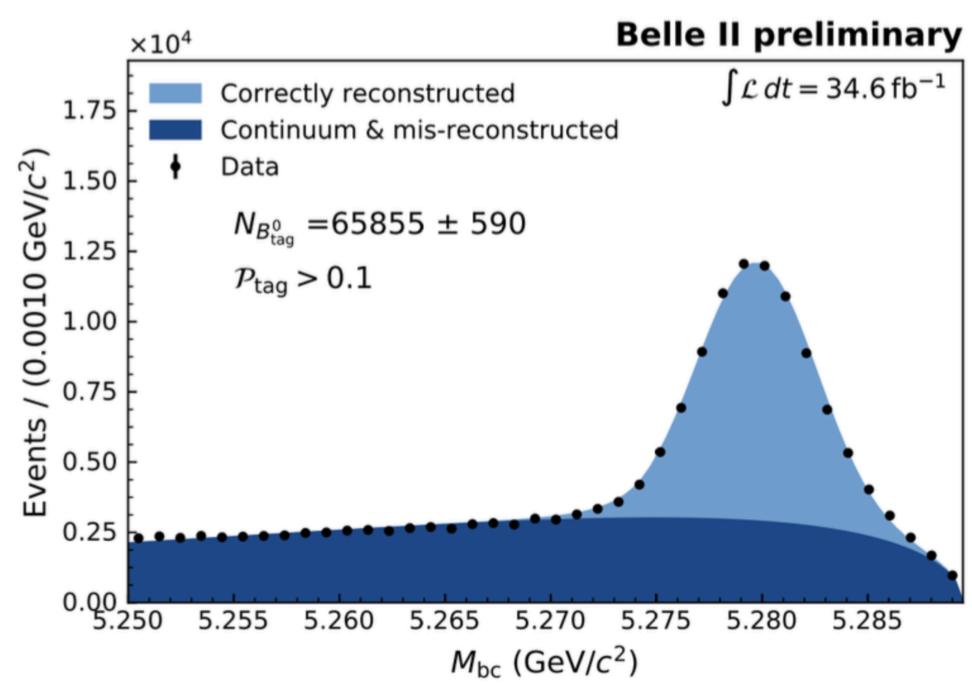
- uses ~200 BDT's to reconstruct $\mathcal{O}(10^4)$ different B decay chains
- assign signal probability of being correct B_{tag}

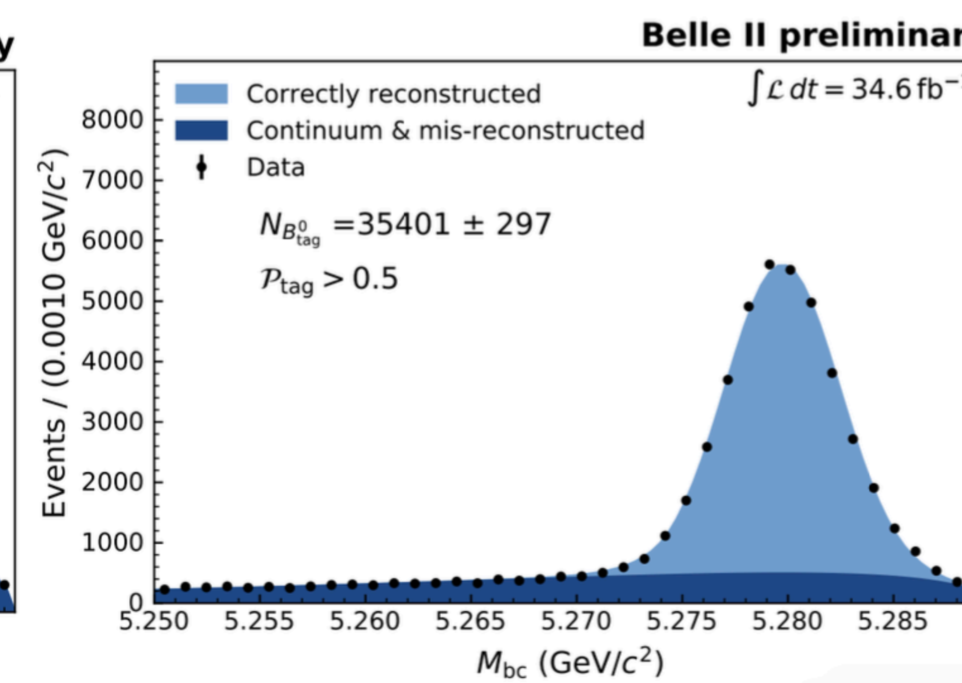


Comput Softw Big Sci 3, 6 (2019)



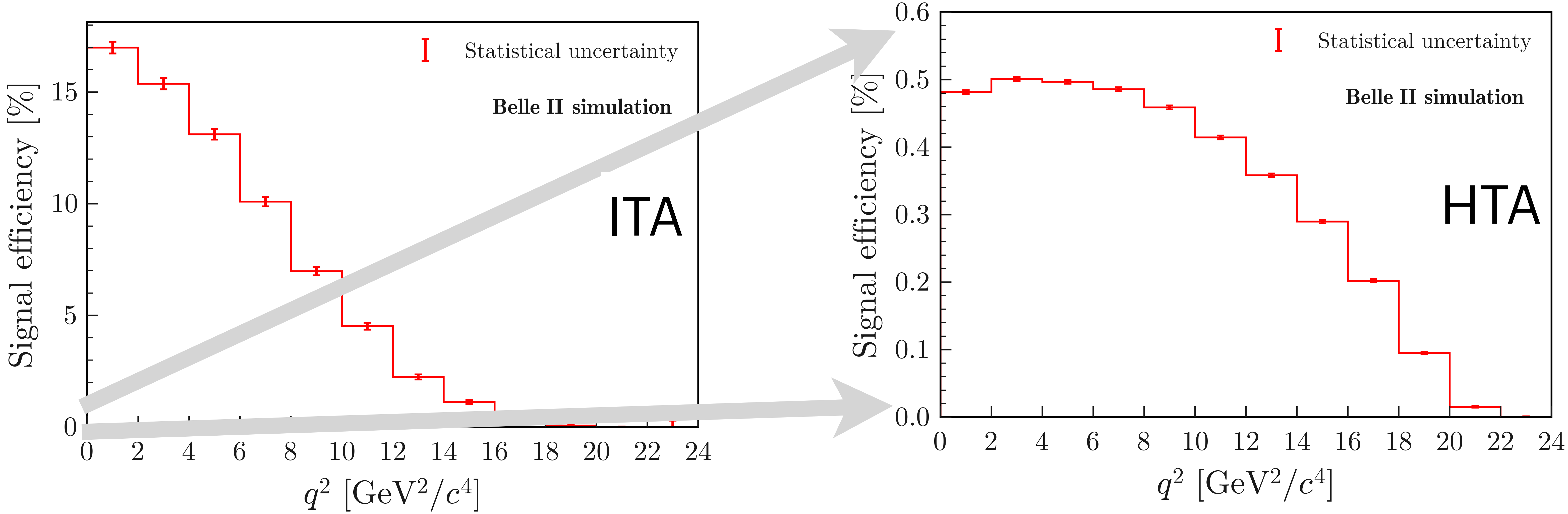
arXiv:2008.060965





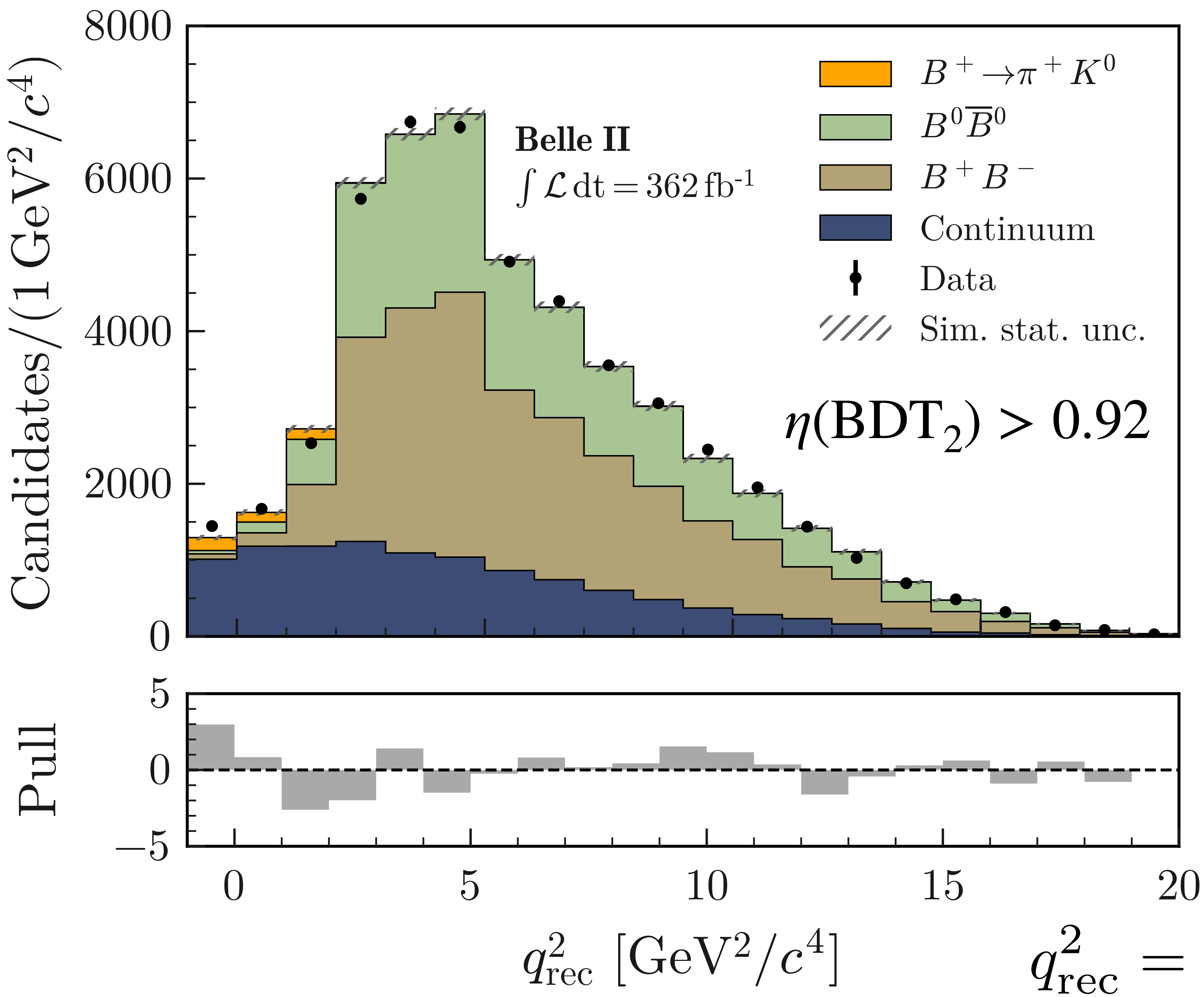
Signal efficiency (ITA vs. HTA)

after multi-variate analysis for ROE with BDT



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

Closure test (ITA)



- Pion ID instead of kaon ID
- Different q^2_{rec} bin boundaries
- Only on-resonance data used for fit
- Only normalization systematics included

Result:

- $\mathscr{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

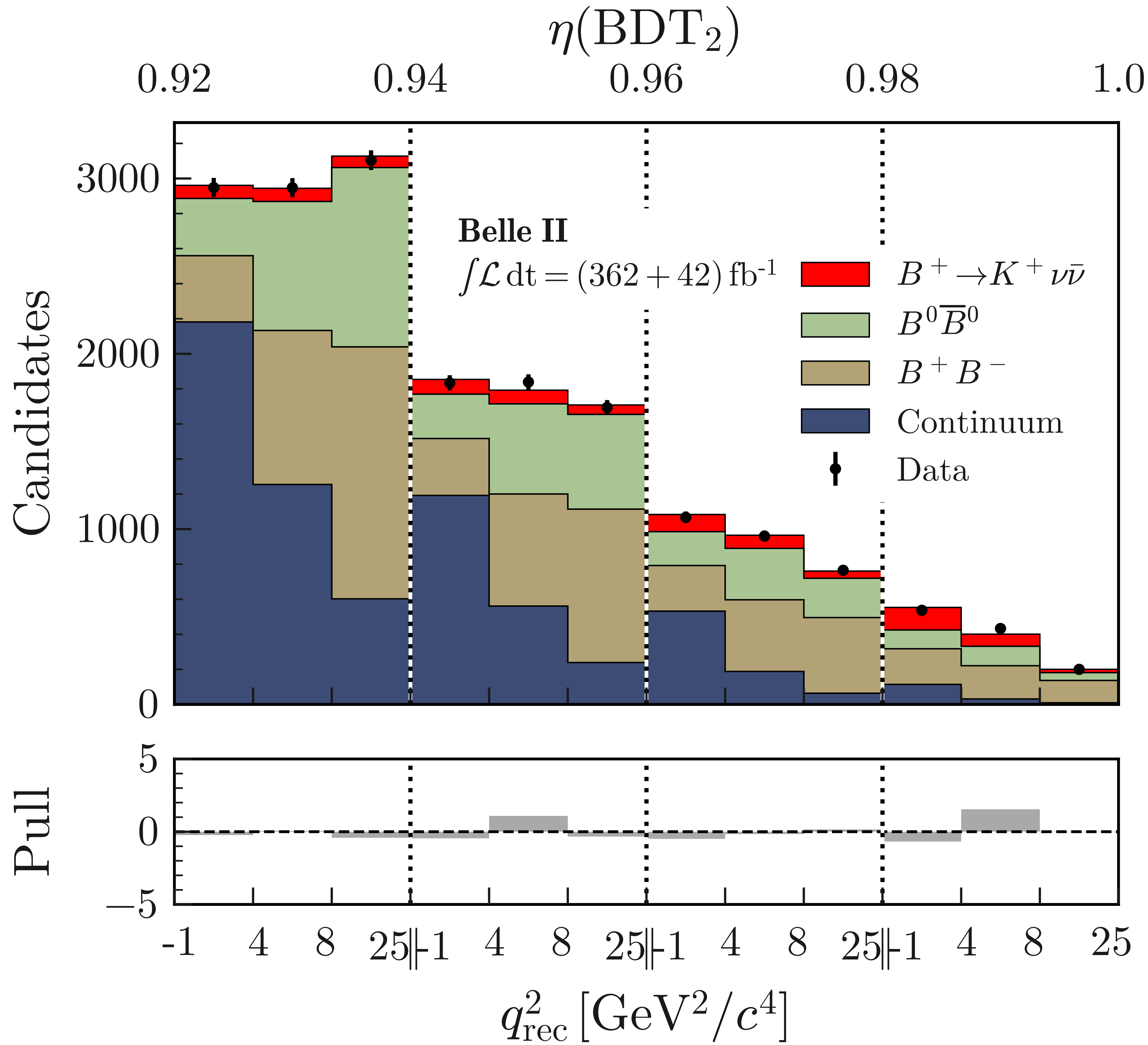
Consistent with PDG:

$\mathscr{B}(B^+ \to \pi^+ K^0) = (2.3 \pm 0.08) \times 10^{-5}$

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

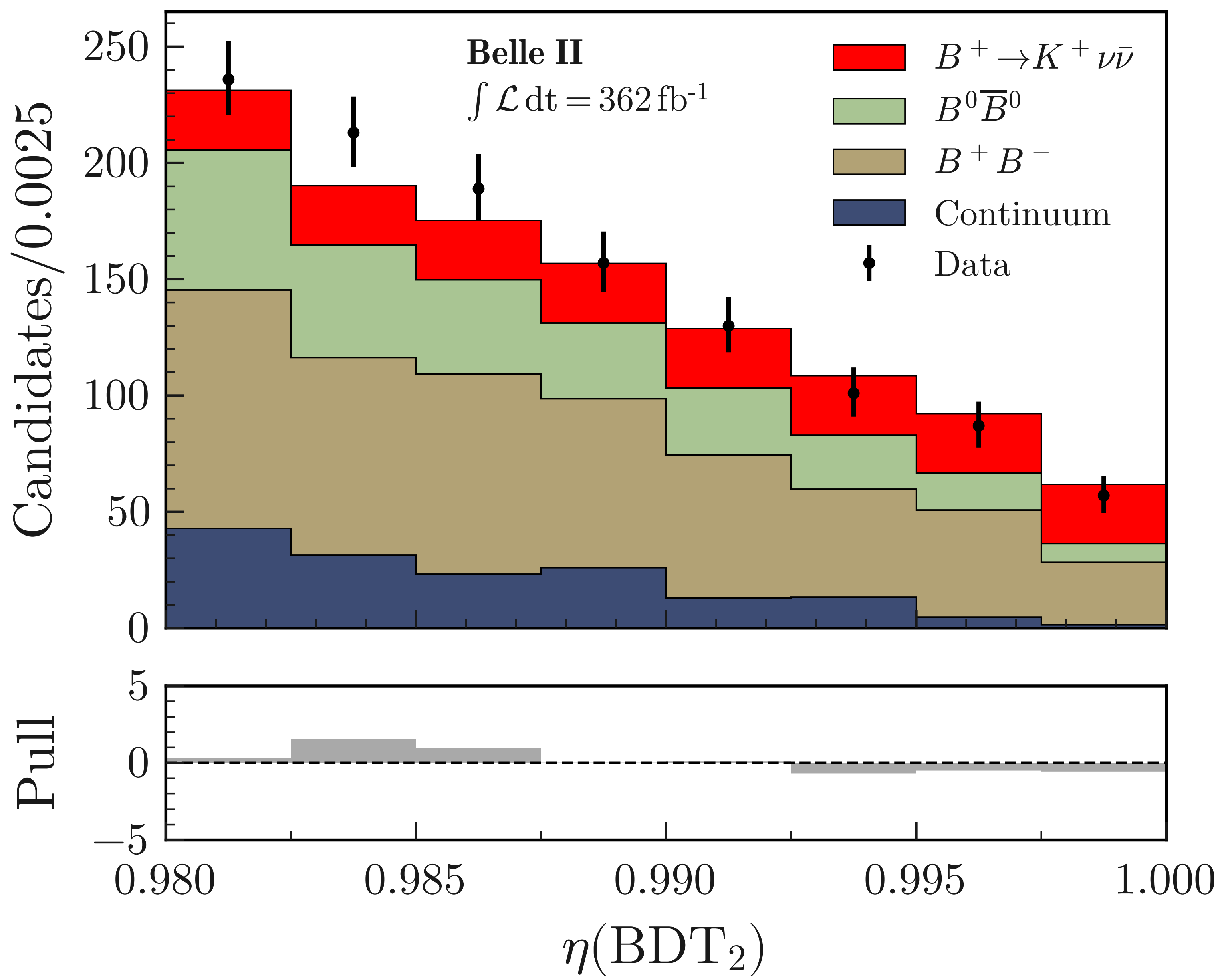
Assume B is at rest in the $\Upsilon(4S)$ rest-frame ($c = 1$)

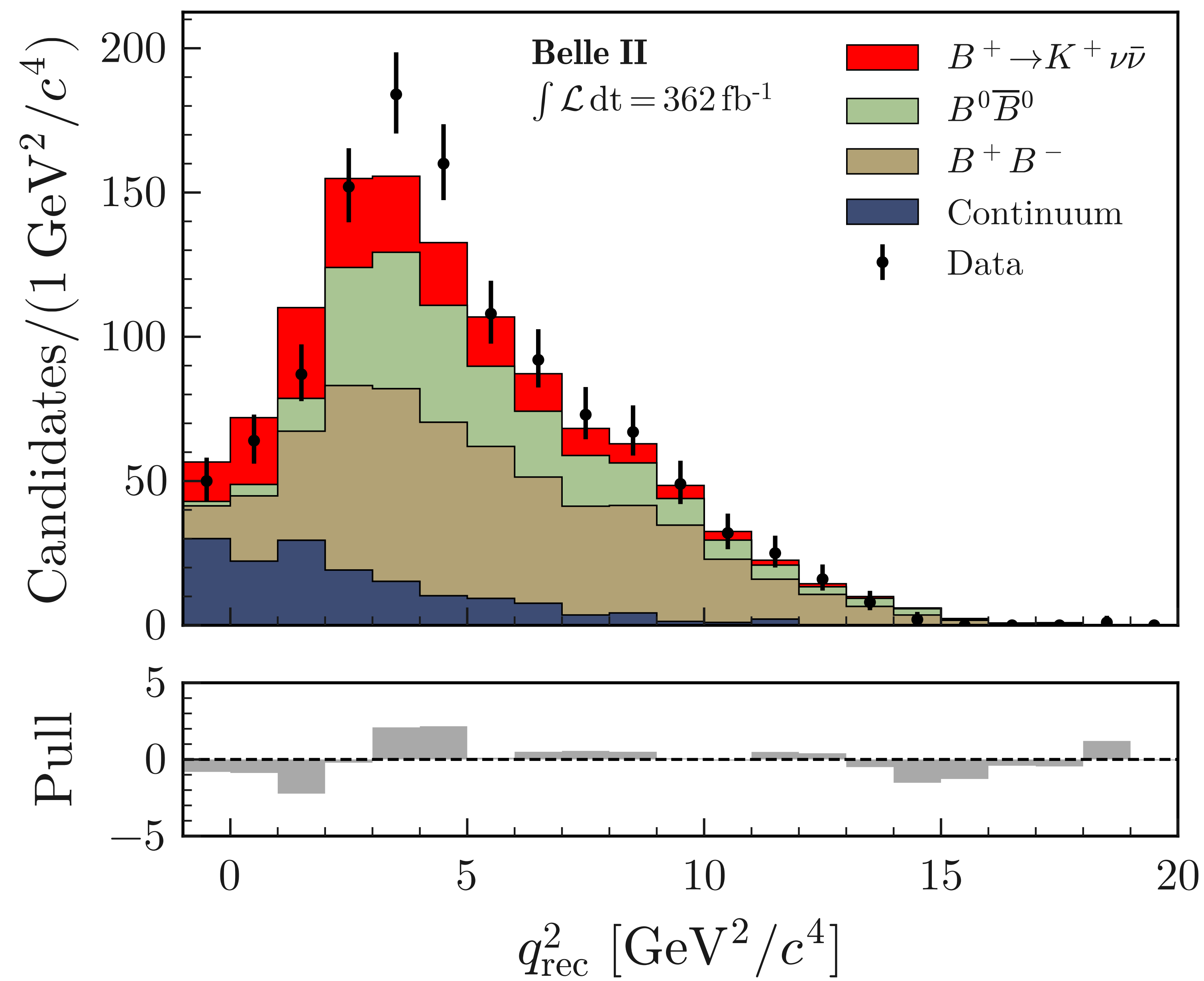
$B^+ \to K^+\nu\bar{\nu}$ result (ITA)



$B^+ \to K^+ \nu\bar{\nu}$ post-fit distributions (ITA)

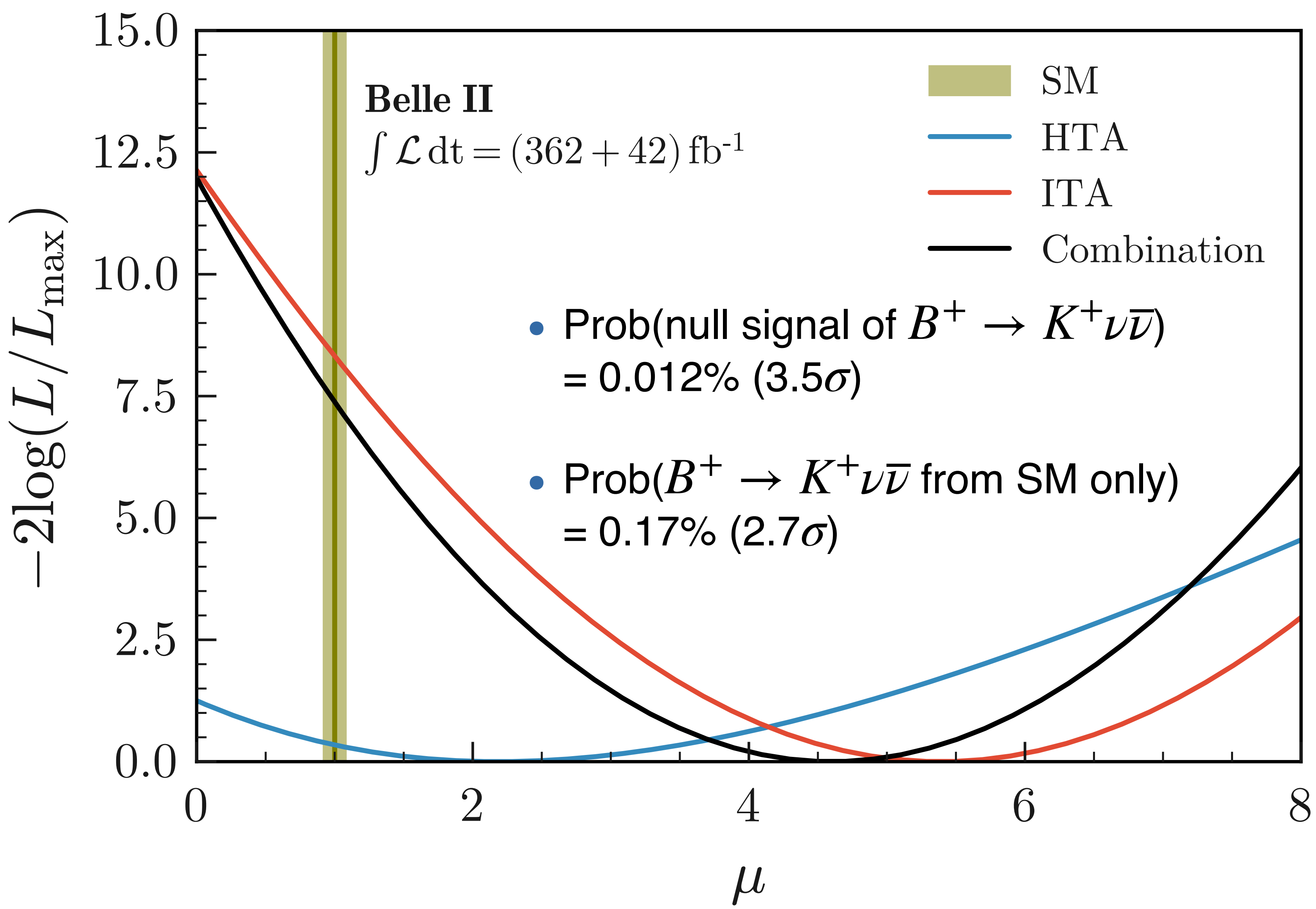
$$\eta(\mathrm{BDT}_2) > 0.98$$

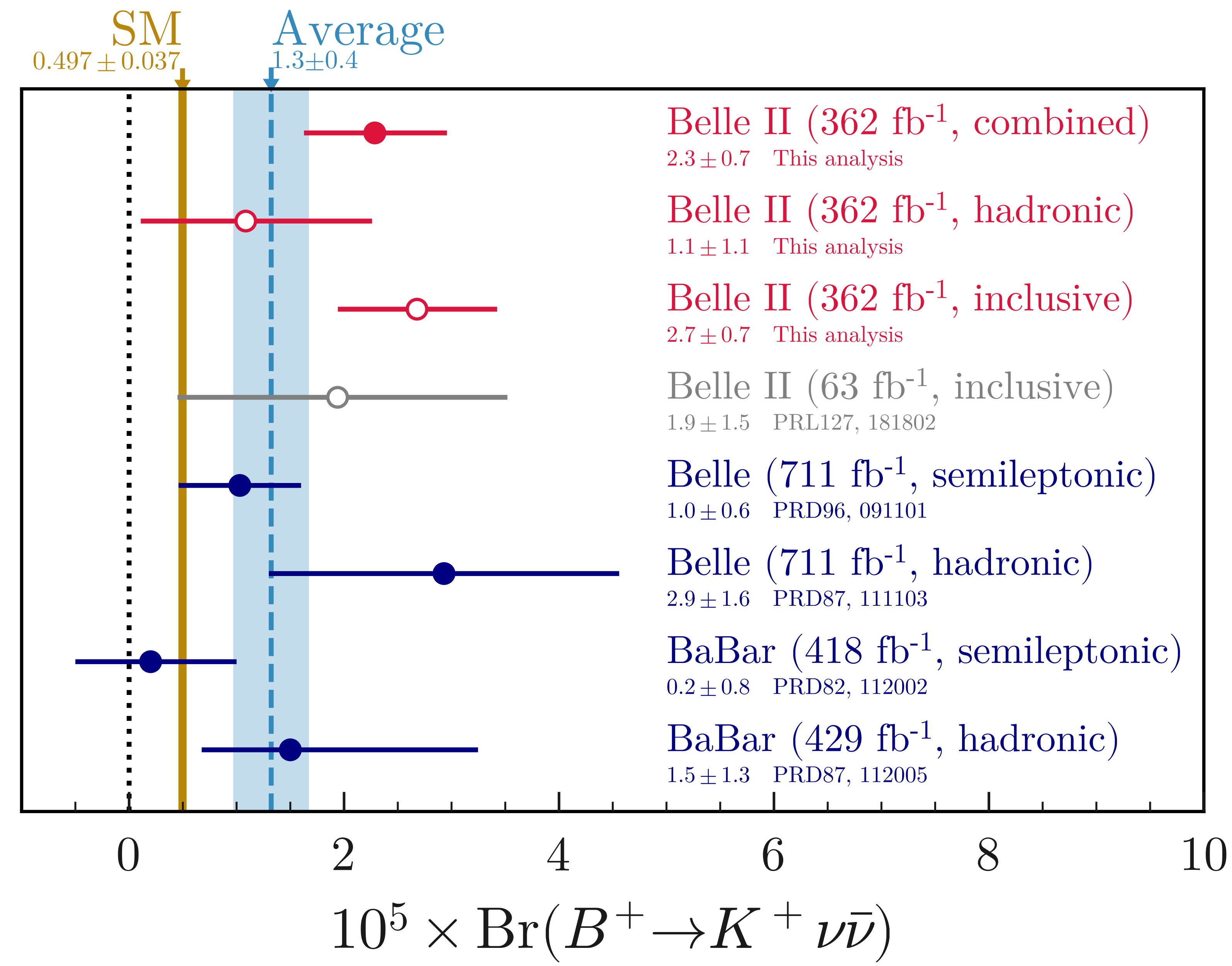




$$q^2_{\mathrm{rec}} = s/4 + M^2_{K^+} - \sqrt{s}E^*_{K^+}$$

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





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

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

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

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

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

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

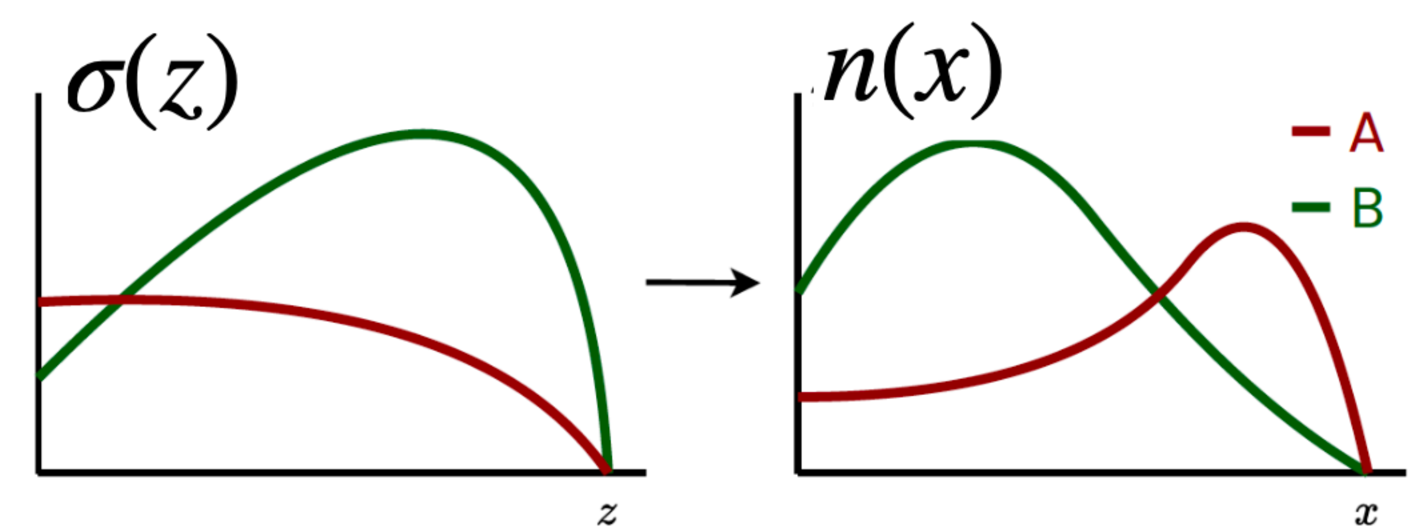
- Method
  - Number density & Joint number density
    ✓ σ = theory, ε = efficiency, x = fit variable
  - Null model (e.g. SM) vs. Alternative model

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

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

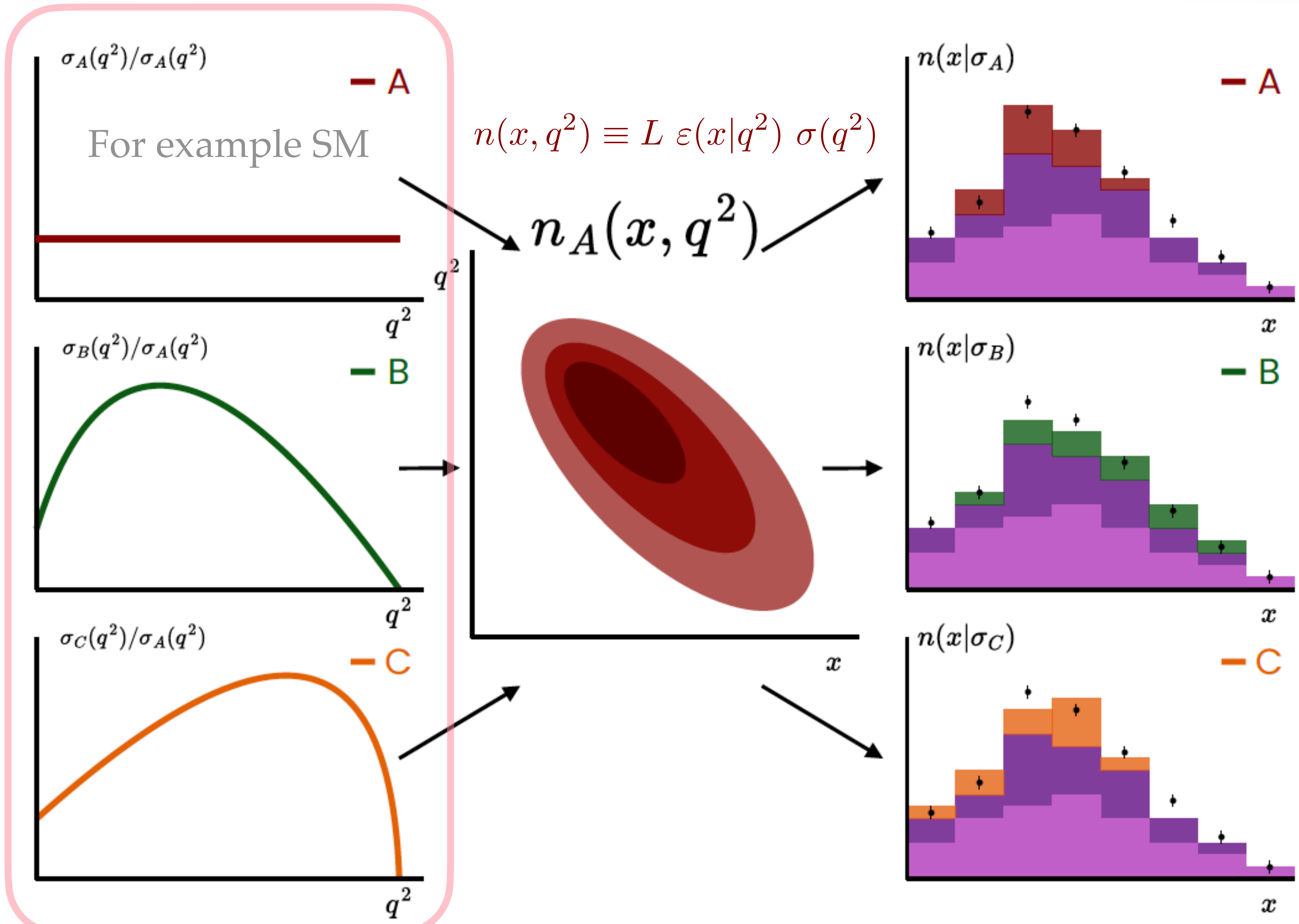
$$n_1(x) = L \int dq^2 \; n_0(x, q^2) \; w(q^2)$$

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



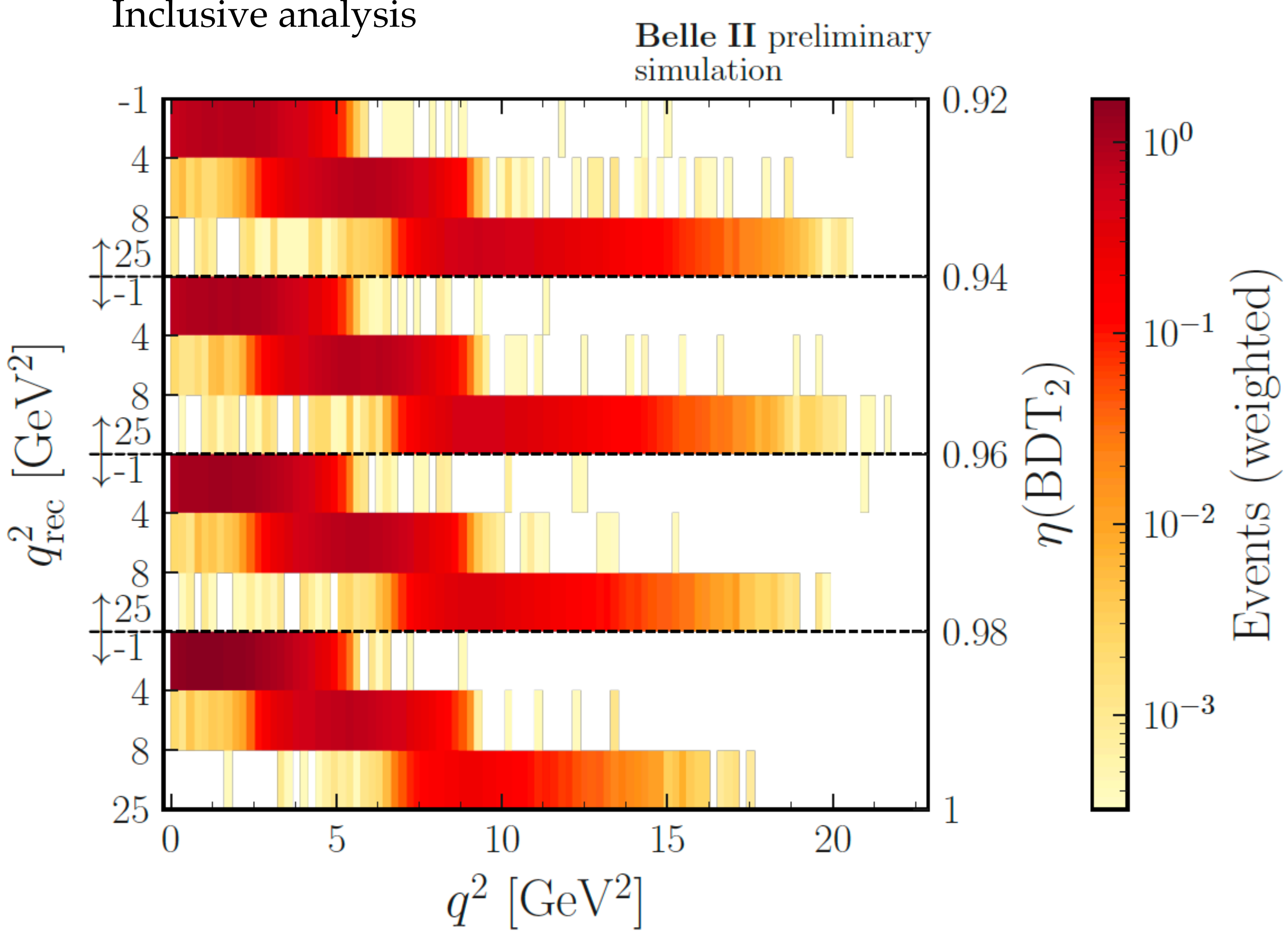
$B^+ \to K^+ \nu\bar{\nu}$, Re-interpretation

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



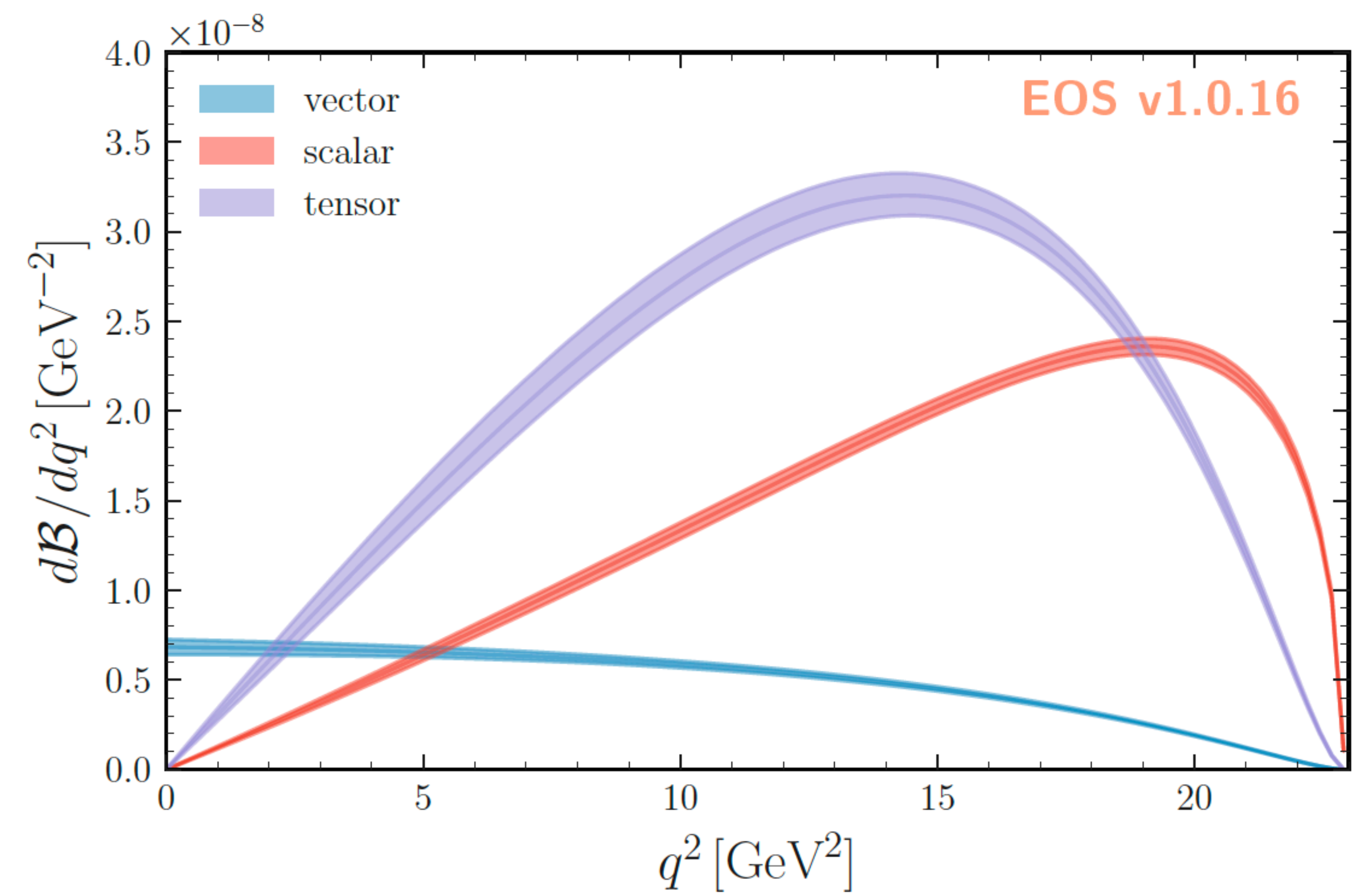
$B^+ \to K^+ \nu\bar{\nu}$, Re-interpretation

Plot for x vs. q^2



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

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



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

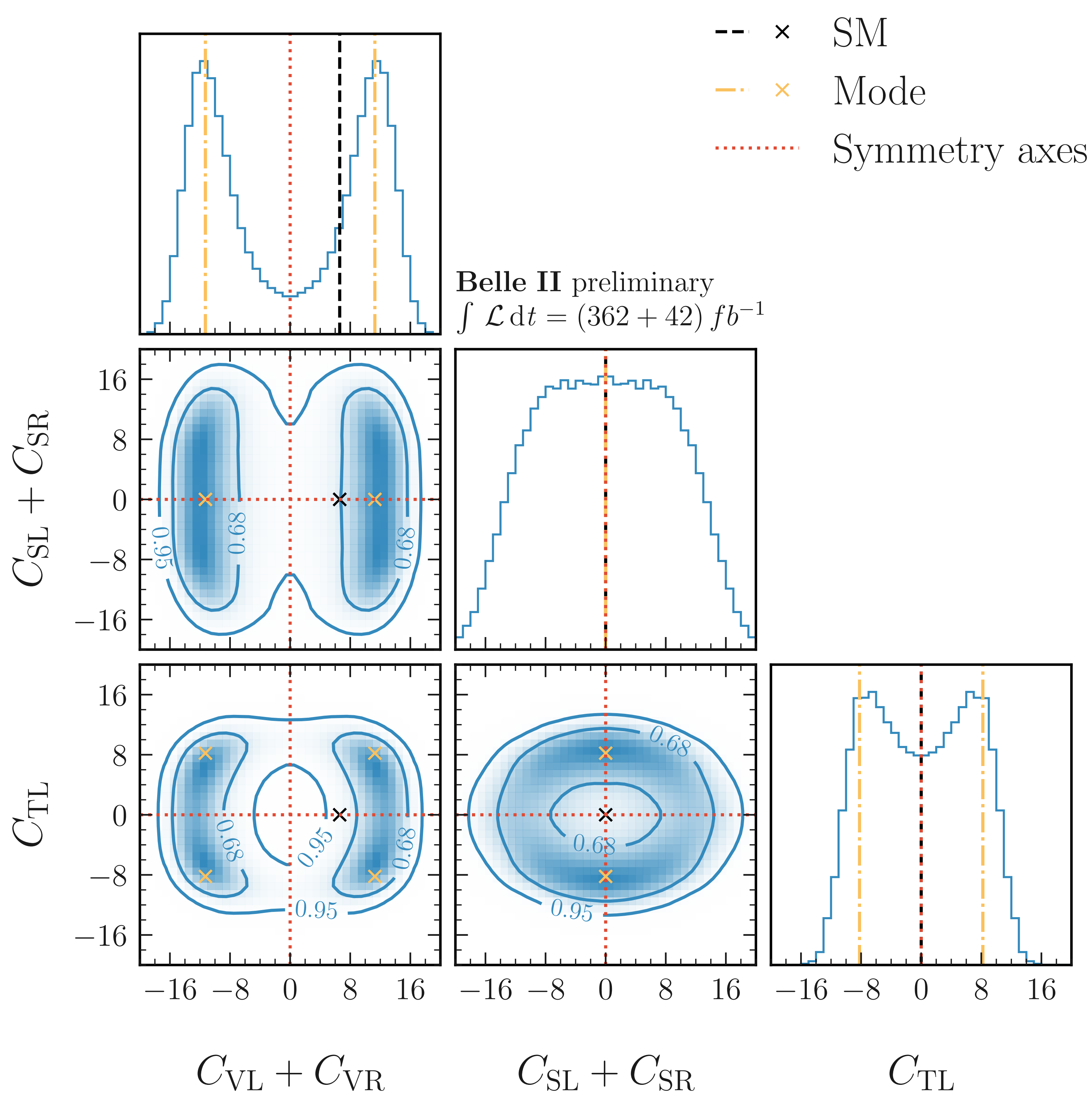
Parameters of interest

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

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

arXiv:2507.12393
submitted to PRD

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



Marginal posterior for the Wilson coeffs.
(Bayesian)

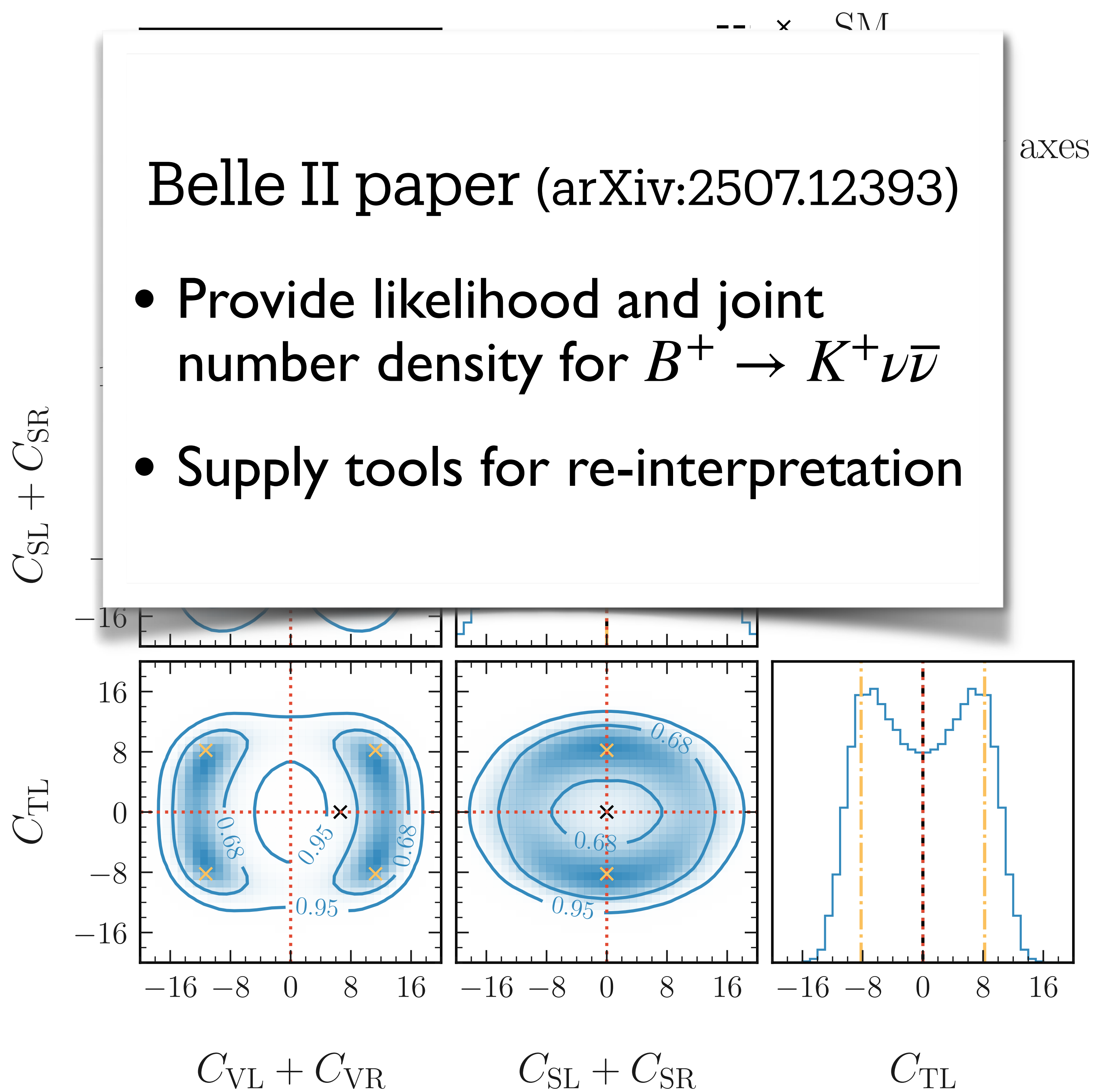
Parameters	Mode	68% HDI	95% HDI
$\lvert C_{VL} + C_{VR} \rvert$	11.3	[7.82, 14.6]	[1.86, 16.2]
$\lvert C_{SL} + C_{SR} \rvert$	0.00	[0.00, 9.58]	[0.00, 15.4]
$\lvert C_{TL} \rvert$	8.21	[2.29, 9.62]	[0.00, 11.2]

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

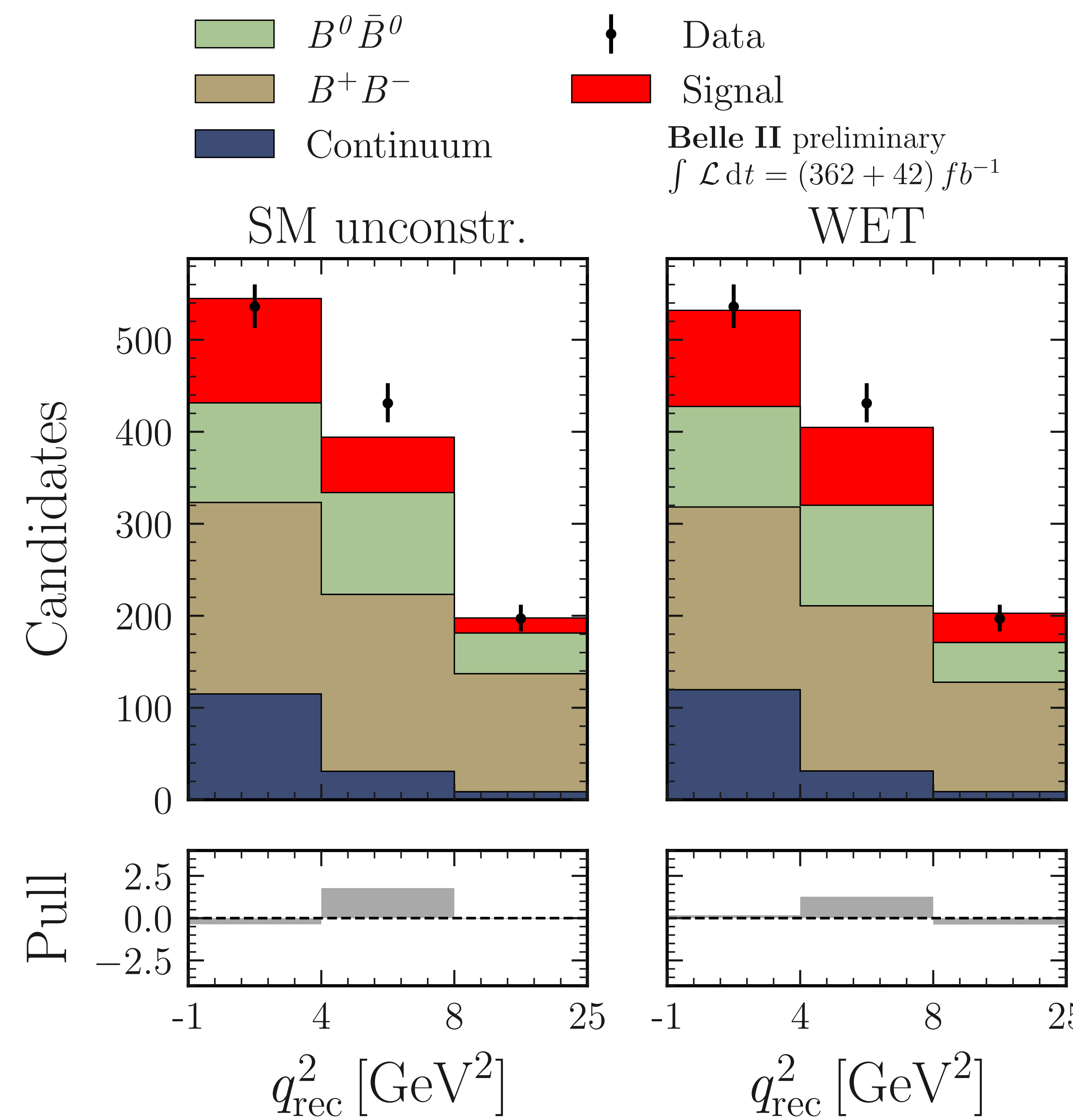
arXiv:2507.12393
submitted to PRD

Belle II paper (arXiv:2507.12393)

- 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)

From: <prd@aps.org>
Date: Fri, 24 Oct 2025, 16:57
Subject: Acceptance DG14356 Abumusabh
To: <lorenz.gaertner@gmail.com>

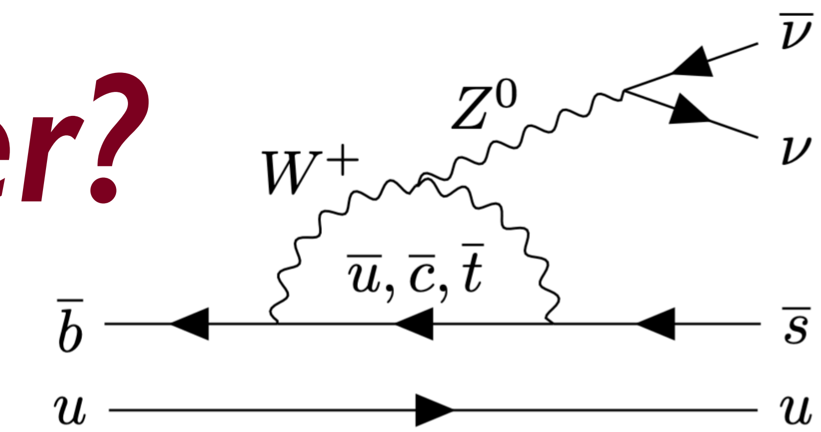
Re: DG14356
Model-agnostic likelihood for the reinterpretation of the B +
rightarrow K +v bar v measurement at Belle II
by M. Abumusabh, I. Adachi, L. Aggarwal, et al.

Dear Lorenz Gärtner,

We are pleased to inform you that your manuscript has been accepted for publication as a Regular Article in Physical Review D.

You should receive page proofs in one to two weeks after your

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

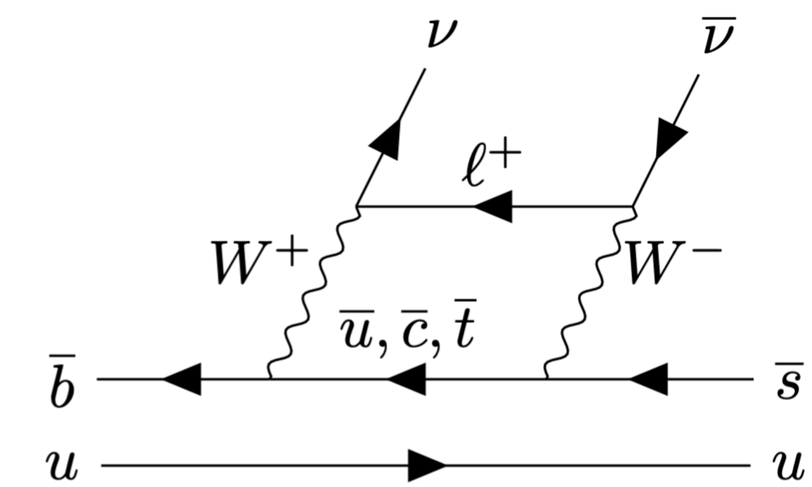


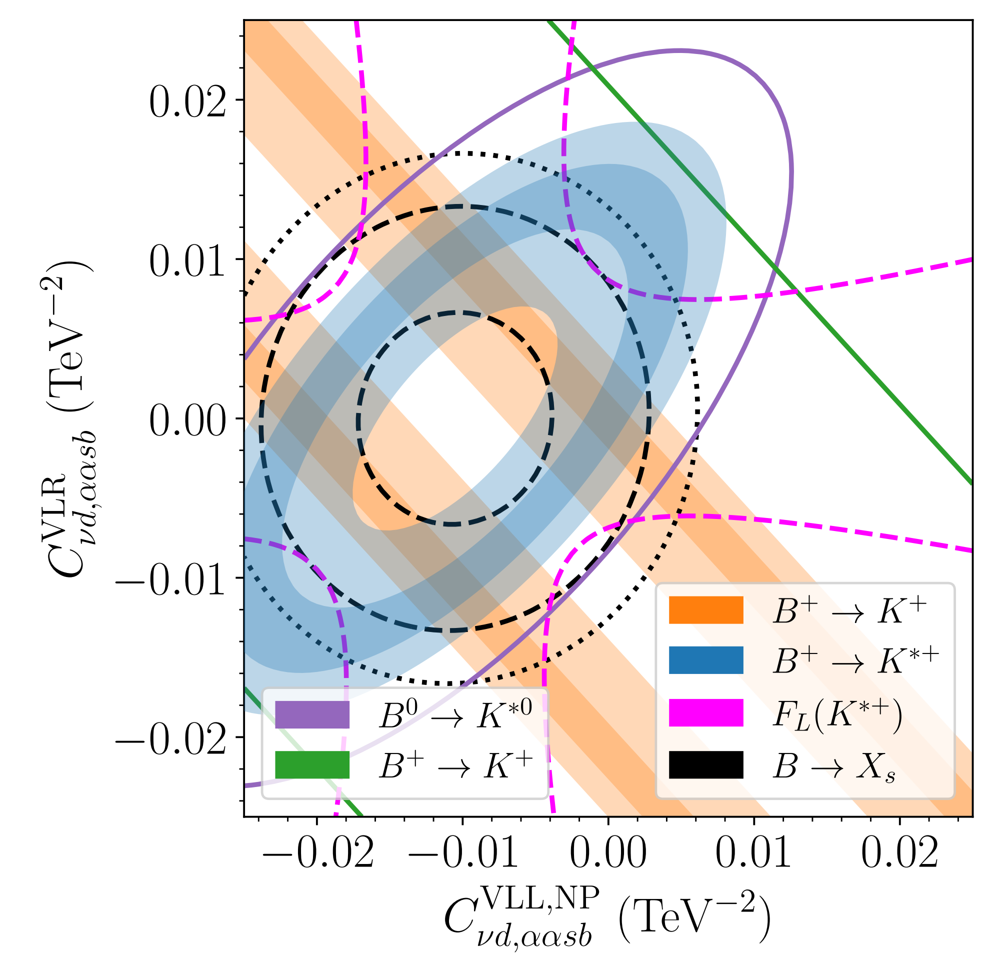
- Things to note
  - Inclusive measurement for X_s (= hadronic system with $S = \pm 1$) final states
  - sensitive to different aspects of SM & NP

    e.g. *not dependent on hadronic FF*
  - not very well-measured

    only by ALEPH (BF < 6.4x10^{-4} @ 90% CL)

    no separate measurement for 'B mesons'





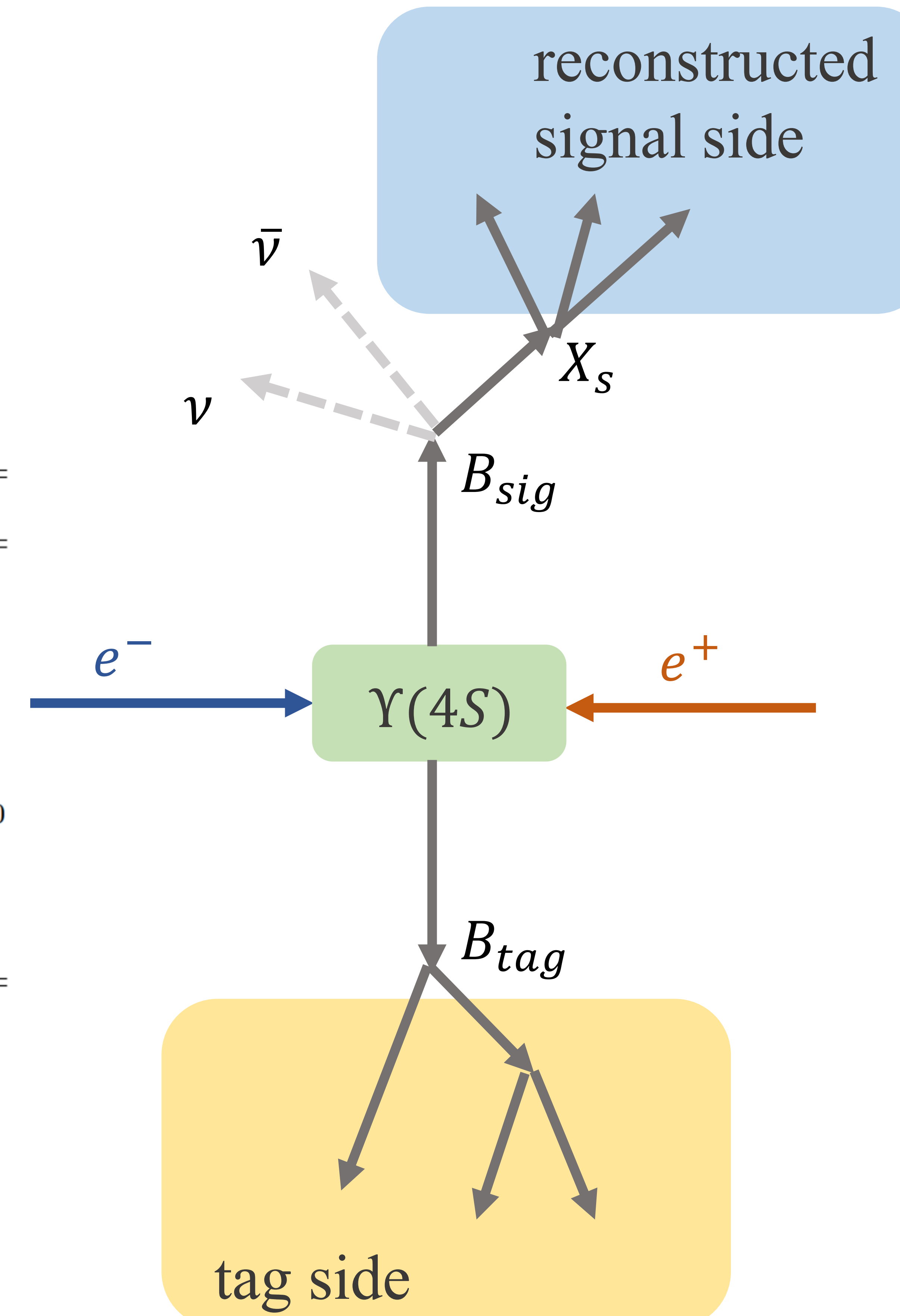
from Felkl, T., Li, S.L. & Schmidt, M.A. "A tale of invisibility: constraints on new physics in $b \to s\nu\nu$". *J. High Energ. Phys.* **2021**, 118 (2021)

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

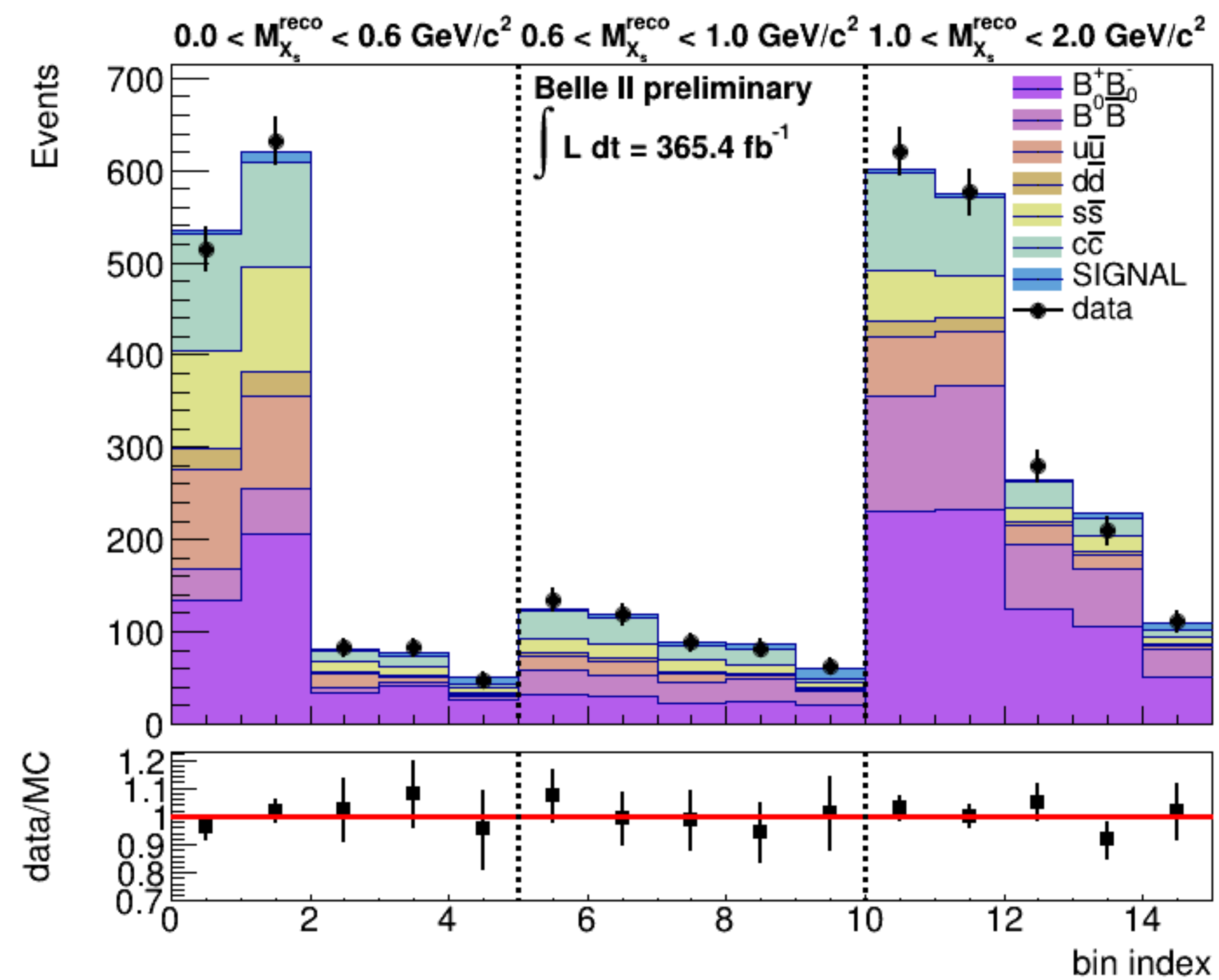
	$B^0\bar{B}^0$			$B^{\pm}$		
K	K_S^0			$K^{\pm}$		
$K\pi$	$K^{\pm}\pi^{\mp}$	$K_S^0\pi^0$		$K^{\pm}\pi^0$	$K_S^0\pi^{\pm}$	
$K2\pi$	$K^{\pm}\pi^{\mp}\pi^0$	$K_S^0\pi^{\pm}\pi^{\mp}$	$K_S^0\pi^0\pi^0$	$K^{\pm}\pi^{\mp}\pi^{\pm}$	$K_S^0\pi^{\pm}\pi^0$	$K^{\pm}\pi^0\pi^0$
$K3\pi$	$K^{\pm}\pi^{\mp}\pi^{\pm}\pi^{\mp}$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

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)



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

- Procedure after X_s reconstruction
  - use BDT for background suppression
    - ✓ 68% efficiency & 97% rejection
  - validation & correction using control samples
    - ✓ off-resonance data
    - ✓ BDT side-band
    - ✓ $B \to X_s J/\psi$
- signal extraction
  - 2D binned max. likelihood fit to $(M_{X_s}^{\text{reco}}, \text{BDT output})$

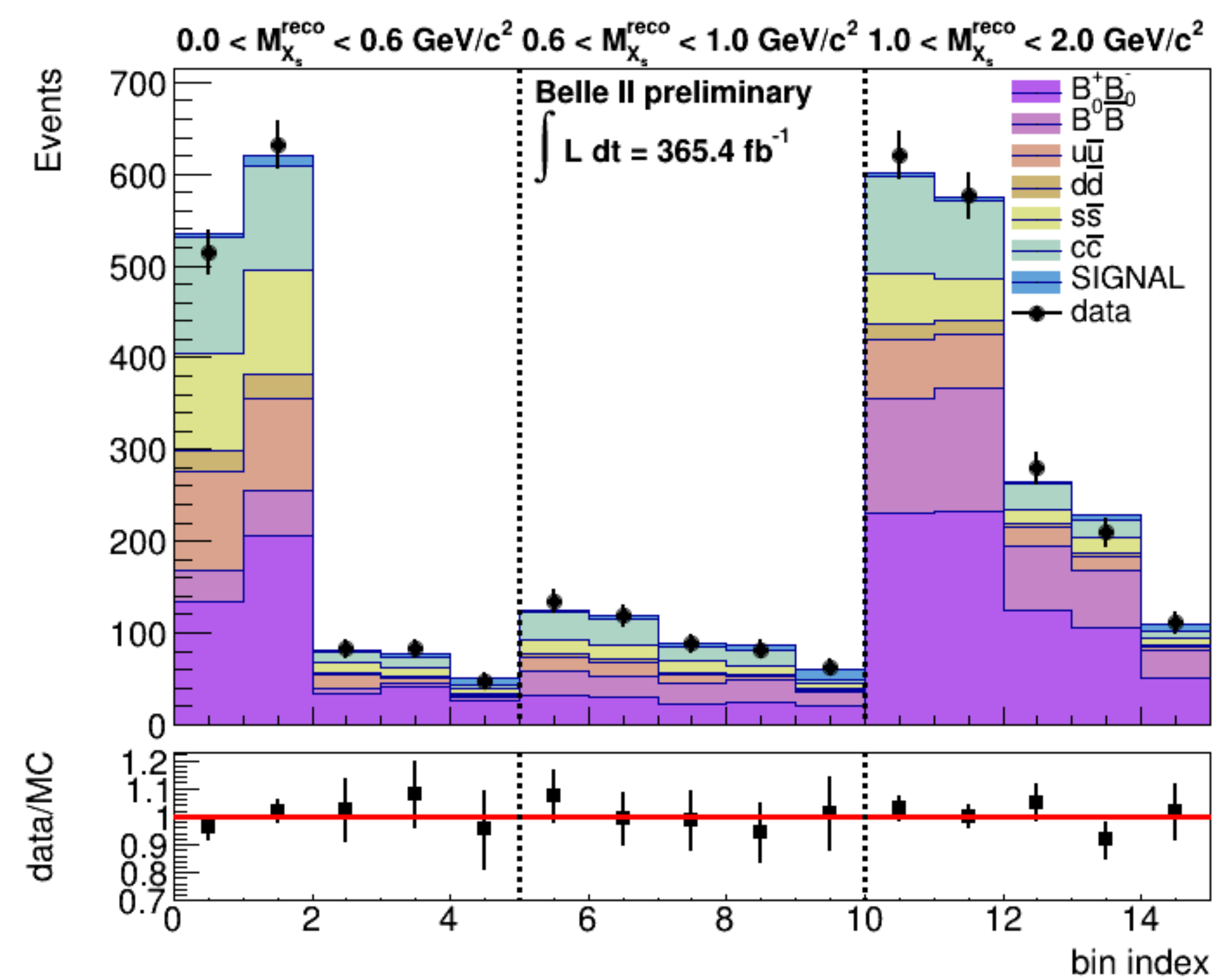


$B \to X_s \nu \bar{\nu}$ Inclusive, *Results*

- 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)

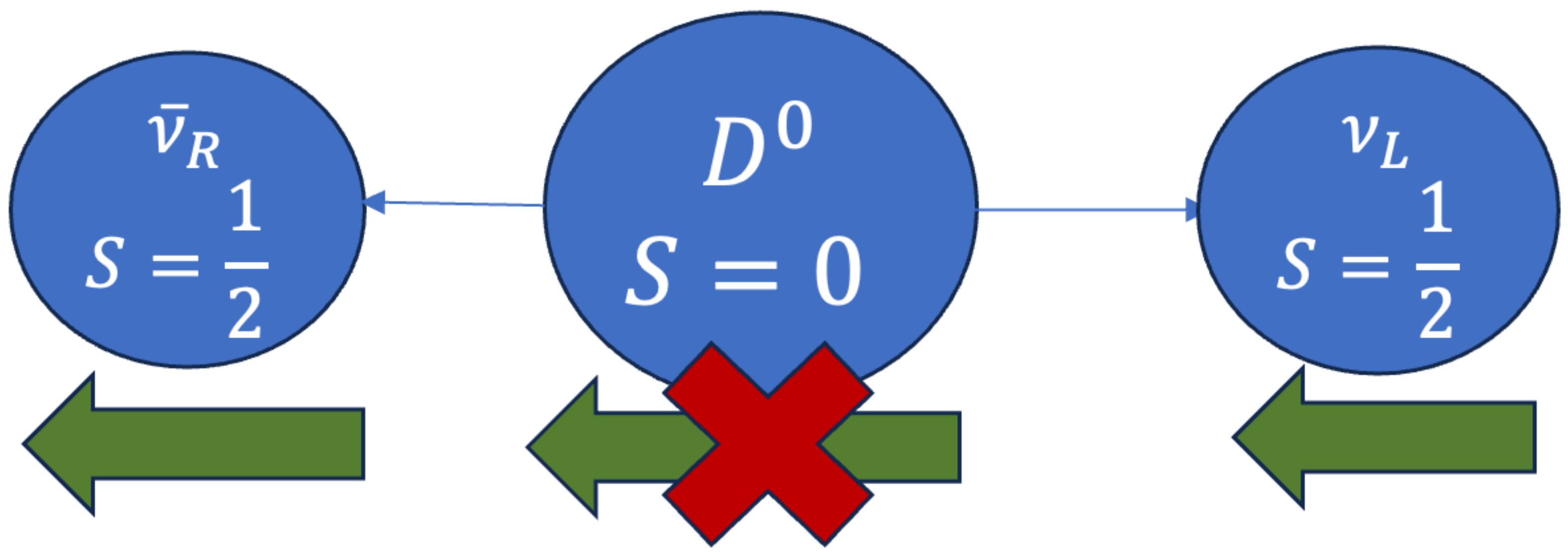
The most stringent limit for inclusive $B \to X_s \nu \bar{\nu}$

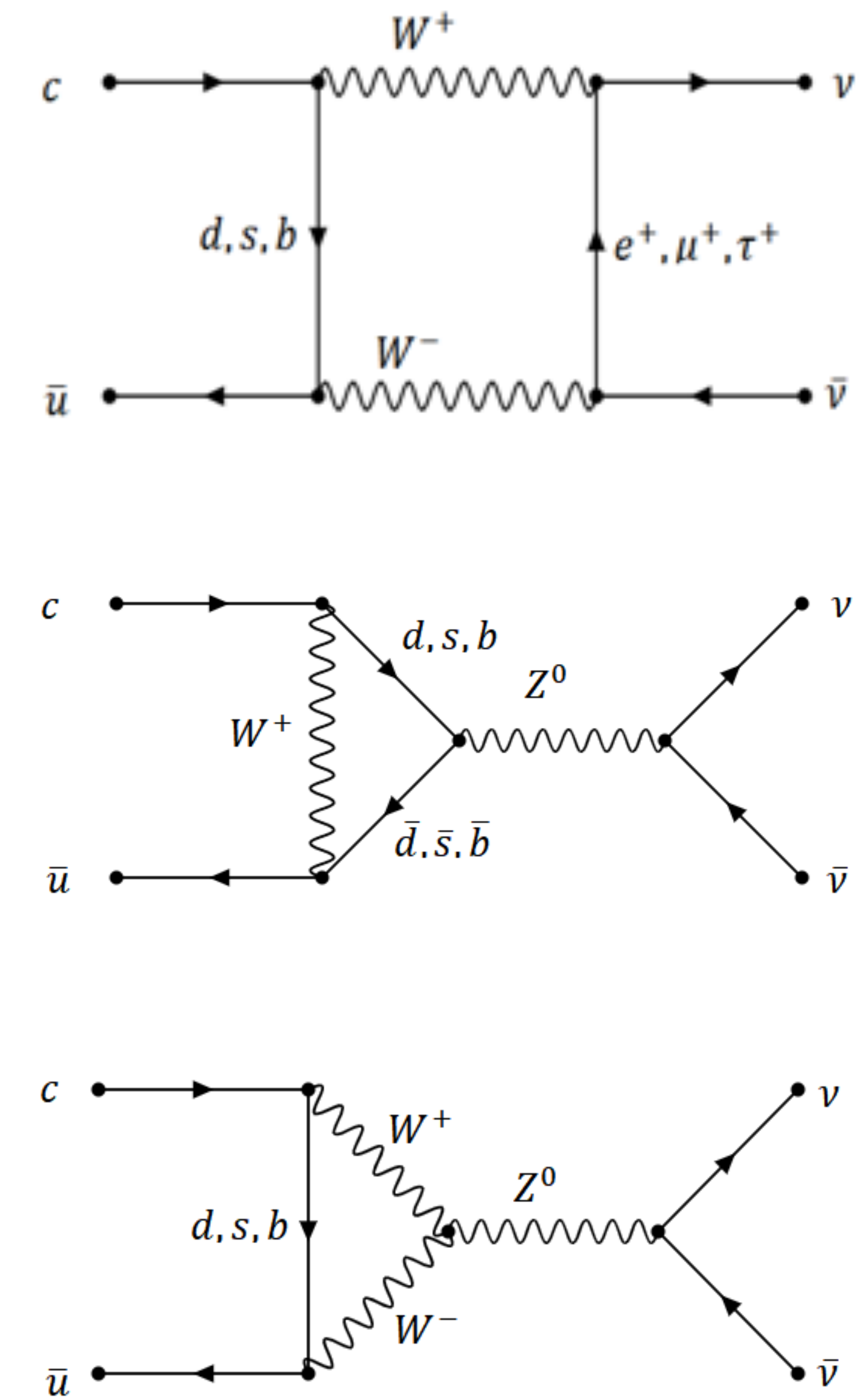
(the first for B-meson)



$$D^0 \to \nu\bar{\nu}$$

Intro. to $D^0 \rightarrow$ *invisibles* decays





- In the SM
  - helicity suppression
  - very small BF $\sim 10^{-30}$, i.e. way beyond Belle II
  - sensitive to New Physics
- Sensitive to DM
  - $\nu\bar{\nu}$ final state is invisible

    $\therefore$ final states consisting of DM particles can appear as signals

$D^0 \to$ *invisibles* analysis tool

"Charm Tagger"

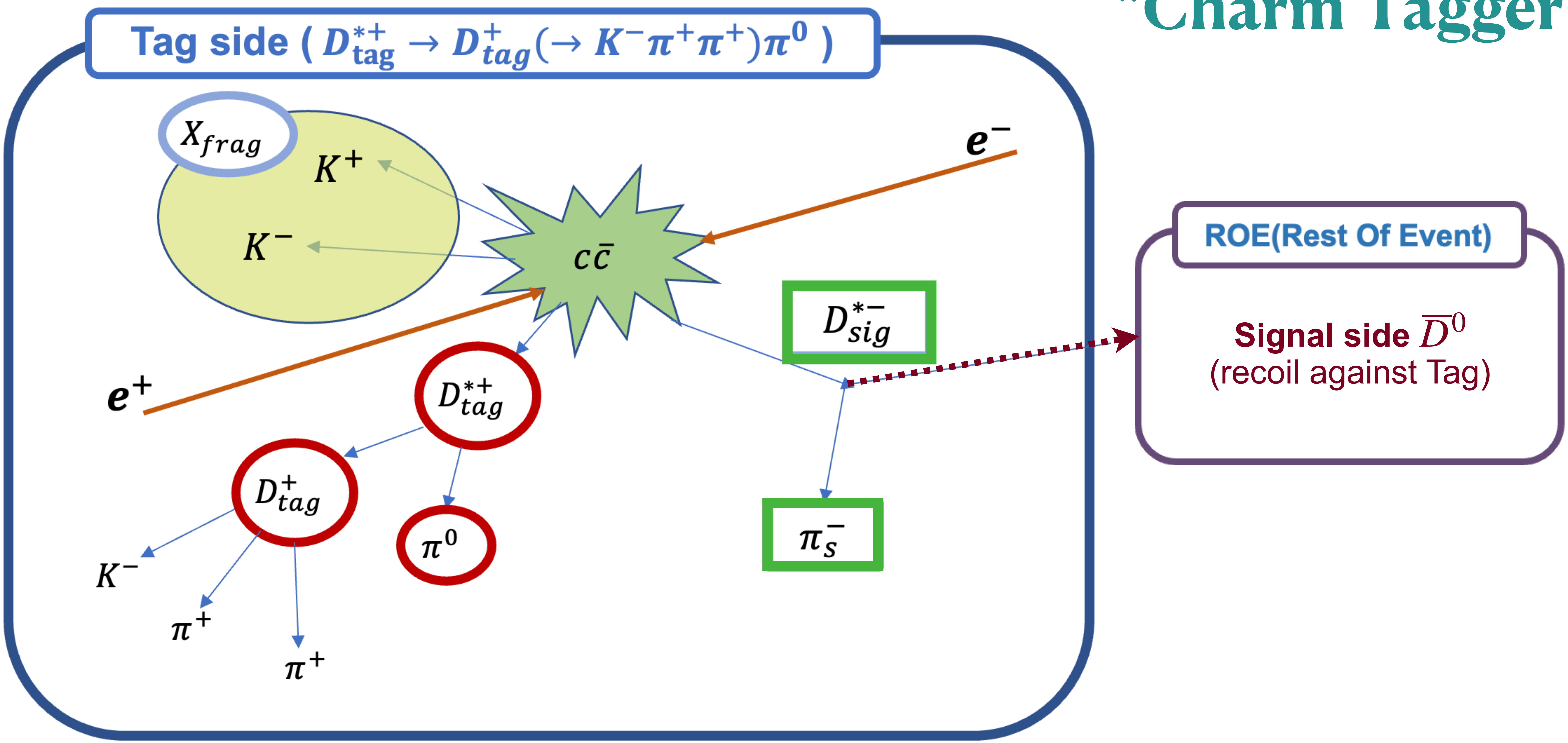


Table1 Tag reconstruction channels

D^0 decay	$Br(\%)$	D^+ decay	$Br(\%)$	Λ_c^+ decay	$Br(\%)$	D_s^+ decay	$Br(\%)$
$K^-\pi^+$	3.9	$K^-\pi^+\pi^+$	9.4	$pK^-\pi^+$	5.0	$K^+K^-\pi^+$	5.5
$K^-\pi^+\pi^0$	13.9	$K^-\pi^+\pi^+\pi^0$	6.1	$pK^-\pi^+\pi^0$	3.4	$K_S^0K^+$	1.5
$K^-\pi^+\pi^+\pi^-$	8.1	$K_S^0\pi^+$	1.5	pK_s^0	1.1	$K_S^0K_S^0\pi^+$	5.4
$K^-\pi^+\pi^+\pi^-\pi^0$	4.2	$K_S^0\pi^+\pi^0$	6.9	$\Lambda^0\pi^+$	1.1	$K^+K^-\pi^+\pi^0$	5.6
$K_S^0\pi^+\pi^-$	2.9	$K_S^0\pi^+\pi^+\pi^-$	3.1	$\Lambda^0\pi^+\pi^0$	3.6	$K_S^0K^-\pi^+\pi^+$	1.5
$K_S^0\pi^+\pi^-\pi^0$	5.4	$K^+K^-\pi^+$	1.0	$\Lambda^0\pi^+\pi^+\pi^-$	2.6	$K^+\pi^-\pi^+K_S^0$	1.0
$K^-\pi^+\pi^0\pi^0$	8.9	$K^-K^+\pi^+\pi^0$	0.7	$p^+\pi^-\pi^+$	0.5	$\pi^+\pi^-\pi^+$	1.0
$\pi^-\pi^+$	0.1	$\pi^-\pi^+\pi^+$	0.3	$p^+K^-K^+$	0.1	$\pi^+K_S^0$	0.1
$\pi^-\pi^+\pi^-\pi^+$	0.8	$\pi^-\pi^+\pi^+\pi^0$	1.2	$p^+K^-\pi^+\pi^0\pi^0$	0.1	$\pi^+\pi^0K_S^0$	0.5
$\pi^-\pi^+\pi^0$	1.5	$K^+K_S^0K_S^0$	0.3	$p^+\pi^-\pi^+\pi^-\pi^+$	0.2	$K^-K^+\pi^+\pi^-\pi^+$	0.7
$\pi^-\pi^+\pi^0\pi^0$	1.0	$\pi^+\pi^0$	0.1	$p^+K_S^0\pi^0$	2.0		
K^-K^+	0.4			$p^+K_S^0\pi^+\pi^-$	1.6		
$K^-K^+\pi^0$	0.3			$\pi^+\pi^-\Sigma^+$	4.5		
$K^-K^+K_S^0$	0.4			$\pi^+\pi^-\pi^0\Sigma^+$	1.2		
$\pi^0K_S^0$	1.2			$\pi^0\Sigma^+$	1.2		
sum	53.1	sum	30.5	sum	28.2	sum	22.8

See p.43, for color code

Tag reconstruction channels

D^{*+} decay	Br(%)	D^{*0} decay	Br(%)	D_s^{*+} decay	Br(%)
$D^0\pi^+$	67.7	$D^0\pi^0$	61.9	$D_s^+\gamma$	93.5
$D^+\pi^0$	30.7	$D^0\gamma$	38.1		
sum	98.4	sum	100.0	sum	93.5

Fragmentation channels for each Tag

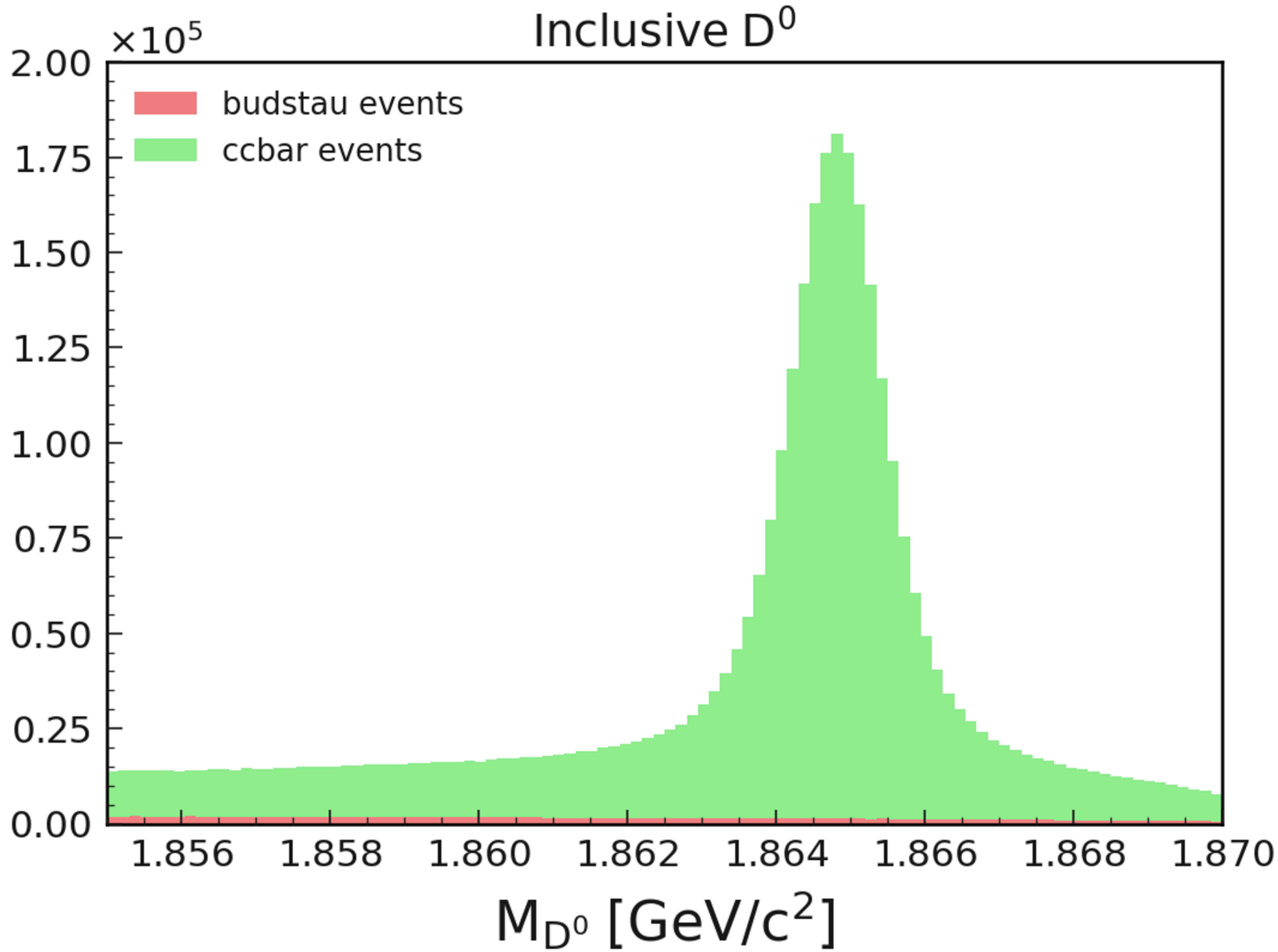
D^{*+} or D^+	D^{*0} or D^0	Λ_c^+	D_s^{*+} or D_s^+
nothing(K^+K^-)	$\pi^+(K^+K^-)$	$\pi^+\bar{p}$	K_S^0
$\pi^0(K^+K^-)$	$\pi^+\pi^0(K^+K^-)$	$\pi^+\pi^0\bar{p}$	$\pi^0K_S^0$
$\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^-\pi^+\bar{p}$	π^+K^-
$\pi^+\pi^-\pi^0(K^+K^-)$			$\pi^+\pi^-\pi^0K_S^0$
			π^+K^-
			$\pi^+\pi^0K^-$
			$\pi^+\pi^-\pi^+K^-$

Setting up Charm-tagger

- Tag-side charm reconstruction ➔ use 56 channels
  - Train BDT for each channel, separately
- Fragment reconstruction ➔ use 24 channels
  - to conserve strangeness, baryon number and charge of the event
  - select one best candidate with highest probability from mass-constrained fit on signal D* recoil mass
- Reconstruct signal D^0 with reconstructing π_s and calculating Δp^μ between this π_s and signal D^*
  - choose one best candidate based on largest opening angle between D and tag-side charm in cm frame

Reconstructed D^0 from charm-tagger

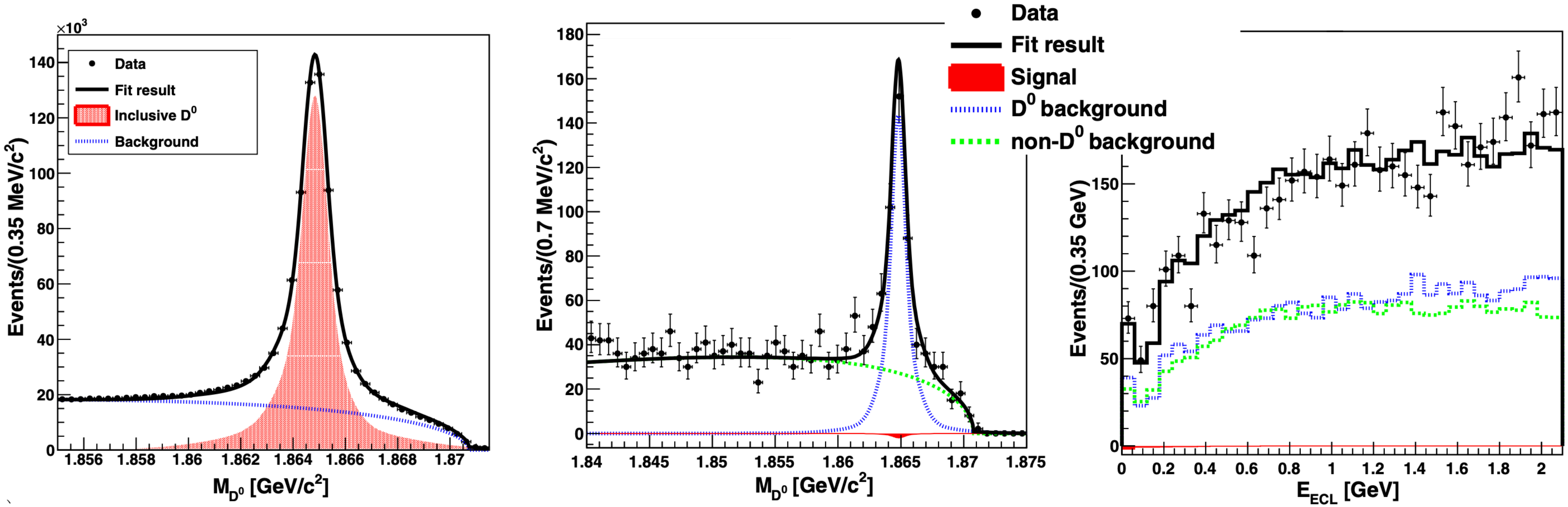
from Belle II generic MC sample



The analysis going on in steady pace; we hope to have results by next summer.

$D^0 \to$ *invisibles*, existing result (Belle, 2017)

based on very similar (this is the original) procedure with the on-going Belle II analysis



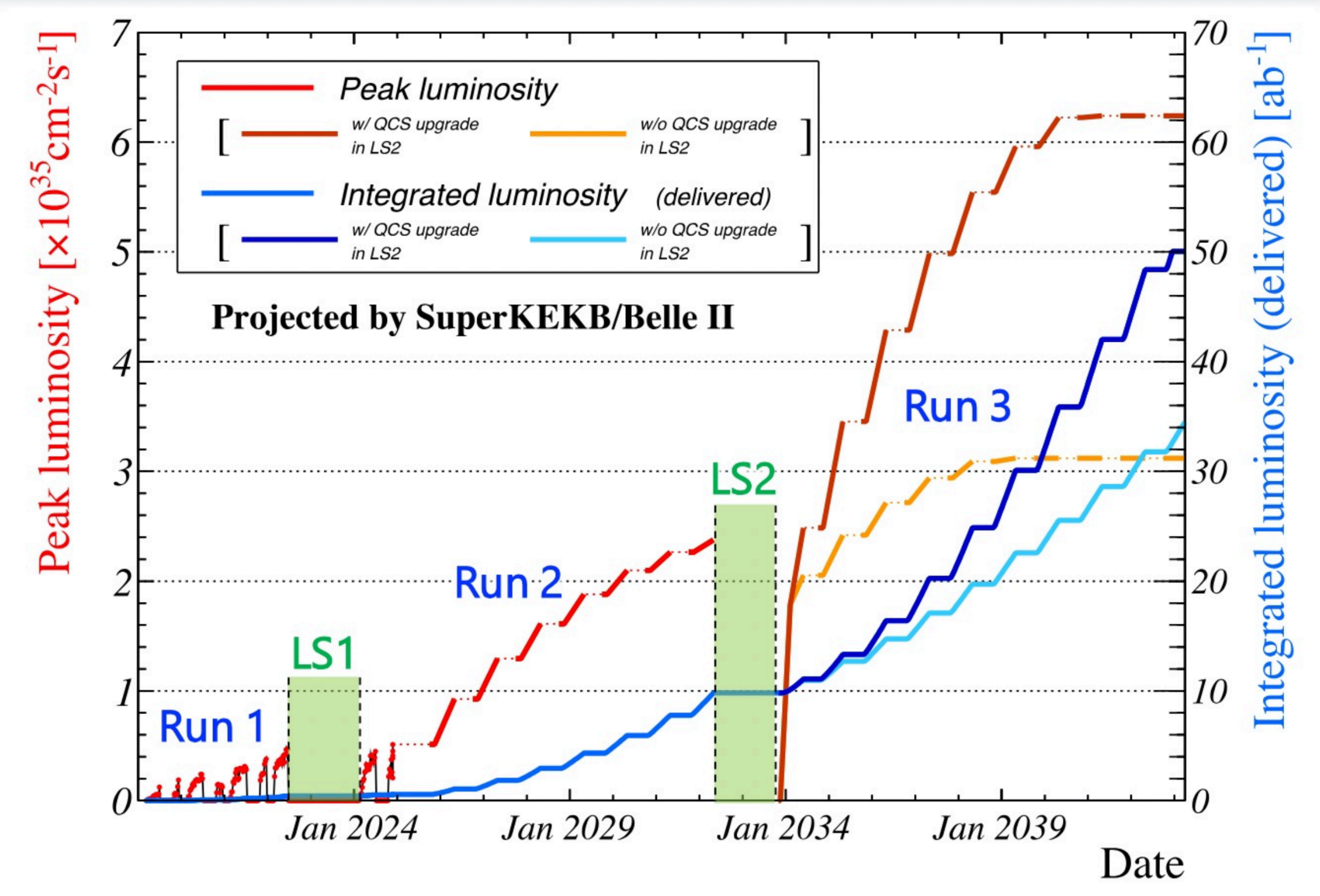
- Result of the first-ever search — Belle, PRD 95, 011102(R) (2017)
  - ✓ $N_{\text{sig}} = -6.3^{+22.5}_{-21.0}$ from 2D fit to $(M_{D^0}, E_{\text{ECL}})$
  - ✓ $\mathcal{B}(D^0 \to \text{invisible}) < 9.4 \times 10^{-5}$ @ 90% CL.

Closing remarks

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

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

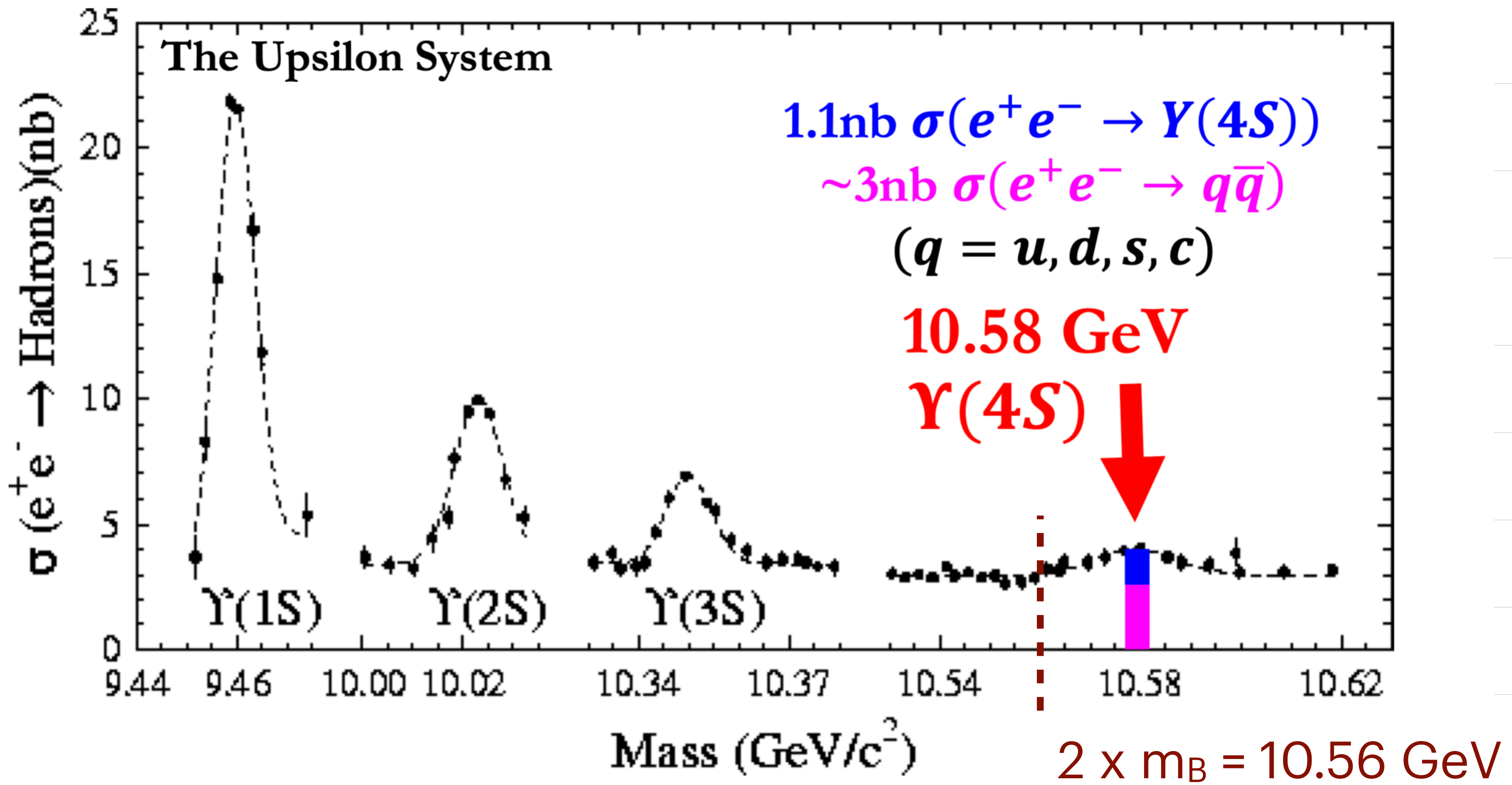
- Belle II Run 2 will resume in this year (*currently in a short break*) with a goal of collecting several ab^{-1} data in the next few years. Please stay tuned!



Thank you!

Appendix

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

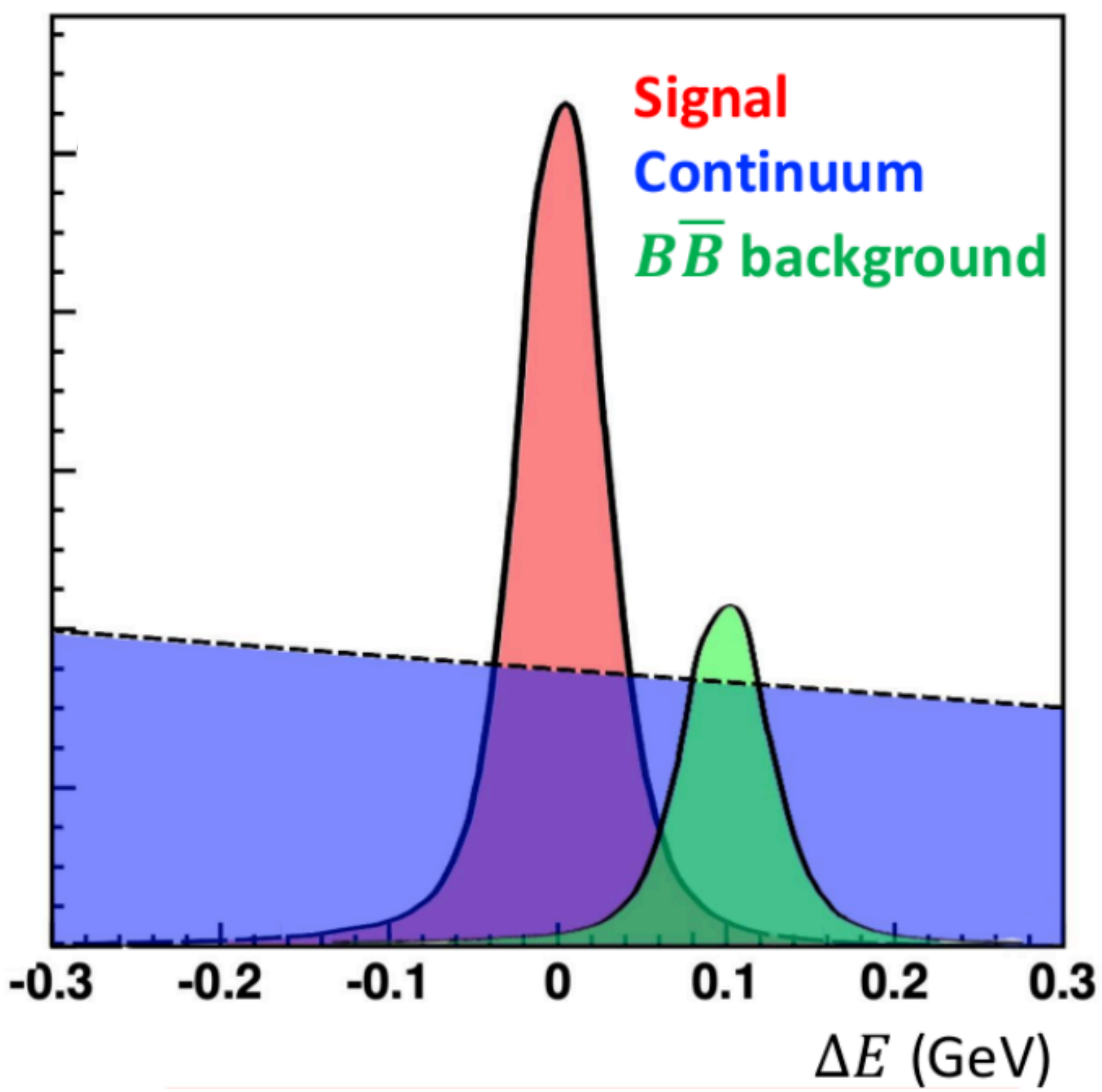


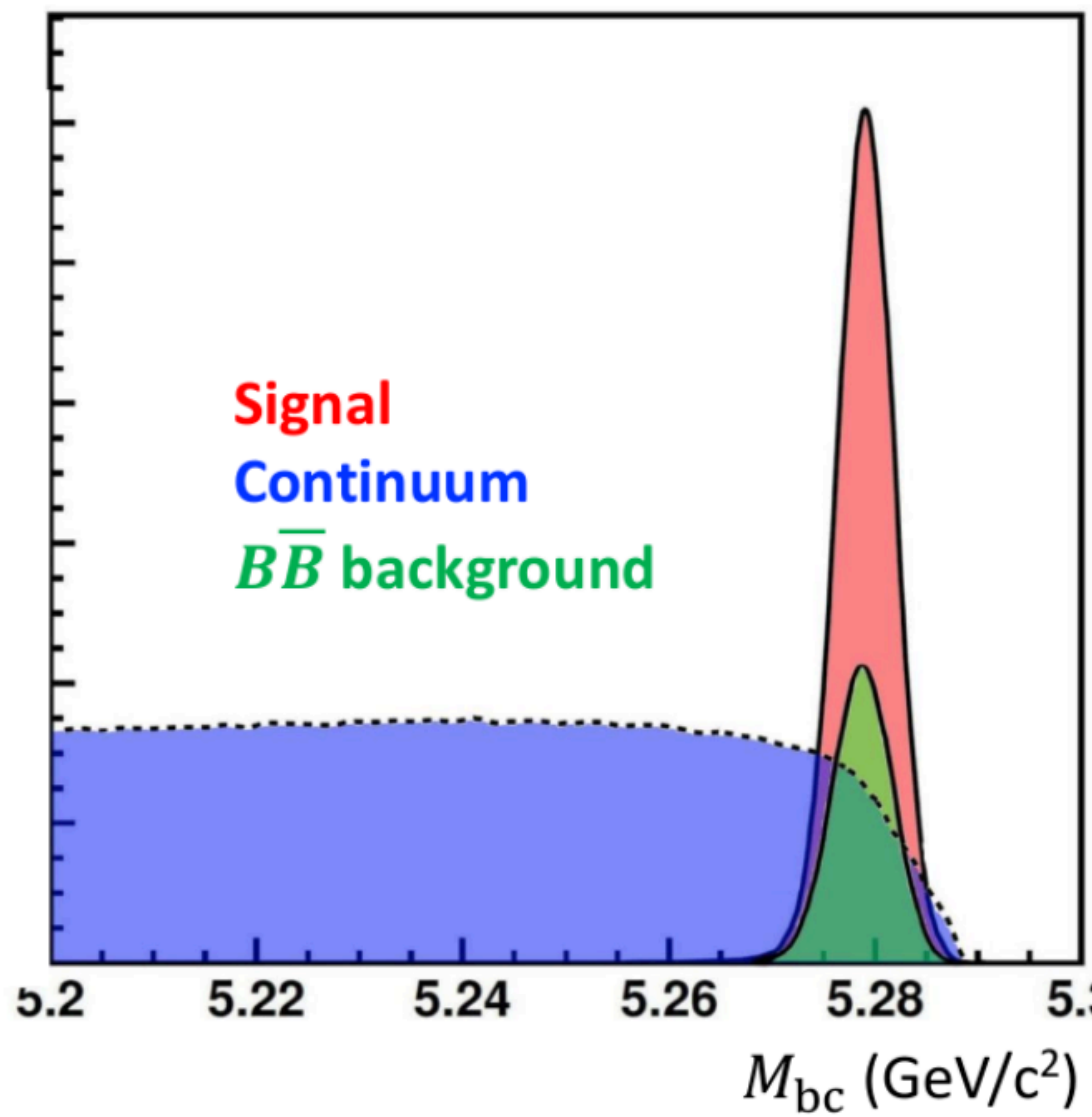
- $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) > 96\%$, with $p_B^{CM} \sim 0.35$ GeV/c
- nothing else but $B\bar{B}$ in the final state
  $\therefore$ if we know $(E, \vec{p})$ of one B, the other B is also constrained

Key variables of B decays

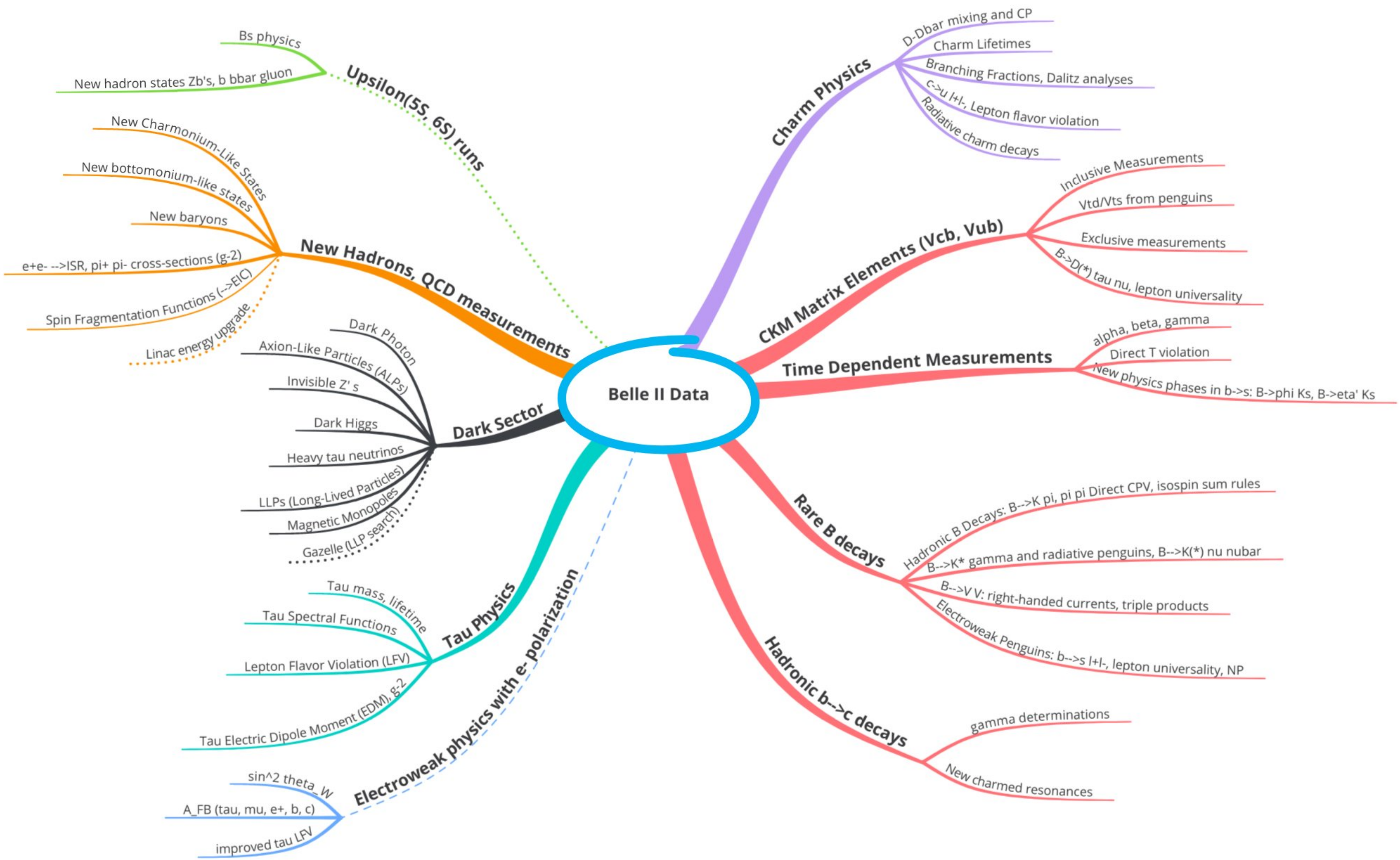
$$\Delta E = E_B^* - \sqrt{s}/2$$

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

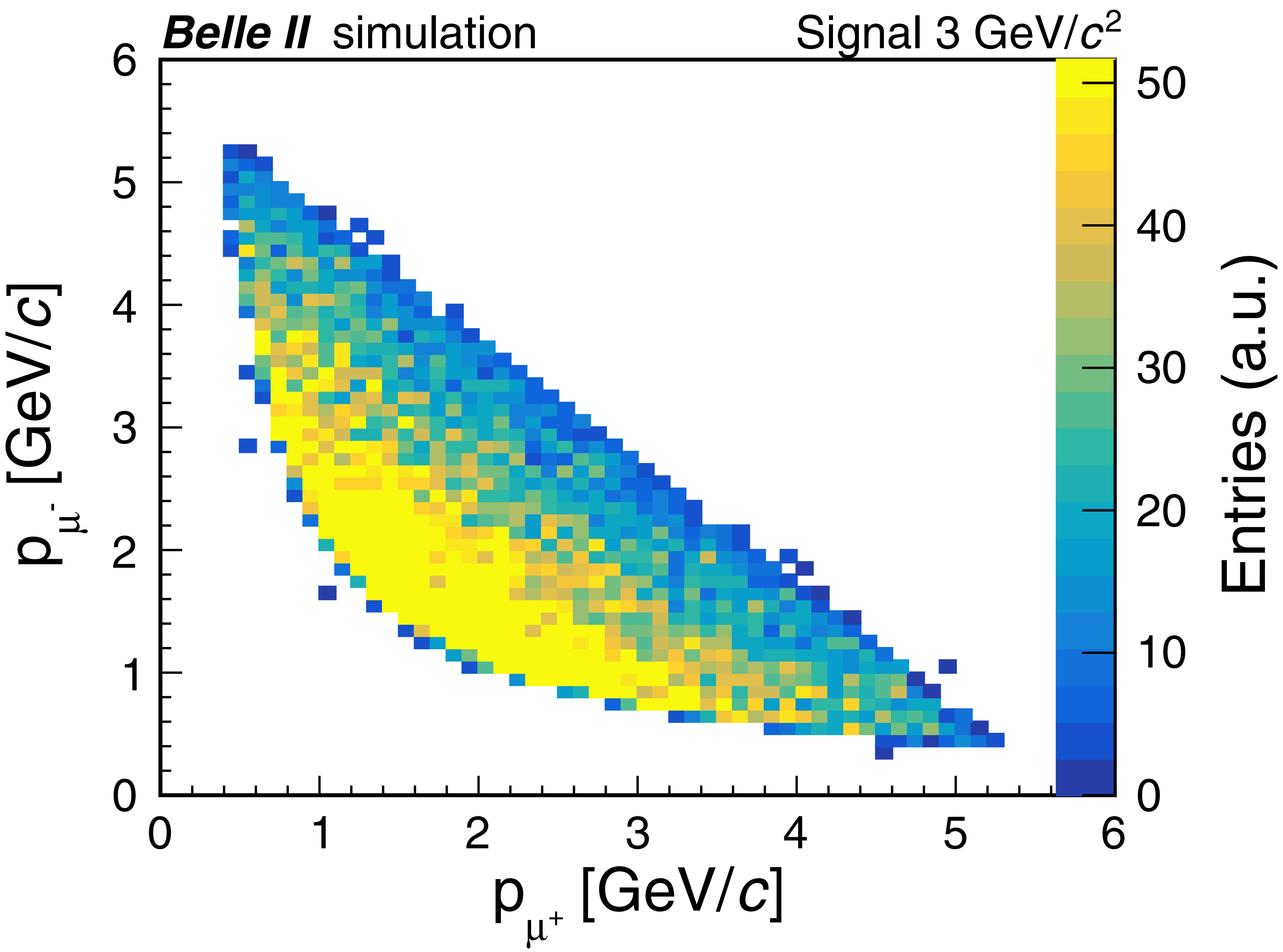


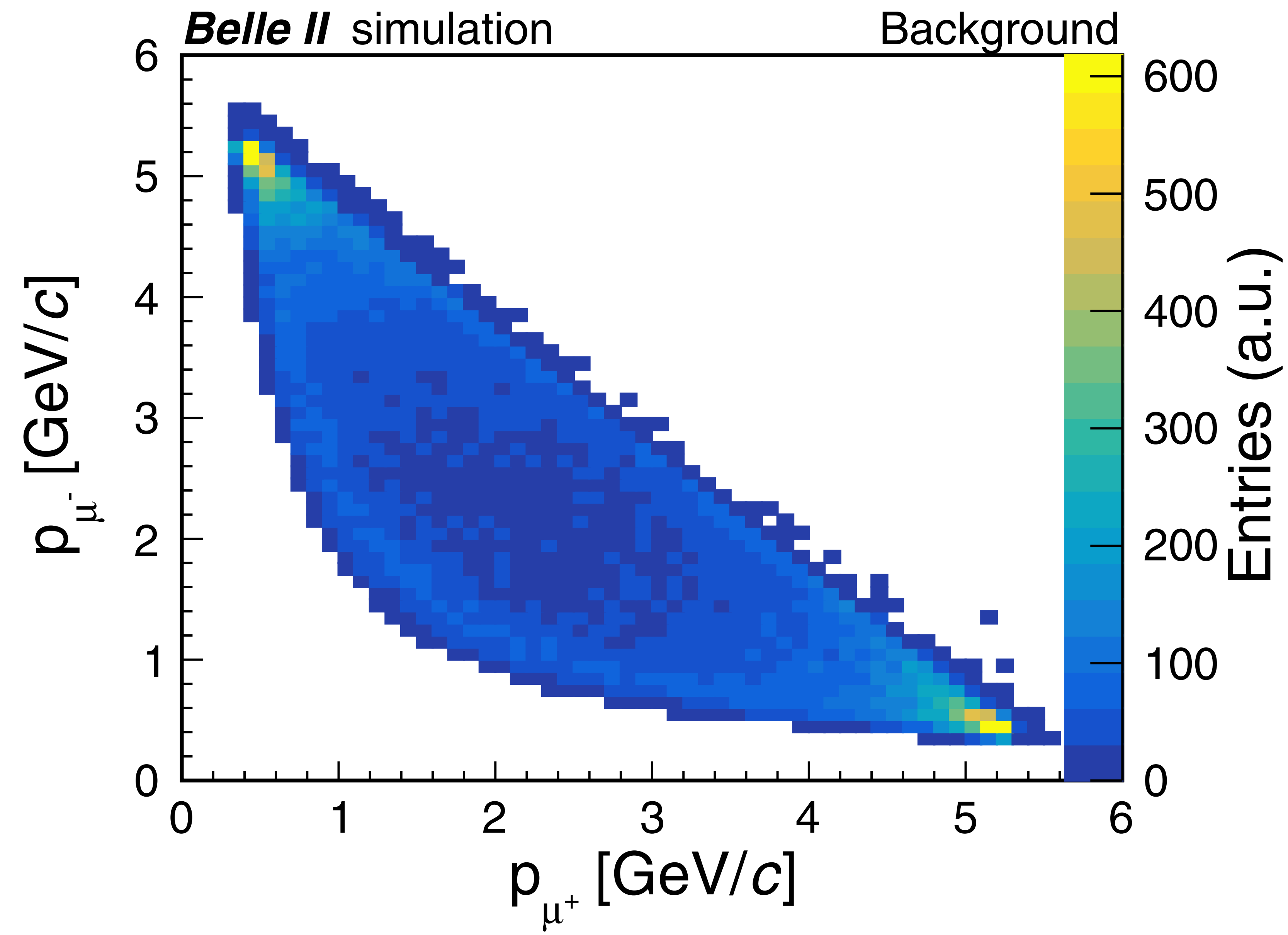


Belle II Physics Mind-map



$X \to \mu^+\mu^-$ MLP variables





- Neural net (NN) for optimization
  - 16 inputs, one output
  - 5 separate NNs in $M(\mu\mu)$ intervals: (0.21=$2m_\mu$, 1.00, 3.75, 6.25, 8.25, 10.00) GeV trained with Z' signal (and generic background) MC samples
  - Most discriminating variable is $p_{\mu\mu}$ (see Fig.), followed by correlation of p_{μ^+} & p_{μ^-}

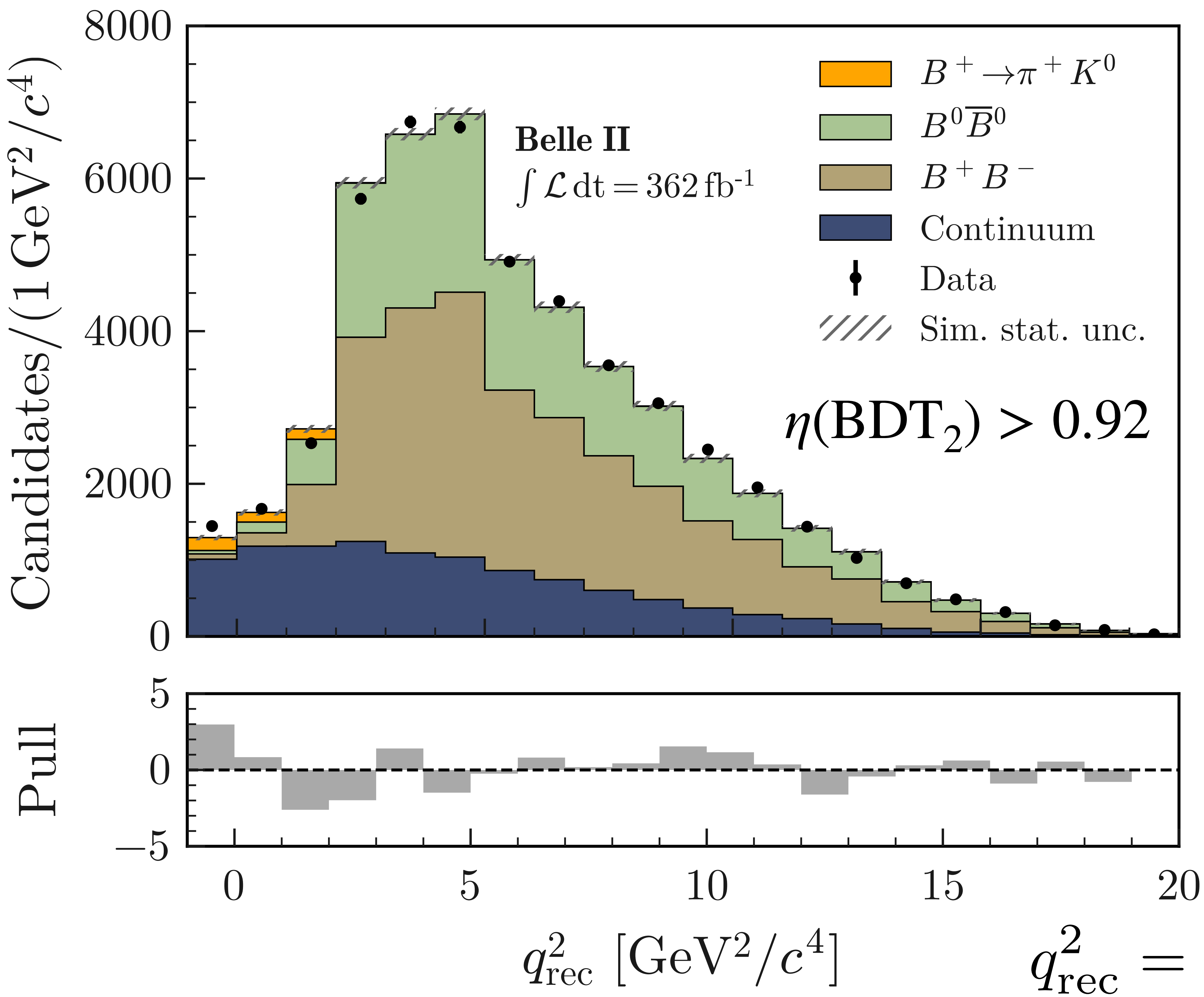
Parameters of dark sector with inelastic DM

- 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.18)

Closure test (ITA)



- Pion ID instead of kaon ID
- Different q^2_{rec} bin boundaries
- Only on-resonance data used for fit
- Only normalization systematics included

Result:

- $\mathscr{B}(B^+ \to \pi^+ K^0) = (2.5 \pm 0.5) \times 10^{-5}$

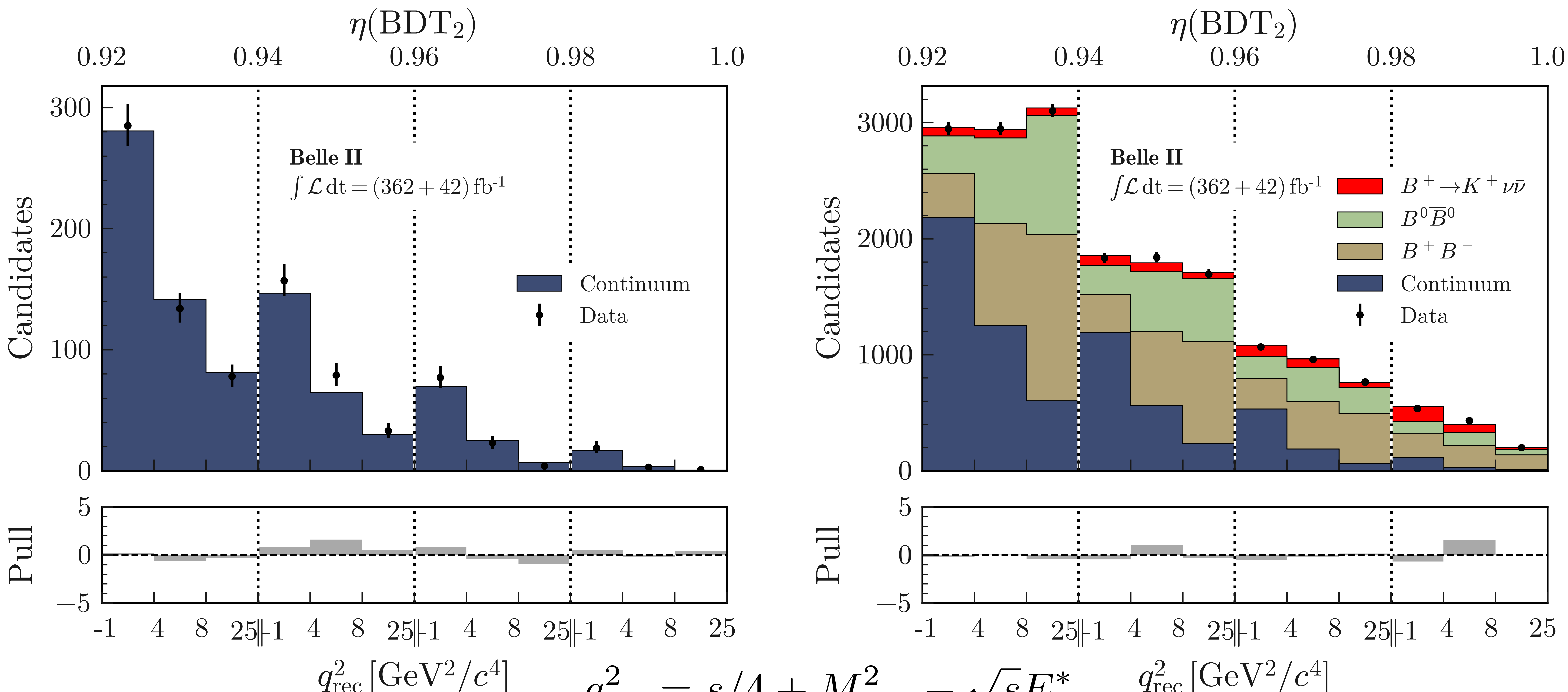
Consistent with PDG:

$\mathscr{B}(B^+ \to \pi^+ K^0) = (2.3 \pm 0.08) \times 10^{-5}$

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

Assume B is at rest in the $\Upsilon(4S)$ rest-frame ($c = 1$)

$B^+ \to K^+\nu\bar{\nu}$ result (ITA)

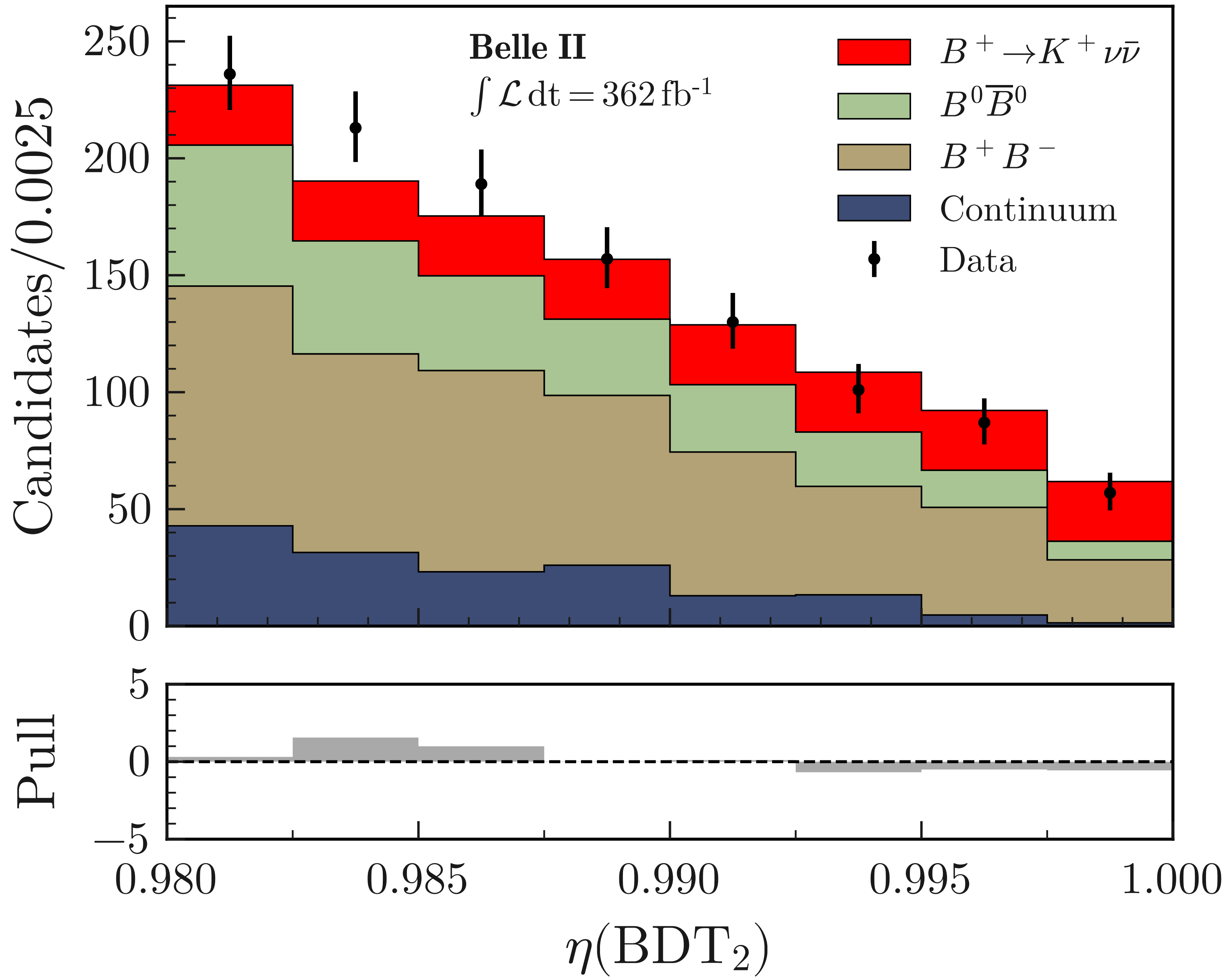


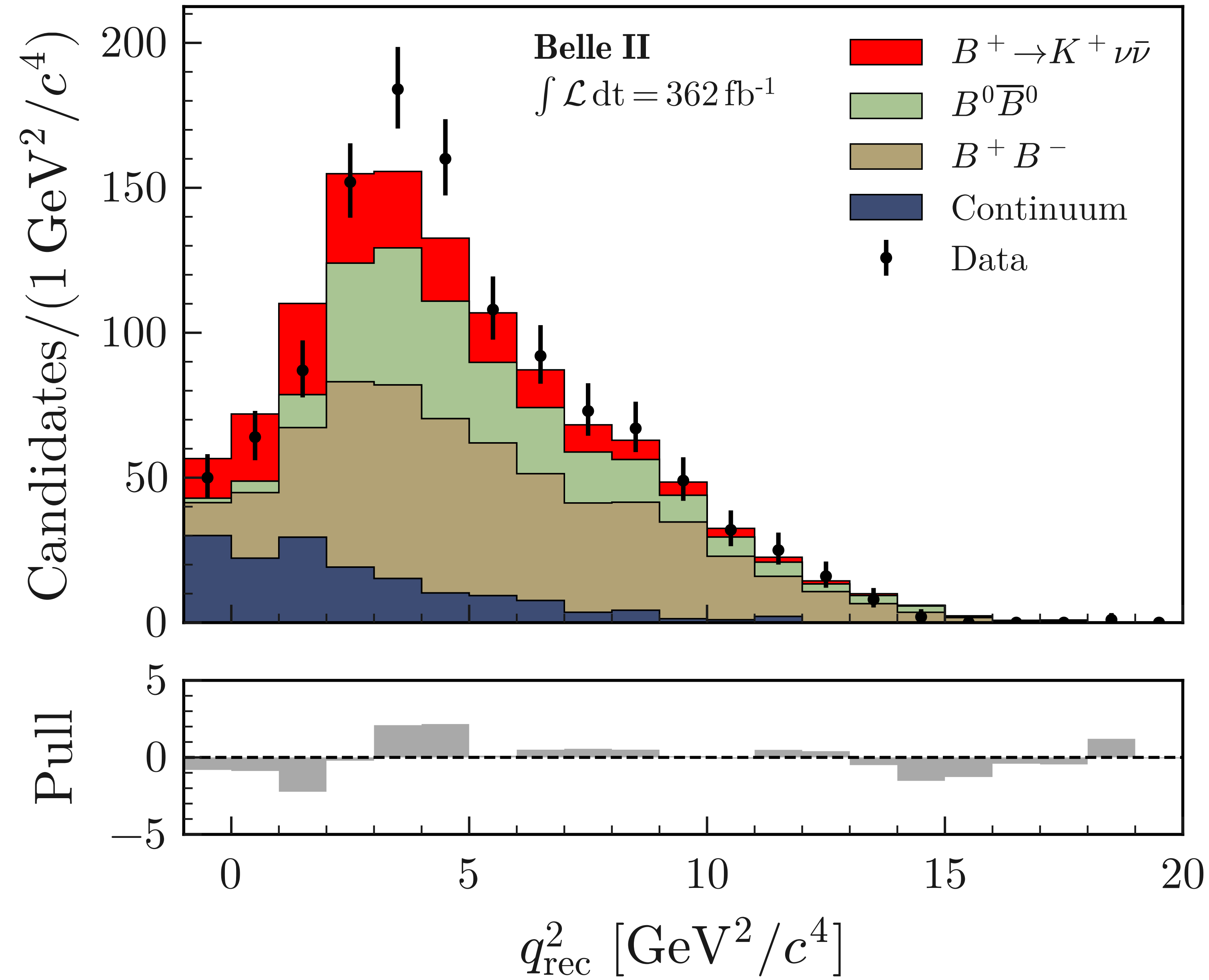
$$q^2_{\mathrm{rec}} = s/4 + M^2_{K^+} - \sqrt{s}E^*_{K^+}$$

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

$B^+ \to K^+\nu\bar{\nu}$ post-fit distributions (ITA)

$\eta(\mathrm{BDT}_2) > 0.98$





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