Seeing the invisible in Belle II

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IJCLab Seminar

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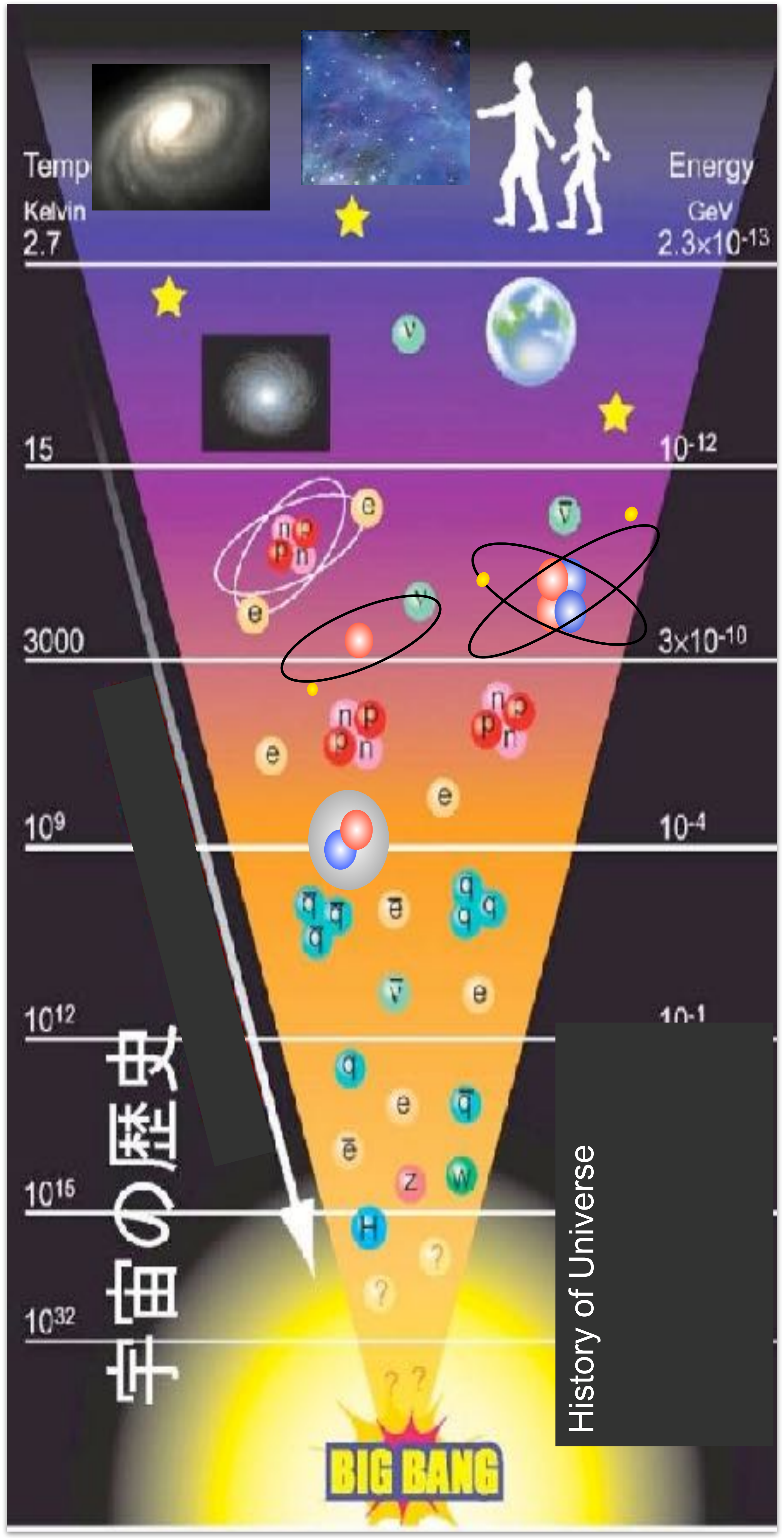
https://jeudepaume.org

The case for new physics

- **Baryon asymmetry of the universe**
  - *Searches for new sources of quark sector CP violation, CKM precision metrology.*
  - *CP violation in the Higgs sector, and in neutrinos.*
  - *Baryon number and lepton number violation.*
- **Quark and Lepton family flavour & mass hierarchy/spectrum. Finite neutrino masses.**
  - *Semileptonic and Leptonic decays, lepton flavour universality violation.*
  - *BSM Higgs in flavour, Leptoquarks etc.*
  - *Direct searches for mass generation mechanisms.*
- **No candidate for dark matter**
  - *Dark photons, axion like particles, and WIMP-like (?) dark matter, via flavour transitions and direct production.*

Observed:
$(N_{baryon}-N_{antibaryon})/N_{\gamma}$ ~10^{-10}
Expected:
SM Quark CPV in leads to 10^{-17}.



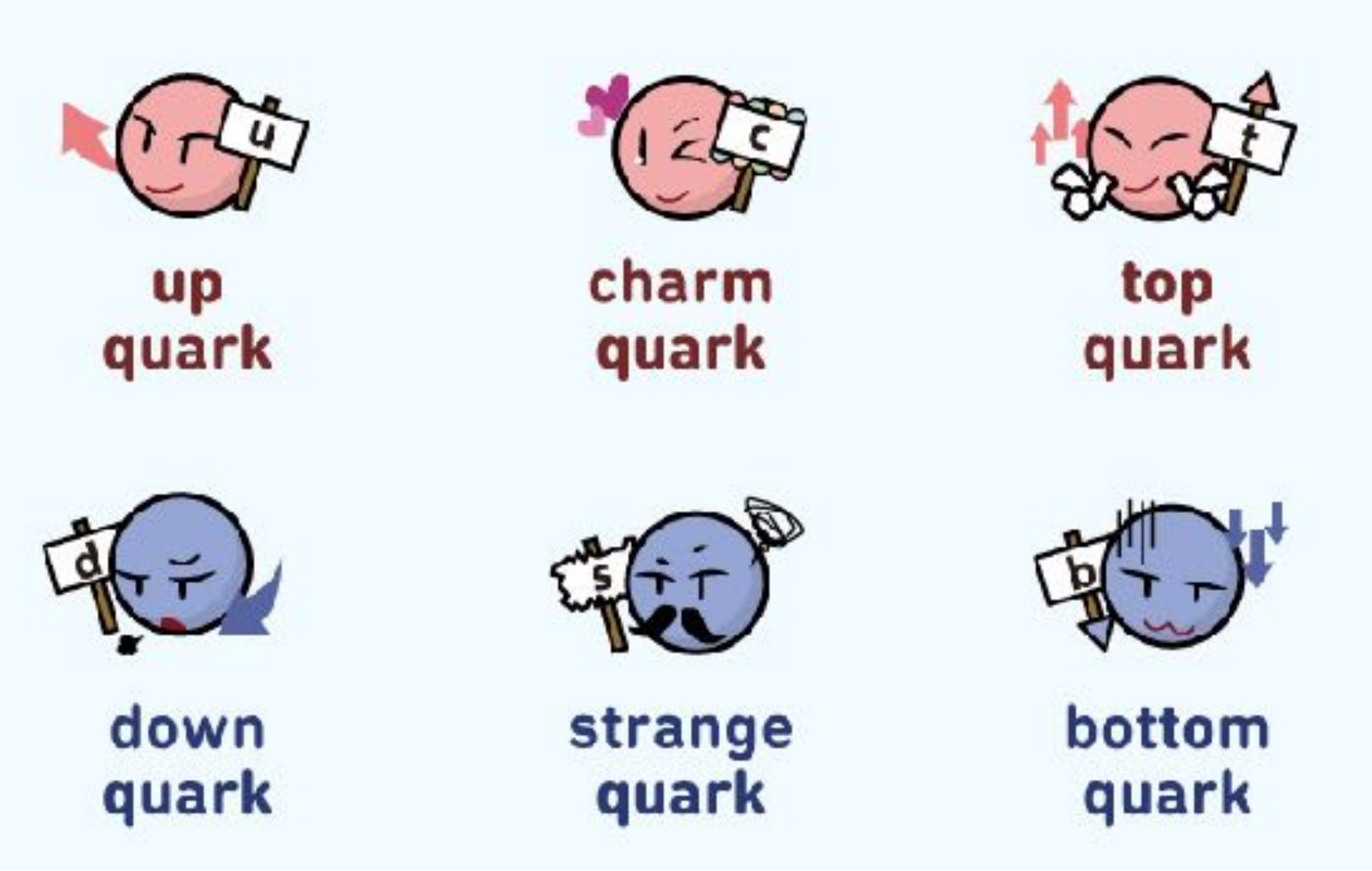
Flavour phenomena & possible absence of new physics at LHC point to existence of new symmetries at energies beyond the LHC or very low mass scale.

Yukawa mechanism in the quark sector

$$-\mathcal{L}^{\rm SM}_{\rm Yukawa} = Y^{ij}_d \bar{Q}^i_L \phi D^j_R + Y^{ij}_u \bar{Q}^i_L \tilde{\phi} U^j_R + Y^{ij}_e \bar{L}^i_L \phi E^j_R + {\rm h.c.}$$

$$Y_d = \lambda_d\ , \qquad Y_u = V^\dagger \lambda_u$$

$$\lambda_d = {\rm diag}(y_d, y_s, y_b)\ , \quad \lambda_u = {\rm diag}(y_u, y_c, y_t)\ , \qquad y_q = \frac{m_q}{v}\ .$$



- The quark **flavour structure** within the SM is described by **6 couplings and 4 CKM parameters**. *Convenient to move the CKM matrix from the Yukawa to the CC sector.*

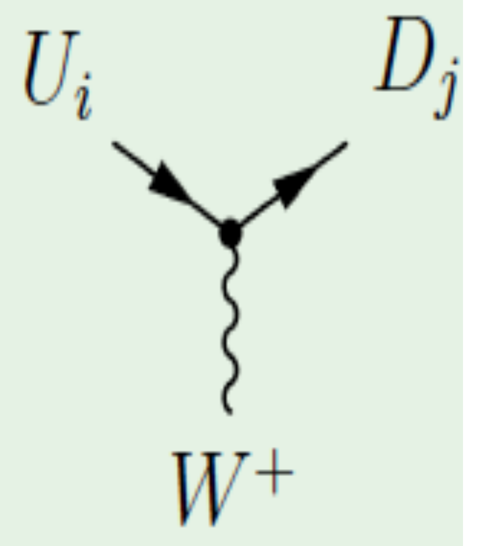
- In the SM quarks are allowed to **change flavour** as a consequence of the **Higgs mechanism to generate quark masses**.
  - Use Wolfenstein parameterisation (A, λ,ρ,η).

$U_i = \{u, c, t\}$: $Q_U = +2/3$

$D_j = \{d, s, b\}$: $Q_D = -1/3$

$$\mathcal{L}_{CC} = \frac{g_2}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t}) \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \gamma^\mu P_L \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^+_\mu$$

~ Cabibbo-Kobayashi-Maskawa (CKM) matrix



- All 4 parameters are of order 1, λ~0.22, A~0.82, ρ~0.22, η~0.34)

$$\mathrm{V} = \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+(1-2(\rho+i\eta))A^2\lambda^5/2 & 1-\lambda^2/2-(1+4A^2)\lambda^4/8 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+(1-2(\rho-i\eta))A\lambda^4/2 & 1-A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

Yukawa Mechanism in the lepton sector

$$-\mathcal{L}^{\text{SM}}_{\text{Yukawa}} = Y_d^{ij}\bar{Q}^i_L\phi D^j_R + Y_u^{ij}\bar{Q}^i_L\tilde{\phi}U^j_R + Y_e^{ij}\bar{L}^i_L\phi E^j_R + \text{h.c.}$$

$$\mathcal{G}_\ell = SU(3)_{L_L} \otimes SU(3)_{E_R}$$

- In the SM the **lepton Yukawa** matrices can be diagonalised independently due to the **global G_l symmetry** of the Lagrangian, therefore there are **no FCNC**.

- *However*, the discovery that **ν oscillate** (and are massive) implies that **Lepton Flavour is not conserved**. The level of **Charged Lepton Flavour Violation** depends on the mechanism to **generate neutrino masses** (for instance, **Seesaw mechanism**).

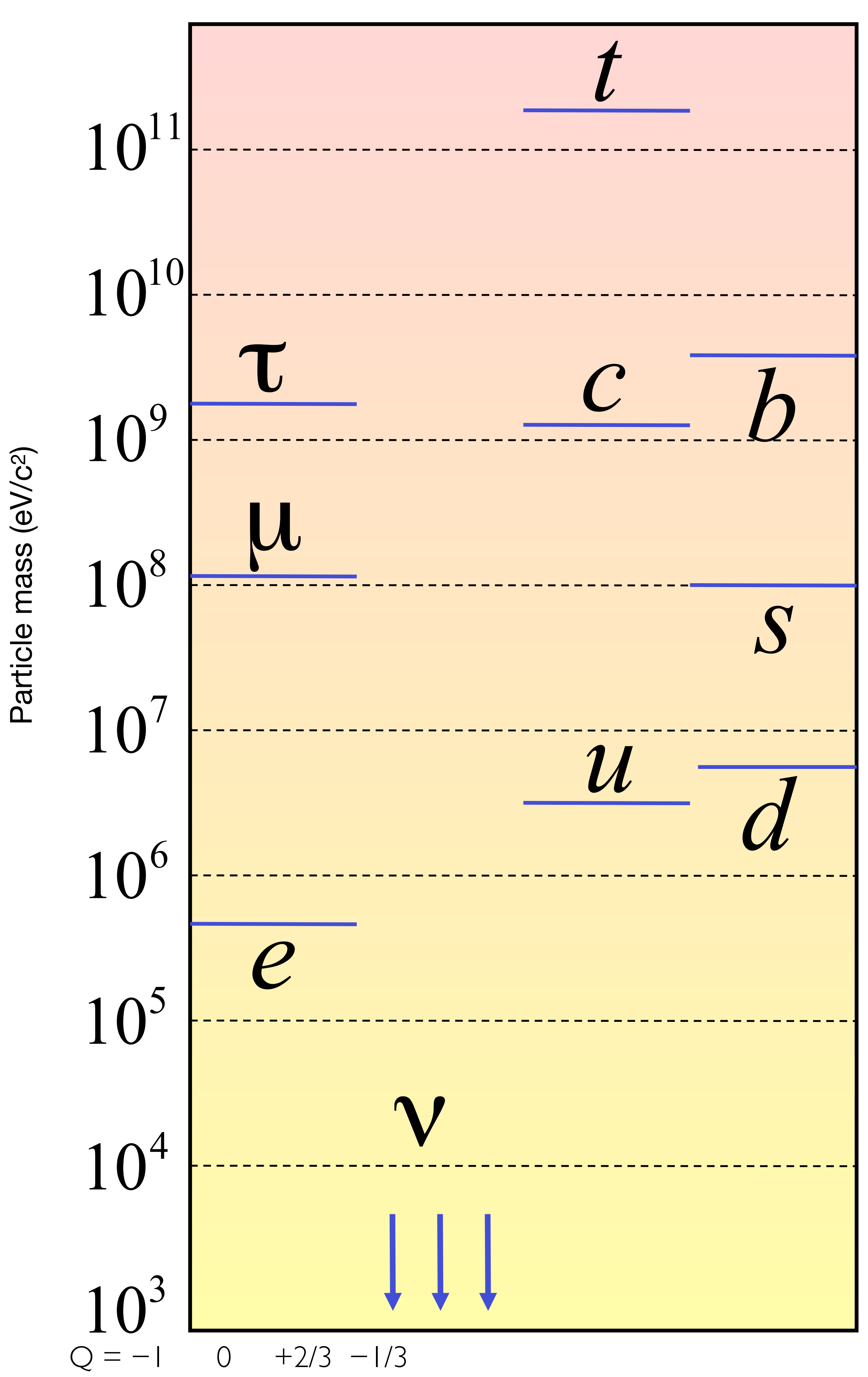
PMNS

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\theta_{12} = 33.44^{\circ}{}^{+0.78^\circ}_{-0.75^\circ}$$
$$\theta_{23} = 49.0^{\circ}{}^{+1.1^\circ}_{-1.4^\circ}$$
$$\theta_{13} = 8.57^{\circ}{}^{+0.13^\circ}_{-0.12^\circ}$$
$$\delta_{\text{CP}} = 195^{\circ}{}^{+51^\circ}_{-25^\circ}$$

Flavour structure, V_{CKM}, V_{PMNS}, Masses

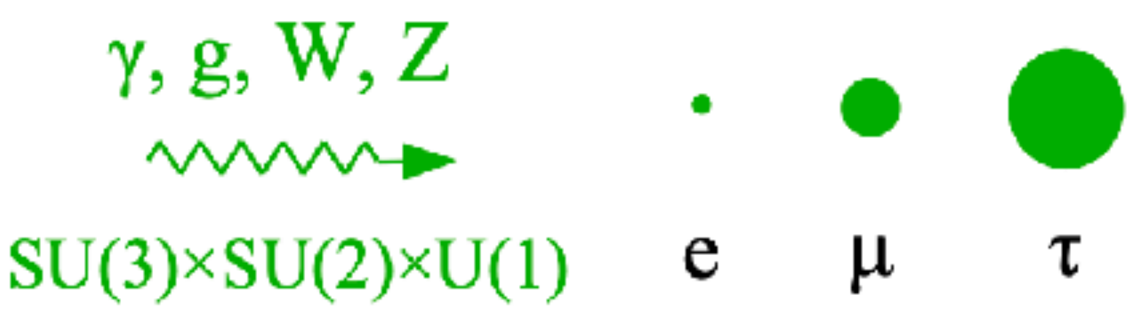
The SM of Particle Physics



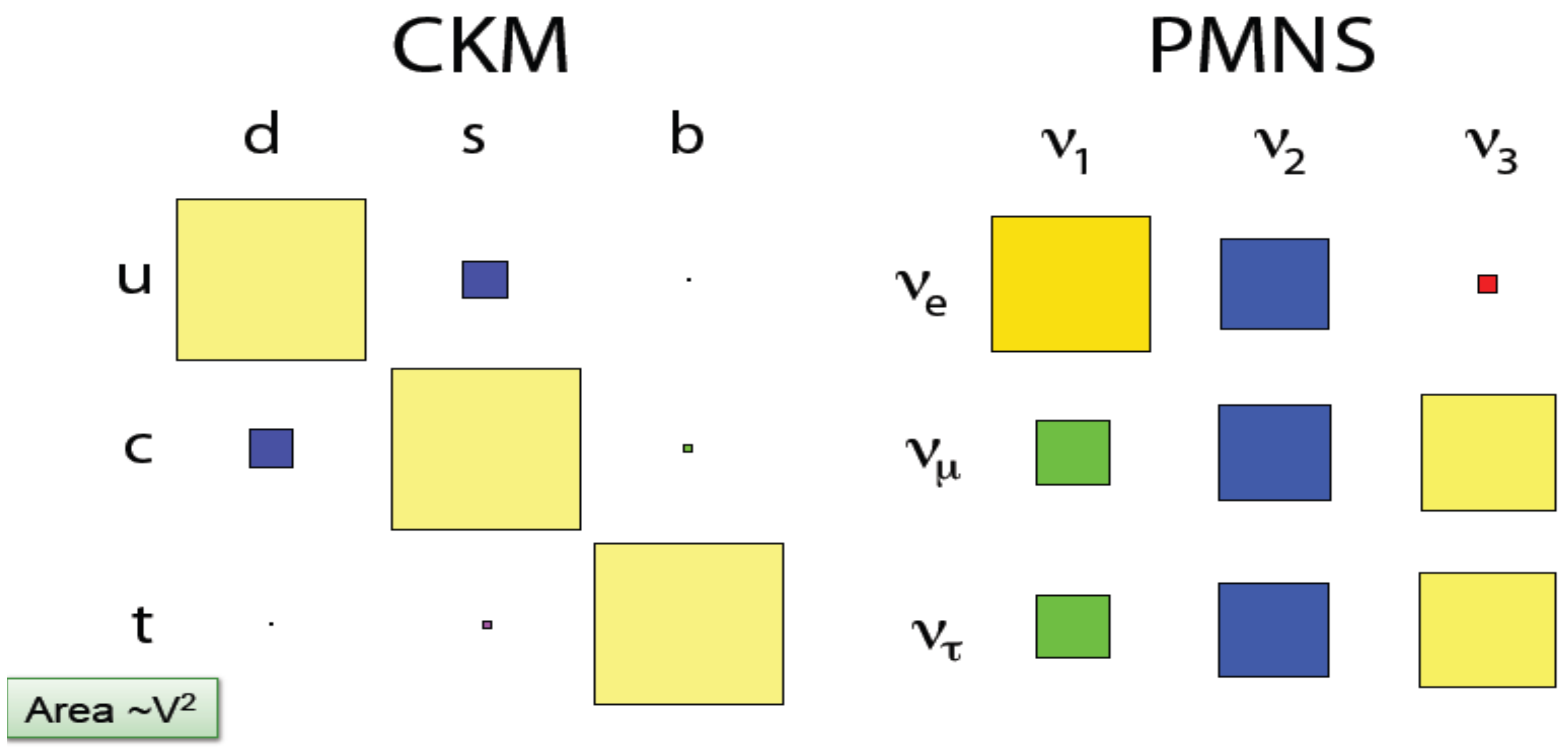
Suppose we could test matter only with long λ photons

We would conclude that these two particles are identical copies except for their mass

This is exactly the same argument we use to infer flavour universality in the SM



These three families of particles seem to be identical copies except for their mass

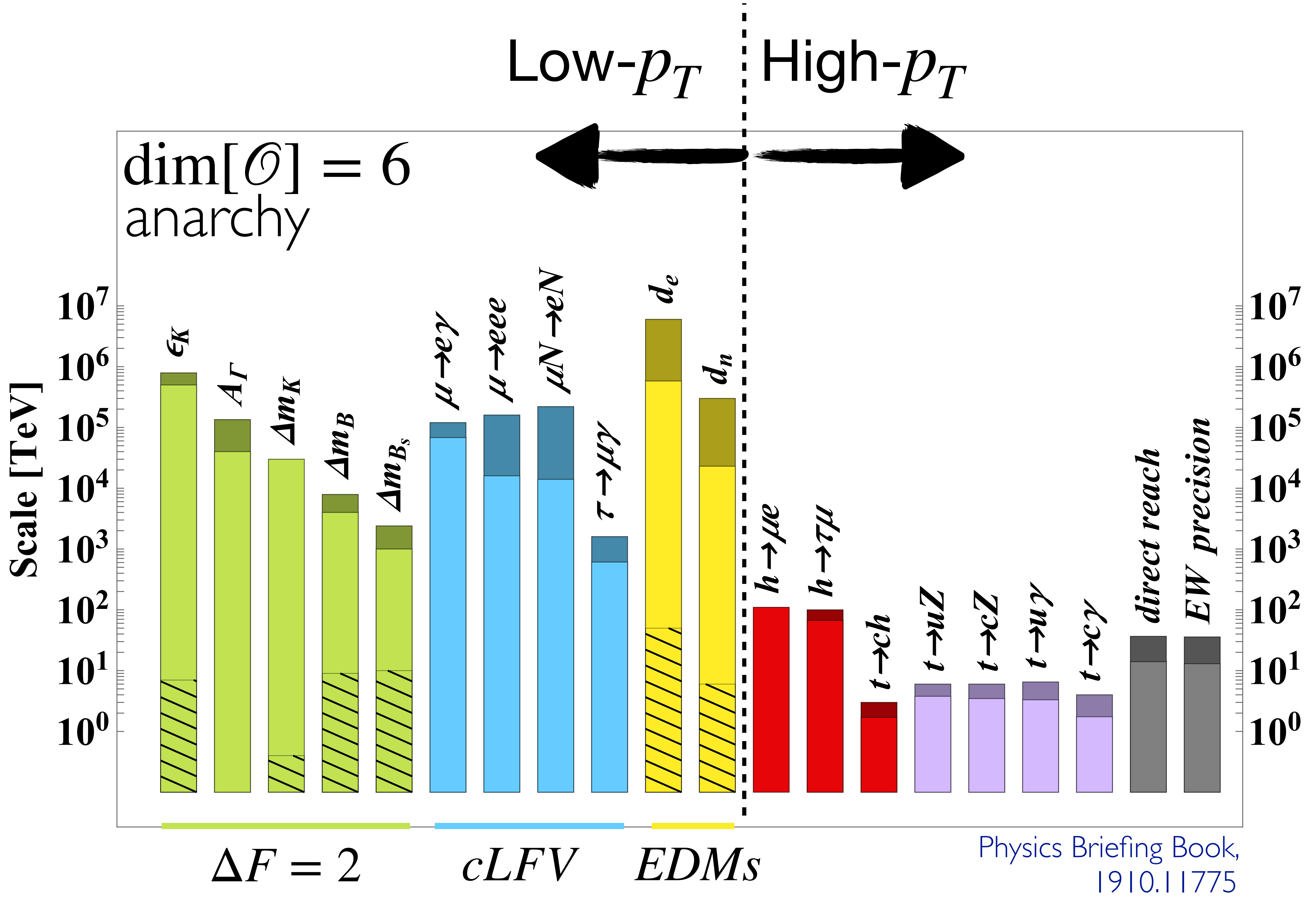


Why these values, are the two related, are they related to masses?

High mass scales

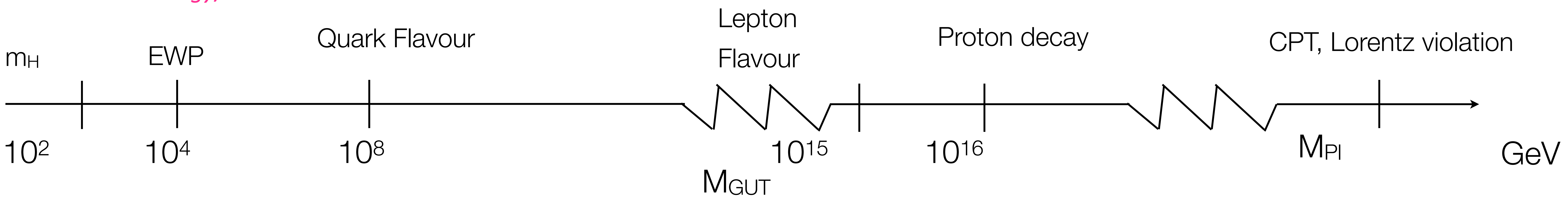
- **Energy Frontier**: Production of **new particles** from *collisions* at high-***Energy*** (**LHC**)
  - *Limited by Beam energy*

- **Flavour Frontier**: **virtual production** to probe *scales* beyond energy frontier.
  - Often **first clues** about new phenomena, e.g. **weak force.**
  - High precision required: very tiny effects



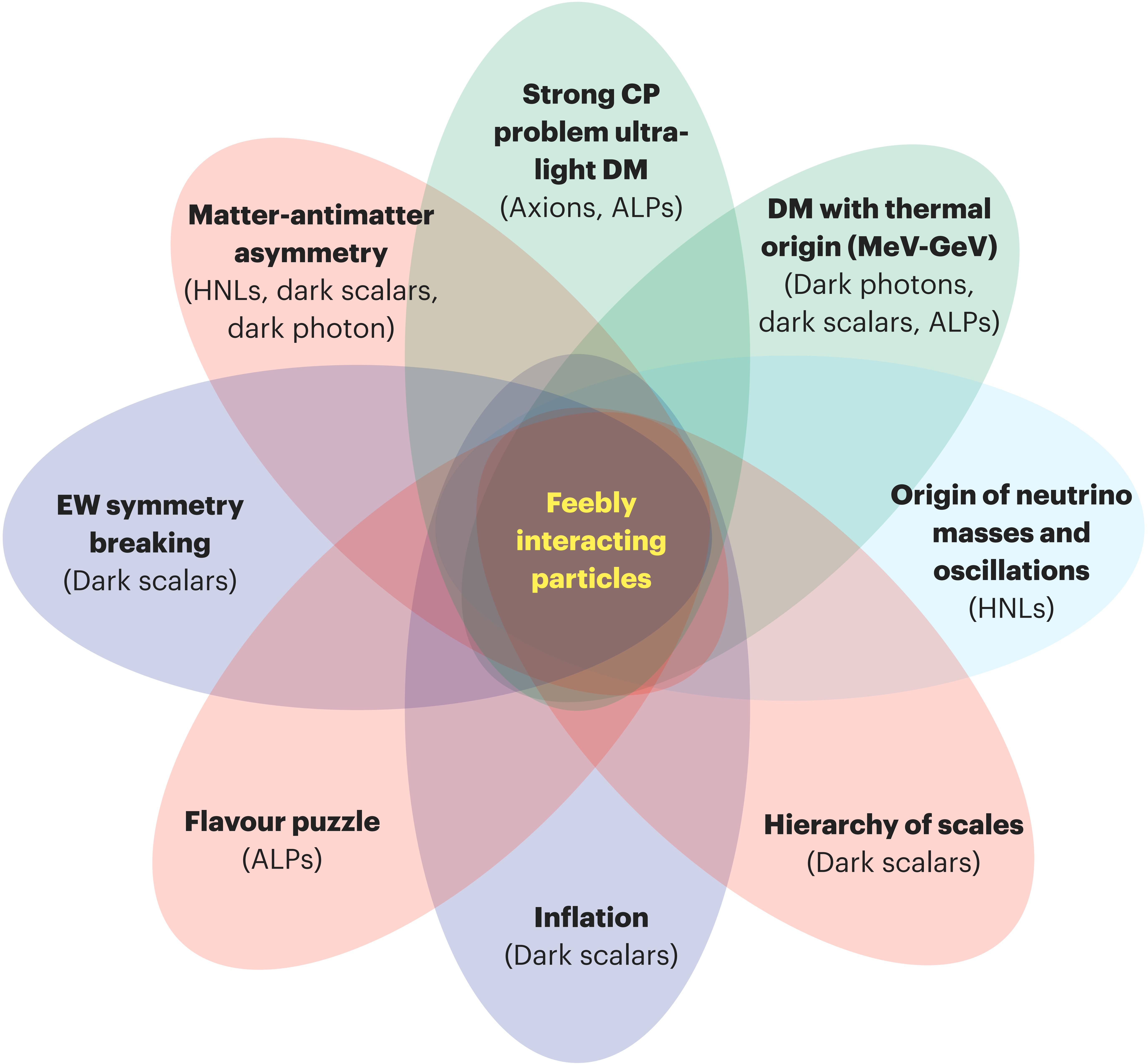
Physics Briefing Book, 1910.11775

Maximum Energy/Mass Scale reach:



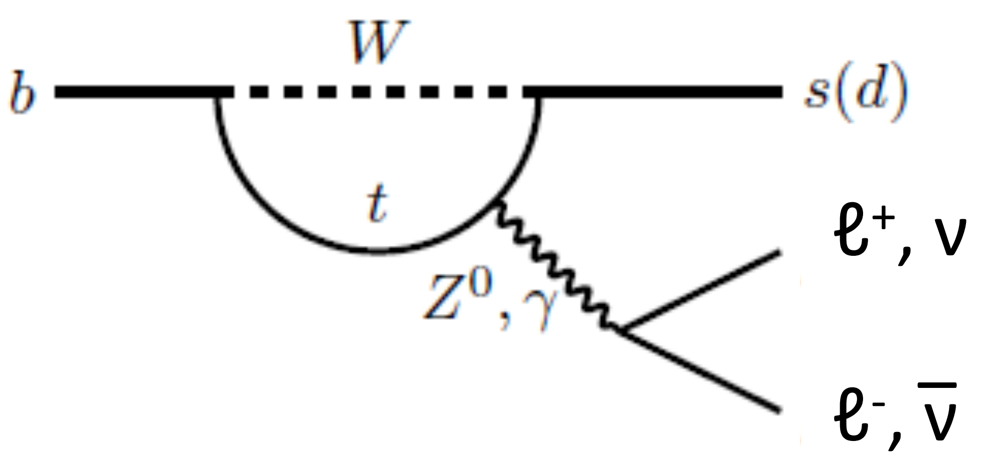
Feeble couplings

- The energy frontier has scoured the high energy scales but have we overlooked the mass scale of ordinary matter? Why haven't we seen anything yet?



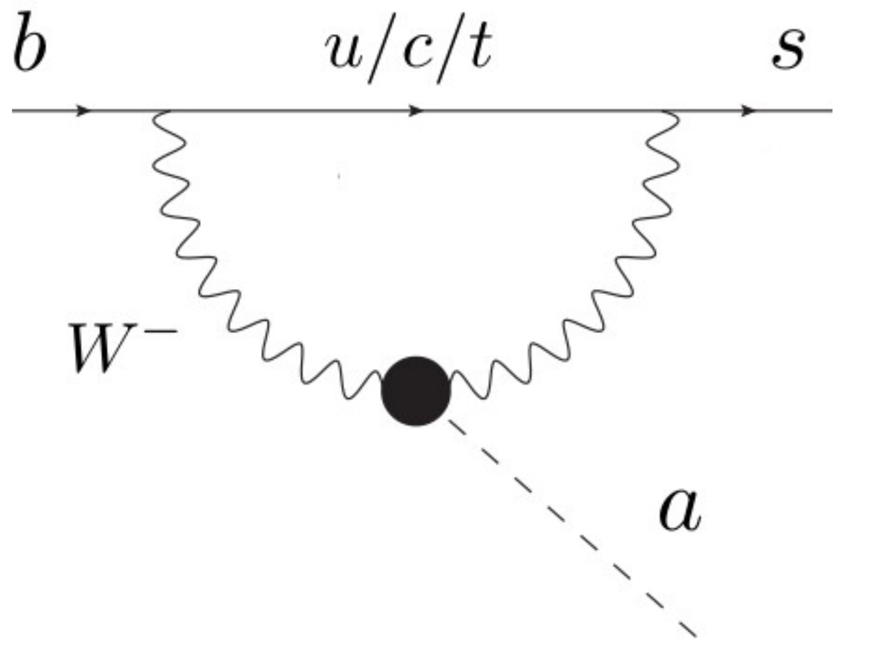
New physics signatures

Flavour changing neutral currents



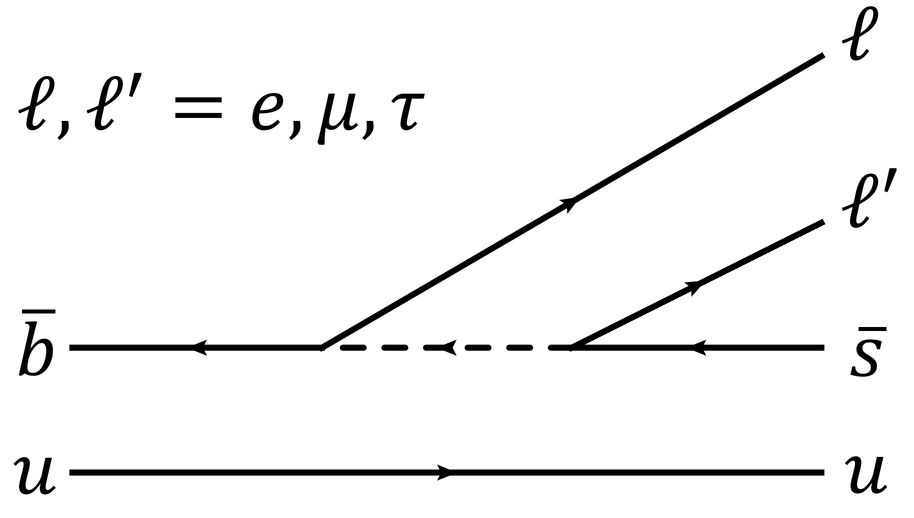
- $B \rightarrow X_s\, l^+ l^-$
- Loop in SM
- Rare at BR < ~10^{-6}

New particle searches



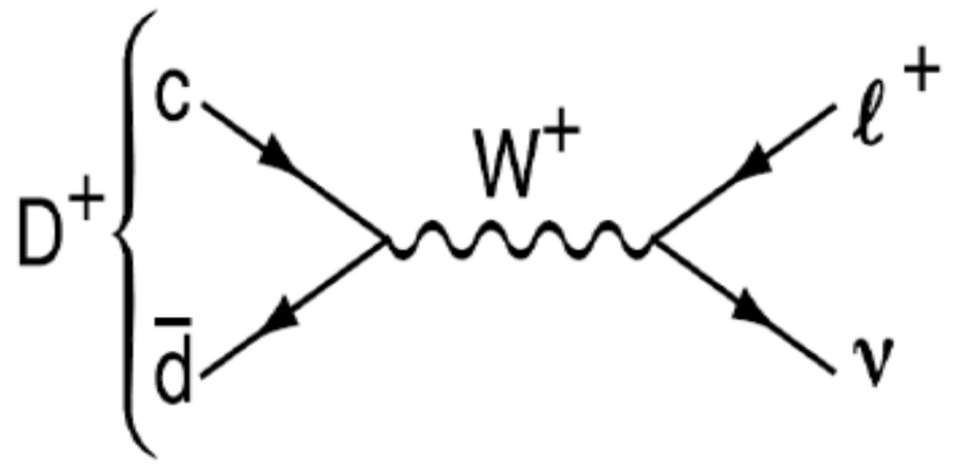
- ALPs (Pseudoscalars)
- Higgs-like (Scalars)
- Dark photons (Vector)

Forbidden decays



- Lepton flavour violating
- Lepton number violating
- Forbidden or very highly suppressed

Tests of lepton flavour universality



- Semileptonic or leptonic
- BR ratios with τ/μ, τ/e, μ/e
- Tree or loop

Phenomenology of missing energy B decays

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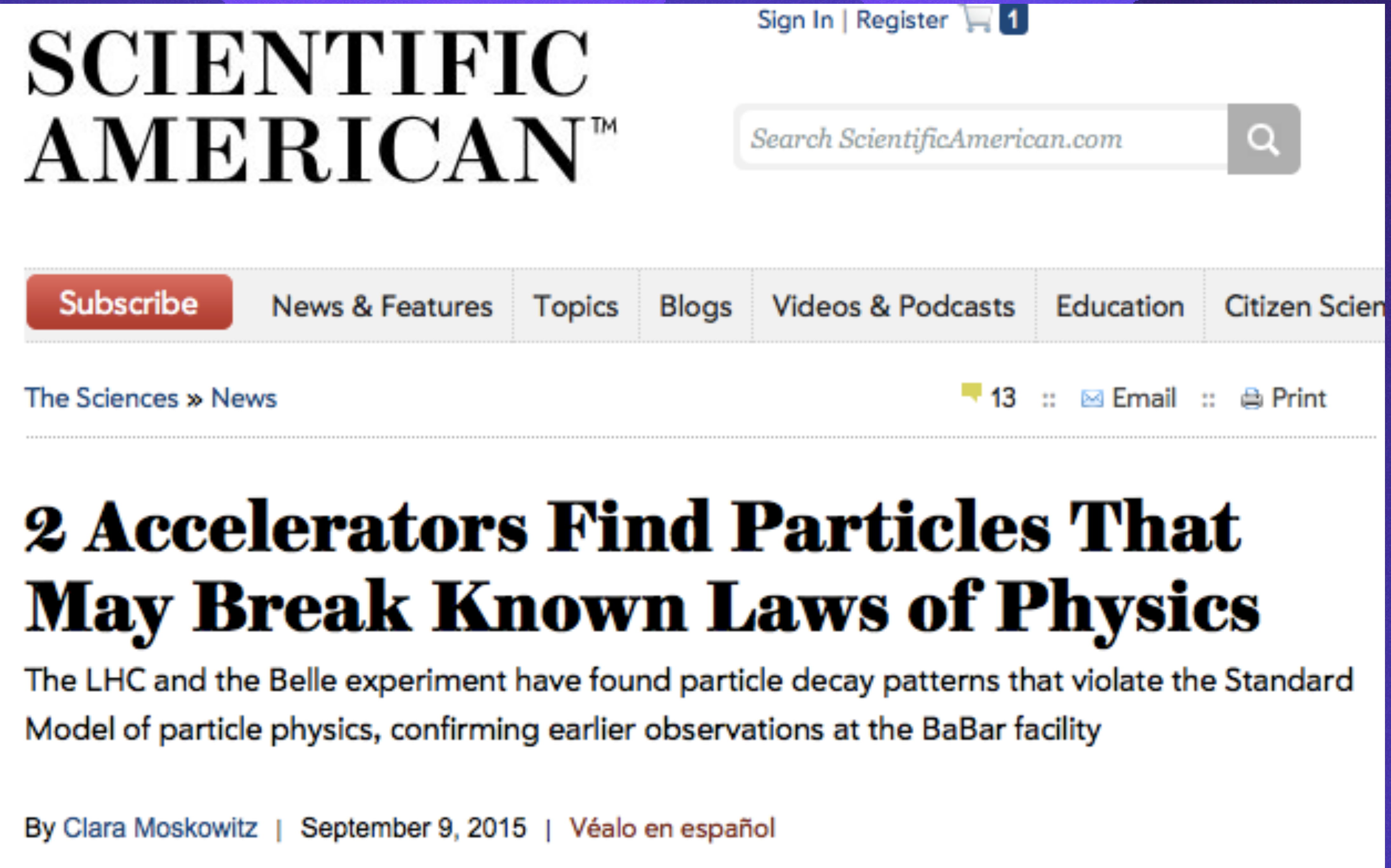
ARC CENTRE OF EXCELLENCE FOR DARK MATTER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2 Accelerators Find Particles That May Break Known Laws of Physics

The LHC and the Belle experiment have found particle decay patterns that violate the Standard Model of particle physics, confirming earlier observations at the BaBar facility

By Clara Moskowitz | September 9, 2015 | Véalo en español

Anomalies: what makes them interesting?

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NEWS FEATURE

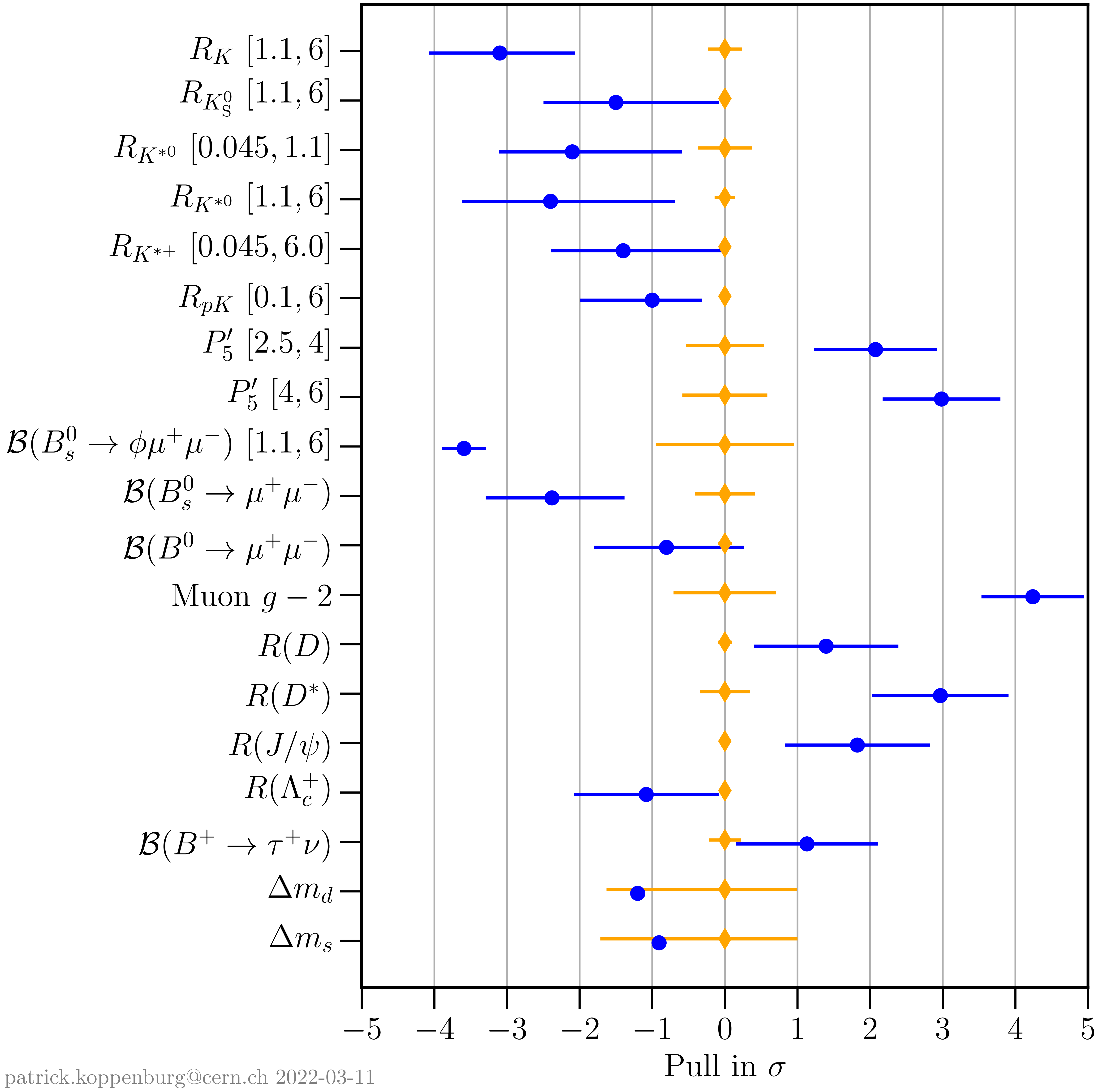
The Era of Anomalies

May 14, 2020 • *Physics* 13, 79

Particle physicists are faced with a growing list of "anomalies"—experimental results that conflict with the standard model but fail to overturn it for lack of sufficient evidence.

Brookhaven National Laboratory

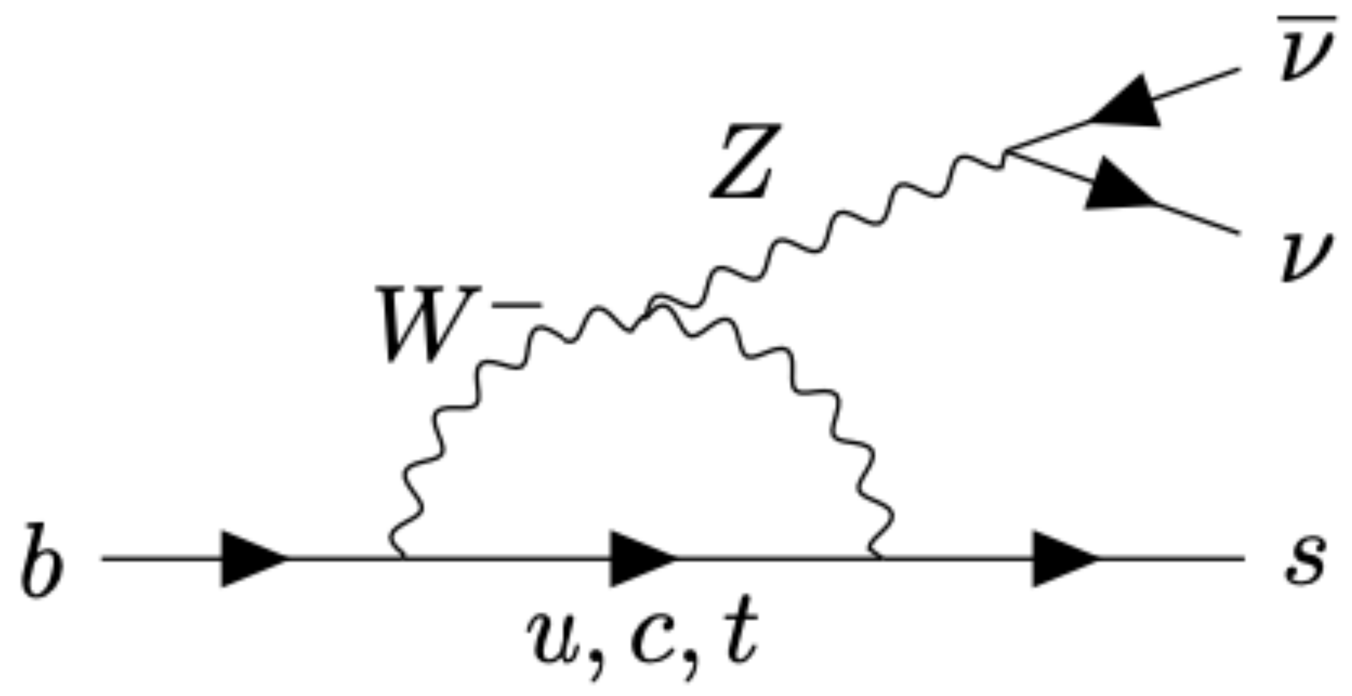
For their study of the muon anomaly, the Muon g-2 Collaboration transported a 50-foot-wide magnet halfway across the US in the summer of 2013.

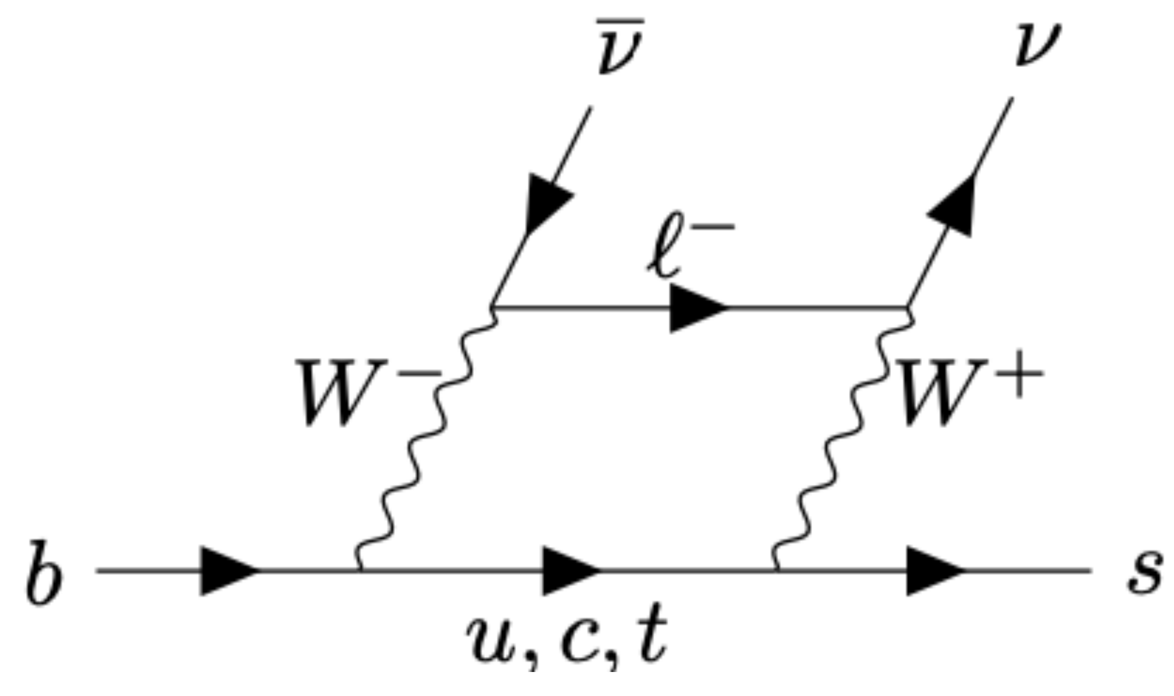


- High precision expectation, free of QCD uncertainties.
- Tend to be anomalous couplings vs generation.

B→ K$^{(*)}$ ν ν

SM: loop, CKM and GIM suppressed $\mathcal{A} \propto \frac{1}{16\pi^2} \sum_{i=u,c,t} V_{ib}^* V_{is} \frac{m_i^2}{m_W^2}$





⇒ good place to search for New Physics

- sensitive to virtual corrections and new exotic final states
- complete factorisation into hadronic and leptonic part
- Belle II is expected to measure with $\mathcal{O}(10\%)$ precision

Generalities

- Since neutrino flavors are not seen, one can only measure

$$\Gamma(P \to P'\nu\overline{\nu}) = \sum_{I,J=1,2,3} \Gamma(P \to P'\nu^I\overline{\nu}^J)$$

- When NP respects the SM gauge symmetries, neutrinos are in doublets,

$$L = \begin{pmatrix} \nu_L \\ \ell^- \end{pmatrix},$$

so $P \to P'\nu^I\overline{\nu}^J$ is necessarily correlated with $P \to P'\ell^I\overline{\ell}^J$.

- Given current bounds, $P \to P'\nu^I\overline{\nu}^J$, $I, J = 1, 2$ should be very suppressed,

but not much is currently known for the third generation...

SMEFT - Comparison to $B \to h\, l^+ l^-$

Interplay of dineutrino modes with semileptonic rare B-decays
Rigo Bause et al. JHEP 12 (2021) 061

Below the electroweak scale, $\mu < \mu_{\rm EW}$, FCNC interactions between two quarks and two leptons, with flavors α, β and i, j, respectively, can be described by the following Hamiltonians for dineutrinos

$$\mathcal{H}_{\rm eff}^{\nu_i\bar{\nu}_j} = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\sum_k \mathcal{C}_k^{P_{\alpha\beta}ij}\, Q_k^{\alpha\beta ij} + \text{H.c.}\,, \tag{2.1}$$

and for charged leptons,

$$\mathcal{H}_{\rm eff}^{\ell_i^-\ell_j^+} = -\frac{4\,G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\sum_k \mathcal{K}_k^{P_{\alpha\beta}ij}\, O_k^{\alpha\beta ij} + \text{H.c.}\,. \tag{2.2}$$

In absence of light right-handed neutrinos,

$$Q_{L(R)}^{\alpha\beta ij} = \left(\bar{q}^{\alpha}_{L(R)}\gamma_\mu q^{\beta}_{L(R)}\right)\left(\bar{\nu}^j_L\gamma^\mu\nu^i_L\right)$$

$$\mathcal{O}_9^{ij} = (\bar{s}_L\gamma_\mu b_L)\,(\bar{\ell}^j\gamma^\mu\ell^i)\,,$$
$$\mathcal{O}_{10}^{ij} = (\bar{s}_L\gamma_\mu b_L)\,(\bar{\ell}^j\gamma^\mu\gamma^5\ell^i)\,,$$
$$\mathcal{O}_9^{\prime ij} = (\bar{s}_R\gamma_\mu b_R)\,(\bar{\ell}^j\gamma^\mu\ell^i)\,,$$
$$\mathcal{O}_{10}^{\prime ij} = (\bar{s}_R\gamma_\mu b_R)\,(\bar{\ell}^j\gamma^\mu\gamma^5\ell^i)\,,$$

$$\mathcal{K}_L^{D_{23}ij} = V_{tb}V_{ts}^*\,(\mathcal{C}_9^{ij} - \mathcal{C}_{10}^{ij})\,,$$
$$\mathcal{K}_R^{D_{23}ij} = V_{tb}V_{ts}^*\,(\mathcal{C}_9^{\prime ij} - \mathcal{C}_{10}^{\prime ij})\,,$$

C9 vector, C10 axial vector

$B \to F_q$	SM, this work $[10^{-8}]$	SM, literature $[10^{-8}]$	Exp. limit (90 % CL) $[10^{-6}]$	Derived EFT limits $[10^{-6}]$	Belle II $5\,\text{ab}^{-1}$ $(50\,\text{ab}^{-1})$ %
$B^0 \to K^0$	391 ± 52	460 ± 50 [36]	26 [11]	15	–
$B^+ \to K^+$	423 ± 56	460 ± 50 [36]	16 [10]	16^a	30 (11) [36]
$B^0 \to K^{*0}$	824 ± 99	960 ± 90 [36]	18 [11]	18^a	26 (9.6) [36]
$B^+ \to K^{*+}$	893 ± 107	960 ± 90 [36]	40 [12]	19	25 (9.3) [36]
$B_s^0 \to \phi$	981 ± 69	1400 ± 500 [37]	5400 [8]	23	–
$B^0 \to X_s$	$(28 \pm 3)\cdot 10^2$	$(29 \pm 3)\cdot 10^2$ [22]	640 [9]	78	–
$B^+ \to X_s$	$(30 \pm 3)\cdot 10^2$	$(29 \pm 3)\cdot 10^2$ [22]	640 [9]	84	–
$B^0 \to \pi^0$	5.4 ± 0.6	7.3 ± 0.7 [38]	9 [11]	6	–
$B^+ \to \pi^+$	12 ± 1	14 ± 1 [38]	14 [11]	14^a	–
$B^0 \to \rho^0$	22 ± 8 $16 \pm 2^\dagger$	20 ± 10 [37]	40 [11]	14	–
$B^+ \to \rho^+$	48 ± 18 $34 \pm 4^\dagger$	42 ± 20 [37]	30 [11]	30^a	–
$B_s^0 \to K^0$	13 ± 3	27 ± 16 [37]	–	26	–
$B_s^0 \to K^{*0}$	36 ± 3	–	–	24	–
$B^0 \to X_d$	$(1.3 \pm 0.1)\cdot 10^2$	$(1.7 \pm 0.5)\cdot 10^2$ [37]	–	114	–
$B^+ \to X_d$	$(1.4 \pm 0.1)\cdot 10^2$	$(1.7 \pm 0.5)\cdot 10^2$ [37]	–	123	–

Generic constraints on new operators LEFT

Tobias Felkl et al. A tale of invisibility: constraints on new physics in b → svv, JHEP 12 (2021) 118

Express everything in terms of LH Weyl spinors $N_R \leftrightarrow \nu_L^c$

$$\mathcal{L} = \sum_{X=L,R} C_{\nu d}^{\mathrm{VLX}} \mathcal{O}_{\nu d}^{\mathrm{VLX}} + \left(\sum_{X=L,R} C_{\nu d}^{\mathrm{SLX}} \mathcal{O}_{\nu d}^{\mathrm{SLX}} + C_{\nu d}^{\mathrm{TLL}} \mathcal{O}_{\nu d}^{\mathrm{TLL}} + \mathrm{h.c.} \right)$$

$$\mathcal{O}_{\nu d}^{\mathrm{VLL}} = (\overline{\nu_L} \gamma_\mu \nu_L)(\overline{d_L} \gamma^\mu d_L) \qquad \mathcal{O}_{\nu d}^{\mathrm{VLR}} = (\overline{\nu_L} \gamma_\mu \nu_L)(\overline{d_R} \gamma^\mu d_R)$$

$$\mathcal{O}_{\nu d}^{\mathrm{SLL}} = (\overline{\nu_L^c} \nu_L)(\overline{d_R} d_L) \qquad \mathcal{O}_{\nu d}^{\mathrm{SLR}} = (\overline{\nu_L^c} \nu_L)(\overline{d_L} d_R)$$

$$\mathcal{O}_{\nu d}^{\mathrm{TLL}} = (\overline{\nu_L^c} \sigma_{\mu\nu} \nu_L)(\overline{d_R} \sigma^{\mu\nu} d_L)$$

- $C_{\nu d}^{\mathrm{SLX}}$ symmetric in neutrino flavour indices
- $C_{\nu d}^{\mathrm{TLL}}$ antisymmetric in neutrino flavour indices
- NP $C_{\nu d}^{\mathrm{VLX}}$ interfere with SM

$$C_{\nu d,\alpha\alpha sb}^{\mathrm{VLL,SM}} = -\frac{4 G_F}{\sqrt{2}} \frac{\alpha}{2\pi} V_{ts}^* V_{tb} \left(\frac{X}{\sin^2 \theta_W} \right)$$

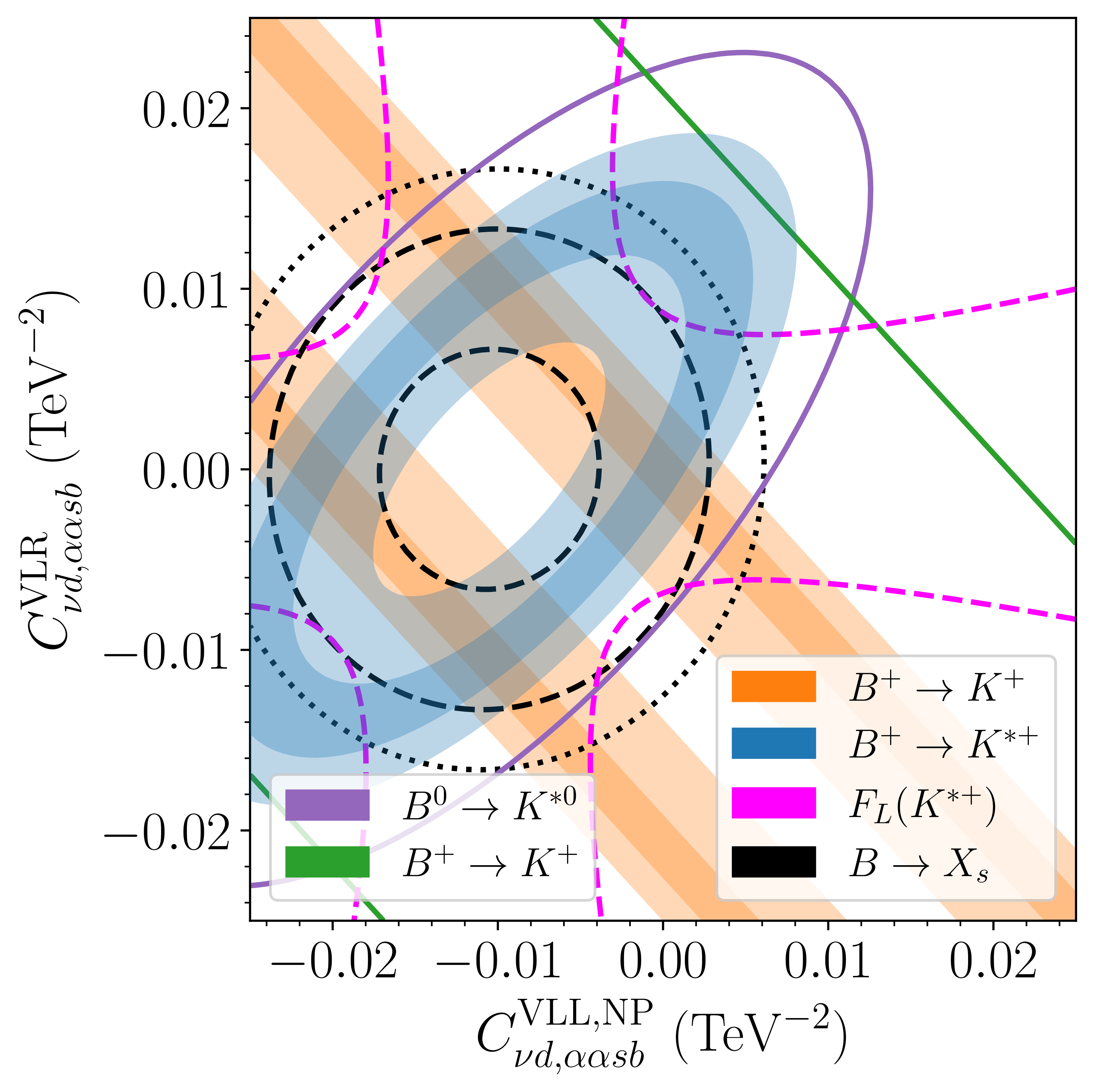
Brod, Gorbahn, Stamou 1009.0947

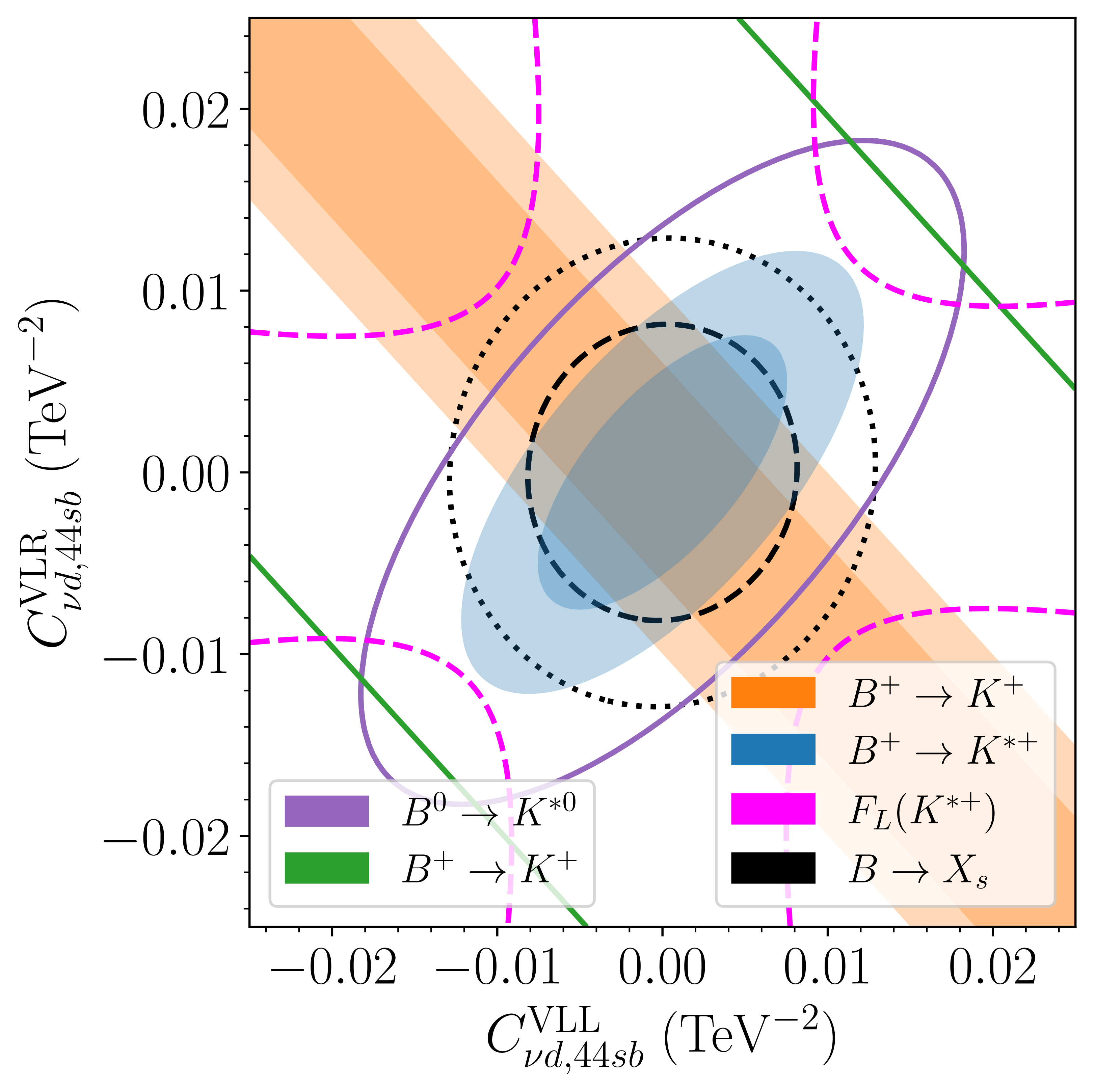
Operator	Current Bound: Value [TeV^{-2}]	NP scale [TeV]	Observable
$\mathcal{O}_{\nu d,\alpha\alpha sb}^{\mathrm{VLL,NP}}$	0.028	6	$B \to K^* \nu\nu$
$\mathcal{O}_{\nu d,\alpha\alpha sb}^{\mathrm{VLR}}$	0.021	7	$B \to K \nu\nu$
$\mathcal{O}_{\nu d,\gamma\delta sb}^{\mathrm{VLL}}$	0.014	9	$B \to K^* \nu\nu$
$\mathcal{O}_{\nu d,\gamma\gamma sb}^{\mathrm{SLL}}$	0.012	10	$B \to K^{(*)} \nu\nu$
$\mathcal{O}_{\nu d,\gamma\delta sb}^{\mathrm{SLL}}$	0.009	10	$B \to K^{(*)} \nu\nu$
$\mathcal{O}_{\nu d,\gamma\delta sb}^{\mathrm{TLL}}$	0.002	25	$B \to K^* \nu\nu$

$\alpha \in \{1,2,3\}$ and $\gamma \neq \delta$ arbitrary

$$\Lambda_{\mathrm{NP}} = \frac{1}{\sqrt{|C_{\nu d}^{XLY}|}}$$

Two operators with massless neutrinos – vector





Tobias Felkl et al. A tale of invisibility: constraints on new physics in b → sνν, JHEP 12 (2021) 118

- Current constraints solid purple and green lines
- Viable light (dark) regions if SM predictions are confirmed by Belle II with 5(50) ab^{-1}
- Black dotted (dashed) $B \to X_s \nu\nu$ with 50% (20%) precision

LFU tests with B→ h νν

Interplay of dineutrino modes with semileptonic rare B-decays
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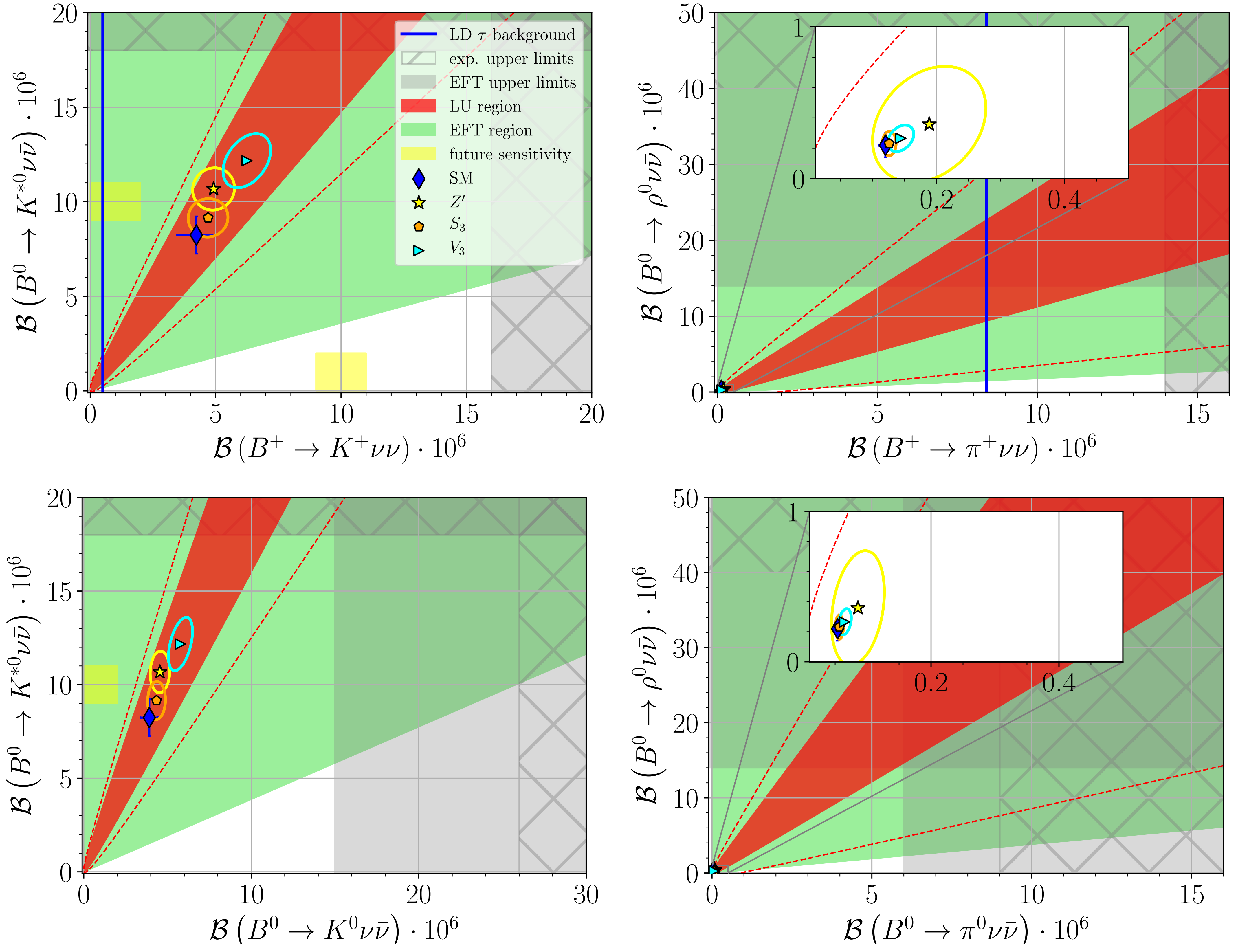


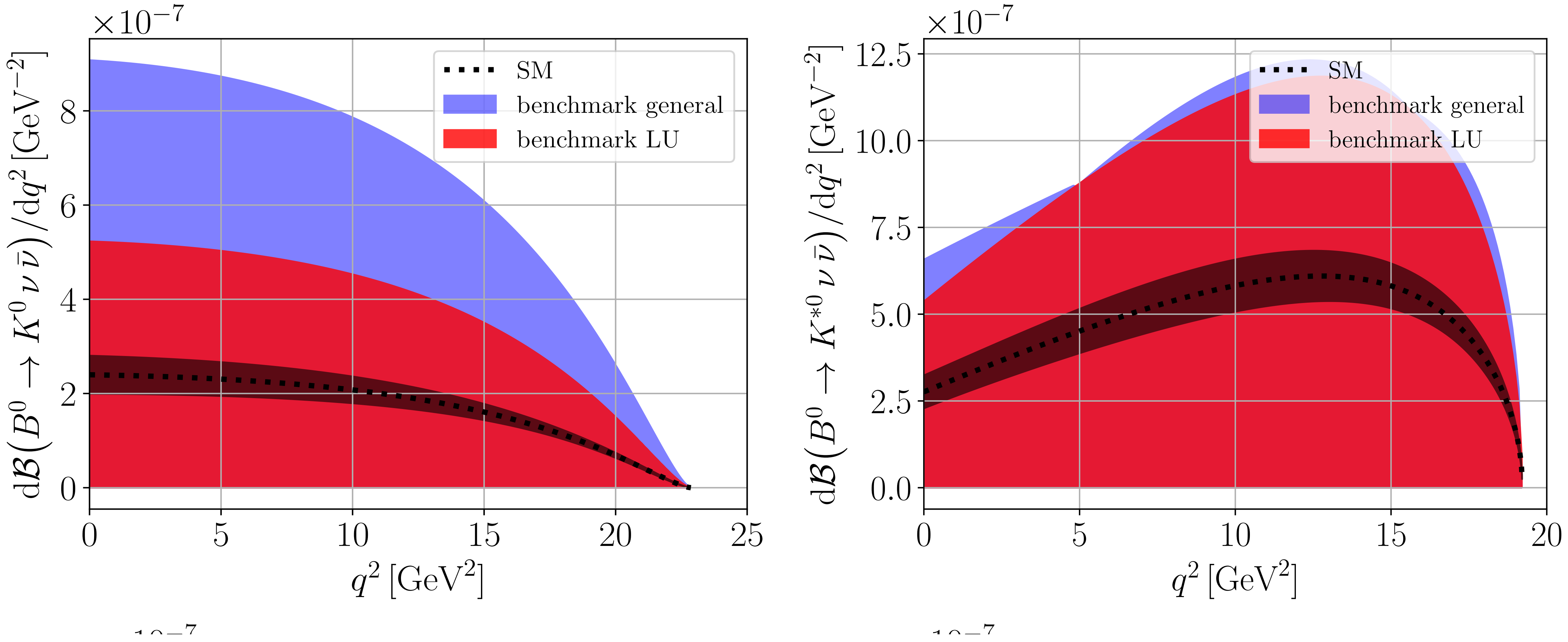
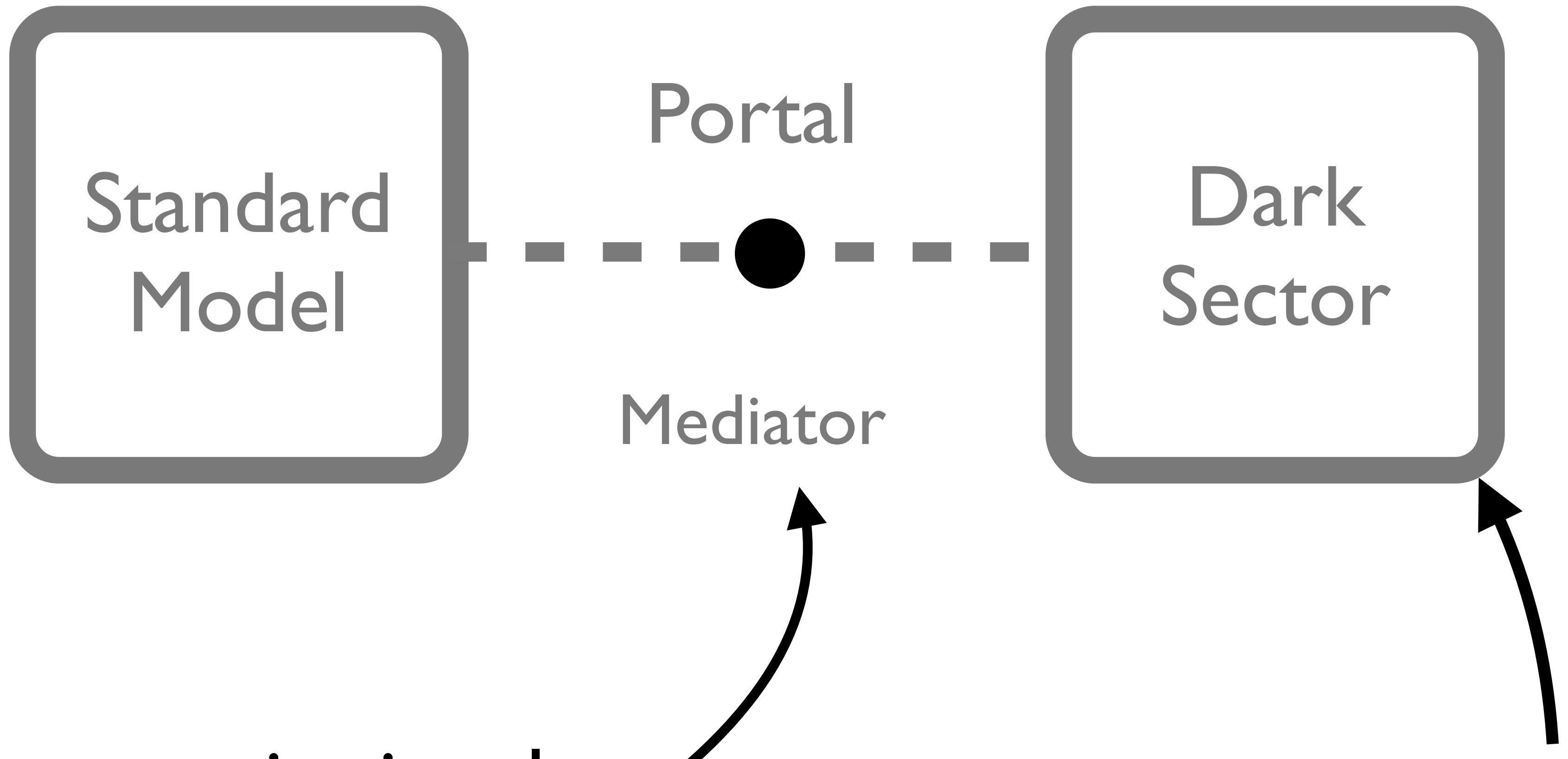


Figure 4. Differential branching ratio for $B^0 \to K^0\nu\bar{\nu}$, $B^0 \to K^{*0}\nu\bar{\nu}$, $B^0_s \to \phi\,\nu\bar{\nu}$, $B^0 \to X_s\,\nu\bar{\nu}$, $B^0 \to \pi^0\,\nu\bar{\nu}$, and $B^0 \to \rho^0\,\nu\bar{\nu}$ in the SM and two NP benchmark scenarios, "benchmark general" using the derived EFT bounds (4.1) and (4.2) for $b \to s\,\nu\bar{\nu}$ and $b \to d\,\nu\bar{\nu}$, respectively, and "benchmark LU" (3.1) together with the experimental limits from Tab. 2. See text for details.

Hidden/Dark Sector

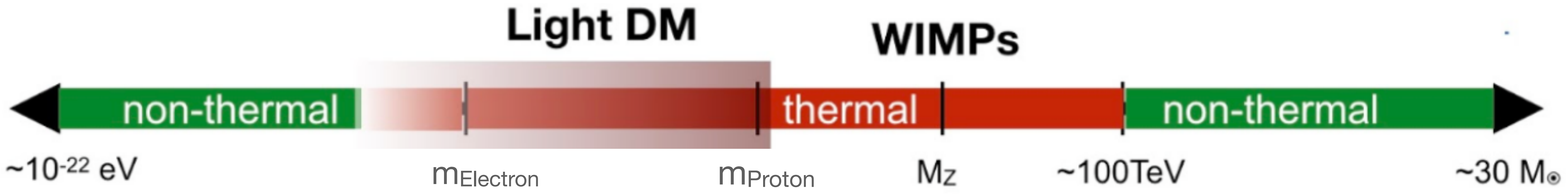


Non-gravitational interaction with ordinary matter

- Dark matter
- Dark forces
- Other dark particles

Light thermal DM interacting via weak interactions generically overproduced.

Lee-Weinberg bound evaded with new light mediators



Collisions e.g. $e^+e^- \rightarrow \gamma X$
Fixed target, beam dumps
Decay e.g. B→K {a', S/H, A'}
Direct Detection e.g. DAMA/LIBRA

- Vector portal
- Pseudoscalar/Axion portal
- Scalar/Higgs portal

$$\epsilon F_{Y}^{\mu\nu} F'_{\mu\nu} \ (dark\ photon\ A'), \sum_{l} \theta g' \bar{l} \gamma^{\mu} Z'_{\mu} l \ (dark\ Z')$$

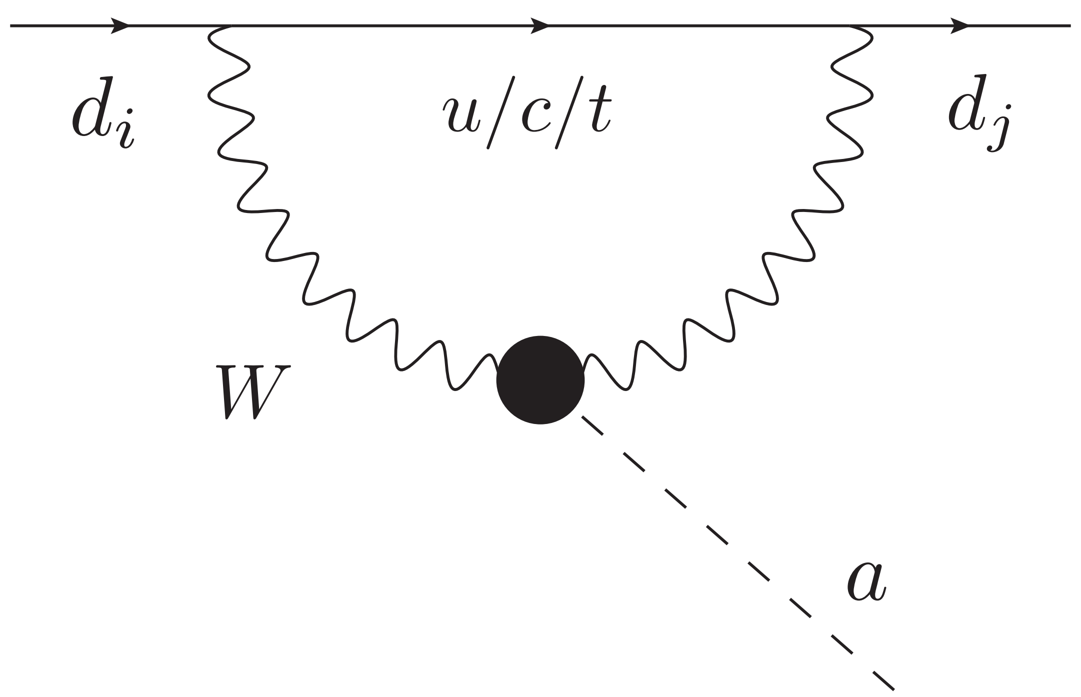
$$\frac{G_{agg}}{4} a G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \ (axion, alps)$$

$$\lambda H^2 S^2 + \mu H^2 S \ (dark\ Higgs)$$

Axion like particles

- Axion-like particles produced in FCNC processes.
- Exploits coupling to W boson.

Izaguirre, Lin, Shuve "Search for Axionlike Particles in Flavor-Changing Neutral Current Processes" DOI: 10.1103/PhysRevLett.118.111802



$$\mathcal{L} = (\partial_\mu a)^2 - \frac{1}{2} M_a^2 a^2 - \frac{g_{aW}}{4} a W_{\mu\nu}^a \tilde{W}^{a\mu\nu},$$

$$g_{ad_id_j} \equiv -\frac{3\sqrt{2} G_F M_W^2 g_{aW}}{16\pi^2} \sum_{\alpha \in c,t} V_{\alpha i} V_{\alpha j}^* f(M_\alpha^2 / M_W^2)$$

$$\Gamma(B \to Ka) = \frac{M_B^3}{64\pi} |g_{abs}|^2 \left(1 - \frac{M_K^2}{M_B^2}\right)^2 f_0^2(M_A^2) \lambda_{Ka}^{1/2},$$

$$\Gamma(B \to K^* a) = \frac{M_B^3}{64\pi} |g_{abs}|^2 A_0^2(M_a^2) \lambda_{K^*a}^{3/2},$$

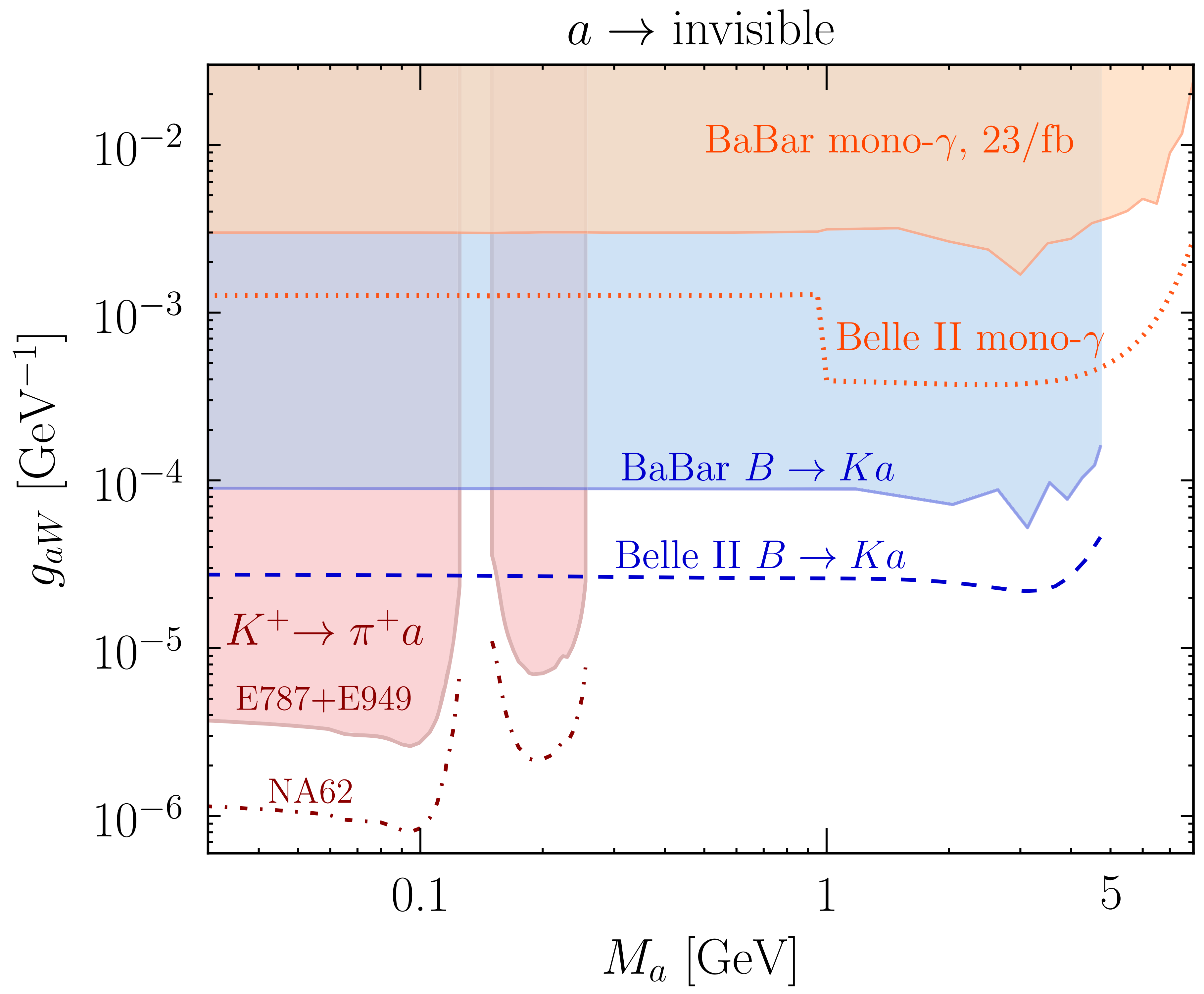
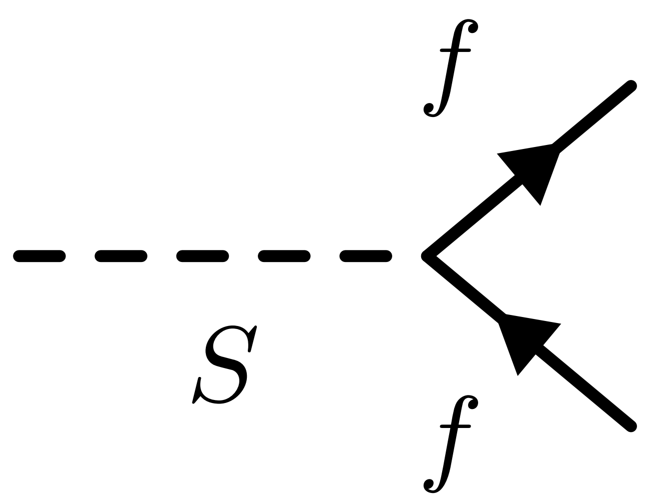


FIG. 3. Sensitivity of existing and planned searches to the ALP parameter space assuming the ALP decays invisibly. We apply a *BABAR* search for $B \to K\nu\bar{\nu}$ to constrain the decay $B \to Ka$ (shaded blue); this bound can be further improved with Belle II (dashed blue). Similarly, data from E787 and E949 are used to constrain $K \to \pi a$ in two mass ranges (shaded red), with expected improvements from NA62 (dot-dashed red). We show bounds on $e^+e^- \to a\gamma$ from a *BABAR* mono $-\gamma$ search (shaded orange) and the estimated reach for the same search at Belle II (dotted).

Hidden Higgs-like Scalars

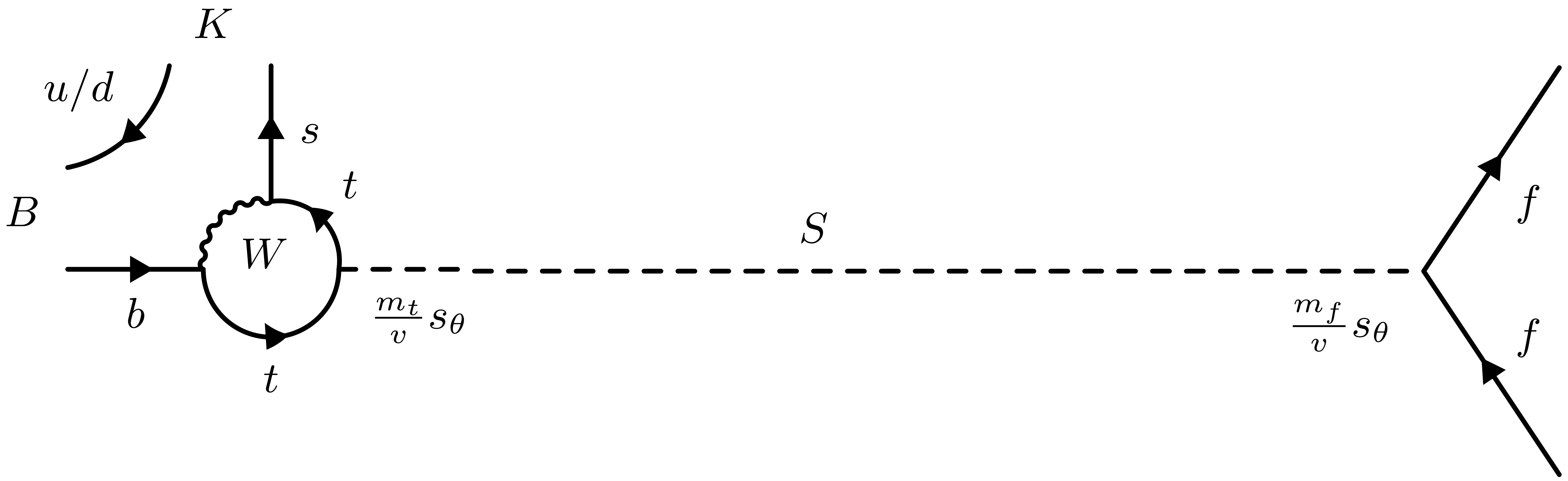
$$\mathcal{L}_{\rm mass} = -\frac{m_\phi^2}{2}\phi^2 - \frac{m_{H_{\rm SM}}^2}{2}H_{\rm SM}^2 - \mu v H_{\rm SM}\phi$$
$$= -\frac{m_h^2}{2}h^2 - \frac{m_S^2}{2}S^2$$



$$s_\theta \frac{m_f}{v}$$

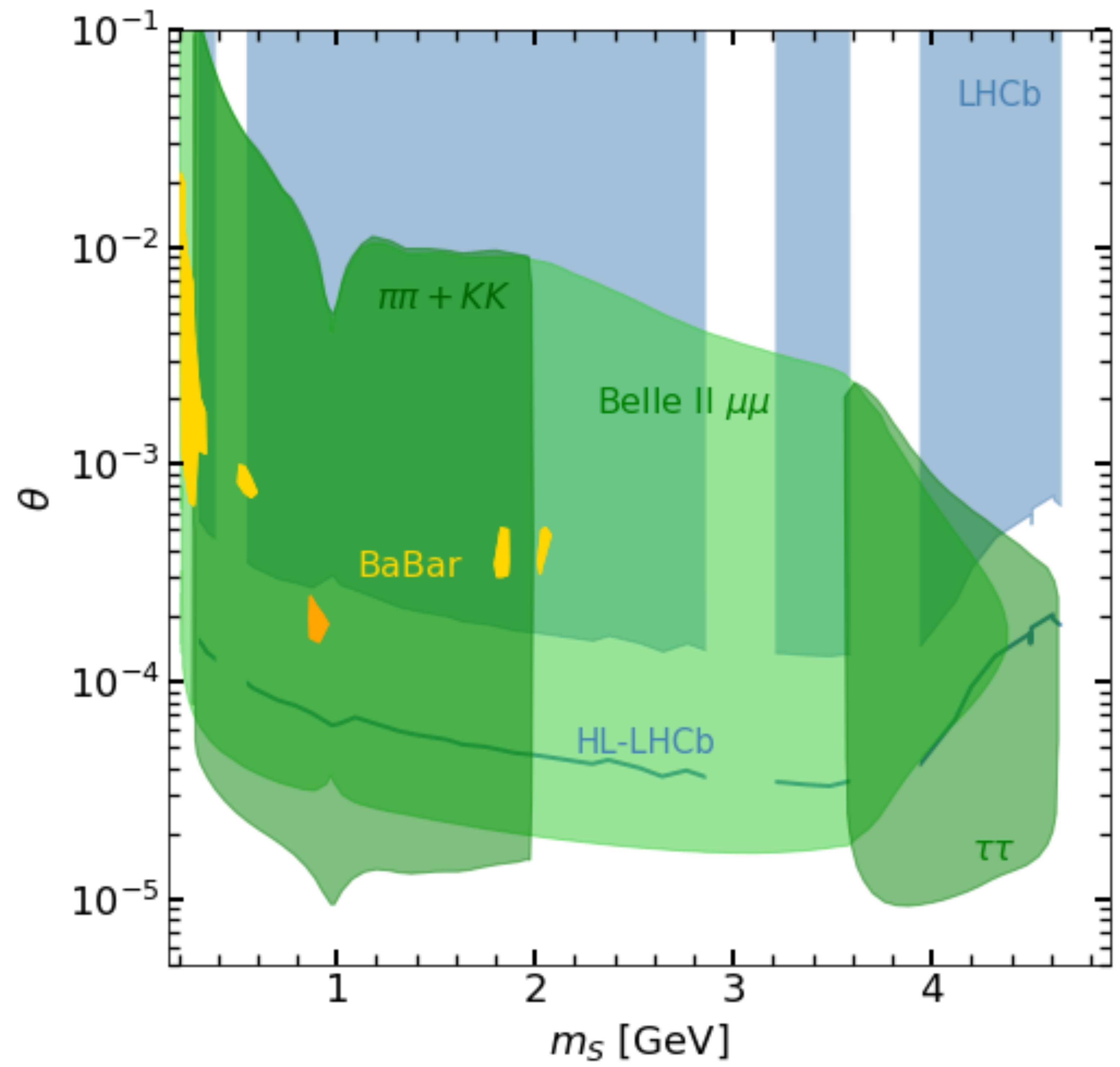
Long lived - Higgs-like scalar
A. Filimonova, et al. PRD 101, 095006 (2020)

Small coupling = small width = long lifetimes



$$\frac{m_t}{v}s_\theta \qquad \frac{m_f}{v}s_\theta$$

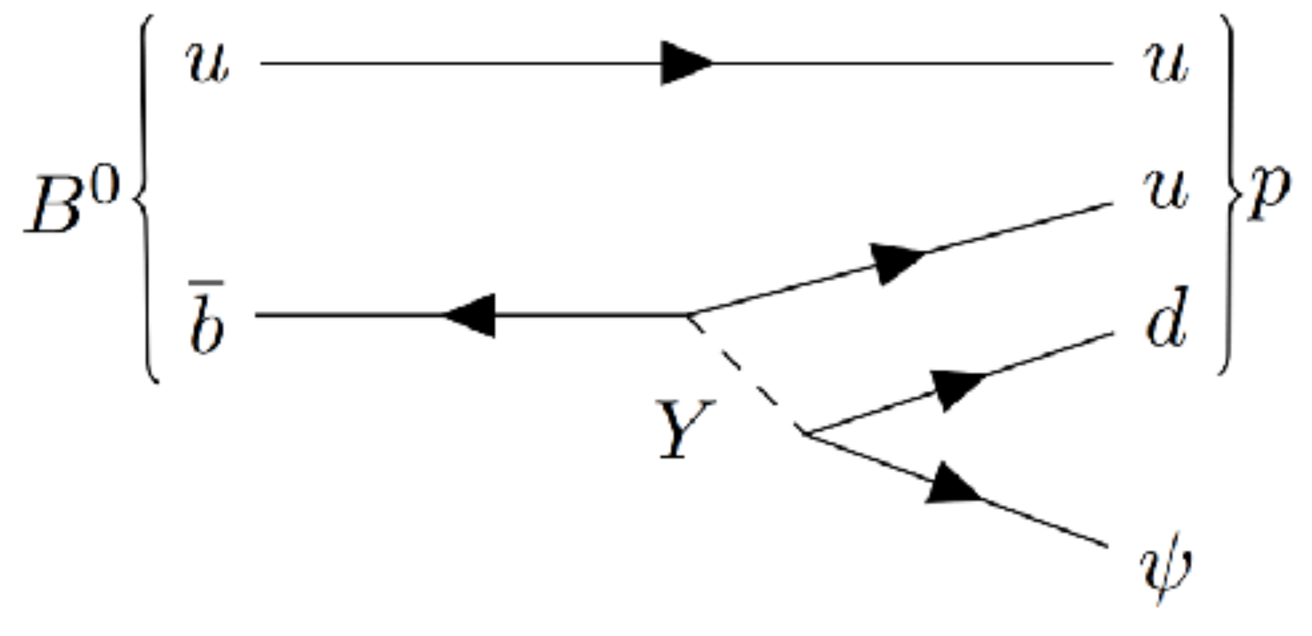
95% C.L. bounds from $B^+ \to K^+S(\mu\mu)$



B-meson baryogenesis

Alonso-Álvarez, Elor, Escudero "Collider Signals of Baryogenesis and Dark Matter from B Mesons: A Roadmap to Discovery"
DOI: 10.1103/PhysRevD.104.035028

- "B-mesogenesis" scenario: Dark matter carries baryon number
  - Produce visible baryon asymmetry whilepreserving total baryon number in universe



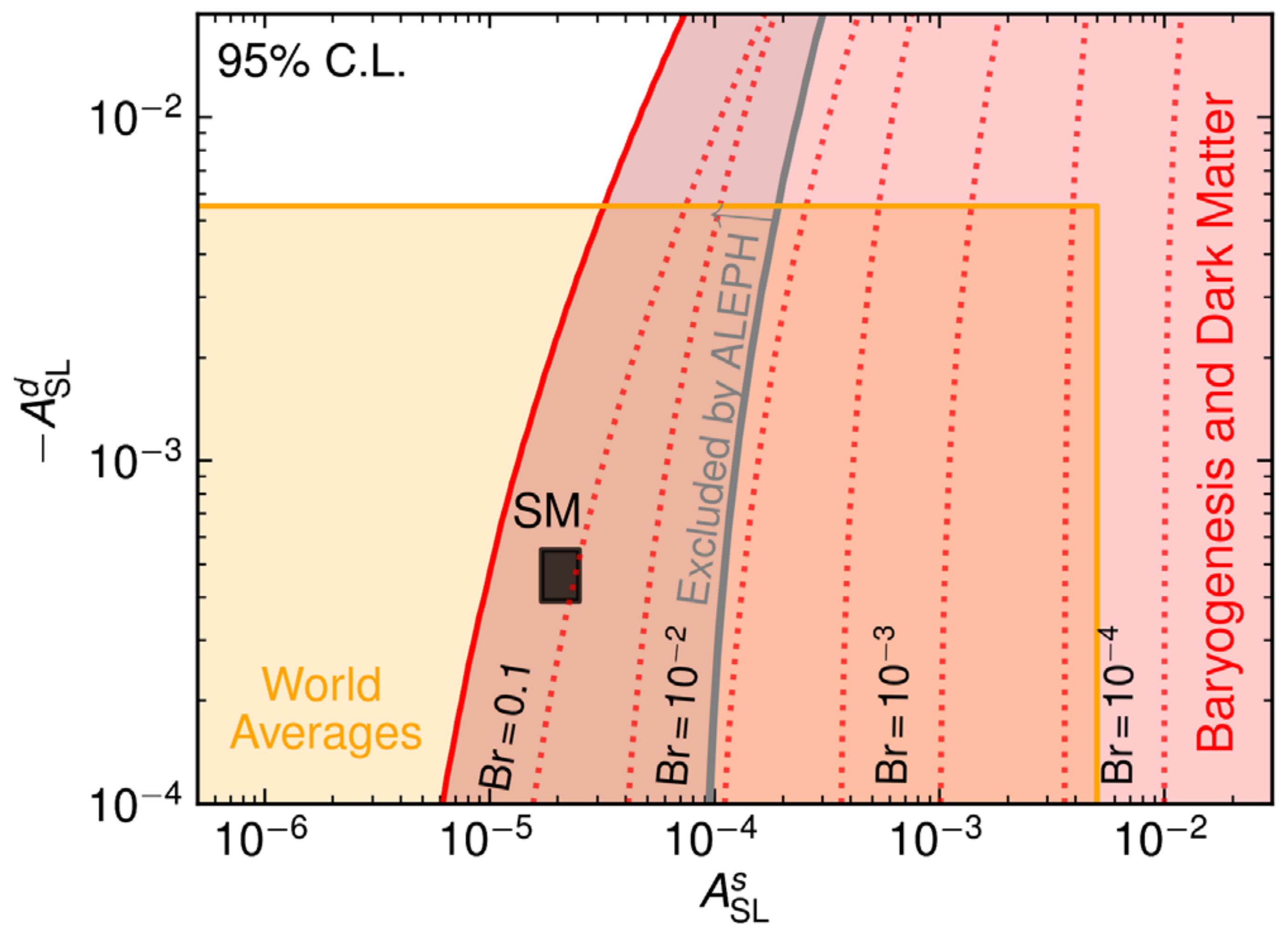
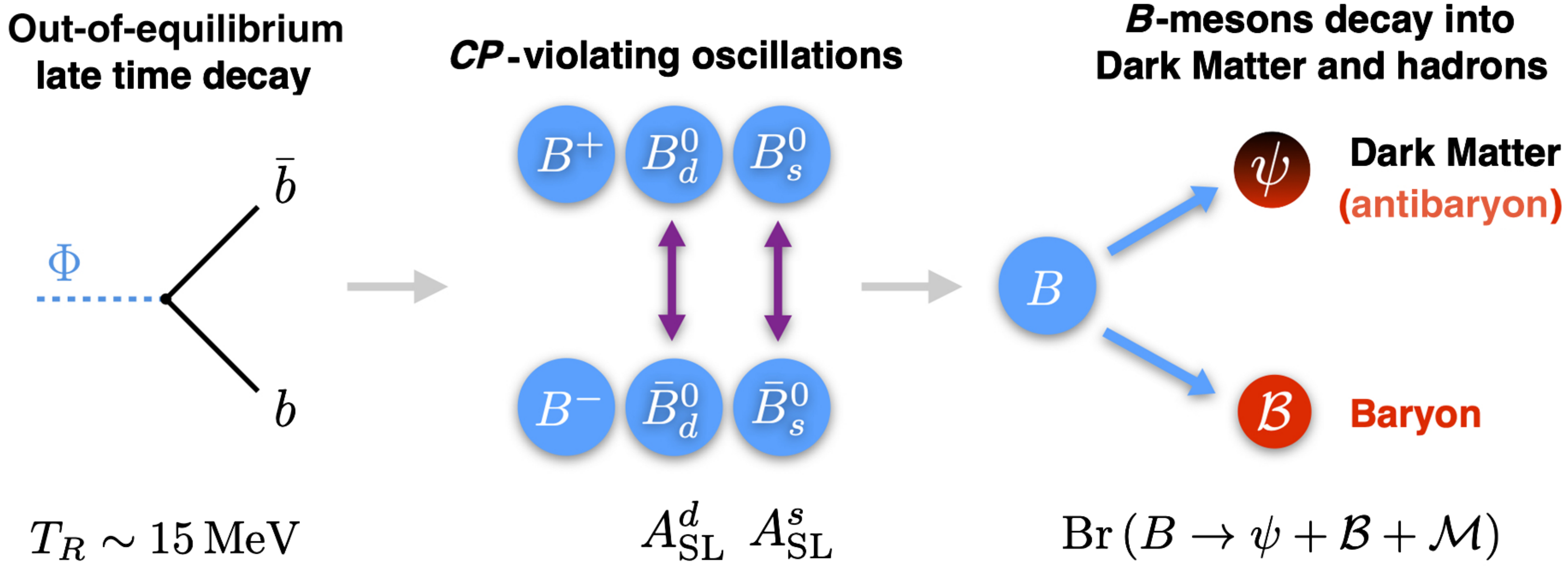


FIG. 3. Contour lines for the minimum $\mathrm{Br}(B \to \psi \mathcal{B} \mathcal{M})$ required for baryogenesis and dark matter generation as a function of the semileptonic asymmetries in B^0_q-meson decays, A^q_{SL}. In red, we show the relevant parameter space in which baryogenesis can successfully occur. The dashed lines delineate the cosmological uncertainties of our predictions (see text for more details). The black rectangle corresponds to the SM prediction for the semileptonic asymmetries [66], while the orange contour corresponds to the current world averages for experimental measurements of these quantities [64]. The gray line highlights the region of parameter space corresponding to $\mathrm{Br}(B \to \psi \mathcal{B} \mathcal{M}) > 0.5\%$, which is disfavored by an ALEPH search as discussed in Sec. IV A 2. All contours are shown at 95% C.L. This figure showcases that, given current measurements of the semileptonic asymmetries, a branching ratio $\mathrm{Br}(B \to \psi \mathcal{B} \mathcal{M}) \gtrsim 10^{-4}$ is required for successful baryogenesis. Similarly, in light of the ALEPH constraint, $A^q_{SL} > 10^{-4}$ is necessary in order to explain the observed baryon asymmetry of the Universe.



$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11} \frac{\mathrm{Br}(B \to \psi \mathcal{B} \mathcal{M})}{10^{-3}} \sum_q \alpha_q \frac{A^q_{SL}}{10^{-3}},$$

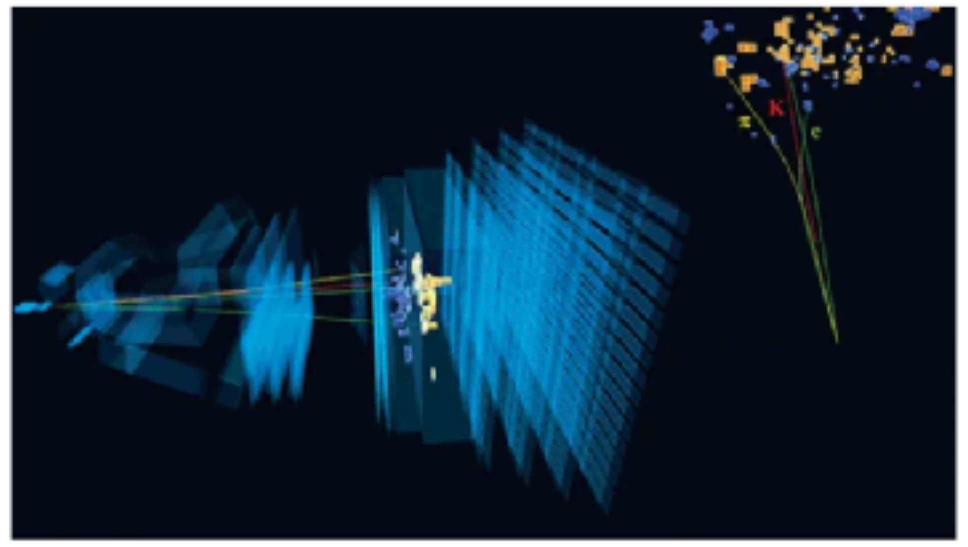
Experimental requirements for missing energy B decays

PARTICLE PHYSICS

Unexplained Results Intrigue Physicists at World's Largest Particle Collider

Muons and electrons might not experience the same fundamental interactions, contrary to Standard Model predictions

By Daniel Garisto on March 25, 2021



Visualization of the very rare decay of a beauty meson as observed by the LHCb experiment. Credit: CERN

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PHYSICS
Physicists Excited by Latest LHC Anomaly
Davide Castelvecchi and Nature

PHYSICS
Muons Bring New Physics within Reach
Elizabeth Gibney and Nature

PHYSICS
Physicists Achieve Best Ever Measurement of Fine-Structure Constant
Dhananjay Khadilkar

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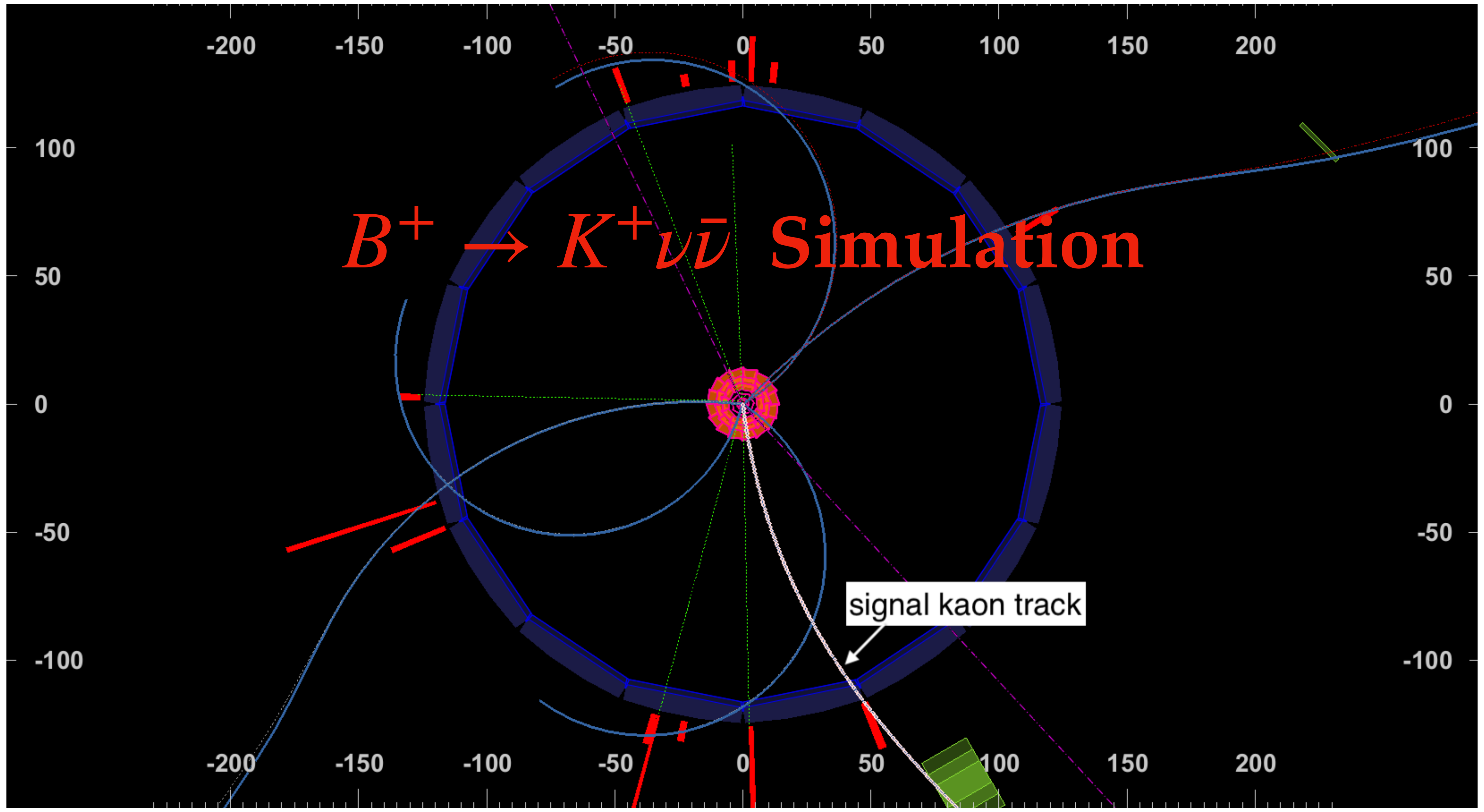
Key ingredients

- Rare B-decay with invisible particle(s) has usually significant missing energy.

Belle II Detector
- Hermetic
- Good Performance

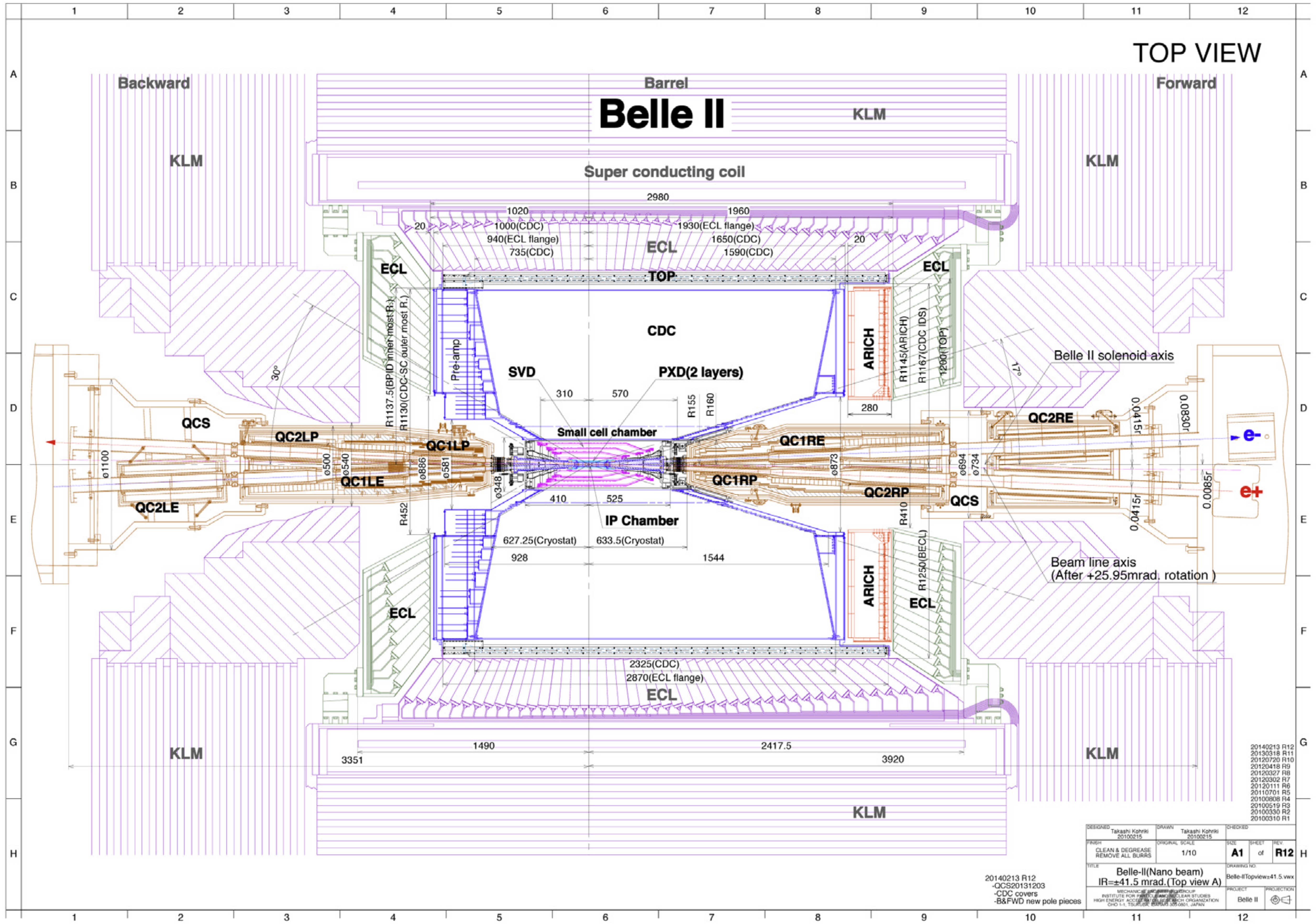


Belle II Event
- Cleaner Environment
- Known Initial State Kinematics

Challenges of rare B-decays
- B-reconstruction: vertexing/tracking
- Good MC modelling (include rare backgrounds)

Challenges of channels with invisible particles
- Understanding of the neutral objects (π^0, K_L, K_s, n, γ)
- Reconstruction approach

Detector coverage



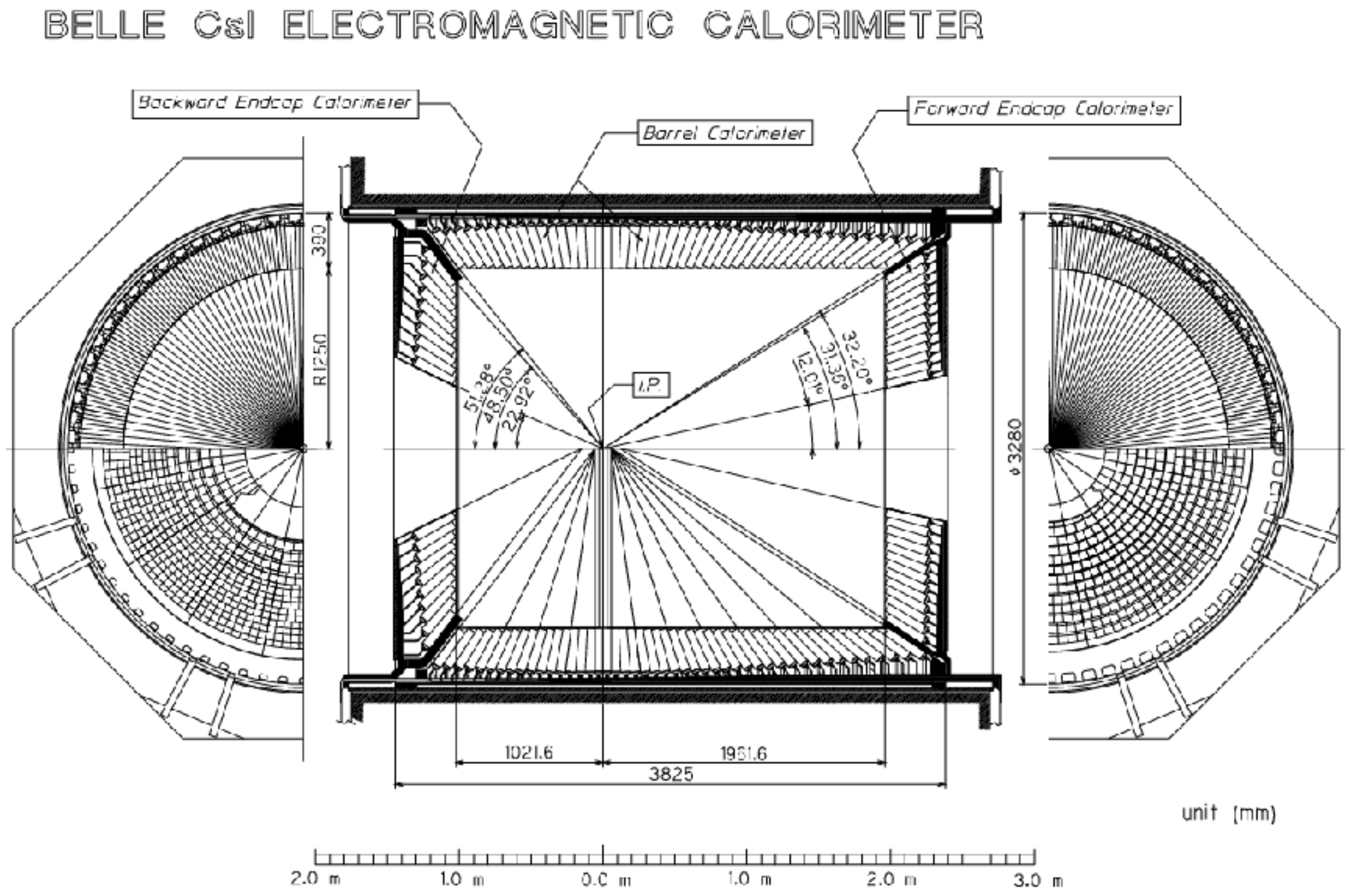
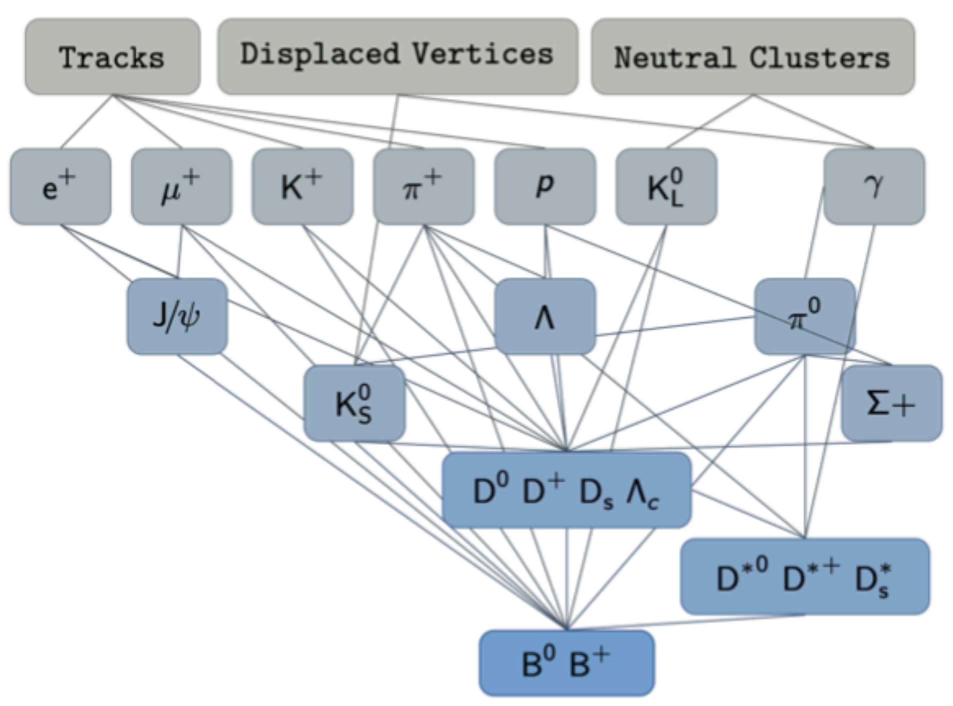
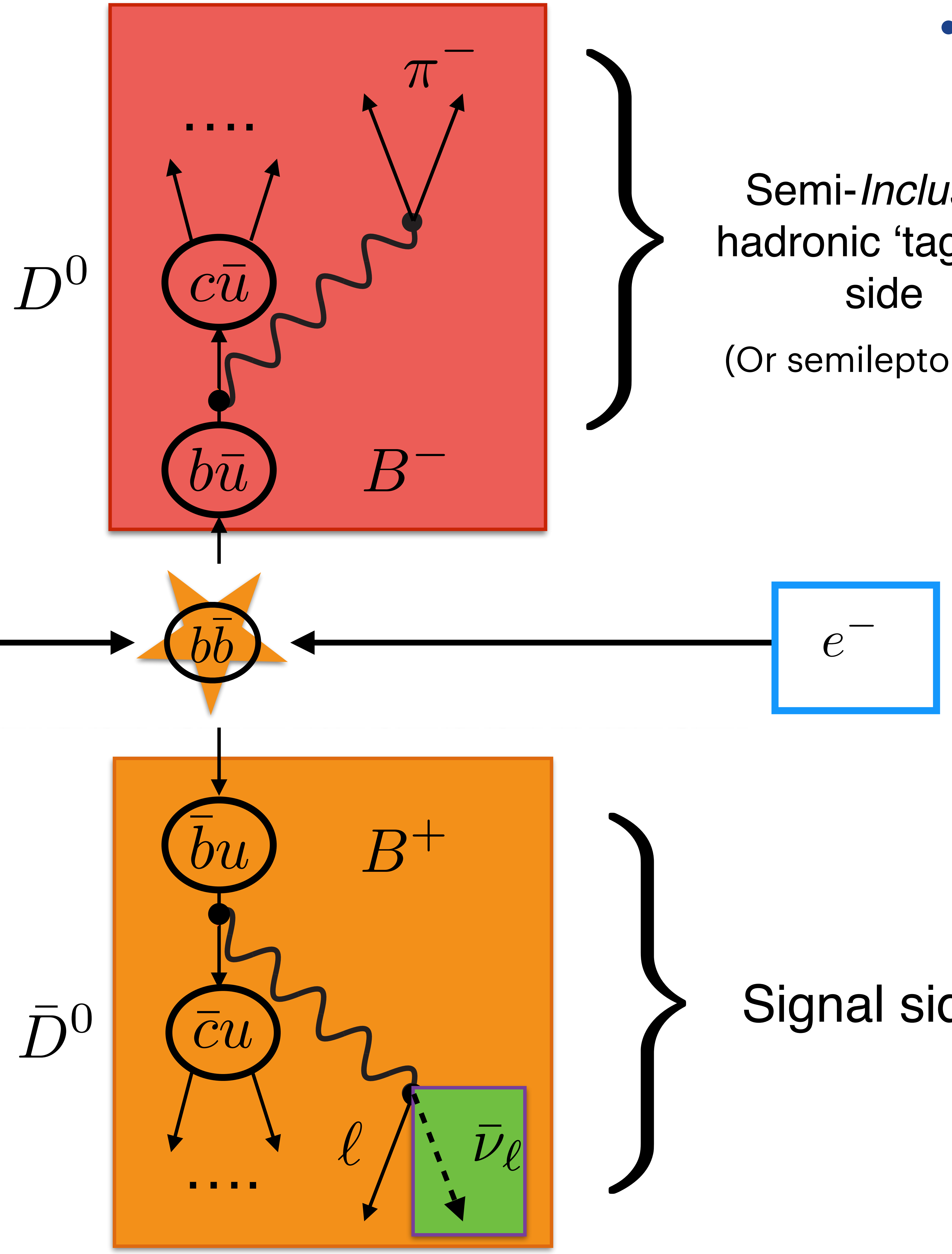


Fig. 69. Overall configuration of ECL.

Reconstructing decays with neutrinos



[Comput. Softw. Big. Sci. (2019) 3: 6]



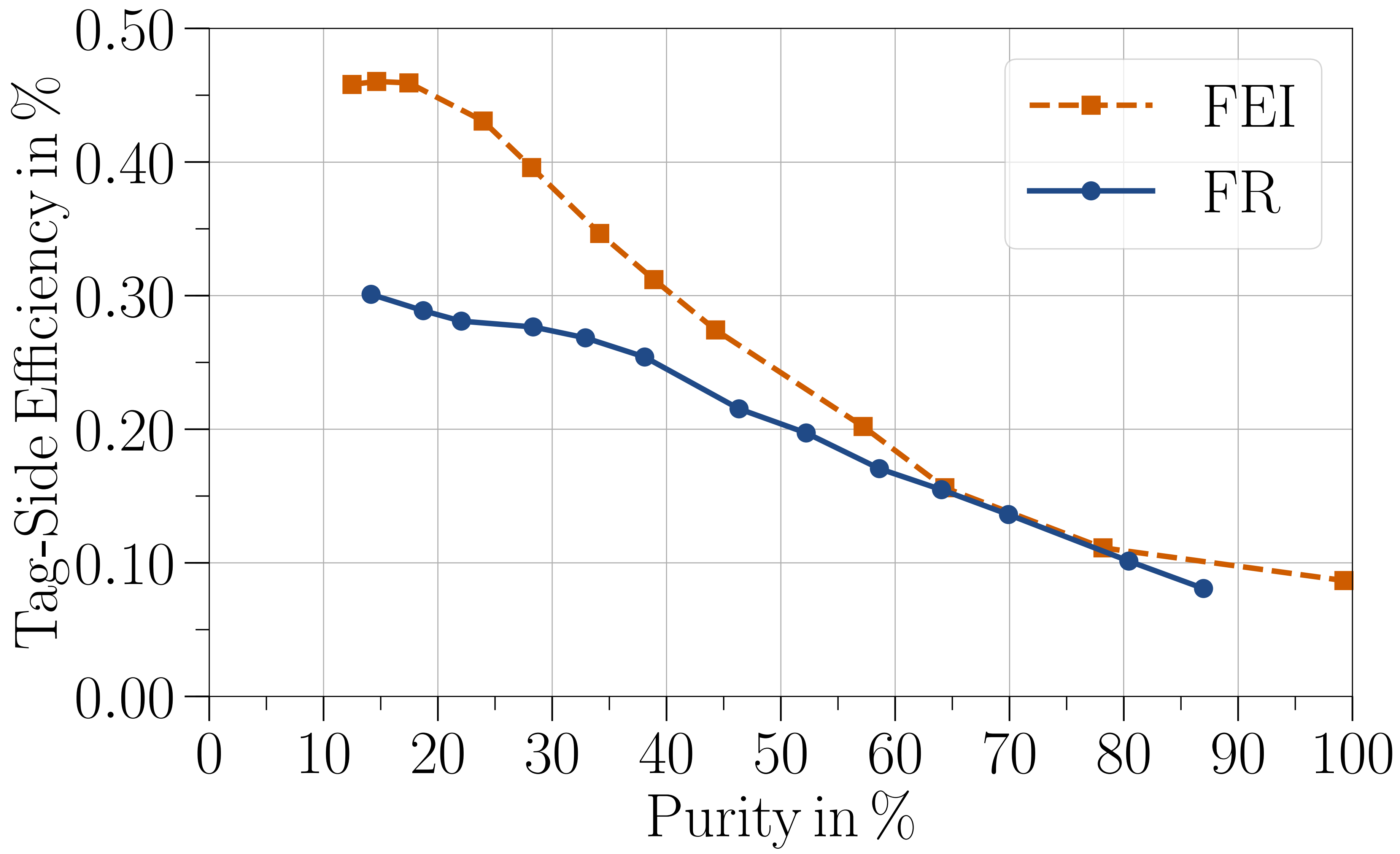
Semi-*Inclusive* hadronic ‘tagging’ side

(Or semileptonic)

Signal side

- Belle (II) analyses use semileptonic and hadronic “tagging” for flavour, charge, kinematics.
- e.g. B→D* l ν

$$\left(p_{e^+e^-} - p^B_{\text{tag}} - p^{D^*} - p_\ell\right)^2 = (p_\nu)^2 = m^2_{\text{miss}} \backsim 0$$



T. Keck, PU et al (Belle II software) Comput Softw Big Sci 3:6. (2019)

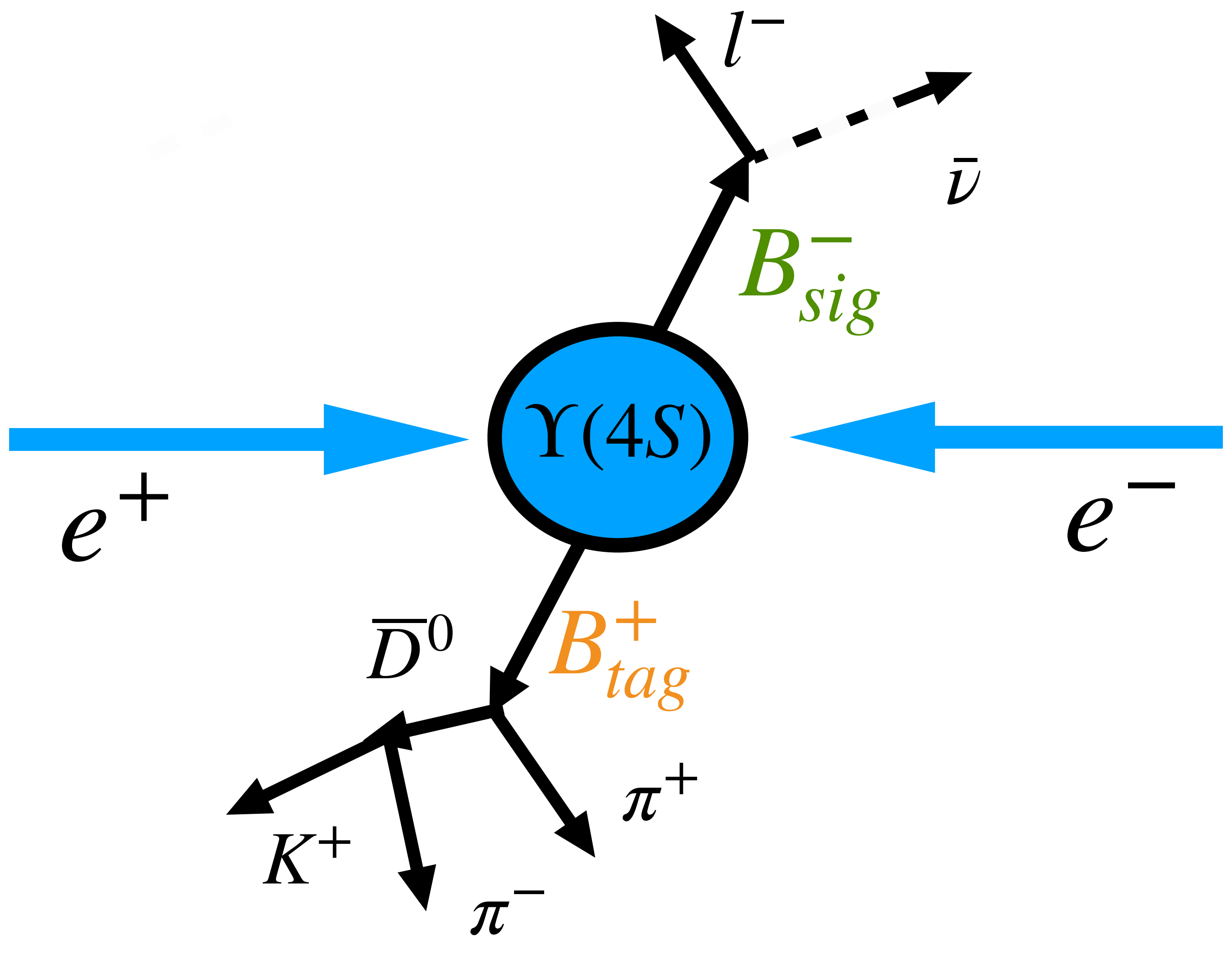
Comparison of tagging approaches

Tagged Approach:

1. step: B^+_{tag} reconstruction in its **semileptonic (SL)** or **hadronic (HAD)** decay chain

2. step: B^-_{sig} reconstruction

- Flavour constraint: $B^+_{tag} \rightarrow B^-_{sig}$
- Kinematically constrained system with hadronic B^+_{tag} : $\vec{p}_{\bar{\nu}} + \vec{p}_{l^-} = \vec{p}_{e^+e^-} - \vec{p}_{B^-_{tag}}$



Inclusive Tagging Approach:

1. step: B^-_{sig} reconstruction

2. step: Constrain the rest of the event

Tagged Approach:

- ☑ Higher intrinsic background rejection
- ☑ Better resolution → analytical fits
- ☐ Lower signal efficiency (<1%)
- ☐ Systematics (B^+_{tag})

Rare B-decay with missing energy

Inclusive Tagging Approach:

- ☑ Higher signal efficiency
- ☐ Lower intrinsic background rejection
- ☐ Worse resolution → binned fits

Neutral particles

- To take advantage of the 'clean event' need to reconstruct every particle possible!

π^0, K_L, K_s, n, γ

- γ = cluster in ECL that are not associated to a track
- K_L, n = cluster in KLM and ECL that is not associated to a track
- $\pi^0 = \gamma\gamma$
- $K_s = \pi^+\pi^-$ or $\pi^0\pi^0$

Background Rejection

- Large fraction of B-decay products have π^0 in its decay chain
- If K_L, n's interact with atomic nuclei in ECL and KLM, then need to devise vetos

Signal Identification

- If signal has π^0, K_s : need to have high reconstruction efficiency and good resolution

ROE / Tagged Reconstruction

- Missing energy related variables (all particles that are not associated to signal/and B_{tag}) often used as discriminating variables/fitting variables
- If K_L, n's do not interact with atomic nuclei in ECL and KLM, potential fakes for invisible particles

Extra energy

Identification of Beam Background Calorimeter Clusters and Fake Photons at Belle II Using BDT Classifiers
P. Cheem et al, BELLE2-NOTE-TE-2022-015

- Need good ECL energy sum that is not diluted by beam background and hadronic split offs.

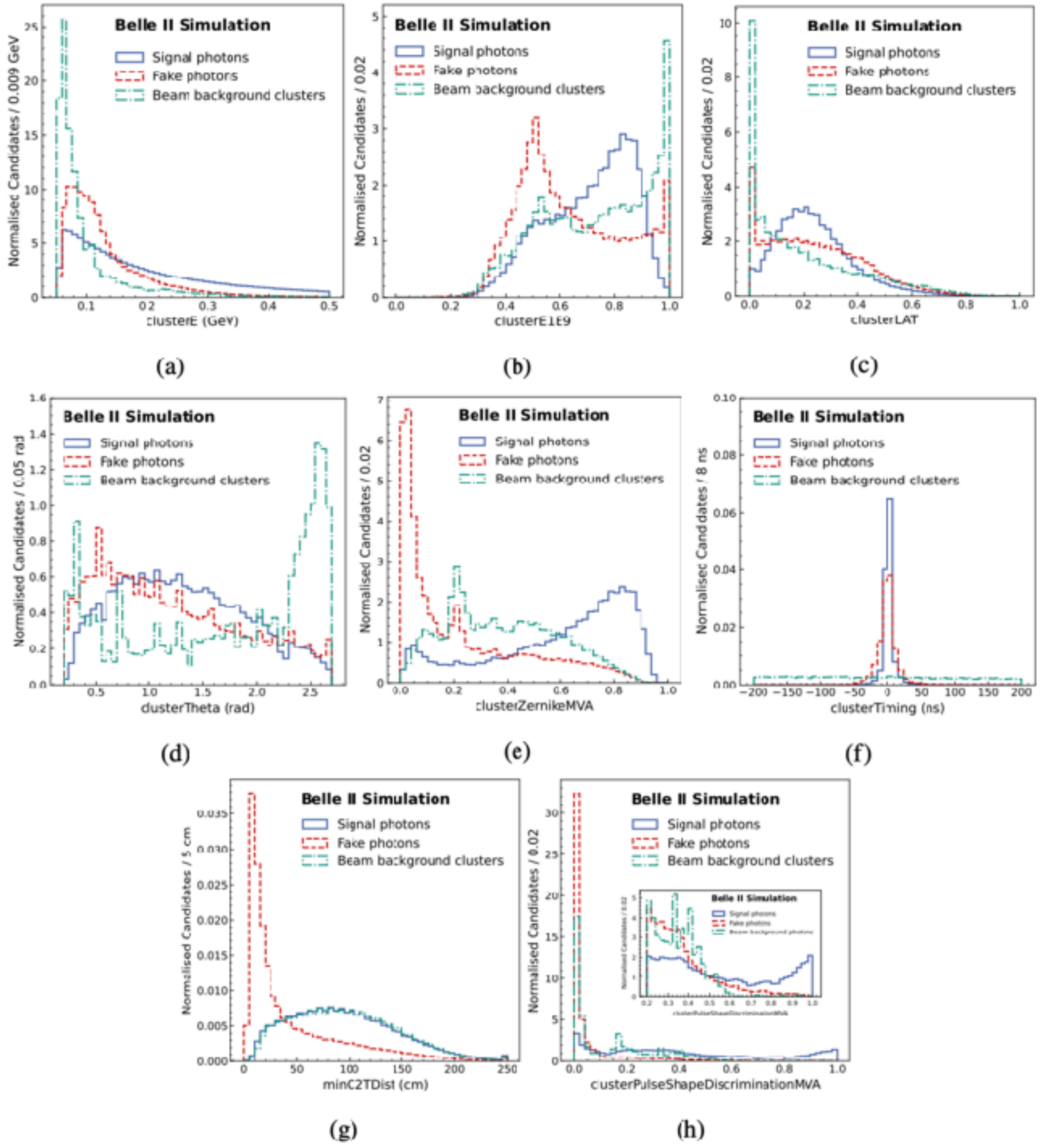


Figure 1. Distributions of the features for signal photons, fake photons and beam background clusters. All distributions are normalised to 1. An inset for *clusterPulseShapeDiscriminationMVA* is provided to show the distributions in the tail region [0.2, 1].

$$B^0 \to D^{*-}\ell^+\nu$$

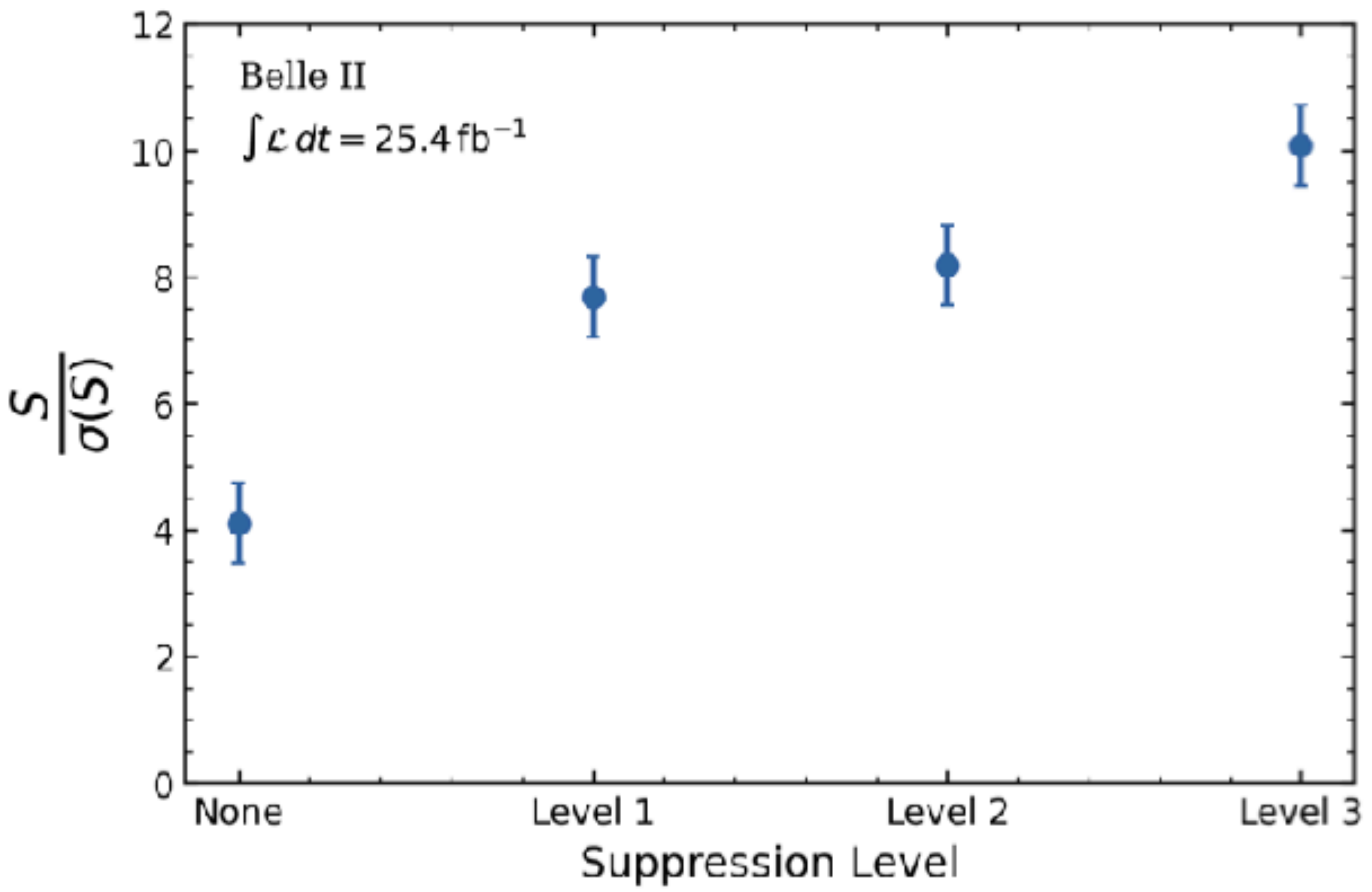
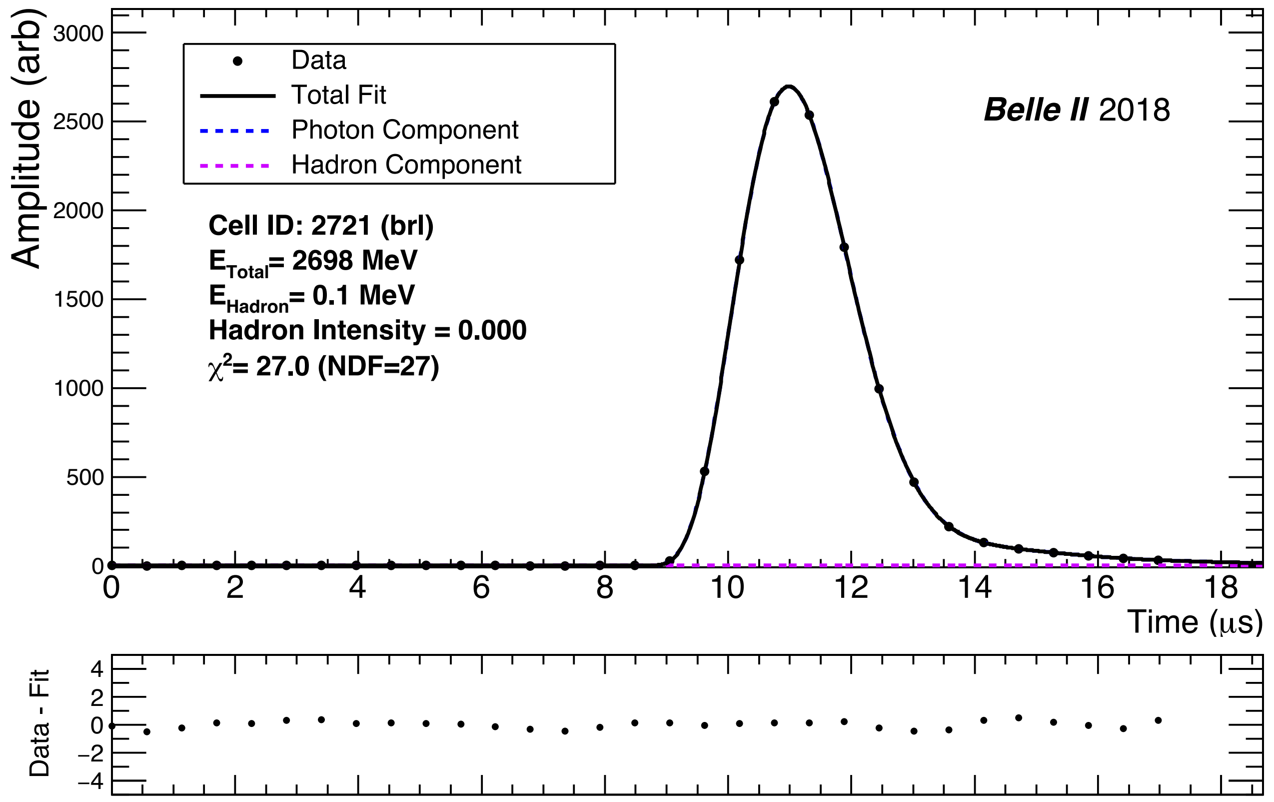


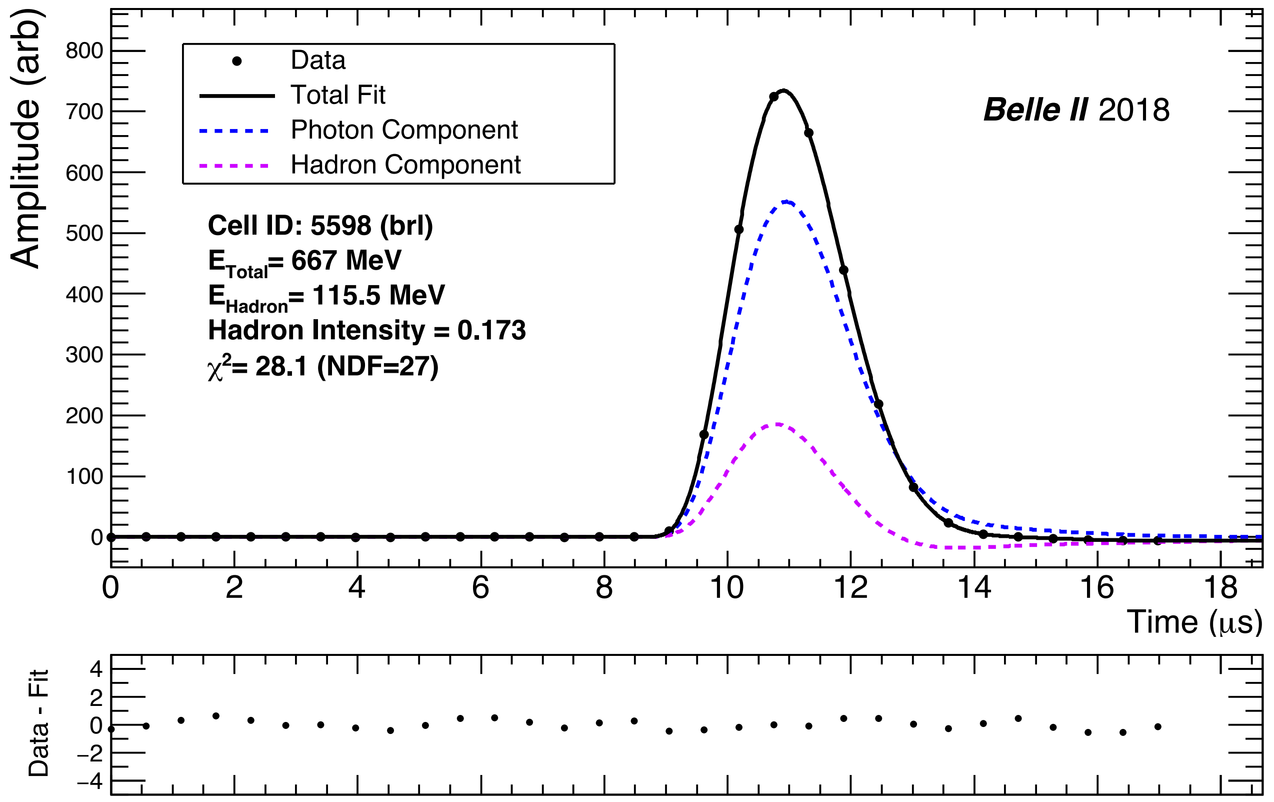
Figure 9. $S/\sigma(S)$ for 4 different suppression levels: no suppression applied and beam background classifier > 0.6 combined with either fake photon classifier > 0.3 (Level 1), fake photon classifier > 0.5 (Level 2), and fake photon classifier > 0.7 (Level 3)

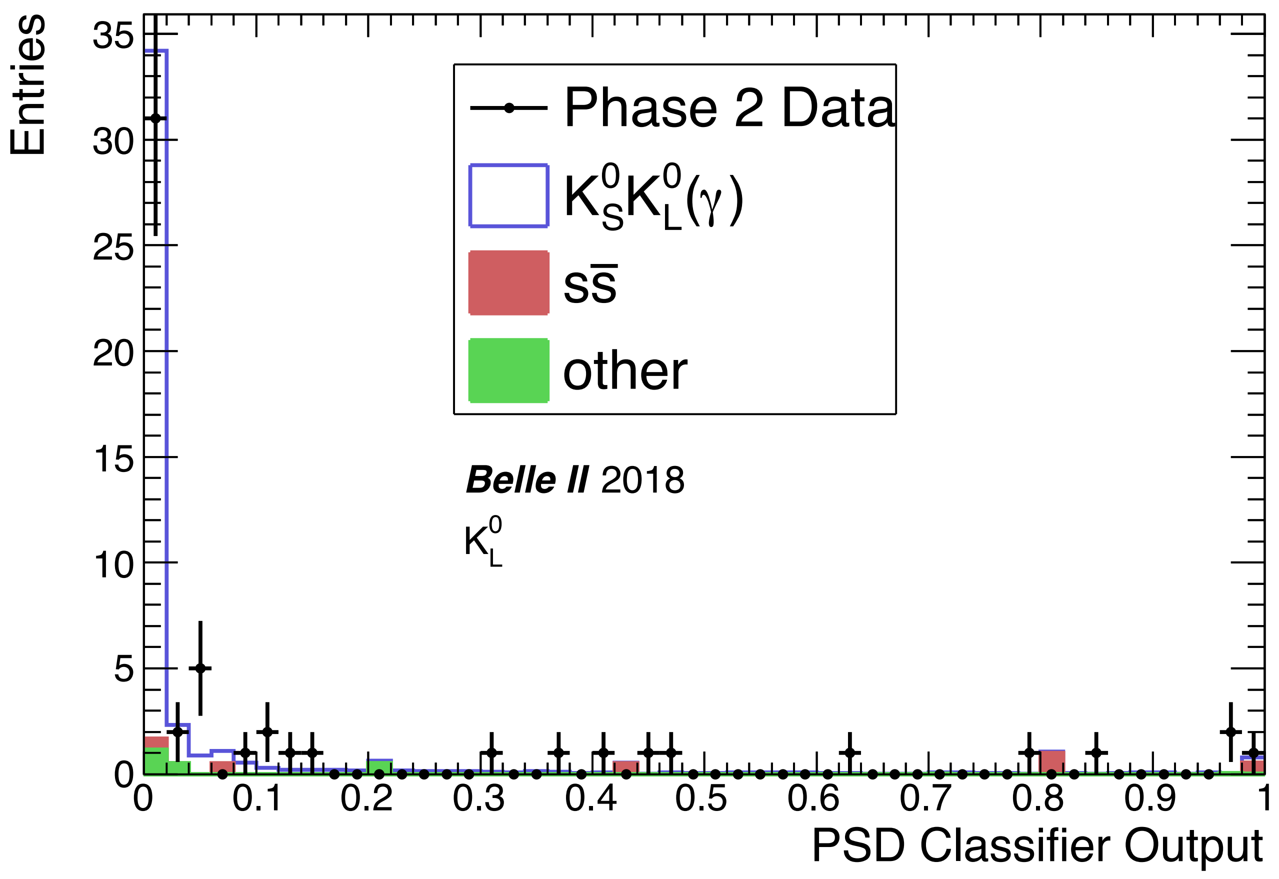
CsI(Tl) Pulse Shape Discrimination

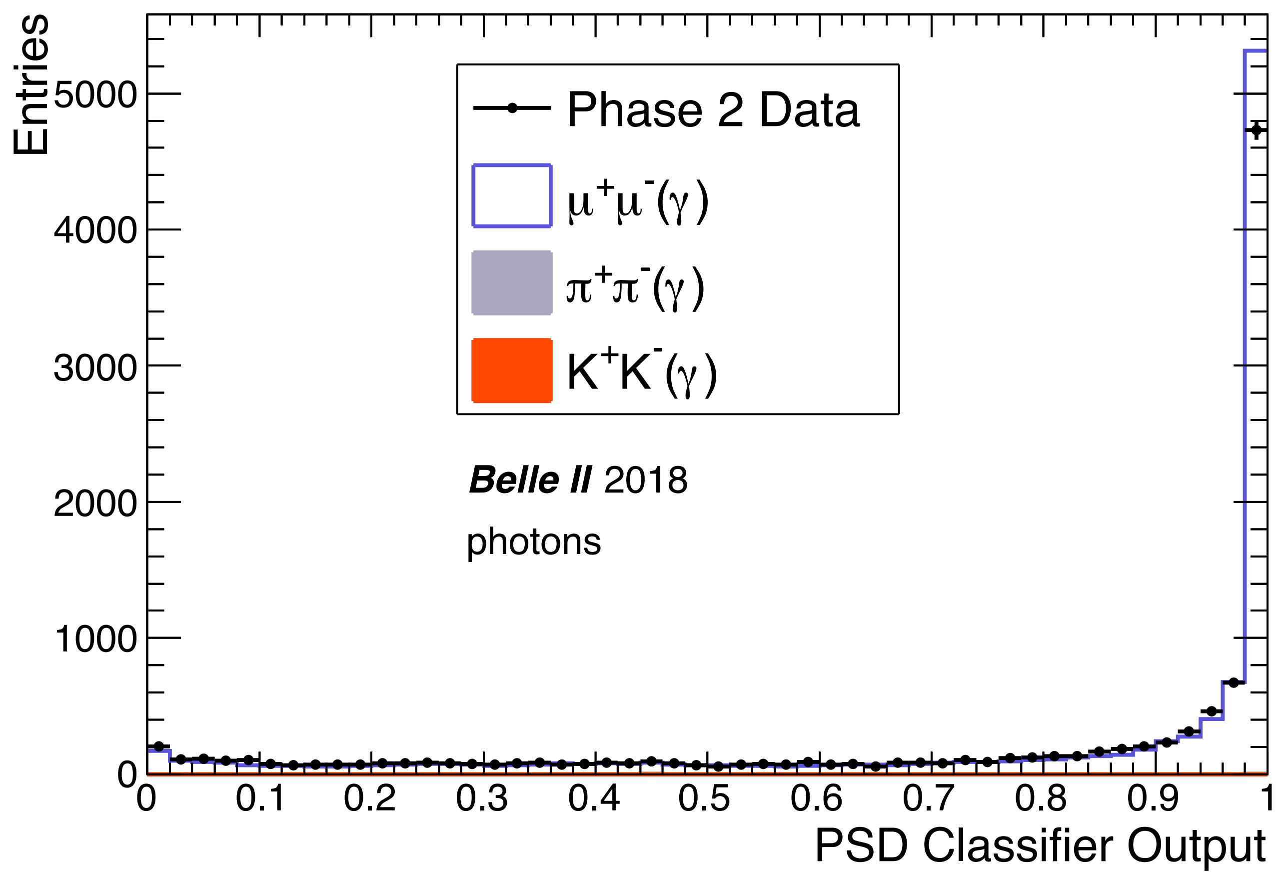
- Controlling KL yield may be crucial - a Belle II technique is PSD.

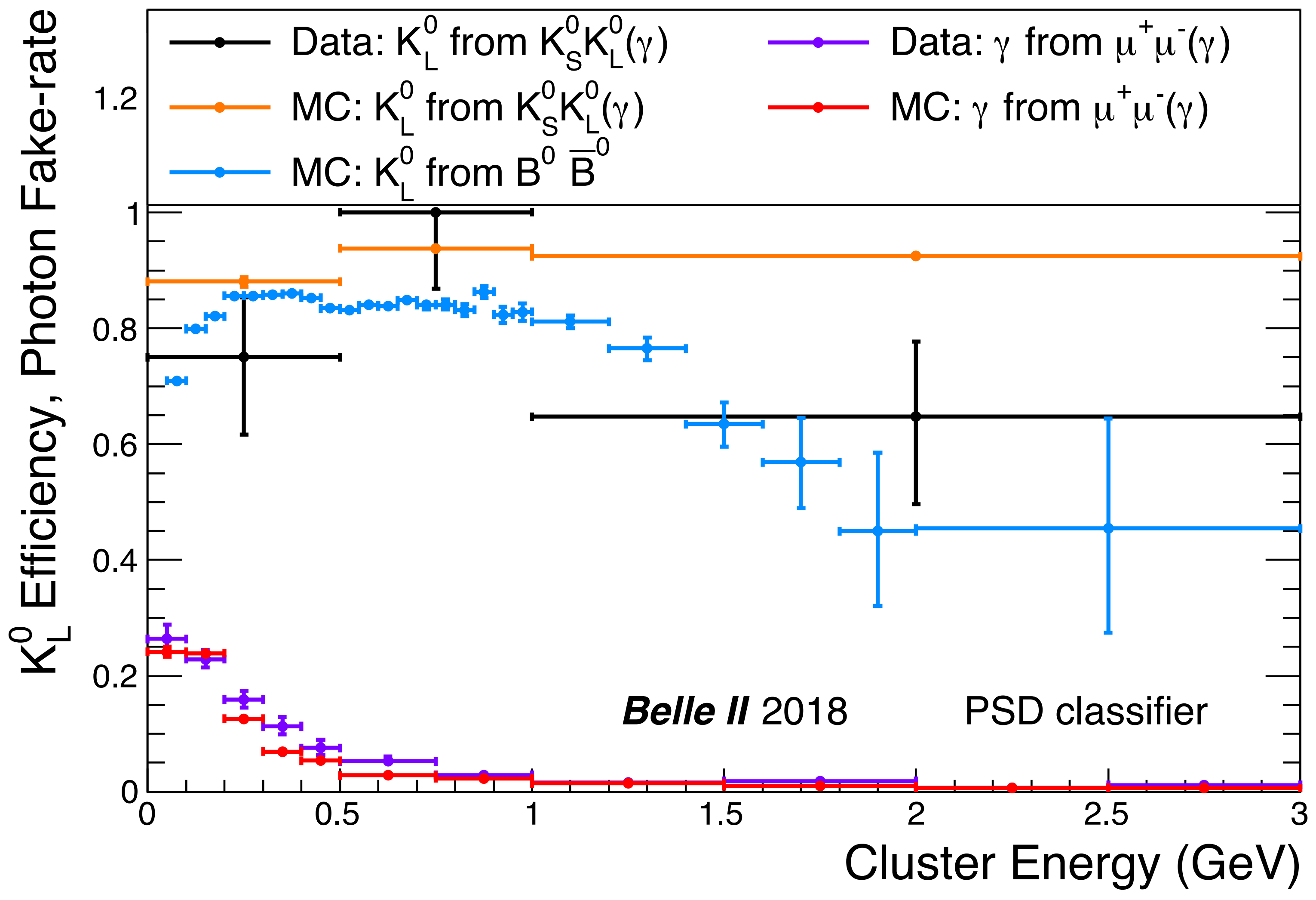
S. Longo (Belle II ECL Group) Nucl.Instrum.Meth.A 982 (2020) 164562











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$B \rightarrow h \nu \nu$

nature

PARTICLE PHYSICS

Hint of Crack in Standard Model Vanishes in LHC Data

A discrepancy in the measurement of a type of particle decay had raised hopes of new physics

By Davide Castelvecchi, Nature magazine on December 22, 2022 أعرض هذا باللغة العربية

Tagged analysis procedure (Belle)

- Begin with either a semileptonic or hadronic tag side.

- Reconstruct one light meson: K^+, K^0_S, K^{*+}, K^{*0}, π^+, π^0, ρ^+, ρ^0. Invariant mass window of K^* & ρ optimized via $N_S/\sqrt{N_S+N_B}$.
- No additional charged tracks or π^0 candidates left in the event.
- Veto events with reconstructed K_L candidates.
- Suppress $e^+e^- \to q\bar{q}$ background with a neural network using topological variables.

Extract the signal yield by fitting the Extra Energy in the Calorimeter:

Sum of energies of neutral clusters not associated with reconstructed particles

$$E_{ECL} = \sum E_{\text{Calor.}} - \left(\sum E_{\text{tag}} + \sum E_{\text{sig}}\right)$$

Train a NN to separate signal from background:

- Optimize a cut on the network output by maximizing a Punzi-FoM: $\varepsilon / \left(\frac{n_\sigma}{2} + \sqrt{B}\right)$

- In Belle SL tag analysis

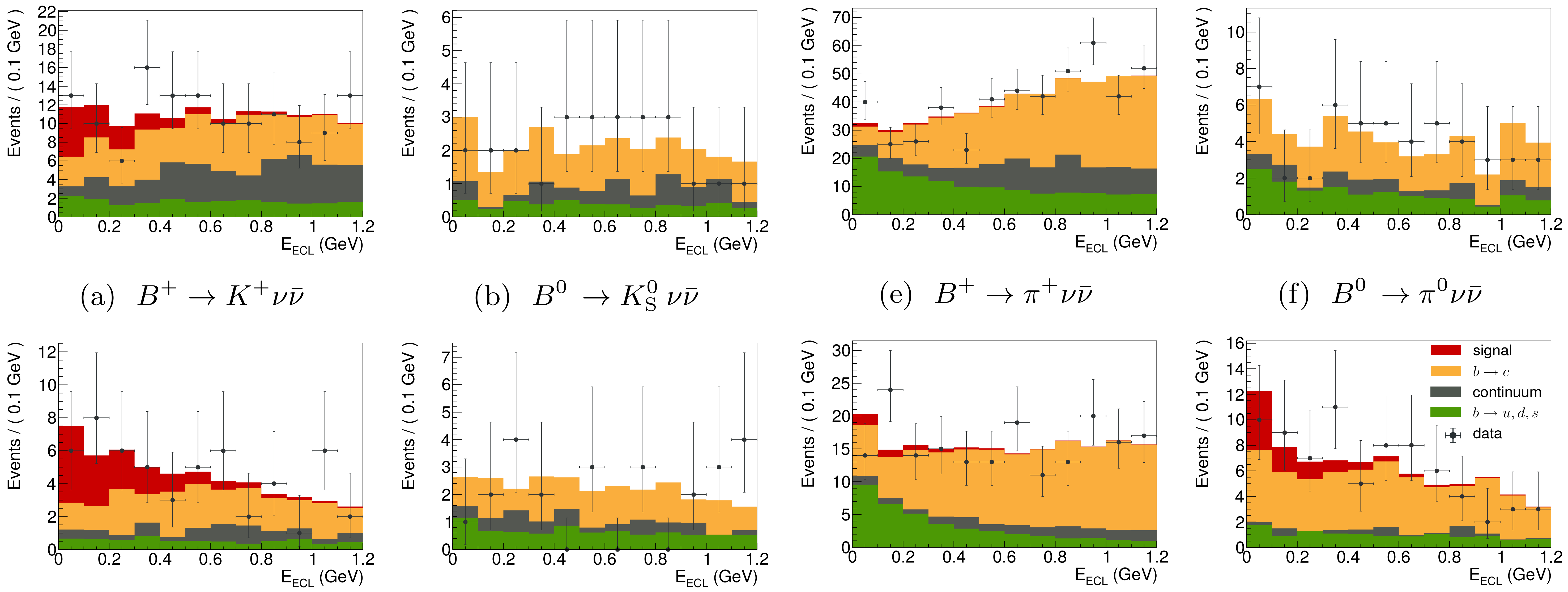
Charm B decay & $q\bar{q}$ background for $K^+\nu\bar{\nu}$ in $E_{ECL} \in (0, 1.2)$ GeV.

	contribution in %
continuum	22.6
2 leptons missing	15.3
K_Ls and lepton missing	6.5
lepton and hadrons missing	24.1
2 charged hadrons missing	1.7
wrong B type	3.8
hadronic, K_L missing	24.1
hadronic π^0 missing	1.0
no match	0.0
other	1.0

Belle SL tag analysis

Belle Collaboration•J. Grygier et al.
Phys.Rev.D 96 (2017) 9, 091101,
Phys.Rev.D 97 (2018) 9, 099902 (addendum)

- Histogram templates to model signal and bkgds from charm B decay, charmless B decay, and continuum.
- Relative fractions of the background components fixed to MC expectations.
- Signal and overall background yield allowed to vary.



(a) $B^+ \to K^+ \nu\bar{\nu}$ (b) $B^0 \to K^0_S \nu\bar{\nu}$ (e) $B^+ \to \pi^+ \nu\bar{\nu}$ (f) $B^0 \to \pi^0 \nu\bar{\nu}$

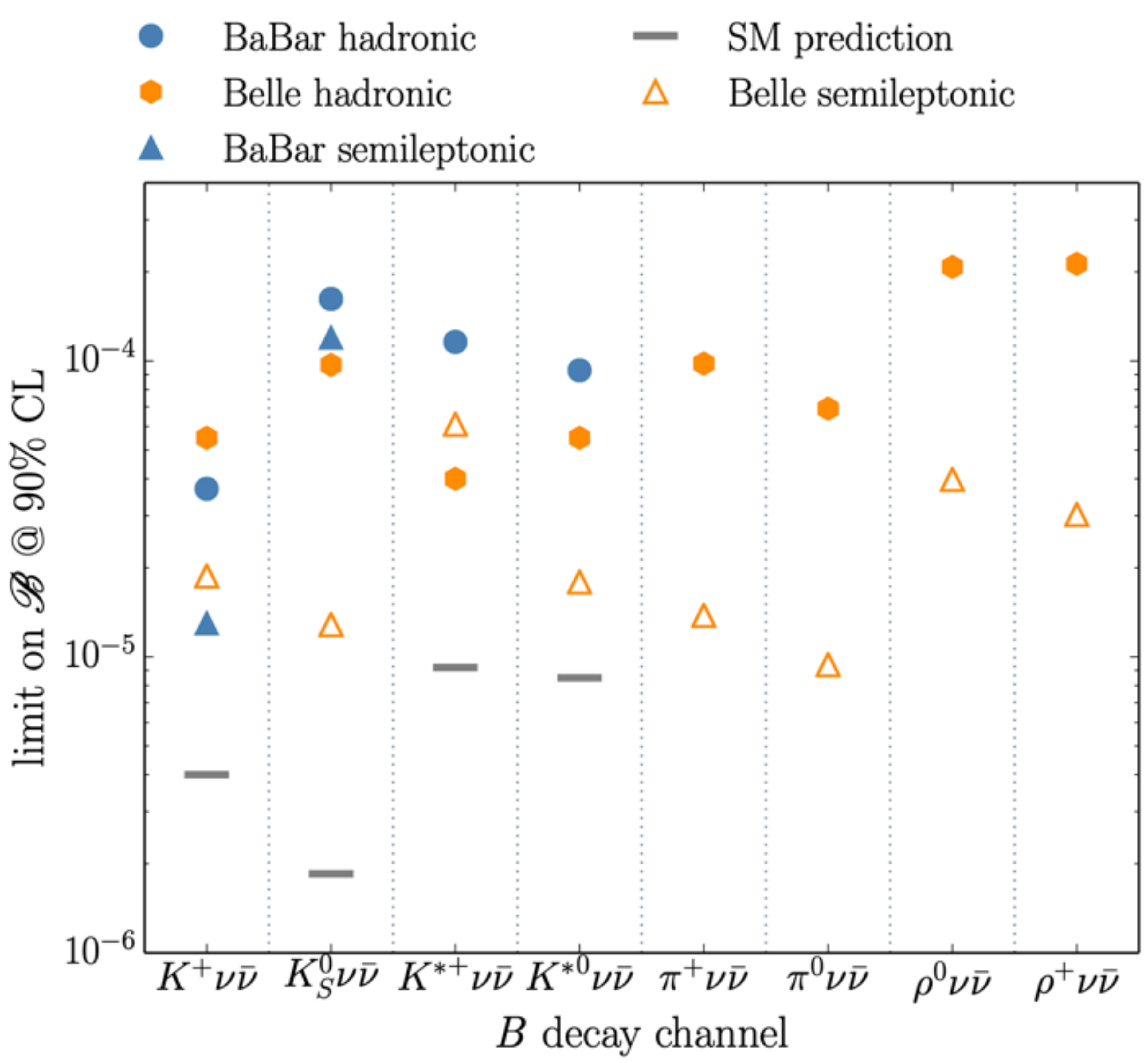
(c) $B^+ \to K^{*+} \nu\bar{\nu}$ (d) $B^0 \to K^{*0} \nu\bar{\nu}$ (g) $B^+ \to \rho^+ \nu\bar{\nu}$ (h) $B^0 \to \rho^0 \nu\bar{\nu}$

Channel	Observed signal yield	Significance
$K^+\nu\bar{\nu}$	$17.7 \pm 9.1 \pm 3.4$	$1.9\,\sigma$
$K^0_S\,\nu\bar{\nu}$	$0.6 \pm 4.2 \pm 1.4$	$0.0\,\sigma$
$K^{*+}\nu\bar{\nu}$	$16.2 \pm 7.4 \pm 1.8$	$2.3\,\sigma$
$K^{*0}\nu\bar{\nu}$	$-2.0 \pm 3.6 \pm 1.8$	$0.0\,\sigma$
$\pi^+\nu\bar{\nu}$	$5.6 \pm 15.1 \pm 5.9$	$0.0\,\sigma$
$\pi^0\nu\bar{\nu}$	$0.2 \pm 5.6 \pm 1.6$	$0.0\,\sigma$
$\rho^+\nu\bar{\nu}$	$6.2 \pm 12.3 \pm 2.4$	$0.3\,\sigma$
$\rho^0\nu\bar{\nu}$	$11.9 \pm 9.0 \pm 3.6$	$1.2\,\sigma$

Based on the values and theoretical uncertainties from Ref. [2], we also give a limit on the ratios between the measured branching fractions of $B \to K\nu\bar{\nu}$ and of $B \to K^*\nu\bar{\nu}$ and the respective SM prediction $\mathcal{R}_{K^*}$. We obtain values of $\mathcal{R}_K < 3.9$ and $\mathcal{R}_{K^*} < 2.7$, respectively, where we included the theoretical uncertainty. Both values are quoted at 90 % C.L.

Systematic uncertainties

	$K^+\nu\bar{\nu}$	$K^0_S\,\nu\bar{\nu}$	$K^{*+}\nu\bar{\nu}$	$K^{*0}\nu\bar{\nu}$	$\pi^+\nu\bar{\nu}$	$\pi^0\nu\bar{\nu}$	$\rho^+\nu\bar{\nu}$	$\rho^0\nu\bar{\nu}$
K^0_L veto	0.2	0.2	0.1	0.2	0.6	0.4	0.6	0.0
Fixed fractions	0.4	0.3	0.1	0.2	1.3	0.1	0.1	1.0
Continuum scaling	2.0	0.0	0.0	0.0	3.1	0.0	0.0	0.0
Tag efficiency correction	0.5	0.2	0.1	0.1	1.9	0.1	0.2	0.5
Shape uncertainty	2.6	1.3	1.8	1.7	4.5	1.5	2.3	3.4
Fit bias	0.2	0.1	0.2	0.1	0.2	0.1	0.2	0.2
Total	3.4	1.4	1.8	1.8	5.9	1.6	2.4	3.6



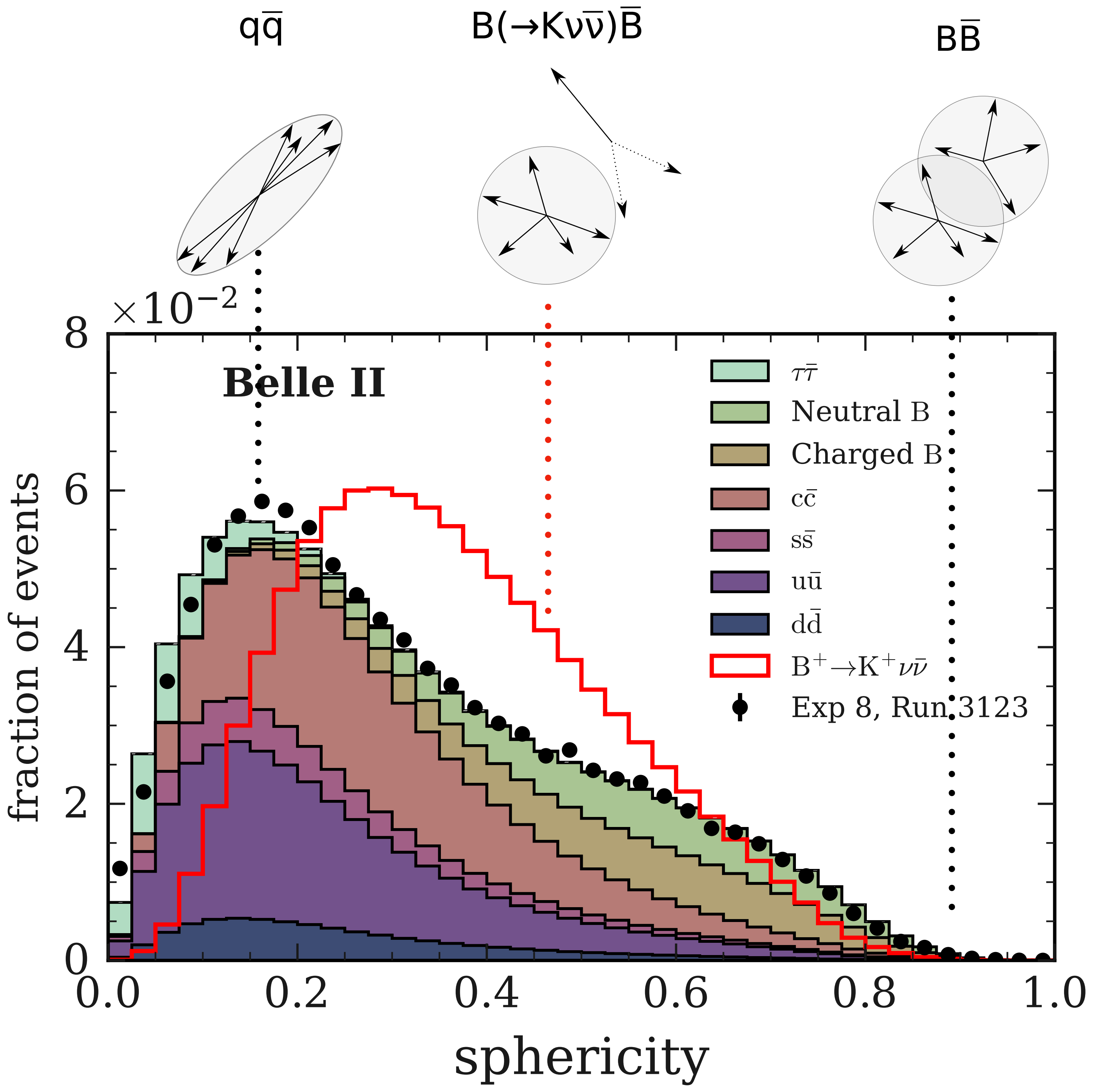
- Uncertainties related to the signal yield (table [absolute]) are estimated by refitting the data with each quantity varied by $\pm 1\sigma$, with the exception of the shape uncertainty which is evaluated from Toy MC studies.

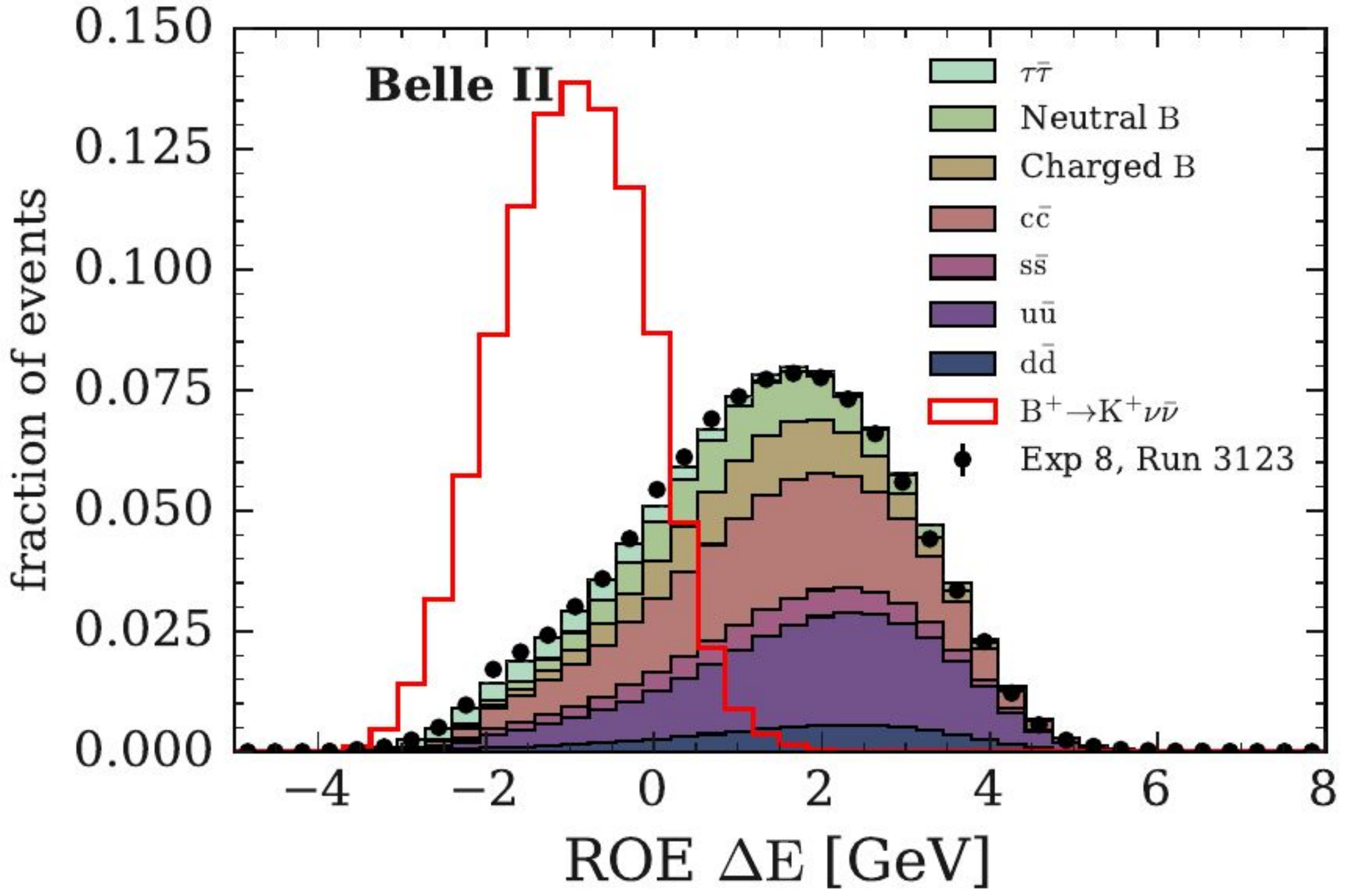
- Remaining uncertainties include: π^0 and charged track veto (4%); raw track requirement (1%); particle ID efficiency (2%) π^0 efficiency (4%), K^0_S efficiency (2.2%) $N_{B\bar{B}}$ (1.4%).

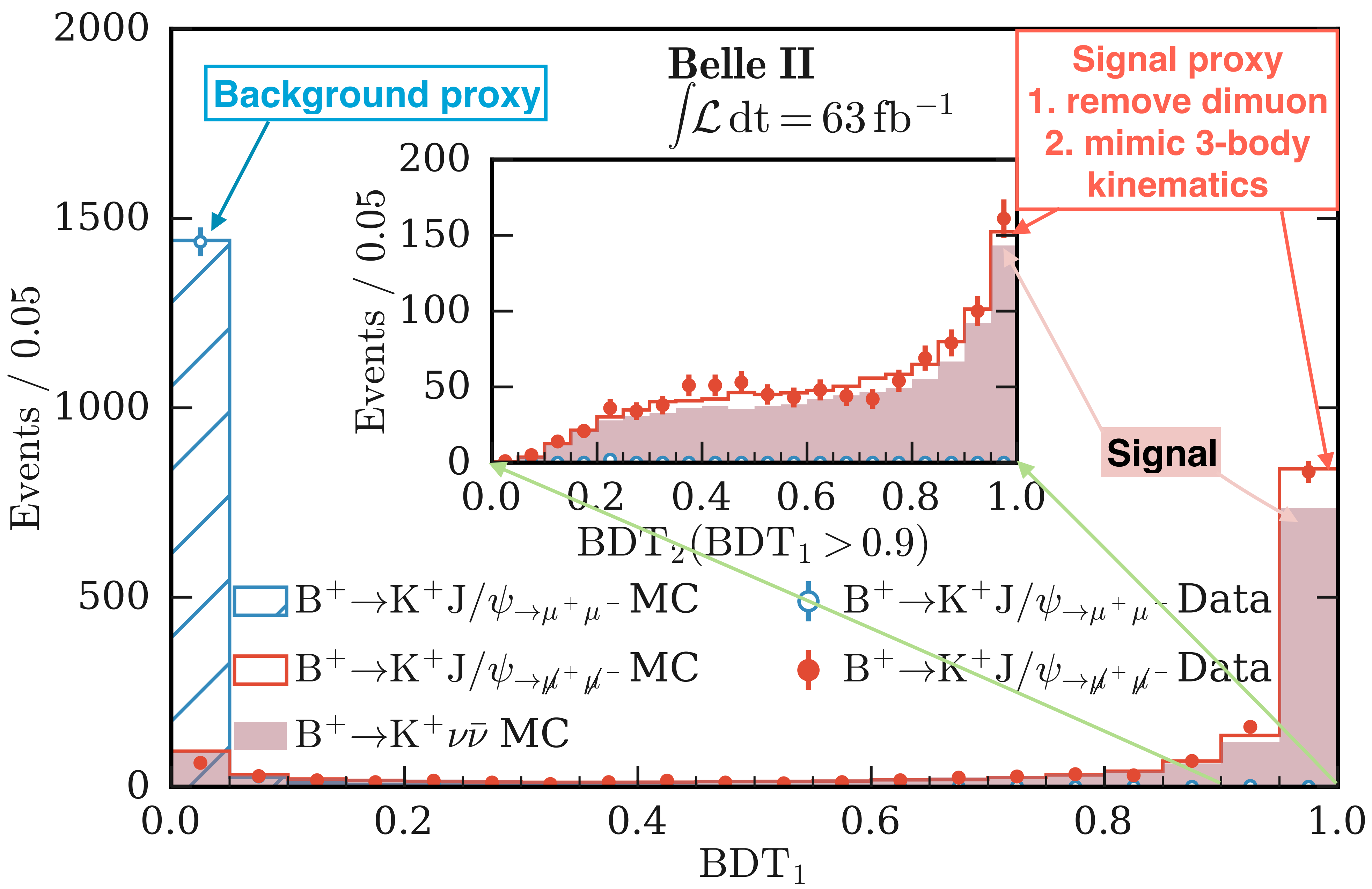
Untagged analysis (Belle II)

Strategy

1. Reconstruct signal: highest-p_T track in the event with at least 1 PXD hit
2. Reconstruct remaining tracks and clusters in the event
3. Minimise the background contamination with two nested BDTs using 51 variables: event topology, missing energy, vertex separation, signal kinematics)
4. **Validation with control channel $B^+ \to J/\psi(\to \mu^+\mu^-)K^+$**



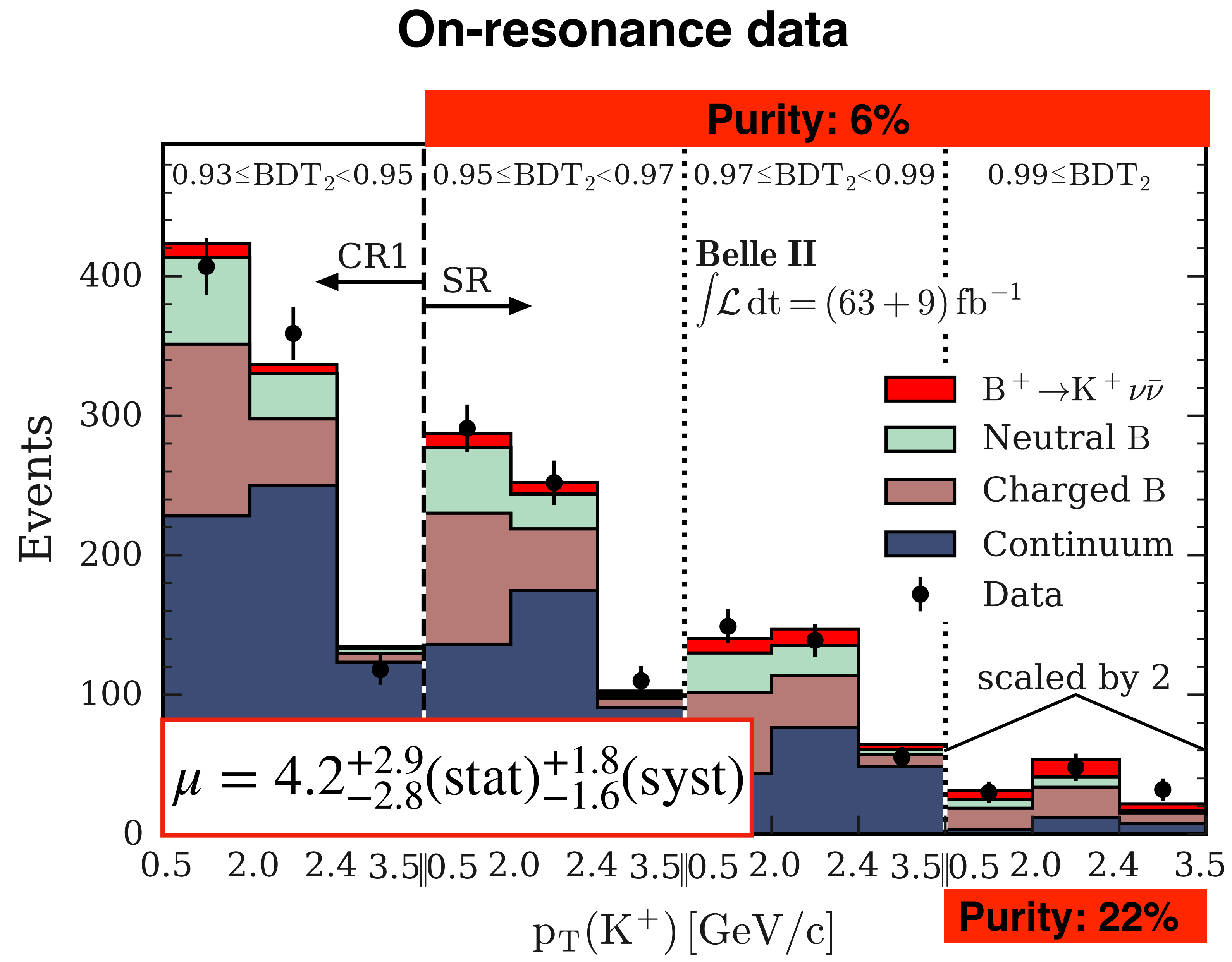


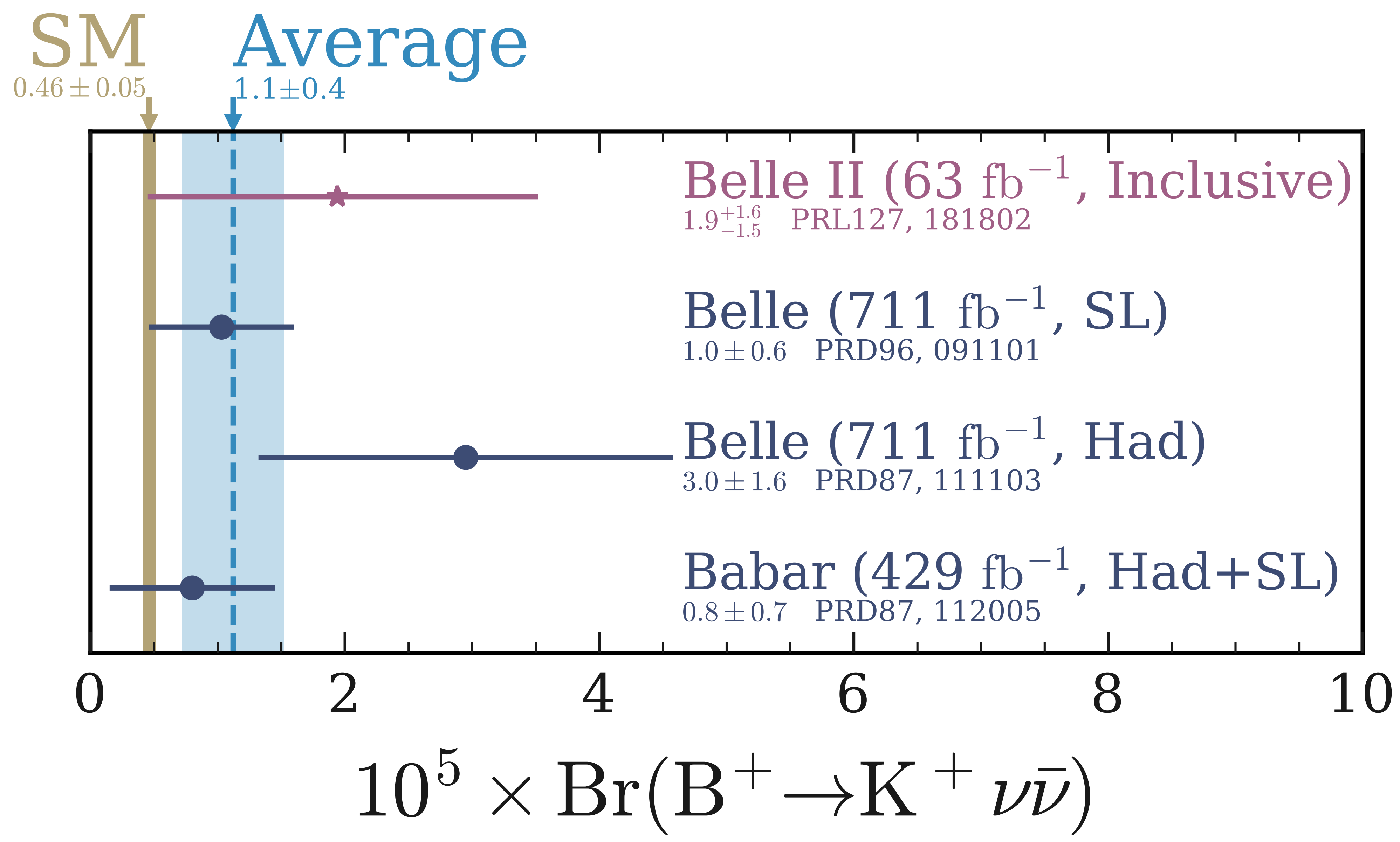


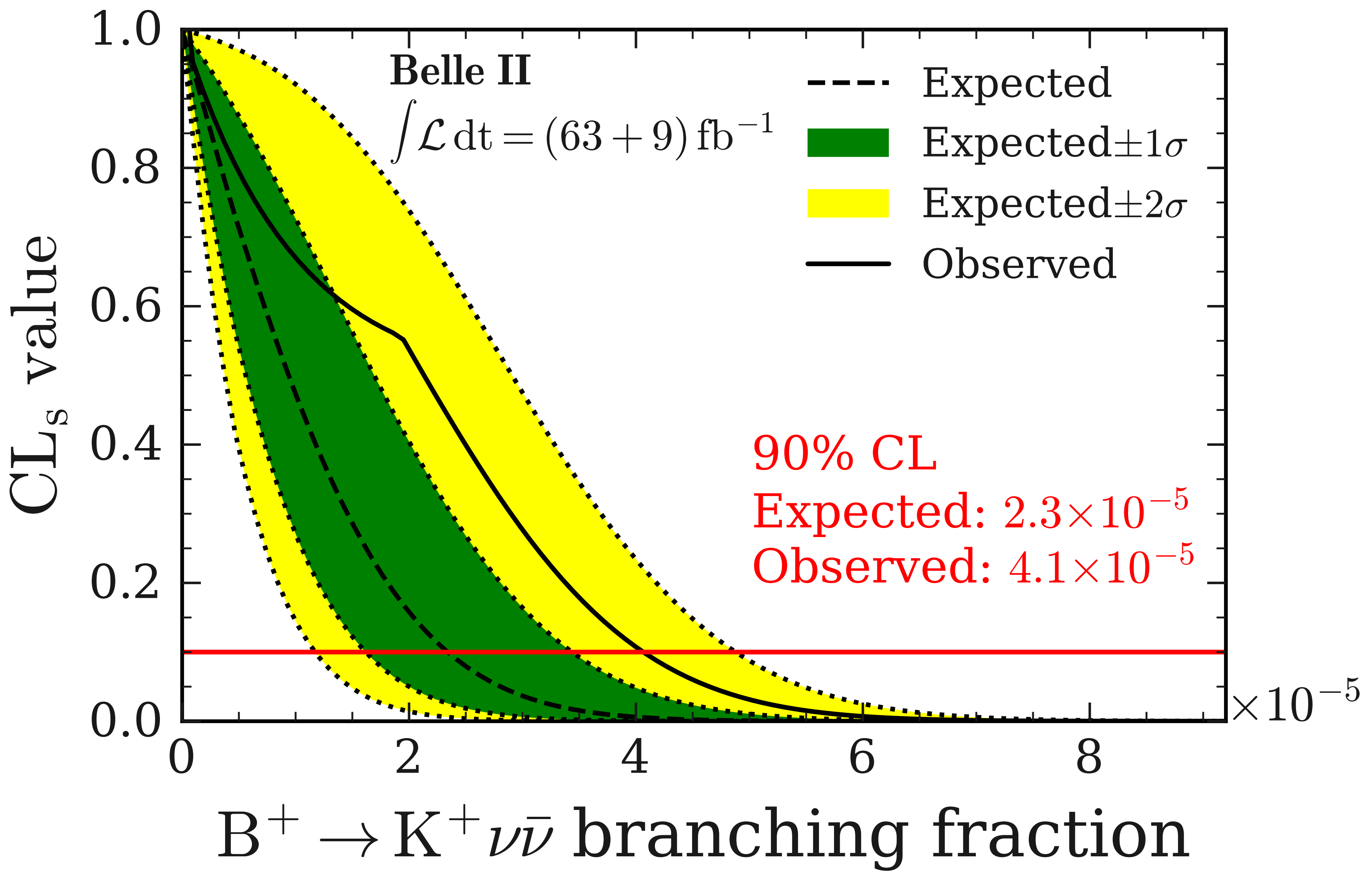
Search for B→K+ νν

Results

- Binned simultaneous ML fit to $p_T(K^+) \times \mathrm{BDT}_2$ to extract signal strength μ (1μ = SM $\mathscr{B} = 4.6 \times 10^{-6}$)
- No significant signal is observed, limit of 4.1×10^{-5} @ 90 C.L. → competitive with *only* 63 fb-1
- Inclusive tag approach shows the best performance

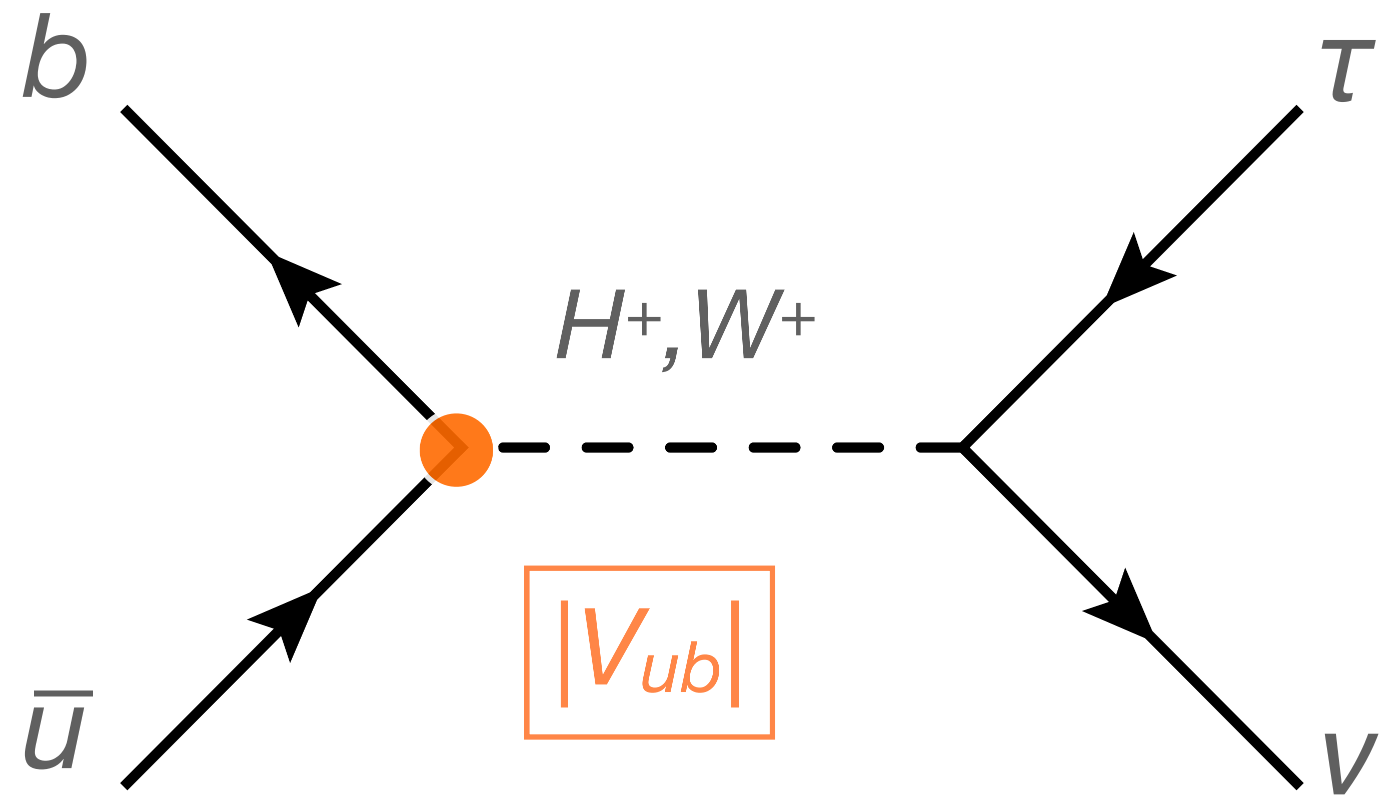






BSM $B^+ \to K^+\nu\bar{\nu}$ already with 1 ab-1

B→τυ, μυ: H⁺ searches



Helicity suppressed - very small in SM.
NP could interfere *e.g.* **charged Higgs.**

BR$_{SM}$ ~ 1 x 10^{-4} (τ), ~ 5 x 10^{-7} (μ)

$$\mathrm{BR}(B_u \to \tau\nu_\tau) = \frac{G_F^2 f_B^2 |V_{ub}|^2}{8\pi}\tau_B m_B m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \left[1 - \left(\frac{m_B^2}{m_{H^+}^2}\right)\lambda_{bb}\lambda_{\tau\tau}\right]^2$$

BF$_{SM}$

r$_H$

Type	λ_{DD}	λ_{LL}
I	$\cot\beta$	$\cot\beta$
II	$-\tan\beta$	$-\tan\beta$
III	$-\tan\beta$	$\cot\beta$
IV	$\cot\beta$	$-\tan\beta$

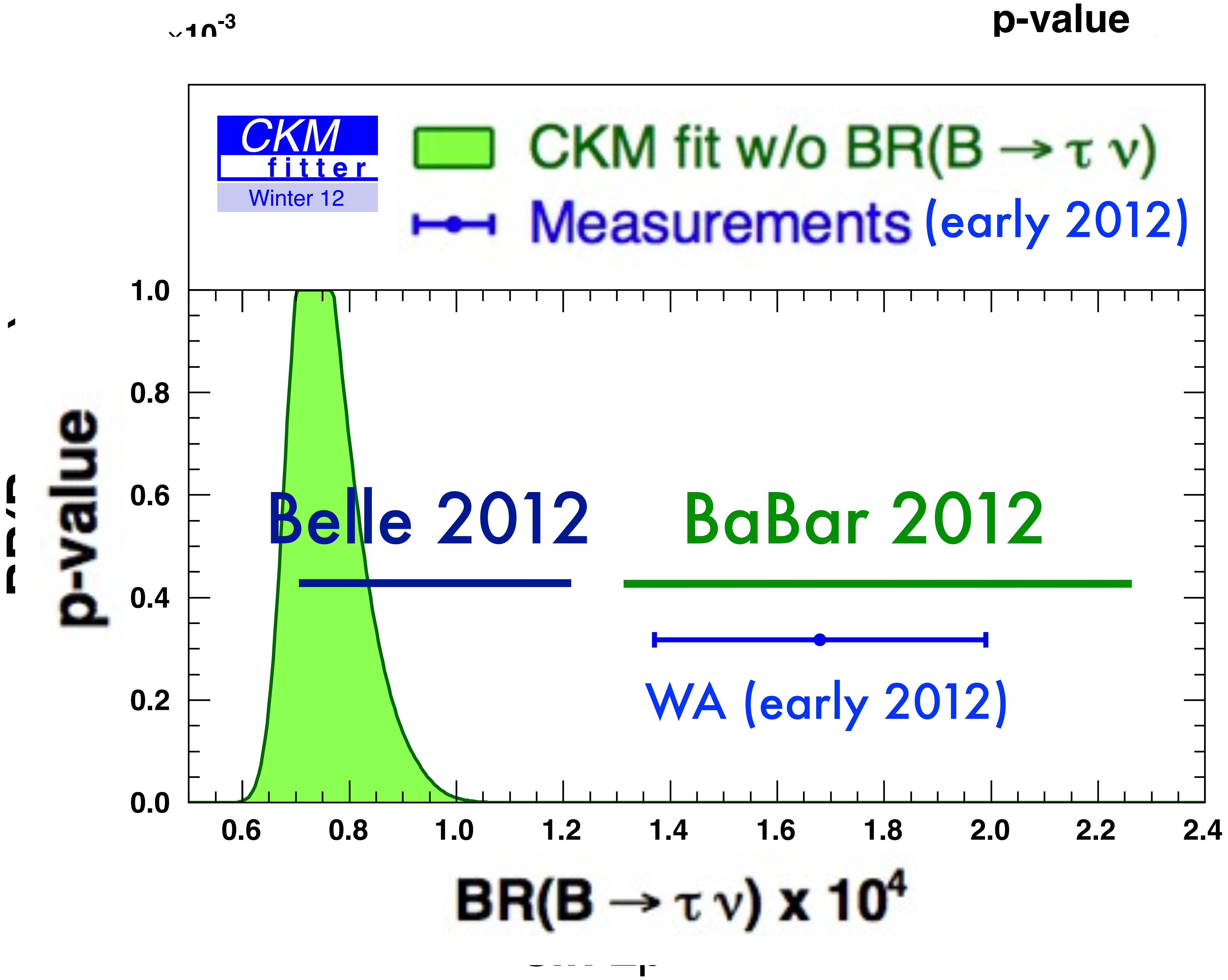
The B meson decay constant

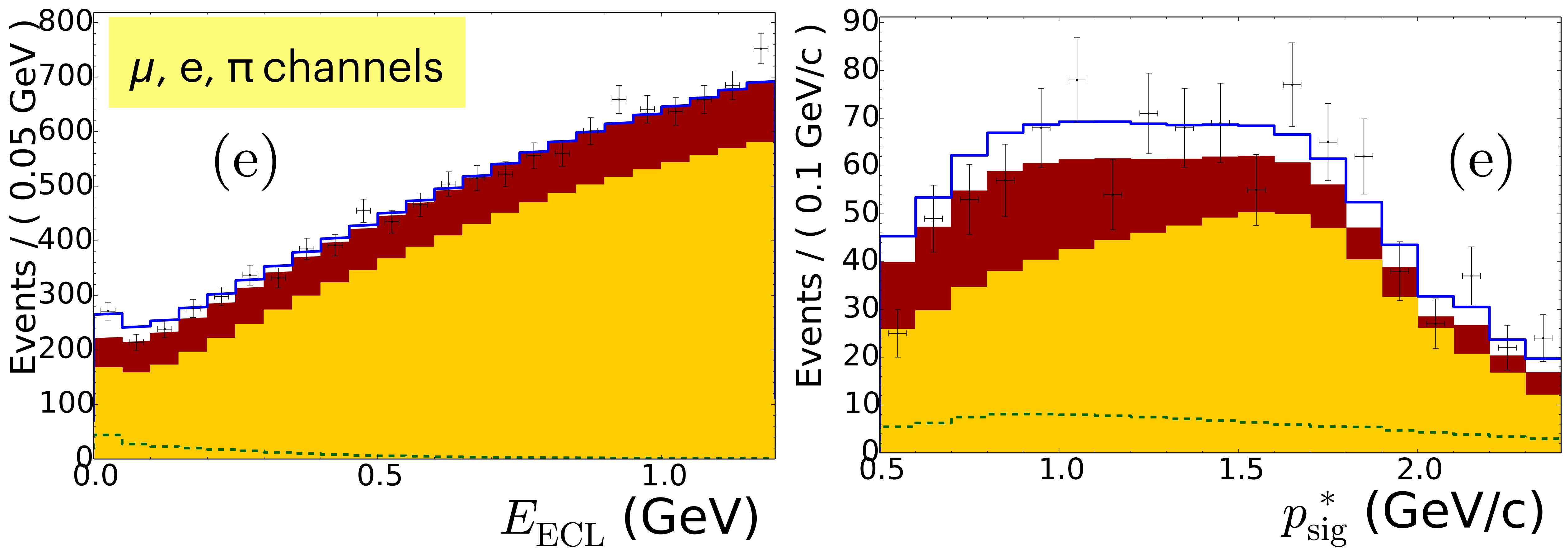
|V$_{ub}$| : from indep. measurements.

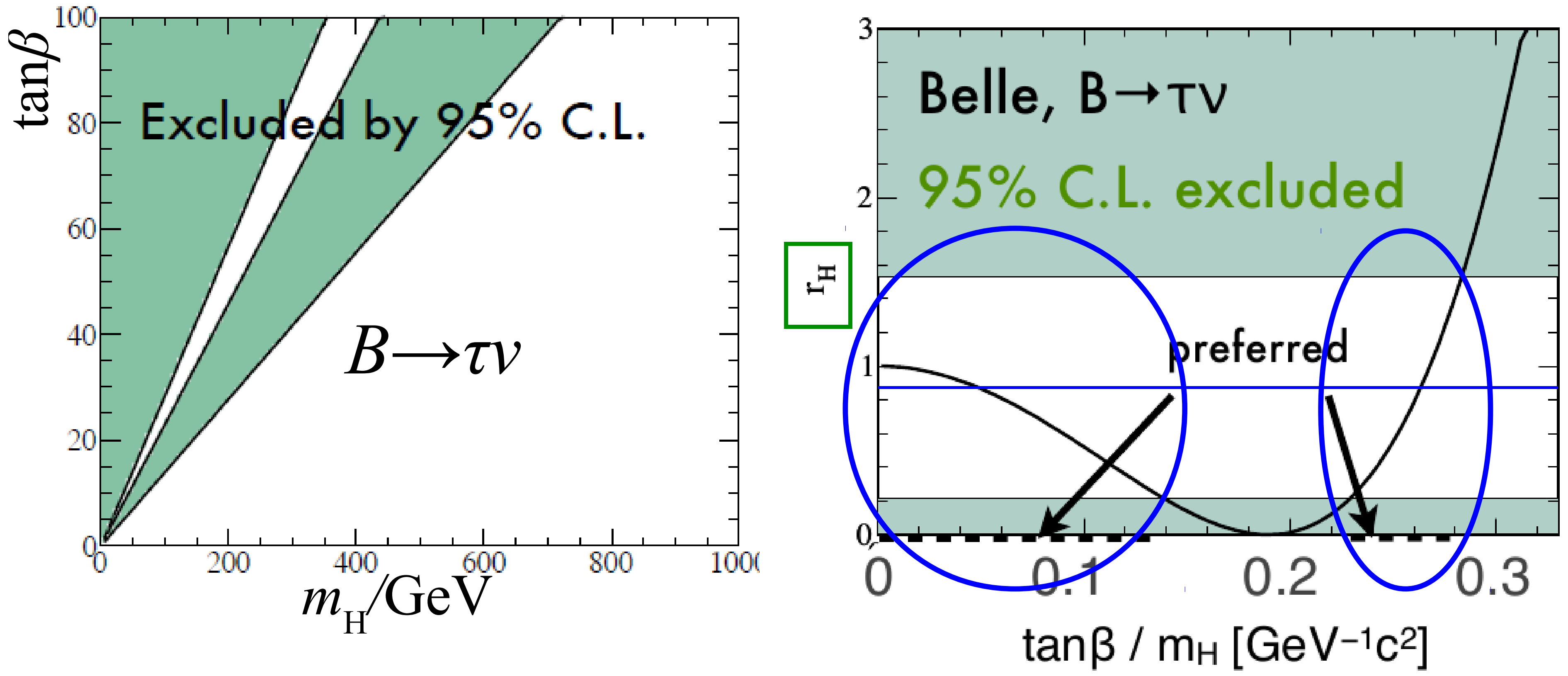
B→τυ, μυ: H⁺ searches

B. Kronenbitter, PU et al. (Belle) PRD 92, 5, 051102 (2015)

I. Adachi, PU et al. (Belle) PRL 110, 13, 131801 (2013)







No "Discovery" in a single measurement yet

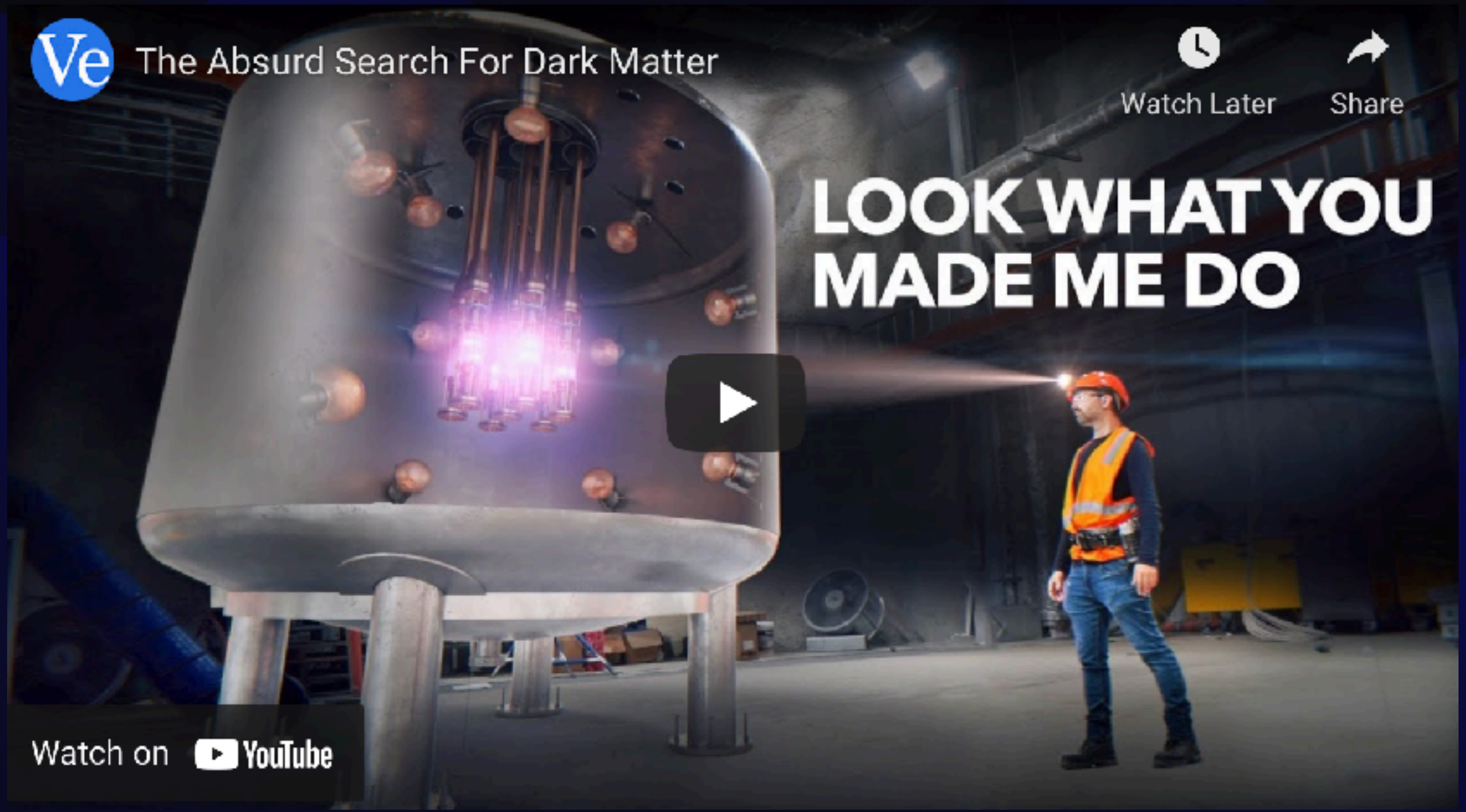
30% → <5% Precision on B→ τ ν at Belle II

<10% Precision on B→ μ ν & e ν γ

A. Sibidanov, et al. (Belle) PRL 121, 3, 031801 (2018)

A. Heller, et al. (Belle) PRD 91, 11, 112009 (2015)

Observables	Belle	Belle II	
		$5\ \text{ab}^{-1}$	$50\ \text{ab}^{-1}$
$\mathcal{B}(B \to \tau\nu)\ [10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)\ [10^{-6}]$	< 1.7	20%	7%

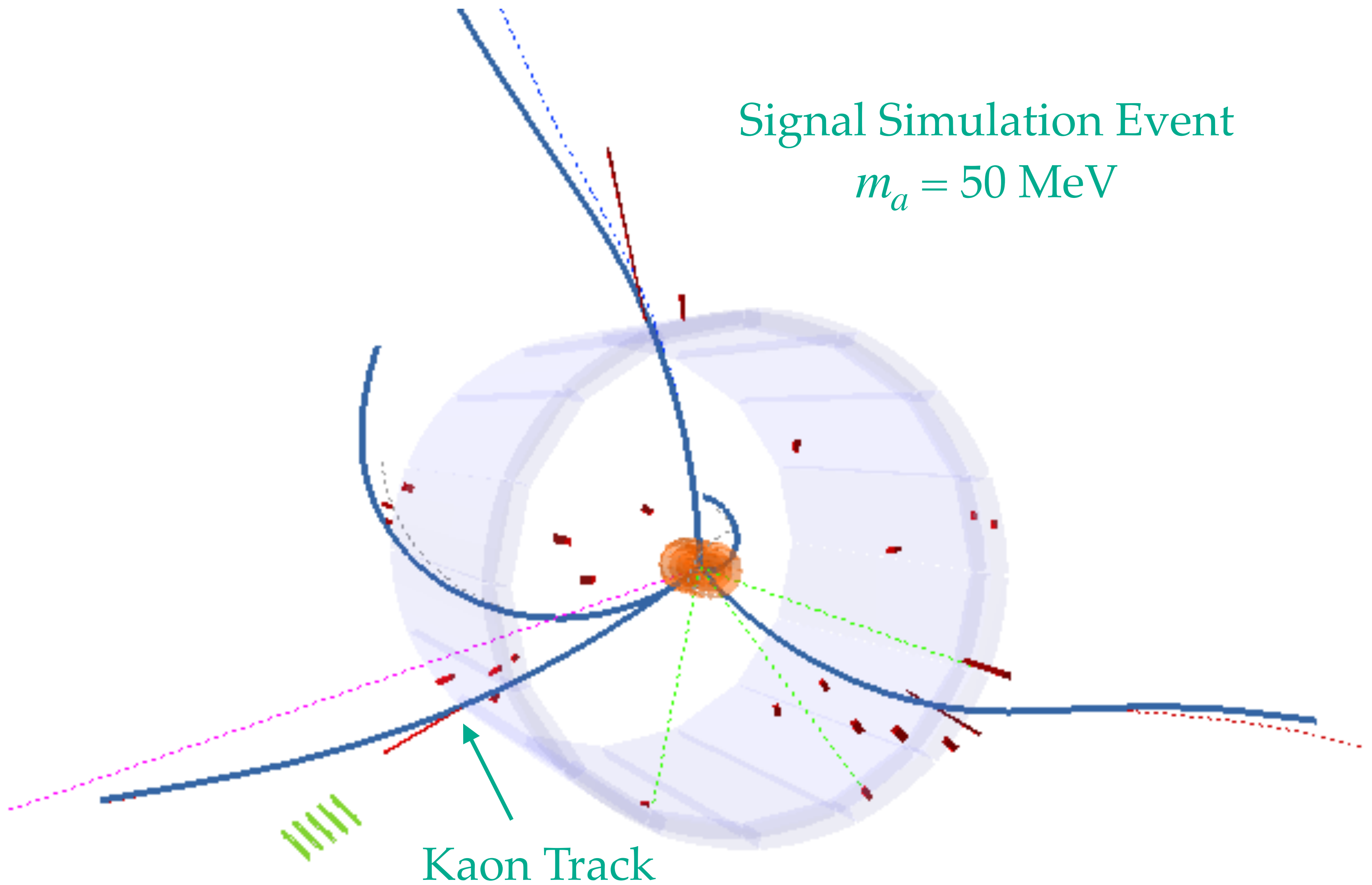


Feeble interactions

ALP search

BSM scenarios of $B^+ \to K^+\nu\bar{\nu}$: **new mediators (a)**

- **a** (= dark scalar or **ALP**) decaying invisibly → very similar to the search for $B^+ \to K^+\nu\bar{\nu}$
- **main experimental difference: two-body vs three-body kinematics**



ALP model from [arxiv: 2201.06580]

$$\mathcal{B}(B^+ \to K^+ a) = 0.25\left(c_{ff}(\Lambda) + 0.0032\, c_{WW}(\Lambda)\right)^2 \frac{f_0^2(m_a^2)}{f_0^2(0)} \frac{\lambda^{1/2}(m_B^2, m_K^2, m_a^2)}{m_B^2 - m_K^2}.$$

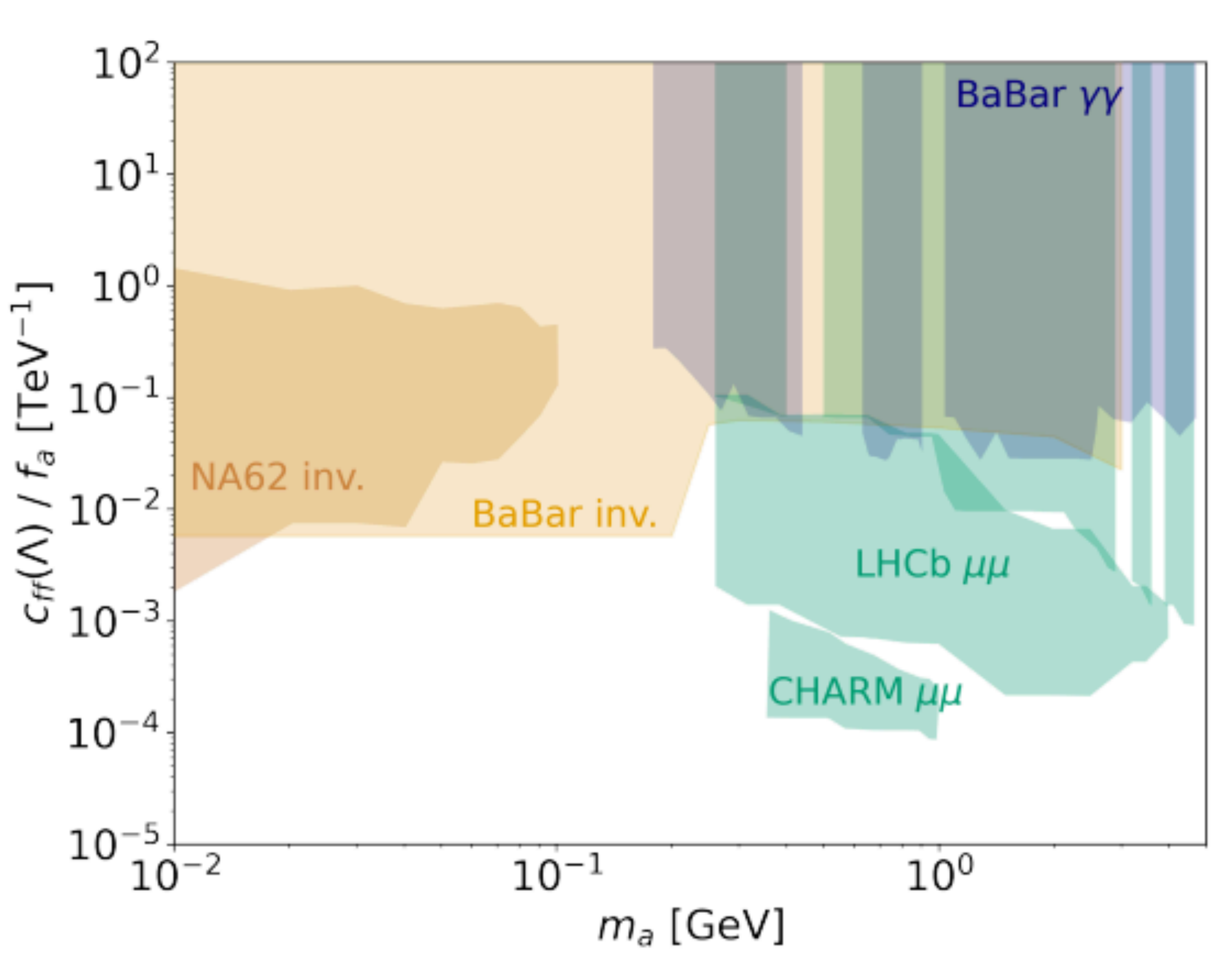
"c_{ff}" : ALP coupling to fermions

"c_{WW}" : ALP coupling to gauge bosons

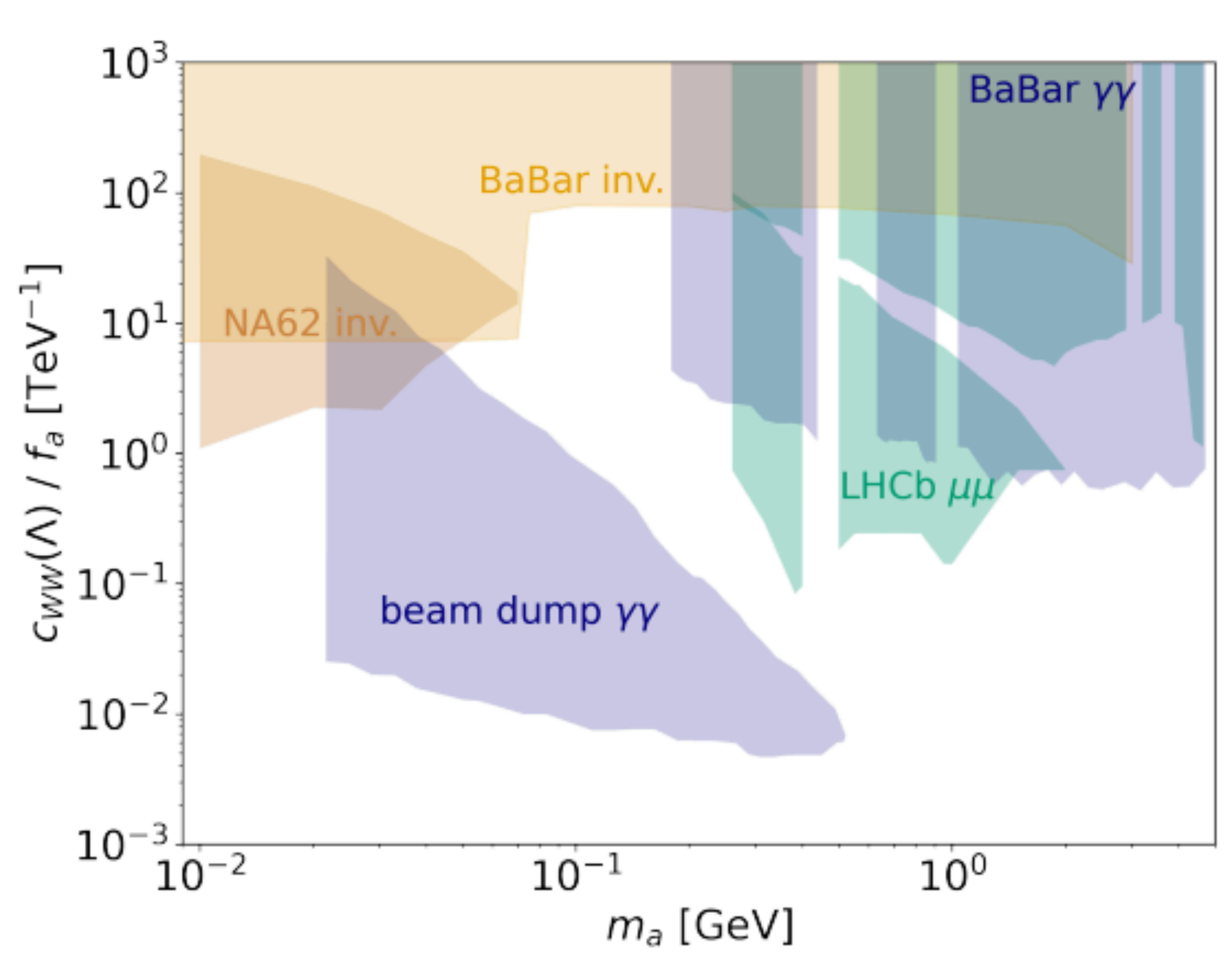
$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$

f_0 = scalar FF

Current bounds:



$c_{ff}(\Lambda)/f_a \lesssim (10^{-3} - 10^{-2})$ TeV^{-1}



$c_{WW}(\Lambda)/f_a \lesssim (10^{-2} - 1)$ TeV^{-1}

B→h a′, a′→ invisible Overview

D. Marcantonio, PU

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DRAFT Version 3.0
March 21, 2023

- Invisible final state inferred can be inferred from momentum of recoiling hadron h in B meson rest frame:

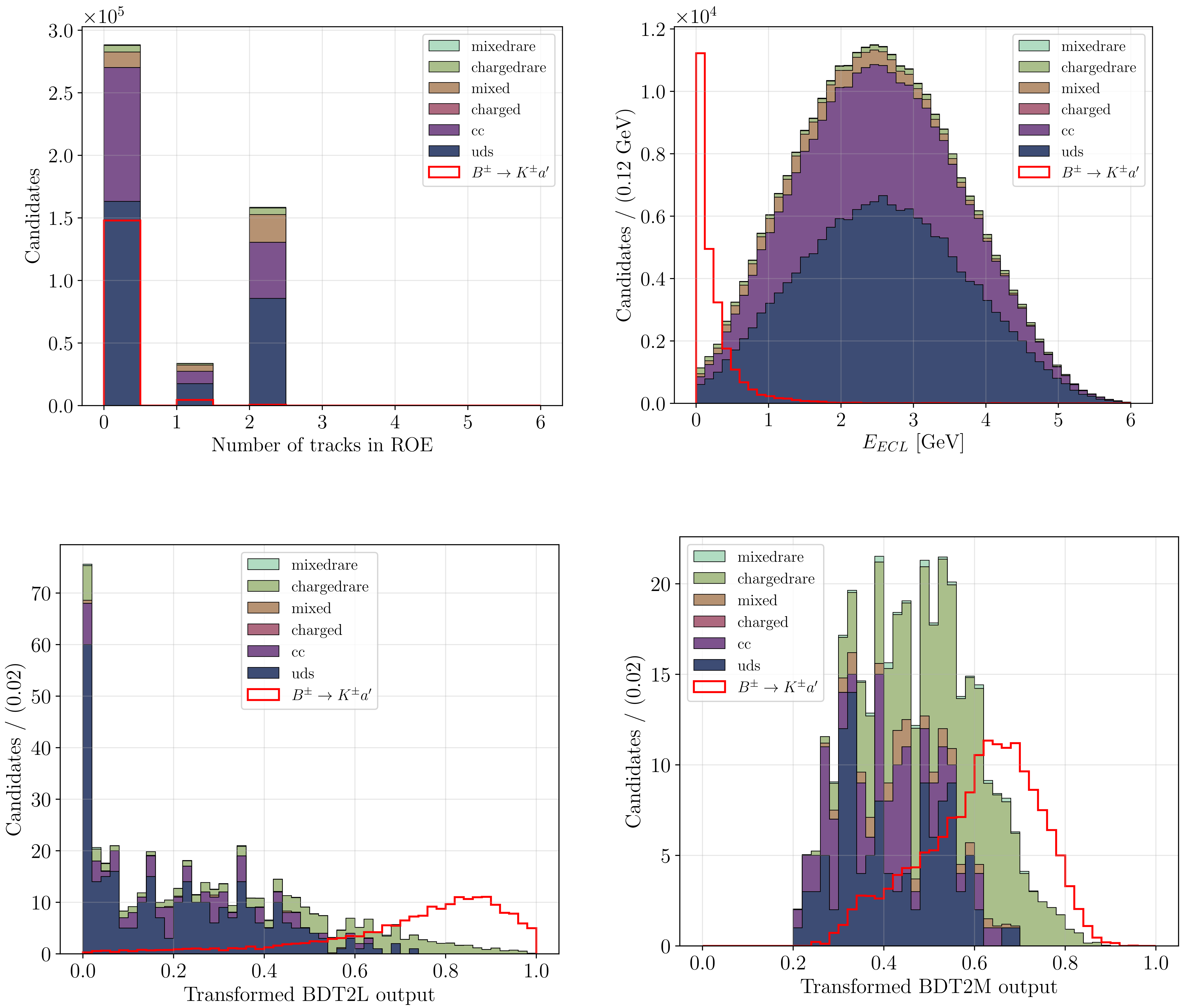
$$\left|p_h^{B_{sig}}\right| = \frac{[(M_B^2 - (m_h + m_{a'})^2(M_B^2 - (m_h - m_{a'})^2]^{\frac{1}{2}}}{2M_B}$$

- Signal-side B meson 4-vector inferred by reconstructing the other B meson in the event with the Full Event Interpretation (FEI) algorithm and the beam energy

Background type	Suppression method
$e^+e^- \to q\bar{q}$	Boosted Decision Tree (BDT) trained on $q\bar{q}$ vs. BB MC. Event shape variables used to train BDT (KSFW moments, CLEO cones, and thrust variables), as well as B_{tag} ΔE and flight distance.
Incorrectly reconstructed events	• B_{tag} beam-constrained mass • FEI probability • ROE ECL energy • No. of tracks in ROE
B decays similar to signal	Boosted Decision Tree trained on SM $B\overline{B}$ vs. Signal MC. Same variables used as the first BDT.

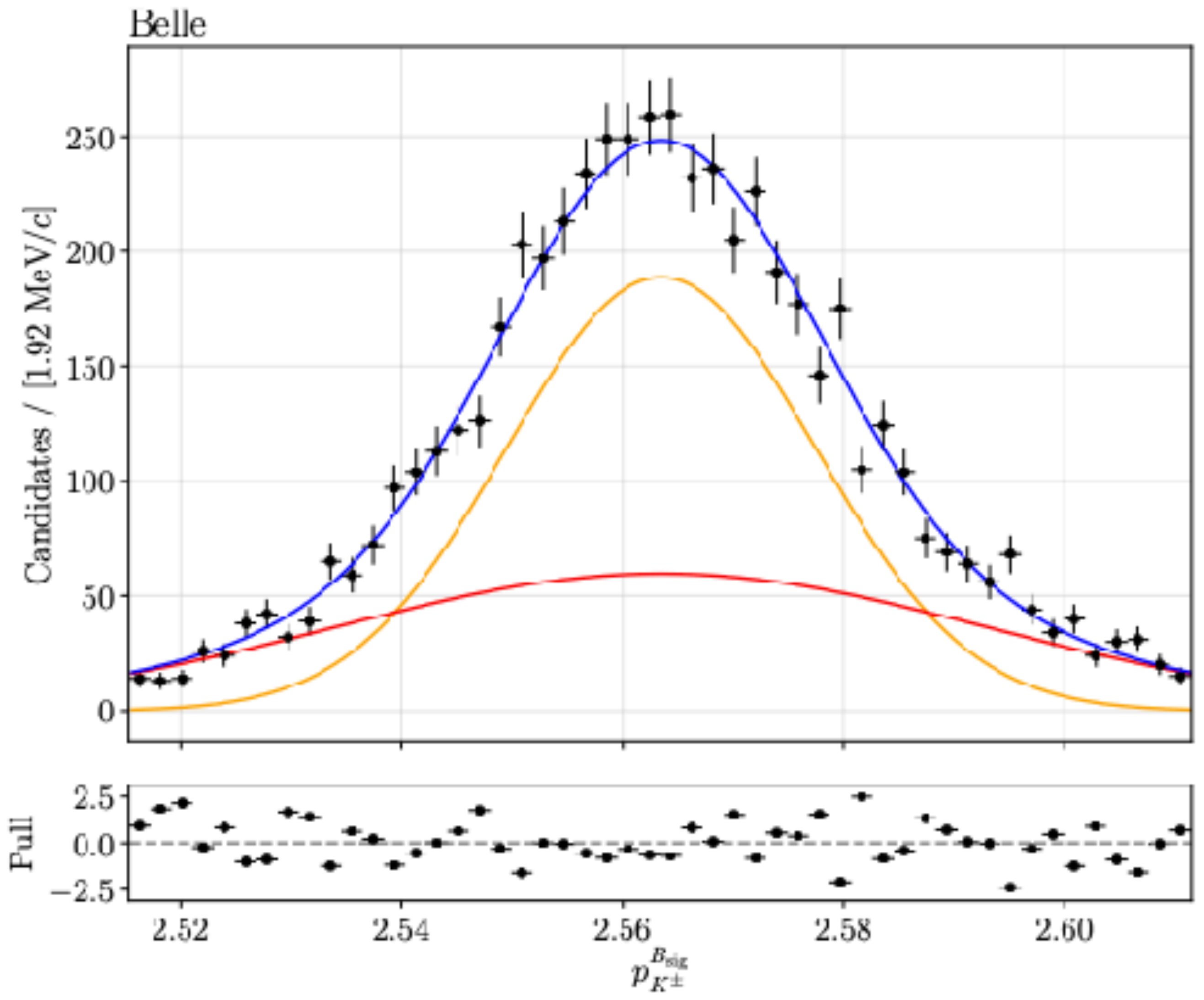
+veto any missing momentum pointing at gaps (beam pipe, ECL gap)

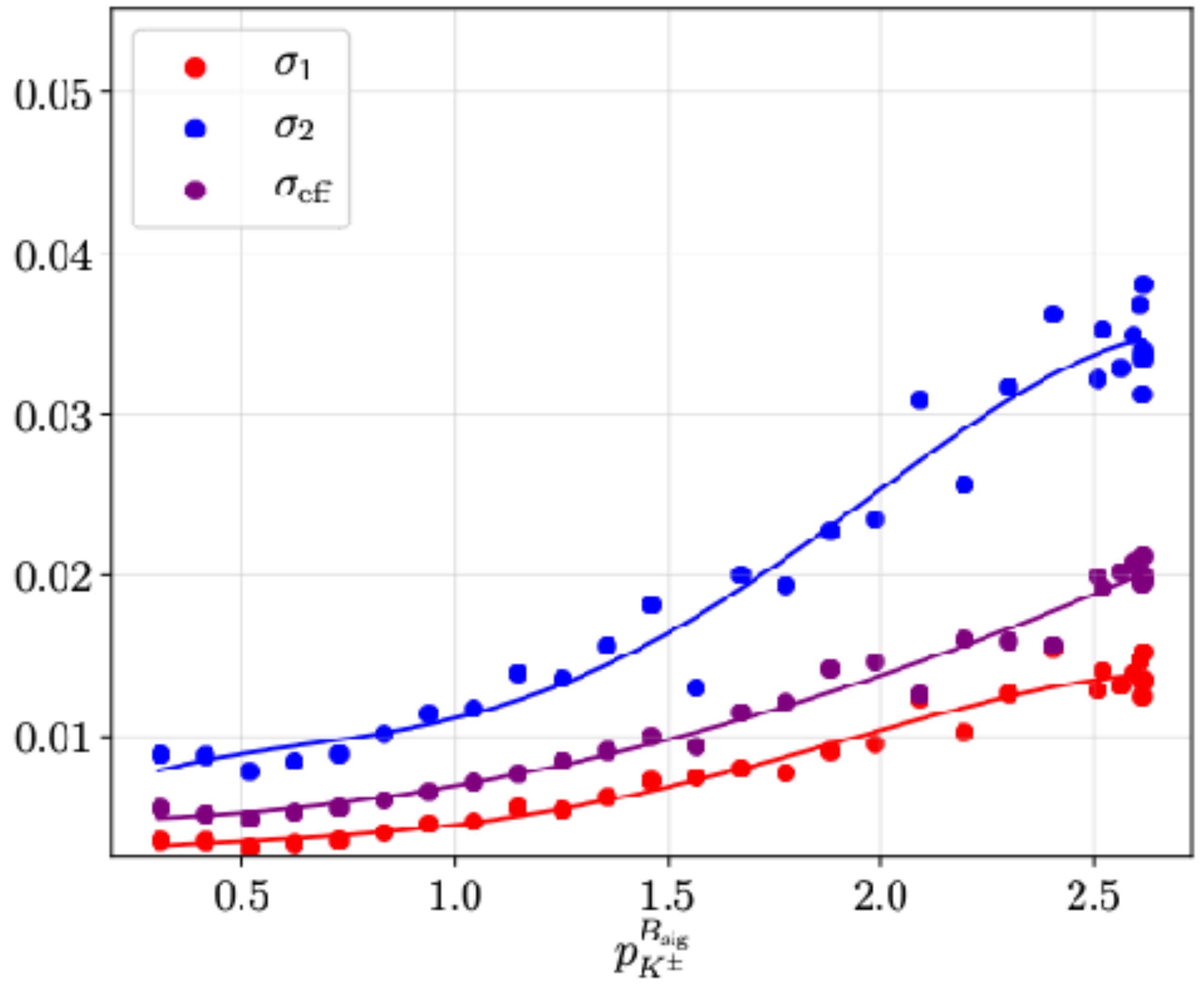
Cut-flow plots



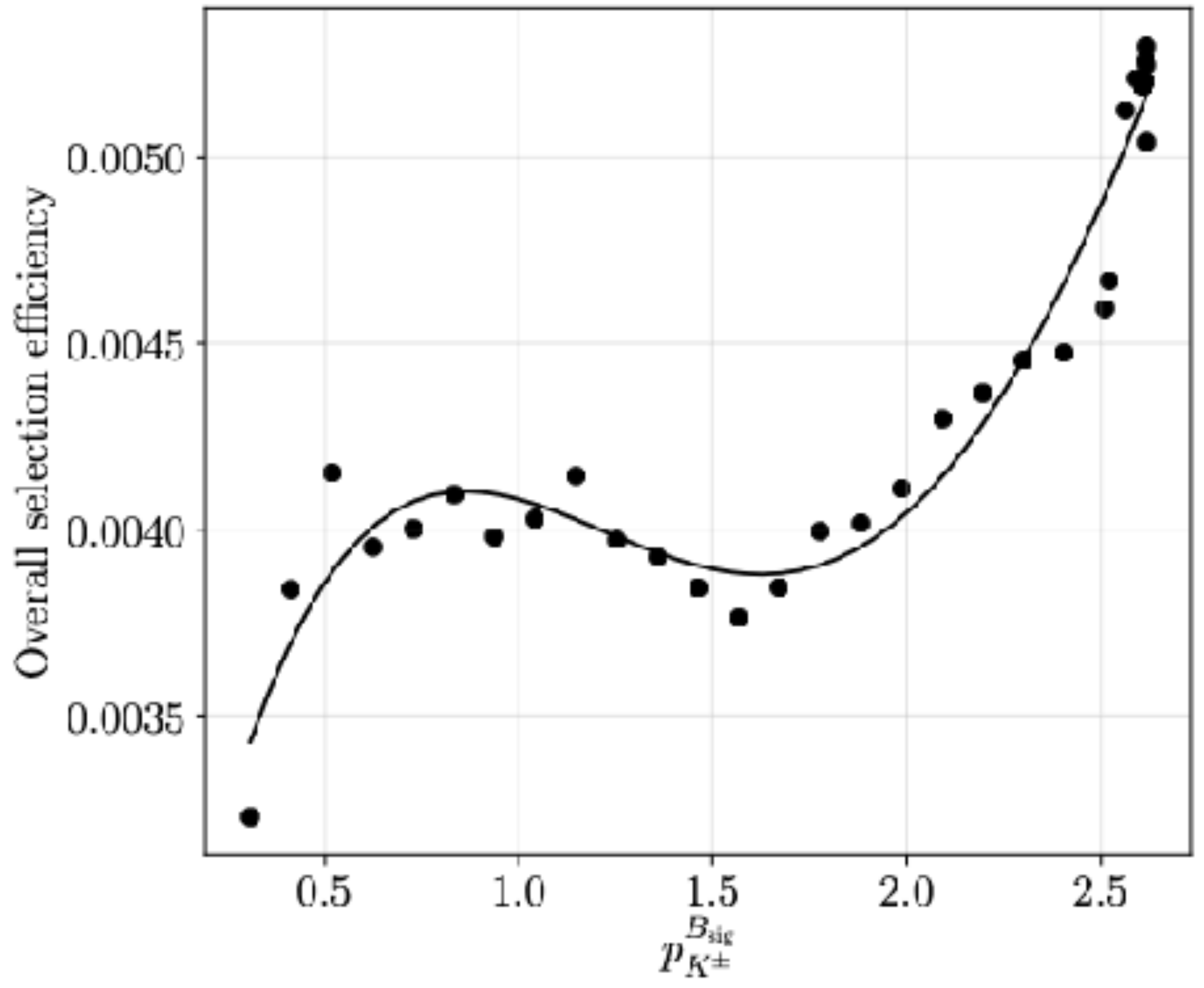
Fit Approach

- PDF determined from MC, calibrated with control channel.
- Parameterise PDF in p_h or m_{recoil} (same) and efficiency then scan from 1 MeV to ~5 GeV.

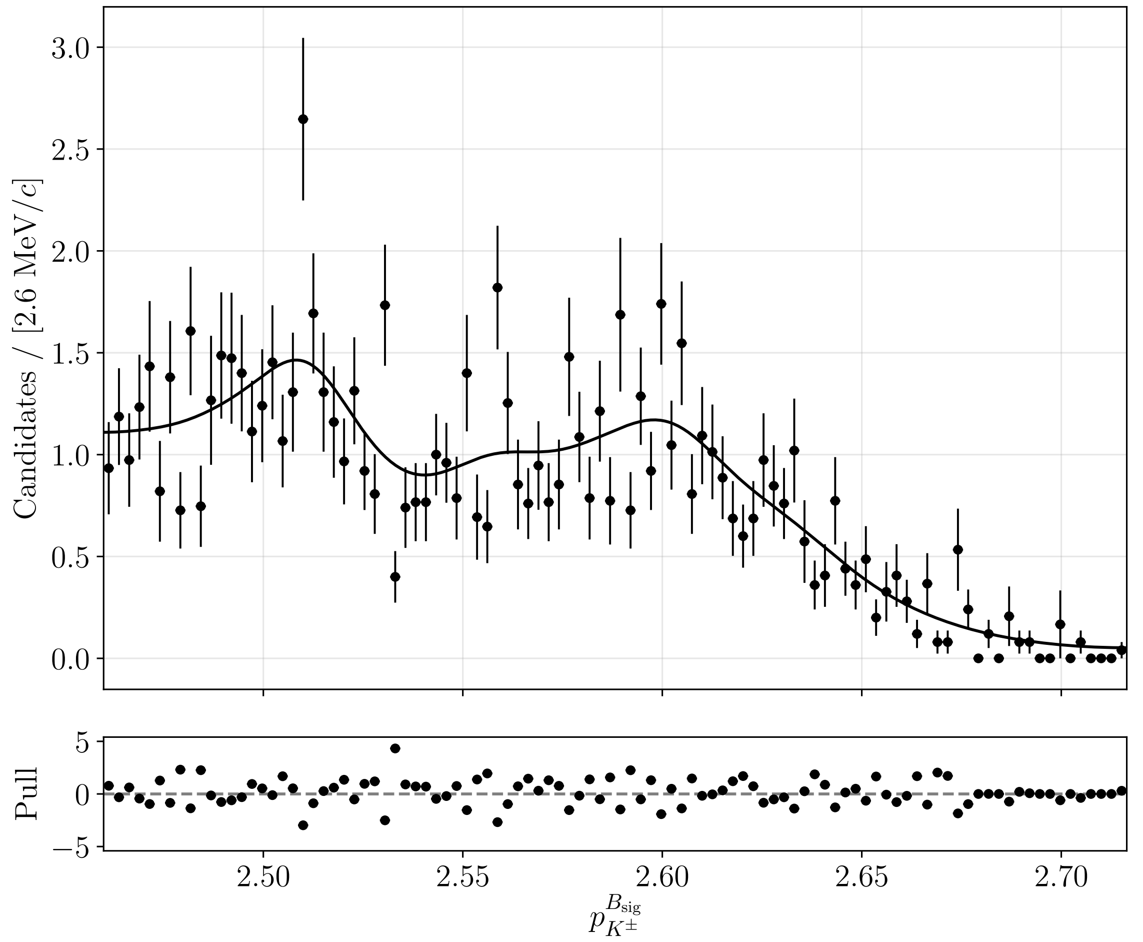




(c) Component Gaussian widths, kaon channel.



(b) Kaon channel.



(f) Kaon channel background in the low-mass region.

$B \to h\ a'$ Sensitivity

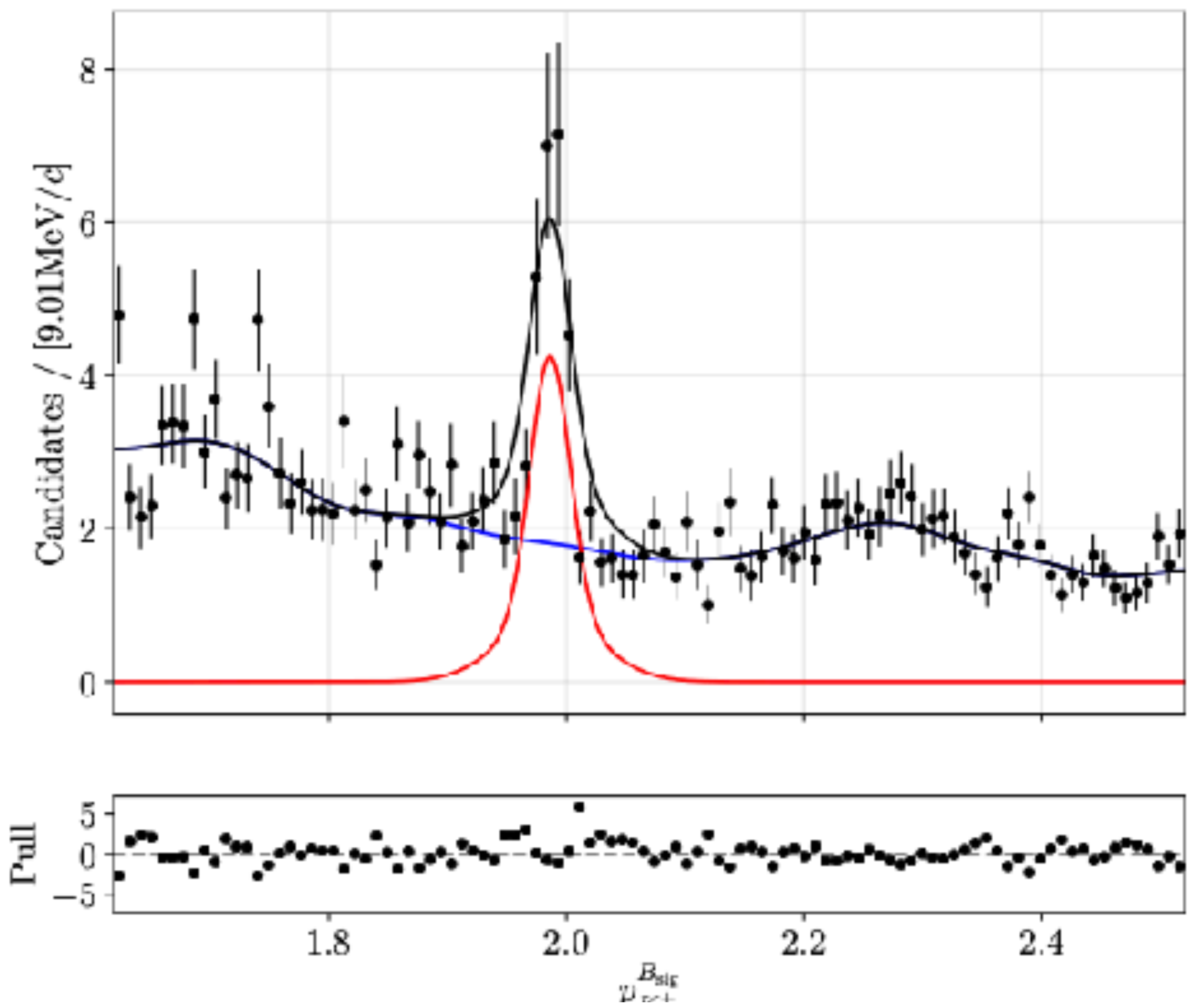


FIG. 14: Example of the combined fit model on a dataset with 20 signal events injected. The KDE defined on the background is shown in blue, the signal PDF in red and the combined PDF in black.

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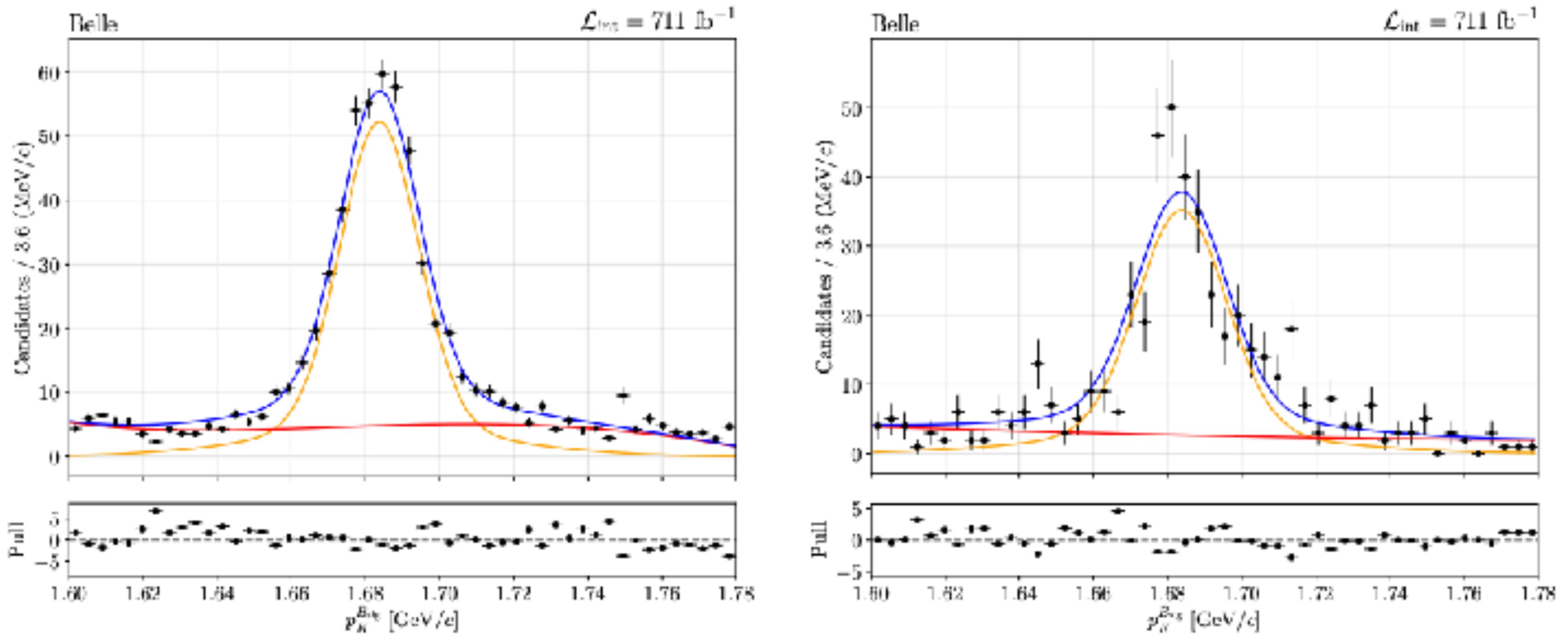


(a) (b)

FIG. 18: Fits to the J/ψ peak in MC (a) and data (b). The small errors in (a) are because there are multiple streams in the MC, and so the yield is scaled down to match the luminosity in data.

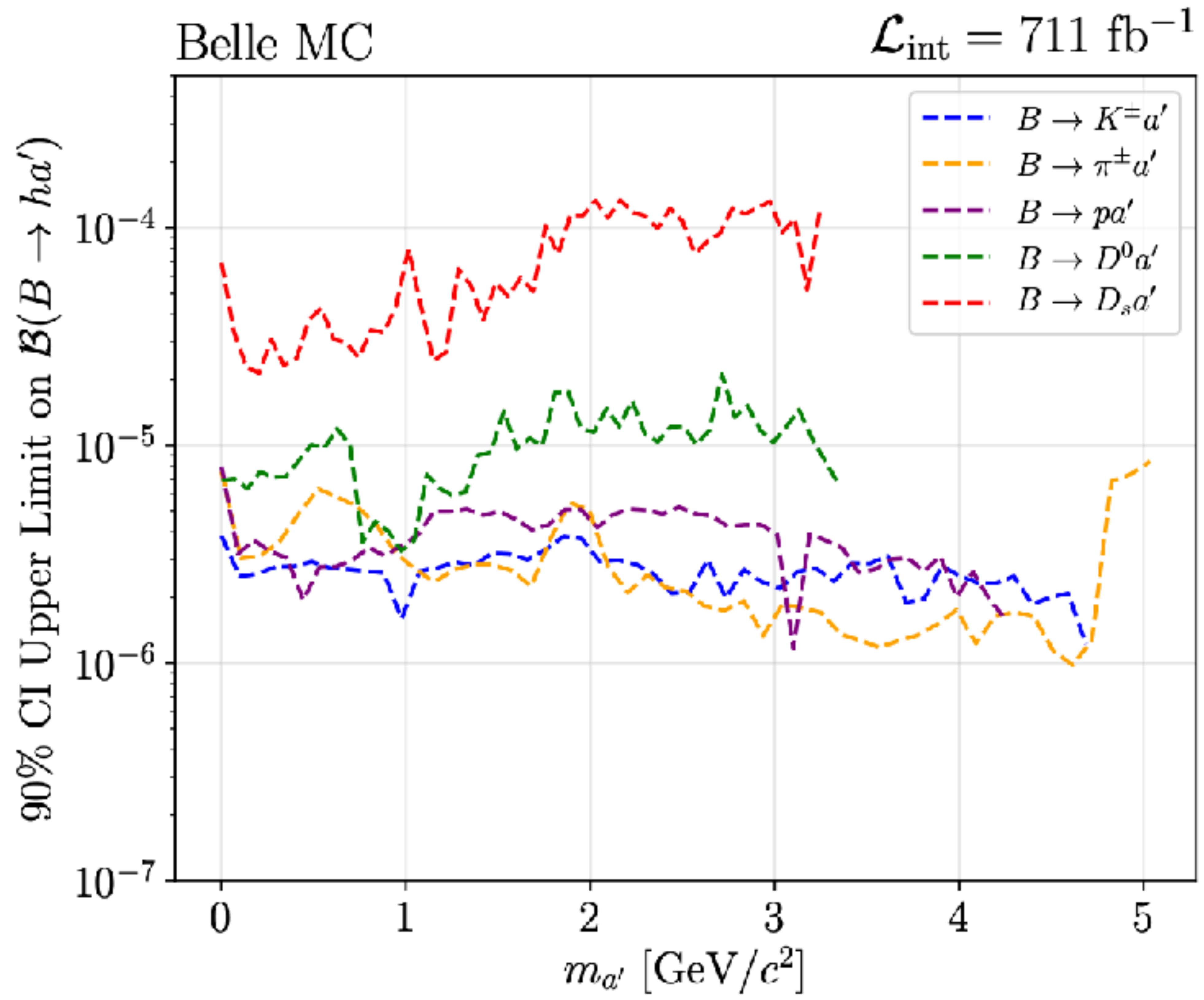


FIG. 19: 90% confidence level upper limits on the branching fractions to the five channels searched for in this work.

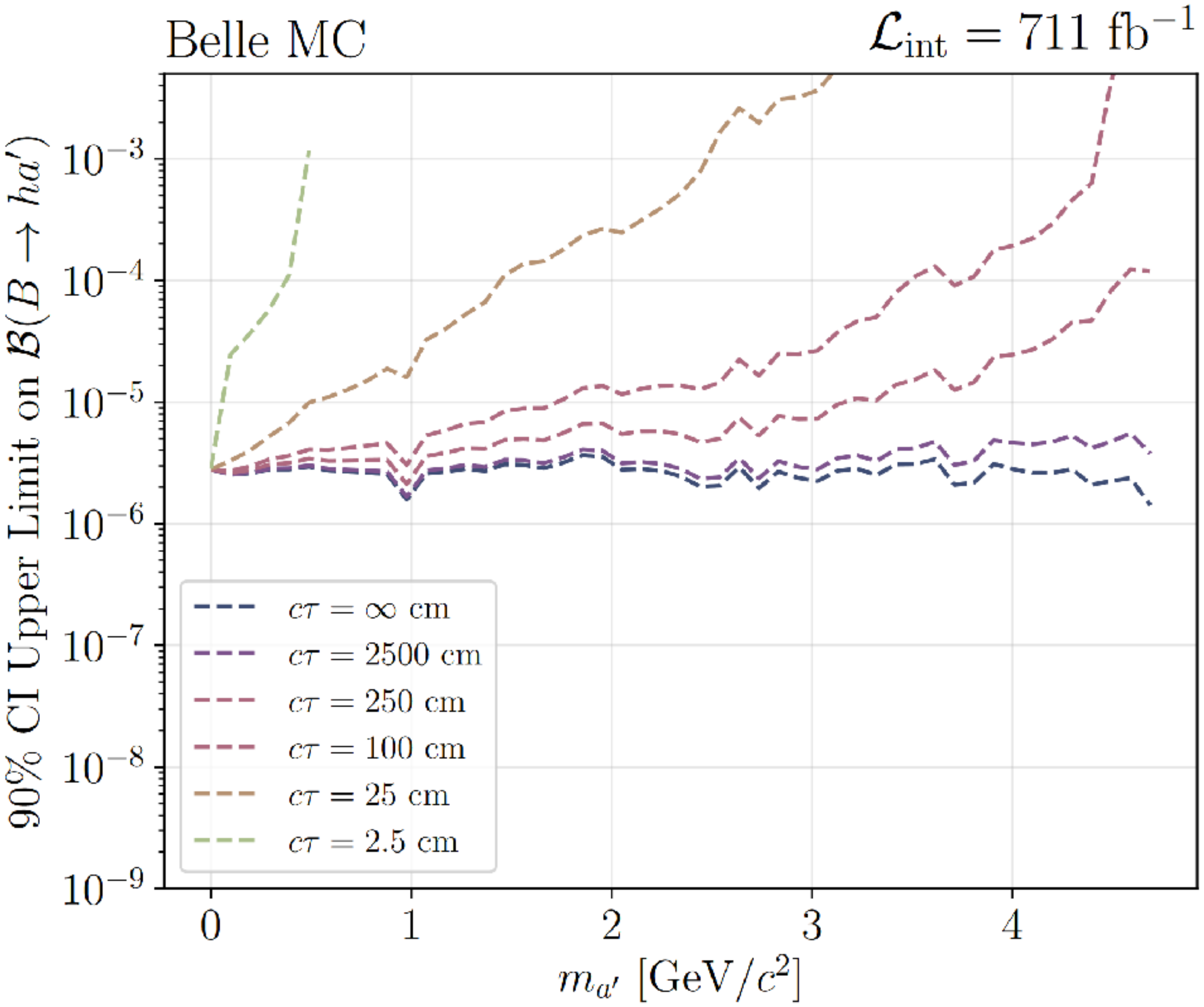
Decay measured in this work	Previous study	Decay measured in previous study	Previous world best	This work at $m_{a'} = 3$ GeV/c^2
$B^{\pm} \to \pi^{\pm}$ inv.	Belle [9]	$B^{\pm} \to \pi^{\pm}\nu\bar{\nu}$	1.4×10^{-5}	2×10^{-6}
$B^{\pm} \to K^{\pm}$ inv.	Belle [9]	$B^{\pm} \to K^{\pm}\nu\bar{\nu}$	1.6×10^{-5}	2×10^{-6}
$B^{\pm} \to p^{\pm}$ inv.	ALEPH [13]	$B^{\pm} \to \tau^{\pm}$ + missing energy	2×10^{-4}	3×10^{-6}
$B^0 \to \bar{D}^0$ inv.	N/A	N/A	N/A	1×10^{-5}
$B^{\pm} \to D_s^{\pm}$ inv.	N/A	N/A	N/A	1×10^{-4}

TABLE XIII: Comparison between our preliminary sensitivity studies on the branching fractions and the reach of similar searches.

Invisible signatures of long lived particles

D. Marcantonio, PU

- Consider a finite lifetime.
- If sufficiently long-lived, the ALP will escape detection.
- Limit then depends on cτ and mass (boost)



$B \to \Lambda$ + missing energy

Belle Collaboration, C. Hadjivasiliou, Phys.Rev.D 105 (2022) 5, L051101

- FEI hadronic tag, $\Lambda \to pK\pi$ reconstructed in

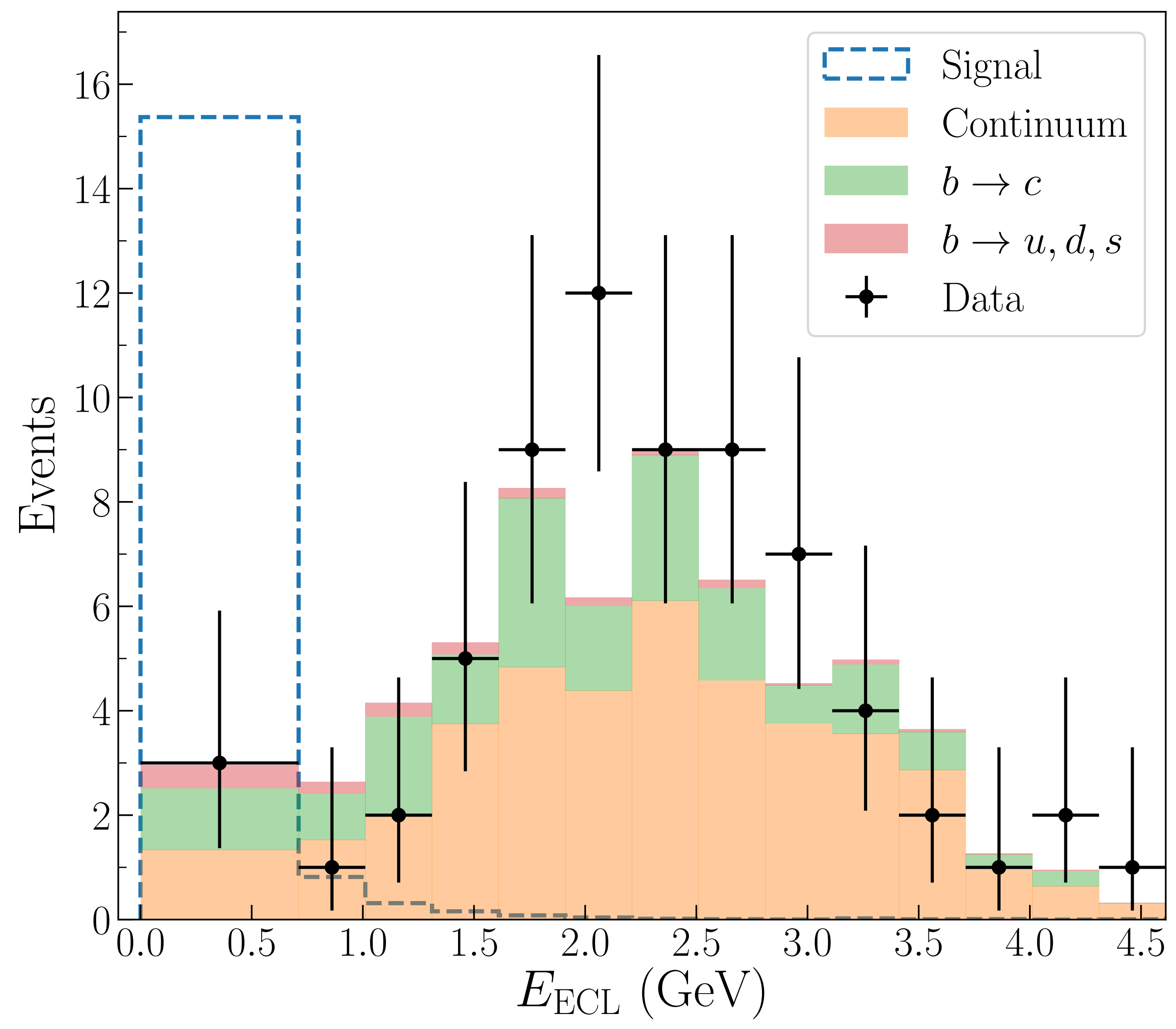
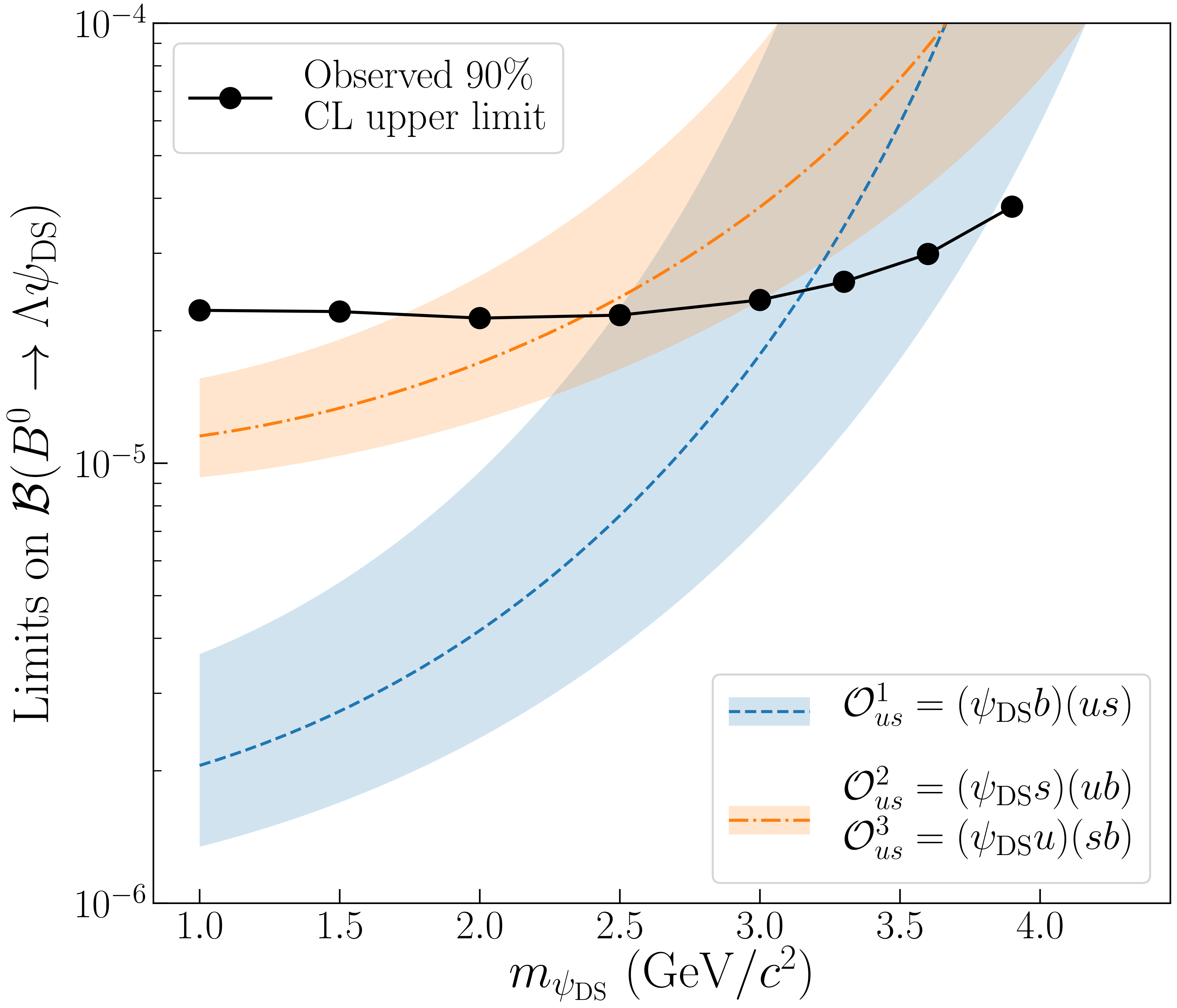


FIG. 2. The observed (solid points) and expected background (stacked shaded histograms) E_{ECL} distributions for $m_{\psi_{\mathrm{DS}}} = 2.5\,\mathrm{GeV}/c^2$, with the first bin representing the signal region. The shape of the continuum contribution is taken from the off-resonance data, while the other two background sources are from MC simulation; each distribution is normalized to the expected number of events in the first bin. The signal shape (dashed line) is taken from MC simulation, assuming a branching fraction of $\mathcal{B}(B^0 \to \Lambda\psi_{\mathrm{DS}}) = 8 \times 10^{-5}$.

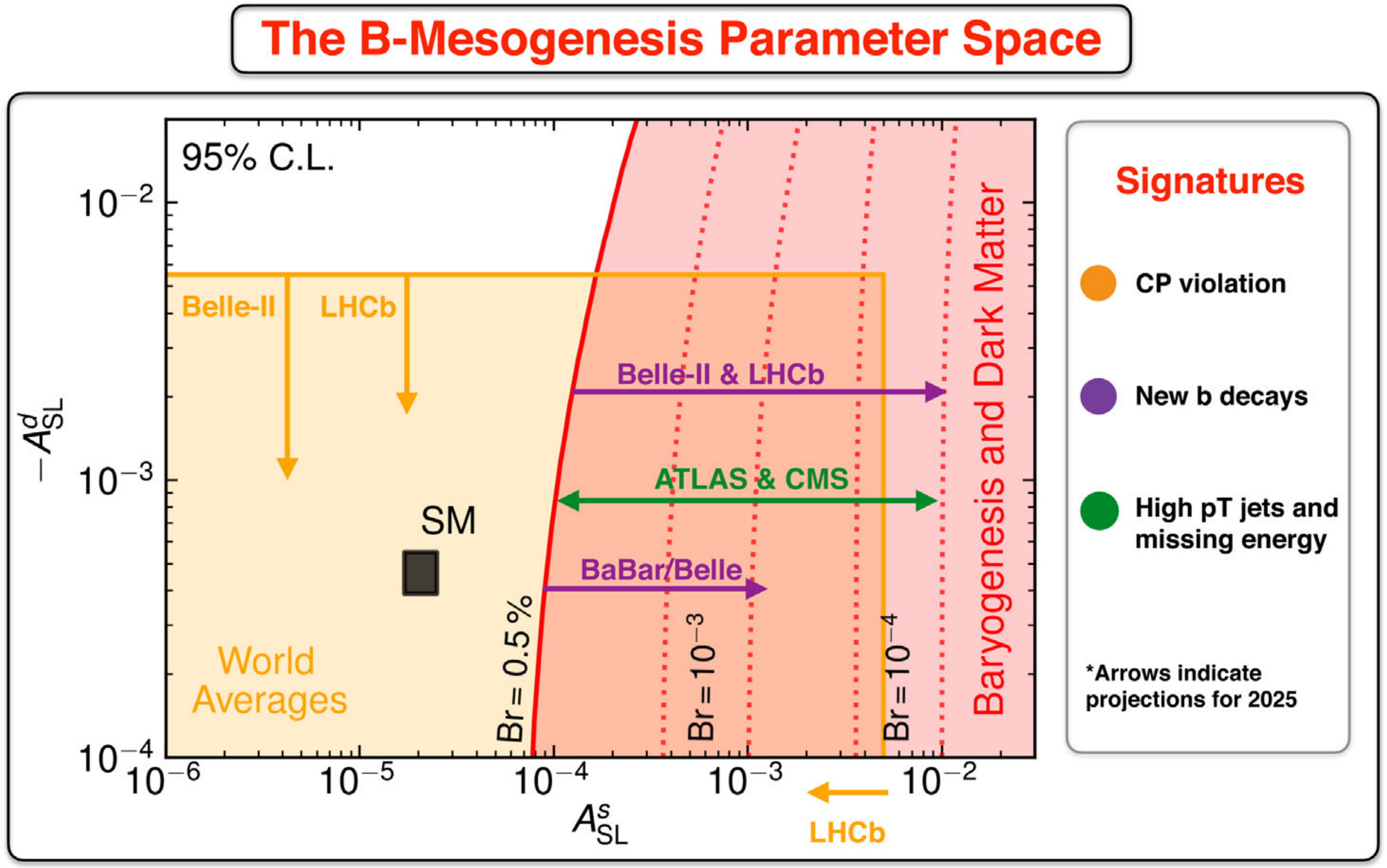
TABLE I. Range of systematic uncertainties in the estimate of the signal efficiencies, $\delta\epsilon$, and the number of expected $B\overline{B}$ background events, $\delta n_{\mathrm{bkg}}^{B\overline{B}}$, across the different values of $m_{\psi_{\mathrm{DS}}}$.

Source	$\delta\epsilon$ (%)	$\delta n_{\mathrm{bkg}}^{B\overline{B}}$ (%)
B_{tag} correction	8.6	8.6
Proton PID	0.5–2.8	4.3–5.7
Tracking efficiency	0.7–1.9	1.1–1.9
Charged track veto	5.3–6.5	5.3–6.5
Λ selection	2.5–3.6	4.4–4.7
Signal MC statistics	1.2–2.0	–
Rare B decays correction	–	10.6–13.4
Branching fractions	–	50.0



B-mesogenesis channels

Operator and decay	Initial state	Final state	ΔM (MeV)
$\mathcal{O}_{ud} = \psi bud$	B_d	$\psi + n(udd)$	4340.1
$\bar{b} \to \psi ud$	B_s	$\psi + \Lambda(uds)$	4251.2
	B^+	$\psi + p(duu)$	4341.0
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\mathcal{O}_{us} = \psi bus$	B_d	$\psi + \Lambda(usd)$	4164.0
$\bar{b} \to \psi us$	B_s	$\psi + \Xi^0(uss)$	4025.0
	B^+	$\psi + \Sigma^+(uus)$	4090.0
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\mathcal{O}_{cd} = \psi bcd$	B_d	$\psi + \Lambda_c + \pi^-(cdd)$	2853.6
$\bar{b} \to \psi cd$	B_s	$\psi + \Xi_c^0(cds)$	2895.0
	B^+	$\psi + \Lambda_c^+(dcu)$	2992.9
	Λ_b	$\bar{\psi} + \bar{D}^0$	3754.7
$\mathcal{O}_{cs} = \psi bcs$	B_d	$\psi + \Xi_c^0(csd)$	2807.8
$\bar{b} \to \psi cs$	B_s	$\psi + \Omega_c(css)$	2671.7
	B^+	$\psi + \Xi_c^+(csu)$	2810.4
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2



More models …

FTPI-MINN-20-07

Pair production of dark particles in meson decays

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Rare decays of K and B mesons provide a powerful probe of dark sectors with light new particles. We show that the pair production of $O(100\,\mathrm{MeV})$ dark states can be probed with the decays of K_L mesons, owing to the enhanced two-body kinematics, $K_L \to X_1 X_2$ or $X_2 X_2$. If either of these two particles is unstable, *e.g.* $X_2 \to X_1 \pi^0$, $X_2 \to X_1 \gamma$ or $X_{1,2} \to \gamma\gamma$, such decays could easily mimic $K_L \to \pi^0 \nu\bar{\nu}$ signatures, while not being ruled out by the decays of charged kaons. We construct explicit models that have enhanced K_L decay signatures, and are constrained by the results of the KOTO experiment. We note that recently reported excess events can also be accommodated while satisfying all other constraints (B decays, colliders, beam dumps). These models are based on the extensions of the gauge and/or scalar sector of the theory. The lightest of $X_{1,2}$ particles, if stable, could constitute the entirety of dark matter.

PREPARED FOR SUBMISSION TO JHEP

Probing R-parity violation in B-meson decays to a baryon and a light neutralino

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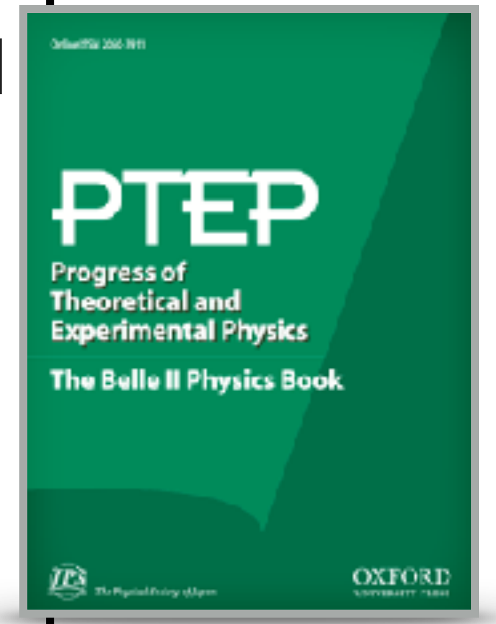
ABSTRACT: We propose a search for B meson decays to a baryon plus missing energy at the Belle II experiment to probe supersymmetry with a GeV-scale lightest neutralino $\tilde{\chi}_1^0$ and R-parity violation (RPV). We perform analytic computations of the signal branching fractions in the framework of effective field theory, with a single nonzero RPV operator $\lambda''_{ij3}\bar{U}_i^c\bar{D}_j^c\bar{D}_3^c$, where $i,j = 1,2$. The hadronic form factors are calculated using an SU(3) phenomenological Lagrangian approach for the proton, as well as several hyperons and charmed baryons. Since the decay of the neutralino is kinematically and CKM suppressed in this theoretical scenario, it decays outside the detector and appears experimentally only as missing energy. We detail the analysis techniques at the experimental level and estimate the background in the $B^+ \to p\tilde{\chi}_1^0$ search using published results for $B^+ \to K^+\nu\bar{\nu}$. Our final sensitivity plots are shown for both λ''_{113} versus the squark mass $m_{\tilde{q}}$ and $\lambda''_{113}/m_{\tilde{q}}^2$ versus the neutralino mass $m_{\tilde{\chi}_1^0}$. We find that the search at Belle II could probe $\lambda''_{113}/m_{\tilde{q}}^2$ down to the order of 10^{-8} GeV^{-2} in the kinematically allowed $m_{\tilde{\chi}_1^0}$ range. We also obtain current limits on λ''_{123} by recasting an existing search interpreted as $B^0 \to \Lambda^0\tilde{\chi}_1^0$, and comment about searches for $B^+ \to \Sigma^+\tilde{\chi}_1^0$, $B^0 \to \Sigma^0\tilde{\chi}_1^0$, $B^+ \to \Lambda_c^+\tilde{\chi}_1^0$, and $B^+ \to \Xi_c^+\tilde{\chi}_1^0$. In closing, we briefly discuss potential searches at the LHCb and BESIII experiments.

Belle II Projections & LHCb Comparison

Belle II
Higher sensitivity to decays with photons and neutrinos (e.g. B→Kνν, μν), inclusive decays, time dependent CPV in B_d, τ physics.



LHCb
Higher production rates for ultra rare B, D, & K decays, access to all b-hadron flavours (e.g. Λ_b), high boost for fast B_s oscillations.

Overlap in various key areas to verify discoveries.

Upgrades
Most key channels will be stats. limited (not theory or syst.).

Observable	2022 Belle(II), BaBar	2022 LHCb	Belle-II 5 ab^{-1}	Belle-II 50 ab^{-1}	LHCb 50 fb^{-1}	Belle-II 250 ab^{-1}	LHCb 300 fb^{-1}
$\sin 2\beta/\phi_1$	0.03	0.04	0.012	0.005	0.011	0.002	0.003
γ/ϕ_3	11°	4°	4.7°	1.5°	1°	0.8°	0.35°
α/ϕ_2	4°	–	2°	0.6°	–	0.3°	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	4.5%	6%	2%	1%	2%	$< 1\%$	1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	–	0.03	0.015	–	0.007	–
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	–	0.07	0.04	–	0.018	–
$S_{CP}(B \to \eta' K^0_S)$	0.32	–	0.11	0.035	–	0.015	–
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.12	0.09	0.03	0.022	0.01	0.009
$R(B \to D^*\tau\nu)$	0.018	0.026	0.009	0.0045	0.0072	<0.003	<0.003
$R(B \to D\tau\nu)$	0.034	–	0.016	0.008	–	<0.003	–
$\mathcal{B}(B \to \tau\nu)$	24%	–	9%	4%	–	2%	–
$\mathcal{B}(B \to K^*\nu\bar{\nu})$	–	–	25%	9%	–	4%	–
$\mathcal{B}(\tau \to e\gamma)$ UL	42×10^{-9}	–	22×10^{-9}	6.9×10^{-9}	–	3.1×10^{-9}	–
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	46×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	1.1×10^{-9}	0.07×10^{-9}	5×10^{-9}

Table 1: Projected precision of selected flavour physics measurements at Belle II and LHCb.(The † symbol denotes the measurement in the $1 < q^2 < 6$ GeV/c^2 bin.)

- The transition to a construction project is needed soon
  - SuperKEKB International Task Force should reach conclusion by summer 2022
  - **The preparation of an Upgrades Conceptual Design Report should start afterwards, ready in 2023**

To discuss

- What happens if/when see something?
- How can we tell its a new physics contribution and not *peaking* background?
- If we can’t see it, how can we decipher what any new contribution is?