Searching for the dark sector in *B* decays

Slavomira Stefkova

Belle II Physics Week

October 18th, 2024

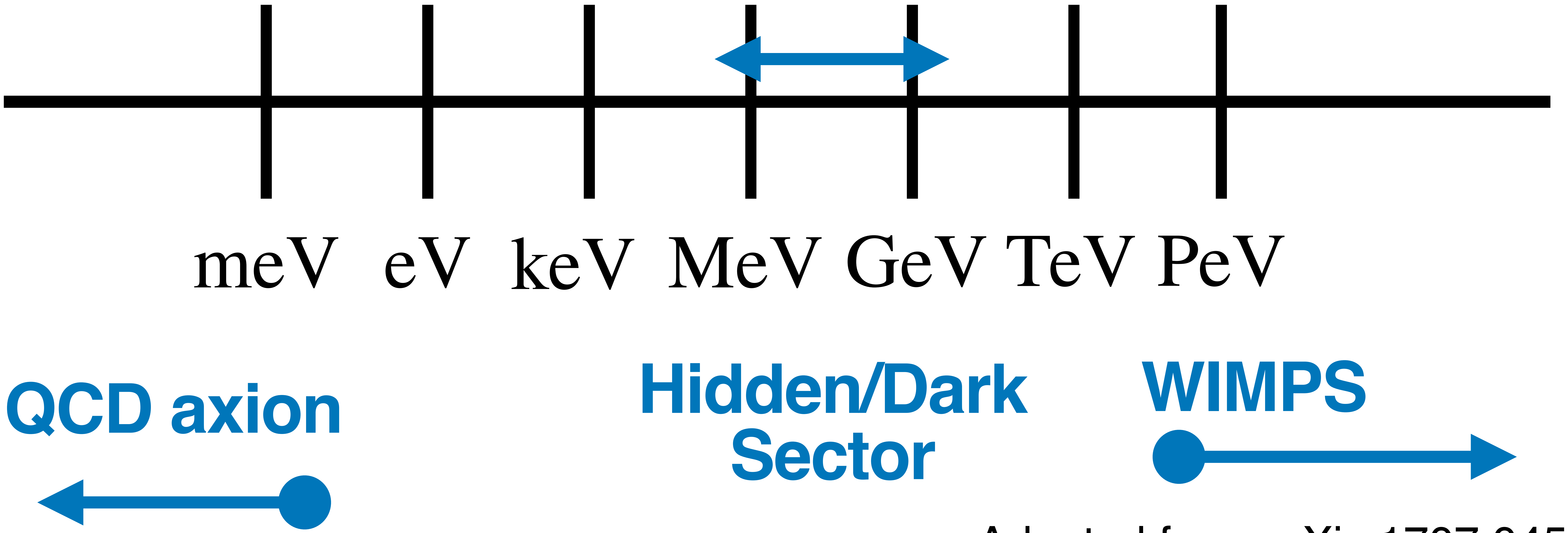
UNIVERSITÄT BONN

Belle II

sstefkov@uni-bonn.de

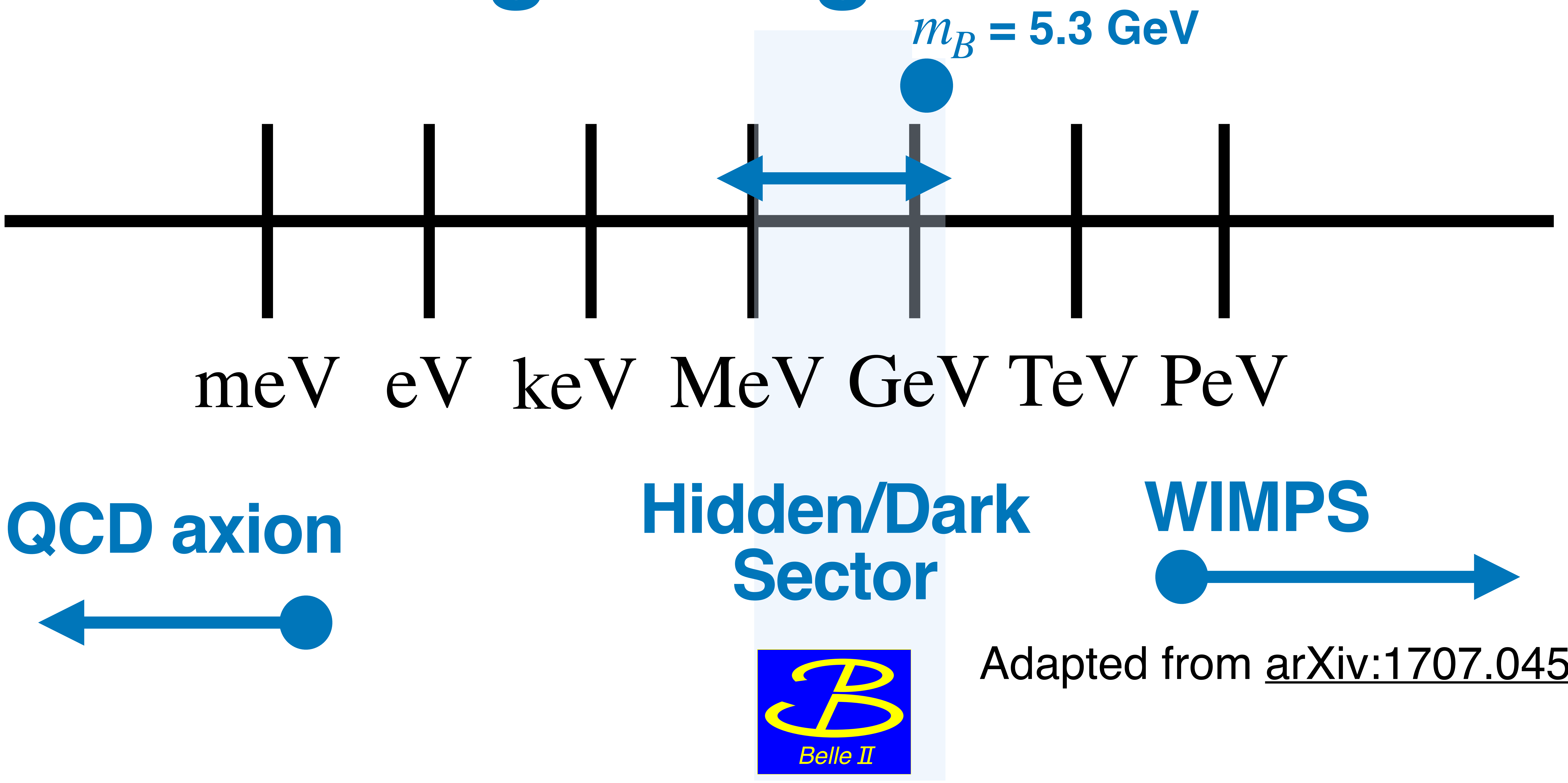
Picture credits: Torben Ferber

Searching for Light Dark Matter



Adapted from arXiv:1707.04591

Searching for Light Dark Matter



Adapted from arXiv:1707.04591

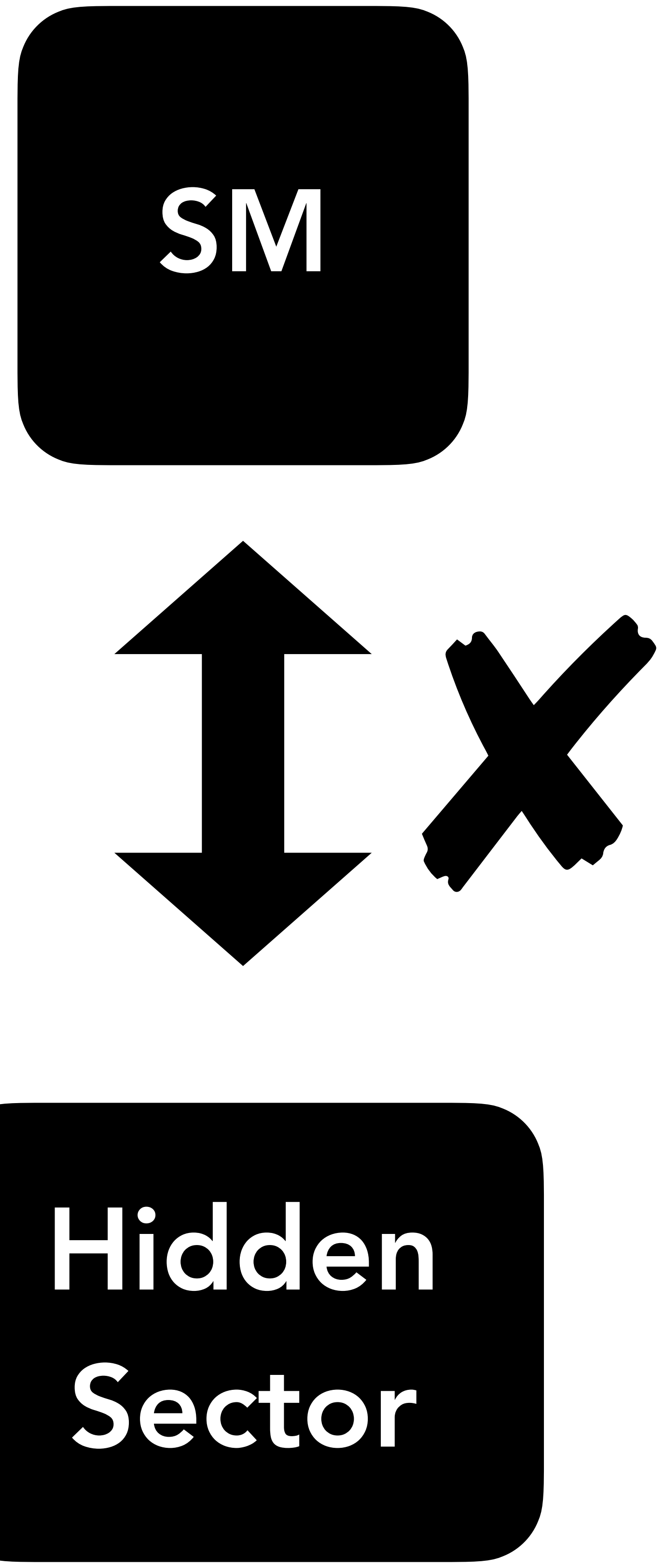
Light Dark Matter @ Accelerators

- Ordinary matter in our universe is outnumbered by dark matter 5:1 (in mass)
- All evidence so far relies only on gravity including the primary measurement ($\Omega_h\chi^2$ = 0.12) [Planck, 1807.06209]
- Best explanations of relic density require additional interactions with SM particles
- Due to the lack of WIMP signatures, light dark matter ($m < 10$ GeV) increasingly appealing

Light Dark Matter @ Accelerators

Focus on **portal interactions** with DM mediator $(\mathcal{O}_{SM} \times \mathcal{O}_{DS})$

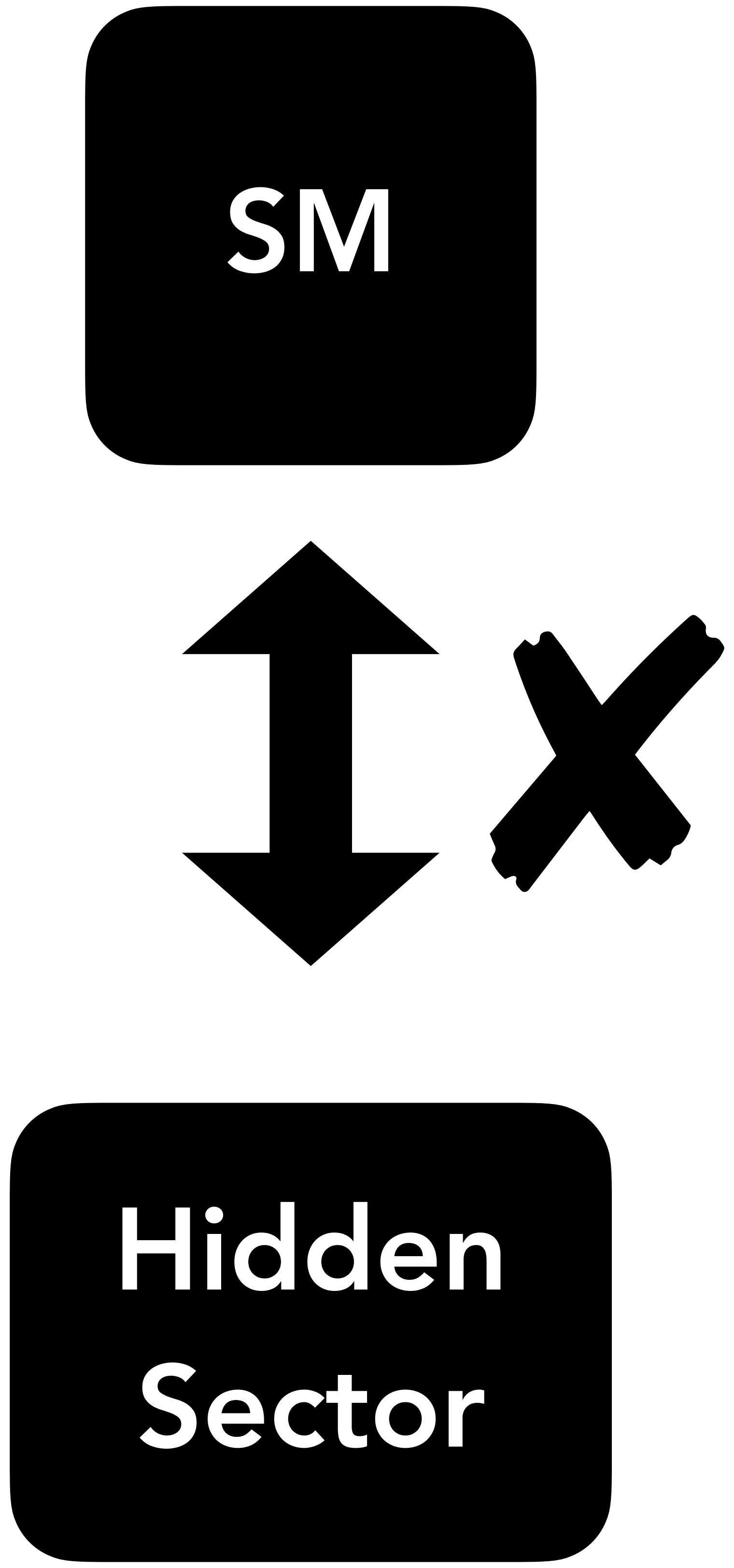
- **Vector portal**: $-\frac{\kappa_Y}{2} F'_{\mu\nu} B^{\mu\nu}$ (→ Dark Photons (A'), Z' bosons)
- **Higgs portal**: $(\lambda_2 \phi + \lambda_4 \phi^2) H^+ H$ (→ Axion Like Particles (ALPs))
- **Axion portal**: $-\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$ (→ Dark Higgsstrahlung/Scalars)
- **Sterile neutrino portal**: $y_N LHN$ (→ Sterile Neutrinos)



Light Dark Matter @ Accelerators

Focus on **portal interactions** with DM mediator ✘ $(\mathcal{O}_{SM} \times \mathcal{O}_{DS})$

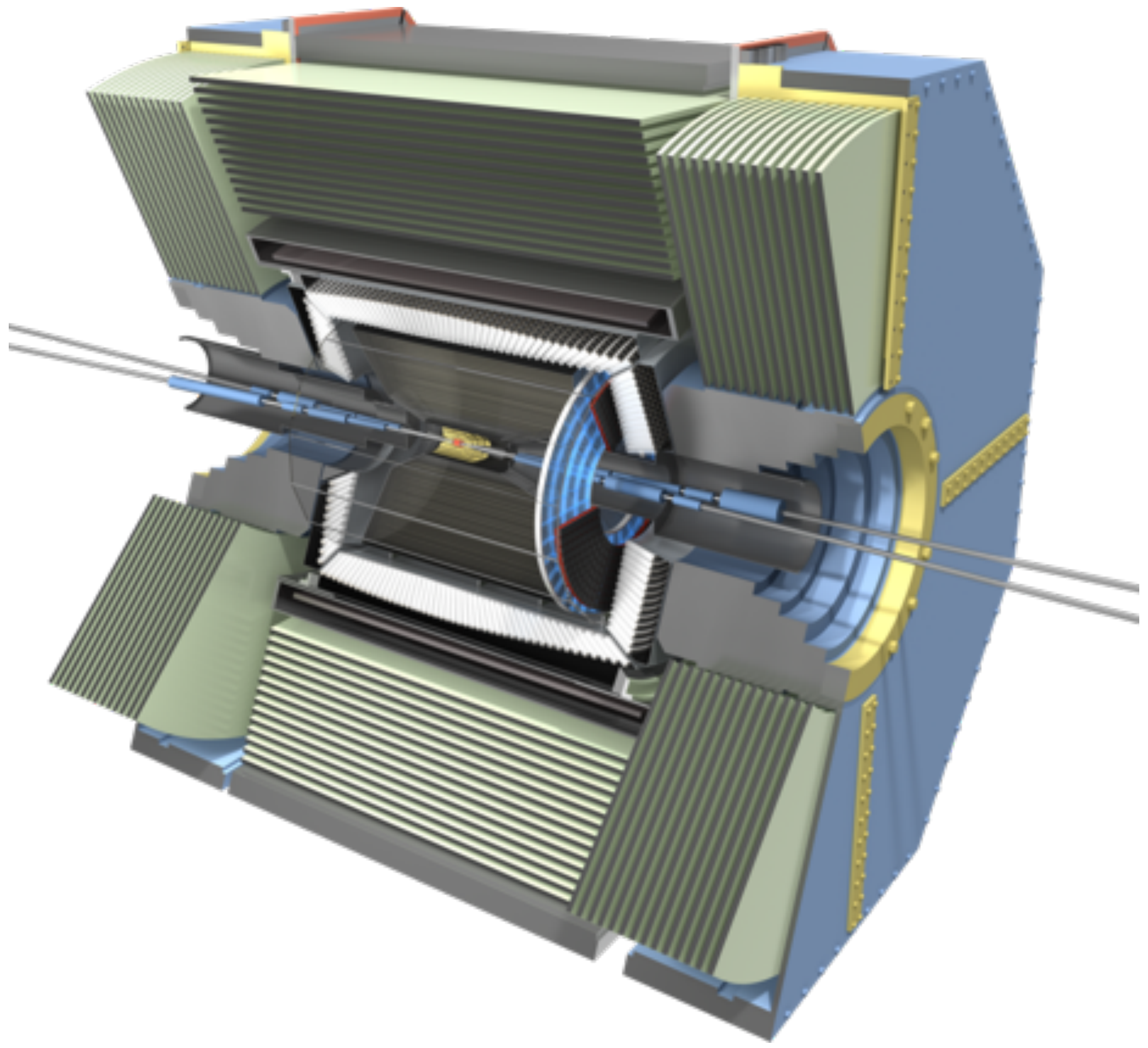
- **Vector portal**: $-\frac{\kappa_Y}{2} F'_{\mu\nu} B^{\mu\nu}$ (→ Dark Photons (A'), Z' bosons)
- **Higgs portal**: $(\lambda_2 \phi + \lambda_4 \phi^2) H^+ H$ (→ Axion Like Particles (ALPs))
- **Axion portal**: $-\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}, \frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$ (→ Dark Higgsstrahlung/Scalars)
- **Sterile neutrino portal**: $y_N LHN$ (→ Sterile Neutrinos)



Further guidance for light DM in reach of Belle II:

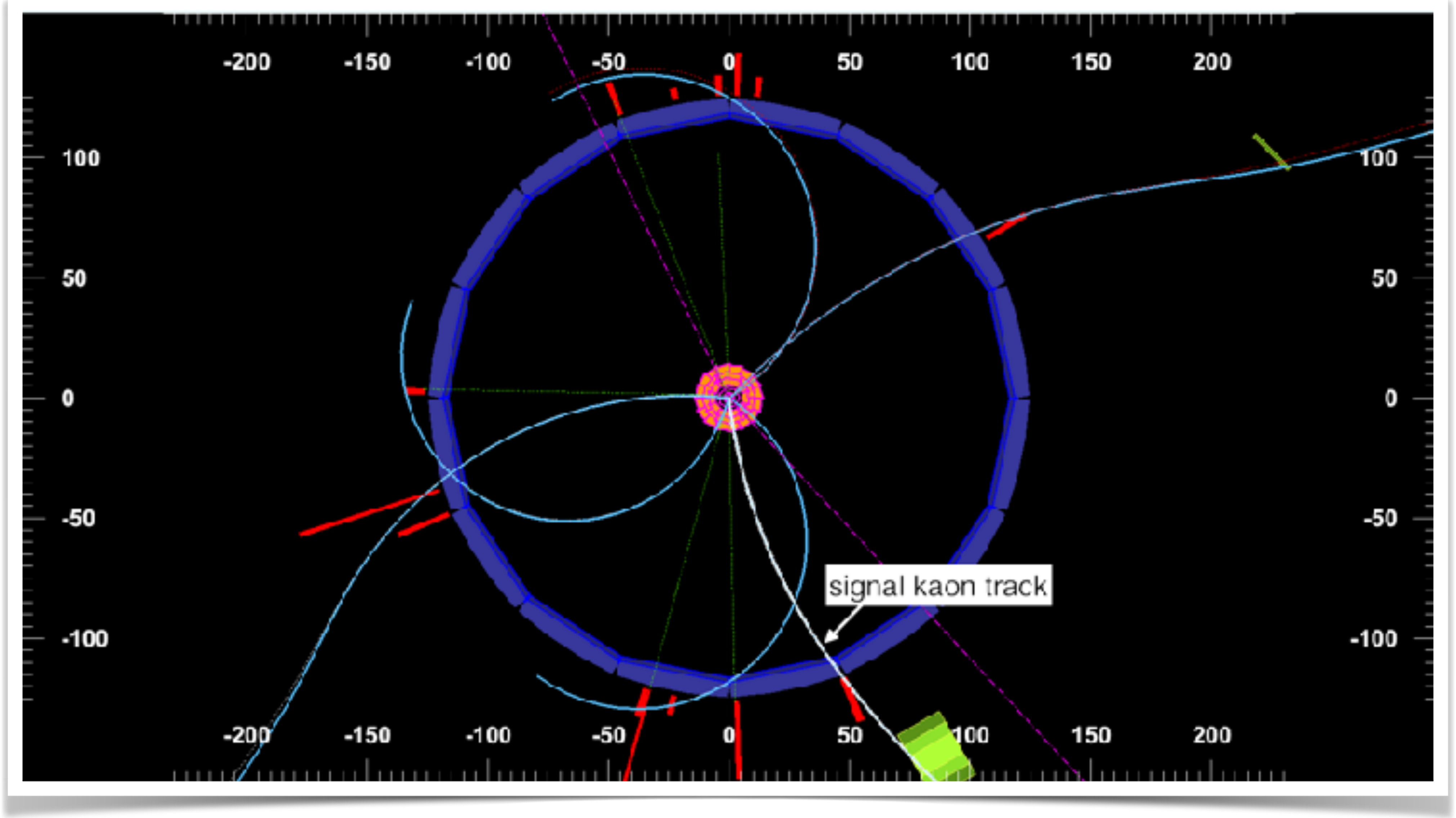
- Residual annihilations $\chi\overline{\chi} \to f\overline{f}$ have to suppressed at late times (low temperatures) to be compatible with cosmo bounds

Belle II detector + $B\bar{B}$-event



- SuperKEKB (7 GeV e^-/4 GeV e^+)
- General purpose detector
- Taking data since 2019
- Collected ~ **500 $\mathbf{fb^{-1}}$ to date**
  - **580 mil. $B\bar{B}$ pairs**

- Very clean environment
- On average: 11 tracks
- Known initial state kinematics
- Near 100% efficiency for B decays
- Sensitive to lower energy deposits

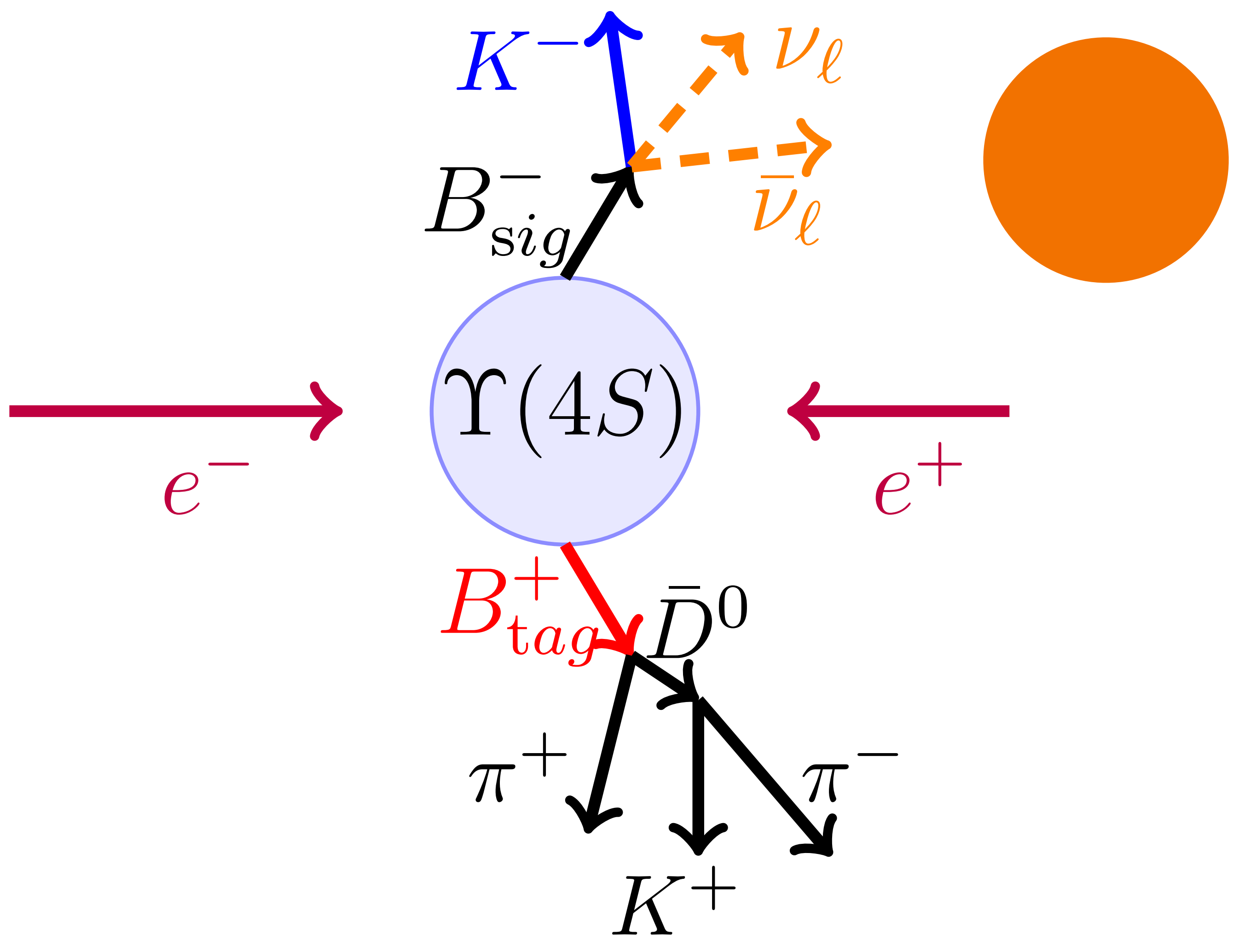


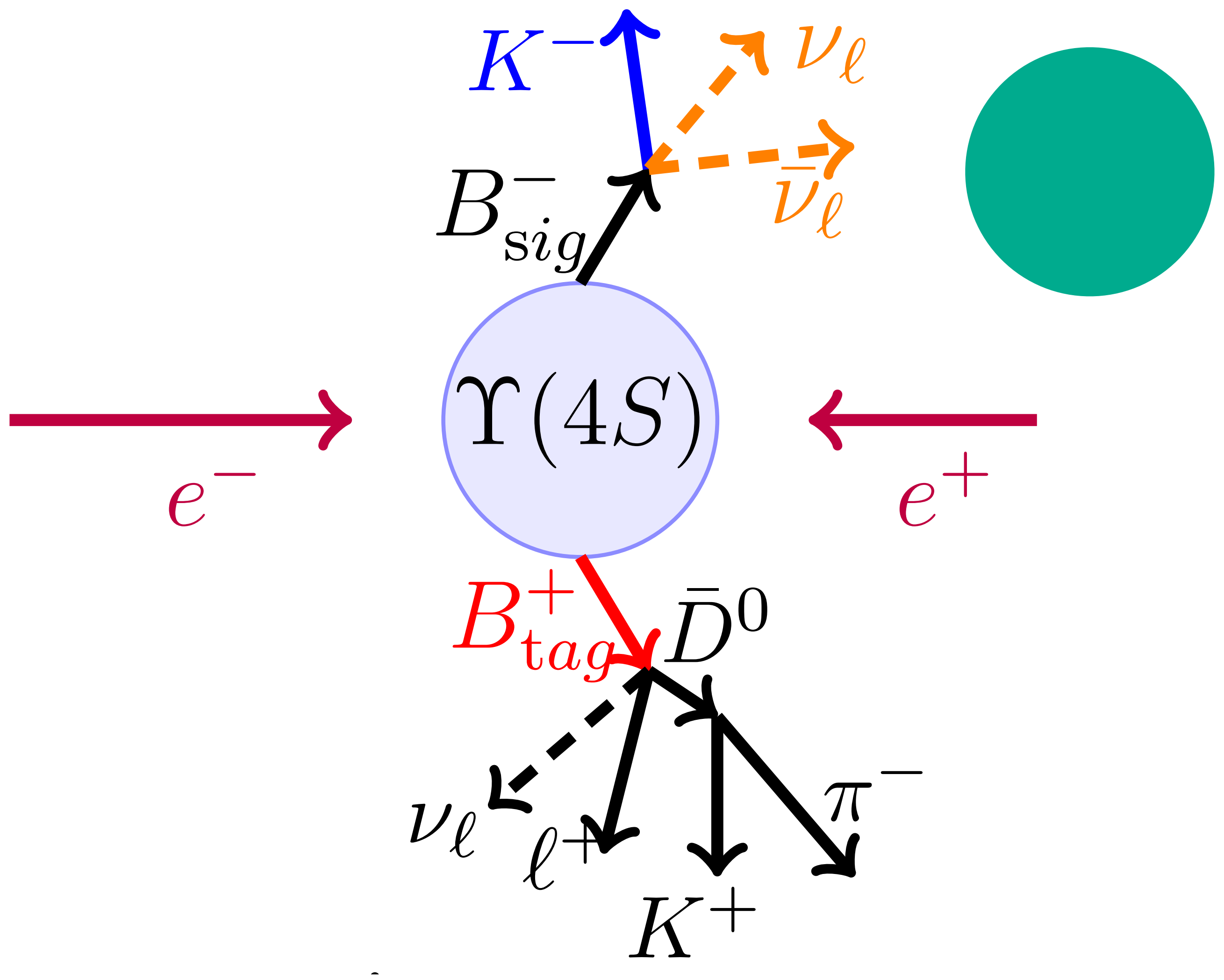
Reconstruction Techniques

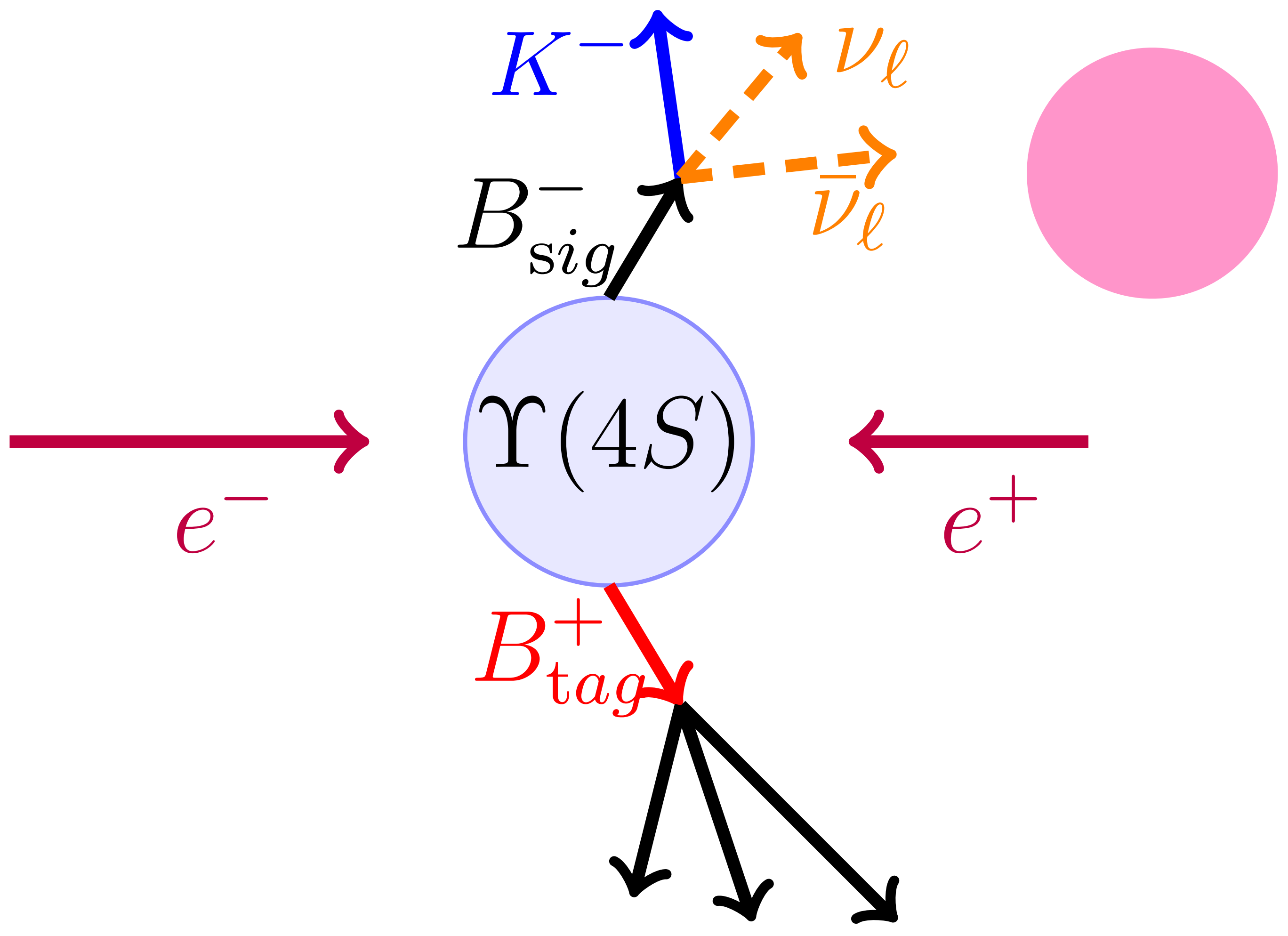
Efficiency

$\epsilon \sim 0.1 - 1\,\%$ | $\epsilon \sim 1 - 3\,\%$ | $\epsilon \sim 1 - 100\,\%$

Exclusive hadronic (HAD) | Exclusive semileptonic | Inclusive (ITA)

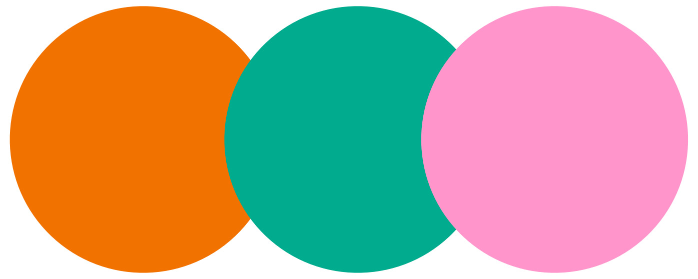






Purity, Resolution

Different reconstruction techniques lead to nearly orthogonal data samples



B-meson tools

Tools:

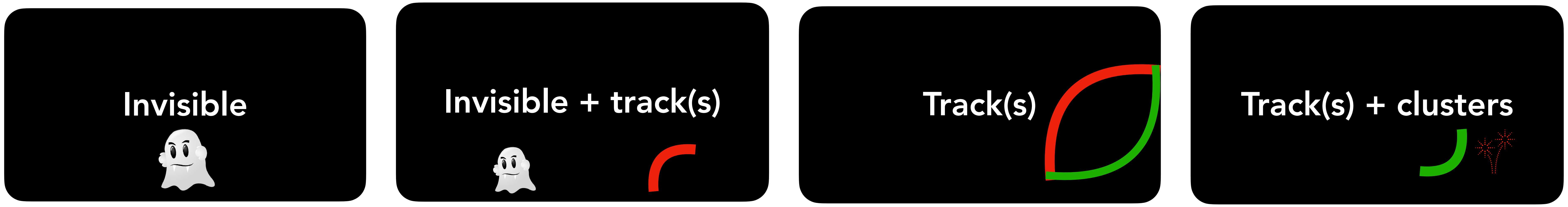
- Large number of B-mesons which **do not need to be triggered**
- Good charged particle identification (kaons, pions, protons, electrons, muons)
- Good knowledge about missing energy due to clean environment
- Good neutral particle identification (photons, pions)

B-meson tools

Tools:

- Large number of B-mesons which **do not need to be triggered**
- Good charged particle identification (kaons, pions, protons, electrons, muons)
- Good knowledge about missing energy due to clean environment
- Good neutral particle identification (photons, pions)

This allows us all to look for final states with these particles

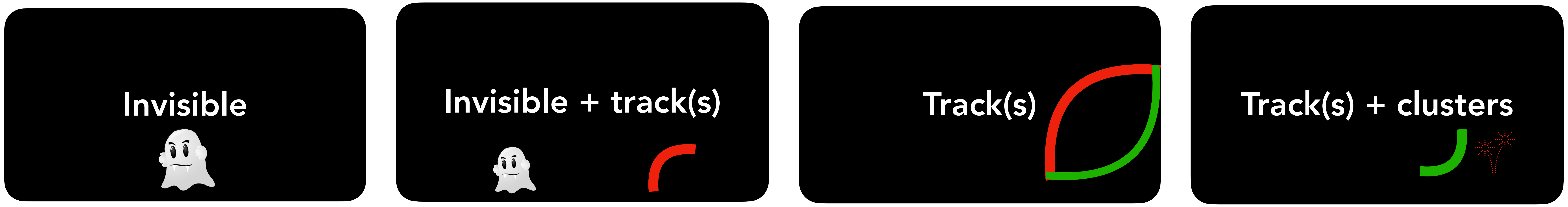


B-meson tools

Tools:

- Large number of B-mesons which **do not need to be triggered**
- Good charged particle identification (kaons, pions, protons, electrons, muons)
- Good knowledge about missing energy due to clean environment
- Good neutral particle identification (photons, pions)

This allows us all to look for final states with these particles



Secret tip: We want SM processes to be small and/or well separable as not to be problematic background

Signature 1.

Invisible

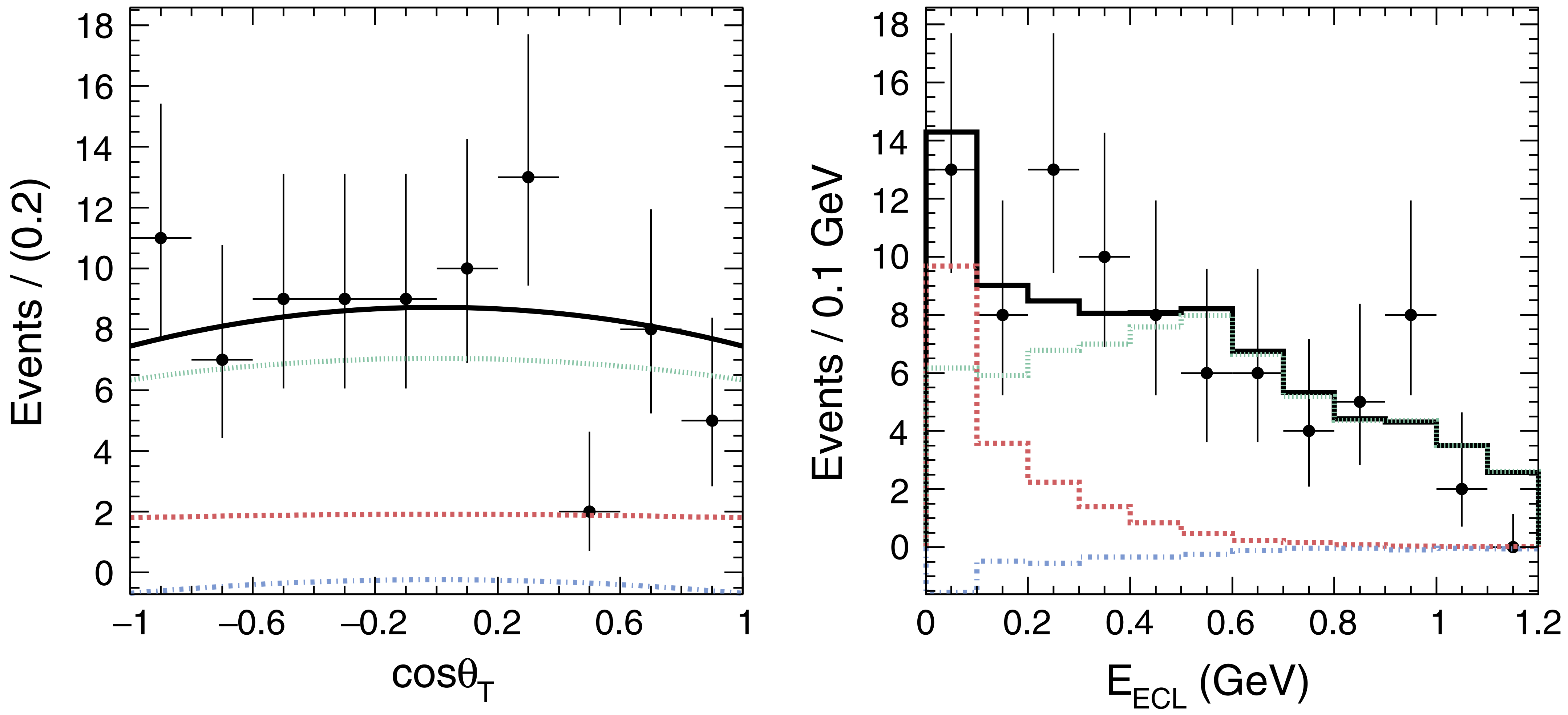
$$e.g.\ B^0 \rightarrow \mathrm{INV}$$

SM $B^0 \to \nu\bar{\nu}$

Invisible

Belle II has the possibility to search for $B^0 \to \nu\bar{\nu}$:

- SM expectations are very low $\mathscr{B}(B^0 \to \nu\bar{\nu}) \sim\ < 10^{-11}$ [EPJC 81 5, 388(2021)]
  - Strong helicity suppression
- BaBar: $\mathscr{B}(B^0 \to \nu\bar{\nu}) < 2.4 \times 10^{-5}$ @ $90\,\%\,\mathrm{C.L}$ [PRD 86, 051105(R) (2012)]
- Belle: $\mathscr{B}(B^0 \to \nu\bar{\nu}) < 7.8 \times 10^{-5}$ @ $90\,\%\,\mathrm{C.L}$ [PRD 102, 012003 (2020)]
- Can search using hadronic and semileptonic tagging: $\epsilon \sim$ few percent



[PRD 102, 012003 (2020)]

Challenges:

- Clean environment
- Good understanding of neutrals
- Separating variables, e.g $\boldsymbol{E_{ECL}}$ = amount of energy not associated to the hadronic *B*-decays needs to well understood

$B^0 \to \mathrm{INV}$

Invisible

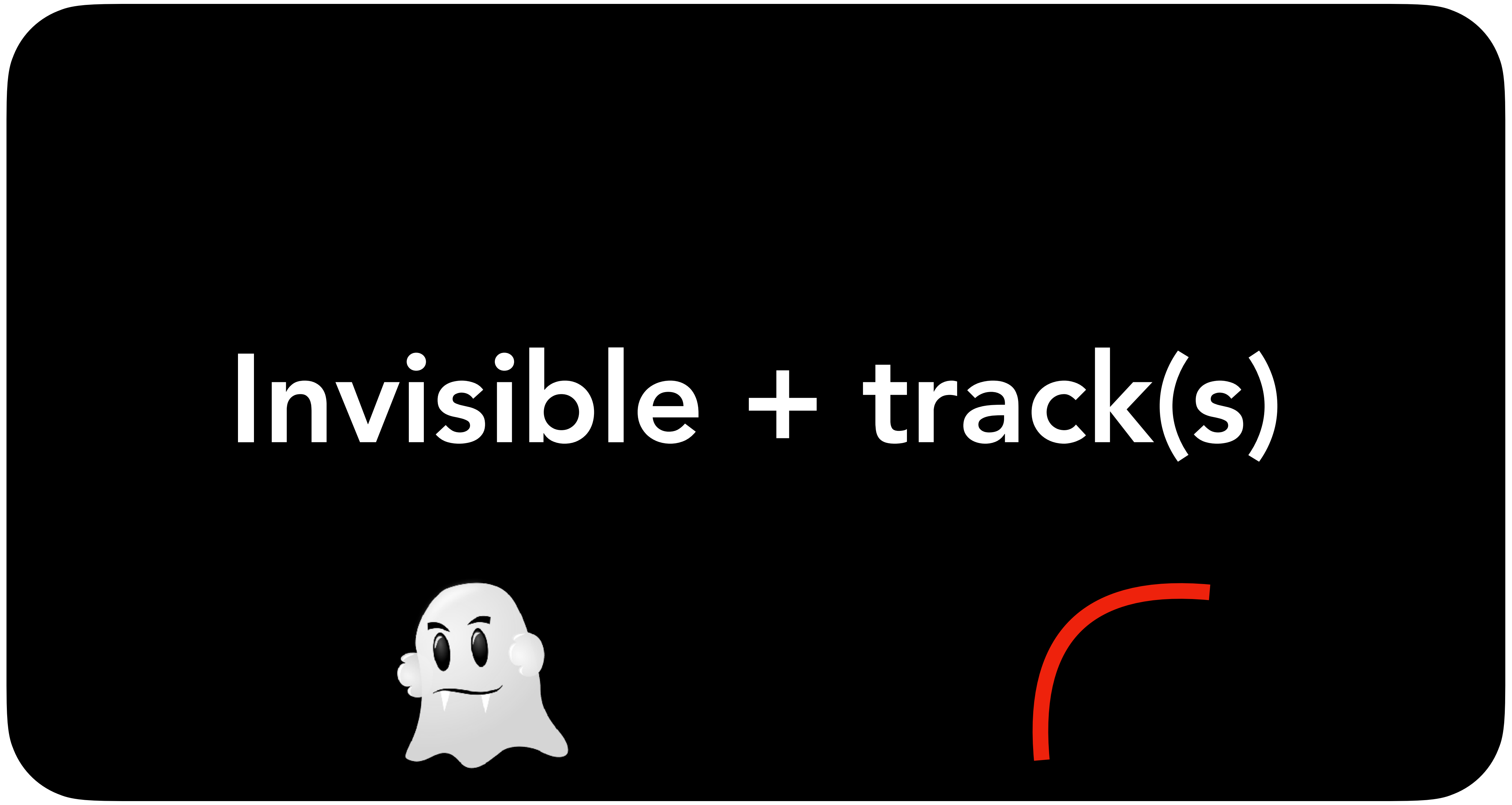
Dark Sector Scenarios:

- Overview of **light** dark models that could interfere: [PRD 82, 034005 (2010)]
- **Heavy**: scalar **X** charged under both QCD and "dark QCD" around a TeV scale, and this mediator has a Yukawa coupling to quarks and dark quarks [JHEP 02, 011 (2022)] → bonus: would also lead to CP asymmetries

$$\mathcal{L}^{int}_{SM-DM} = -\lambda_{ij}\bar{d}_{iR}Q_j X + \mathrm{h.c}$$

- Useful parametrisation: SM extended by additional singlet fermions [EPJC 81 5, 388 (2021)]

Signature 2.



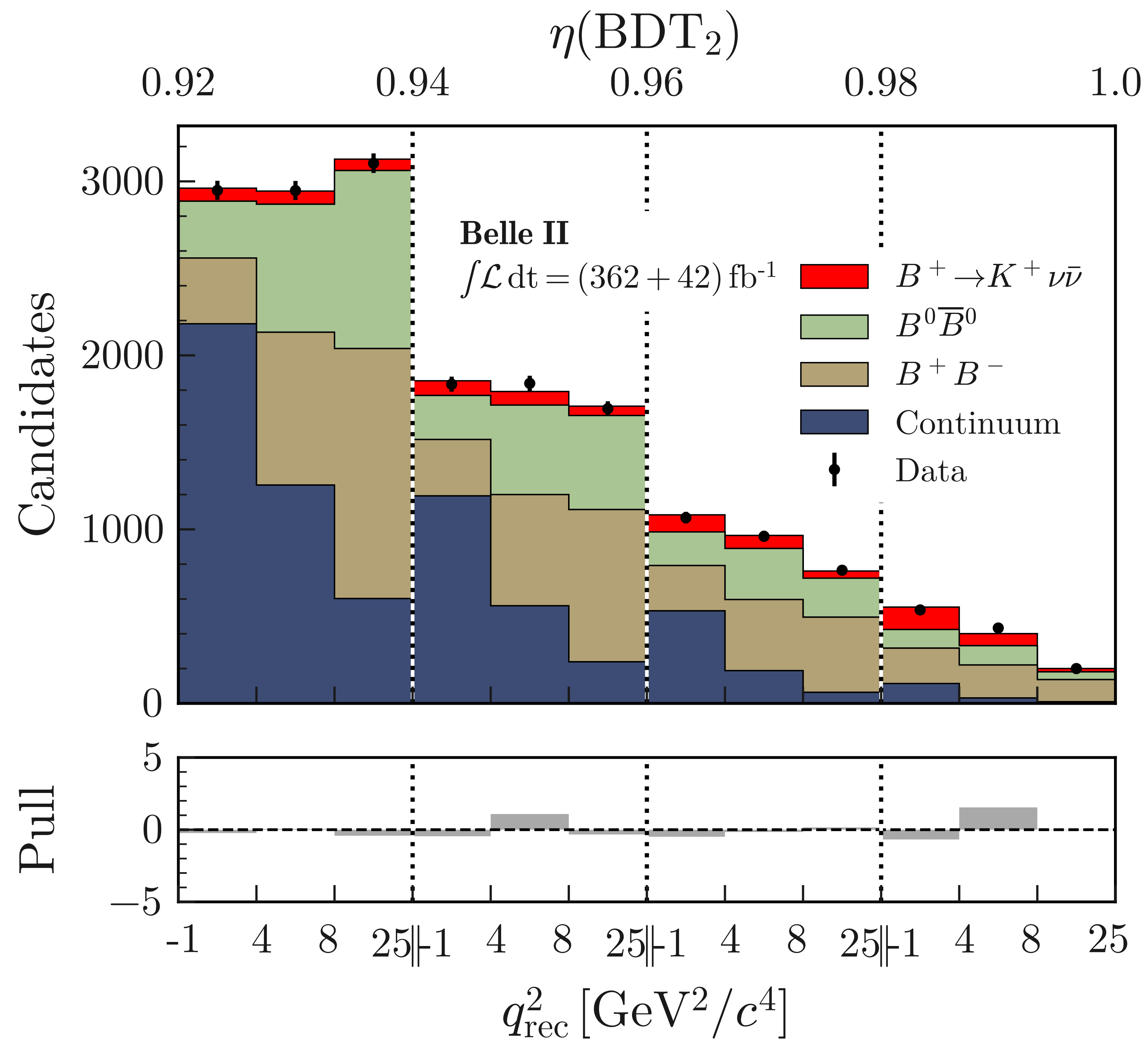
$$\mathrm{e.g.}\ B^+ \rightarrow K^+ + \mathrm{INV}$$

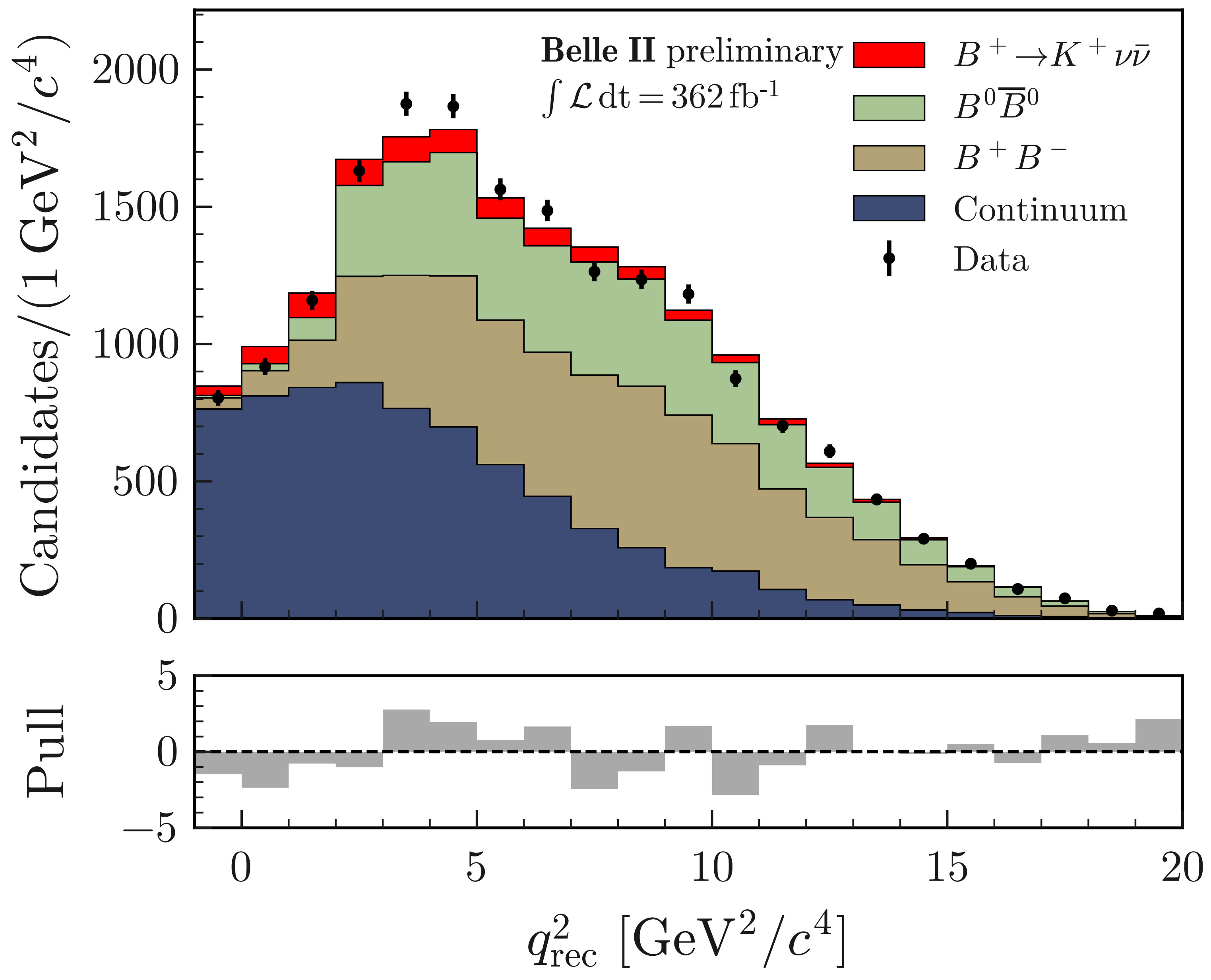
Invisible + track(s)

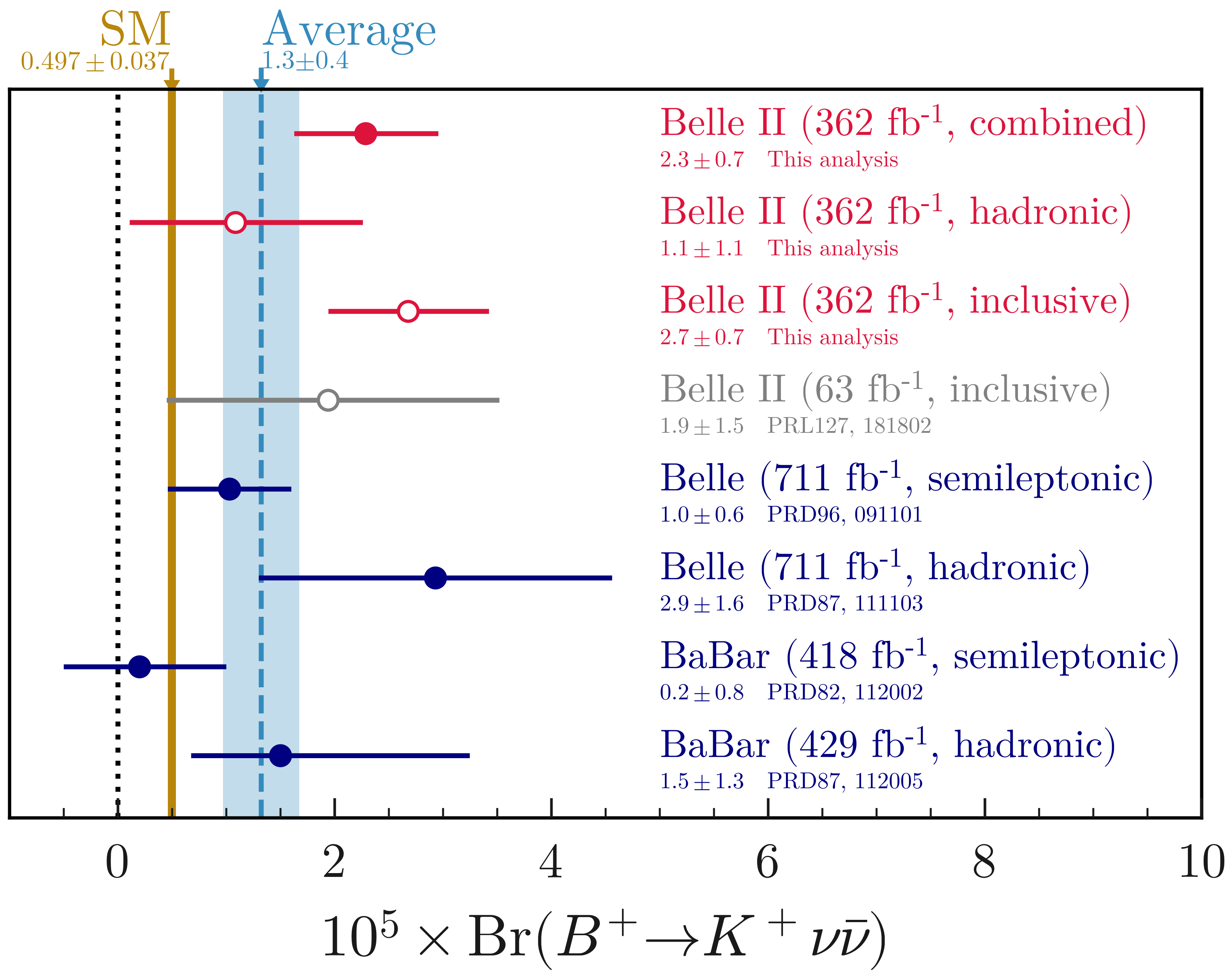
SM $B^+ \to K^+\nu\bar{\nu}$

Belle II searched for $B^+ \to K^+\nu\bar{\nu}$ [PRD 109, 075006 (2024)]:

- SM $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = 5.5 \times 10^{-6}$ [PRD 107, 1324 014511 (2023), PRD 107, 119903 (2023)]
- Roughly 10% uncertainty due to hadronic form factors







$$\mu = 4.6 \pm 1.0(\mathrm{stat}) \pm 0.9(\mathrm{syst})$$

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

Belle II

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

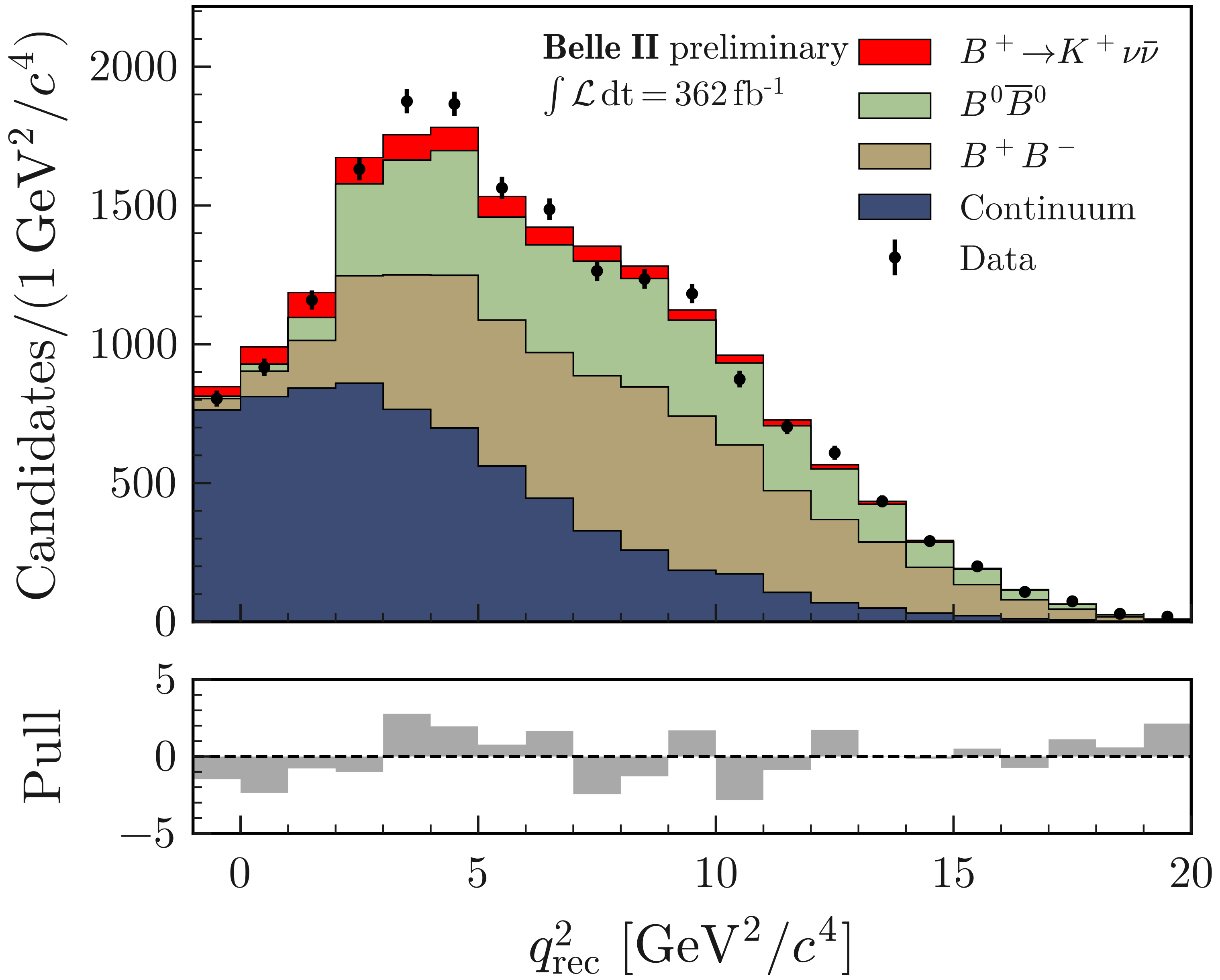
Invisible + track(s)

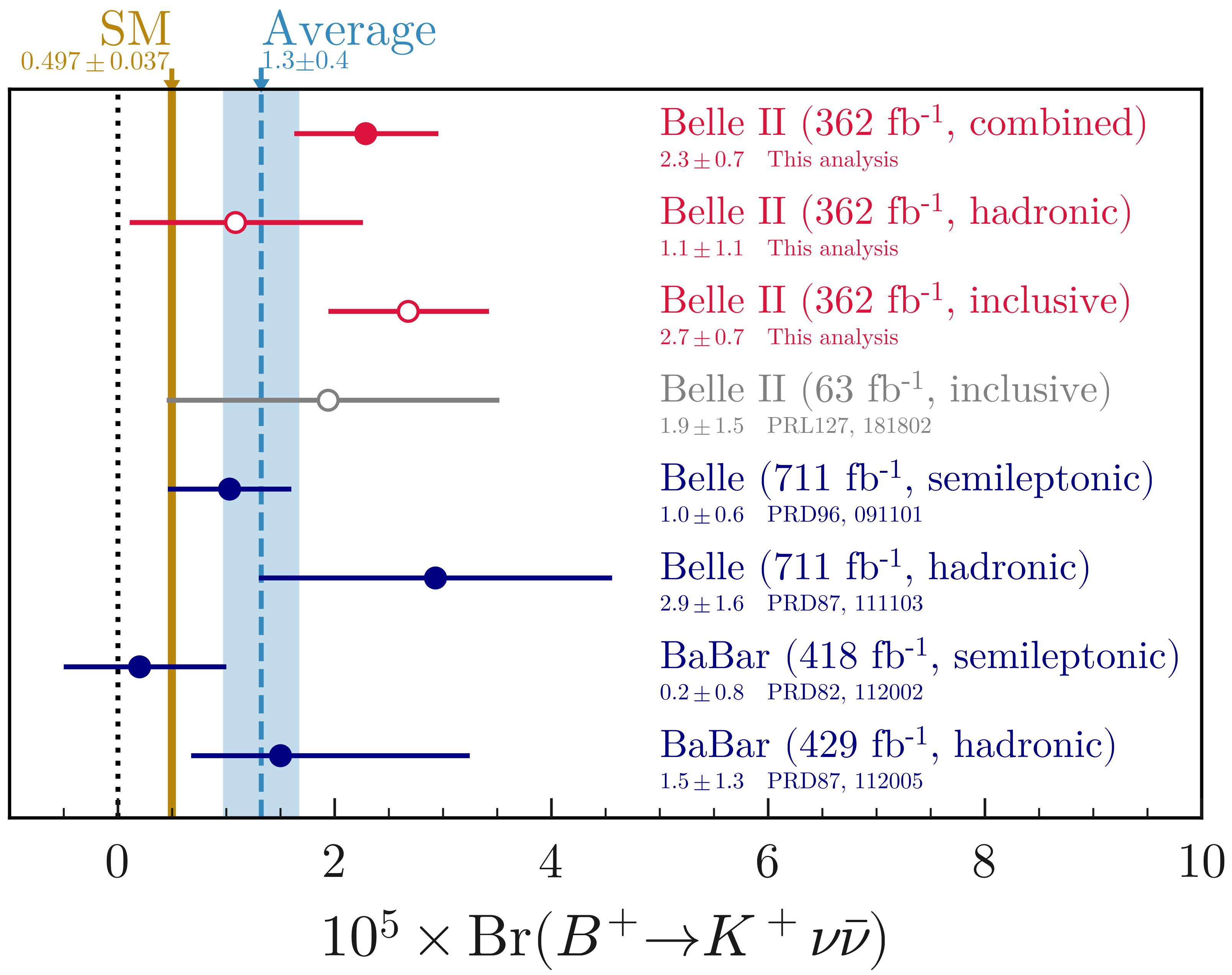
Belle II searched for $B^+ \to K^+\nu\bar{\nu}$ [PRD 109, 075006 (2024)]:

- SM $\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = 5.5 \times 10^{-6}$ [PRD 107, 1324 014511 (2023), PRD 107, 119903 (2023)]
- Roughly 10% uncertainty due to hadronic form factors

Challenges:

- Clean environment
- Good understanding of neutrals
- Separating variables needs to well understood
- Keep high tracking efficiency





$$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$$

$$\mathscr{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{syst})] \times 10^{-5}$$

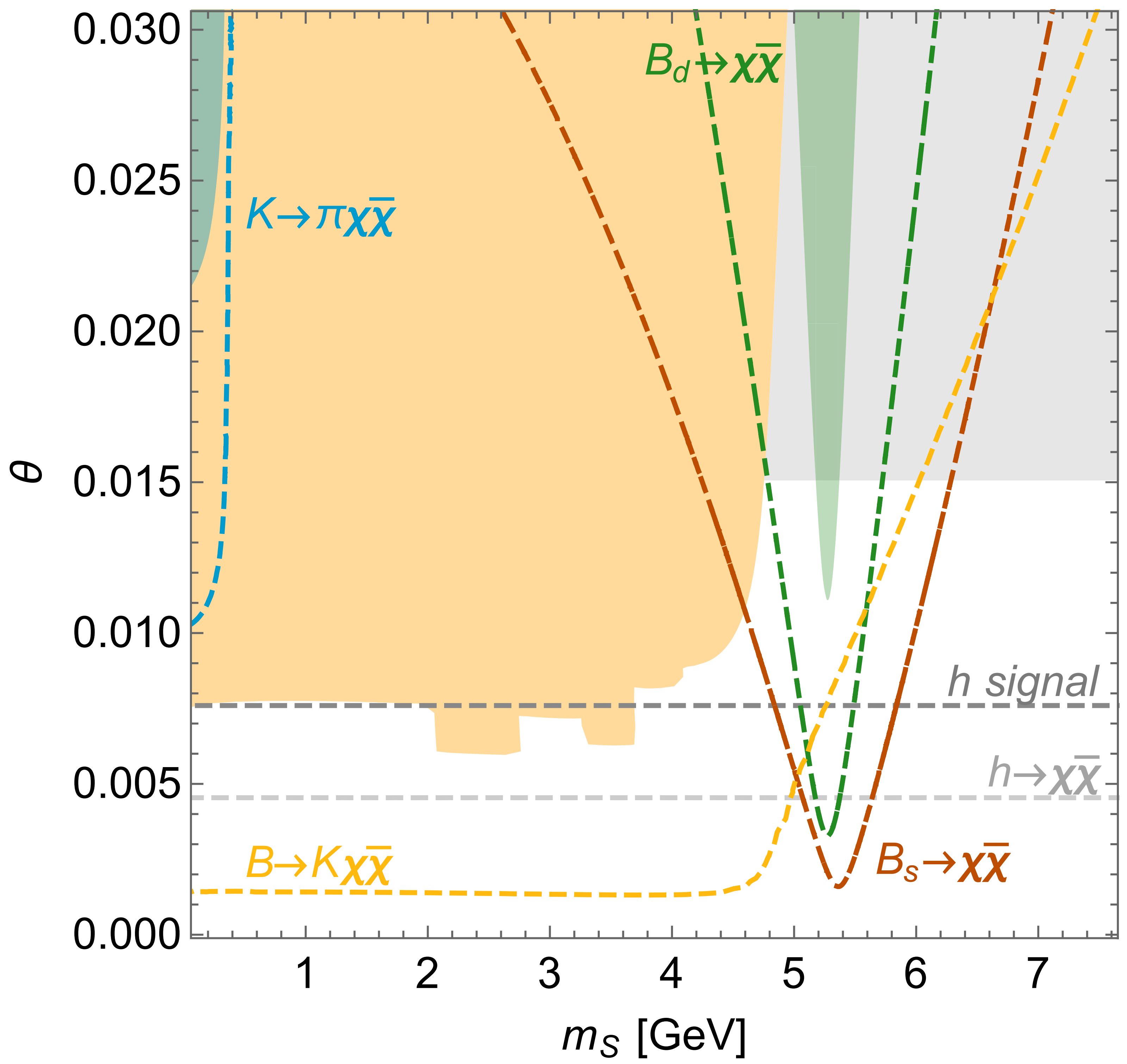
Scalar Mediators

Invisible + track(s)

Scalar decay of $S \to \chi\bar{\chi}$:

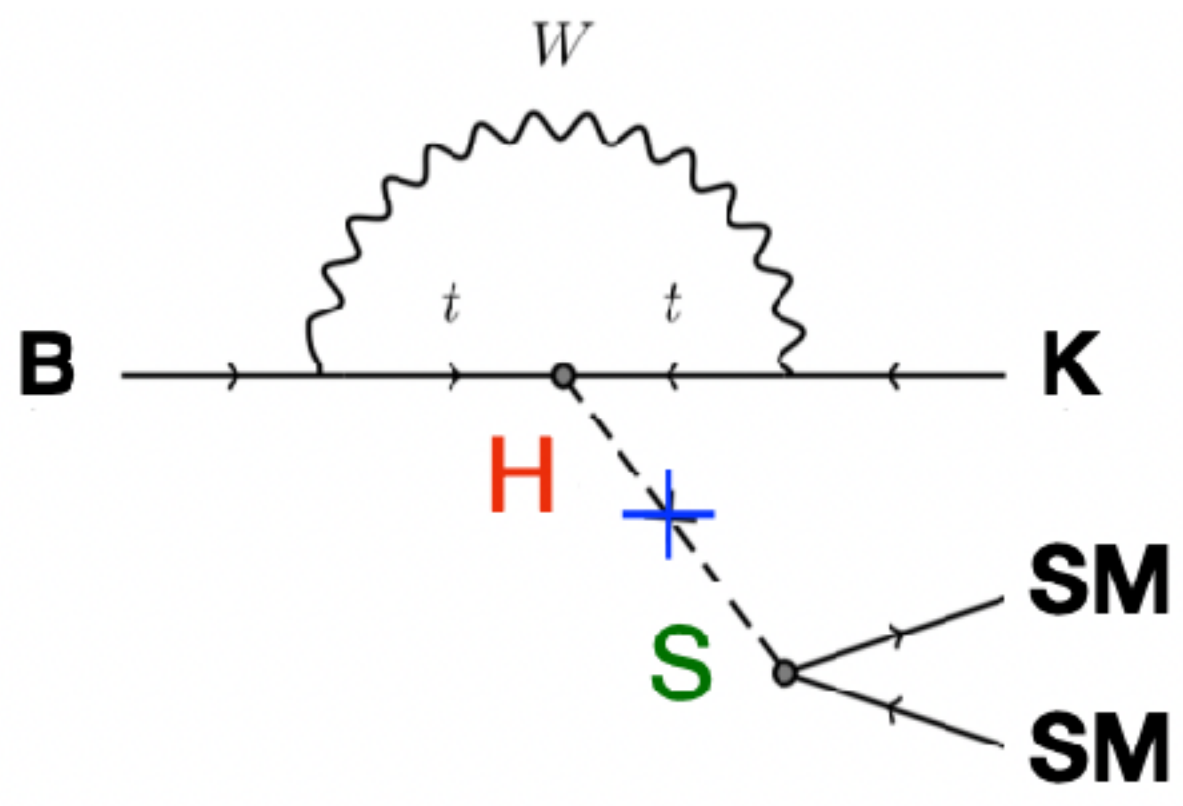
- Requires $m_S > 2m_\chi$
- Parameter space heavily ruled out with right relic density ruled out by direct detection + BABAR

[PRD 101, 095006 (2020)]



$$\mathscr{L} \supset -\frac{1}{2}m_\phi^2\phi^2 - m_\chi\bar{\chi}\chi - \lambda_3\phi H^\dagger H - y_\chi\bar{\chi}\chi\phi$$

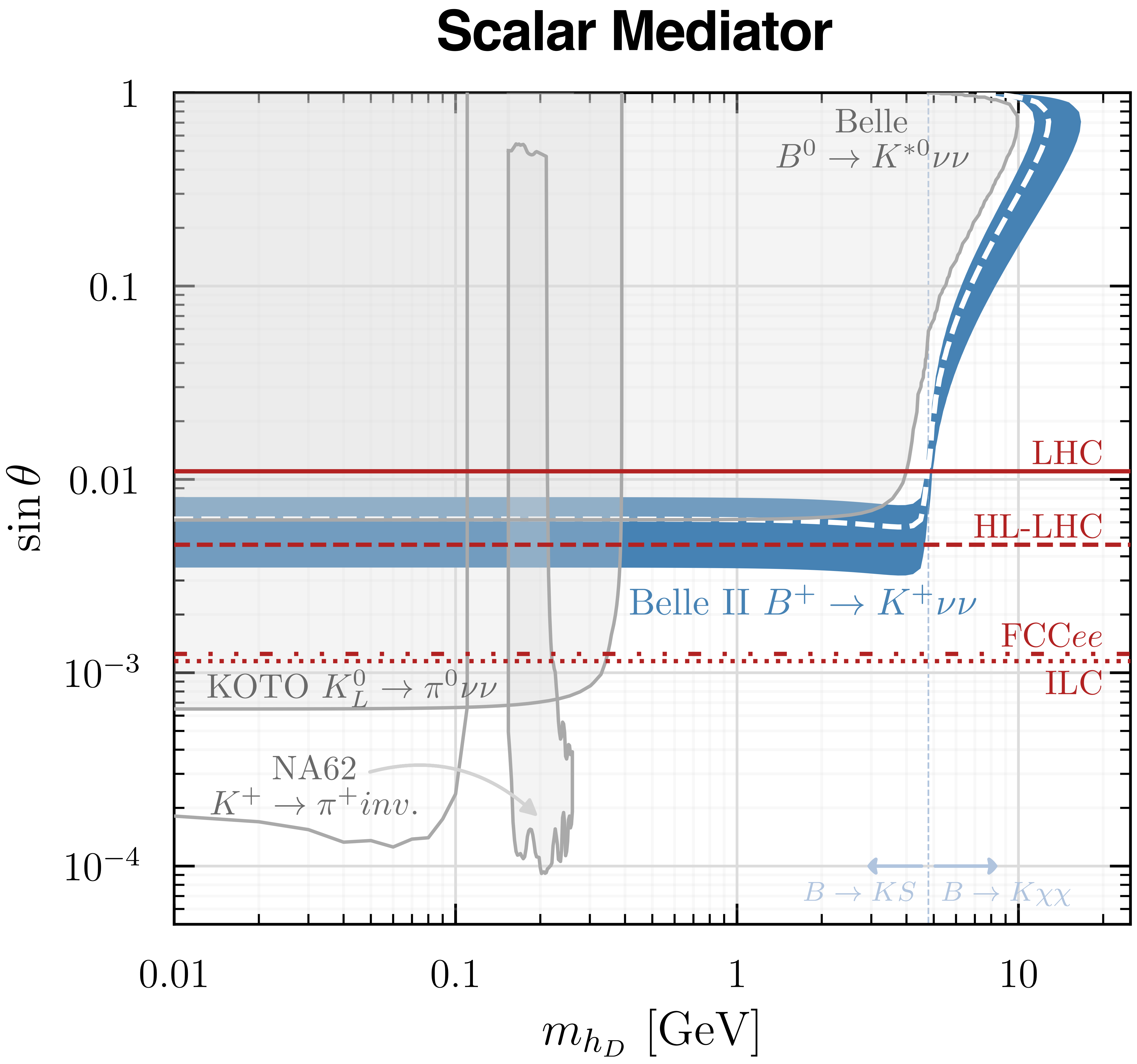
- BABAR
- Belle
- invisibly decay Higgs



UNIVERSITÄT BONN

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

Invisible + track(s)



[PRD 109, 075006 (2024)]

Pseudoscalar ALPs

Invisible + track(s)

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

$$\mathscr{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a}{2}a^2 + \frac{\partial^\mu a}{f_a}\sum_f \frac{c_f}{2}\bar{f}\gamma_\mu\gamma_5 f + \frac{c_\chi}{2}\frac{\partial^\mu a}{f_a}\bar{\chi}\gamma_\mu\gamma_5\chi$$

$$+ c_{GG}\frac{g_s^2}{(4\pi)^2}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{A,\mu\nu} + c_{BB}\frac{g'^2}{(4\pi)^2}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{WW}\frac{g^2}{(4\pi)^2}\frac{a}{f_a}W^A_{\mu\nu}\tilde{W}^{A,\mu\nu}$$

"c_{ff}" : ALP coupling to fermions

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

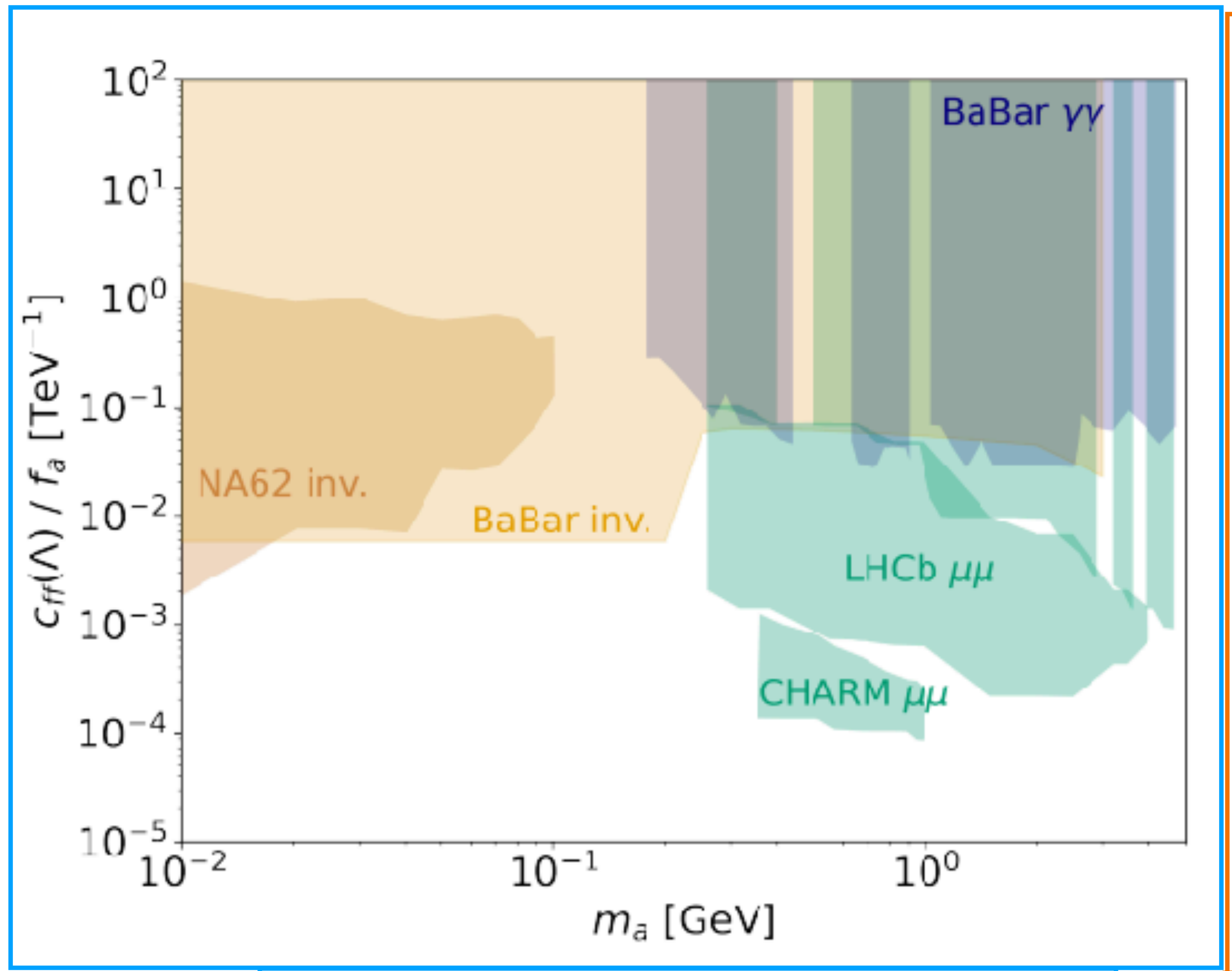
$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + ac + bc)$

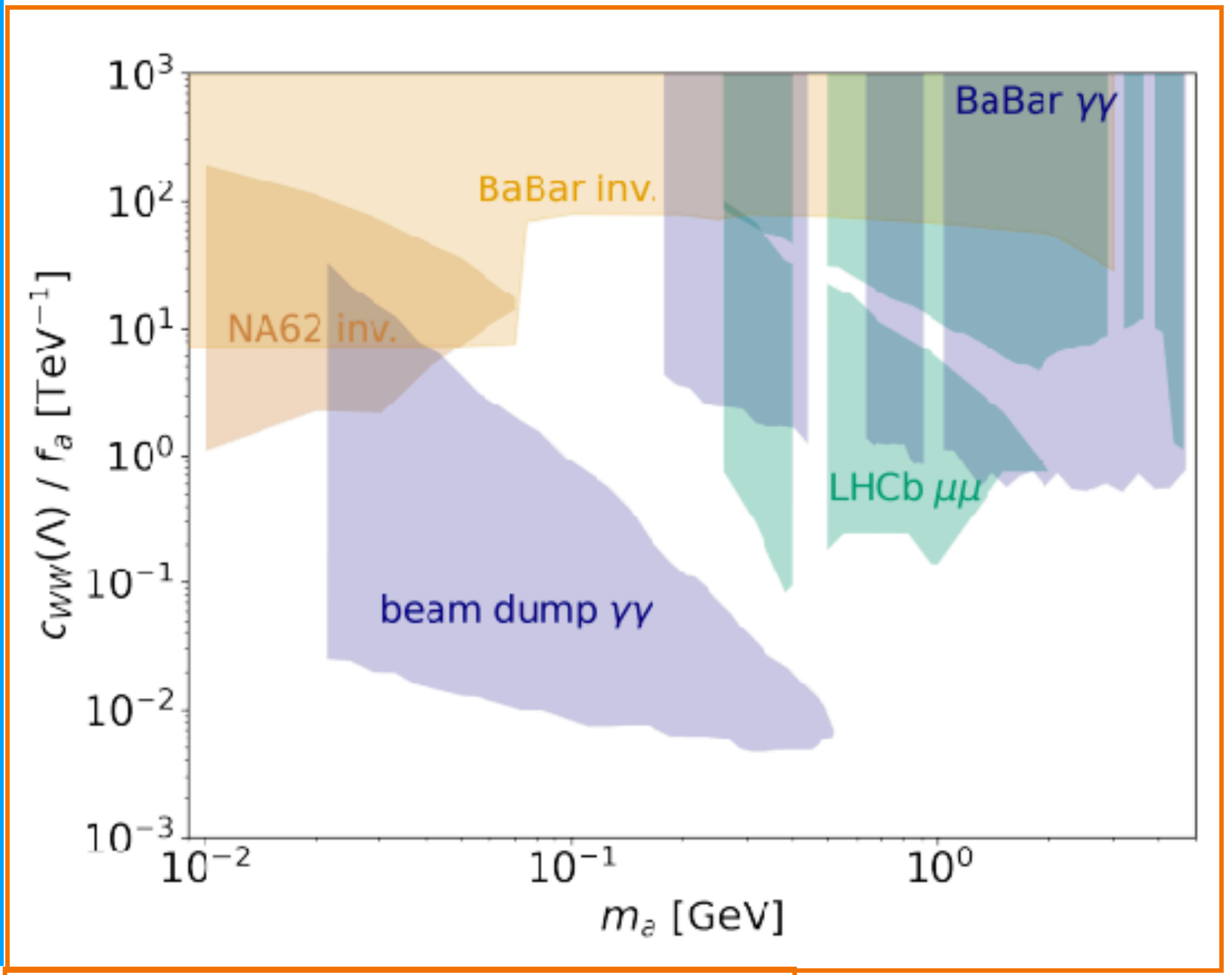
f_0 = scalar FF

[JHEP 04, 131 (2023)]

Pseudoscalar mediator with fermionic DM avoids direct detection:

- Special type of pseudoscalar: axion-like particle defined by shift symmetry a → a + c





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

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

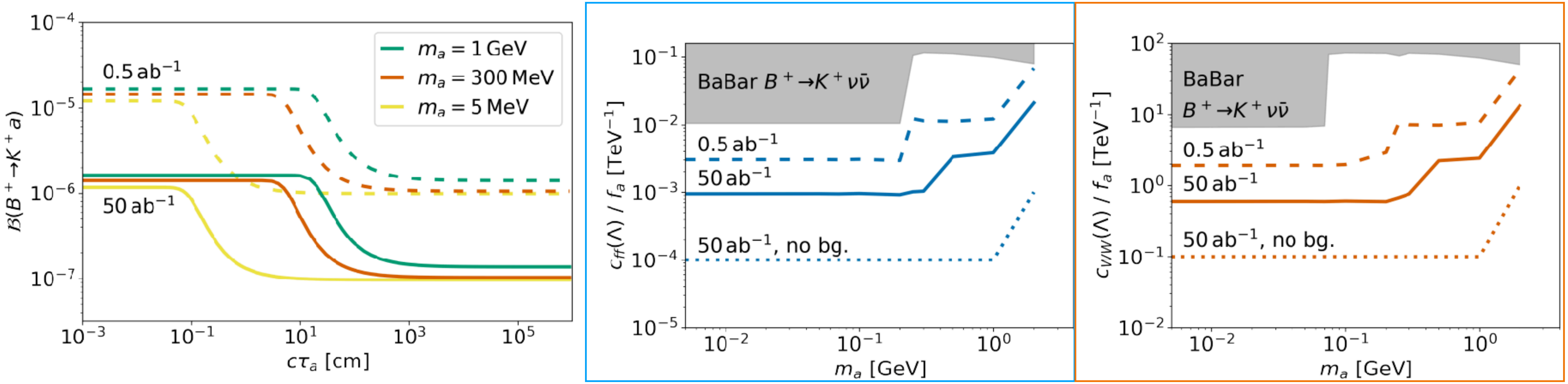
Pseudoscalar ALPs

Invisible + track(s)

Simplified sensitivity study probing different m_A scenarios for $m_a \in (5\mathrm{MeV}, 4.6\mathrm{GeV})$:

- With $0.5\mathrm{ab}^{-1}$ limit on $\mathscr{B}(B^+ \to K^+ a) < 10^{-5} @ 90\ \mathrm{C.L.}$ → expect 1 order of magnitude improvement
- With $50\ \mathrm{ab}^{-1}$ limit on $\mathscr{B}(B^+ \to K^+ a) < 10^{-7} @ 90\,\%\,\mathrm{C.L}$ → expect 2 orders of magnitude improvement

[JHEP 04, 131 (2023)]

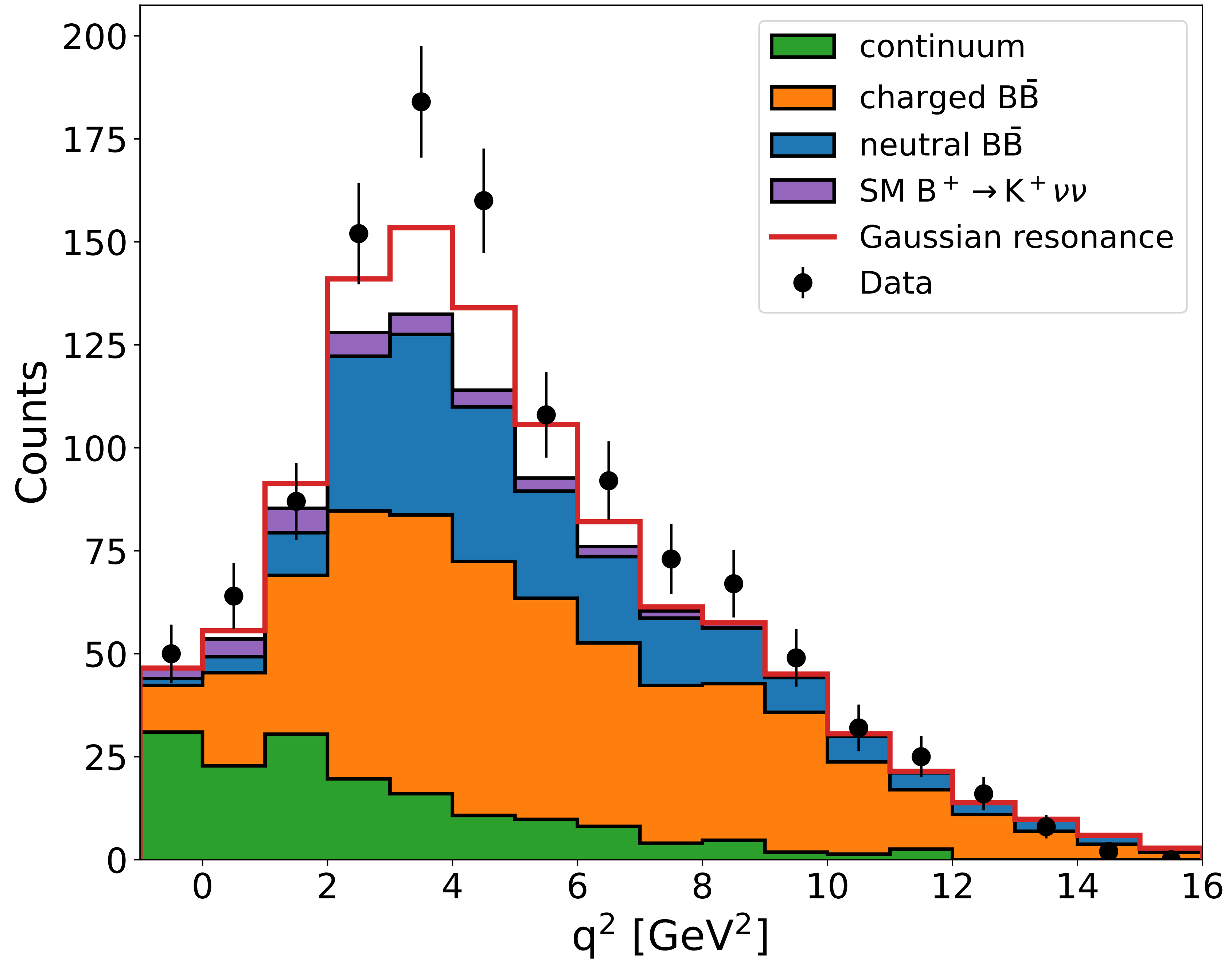


Reinterpreted $B^+ \to K^+\nu\bar{\nu}$

Invisible + track(s)

Pseudoscalar ALPs

[arxiv: 2311.14629]

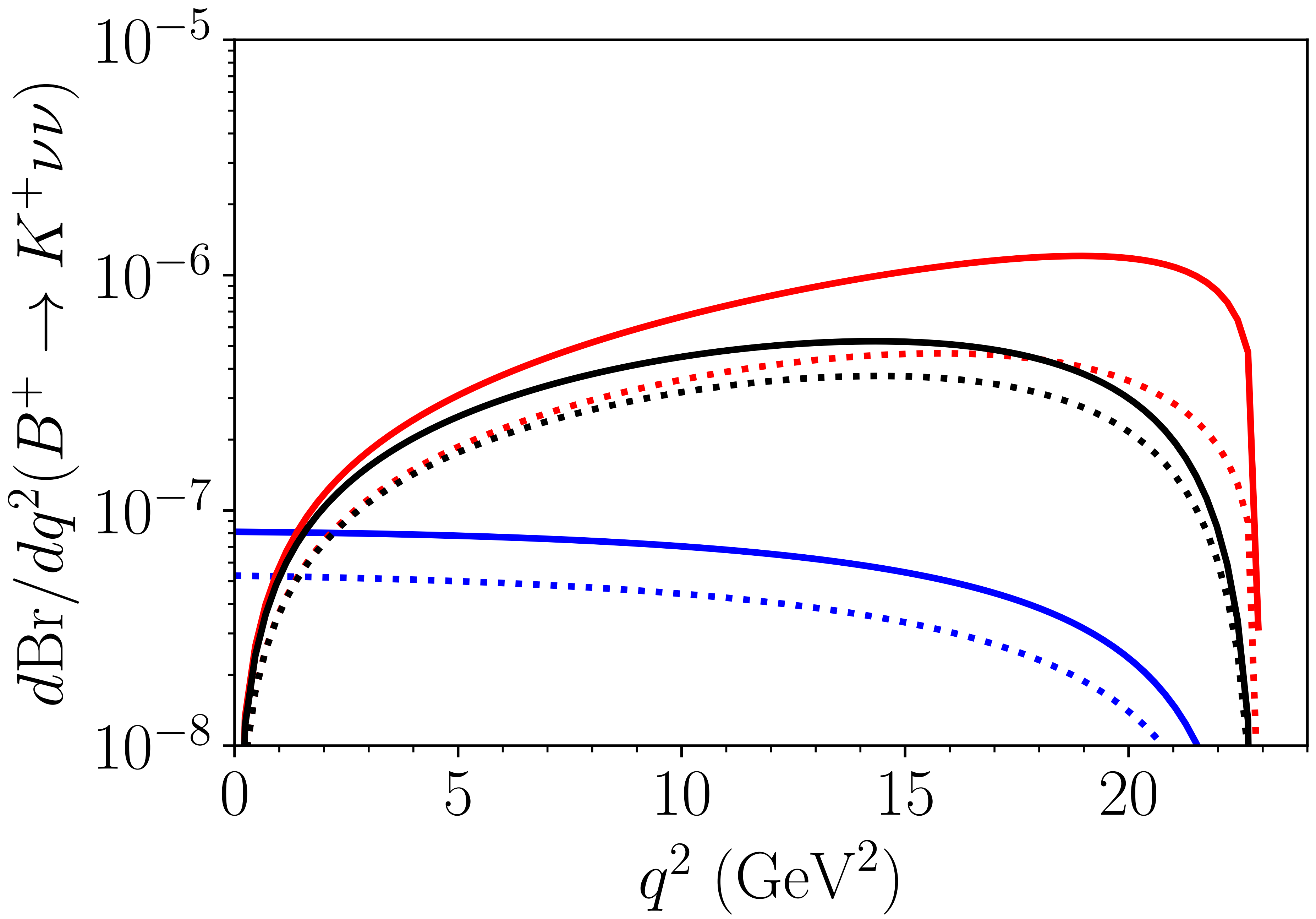


Main outcome:

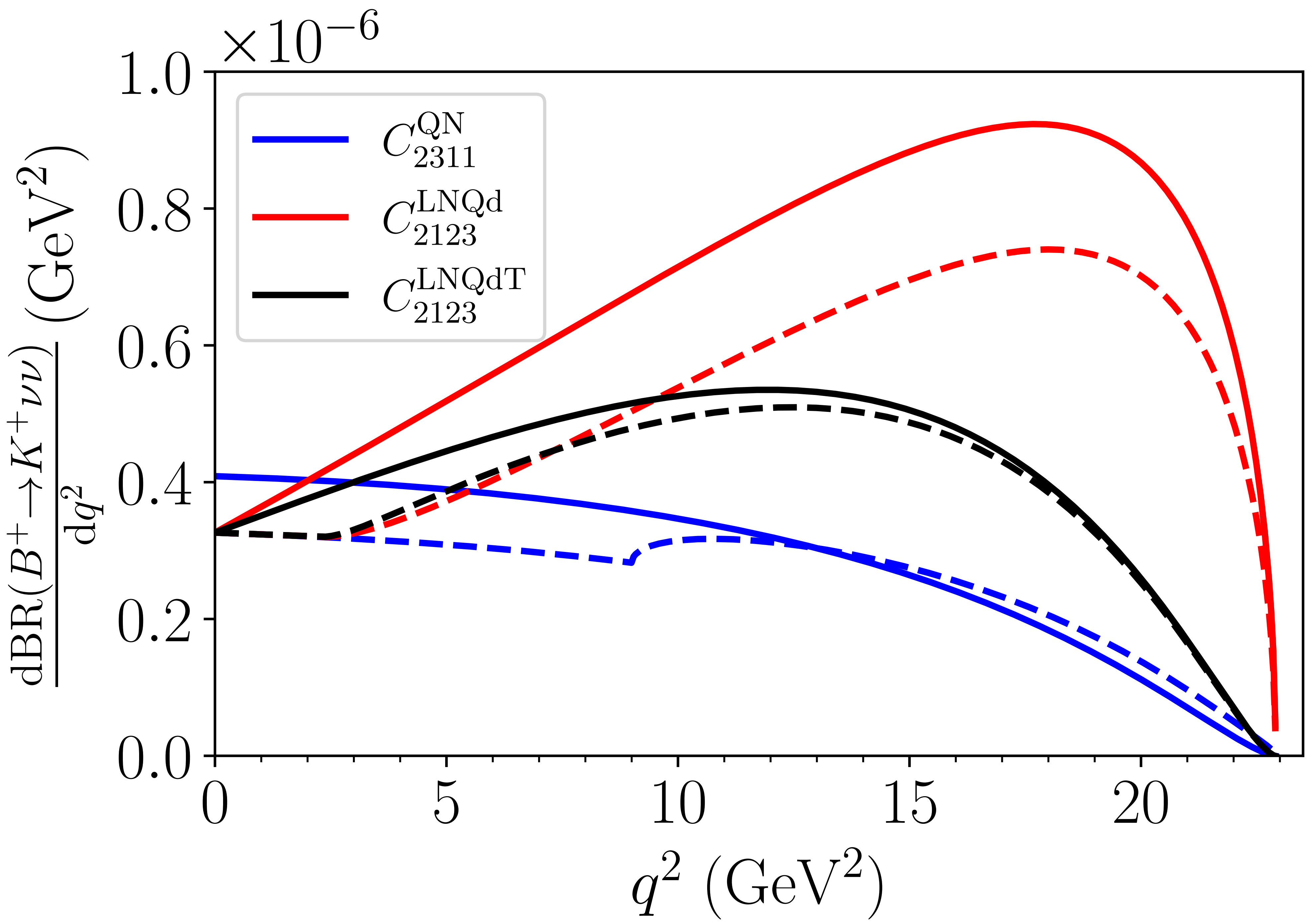
- In terms of the ALP decay constant, implies $F_V = 2f/gV = 3.1^{+1.0}_{-0.5} \times 10^{-8}$ for m_a = 2 GeV
- Upper limit from $B \to K^*a$ $F_A = 2f/gA >= 1.7 \times 10^{-8} @ 2\sigma$

Invisible + track(s)

Sterile Neutrinos



[JHEP 12, 118 (2021)]



[EPJC 83 12, 1135 (2023)]

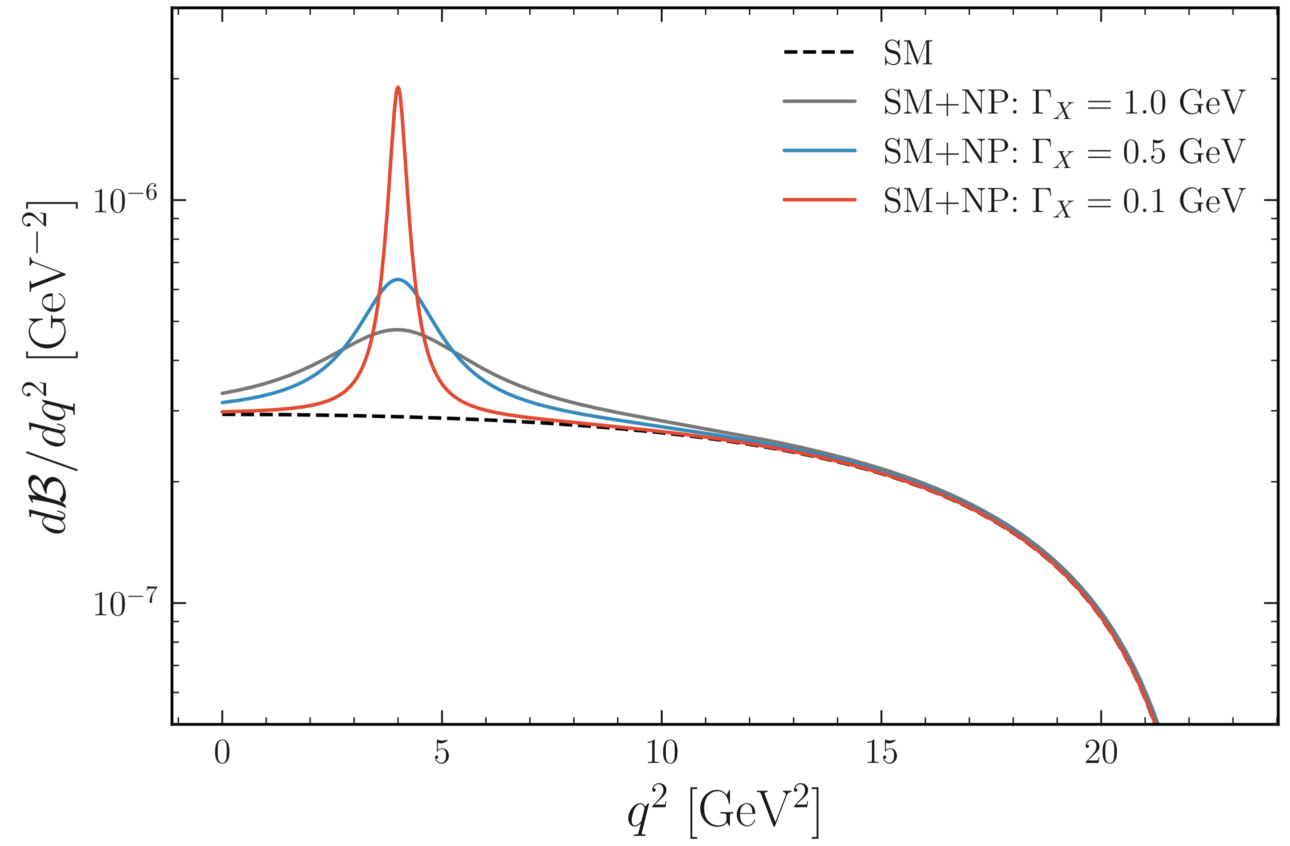
Changes the branching fraction as a function of q^2

UNIVERSITÄT BONN

Belle II Reinterpretation

Invisible + track(s)

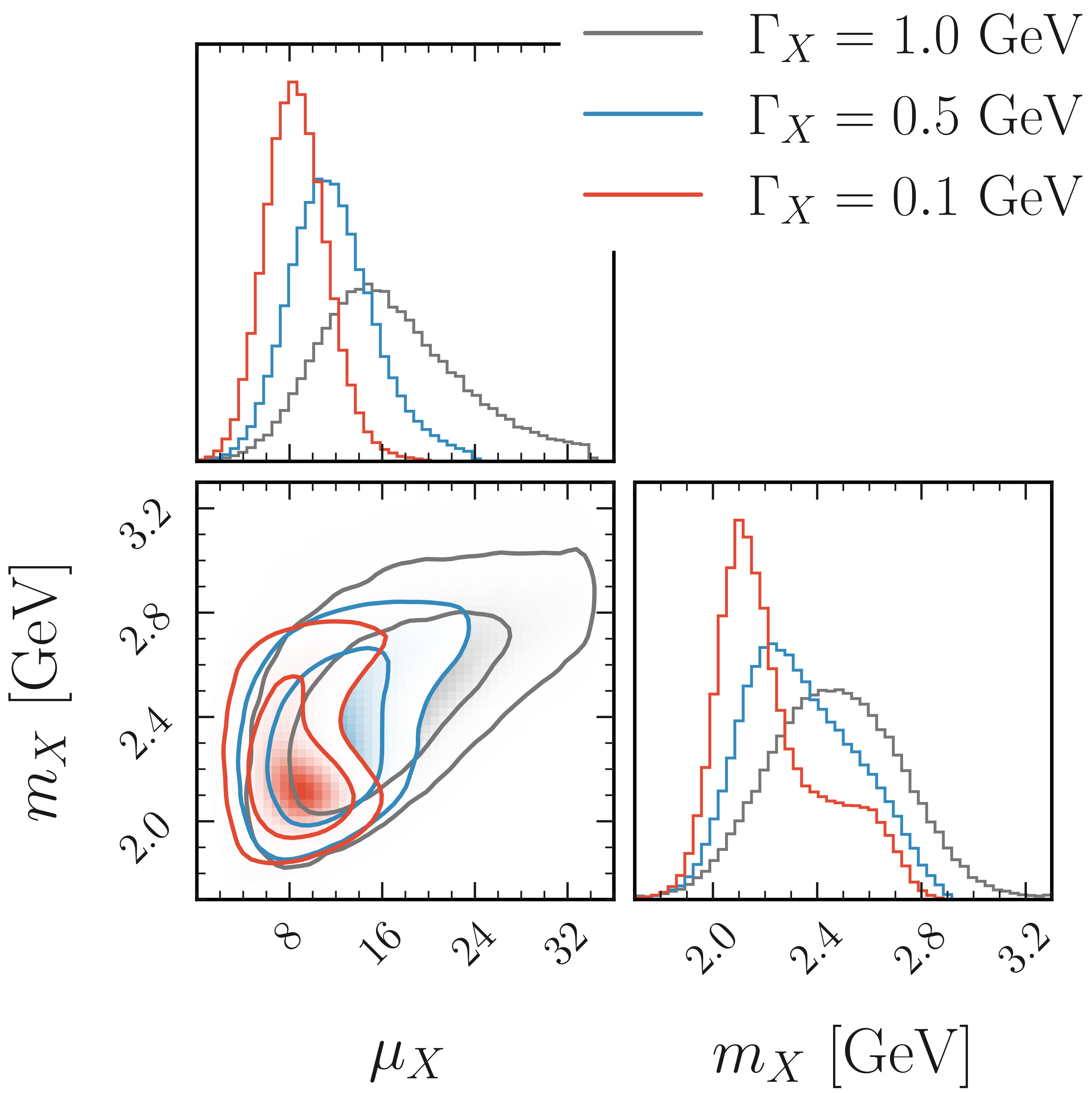
Belle II will provide its own reinterpretation as $B^+ \to K^+X$, see [Lorenz Gartner talk this week]



Model shown for $\mu_X = 1$, $m_X = 2$ GeV.

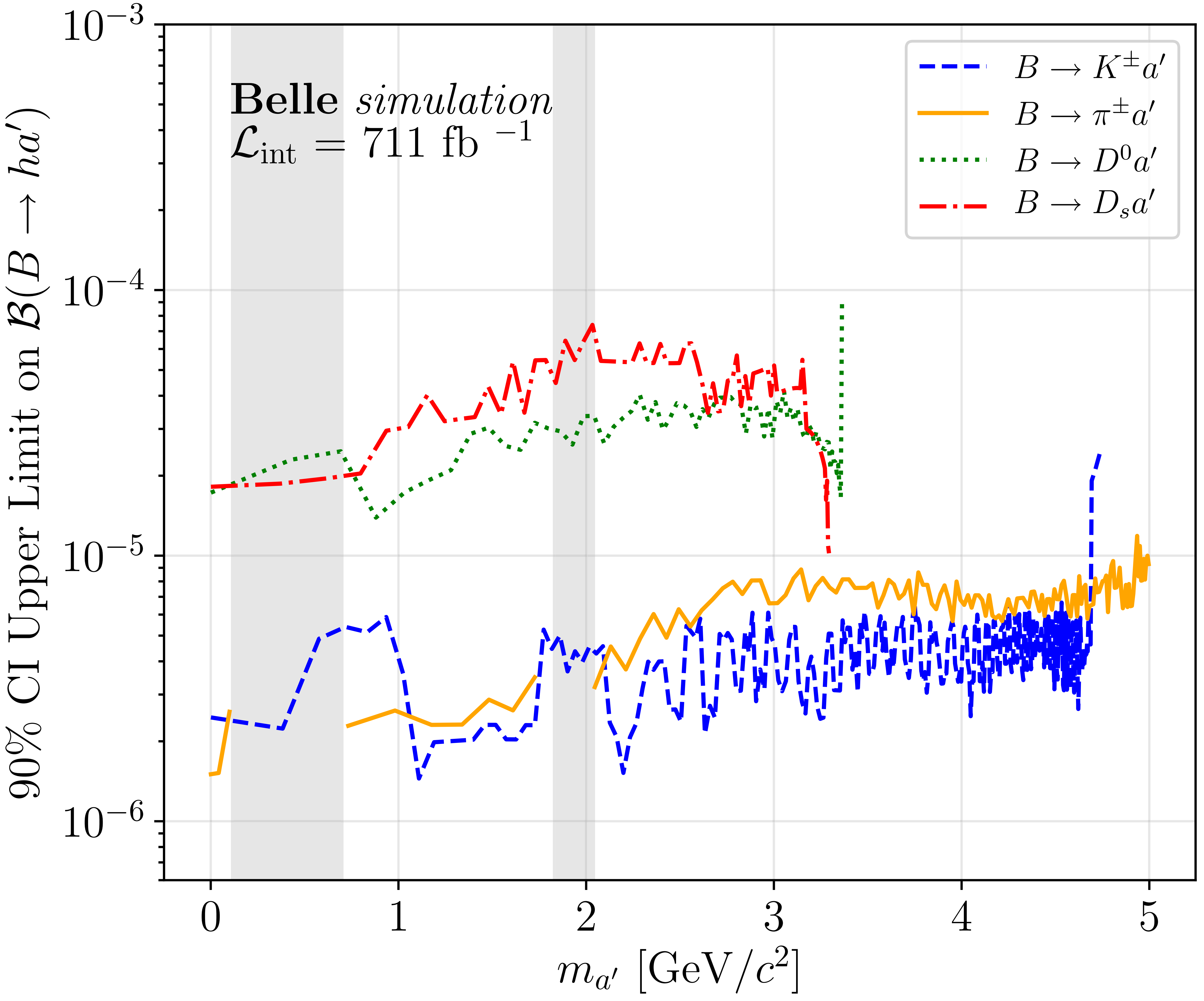
$$\mathcal{B}(B^+ \to K^+X) \in [0.34, 1.4] \times 10^{-5}$$
$$m_X \in [1.9, 2.7]\ \text{GeV}$$

- Consistent with results of arXiv:2311.14629 [hep-ph], arXiv:2312.12507 [hep-ph]



Non-$b \to s$ transitions

Invisible + track(s)



[PRD 109 1, 016008 (2024)]

B- mesogenesis

Invisible + track(s)

See more in Gilly Elor's talk from this week

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

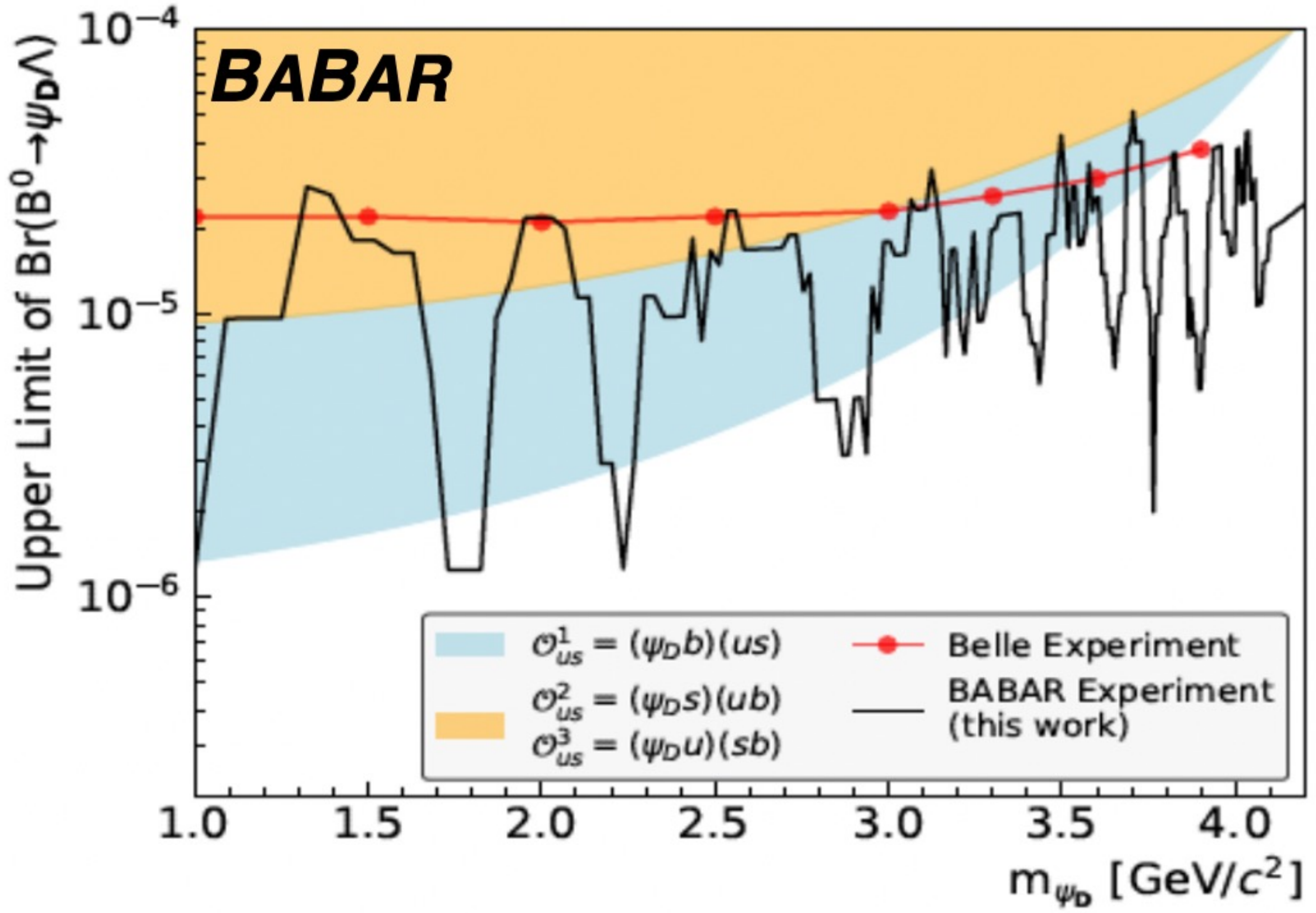
Processes we can search for:

- $B^+ \to p + \Psi_D$
- $B^0 \to \Lambda + \Psi_D$
- $B^0 \to \pi^- + \Lambda_C^+ + \Psi_D$

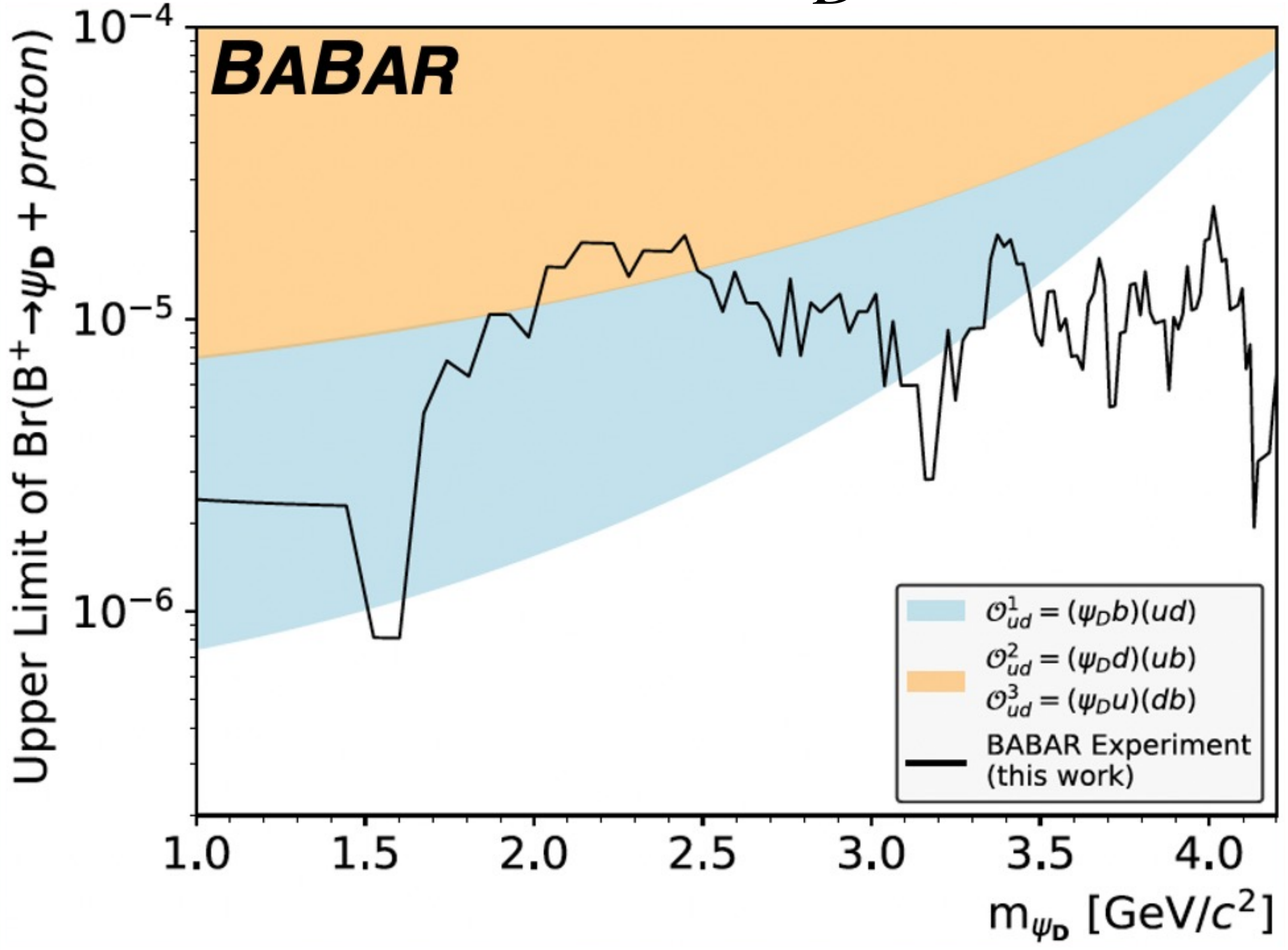
Belle & BaBar set limits:

- [PRD 105 5, L051101 (2022)]
- [PRL 131, 201801 (2023)]

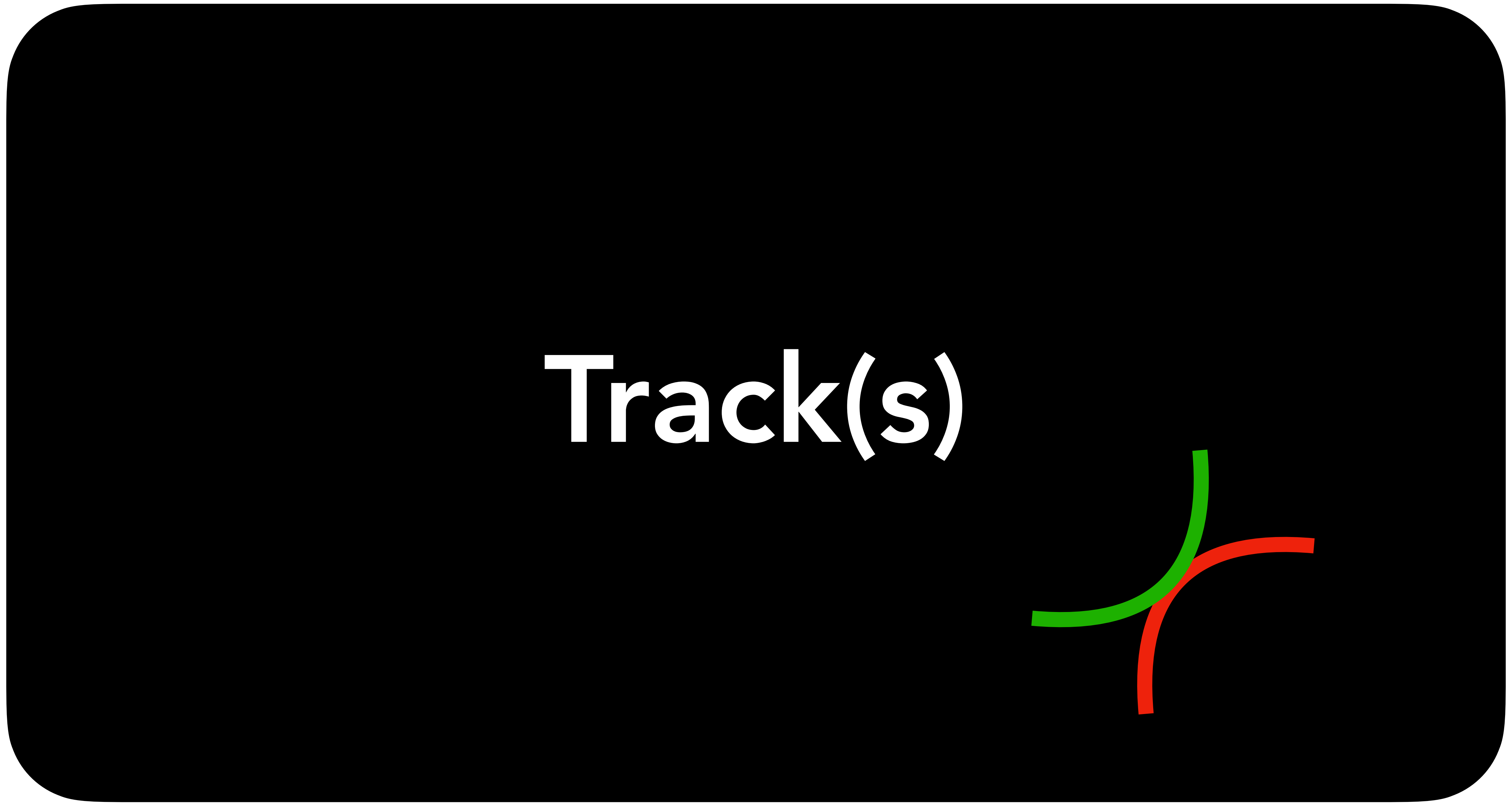
$B^0 \to \Psi_D + \Lambda$



$B^+ \to \Psi_D + p$



Signature 3.



$$e.g.\ B \to KX(X \to Y^+Y^-)$$

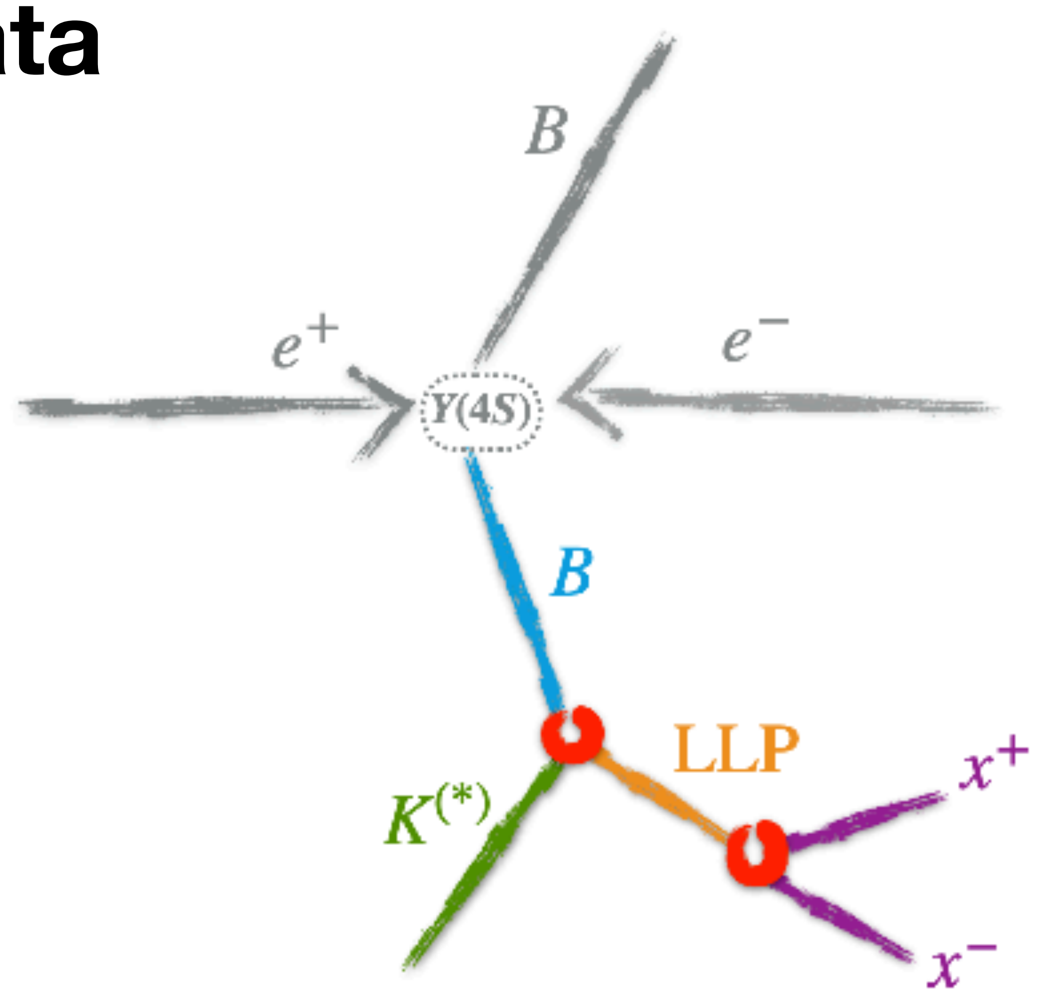
First Search for $B \to KS$ @ Belle II

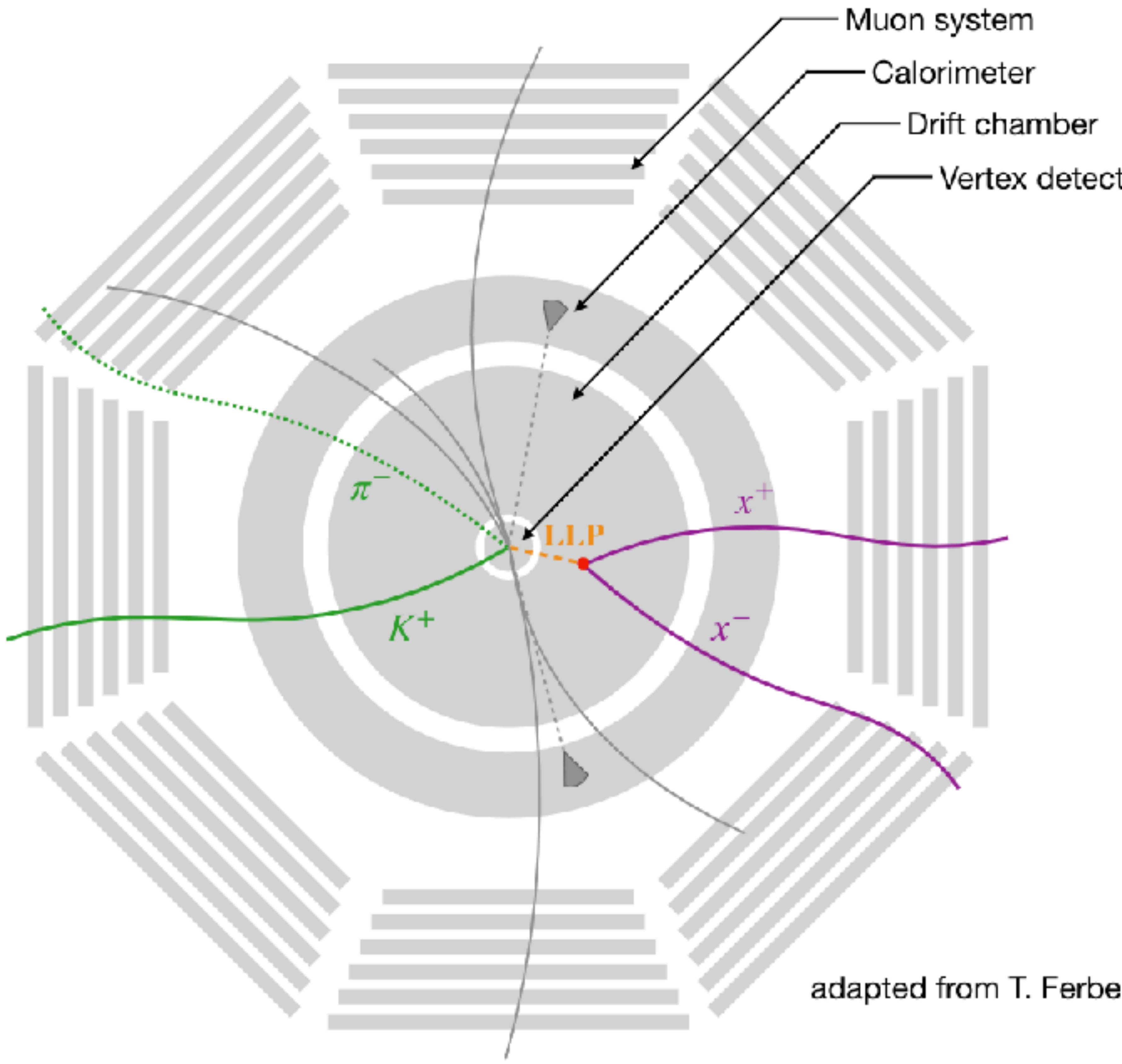
Tracks

[PRD 108, L111104(2023)]

Search Strategy: ***long-lived scalar particle = LLP*** **that decays visibly into pair of charged particles** $x^+x^-, x \in (e, \mu, \pi, K)$**:**

- Both $B^+ \to K^+$ LLP and $B^0 \to K^{*0}[K^+\pi^0]S$
- Bump hunt in the invariant mass m_{LLP} for each lifetime separately
  - Separately for $x \in (e, \mu, \pi, K)$
  - Separately for different lifetimes ($0.001 < c\tau < 400$ cm)
  - Vertex radial distance $dr >$ 0.05 & $dr >$ 0.2 cm around reson.
- Used first **189 fb^{-1} data**





adapted from T. Ferbe

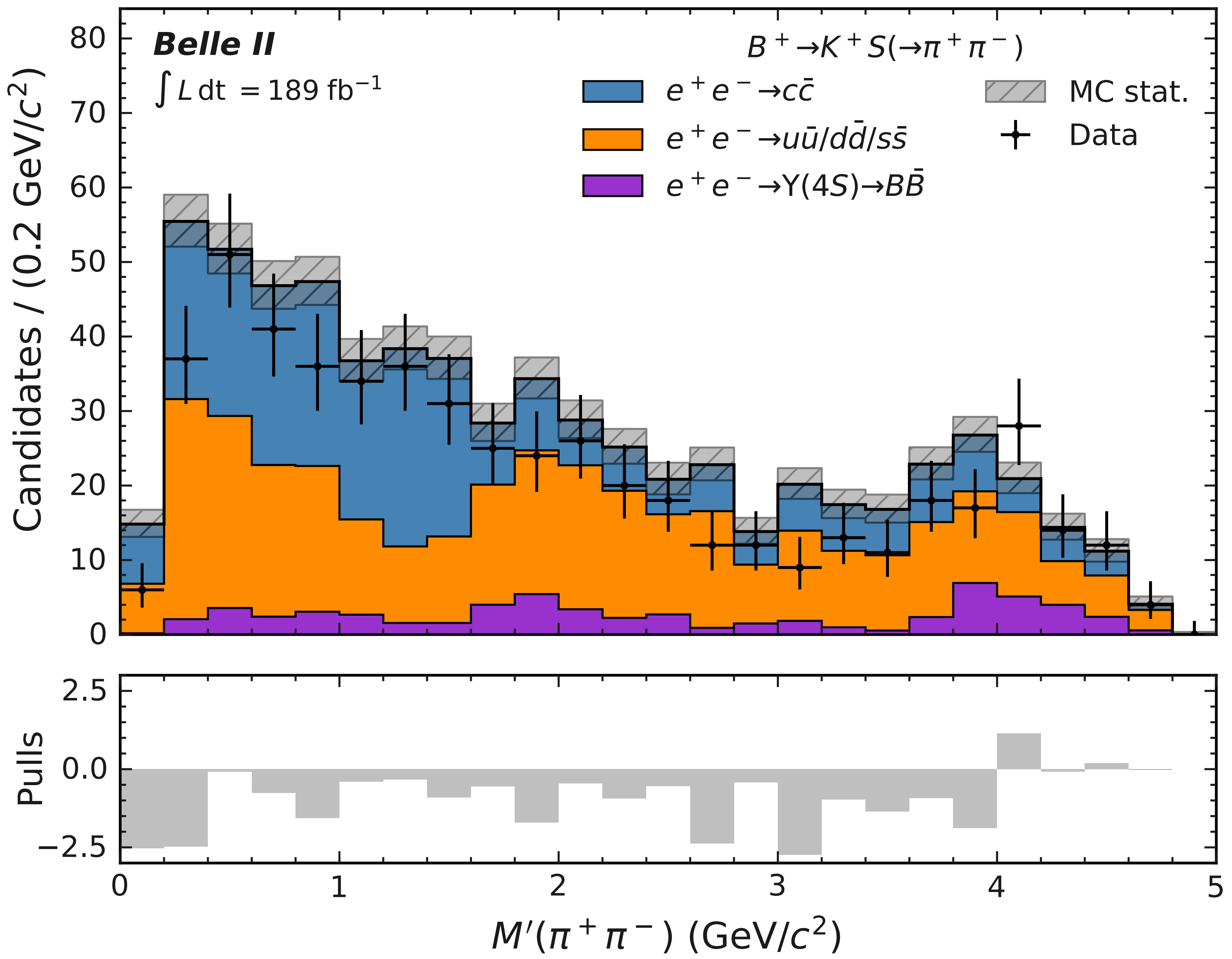
First Search for $B \to KS$ @ Belle II

Tracks

[PRD 108, L111104(2023)]

Experimental challenges:

- Simulation generation for all mass hypotheses and lifetimes
- Performance with displaced vertex signature → use K_S^0 as guinea pig
  - PID
  - Reconstruction efficiency
  - m_{LLP} shape
- Low count fitting

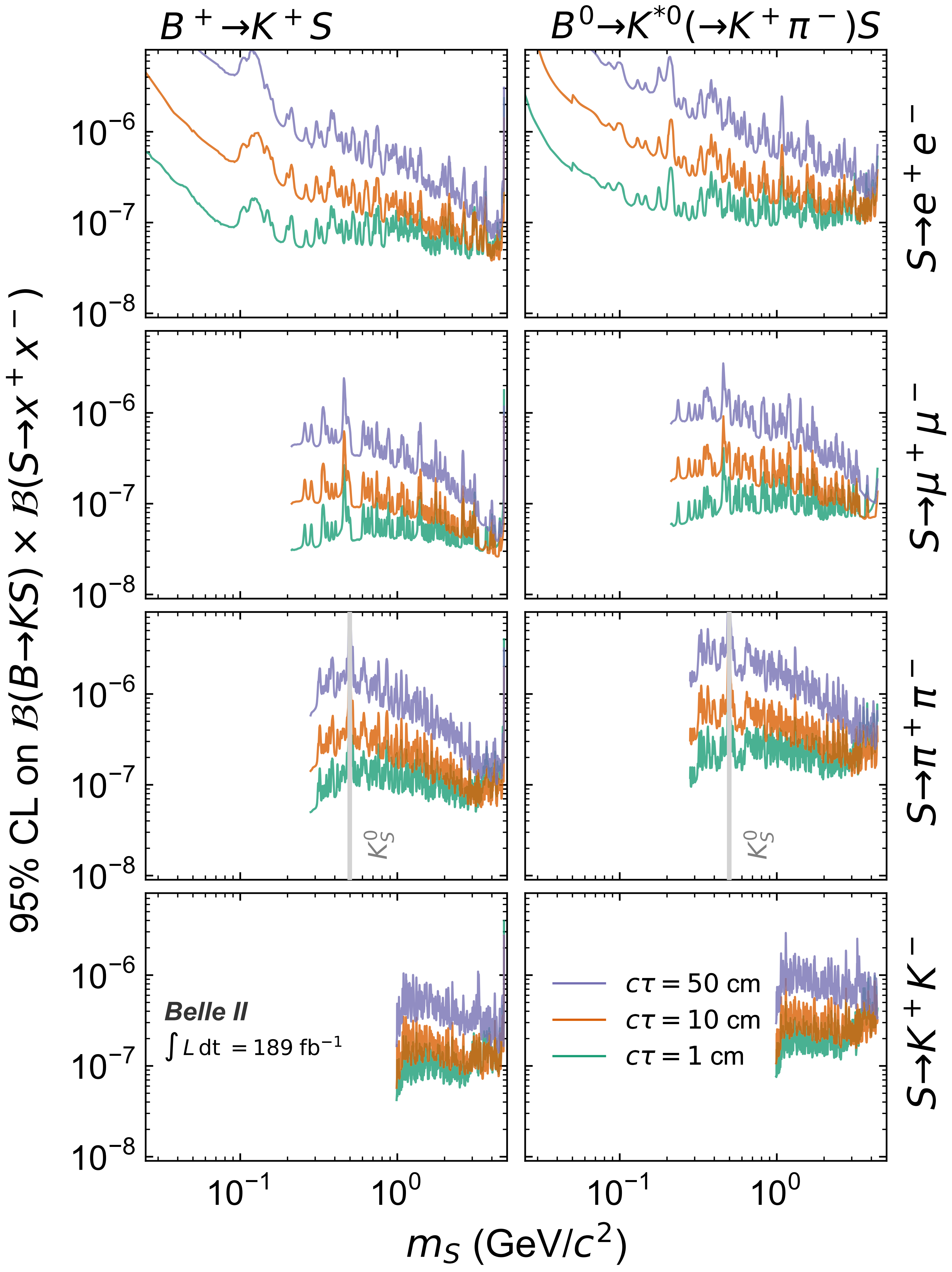


Fits to other channels also available on HEPdata repository

HEPData

First Results for $B \to KS$ @ Belle II

Tracks



[PRD 108, L111104(2023)]

Results (Step 0):

- Extract model independent limits
- Different colors represent independent lifetime!

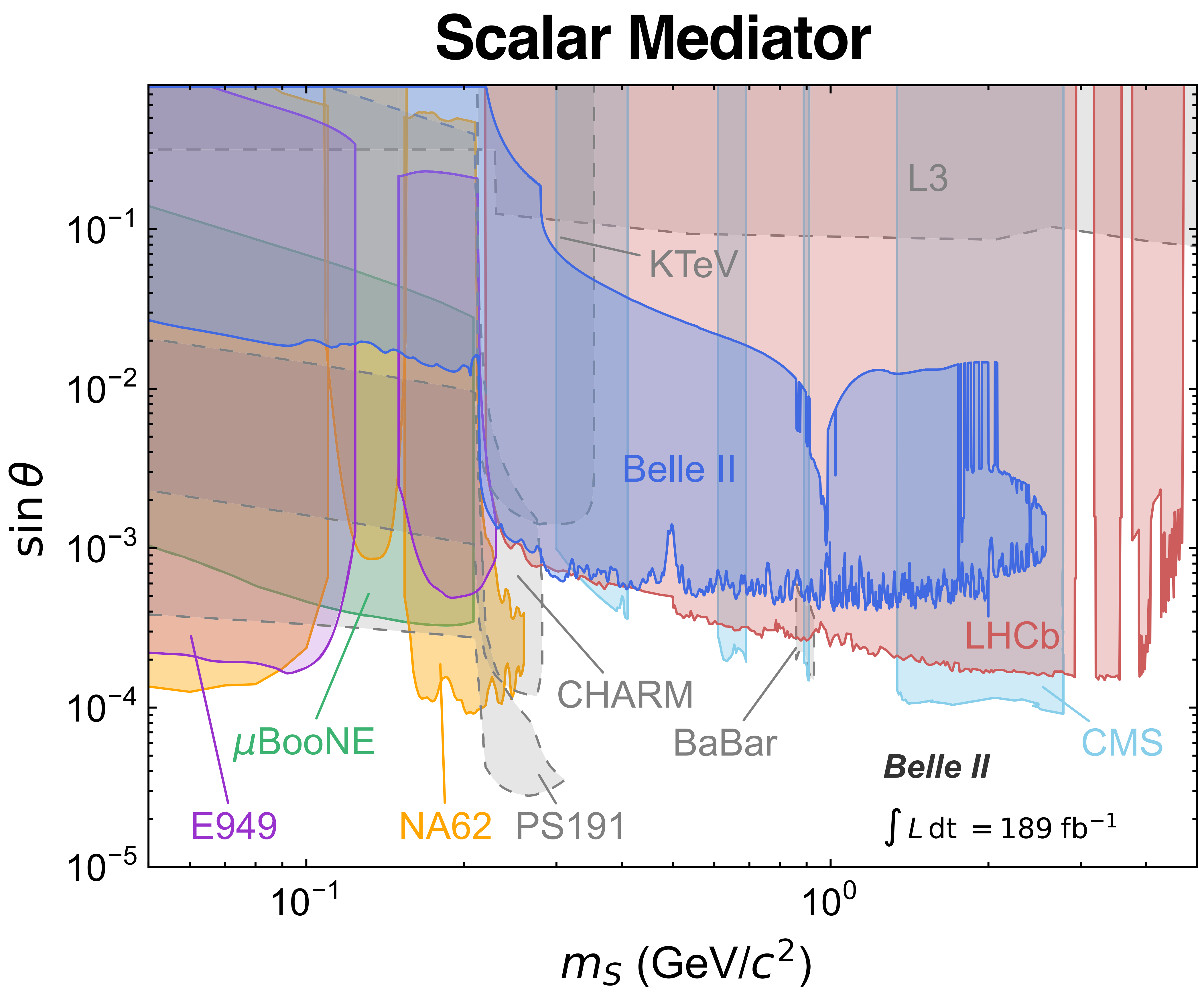
First Results for $B \to KS$ @ Belle II

Tracks

Results (Step1):

- B-meson & scalar BF fixed to the theoretical predictions from [PRD 101, 095006 (2020)] and [JHEP 01 (2019) 150] → extract exclusion contours for $B \to K$ + Scalar Mediator

[PRD 108, L111104(2023)]

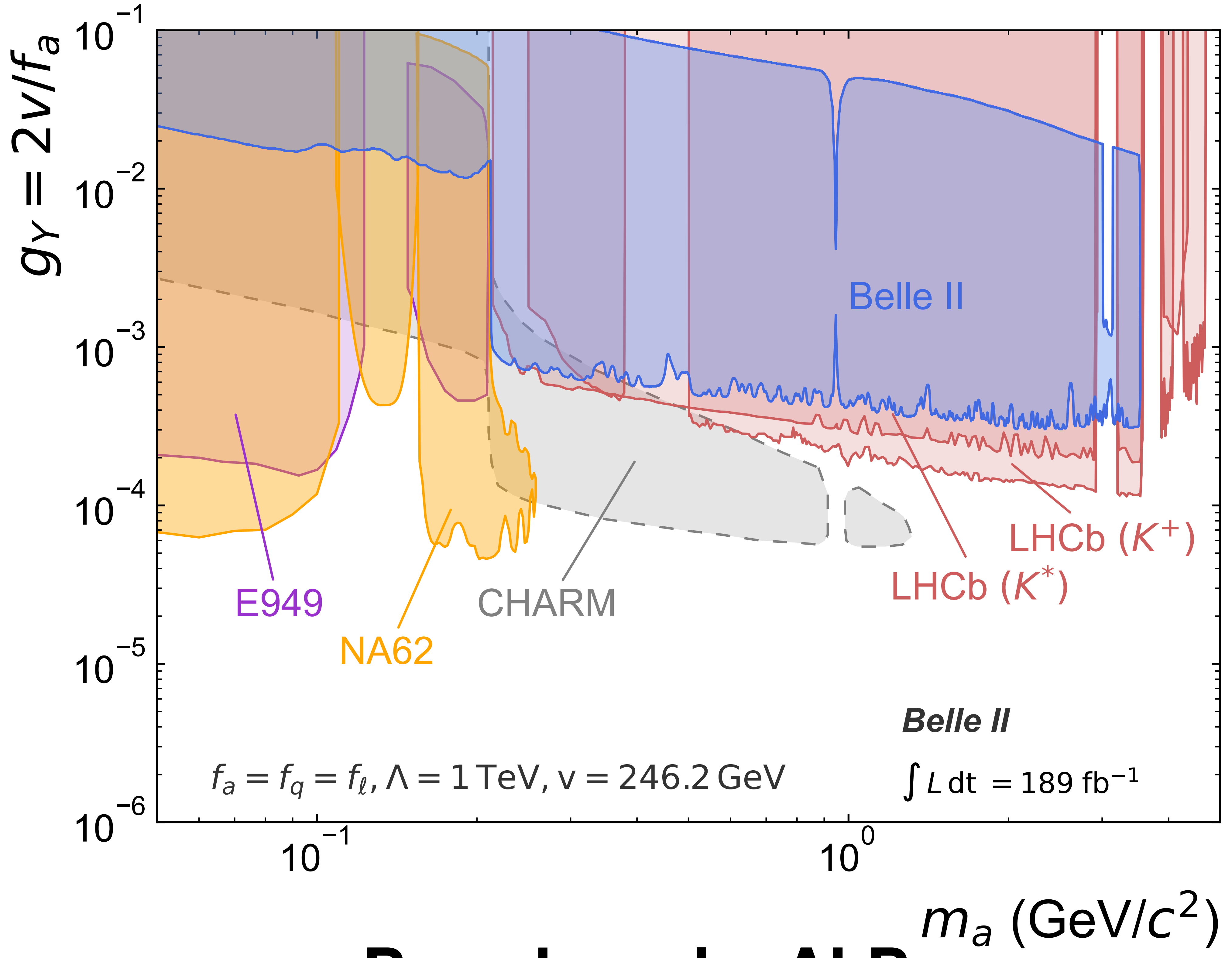


First Results for $B \rightarrow KS$ @ Belle II

Tracks

Results (Step 2): Reinterpretation with [J. Phys. G 47, 010501 (2020)] and [PRD 83, 054005 (2011)] → extract exclusion contours for $B \rightarrow K + \text{ALP}$

[PRD 108, L111104(2023)]



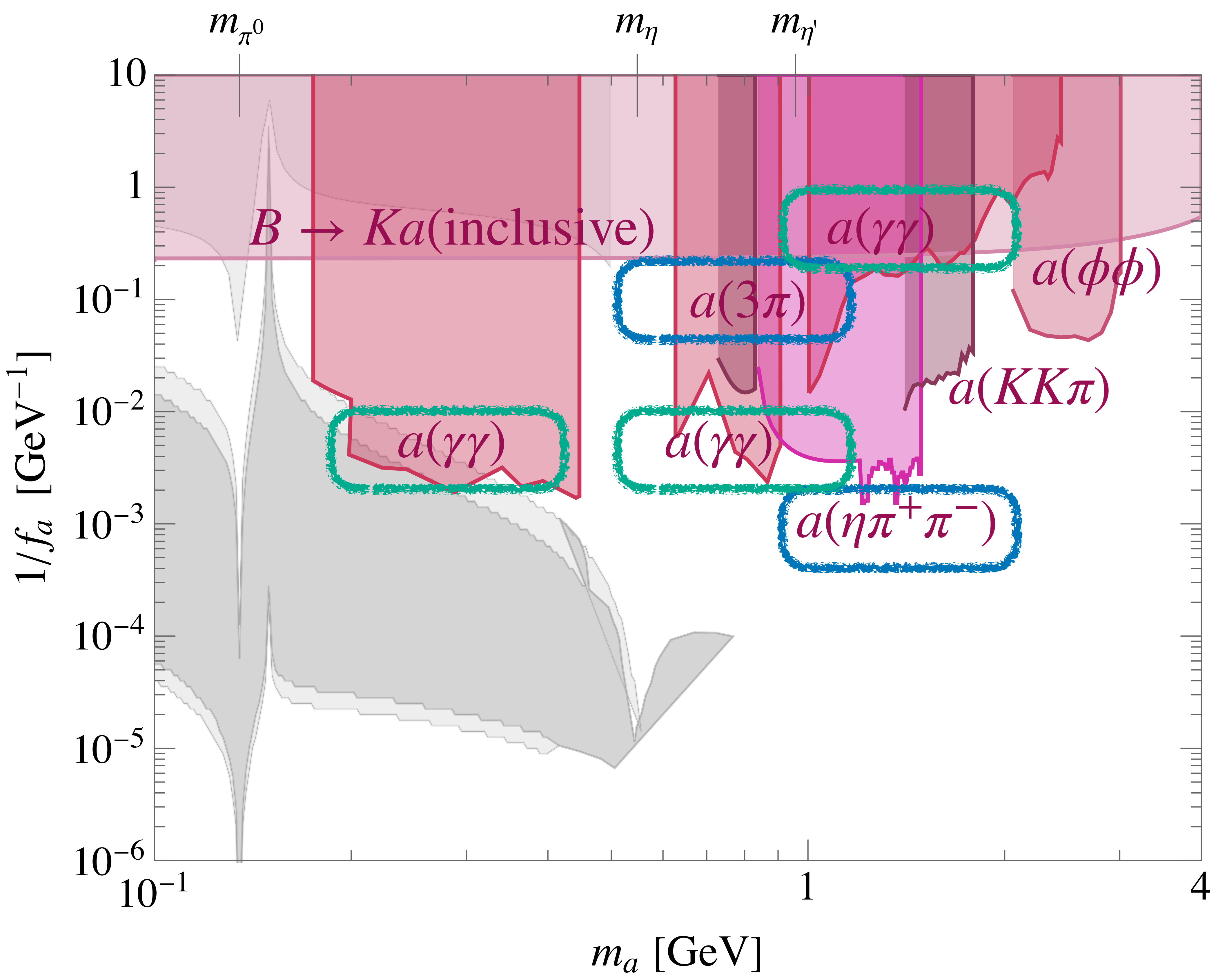
Pseudoscalar ALPs

Constraints from LHCb
Constraints from E949
Constraints CHARM
Limit from Belle II

What are next options?

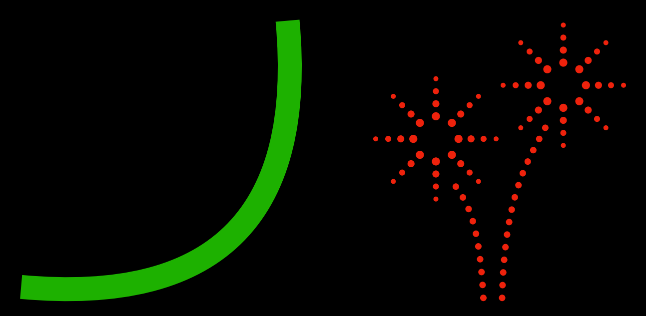
1. **Other channels with K:**
   - $B \to Kaa'(a \to ll')$
   - More ideas in [Kohsaku Tobioka slide from this week]
     - $B \to Ka(a \to \pi^+\pi^-\pi^0)$
     - $B \to Ka(a \to \eta\pi^+\pi^-)$
2. **Test others than $b \to s$ transitions**

[Kohsaku Tobioka slide from this week]



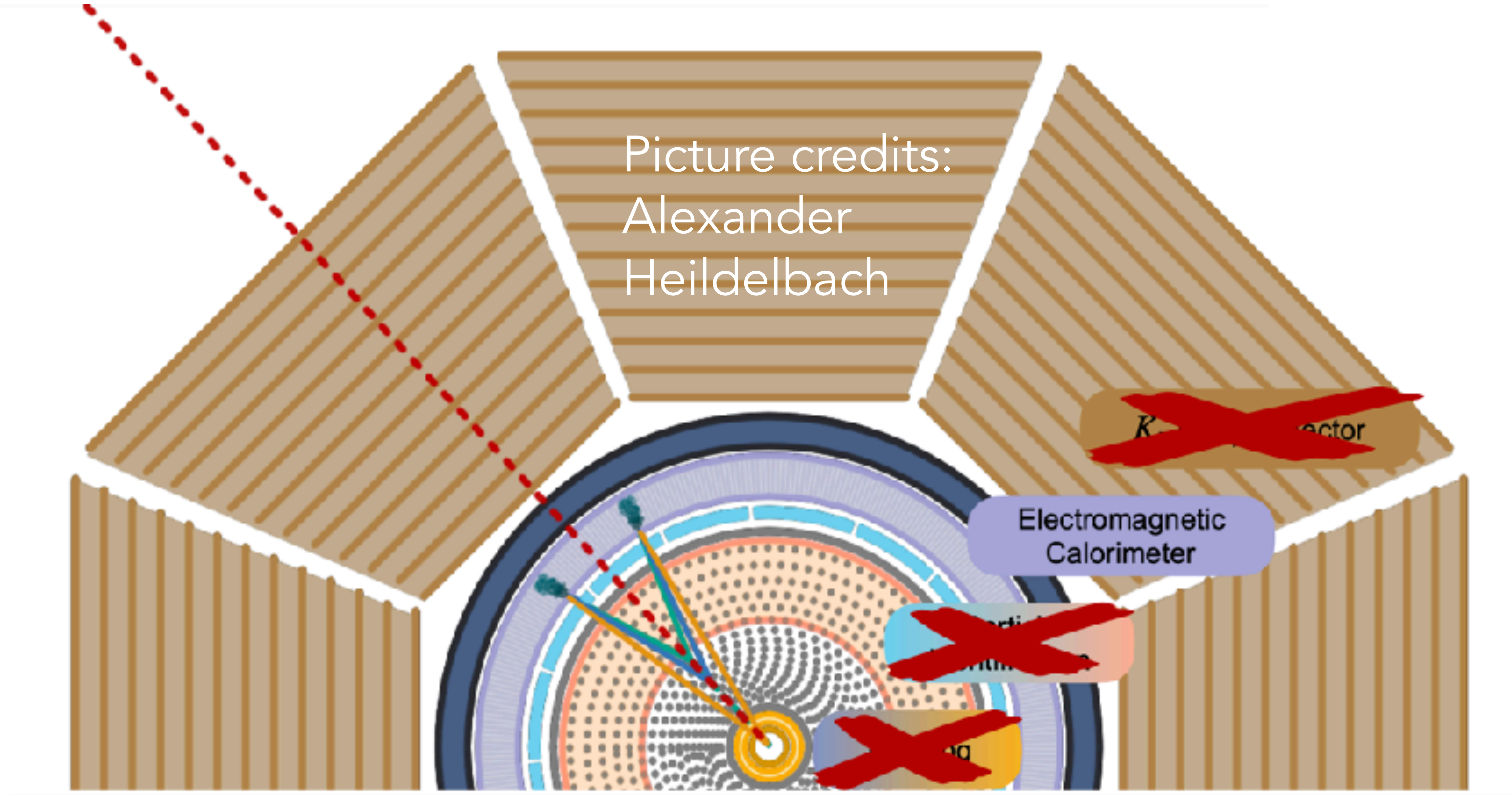
Signature 4.

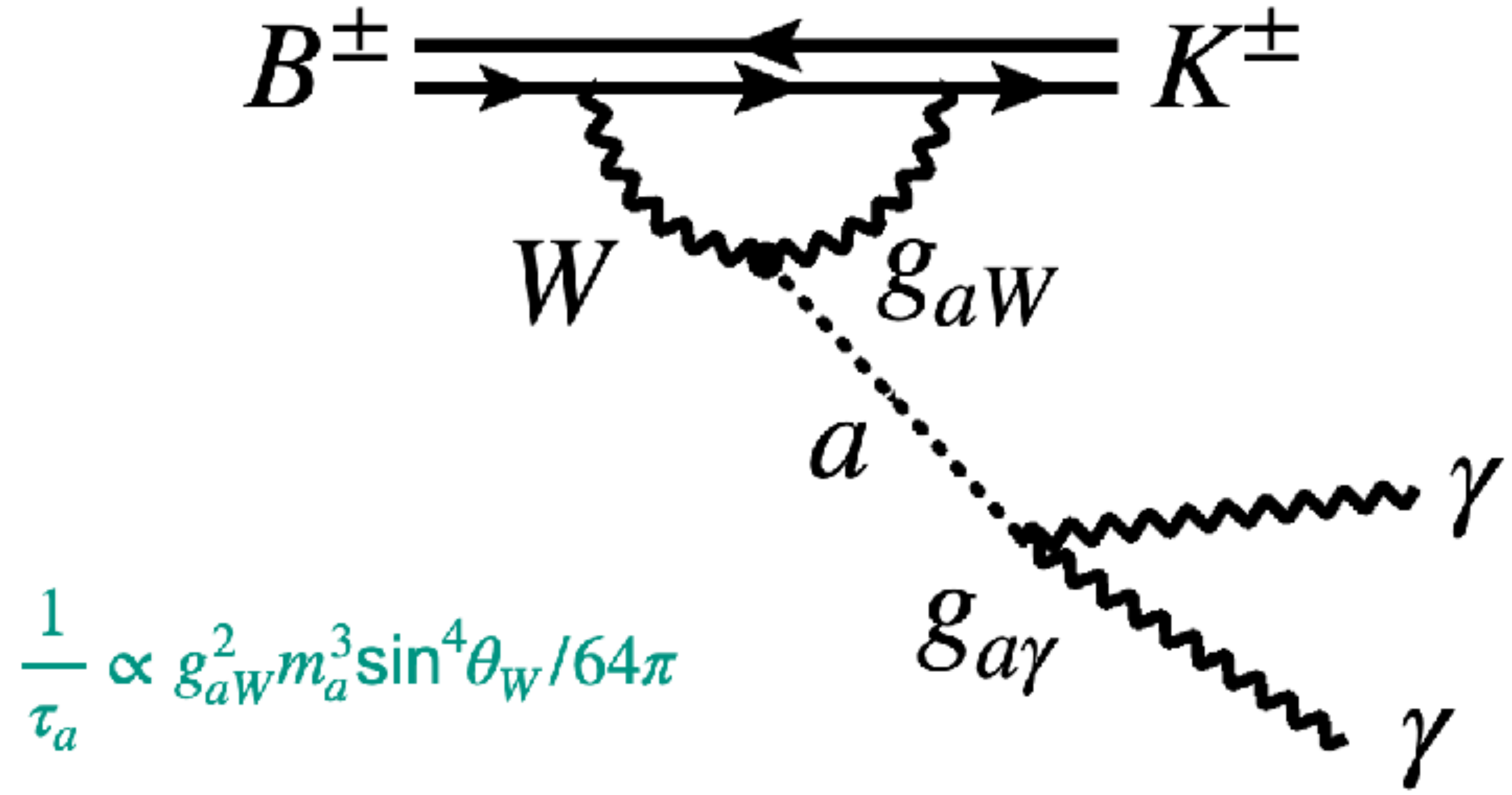
Track(s) + clusters



$$e.g.\ B \rightarrow KX(X \rightarrow \gamma\gamma)$$

Search for $B \to Ka(\to \gamma\gamma)$





Search Strategy: ***long-lived pseudoscalar = ALP*** **that decays visibly into pair of photons $\gamma\gamma$:**

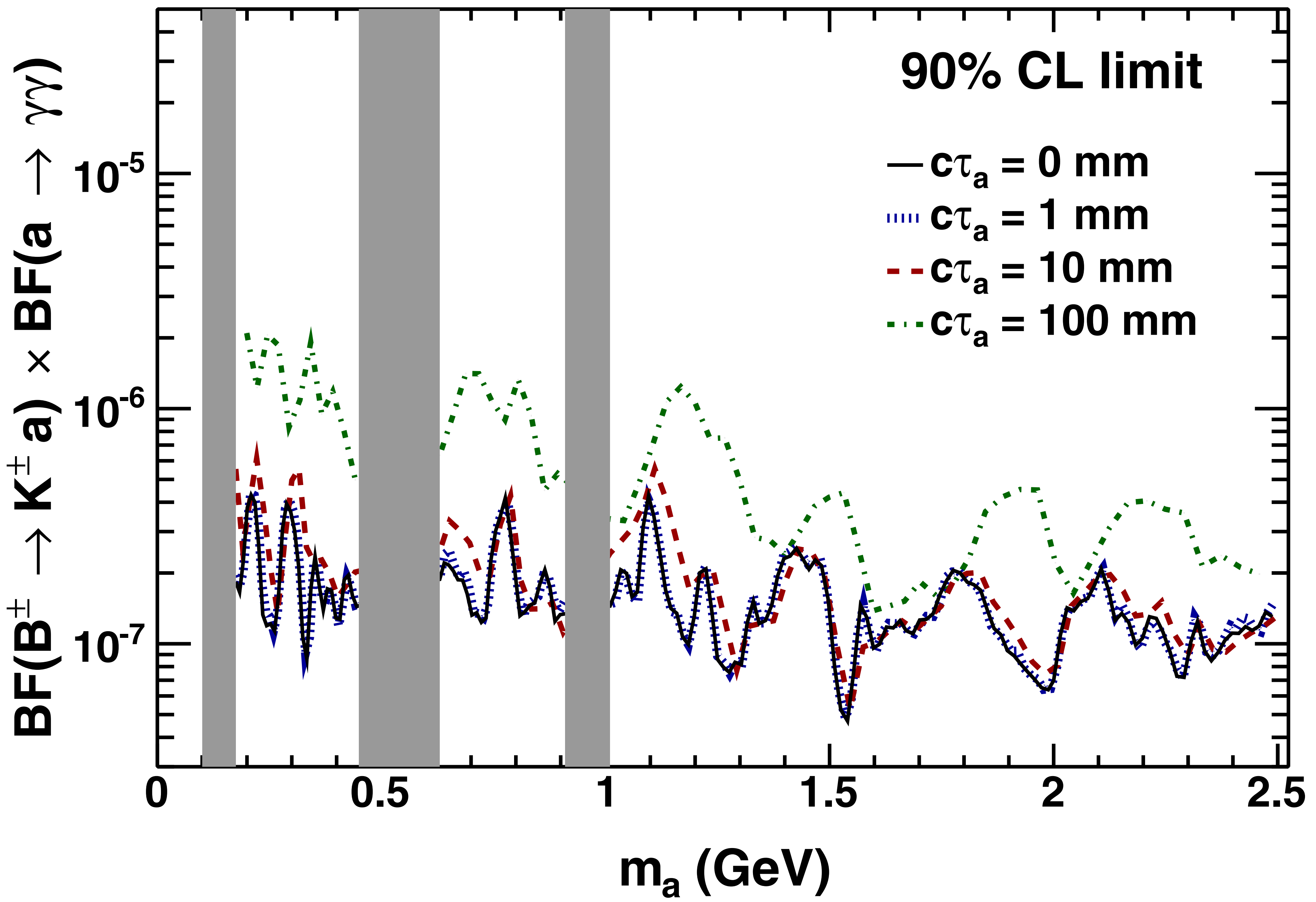
- Bump hunt in the invariant mass m_a for each lifetime separately

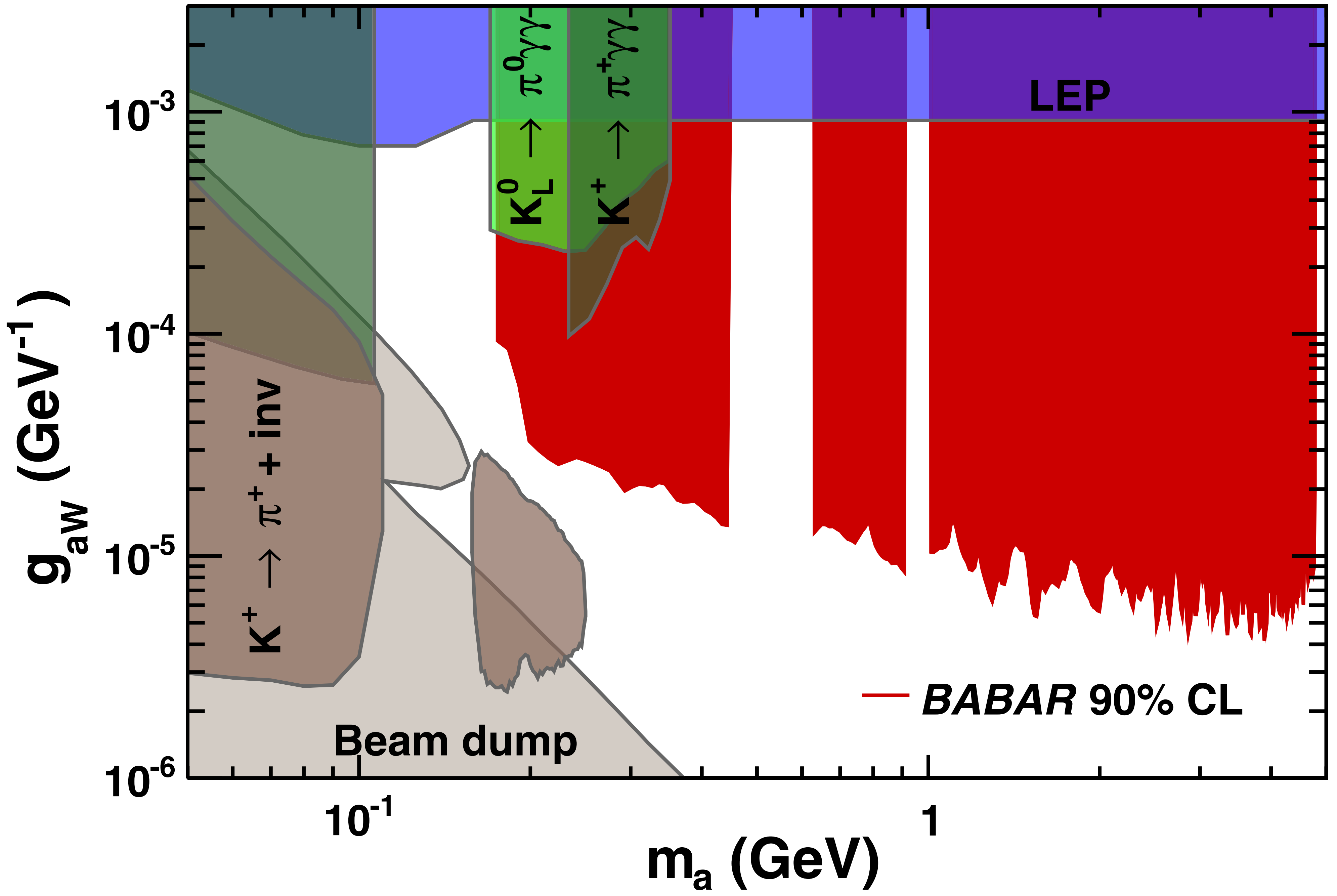
Experimental challenges:

- Simulation generation for all mass hypotheses and lifetimes
- Limited acceptance for photons
- Degrading resolution of $M_{\gamma\gamma}$ with increasing lifetime
- Interpolation stability between the masses
- Modelling close to SM resonant windows (e.g π^0, η_c)

Search for $B \to Ka(\to \gamma\gamma)$

[PRL 128 (2022) 131802]





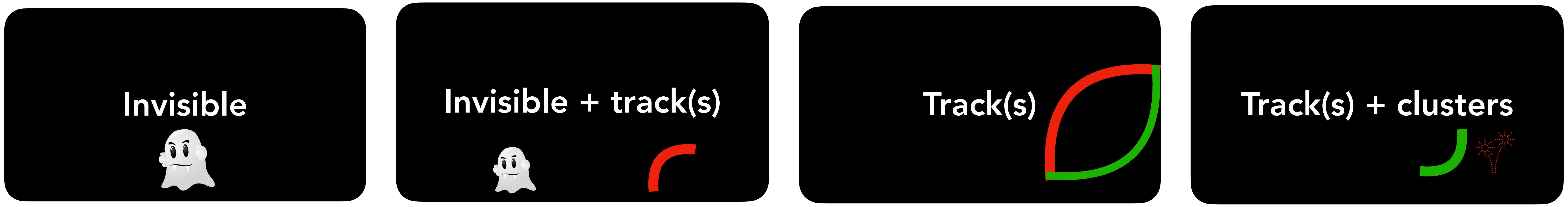
- So far only limit from BaBar

Slavomira Stefkova, slavomira.stefkova@uni-bonn.de

Summary

In conclusion

- Belle II : excellent place to search for different signatures and reinterpret them in many models
- We are only at the beginning of the journey

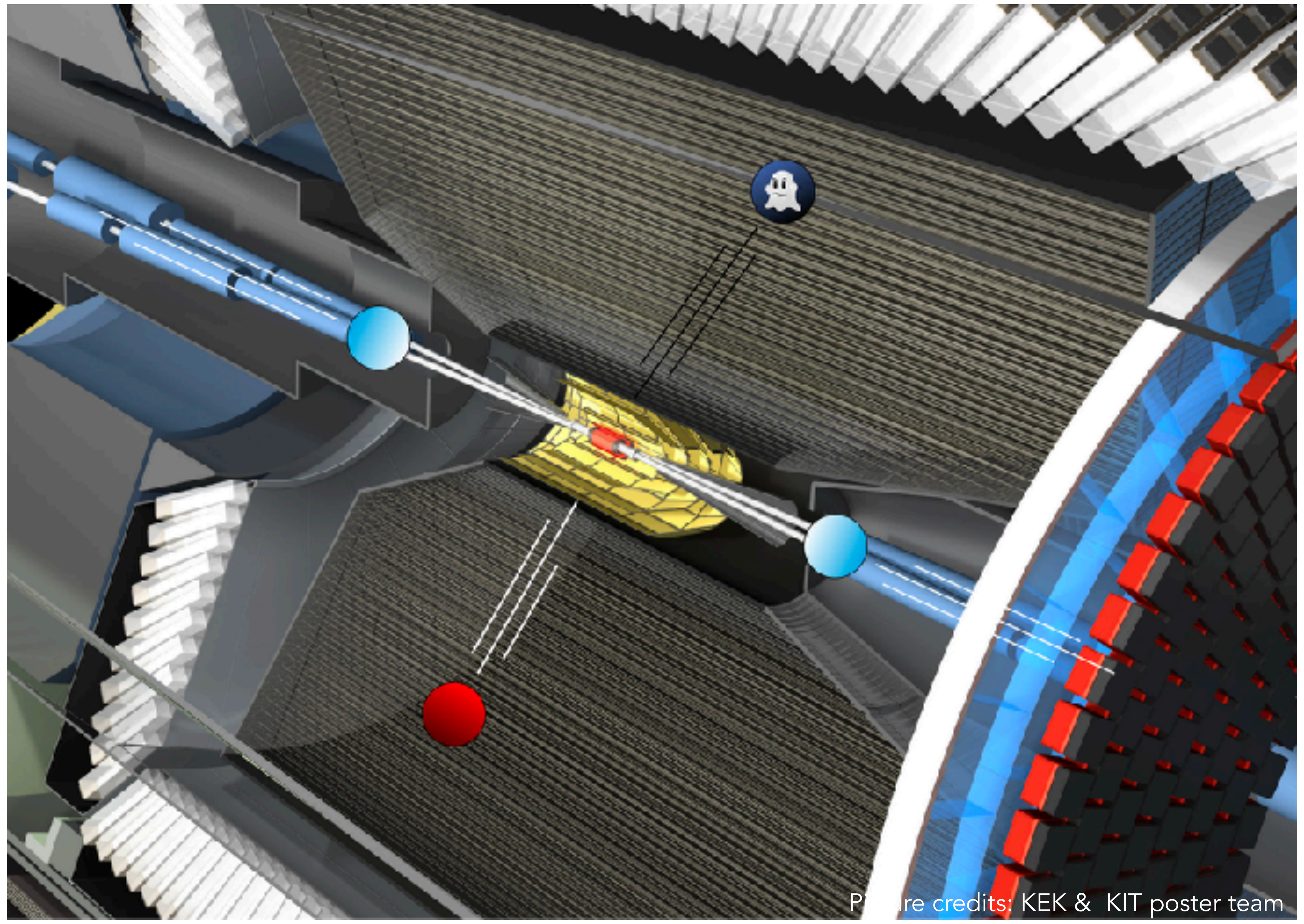


[PRD 108, L111104(2023)]

Slavomira Stefkova, slavomira.stefkova@uni-bonn.de

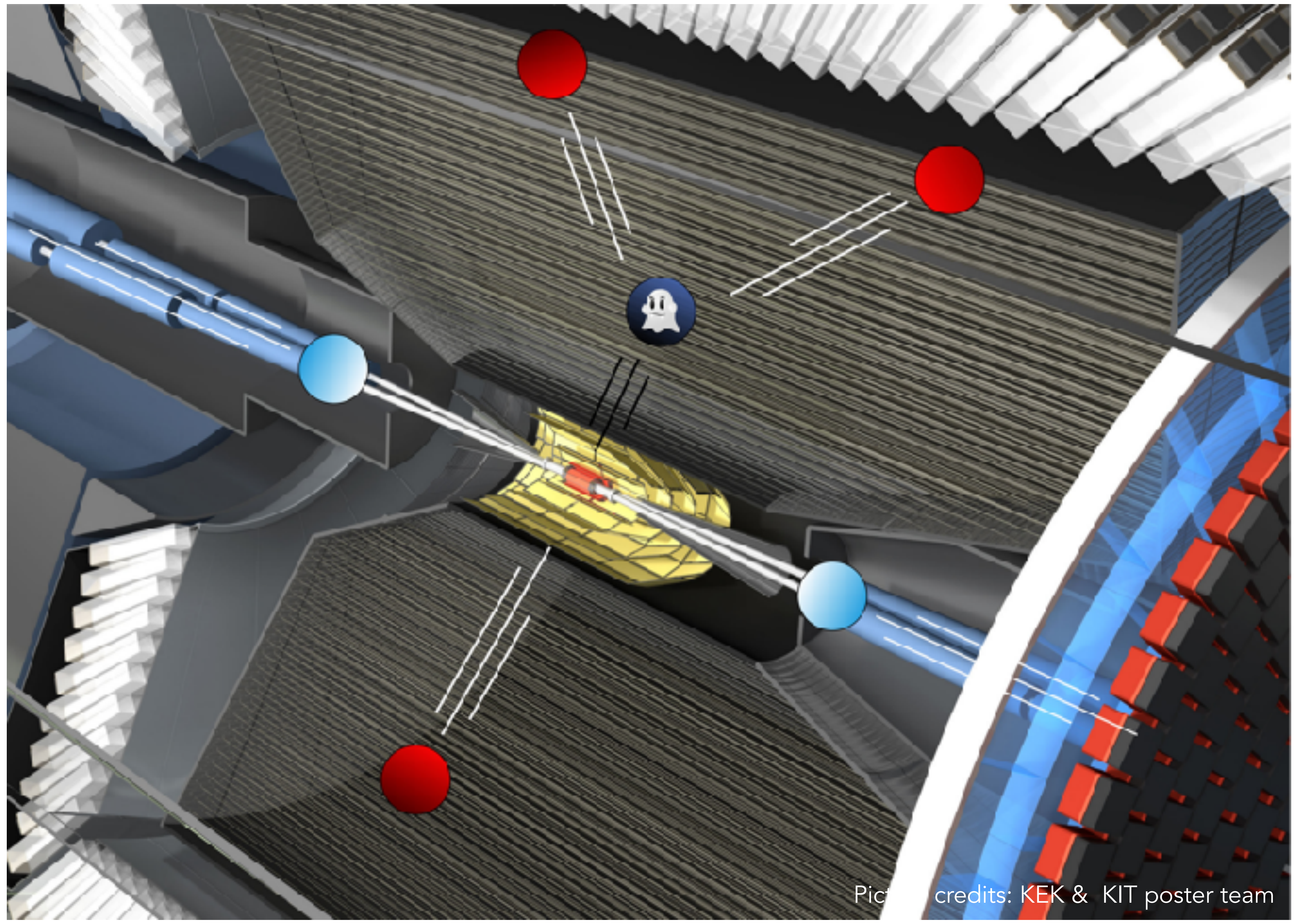
Backup

Searching for Dark Sector in Belle II



Approach 1: a trace of a new particle from *B*-meson decay

Trick: Summing the energy

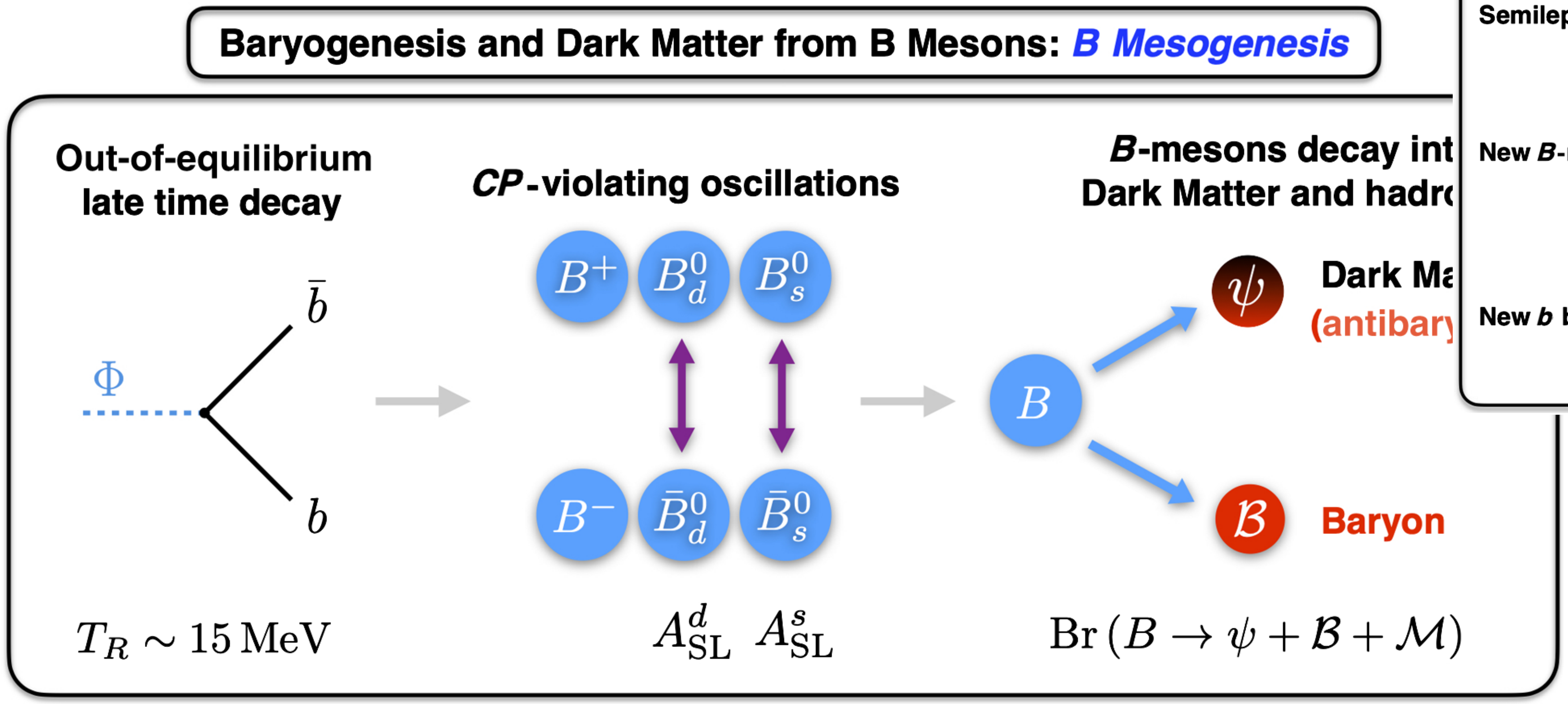


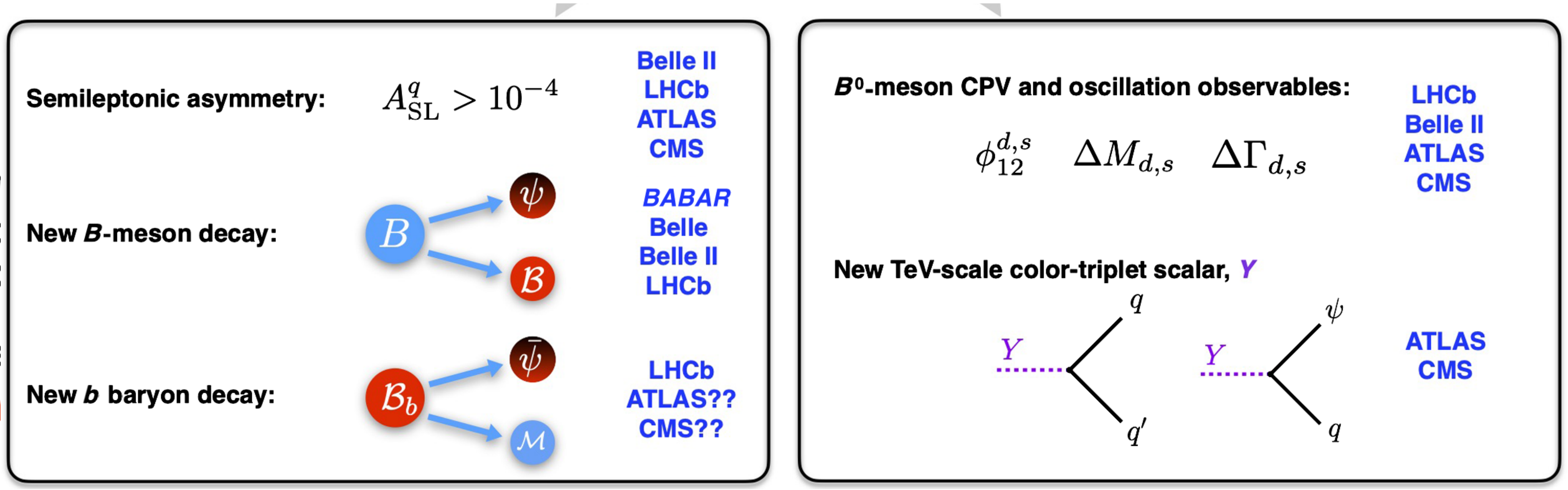
Approach 2: created out of nowhere in the detector from *B*-meson decay and then decay in the SM

B-mesogenesis

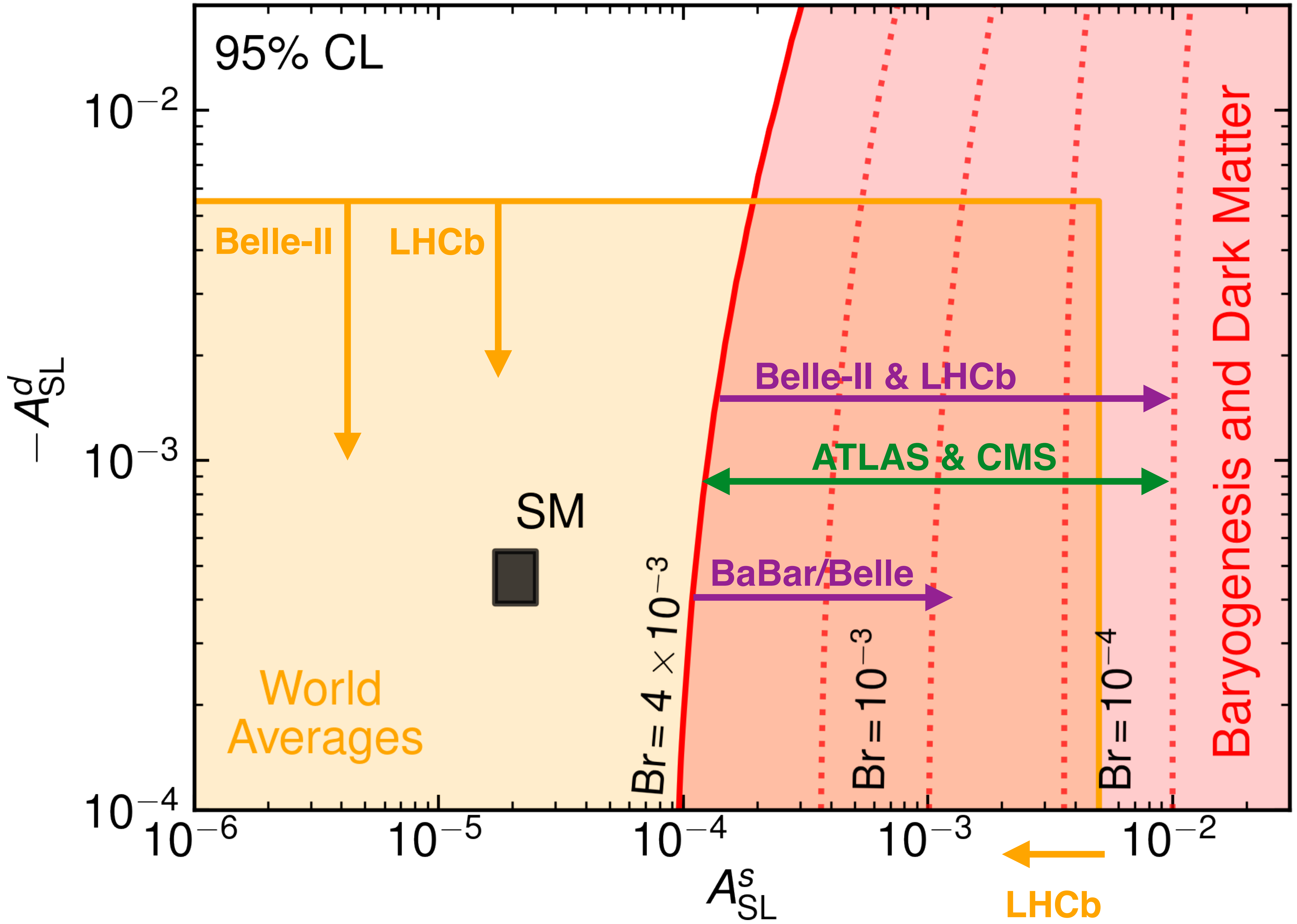
[PhysRevD.104.035028]

- Baryogenesis is required in order to produce an initial excess of baryons over antibaryons consistent with observations
- *B*-mesogenesis paradigm explains baryonic + dark matter of the Universe → baryo- and dark matter genesis from B-Meson give rise to distinctive signals at collider experiments
- A new dark anti-baryon is proposed Ψ which can also explain the Baryon Asymmetry of the Universe
- Kinematic constraints → 0.94 < M(Ψ) < 4.34 GeV





B-mesogenesis



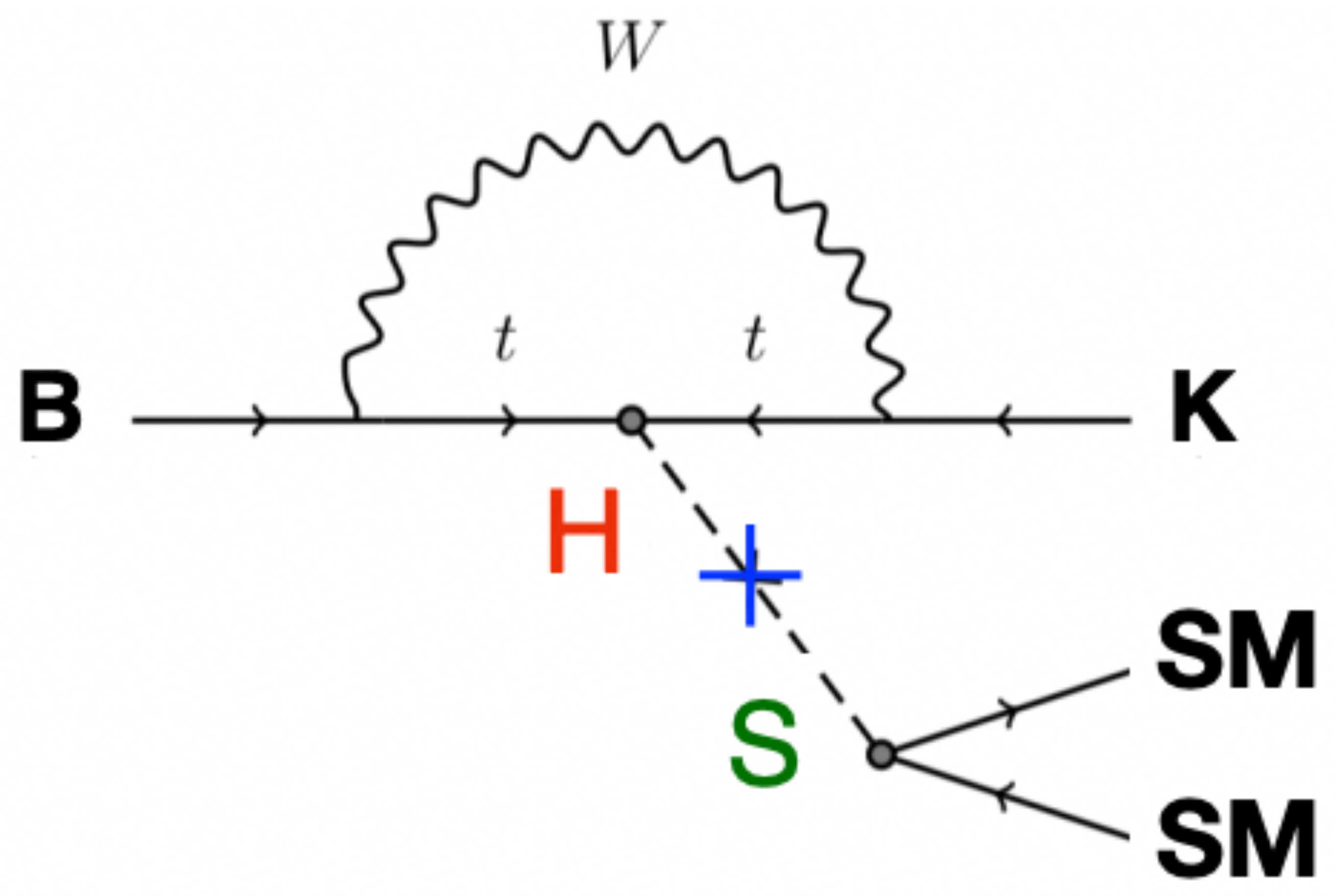
Signatures

- **CP violation**
- **New b decays**
- **High pT jets and missing energy**

Scalar Mediators @ Belle II

Scalar mediator + fermionic DM avoids strong CMB constraints through velocity-suppressed (p-wave) annihilation $\langle \sigma v \rangle \sim v^2$

$$\mathscr{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - m_\chi \bar{\chi}\chi - \lambda_3 \phi H^\dagger H - y_\chi \bar{\chi}\chi\phi$$



Mixing after EW symmetry breaking h_{125} and a new scalar *S*

- $Sf\bar{f}$ couplings $\sim \frac{m_f}{v} sin\theta$

Direct production from e^+e^- suppressed $\rightarrow$ heavy quark loops in *B*-meson decays

Pseudoscalar ALPs @ Belle II

Pseudoscalar mediator with fermionic DM avoids direct detection

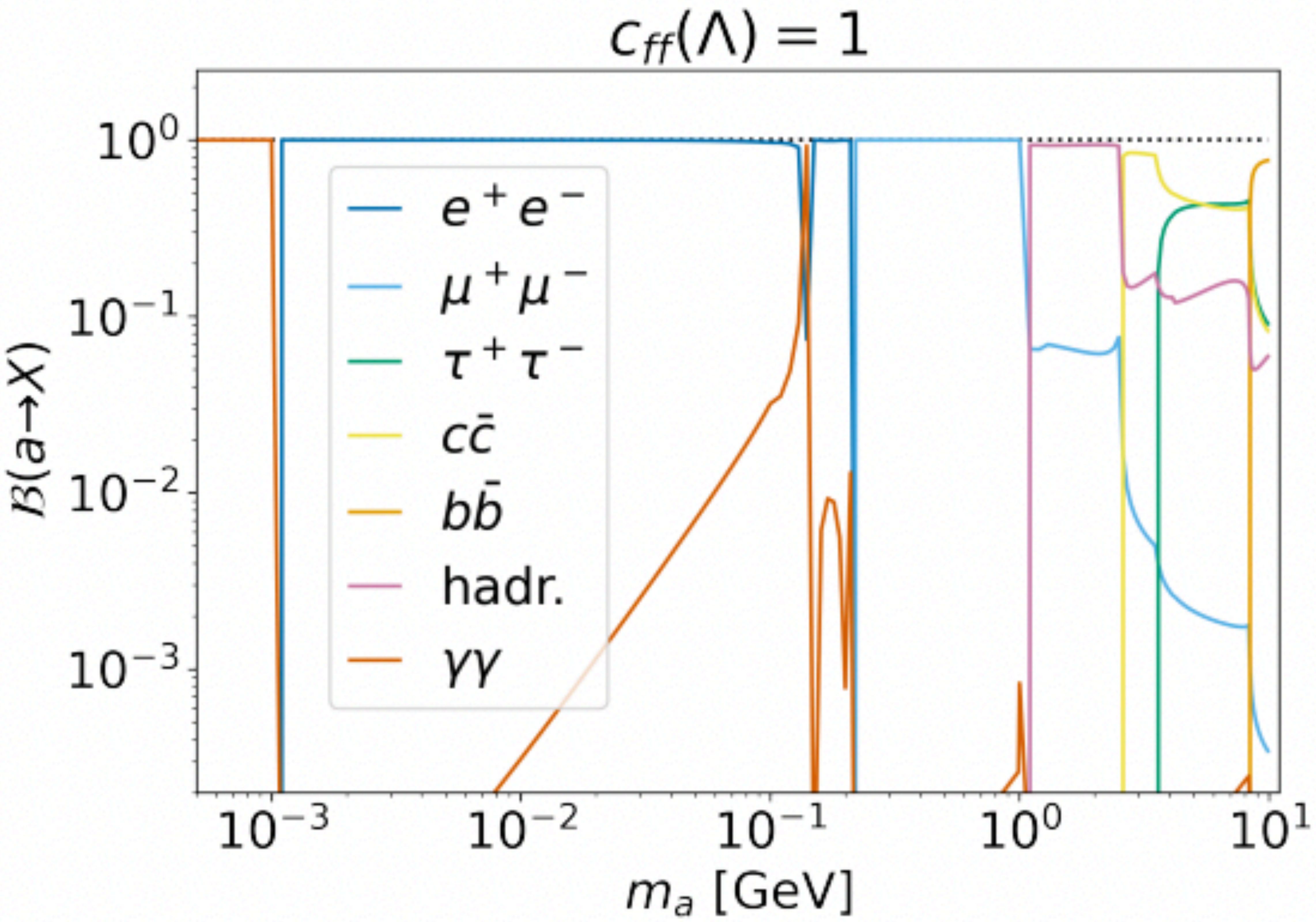
Special type of pseudoscalar: Axion-like particle defined by shift symmetry a → a + c

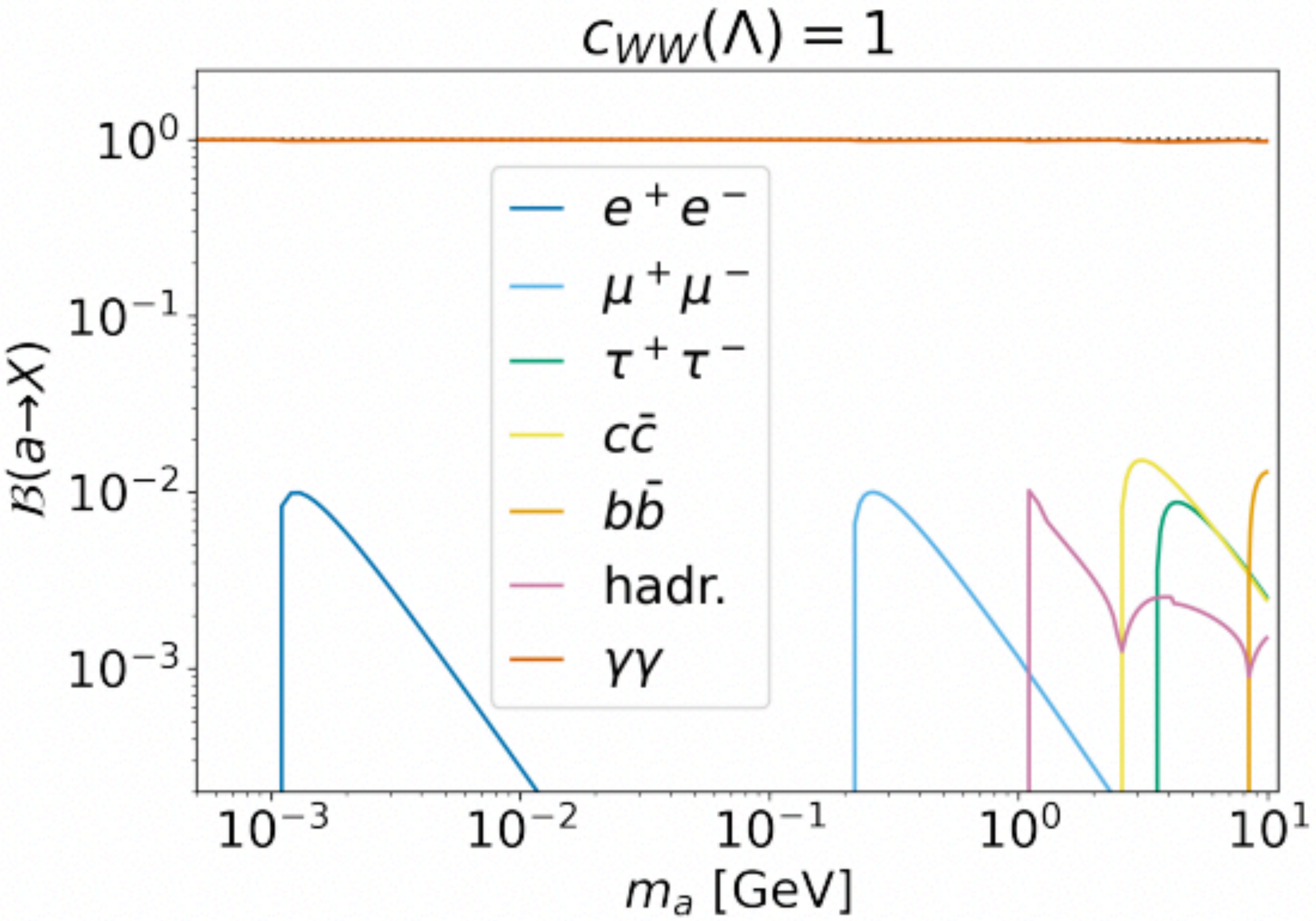
$$\mathscr{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{m_a}{2}a^2 + \frac{\partial^\mu a}{f_a}\sum_f \frac{c_f}{2}\bar{f}\gamma_\mu\gamma_5 f + \frac{c_\chi}{2}\frac{\partial^\mu a}{f_a}\bar{\chi}\gamma_\mu\gamma_5\chi$$
$$+c_{GG}\frac{g_s^2}{(4\pi)^2}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{A,\mu\nu} + c_{BB}\frac{g'^2}{(4\pi)^2}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{WW}\frac{g^2}{(4\pi)^2}\frac{a}{f_a}W^A_{\mu\nu}\tilde{W}^{A,\mu\nu}$$

- **Production mechanism I** $B \to Ka(\to \gamma\gamma)$
- **Production mechanism II** $B \to Ka(\to inv)$
- **Production mechanism III** $B \to Ka(\to \text{hadrons})$

Pseudoscalar ALPs @ Belle II

JHEP 04 (2023) 131

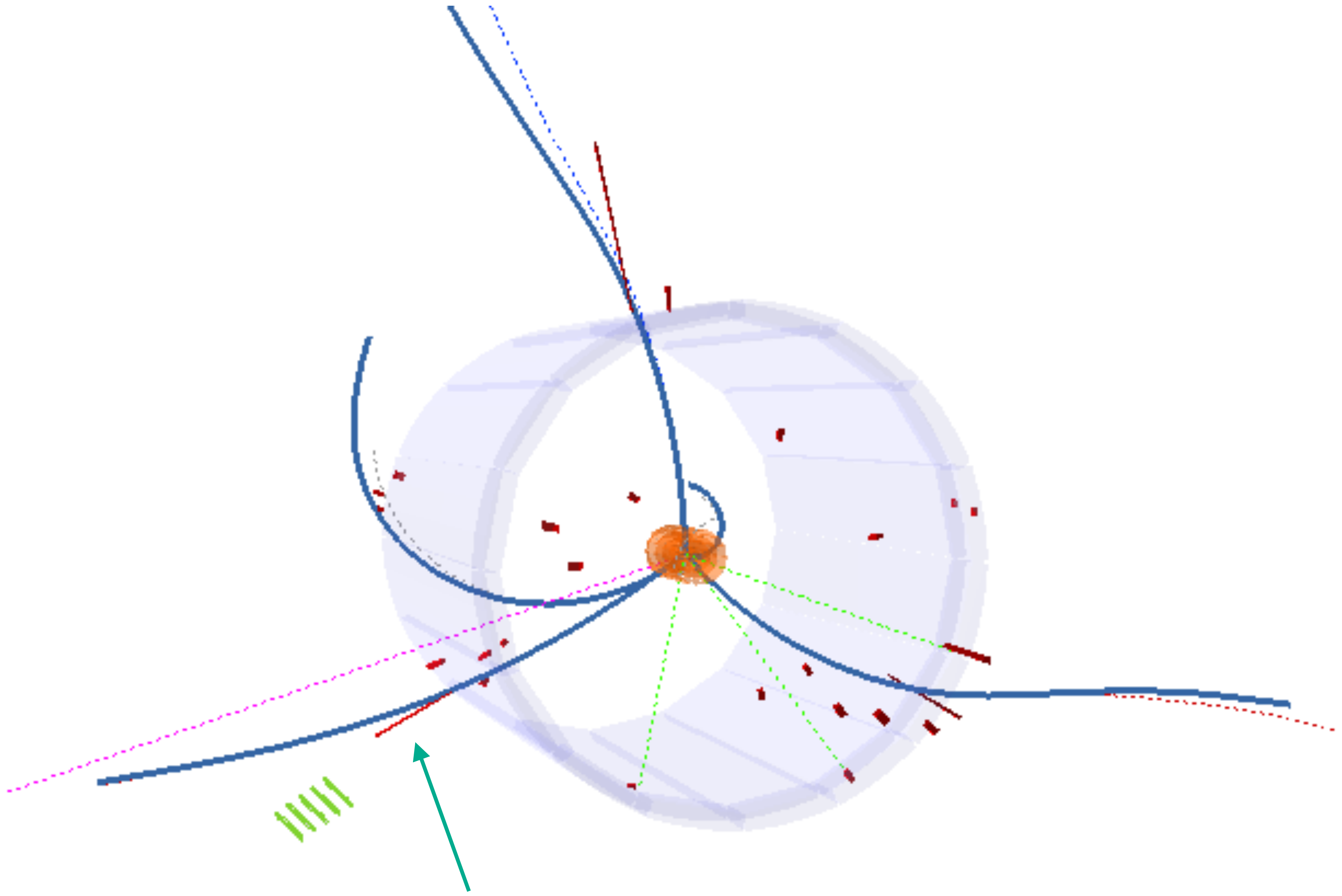




Branching ratios for ALP decays $a \to X$ in the C_{ff} scenario (left) and the C_{WW} scenario (right). The ALP couplings are fixed to $C_{ff}(\Lambda) = 1$ and $C_{WW}(\Lambda) = 1$ at the cutoff scale $\Lambda = 4\pi \mathrm{TeV}$

Pseudoscalar ALPs @ Belle II

[JHEP 04 (2023) 131]



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

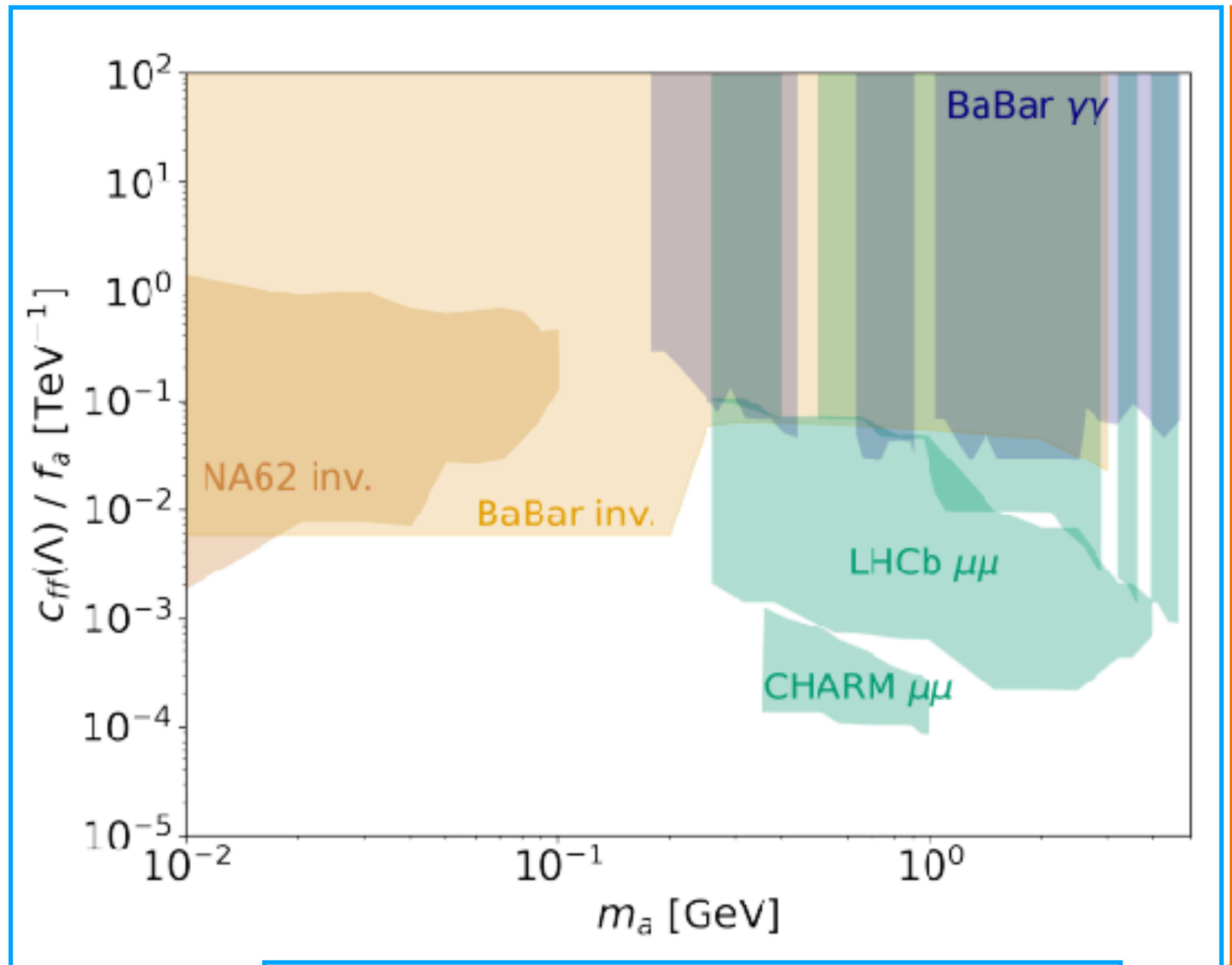
"c_{ff}" : ALP coupling to fermions

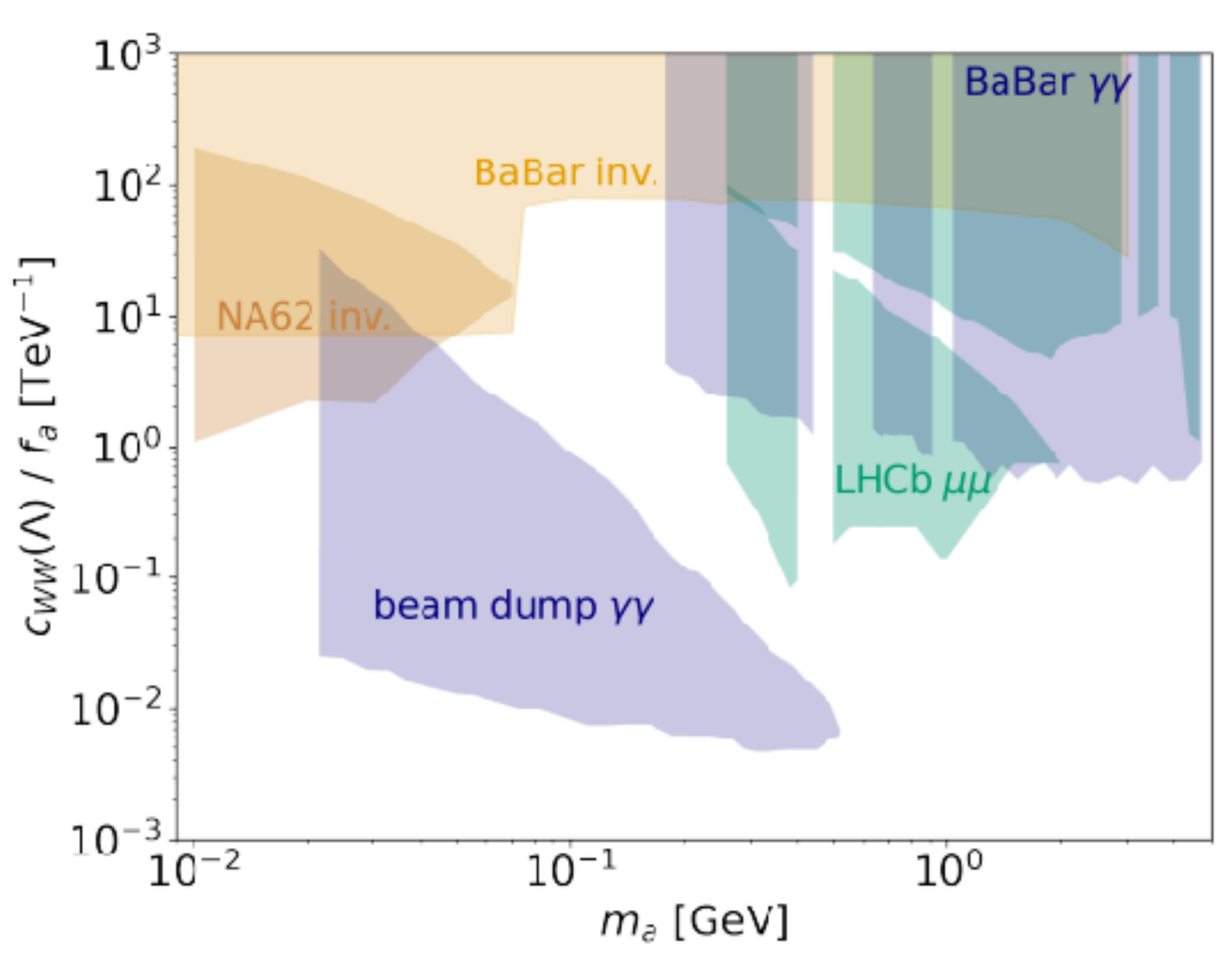
"c_{WW}" : ALP coupling to gauge bosons

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

f_0 = scalar FF

Current bounds:





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

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

Search for $B \rightarrow K$ + invisible @ Belle II

So far no direct measurement of $B \rightarrow KX$

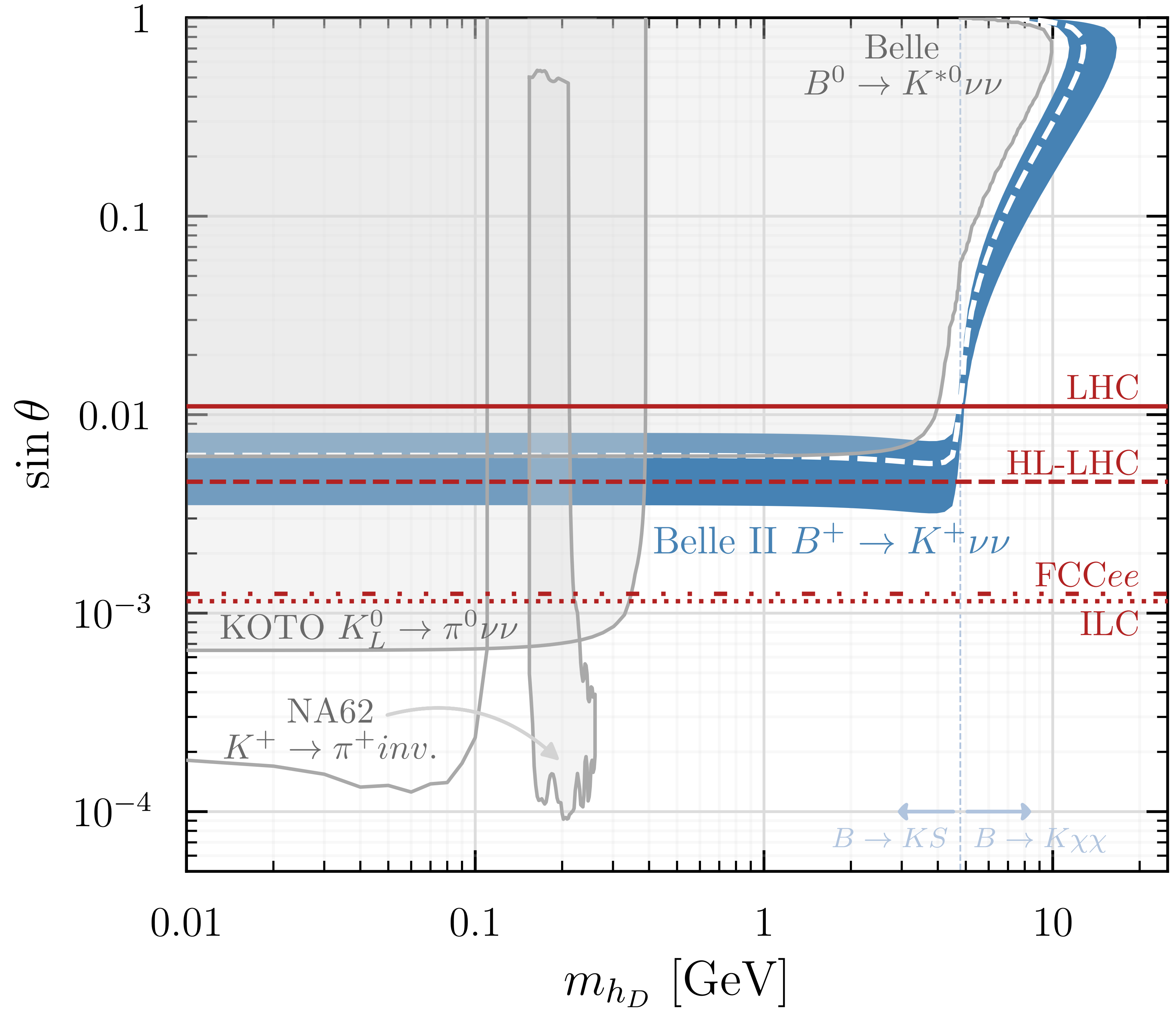
- However Belle II searched for $B^+ \rightarrow K^+\nu\bar{\nu}$ and can be reinterpreted in these dark scalar models [PhysRevD.109.075006]

Singlet Higgs portal model

[PhysRevD.109.075006]

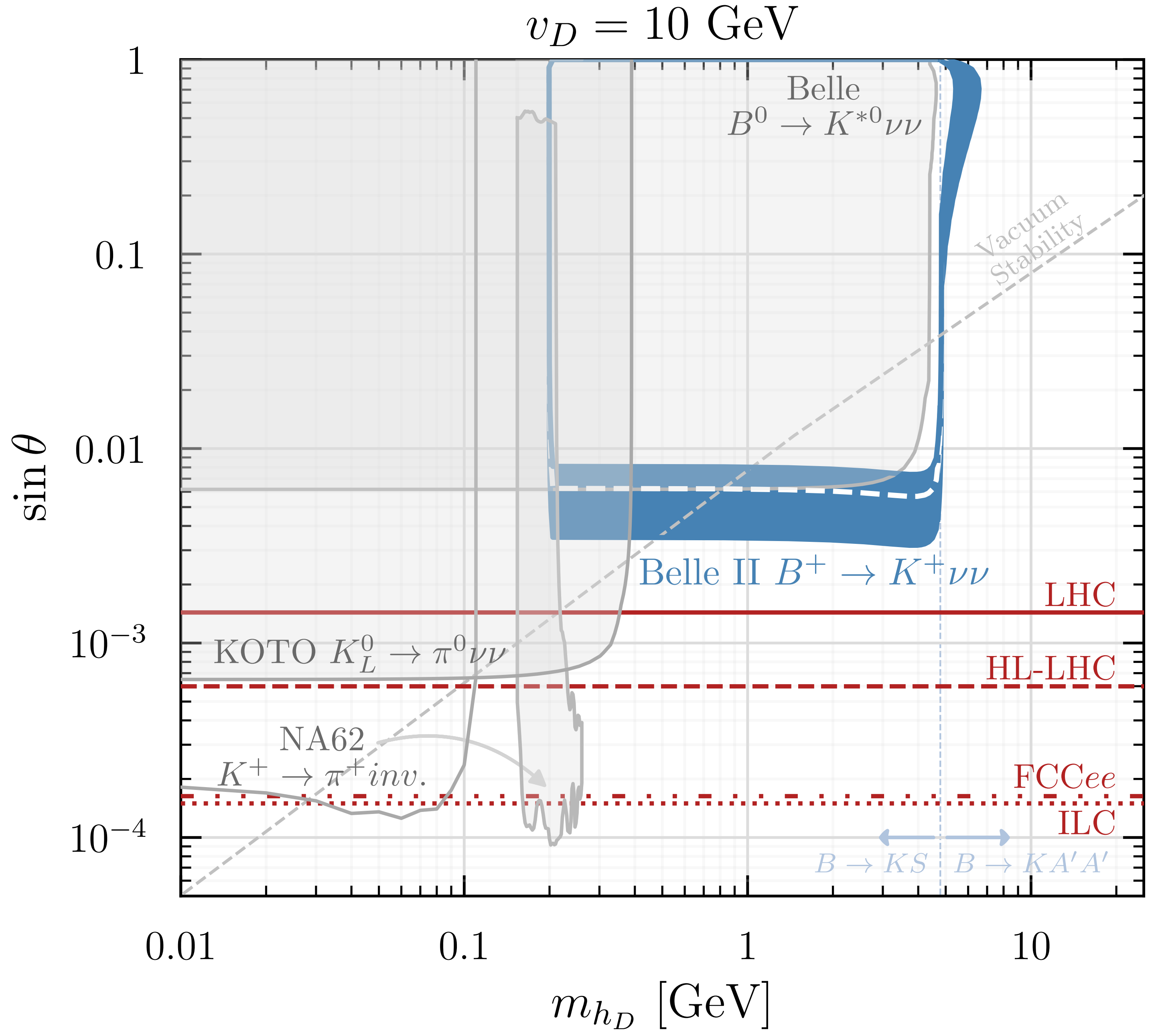
https://arxiv.org/pdf/2309.03706

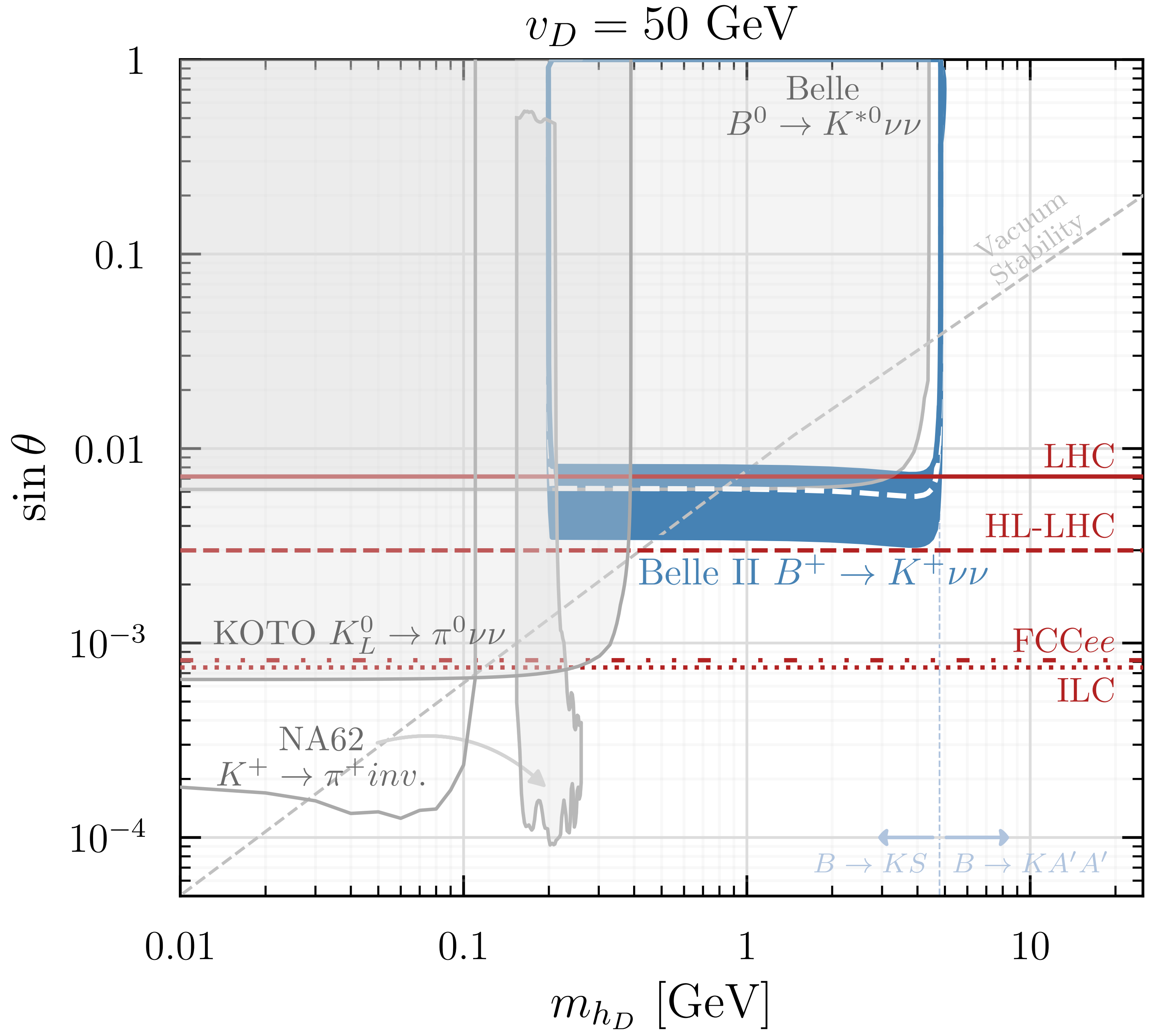
https://inspirehep.net/literature/2769996



Dark Abelian Models

[PhysRevD.109.075006]

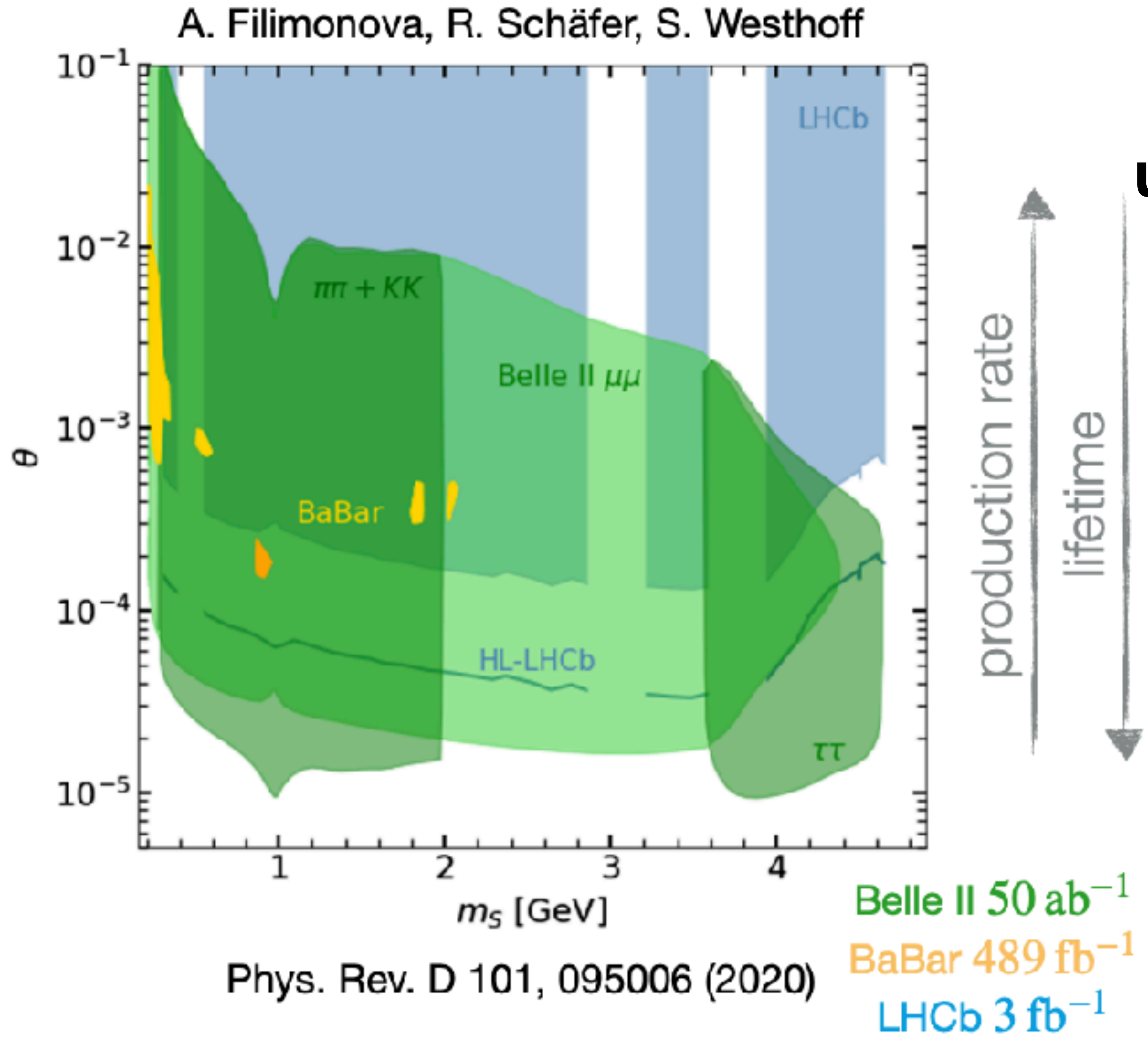




$B \to KS$ scalar predictions

[Phys. Rev. D 101, 095006]

Belle II signature: $B \to K$ + two charged tracks



Phys. Rev. D 101, 095006 (2020)

Set unique upper bounds with 50 ab^{-1} !

Prediction does not contain e^+e^- Channel

Invisible Decays of J/psi and Psi(2S)

https://arxiv.org/pdf/1303.7465 (Conversely, a low-mass U(1) gauge boson U could enhance the invisible decay rates of quarkonium states by several orders of magnitude by coupling to LDM particles [12, 13]. The U boson could decay into a pair of spin-1/2 Majorana (χχ), spin-1/2 Dirac (χχ), or spin-0 (ϕϕ) LDM particles

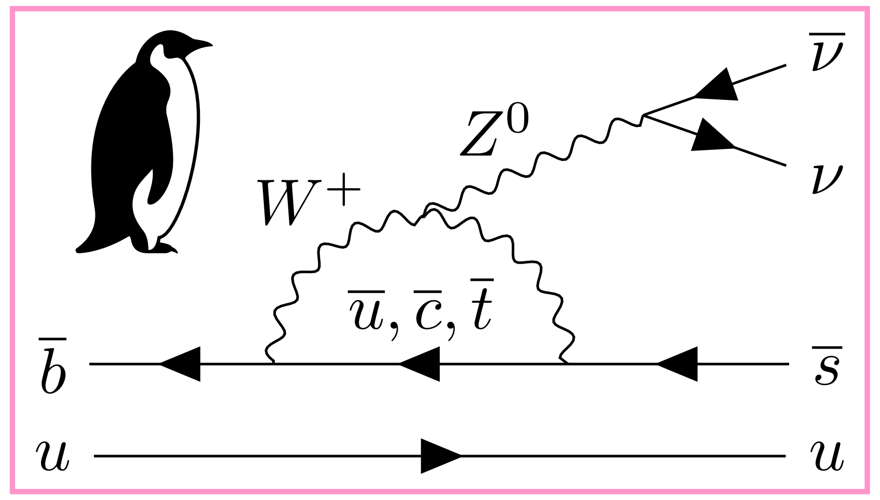
Rare B Decays

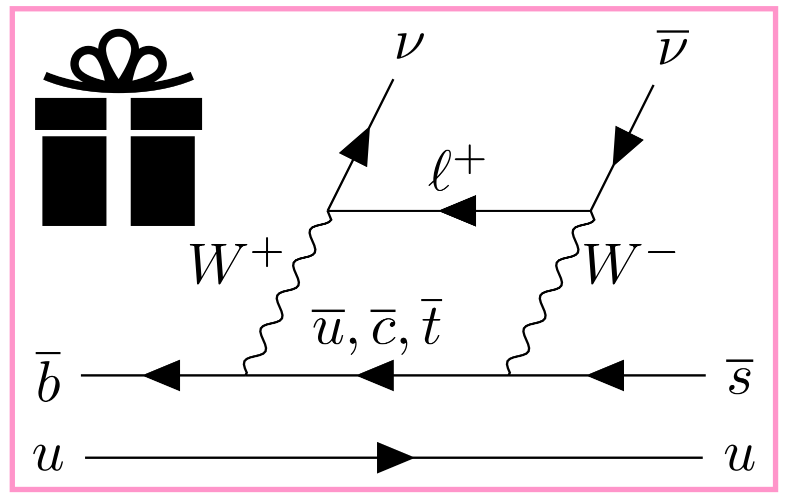
Rare B decays:

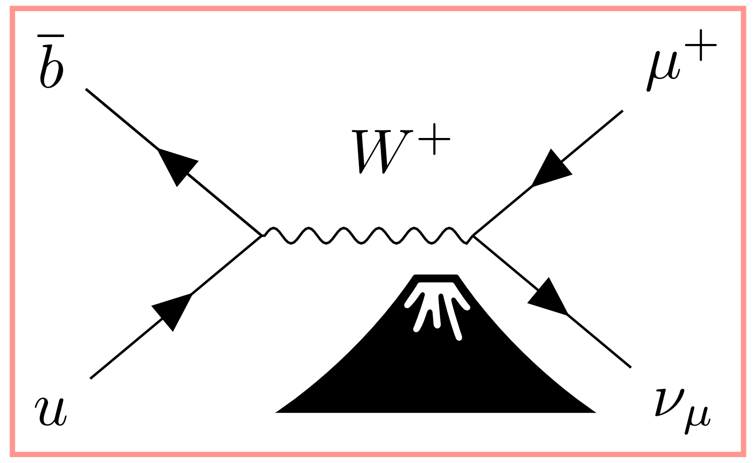
- GIM suppressed flavour changing neutral currents (FCNC)

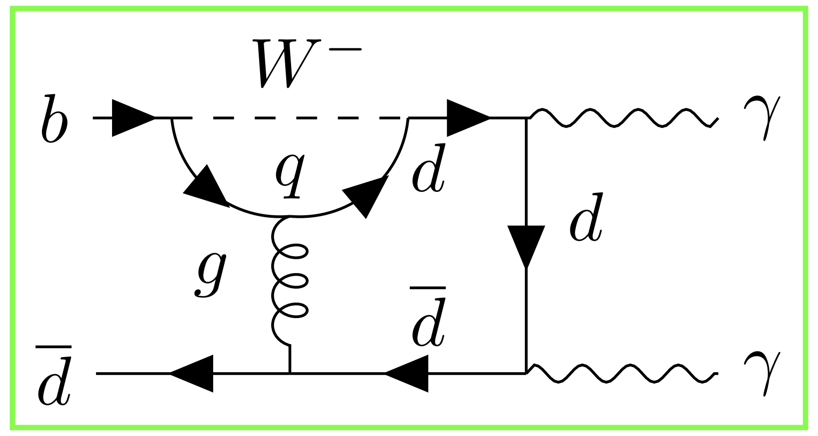
  $\rightarrow \quad b \rightarrow s/d(\gamma)$

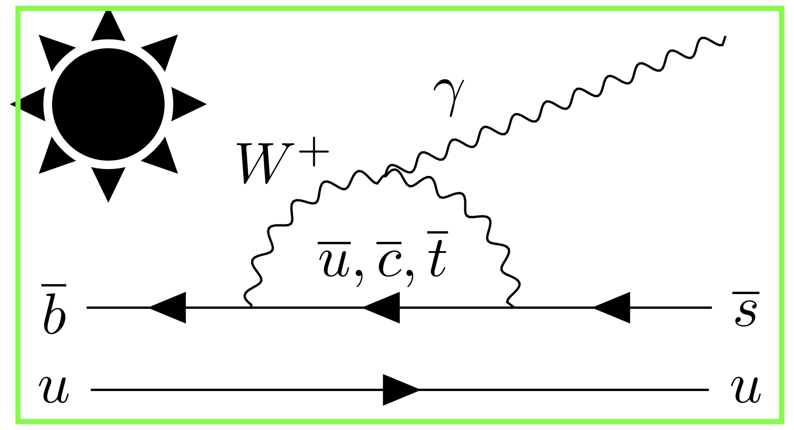
  - forbidden at tree level, allowed at loop level
  - electroweak decays, radiative electroweak decays
  - m_ν^2/M_W^2 suppressed lepton flavour violating decays
- Helicity suppressed purely leptonic decays

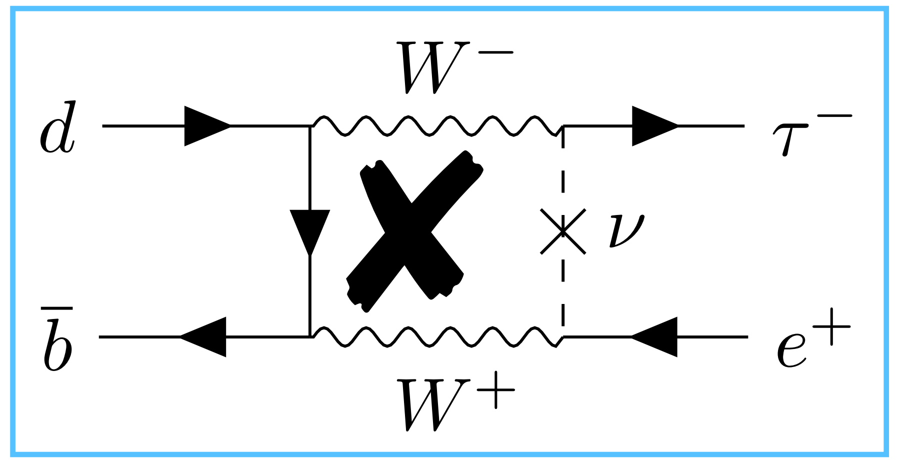










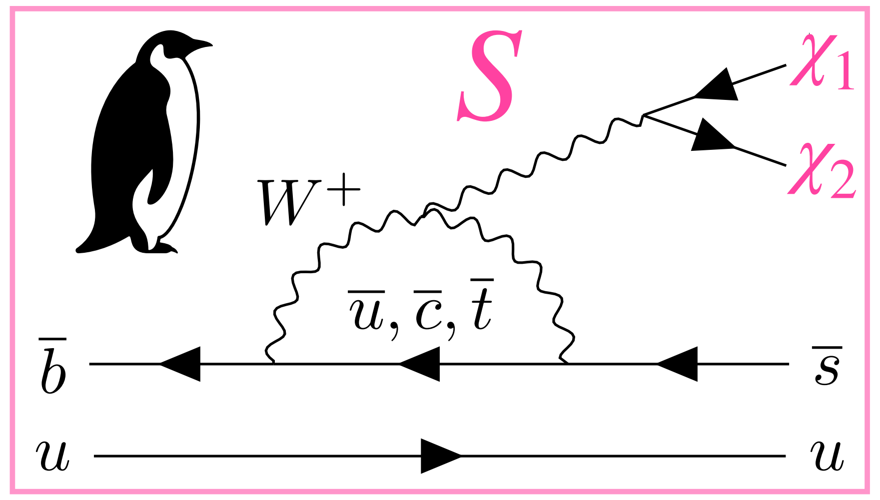


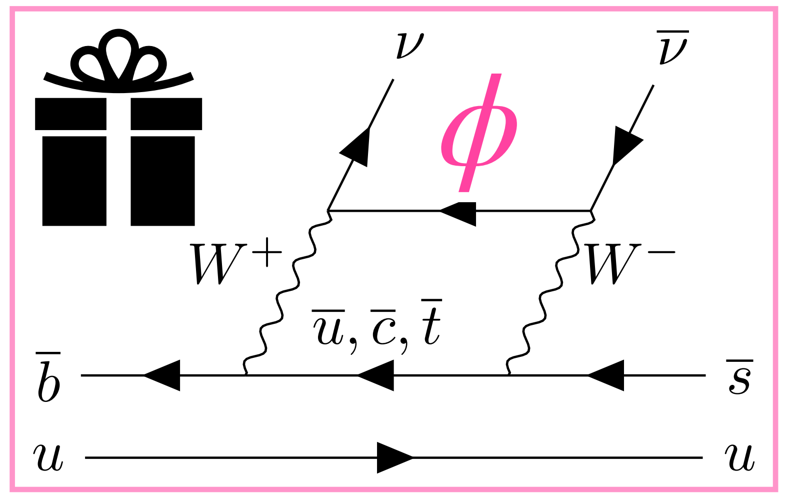
Rare B Decays

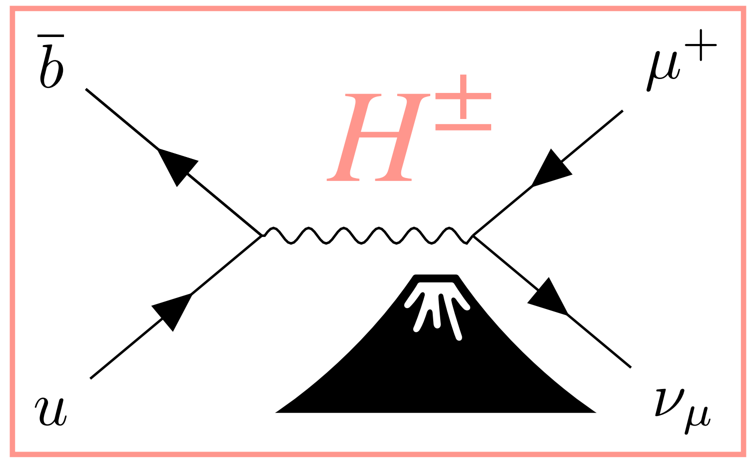
Rare B decays:

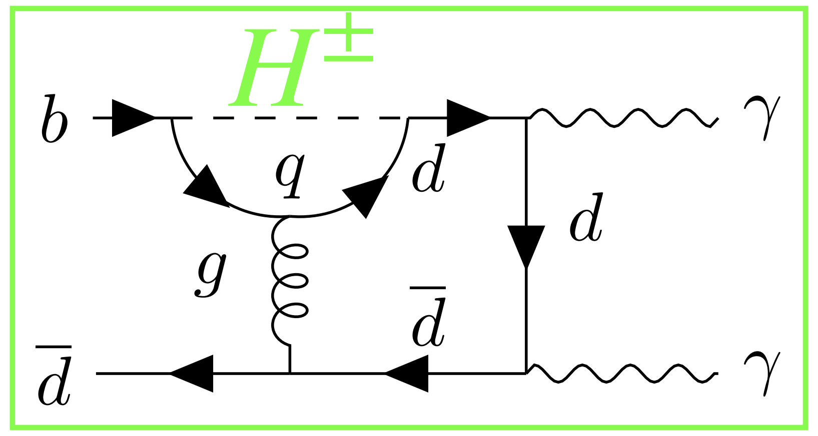
- GIM suppressed flavour changing neutral currents (FCNC)
  $\rightarrow \quad b \rightarrow s/d(\gamma)$
  - forbidden at tree level, allowed at loop level
  - electroweak decays, radiative electroweak decays
  - m_ν^2/M_W^2 suppressed lepton flavour violating decays
- Helicity suppressed purely leptonic decays

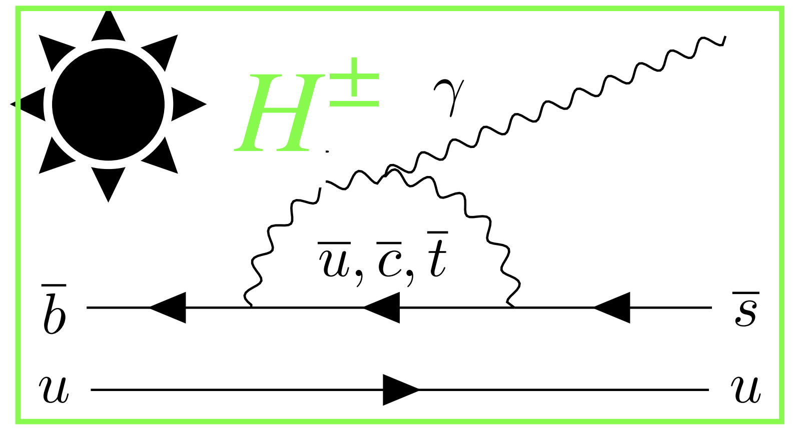
Very sensitive to NP since SM contribution small!

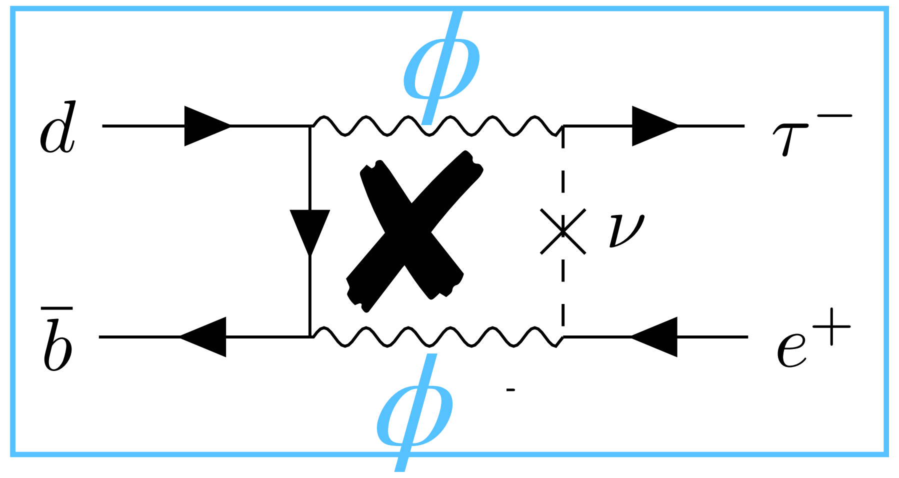












UNIVERSITÄT BONN

Rare B Decays

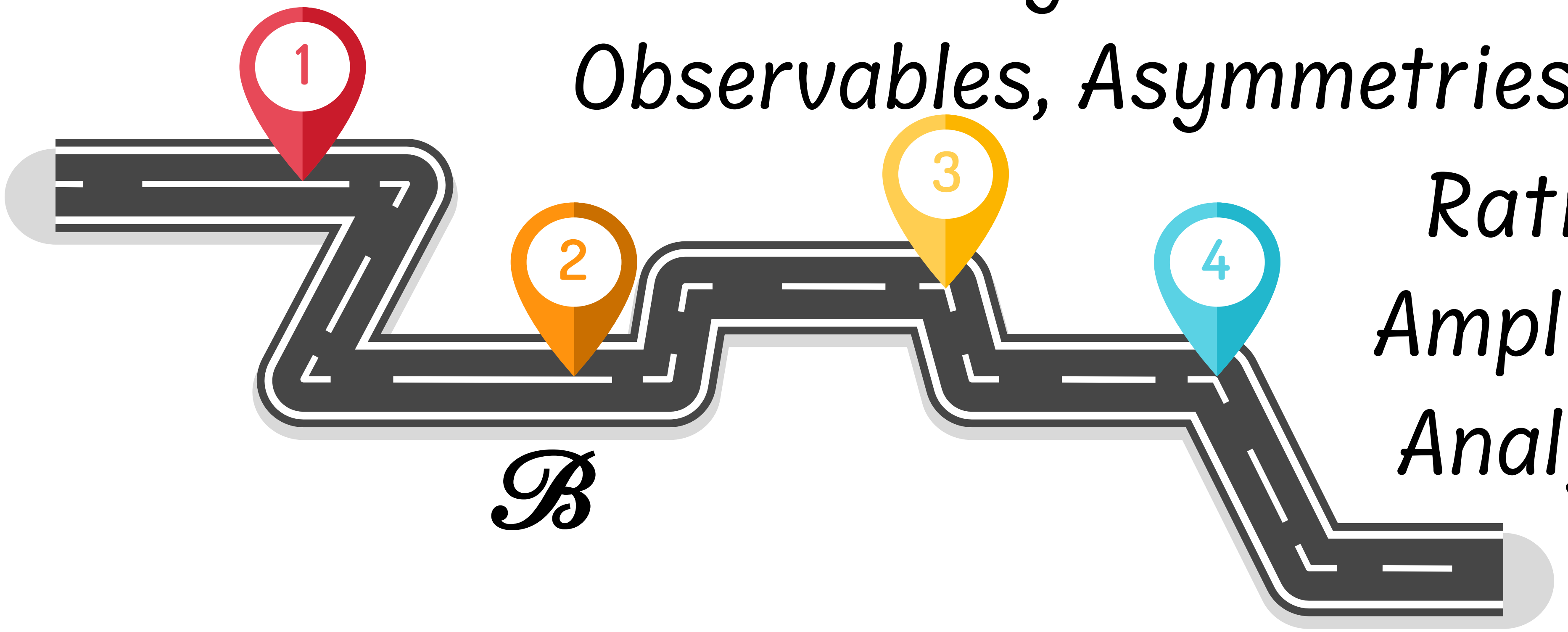
Rare B decays:

- GIM suppressed flavour changing neutral currents (FCNC)
  $\rightarrow \quad b \rightarrow s/d(\gamma)$
  - forbidden at tree level, allowed at loop level
  - electroweak decays, radiative electroweak decays
  - m_ν^2/M_W^2 suppressed lepton flavour violating decays
- Helicity suppressed purely leptonic decays

Very sensitive to NP since SM contribution small!

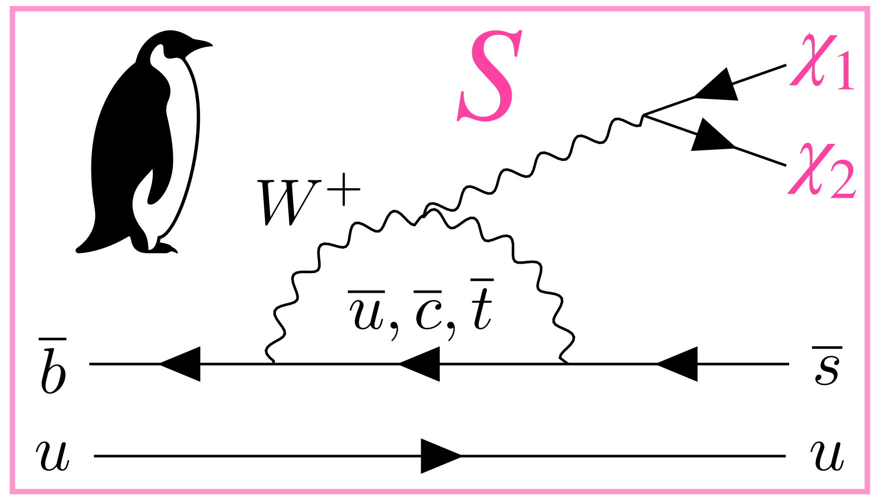
Limit

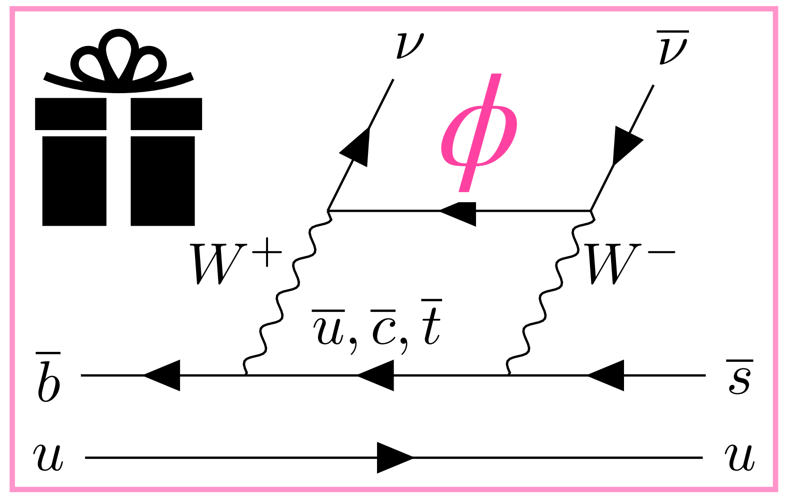
Angular Observables, Asymmetries

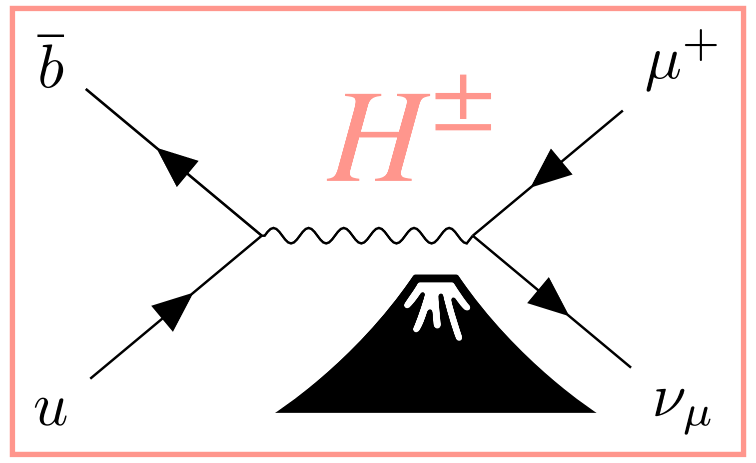


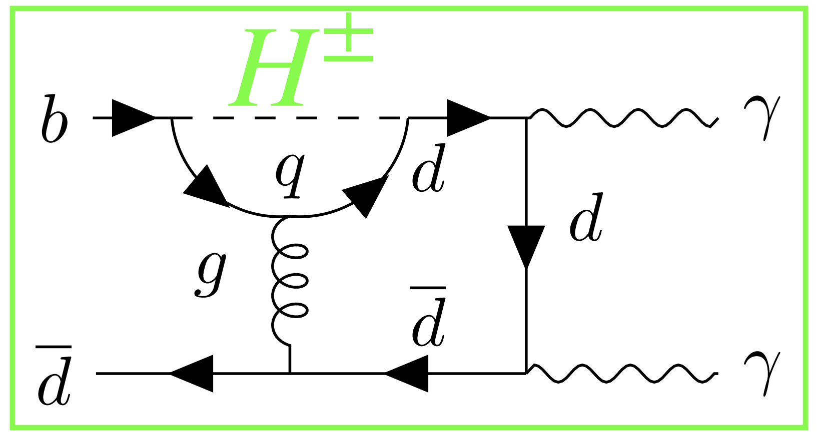
Ratios , Amplitude Analyses

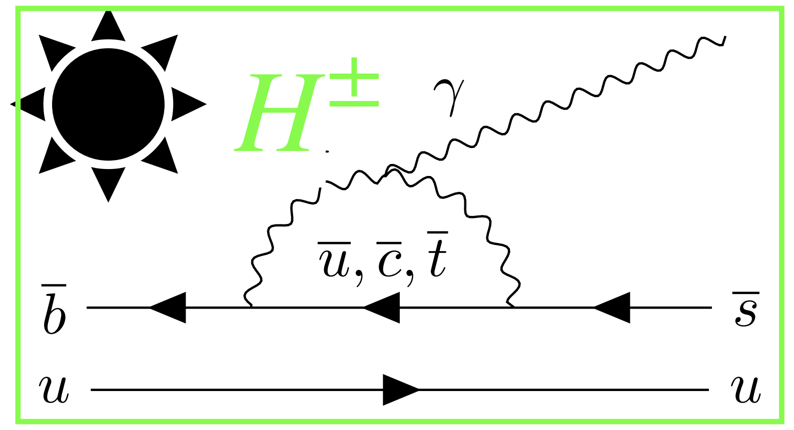
CP observables

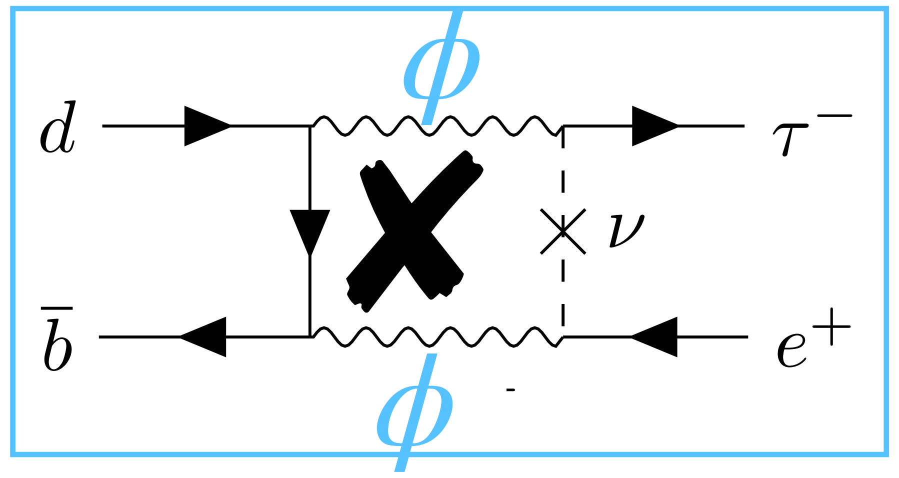




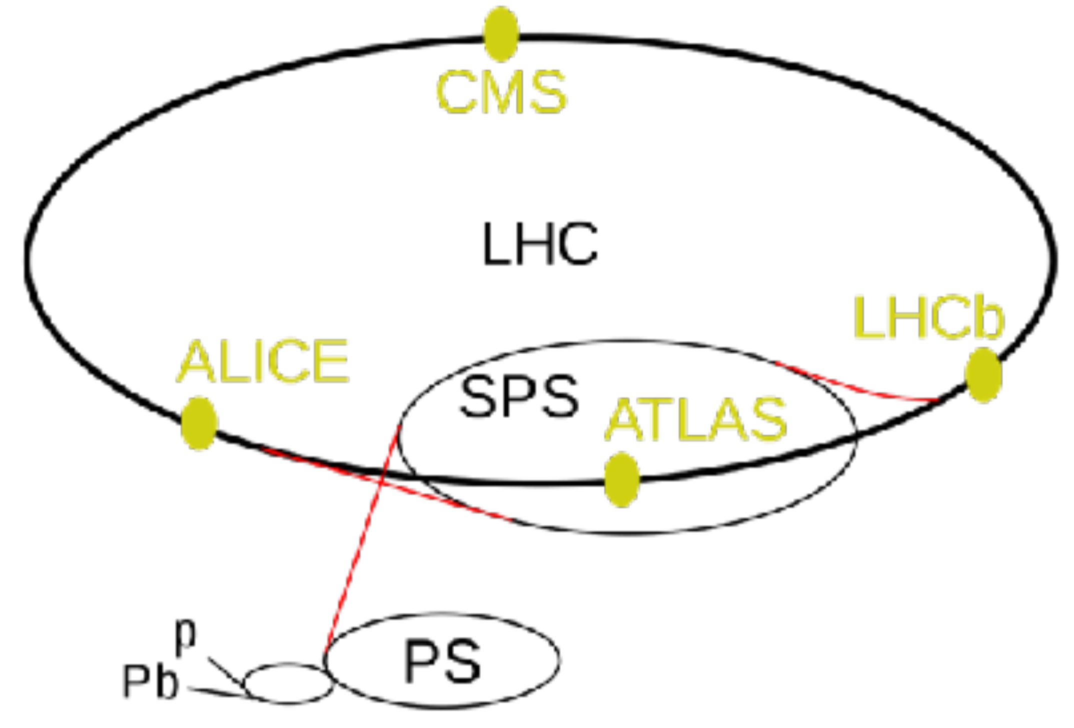


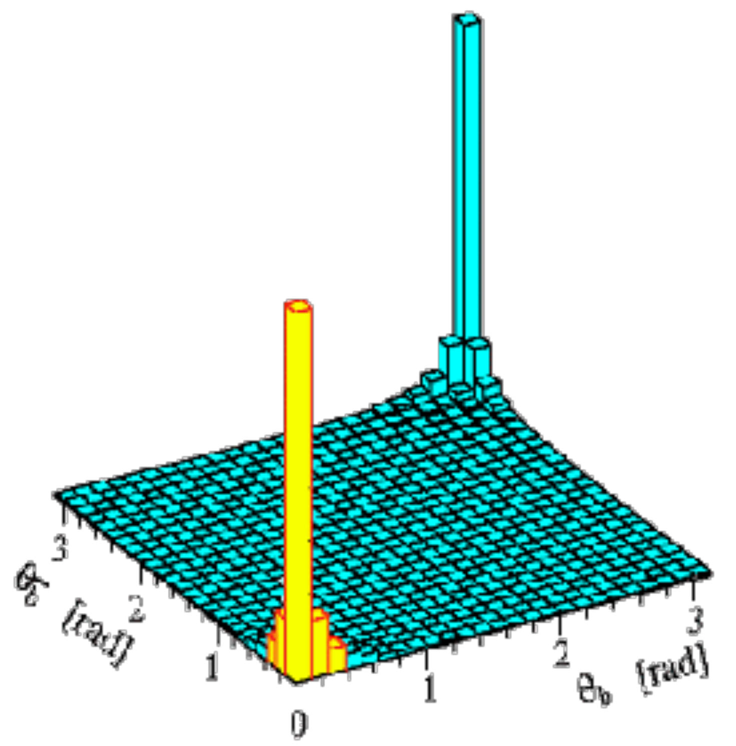






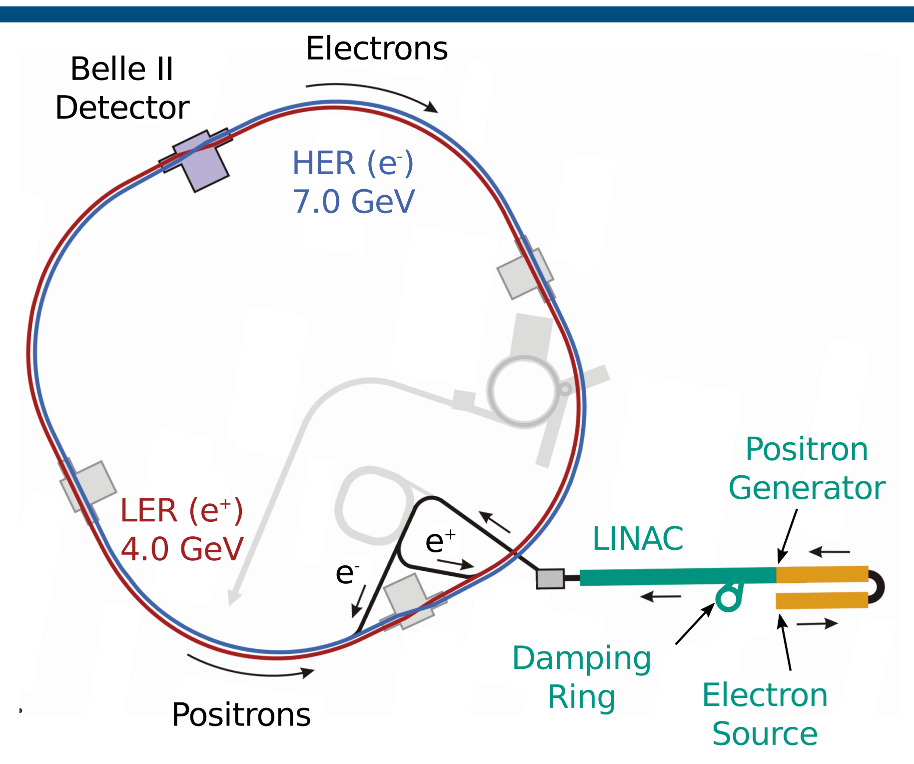
Accelerators

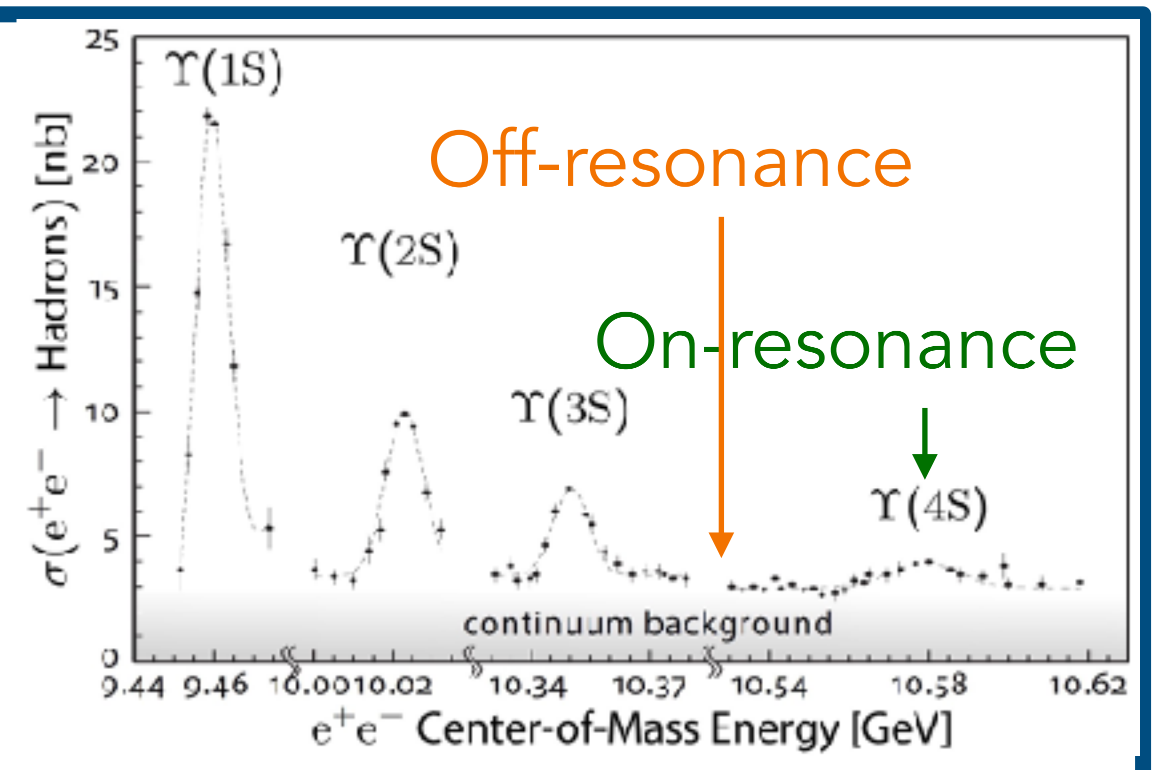




LHC

- pp collisions at 7,8,13 TeV
- b-quarks produced by gluon fusion
- All b-hadron species (b-baryons)
- Highly boosted topology
- $\sigma_{bb} = 100\ \mu$b
- Noise/Signal=1000

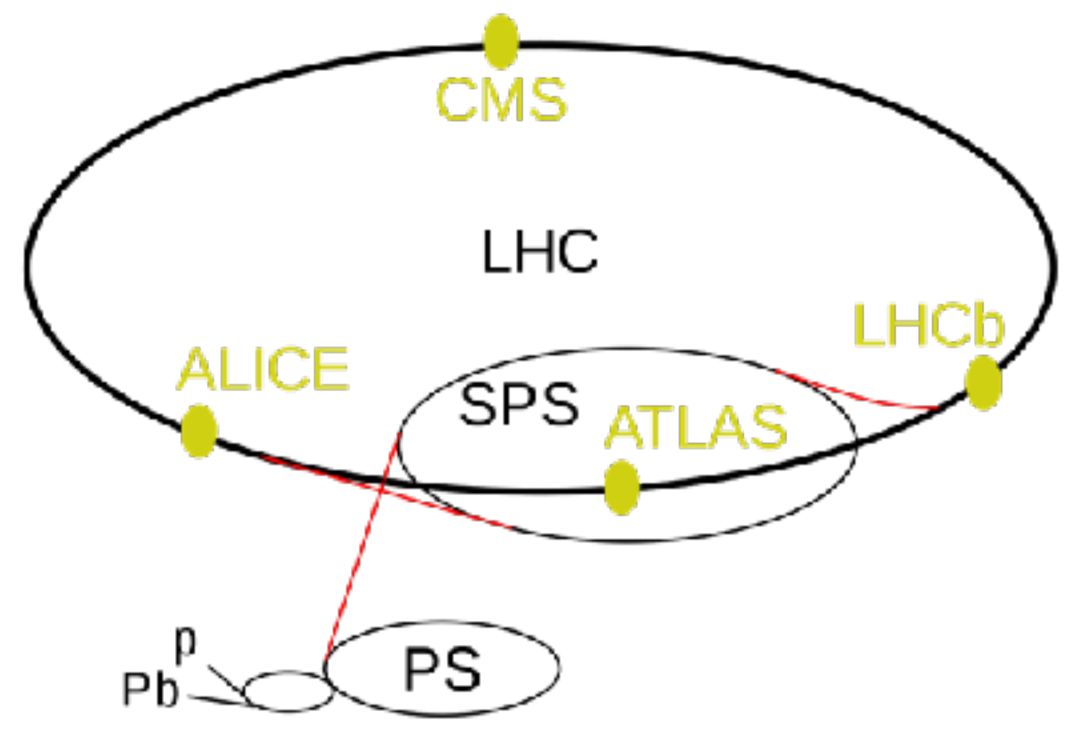


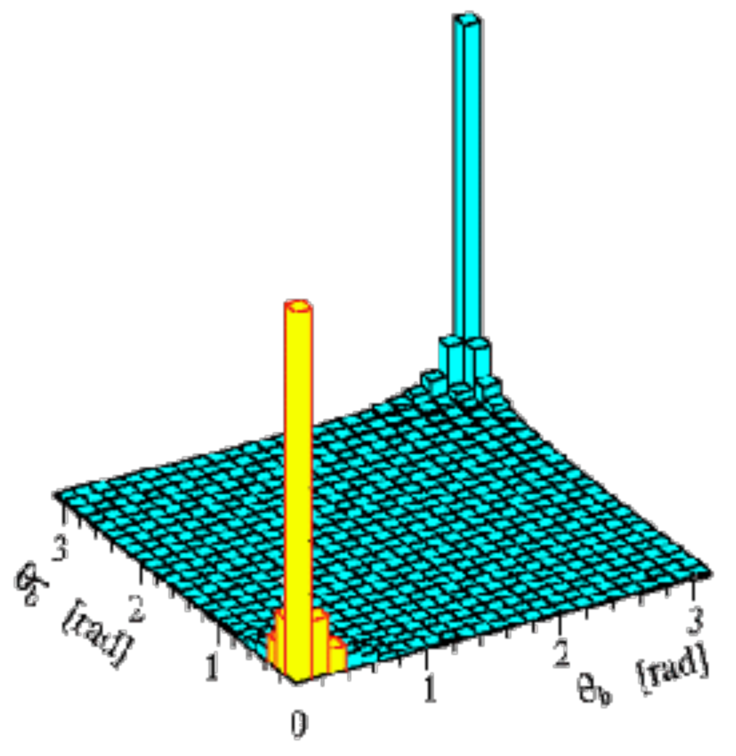


SuperKEKB

- e^+e^- energy-asymmetric collisions at $\sqrt{s} = 10.58$ GeV (on-resonance data)
- 60 MeV below to constrain $e^+e^- \to q\bar{q}$ (continuum) bkgs (off-resonance data)
- $B\bar{B}$ produced via $\Upsilon(4(S))$
- Exclusive $B\bar{B}$ production
- Asymmetric beam energy → boost
- $\sigma_{bb} = 1.1$ nb
- Noise/Signal=4

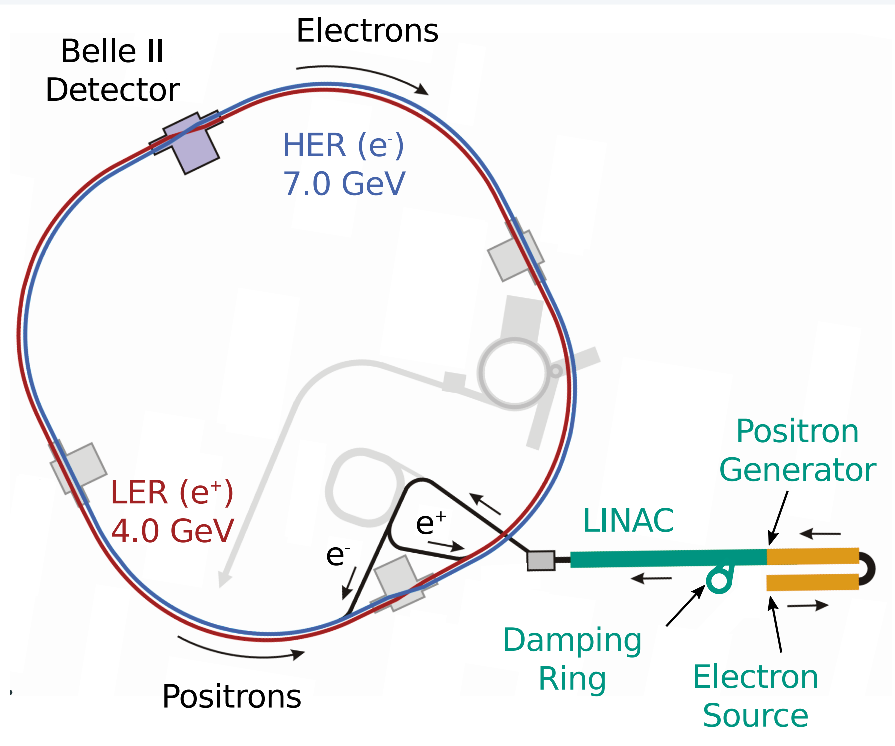
Accelerators

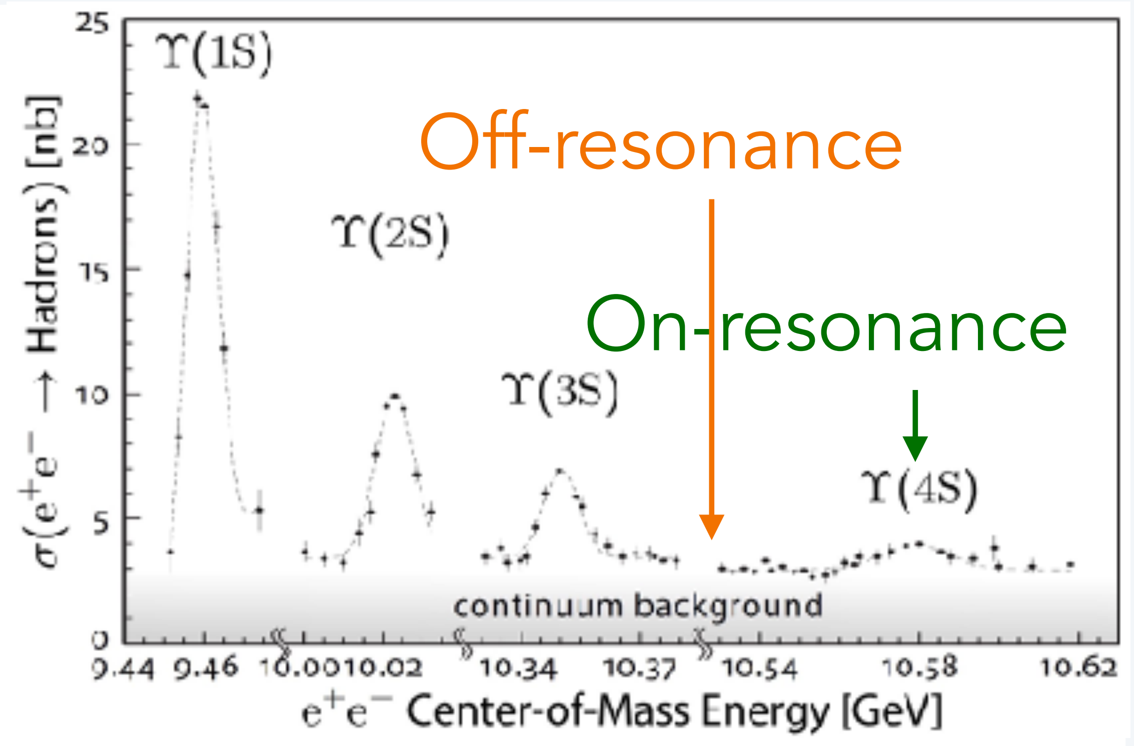




LHC

- pp collisions at 7,8,13 TeV
- b-quarks produced by gluon fusion
- all b-hadron species (b-baryons)
- Highly boosted topology
- $\sigma_{bb} = 100\mu b$
- Different backgrounds (Noise/Signal=1000)





SuperKEKB

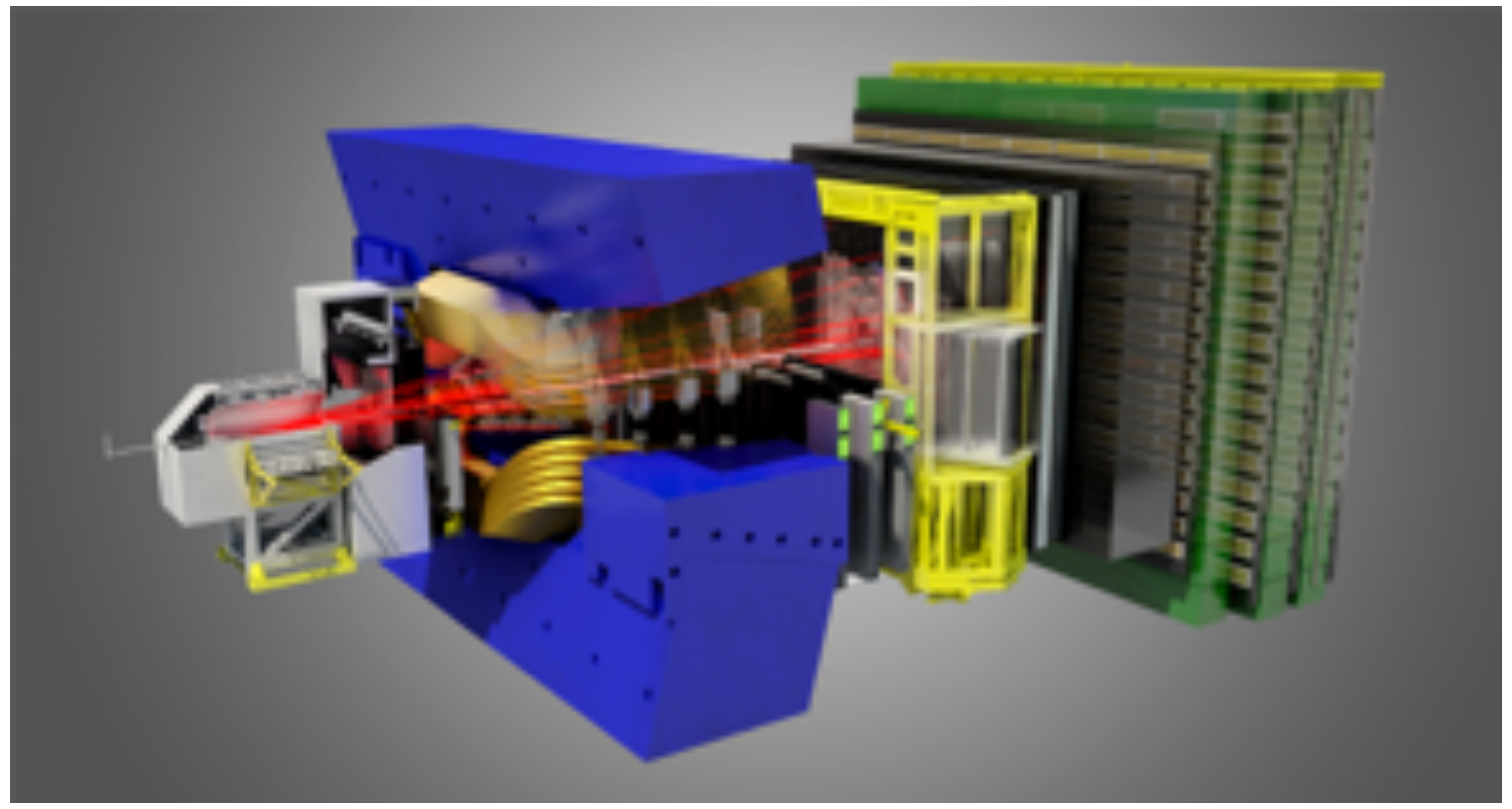
- e^+e^- energy-asymmetric collisions at $\sqrt{s} = 10.58$ GeV (on-resonance data)
- 60 MeV below to constrain $e^+e^- \to q\bar{q}$ (continuum) bkgs (off-resonance data)
- $B\bar{B}$ produced via $\Upsilon(4(S))$
- Exclusive $B\bar{B}$ production
- Asymmetric beam energy → boost
- $\sigma_{bb} = 1.1$ nb
- Different backgrounds (Noise/Signal=4)

Approximate rule:

1 fb⁻¹ = 1 ab⁻¹

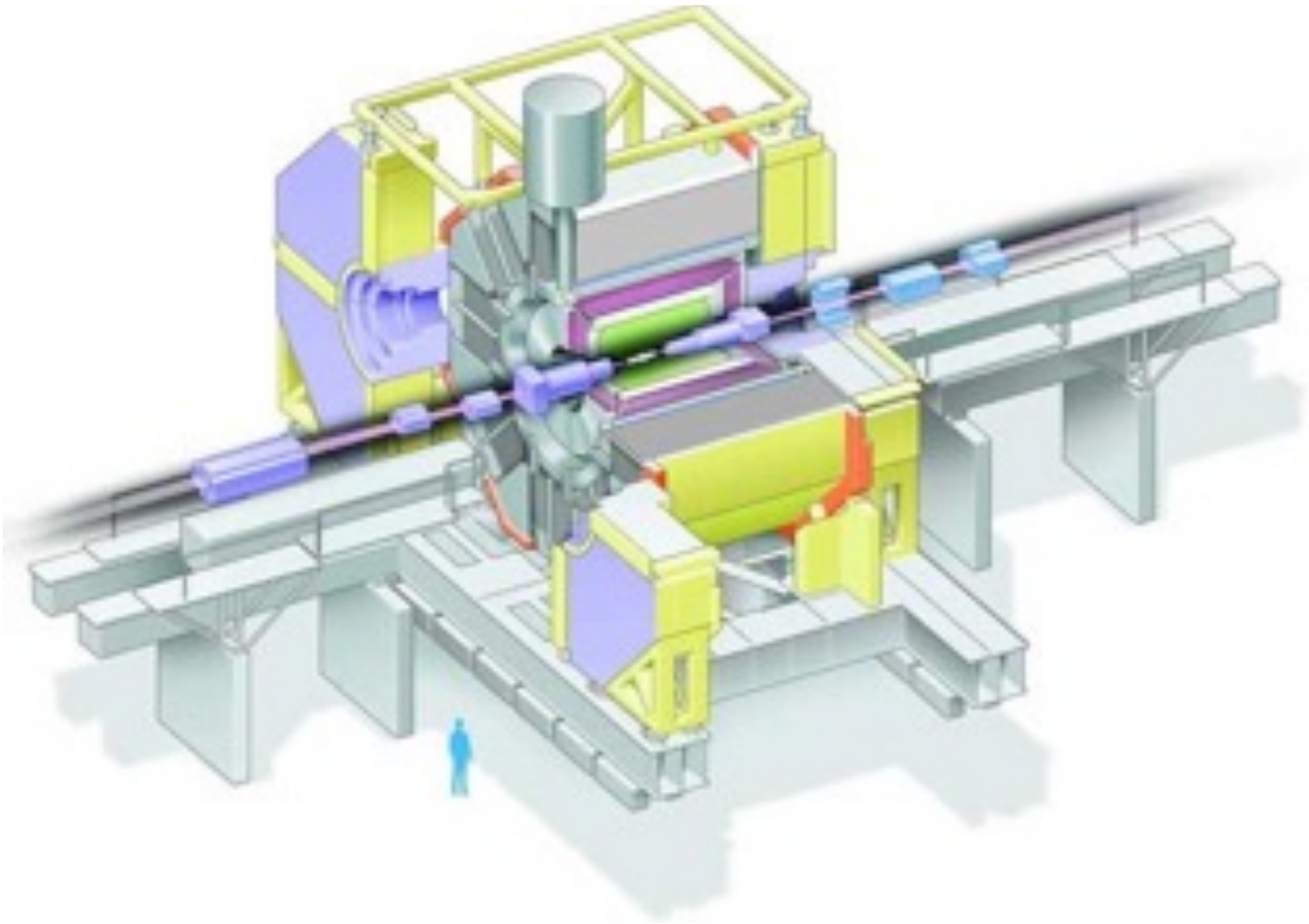
$$1\ fb^{-1} = 1\ ab^{-1}$$

The Three Beasts



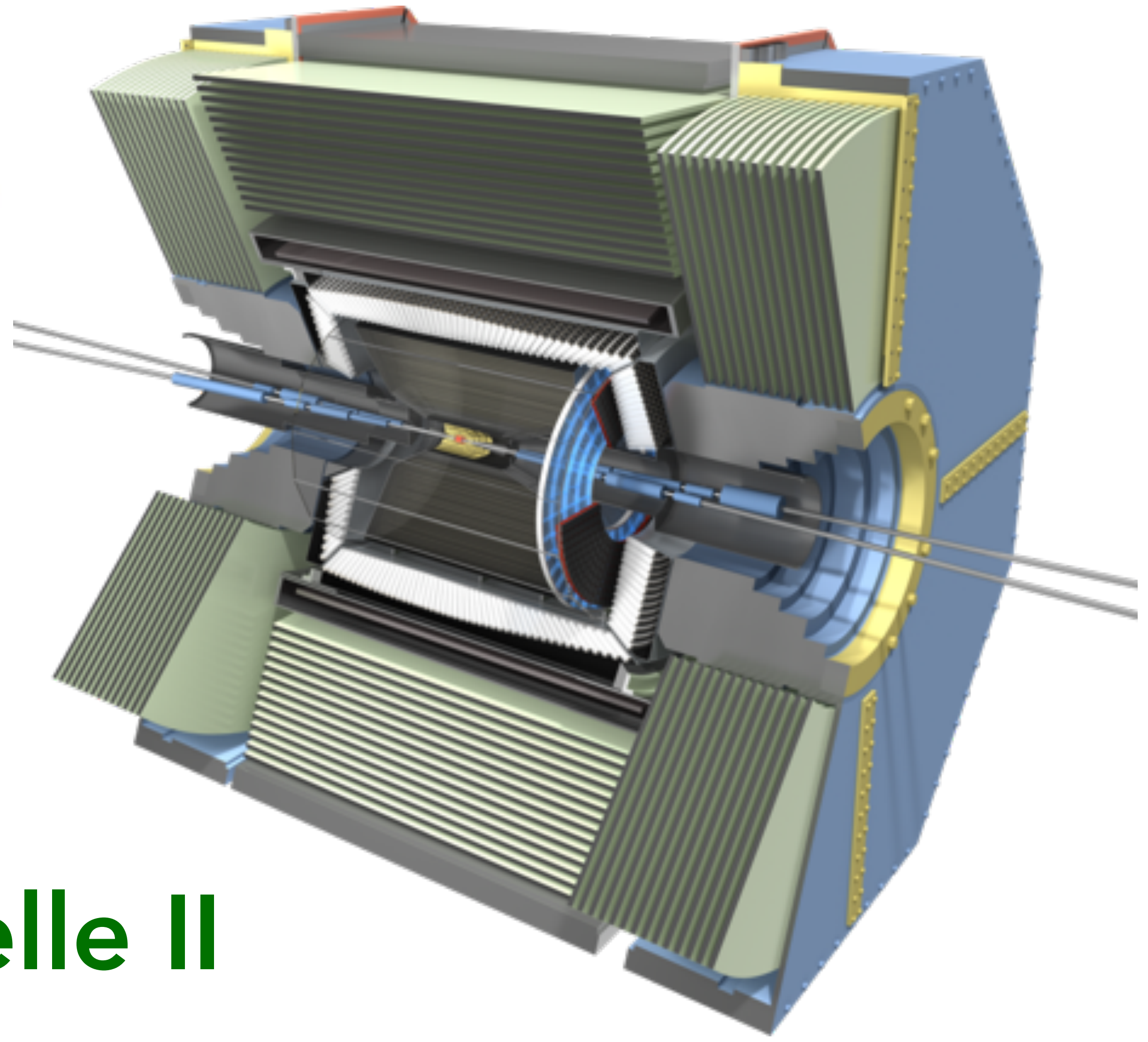
LHCb

- LHC (pp collisions at 7,8,13 TeV)
- Forward-looking spectrometer
- Taking data since 2011
- Collected **9 $\mathbf{fb^{-1}}$ data so far**
  - **4x10^{12} $b\bar{b}$ pairs**
  - B_u (40%), B_d(40%), B_s(10%), B_c and b-baryons (10%)



Belle

- KEKB (8 GeV e^-/ 3.5 GeV e^+)
- General purpose detector
- Took data from 1999-2010
- Collected **711 $\mathbf{fb^{-1}}$** data
  - **770 mil. $B\bar{B}$ pairs**



Belle II

- SuperKEKB (7 GeV e^-/4 GeV e^+)
- General purpose detector
- Taking data since 2019
- Collected **362 $\mathbf{fb^{-1}}$ data in Run 1**
  - **370 mil. $B\bar{B}$ pairs**
- Resumed data-taking this year after ~ 1.5y long shut-down

The Three Beasts

Increasing instantaneous luminosity is the key!

LHCb

- LHC (pp collisions at 7,8,13 TeV)
- Forward-looking spectrometer
- Taking data since 2011
- Collected **9 $\mathbf{fb^{-1}}$ data so far**
  - **4x10^{12} $b\bar{b}$ pairs**
  - B_u (40%), B_d(40%), B_s(10%), B_c and b-baryons (10%)
- **Plan: 300 $\mathbf{fb^{-1}}$**

Belle

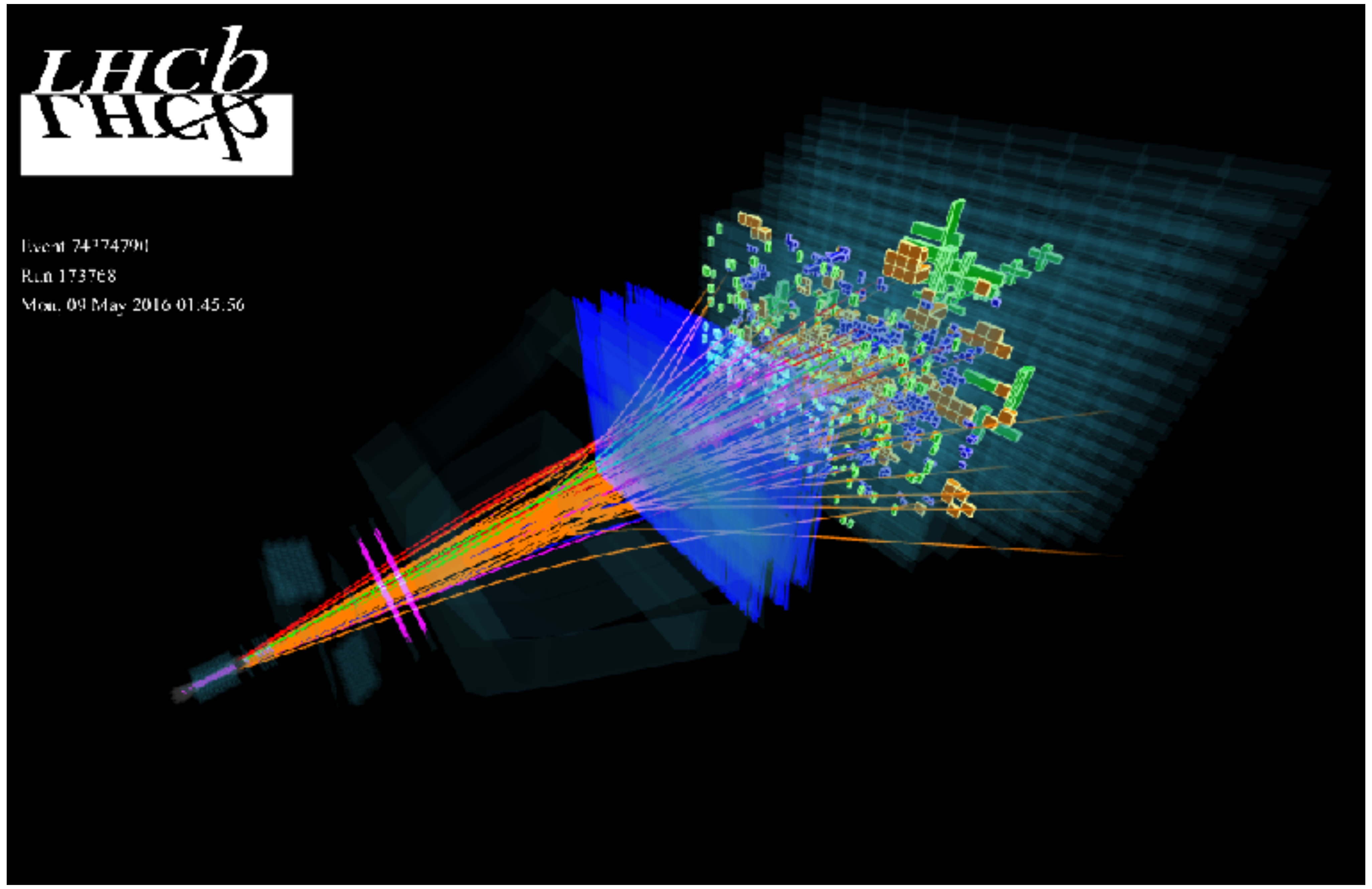
- KEKB (8 GeV e^-/ 3.5 GeV e^+)
- General purpose detector
- Took data from 1999-2010
- Collected **711 $\mathbf{fb^{-1}}$** data
  - **770 mil. $B\bar{B}$ pairs**

Belle II

- SuperKEKB (7 GeV e^-/4 GeV e^+)
- General purpose detector
- Taking data since 2019
- Collected **362 $\mathbf{fb^{-1}}$ data in Run 1**
  - **370 mil. $B\bar{B}$ pairs**
- Resumed data-taking this year after ~ 1.5y long shut-down
- **Plan: 50 $\mathbf{ab^{-1}}$**

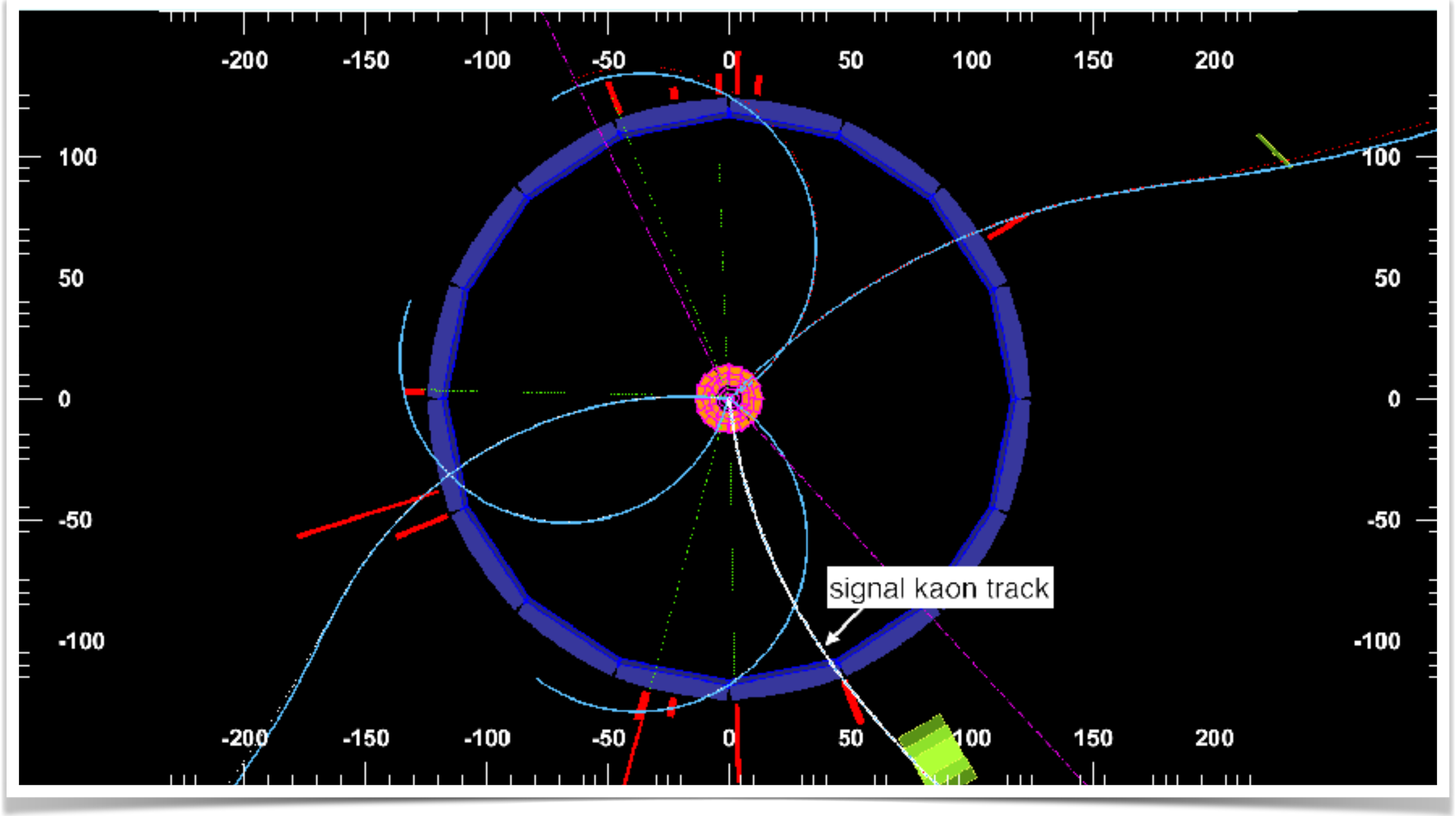
Typical Event

LHCb



- Rather busy environment
- On average 100 tracks
- Longitudinal momentum of the B not known
- Lower trigger efficiency in general

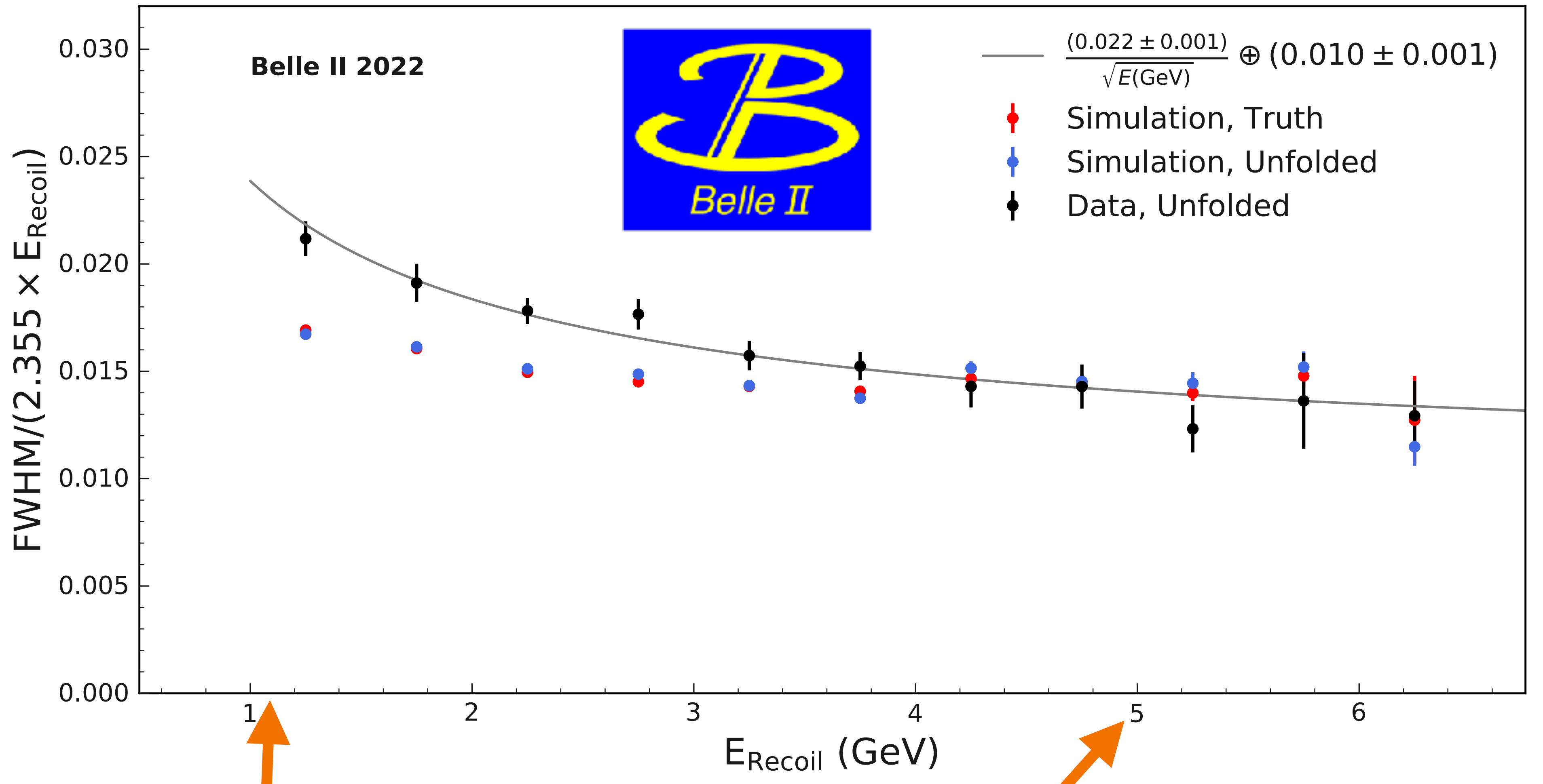
Belle II

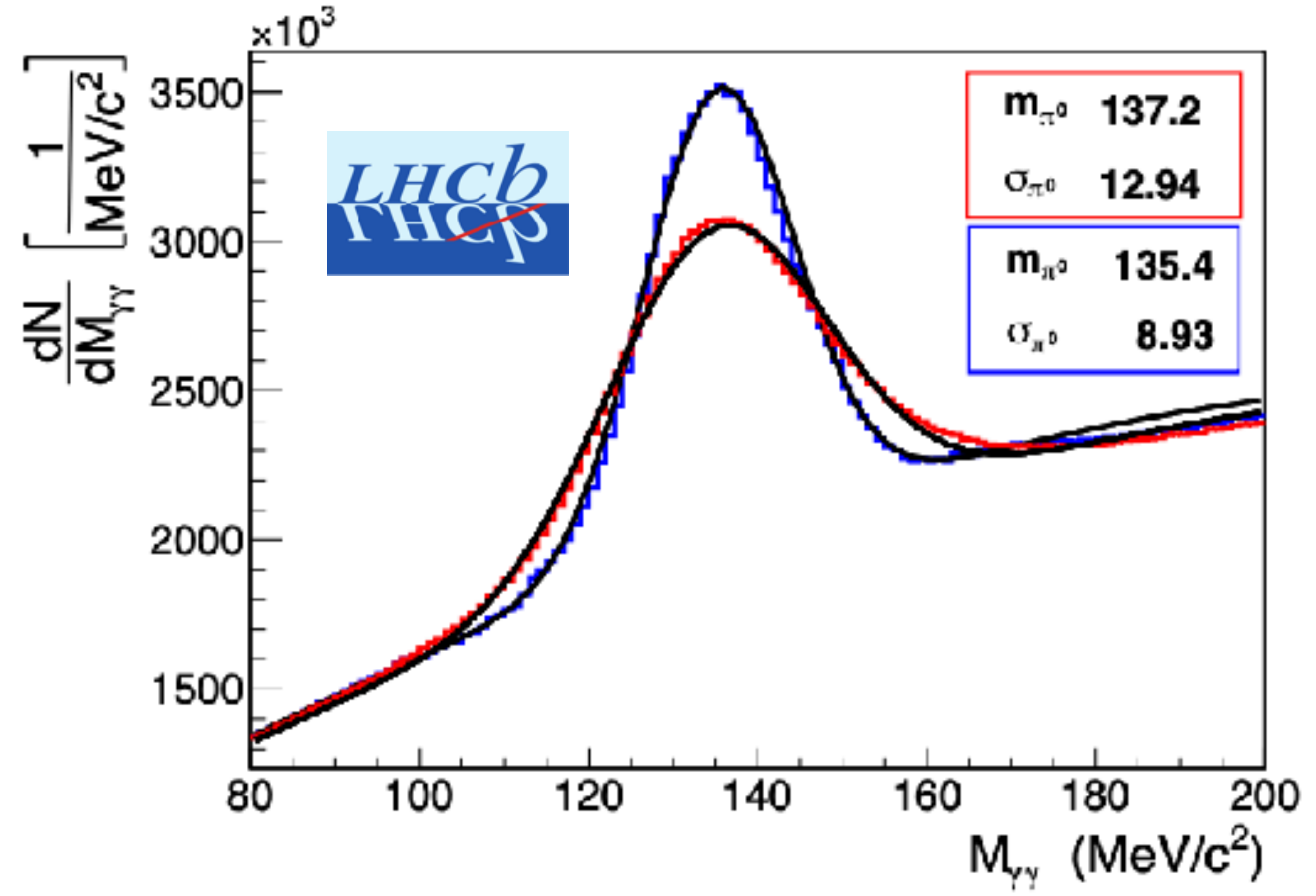


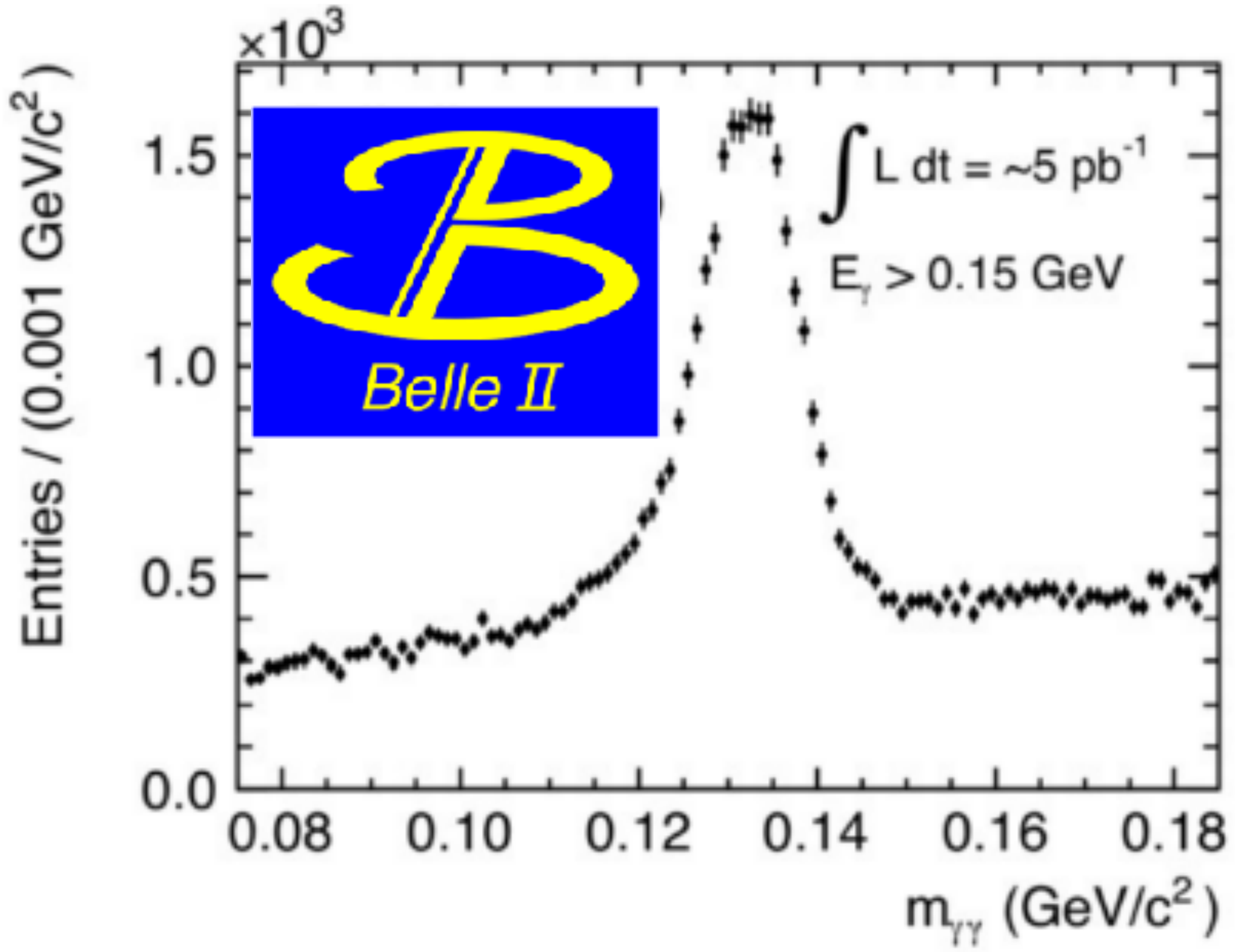
- Very clean environment
- On average: 11 tracks
- Known initial state kinematics
- Near 100% efficiency for B decays
- Sensitive to lower energy deposits

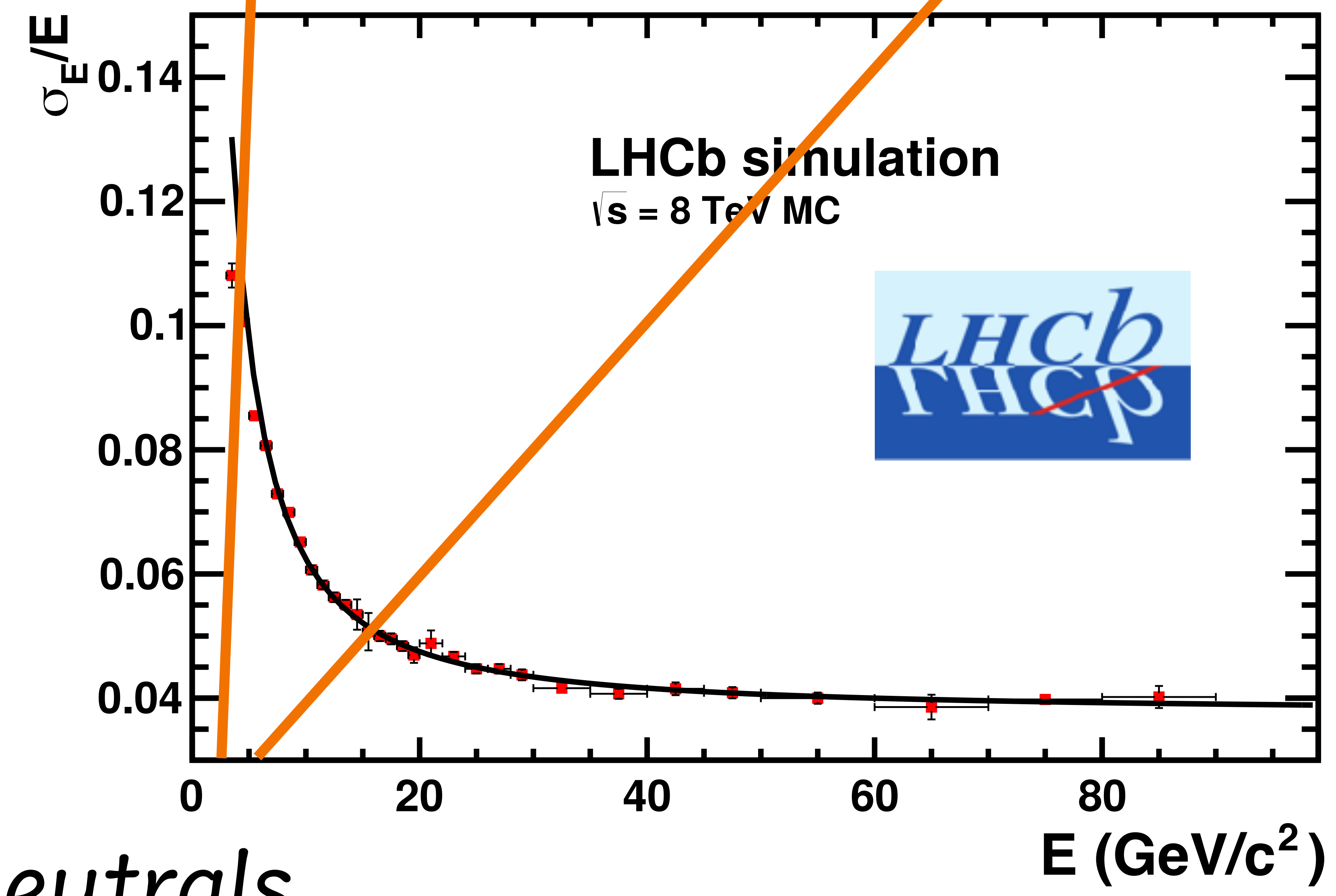
Neutral Performance

	Belle II	LHCb
γ detection efficiency	99.9%	95 %
$\sigma(E)/E$	$\frac{2.2\,\%}{\sqrt{E}} \oplus 1\,\%$	$\frac{10\,\%}{\sqrt{E}} \oplus 1\,\%$
π^0 reconstruction	Better mass resolution	Worse mass resolution









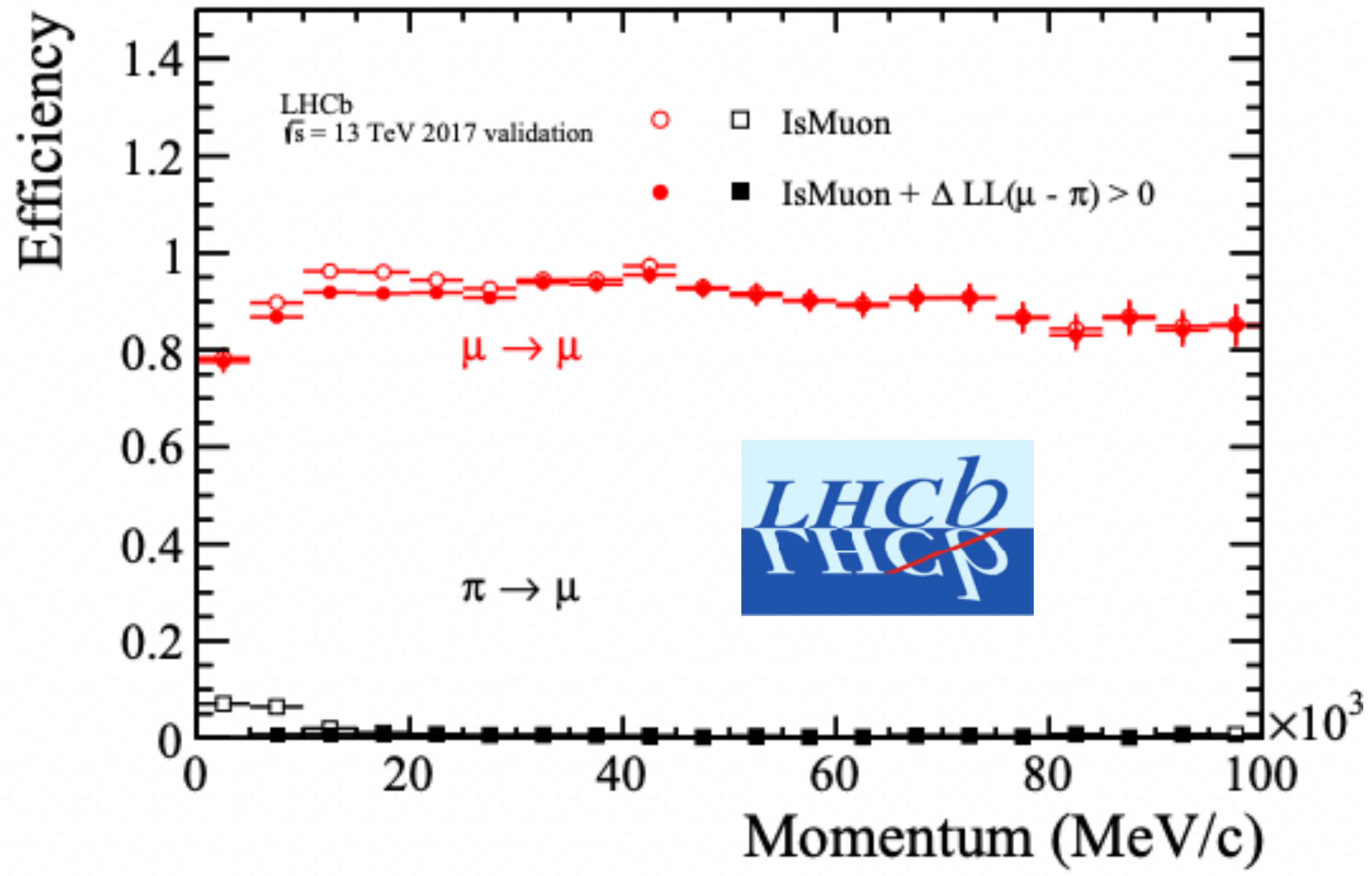
Belle II is generally better with neutrals

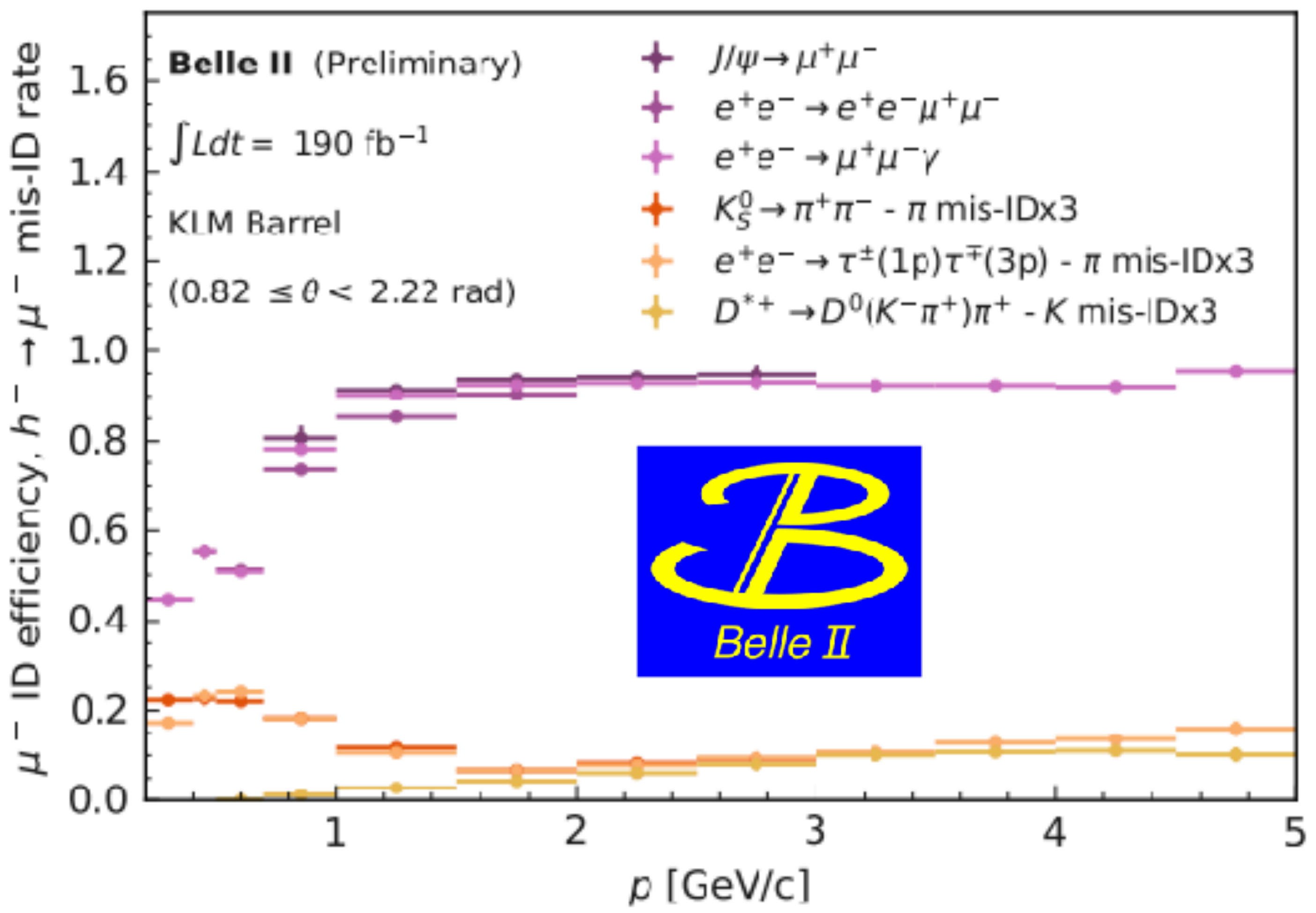
Charged Track Performance

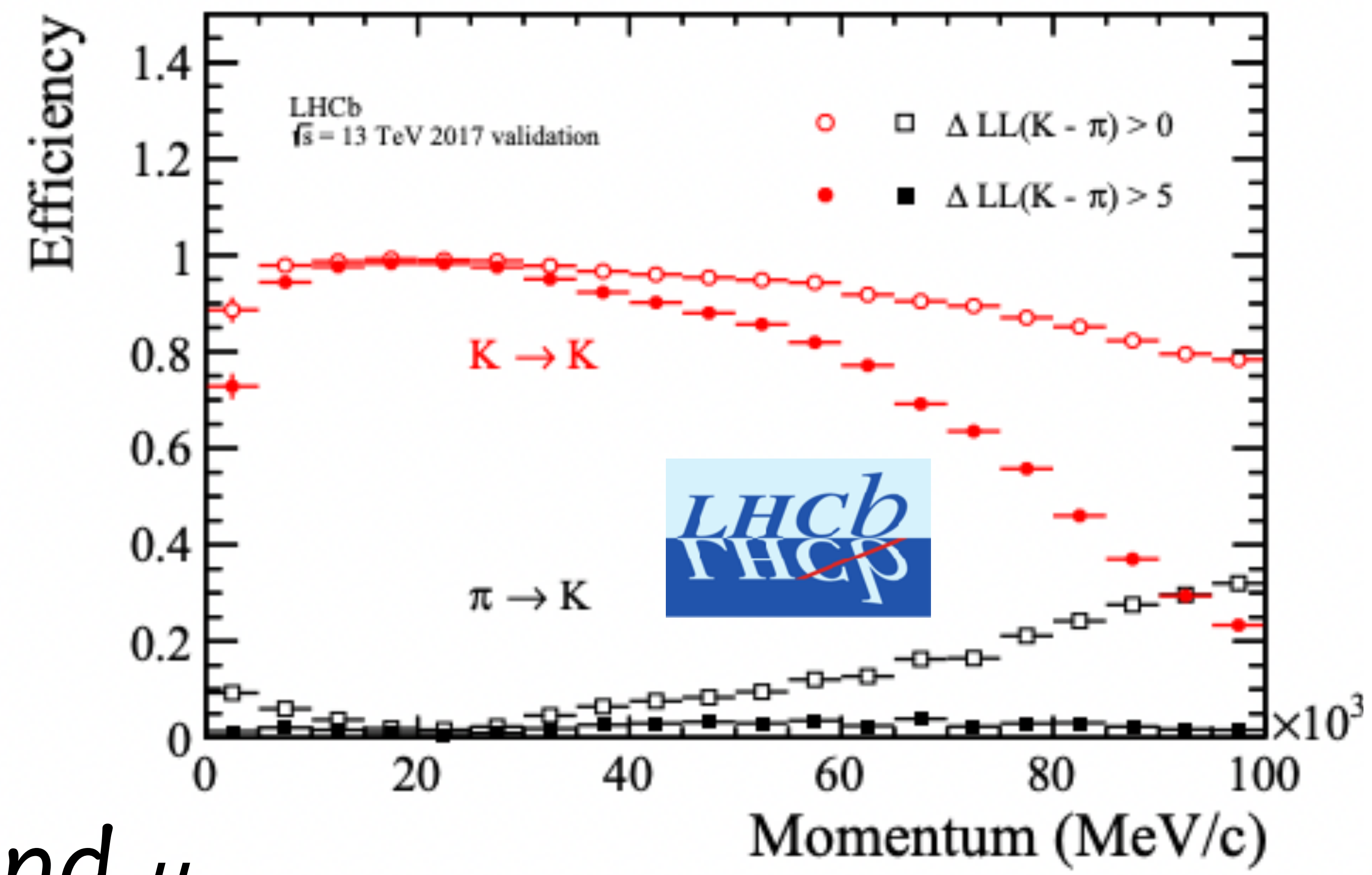
	Belle II	LHCb
Muon trigger efficiency	100 %	90 %
Muon ID efficiency	95 %	97 %
$\pi \rightarrow \mu$ misID	7 %	1-3%

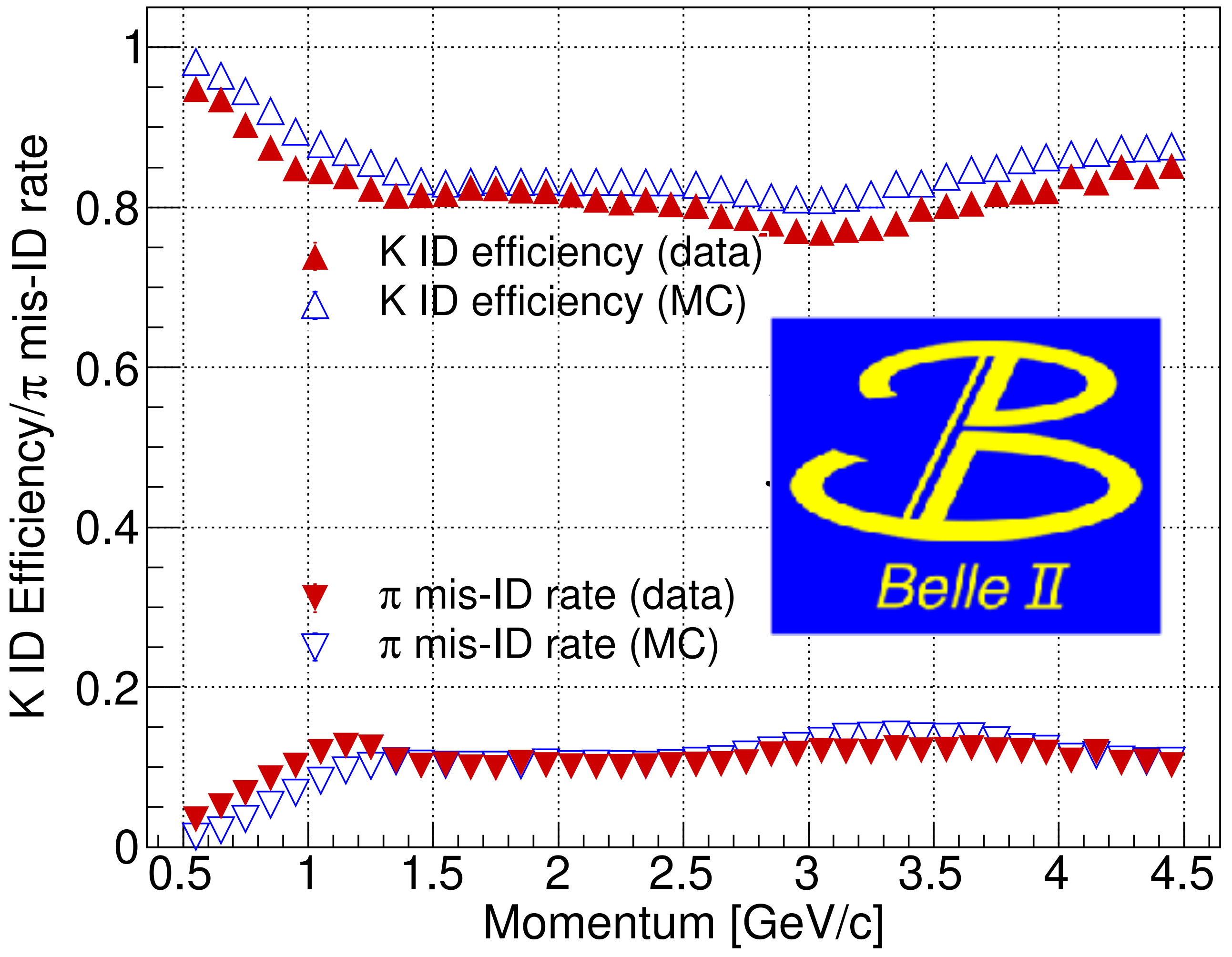
	Belle II	LHCb
Kaon ID efficiency	90 %	95 %
$K \rightarrow \pi$ misID	5 %	5 %

	Belle II	LHCb
Total $B^+ \rightarrow K^+\mu^+\mu^-$ efficiency	30 %	5 %
Total $B^+ \rightarrow K^+e^+e^-$ efficiency	30 %	< 5 %





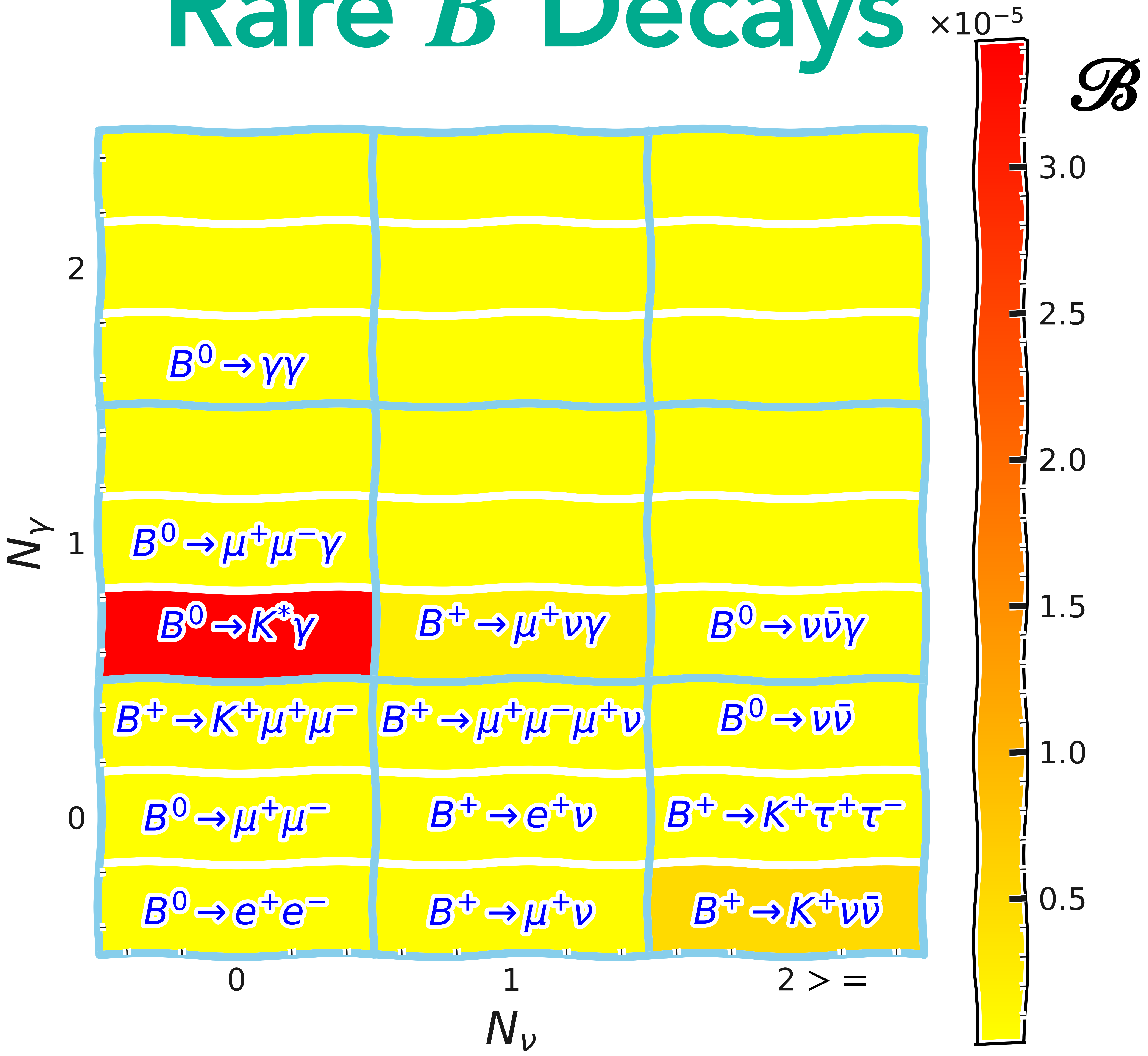




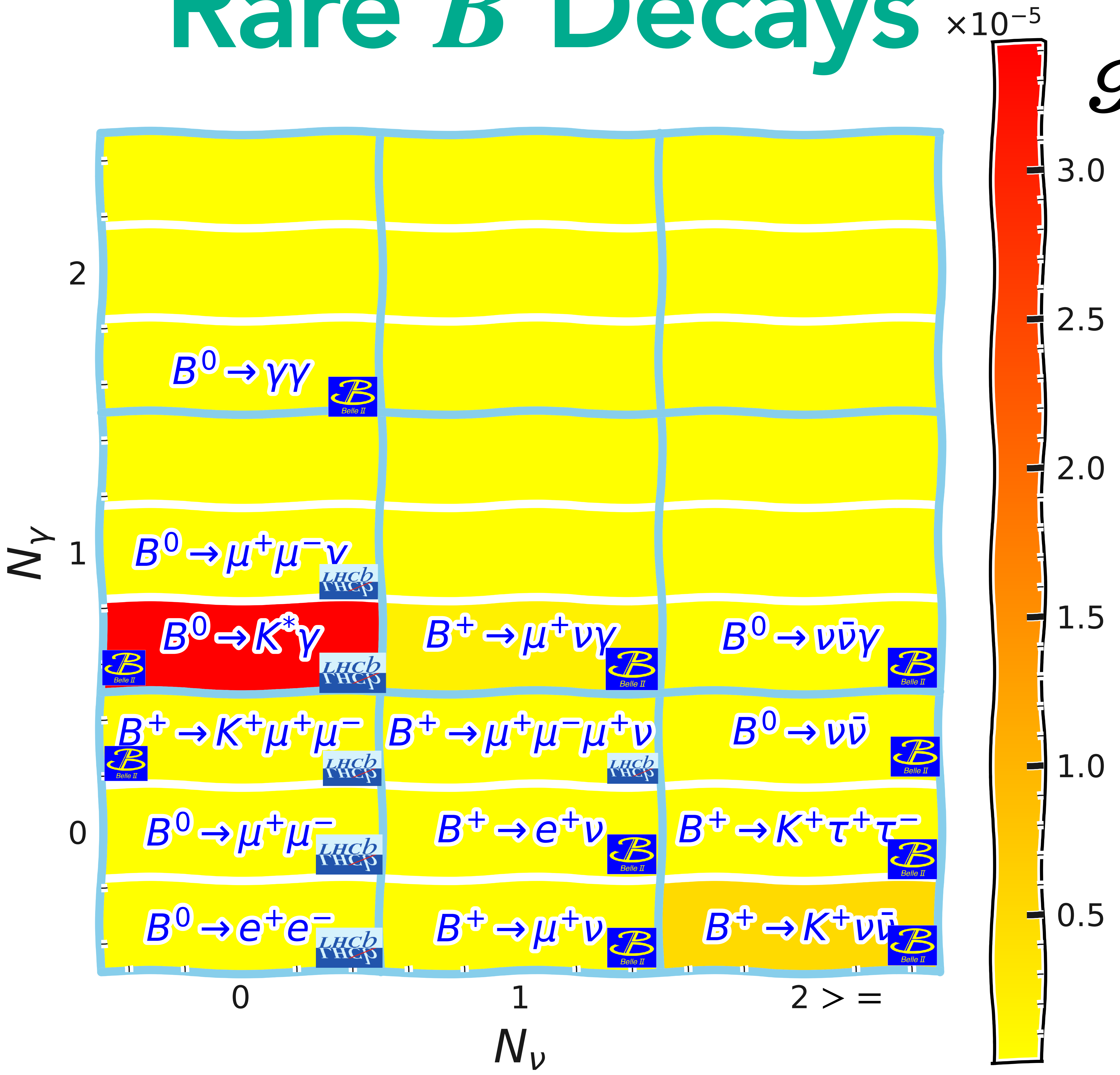
LHCb is very good with muons

Belle II has similar sensitivity for e and μ

Rare B Decays



Rare B Decays

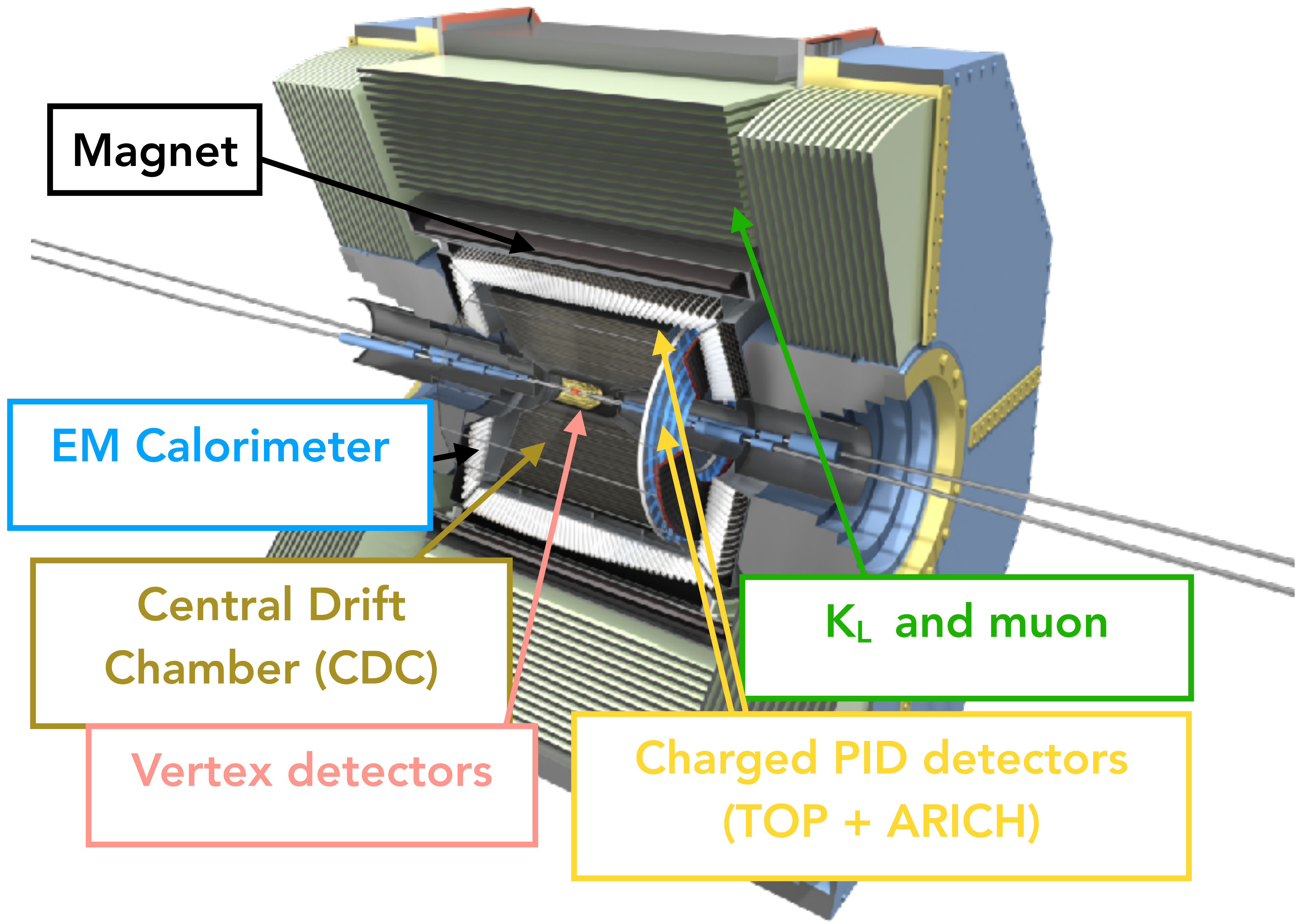


Better with multiple muons/ charged tracks that can be vertexed

Better with higher number of γ and ν

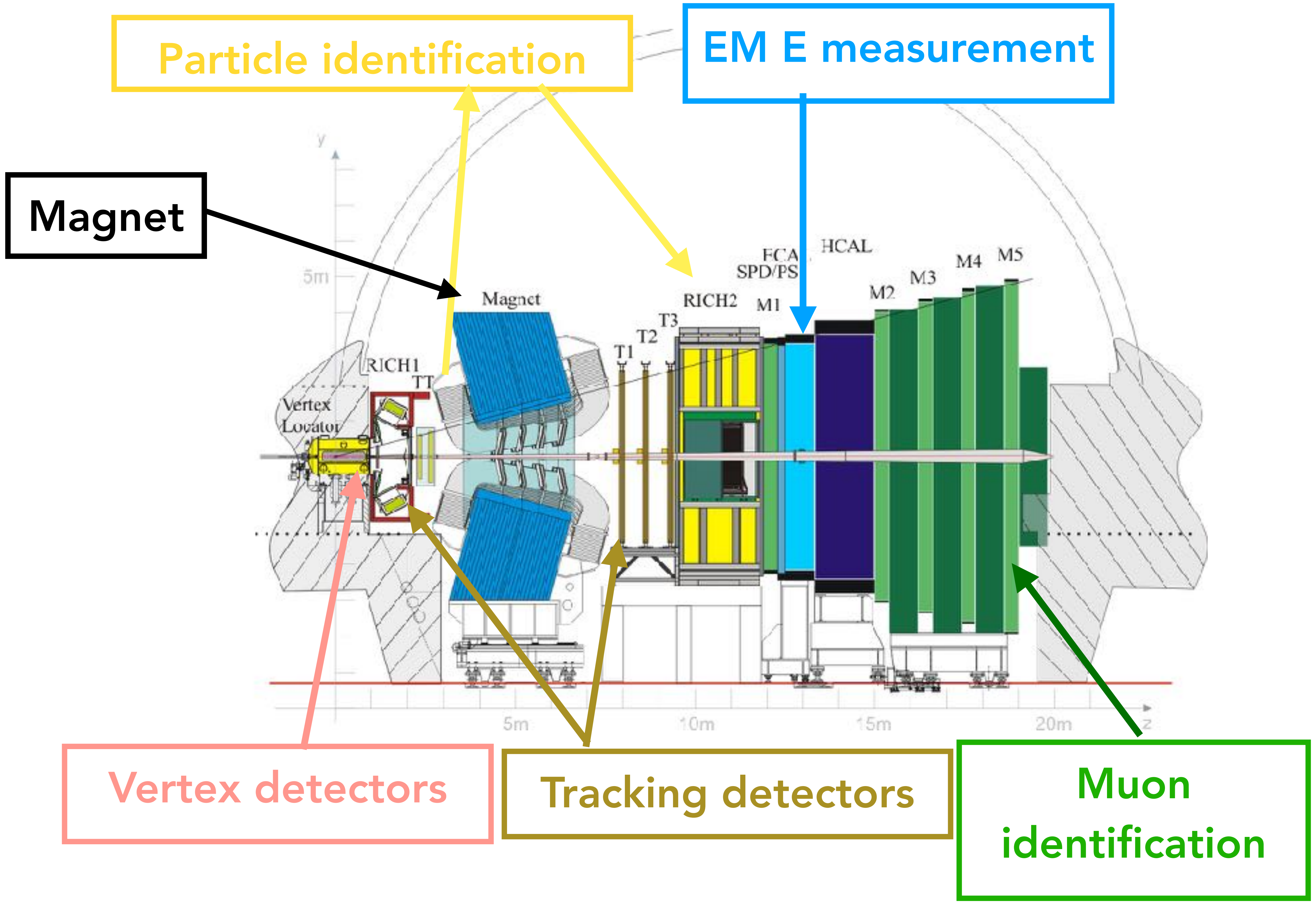
Detectors

Belle II



- Hermetic detector
- Sensitive to lower energy/charge deposits
- Known initial state kinematics

LHCb



- Single arm spectrometer
- Longitudinal momentum of the B not known