Karlsruhe Institute of Technology

B physics at Belle II

KSETA Plenary Workshop, 16.03.2022

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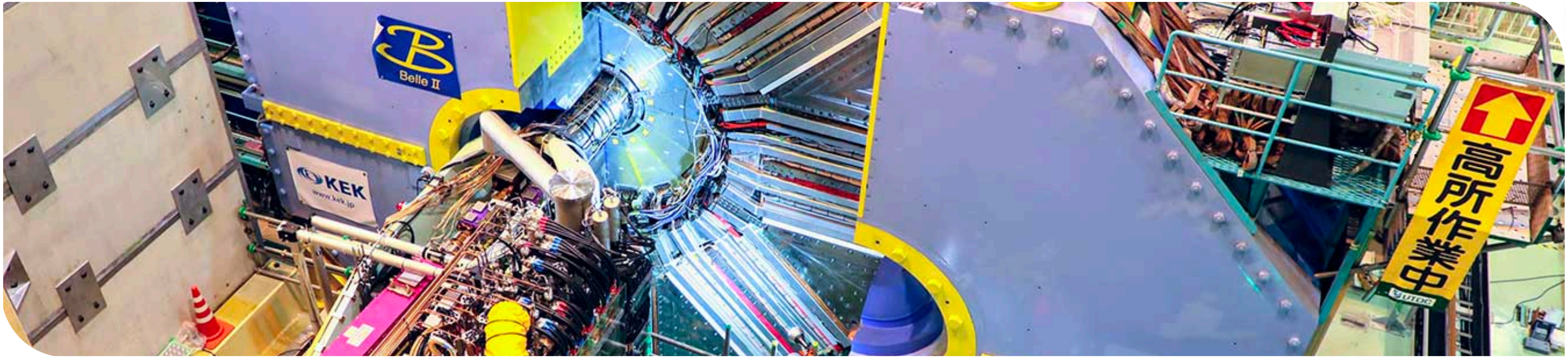
with input by Sascha Dreyer, Felix Metzner, Alex Heidelbach, Giacomo De Pietro, …



Outline

- Flavour physics and flavour anomalies
  (heavy new physics)

- Belle II

- Long lived particles
  (light new physics)

Flavour physics

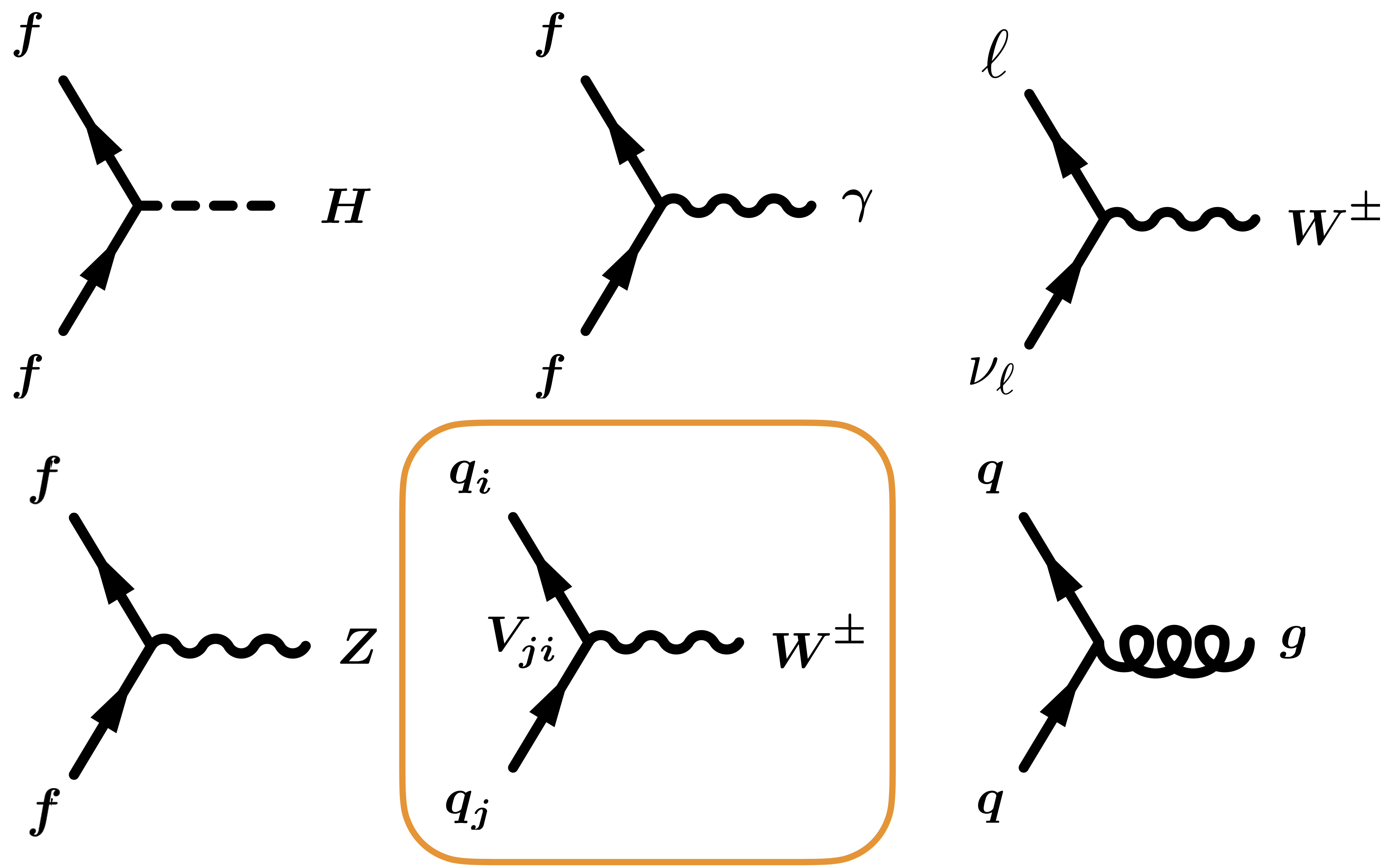
DEFINITION: **Flavour**
is a quantum number used to distinguish particles/fields that have the same gauge quantum numbers

In the SM: quarks and leptons come in three copies with the same colour representation and electric charge

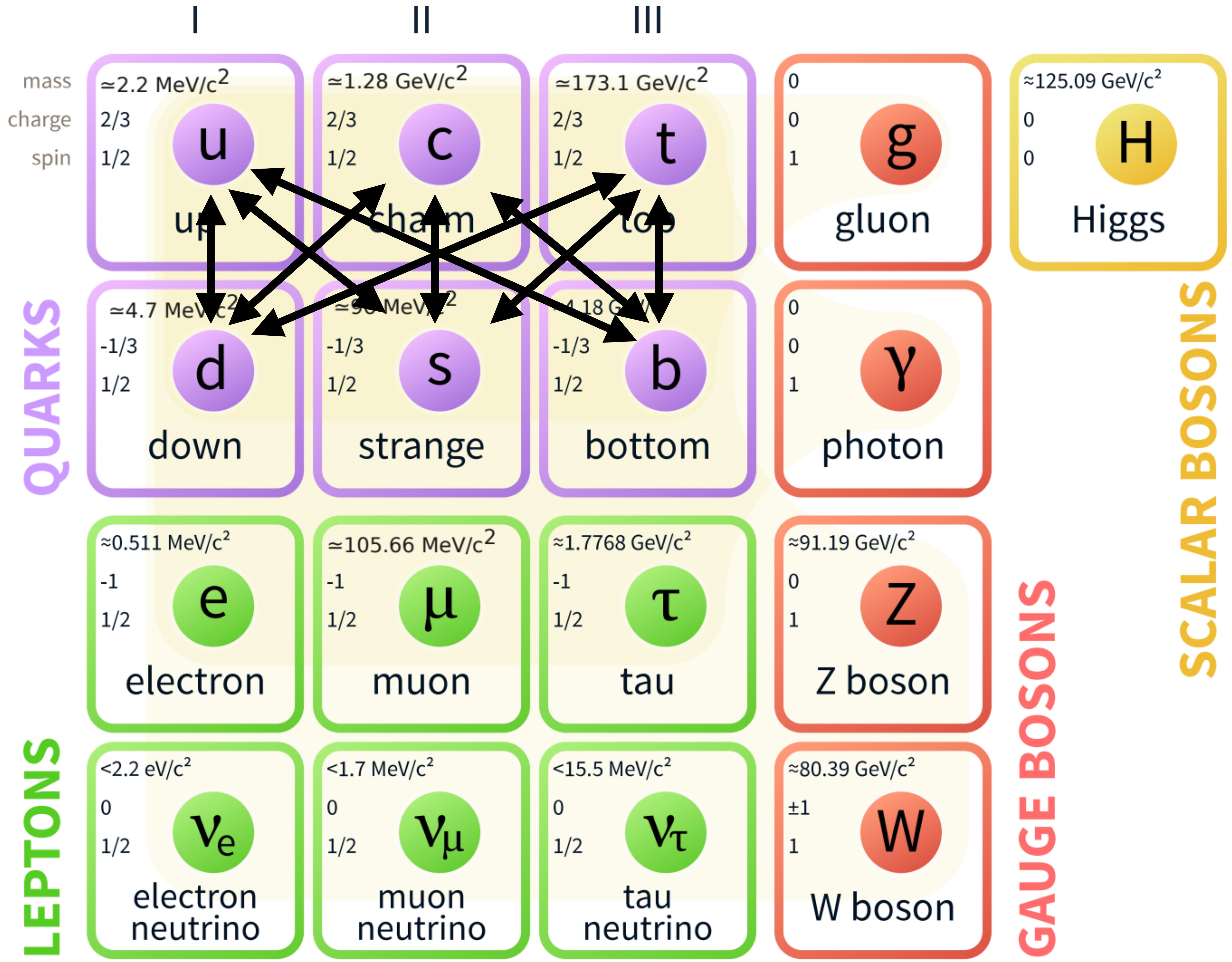
DEFINITION: **Flavour physics**
deals with interactions that distinguishes between flavours

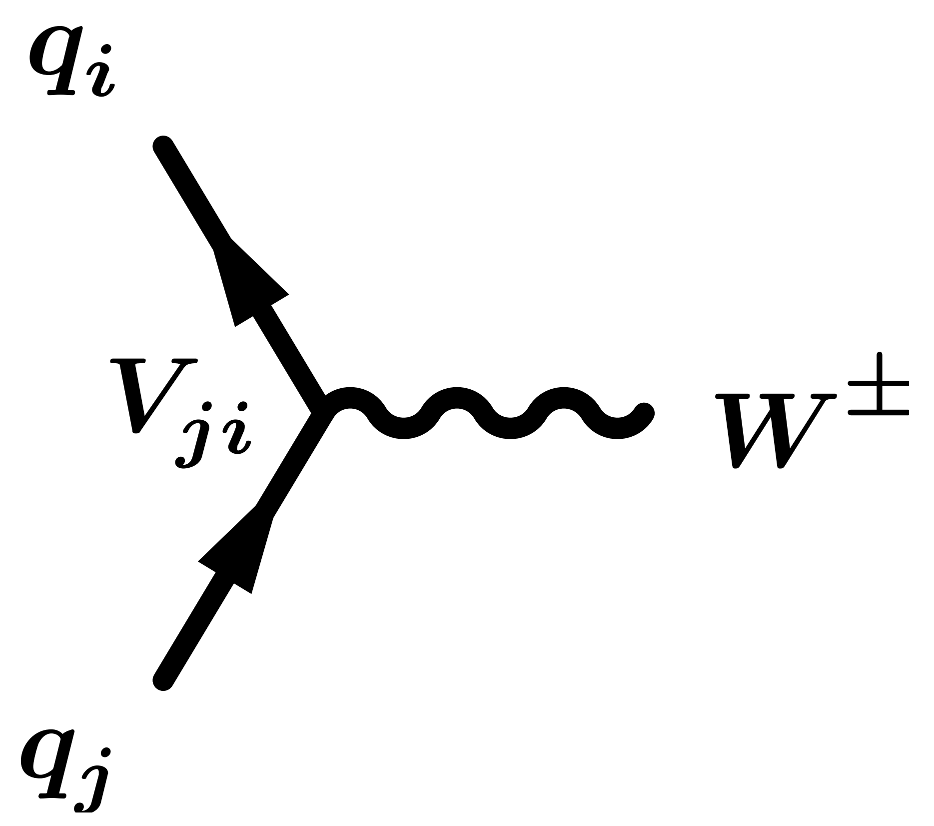
In the SM: QED and QCD interactions do not distinguish between flavours, while the weak interactions (and the couplings to the Higgs field) do

Charged and neutral currents

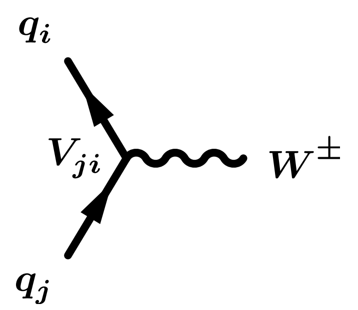


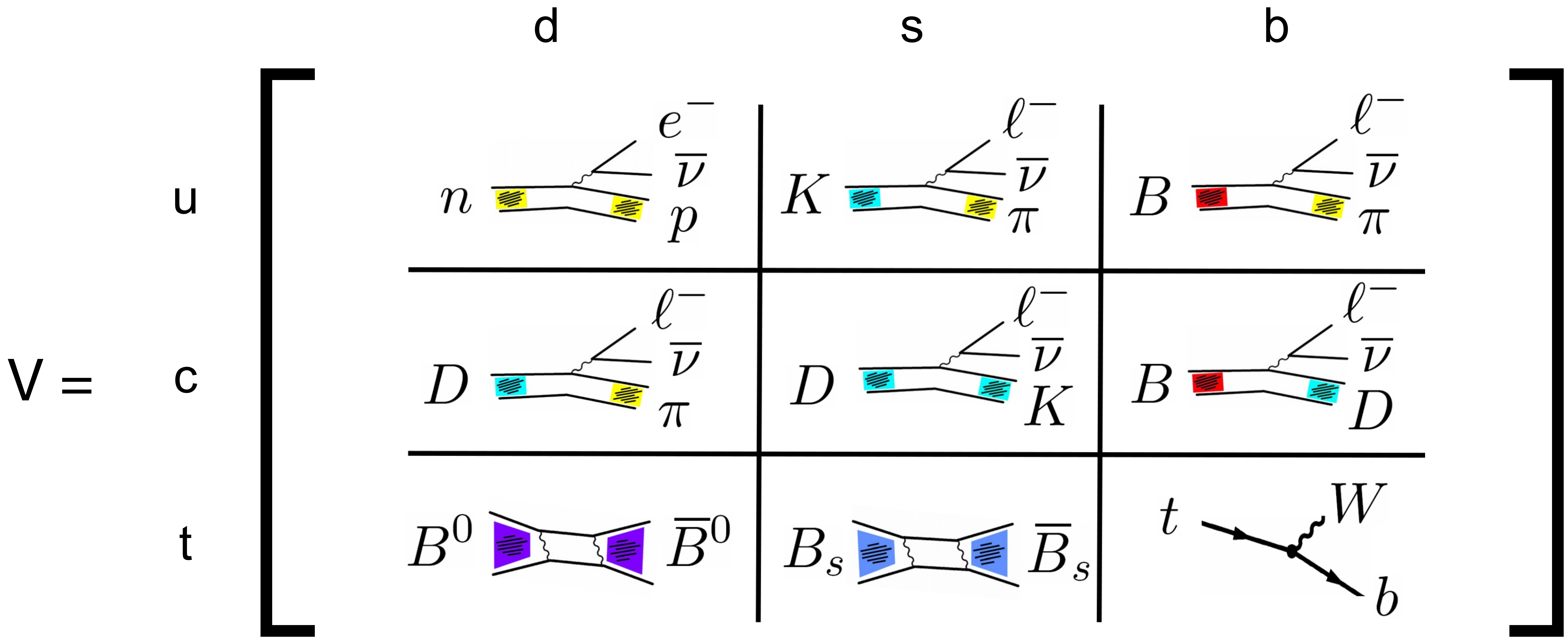
Flavour changing charged currents





CKM matrix V





$d \to u$: Nuclear physics (superallowed β decays)
$s \to u$: Kaon physics (KLOE, KTeV, NA62)
$c \to d, s$: Charm physics (CLEO-c, Babar, Belle, BESIII)
$b \to u, c$ and $t \to d, s$: B physics (Babar, Belle, CDF, DØ, LHCb)
$t \to b$: Top physics (CDF/DØ, ATLAS, CMS)

CKM matrix V: Unitarity conditions

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$

$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1$$

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$$

$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$$

$$V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} = 0$$

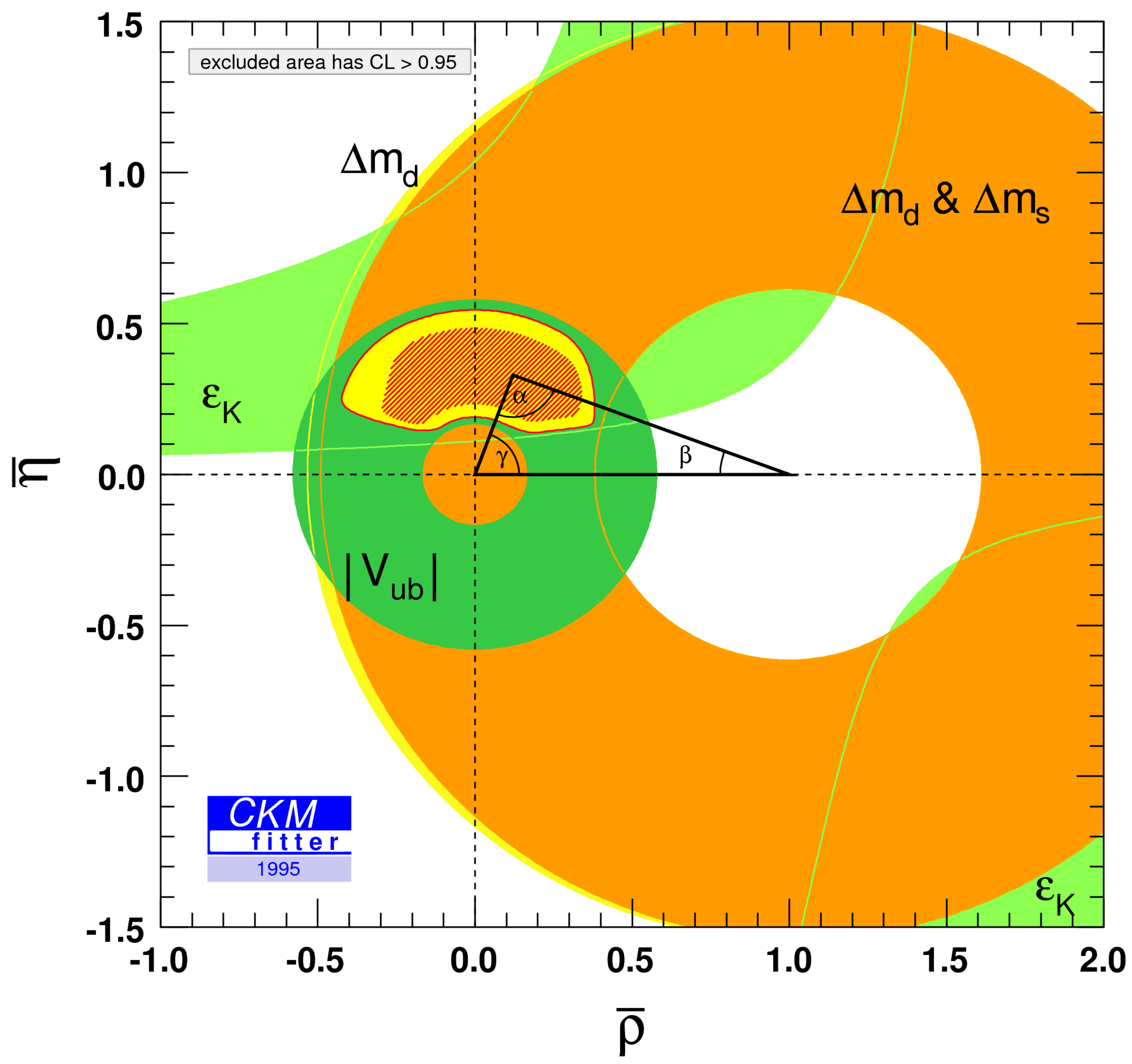
$$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$$

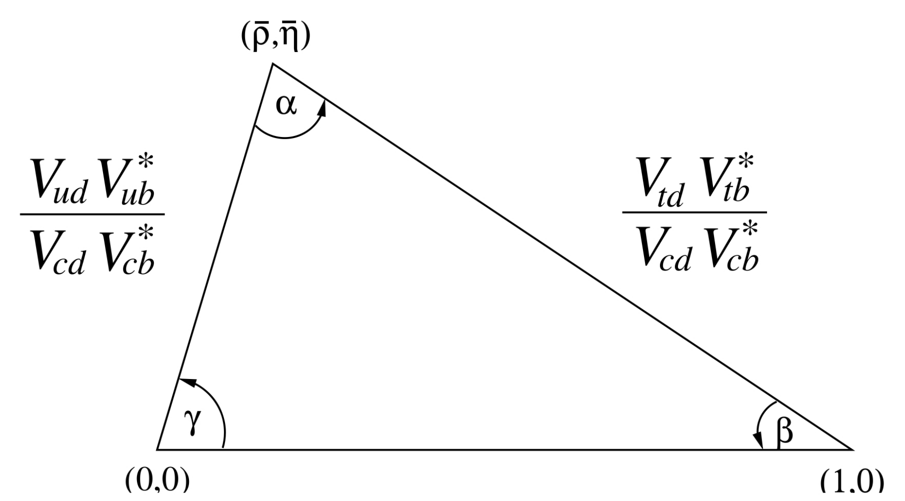
$$\boxed{V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0}$$

"The" unitary triangle

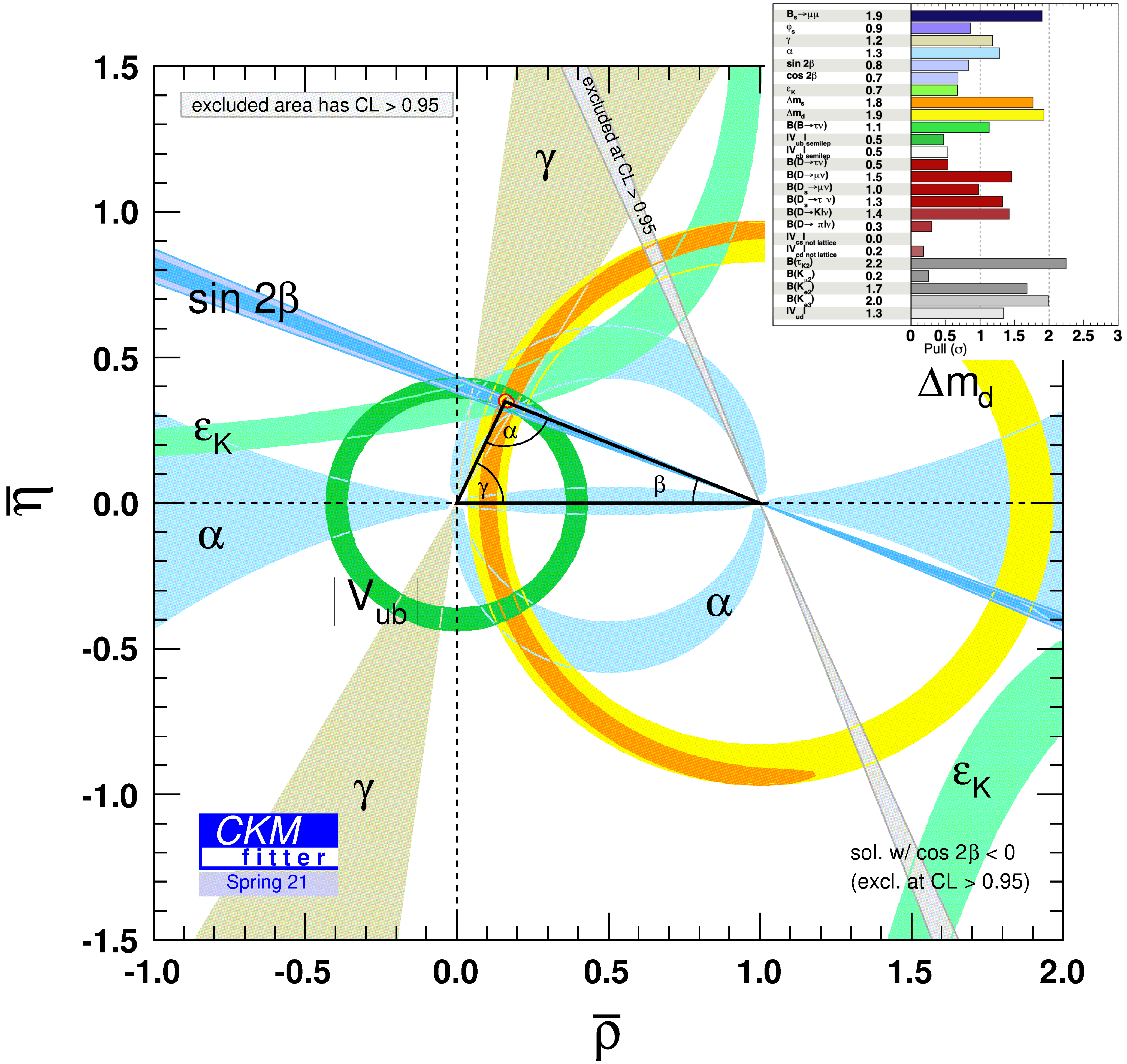
$$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$$

CKM matrix V: Unitarity conditions





β,α,γ = Φ_1, Φ_2, Φ_3

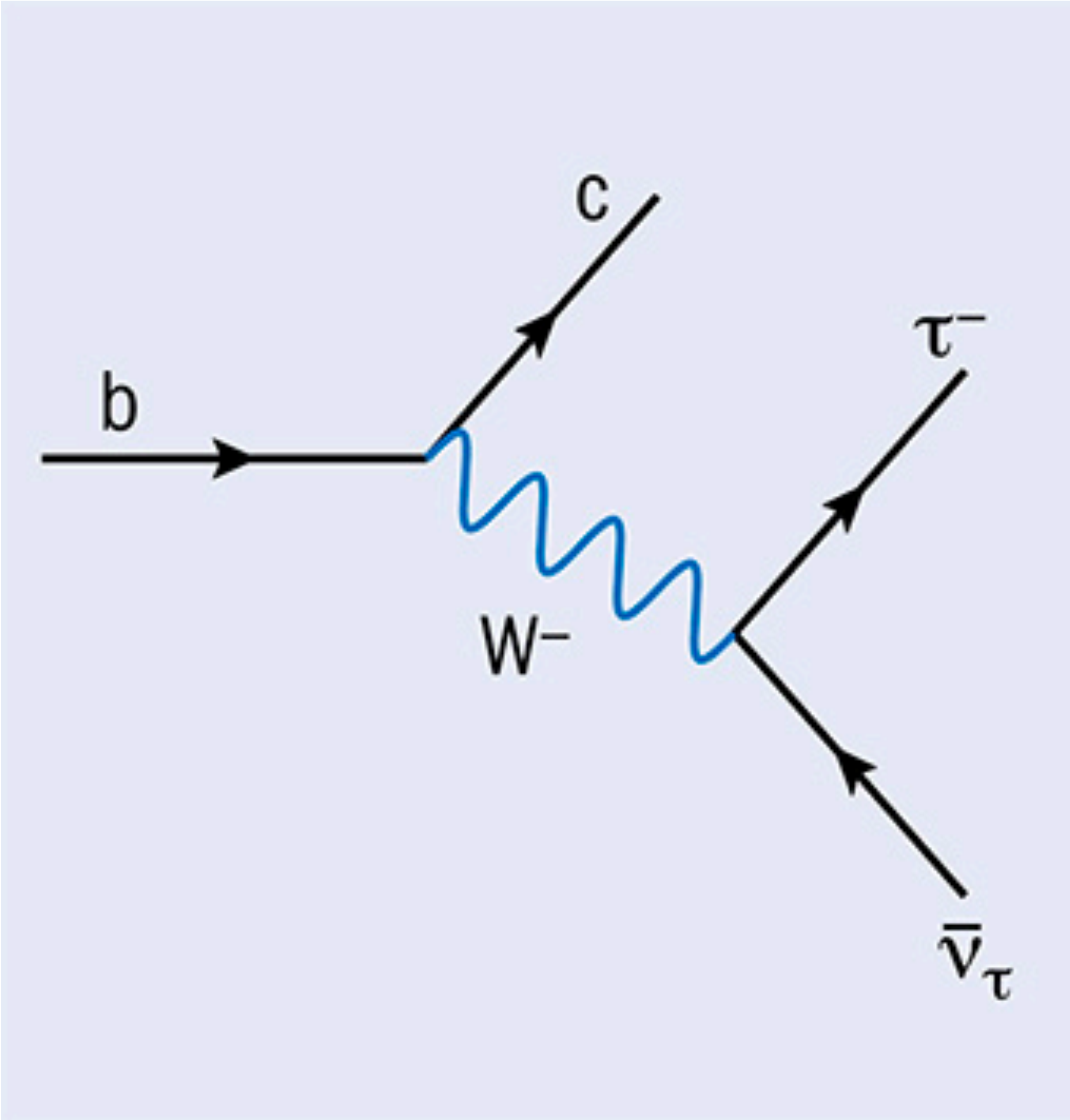


Jargon

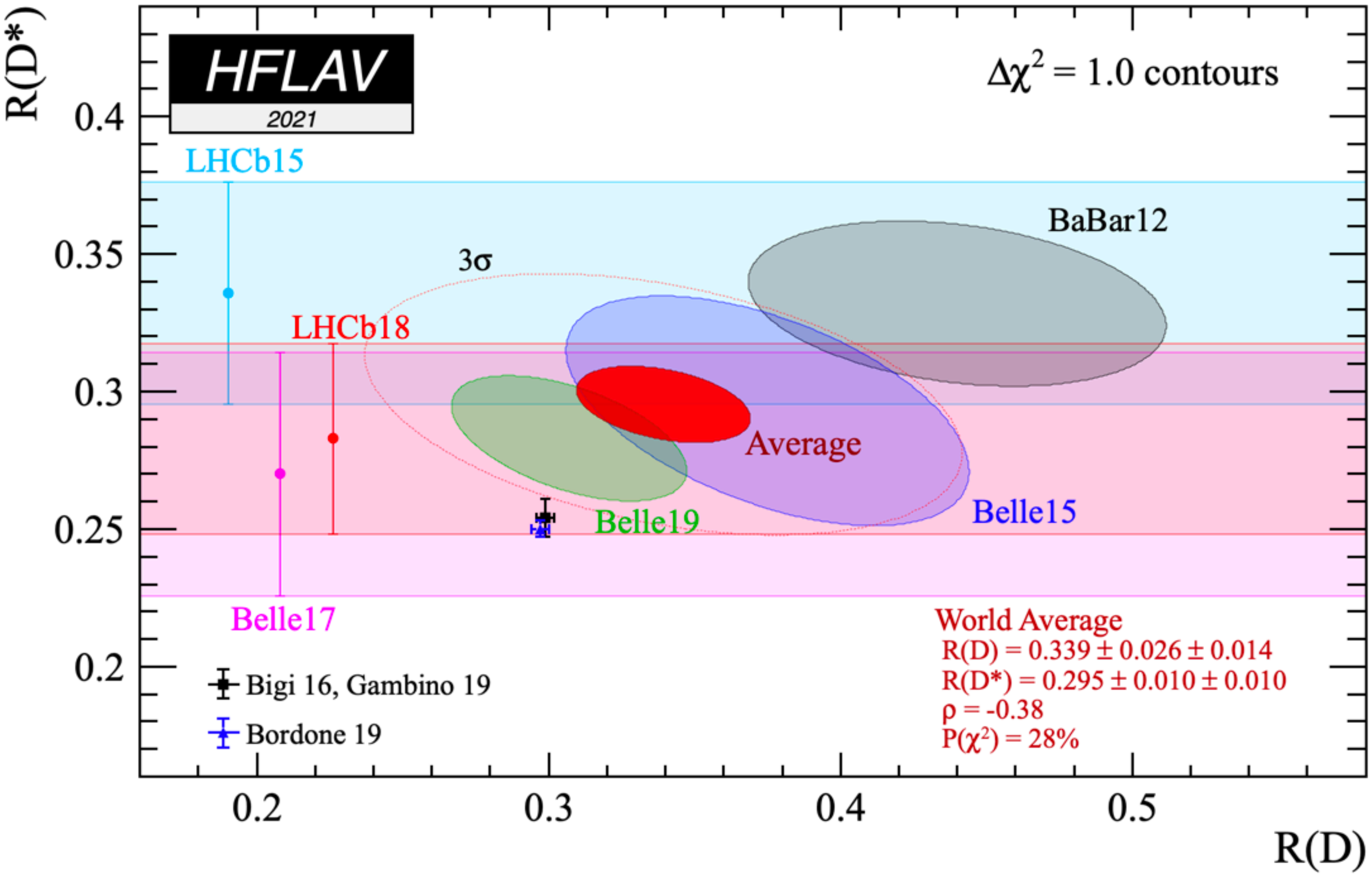
- "Charge conjugation implied"
  - We will only write down one specific charge (e.g. B^+), but always mean the charge conjugate as well (e.g. B^-). Can become a bit messy with (anti-)neutrals.
- D^* and K^* are excited mesons that immediately decay
  - $D^{+*} = D^{+*}(2010)$, decays to $D^+\pi^0$ or $D^0\pi^+$
  - $D^{0*} = D^{0*}(2007)$, decays to $D^0\pi^0$ or $D^0\gamma$
  - $K^* = K^{*0} = K^{*0}(892)$, decays to $K^+\pi^-$ or $K^0\pi^0$
    - K^0 is either a K^0_S (decays to $\pi^-\pi^+$) or a K^0_L

Flavour anomaly 1: Charged current

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^- \bar{\nu}_\ell)}$$

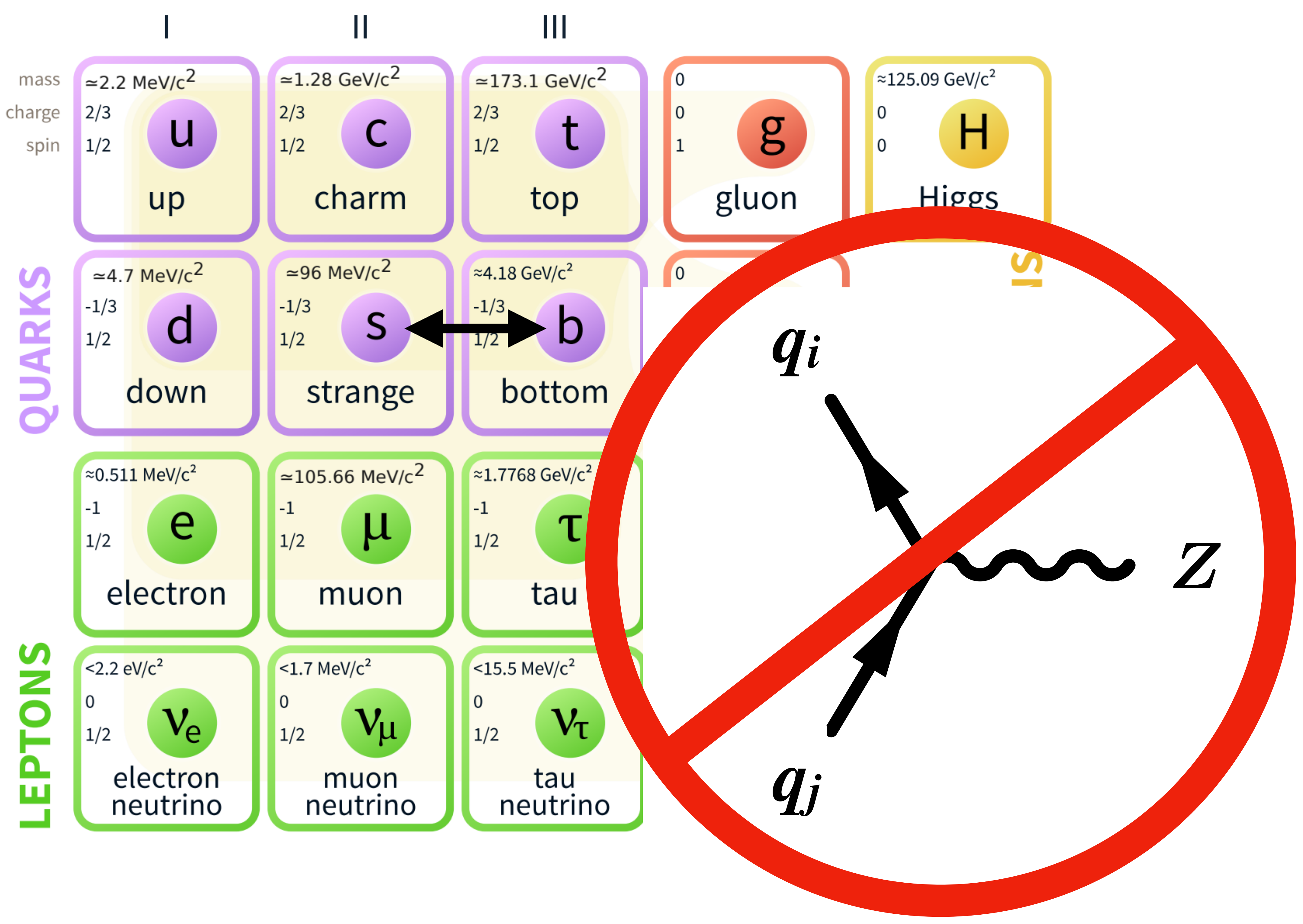


Flavour anomaly 1: Charged current

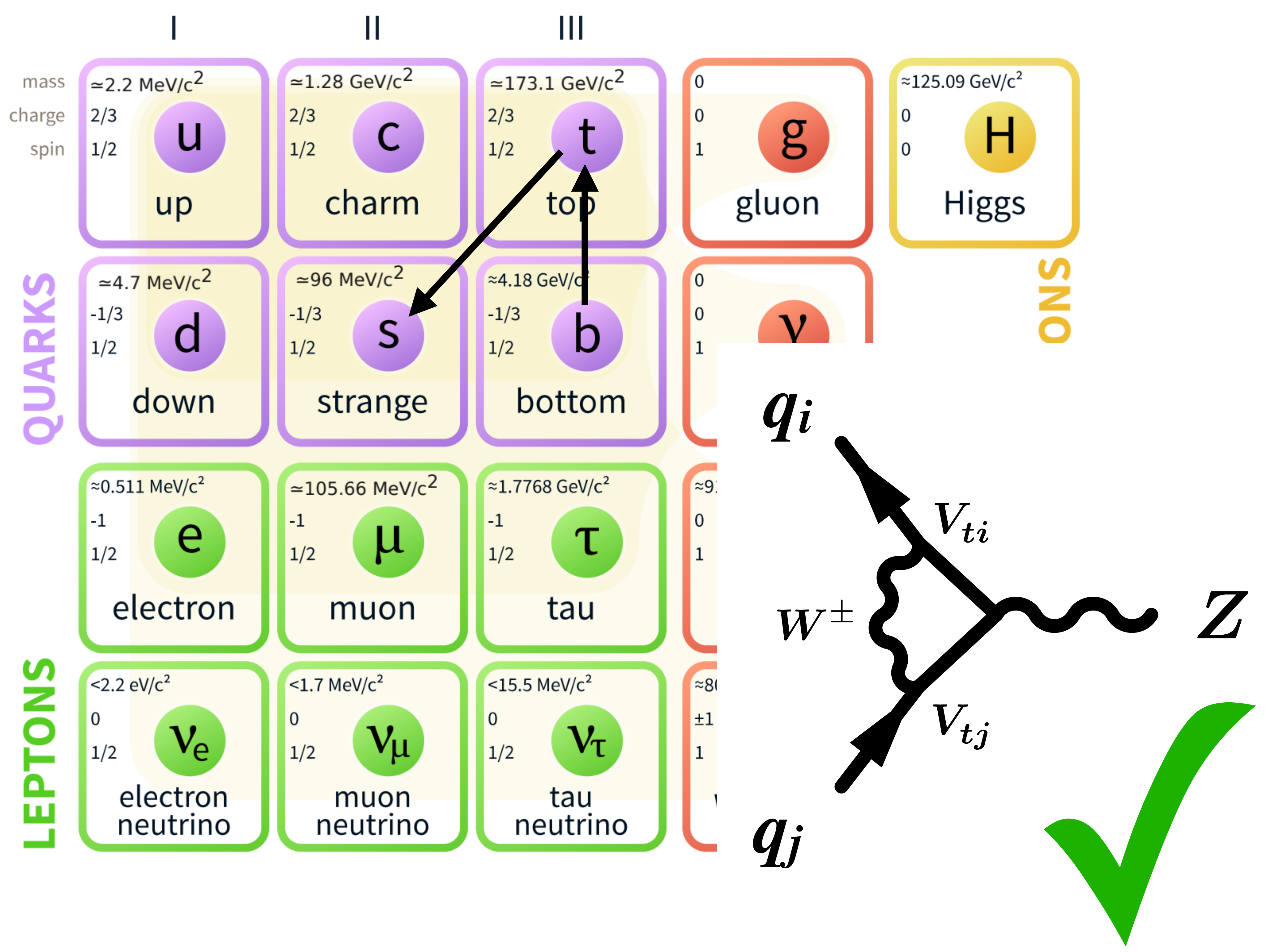


$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

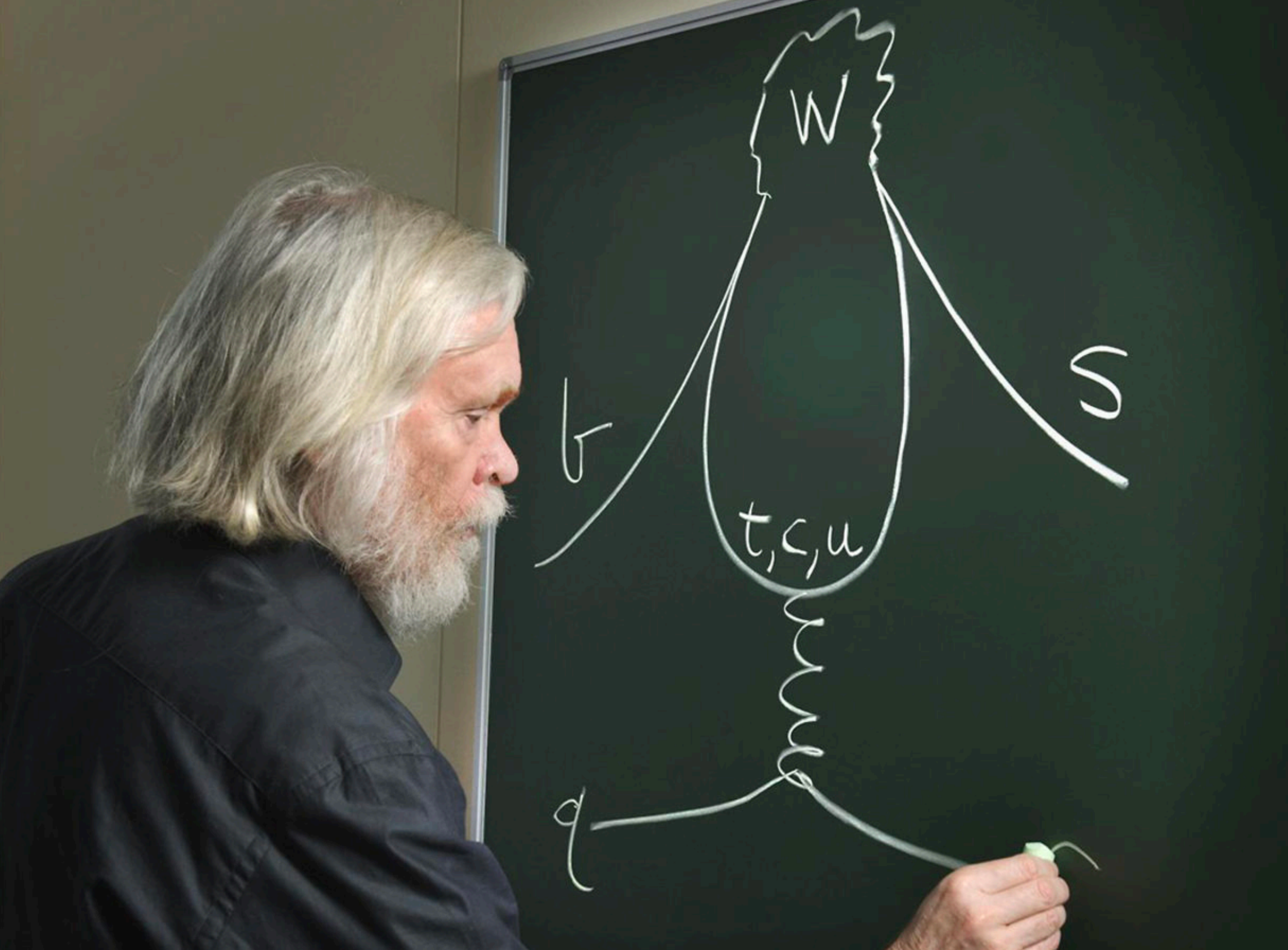
Flavour anomaly 2: b→sℓ⁺ℓ⁻

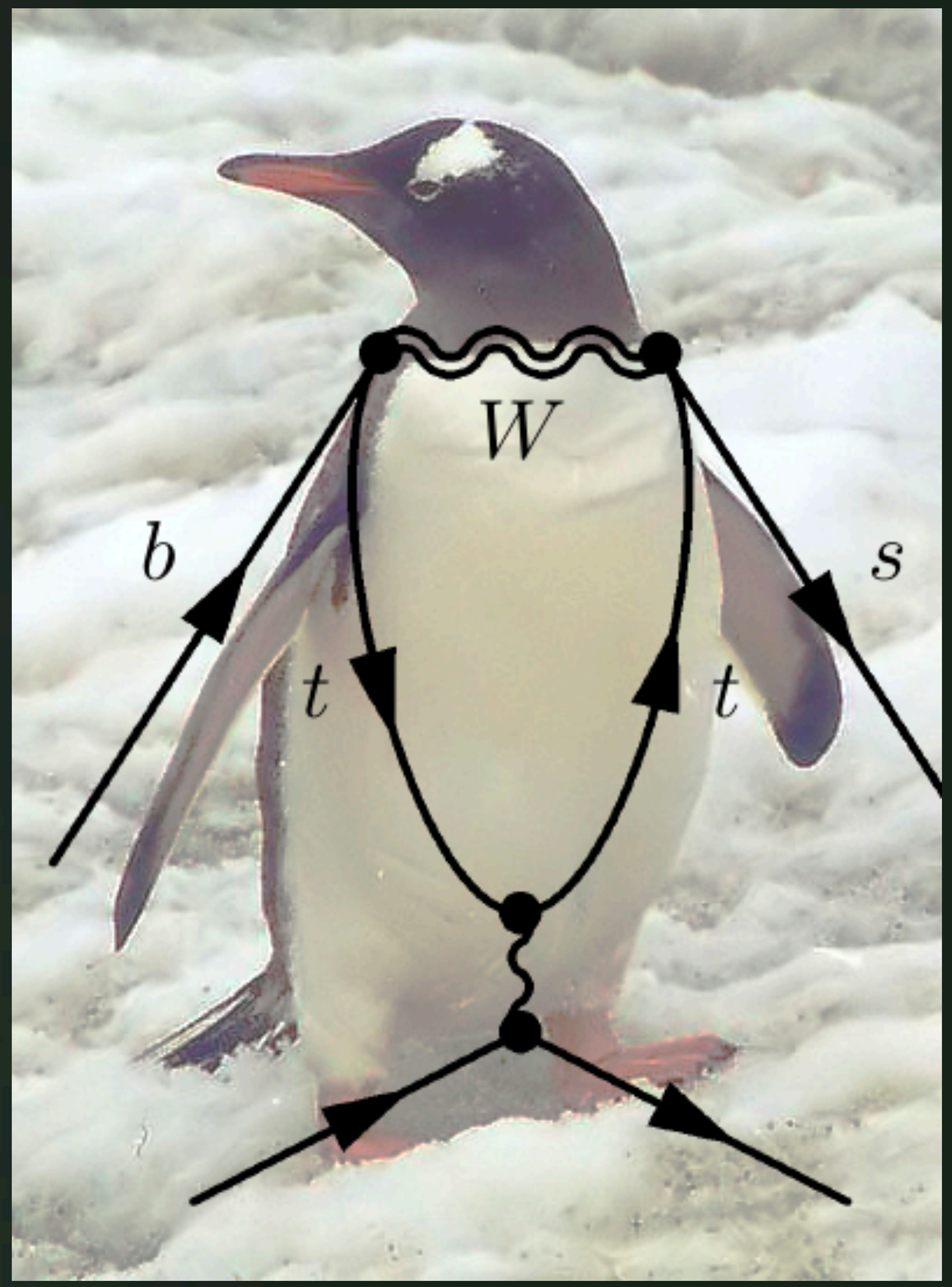


Forbidden at tree-level

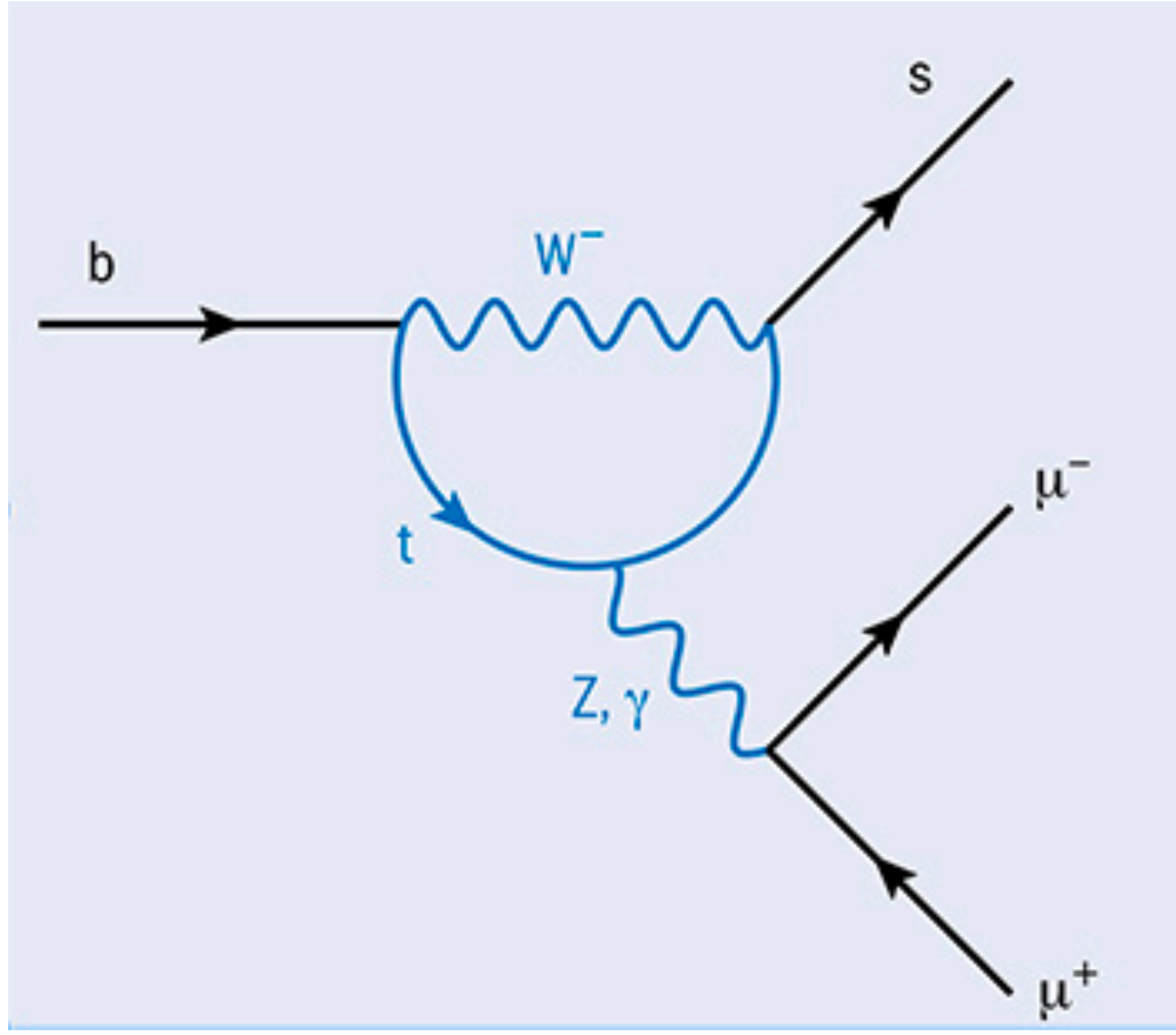


Allowed at one-loop level


W
b
s
t,c,u
q


W
b
s
t
t

Flavour anomaly 2: b→sℓ⁺ℓ⁻

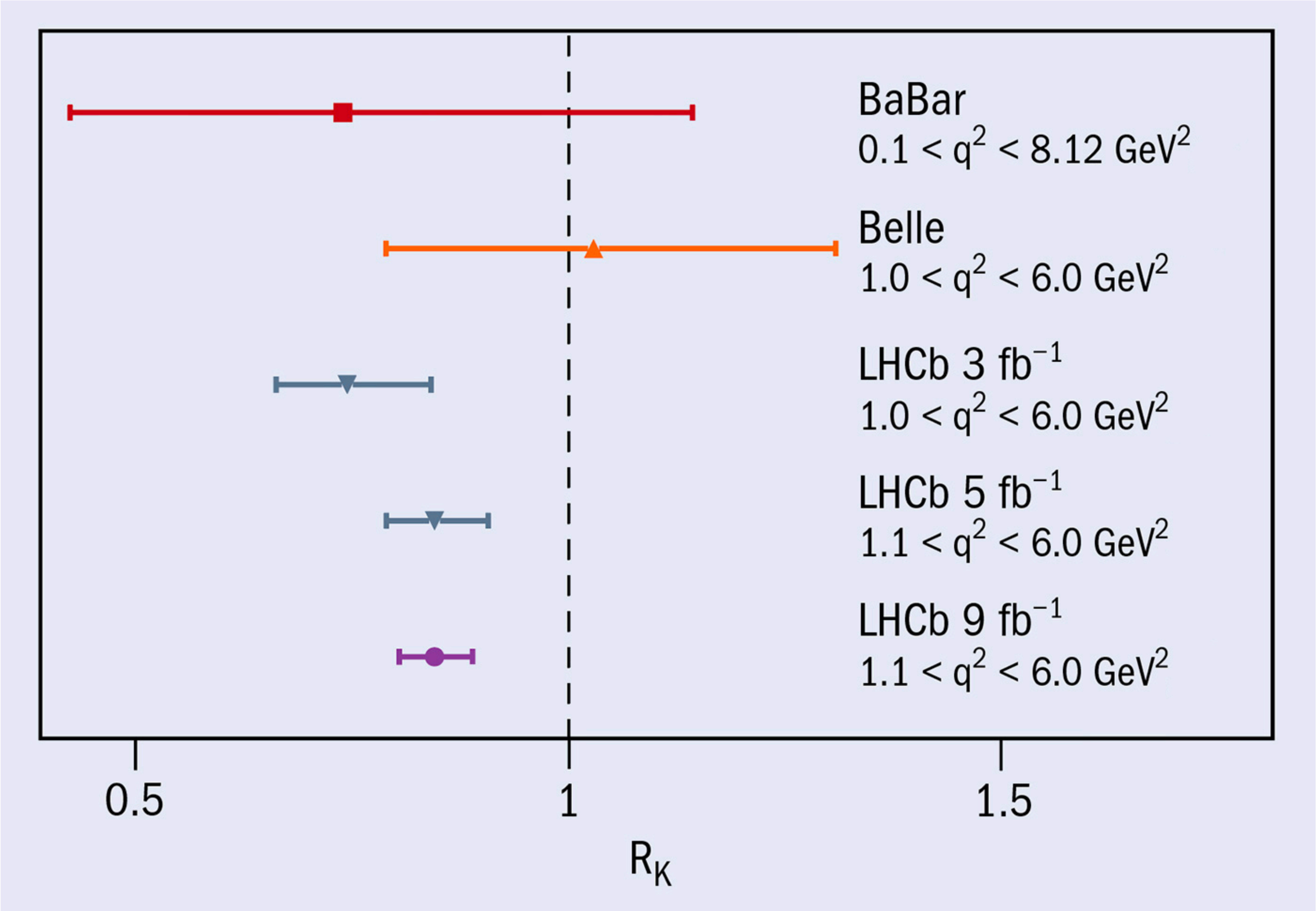


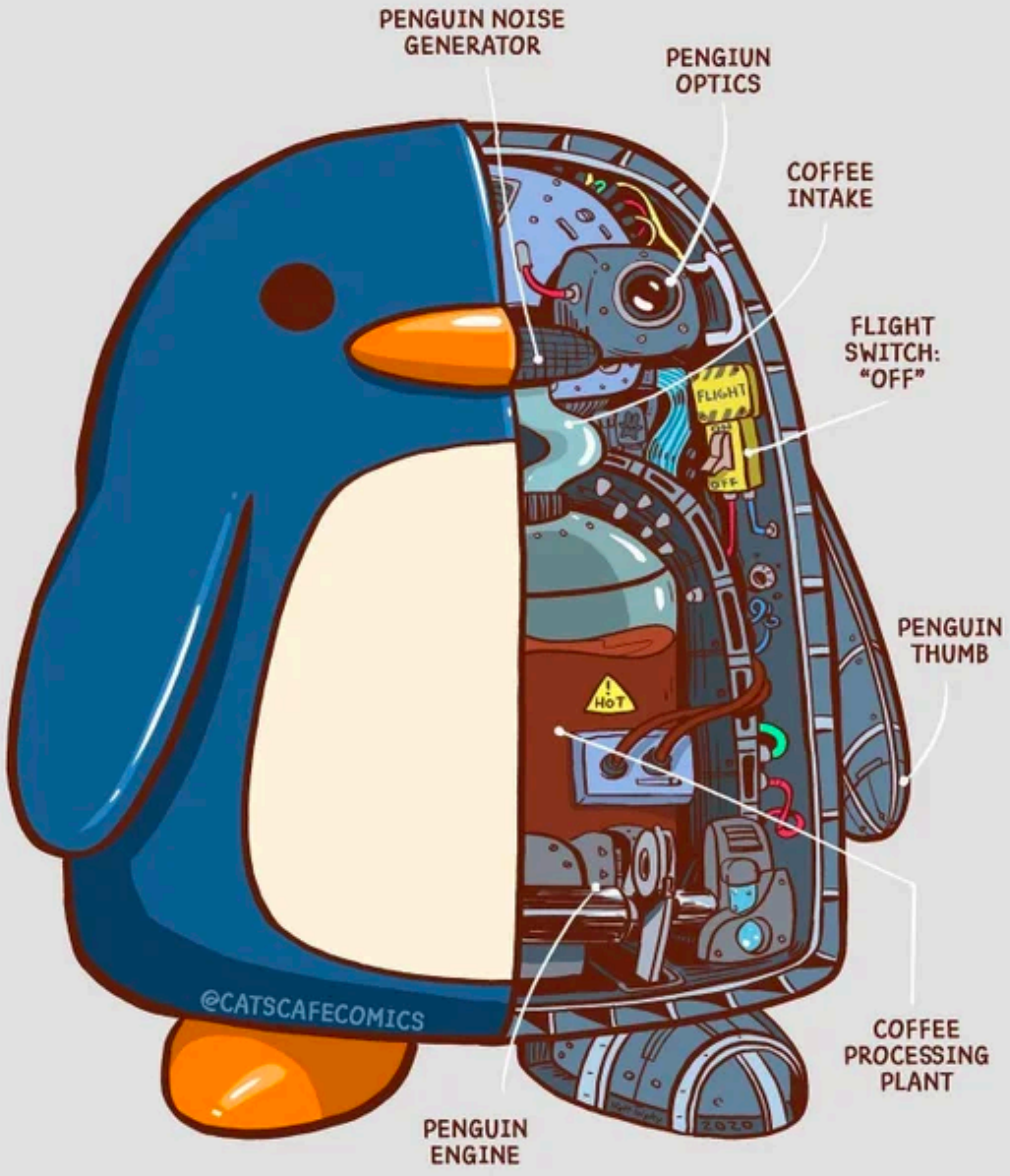
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu^+ \mu^-)}{\mathcal{B}(B \to K^* e^+ e^-)}$$

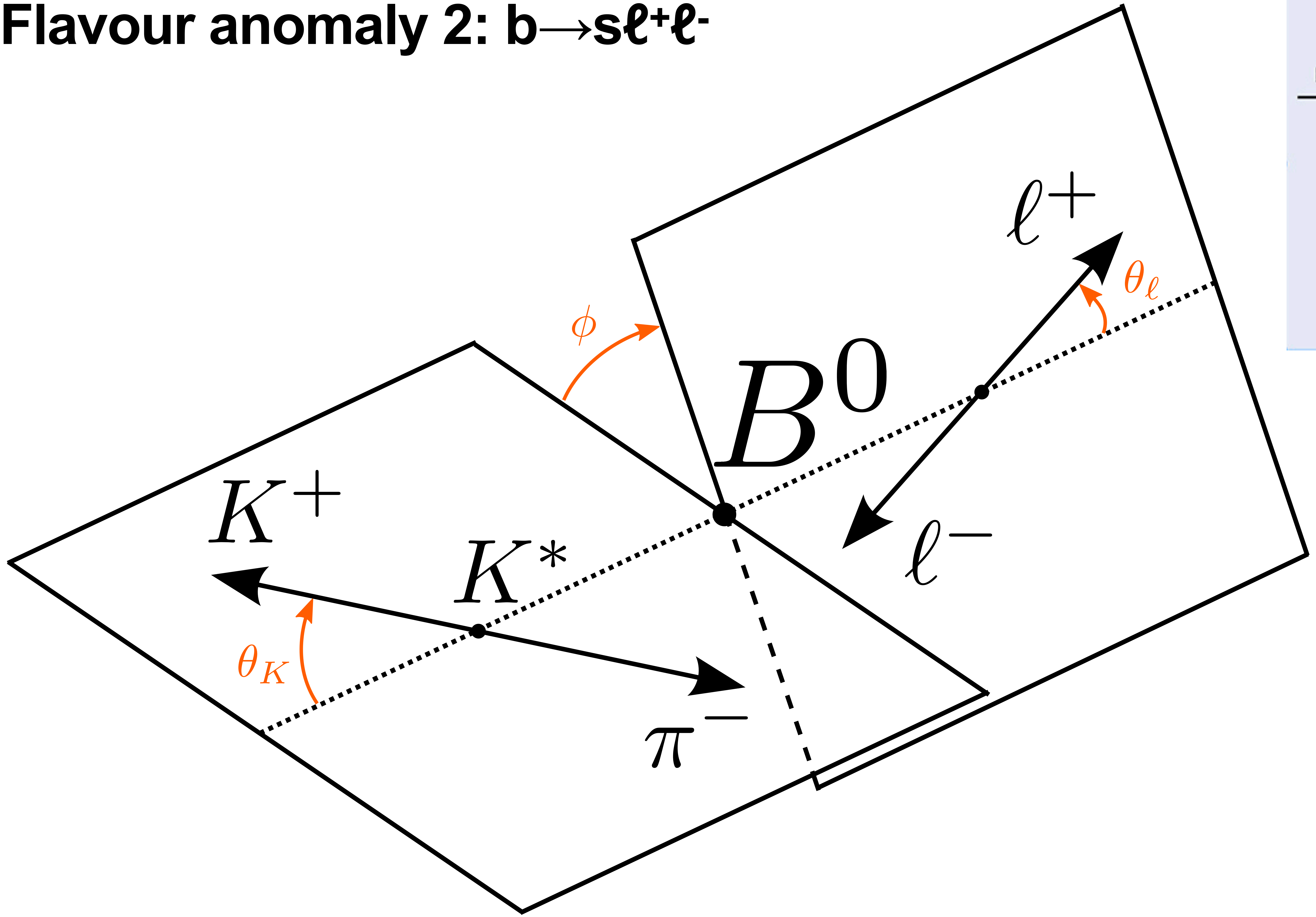
$$R_\phi = \frac{\mathcal{B}(B_s \to \phi\, \mu^+ \mu^-)}{\mathcal{B}(B_s \to \phi\, e^+ e^-)}$$

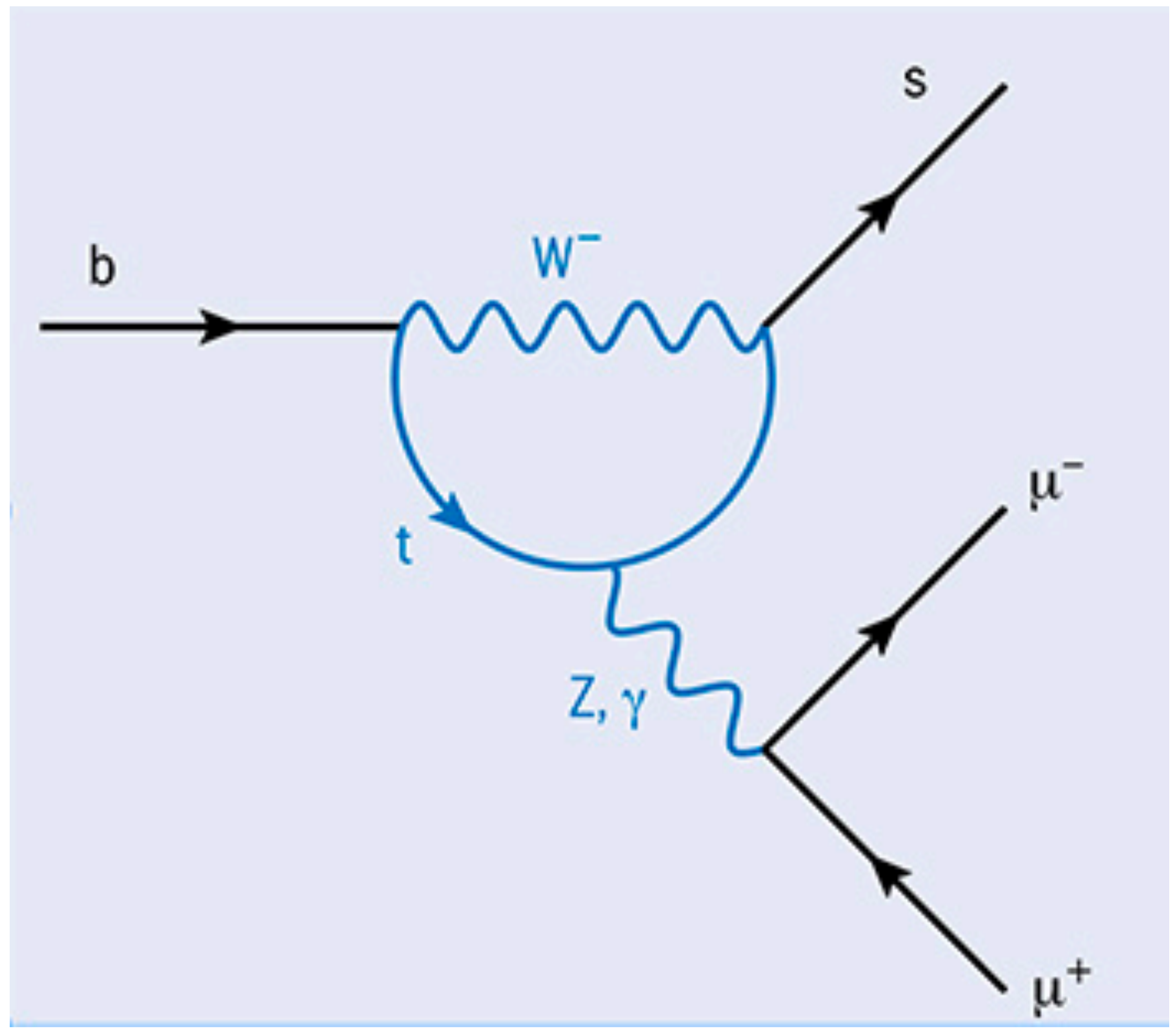
Flavour anomaly 2: $b \to s\ell^+\ell^-$



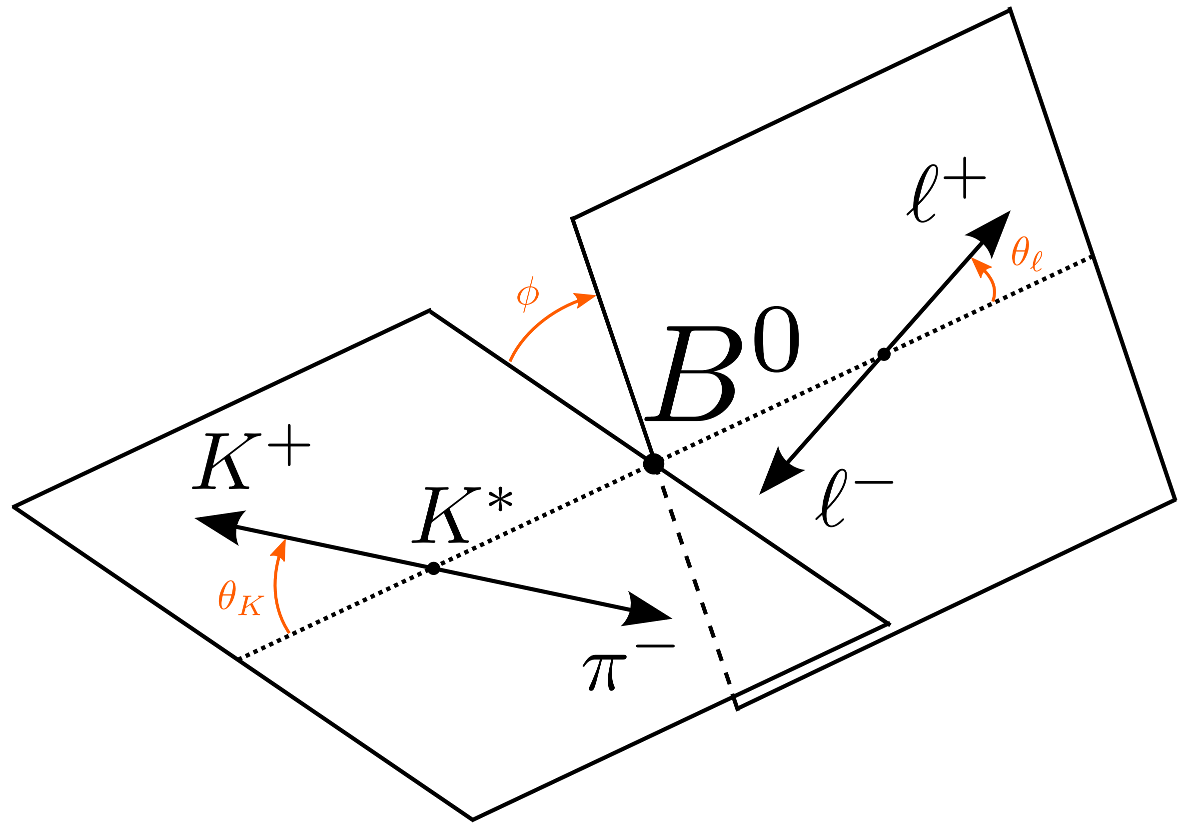

PENGUIN NOISE GENERATOR
PENGIUN OPTICS
COFFEE INTAKE
FLIGHT SWITCH: "OFF"
PENGUIN THUMB
COFFEE PROCESSING PLANT
PENGUIN ENGINE
@CATSCAFECOMICS

Flavour anomaly 2: b→sℓ⁺ℓ⁻





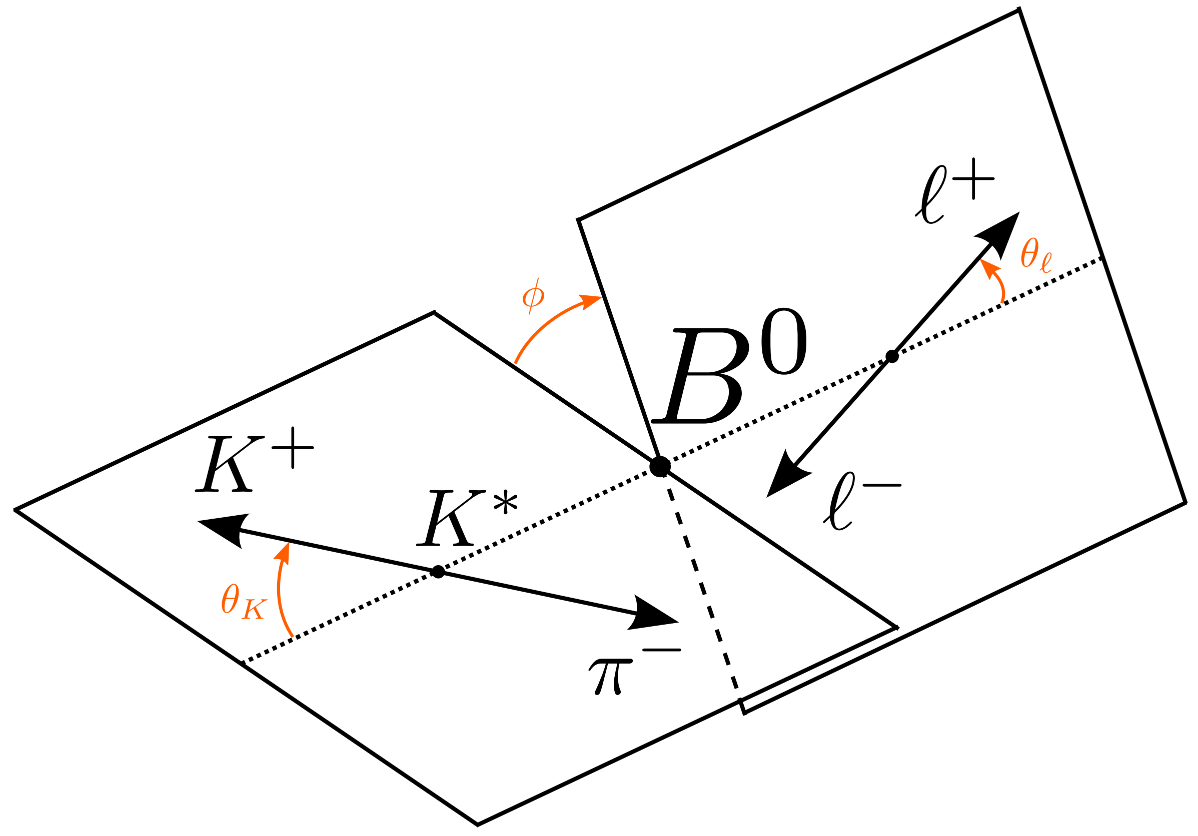
Flavour anomaly 2: b→sℓ⁺ℓ⁻



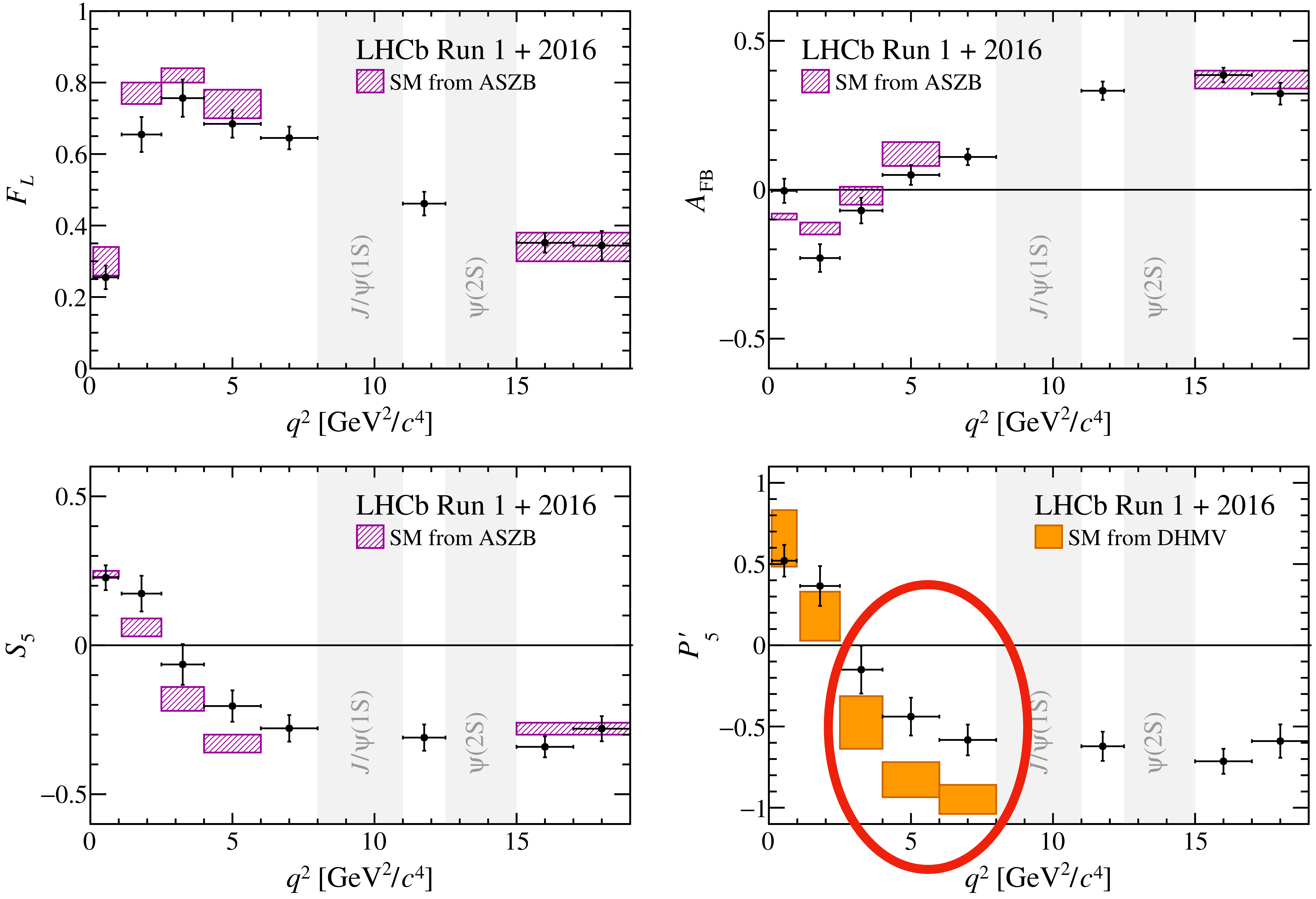
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$

Flavour anomaly 2: $b \to s\ell^+\ell^-$



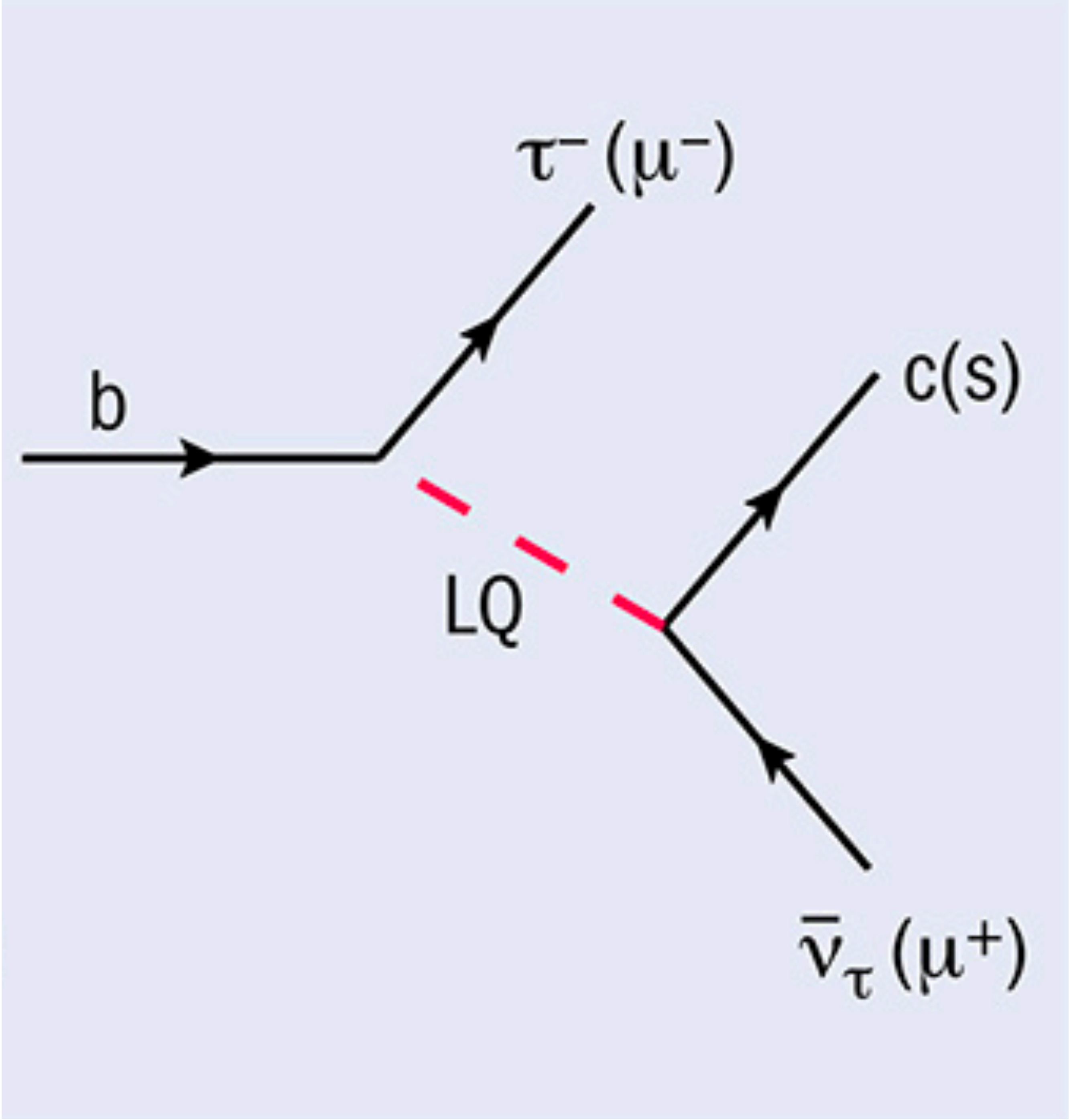
Phys. Rev. Lett. 125, 011802



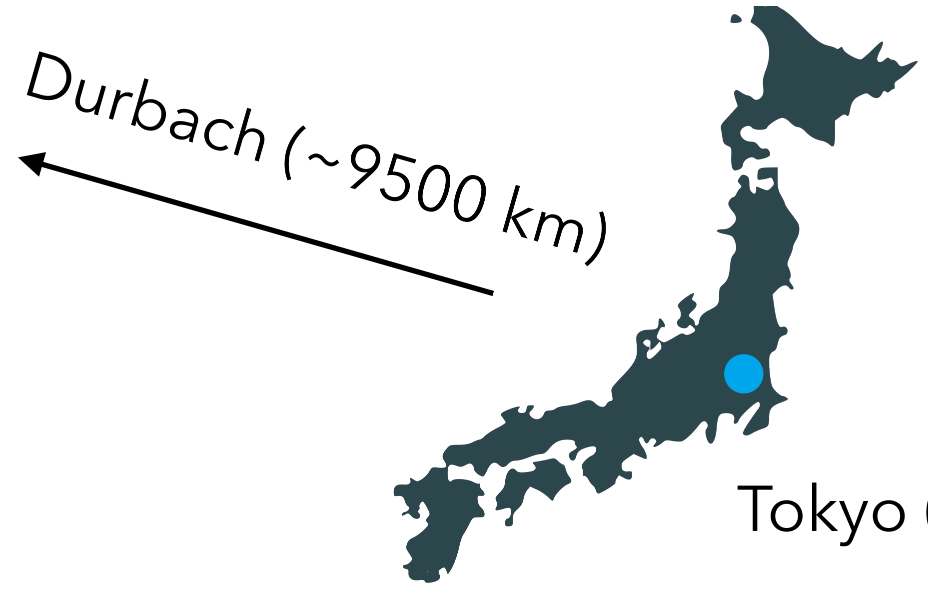
3σ

Now what?

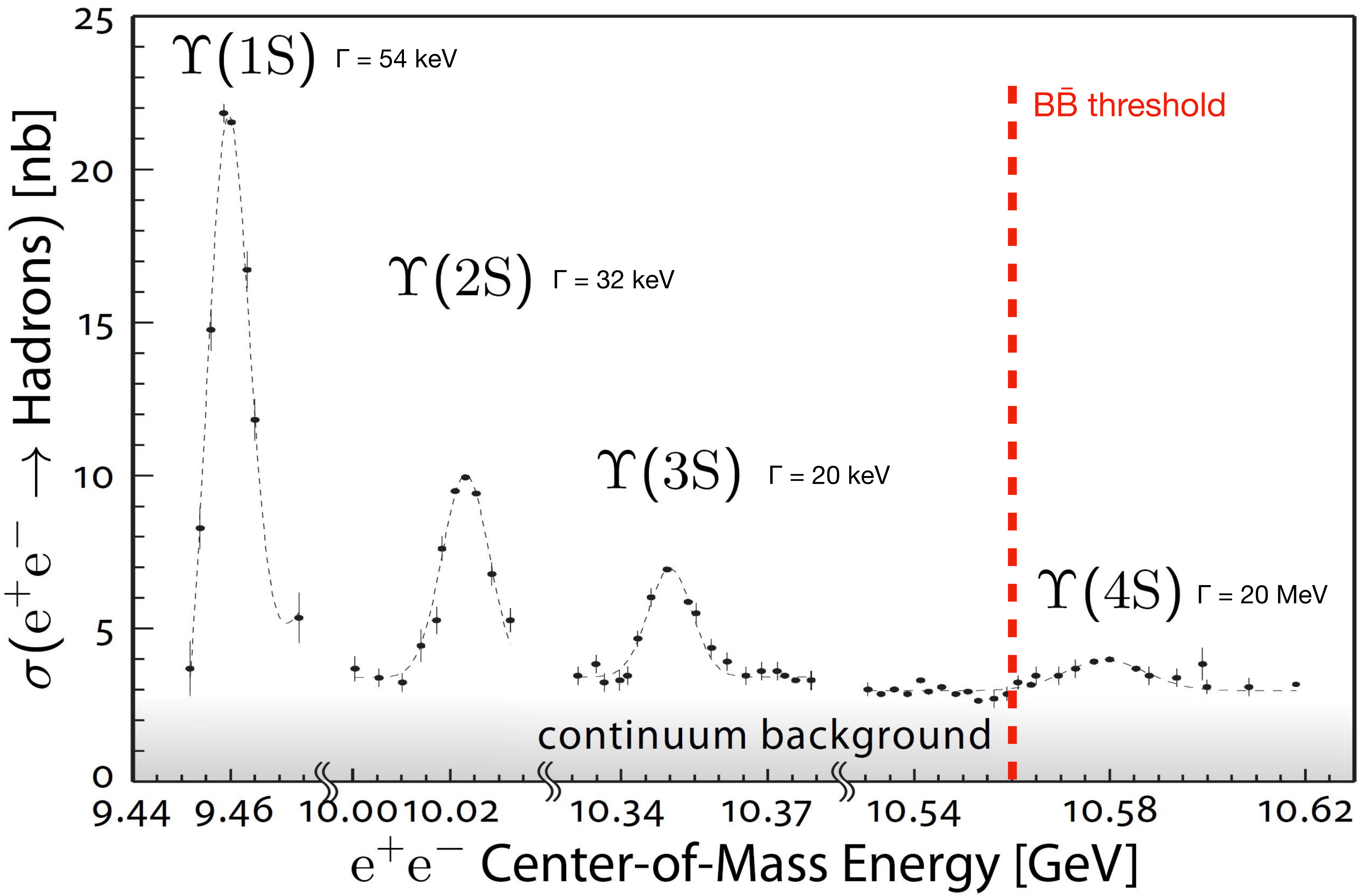
- $B \to K^{(*)}\nu\bar{\nu}$ (only upper limits so far)
  - Much harder experimentally, much smaller theory uncertainty, but angular analysis is limited to Kaon…
- $B \to K^{(*)}\tau^+\tau^-$ (only upper limits so far)
  - Much harder experimentally…
- Did we break the SM? (Very heavy) Leptoquarks?



How to produce B-mesons?



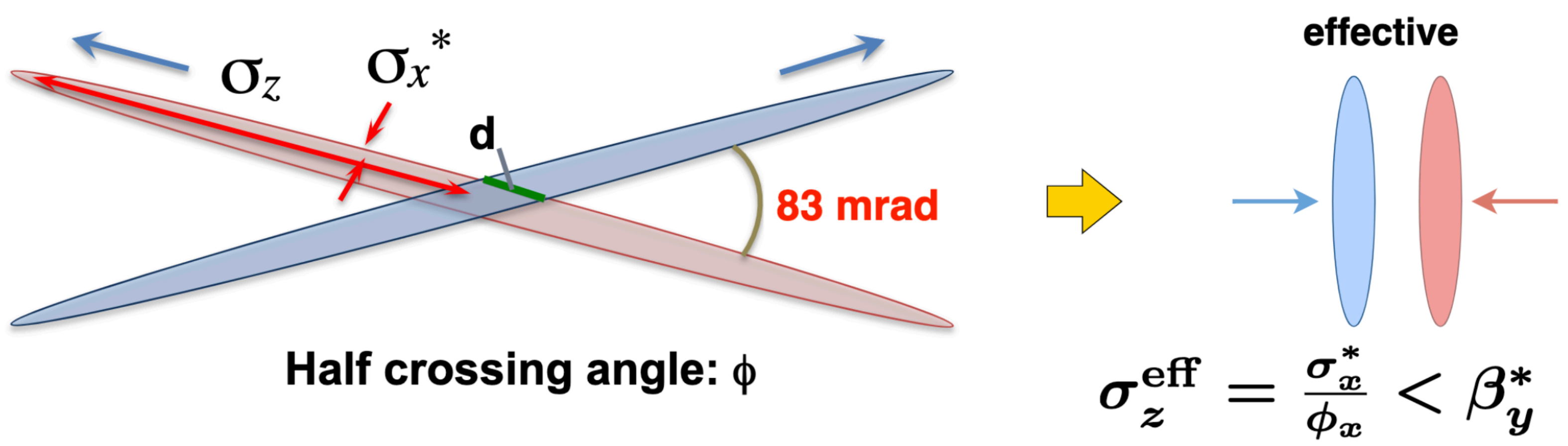
How to produce B-mesons?



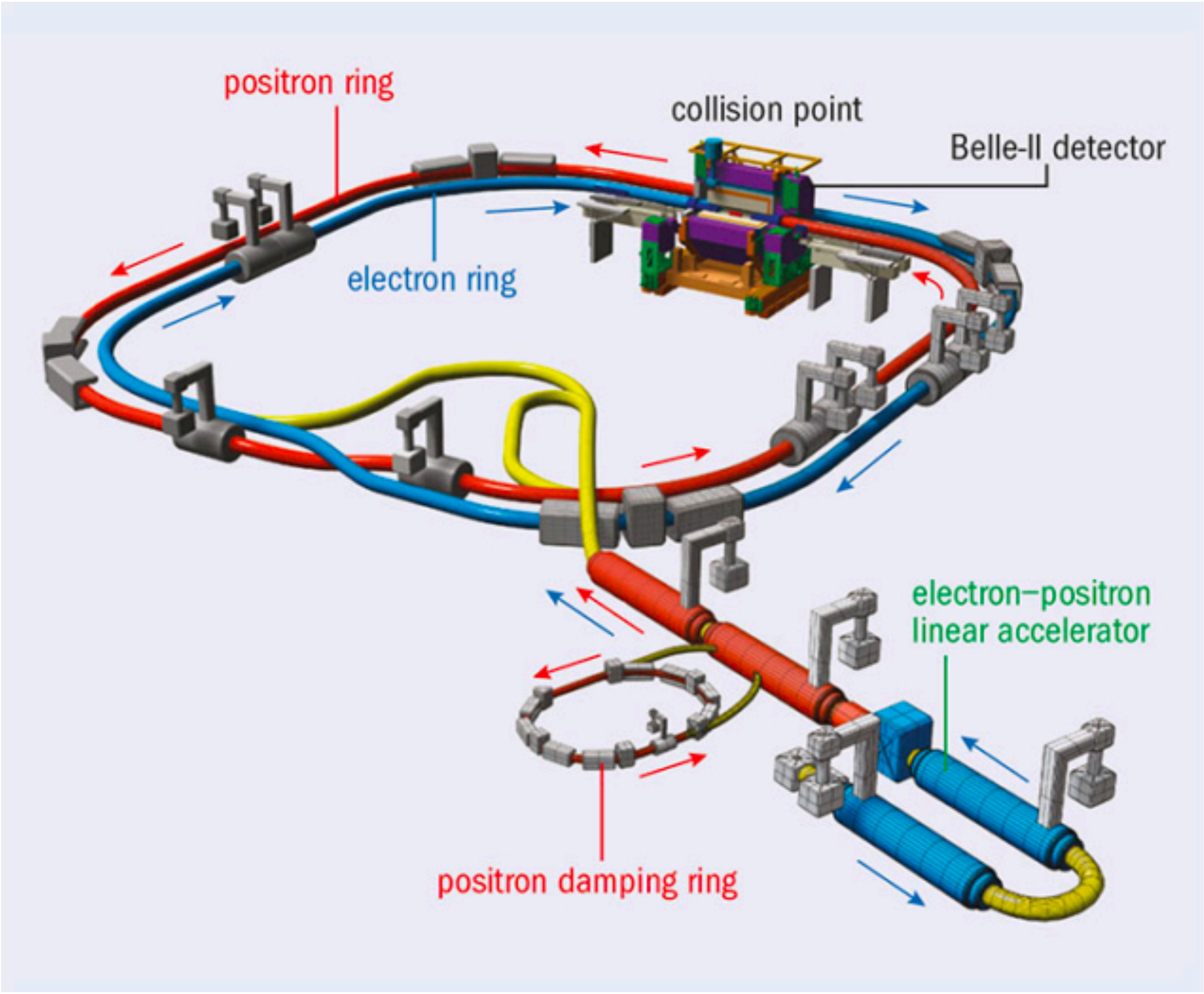
- SuperKEKB nominally operates at 10.58 GeV collision energy
- ~9-12 GeV accessible
- B_sB_s threshold at 10.74 GeV (below Y(5S) resonance)

SuperKEKB accelerator

- Asymmetric ee collider
  - 4 GeV e+, 7 GeV e- $\sqrt{s} = 10.58\,\mathrm{GeV}$
  - Large crossing angle: 83 mrad

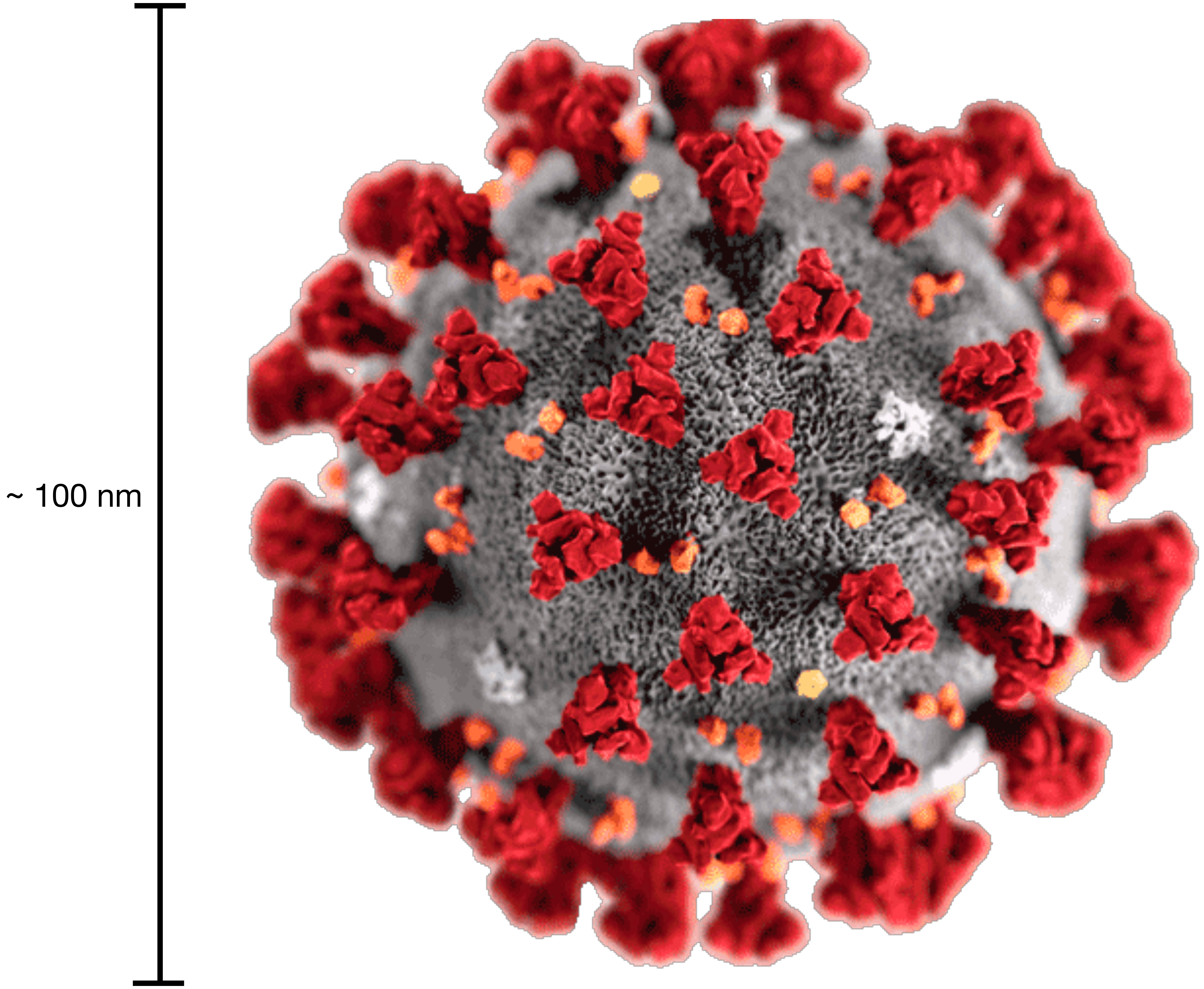


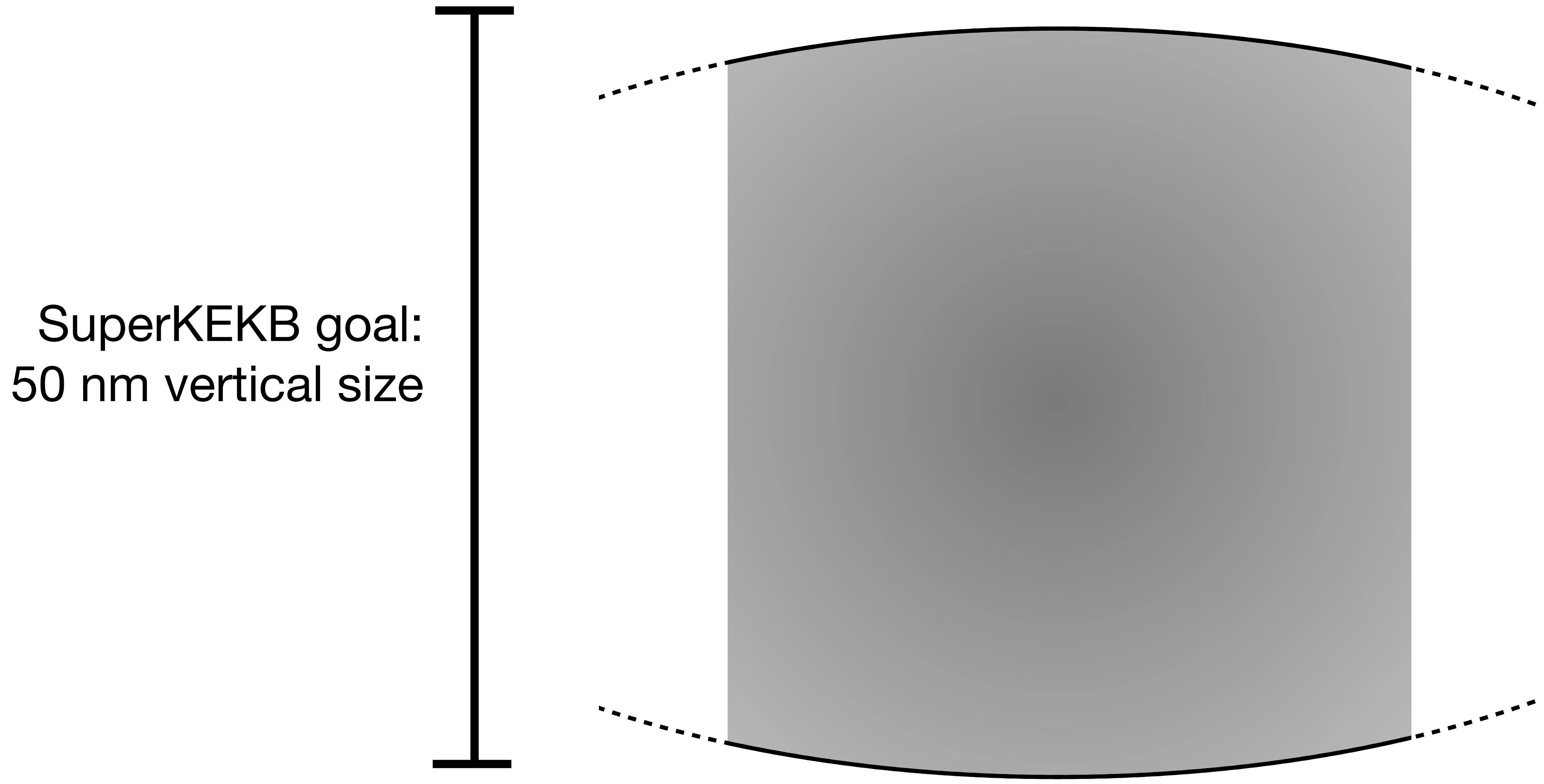
- Major upgrade to the accelerator with 30× the KEKB design luminosity (6×10^{35} $\mathrm{cm^{-2}s^{-1}}$, 50 $\mathrm{ab^{-1}}$ (50× Belle))
  - 1.5× higher beam currents, 20× smaller beam spot



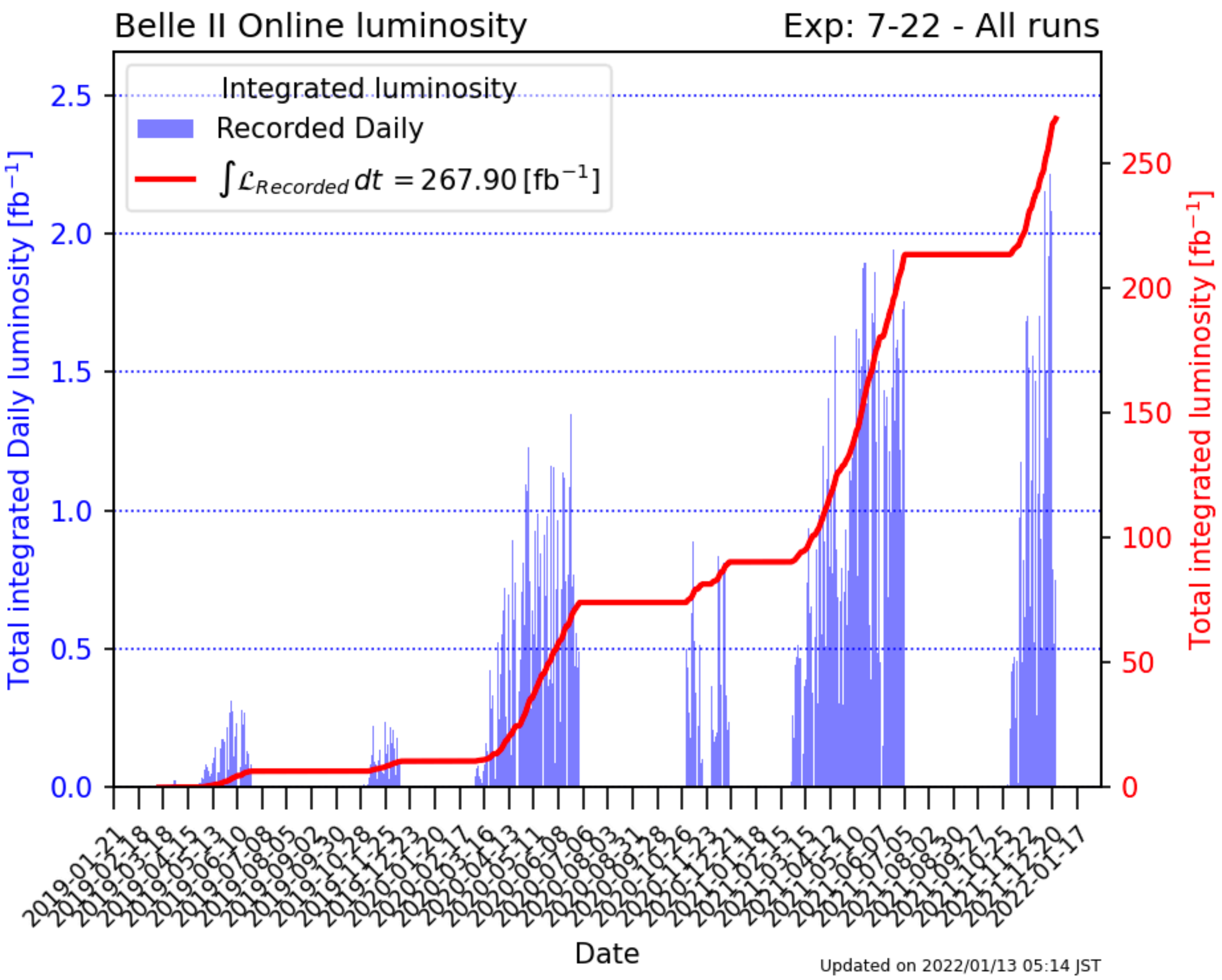
- Record: 3.12×10^{34} $\mathrm{cm^{-2}s^{-1}}$ (June 22 2021)

SuperKEKB accelerator





Luminosity



Belle: ~1000 fb^{-1}
BaBar: ~500 fb^{-1}

Belle II summer 2022: ~500 fb^{-1}

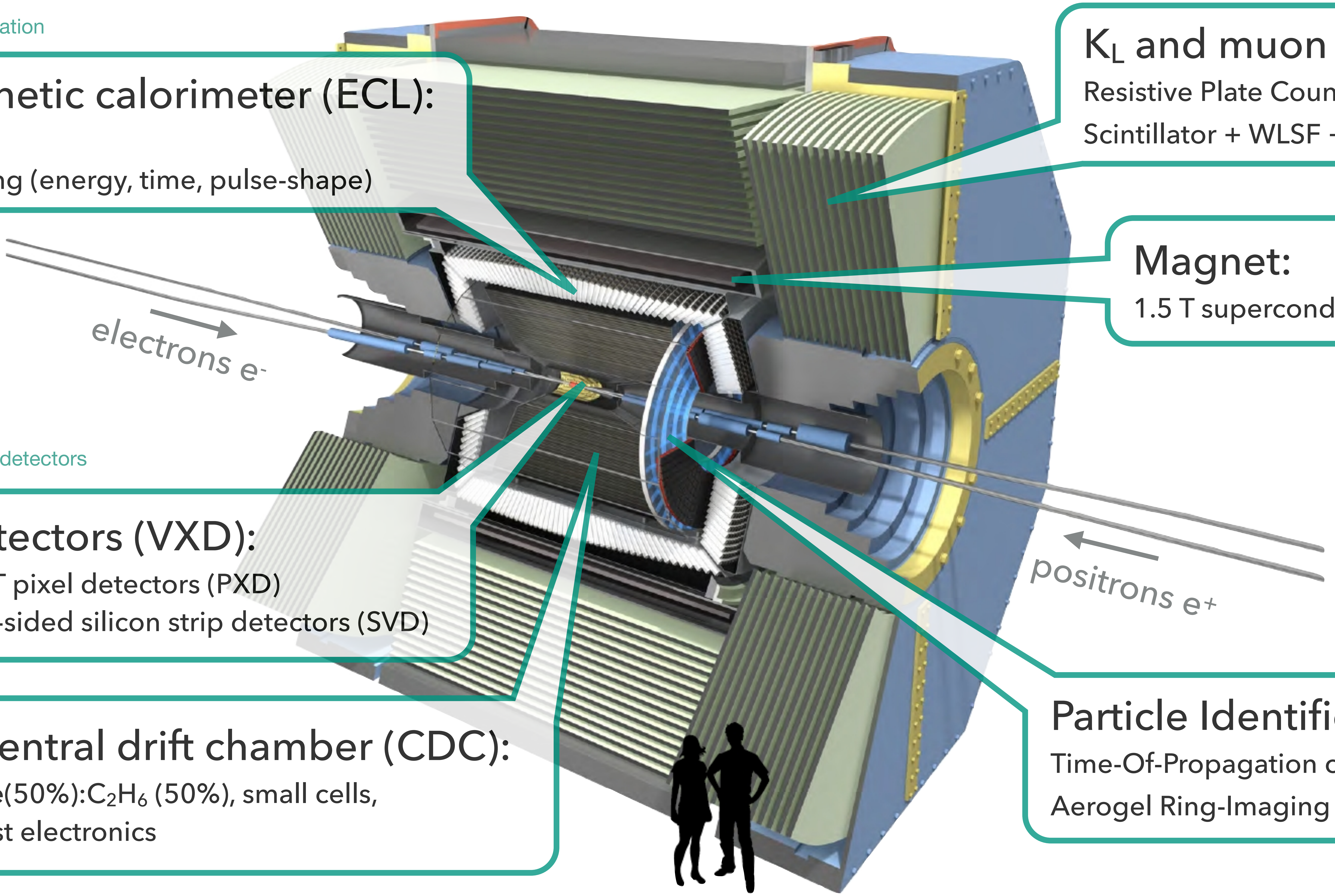
$$N = \sigma \int \mathscr{L}\, dt$$

$$\sigma(\Upsilon(4S)) \approx 1.05\,\mathrm{nb}$$

$$N(B^+)?$$


Belle II
KEK
www.kek.jp

Belle II Experiment



Software, Calibration

Electromagnetic calorimeter (ECL):
CsI(Tl) crystals
waveform sampling (energy, time, pulse-shape)

K_L and muon detector (KLM):
Resistive Plate Counters (RPC) (outer barrel)
Scintillator + WLSF + MPPC (endcaps, inner barrel)

Magnet:
1.5 T superconducting

ML-based hardware trigger

Trigger:
Hardware: < 30 kHz
Software: < 10 kHz

PXD silicon detectors

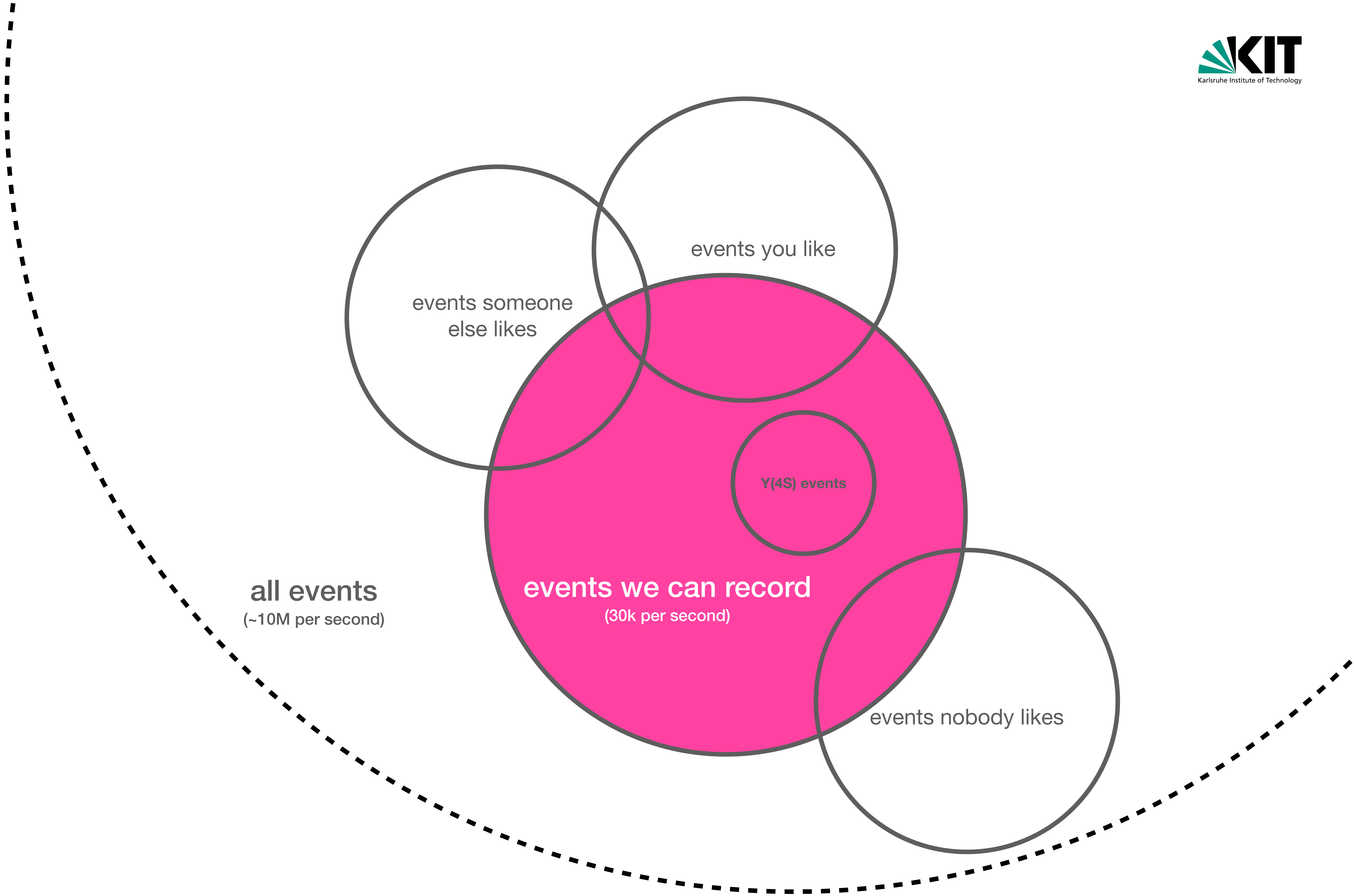
Vertex detectors (VXD):
2 layer DEPFET pixel detectors (PXD)
4 layer double-sided silicon strip detectors (SVD)

Central drift chamber (CDC):
He(50%):C_2H_6 (50%), small cells,
fast electronics

Particle Identification (PID):
Time-Of-Propagation counter (TOP) (barrel)
Aerogel Ring-Imaging Cherenkov Counter (ARICH) (FWD)

DEPFET: depleted p-channel field-effect transistor
WLSF: wavelength-shifting fiber
MPPC: multi-pixel photon counter

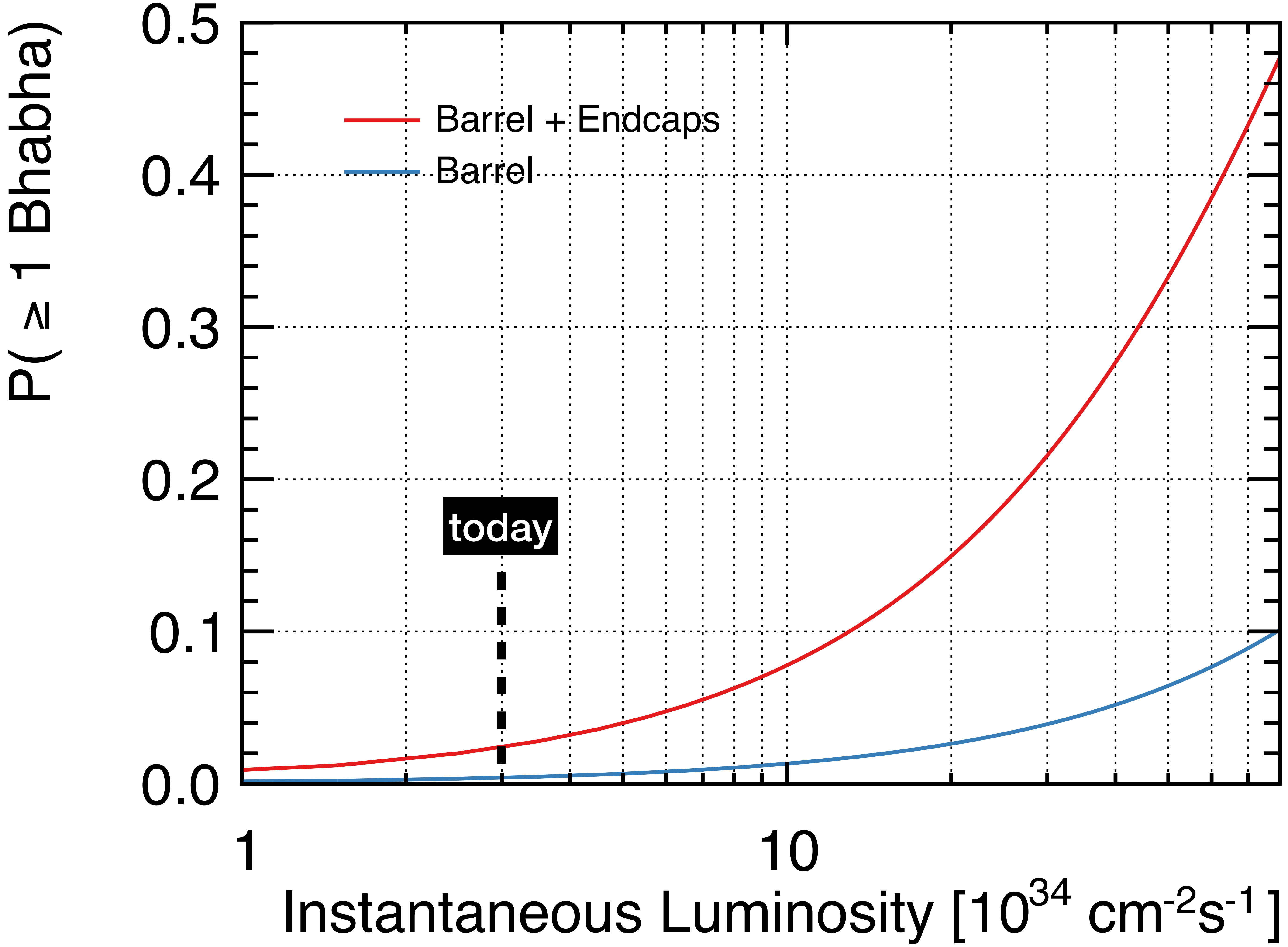
Trigger



events you like
events someone else likes
Υ(4S) events
all events
(~10M per second)
events we can record
(30k per second)
events nobody likes

No jets

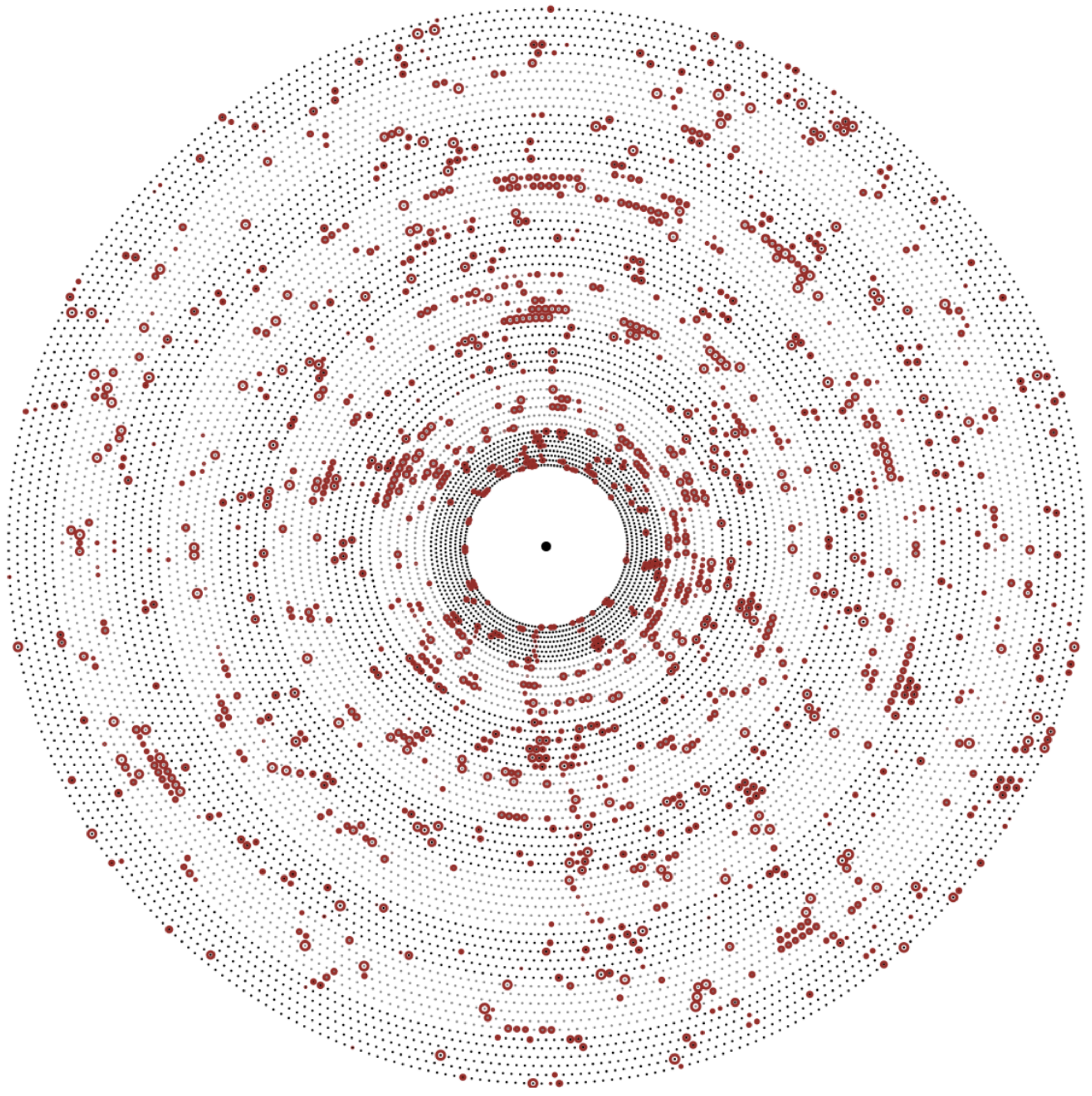
Pile-up?



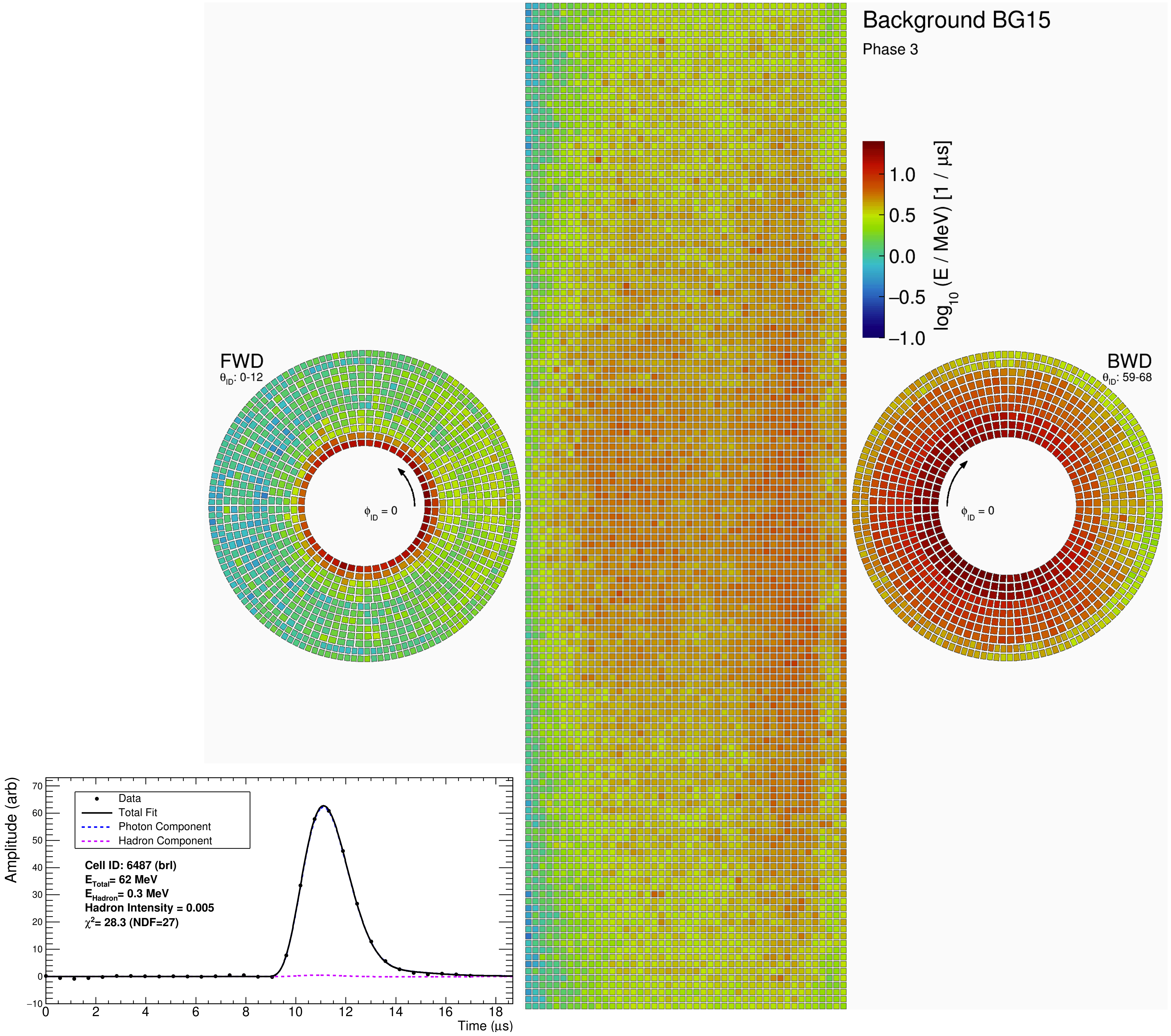
P(≥ 1 Bhabha)
0.5
0.4
0.3
0.2
0.1
0.0
Barrel + Endcaps
Barrel
today
1
10
Instantaneous Luminosity [10^{34} cm^{-2}s^{-1}]

High beam-induced backgrounds

Central drift chamber

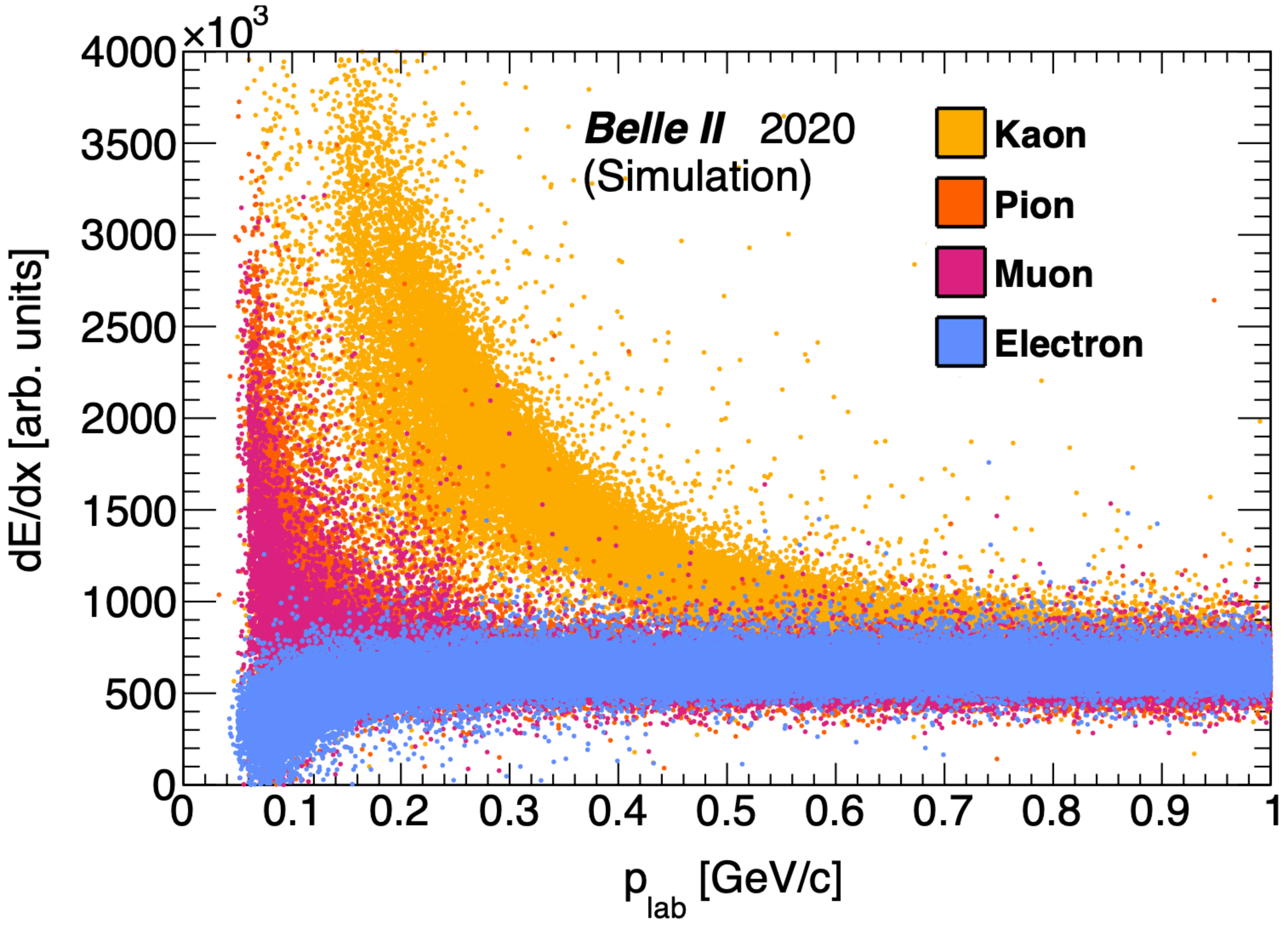


Electromagnetic calorimeter

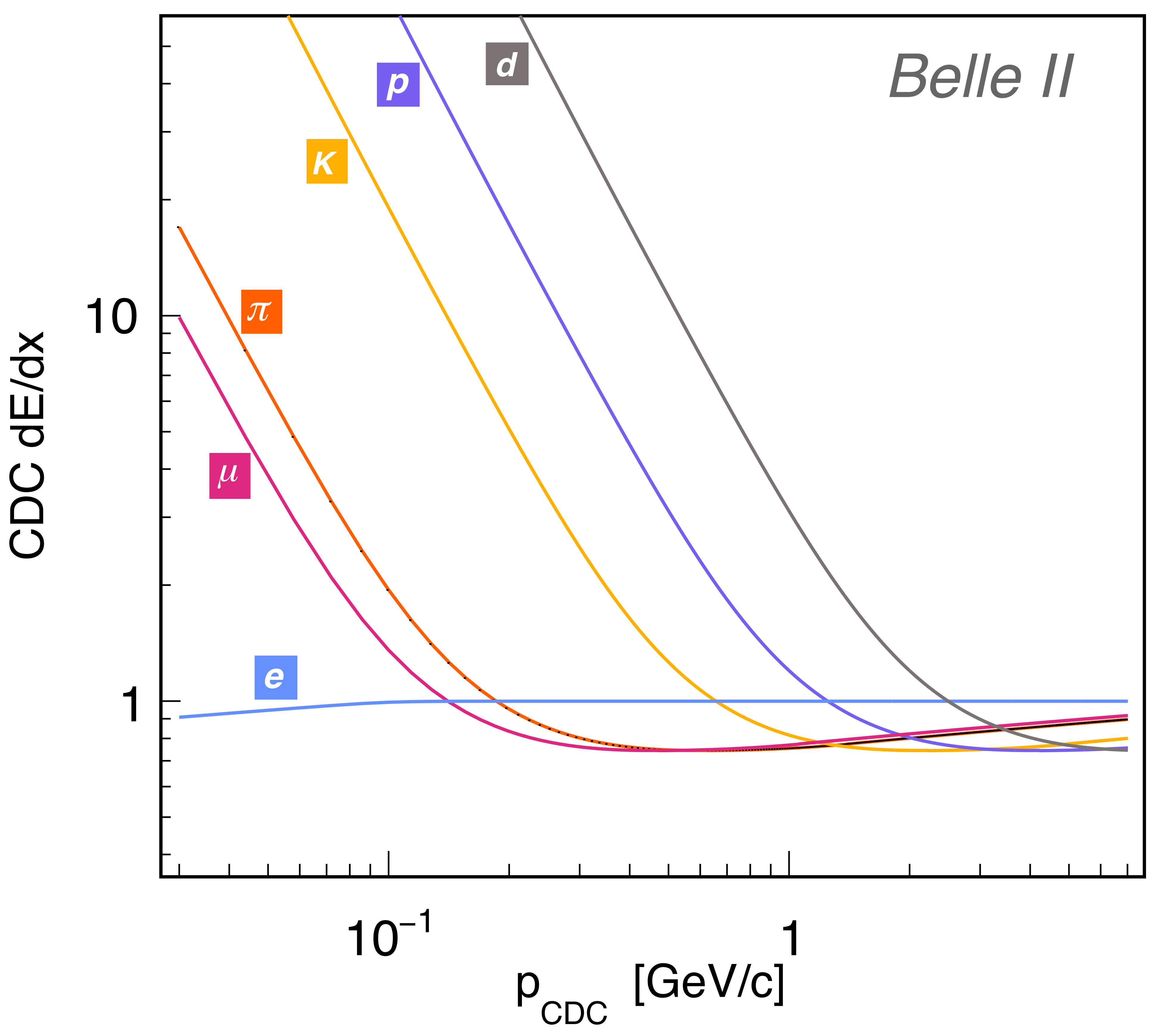


Particle identification: Leptons

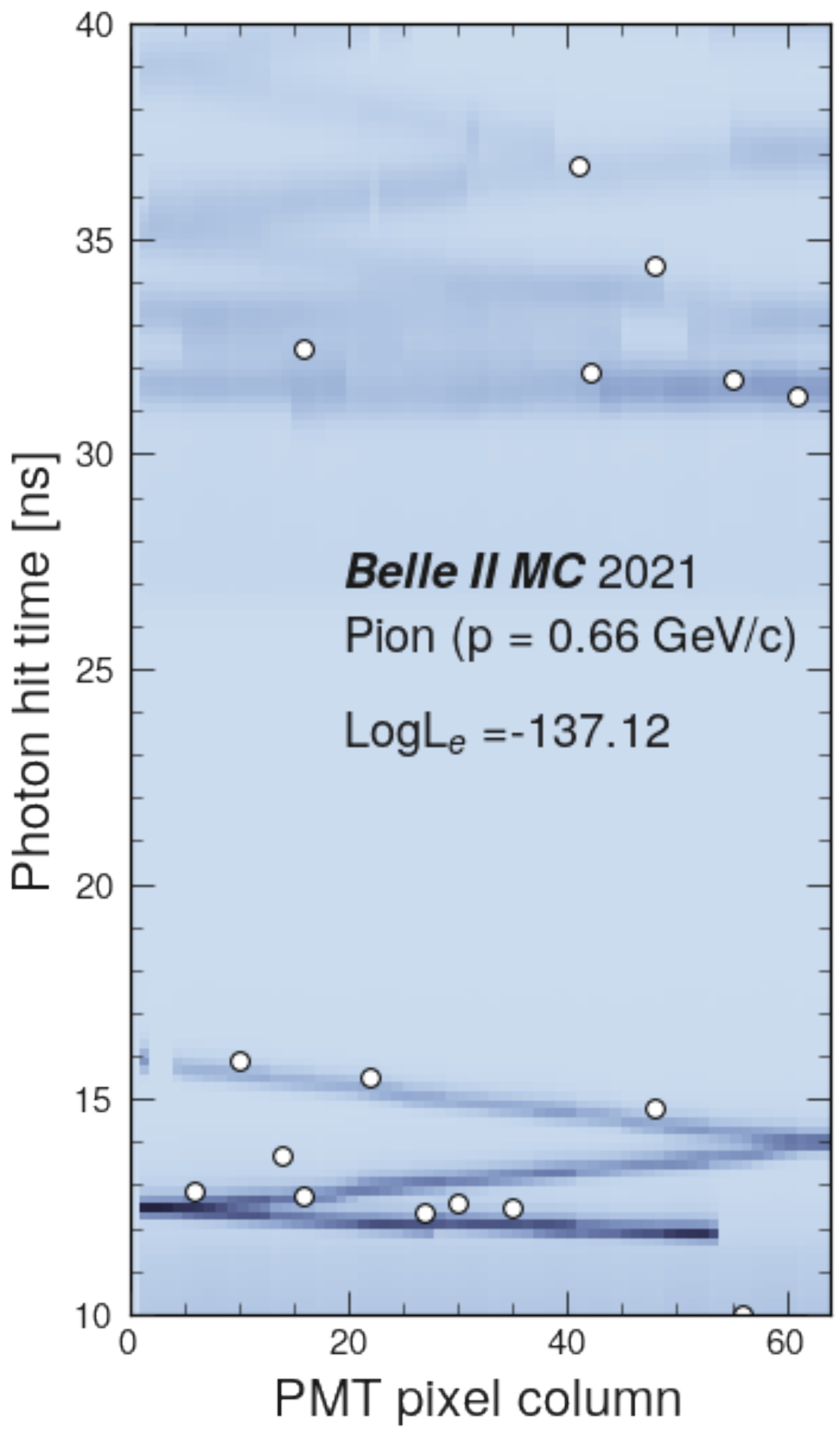
Silicon strip detectors

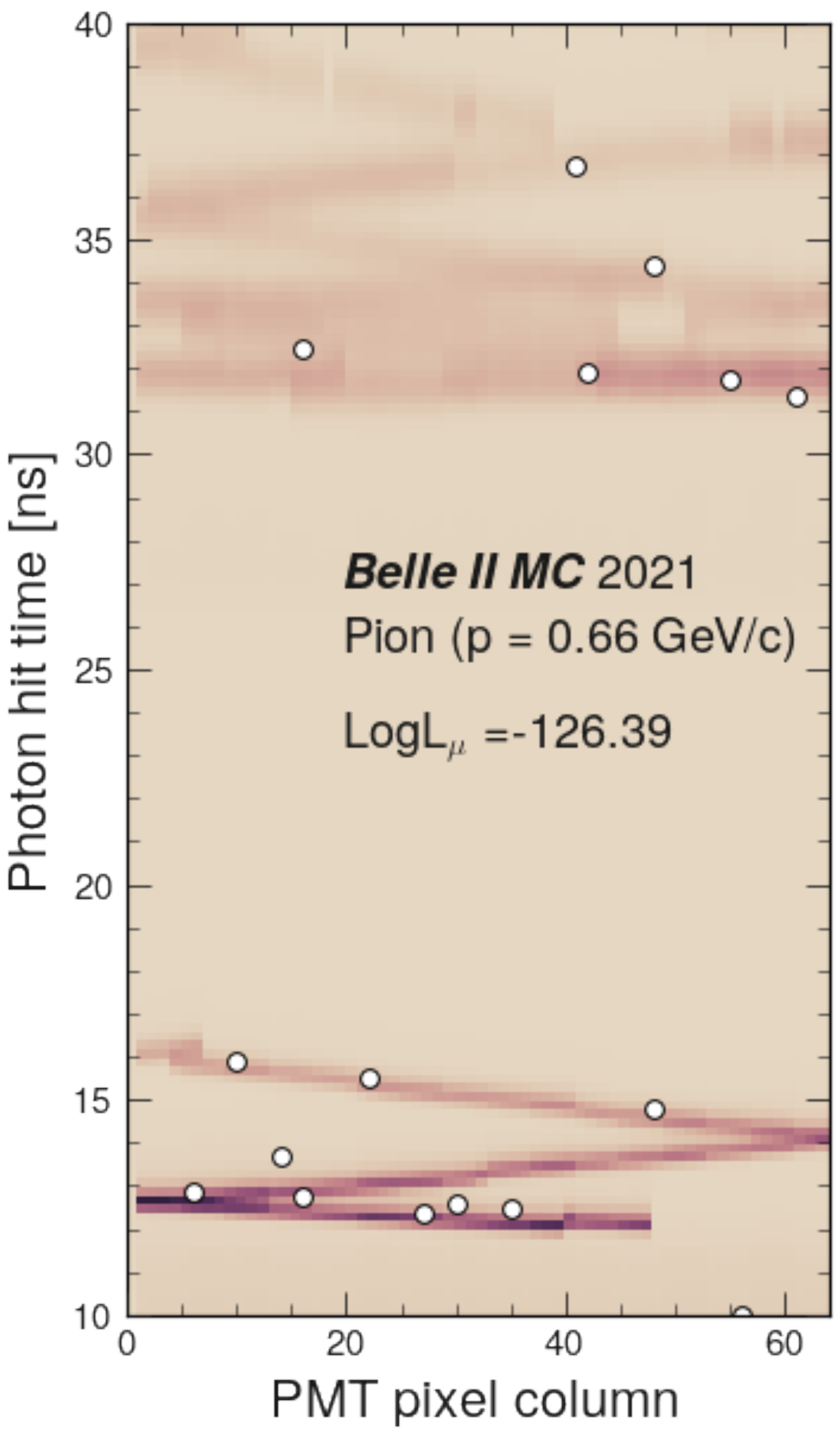


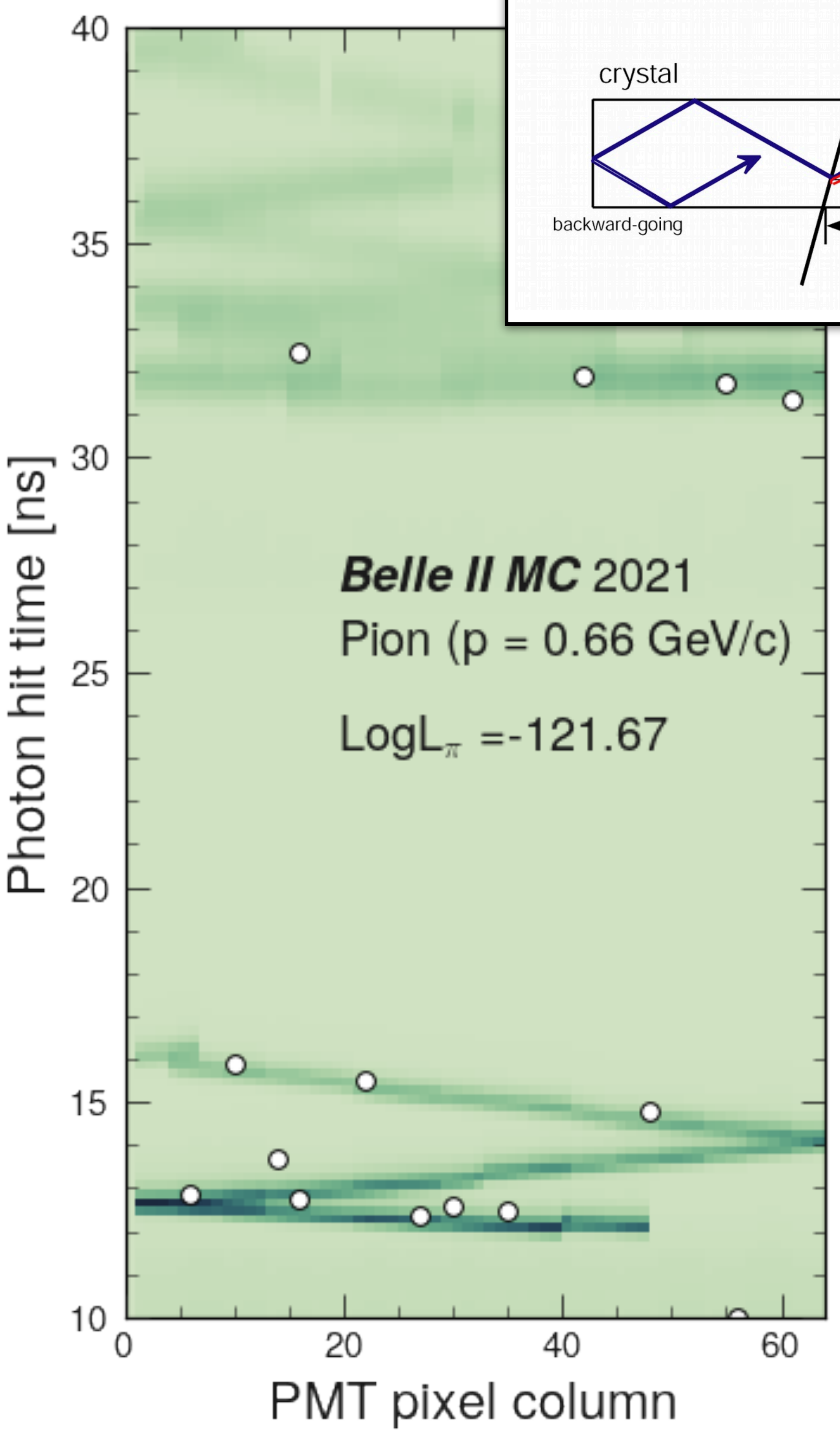
Central drift chamber

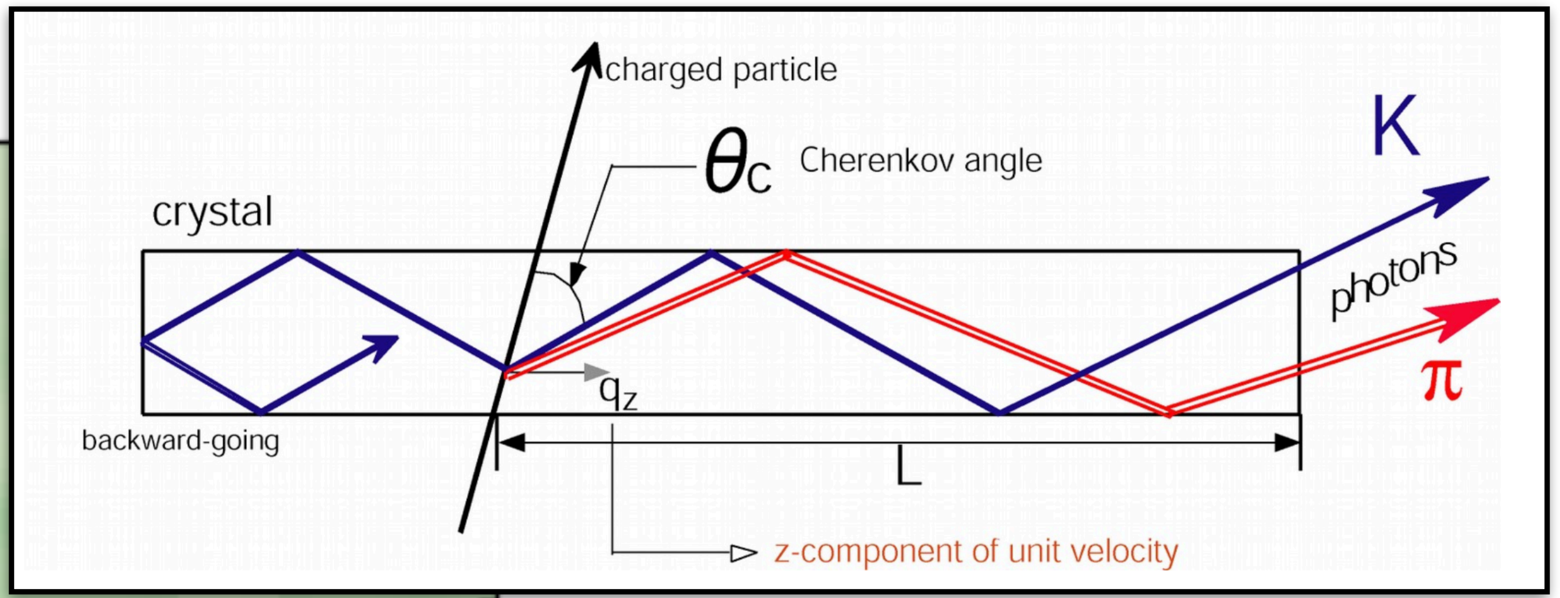


Particle identification: Leptons



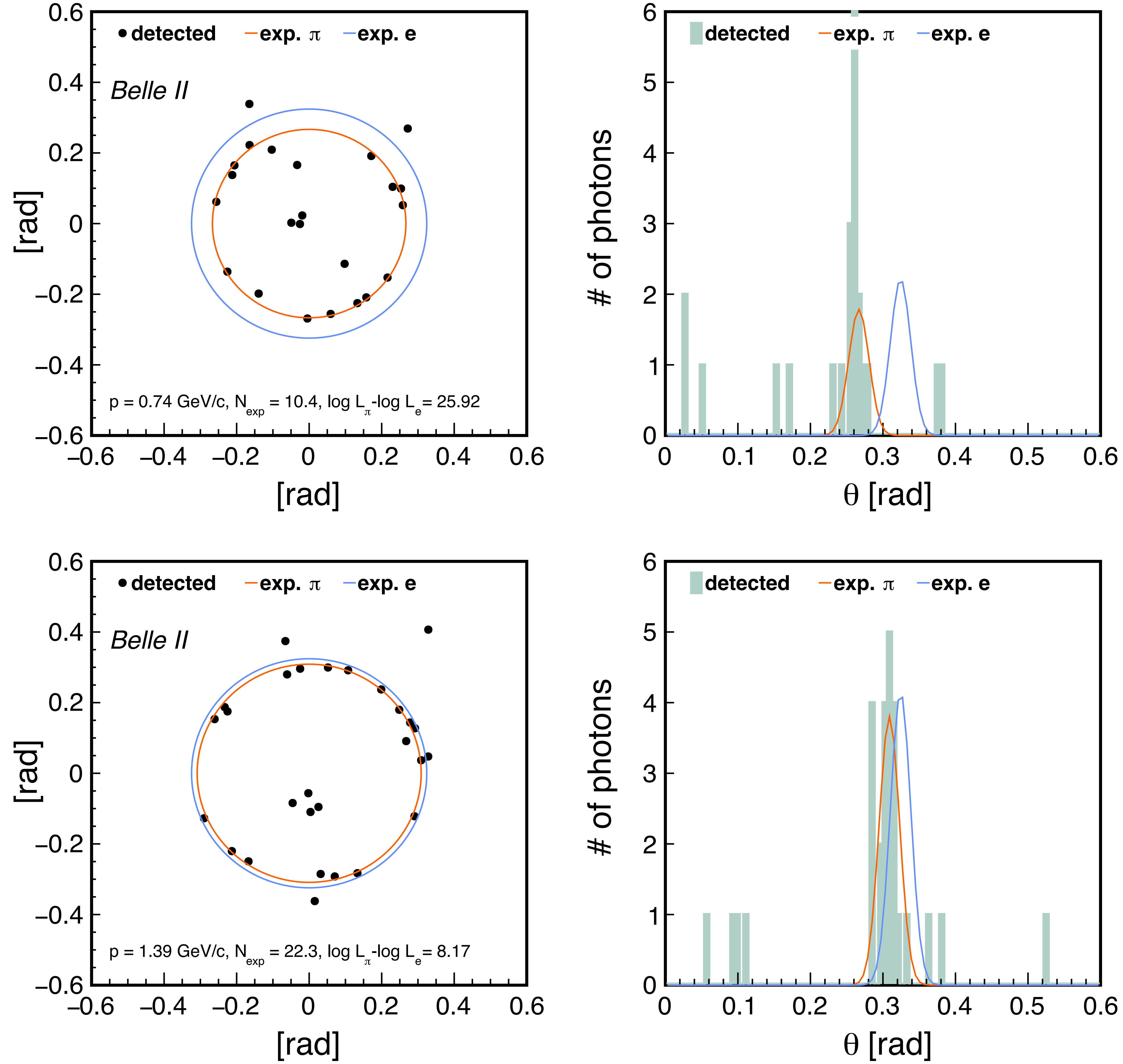






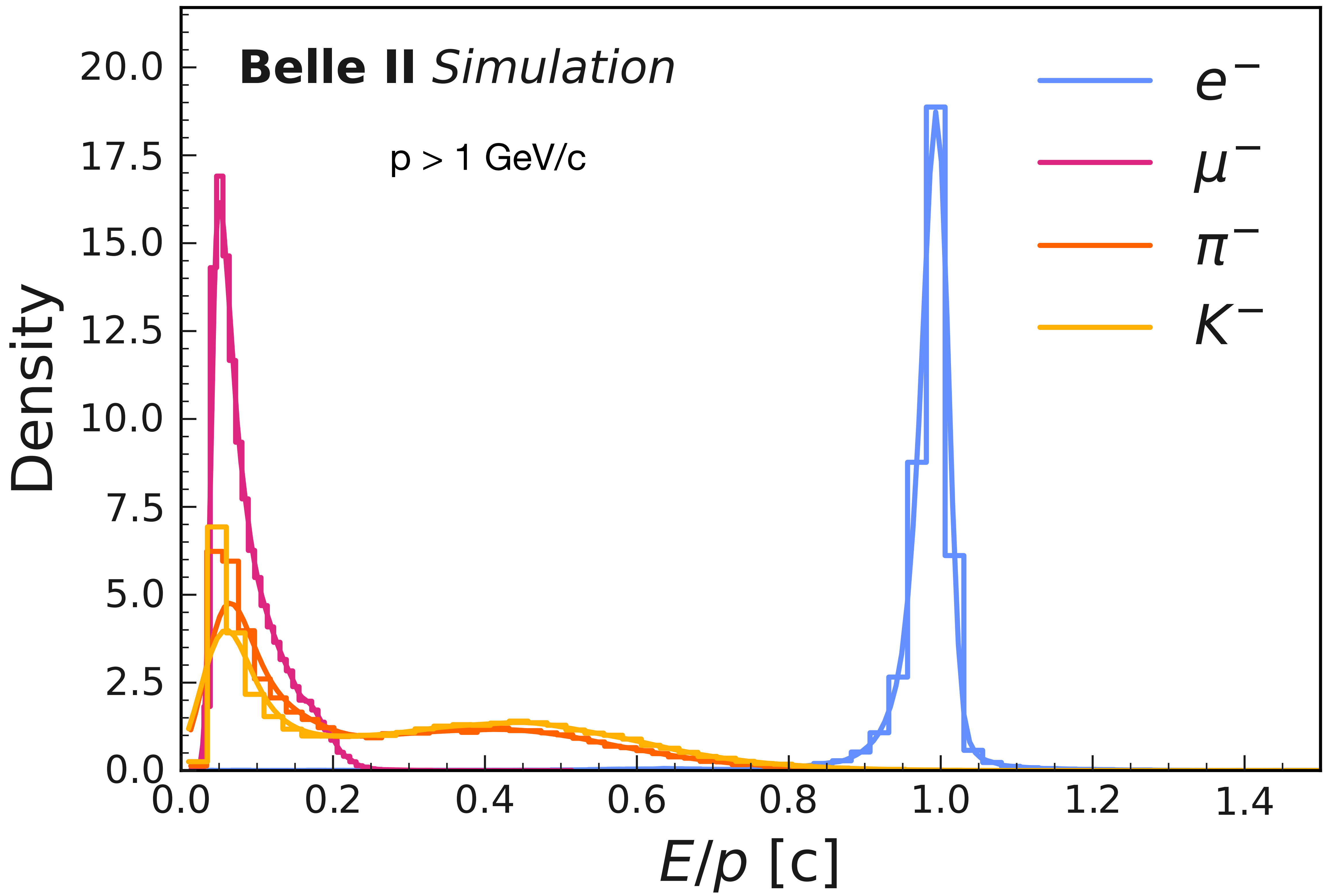
Particle identification: Leptons

Aerogel Ring-Imaging Cherenkov counter

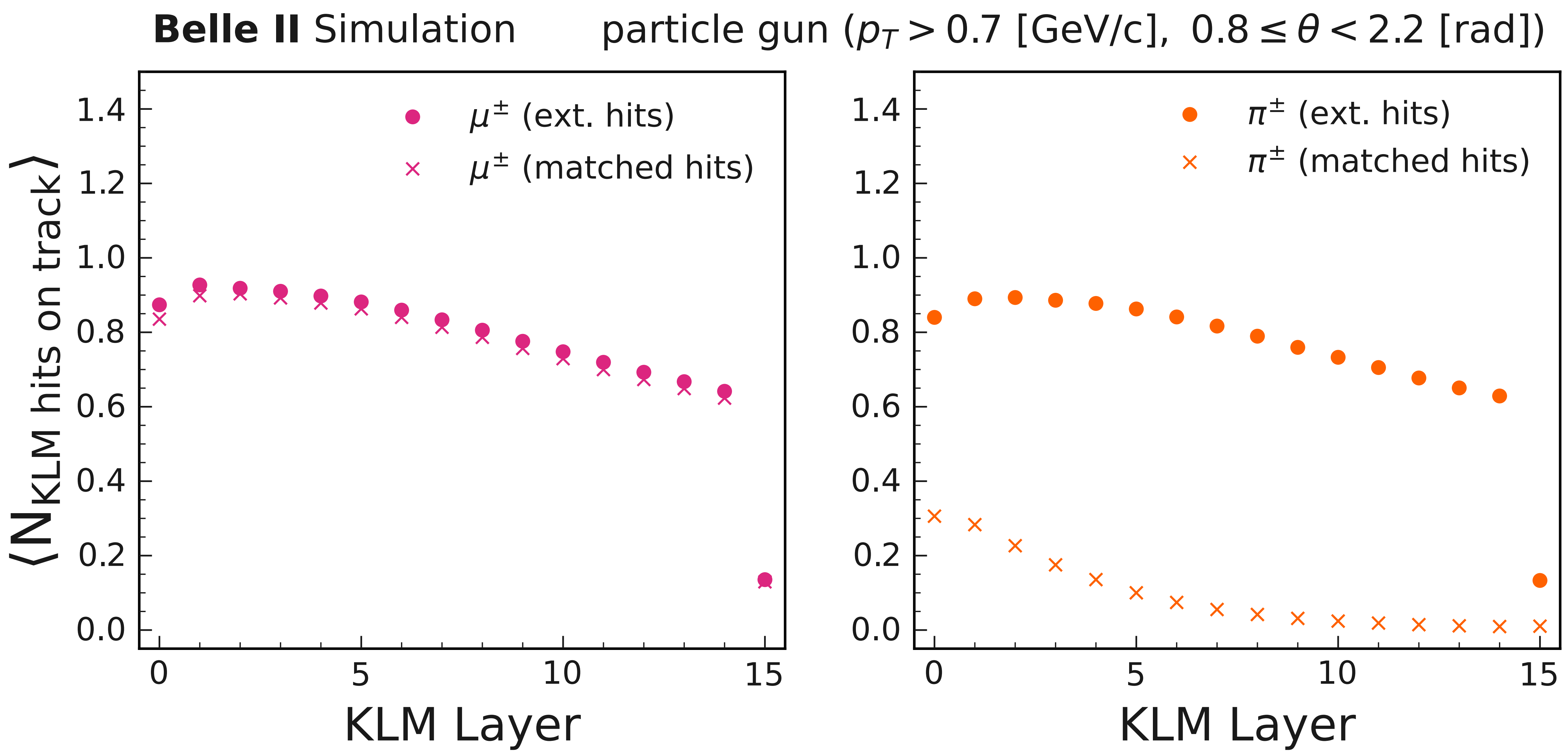


Particle identification: Leptons

Electromagnetic calorimeter

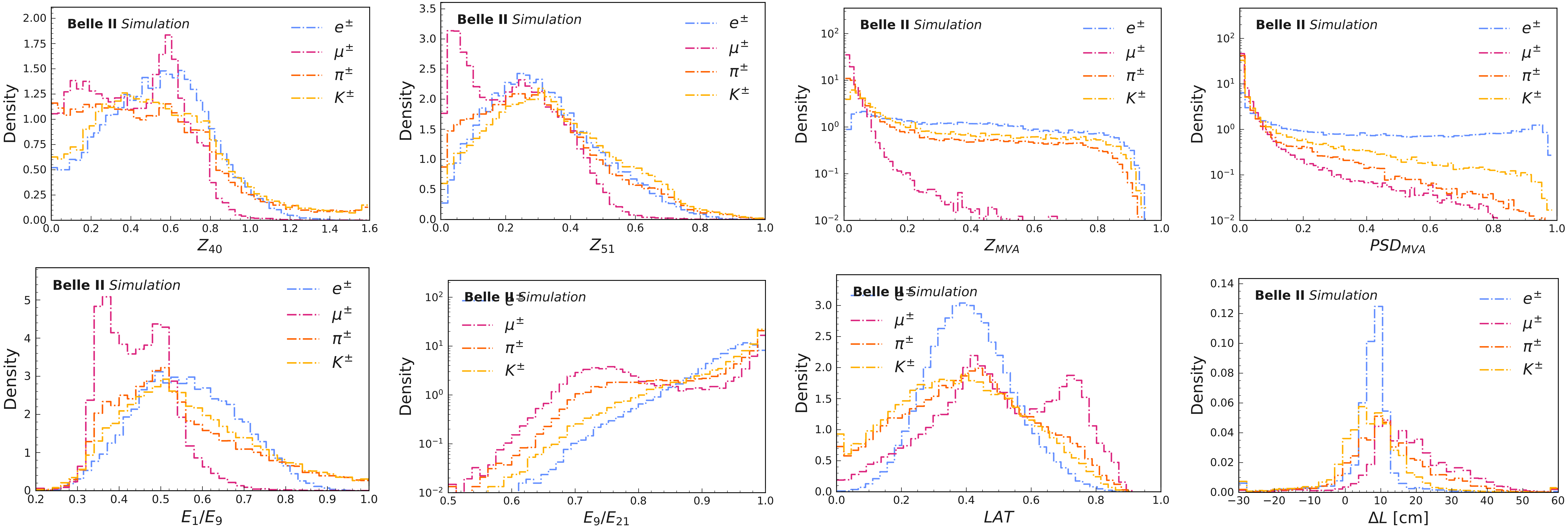


Muon detector



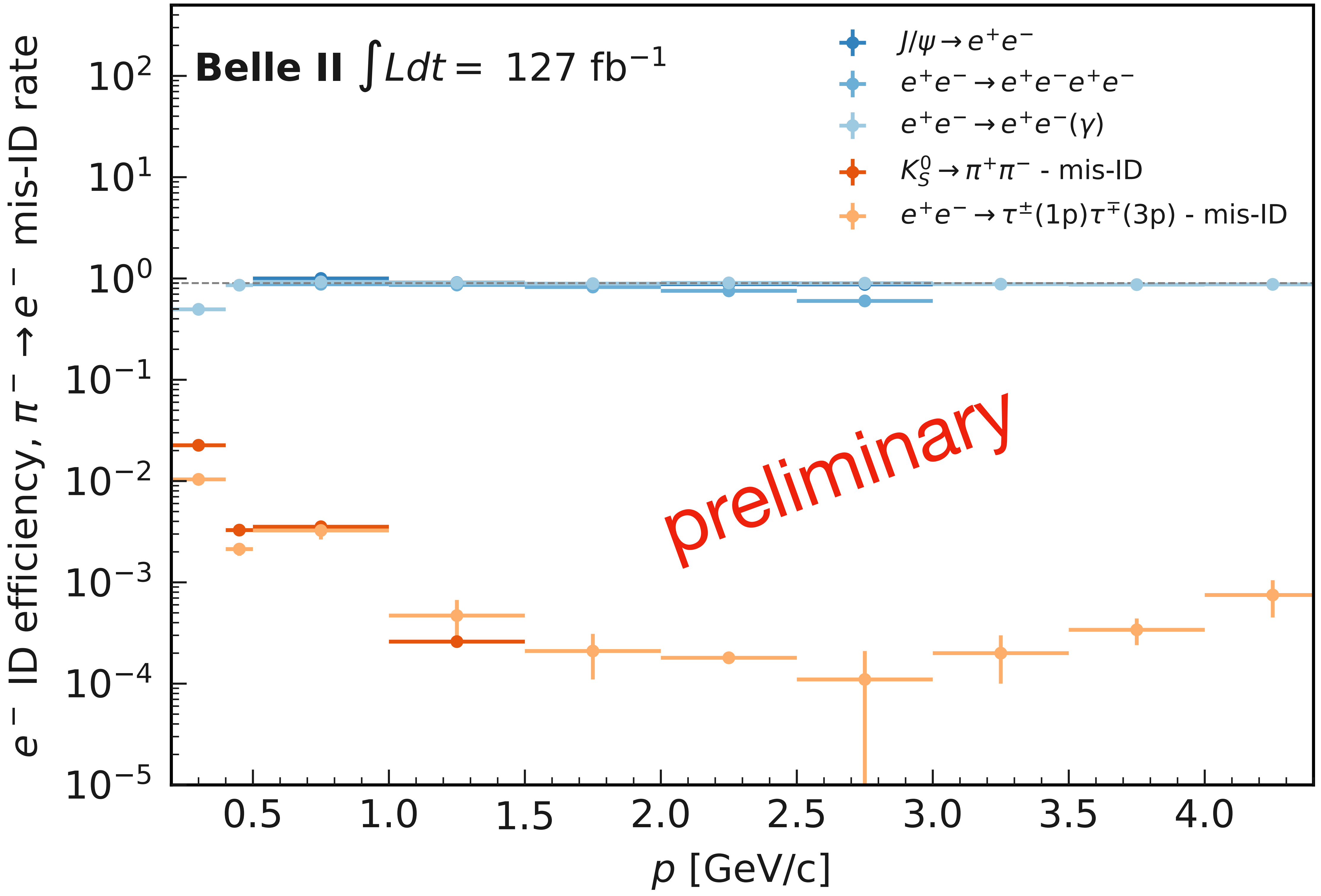
Particle identification: Leptons

Electromagnetic calorimeter 0.2 < p < 0.6 GeV/c

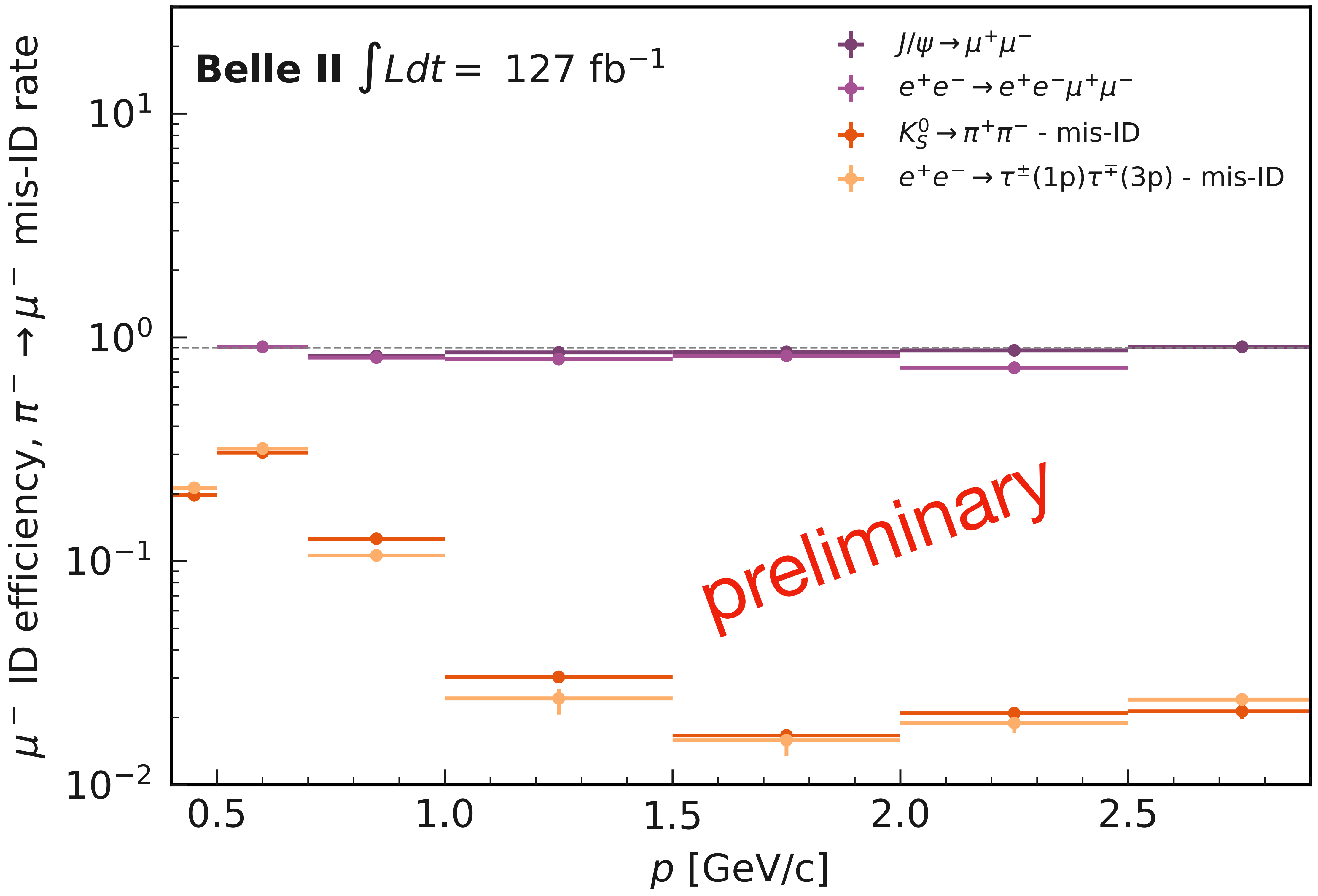


Particle identification: Leptons

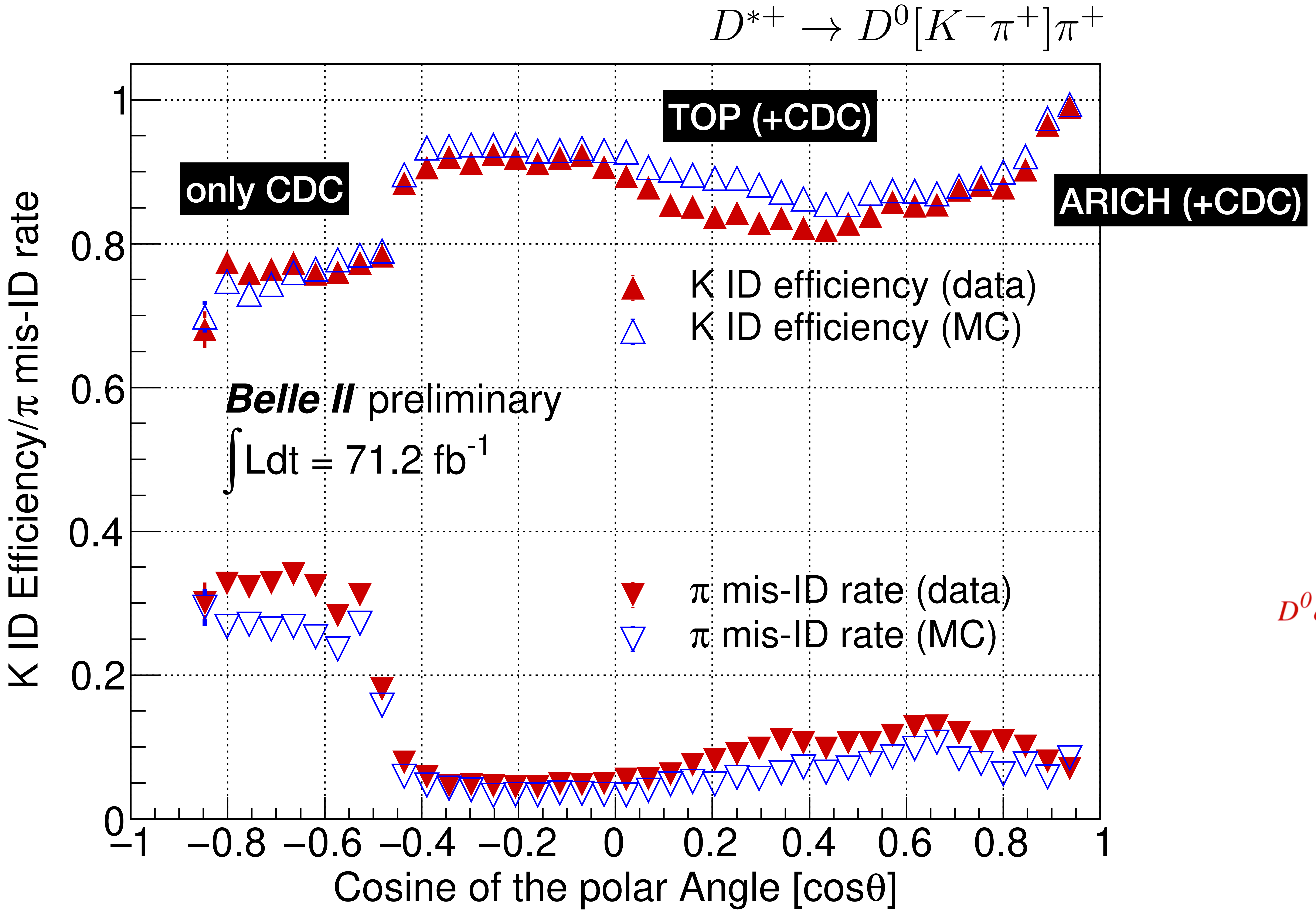
electron identification

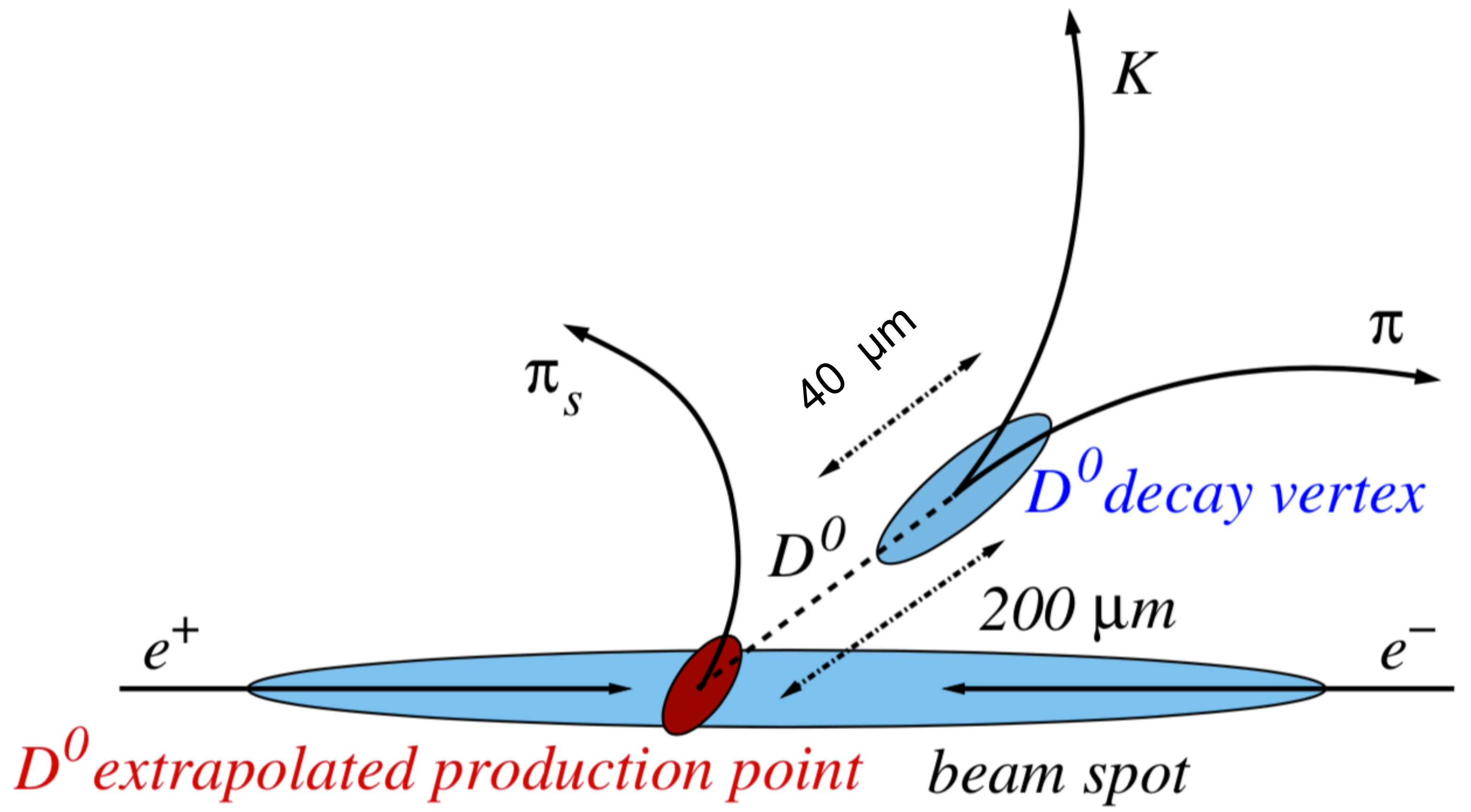


muon identification



Particle identification: Hadrons

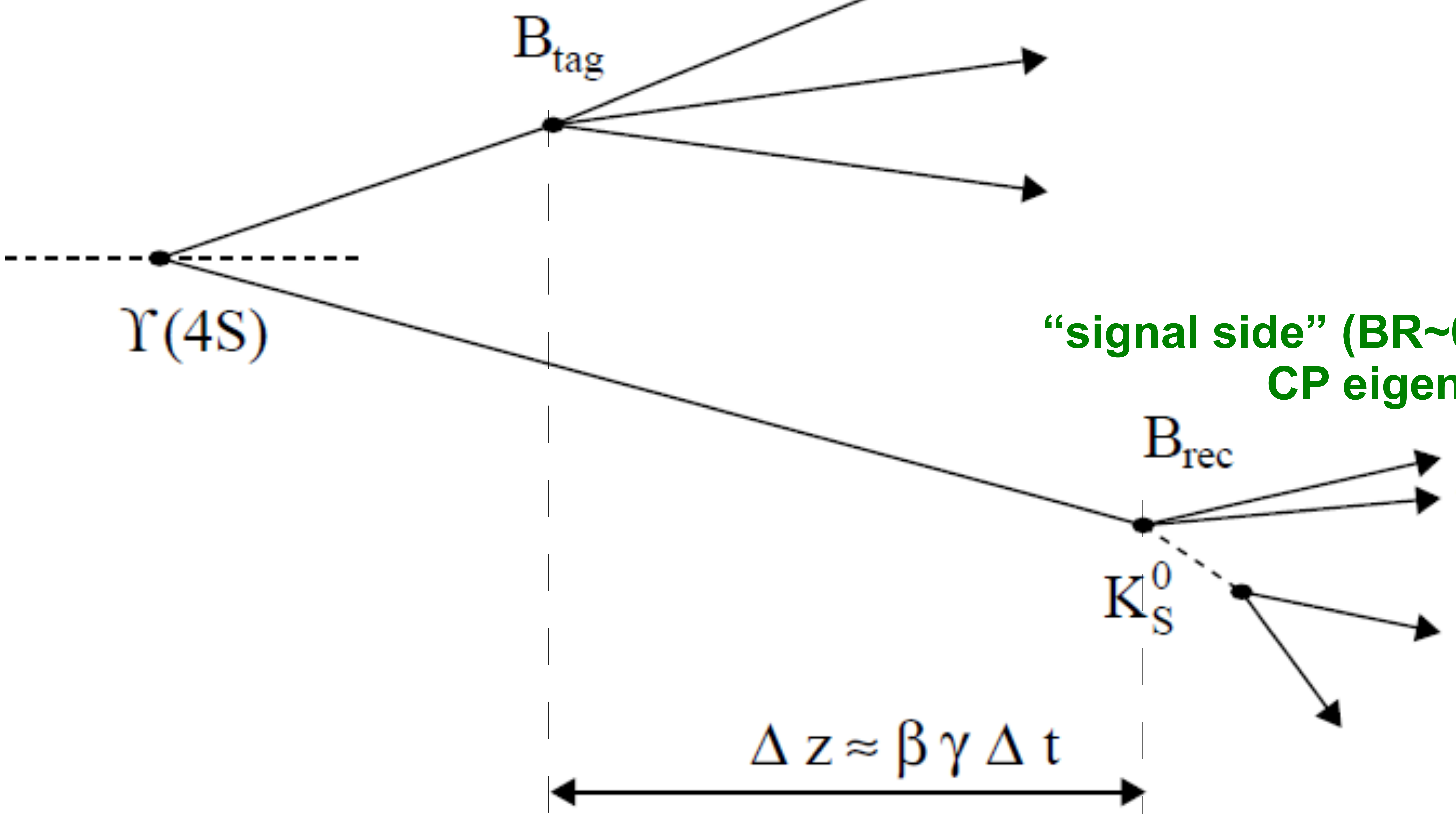




Why asymmetric collision energies?

“tag side” (BR ~80%)
flavour eigenstate, i.e. a decay, where B and $\overline{B}$ decay differently

“signal side” (BR~0.1%)
CP eigenstate



Flavour tagging

Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	ℓ^-
Intermediate Kinetic Lepton	ℓ^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum p^*	ℓ^-, π^-
Fast-Slow-Correlated (FSC)	ℓ^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ

Underlying decay modes

$$\overline{B}^0 \to D^{*+}\ \bar{\nu}_\ell\ \ell^-$$
$$\hookrightarrow D^0\ \pi^+$$
$$\hookrightarrow X\ K^-$$

$$\overline{B}^0 \to D^+\ \pi^-\ (K^-)$$
$$\hookrightarrow \overline{K}^0\ \nu_\ell\ \ell^+$$

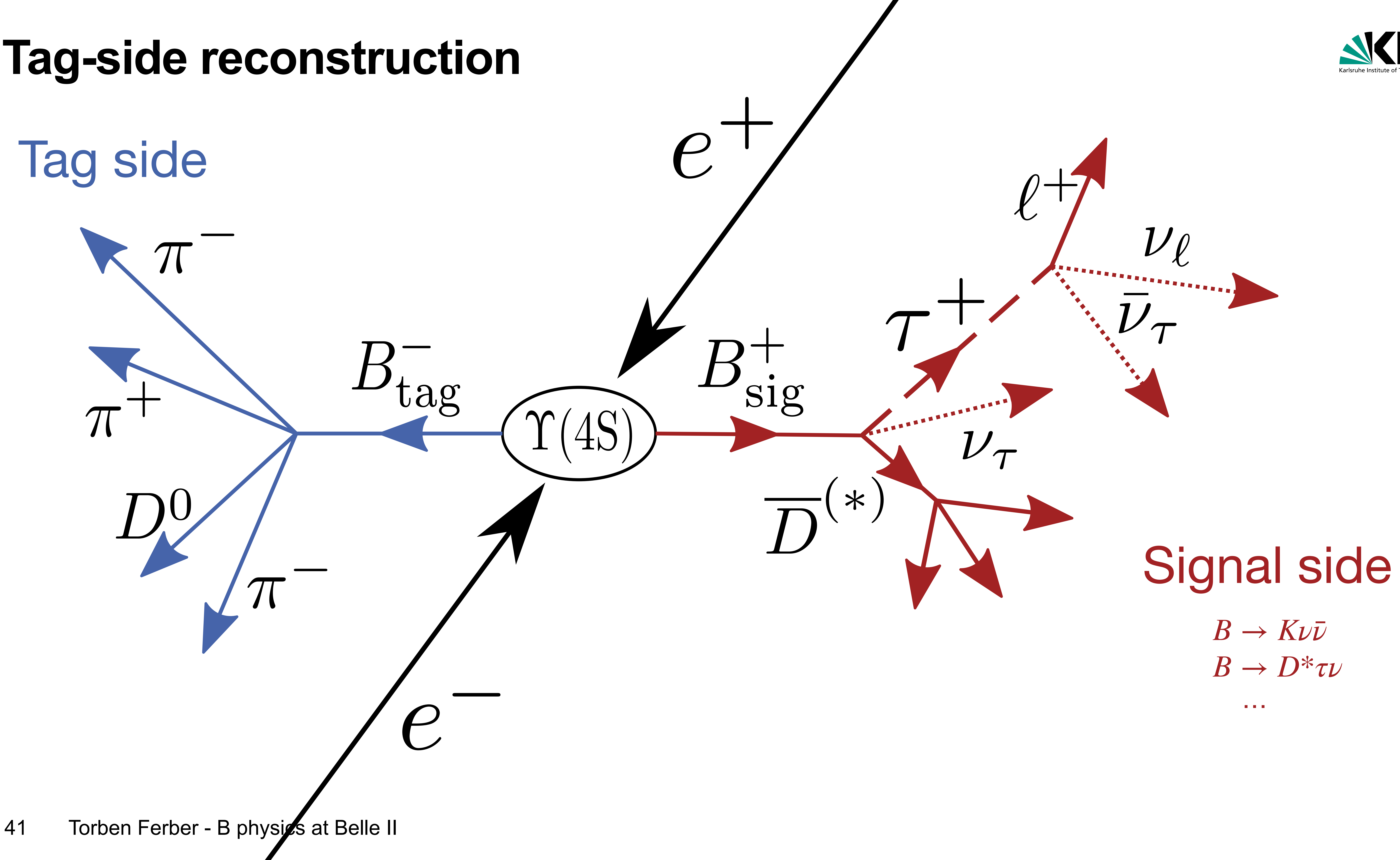
$$\overline{B}^0 \to \Lambda_c^+\ X^-$$
$$\hookrightarrow \Lambda\ \pi^+$$
$$\hookrightarrow p\ \pi^-$$

Neutral B^0: ~30 % efficiency

Charged B$^+$: ~40 % efficiency

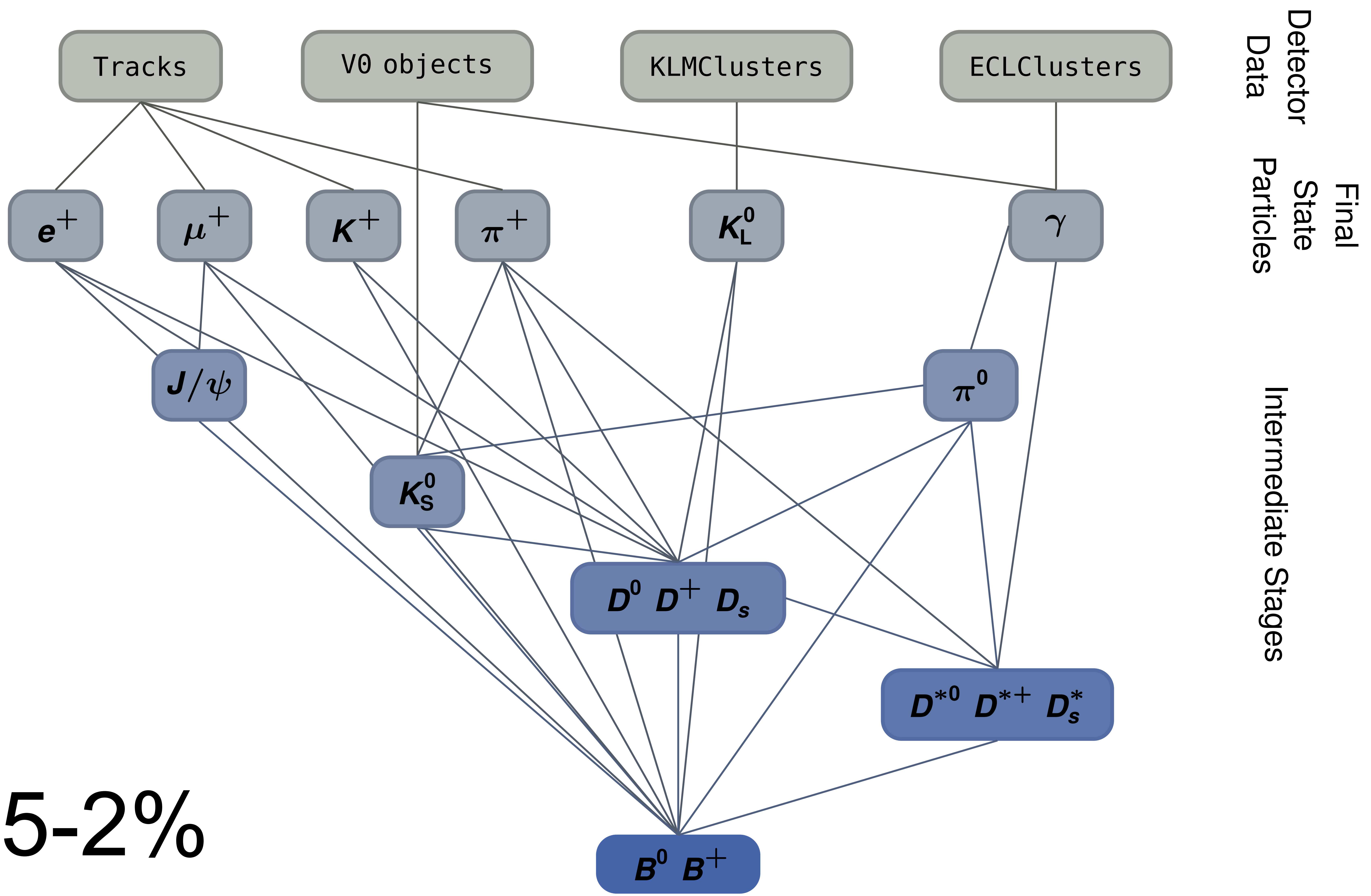
https://arxiv.org/abs/2110.00790

Tag-side reconstruction

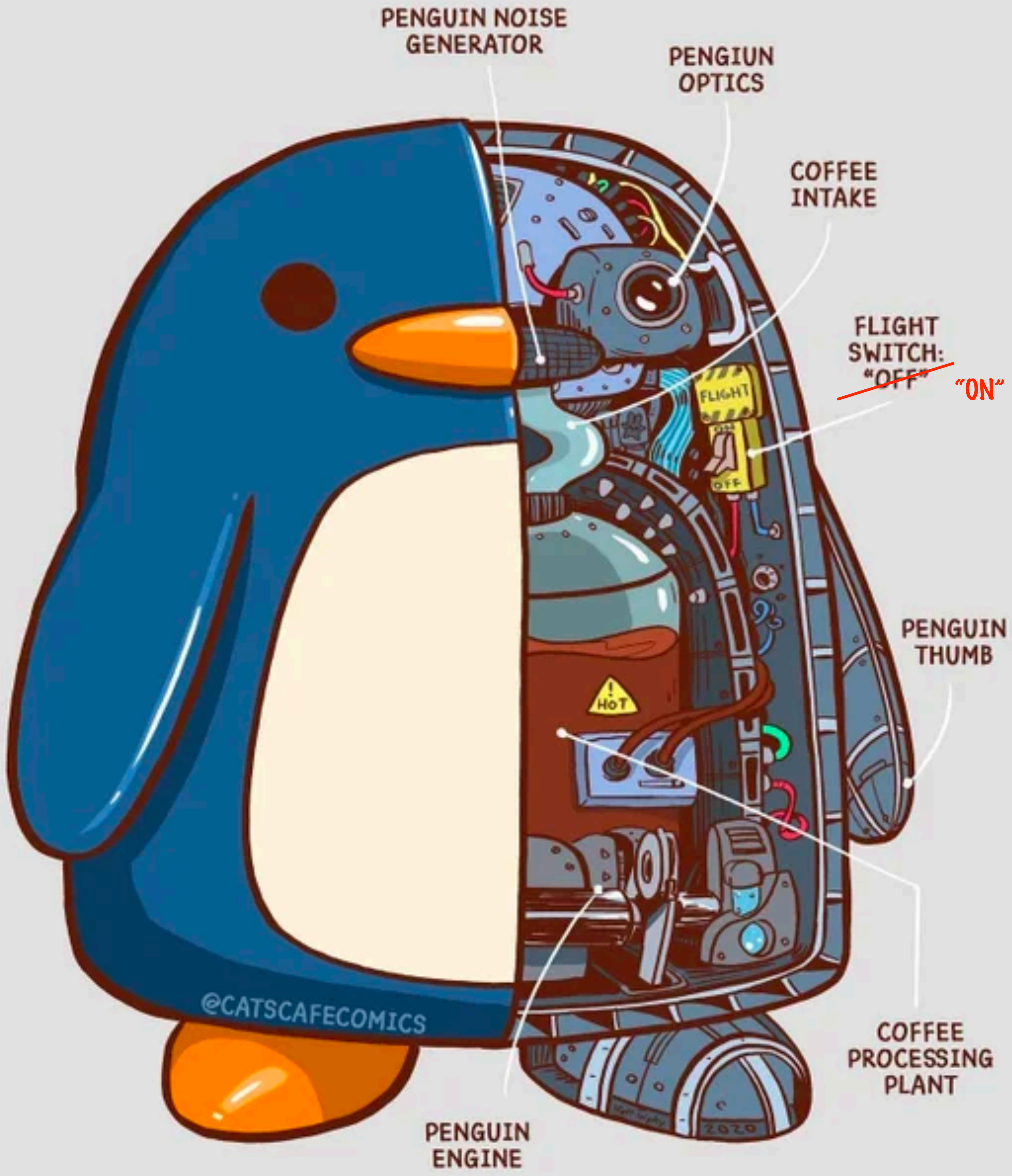


$B \to K\nu\bar{\nu}$
$B \to D^*\tau\nu$
…

Tag-side reconstruction: Full Event Interpretation



$\varepsilon \approx 0.5\text{-}2\%$


PENGUIN NOISE GENERATOR
PENGIUN OPTICS
COFFEE INTAKE
FLIGHT SWITCH: ~~"OFF"~~ "ON"
PENGUIN THUMB
COFFEE PROCESSING PLANT
PENGUIN ENGINE
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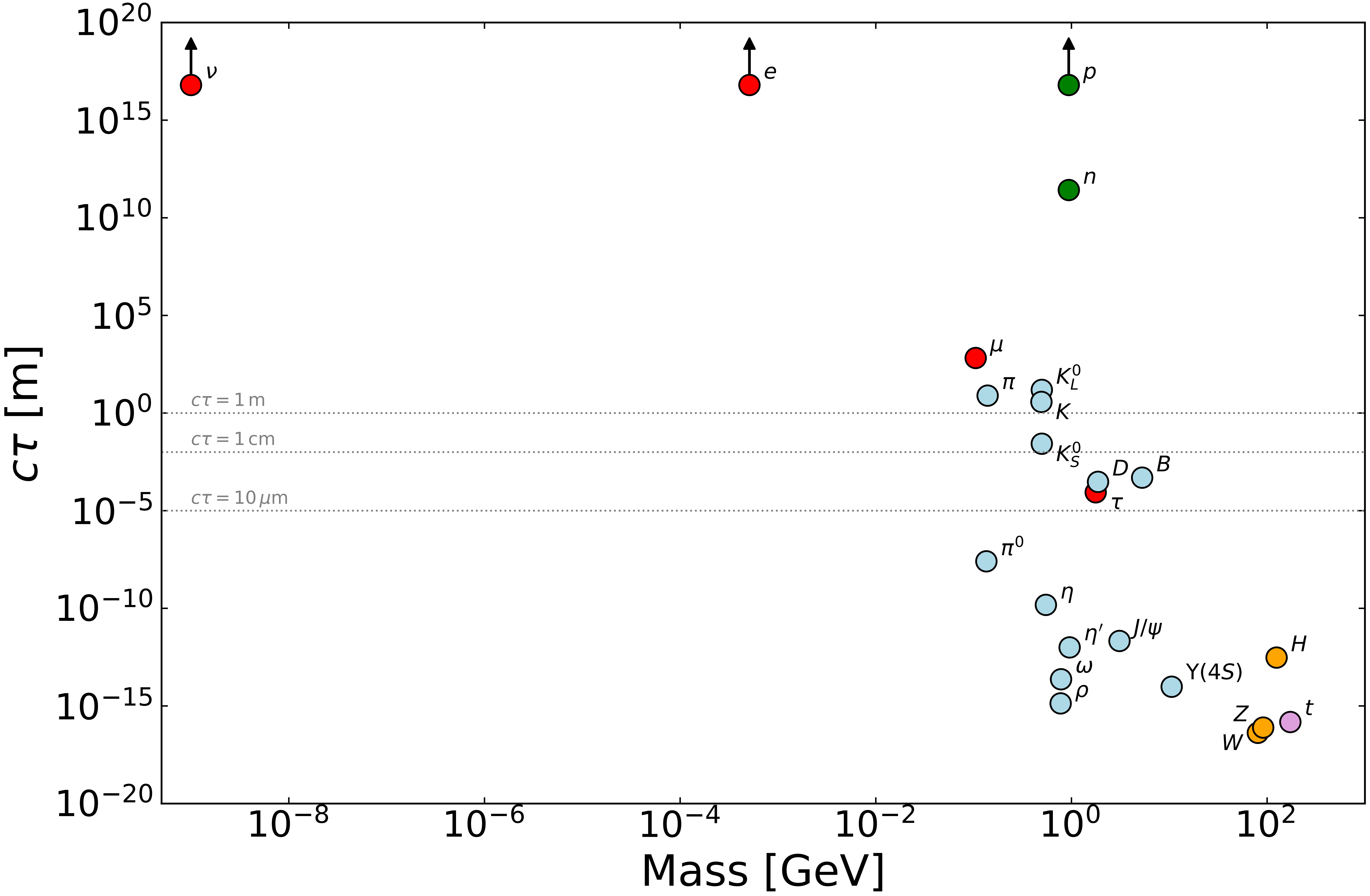
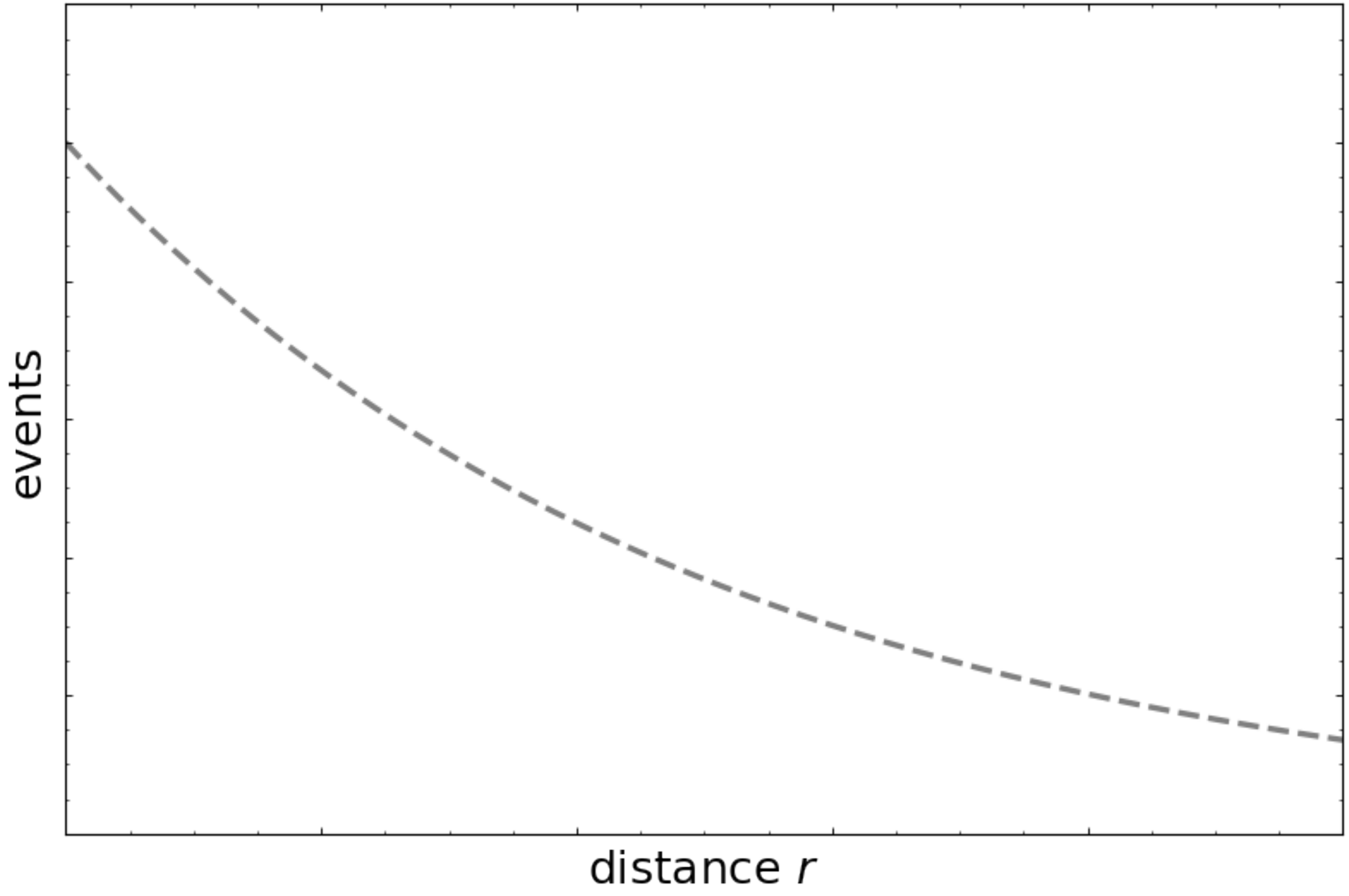
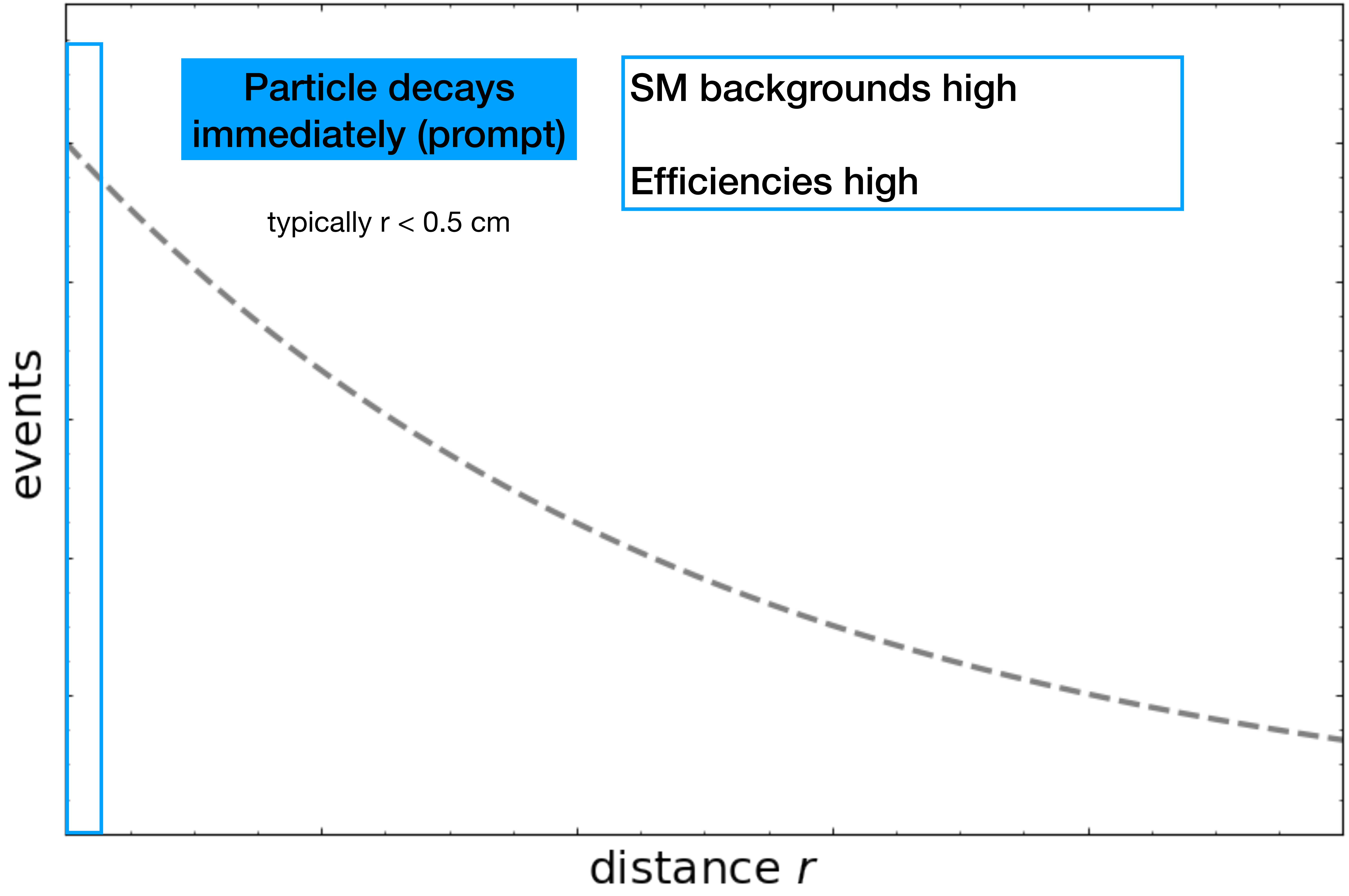
Lifetime: Standard model



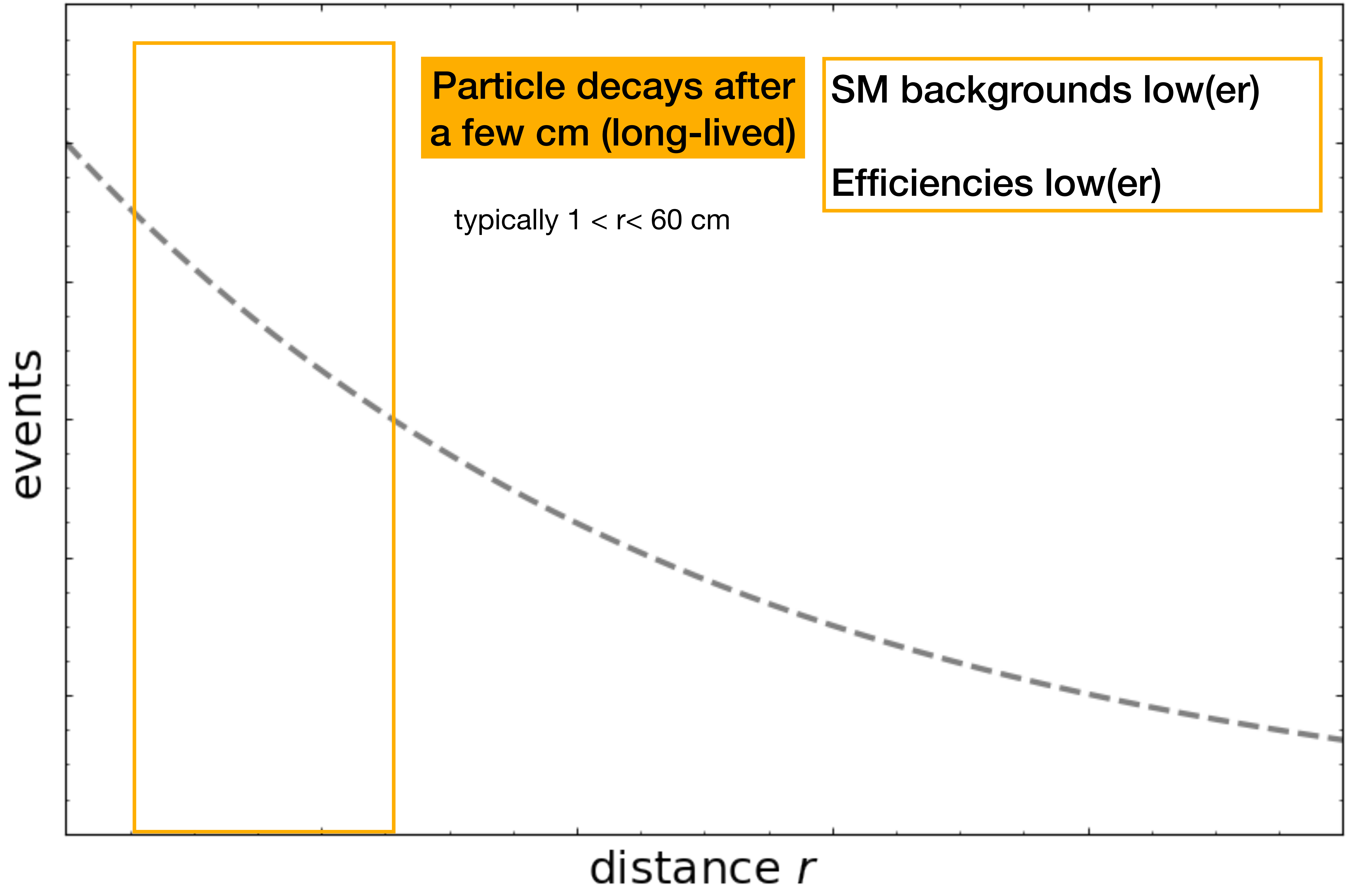
Lifetime



Lifetime: Prompt decays



Lifetime: Displaced decays



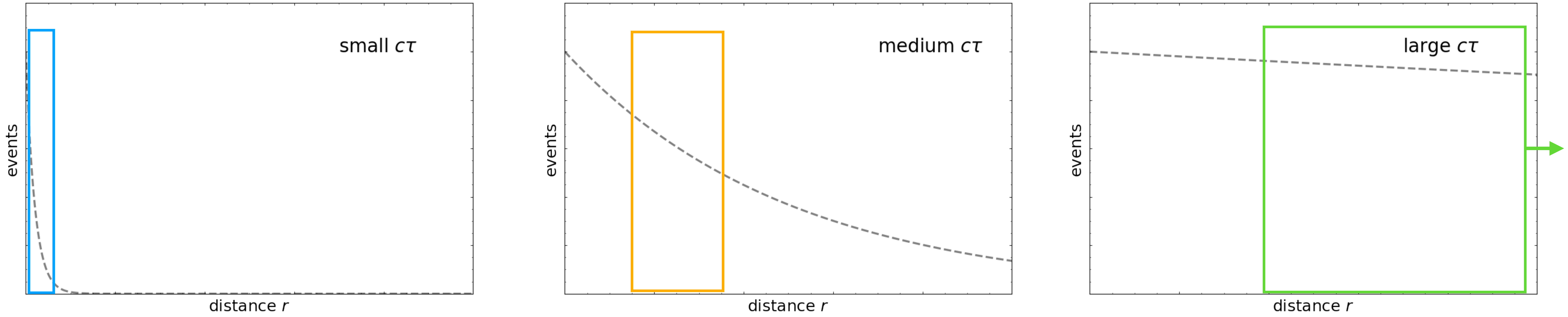
Lifetime: Invisible decays

Particle decays after a few m (invisible)

SM and efficiencies very analysis dependent

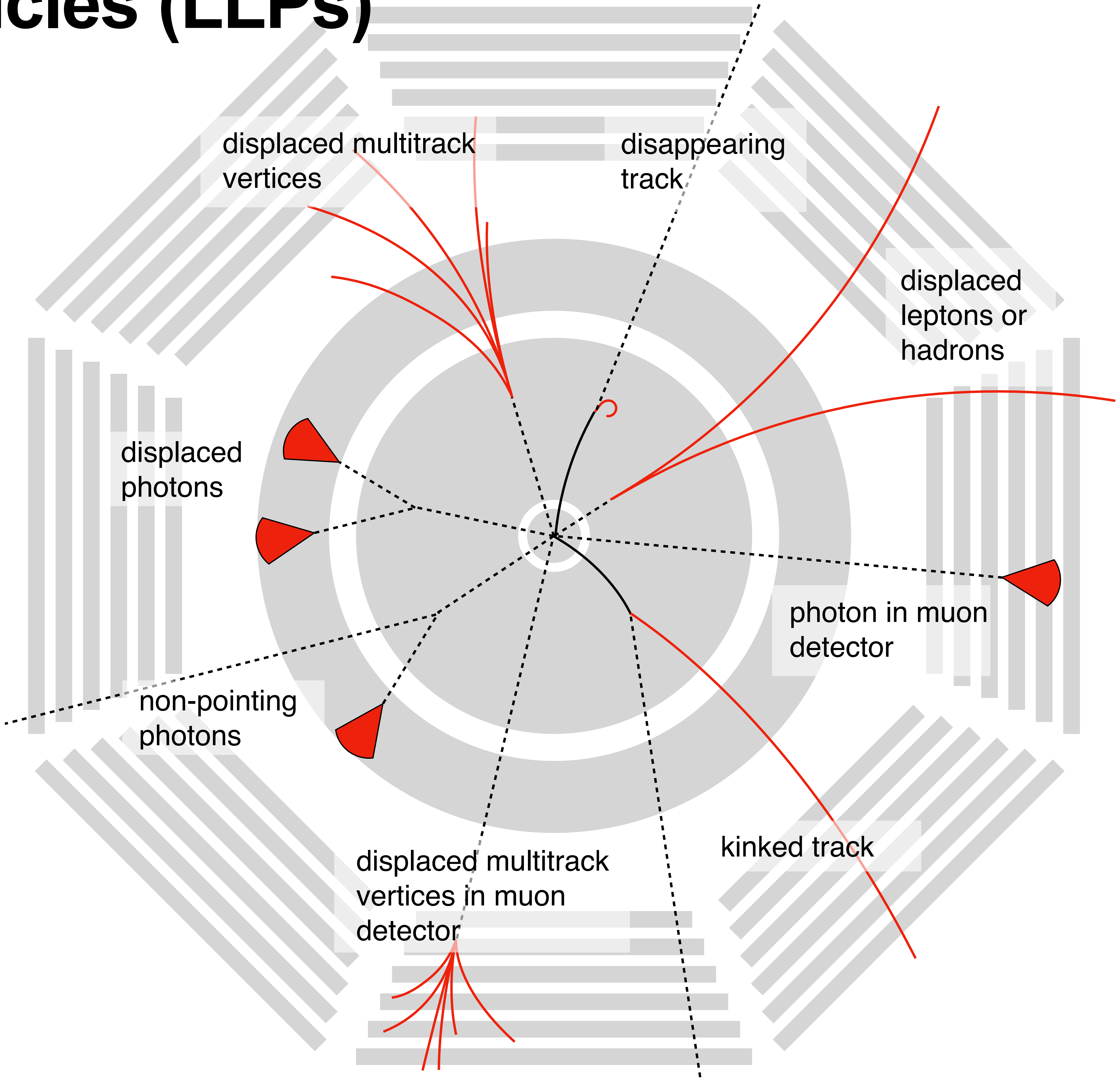
typically r > 150 cm

Lifetime

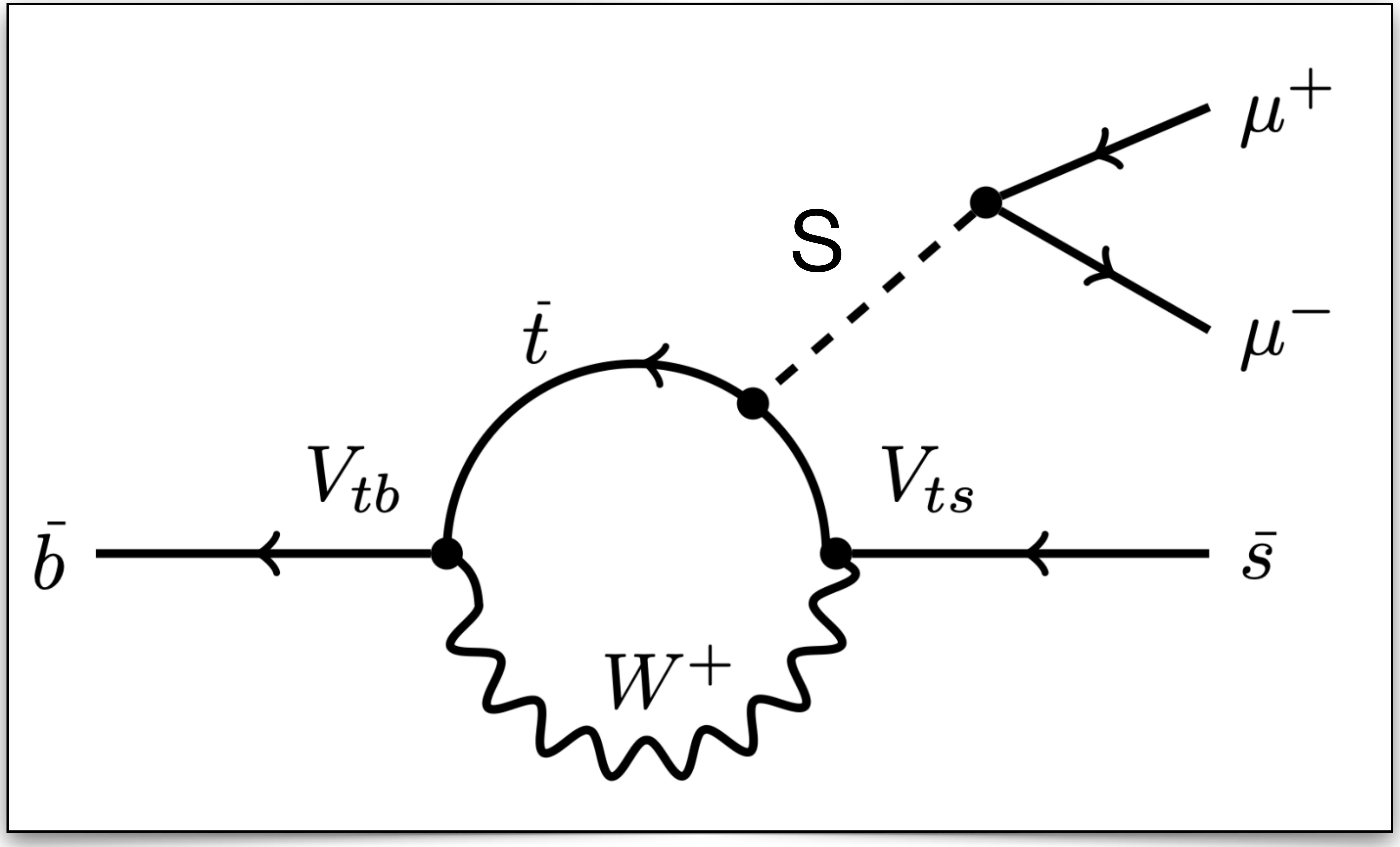


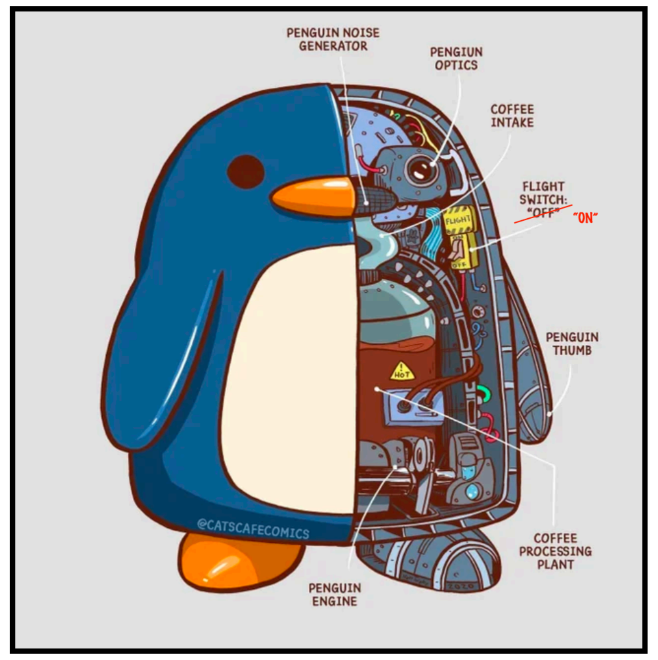
small $c\tau$
events
distance r
medium $c\tau$
events
distance r
large $c\tau$
events
distance r

Long-lived particles (LLPs)



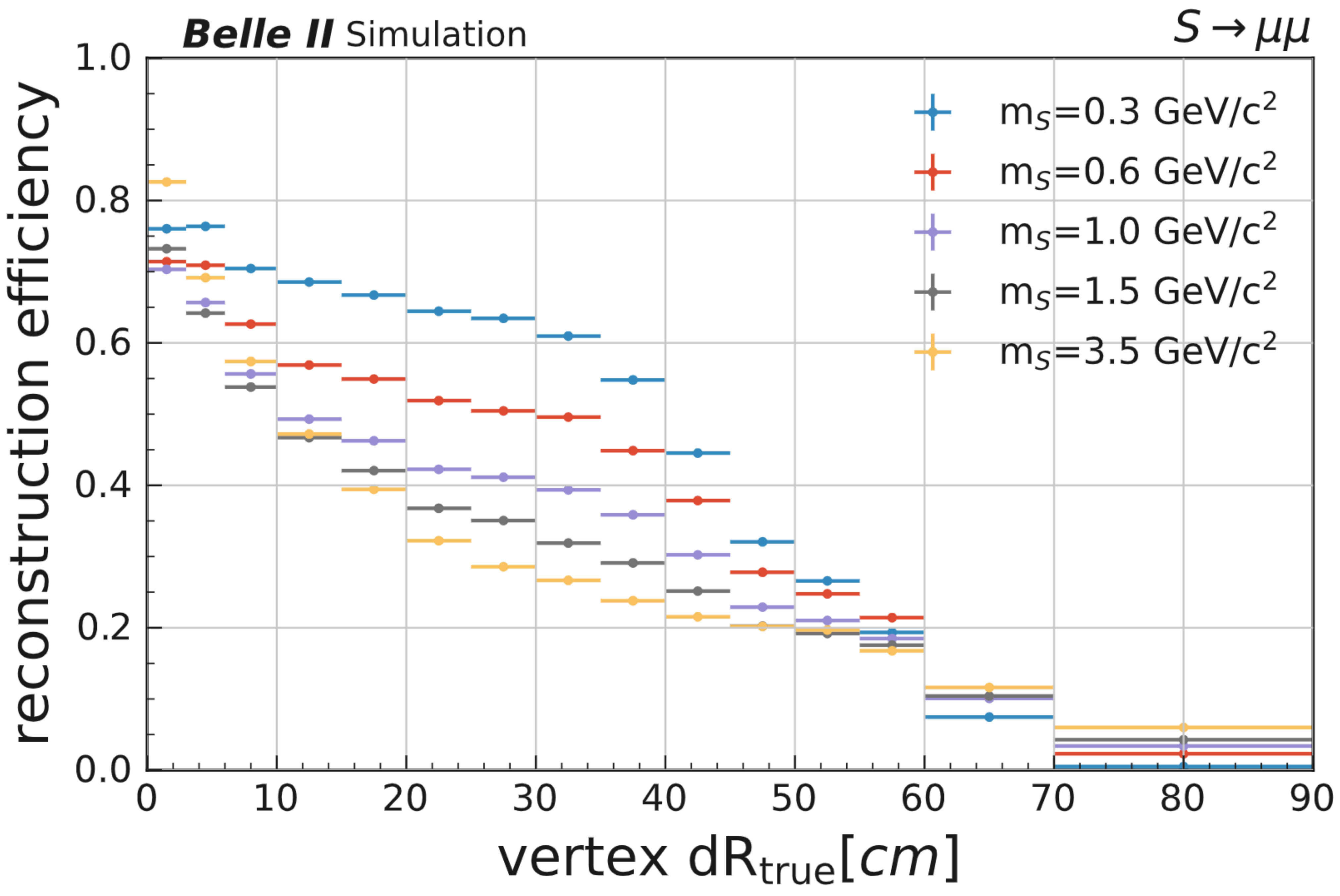
B→KS

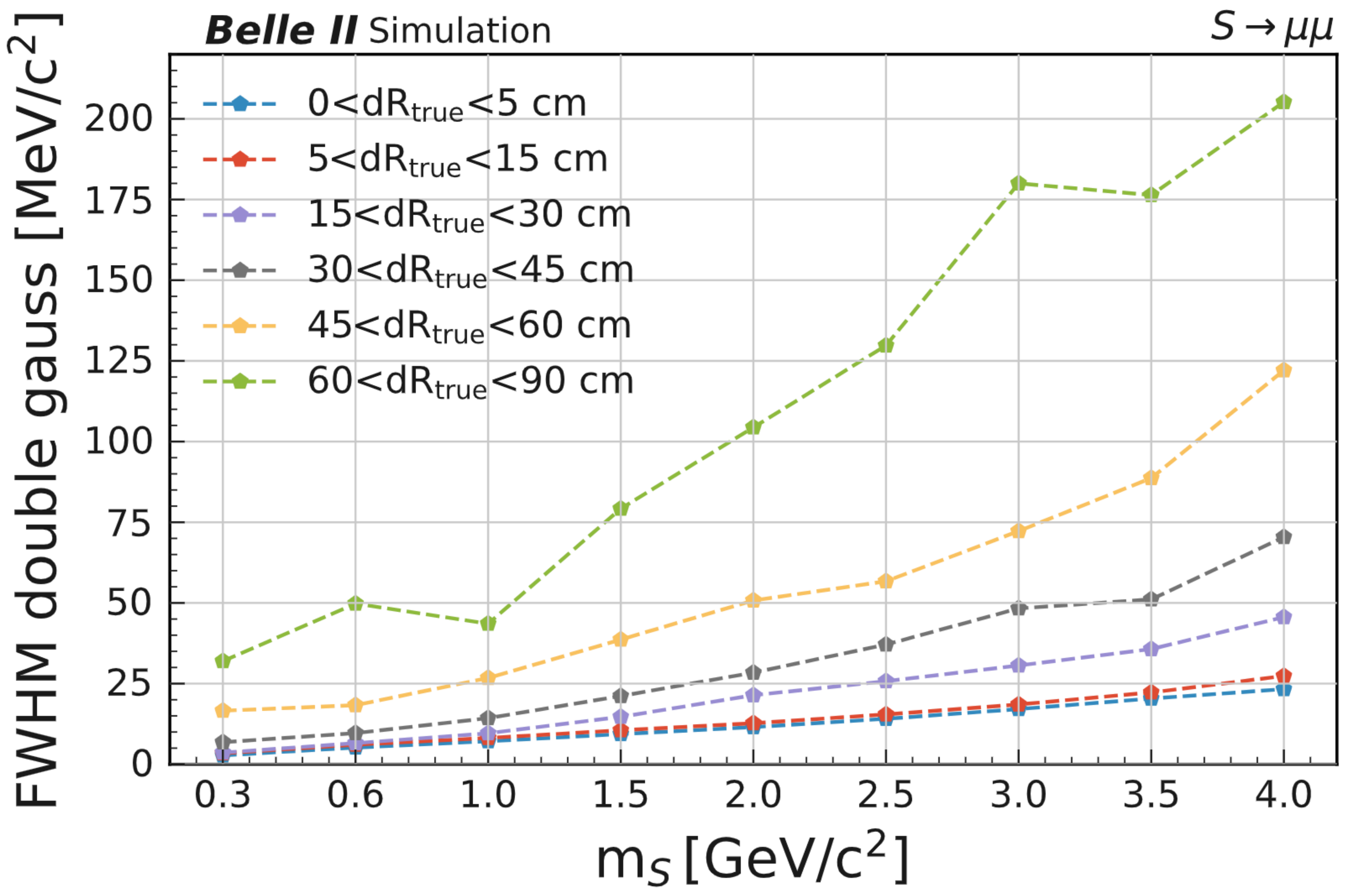




$B^+ \to K^+ S$

- Vertex reconstruction efficiency decreases with more displacement (shorter tracks)

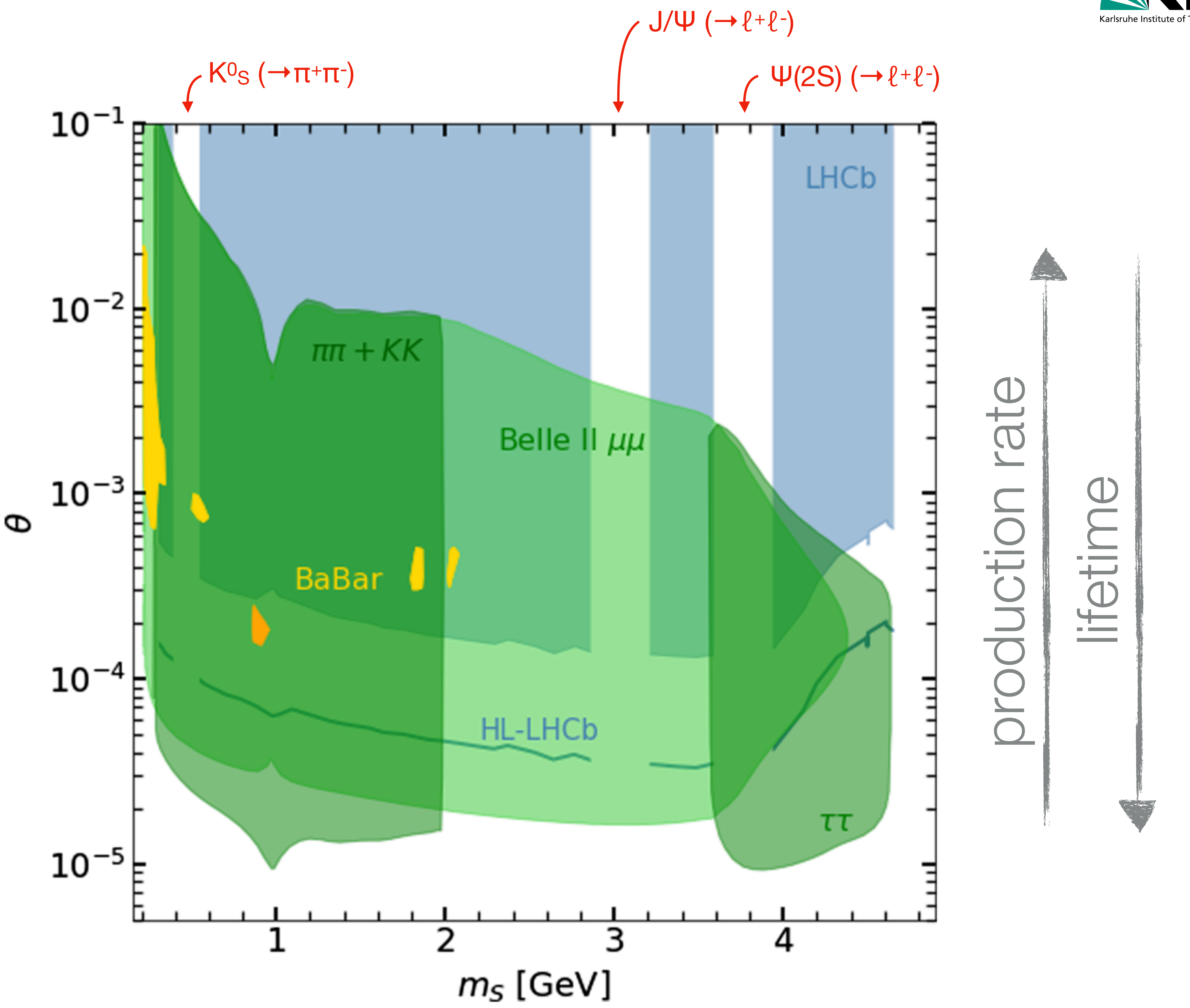




- Mass resolution increases with with more displacement

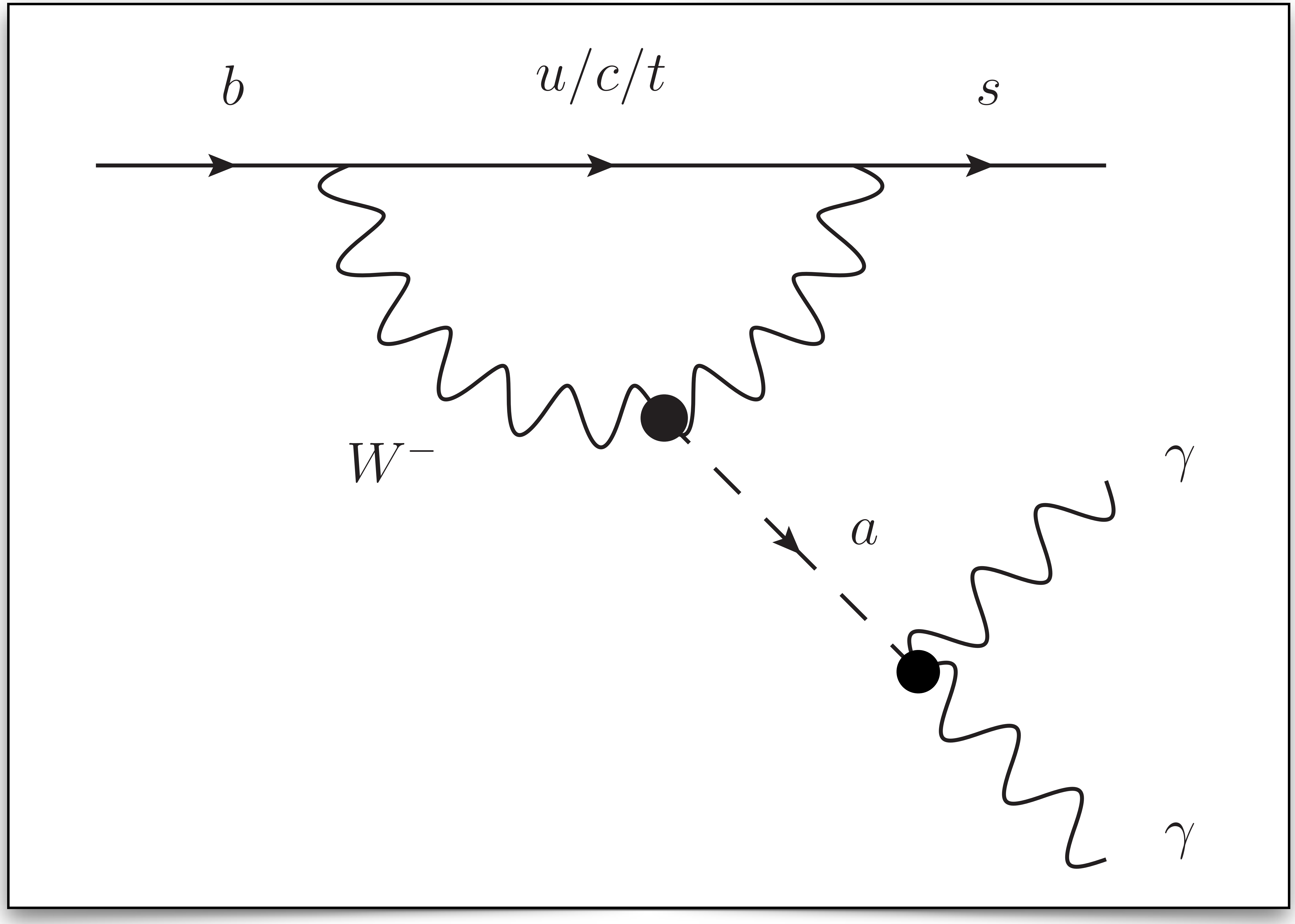
B→KS

- Standard model background very small for significant (>0.5cm) displacement
- Very optimistic assumptions in pheno studies…

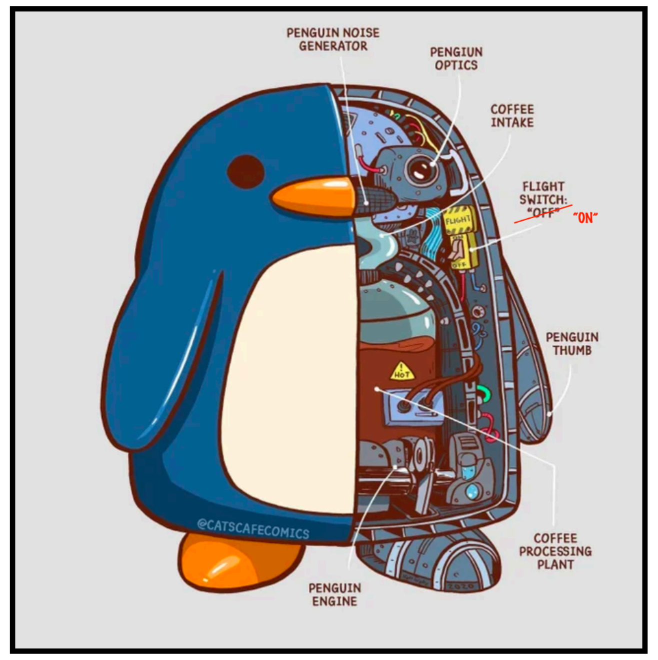


A. Filimonova, R. Schäfer, S. Westhoff, Phys. Rev. D 101, 095006 (2020)
A. Kachanovich, U. Nierste, I. Nišandžić, Eur.Phys.J.C 80 (2020)

B→Ka



b
$u/c/t$
s
W^-
a
γ
γ



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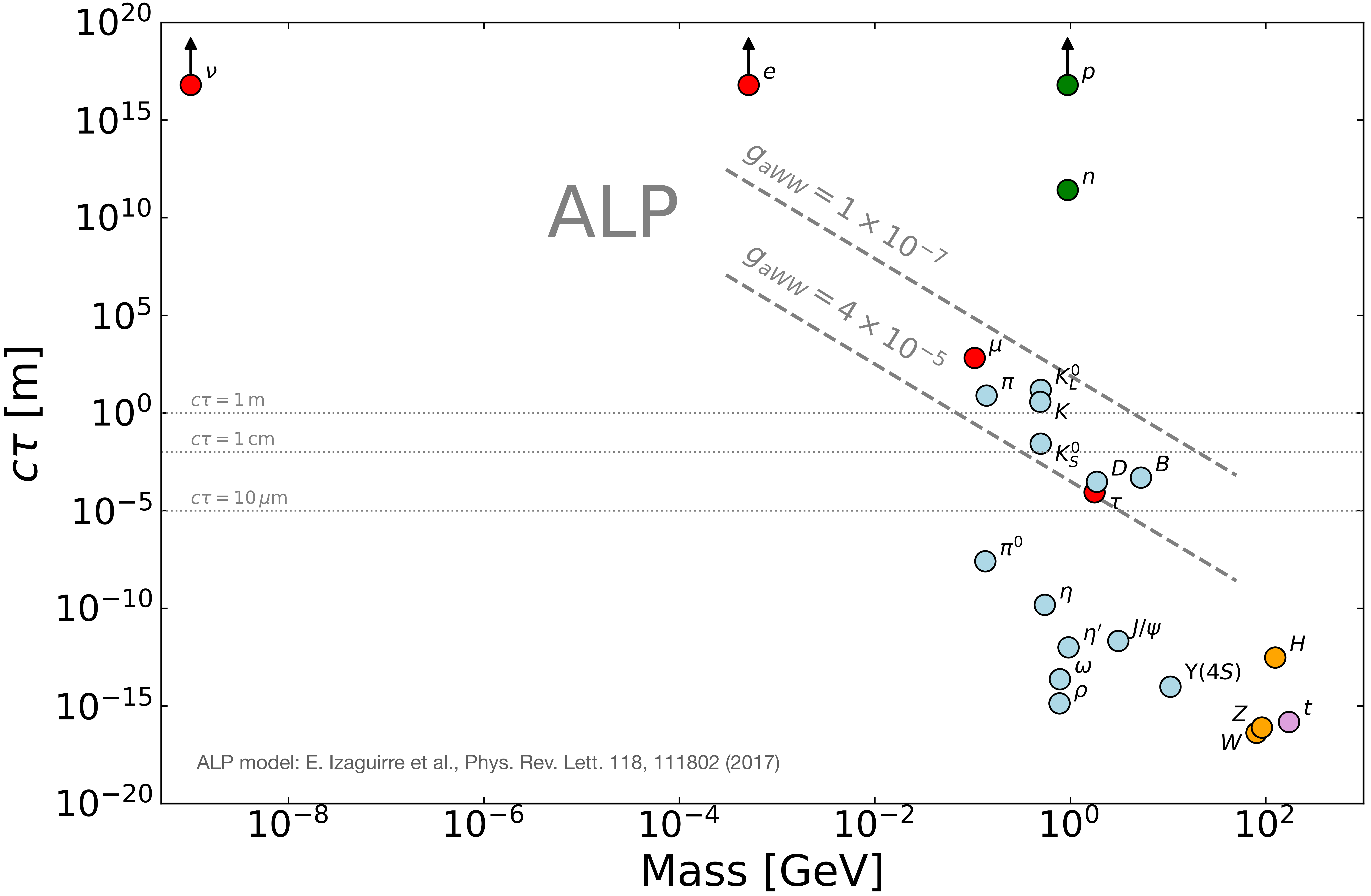
B→Ka



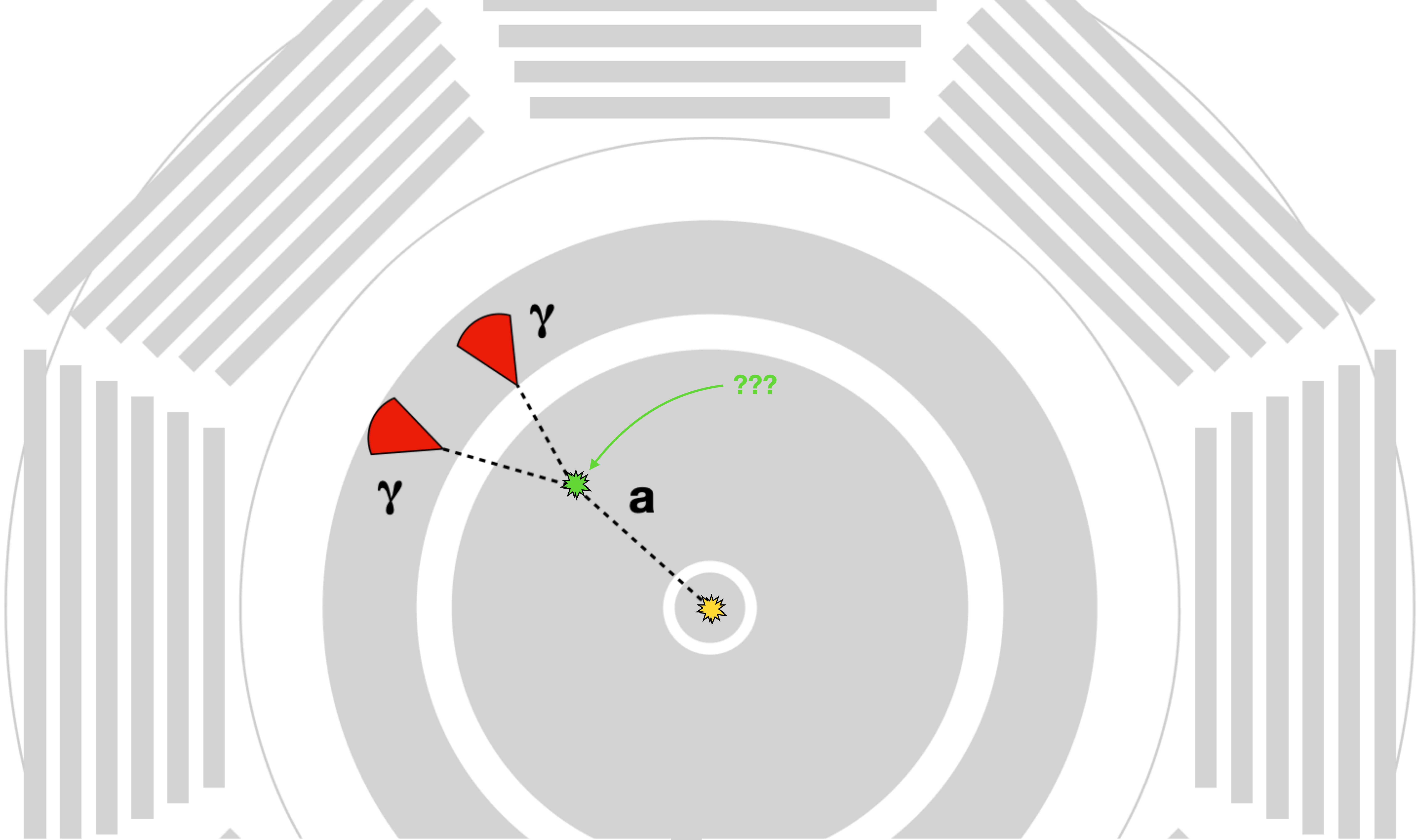
ALP
$g_{aWW} = 1 \times 10^{-7}$
$g_{aWW} = 4 \times 10^{-5}$
$c\tau = 1\,\mathrm{m}$
$c\tau = 1\,\mathrm{cm}$
$c\tau = 10\,\mu\mathrm{m}$
ν
e
p
n
μ
π
K_L^0
K
K_S^0
D
B
τ
π^0
η
η'
J/ψ
H
ω
ρ
$\Upsilon(4S)$
Z
W
t
ALP model: E. Izaguirre et al., Phys. Rev. Lett. 118, 111802 (2017)
$c\tau$ [m]
Mass [GeV]

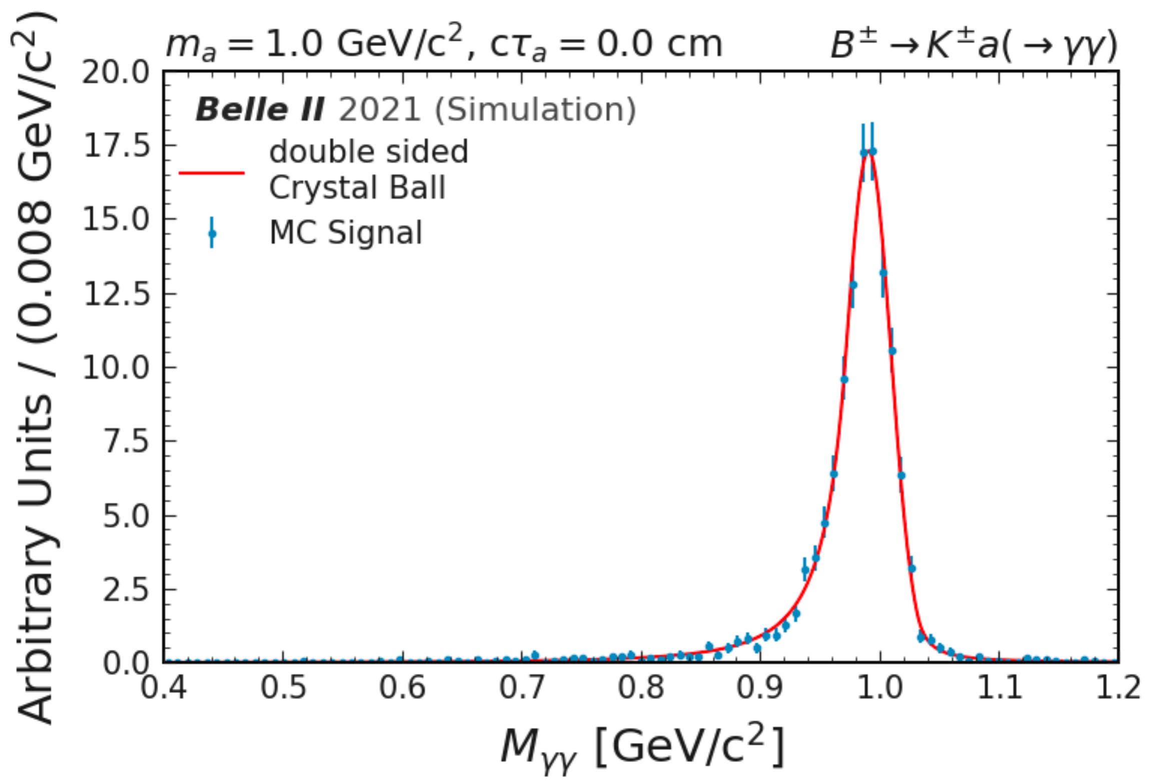
B→Ka

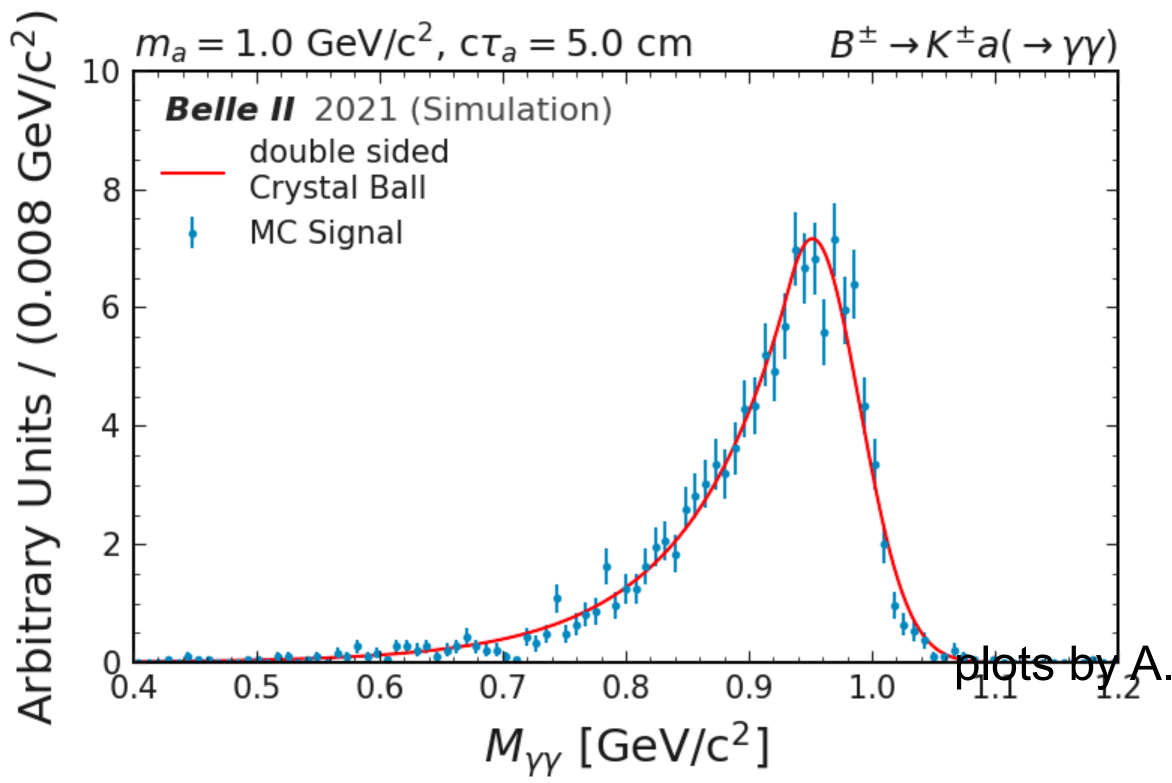
$$\Gamma(a \to \gamma\gamma) = \frac{g_{aW}^2 \sin^4\theta_\mathrm{W} M_a^3}{64\pi}$$

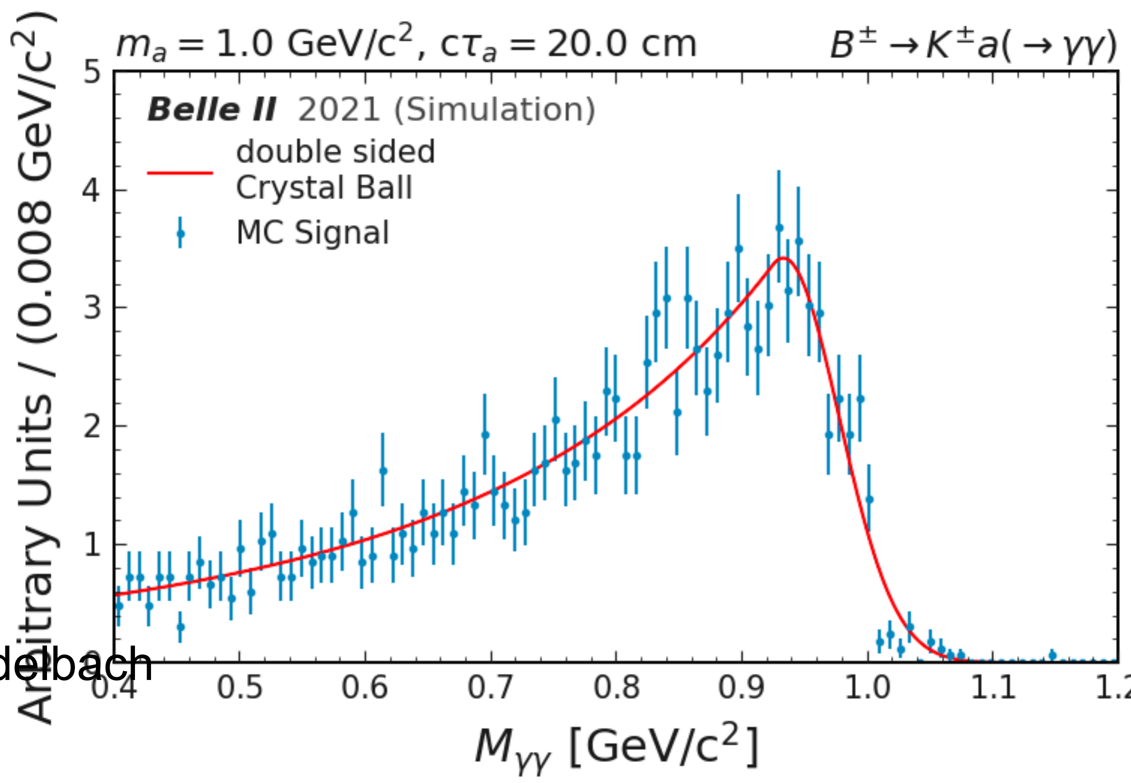
plots by A. Heidelbach

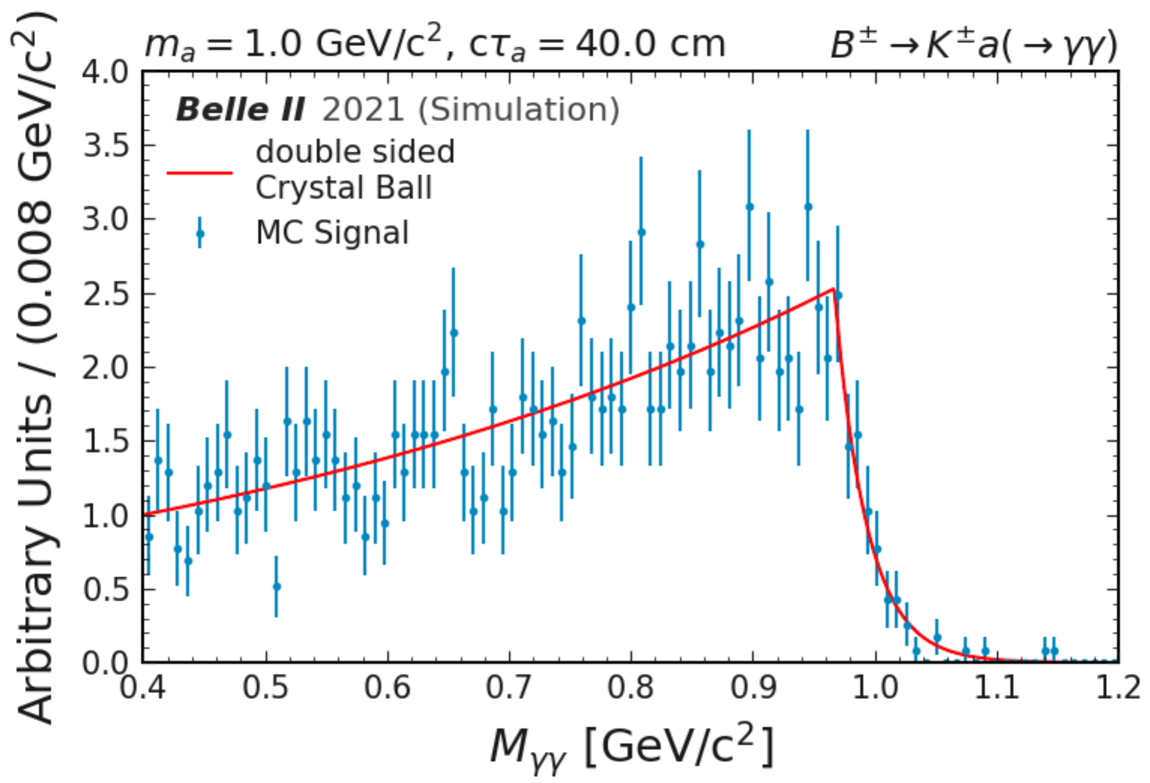
B→Ka





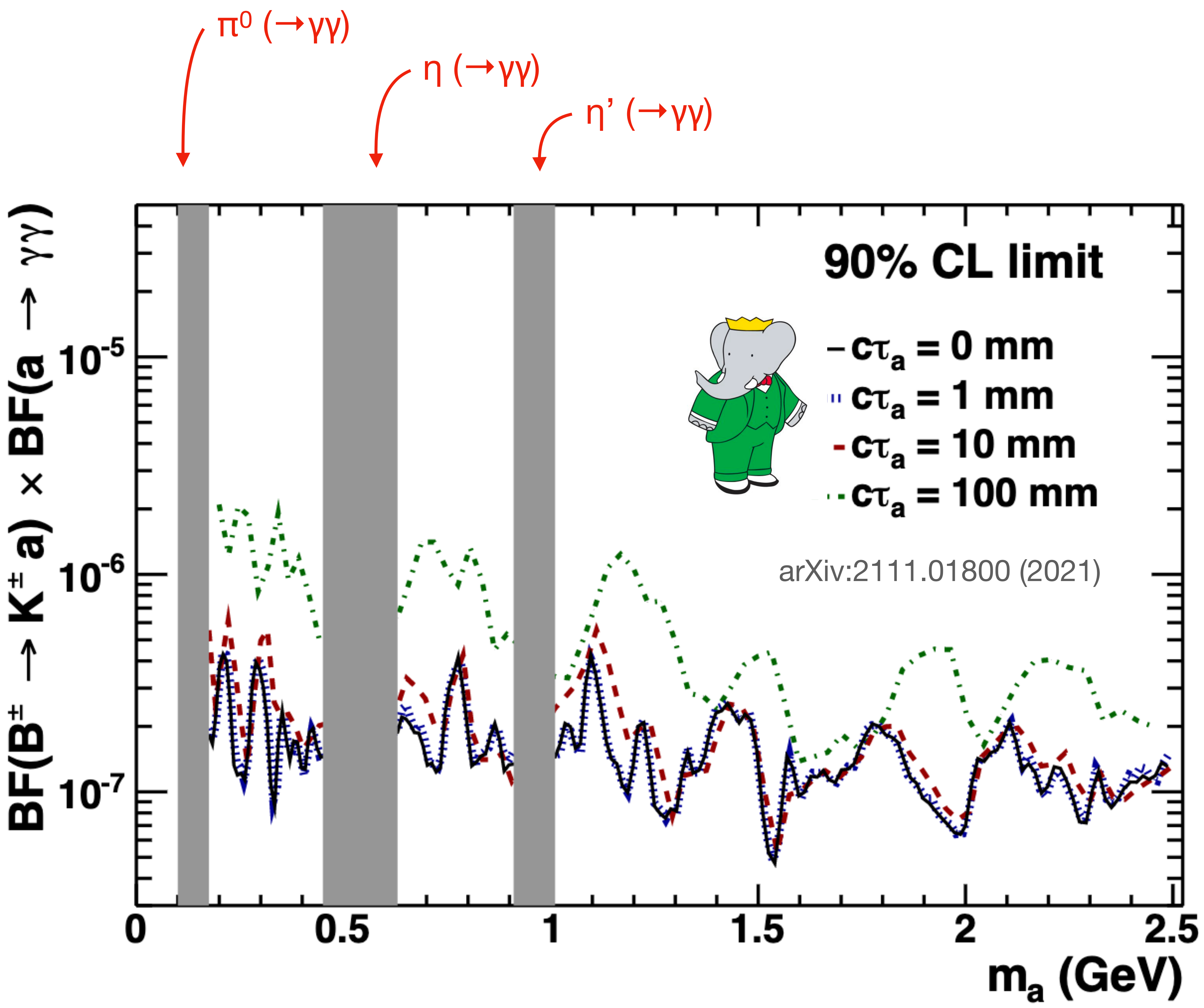




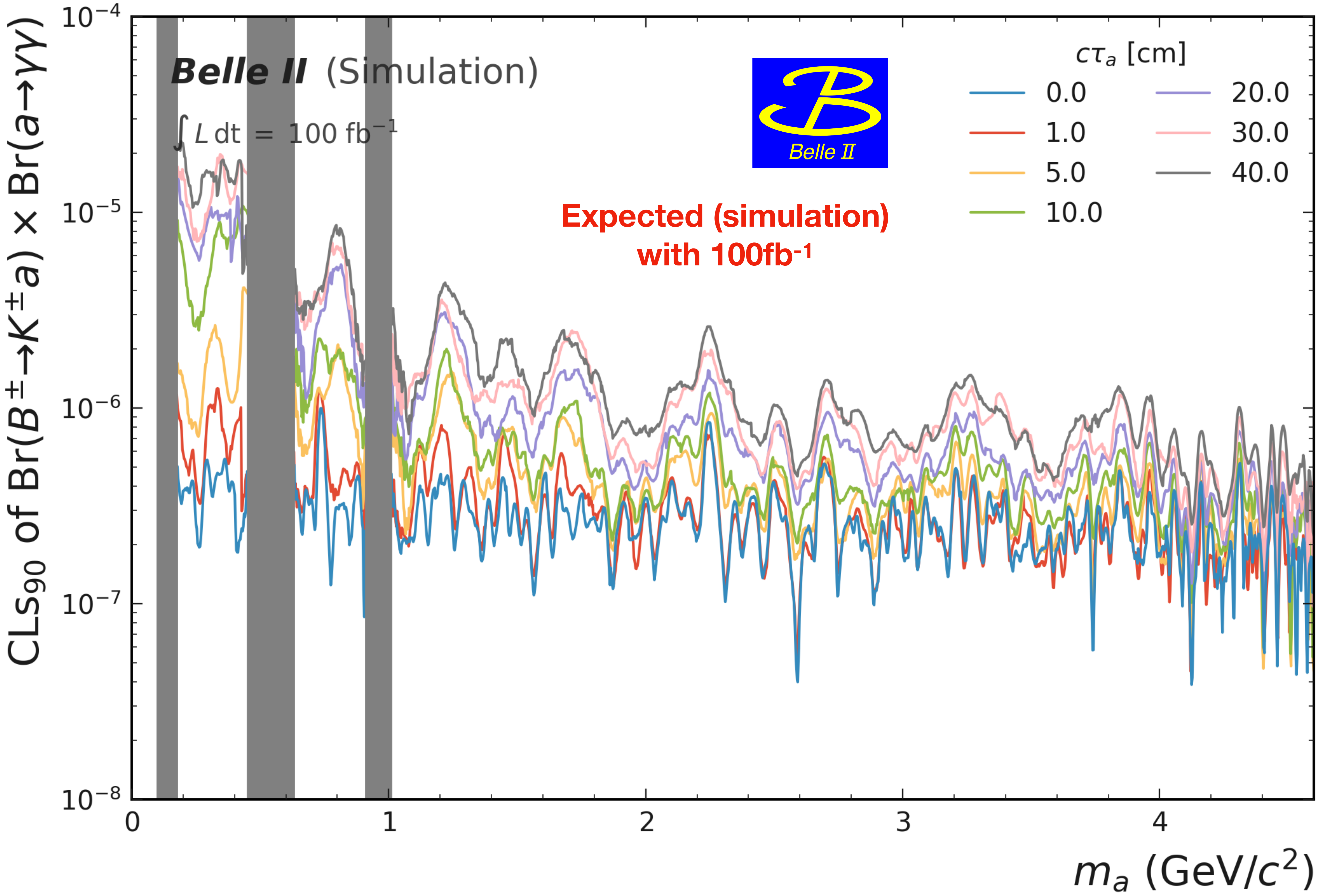


plots by A. Heidelbach

B→Ka



π0 (→γγ)
η (→γγ)
η’ (→γγ)
90% CL limit
cτa = 0 mm
cτa = 1 mm
cτa = 10 mm
cτa = 100 mm
arXiv:2111.01800 (2021)
BF(B± → K± a) × BF(a → γγ)
ma (GeV)

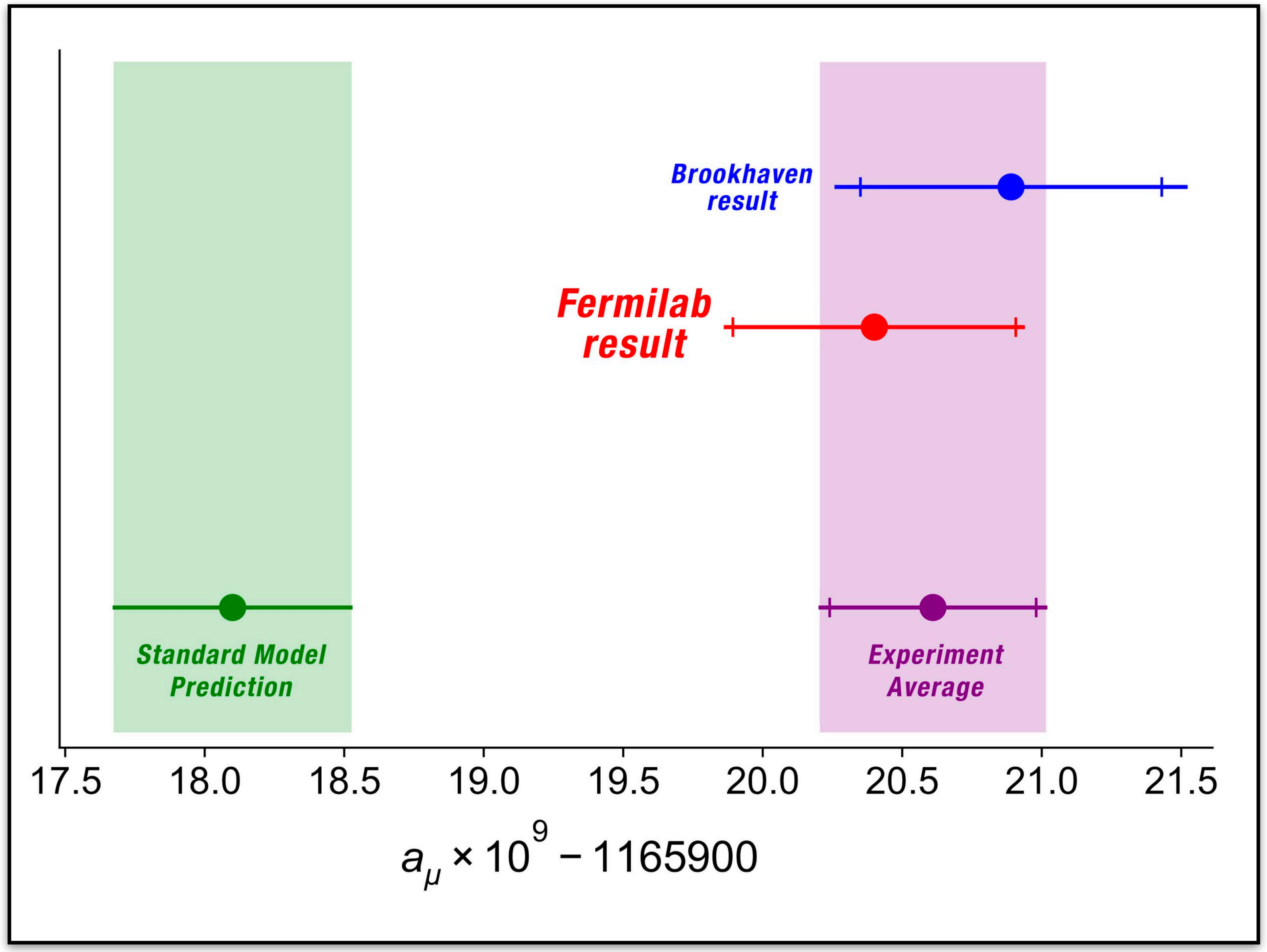


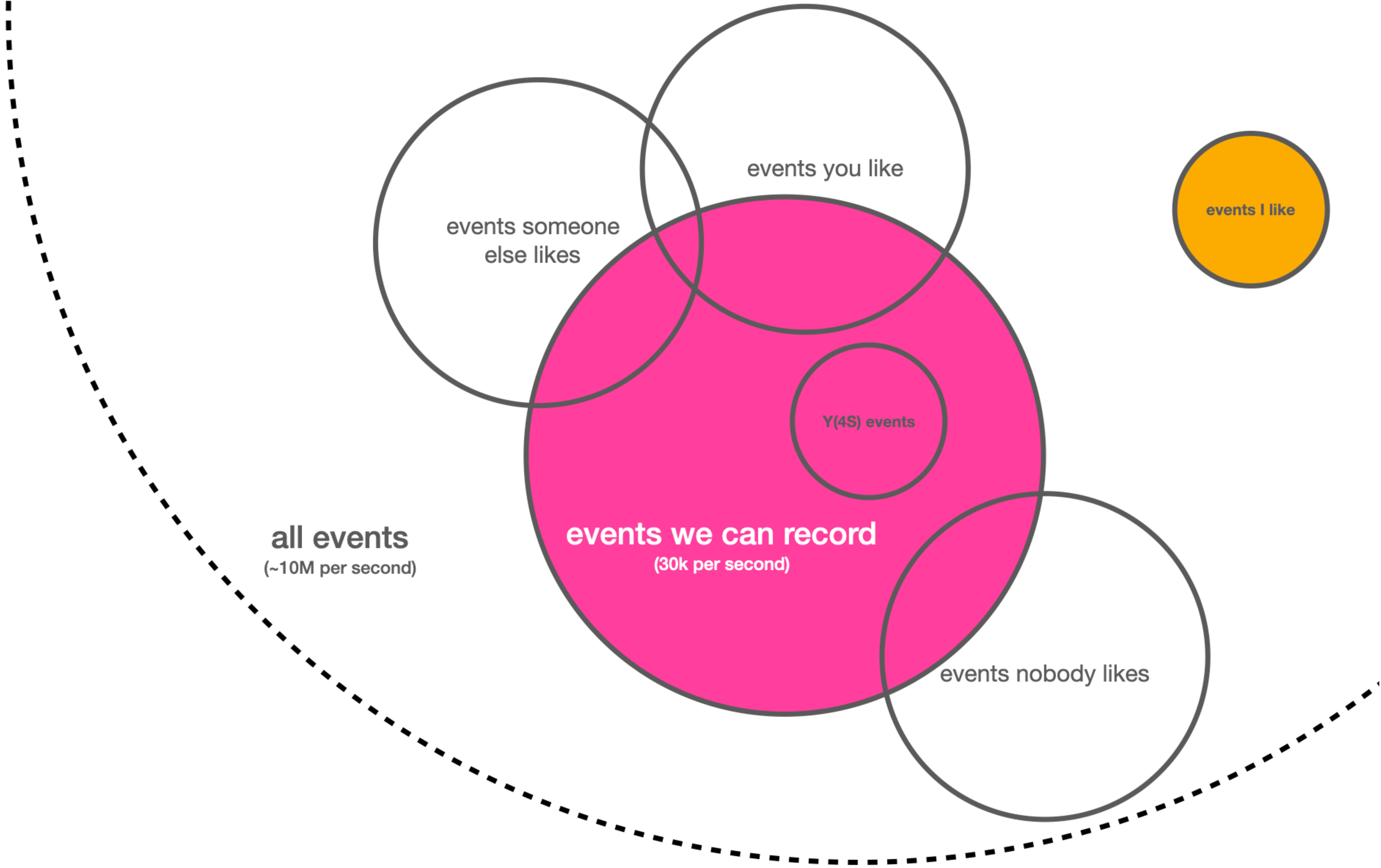
Belle II (Simulation)
∫L dt = 100 fb−1
Belle II
cτa [cm]
0.0
1.0
5.0
10.0
20.0
30.0
40.0
Expected (simulation)
with 100fb-1
CLs90 of Br(B±→K±a) × Br(a→γγ)
ma (GeV/c2)

Effect of longer lifetime: It is difficult!

performance compared to prompt	$B \to KS(\to \mu\mu)$	$B \to Ka(\to \gamma\gamma)$	$A' \to ee$
Efficiency*	worse	constant	worse
Resolution	slightly worse	much worse	slightly worse
Background	much smaller	constant	it depends…

This is just the beginning…



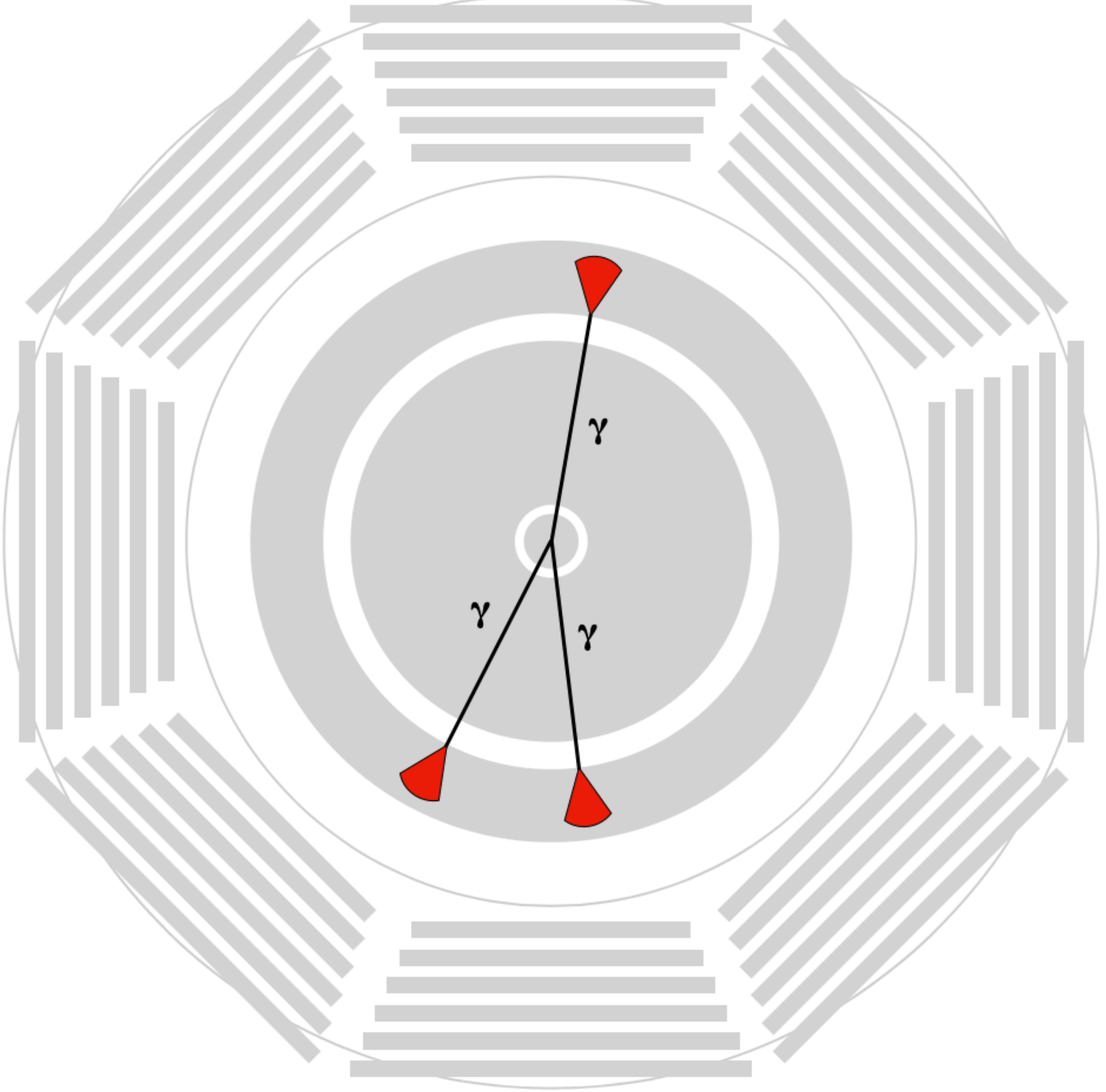


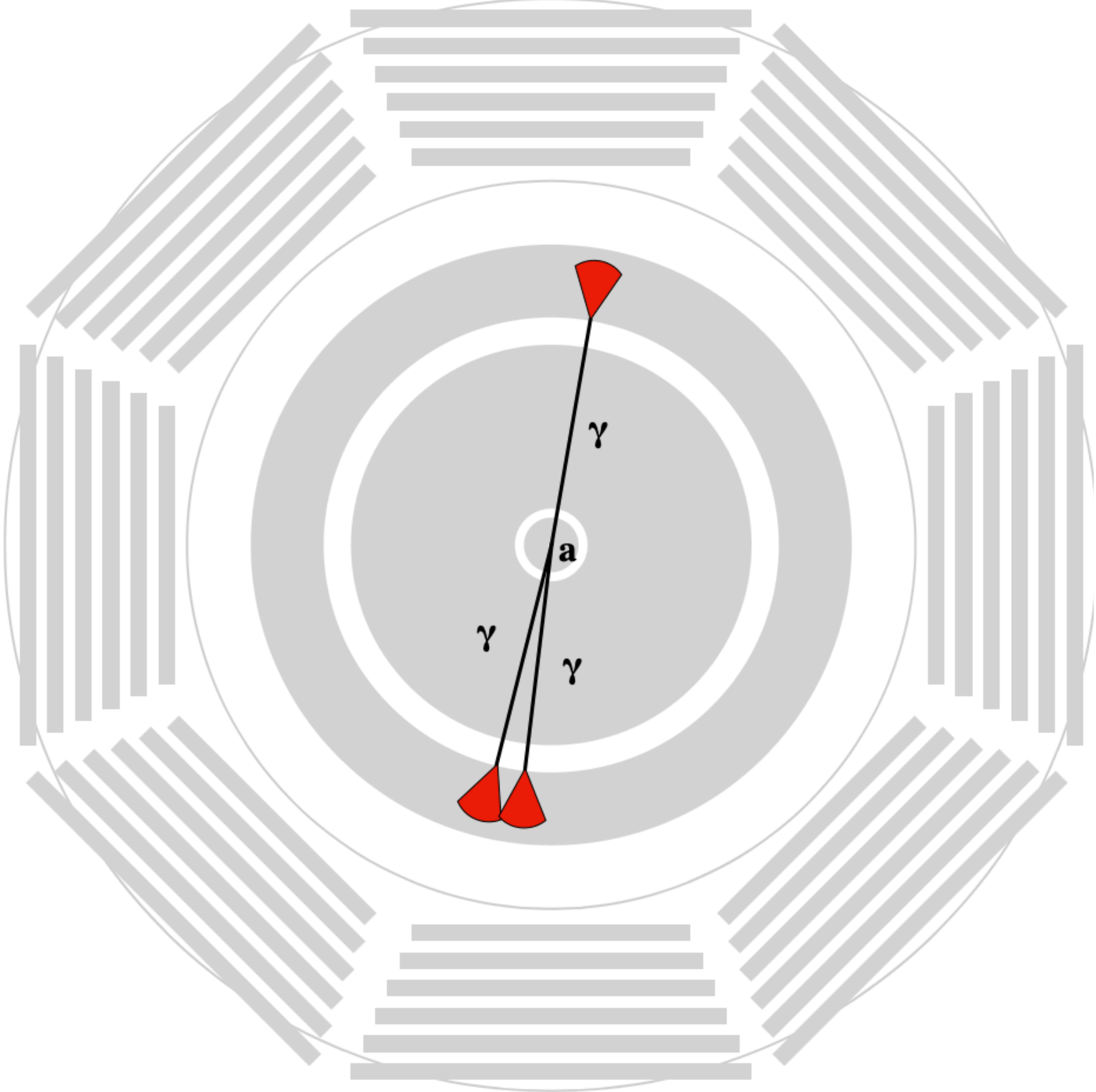
Backup

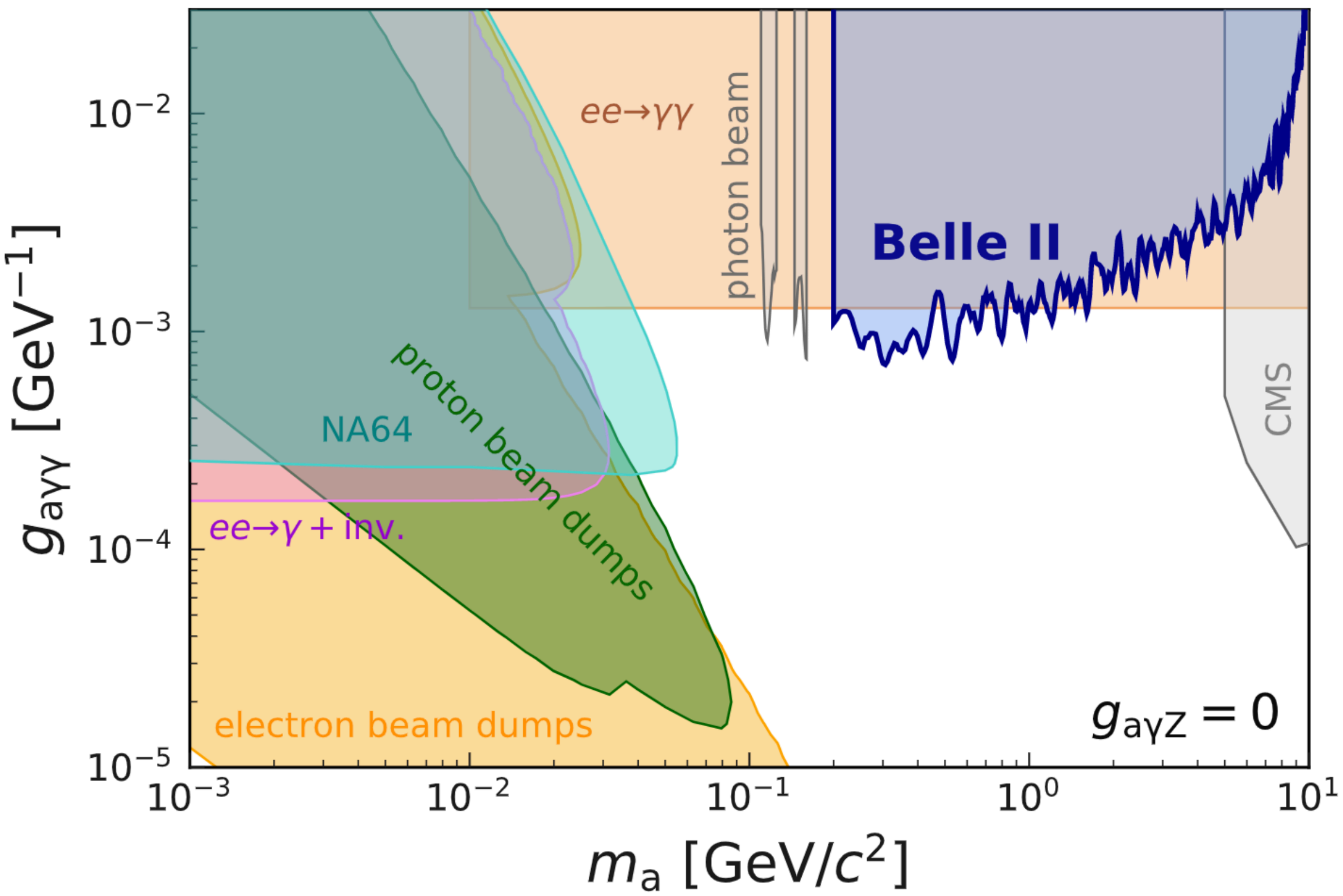
Upgrade

Subdector	Function	upgrade idea	time scale
PXD	Vertex Detector	2 layer installation	short-term
		new DEPFET	medium-term
SVD	Vertex Detector	thin, double-sided strips, w/ new frontend	medium-term
PXD+SVD	Vertex Detector	all-pixels: SOI sensors	medium-term
		all-pixels: DMAPS CMOS sensors	medium-term
CDC	Tracking	upgrade front end electronics	short/medium-term
		replace inner part with silicon	medium/long term
		replace with TPC w/ MPGD readout	long-term
TOP	PID, barrel	Replace conventional MCP-PMTs	short-term
		Replace not-life-extended ALD MCP-PMTs	medium-term
		STOPGAP TOF and timing detector	long-term
ARICH	PID, forward	replace HAPD with Silicon PhotoMultipliers	long-term
		replace HAPD with Large Area Picosecond Photodetectors	long-term
ECL	γ, e ID	add pre-shower detector in front of ECL	long-term
		Replace ECL PiN diodes with APDs	long-term
		Replace CsI(Tl) with pure CsI crystals	long-term
KLM	K_L, μ ID	replace 13 barrel layers of legacy RPCs with scintillators	medium/long-term
		on-detector upgraded scintillator readout	medium/long-term
		timing upgrade for K-long momentum measurement	medium/long-term
Trigger		firmware improvements	continuos
DAQ		PCIe40 readout upgrade	ongoing
		add 1300-1900 cores to HLT	short/medium-term

ALPs

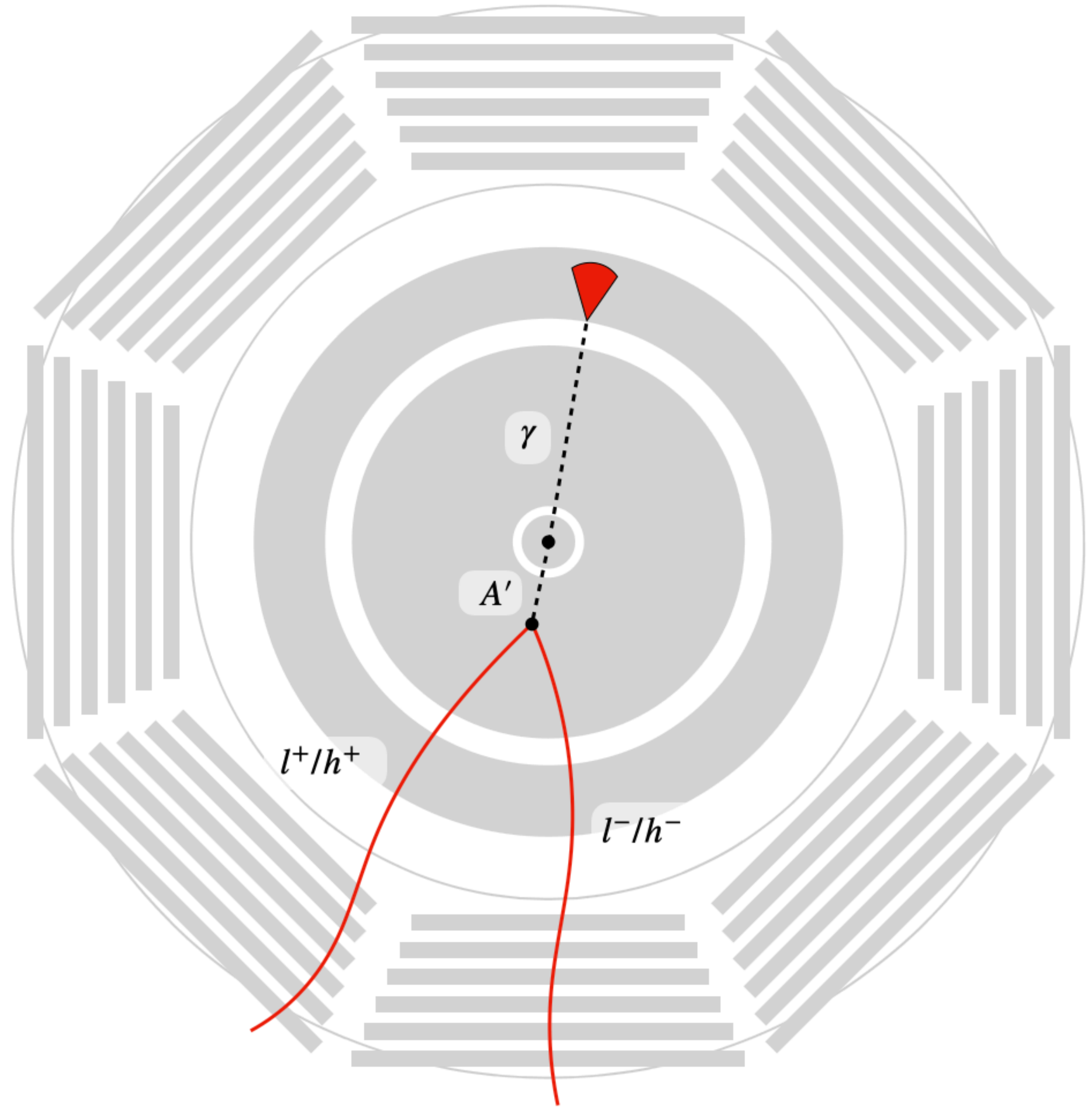


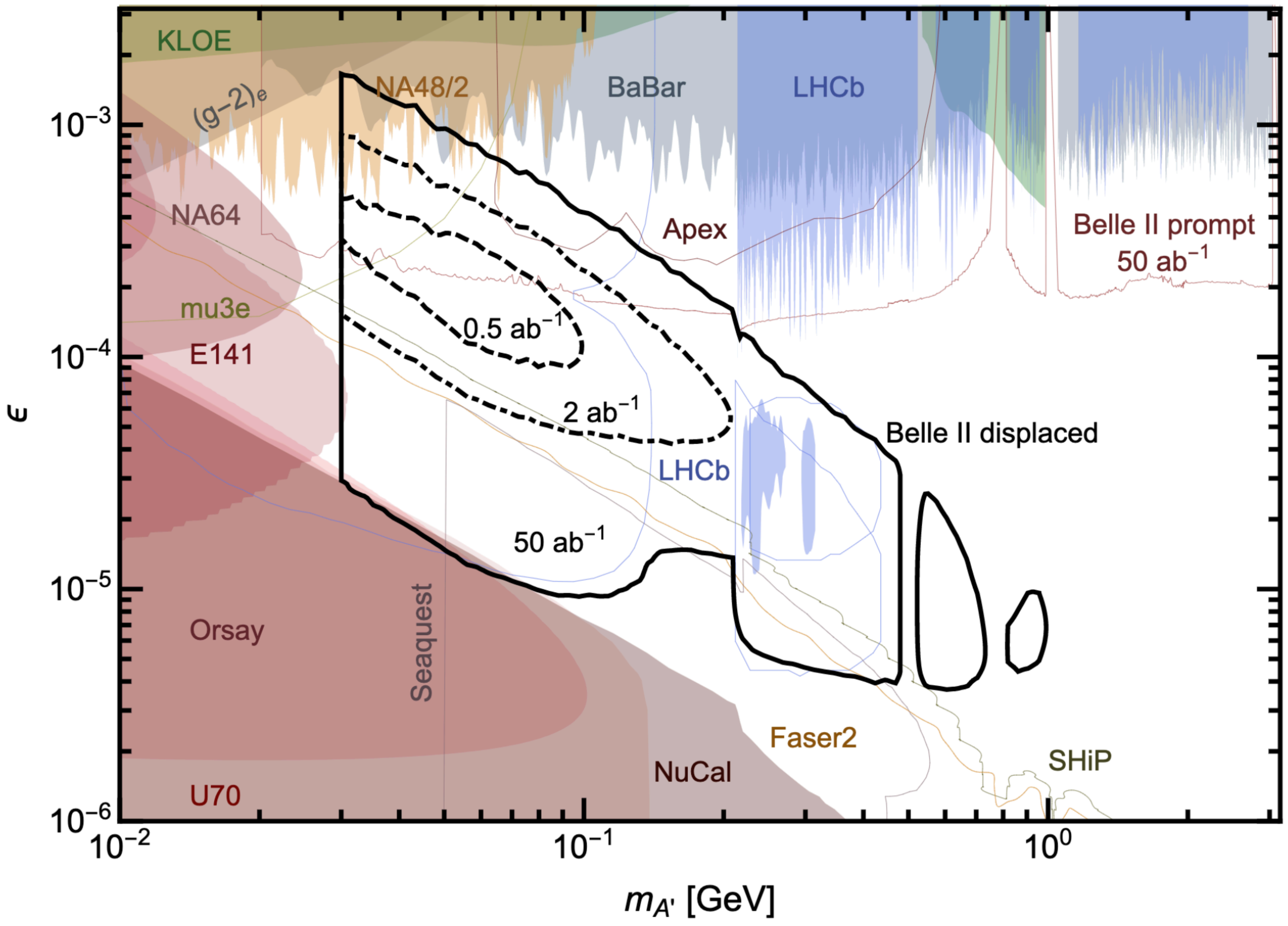




https://arxiv.org/abs/2007.13071

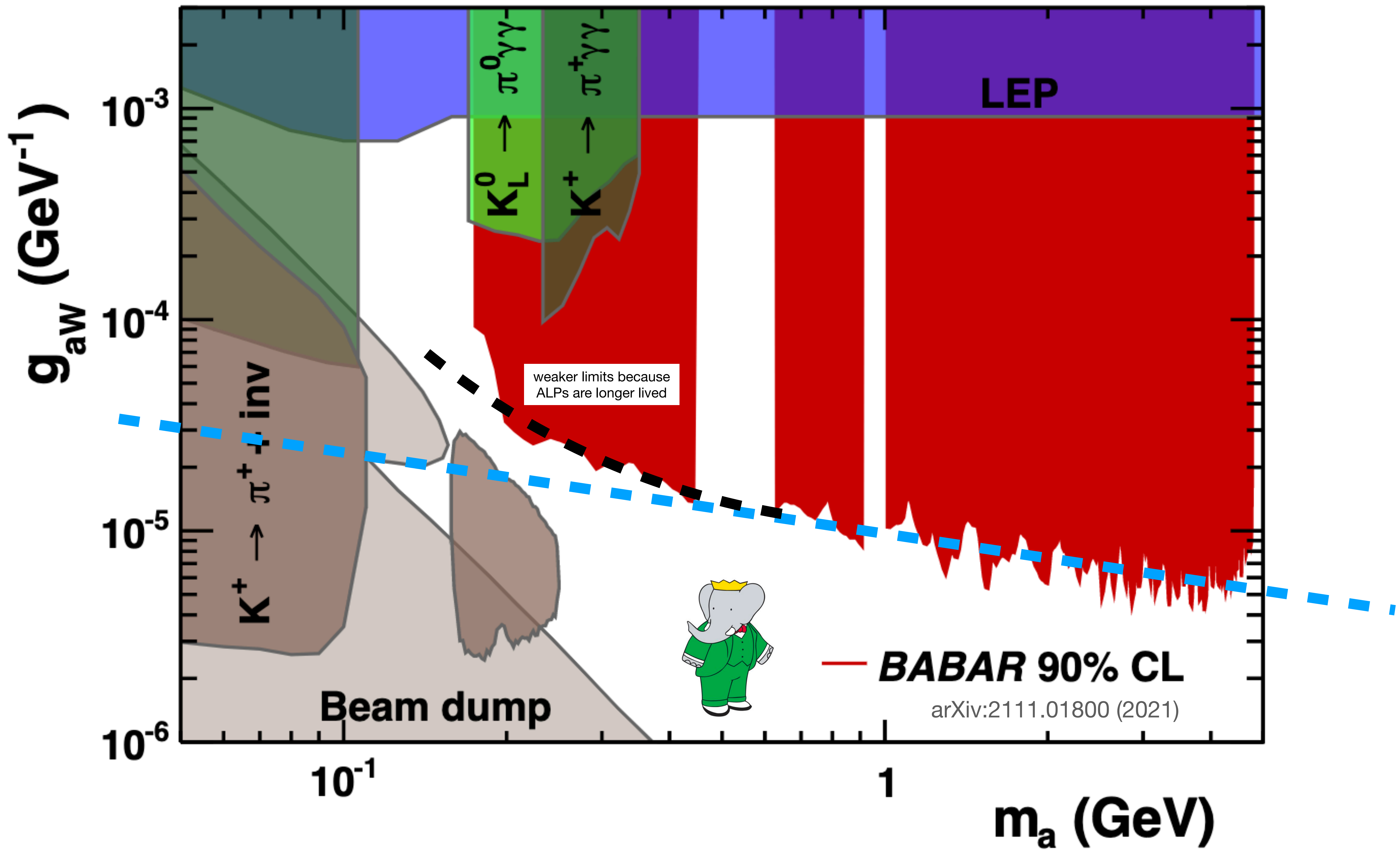
Dark Photons





https://arxiv.org/abs/2202.03452

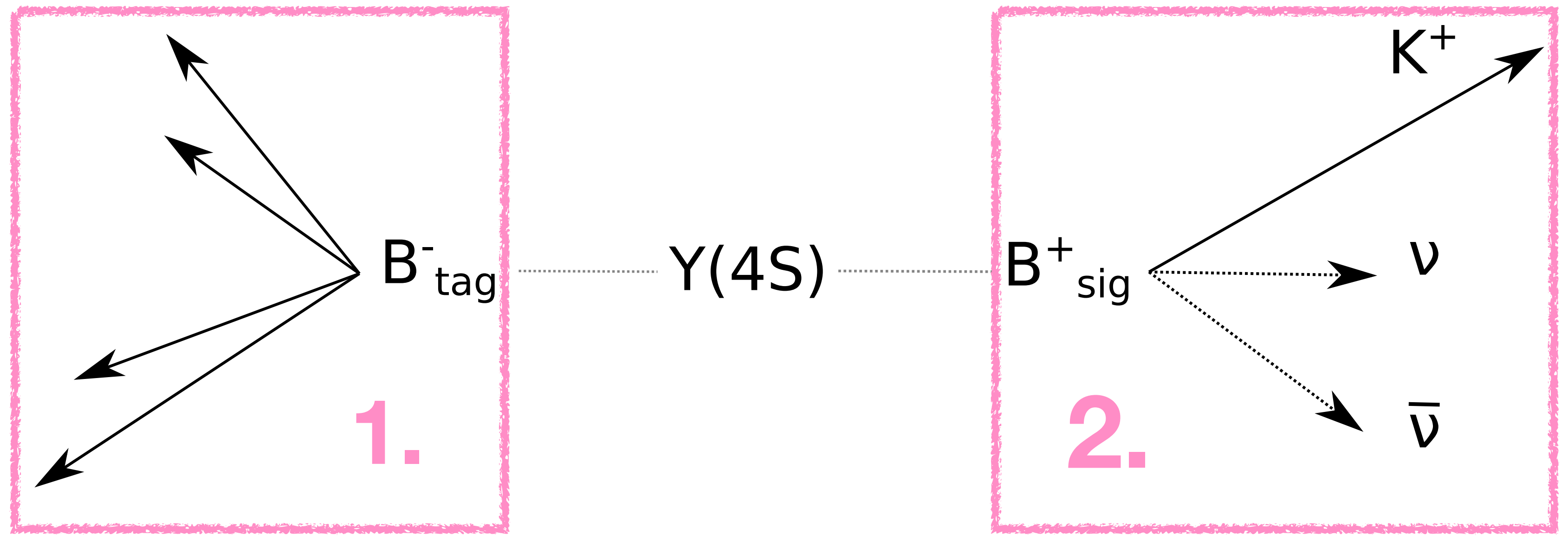
B→Ka


LEP
$K^0_L \to \pi^0\gamma\gamma$
$K^+ \to \pi^+\gamma\gamma$
$K^+ \to \pi^+ + inv$
Beam dump
weaker limits because ALPs are longer lived
BABAR 90% CL
arXiv:2111.01800 (2021)
g_{aW} (GeV^{-1})
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-1}
1
m_a (GeV)

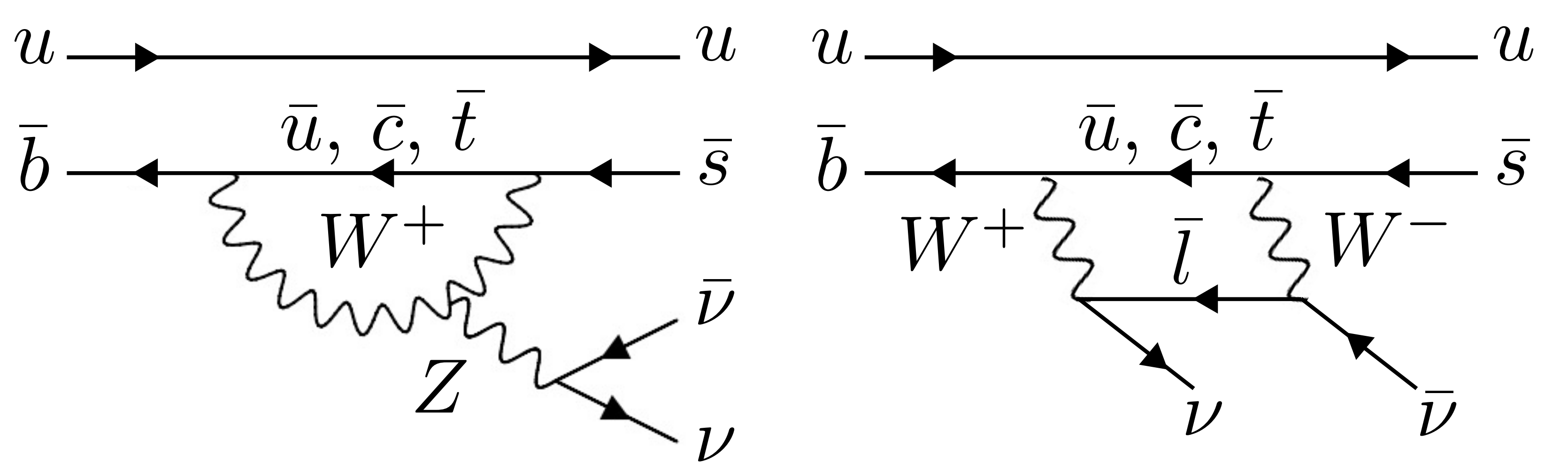
$B \to K\nu\nu$

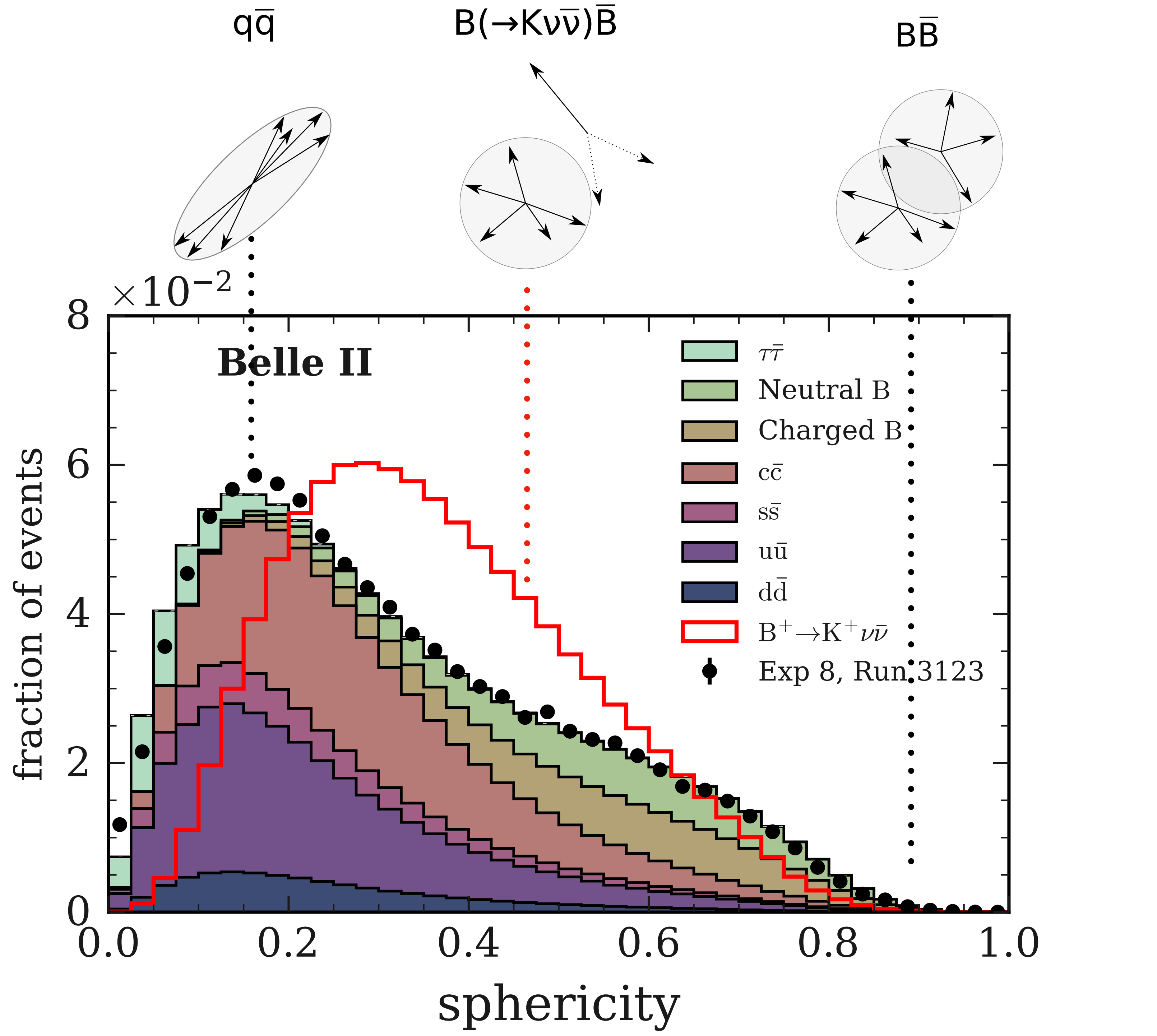
T. Blake et al, Prog.Part.Nucl.Phys. 92 (2017)
BaBar collaboration, Phys. Rev. D 87, 112005 (2013)
Belle II collaboration, Phys. Rev. Lett. 127, 181802 (2021)

- Branching rate prediction: BR=$(4.6\pm0.5)\times10^{-6}$
- So far, only upper limits measured using fully reconstructed B_{tag} (ε~0.04-0.2 %): BR < 1.6×10^{-5} (90 % CL) with 424 fb^{-1}



- Belle II used a "inclusive tag" and several boosted decision trees (ε=4.3 %): BR < 4.1×10^{-5} (90 % CL) with 63 fb^{-1}





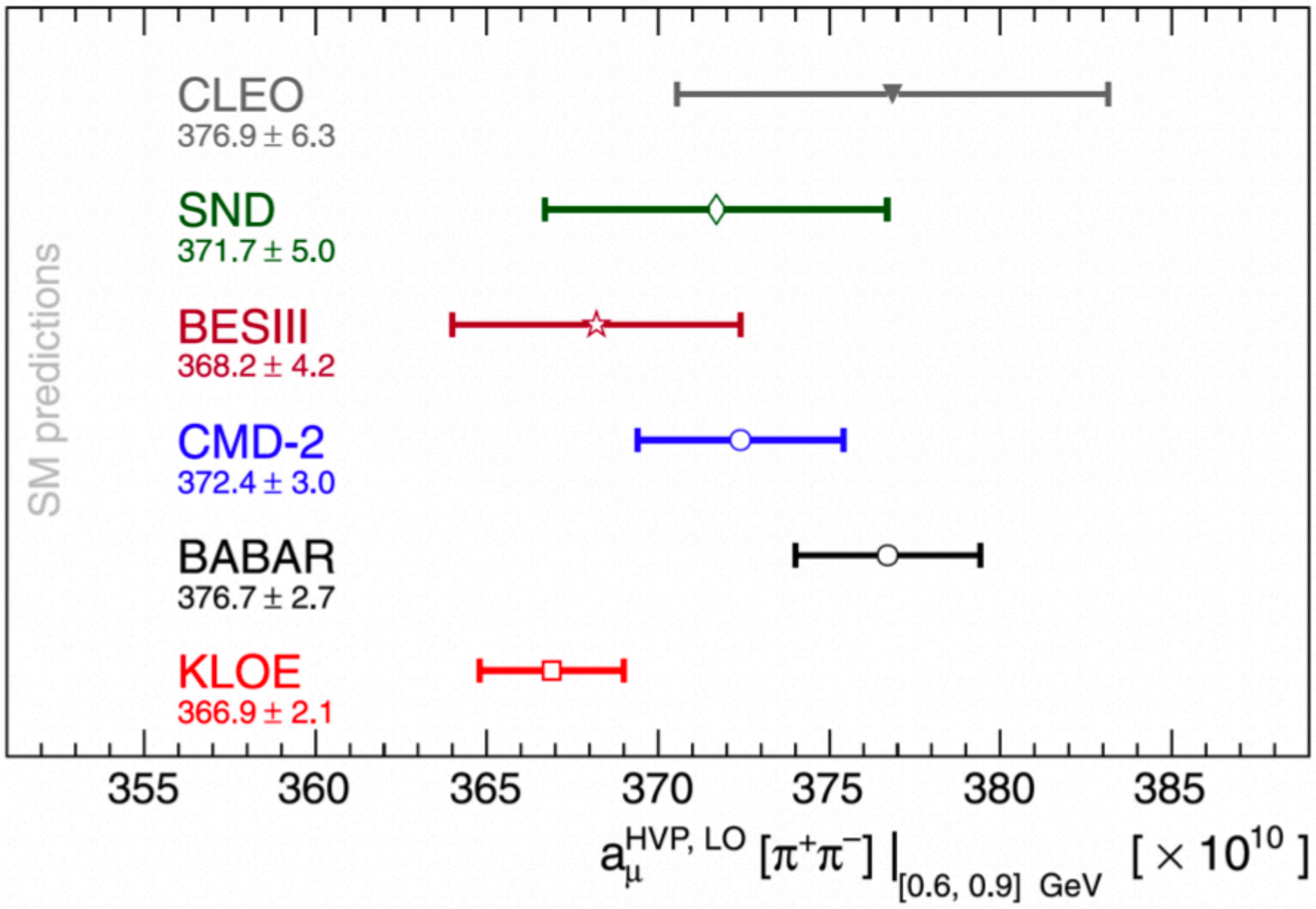
plots by S. Stefkova

SuperKEKB parameters

LER / HER	KEKB	SuperKEKB	Effect
Energy [GeV]	3.5 / 8	4.0 / 7.0	**boost x 2/3**
Crossing angle $2\phi_x$ [mrad]	22	**83**	
β_y^* [mm]	5.9 / 5.9	**0.27 / 0.30**	**L x 20**
$I_\pm$ [A]	1.64 / 1.19	**2.8 / 2.0**	**L x ~1.5**
$\varepsilon_y = \sigma_y \times \sigma_{y'}$ [pm]	140 / 140	**13 / 16**	
$\xi_y \sim (\beta_y^*/\varepsilon_y)^{1/2} / \sigma^*_x$	0.129 / 0.09	**0.09 / 0.09**	**L x 1**
Luminosity [10^{34} cm^{-2} s^{-1}]	2.1	**60**	**L x 30**

Backup g-2

T. Aoyama et al. (2020). Phys. Rept., 887:1–166



CsI and CsI(Tl) pulse-shape discrimination