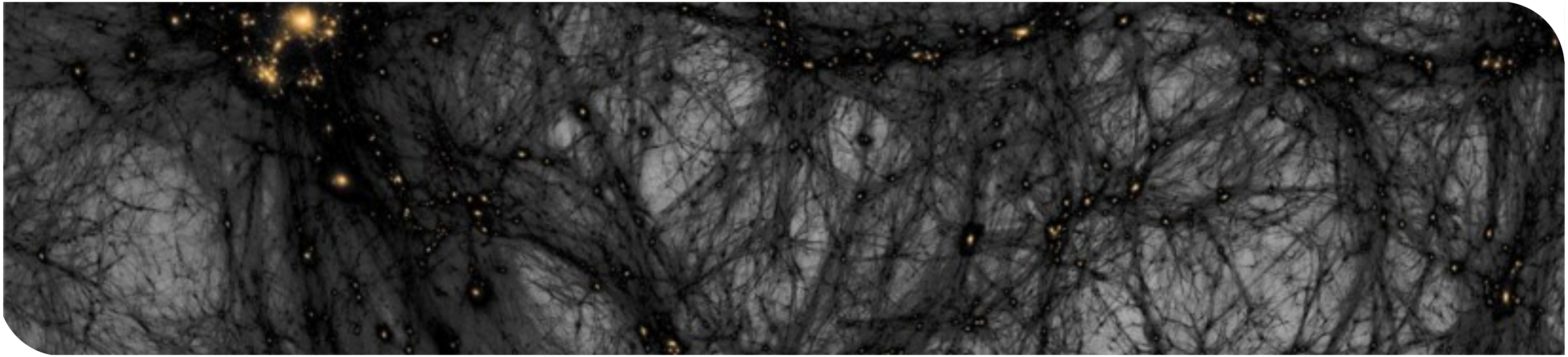
Karlsruher Institut für Technologie

Institut für Experimentelle Teilchenphysik

Dark sectors at flavour experiments

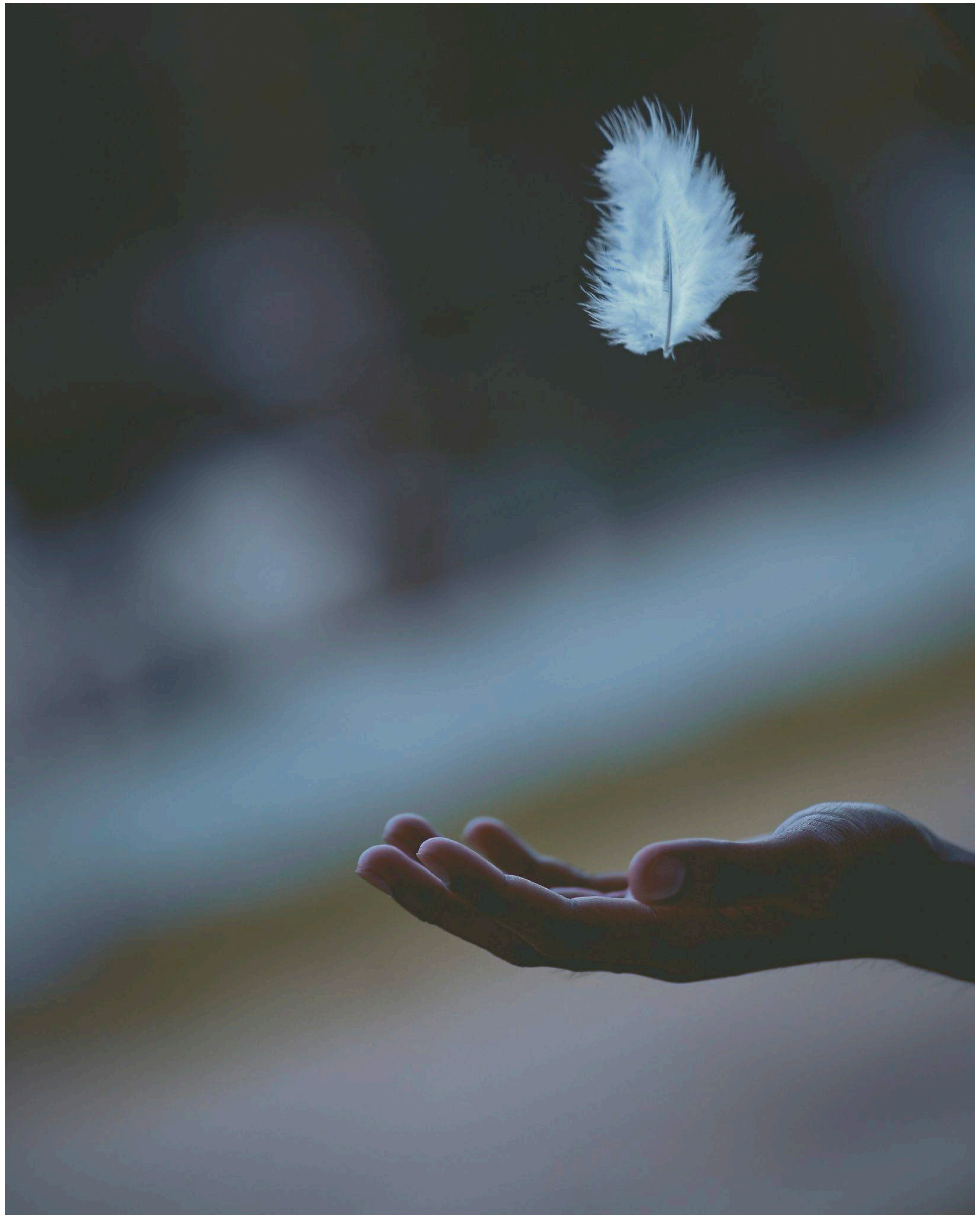
FPCP, Lyon, 02.06.2023

Torben Ferber (torben.ferber@kit.edu, he/him) on behalf of Belle II, BaBar, NA62 and BESIII
Institute of Experimental Particle Physics (ETP)

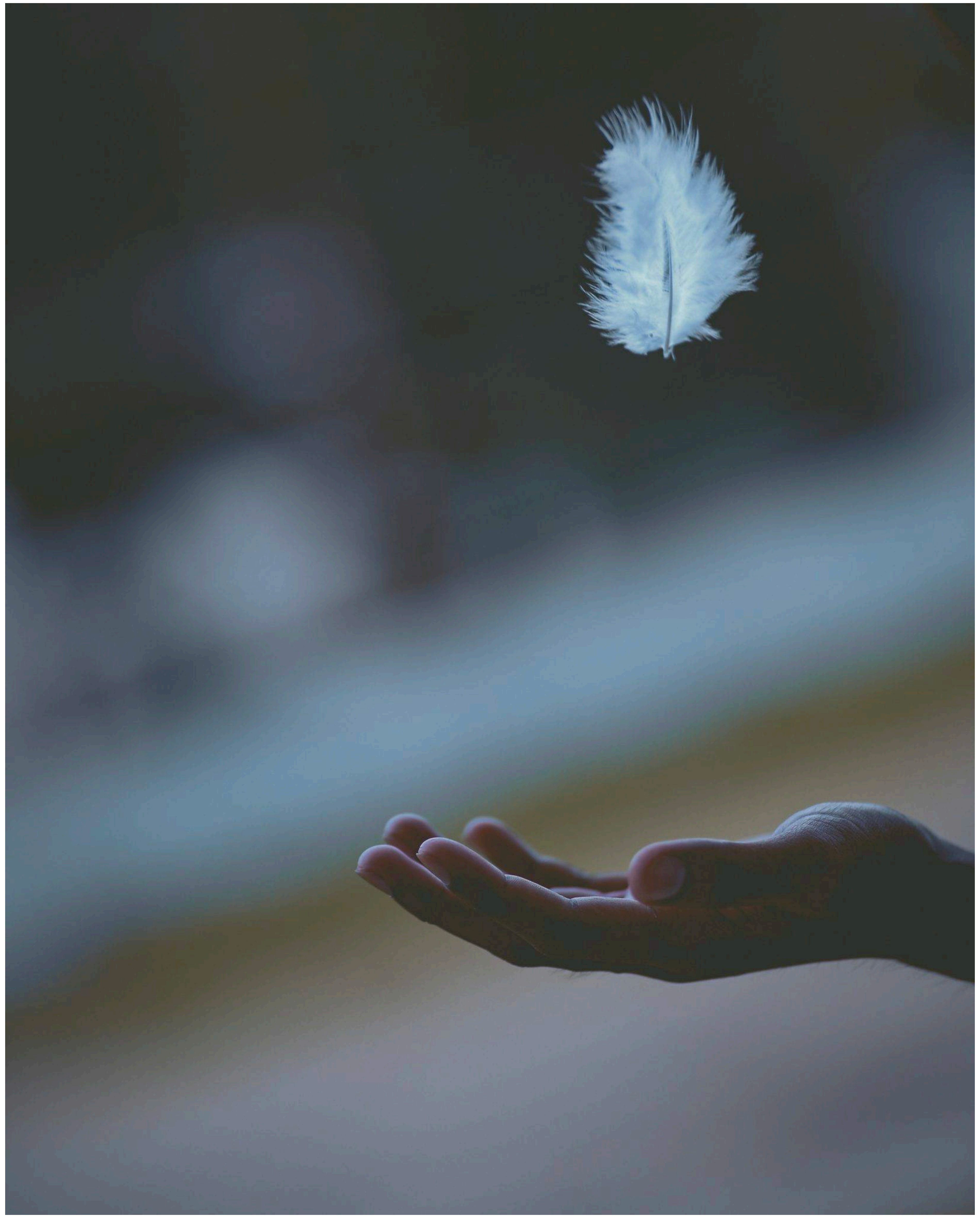


Introduction

"I shall not today attempt further to define the kinds of material, but I know it when I see it." (P. Stewart)



Introduction



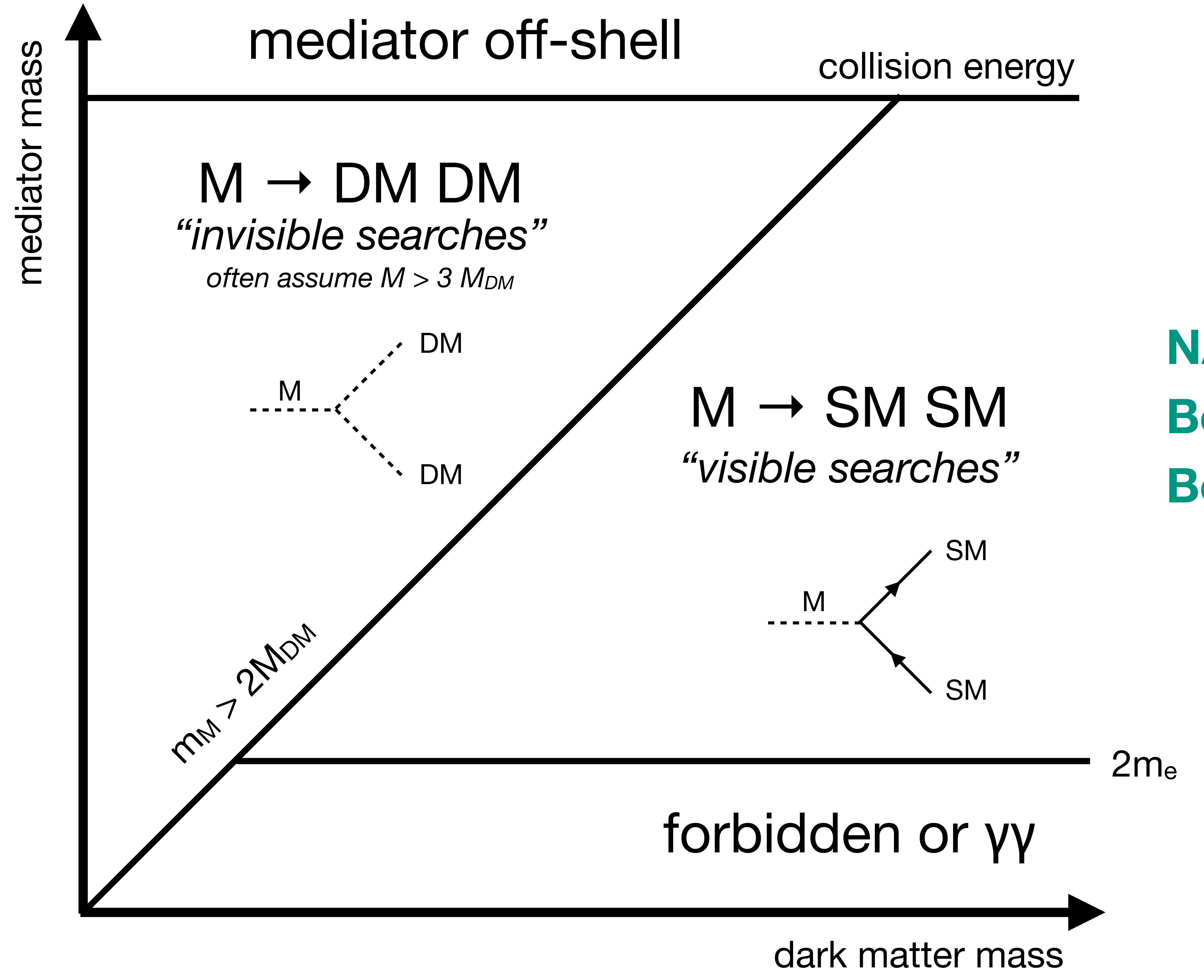
- Not excluded (or discovered) yet
- "Light", typically less than 10 GeV
- Very small coupling "<<< 1"
  - not charged under SM strong force
  - some parameter space has interactions stronger than the SM weak force
- Often provide viable (often long-lived) mediators to the dark sector
- Sometimes provide viable dark matter candidates

BES III $e^+e^- \to \gamma A'(\to \chi\chi)$

Belle II $e^+e^- \to \mu^+\mu^- Z'(\to \chi\chi)$

BaBar $B \to \psi_D \Lambda$

BaBar $B \to \psi_D p$



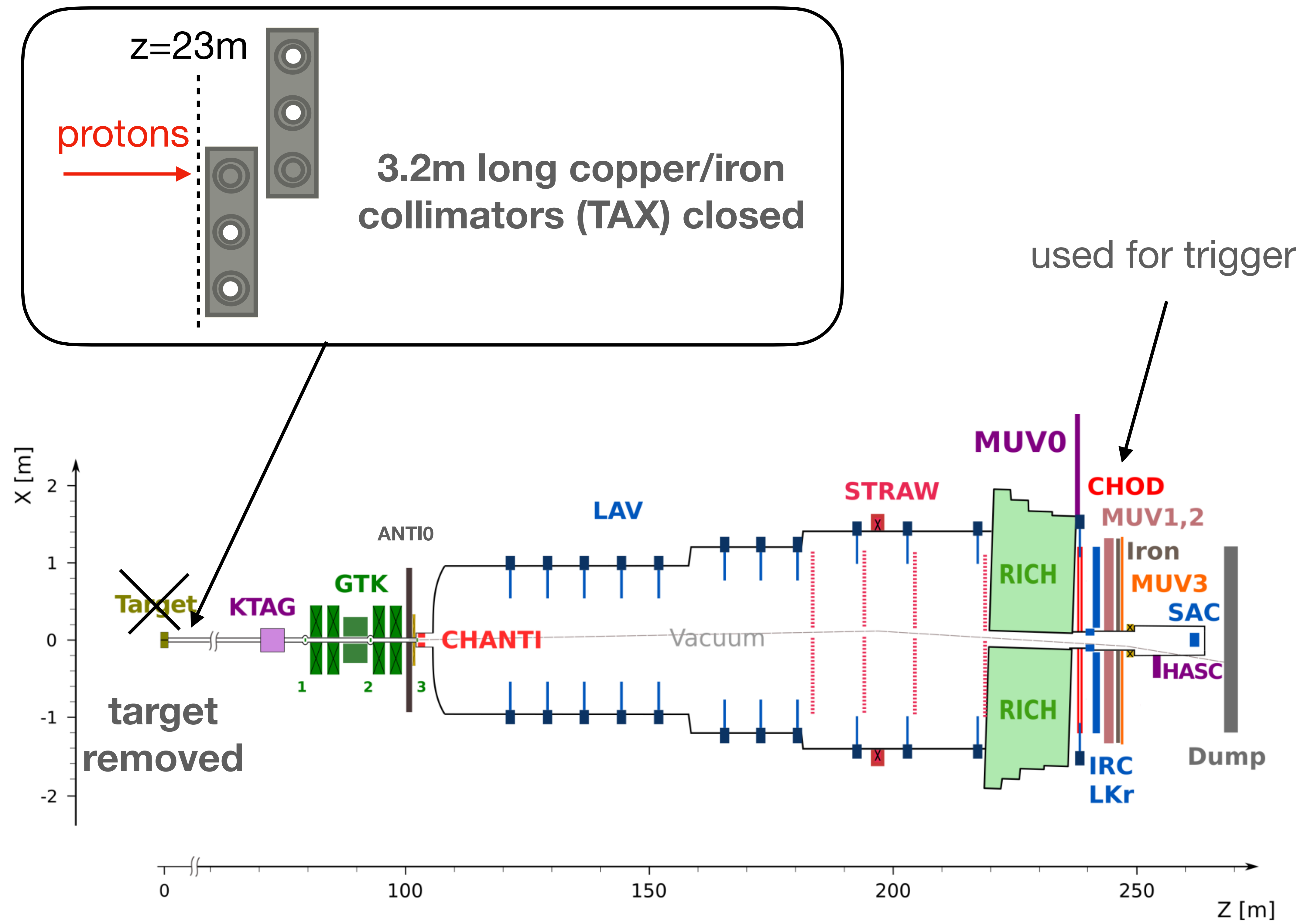
NA62 $A' \to e^+e^-, \mu^+\mu^-$

Belle II $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

Belle II $S \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$

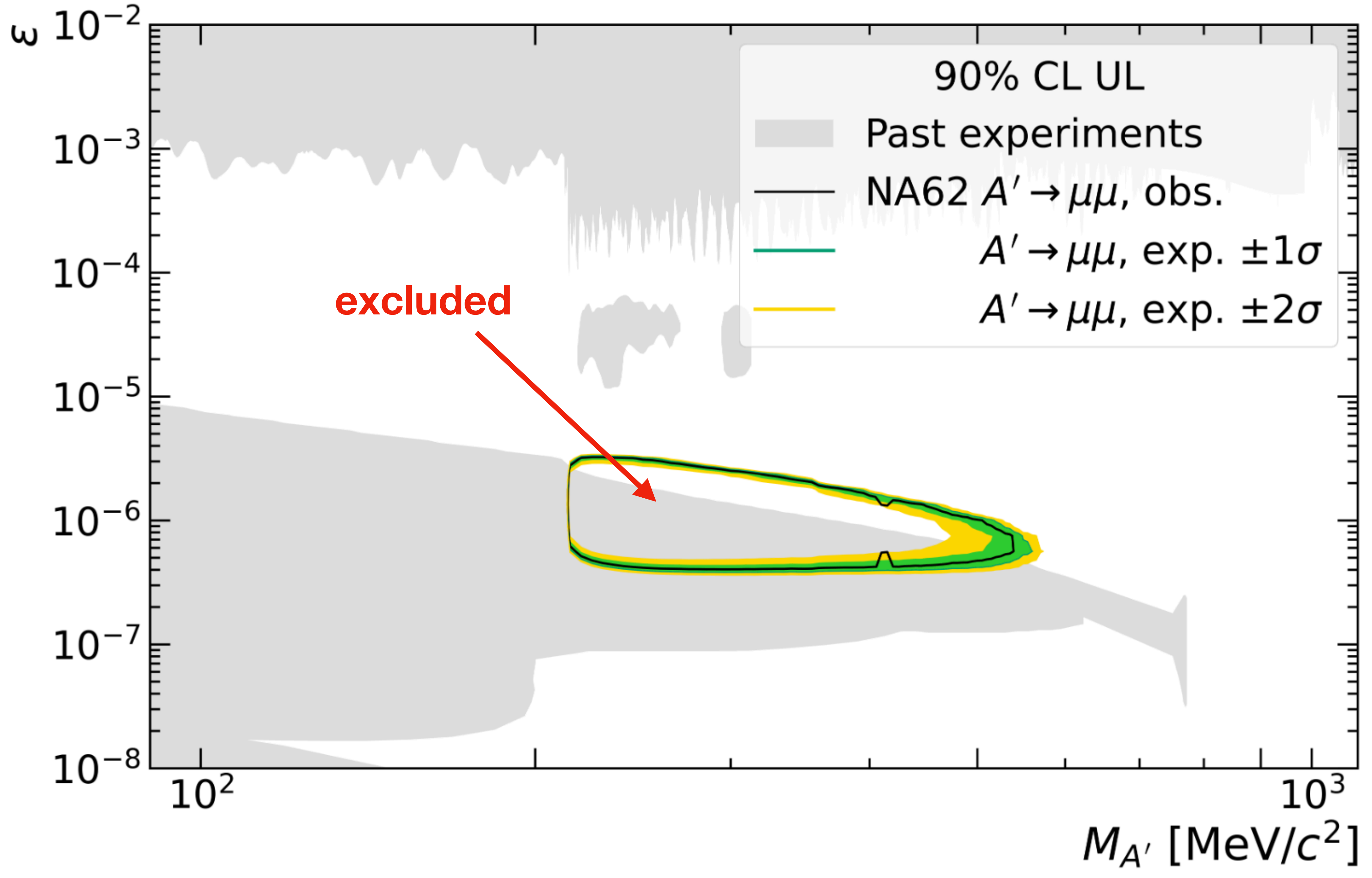
NA62

- Proton fixed target experiment at CERN SPS, 10^{12} p/sec
- Beam-dump data taking:
  - TAXes closed, target removed
  - 1.5 higher beam intensity
  - Better dipole sweeping
- Collected $1.4{\times}10^{17}$ p.o.t. in 10 days of data taking in 2021
- 10× more beam-dump data planned by 2025



NA62: $A' \to \mu^+\mu^-$

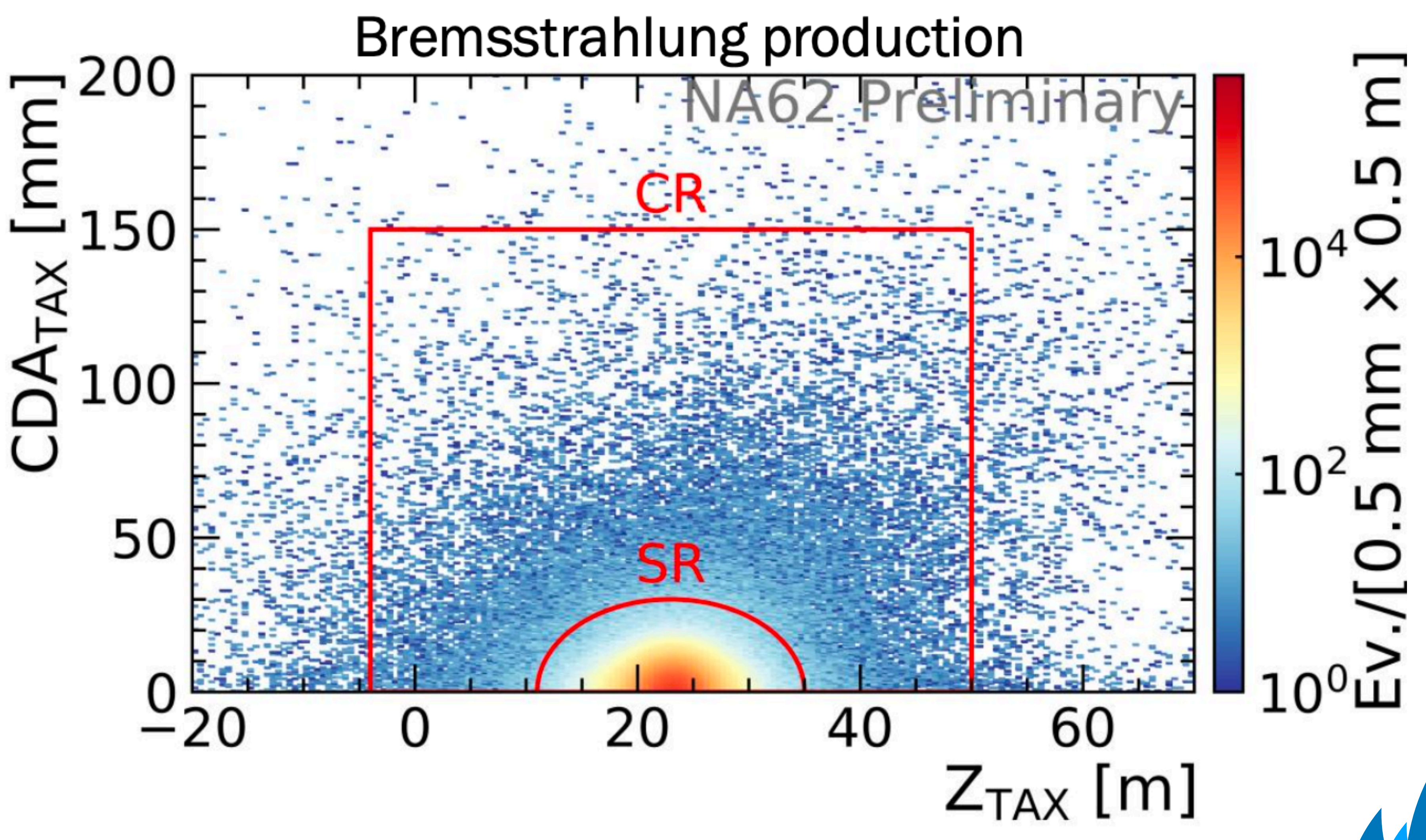
- Dark Photon via:
  - Bremsstrahlung: $pN \to XA'$
  - Meson-mediated: $pN \to XM, M \to \gamma A'$ with $M = \pi^0, \omega, \rho, \ldots$
- $\mu^+\mu^-$ vertex in fiducial volume, and primary vertex in the direction of the $\mu^+\mu^-$ pair and the proton beam at the TAXes
- Dominant background 0.016±0.002 events from two random muons (combinatorial), negligible background from secondaries of a muon interaction with the traversed material (in-time)



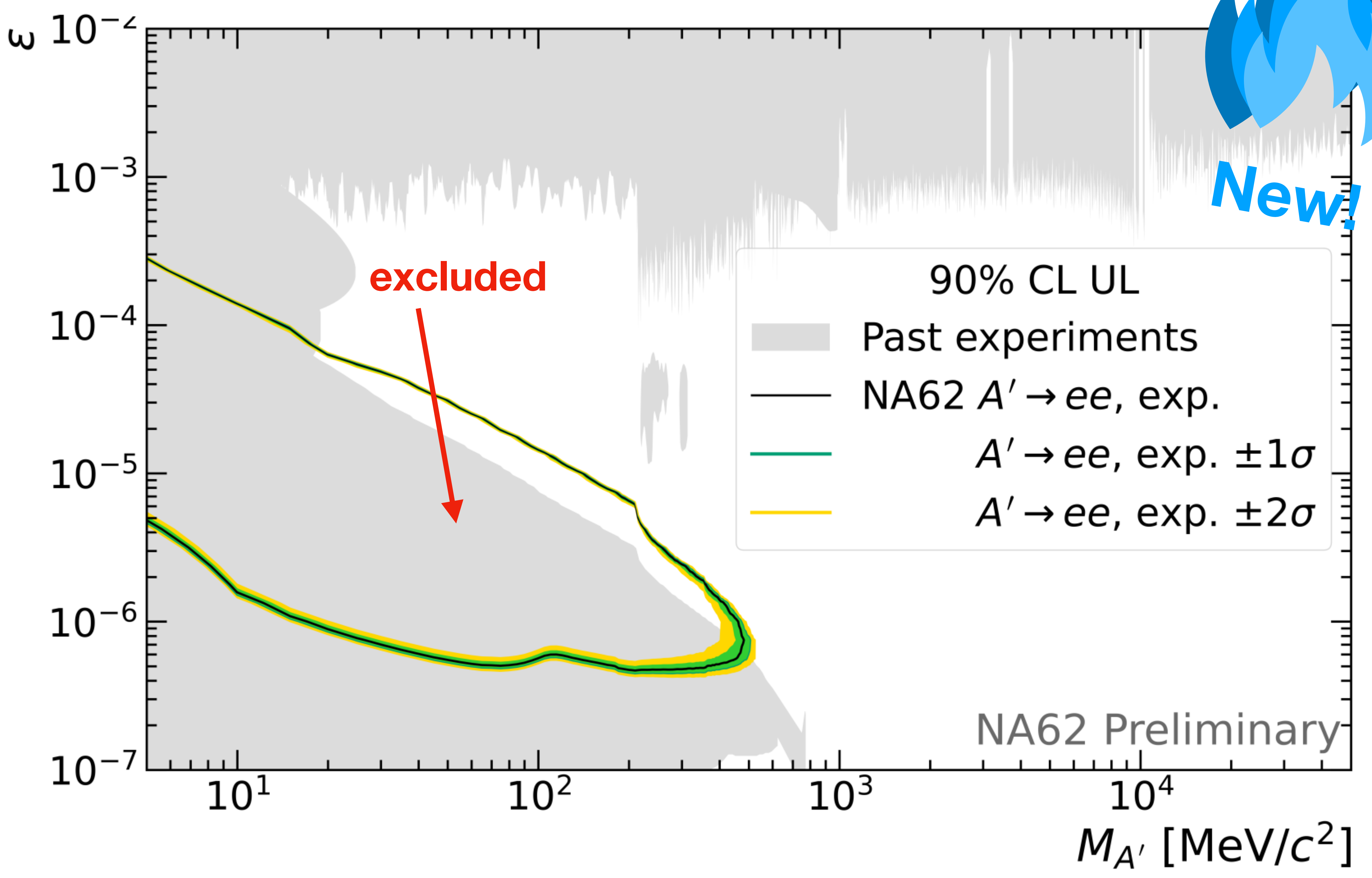
[1] https://arxiv.org/abs/2303.08666

NA62: $A' \to e^+e^-$

- Re-optimized particle identification and signal projection region
- Tighter veto (halo particle veto (ANTI0) and large angle veto (LAV)) to reject incoming particles
- Negligible combinatorial background, dominant background $0.0094^{+0.0049}_{-0.009}$ events from in-time interactions in material



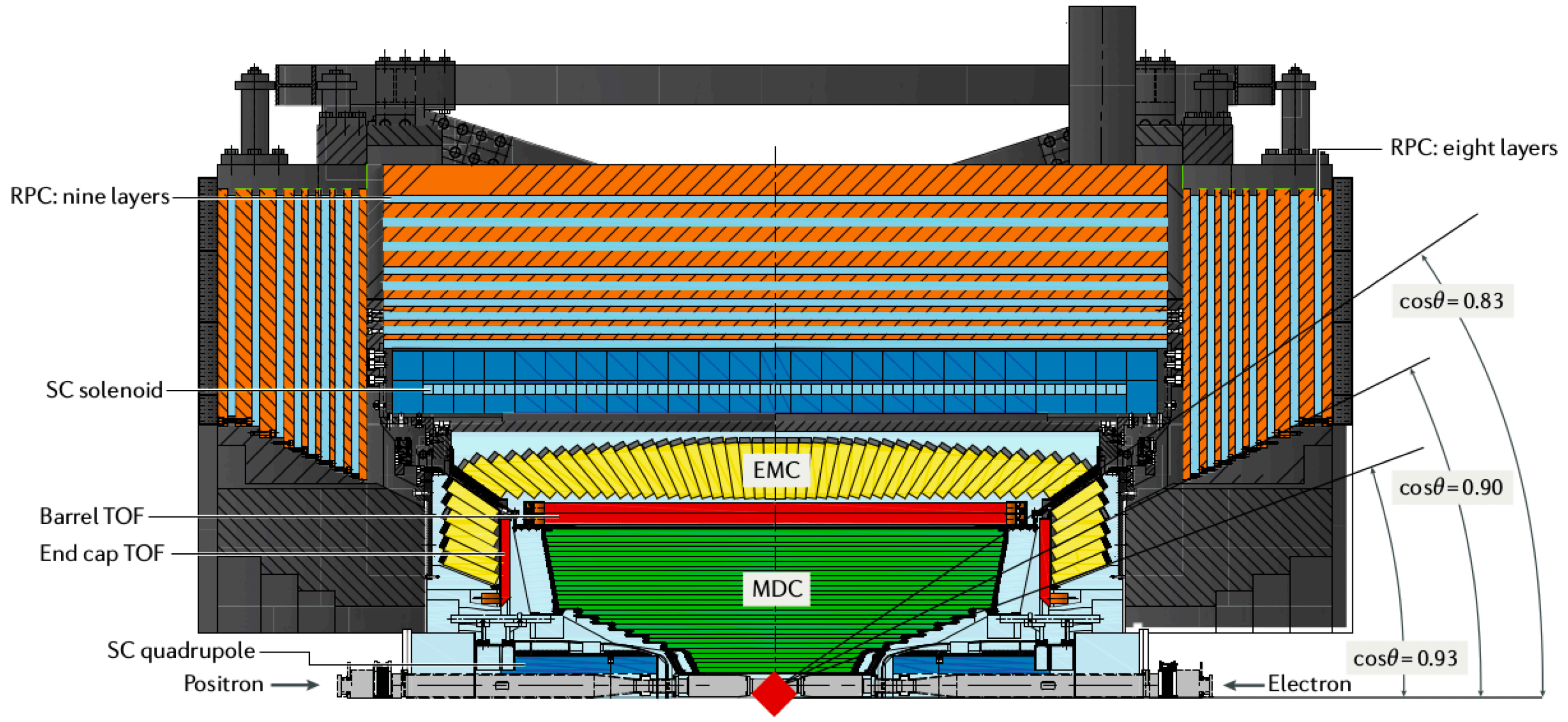
New!



[1] S. Ghinescu, Moriond 2023

BES III

- Symmetric e^+e^- collider BEPCII
  - around the charm/tau-pair threshold
- Taking data since 2009
- Total dataset 37 fb^{-1} at energies between 2 and 4.95 GeV
- Well known initial conditions
- Little/no pile-up - clean environment
- Special single photon trigger

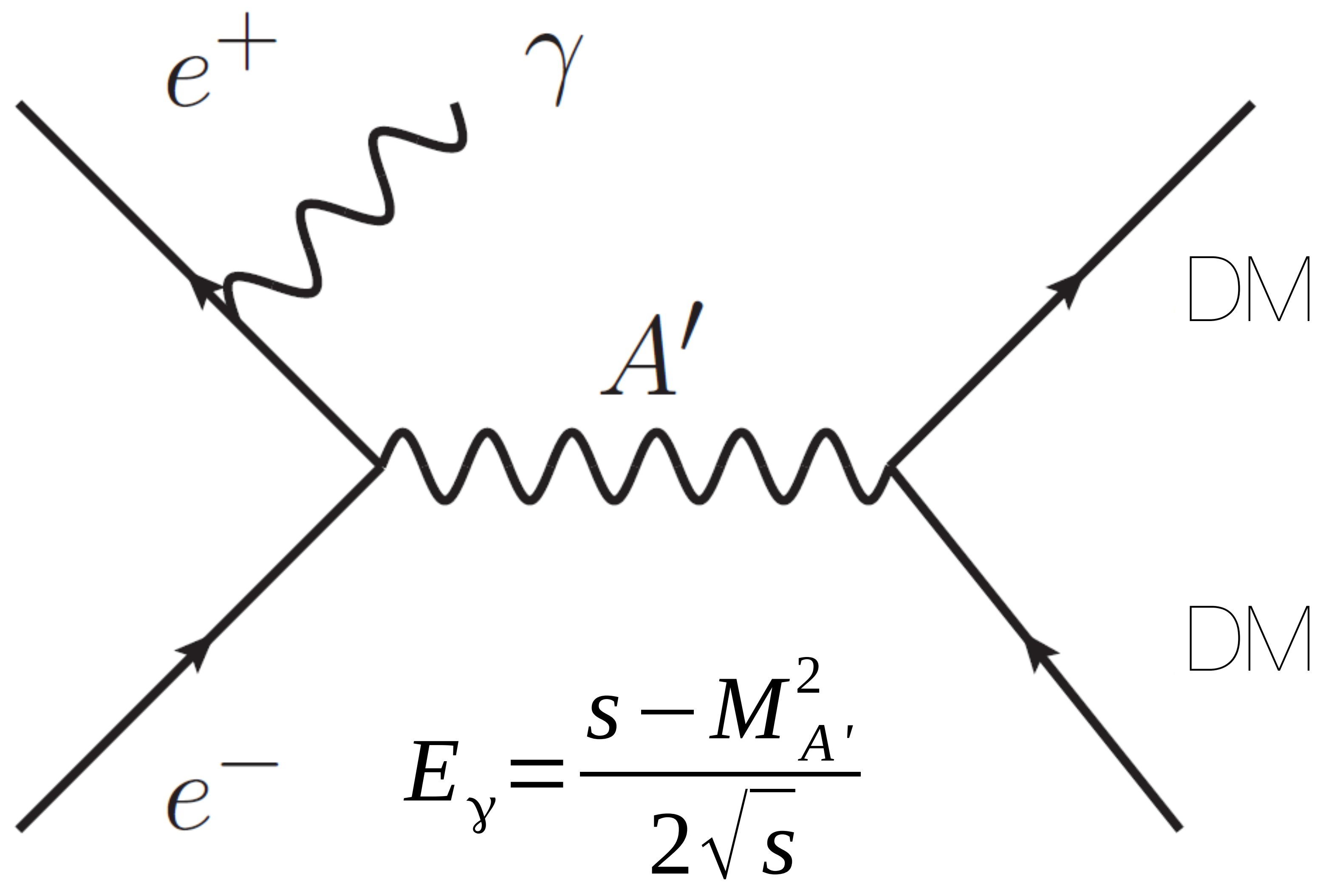


2009: 106M $\psi(2S)$
225M J/ψ
2010: 0.98 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$)
2011: 2.93 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$, total)
0.48 fb^{-1} @4.01 GeV
2012: 0.45B $\psi(2S)$ (total)
1.30B J/ψ (total)
2013: 1.09 fb^{-1} @4.23 GeV
0.83 fb^{-1} @4.26 GeV
0.54 fb^{-1} @4.36 GeV
10×0.05 fb^{-1} XYZ scan@3.81-4.42 GeV
2014: 1.03 fb^{-1} @4.42 GeV
0.11 fb^{-1} @4.47 GeV
0.11 fb^{-1} @4.53 GeV
0.05 fb^{-1} @4.575 GeV
0.57 fb^{-1} @4.60 GeV (for Λ_c^+)
0.80 fb^{-1} R scan @3.85-4.59 GeV

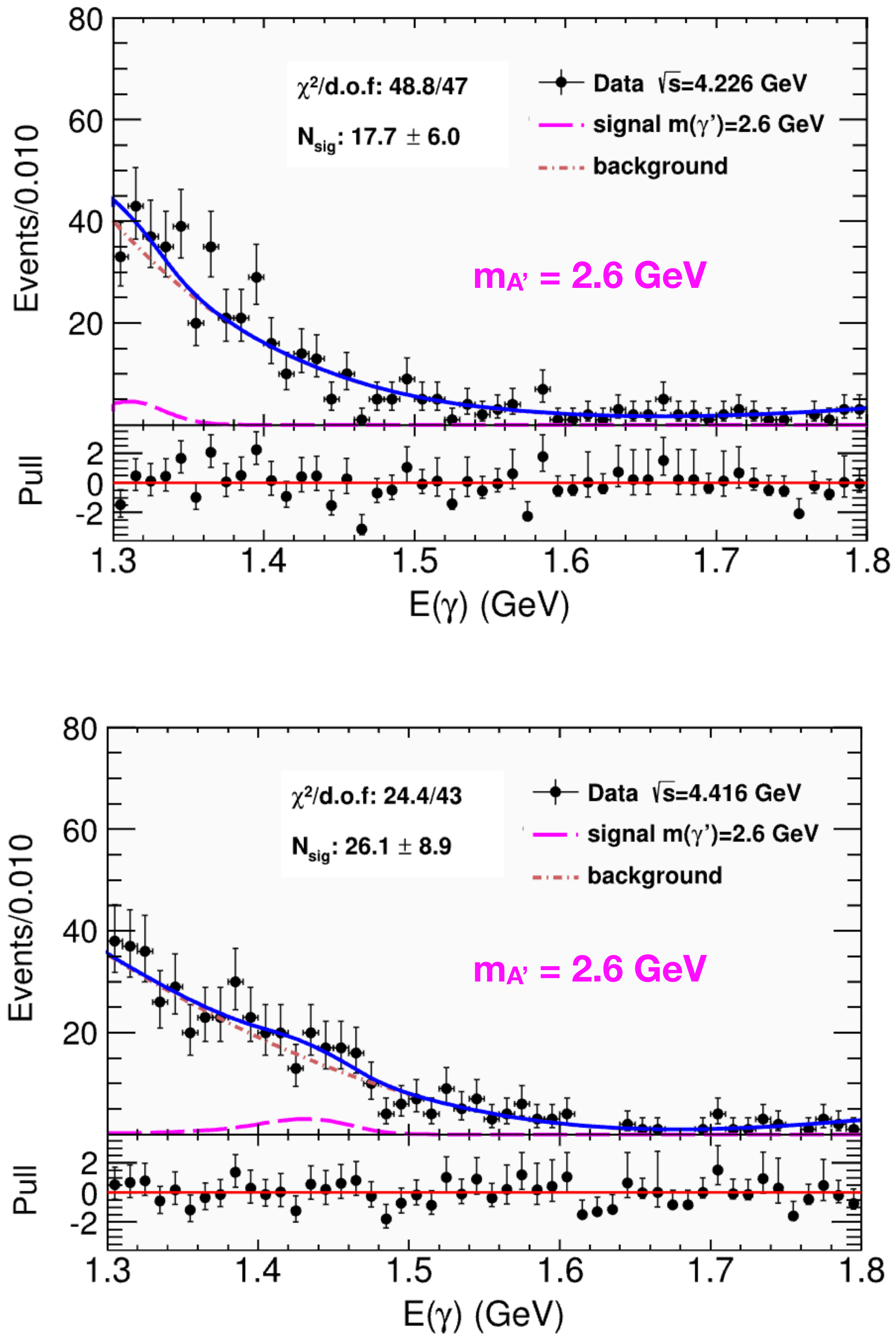
2015: R-scan 2-3 GeV+2.175 GeV
2016: 3.20 fb^{-1} @4.178 GeV (for D_s^+)
2017: 7×0.50 fb^{-1} XYZ scan@4.19-4.27 GeV
2018: More J/ψ+tuning new RF cavity
2019: 10B J/ψ (total)
8×0.50 fb^{-1} XYZ scan@4.13, 4.16, 4.29-4.44 GeV
2020: 3.8 fb^{-1} @ 4.61-4.7 GeV (XYZ&Λ_c^+)
2021: 2.0 fb^{-1} @ 4.74-4.946 GeV
2021: 2.7B $\psi(2S)$ (total)
2022: 2×0.4 fb^{-1}@3.65, 3.682 GeV,
8 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$, total)

BES III: $A' \rightarrow \text{invisible}$

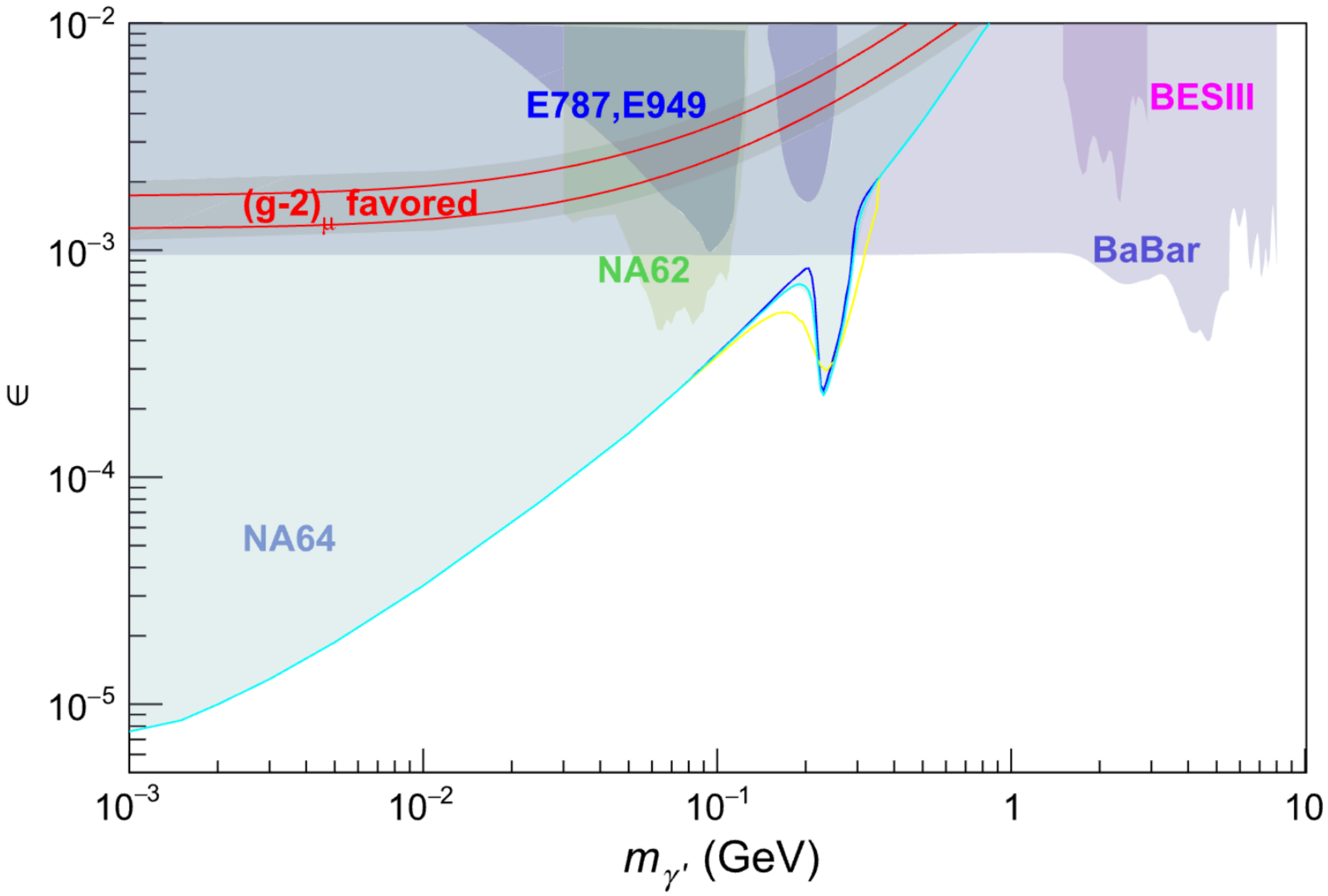
- Bump hunt in photon energy $1.3 < E_\gamma < 1.8$ GeV ($1.5 < m_{A'} < 2.9$ GeV)
  - limited by trigger threshold and ECAL saturation
- Background determined directly in data
  - Major background: $e^+e^- \rightarrow \gamma\gamma(\gamma)$ with one photon undetected
  - $e^+e^- \rightarrow e^+e^-(\gamma)$ negligible due to large polar angle requirement $|\cos\theta| < 0.6$
- Dataset with single photon trigger: Center of mass energies from 4.13 to 4.6 GeV (14.9 fb^{-1})



BES III: $A' \to$ invisible



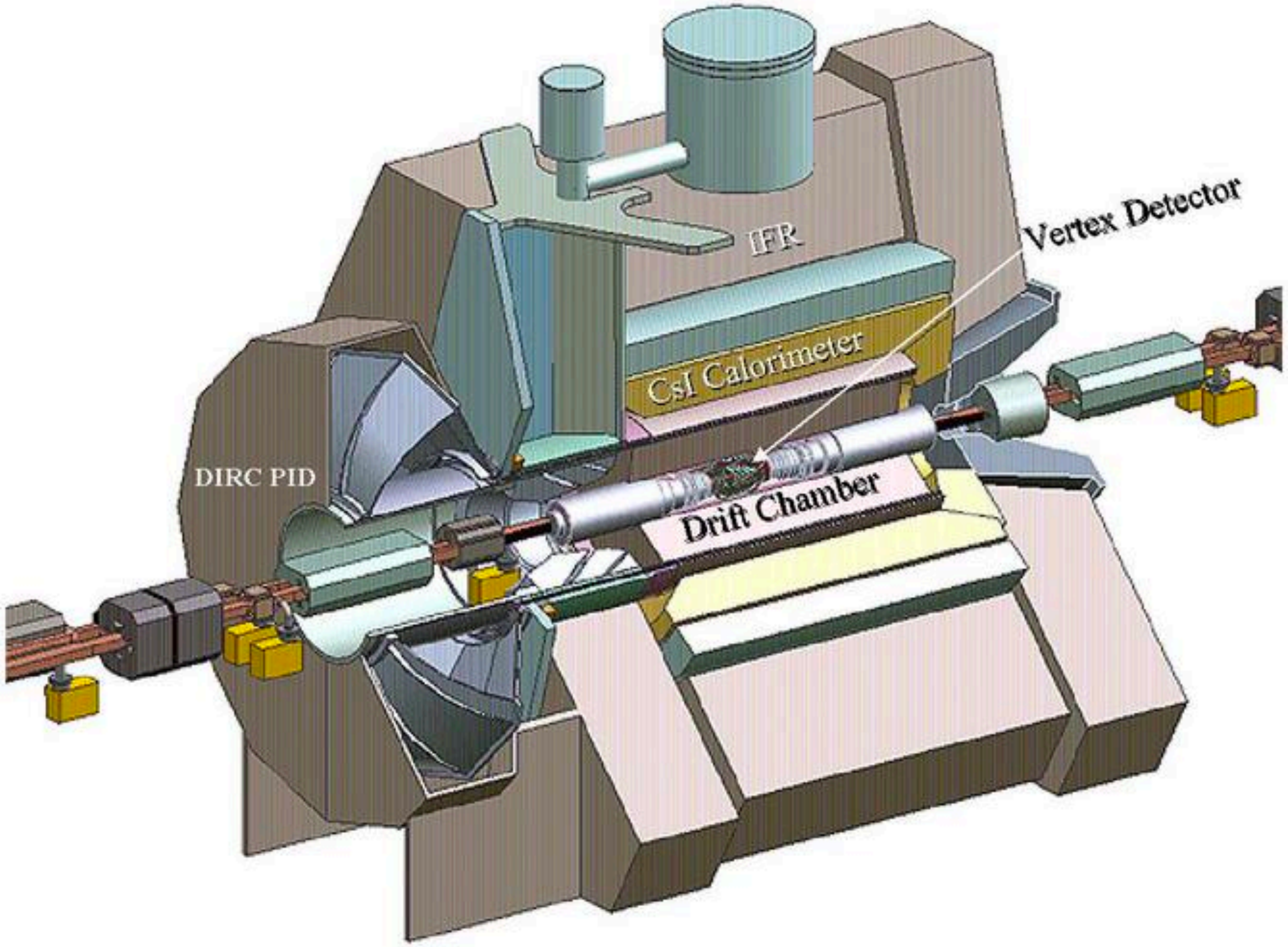
$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$



[1] Physics Letters B 839 (2023) 137785

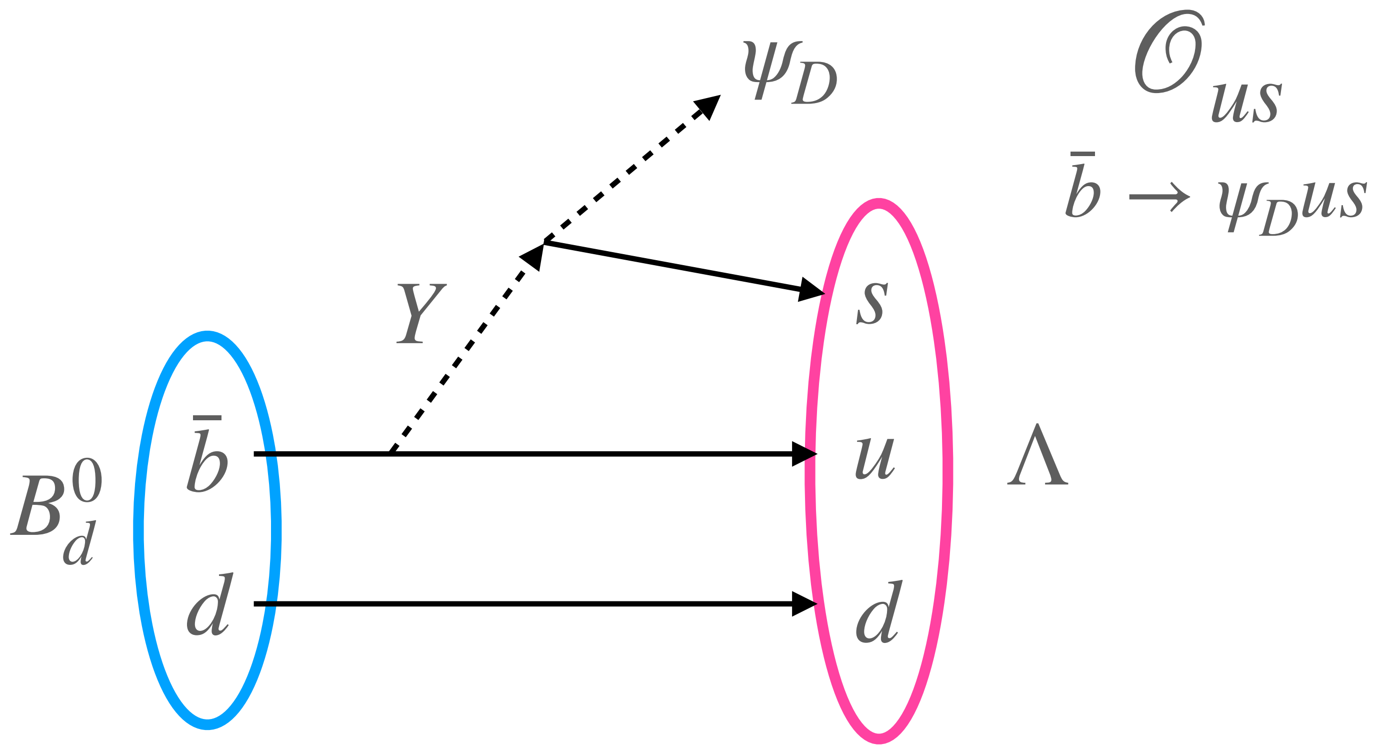
BaBar

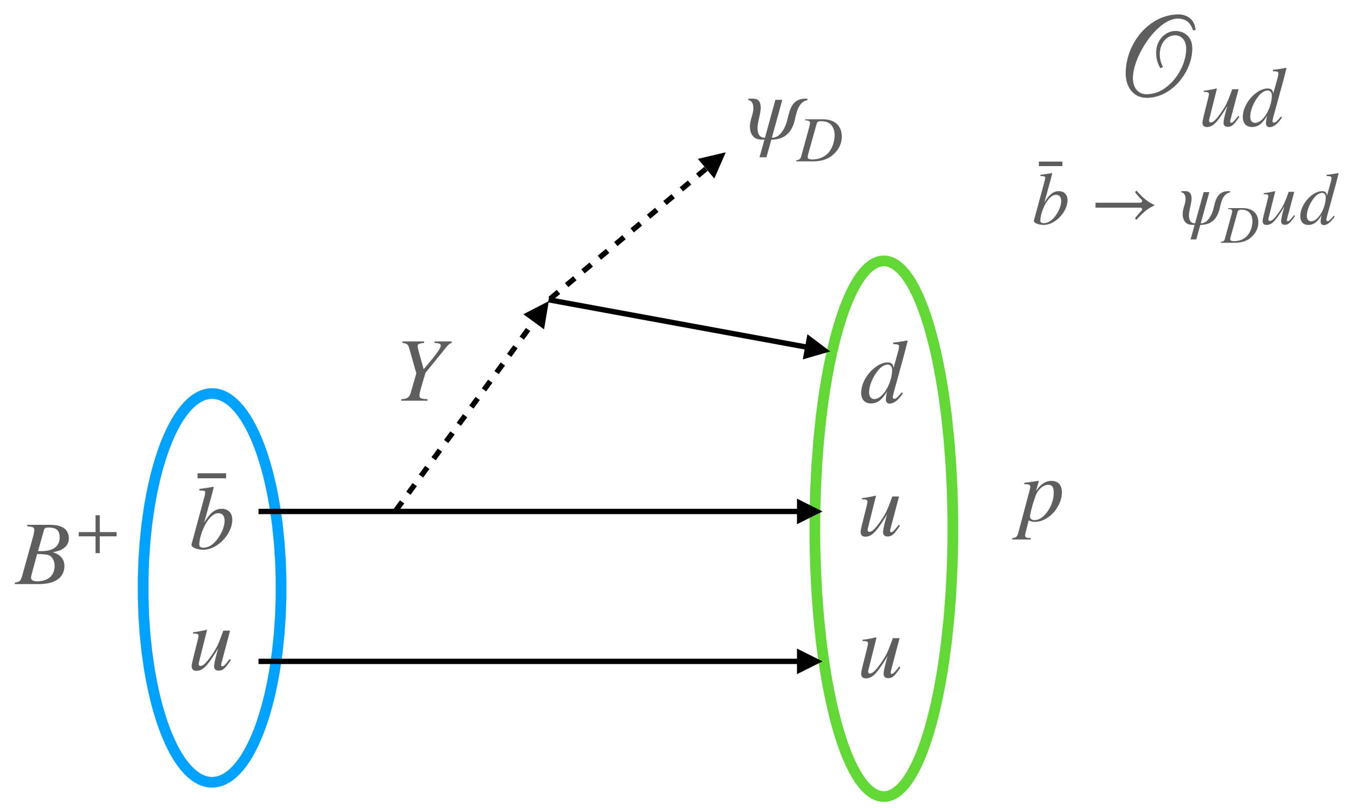
- Asymmetric e^+e^- collider PEP-II the US
  - running at the Υ(4S)
  - 9 GeV electrons, 3 GeV positrons
- Collected 432 fb^{-1} (until 2008)
- Well known initial conditions
- Little/no pile-up - clean environment



BaBar: Search for B-Mesogenesis

- Baryon asymmetry and dark matter abundance explained simultaneously
  - Light unstable dark baryon ψ_D and heavy (TeV-scale) color-triplet boson mediator particle Y
  - Baryogenesis via out-of-thermal-equilibrium decays of heavy scalar $\Phi \to b\bar{b}$ that hadronize into B and $\bar{B}$ mesons. These mesons oscillate and violate CP before decaying to “visible baryon”/“dark anti-baryon” pairs.
    - matter-antimatter asymmetries are generated in the visible and dark sectors with equal but opposite magnitudes
    - total baryon number conserved
- Model has five new particles ($\Phi, Y, \psi_D, \phi, \xi$) and four different flavour operators $\mathcal{O}_{ud}, \mathcal{O}_{us}, \mathcal{O}_{cd}, \mathcal{O}_{cs}$
  - Three possible ways to write down matrixelements involving the operator that depend on the precise pairing of the spinors (e.g. $\mathcal{O}_{ud}: \mathcal{O}^1_{ud} = (\psi b)(ud), \mathcal{O}^2_{ud} = (\psi d)(ub), \mathcal{O}^3_{ud} = (\psi u)(db)$.

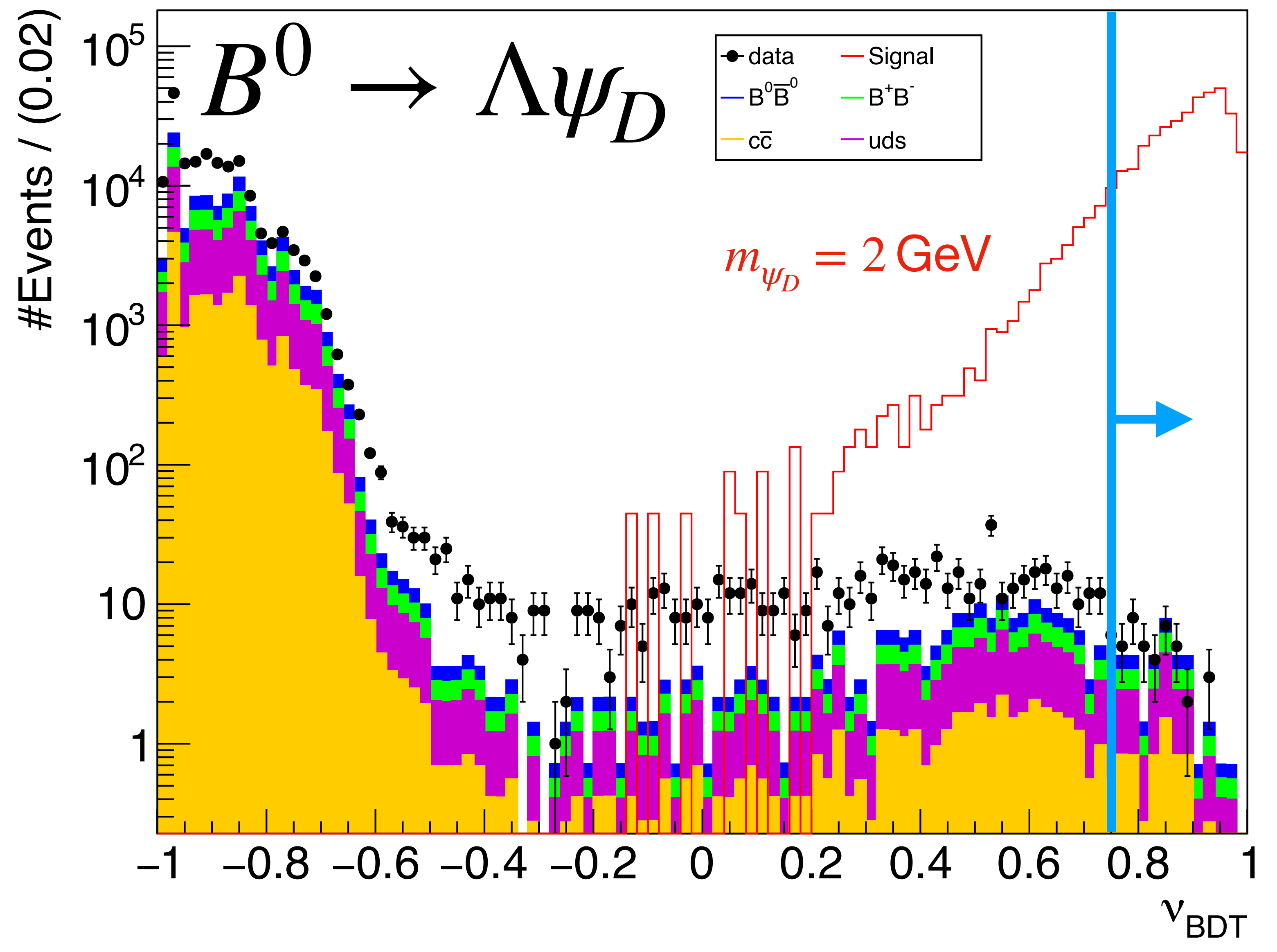


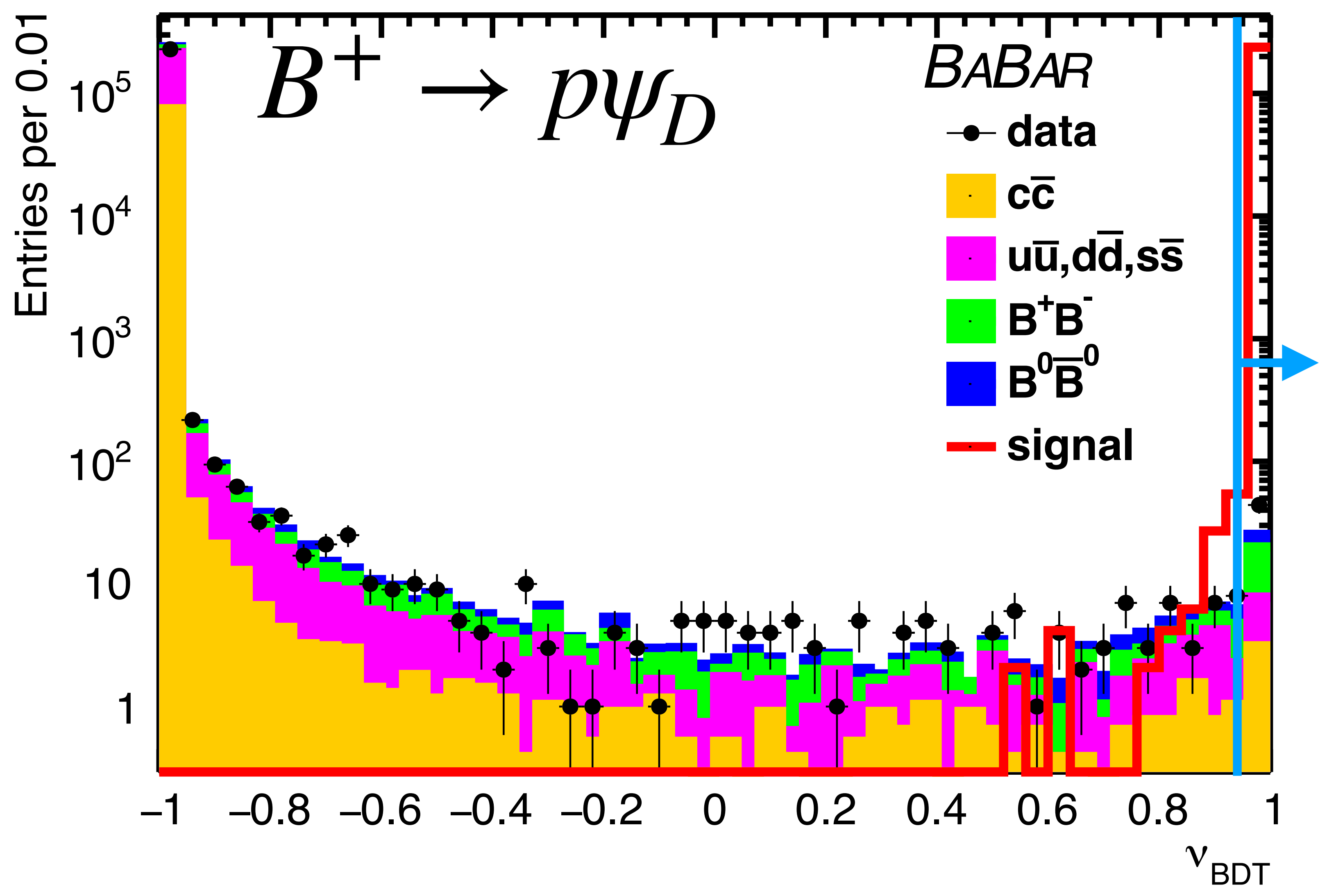


[1] Phys. Rev. D 99, 035031 (2019)
[2] Phys. Rev. D 104, 035028 (2021)
[3] https://arxiv.org/abs/2208.06421

BaBar: Search for B-Mesogenesis

- Dark sector particle ψ_D escapes detection → missing mass
- Hadronic Recoil Tagging: Reconstruct B_{tag} and look for signal signature in the remainder of the event (B_{sig})
- Reconstruct ψ_D from the missing energy 4-vector on signal side
- Background suppression via BDTs



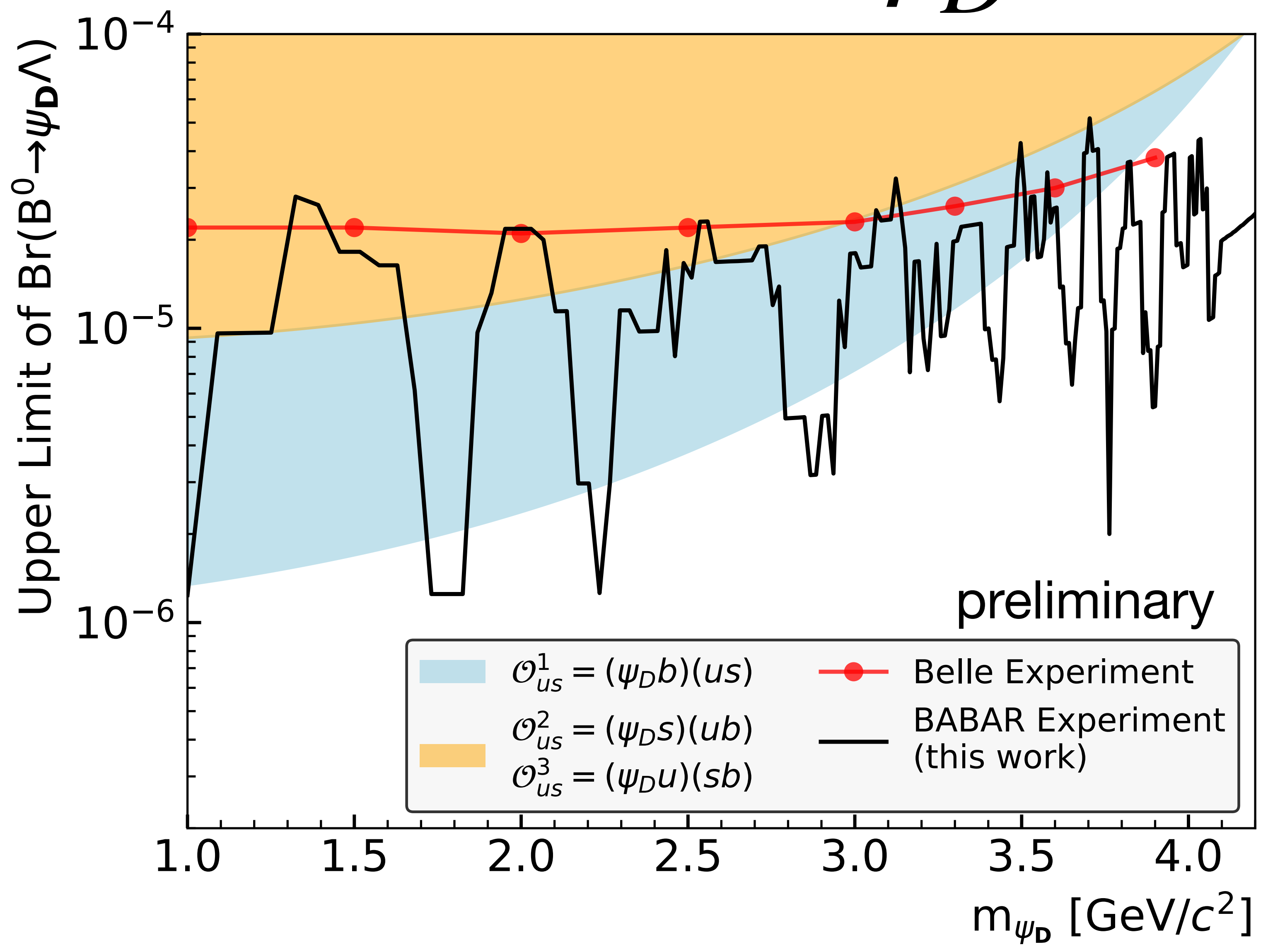


[1] https://arxiv.org/abs/2302.00208
[2] Phys. Rev.D105, L051101 (2022) (Belle)

BaBar: Search for B-Mesogenesis

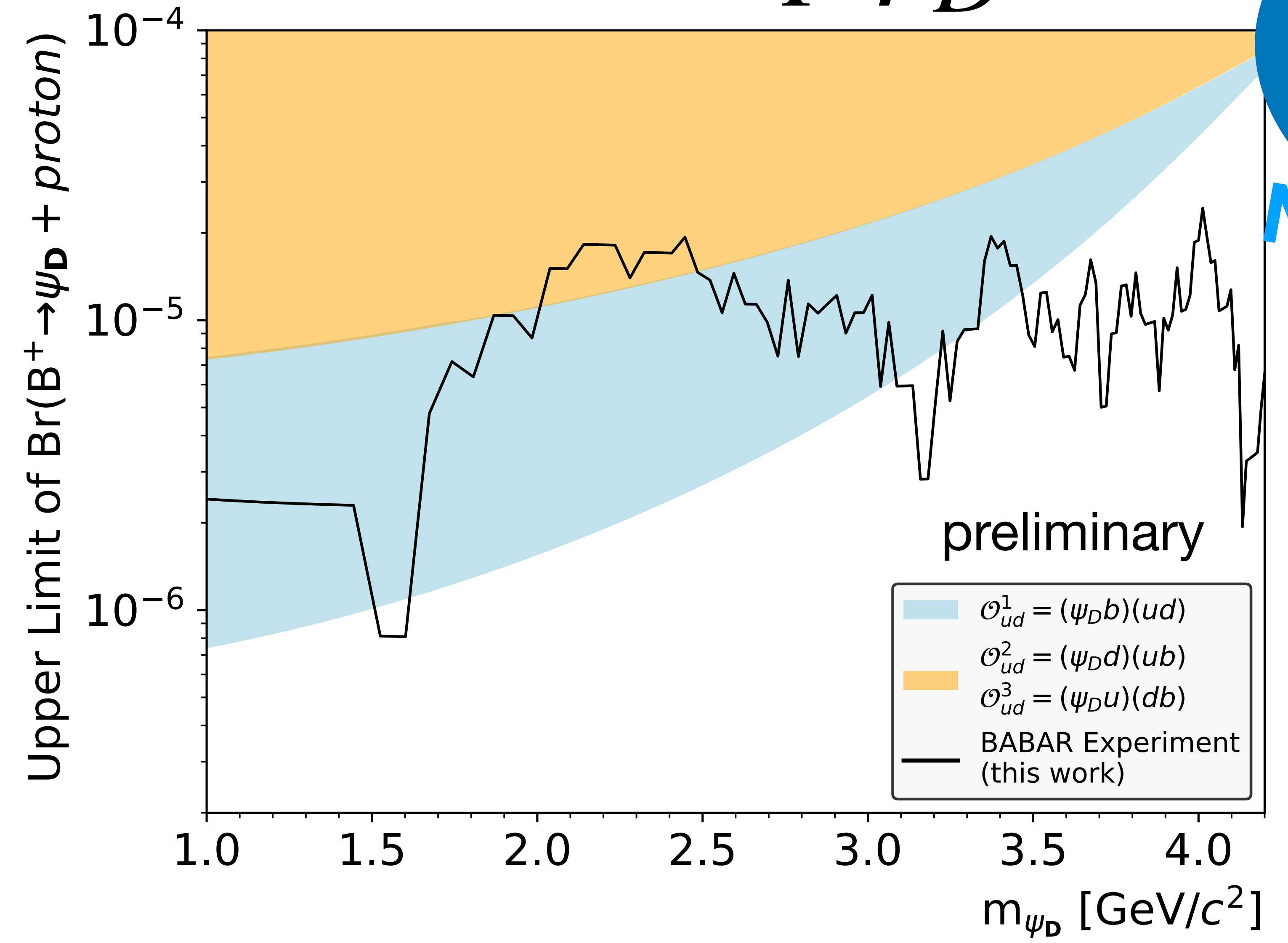
- Search for $B^0 \to \Lambda\psi_D$ probes $\mathcal{O}_{us}$
  - Largest local significance at 3.7 GeV at 2.3σ (0.4σ global), all consistent with null hypothesis
  - Limits improve over Belle by up to 10 and exclude heavy ψ_D for $\mathcal{O}^1$ and almost all masses for $\mathcal{O}^{2,3}$
- Search for $B^0 \to p\psi_D$ probes $\mathcal{O}_{ud}$
  - First direct search!
  - Limits exclude heavy ψ_D for $\mathcal{O}^1$ and almost all masses for $\mathcal{O}^{2,3}$

$B^0 \to \Lambda\psi_D$



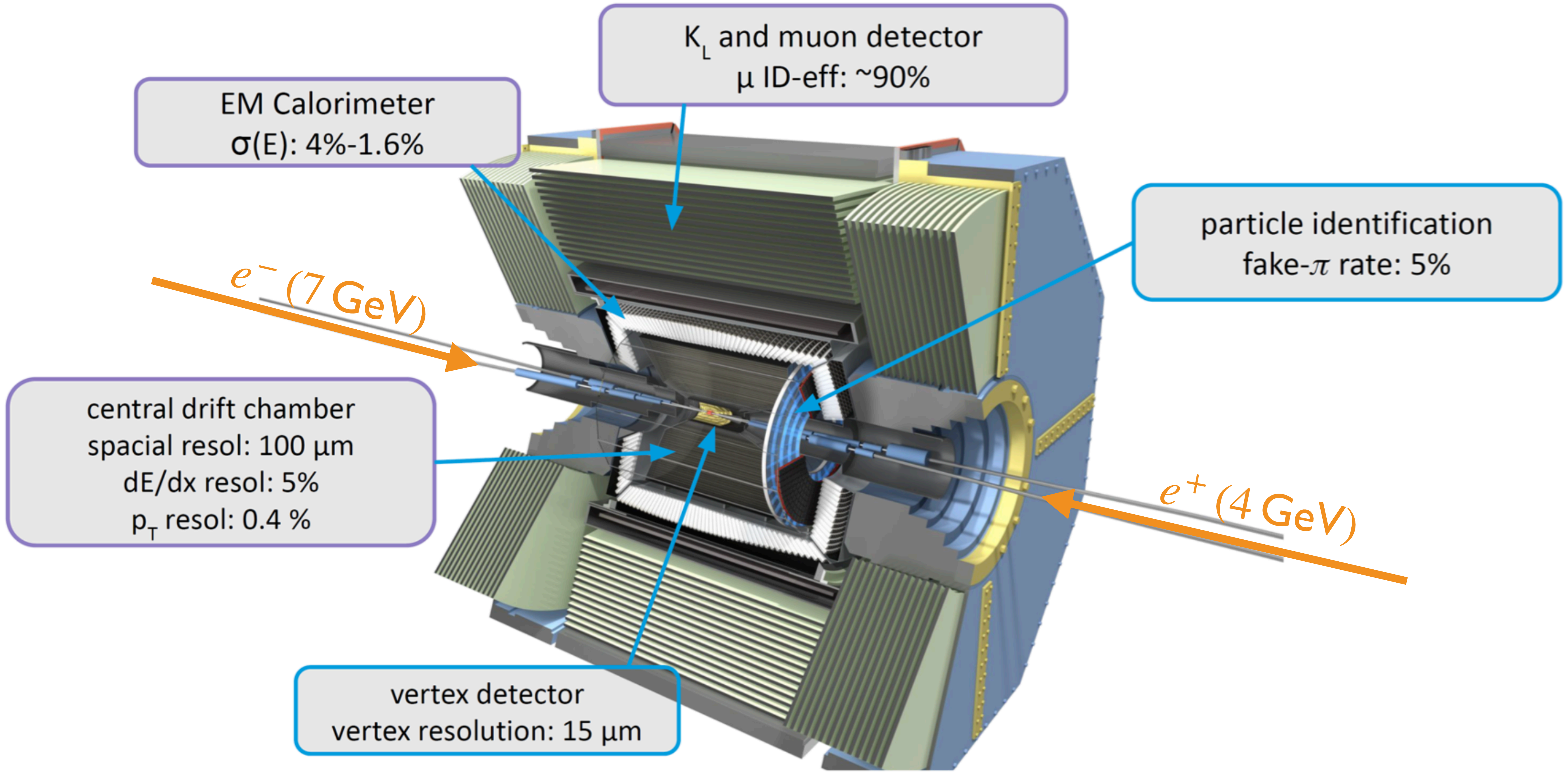
$B^+ \to p\psi_D$

New!



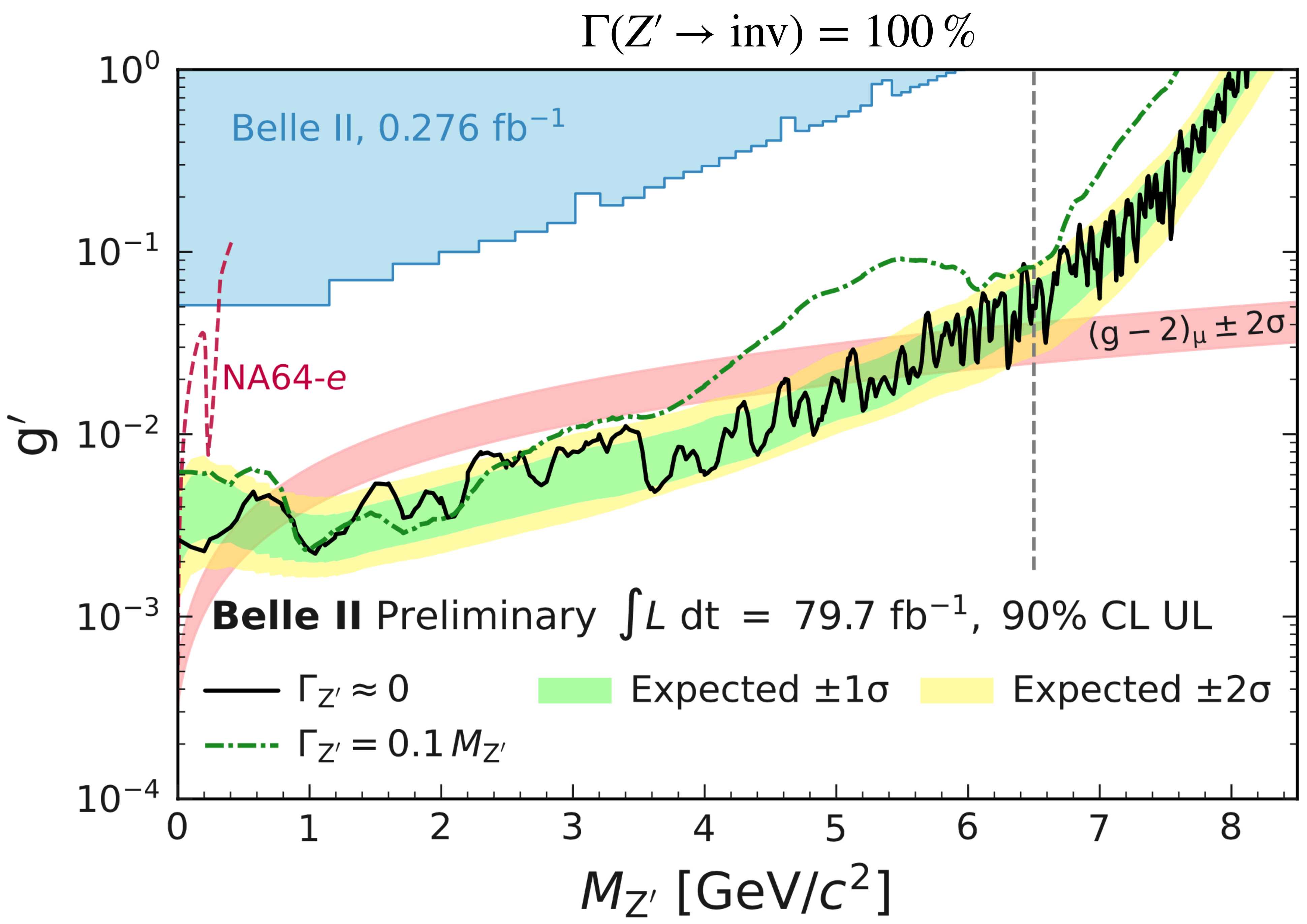
Belle II

- Asymmetric e^+e^- collider SuperKEKB in Japan
  - running at the $\Upsilon(4S)$
  - 7 GeV electrons, 4 GeV positrons
- Collected 428 fb^{-1}, currently in LS1
  - Most analyses use a subset of this
- Well known initial conditions
- Little/no pile-up - clean environment
- Special triggers for low multiplicity
  - Single photon trigger (not available at Belle)
  - Single muon trigger
  - Single track trigger using neural networks



Belle II: $\mu\mu Z'(\to \text{invisible})$

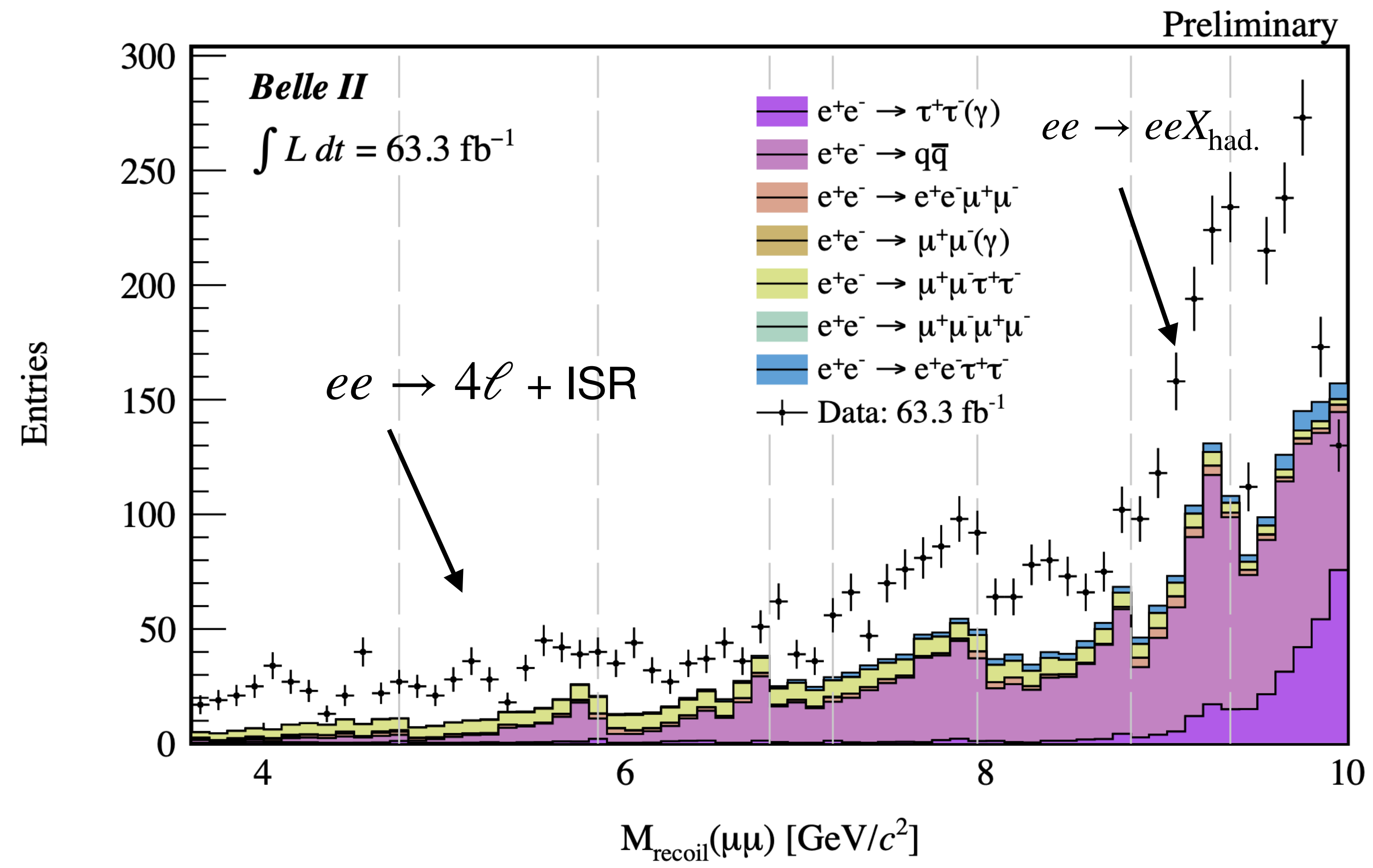
- Additional massive gauge boson Z' with $L_\mu - L_\tau$ model
  - Coupling only to second and third generation leptons
- Could explain discrepancies in $(g-2)_\mu$ [1]
- Study invisible system recoiling against $\mu\mu$
  - $2d$ fit in M^2_{recoil} and $\theta^{\text{CMS}}_{\text{recoil}}$
- Challenging $\tau\tau$ background tackled with neural network simultaneously trained for all Z' masses [2]
- Systematics and corrections from and control samples
- Update of first Belle II analysis [3] with 300x dataset
- $(g-2)_\mu$ preferred region excluded for 0.8 < $0.8 < m_{Z'} < 4$ GeV [4]

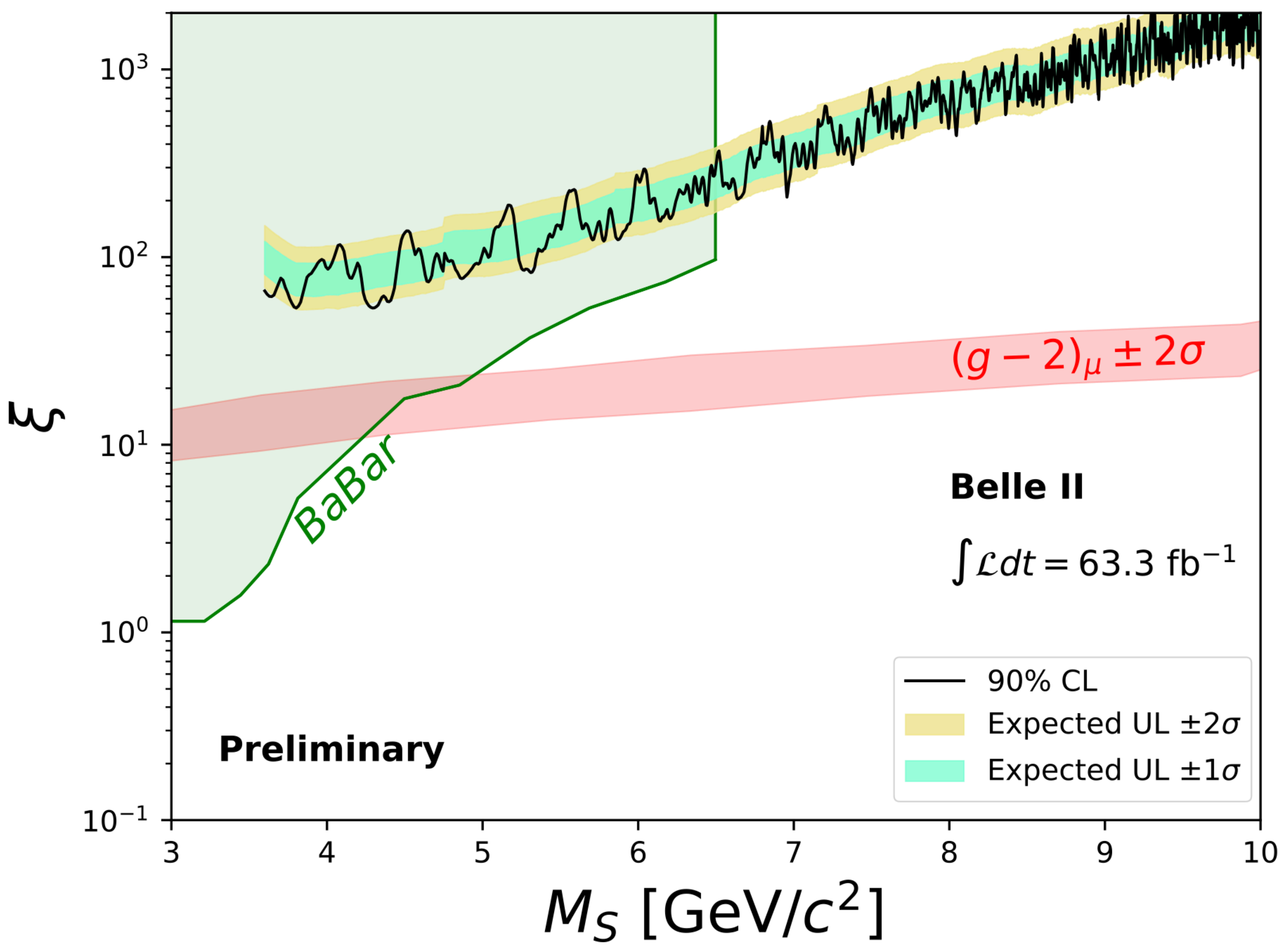


[1] B. Shuve et al., Phys. Rev. D 89, 113004
[2] F. Abudinén et al., Eur.Phys.J.C 82 (2022) 2, 121
[3] Belle II Collaboration, Phys. Rev. Lett. 124, 141801 (2020)
[4] https://arxiv.org/abs/2212.03066 (accepted by PRL)

Belle II: $\mu\mu Z'(\to \tau\tau)$

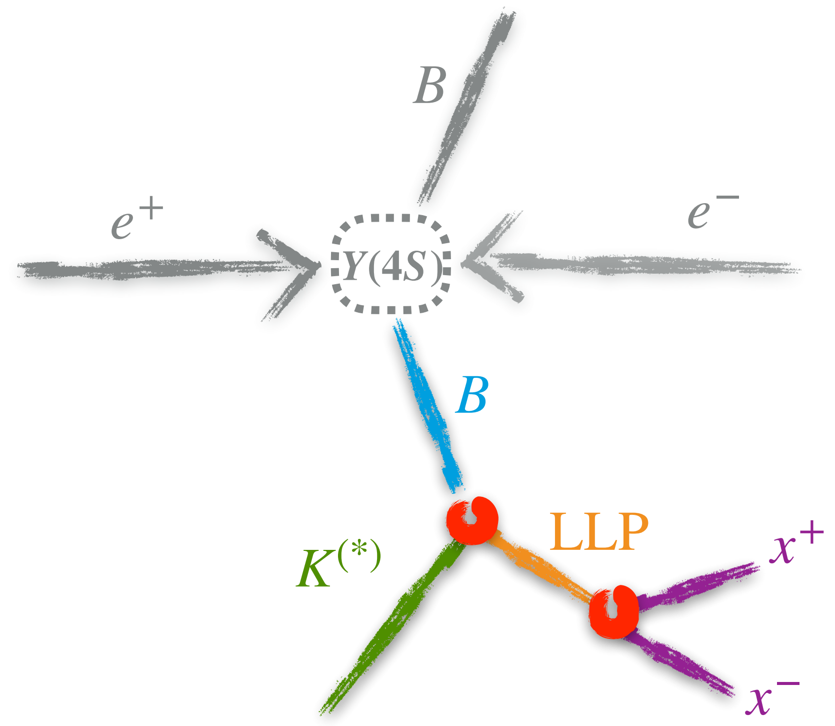
- Four track final-state: one-prong τ decays $\tau^{\pm} \to \pi^{\pm}(\pi^0)\nu, \ell\nu\nu$ with $\ell = e, \mu$
- Challenging backgrounds in final-state with neutrinos
  - Require missing energy $M_{4\ \text{tracks}} < 9.5$ GeV
  - Eight classifiers in different mass regions
- Signal extracted in fits to $M_{\text{recoil}}(\mu\mu)$
- Background determined directly in data
- Strongest constraints for $M_S > 6.5$ GeV in leptophilic scalar model [1] [1] B. Batell et. al. PRD 95 (2017) 075003

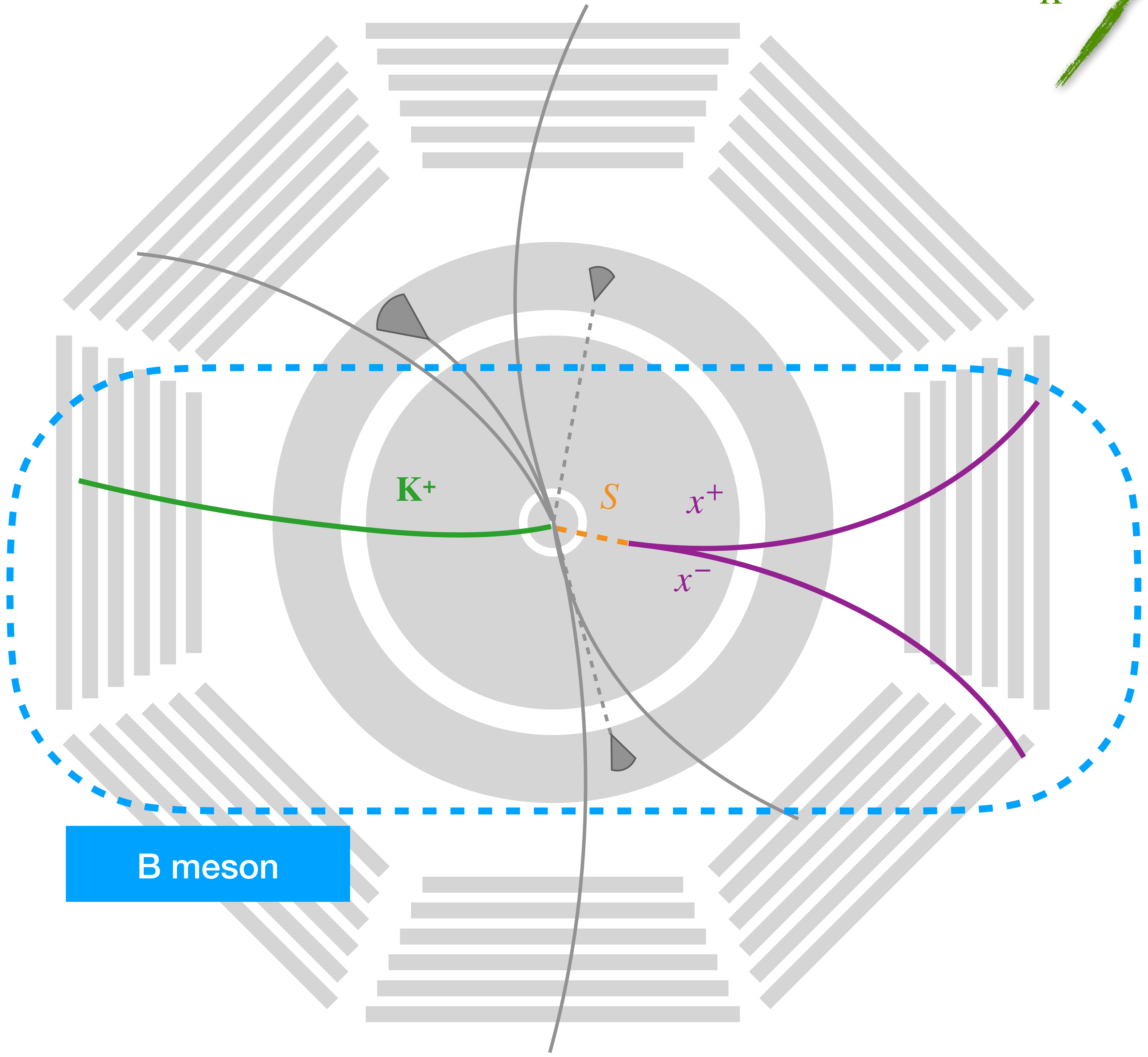




Belle II: Search for a long-lived spin-0 mediator in $b \to s$ transitions

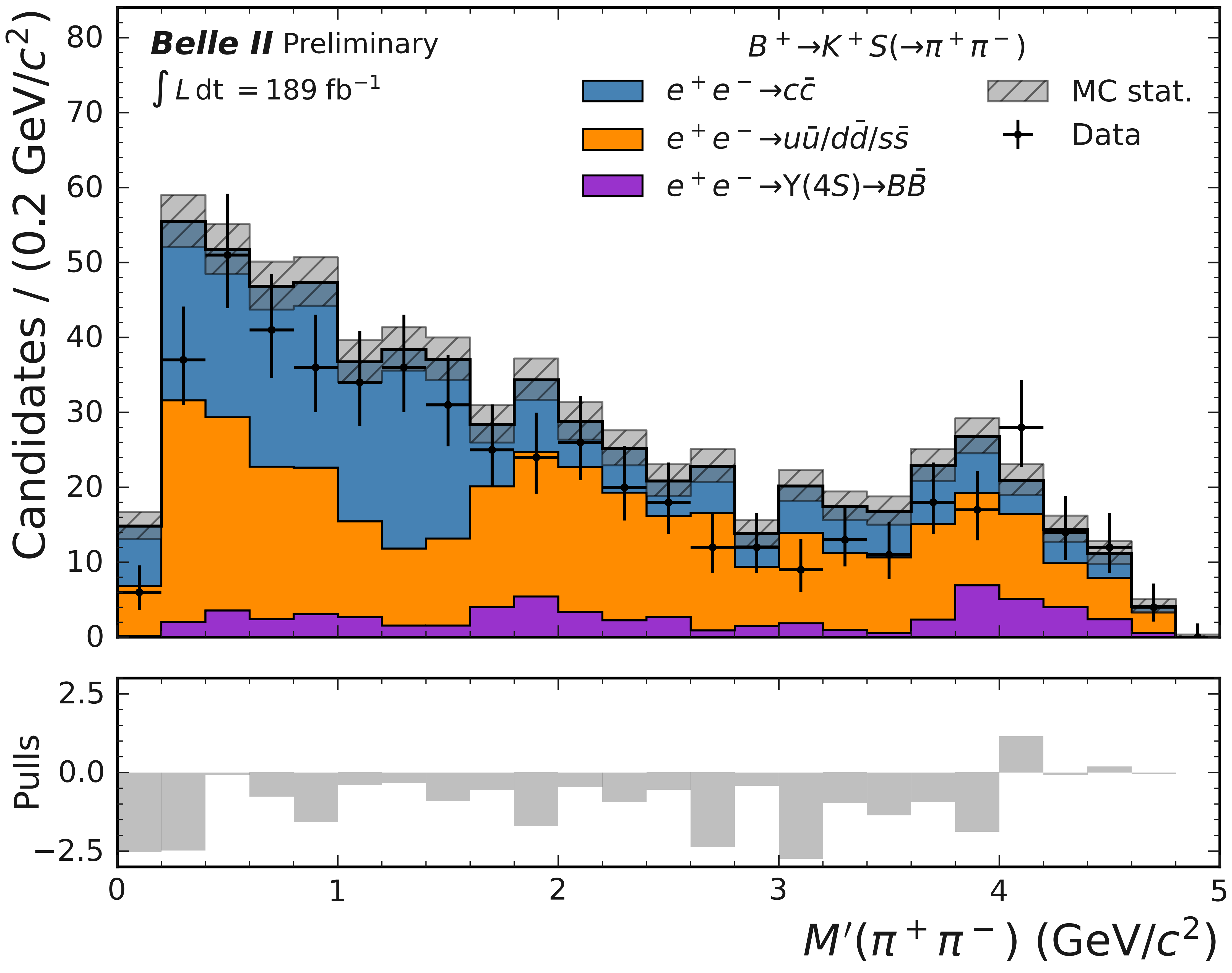
- First Belle II long-lived particle (LLP) search!
- Search in eight exclusive visible channels: $B^+ \to K^+ S$ and $B^0 \to K^{*0}(\to K^+\pi^-)S$
- Signal B-meson fully reconstructed
- Backgrounds:
    - Combinatorial $ee \to q\bar{q}$ reduced by requiring kinematics similar to B-meson expectations
- K_S^0 window vetoed in $M_{\pi\pi}$
- Further peaking backgrounds suppressed by tighter displacement selection





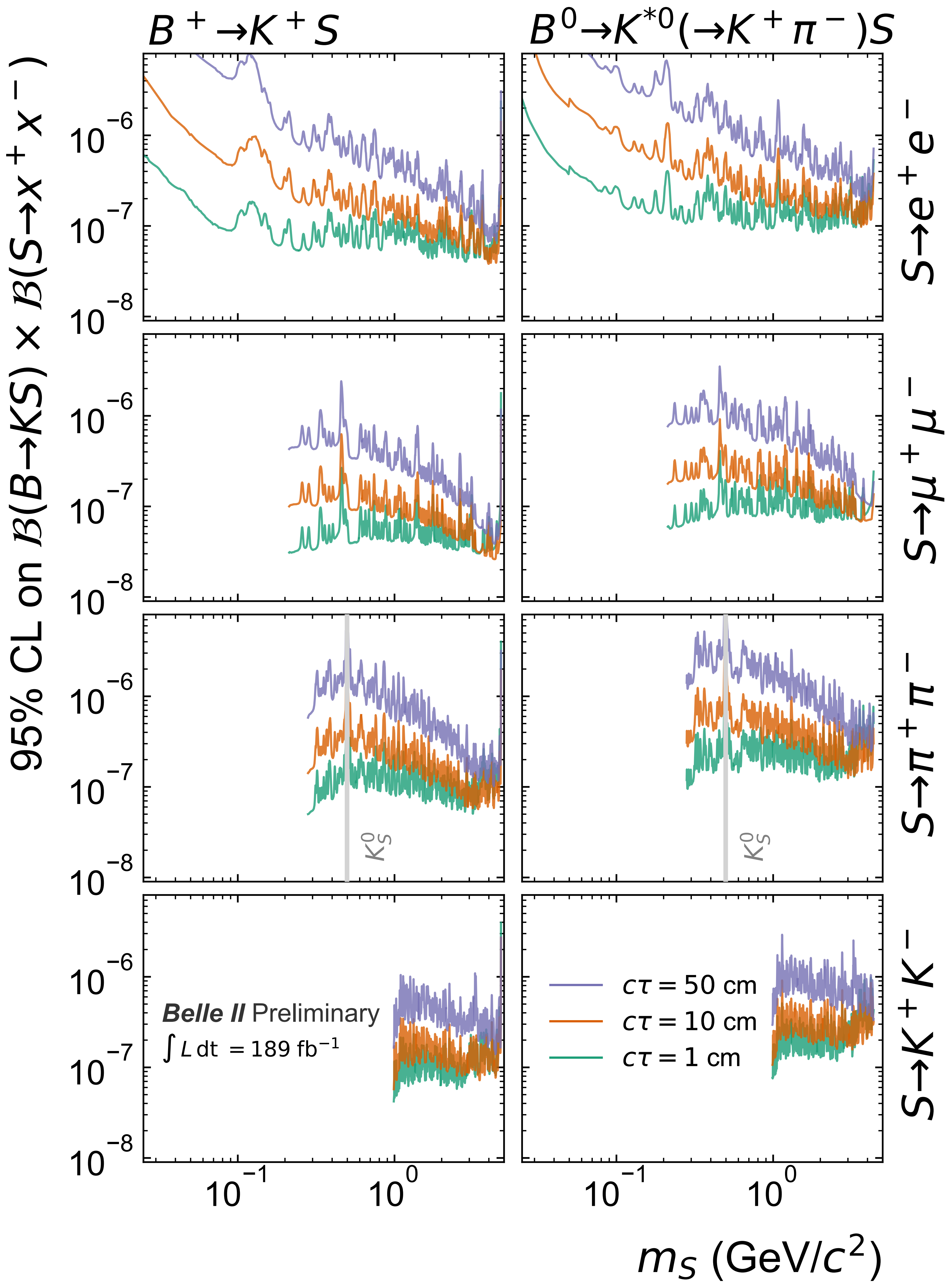
Belle II: Search for a long-lived spin-0 mediator in $b \to s$ transitions

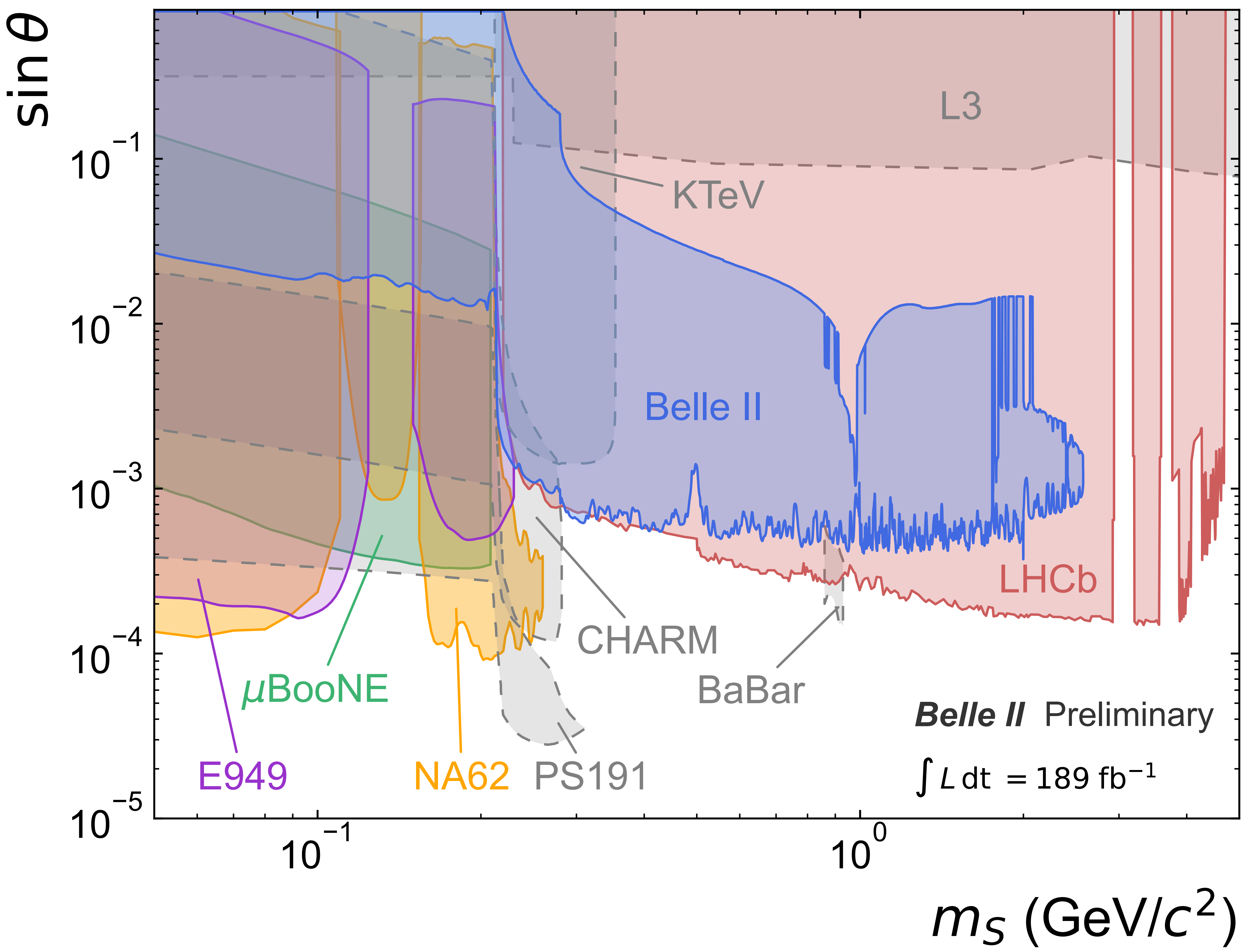
- Bump hunt in LLP mass distribution using unbinned maximum likelihood fits
- Background determined directly in data (un-modelled non-peaking background are not problematic)
- Challenge: LLP performance
  - Study K_S^0 control sample and derive corrections (efficiency, M_S shape, particle identification)
- Probe lifetimes between $10^{-5} < c\tau < 4\,\mathrm{m}$



[1] S. Dreyer, Moriond 2023

Belle II: Search for a long-lived spin-0 mediator in $b \to s$ transitions





- First model-independent limits for exclusive $B \to K^{(*)}S, S \to$ hadrons
- Interpretation as dark scalar or ALP with fermion couplings

[1] S. Dreyer, Moriond 2023

Summary

KIT Karlsruhe Institute of Technology

- Very active and very diverse program of direct searches at flavour factories
- Searches presented are a subset of the results from the past year
- All searches presented target parameter space with viable DM candidates or they offer solutions to SM anomalies

More results from the last months not covered in this talk:

BaBar:

- *"Search for an Axionlike Particle in B-Meson Decays"*
  Phys. Rev. Lett. 128.131802 (2022)
- *"Search for Heavy Neutral Leptons Using Tau Lepton Decays at BABAR"*
  arXiv:2207.09575 (2022)
- *Search for Darkonium in e+e− Collisions*
  Phys. Rev. Lett. 128 021802 (2022)

Belle II

- *"Search for Lepton-Flavor-Violating τ Decays to a Lepton and an Invisible Boson at Belle II"*
  Phys. Rev. Lett. 130, 181803 (2023)
- *"Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment"*
  Phys. Rev. Lett. 130, 071804 (2023)

BES III

- *"Search for a CP-odd light Higgs boson in $J/\psi \to \gamma A^0$"*
  Phys. Rev. D 105,012008 (2022)
- *"Search for a massless dark photon in $\Lambda_C^+ \to p\gamma'$ decay"*
  Phys. Rev. D 106, 072008 (2022)