Dark Photon Study at BESIII

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on behalf of BESIII Collaboration

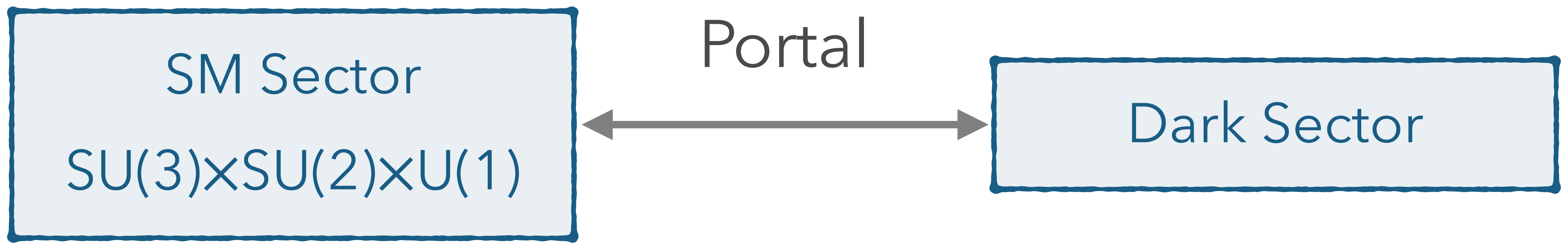
第三届地下和空间粒子物理与宇宙物理前沿问题研讨会

Conference on frontiers of underground and space particle physics and cosmophysics

2024年5月7日-11日，四川西昌

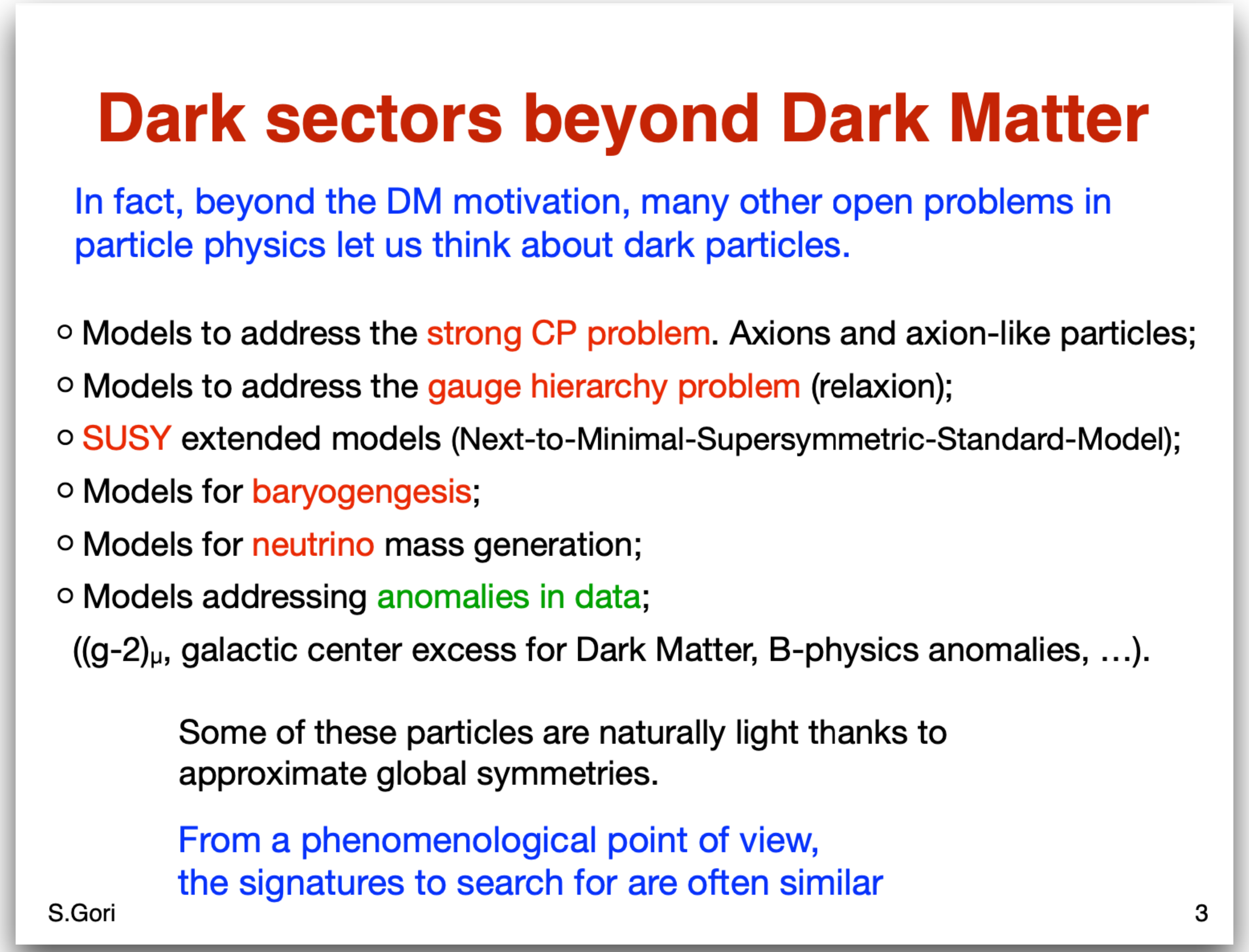
Dark Sector

- Consisting of (light) particles do not interact with the known strong, weak, or electromagnetic forces
- Weakly coupled to visible sector through a mediator or "portal"



Portal	Operators
Dark photon (Spin 1)	$\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$
Axion (Spin 0)	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{f_a} \partial_\mu \bar{\psi} \gamma^\mu \gamma_5 \psi$
Scalar (Spin 0)	$(\mu S + \lambda S^2) H^\dagger H$
Sterile neutrino (Spin 1/2)	$y_N \bar{L} H N$

arXiv:2005.01515v3 [hep-ph]

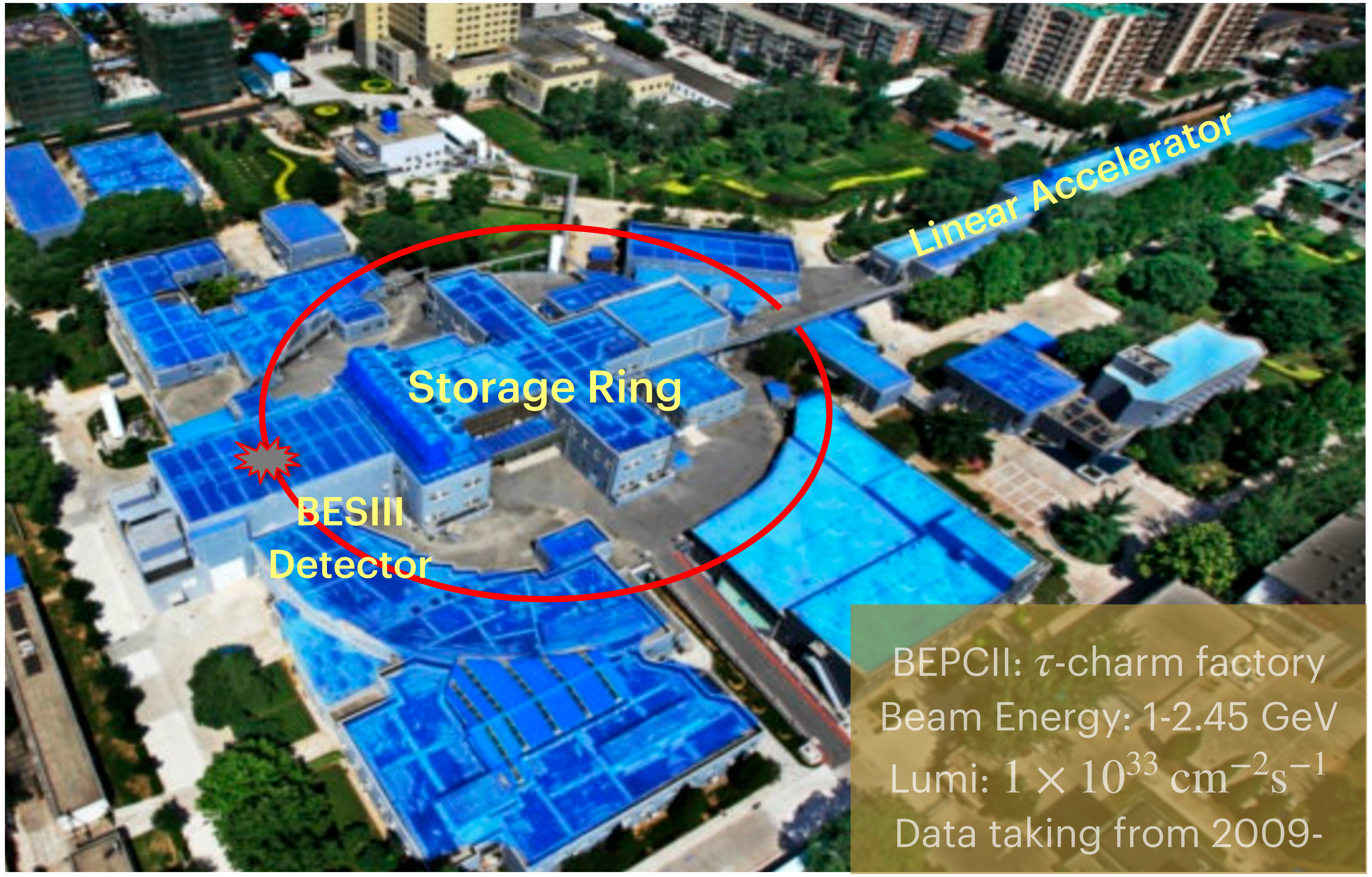


Borrowed from S. Gori, Dark Sector at Snowmass
HPS Collaboration Meeting, Nov.6, 2022

Dark Photon

- New Abelian gauge group U(1) force carrier
- Kinetic mixing with SM U(1) with mixing coefficient ϵ *B. Holdom, PLB 166,196 (1986)*
- Typical mix strength: 10^{-2} - 10^{-5}, could be smaller
- Expected mass scale: MeV/c^2-GeV/c^2, can be accessible by high intensity e^+e^- collider experiments
- Massless dark photon and massive dark photon
  - Massless kind: does not couple directly to any of the SM currents and interacts with ordinary matter only through operators of dimension higher than four
  - Massive kind: couples to ordinary matter through a current

BEPCII and BESIII



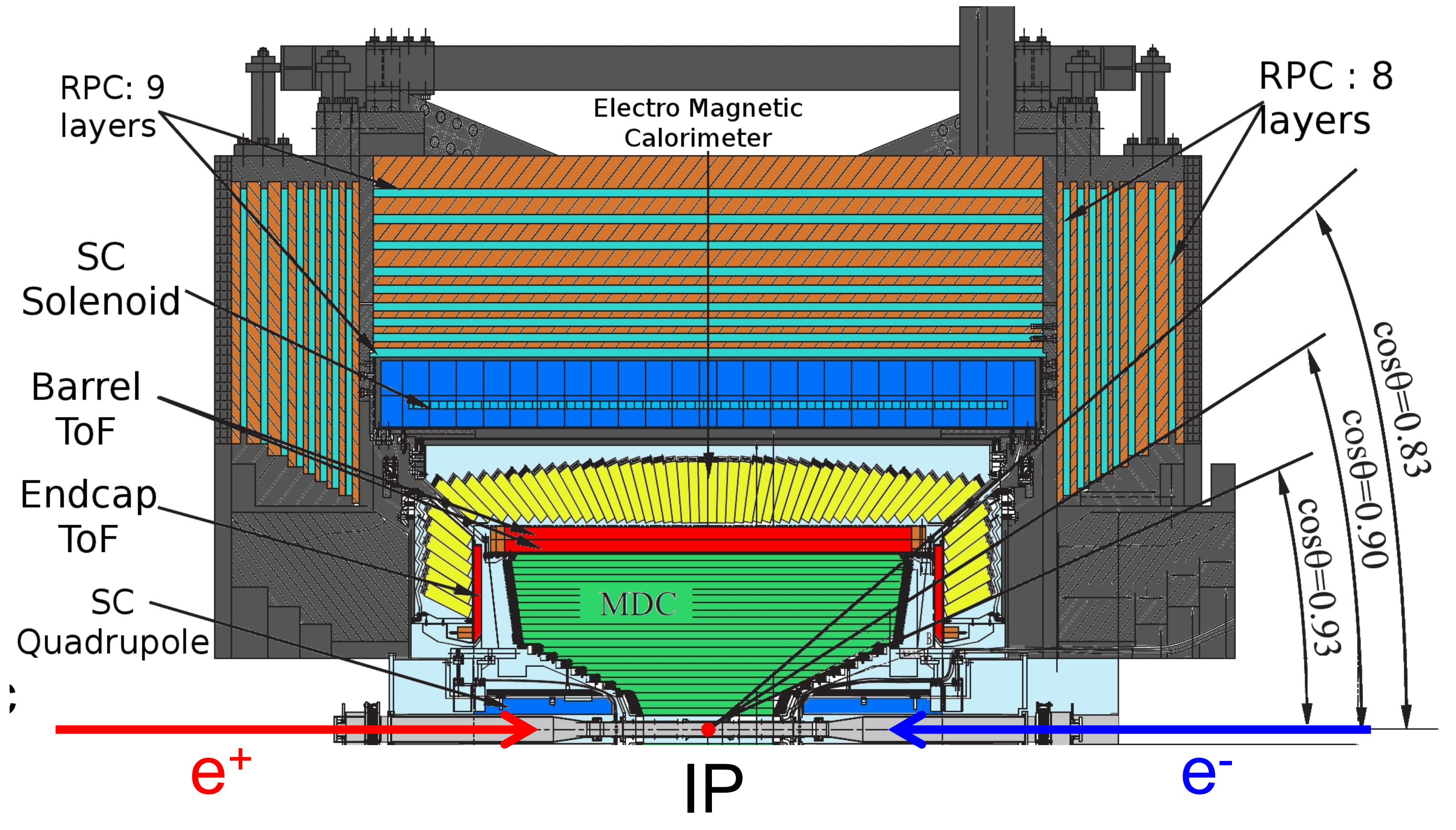
BEPCII: τ-charm factory

Beam Energy: 1-2.45 GeV

Lumi: $1 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Data taking from 2009-

Solenoid Magnet: 0.9/1.0 T



MUC $\sigma_{R\Phi}$: 2 cm

TOF

σ_T :80 ps

110 ps (60 ps)

MDC

dE/dx: 6%

σ_p/p: 0.5% at 1GeV/c

EMC

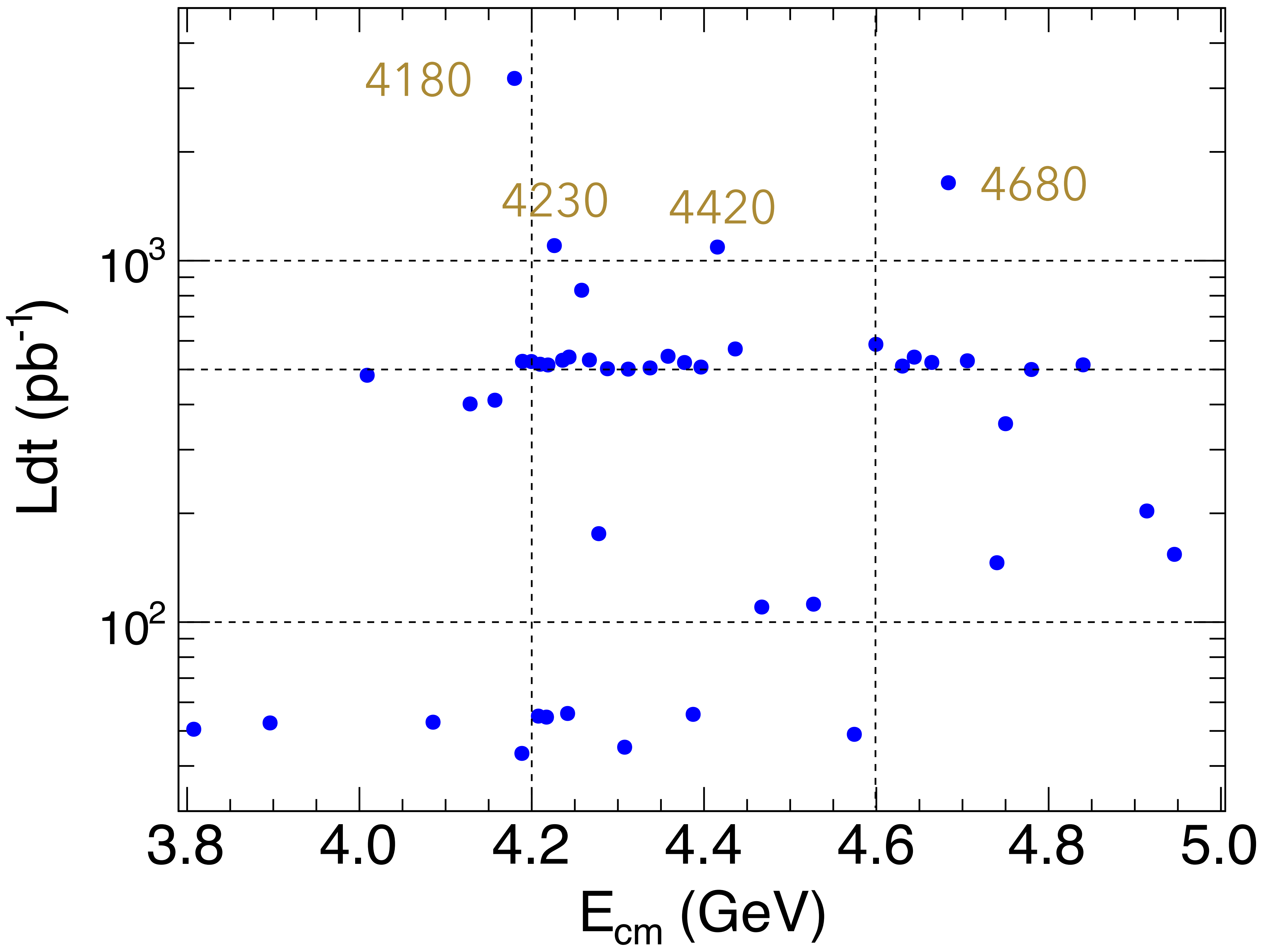
$\Delta E/E$: at 1GeV

2.5%

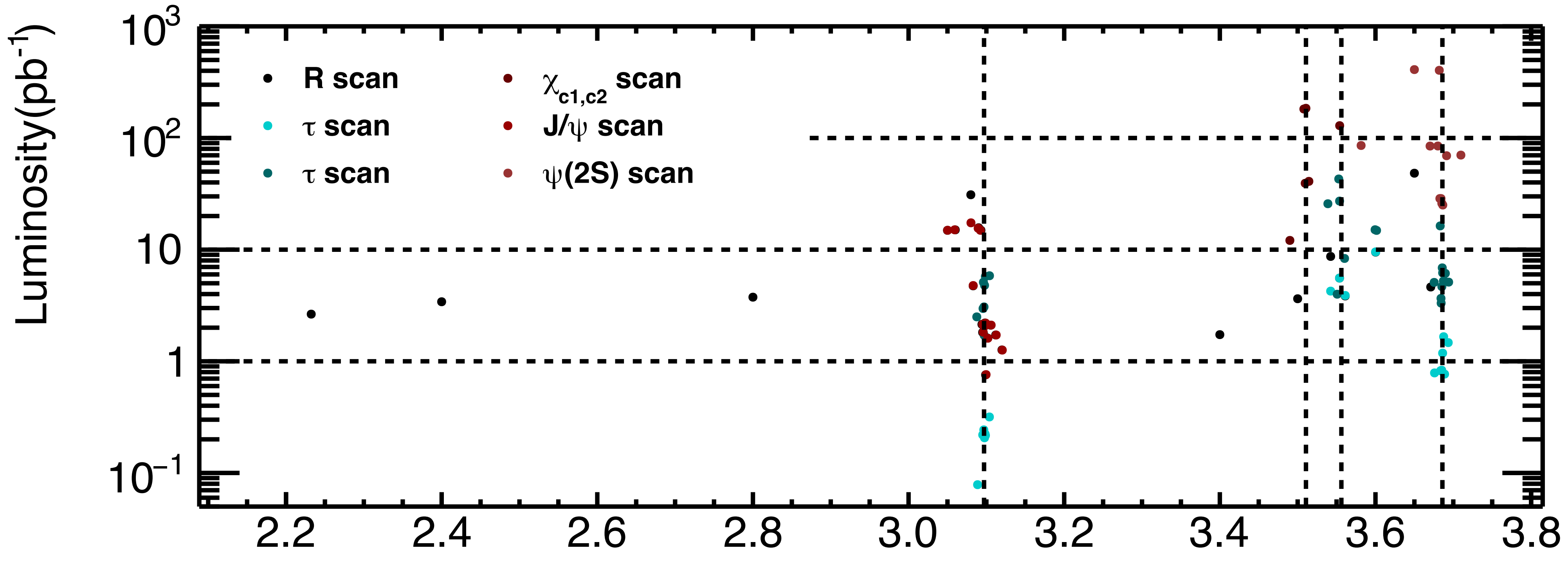
5.0%

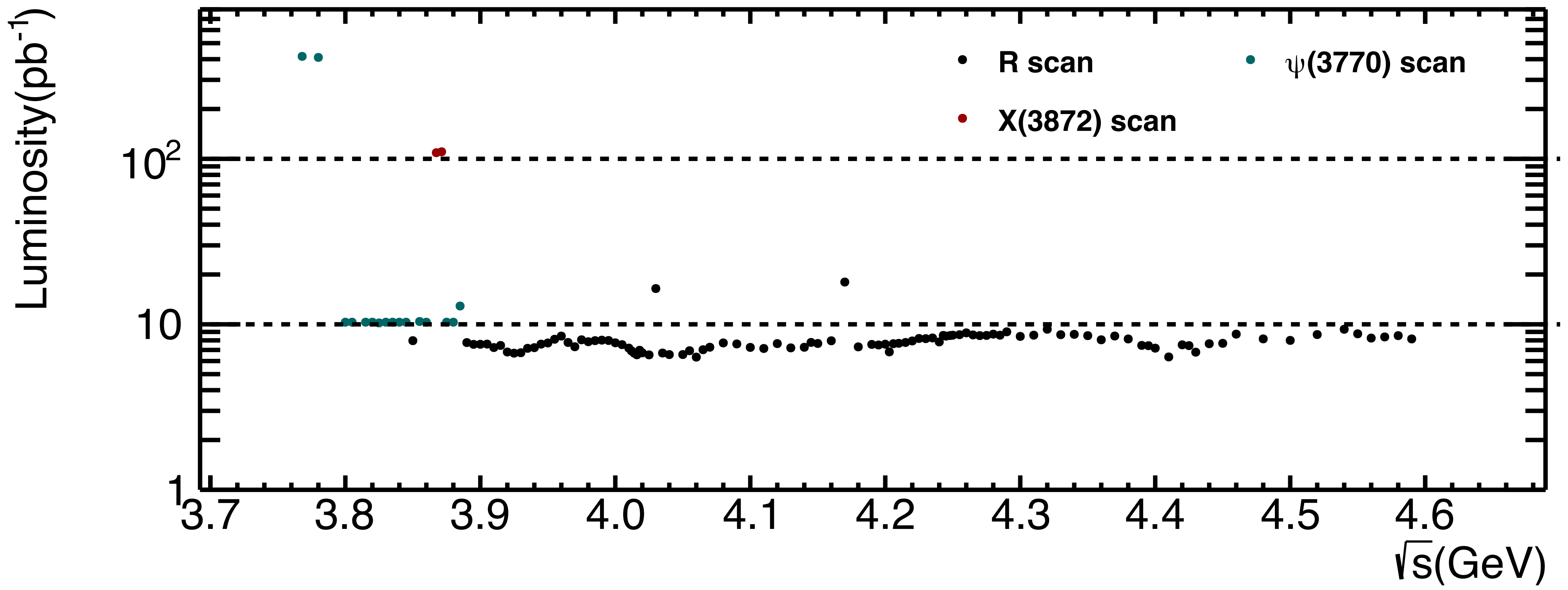
σ_Z: 0.6 cm/$\sqrt{E}$

BESIII Data Samples



46 sample, ~22 fb^{-1}





+ Small scan sample, ~3.5 fb^{-1}

+ 10 Billion J/ψ, 2.7 Billion $\psi(3686)$, 20 fb^{-1} $\psi(3770)$

Dark Photon Studies at BESIII

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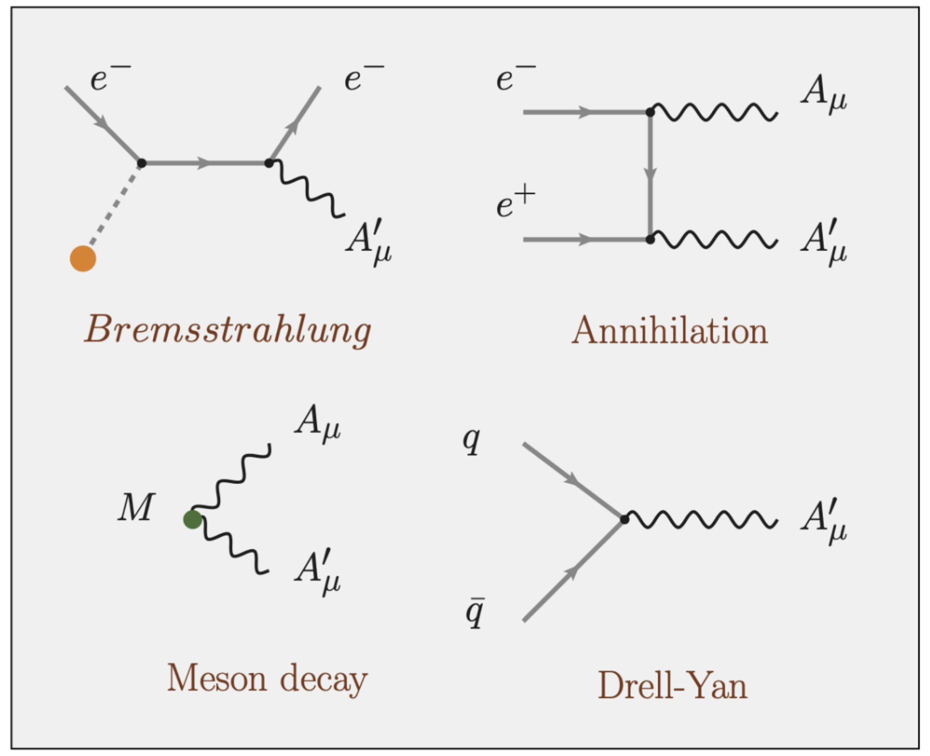
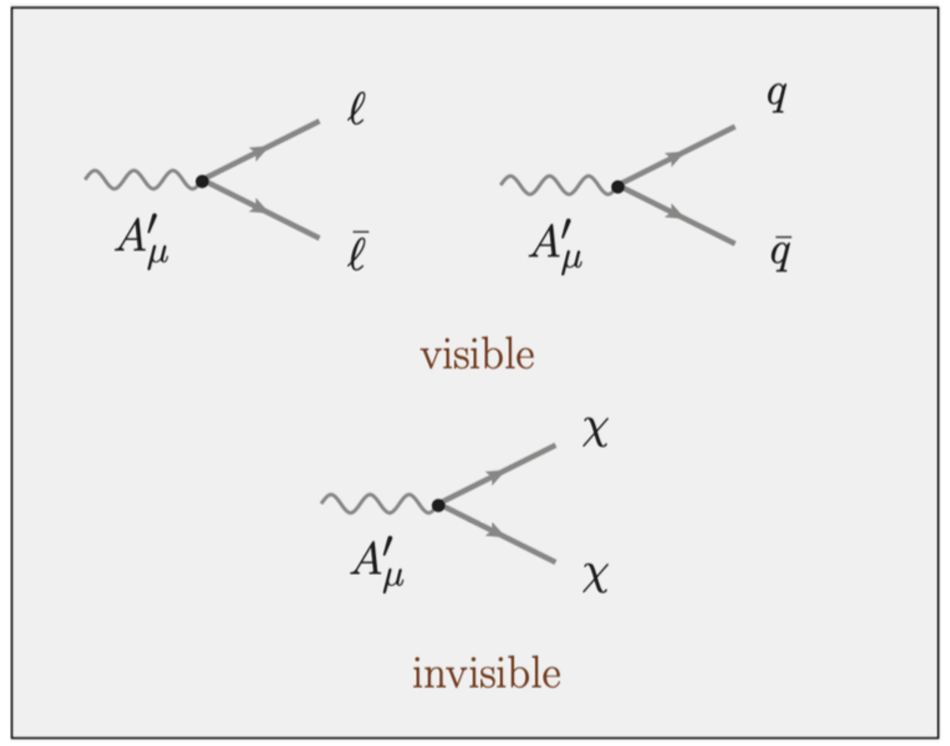
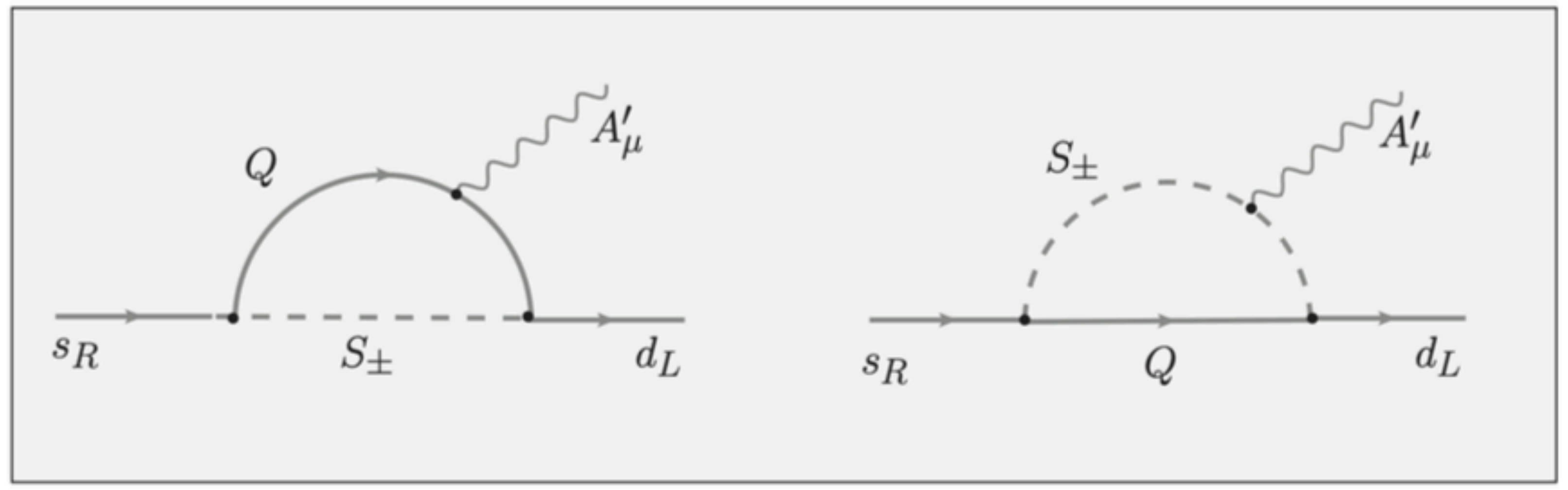
- Massive dark photon
  - $e^+e^- \to \gamma\gamma', \gamma' \to l^+l^-$ PLB774, 252 (2017)
  - $J/\psi \to \gamma'\eta, \gamma' \to e^+e^-$ PRD99, 012006 (2019)
  - $J/\psi \to \gamma'\eta', \gamma' \to e^+e^-$ PRD99, 012013 (2019)
  - $e^+e^- \to \gamma\gamma', \gamma \to$ invisible PLB839, 137785 (2023)
  - $J/\psi \to \gamma'\eta', \gamma' \to \gamma\pi^0$ PRD102, 052005 (2022), not included in this talk





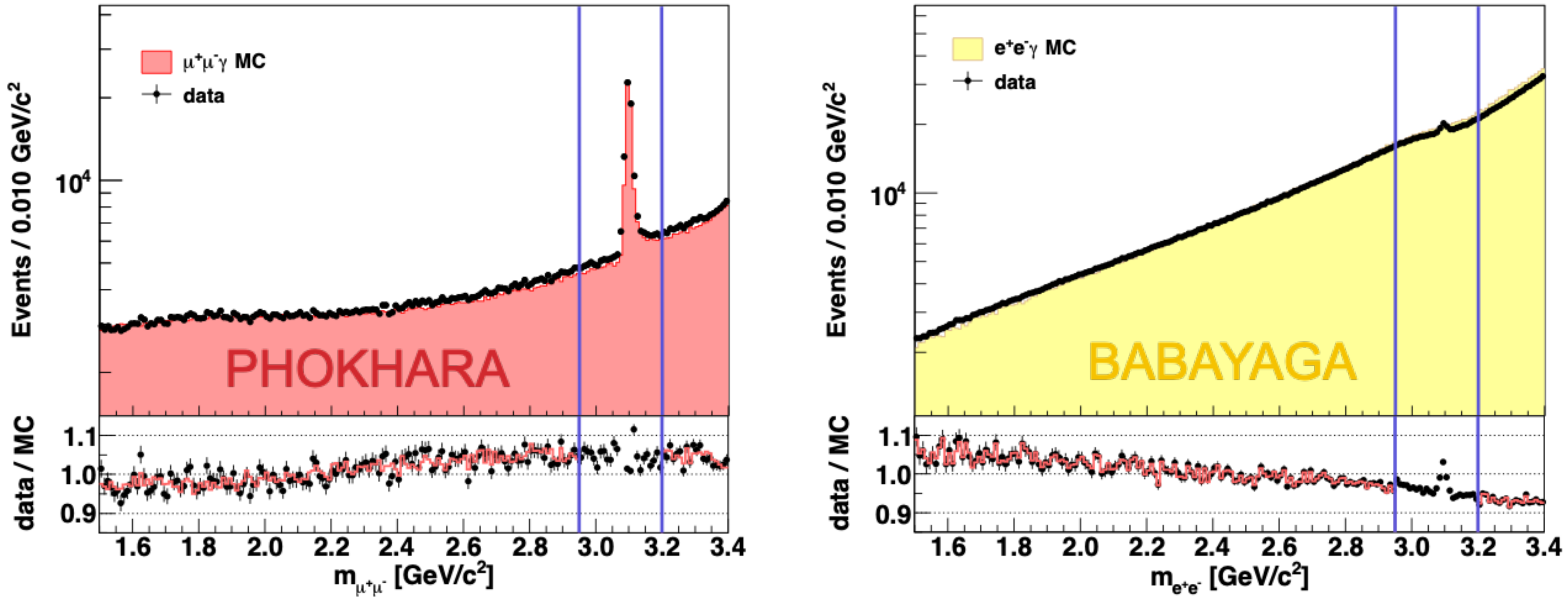
- Massless dark photon in hyperon decays
  - $\Lambda_c \to p+$invisible PRD106, 072008 (2002)
  - $\Sigma \to p+$invisible PLB852, 138614 (2024)

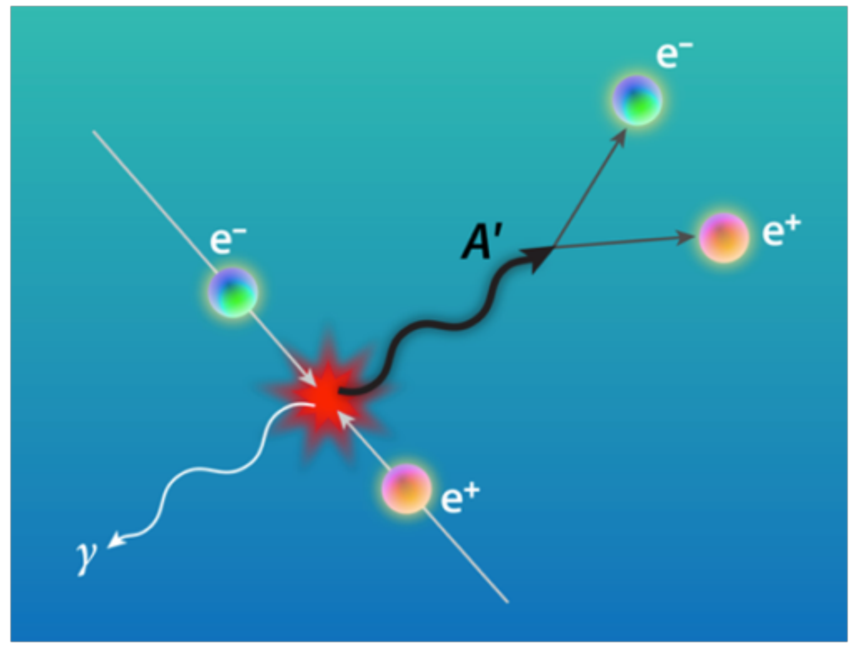


Massive Dark Photon Decays to Lepton Pair

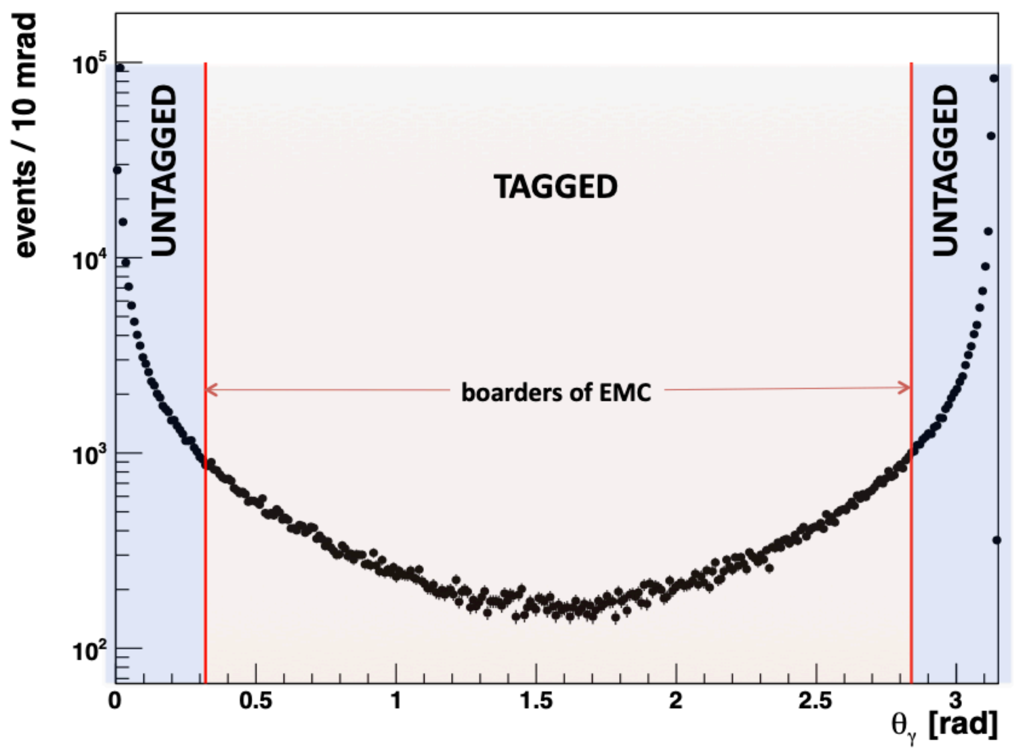
- $e^+e^- \to \gamma_{\rm ISR}\gamma', \gamma' \to l^+l^-$, based on 2.93 fb^{-1} data sample taken at $\psi(3770)$, untagged method
- Search for narrow structure on top of the continuum QED background

PLB774, 252 (2017)





APS/Alan Stonebreaker



- Cover mass region: 1.5 GeV/c^2 to 3.4 GeV/c^2
  - <1.5 GeV/c^2: $\pi^+\pi^-$ background dominant
  - >3.4 GeV/c^2: hadronic $q\bar{q}$ background dominant

Massive Dark Photon Decays to Lepton Pair

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- Number of signal events determined by fitting the $M(l^+l^-)$ distribution, combined statistical significance less then 3σ in the explored mass region
- 90% confidence level limit obtained with profile likelihood approach with systematic uncertainty included
- Kinetic mixing parameter ϵ determined with

Mixing coefficient

Number of dark photon events

Dark photon mass

$$\frac{\sigma_i(e^+e^- \to \gamma'\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR})}{\sigma_i(e^+e^- \to \gamma^*\gamma_{\rm ISR} \to l^+l^-\gamma_{\rm ISR})} = \frac{3\pi}{2N_f^{l^+l^-}} \cdot \frac{\varepsilon^2}{\alpha} \cdot \frac{m_{\gamma'}}{\delta_m^{l^+l^-}}$$

Number of QED events from annihilation process

Bin width

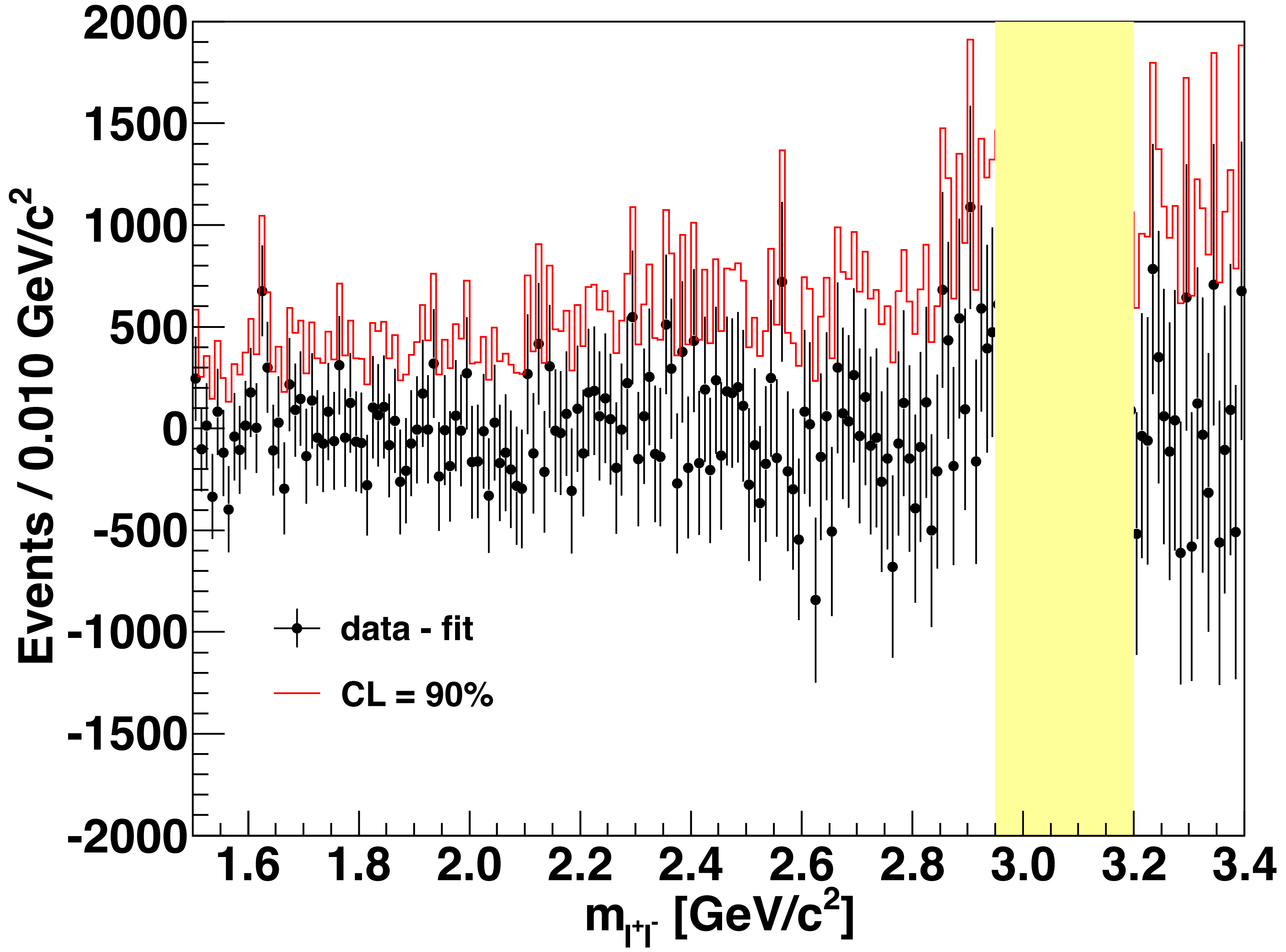
Fine structure constant

Ratio of possible decay channels of the dark photon and the phase space

$$N_f^{l^+l^-} = \frac{\Gamma_{\rm tot}}{\Gamma(\gamma' \to l^+l^-)} = 1 + \frac{\Gamma_{\mu\mu}}{\Gamma_{ee} + \Gamma_{\mu\mu}} \cdot (1 + R(\sqrt{s}))$$

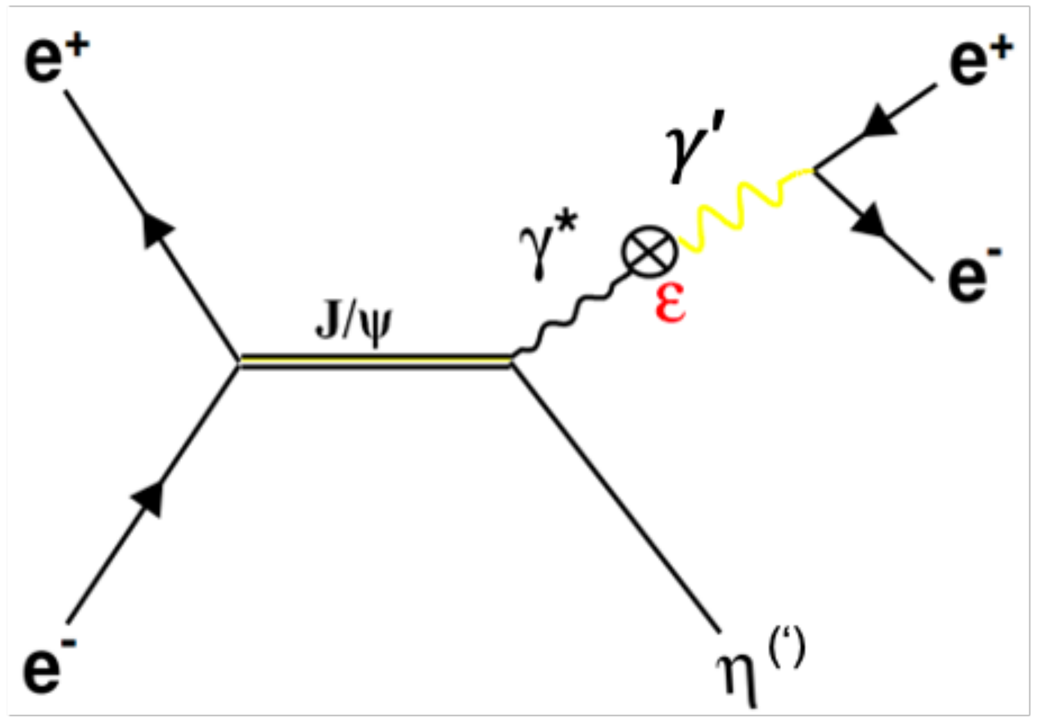
J. D. Bjorken, R. Essig, P. Schuster, N. Toro, PRD 80, 075018 (2009)

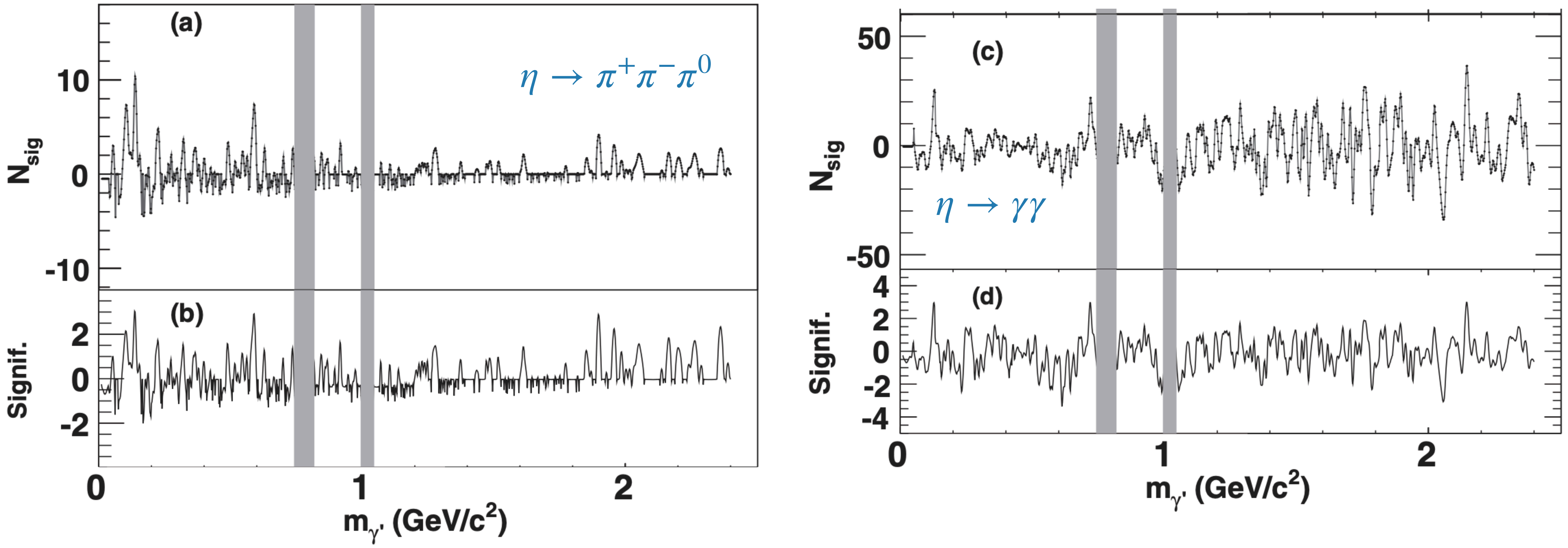
PLB774, 252 (2017)

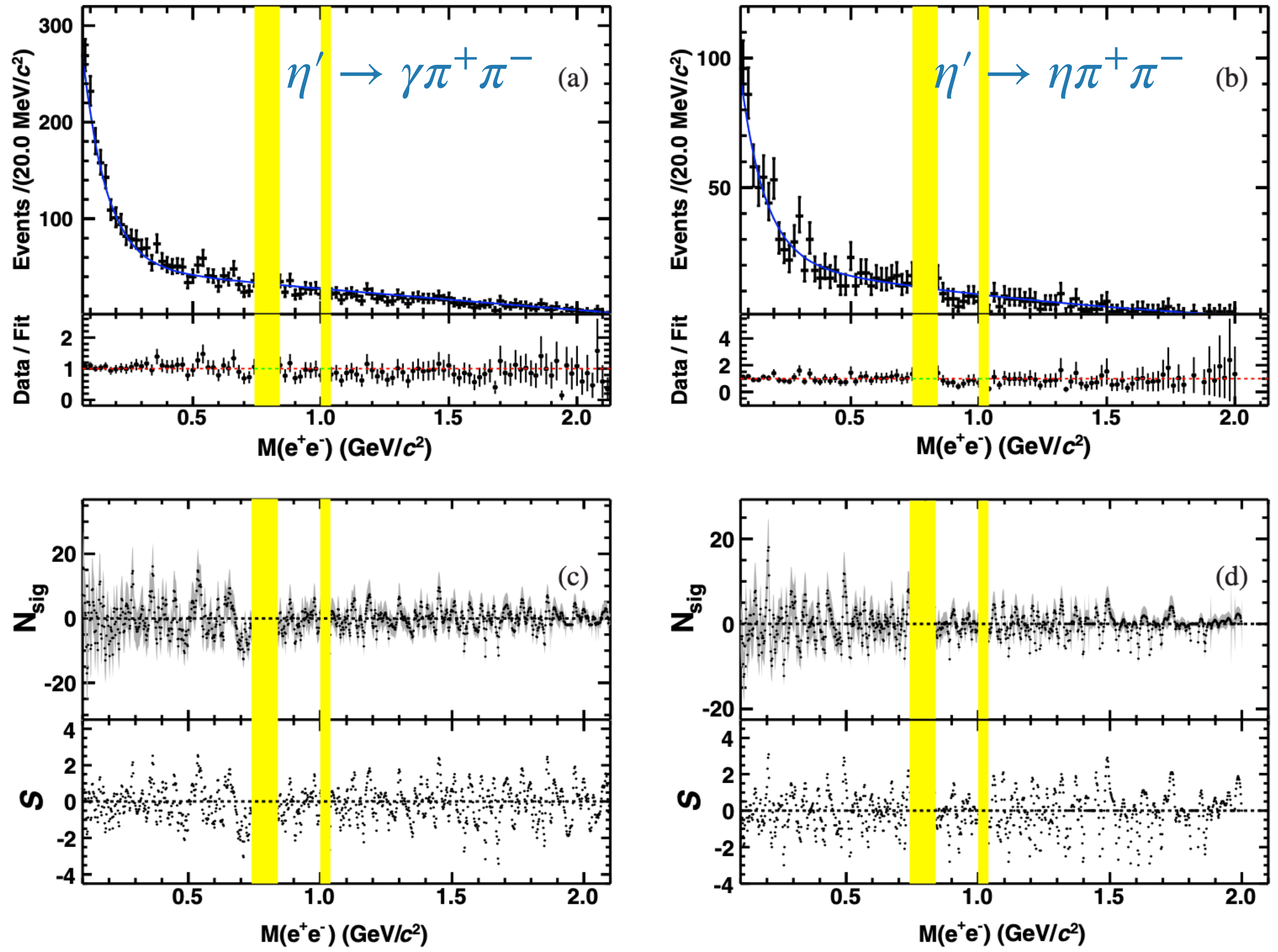


Massive Dark Photon Decays to Lepton Pair

- Electromagnetic (EM) Dalitz decay, based on $(1310.67 \pm 7.0) \times 10^6$ J/ψ events
  - $J/\psi \to \gamma'\eta \to e^+e^-\eta, \eta \to \gamma\gamma/\pi^+\pi^-\pi^0$ PRD99, 012006 (2019)
  - $J/\psi \to \gamma'\eta' \to e^+e^-\eta', \eta' \to \gamma\pi^+\pi^-/\eta\pi^+\pi^-$ PRD99, 012013 (2019)
  - Fit to $M(e^+e^-)$ distribution in 2 MeV/c^2 step, exclude ρ, ω, ϕ mass region
  - $M(\gamma') \in [0.01, 2.40]$ GeV/c^2 in η mode, $[0.07, 2.13]$ GeV/c^2 in η' mode







Massive Dark Photon Decays to Lepton Pair

Branching fraction of J/ψ→γ'η(')

Dark photon mass

Mixing coefficient

$$\frac{B(J/\psi \to \gamma'\eta^{(\prime)})}{B(J/\psi \to \gamma\eta^{(\prime)})} = \varepsilon^2 |F_{J/\psi\eta^{(\prime)}}(m^2_{\gamma'})|^2 \cdot \frac{\Lambda^{3/2}(m^2_{J/\psi}, m^2_{\eta^{(\prime)}}, m^2_{\gamma'})}{\Lambda^{3/2}(m^2_{J/\psi}, m^2_{\eta^{(\prime)}}, 0)}$$

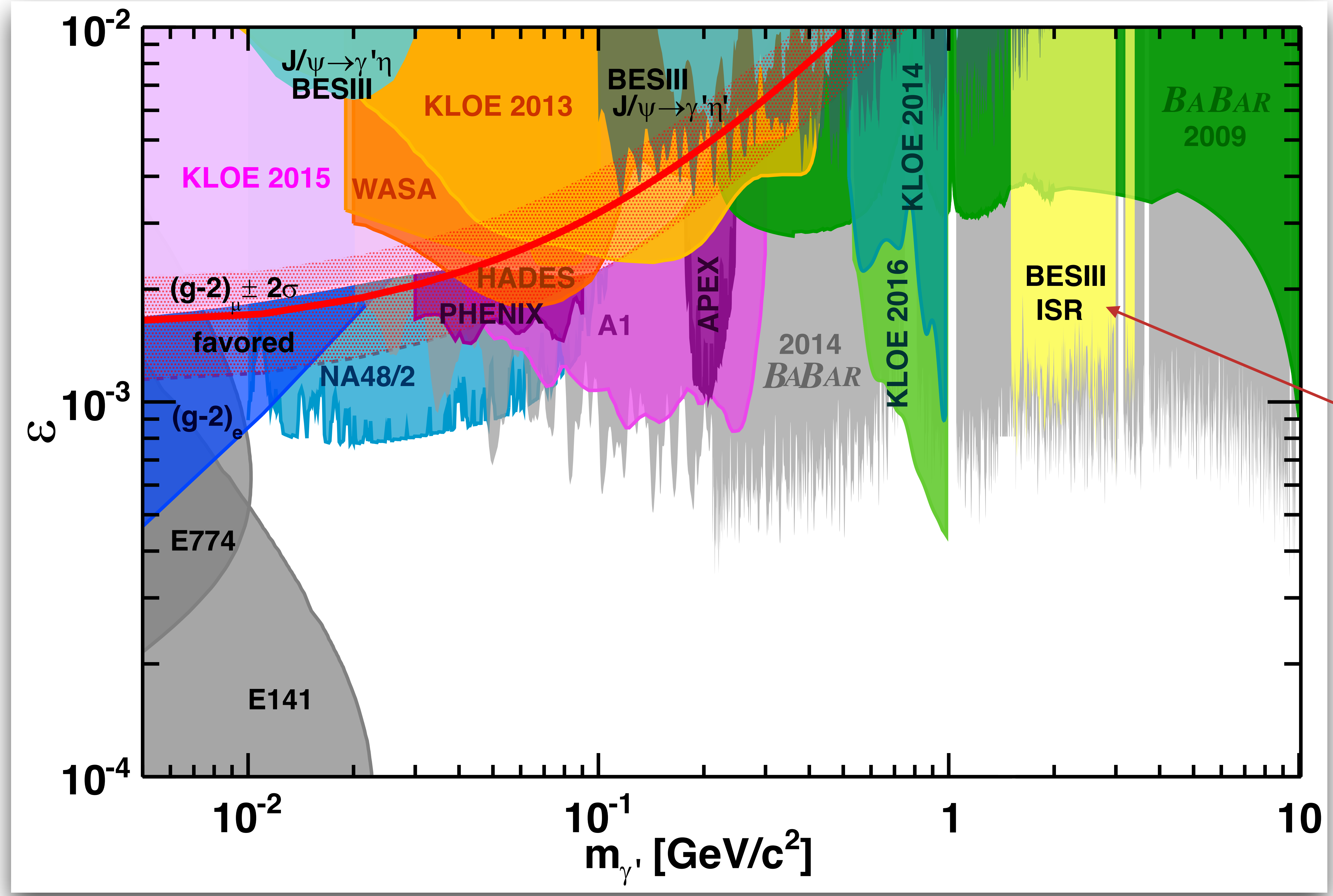
Branching fraction of J/ψ→γη(')

$$\Lambda^{3/2}(m_1^2, m_2^2, m_3^2) = (1 + \frac{m_3^2}{m_1^2 - m_2^2})^2 - \frac{4m_1^2 m_3^2}{(m_1^2 - m_2^2)^2}$$

Form factor for J/ψ→γ*η(') transition
evaluated at γ' mass

M. Reece and L. T. Wang JHEP07, 051 (2009)

Kinetic Mixing Coefficient ϵ



$\epsilon < (0.6 - 2.0) \times 10^{-3}$

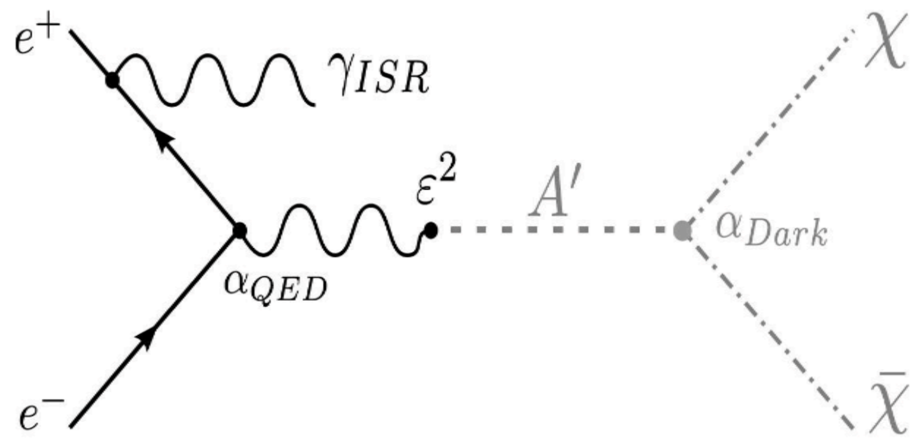
for $m_{\gamma'} \in [1.5, 3.4]$ GeV/c^2

Results compatible with BaBar measurement based on 514 fb^{-1} Υ data sample

Larger $\psi(3770)$ (2.93 ⇒ 20 fb^{-1}) and J/ψ (1 billion ⇒ 10 billion) data sample already collected

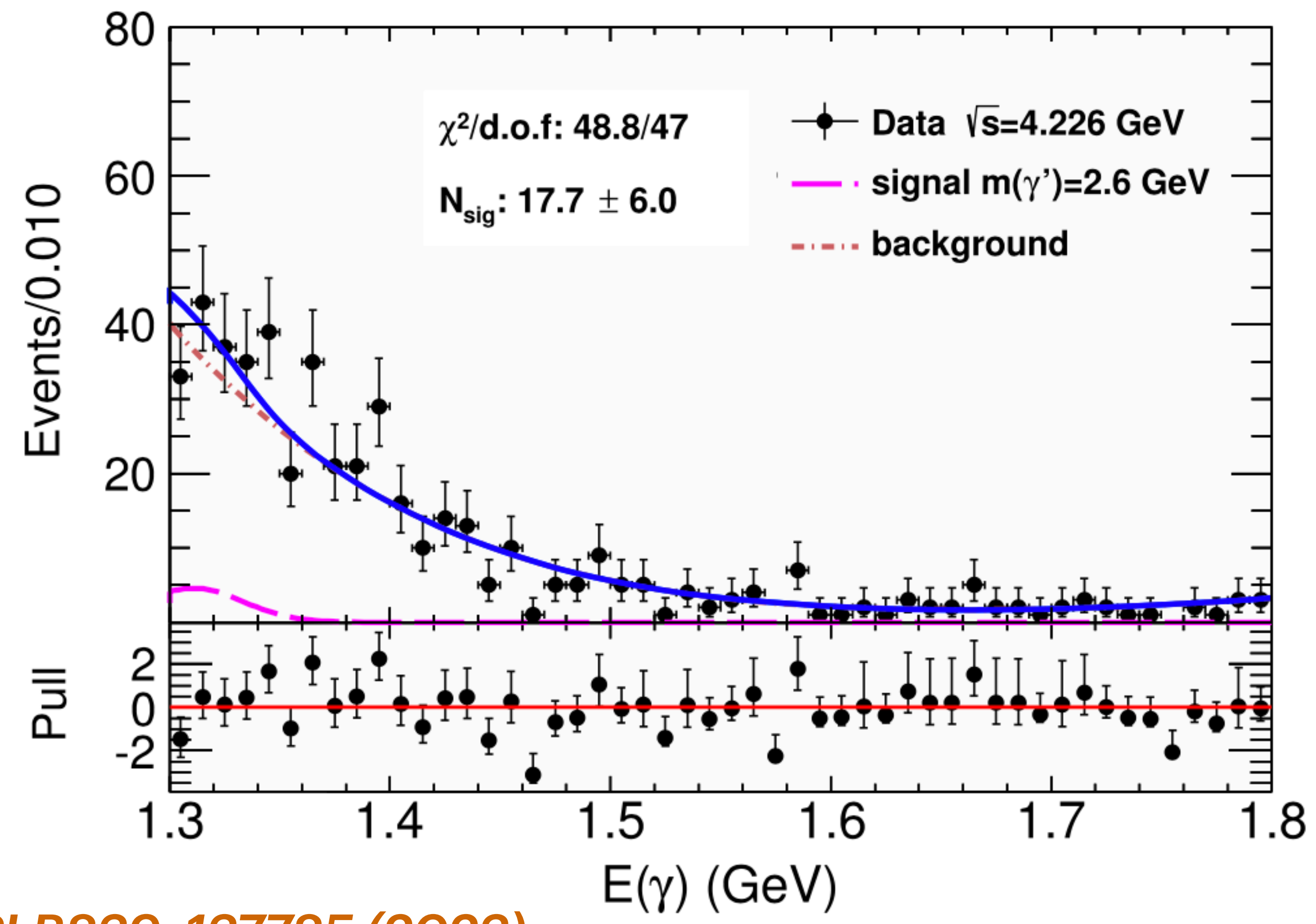
Massive Dark Photon Decays to Invisible

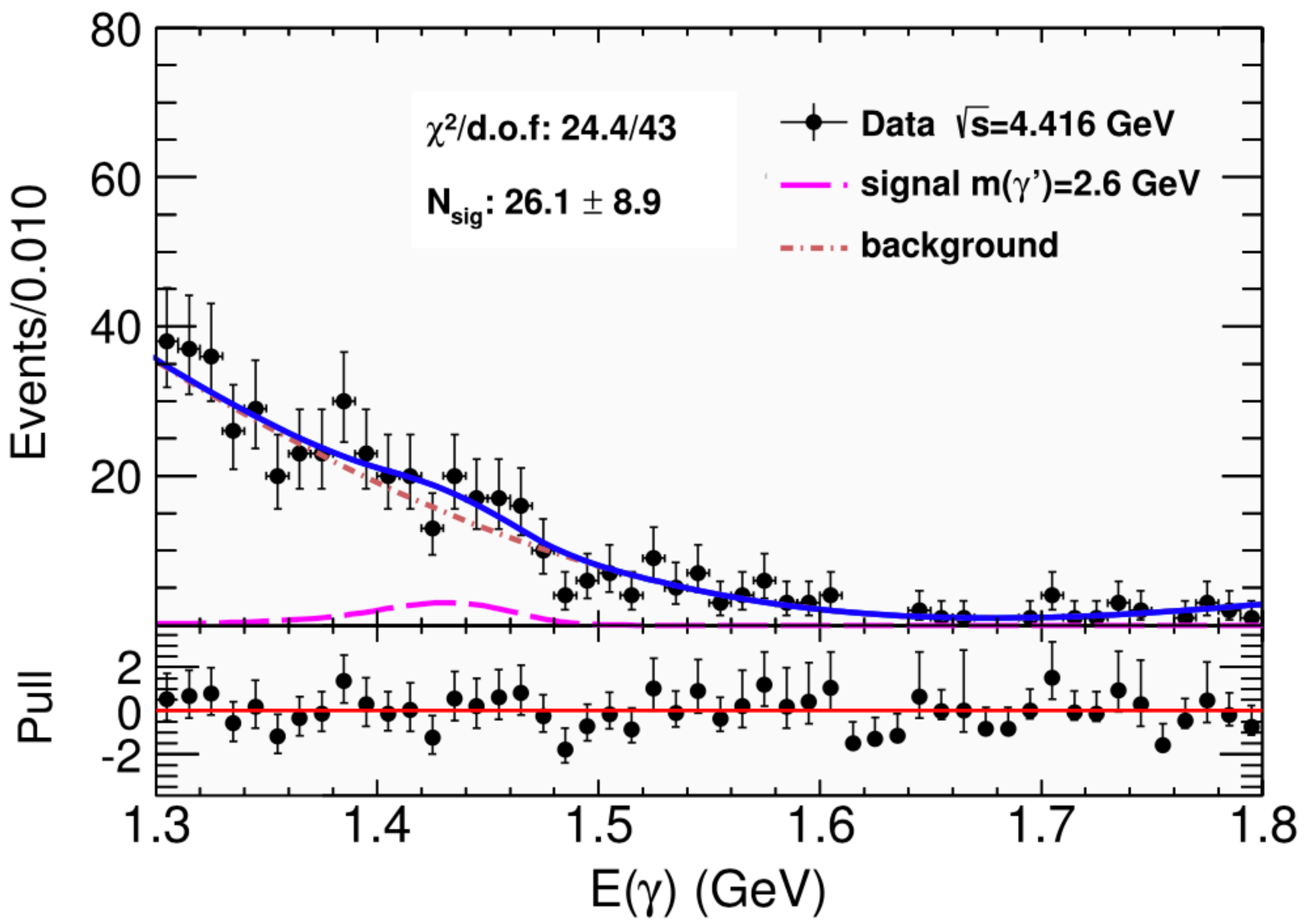
- Based on 14.9 fb^{-1} data sample taken at $\sqrt{s} = 4.13 - 4.60$ GeV
- Dark photon candidate would be signified by the presence of a the monochromatic photon $E_\gamma = \frac{s - m_{\gamma'}^2}{2\sqrt{s}}$
- $E(\gamma)$<1.3 GeV discarded due to low trigger efficiency
- Maximum local significance: 3.1σ at $m_{\gamma'} = 2.6$ GeV/c^2



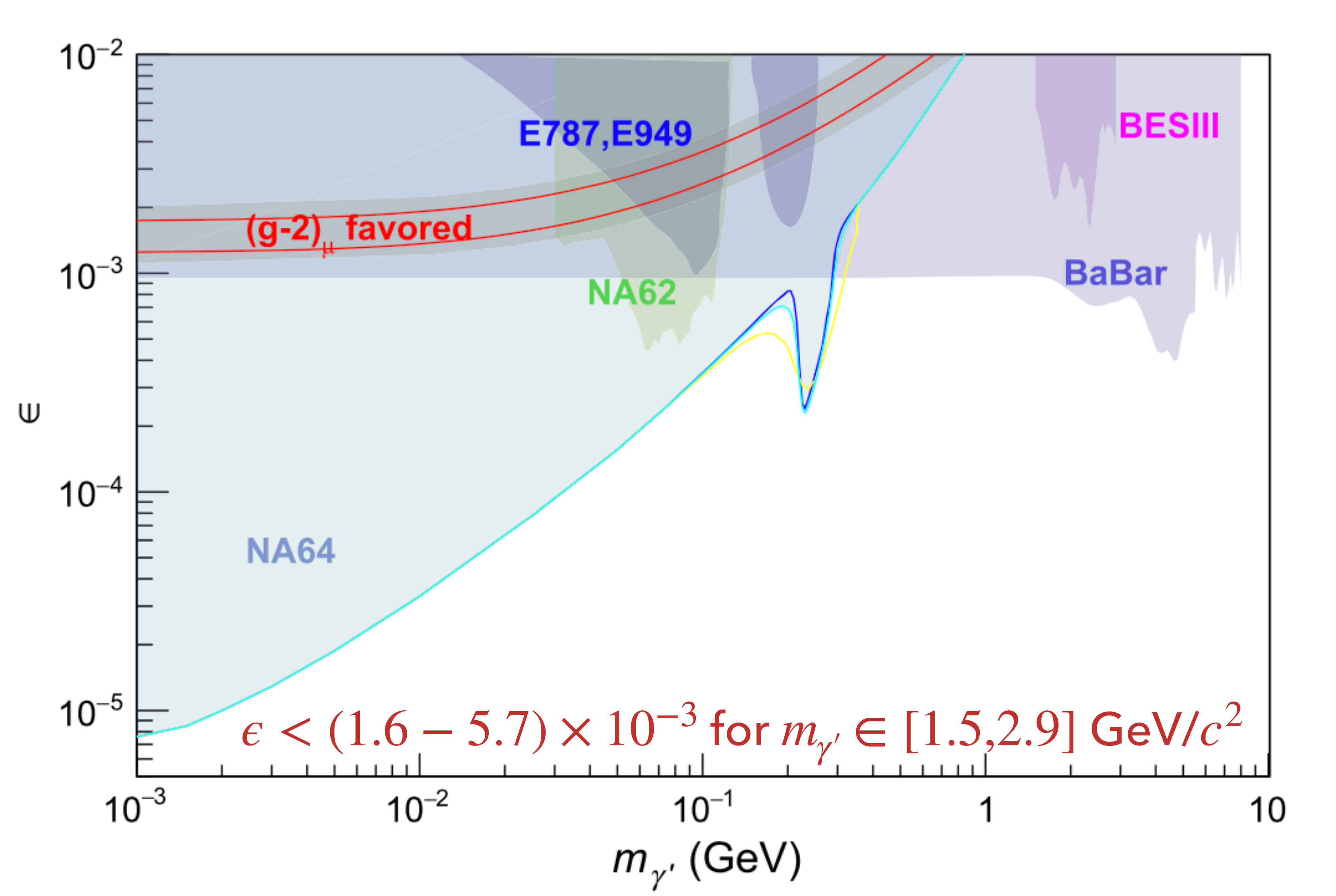
$$\sigma(e^+e^- \to \gamma\gamma') = \frac{2\pi\alpha^2}{s}\epsilon^2((1 + \frac{2x}{(1-x)^2})\log\frac{(1+\cos\theta_c)^2}{(1-\cos\theta_c)^2} - 2\cos\theta_c)$$

R. Essig, P. Schuster, N. Toro, PRD 80, 015003 (2009)





PLB839, 137785 (2023)



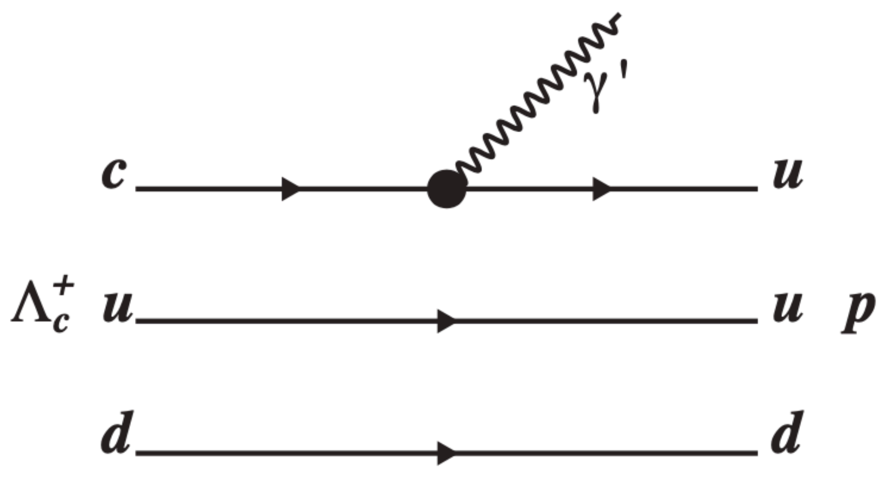
Massless Dark Photon in Λ_c Decays

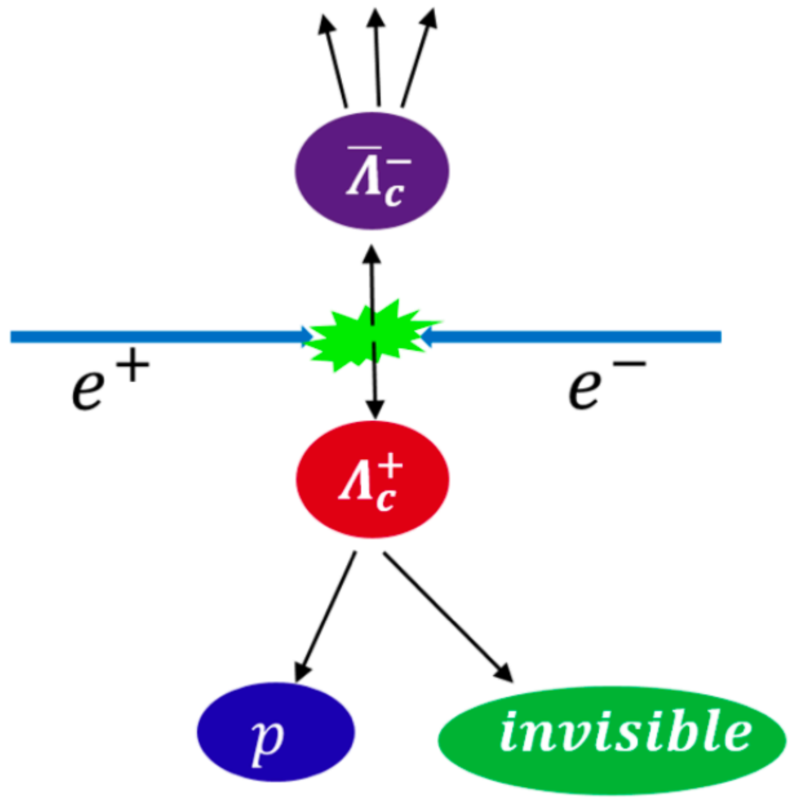
- The massless dark photon is a gauge boson associated with a new unbroken $U(1)_d$ symmetry

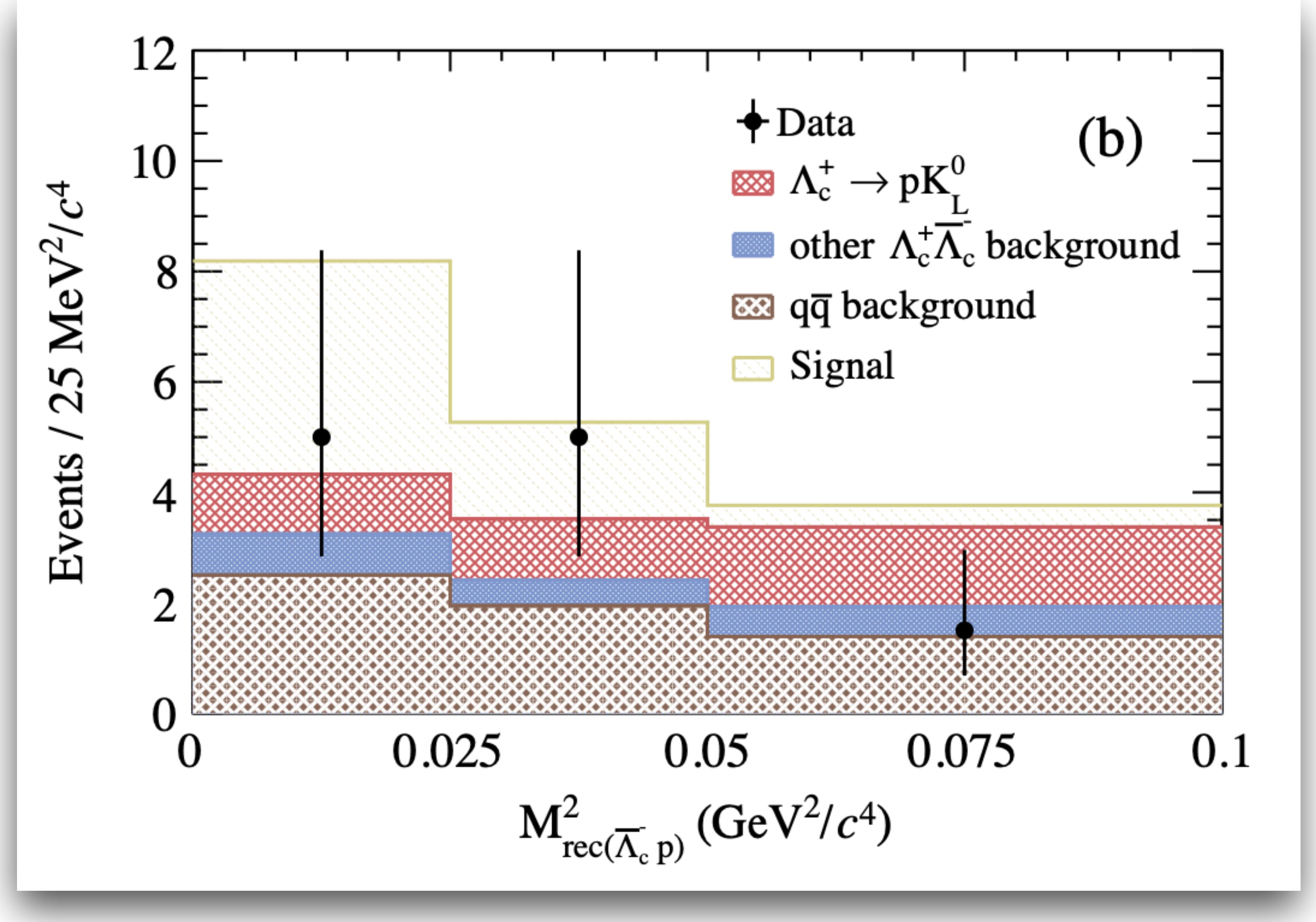
B. Holdom, PLB 166,196 (1986)

B. A. Dobrescu, PRL94, 151802 (2005)

- Do not interact with SM particle directly, but can exert influence on the SM via higher-dimensional operators generated by loop diagrams
  - May enhance the branching fractions of flavor changing neutral current (FCNC) decays
- Based on 4.5 fb^{-1} data sample at $\sqrt{s} = 4.6 - 4.7$ GeV







105244 ± 384 tagged $\Lambda_c\bar{\Lambda}_c$ pair

$$B(\Lambda_c^+ \to p\gamma') = \frac{N_{\rm obs} - N_{\rm bkg}}{\sum_i N_i^{\rm ST} \cdot (\epsilon_i^{\rm DT}/\epsilon_i^{\rm ST})}$$

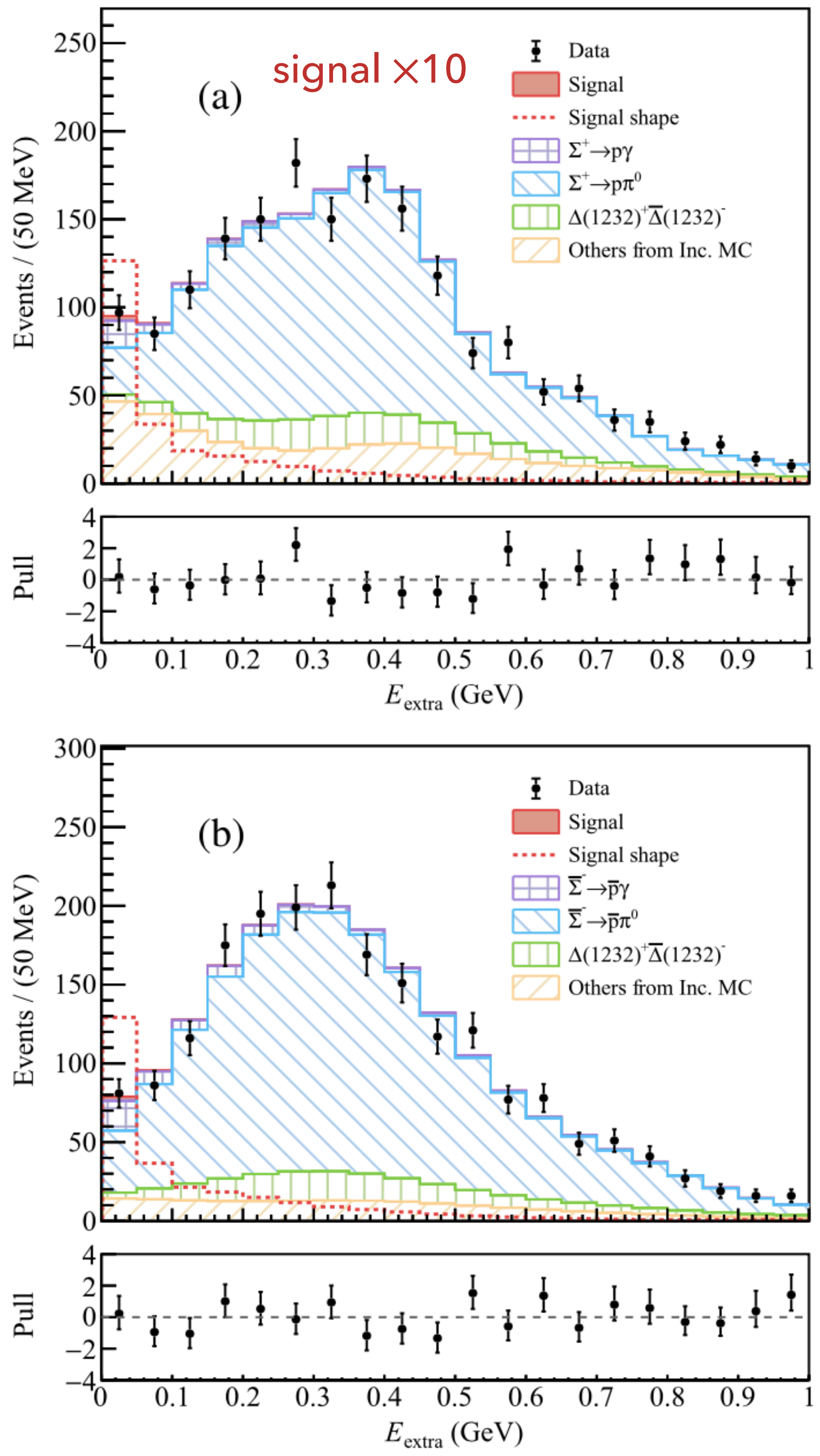
$N_{\rm obs} = 13, N_{\rm bkg} = 14.6 \pm 1.5$

$B(\Lambda_c^+ \to p\gamma') < 8.0 \times 10^{-5}$ at 90% C.L.

Massless Dark Photon in Σ Decays

- Based on 10 billion J/ψ events, about 4 million tagged $\Sigma^{\pm}$ using $p\pi^0$ mode
- In search for massless dark photon, QCD axion, …
- $B_{\mathrm{sig}} = \dfrac{N_{\mathrm{DT}}^{\mathrm{obs}}/\epsilon_{\mathrm{DT}}}{N_{\mathrm{ST}}^{\mathrm{obs}}/\epsilon_{\mathrm{ST}}}$
- DT signal extracted from the missing energy, defined as $E_{\mathrm{extra}} = E_{\mathrm{extra}}^{\mathrm{DT}\pi^0/\gamma} + E_{\mathrm{extra}}^{\mathrm{other}}$
  - $E_{\mathrm{extra}}^{\mathrm{DT}\pi^0/\gamma}$ expected to be 0 for signal events
  - $E_{\mathrm{extra}}^{\mathrm{other}}$: 93% contribution from interaction between the $\bar{p}$ and the detector, determined using data-driven approach
- $B(\Sigma^+ \to p + \mathrm{invisible}) < 3.2 \times 10^{-5}$

PLB852, 138614 (2024)



Summary

- Electron-Positron colliders provide clean environment for the study of particles beyond SM, in bot visible and invisible decays
- BESIII works on tau-charm energy region, can probe lower mass region, and can provide better mass resolution
- Massive and massless dark photon has been studied in visible or invisible final states, based on part of the data samples
- More results to be expected in the near future, with larger data samples

Thank You!