Dark Photon Searches at BESIII

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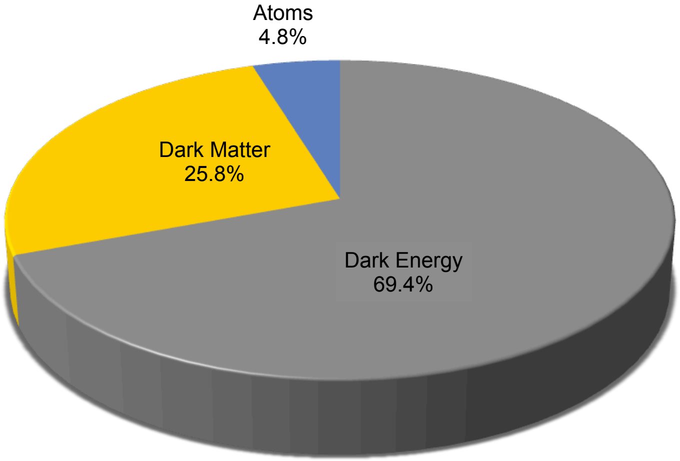
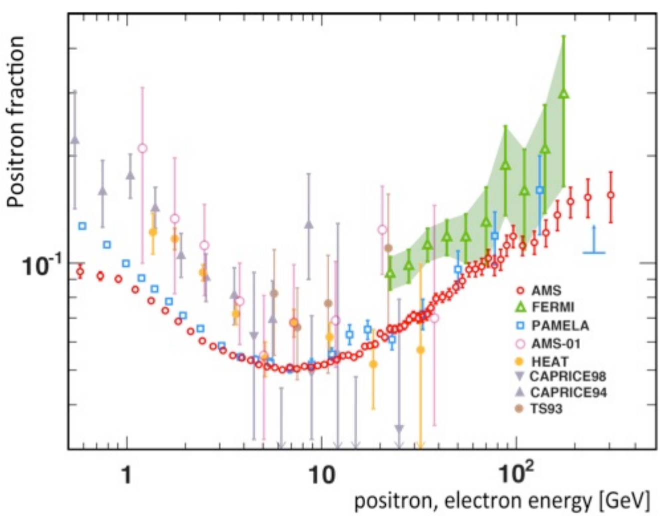
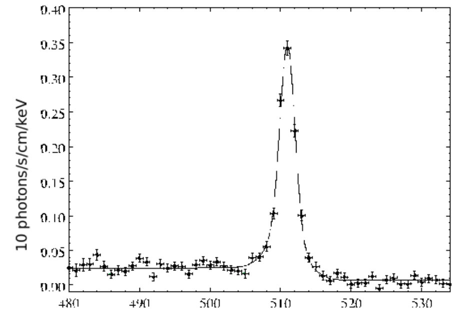
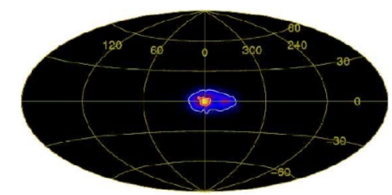
PANIC2017, Beijing, Sep 1 2017

Motivation for Dark Sector



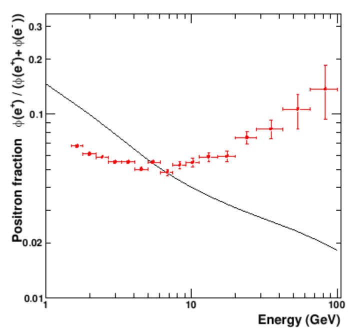






511 keV line - sky map

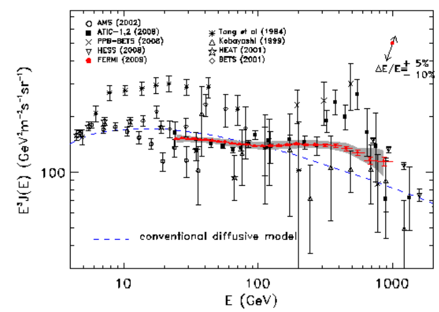
G. Weidenspointner et al., Nature **451** (2008) 159



PAMELA: positron fraction

(confirmed by Fermi)

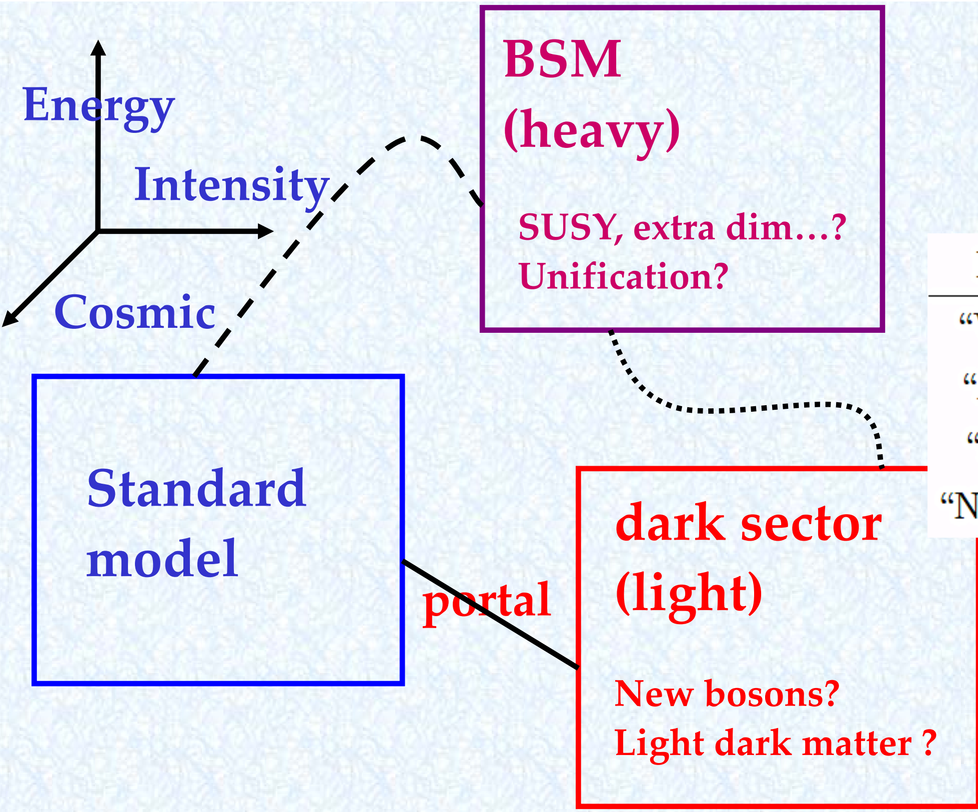
O. Adriani et al., Nature **458** (2009) 607



Fermi: $e^+ + e^-$ spectrum

A.A. Abdo et al., Phys. Rev. Lett. **102** (2009) 181101

Dark sector and portal



It is also referred as to heavy photon, hidden photon, A’, γ’ or U boson in the literature

Portal	Particles	Operator(s)
“Vector”	Dark photons	$-\frac{\epsilon}{2\cos\theta_W}B_{\mu\nu}F'^{\mu\nu}$
“Axion”	Pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\widetilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i\mu\nu}\widetilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
“Higgs”	Dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
“Neutrino”	Sterile neutrinos	$y_N LHN$

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan Krnjaic (DMA Convener),[7] Jeremy Mardon (DD Convener),[8] David Morrissey (RDS Convener),[9] Tim Nelson (Organizer),[5,§] Maxim Perelstein (VDP Convener),[1] Matt Pyle (DD Convener),[10] Adam Ritz (DMA Convener),[11] Philip Schuster (Organizer),[5,6,¶] Brian Shuve (RDS Convener),[5] Natalia Toro (Organizer),[5,6,**] Richard G Van De Water (DMA Convener),[12] … [15] David

arxiv: 1608.08632

The Jefferson Lab's Free-Electron Laser is a low-cost option in the bid to discover dark-se

PARTICLE PHYSICS

Physicists hunt for dark forces

NATURE
2012.4

Dark photon: characteristics

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{DM} \otimes \ldots$$

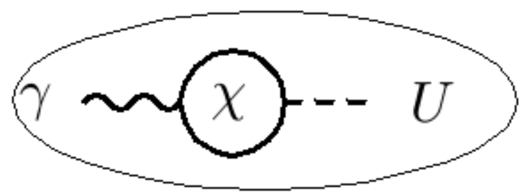
$$\mathcal{L}_{SM} = \mathcal{L}^F_{SM} + \mathcal{L}^B_{SM} + \mathcal{L}^H_{SM}$$

$$\mathcal{L}_{DM} = \mathcal{L}^F_{DM}(\chi) \Rightarrow M_\chi \sim 100 - 1000 \text{ GeV WIMP}$$

$$+ \ \mathcal{L}^B_{DM}(\mathbf{U}) \Rightarrow m_U \sim \text{GeV } \textbf{Dark Photon U or } V, A' \ldots$$

$$+ \ \mathcal{L}^B_{DM}(h') \Rightarrow \text{Higgs potential breaking } U(1)_{DM}$$

$$\mathcal{L}_{mix} = \epsilon F^{\mu\nu DM} F^{EM}_{\mu\nu}$$

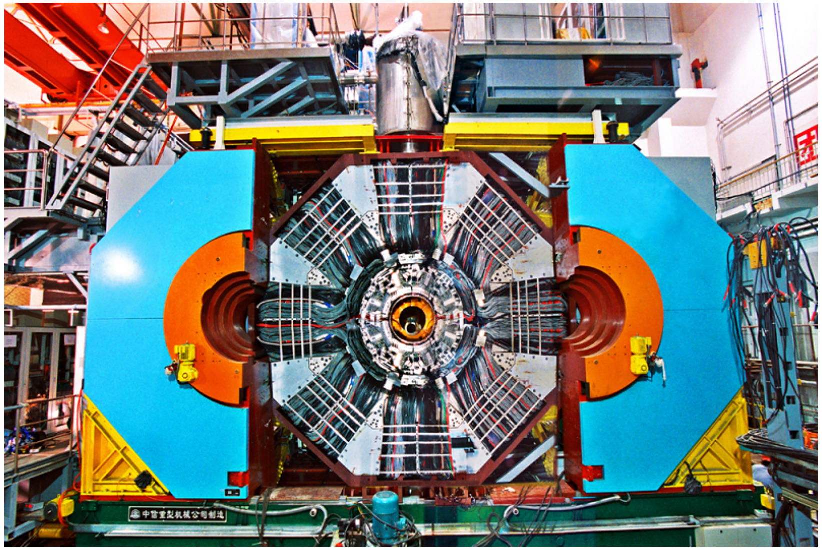


$$+ \ \text{Higgs–Dark Photon int.} + \ldots$$

ϵ (or κ): **kinetic mixing parameter** $\epsilon \sim 10^{-3} \longrightarrow$ milli–charged SM fermions with coupling ϵe to the dark photon (neglecting mixing with the Z)

Low energy, high luminosity e+ e- colliders are believed to be good places to search new physics models with dark sector phenomenology.

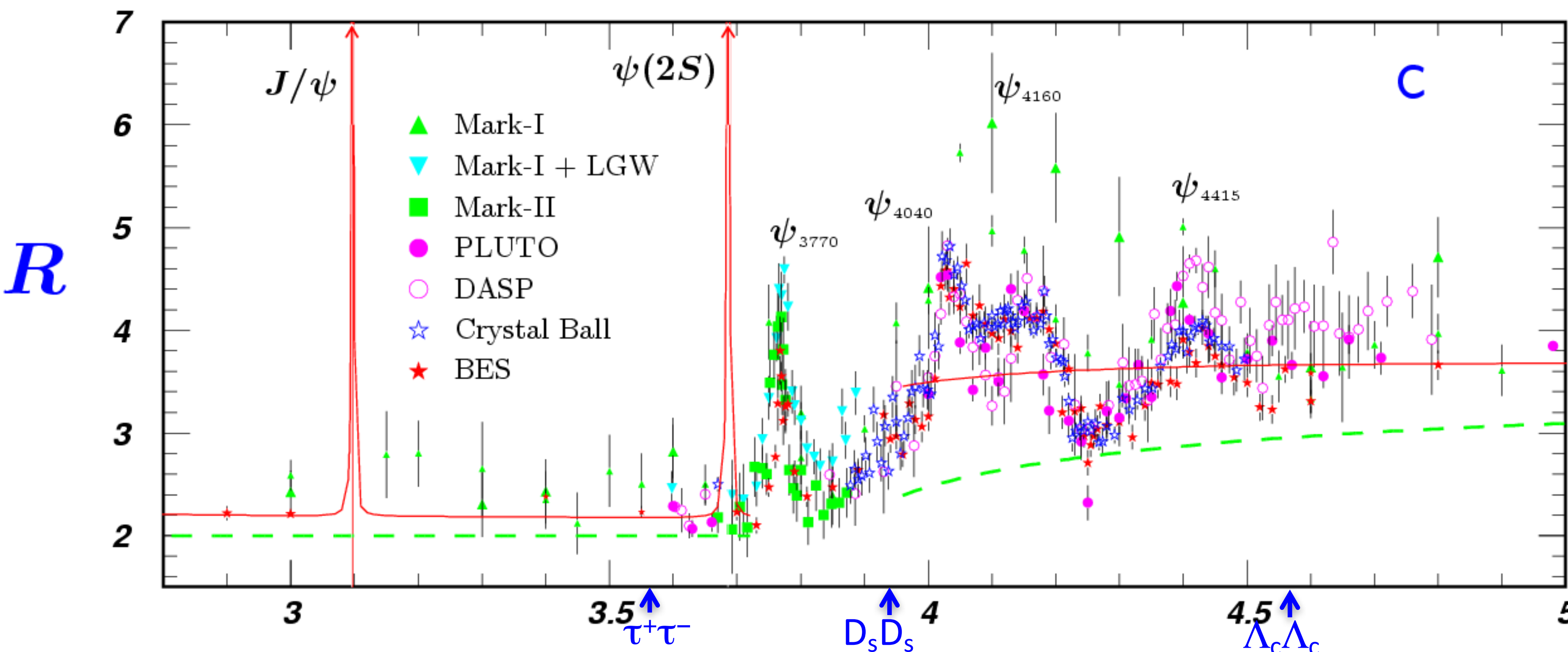
BEPCII and BESIII Exp



- BEPCII is the only collider currently running at τ-charm energy
- First collision in 2008, physics run started in 2009
- BEPCII reached peak lumi of $1\text{x}10^{33}$ $cm^{-2}s^{-1}$@1.89GeV in April 2016
- BESIII collaboration includes 61 institutes: 36 Chinese institutes , 14 European ones , 5 US ones and 6 from other Asian countries, ~450 collaborators

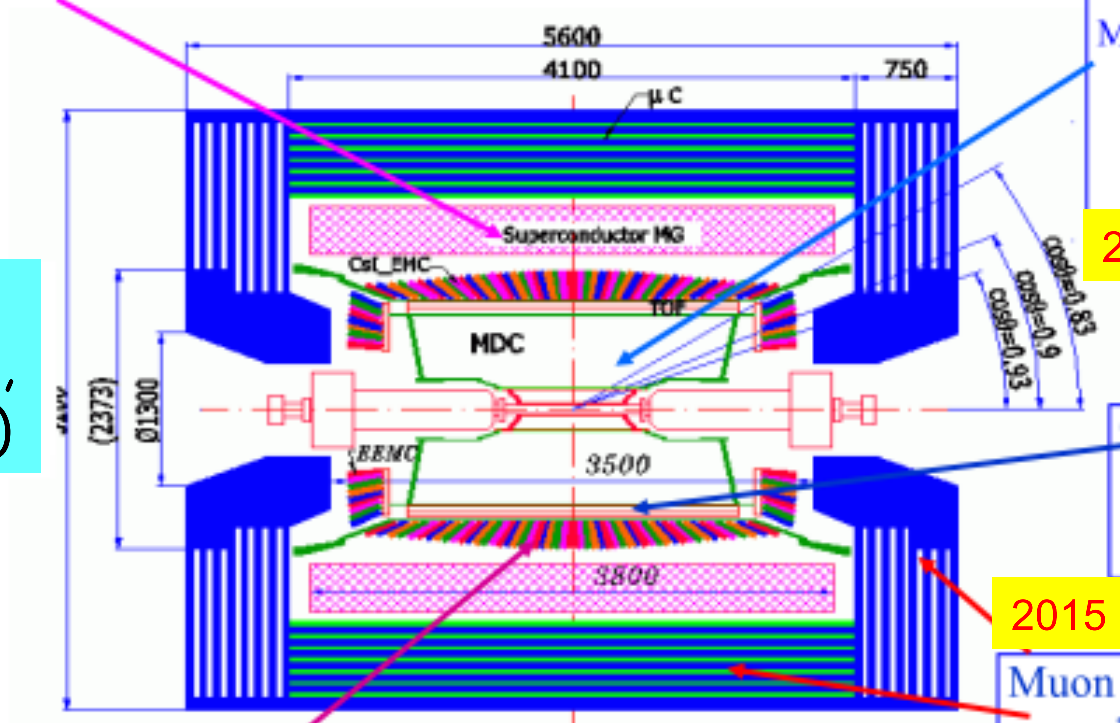
BEPCII: a τ-c Factory

- Rich of **resonances**, charmonia and charmed mesons.
- **Threshold** characteristics (pairs of τ, D, D_s, charmed baryons…).
- **Transition** between perturbative and non-perturbative **QCD**.
- **New hadrons: glueballs, hybrids, multi-quark states**
- **New Physics: high lumi, large datasets, hermetic detector with good performance**



BESIII Detector

Solenoid Magnet: 1 T Super conducting



MDC: small cell & He gas
σ_{xy}=130 μm
$\delta p/p$ = 0.5% @1GeV
dE/dx=6%

2018: Inner upgrade

Ref:
NIM A614, 345 (2010)

TOF:
σ_T = 90 ps Barrel
110 ps Endcap

2015 ETOF upgrade: 60ps

Muon ID: 8~9 layer RPC
$\sigma_{R\Phi}$=1.4 cm~1.7 cm

EMCAL: CsI crystal
$\Delta E/E$ = 2.5% @1 GeV
$\sigma_{\varphi,z}$ = 0.5~0.7 cm/$\sqrt{E}$

Data Acquisition:
Event rate = 3 kHz
Throughput ~ 50 MB/s

Trigger: Tracks & Showers
Pipelined; Latency = 6.4 μs

Clean environment and high luminosity at BESIII are helpful for indirect probe of new physics

BESIII data samples

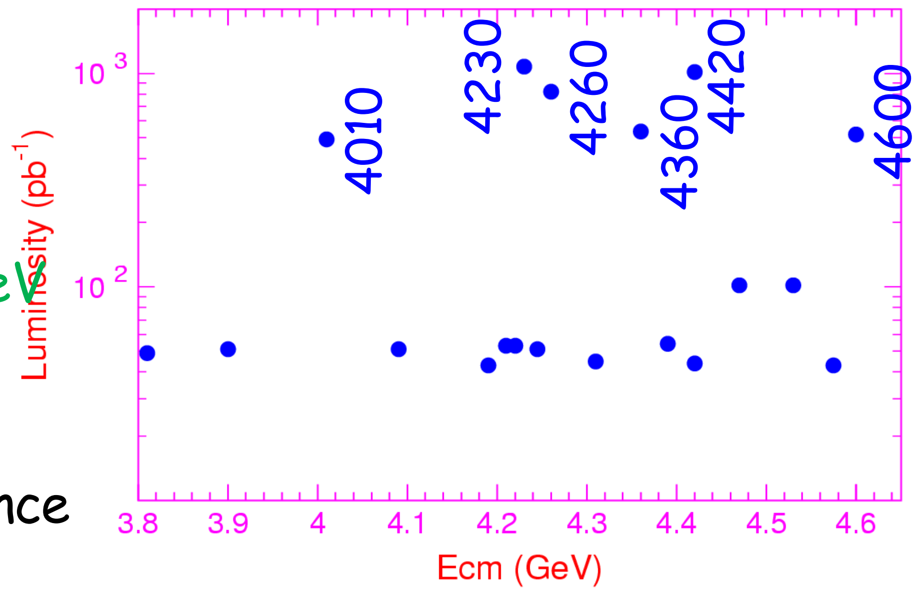
~ 0.5 B $\psi(3686)$ events ~ 24×CLEO-c

~ 1.3 B J/ψ events ~ 21×BESII

~ 2.9/fb $\psi(3770)$ ~ 3.5×CLEO-c

~ 9/fb **XYZ** states above 4 GeV Unique

- 20 points for R &QCD Scan: 500/pb finished in May 2015
- Y(2175) resonance: 100 /pb : finished in June 15, 2015
- 2016: 3/fb Ds data at 4170 MeV ~ 5×CLEO-c
- 2017-2018: 6-8B J/ψ (NEW)

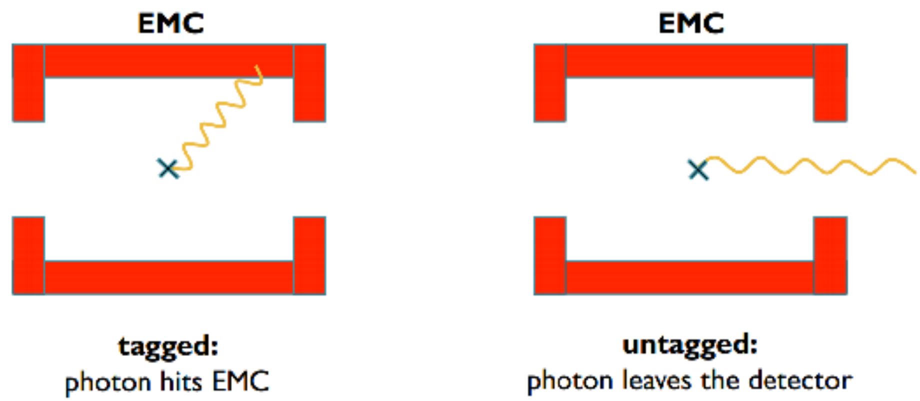


~ other data sets: tau, Λ_c, resonance scan and continuum, etc.

Dark photon search with ISR

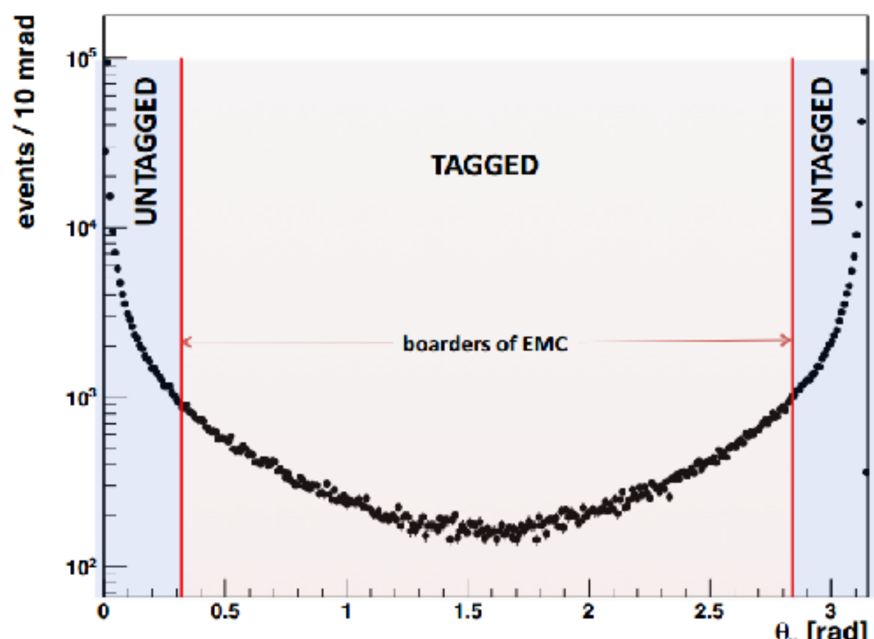
Search for narrow structure on top of the continuum QED background
$e^+ e^- \to \gamma_{ISR}\, l^+ l^-$

- Use an untagged photon method to perform this analysis.



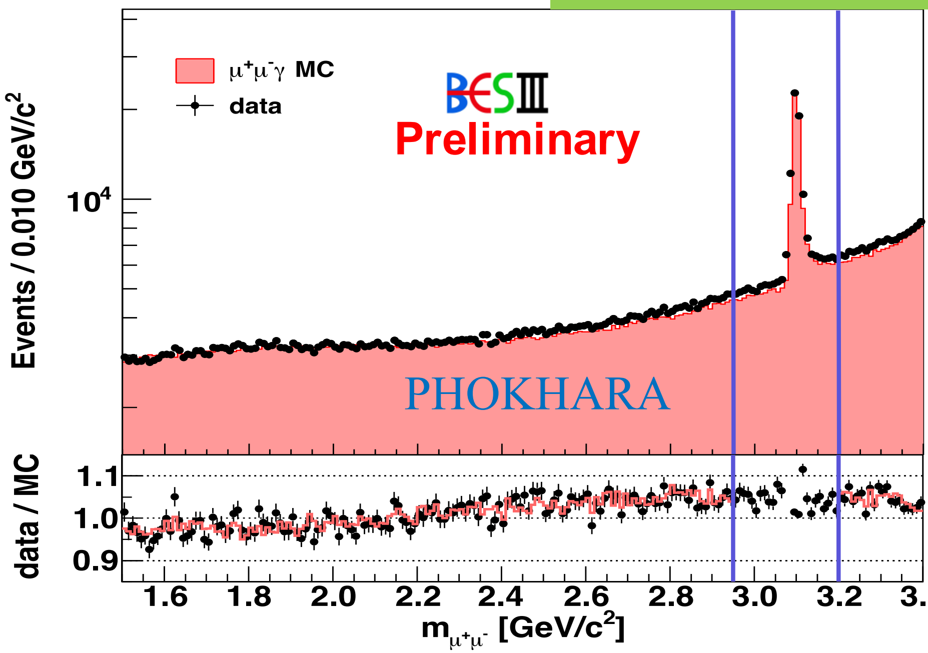
Event selection: $e^+e^- \to \mu^+\mu^-\gamma_{ISR}$ and $e^+e^- \to e^+e^-\gamma_{ISR}$

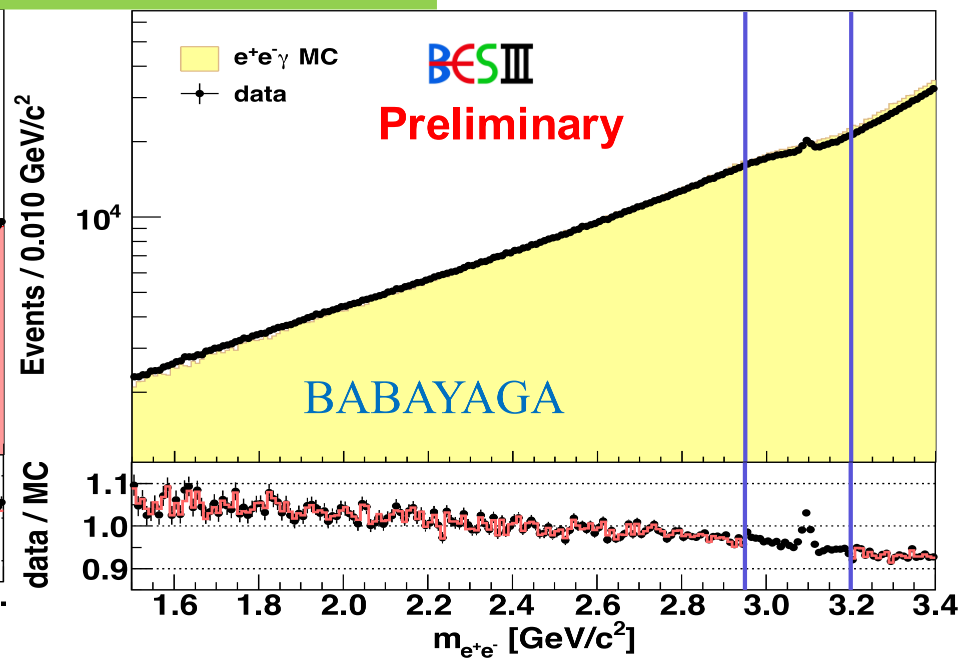
distance to interaction point	$R_{xy} < 1.0$ cm $R_z < 10.0$ cm
acceptance	0.4 rad < θ < $\pi - 0.4$ rad
to supress background	PID
# charged tracks	= 2
total charge	= 0
# photons	= 0 (untagged analysis)
missing photon angle	< 0.1 rad or > $\pi - 0.1$ rad
1C kinematic fit	$\chi^2_{1C} < 20$



Mass spectrum of mumu and ee

$2.9 fb^{-1}$ psi(3773) dataset(2010+2011)



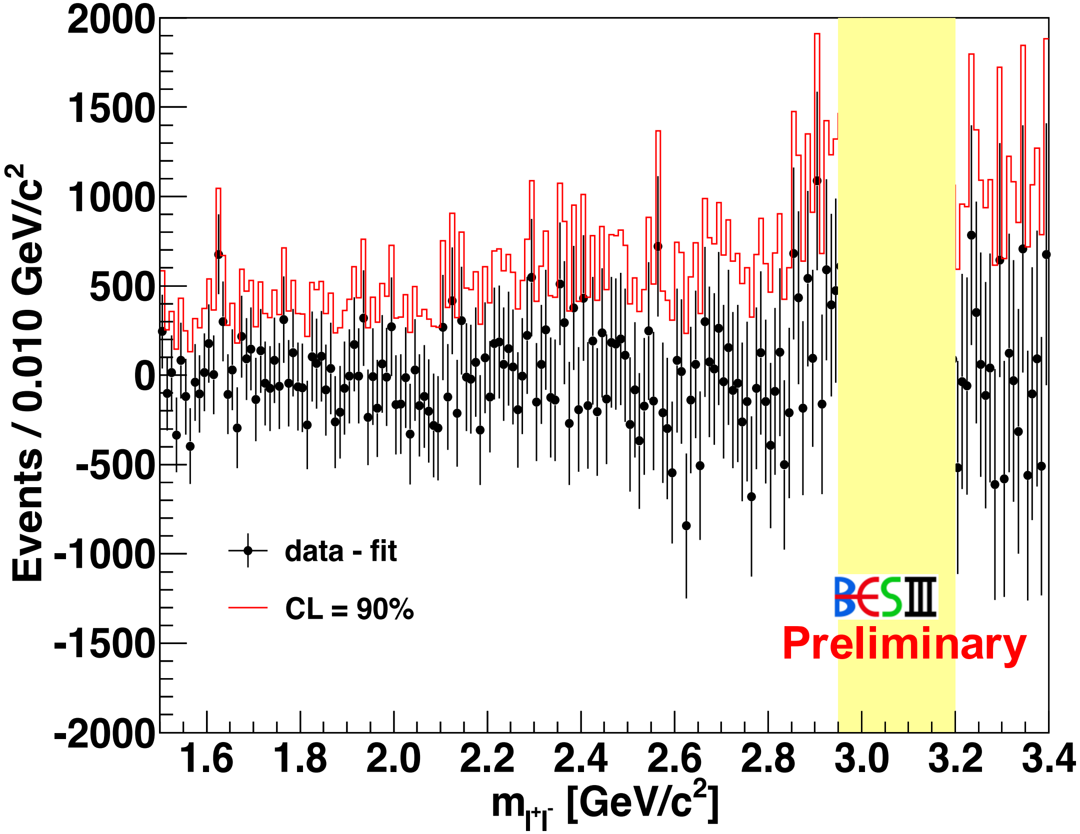


Cover mass region: 1.5 GeV/c 2 ~ 3.4 GeV/c

- <1.5 GeV/c 2 : $\pi^+\pi^-$ background dominates
- \>3.4 GeV/c 2 : hadronic qq-bar process

arXiv:1705.04265, submitted to Phy. Lett. B

Number of signal events

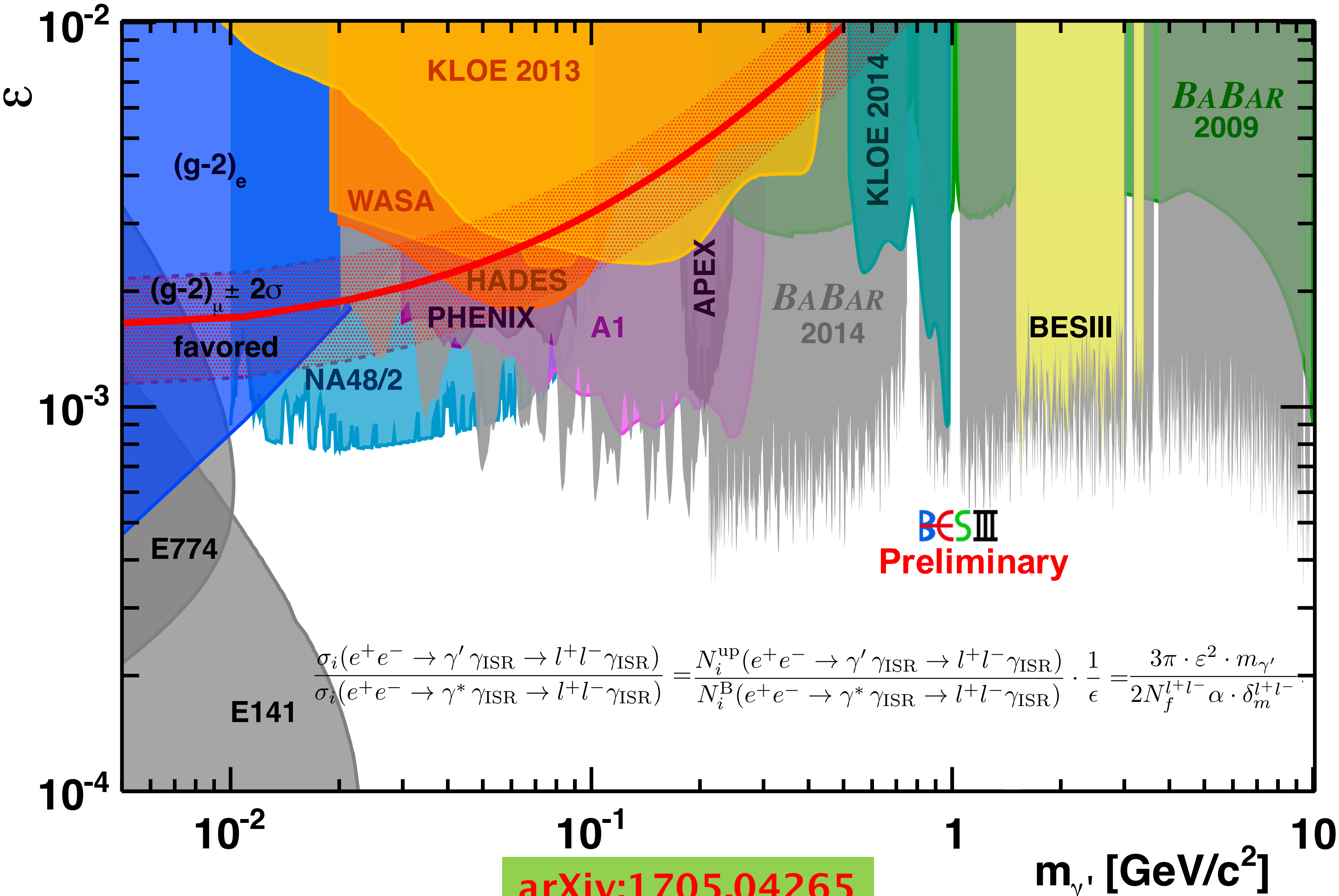


- Fit QED background with 4 order polynomial
- No peaking structure observed
- Combined statistical significance less than 3 σ
- 90% confidence level limit obtained
  - with profile likelihood approach

    W. Rolke et al., NIM A 551, 493 (2005)
  - systematic uncertainty included

arXiv:1705.04265,

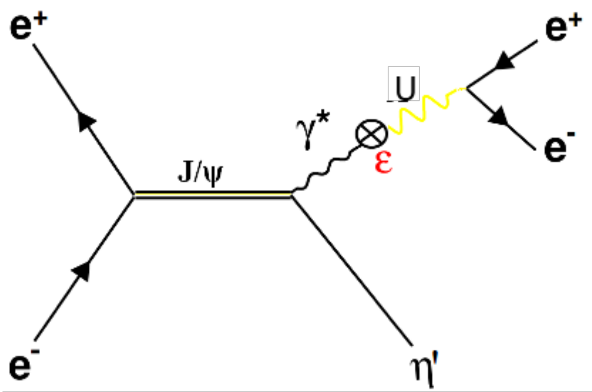
BESIII ISR search results



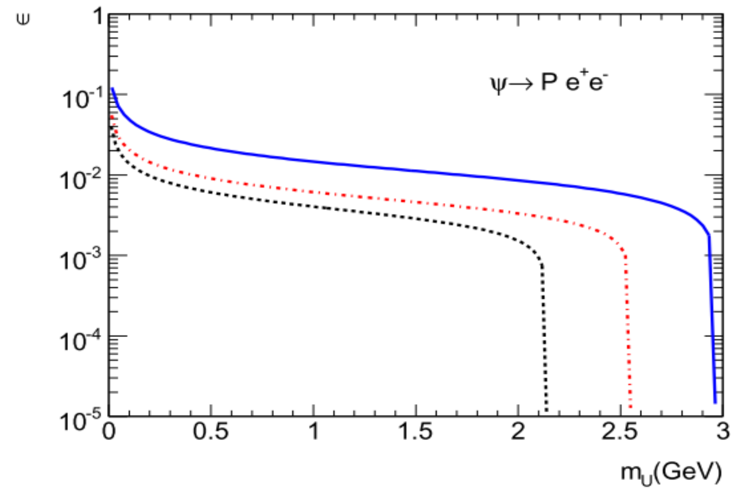
arXiv:1705.04265

DP search through meson decays

Theoretical prediction for the reach of dark photon.
The black dashed line represents P= η'



$$\frac{d\Gamma(\psi \to P l^+ l^-)}{dq^2 \Gamma(\psi \to P\gamma)} = \frac{\alpha}{3\pi} \left| \frac{f_{\psi P}(q^2)}{f_{\psi P}(0)} \right|^2 \frac{1}{q^2} \left(1 - \frac{4m_l^2}{q^2}\right)^{\frac{1}{2}} \left(1 + \frac{2m_l^2}{q^2}\right)$$
$$\times \left[\left(1 + \frac{q^2}{m_\psi^2 - m_P^2}\right)^2 - \frac{4m_\psi^2 q^2}{(m_\psi^2 - m_P^2)^2} \right]^{\frac{3}{2}}$$
$$= |F_{\psi P}(q^2)|^2 \times [\mathrm{QED}(q^2)],$$



J Fu et al.,
Mod. Phys. Lett. A 27, 1250223 (2012)

This process was first observed by BESIII with 225M J/ψ sample
Phys. Rev. D 89, 092008 (2014)

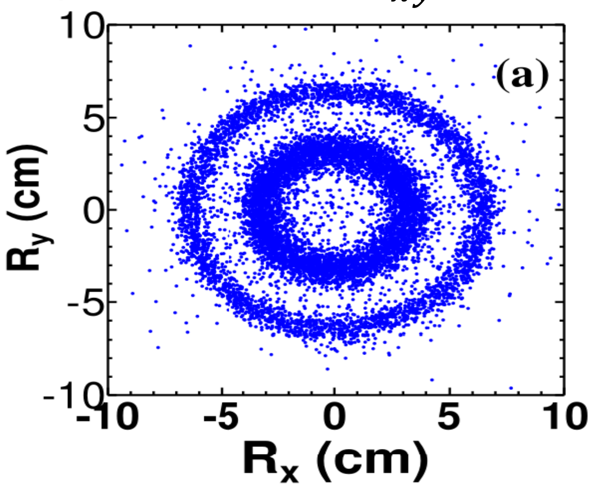
With 1.3 billion J/ψ data, it is a good opportunity to improve the precision of B($J/\psi \to \eta' e^+ e^-$) and search for the dark photon through decays $J/\psi \to \eta' \mathrm{U}, \mathrm{U} \to e^+ e^-$ at BESIII.

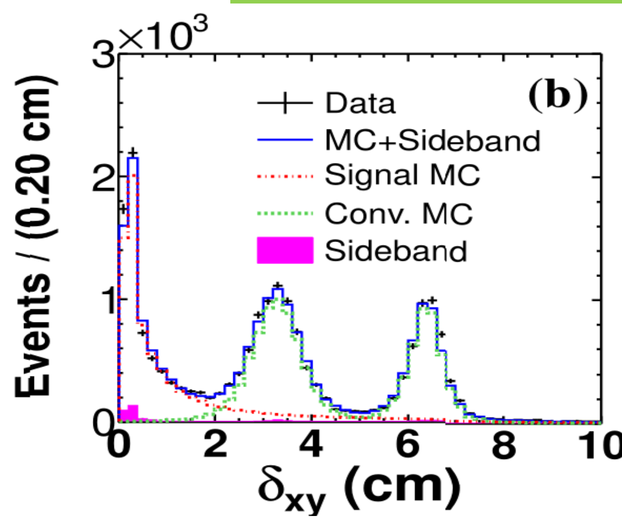
$J/\psi \to \eta' e^+ e^-$ Event selection

- Selection of $\gamma e^+ e^- \pi^+ \pi^- / \gamma\gamma e^+ e^- \pi^+ \pi^-$
  - Four good charged tracks with $e^+ e^-$ identified successfully
  - At least one/two good photons in EMC
  - $e^+ e^- \pi^+ \pi^-$ successful vertex fit
  - $\gamma e^+ e^- \pi^+ \pi^- / \gamma\gamma e^+ e^- \pi^+ \pi^-$ 4C fit with$x^2_{4c} < 100$

1.3B J/psi dataset(2009+2012)

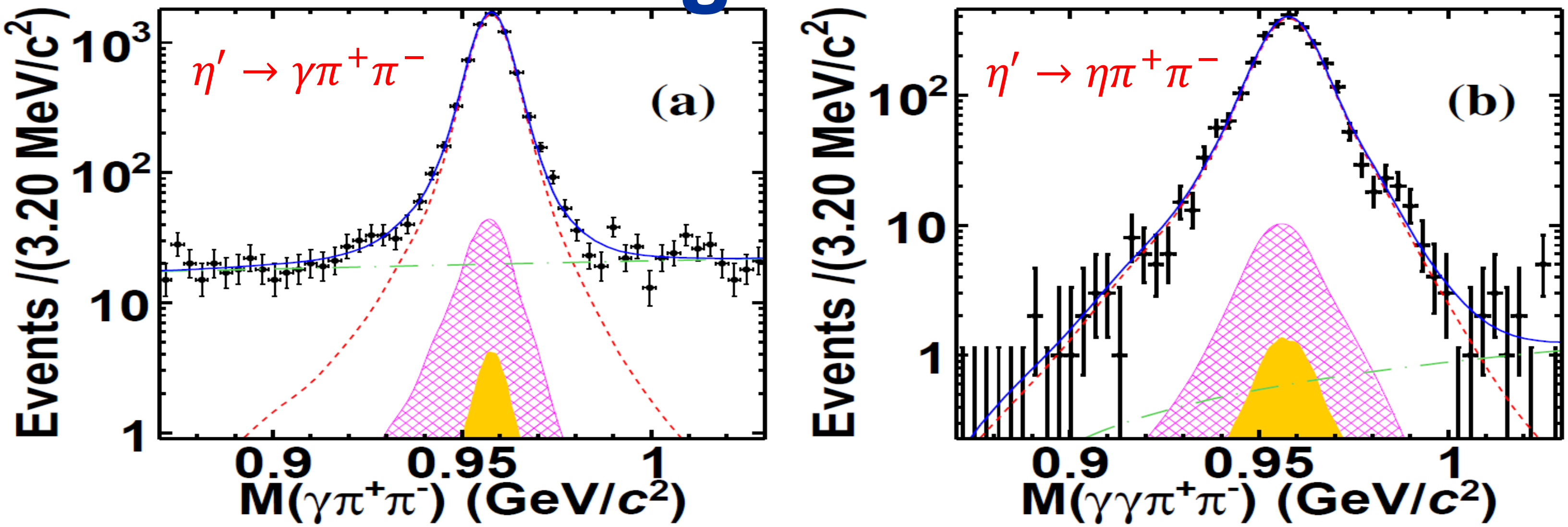
- Veto of γ conversion : δ_{xy} < 2cm





- Addition selection for each mode
  - $\eta' \to \gamma \pi^+ \pi^-$
    Veto π^0: M($\gamma e^+ e^-$) $\notin$ (0.10,0.16) GeV/c²
  - $\eta' \to \eta \pi^+ \pi^-$
    Select η: M($\gamma\gamma$) $\in$ (0.48,0.60) GeV/c²

Branching fraction result



- Signal: MC shape $\otimes$ Gaussian
- Non-peaking background: Chebychev Polynomial
- Peaking background: MC shape (γ conversion/ $J/\psi \to \Phi\eta'$)

	$\eta' \to \gamma\pi^+\pi^-$	$\eta' \to \eta\pi^+\pi^-$
Signal Yield	6436.9 ± 87.1	2494.4 ± 51.3
Background Yield	981.4 ± 43.8	27.3 ± 10.0
Efficiency (%)	28.21	19.94
B($J/\psi \to \eta' e^+e^-$) (10^{-5})	$5.98 \pm 0.08_{stat} \pm 0.32_{syst}$	$5.65 \pm 0.12_{stat} \pm 0.33_{syst}$
Combined result(10^{-5})	$5.81 \pm 0.07_{stat} \pm 0.29_{syst}$	

BESIII **Preliminary**

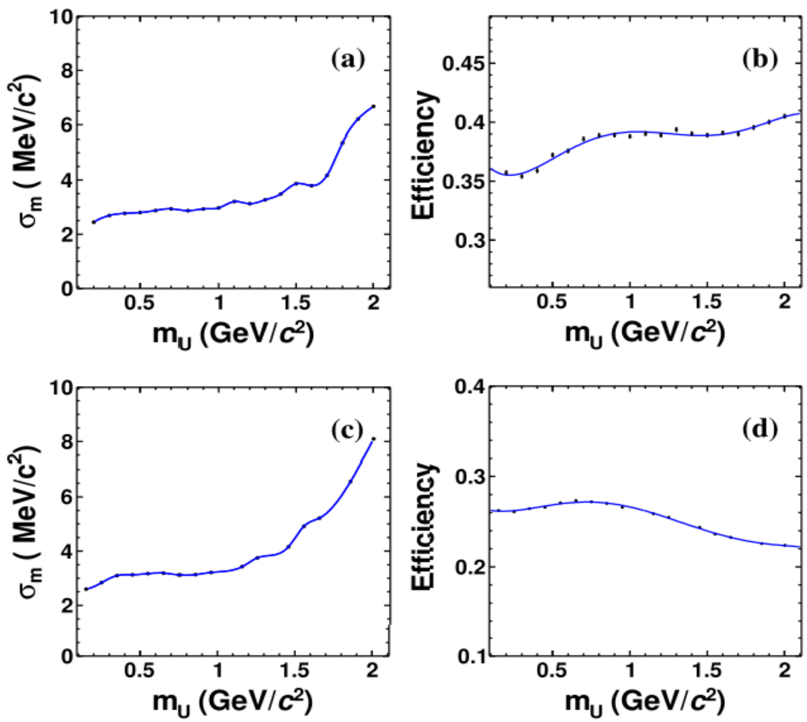
Improves on the previous BESIII measurement of B($J/\psi \to \eta' e^+e^-$)

Phys. Rev. D 89, 092008 (2014)

DP search: selection,resolution,efficiency

- Additional event selection criteria
  1. Without γ conversion veto
  2. η' signal region [0.93,0.98] GeV
  3. M(e^+e^-) > 70 MeV/c^2

- Resolution and selection efficiency from signal MC
  - The resolution σ_m of dark photon signal and selection efficiency depend on dark photon mass m_U.



$\eta' \to \gamma\pi^+\pi^-$

- σ_m : 2 - 7 MeV
- Efficiency: 35 - 41 %

$\eta' \to \eta\pi^+\pi^-$

- σ_m : 2 - 8 MeV
- Efficiency: 22 - 28 %

Dark photon search strategy

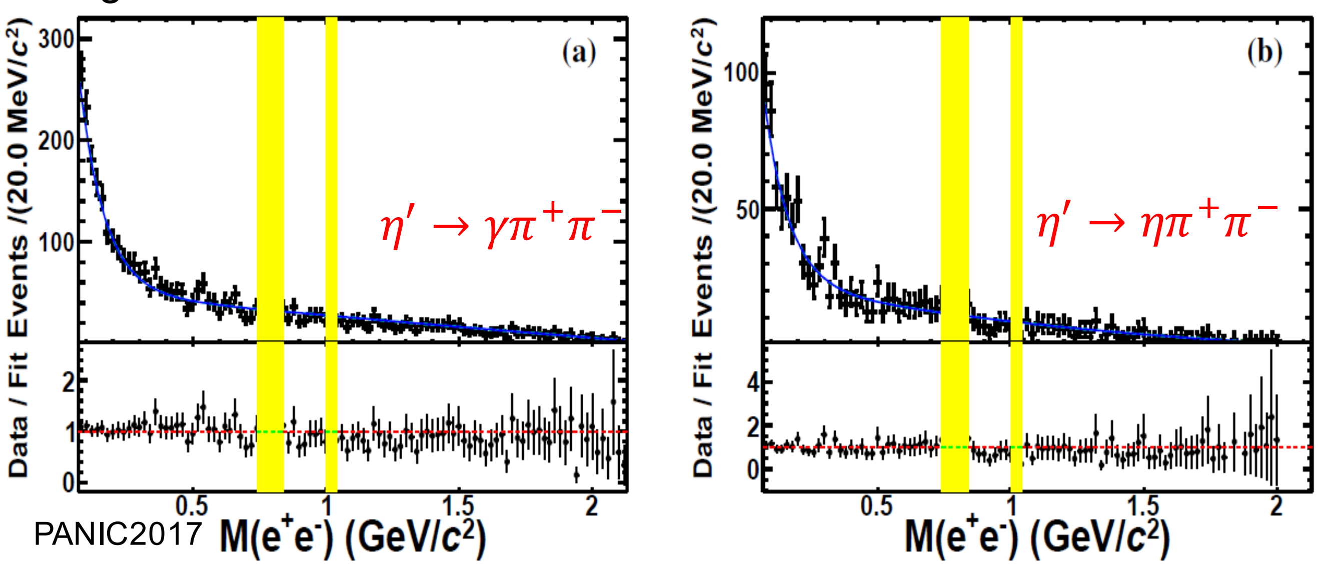
- Strategy:
  - Assuming the background is smooth, dark photon would appear as a narrow peak on the top of the background.
  - We look for a narrow peak signal on invariant mass of e^+e^- by a step of 2 MeV in [0.1, 2.1] GeV range.
- Signal description:
  - Shape: A sum of two Crystal Ball (CB) functions with opposite tails.

$$y = CB_1(x;\mu,\sigma_1,n1,\alpha_1) + f * CB_2(x;\mu,\sigma_2,n2,\alpha_2)$$

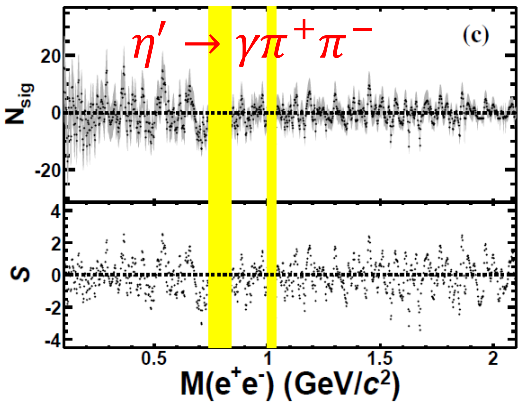
  - Parameters are interpolated based on signal MC samples generated with different m_U hypotheses.
- Background description:
  - Shape: A sum of 2nd order polynomial and exponential, parameters are determined from data fit.

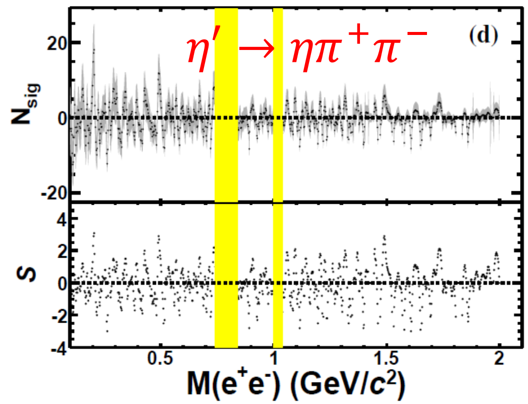
$$y = p0 + p1\cdot x + p2\cdot x^2 + e^{\tau\cdot x}$$

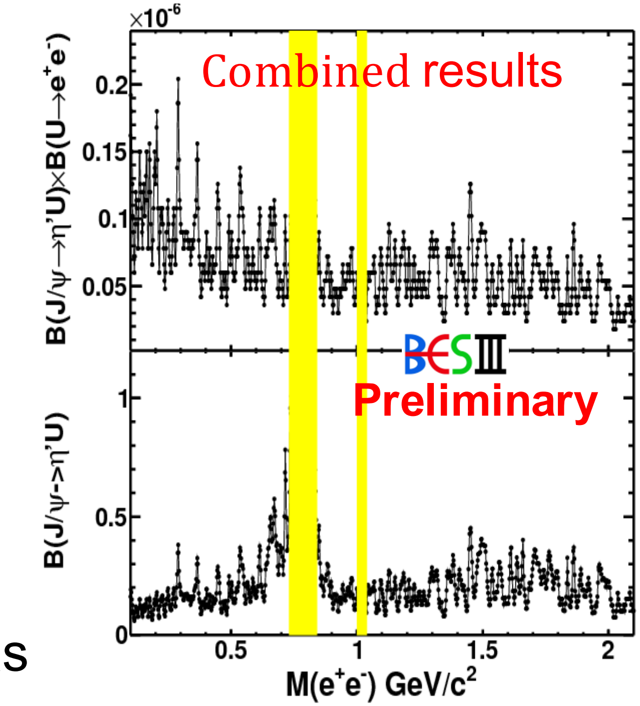
  - ω and Φ regions are excluded.



Dark photon search results







- N_{sig} : Number of signal yield.
- S : Statistical significance of signal , defined as

$$\mathcal{S} = \mathrm{sign}(N_{\mathrm{sig}})\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\mathrm{max}})}$$

- No significant dark photon signal is observed.
- Set combined limits @ 90% C.L. on the branching fractions
  1. B($J/\psi \to \eta'$U) ×B(U → e^+e^-)
  2. B($J/\psi \to \eta'$U): B(U → e^+e^-) is considered as a function of m_U from Phys. Rev. D 79, 115008 (2009).

Exclusion limit on mixing strength ε

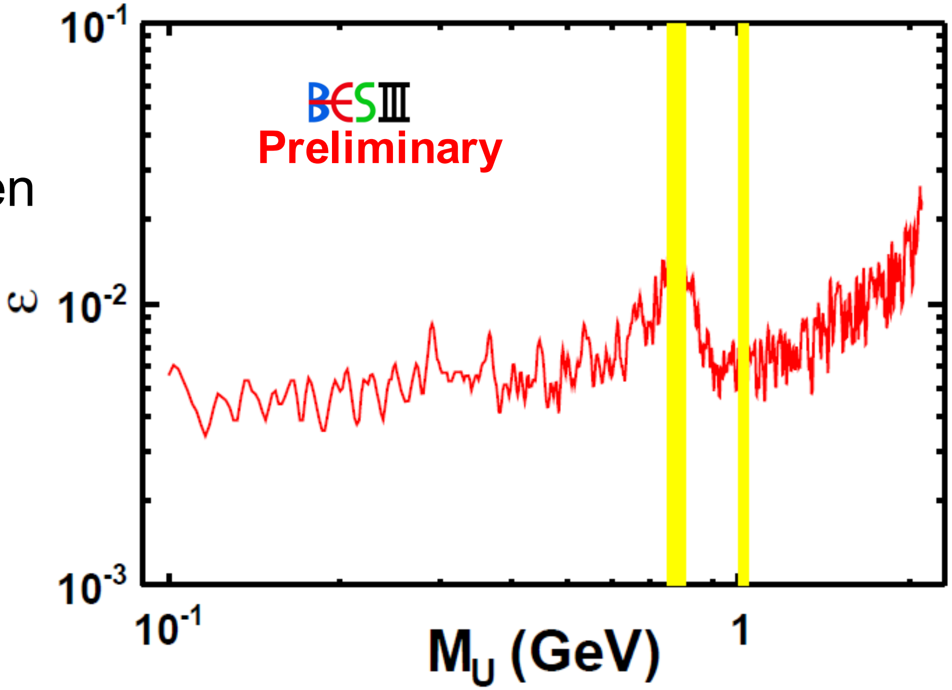
$$\frac{\mathcal{B}(J/\psi \to \eta' \mathrm{U})}{\mathcal{B}(J/\psi \to \eta' \gamma)} = \varepsilon^2 |F(m_{\mathrm{U}}^2)|^2 \frac{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, m_{\mathrm{U}}^2)}{\lambda^{3/2}(m_{J/\psi}^2, m_{\eta'}^2, 0)}$$

m_X :Mass of particle X

arXiv: 0904.1743

$\mathcal{B}$:Branching fraction

ε :Kinematic mixing strength between SM photon and dark photon



F :Form factor

$$|F(q^2)| = 1/(1 - q^2/\Lambda^2)$$

Λ= 3.686 GeV

Mod. Phys. Lett. A 27, 1250223 (2012)

λ : Kinematic factor

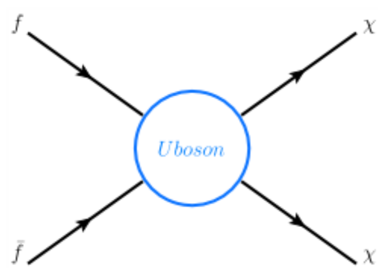
$$\lambda(m_1^2, m_2^2, m_3^2) = (1 + \frac{m_3^2}{m_1^2 - m_2^2})^2 - \frac{4 m_1^2 m_3^2}{(m_1^2 - m_2^2)^2}$$

Other related searches at BESIII

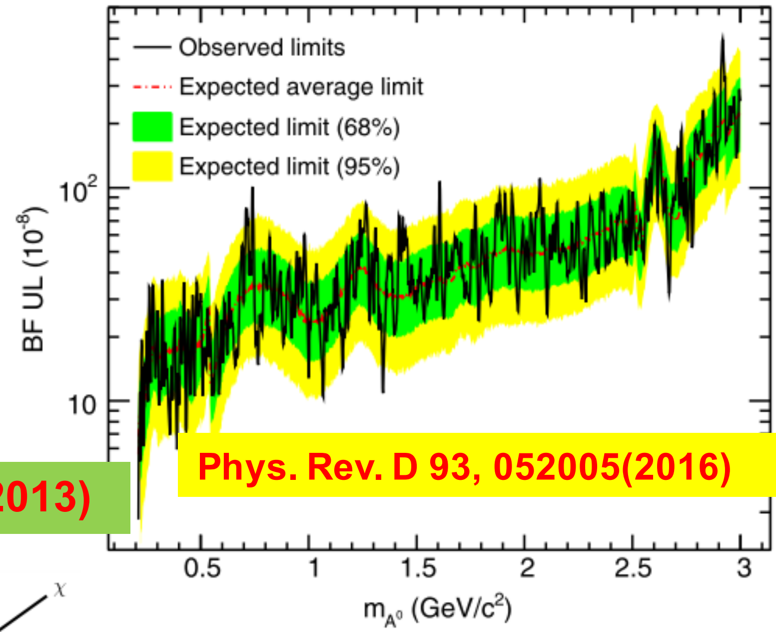
- **Light Exotica searches**

  Phys.Rev. D 85, 092012 (2012)
  Phys.Rev. D 93, 052005(2016)

- **Meson invisible decays**
  - eta/eta'->inv: Phys.Rev. D 87, 012009 (2013)
  - Ongoing:
    - Jpsi -> inv,
    - Jpsi -> gam+inv
    - phi/omega -> inv

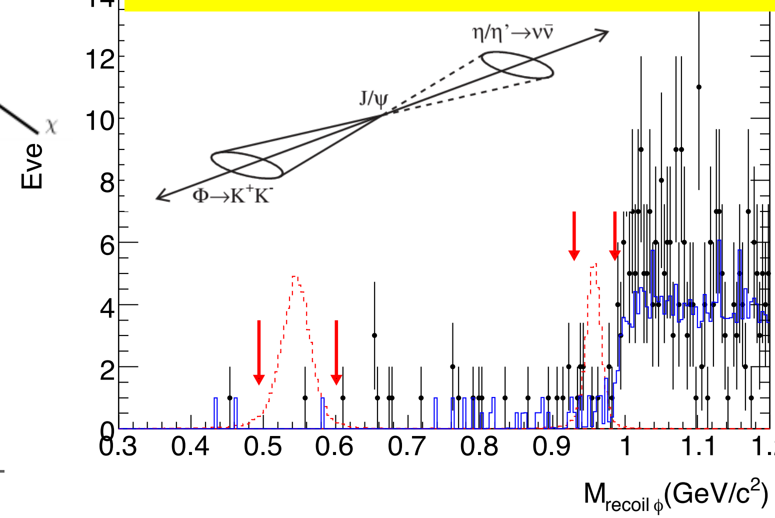


- **Ongoing DP search channels**
  - Invisible DP in ISR process
  - $J/\psi \to \eta e^+ e^-$
  - … and more



Phys. Rev. D 93, 052005(2016)

Phys.Rev. D 87, 012009 (2013)



Summary

- **BESIII has joined the world wide efforts of DP search.**
- **DP search with untagged ISR events in 1.5 GeV/c^2 ~ 3.4 GeV/c^2 set competitive limit on the mixing strength between 10^{-3} and 10^{-4} in this region**
- **The branching fraction of $J/\psi \to \eta' e^+e^-$ is updated with 1.3 billion J/ψ data to be $(5.81 \pm 0.07_{stat} \pm 0.29_{syst})\times 10^{-5}$.**
- **DP is searched $J/\psi \to \eta'\mathrm{U},\ \mathrm{U} \to e^+e^-$. Upper limits on B($J/\psi \to \eta'\mathrm{U}$) ×B($\mathrm{U} \to e^+e^-$) and B($J/\psi \to \eta'$U) is set for the first time, the mixing strength ε constrained**
- **As the only currently running tau-charm factory, BESIII has great potential with unique datasets: More to come, stay tuned!**

Thanks!

Extra slides…