# Dark matter/new physics searches at BESIII


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**(On behalf of the BESIII experiment)**

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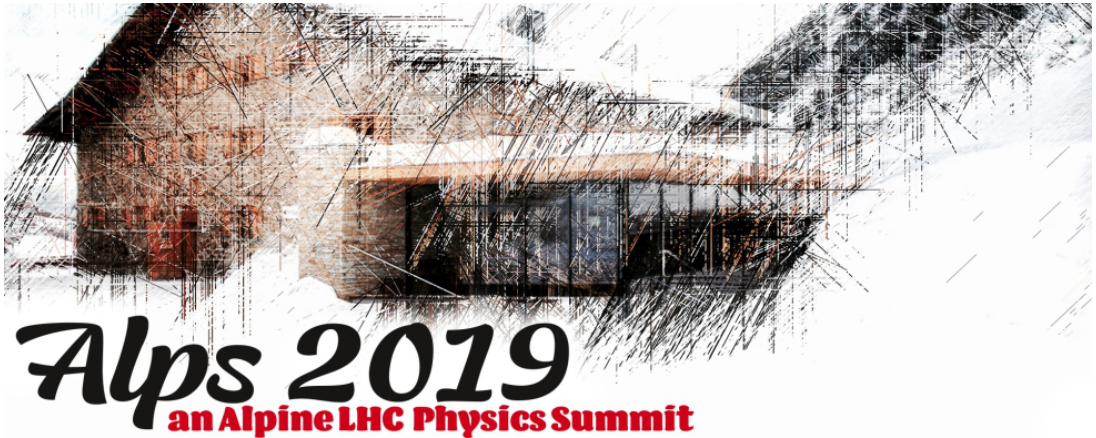
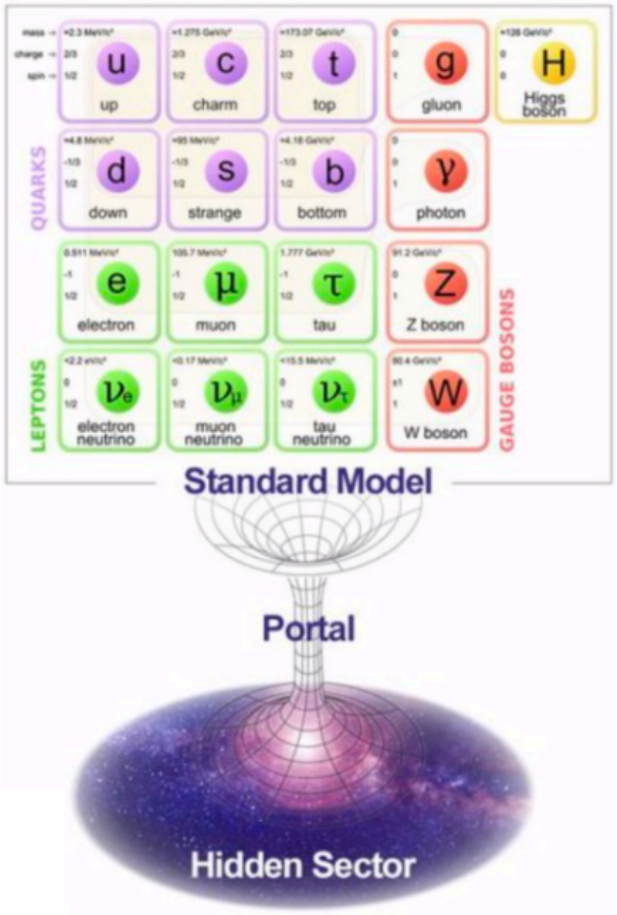


# Motivation

- Many extensions of the Standard Model (SM) introduce light weak interacting dark matter (DM) hidden sectors
  - ✓ Motivated by recent experimental anomalies (see backup slide no.18) and theoretical prejudice
  - ✓ The DM hidden sectors couple to the SM particles via the so called "portals"

| 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 | $y_N L H N$ |

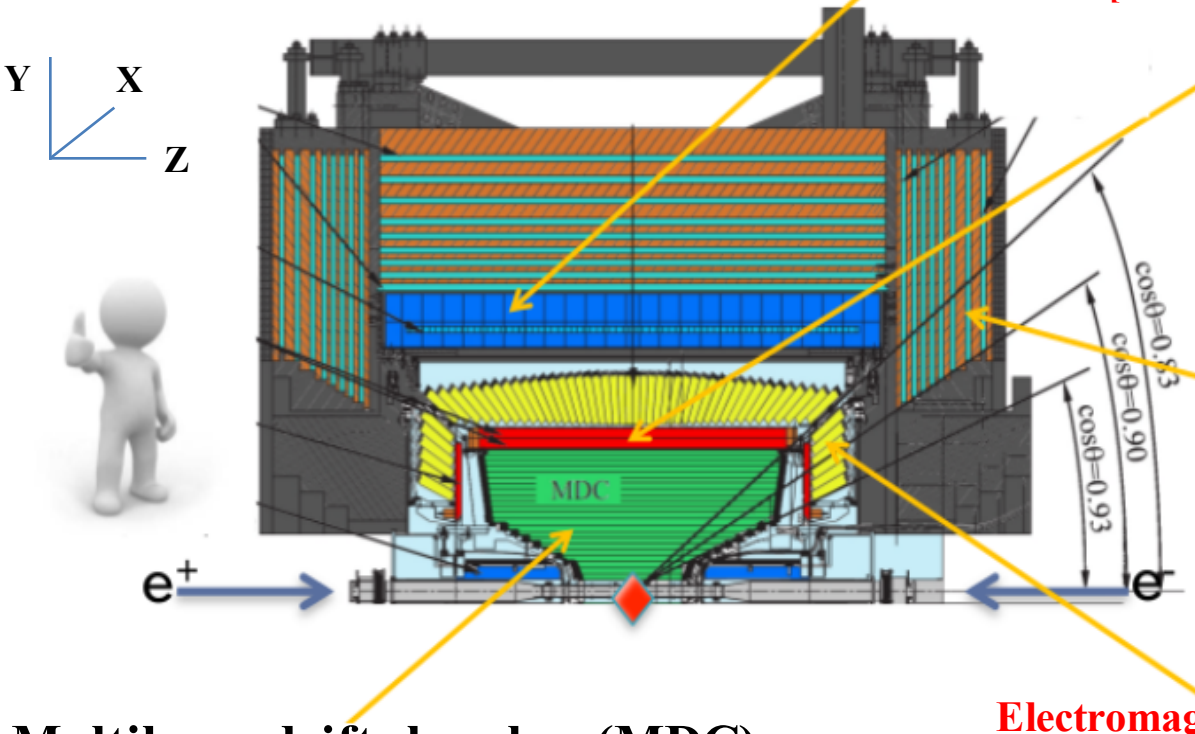



- ✓ These new particles can be accessible by high intensity $e^+e^-$ collider experiments, such as **BESIII experiment**, if their masses are in the MeV-GeV range.

R. Essig et al., arXiv: 1311.0029 (2013)

# BESIII Experiment

BESIII experiment is a symmetric electron positron collider running at tau-charm region.




## Super conducting magnet

✓ 1 Tesla

[Nucl. Instrum. Meth. A614, 345-399 (2010)]

## Time of Flight (TOF)

- 2 layer plastic scintillators
- $\sigma_T \approx 80$ ps (barrel)
- $\sigma_T \approx 110$ ps (endcap) (~65 ps after upgradation with MRPC)
- Particle id

## Muon system

- 9 layers of RPC
- P > 400 MeV/c
- $\delta R\phi \approx 1.4 - 1.7$ cm

## Multilayer drift chamber (MDC)

- $He/C_3H_8$ (60/40)
- 43 layers
- Momentum resolution $\sigma_p/p \approx 0.5\%$ @ 1 GeV
- Spatial resolution $\sigma_{xy} \approx 130$ μm.

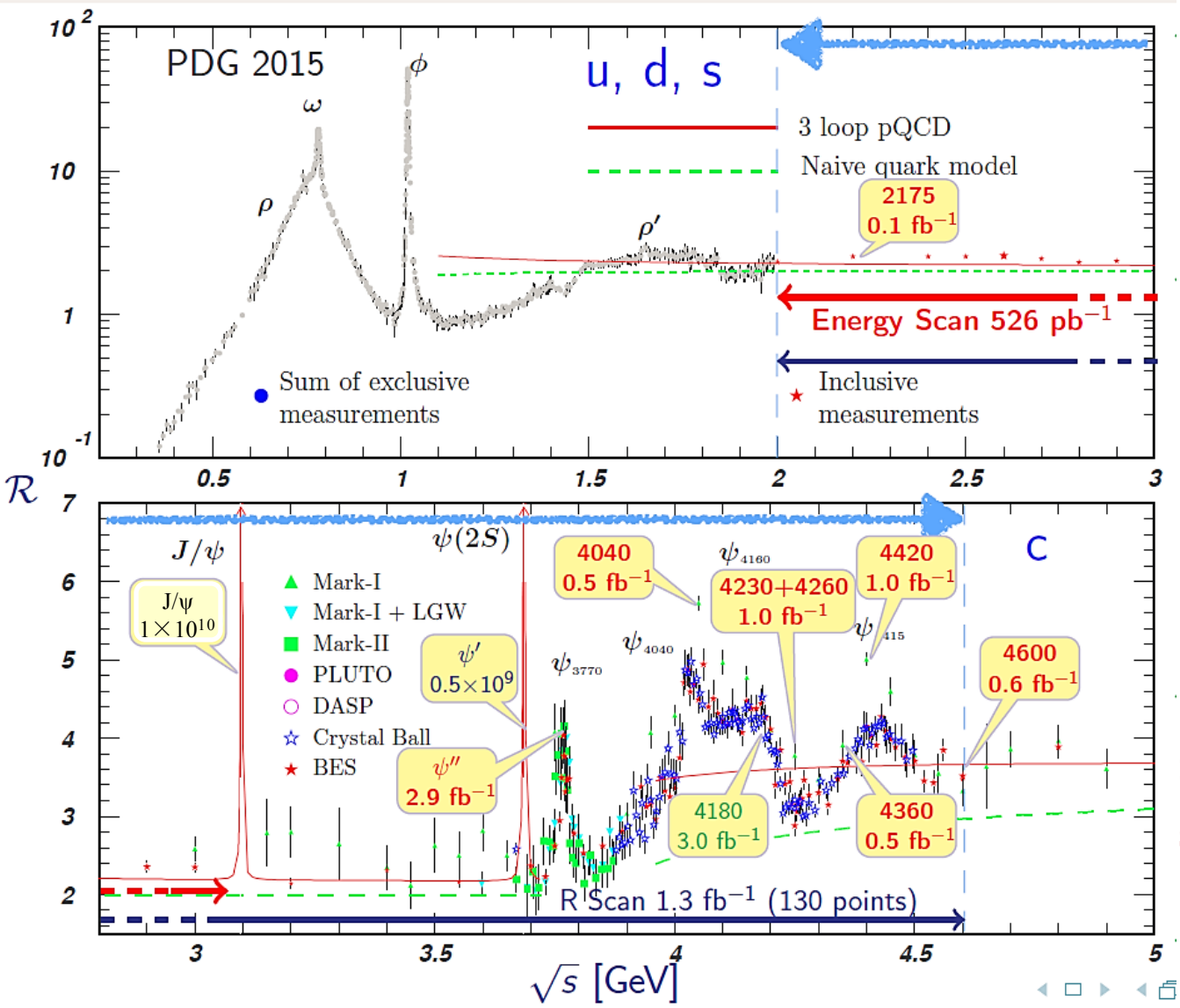
## Electromagnetic calorimeter (EMC) (CsI(Tl))

→ 6240 crystals overall

- $\sigma(E)/E \approx 2.5\%$
- $\sigma_{Z,\phi}(E) \approx 0.5 - 0.7$ cm

**Will replace the inner part of the drift chamber by the three layers of CGEM detector during June-Dec., 2019

# BESIII Dataset




**World largest data for**

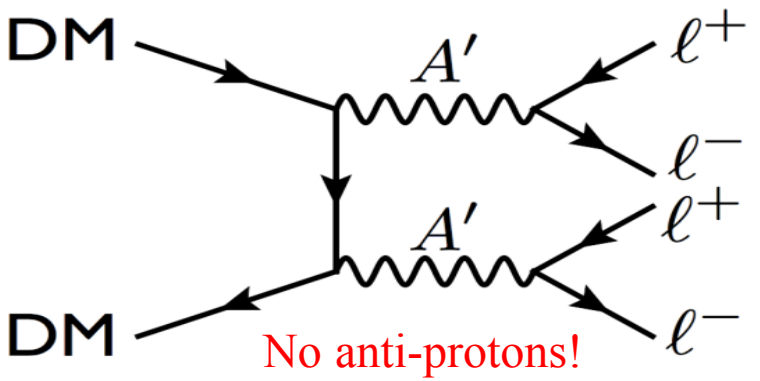
- ✓ Charmonium spectroscopy
- ✓ Charm physics
- ✓ Light hadrons
- ✓ New physics search

**IDEAL ENVIRONMENT TO STUDY HADRON SPECTROSCOPY & SEARCH FOR NEW PHYSICS PHENOMENA!!**

# Dark gauge boson

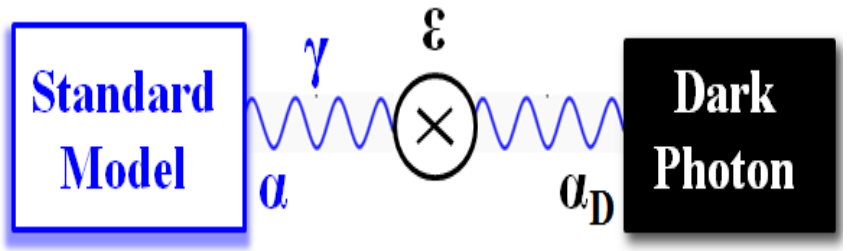
- New Models introduce new dark force carriers (e.g. dark-photon A′ or γ′) with light hidden sectors.

**N. Arkani-Hamad et al, PRD 79, 015014 (2009)**




- Produces high-energy (~100 GeV) cosmic-ray electrons and positrons.
- Could explain the features of astrophysical observations.

- Interaction with SM via kinetic mixing with mixing strength (ε).




$$\Delta L = \varepsilon F^{\mu\nu} F^{D}_{\mu\nu}$$

**ε = hypercharge mixing strength.**

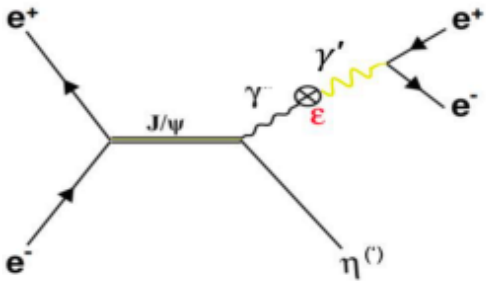
- Kinematic mixing generates non-zero coupling of SM fermions to A': $\alpha_D = \alpha\varepsilon$

**B. Batell, et al, PRD79, 115008 (2009);**
**R. Essig, et al, PRD80 015003 (2009)**

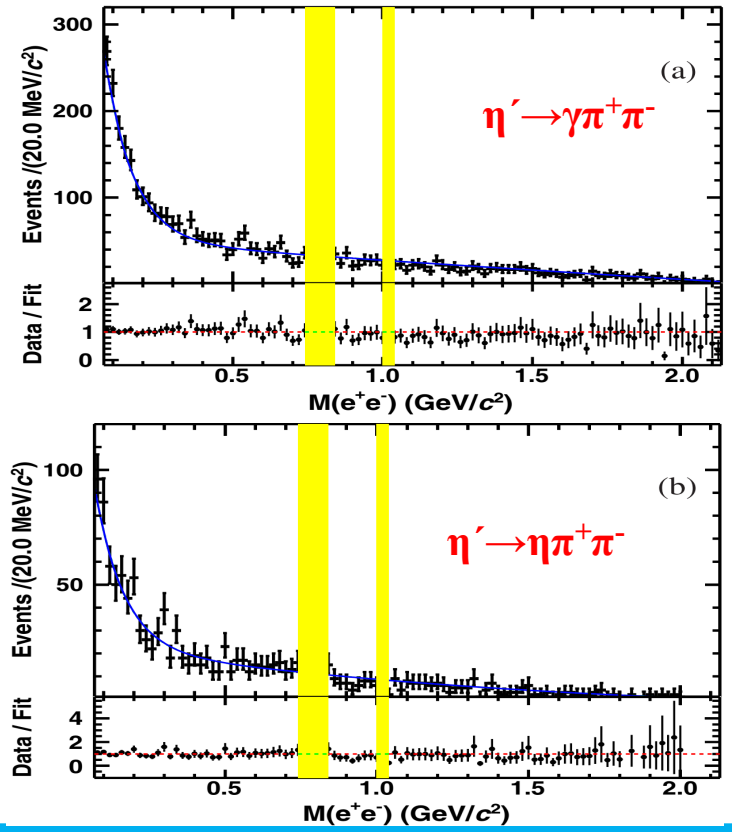
# Dark photon search via $J/\psi \to \gamma' \eta(')$, $\gamma' \to e^+e^-$

Phys. Rev. D 99, 012013 (2019); Phys. Rev. D 99, 012006 (2019)

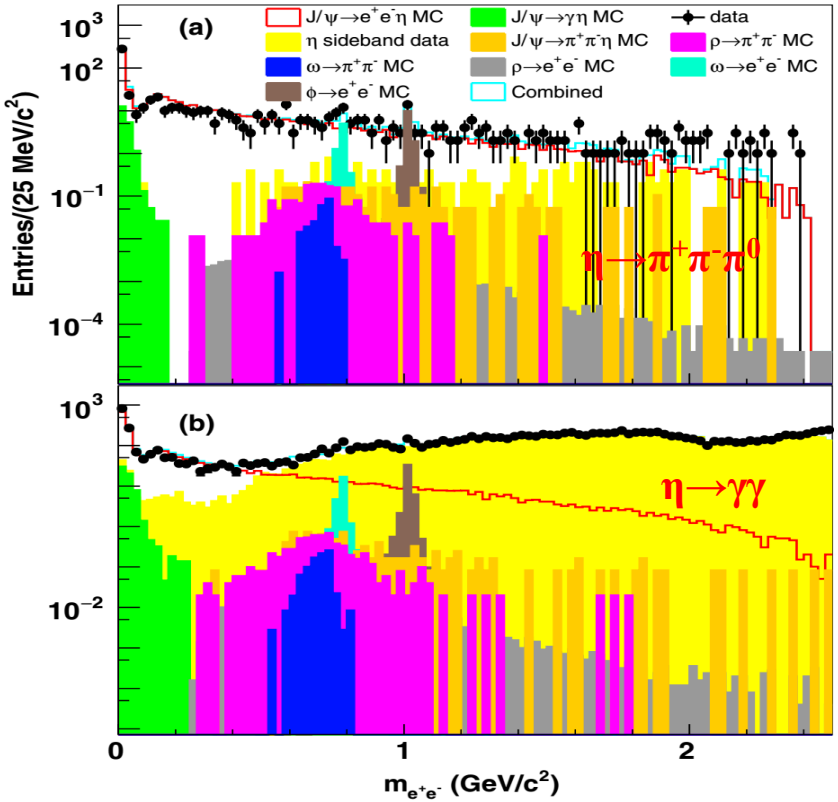
- First search for dark photon via electromagnetic Dalitz decays @ 1.3 billion BESIII J/ψ data
- Search for a narrow structure in the $m_{e^+e^-}$ distribution of data




$J/\psi \to \gamma' \eta'$, $\gamma' \to e^+e^-$ [Phys. Rev. D 99, 012013 (2019)]




$J/\psi \to \gamma' \eta$, $\gamma' \to e^+e^-$ (Phys. Rev. D 99, 012006 (2019))



# Dark photon search via $J/\psi \to \gamma' \eta(')$, $\gamma' \to e^+e^-$

Phys. Rev. D 99, 012013 (2019); Phys. Rev. D 99, 012006 (2019)

- Exclude the ω and ϕ mass regions for the γ′ searches, and no any obvious peaking structures are observed.

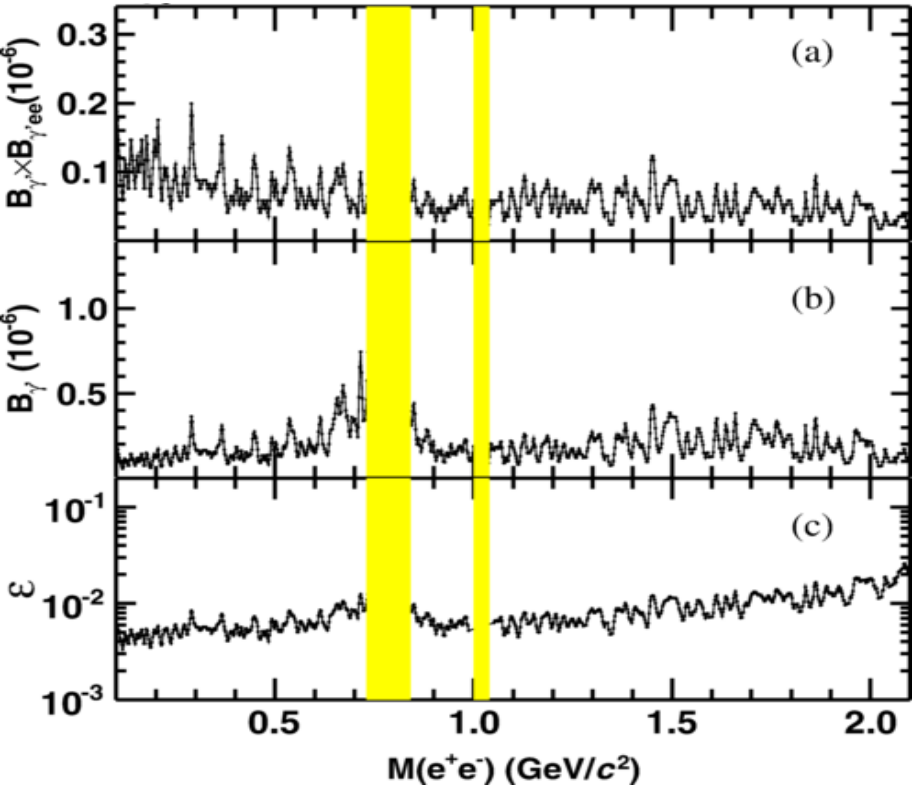
- Combined results of 90% C.L. upper limits on BF and ε

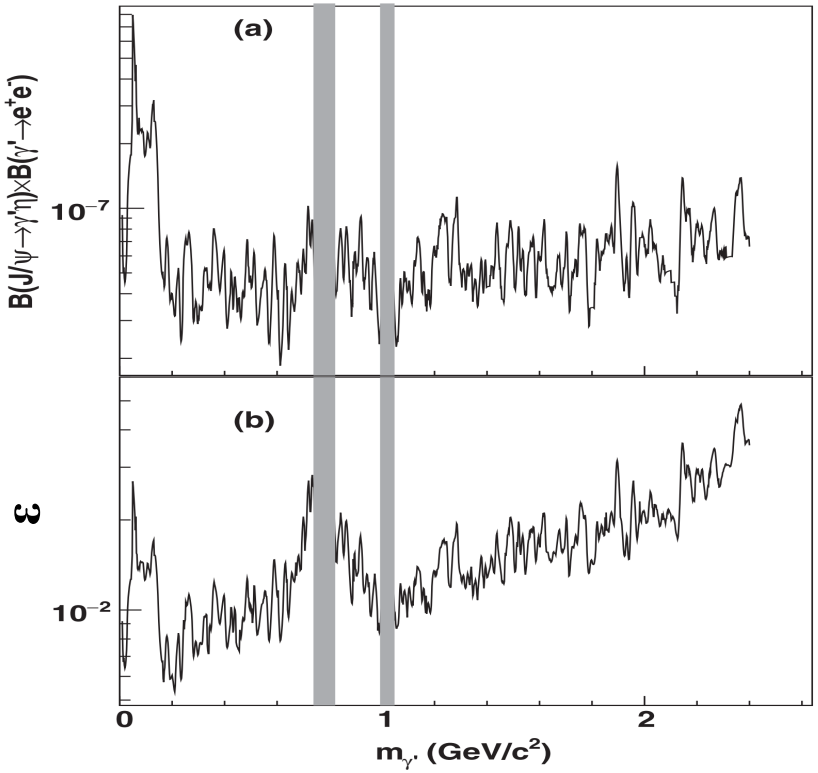
$\mathcal{B}(J/\psi \to \eta'\gamma') \times \mathcal{B}(\gamma' \to e^+e^-)$ **< (1.8-20.0)×10$^{-8}$**

**ε < 3.4×10$^{-3}$ – 2.6×10$^{-3}$**

$\mathcal{B}(J/\psi \to \gamma'\eta) \times \mathcal{B}(\gamma' \to e^+e^-)$ **< (1.9-91.1)×10$^{-8}$**

**ε < 10$^{-3}$ – 10$^{-2}$**



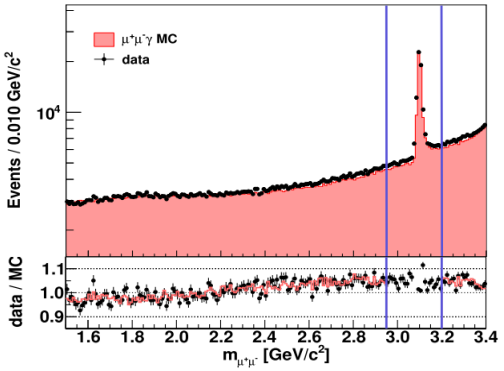



# Dark photon search via $e^+e^- \to \gamma_{ISR}\gamma', \gamma' \to l^+l^-$

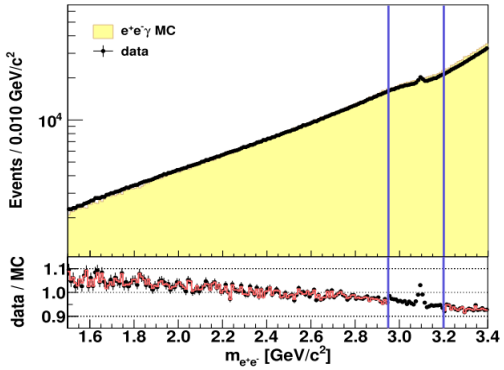
Phys. Lett. B 774, 252 (2017)

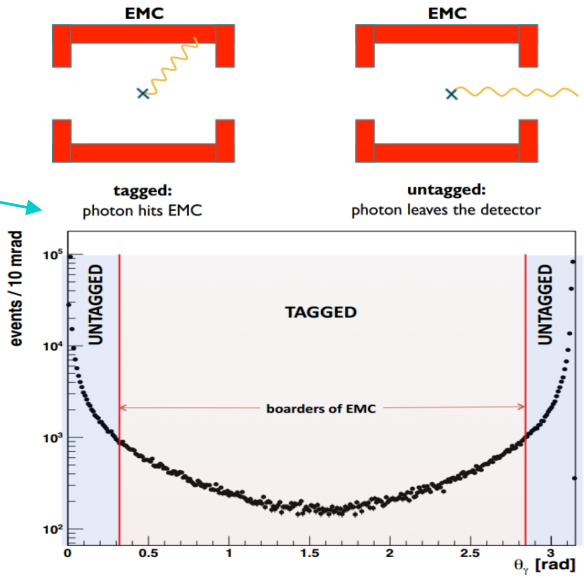
Use an **untagged photon** method to perform this analysis via initial state radiation processes:

$e^+e^- \to \gamma_{ISR}\gamma', \gamma' \to \mu^+\mu^-$



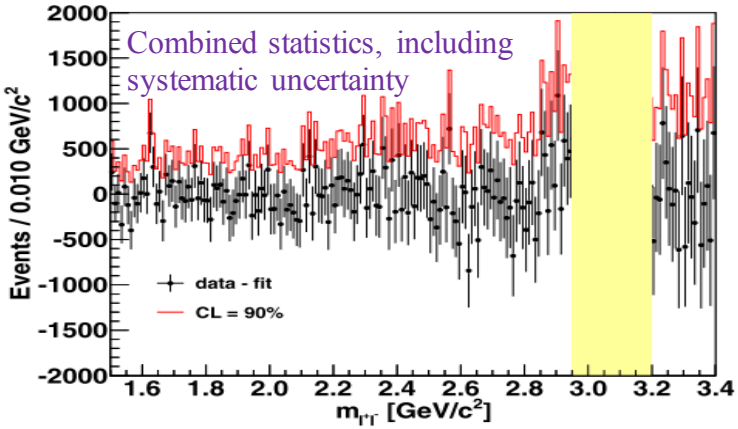

$e^+e^- \to \gamma_{ISR}\gamma', \gamma' \to e^+e^-$



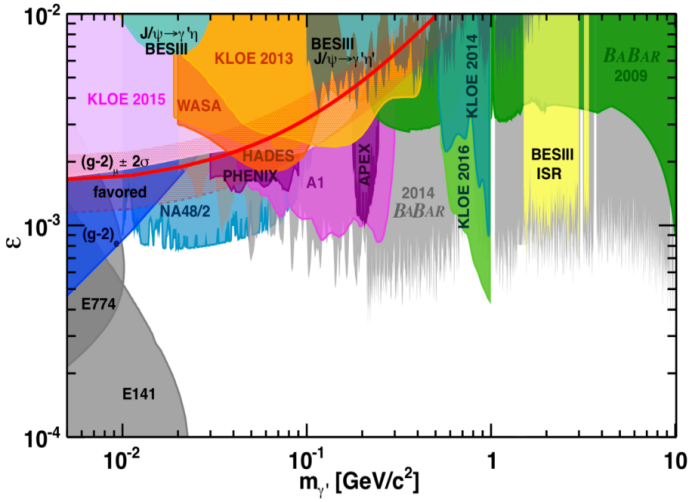

**Dominant QED backgrounds:** $e^+e^- \to \gamma_{ISR}l^+l^- \ (l = e, \mu)$

Search for a narrow structure in $m_{l^+l^-}$ spectrum




- No evidence of $\gamma'$ production
- Set 90% C.L. upper limits using the TRolke method.

Nucl.Instrum.Meth., A551, 493-503 (2005)

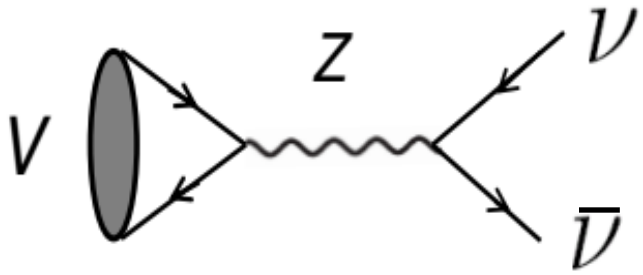


# Invisible decays

- Quarkonium states ($q\bar{q}$) can annihilate into $\nu\bar{\nu}$ via virtual $Z^0$ boson

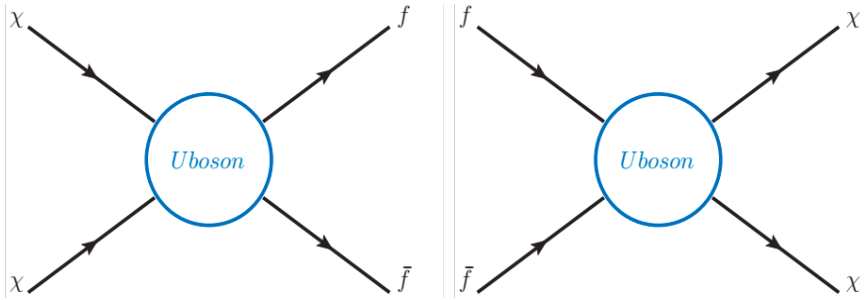
$$B(\omega \to \nu\bar{\nu}) = (2.79 \pm 0.05)\times 10^{-13}$$

$$B(\phi \to \nu\bar{\nu}) = (1.67 \pm 0.02)\times 10^{-11}$$




Phys. Rev. D **98**, 113006 (2018)

- Branching fraction of invisible decays of quarkoinum state might be enhanced in the presence of light DM particles.




Computed by assuming the same cross-section for the time reversed processes:

$$\sigma(q\bar{q} \to \chi\chi) \simeq \sigma(\chi\chi \to q\bar{q})$$

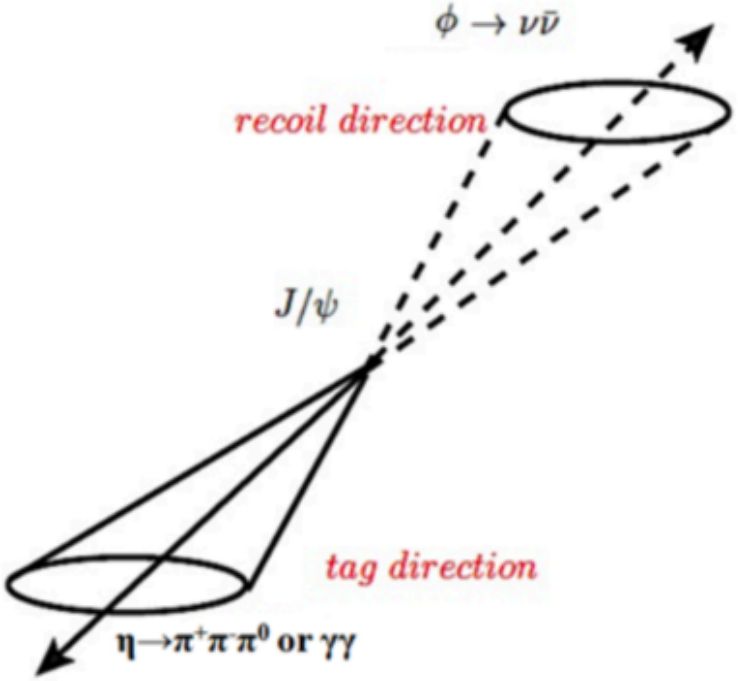
| mode | $s$-wave | $p$-wave |
|---|---|---|
| $\mathrm{BR}(\Upsilon(1S) \to \chi\chi)$ | $4.2 \times 10^{-4}$ | $1.8 \times 10^{-3}$ |
| $\mathrm{BR}(\Upsilon(1S) \to \nu\bar{\nu})$ | $9.9 \times 10^{-6}$ | |
| $\mathrm{BR}(J/\Psi \to \chi\chi)$ | $2.5 \times 10^{-5}$ | $1.0 \times 10^{-4}$ |
| $\mathrm{BR}(J/\Psi \to \nu\bar{\nu})$ | $2.7 \times 10^{-8}$ | |
| $\mathrm{BR}(\eta \to \chi\chi)$ | $3.4 \times 10^{-5}$ | $1.4 \times 10^{-4}$ |
| $\mathrm{BR}(\eta' \to \chi\chi)$ | $3.7 \times 10^{-7}$ | $1.5 \times 10^{-6}$ |
| $\mathrm{BR}(\eta_c \to \chi\chi)$ | $1.3 \times 10^{-7}$ | $5.3 \times 10^{-7}$ |
| $\mathrm{BR}(\chi_{c0}(1P) \to \chi\chi)$ | $2.7 \times 10^{-8}$ | $1.2 \times 10^{-7}$ |
| $\mathrm{BR}(\phi \to \chi\chi)$ | $1.9 \times 10^{-8}$ | $7.8 \times 10^{-8}$ |
| $\mathrm{BR}(\omega \to \chi\chi)$ | $7.2 \times 10^{-8}$ | $3.0 \times 10^{-8}$ |

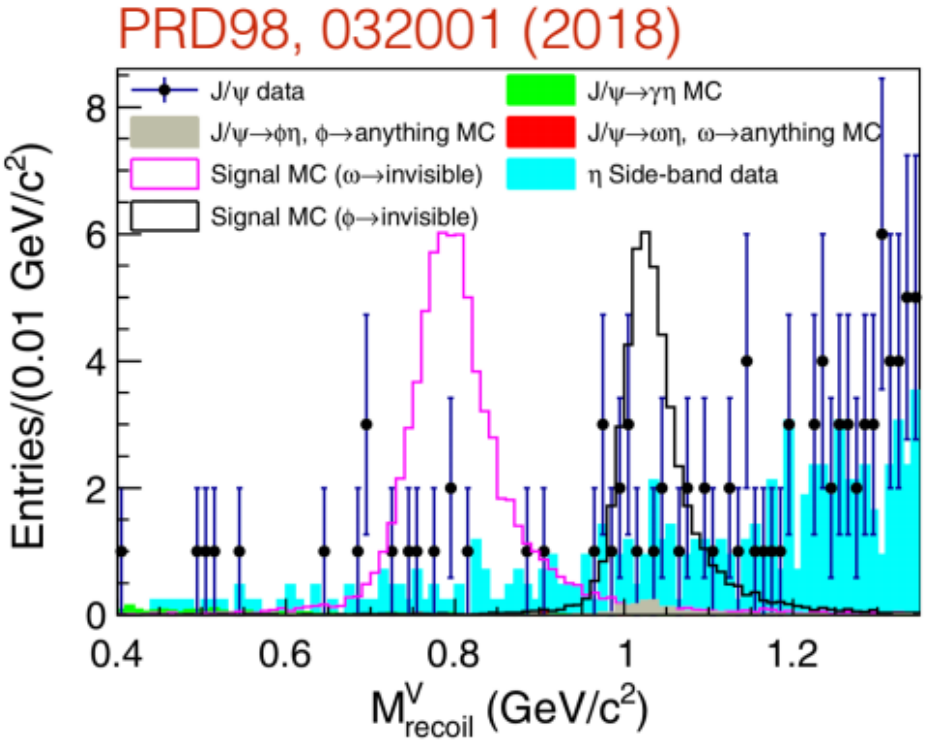
B. McElrath, eConf C070805, 19 (2007)

# Invisible decays of ω and ϕ mesons in J/ψ→ηω/ϕ

Phys. Rev. D 98, 032001 (2018)

- First search for J/ψ→ηω/ϕ, ω/ϕ→invisible using 1.3 billion J/ψ events
- Define recoiling mass against η: $M^V_{recoil} = \sqrt{(E_{CM} - E_{\pi^+\pi^-\pi^0})^2 - \vec{p}^{\,2}_{\pi^+\pi^-\pi^0}}$



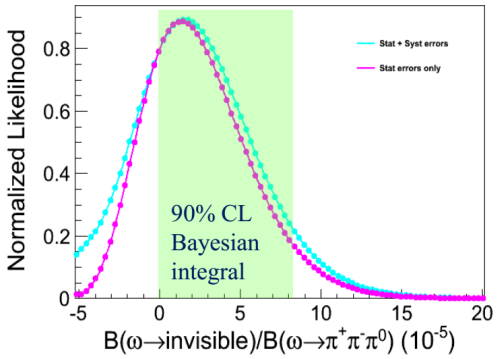



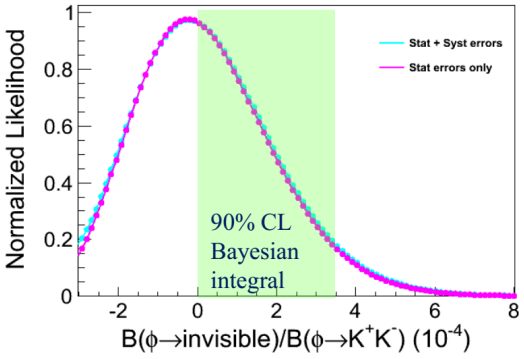

Only $\eta \to \pi^+\pi^-\pi^0$ decay mode is utilized for this measurement

# Invisible decays of ω and ϕ mesons in J/ψ→ηω/ϕ

Phys. Rev. D 98, 032001 (2018)

- Fit to $M^{V}_{recoil}$ to extract the signal yields
- No any obvious signal is found, and we set the 90% C.L. upper limits on the branching fraction after including the systematic uncertainties.



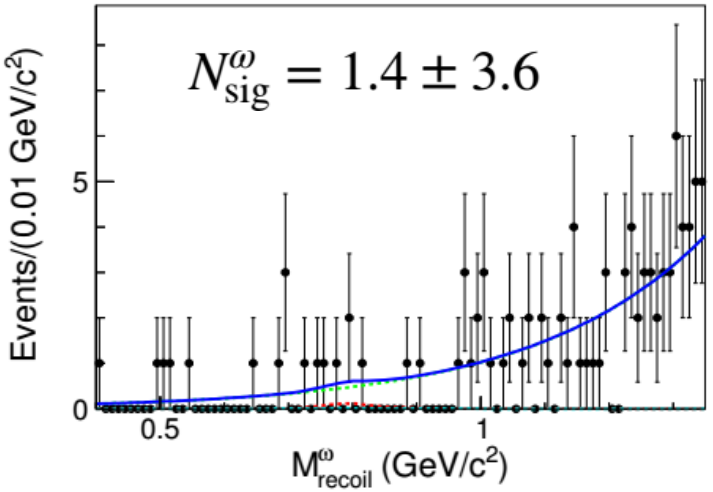



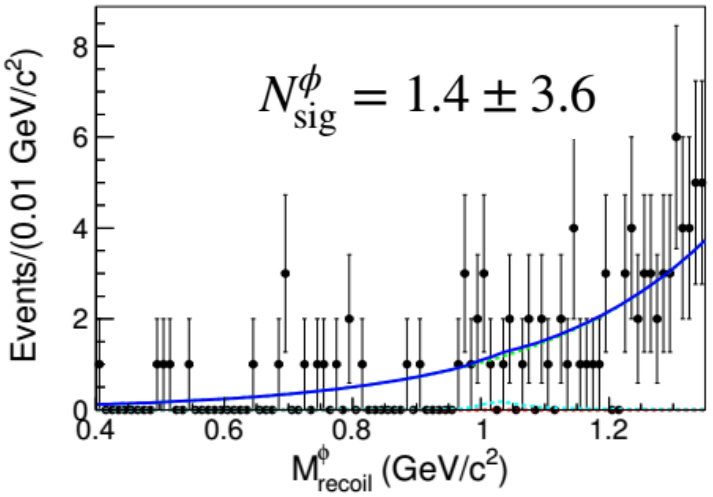

$$\frac{\mathcal{B}(\omega \to invisible)}{\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)} < 8.1 \times 10^{-5}$$

$$\mathcal{B}(\omega \to invisible) < 7.3 \times 10^{-5}$$

$$\frac{\mathcal{B}(\phi \to invisible)}{\mathcal{B}(\phi \to K^+K^-)} < 3.4 \times 10^{-4}$$

$$\mathcal{B}(\phi \to invisible) < 1.7 \times 10^{-4}$$




✓ **Published in Phys. Rev. D 98, 032001 (2018)**

First experimental limits on the invisible decays of ω and ϕ mesons.

# An introduction to the light Higgs boson

- A light Higgs boson is predicted by many extensions of Standard Model, such as Next-to-Minimal Supersymmetric Standard Model (NMSSM).

➢ NMSSM contains a total of three CP-even, two CP-odd and two charged Higgs bosons.

➢ **The lighter state of the $A^0$ is defined as:**

$$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_s$$

Non-singlet; Singlet

**[PRD 76, 051105 (2007)]**

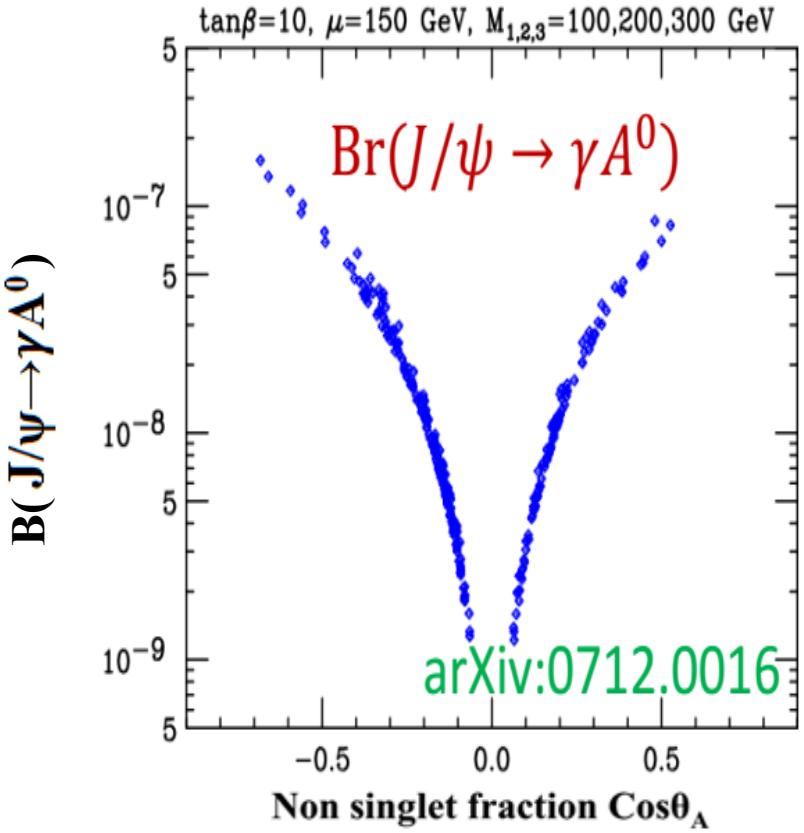
➢ Coupling of fermions and the CP-odd Higgs $A^0$

$$L_{int}^{f\bar{f}} = -\cos\theta_A \tan\beta \frac{m_f}{v} A^0 \bar{d}(i\gamma_5)d, \quad d = d,\ s,\ \mathbf{b},\ e,\ \mu,\ \tau$$

$$L_{int}^{f\bar{f}} = -\cos\theta_A \cot\beta \frac{m_f}{v} A^0 \bar{u}(i\gamma_5)u, \quad u = u,\ \mathbf{c},\ t,\ \nu_e,\ \nu_\mu,\ \nu_\tau$$

$$\tan\beta = \frac{v_u}{v_d}$$

**E. Fullana et. al, Phys. Lett. B 653, 67 (2007)**

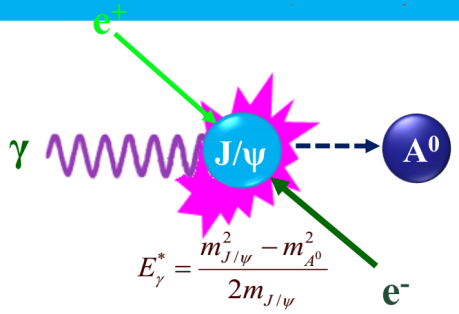



➢ Can be detectable via radiative decays of J/ψ and ϒ(1S)

[Phys. Rev. Lett. **39**, 1304 (1977)]

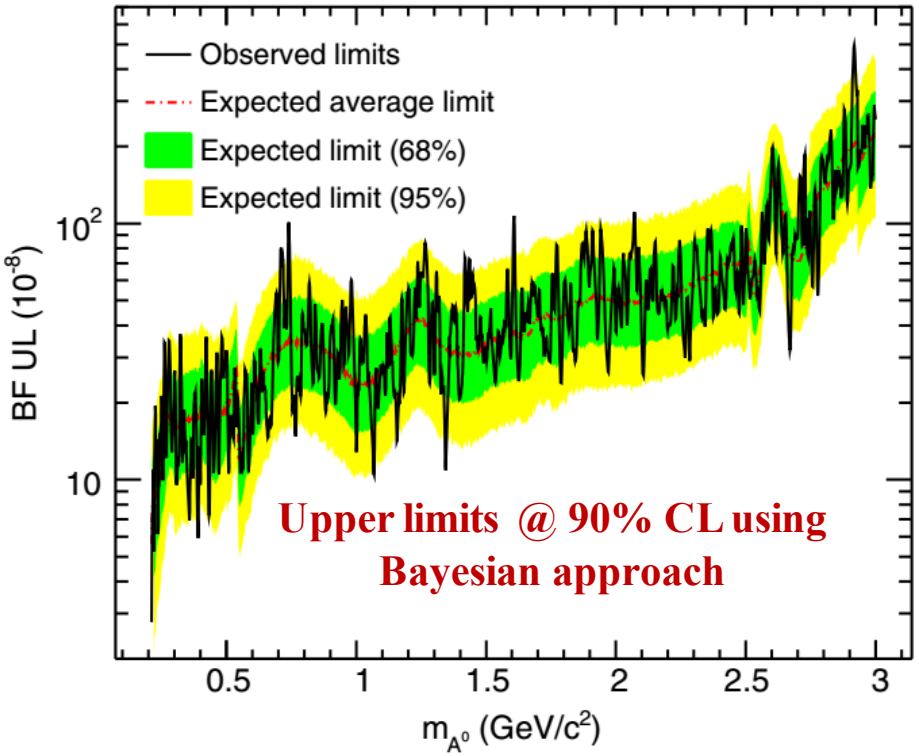
# Light Higgs boson search via $J/\psi \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

Phys. Rev. D 93, 052005 (2016)




Use 225 million J/ψ events collected by BESIII experiment to perform this study.

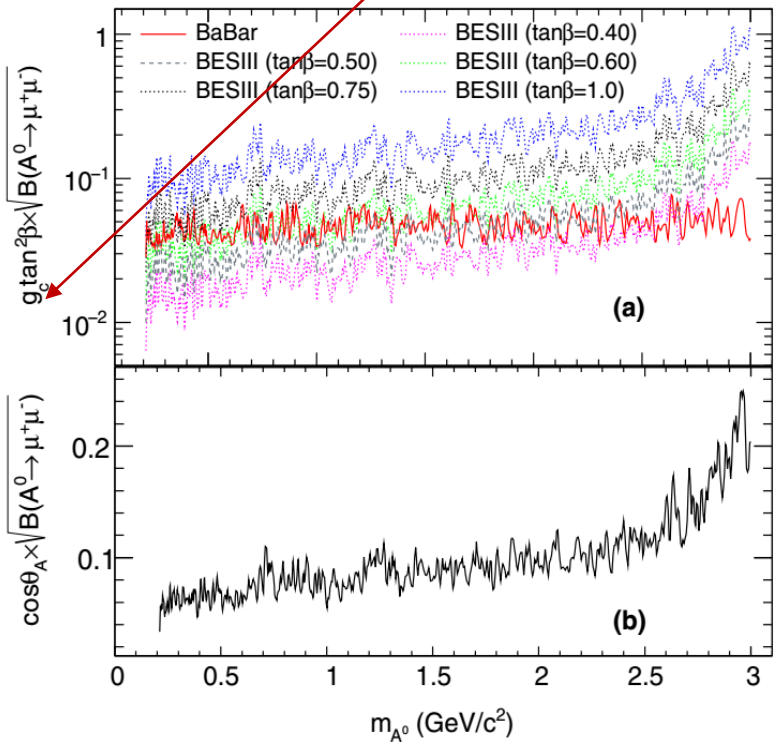
No evidence of $A^0$ production is found




➢ The results are 5 times below than the previous BESIII measurement [PRD 85, 092012 (2012)]

**Effective Yukawa coupling**

$$\frac{\mathcal{B}(V \to \gamma A^0)}{\mathcal{B}(V \to l^+ l^-)} = \frac{G_F m_q^2 g_q^2 C_{QCD}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m^2_{A^0}}{m^2_V}\right)$$




➢ The combined results of BaBar and BESIII reveal that the $A^0$ is constrained to be mostly singlet in nature.

➢ **Published in Phys. Rev. D 93, 052005 (2016).**

# Summary

- BESIII has a very rich programs for the new physics searches beyond the Standard Model using the data collected at several energy points in the tau-charm region

- Many recent results on the Dark matter searches:
  - ✓ Dark photon searches: $e^+e^- \to \gamma_{ISR}\gamma', \gamma' \to l^+l^-$ Phys. Lett. B **774**, 252 (2017)
    $J/\psi \to \gamma'\eta/\eta', \gamma' \to e^+e^-$ Phys. Rev. D **99**, 012013 (2019); Phys. Rev. D **99**, 012006 (2019)
  - ✓ Invisible decay of light quarkonium states: $J/\psi \to \eta\omega/\phi$, $\omega/\phi \to$ invisible, $\eta \to \pi^+\pi^-\pi^0$ Phys. Rev. D **98**, 032001 (2018)
  - ✓ Light CP-odd Higgs boson: $J/\psi \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ Phys. Rev. D **93**, 052005 (2016)

- Ongoing study related to the dark sector:
  - ✓ Search for dark gauge boson $U'$ decaying into $\gamma\pi^0$ in $J/\psi \to U'\eta'$
  - ✓ Light Higgs boson search via $J/\psi \to \gamma A^0$, $A^0 \to$ invisible

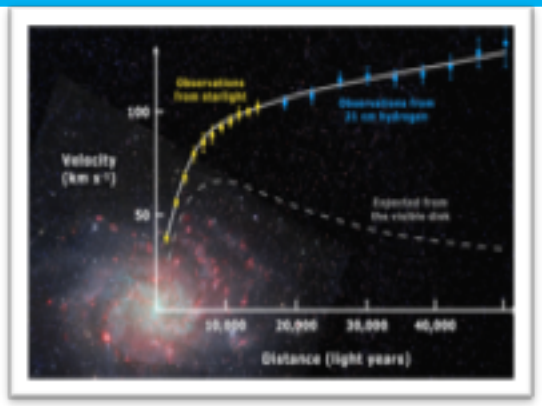
- Many more to come with recently collected 10 billion of the J/ψ data-set.

**http://bes3.ihep.ac.cn/doc/3313.html**

# Thank you!

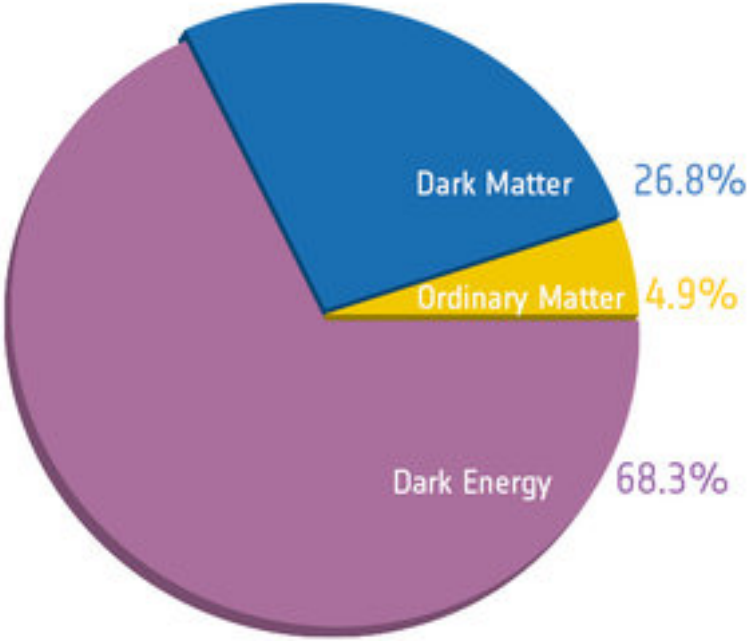
# Back up Slide

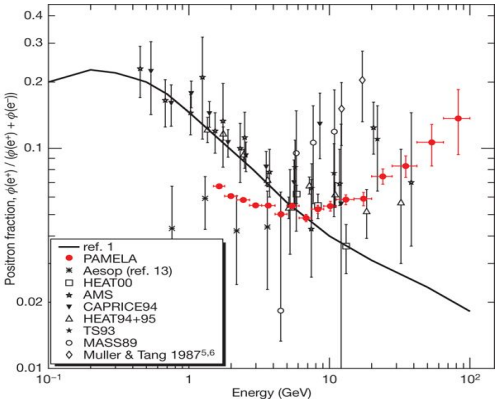
# Motivation




**Galaxy Rotation Curve (M33)**

https://en.wikipedia.org/wiki/Galaxy_rotation_curve



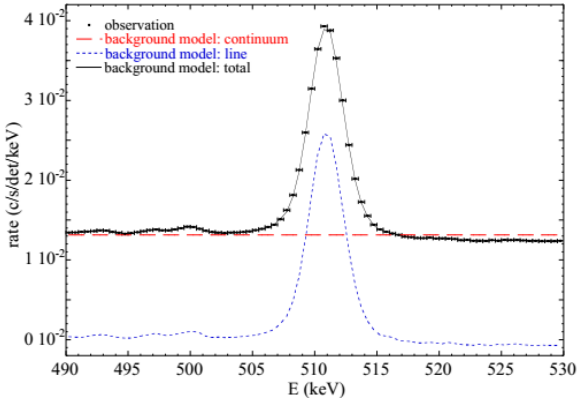




**PAMELA: Positron fraction**

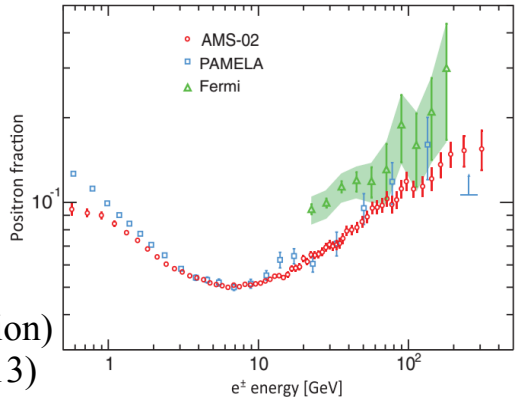
O Adriani et al.,
Nature 458 (2009) 607

**SPI/Integral**

P. Jean et al.,
A7A 407, L-55-L58 (2003)




**Overwhelming astrophysical evidence for dark matter (DM), but its precise nature and origin remain elusive.**




**AMS: Positron fraction**

M. Aguilar et al. (AMS Collaboration)
Phys. Rev. Lett. **110**, 141102 (2013)

# Calculation of ε in Dalitz decays $J/\psi \to \eta/\eta' e^+e^-$

Branching fraction of $J/\psi \to \gamma'\eta^{(\prime)}$

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 $J/\psi \to \gamma\eta^{(\prime)}$

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

Form factor for $J/\psi \to \gamma^*\eta^{(\prime)}$ transition evaluated at γ' mass

$$|F_{J/\psi\eta^{(\prime)}}(m^2_{\gamma'})|^2 = \frac{\Lambda^2}{\Lambda^2 - m^2_{\gamma'}} \qquad \Lambda^2 = m_{\psi(2S)}$$

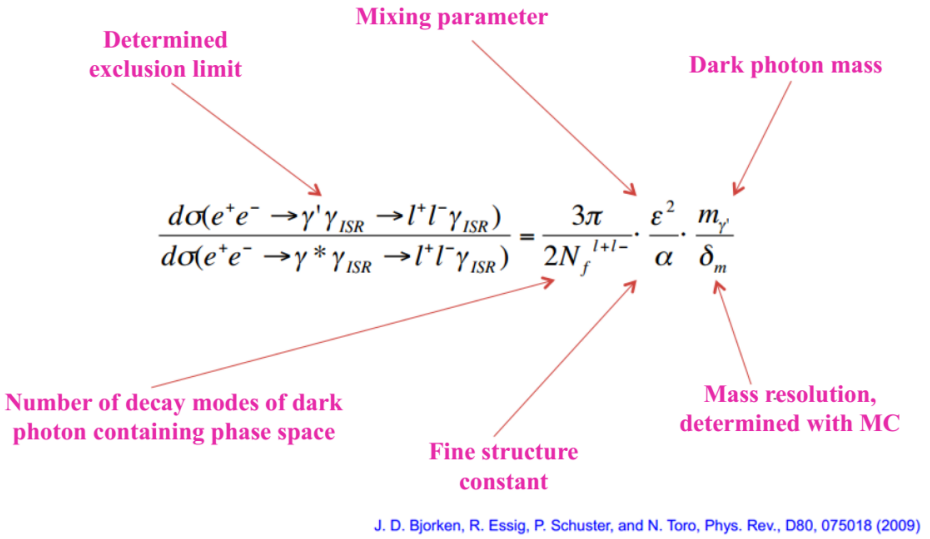
M. Reece and L. T. Wang
JHEP07, 051 (2009)

# Event selection and calculation of ε in $e^+e^- \to \gamma_{ISR}\gamma', \gamma' \to l^+l^-$

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<br>$R_z$ < 10.0 cm |
| acceptance | 0.4 rad < θ < π – 0.4 rad |
| to supress background | PID |
| # charged tracks | = 2 |
| total charge | = 0 |
| # photons | = 0 (untagged analysis) |
| missing photon angle | < 0.1 rad or > π – 0.1 rad |
| 1C kinematic fit | $\chi^2_{1C}$ < 20 |

## Calculation of ε

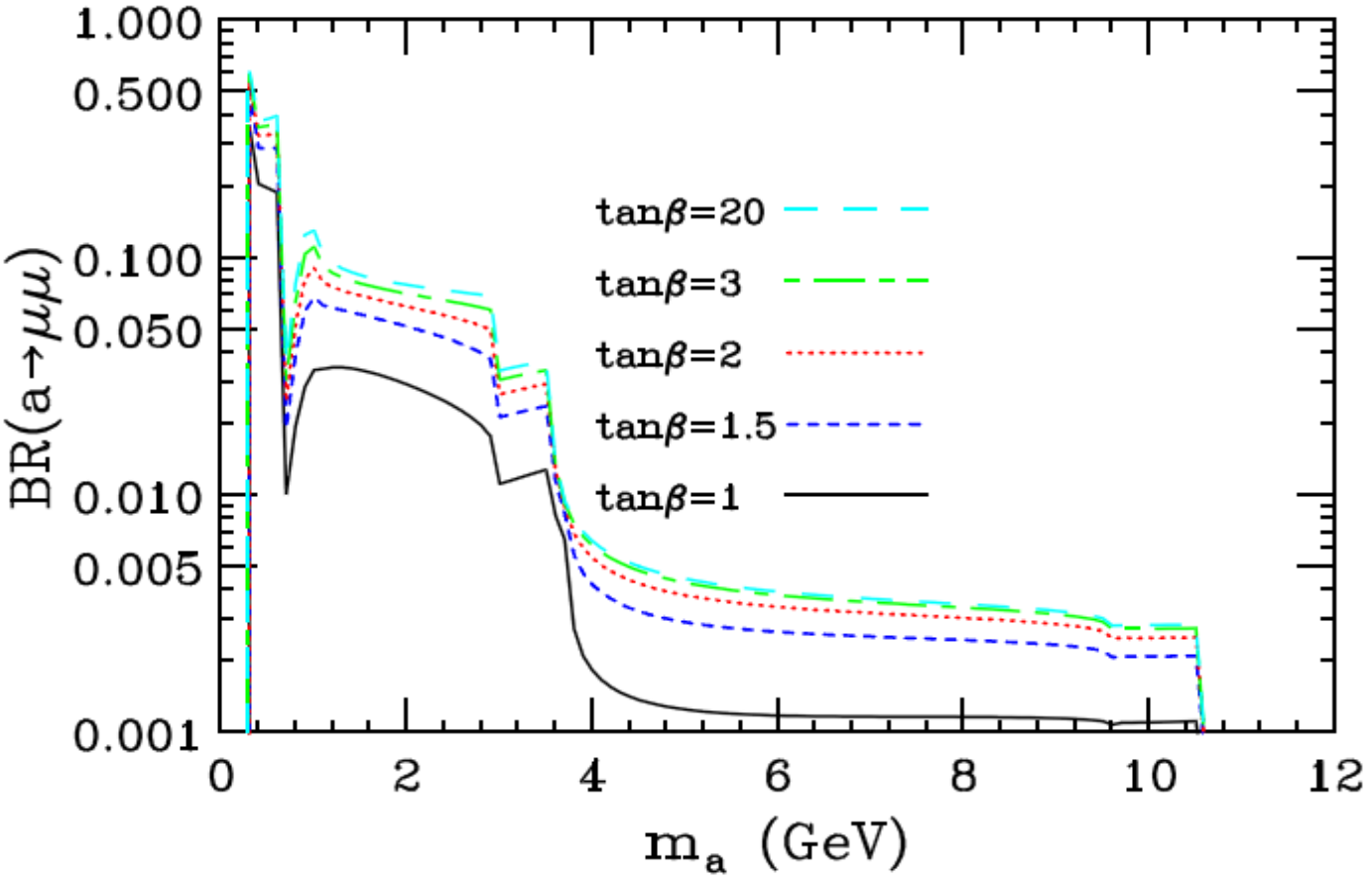



J. D. Bjorken, R. Essig, P. Schuster, and N. Toro, Phys. Rev., D80, 075018 (2009)

# Light Higgs boson search via $J/\psi \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

Phys. Rev. D 93, 052005 (2016)

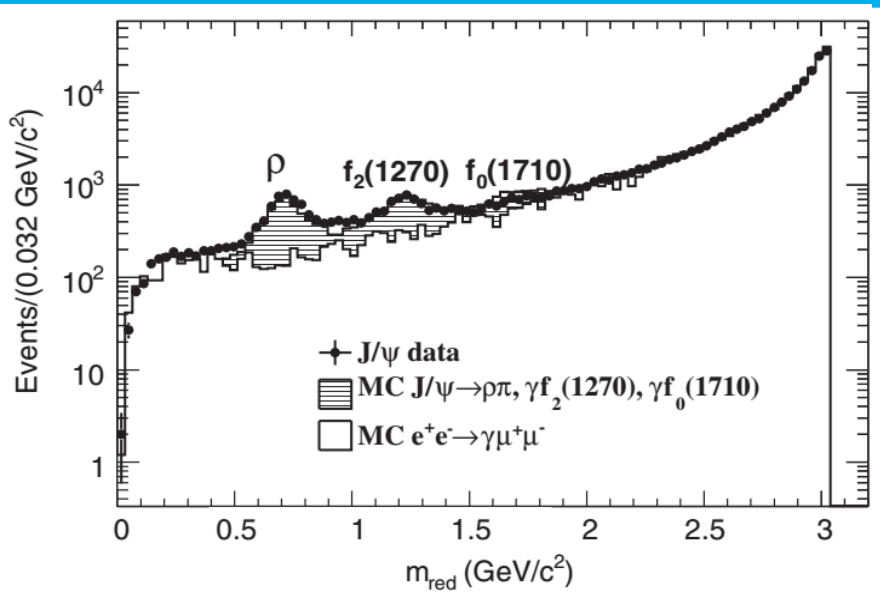
$A^0$ can decays into DM (neutralinos) or SM particles, such as $\mu^+\mu^-$

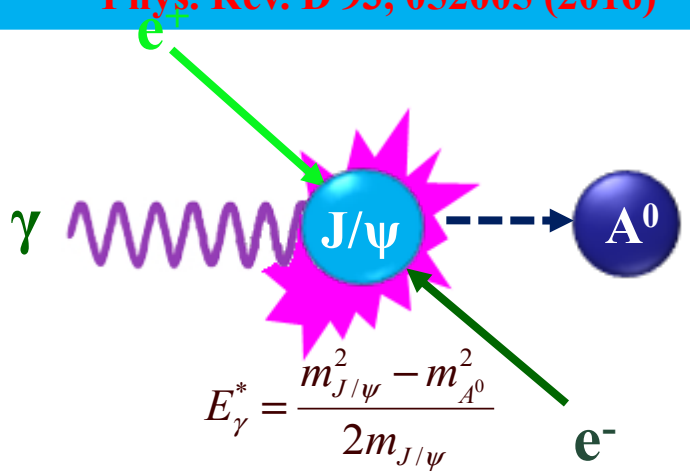



Phys. Rev. D 81, 075003 (2010)]

# Light Higgs boson search via $J/\psi \to \gamma A^0$, $A^0 \to \mu^+\mu^-$

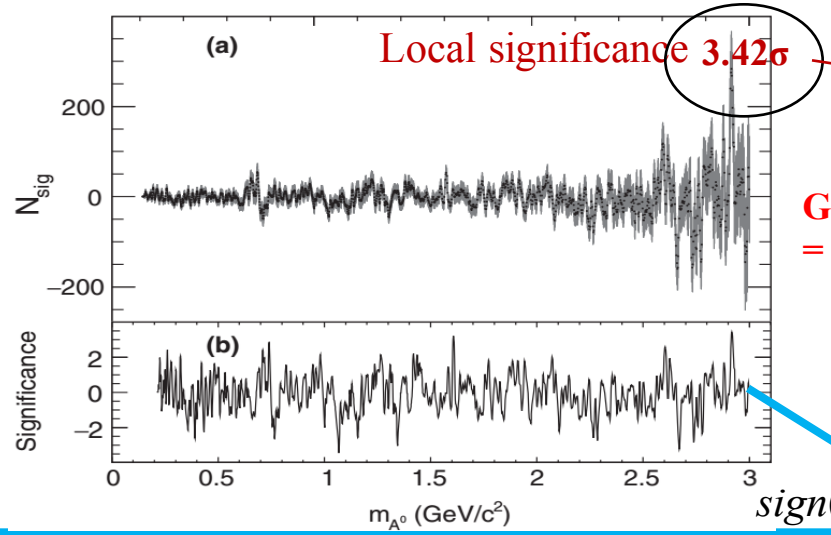
Phys. Rev. D 93, 052005 (2016)



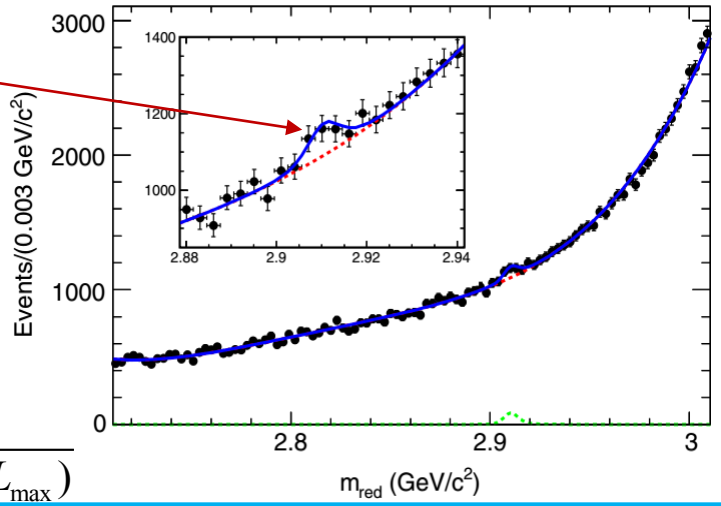




- Use 225 million J/ψ events collected by BESIII experiment to perform this study.

- Perform the ML fit to the $m_{red}$ distribution at 2035 mass points in the steps of 1-2 MeV/$c^2$.




**Global significance = 0.64 σ**




$$sign(N_{sig})\sqrt{-2\ln(L_0 / L_{max})}$$