# Search for low-mass Higgs and dark photons at BESIII

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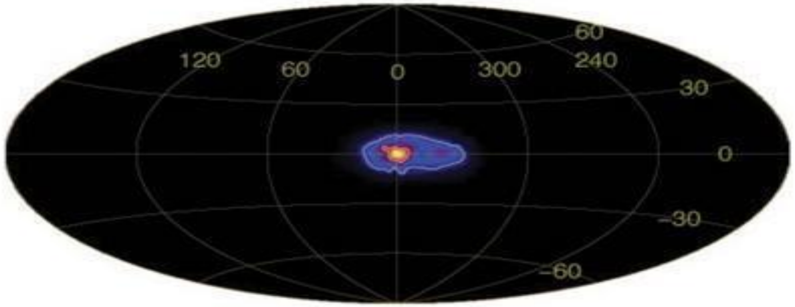
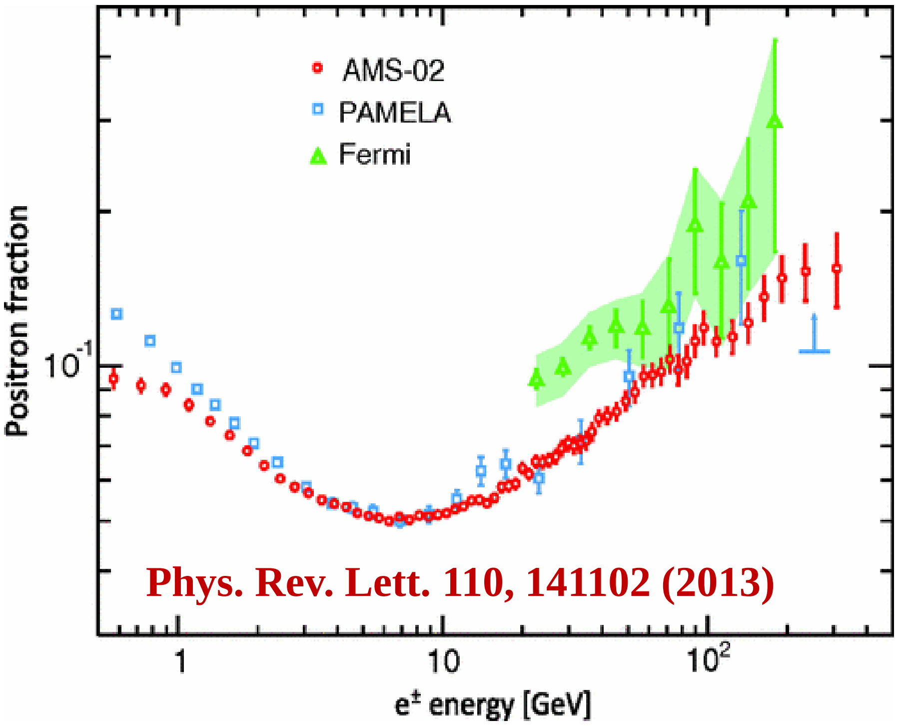
*CHARM 2015: The 7th International Workshop on Charm Physics*

# Motivation

- Many extensions of Standard Model (SM) introduce light weak-interacting degrees of freedom.
  - Motivated by recent experimental anomalies and theoretical prejudice.
  - 511 keV gamma ray excess from galactic center (INTEGRAL).



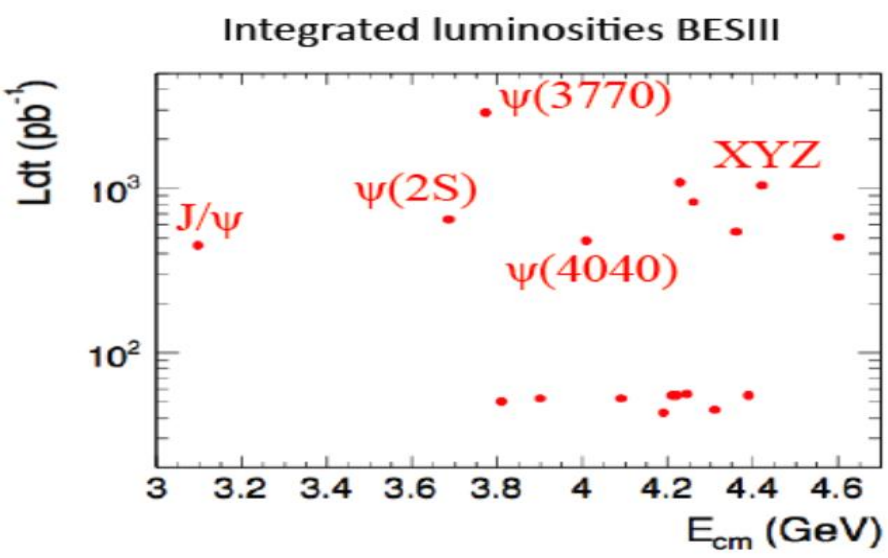

**ESA/Integral/MPE (G. Weidenspointner et al.)**

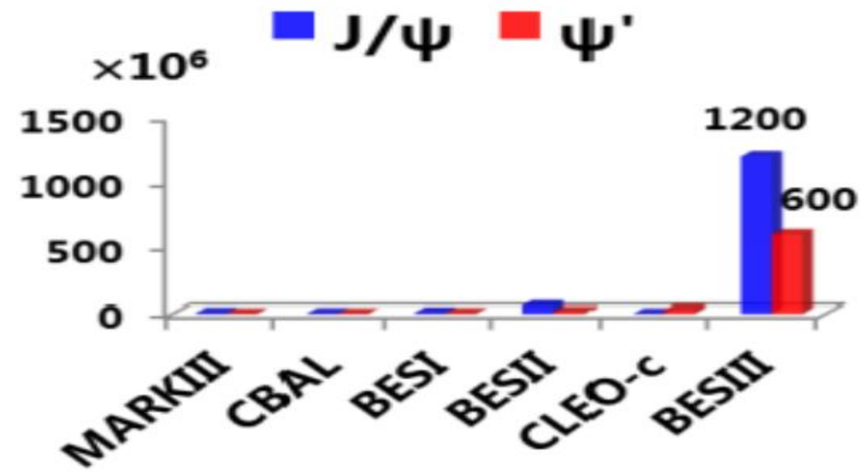



  - Positron excess in cosmic ray from PAMELA.
  - Hints of low-mass direct dark-matter (DM) detection (DAMA, CoGent, CRESST)

❖ Typical models: low-mass gauge bosons and/or scalars (Higgs).

# Light Higgs boson search @ BESIII

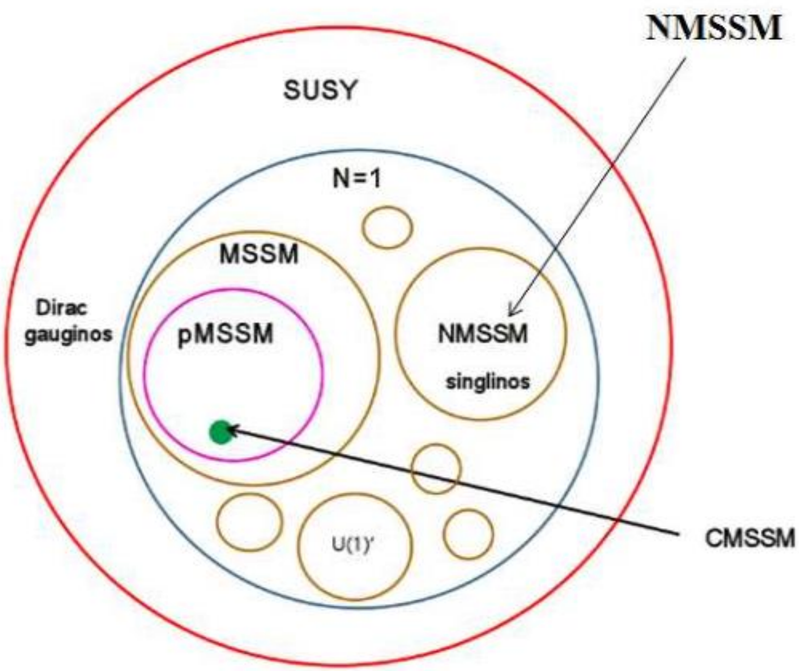



- Perform the search for di-muon decays of a light Higgs boson in radiatve decay of J/ψ using 225 million J/ψ events **[Chinese Phys. C (HEP & NP) 36(10), 915 (2012)]** and $1.06\times10^{8}$ ψ(2S) events collected by BESIII experiment.

# Introduction

- The Next-to-Minimal Supersymmetric Standard Model (NMSSM) is a Supersymmetric extensions of the SM.
- Solves the fine tuning problem of the Minimal Supersymmetric Standard Model (MSSM) by adding an additional chiral singlet superfield to the MSSM.
- NMSSM contains a total of three CP-even, two CP-odd and two charged Higgs bosons.
- The lightest CP-odd Higgs boson ($A^0$) could have a mass smaller than twice the mass of the c-quark.




T. Rizzo (SLAC summer institute 2012)

❖ Can be detectable via $J/\psi \rightarrow \gamma A^0$ decay. **[PRL 39, 1304 (1977)]**

- Observable branching fraction (BF) for $J/\psi \rightarrow \gamma A^0$ is possible in the range of $\mathbf{10^{-9} - 10^{-7}}$.

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

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

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

$\cos\theta_A A_{MSSM}$ → Non-singlet

$\sin\theta_A A_s$ → Singlet

# Intordution

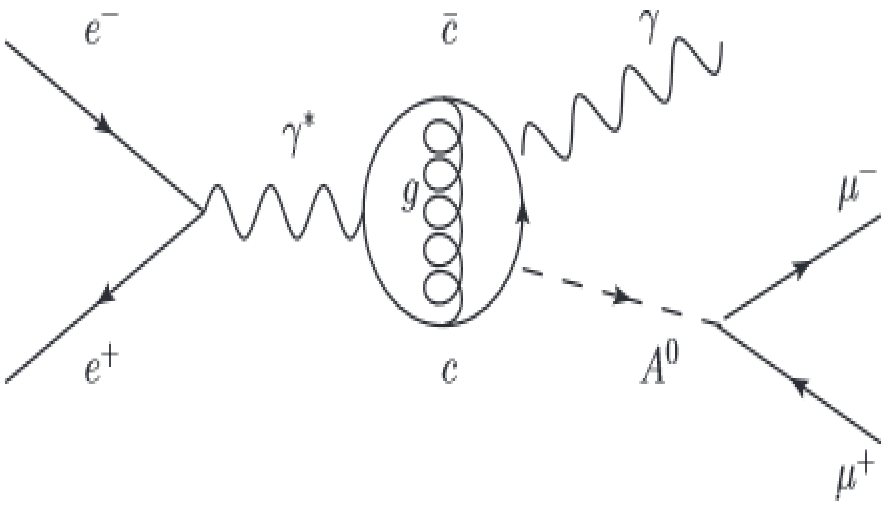
➢ Coupling of fermions and the CP-odd Higgs $A^0$

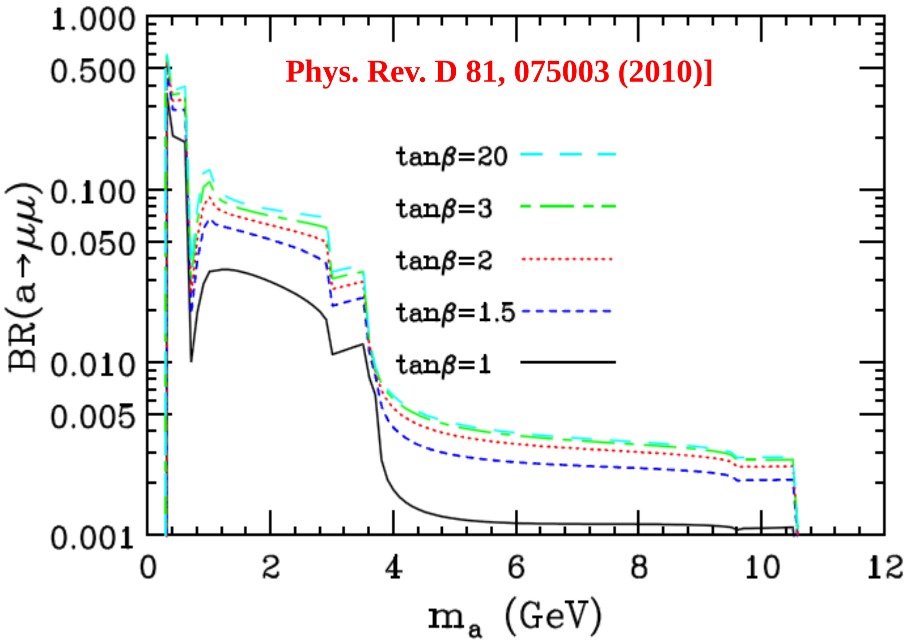
$$L_{\text{int}}^{f\bar{f}} = -\cos\theta_A \tan\beta \frac{m_f}{v} A^0 \bar{d}(i\gamma_5)d, \quad d = d,\ s,\ \mathbf{b},\ e,\ \mu,\ \tau$$

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

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

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



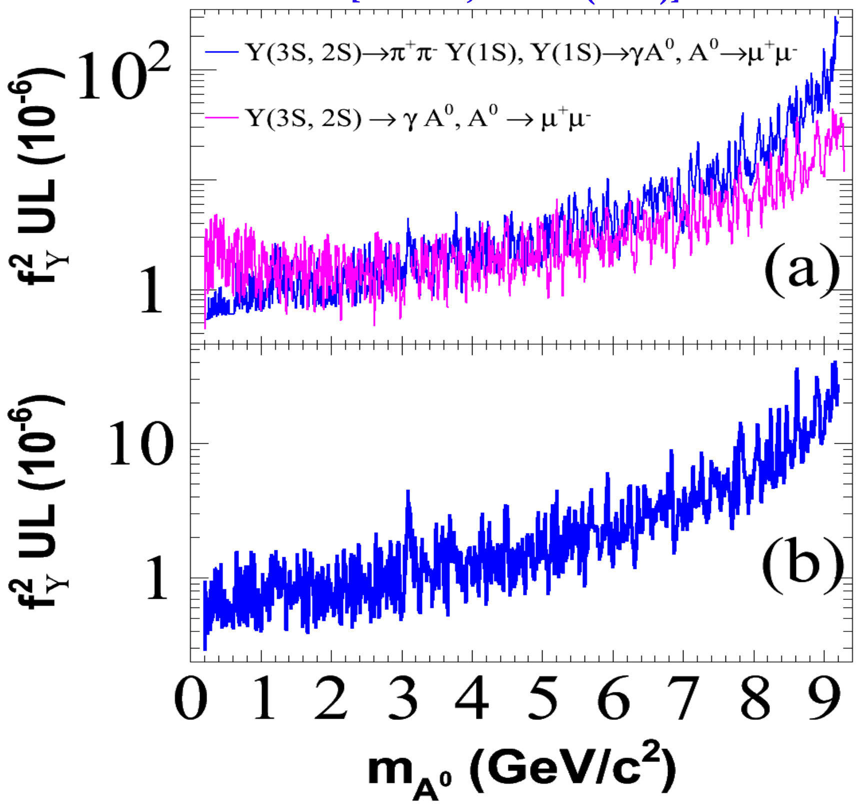

❖ The CLEO [PRL101, 151802 (2008)], BaBar [PRL 103, 081803 (2009); PRD 87, 031102 (R) (2013)], BESIII [PRD 85, 092012 (2012)] and CMS [PRL 109, 121801 (2012)] experiments have reported negative results for the $A^0$ decaying to muon pair using various decay channels and in five different $A^0$ mass ranges.

# Where do we stand now

## Coupling of b-quark to the $A^0$:

**Expected BF: $10^{-3}$ - $10^{-7}$**

[PRD 76, 051105 (2007)]




V. Prasad Thesis: SLAC-R-1008, PRD 87, 031102(R) (2013)

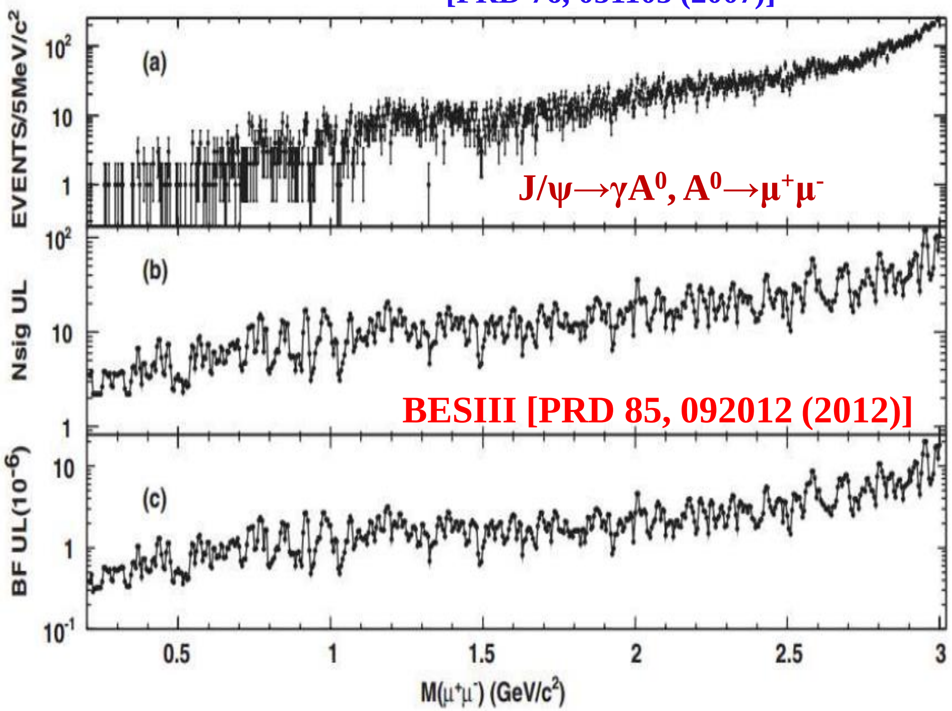
PRL 103, 081803 (2009)

- **Very strong exclusion limit is placed by BaBar experiment.**

## Coupling of c-quark to the $A^0$:

**Expected BF: $10^{-7}$ - $10^{-9}$**

[PRD 76, 051105 (2007)]

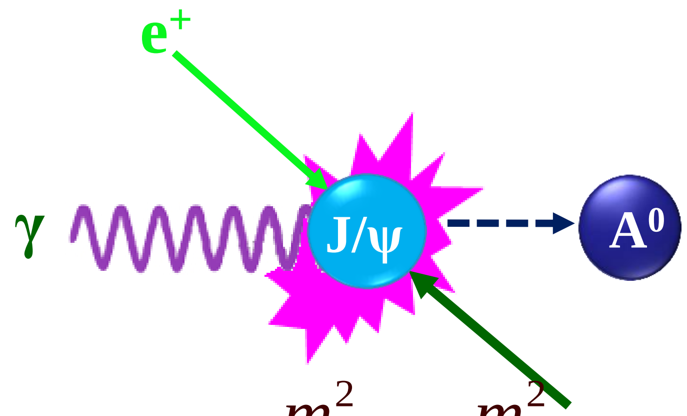



**Previous BESIII exclusion limit ranges from $4\times10^{-7}$ - $2.1\times10^{-5}$ depending on $A^0$ mass points.**

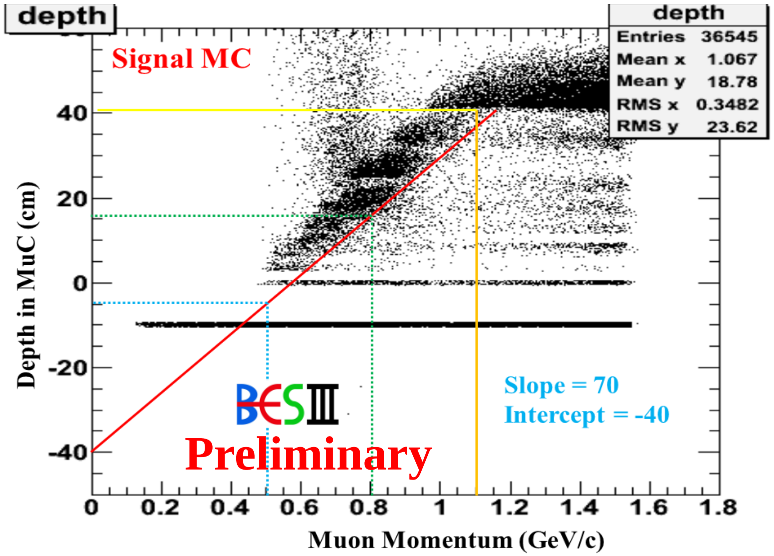
**Large data-sets collected by BESIII at J/ψ resonance allow us to check this prediction once again with high precision.**

# Event Reconstruction

- Reconstruct the event of interests with two charged tracks and an energetic photon.
- Perform the 4-constraint (4C) kinematic fit with two charged tracks and an energetic photon to improve the Higgs mass resolutions.
- Perform a blind analysis.
- Energy deposited in the EMC by showering particle ( $E^{\mu}_{cal}$ ) must be in the range of [0.1,0.3] GeV.
- The absolute value of time difference between TOF and expected muon time ($\Delta t^{TOF}$) must be less than 0.26 ns.
- The cosine of muon helicity angle ( $Cos\theta^{heli}_{\mu}$ ) to be within range of 0.92.
- Require the momentum dependent selection criteria of penetration depth of muon counter (MuC).




$$E^{*}_{\gamma} = \frac{m^2_{J/\psi} - m^2_{A^0}}{2m_{J/\psi}}$$

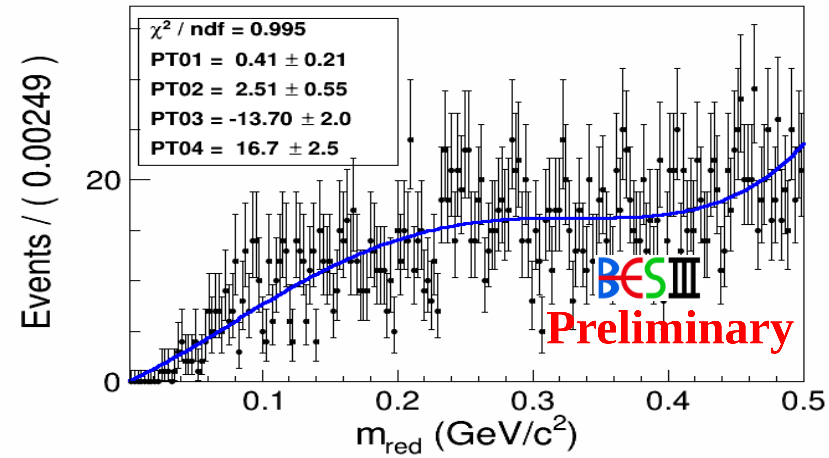


# Maximum likelihood fit

- Perform 1d maximum likelihood (ML) fit to the reduced mass, $m_{red} = \sqrt{m_{A^0}^2 - 4m_\mu^2}$ spectrum.
- Fits are done in some $m_{red}$ intervals at different Higgs mass points.

## Background PDF

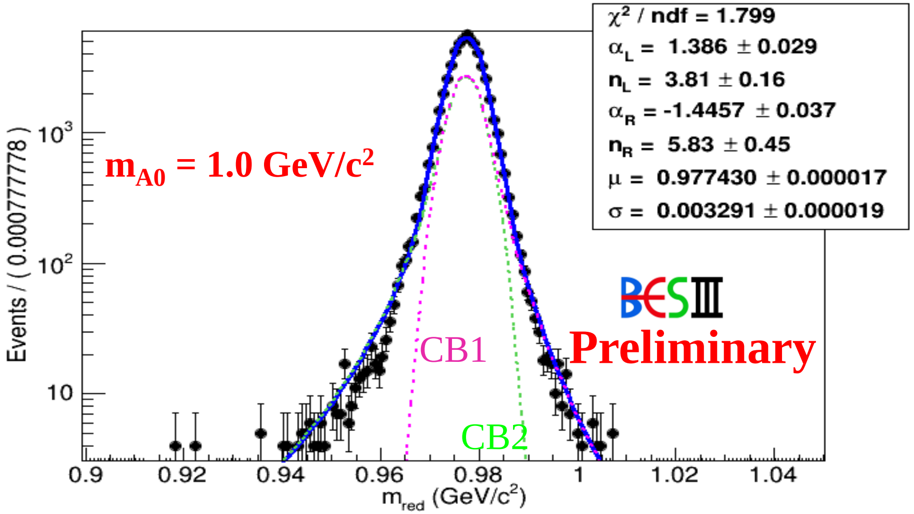
$$f(m_{red}) = \sum_{l=1}^{4} p_l m_{red}^{\ l}$$

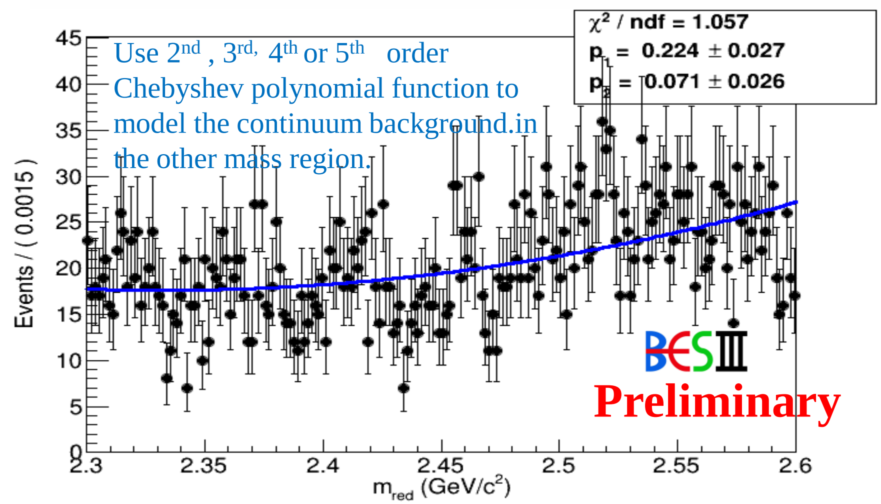



## Signal PDF

- Use sum of the two crystal-Ball (CB) functions with opposite side tails. The CB is defined as:

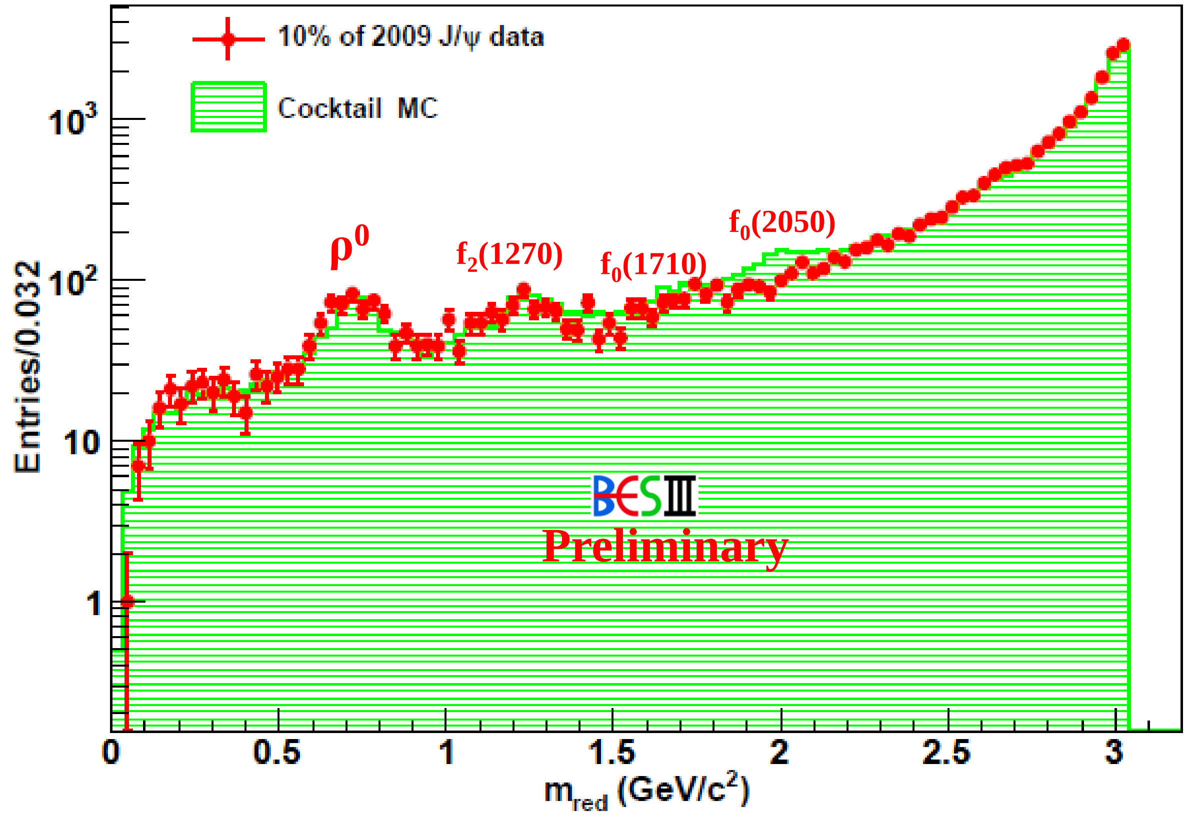
$$f(x|\mu,\sigma,\alpha,n) = C.\begin{cases} \exp\left(\dfrac{-(x-\mu)^2}{2\sigma^2}\right), & \dfrac{x-\mu}{\sigma} > -\alpha \\ \left(\dfrac{n}{|\alpha|}\right)^n \exp\left(-\dfrac{\alpha^2}{2}\right).\left(\dfrac{n}{|\alpha|} - |\alpha| + \dfrac{x-\mu}{\sigma}\right)^{-n}, & \dfrac{x-\mu}{\sigma} \le -\alpha \end{cases}$$




➢Validate the fitting procedure using the toy data and a composite sample of inclusive $J/\psi$ decays and $\gamma\mu^+\mu^-$ MCs

# Data vs. MC




Cocktail MC contains 10 times more statistics than 10% of J/ψ data.

The $f_0(2050)$ peak is not seen in the 10% of J/ψ data due to low-statistics.

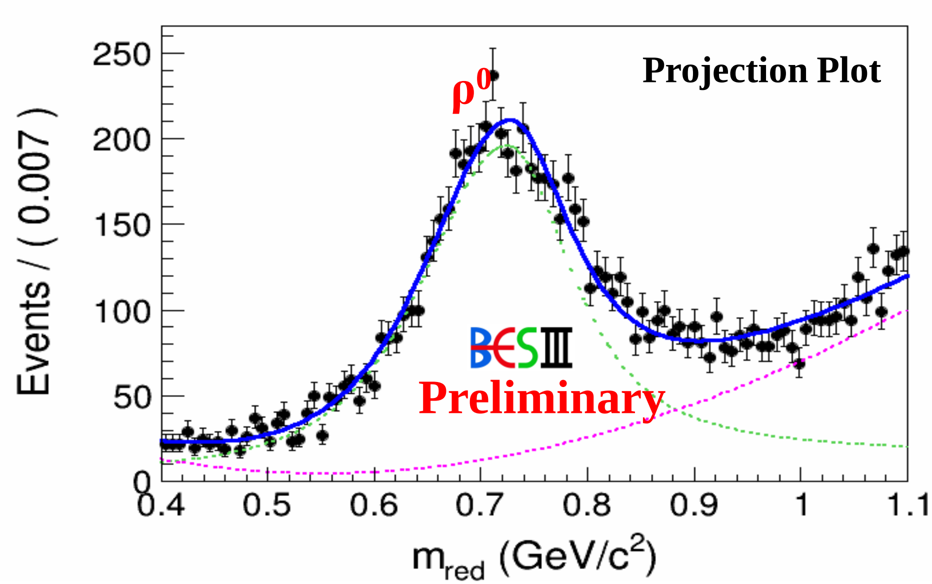
- Model the $\rho^0$ peak using a modified Gaussian function defined as:

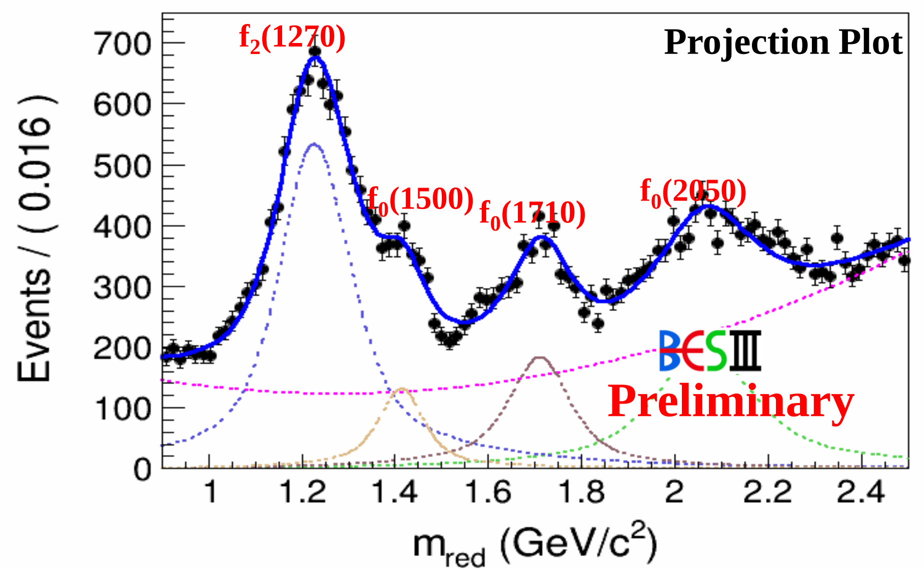
$$f_{L,R}(m_{\rm red}) = exp[-(m_{\rm red}-\mu)^2/(2\sigma^2_{L,R}+\alpha_{L,R}(m_{\rm red}-\mu)^2)]$$

- Use sum of the two CB functions to model the peaking components of $f_2(1270)$, $f_0(1710)$ and $f_4(2050)$ mesons.

# Branching fractions (BFs) of peaking backgrounds

- The mean and sigma values of the peaking backgrounds in MC are corrected using a control sample of $J/\psi \to l^+l^-(\gamma)$ ($l=\mu,\pi$) decay, which does not require the selection criteria of depth in MuC.




BESIII

## Results from $m_{red}$ distribution

| Preliminary | data | | MC | |
|---|---|---|---|---|
| Decay process | Mean (GeV/$c^2$) | sigma (GeV/$c^2$) | Mean (GeV/$c^2$) | sigma (GeV/$c^2$) |
| $J/\psi \to \rho\pi$ | $0.725 \pm 0.0030$ | $\sigma_L = 0.073 \pm 0.0090$<br>$\sigma_R = 0.056 \pm 0.0082$ | $0.757 \pm 0.0029$ | $\sigma_L = 0.072 \pm 0.0030$<br>$\sigma_R = 0.055 \pm 0.0028$ |
| $J/\psi \to \gamma f_2(1270)$ | $1.228 \pm 0.0037$ | $0.0746 \pm 0.0047$ | $1.246 \pm 0.0003$ | $0.0798 \pm 0.0004$ |
| $J/\psi \to \gamma f_0(1500)$ | $1.416 \pm 0.0002$ | $0.0440 \pm 0.0005$ | $1.483 \pm 0.0002$ | $0.0443 \pm 0.0003$ |
| $J/\psi \to \gamma f_0(1710)$ | $1.712 \pm 0.0008$ | $0.0603 \pm 0.0151$ | $1.707 \pm 0.0002$ | $0.0542 \pm 0.0004$ |
| $J/\psi \to \gamma f_4(2050)$ | $2.065 \pm 0.0028$ | $0.0958 \pm 0.0016$ | $2.003 \pm 0.0003$ | $0.0926 \pm 0.0005$ |

The branching fractions of the peaking backgrounds are almost consistent with their PDG values.

**[PDG, Chin. Phys. C 38, 090001 (2014)]**

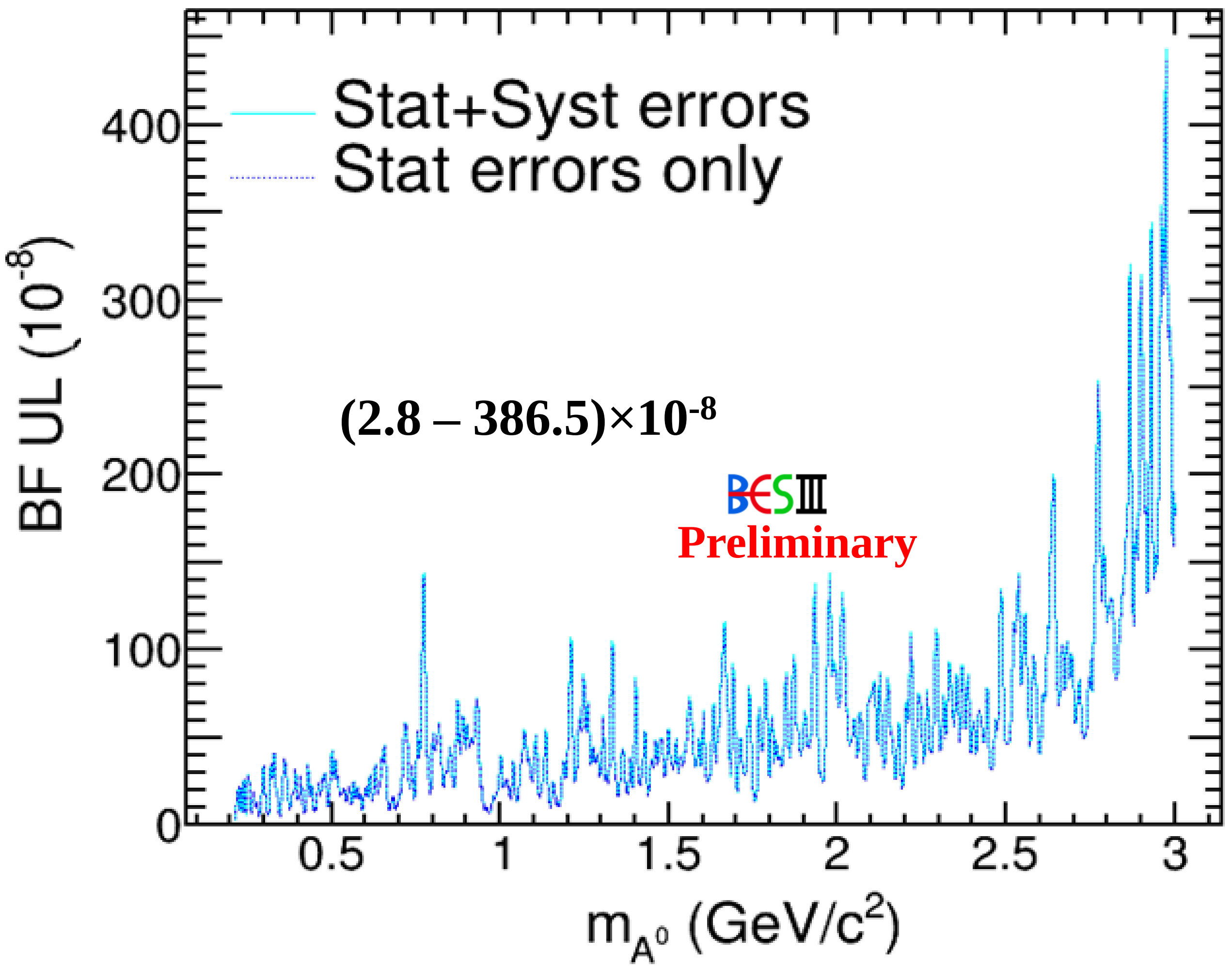
# Systematic Uncertainties

| Source | Uncertainty |
| --- | --- |
| Additive systematic uncertainties (events) | |
| $N_s$ PDF | (0.00 – 0.58) |
| Fit Bias | 0.502 |
| Total | 0.502 – 0.767 |
| Multiplicative systematic uncertainties (%) | |
| Peaking background modeling | 0.00 – 6.7 |
| Non-peaking background modeling | 3.18 |
| Depth in MuC | 4.00 |
| $E^{\mu}_{cal}$ | 0.05 |
| $\Delta t^{TOF}$ | 0.11 |
| $\mathrm{Cos}\theta^{hel}_{\mu}$ | 0.34 |
| Charged tracks | 2.00 |
| Photon detection efficiency | 1.00 |
| $\chi^2_{4C}$ | 1.56 |
| $J/\psi$ counting | 1.30 |
| Total | 5.95 – 8.96 |

BESIII
**Preliminary**

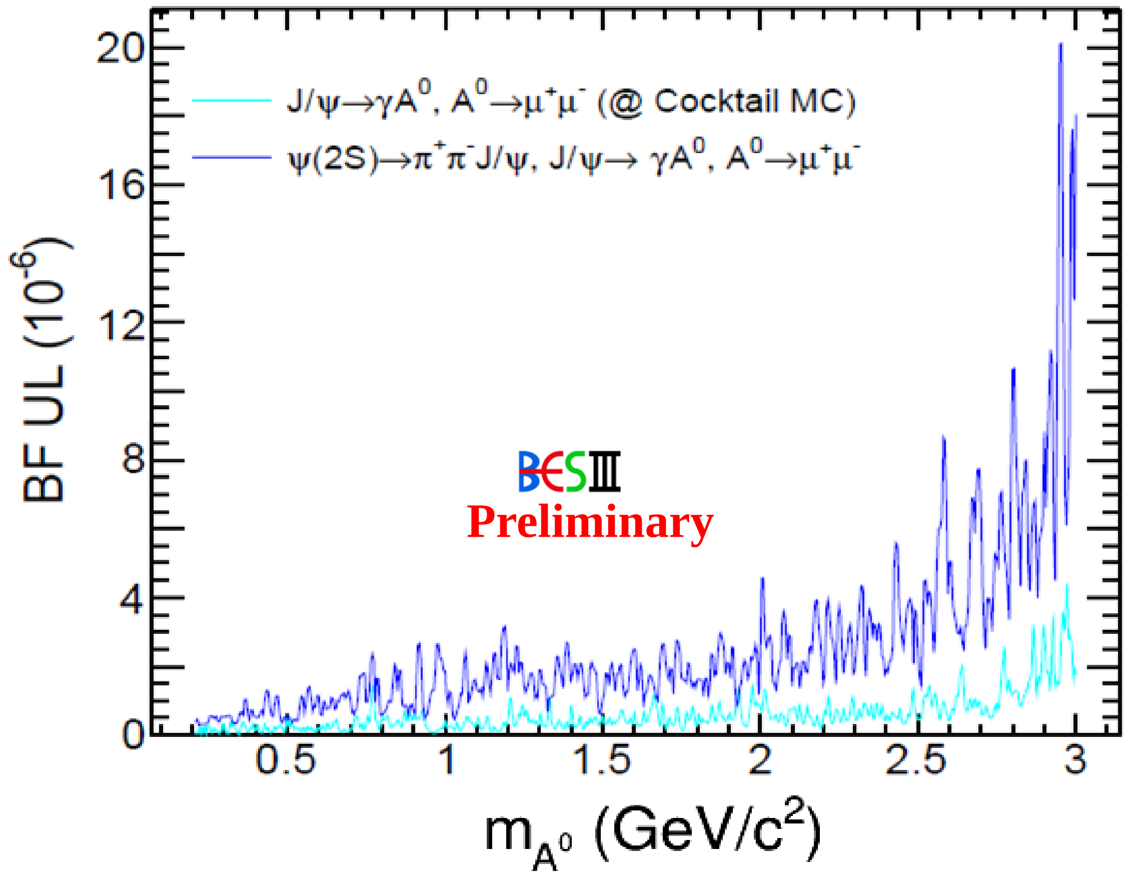
➢ Additive systematic uncertainty is based on the cocktail MC sample and multiplicative systematic uncertainty based on the different control samples of data and MC.

# Expected upper limits




The expected 90% C.L. upper limit on product branching fraction of $\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$ as a function of $m_{A^0}$ in the full 2009 $J/\psi$ data-set, based on a cocktail MC sample.

# New vs. old BESIII measurements




- Based on the cocktail MC studies, we expect to achieve an order of magnitude better upper limits than previous BESIII measurements.

**PRD 85, 092012 (2012) (BESIII experiment)**

- Will unblind the full $J/\psi$ data very soon.

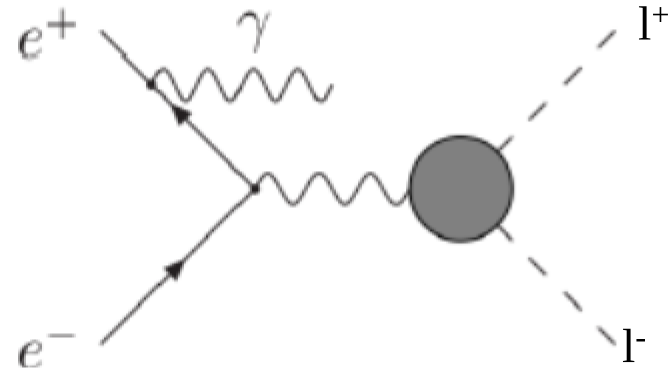
# Search for dark photon at BESIII

## Using the initial state radiation (ISR) process:

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

and

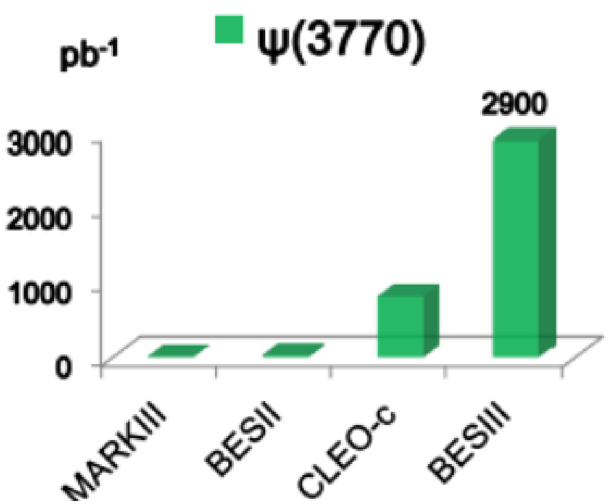
$$e^+e^- \to \gamma_{ISR}\gamma' \to \gamma_{ISR}e^+e^-$$




use 2.9 $fb^{-1}$ data, taken at 3.77 GeV

at

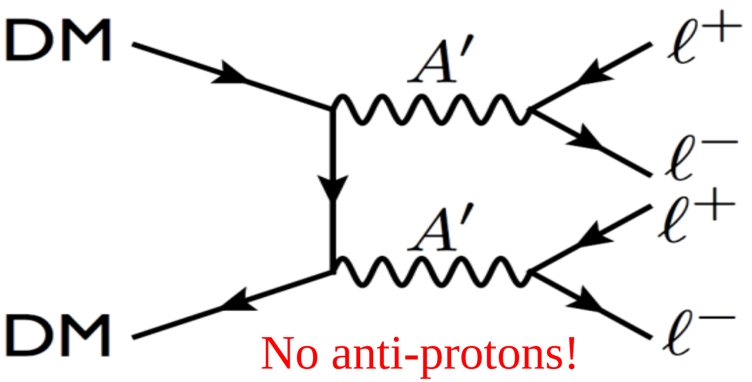
BESIII



# Gauge bosons in the "Dark Sector"

➢ New Models introduce new dark force carriers (e.g. dark-photon A') with light hidden sectors.

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

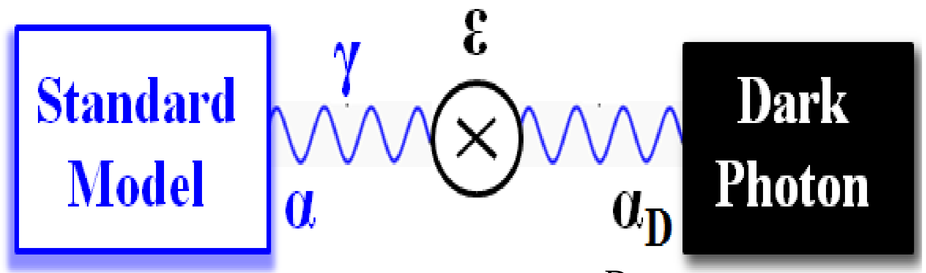



$m_{DM} \sim$ TeV  MeV $\lesssim m_{A'} \lesssim$ GeV

❖ Produces high-energy (~100 GeV) cosmic-ray electrons and positrons.

❖ Could explain cosmic ray excesses (PAMELA/ATIC features).

❖ 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':

$\alpha_D = \alpha\varepsilon$

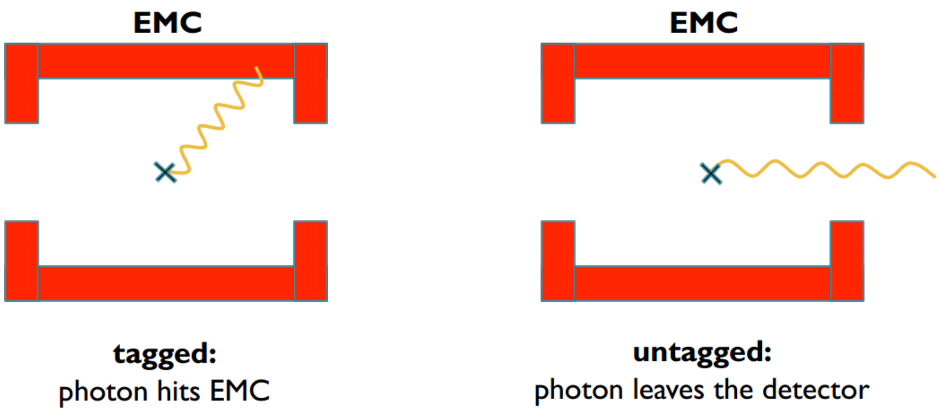
**B. Batell, et al, PRD79, 115008 (2009);**
**R. Essig, et al, PRD80 015003 (2009)**

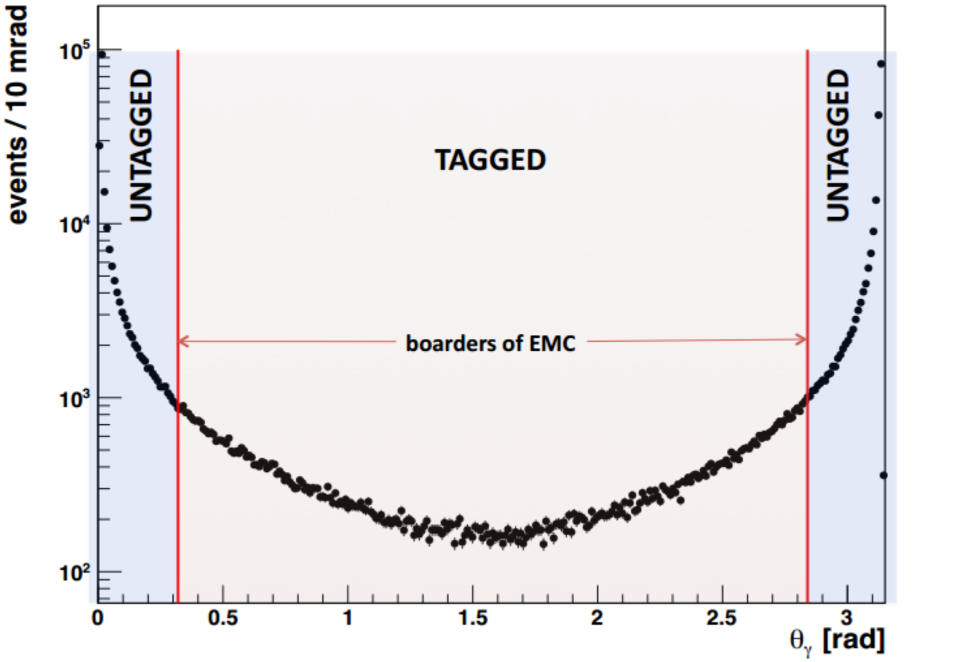
# Event Selection and reconstruction

- Use an untagged photon method to perform this analysis.

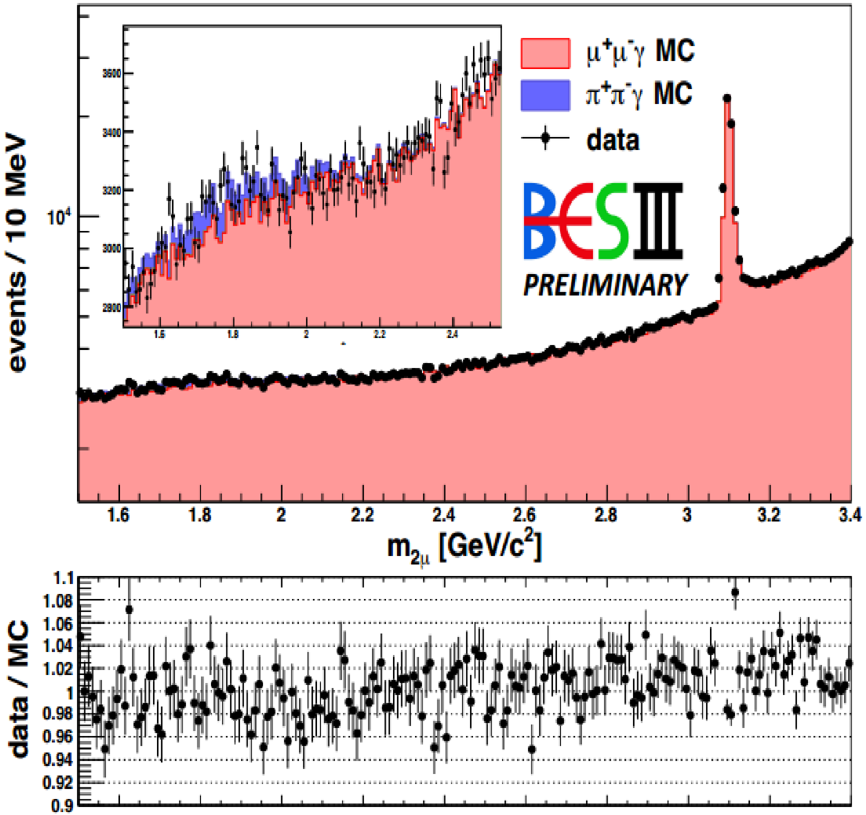
Event selection: $e^+e^- \rightarrow \mu^+\mu^-\gamma_{ISR}$ and $e^+e^- \rightarrow e^+e^-\gamma_{ISR}$

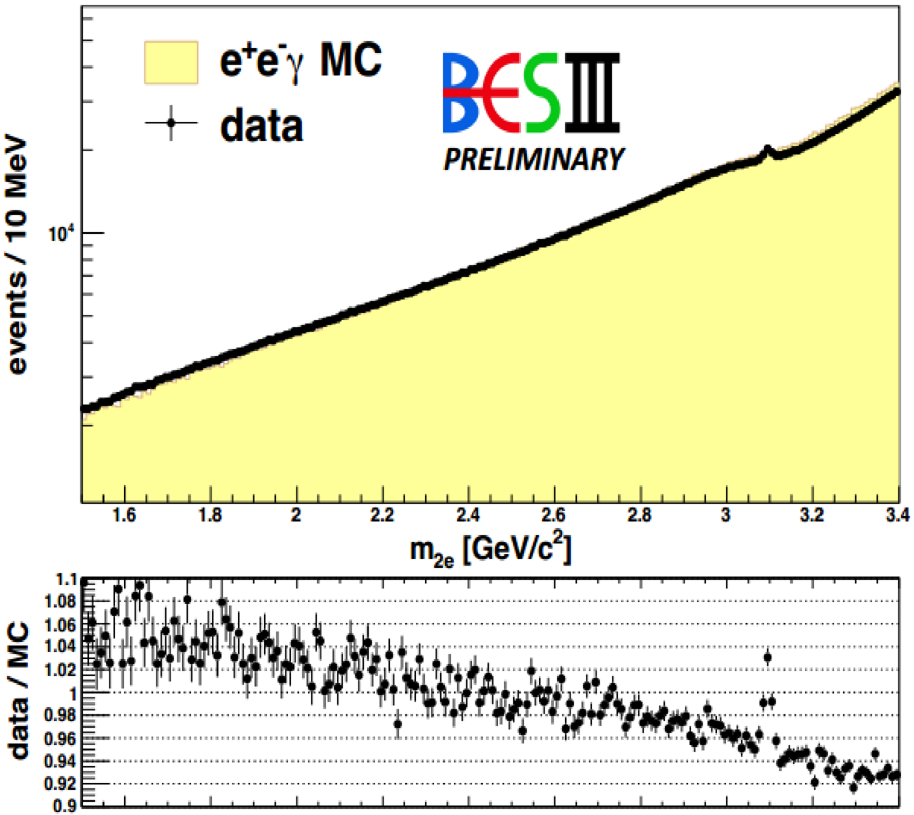
| | |
|---|---|
| distance to interaction point | $R_{xy}$ < 1.0 cm<br>$R_z$ < 10.0 cm |
| acceptance | 0.4 rad < $\theta$ < π – 0.4 rad |
| to supress background | PID |
| # charged tracks | = 2 |
| total charge | = 0 |
| # photons | = 0 (untagged analysis) |
| missing photon angle | < 0.1 rad or >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



# Di-lepton invariant mass distribution



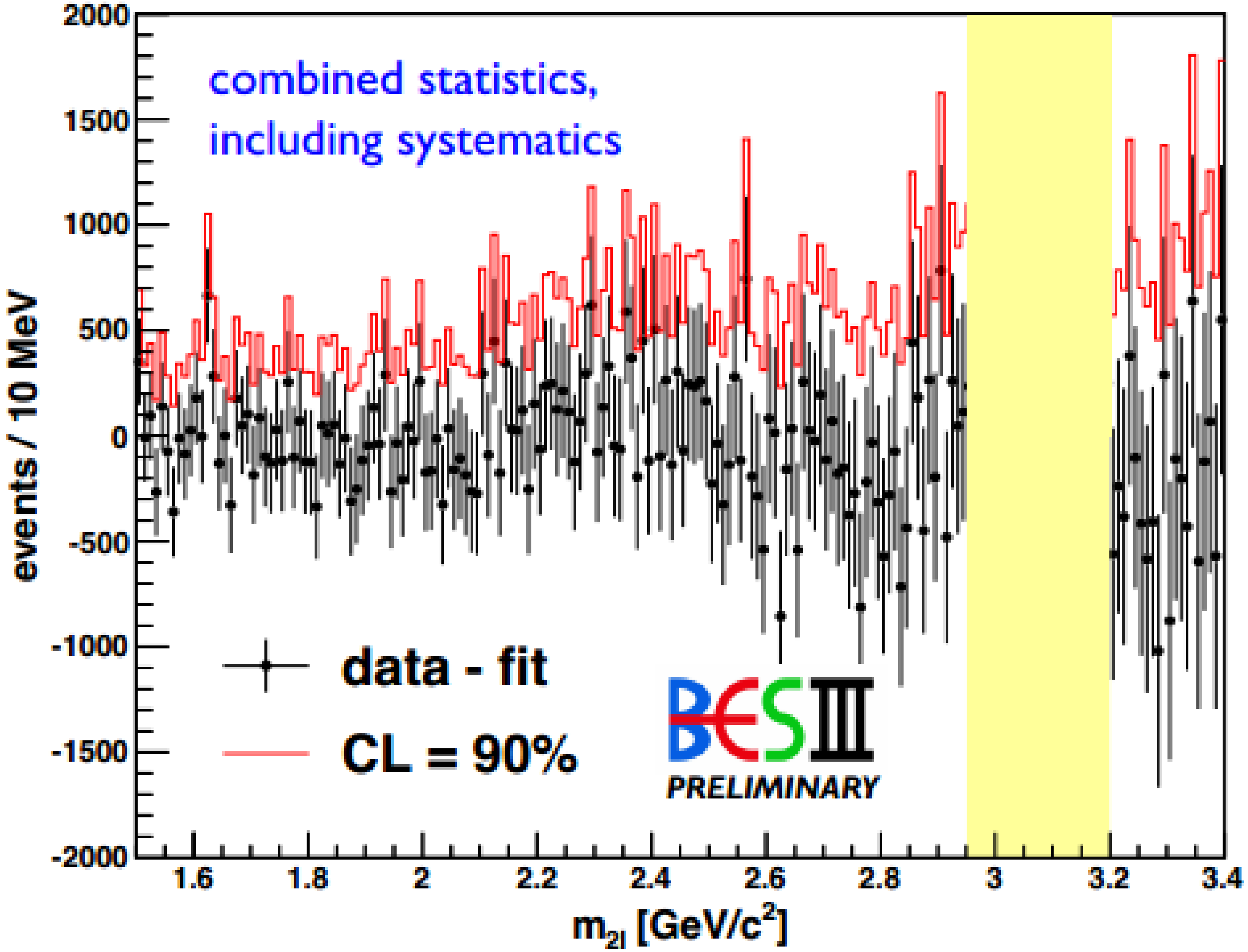




Since objective of this search is to search for a narrow resonance, this little discrepancy between data and MC has little impact on search.

# Exclusion limits

- Set the 90% C.L. upper limit using TRolke method.

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



# Kinetic mixing strength ($\varepsilon^2$) formula

Mixing parameter

Determined exclusion limit

Dark photon mass

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

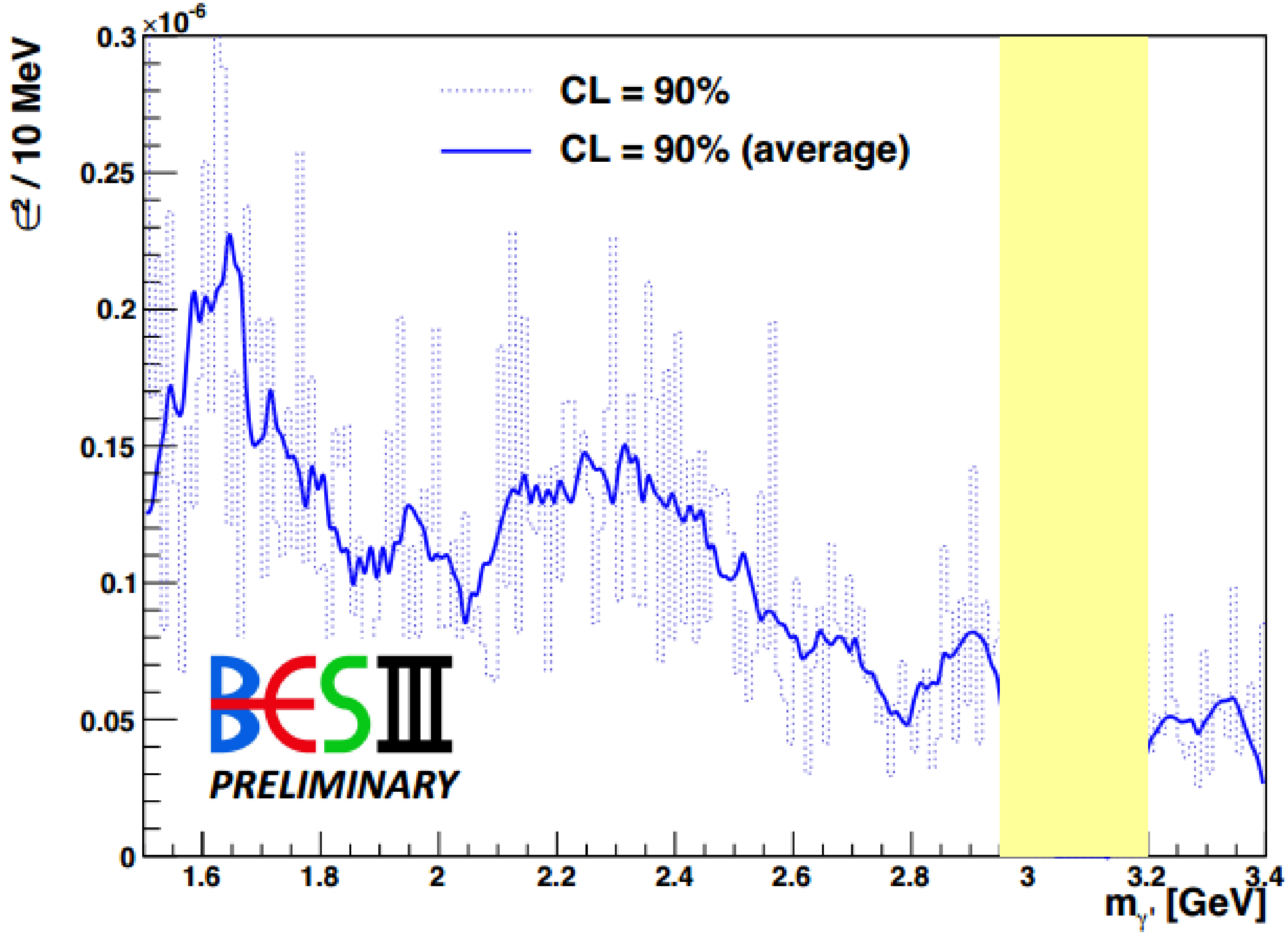
Number of decay modes of dark photon containing phase space

Fine structure constant

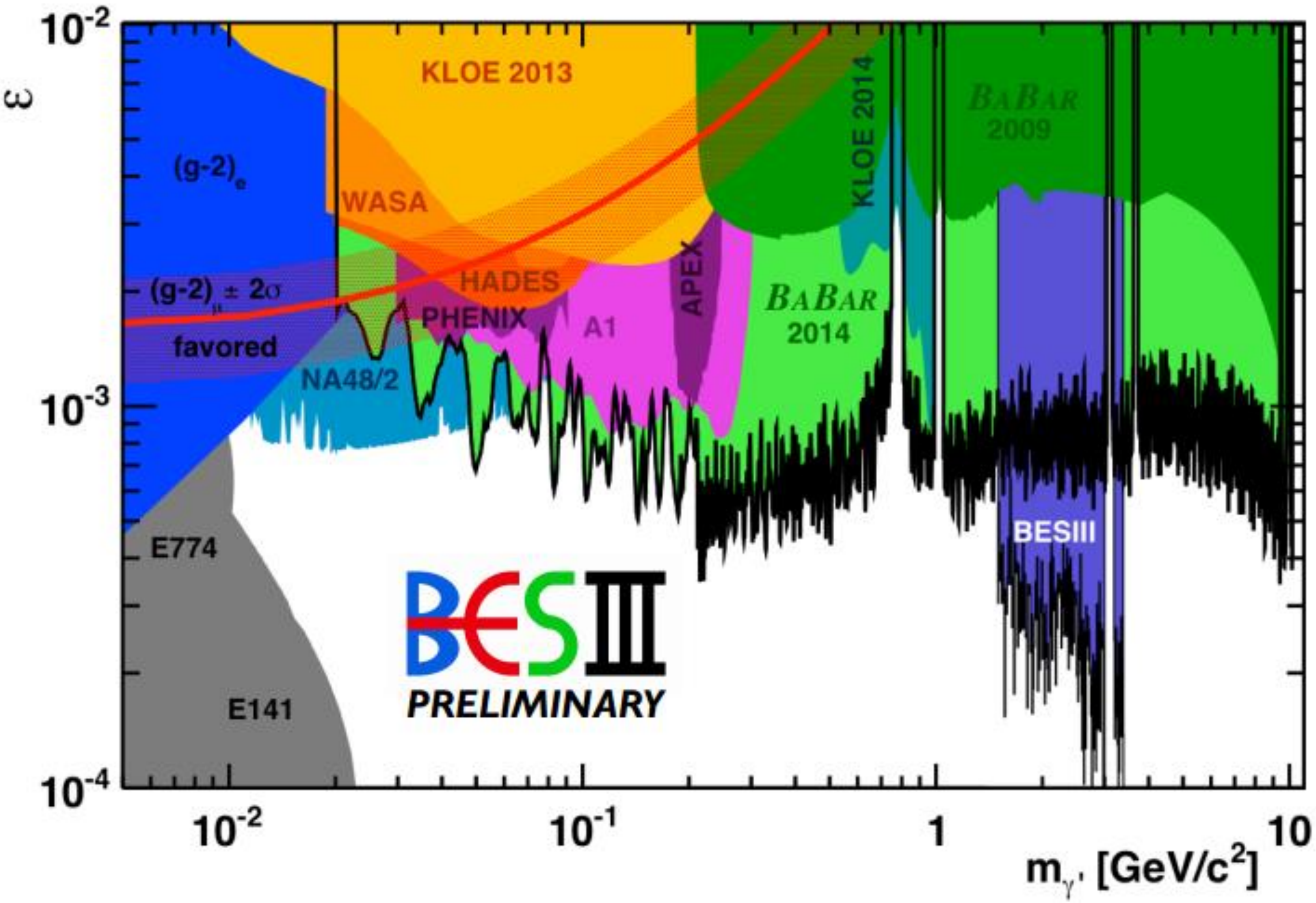
Mass resolution, determined with MC

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

# Combined exclusion limits on ε²



# Old vs. new Results



# Summary

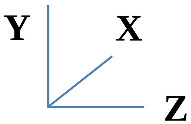
- We perform the search for low-mass Higgs and dark photons using the data of BESIII experiment.
- Based on the MC studied, we expect to achieve an order of magnitude better results than the previous BESIII measurements on the light Higgs boson search [PRD 85, 092012 (2012)].
- Will unblind the full J/ψ data after getting the permission from the review committee members appointed by BESIII internal publication board.
- We also find no evidence of dark photon production in the ψ(3770) data-set and set one of most stringent exclusion limits on "ε" in the dark photon mass range of 1.5 to 3.4 GeV/$c^2$.
- All the results are preliminary.

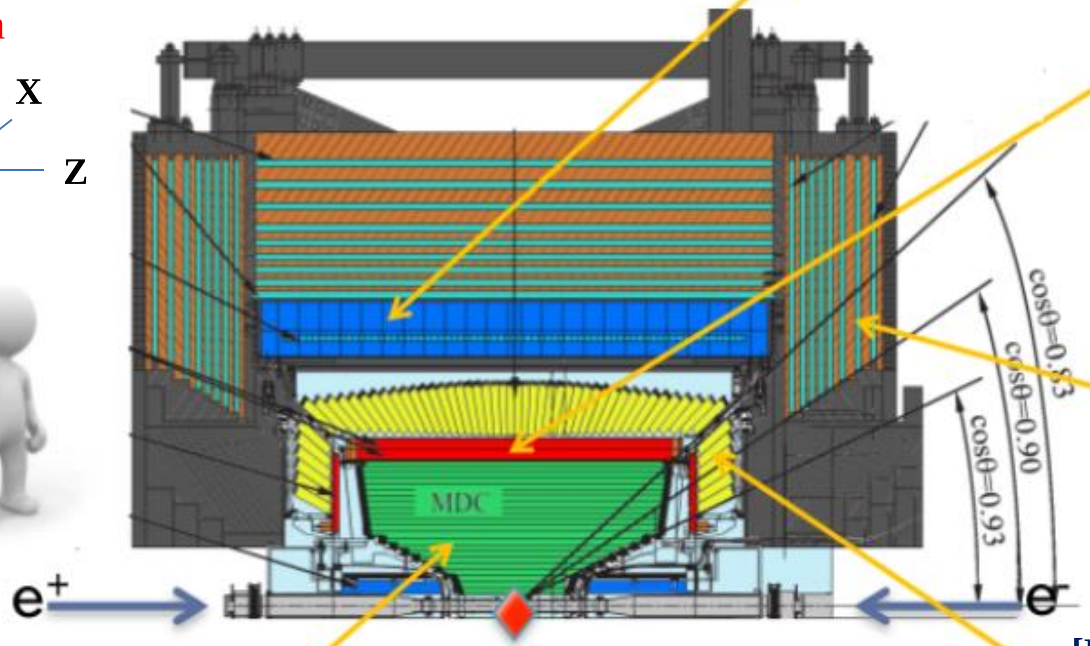
# Thank you!

# Back up Slide

# BESIII Experiment

BESIII experiment is a symmetric electron positron collider experiment running as tau-charm region located at Institute of High Energy Physics, Beijing, China




**Super conducting magnet**

- ✓ **1 Tesla**

**Time of Flight (TOF)**

- **2 layer plastic scintillators**
- **Time resolution $\sigma_T$ = 100 ps**
- **Particle id**

**Muon system**

- **9 layer RPC**

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

**Multilayer drift chamber (MDC)**

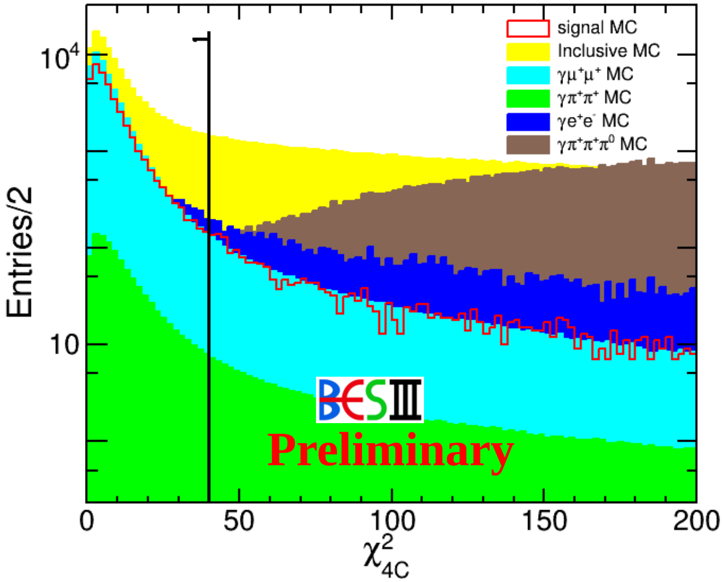
- **$He/C_3H_8$ (60/40)**
- **43 layers**
- **Momentum resolution σp/p = 0.5% @ 1 GeV**
- **Spatial resolution $\sigma_{xy}$ = 130 μm.**

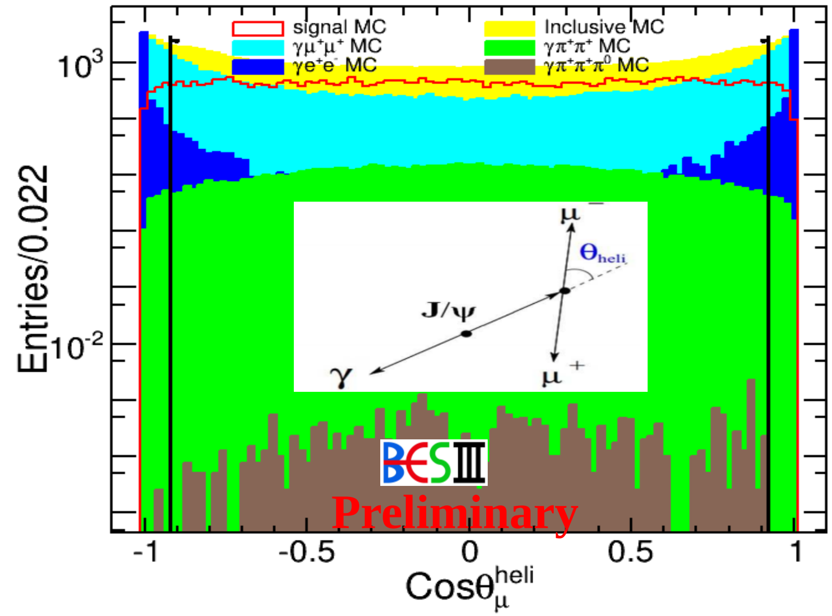
**Electromagnetic calorimeter (EMC) (CsI(Tl))**

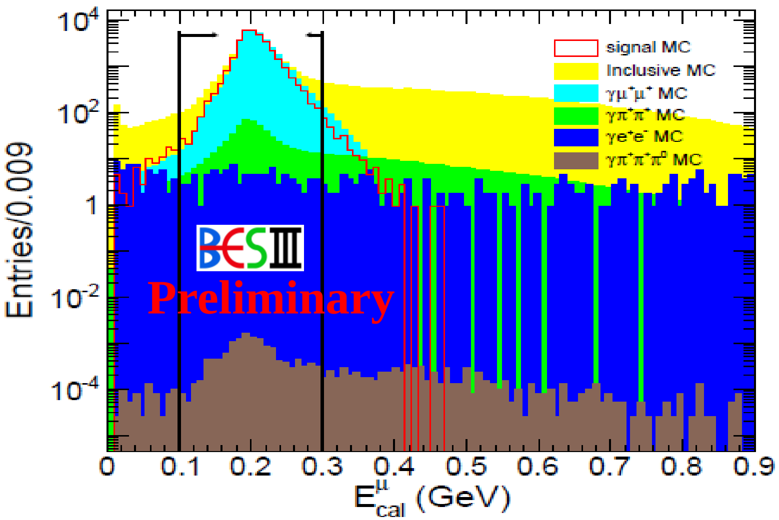
- **Barrel: 44 rings ($\theta_{index}$) with 120 crystals**
- **Endcaps consists of 6 rings**

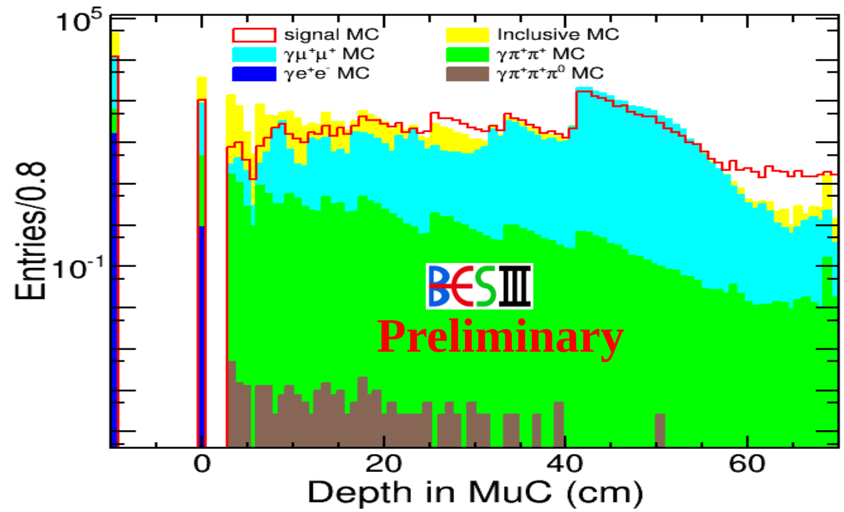
**→ 6240 crystals overall**

# Some important plots related to Light Higgs boson search



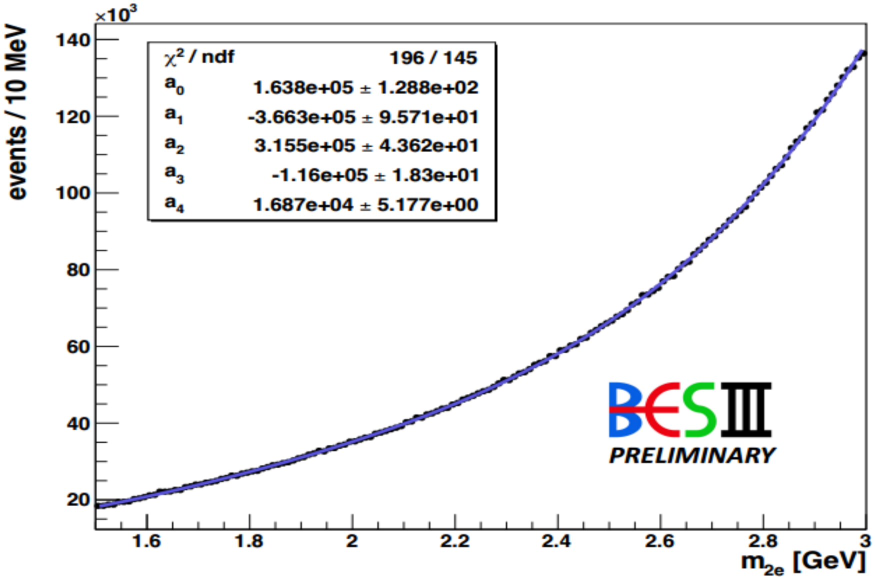
# Dark photon search at BESIII

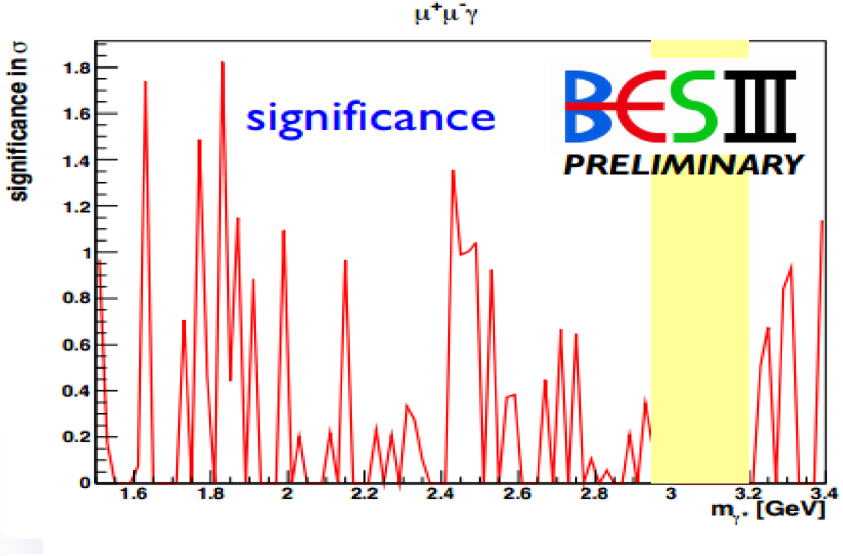
# Fit to data

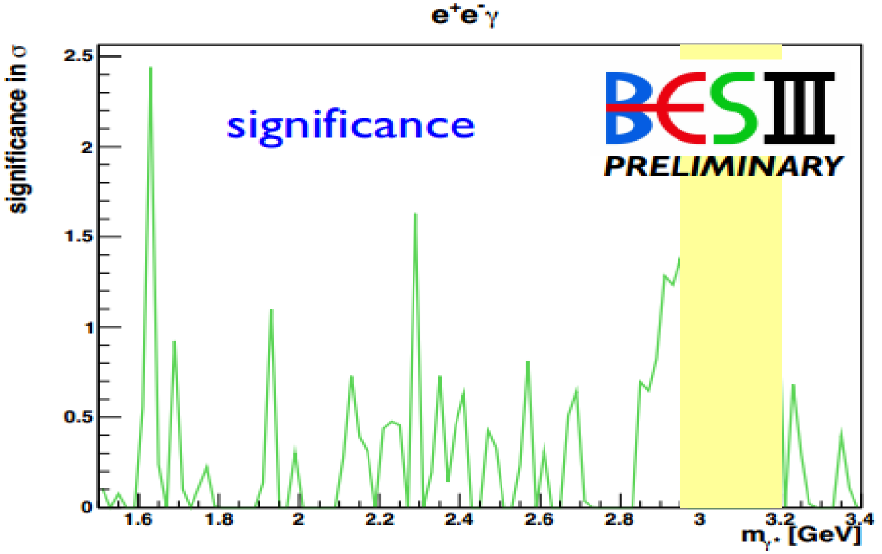
Fit of the mass spectrum in data with a polynomial and look for a peak in data:

$$p(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4$$

**No peaking structure found.**



# Number of decay modes $N_f$

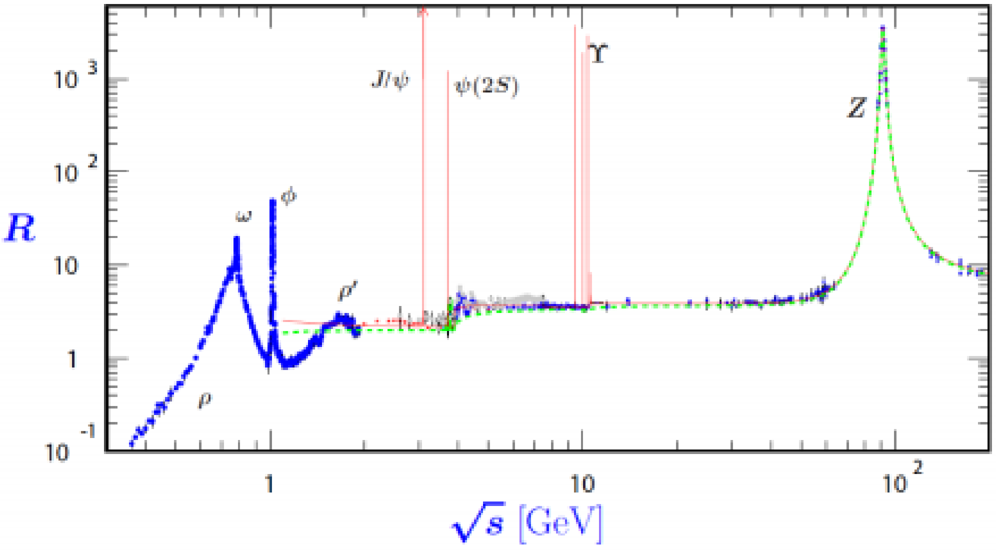
$$N_f^{l+l-} = \frac{\Gamma_{tot}}{\Gamma(\gamma' \to l^+ l^-)}$$

$$\Gamma_{tot} = \Gamma(\gamma' \to e^+ e^-) + \Gamma(\gamma' \to \mu^+ \mu^-) \cdot (1 + R(\sqrt{s}))$$

$$\Gamma(\gamma' \to l^+ l^-) = \frac{\alpha \varepsilon^2}{3 m_{\gamma'}^2} \sqrt{m_{\gamma'}^2 - 4 m_l^2} (m_{\gamma'}^2 + 2 m_l^2)$$ Phys. Rev. D**88**, 015032 (2013)

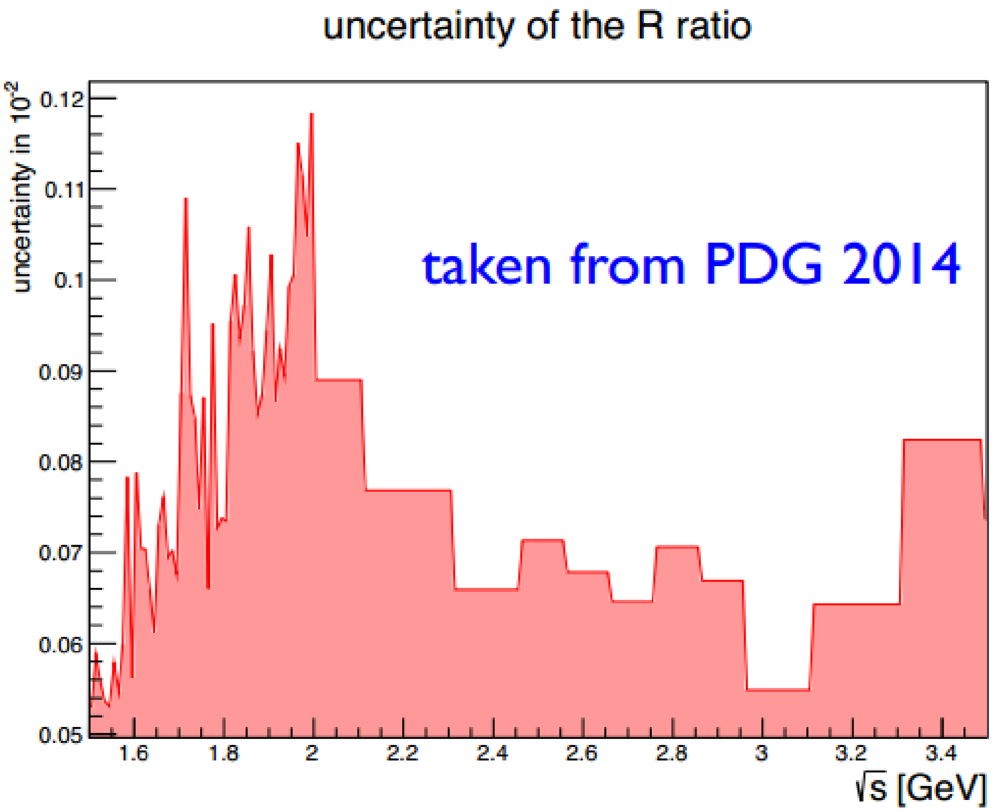
$$R = \frac{\sigma(e^+ e^- \to hadrons)}{\sigma(e^+ e^- \to \mu^+ \mu^-)}$$

taken from PDG 2014



# Systematic uncertainty

Completely dominated by the uncertainty of the R ratio
(everywhere above 5%)




| | |
|---|---|
| background subtraction | $< 0.5\%$ |
| fitting error | $< 1\%$ |
| mass resolution | $< 1\%$ |
| R ratio | $> 5\%$ |
| **sum** | $> 5\%$ |