QWG 2022 – The 15th International Workshop On Heavy Quarkonium

# Recent results of rare decay searches at BESIII


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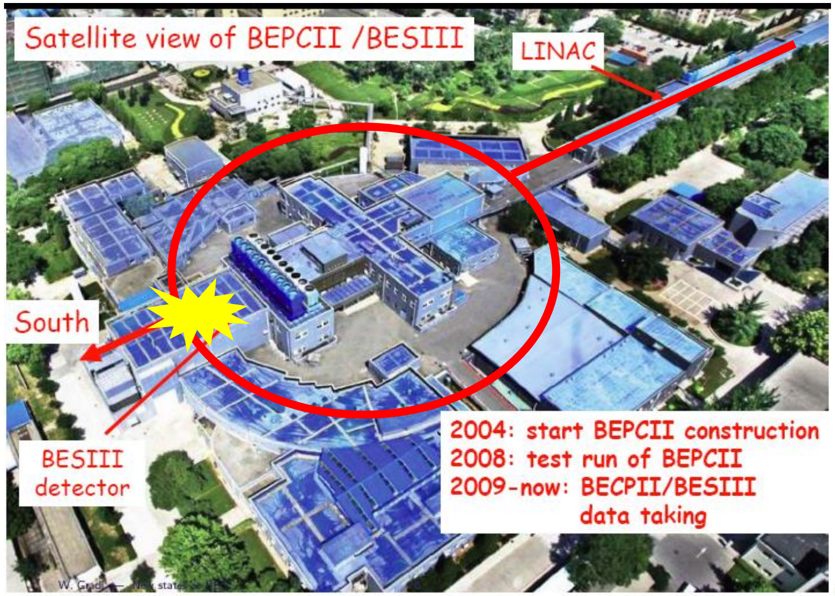
# Outline

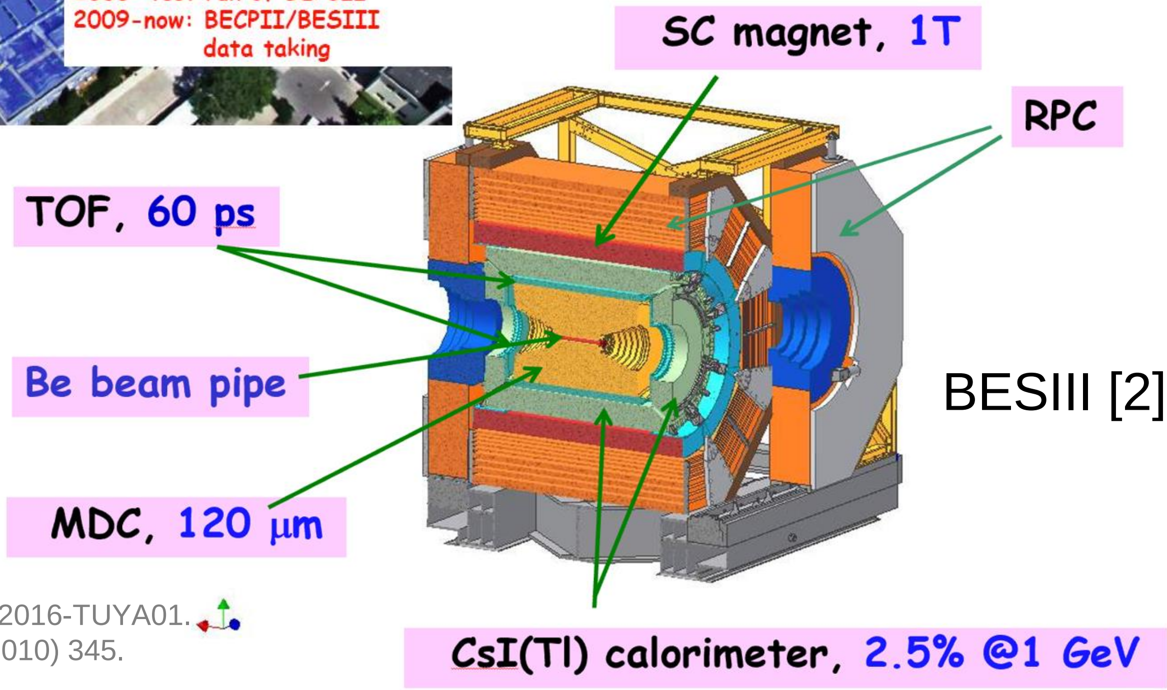
- Introduction of BEPCII and BESIII
- New physics at BESIII
- Light Higgs ($A^0$) search in radiative decays of $J/\psi$
  - Search for a light Higgs ($A^0$) in $J/\psi \to \gamma A^0$
- Recent results of Charmonium rare decay searches
  - Search for invisible decays of the $\Lambda$ baryon
  - Search for the $J/\psi$ weak decay $J/\psi \to D^- e^+ \nu_e + c.c.$
- Summary

# BEPCII and BESIII




BEPCII [1]:

- Beijing Electron Positron Collider
- Center-of-mass energy: 2.0 - 4.95 GeV
- Peak luminosity: $1 \times 10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$




BESIII [2]


[1] Proceedings of IPAC2016, DOI: 10.18429/JACoW-IPAC2016-TUYA01.
[2] Nucl. Instrum. Meth. A 614 (2010) 345.

# New physics at BESIII

- The world's largest $J/\psi$ and $\psi(2S)$ data produced in $e^+e^-$ annihilation, and other unique data samples, provide a good opportunity to search for new physics at BESIII, such as

  - Rare or forbidden processes searches

    ($J/\psi$ weak decay, symmetry violation, flavor changing neutral current, etc.)

  - Exotic phenomena searches

    (Light Higgs, invisible decays, dark photon, etc.)

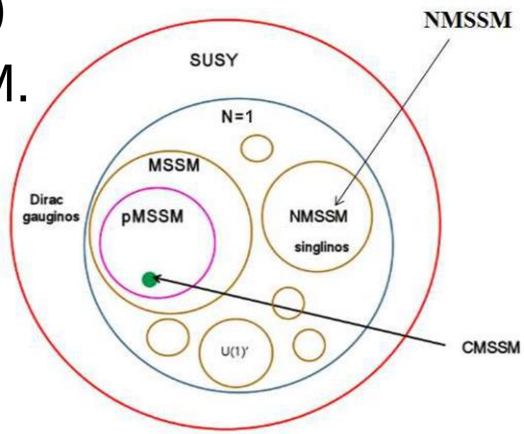
- The future program of new physics at BESIII could be found at Chapter 6 of BESIII white paper [3].

[3] Chin. Phys. C 44, 040001 (2020).

# Search for a light Higgs ($A^0$) in $J/\psi \rightarrow \gamma A^0$

Phys. Rev. D **105**, 012008 (2022)

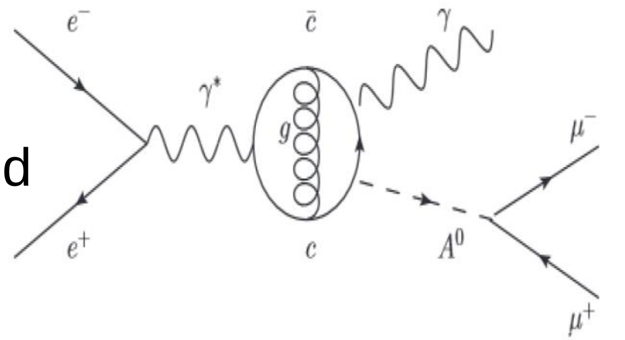
- To alleviate the "little hierarchy problem", the next-to-minimal supersymmetric Standard Model (NMSSM) adds an additional singlet chiral superfield to MSSM.




T. Rizzo (SLAC summer institute 2012)

- The NMSSM contains three CP-even, two CP-odd, and two charged Higgs bosons [4][5].

- The mass of the lightest Higgs boson, $A^0$, may be smaller than twice the mass of the charmed quark, thus making it accessible via $J/\psi \rightarrow \gamma A^0$ [6]




- The branching fraction of $J/\psi \rightarrow \gamma A^0$ is predicted to be in the range of $10^{-9} - 10^{-7}$ [5].


[4] Phys. Rev. D 70, 034018 (2004); Phys. Rev. Lett. 95, 041801 (2005).
[5] Phys. Rev. D 76, 051105 (2007).
[6] Phys. Rev. Lett. 39, 1304 (1977).

# Search for a light Higgs ($A^0$) in $J/\psi \to \gamma A^0$

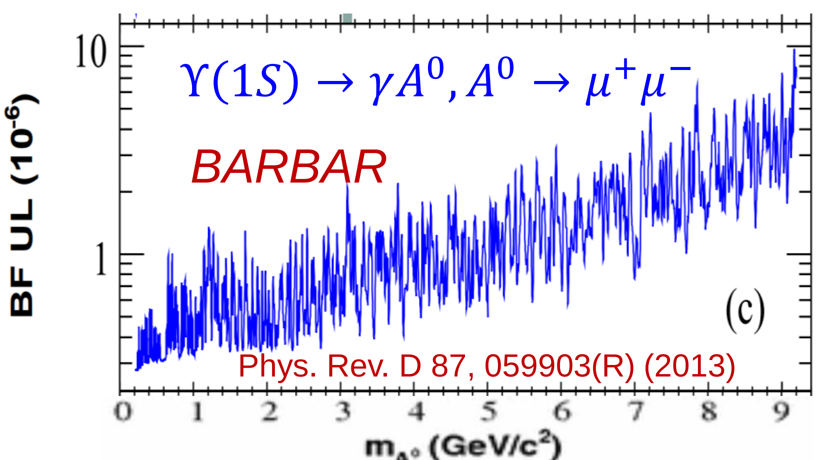
- The CLEO [7], CMS [8], BESIII [9] and BABAR [10] experiments have reported negative results for $A^0 \to \mu^+\mu^-$.

$$\frac{\mathcal{B}(V \to \gamma A^0)}{\mathcal{B}(V \to l^+l^-)} = \frac{G_F m_q^2 g_q^2 C_{\mathrm{QCD}}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_V^2}\right) \quad (V = \Upsilon, J/\psi)$$

[6][11]

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

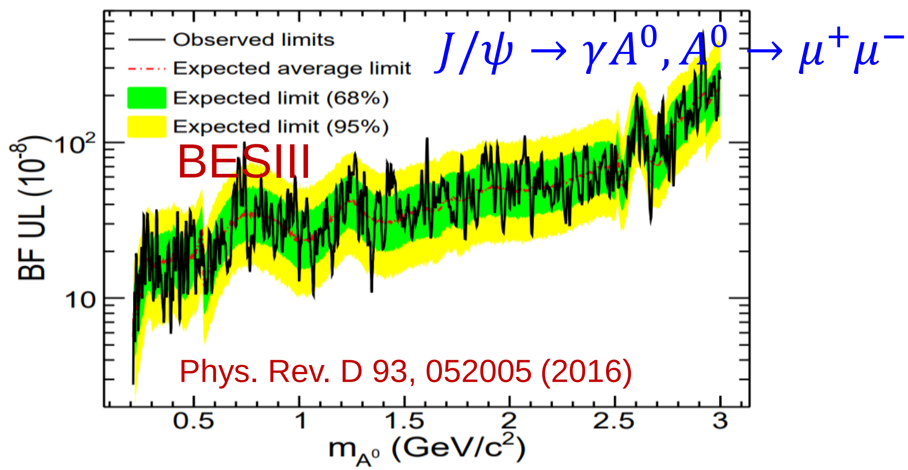
Expected BF: $10^{-7} - 10^{-3}$ [5]




- ✓ Strong exclusion limit on BF $(0.28 - 9.7) \times 10^{-6}$ is placed by *BABAR* [10]

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

Expected BF: $10^{-9} - 10^{-7}$ [5]

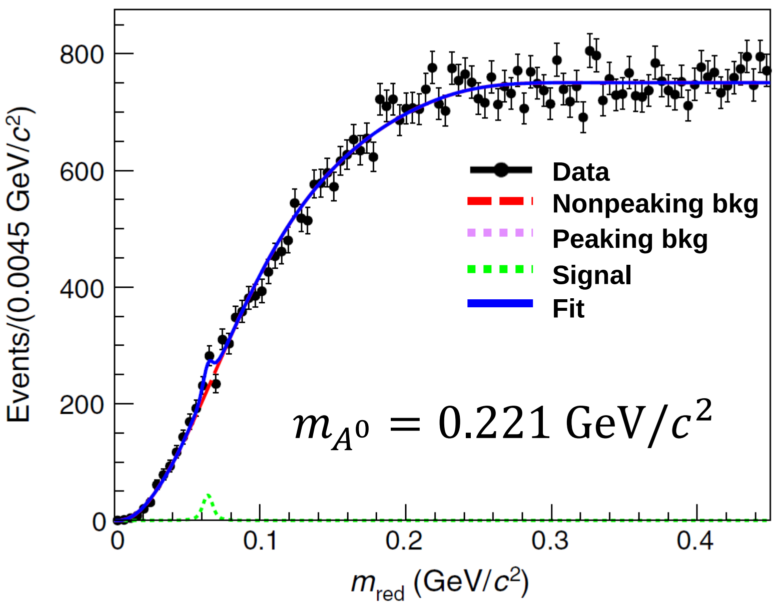



- ✓ BESIII exclusion limit $(2.8 - 495.3) \times 10^{-8}$
- ✓ An order of magnitude above the theoretical predictions [5].
- ✓ Using larger data sets (39 times) to check this prediction again with high precision.

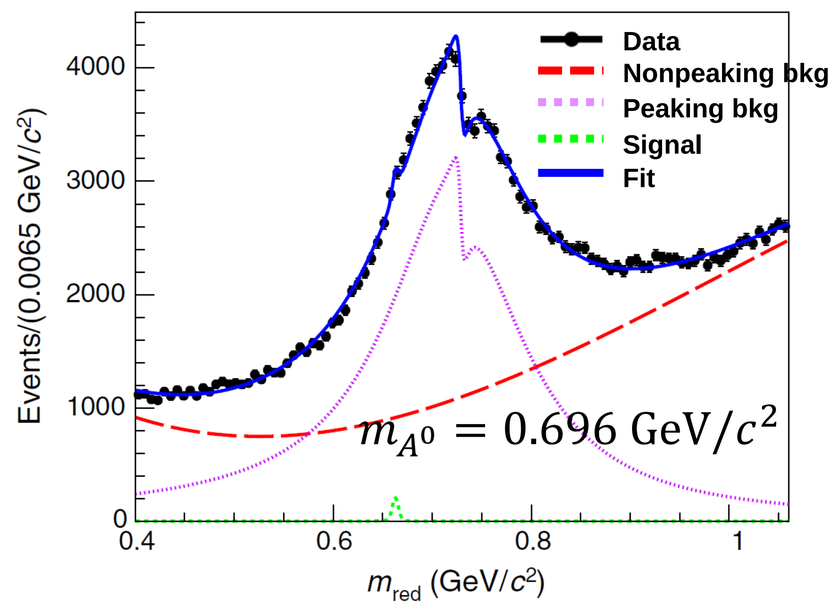

[7] Phys. Rev. Lett. 101,151802 (2008).
[8] Phys. Rev. Lett. 109, 121801 (2012).
[9] Phys. Rev. D 93, 052005 (2016).
[10] Phys. Rev. D 87, 059903(R) (2013);
[11] Mod. Phys. Lett. A 22, 1373 (2007);
Phys. Lett. B 175, 223 (1986).

# Search for a light Higgs ($A^0$) in $J/\psi \to \gamma A^0$

- Using 9 billion $J/\psi$ events collected by the BESIII in 2009, 2018, and 2019, we search for a CP-odd light Higgs in $J/\psi \to \gamma A^0(\to \mu^+\mu^-)$
- Reduced mass: $m_{\text{red}} = \sqrt{m_{\mu^+\mu^-}^2 - 4m_\mu^2}$




Global (local) significance: ~1σ (3.3σ)




Global (local) significance: ~1σ (3.5σ)

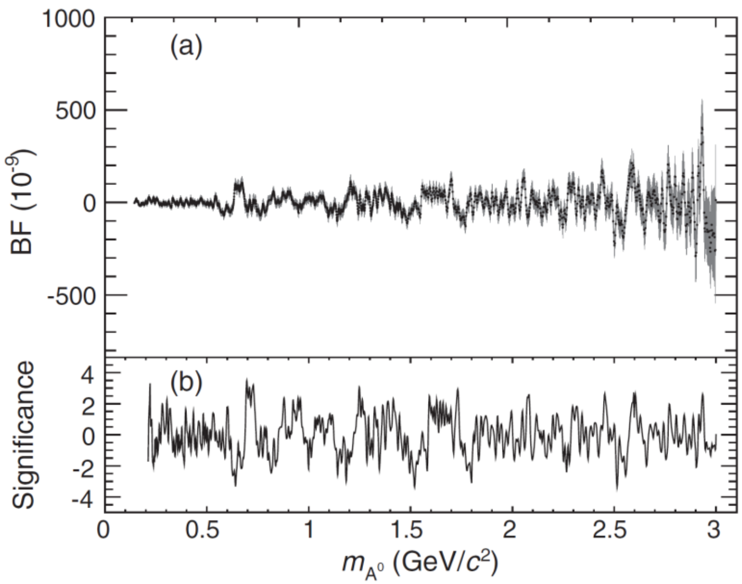
No evidence of Higgs production is found

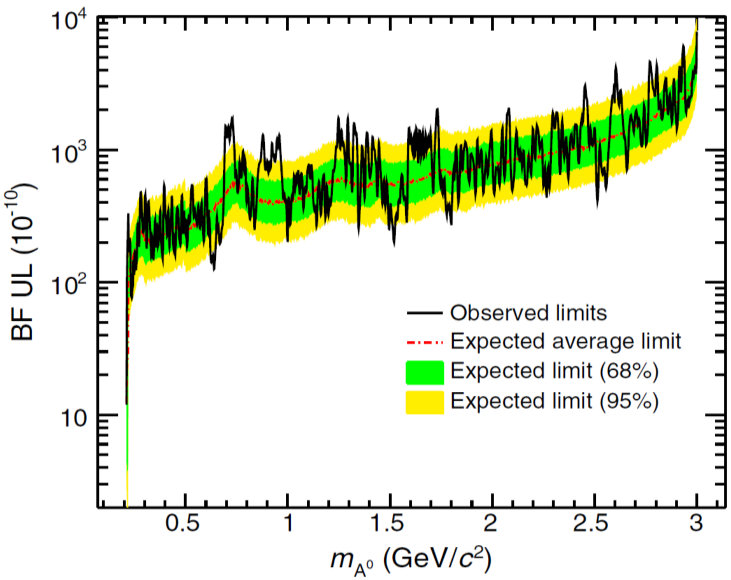
# Search for a light Higgs ($A^0$) in $J/\psi \to \gamma A^0$

- The product branching fraction of $J/\psi \to \gamma A^0 (\to \mu^+\mu^-)$:

$$\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-) = \frac{N_{\mathrm{sig}}}{\epsilon \cdot N_{J/\psi}}$$

- The 90% CL upper limits on the $\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$ is set to be $(1.2 - 778.0) \times 10^{-9}$ ($m_{A^0} = (0.212, 3.0)\mathrm{GeV}$) using a Bayesian method

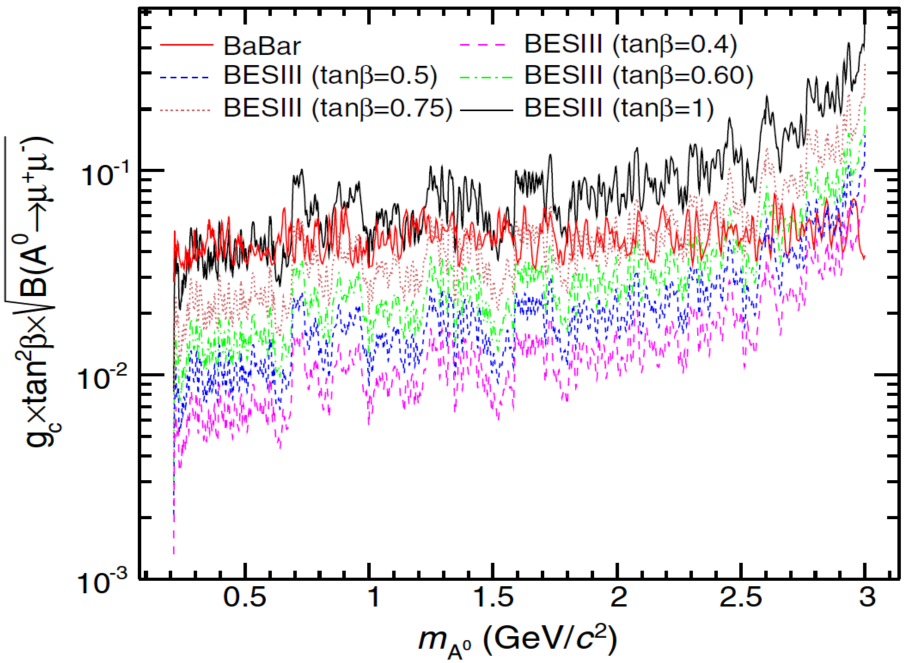



This result has an improvement by a factor of 6-7 over the previous BESIII measurement [9].

# Search for a light Higgs ($A^0$) in $J/\psi \to \gamma A^0$

- To compare our results with the BABAR [10], we also compute 90% CL upper limits on the effective Yukawa coupling of the Higgs fields to the b-quark pair: $g_b(= g_c \tan^2\beta) \times \sqrt{\mathcal{B}(A^0 \to \mu^+\mu^-)}$



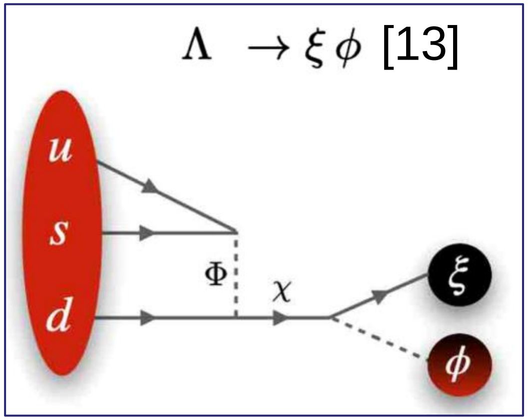

This result is slightly better than the BABAR measurement [10] in the low-mass region $m_{A^0} \leq 0.7\ \mathrm{GeV}/c^2$ for $\tan\beta = 1$.

$\tan\beta$ is the ratio of up- and down-type Higgs doublets

# Search for invisible decays of the $\Lambda$ baryon

Phys. Rev. D **105**, L071101 (2022)

- In the asymmetric dark matter scenario [12], the dark matter and baryon asymmetry puzzles may be related.
- Dark matter may be represented by baryon matter with invisible final state [13].



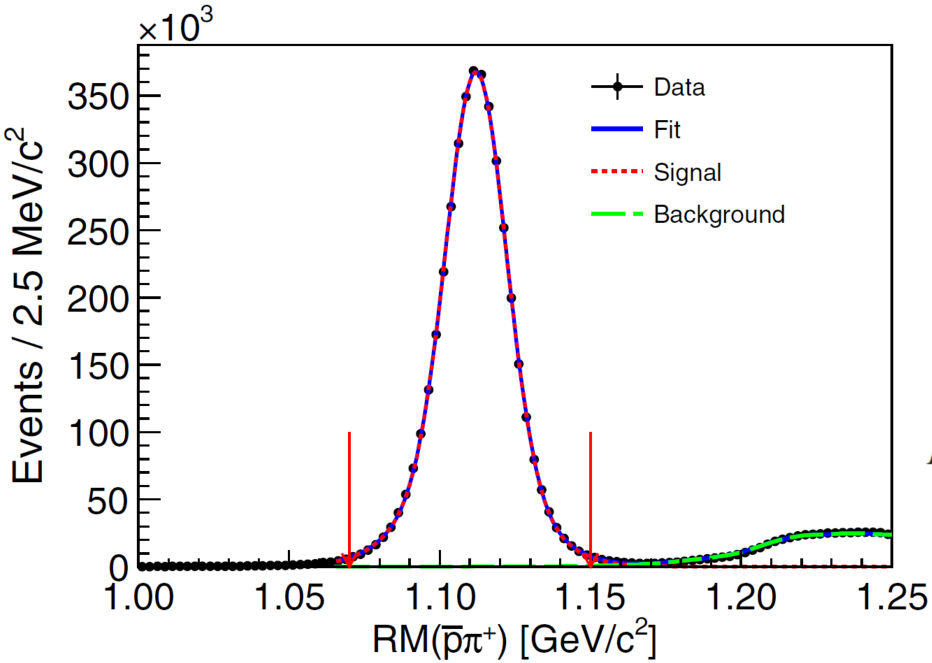

- Stringent limits on the invisible decays of $\Upsilon$, $J/\psi$, $B^0$, $\eta^{(\prime)}$, $\pi^0$, $D^0$, $\omega$ and $\phi$ mesons [14] have already been determined by several experiments.
- No experimental study of invisible baryon decays has been carried out yet.
- BESIII has the ability to probe $\Lambda$ invisible decays, benefiting from a well-defined production process and a clean reaction environment.


[12] Phys. Lett. B 165, 55 (1985); Phys. Rev. Lett. 96, 041302 (2006)
[13] Phys. Rev. D 105, 115005 (2022).
[14] PRL 103, 251801 (2009); PRL. 100, 192001 (2008); PRD 86, 032002 (2012); PRD 87, 012009 (2013); JHEP 02 (2021) 201; PRD 95, 011102 (2017); PRD 98, 032001 (2018).

# Search for invisible decays of the $\Lambda$ baryon

- Using 10 billion $J/\psi$ events collected by the BESIII, we search for invisible decays of the $\Lambda$ baryon in $J/\psi \to \Lambda\bar{\Lambda}$.
- Tag method is performed:
  - One $\bar{\Lambda}$ is reconstructed via $\bar{\Lambda} \to \bar{p}\pi^+$ (Tag);
  - The $\Lambda$ invisible decays are searched for in the $\bar{\Lambda}$ recoiling side (Signal).

$$\mathcal{B}(\Lambda \to \text{invisible}) = \frac{N_{\text{sig}}}{N_{\text{tag}} \cdot (\varepsilon_{\text{sig}}/\varepsilon_{\text{tag}})}$$

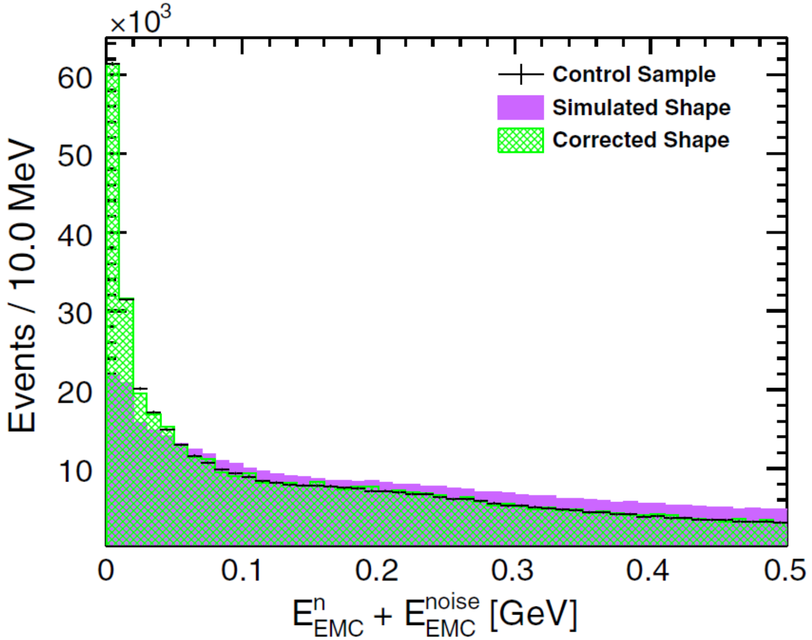



$$N_{\text{tag}} = (4154428 \pm 2040)$$
$$\varepsilon_{\text{tag}} = (32.11 \pm 0.01)\%$$

# Search for invisible decays of the $\Lambda$ baryon

- Signal candidate selection:
  - The invisible $\Lambda$ decay final states do not deposit any energy in the EMC
  - The sum of energies of all the EMC showers not associated with any charged tracks, $E_{EMC}$, can be used as a discriminator

$$E_{\mathrm{EMC}} = E_{\mathrm{EMC}}^{\pi^0} + E_{\mathrm{EMC}}^{n} + E_{\mathrm{EMC}}^{\mathrm{noise}}$$

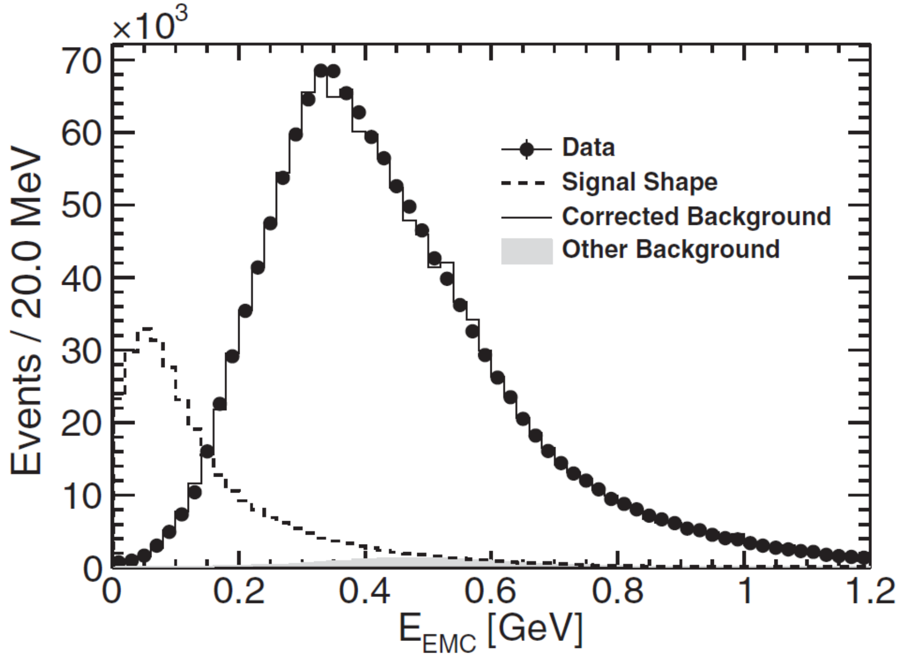



The $E_{\mathrm{EMC}}^{n} + E_{\mathrm{EMC}}^{\mathrm{noise}}$ distribution in $J/\psi \to \bar{p}\pi^+ n$

- Dominant background: $\Lambda \to n\pi^0$
- Neutron interactions in the detector material is simulated inaccurately
- Data-driven approach is adopted to improve the background modeling

# Search for invisible decays of the $\Lambda$ baryon

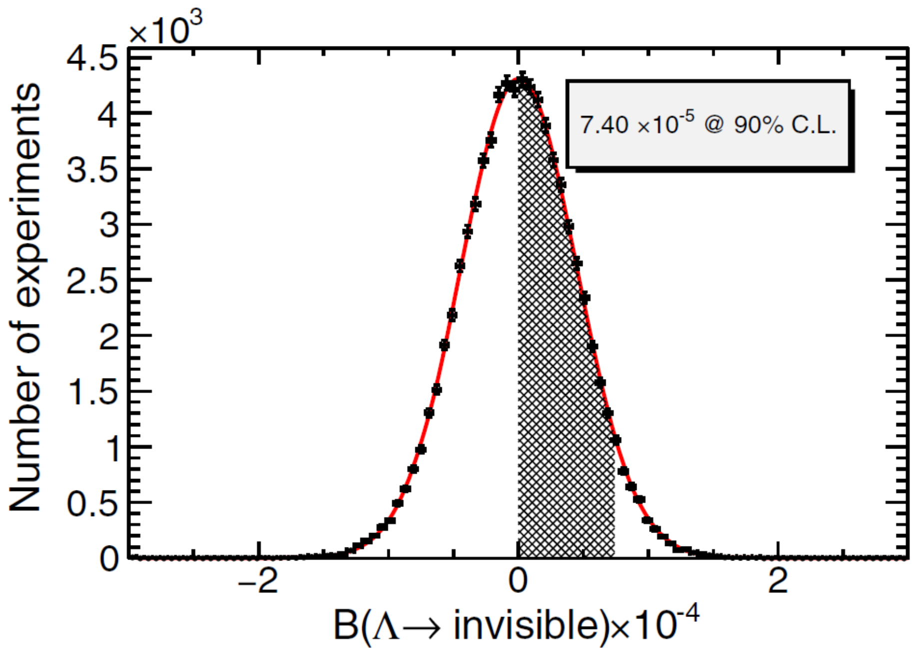
- Signal candidate selection:
  - The $E_{EMC}$ of signal $\Lambda$ invisible decays is expected to peak close to zero. (noise + small contribution from charged-particle showers leaking)




No signals are found for invisible decays of the $\Lambda$ baryon

# Search for invisible decays of the Λ baryon

- The upper limit at 90% CL is set using a modified frequentist approach [15].




$$\mathcal{B}(\Lambda \to \text{invisible}) < 7.4 \times 10^{-5}$$

This result is consistent with the prediction of $4.4 \times 10^{-7}$ from the mirror model [16].

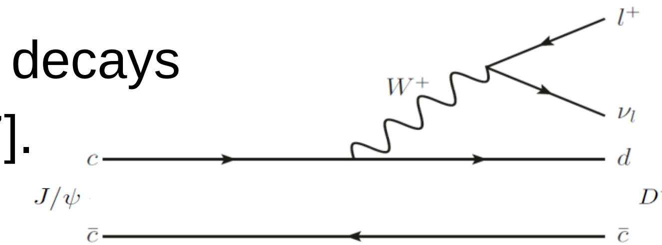


[15] Phys. Rev. D 91, 112015 (2015); Phys. Rev. D 95, 071102 (2017).
[16] arXiv:2006.10746.

# Search for $J/\psi \to D^- e^+ \nu_e + c.c.$

J. High Energ. Phys. **2021**, 157 (2021)

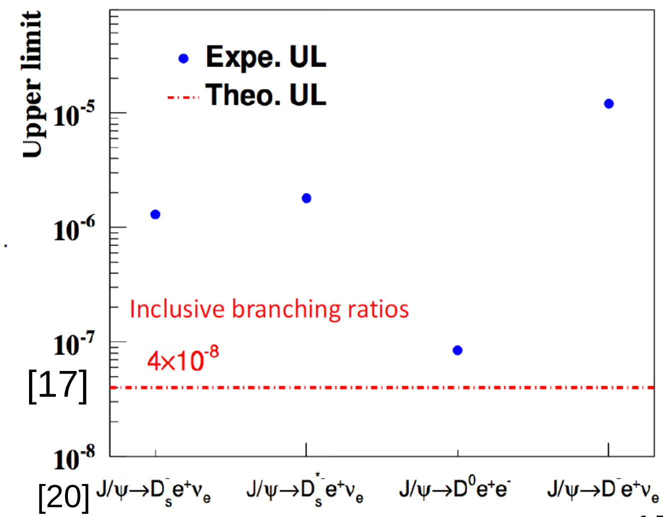
- The $J/\psi$ weak decays have not yet been observed.
- The SM predicts the inclusive BF of $J/\psi$ weak decays to a $c$-meson at the order of $10^{-8}$ or below [17].
- The BFs of $J/\psi$ weak decays could be larger ($\sim10^{-5}$) in beyond the SM such as the Top-color model, and the two-Higgs doublet model [18].




[19]

| Decay mode | QCDSR [6] | LFQM [7] | BSW [8] | CCQM [9] | BSM [10] |
|---|---|---|---|---|---|
| $J/\psi \to D^- e^+ \nu_e$ | $0.73^{+0.43}_{-0.22}$ | 5.1–5.7 | $6.0^{+0.8}_{-0.7}$ | 1.71 | $2.03^{+0.29}_{-0.25}$ |

**Table 1.** Theoretical results for the BF of the semi-leptonic decay $J/\psi \to D^- e^+ \nu_e$ ($\times10^{-11}$).




[17] Phys. Lett. B 252 (1990) 690; Z. Phys. C 62 (1994) 271;
Eur. Phys. J. C 54 (2008) 107; J. Phys. G 44 (2017) 045004.
[18] Phys. Rev. D 60, 014011 (1999); Phys. Lett. B 345 (1995) 483.
[19] Eur. Phys. J. C 54 (2008) 107; Phys. Rev. D 78 (2008) 074012;
Adv. High Energy Phys. 2013 (2013) 706543;
Phys. Rev. D 92 (2015) 074030; J. Phys. G 44 (2017) 045004.
[20] Phys. Rev. D 90, 112014 (2014); Phys. Rev. D 96, 111101(R) (2017);
Phys. Lett. B 639, 418 (2006);



BESIII data are 170 times larger than BESII

# Search for $J/\psi \to D^- e^+ \nu_e + c.c.$

- Using 10 billion $J/\psi$ events collected by the BESIII, we search for the $J/\psi$ weak decay $J/\psi \to D^- e^+ \nu_e + c.c.$ ($D^- \to K^+ \pi^- \pi^-$).

- Discriminator variable for the signal yield:

  - The undetected neutrino $\nu_e$ carries a missing-energy $E_{miss}$ and a missing-momentum $\vec{p}_{miss}$ .

$$E_{\rm miss} = E_{J/\psi} - E_{D^-} - E_{e^+}$$

$$\vec{p}_{\rm miss} = \vec{p}_{J/\psi} - \vec{p}_{D^-} - \vec{p}_{e^+}$$

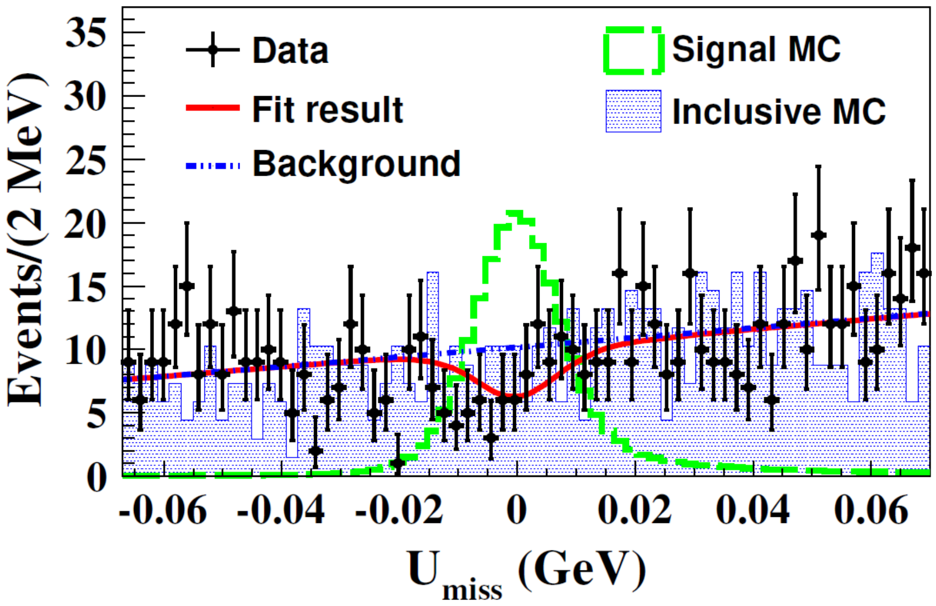
  - We extract the signal yield by examining the variable

$$U_{\rm miss} = E_{\rm miss} - c|\vec{p}_{\rm miss}|$$

The $U_{miss}$ distribution of the signal candidates is expected to peak around zero.

# Search for $J/\psi \to D^- e^+ \nu_e + c.c.$

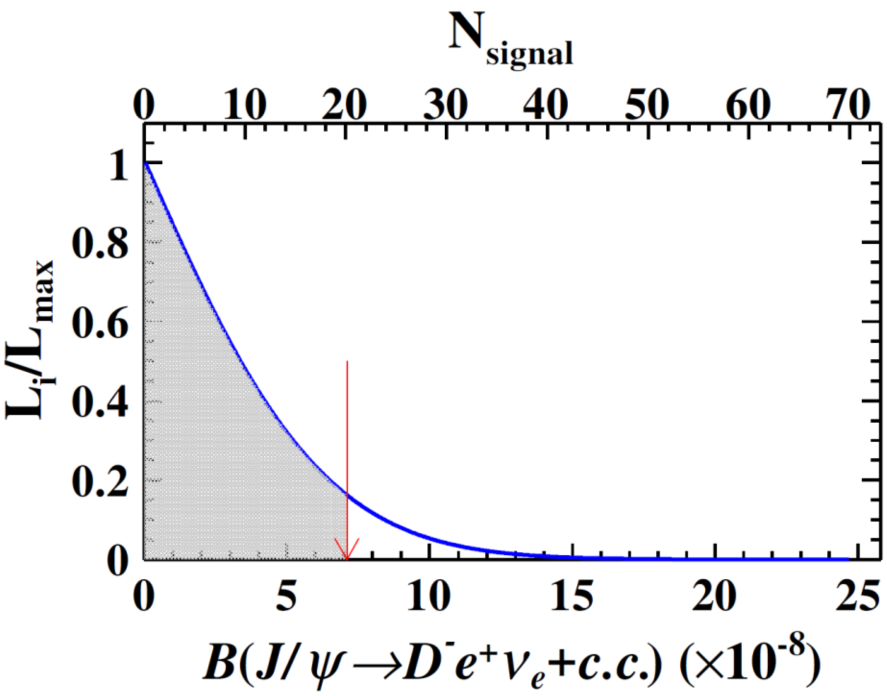
- The background contributions are investigated using an inclusive MC simulation, whose size corresponds to that in data.
- The detection efficiency for $J/\psi \to D^- e^+ \nu_e + c.c.$ is determined to be $(29.93 \pm 0.10)\%$




No excess of signal above background is observed.

# Search for $J/\psi \to D^- e^+ \nu_e + c.c.$

- The upper limit at 90% CL is set using a Bayesian approach [21]




$$\mathcal{B}(J/\psi \to D^- e^+ \nu_e + \text{c.c.}) = \frac{N_{\text{signal}}}{N_{J/\psi} \times \epsilon \times \mathcal{B}_{\text{sub}}}$$

$$\mathcal{B}(J/\psi \to D^- e^+ \nu_e + \text{c.c.}) < 7.1 \times 10^{-8}.$$

- This result improves previous best limit [22] by a factor of 170.
- Compatible with the SM predictions and stringent constraint on the BSM predicting BFs of the order of $10^{-5}$.


[21] J.M. Bernardo and A.F.M. Smith, Bayesian Theory, Wiley (2000);
Y. S. Zhu, Nucl. Instrum. Methods Phys. Res., Sect. A 578, 322 (2007).
[22] Phys. Lett. B 639 (2006) 418.

# Summary

- BESIII collaboration searched for rare decays using the world's largest data sample of $J/\psi$ decays produced in $e^+e^-$ annihilation:
  - No excess of signal above background is observed.
    - ✓ $\mathcal{B}(J/\psi \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-) < (1.2 - 778.0) \times 10^{-9}$ @ 90% CL
      
      ($A^0$: light Higgs) $\quad (m_{A^0} = (0.212, 3.0)\ \mathrm{GeV}/c)$
    - ✓ $\mathcal{B}(\Lambda \to \text{invisible}) < 7.4 \times 10^{-5}$ @ 90% CL
    - ✓ $\mathcal{B}(J/\psi \to D^- e^+ \nu_e + c.c.) < 7.1 \times 10^{-8}$ @ 90% CL
  - More results of different rare decays using 10 billion $J/\psi$ data will come soon.

*Thank you for your attention!*