Search for invisible decays at BESIII

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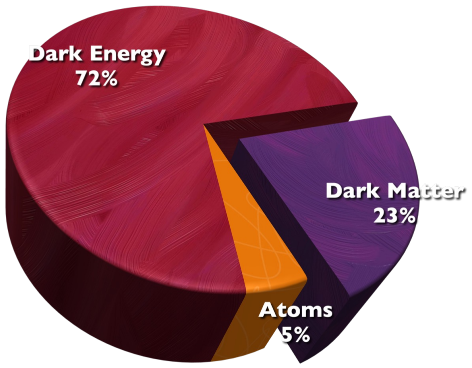
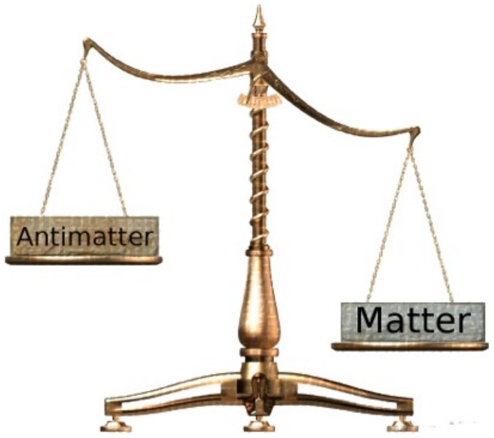
Introduction





- ✓ The SM still leaves many questions unanswered:
  - The quest for dark matter
  - Matter-antimatter asymmetry
  - ……

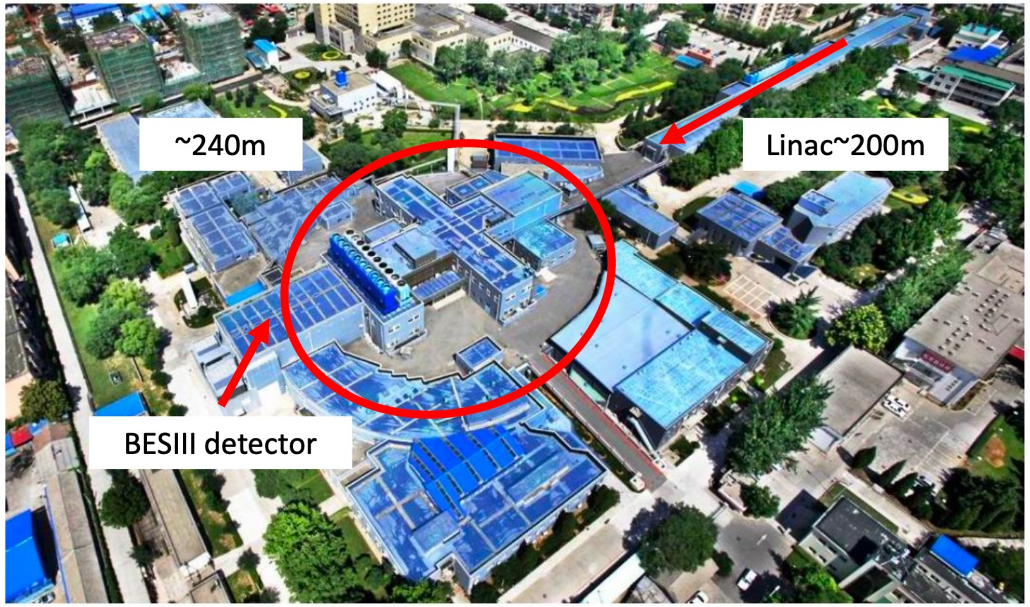
- ✓ Search for invisible decays is one way to search for dark matter and might provide a window into what may lie beyond SM

- ✓ e^+e^- collision experiments have the ability to probe invisible decays, benefiting from a well measured CM energy and a clean environment

- ✓ Topics in this talk:
  - Search for the decay $J/\psi \to \gamma$+invisible *Phys. Rev. D 101, 112005(2020)*
  - Search for invisible decays of the Λ baryon $\Lambda \to$ invisible *Phys. Rev. D 105, L071101(2022)*

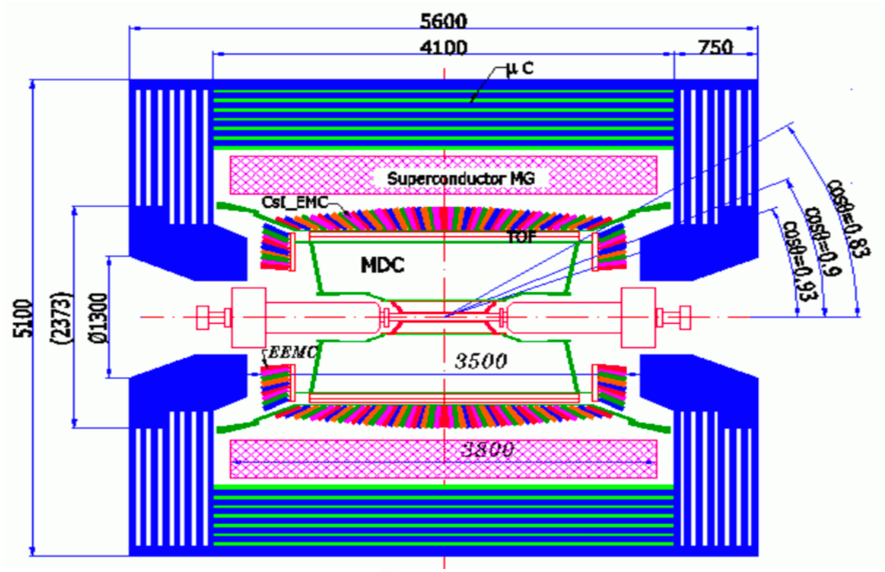
BEPCII & BESIII

Beijing Electron Positron Collider II



- Double rings;
- Ecm= 2.0-4.6 GeV (2.0-4.9 GeV since 2019);
- Energy spread: $\Delta E \approx 5 \times 10^{-4}$GeV;
- Design luminosity @Ecm= 3.77 GeV: ~1× $10^{33}\ cm^{-2}s^{-1}$
  Reached in 2016;
- 2009~ today: BESIII physics runs;

Beijing Spectrometer III



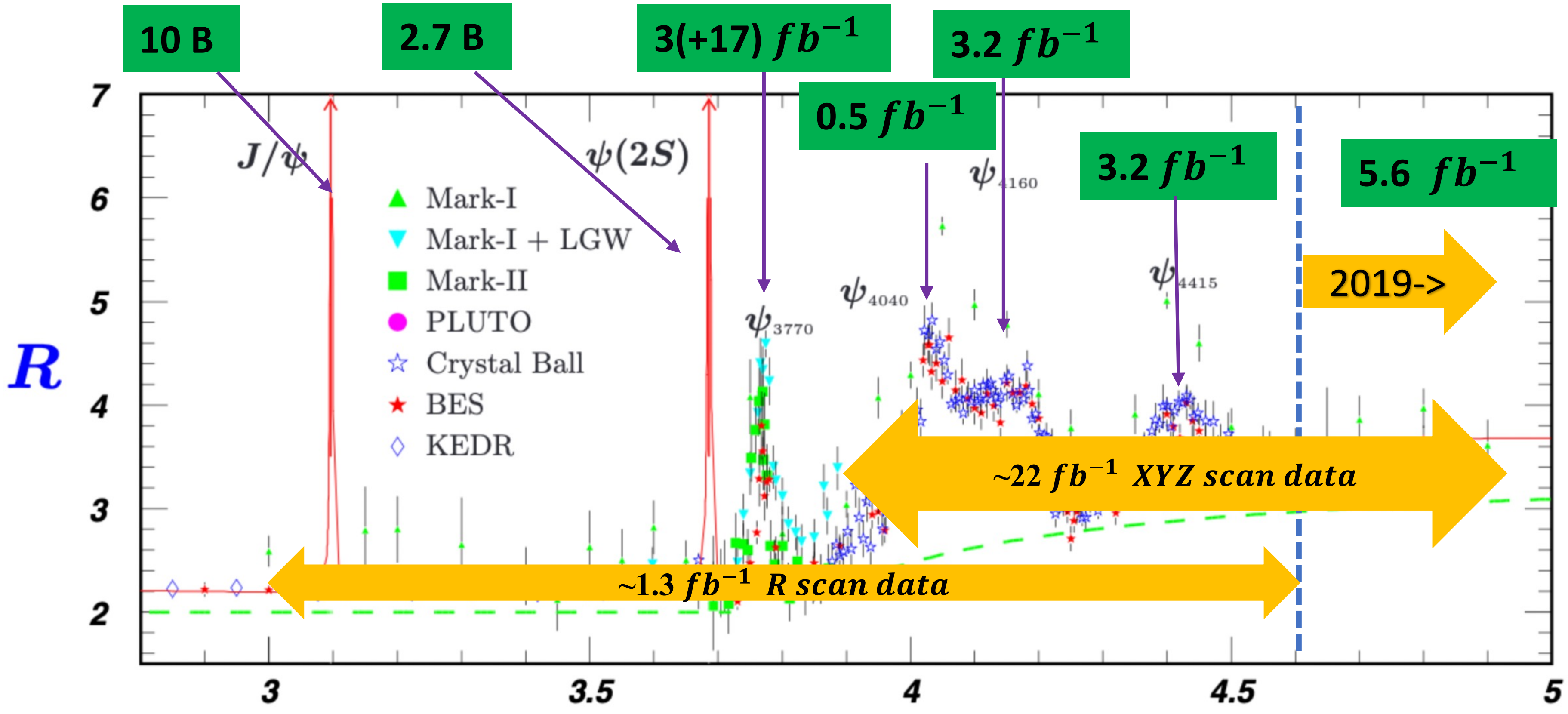
Main Drift Chamber
σ_p/p <0.5% (@1GeV) (1T)
$\sigma_{xy} \sim 120\ \mu m$
$dE/dx \sim 6\%$

Time Of Flight
$\sigma_t < 68ps$(barrel)
$\sigma_t <$ 60ps (endcap)

Electromagnetic Calorimeter
σ_E/E<2.5%(5%) @1GeV
$\sigma_{xy} \sim 6mm$ (@1GeV)

Muon Counter
$\sigma_{\text{spatial}} < 2cm$

Data samples at BESIII



- ✓ Largest e^+e^- annihilation data sets in $\tau - c$ energy region
- ✓ World largest: 10-B J/ψ, 2.7-B ψ', coming 20 fb^{-1} ψ'' data samples. *Chin. Phys. C 44, 040001*

Phys. Rev. D 101, 112005(2020)

I: Search for the decay $J/\psi \rightarrow \gamma$+invisible

✓ **Motivation**: the supersymmetric Standard Models, including Next-to-Minimal Supersymmetric Model, predict a CP-odd pseudoscalar Higgs A^0. The A^0 can be produced in quarkonium radiative decay

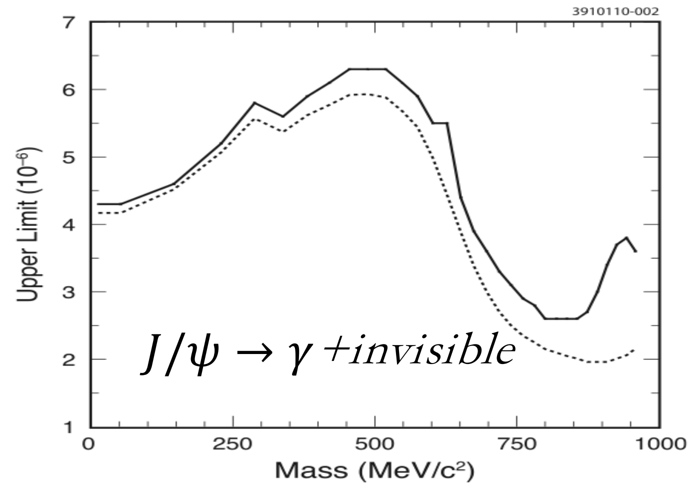
$$\frac{\mathcal{B}(V \rightarrow \gamma A^0)}{\mathcal{B}(V \rightarrow \mu^+\mu^-)} = \frac{G_F m_q^2 g_q^2 C_{\mathrm{QCD}}}{\sqrt{2}\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_V^2}\right),$$

Yukawa coupling of the A^0 field to the quark-pair:

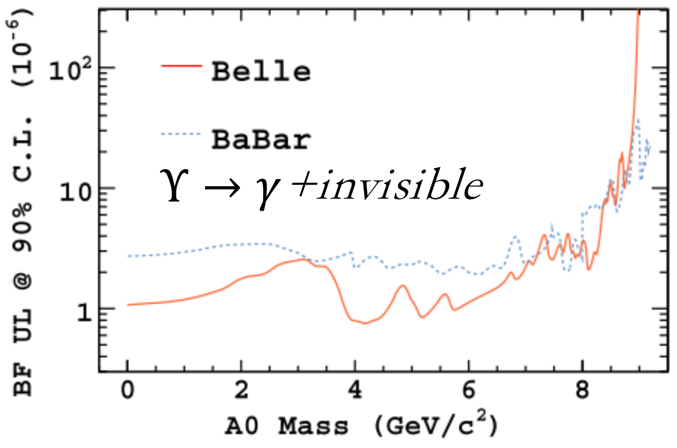
$g_c = \cos\theta_A / \tan\beta$, $g_b = \cos\theta_A \tan\beta$

✓ The A^0 can decay to two neutralinos (DM candidates)

✓ Search for the J/ψ radiative decay into a weakly interacting neutral particle in the process



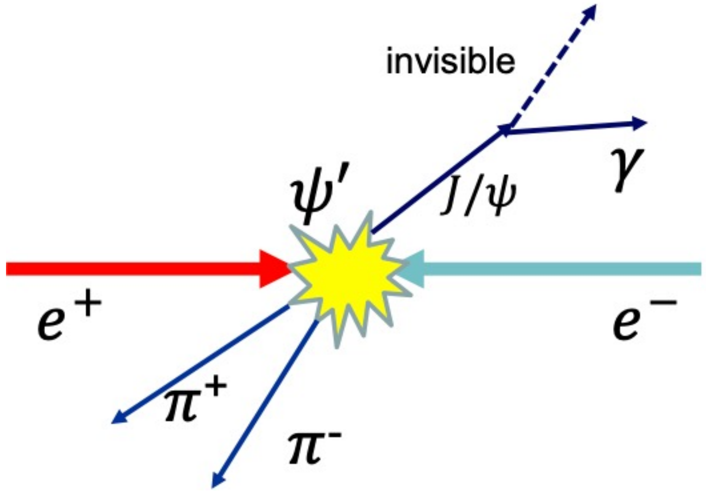
Phys. Rev. D 81, 091101



Phys. Rev. Lett. 122, 011801

Phys. Rev. D 101, 112005(2020)

Search for the decay $J/\psi \to \gamma$+invisible



✓ Data sample: $448.1\times10^6\ \psi(3686)$

✓ Analysis strategy:

- Search for $J/\psi \to \gamma$+invisible with J/ψ from $\psi(3686)\to \pi^+\pi^- J/\psi$
- Clean environment and high trigger efficiency
- First tag J/ψ events by selecting two charged pions, then search for $J/\psi \to \gamma$+invisible, the branching fraction is calculated:

$$\boxed{\mathcal{B} = \frac{N_{\rm sig}\cdot \epsilon_{J/\psi}}{N_{J/\psi}\cdot \epsilon_{\rm sig}},}$$

✓ Perform semi-blind procedure to avoid possible bias

Phys. Rev. D 101, 112005(2020)

Search for the decay $J/\psi \to \gamma$+invisible

✓ **Selections:**

- only $\pi^+\pi^-$ and one good shower is required
- Signal shower and recoiled invisible must direct to the barrel region ($|\cos\theta| < 0.8$)

✓ Fit to the recoil mass $\mathrm{RM}(\pi^+\pi^-)$, There are 8.848×10^7 J/ψ events

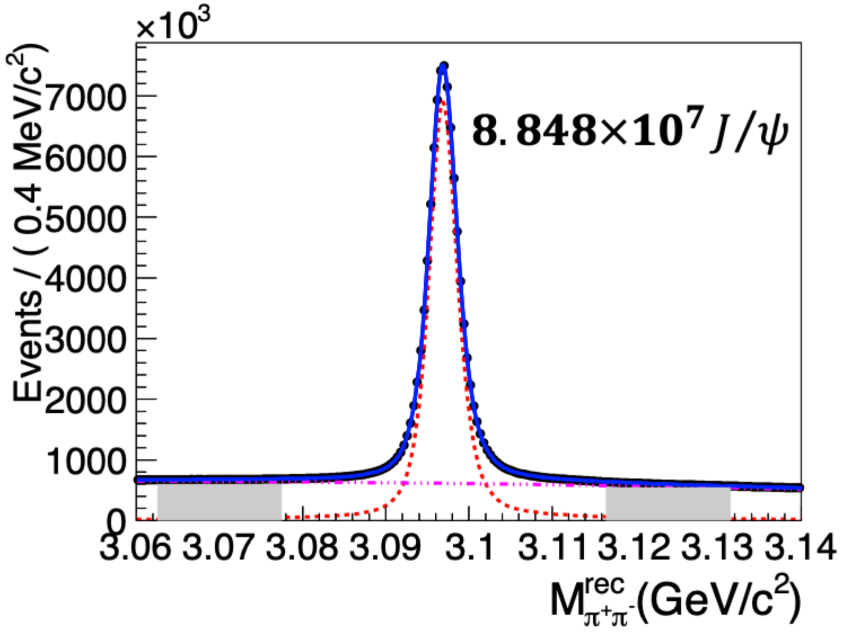
✓ **Huge background** from $J/\psi \to n\bar{n}, \gamma n\bar{n}, \gamma K_L K_L$:

- Using shower shape in EMC to identify γ from $n, \bar{n}, K_L$
- The EMC shapes are studied using control samples

γ: $J/\psi \to \rho\pi^0(\pi^0 \to \gamma\gamma)$

$n/\bar{n}$: $J/\psi \to p\pi n$;

K_L: $J/\psi \to K\pi K_L$ & $J/\psi \to \pi\pi\phi(\phi \to K_S K_L)$

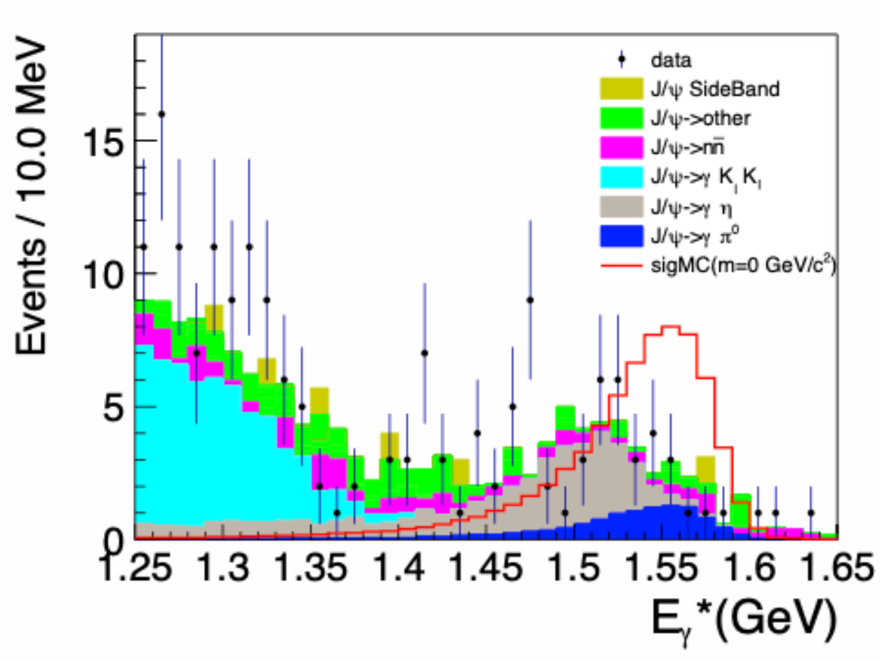


Search for the decay $J/\psi \to \gamma$+invisible

✓ **Signal extraction**: The signal are searched on the E^*_γ range from 1.25 to 1.65 GeV, corresponding to a mass from 0 to 1.2 GeV/c^2 for the invisible particle

✓ Fit method:
- Signal: Signal MC shape
- Peaking background from $J/\psi \to \gamma\pi^0/\eta$: fixed
- No-peak: exponential function

✓ No significant signal, max significance is 1.2σ



Search for the decay $J/\psi \rightarrow \gamma$+invisible

- ✓ **Upper limits**: Use the modified frequentist method to calculate upper limits of branching fraction $\mathcal{B}(J/\psi \rightarrow \gamma\text{+invisible})$

  A.L. Read, J. Phys. G 28, 2693

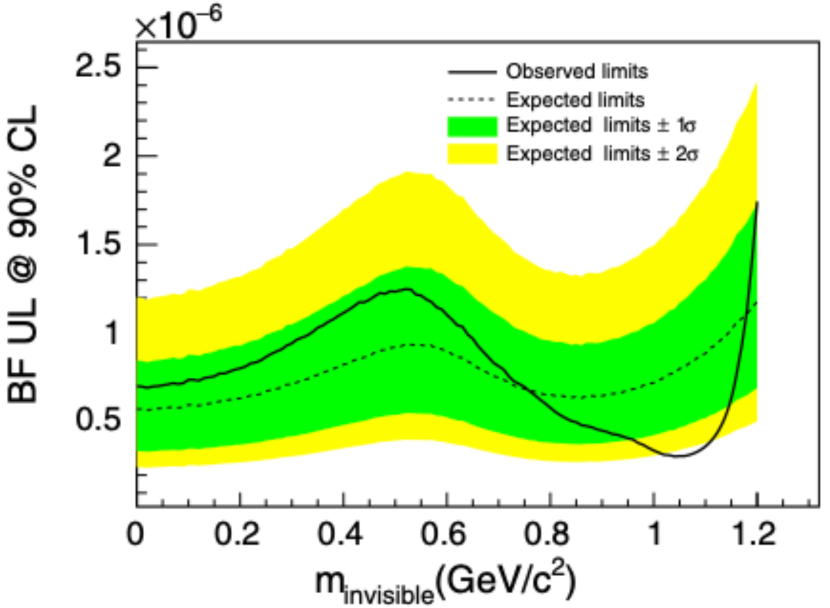
- ✓ For the zero mass assumption of the invisible particle, the upper limit is 7.0×10^{-7} 90% C.L., which is improved by a factor 6.2 compared to the previous CLEO result

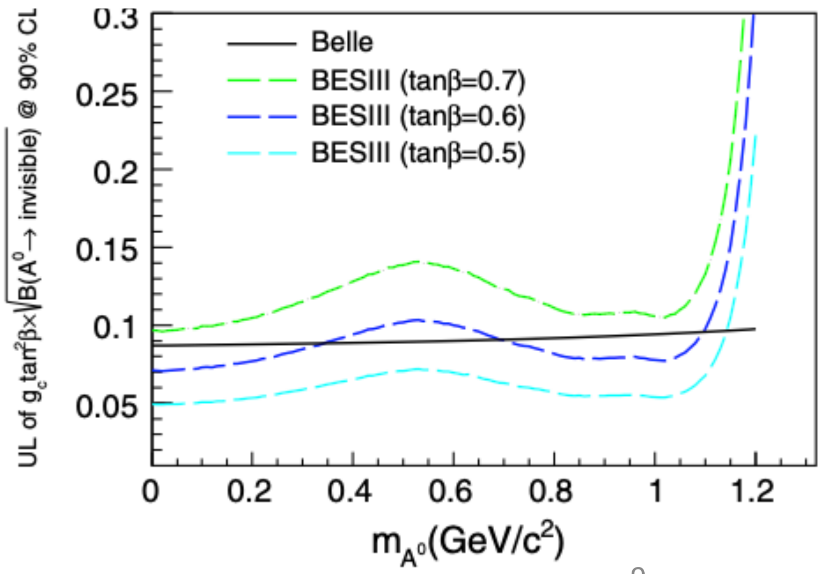
  Phys. Rev. D 81, 091101

- ✓ The upper limits of $g_c \times tan^2\beta \times \sqrt{\mathcal{B}(J/\psi \rightarrow \gamma\text{+invisible})}$ for $\tan\beta$ = 0.5, 0.6, and 0.7 are also reported. We obtain better sensitivity in the range $\tan\beta < 0.6$ compared to the Belle result

  Phys. Rev. Lett. 122, 011801

$$g_b = g_c \times tan^2\beta$$

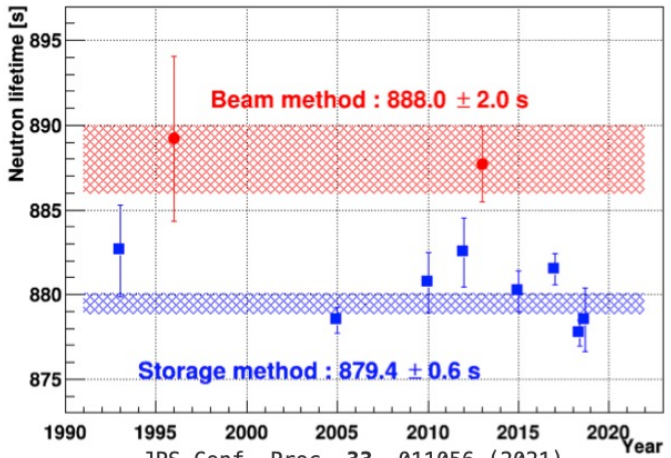




Phys. Rev. D 105, L071101(2022)

II: Search for invisible decays of the Λ baryon

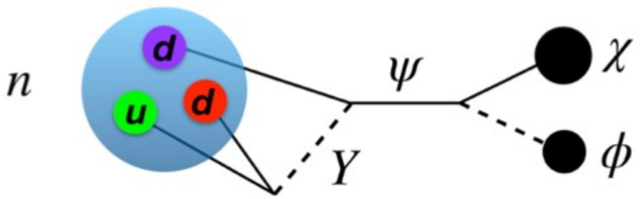
- ✓ Motivation: Dark matter may be represented by baryon matter with invisibles, and many theories suggest a potential correlation between baryon symmetry and dark sector; *Phys. Rev. D 105, 115005*
- ✓ Discrepancy of neutron lifetime in beam method and the storage methods (4.1σ)

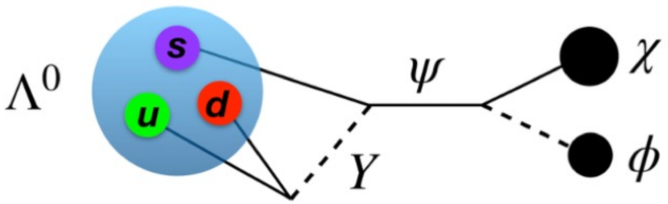


JPS Conf. Proc. 33, 011056 (2021)

$$\boxed{\tau_n^{beam} = \frac{\tau_n}{\mathcal{B}(n \to p + X)} > \tau_n^{bottle}} \Rightarrow \boxed{\mathcal{B}(n \to p + X) \approx 99\%}$$

can be explained by 1% of the neutron decay into dark matter





Phys. Rev. D 99, 035031

- ✓ The first study of invisible baryon decays

Phys. Rev. D 105, L071101(2022)

Search for invisible decays of the Λ baryon

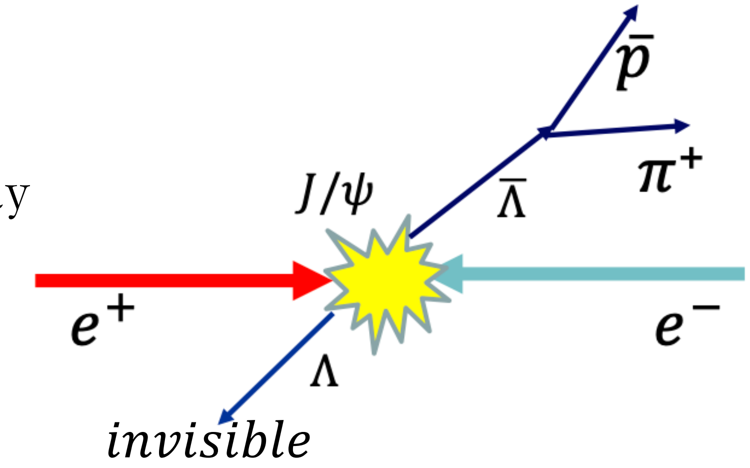
✓ Data sample: 10B J/ψ events

✓ Analysis strategy:

- $J/\psi \to \Lambda\bar{\Lambda}$ provide a clean environment for Λ invisible decay

Double Tag Method:

- Tag side: $\bar{\Lambda}$ is tagged by $\bar{\Lambda} \to \bar{p}\pi^+$, fit on recoil mass $RM(\bar{p}\pi^+)$ to obtain the $\bar{\Lambda}$ signal yield
- Signal side: Λ decays invisibly



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

✓ The $\bar{\Lambda}$ invisible decay is not pursued, because the dominant background from $\bar{\Lambda} \to \bar{n}\pi^0$ is hard to estimate and simulate

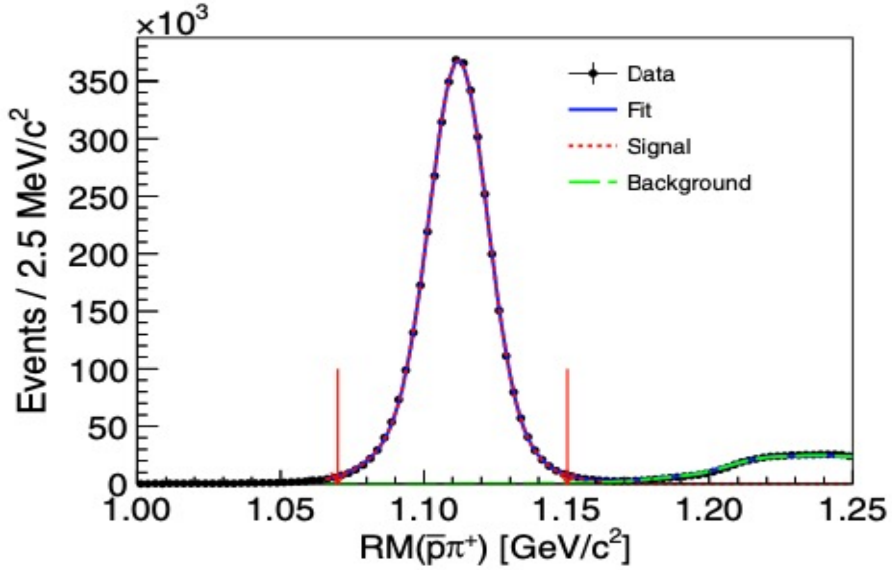
Phys. Rev. D 105, L071101(2022)

Search for invisible decays of the Λ baryon

✓ **Tag side selections**:

- Reconstruct $\bar{p}, \pi^+$, $|\cos(\theta_{\bar{\Lambda}})|<0.7$;
- One of tracks is required TOF hit for good resolution of the event start time;

✓ **Signal side selections**: No additional charged track



4.1M Λ events

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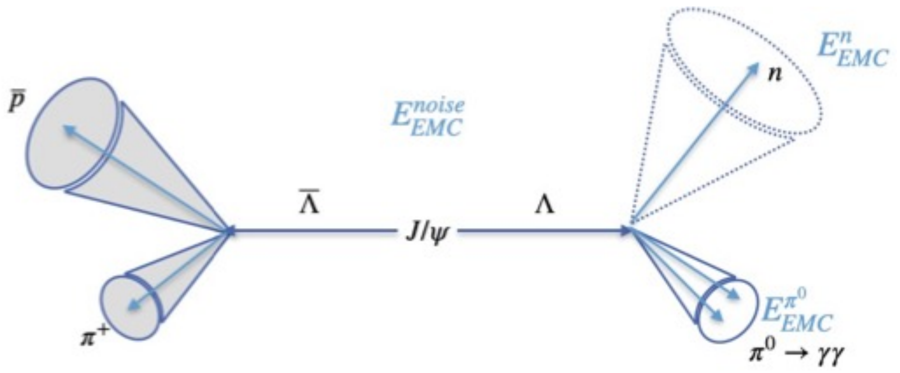
Search for invisible decays of the Λ baryon

✓ **Signal extraction**: Search for signal on total energy in EMC E_{EMC} (not charged tracks);

- Dominating background: $\Lambda \to n\pi^0$

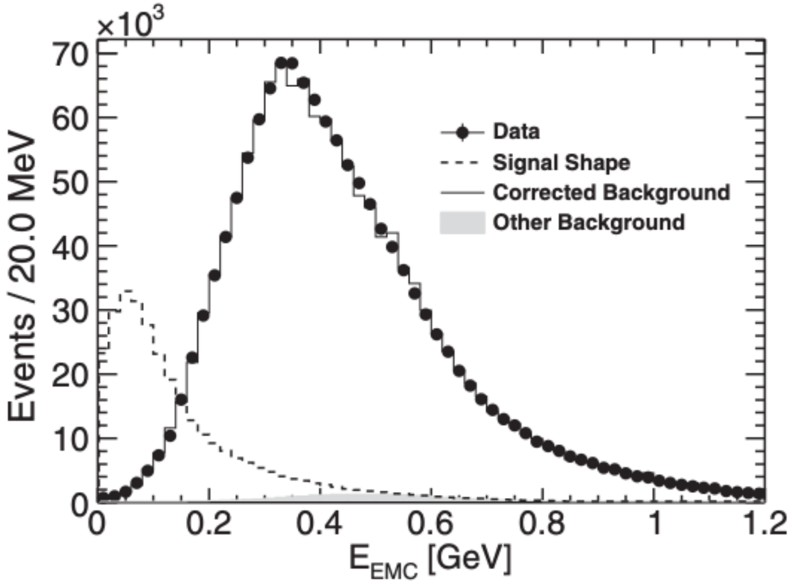
$$\boxed{E_{\rm EMC} = E^{\pi^0}_{\rm EMC} + E^{n}_{\rm EMC} + E^{\rm noise}_{\rm EMC},}$$

- $E^{\pi^0}_{EMC}$: Based on the MC simulations
- E^{n}_{EMC}+ E^{noise}_{EMC}: Based on control sample $J/\psi \to \Lambda(n\pi^0)\bar{\Lambda}(\bar{p}\pi^+)$;



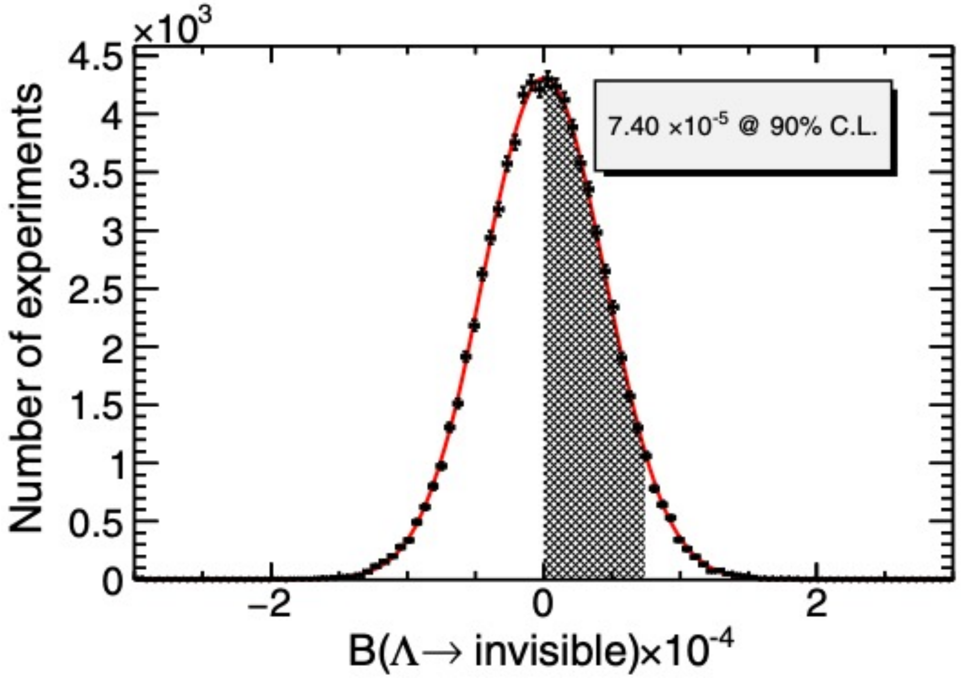
✓ The corrected E_{EMC} for $\Lambda \to n\pi^0$ is derived by combining $E^{\pi^0}_{EMC}$ with a random value of the sum of E^{n}_{EMC}+ E^{noise}_{EMC}

✓ No obvious signals are observed



Search for invisible decays of the Λ baryon

✓ Upper limit：A modified frequentist approach is adopted to estimate the UL of $\mathcal{B}(\Lambda \to invisible)$ *A.L. Read, J. Phys. G 28, 2693*



✓ The upper limit is $\mathcal{B}(\Lambda \to invisible) < 7.4\times10^{-5}$ at 90% C.L.

✓ The UL is consistent with the prediction of 4.4×10^{-7} from the mirror model *arXiv:2006.10746*

✓ This result sheds light on the neutron lifetime measurement puzzle and helps to constrain dark sector models related to the baryon asymmetry

Summary

- ✓ The invisible decays is one of the important ways to search for physics beyond SM
- ✓ In this talk, we reported:
  - $J/\psi \to \gamma$+invisible: Using 448.1×10^6 $\psi(3686)$ data sample, no obvious signal is observed. The upper limits @ 90% C.L. mass(invisible) in [0,1.2] $\mathrm{GeV/c^2}$ are measured, which is 6.2 time improved compared to the previous results
    Phys. Rev. D 101, 112005(2020)
  - $\Lambda \to invisible$: With 10 B J/ψ data sample, first search for Λ invisible decay and no obvious signals are observed. The upper limit is $\mathcal{B}(\Lambda \to invisible) < 7.4\times10^{-5}$ at 90% C.L. The result helps to constrain dark sector models related to the baryon asymmetry
    Phys. Rev. D 105, L071101(2022)
- ✓ With the world's largest e^+e^- annihilation, more exciting results is ongoing and coming soon

Thank you!