Experimental Study of Charmonium Decay and Hyperon-Nucleon Scattering and Development of High-Energy-Physics Software

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BESIII PhD Thesis Award

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CONTENTS

01

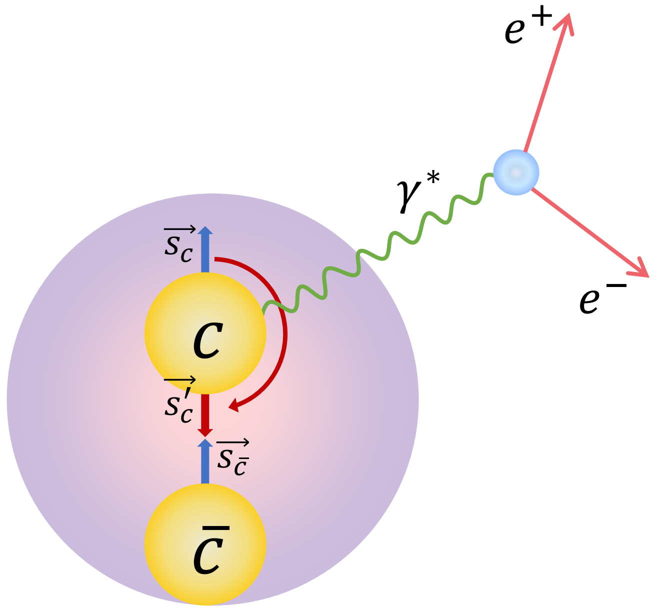
Study of the EM Transition

$\psi(3686) \to \eta_c$

Physics Background

- As a hindered M1 transition， the EM transition from $\psi(3686)$ to η_c is vital for the study of spin-related transition mechanism of charmonium [Phys. Rept. 128, 301 (1985)]
- The potential interference effect is not taken into consideration in the previous measurements of the branching fractions of the transition [Phys. Rev. Lett. 102 (2009) 011801, Phys. Rev. D 106 (2022) 112002], introducing uncertainties
- The radiation decay $\psi(3686) \to \gamma\eta_c$ has been observed, while the corresponding Dalitz decay $\psi(3686) \to e^+e^-\eta_c$ has not been discovered yet， of which the branching fraction is predicted to be $\mathcal{B}(\psi(3686) \to e^+e^-\eta_c) = 3.03 \times 10^{-5}$ [Phys. Rev. D 100, 016018 (2019), Int. J. Mod. Phys. A 34, 1950129 (2019)]

Decay Channel	$\mathcal{B}^{\mathrm{VMD}}_{e^+e^-}$	$\mathcal{B}^{\mathrm{VMD}}_{\mu^+\mu^-}$
$J/\psi \to \eta_c l^+l^-$	$(1.03 \pm 0.25) \times 10^{-4}$	$-$
$\psi(3686) \to \eta_c l^+l^-$	$(3.03 \pm 0.45) \times 10^{-5}$	$(2.79 \pm 0.41) \times 10^{-6}$
$\Upsilon(2S) \to \eta_b l^+l^-$	$(3.38 \pm 1.31) \times 10^{-6}$	$(2.56 \pm 1.00) \times 10^{-7}$
$\Upsilon(3S) \to \eta_b l^+l^-$	$(4.77 \pm 0.79) \times 10^{-6}$	$(6.20 \pm 1.03) \times 10^{-7}$



Physics Background

- In the assumption that $\psi(3686)$ and η_c are both point-like particles, the ratio of the decay widths between the Dalitz decay and the radiative decay is the fine structure constant α [Mod. Phys. Lett. A 27, 1250223 (2012)]
- The q^2-dependent decay width of the Dalitz decay $\mathrm{d}\Gamma(\psi(3686) \to e^+e^-\eta_c)/\mathrm{d}q^2$ can be normalized into the radiative decay width $\Gamma(\psi(3686) \to \gamma\eta_c)$ as

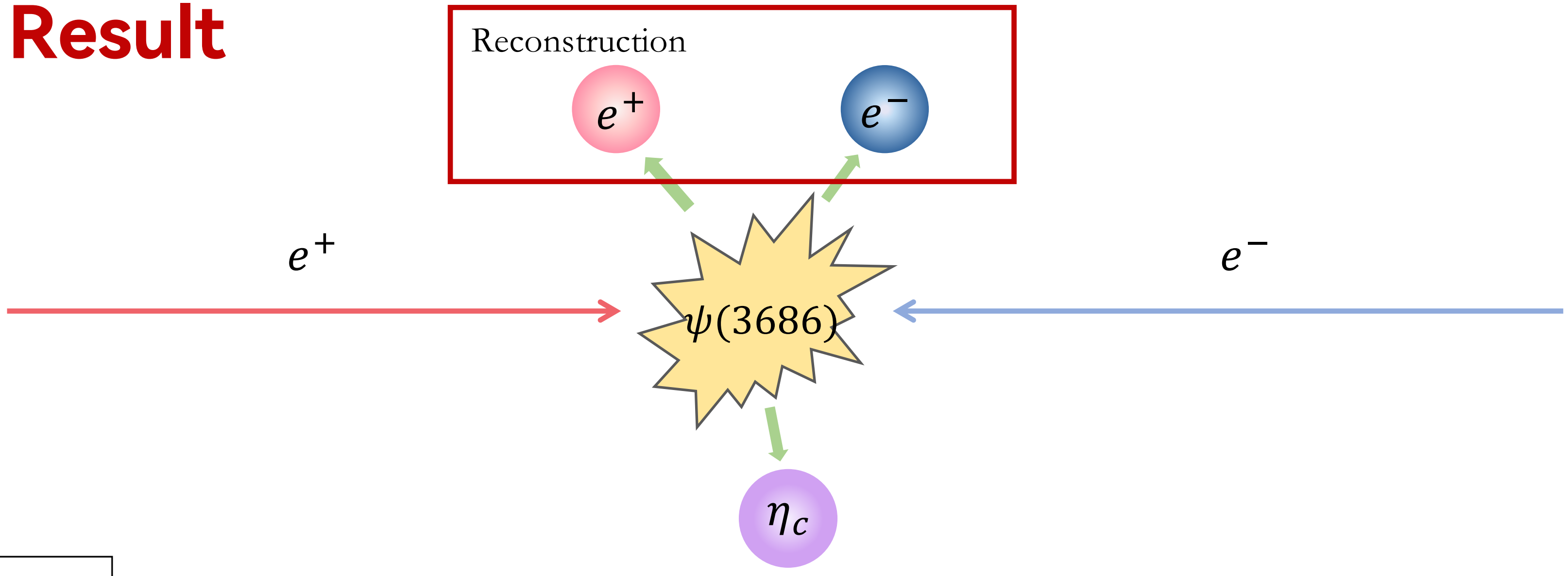
$$\frac{\mathrm{d}\Gamma(\psi(3686) \to e^+e^-\eta_c)}{\mathrm{d}q^2\Gamma(\psi(3686) \to \gamma\eta_c)} = |F_{\psi(3686)\eta_c}(q^2)|^2 \times \mathrm{QED}(q^2)$$

- The interaction between the charmonium and the virtual photon, and the potential vacuum polarization effect during the propagating are described via transition form factor (TFF) $F_{\psi(3686)\eta_c}(q^2)$, which, in the single-pole approximation of the vector meson dominance (VMD), has the form as [Phys. Rev. 124, 953 (1961), Rev. Mod. Phys. 50, 261 (1978)]

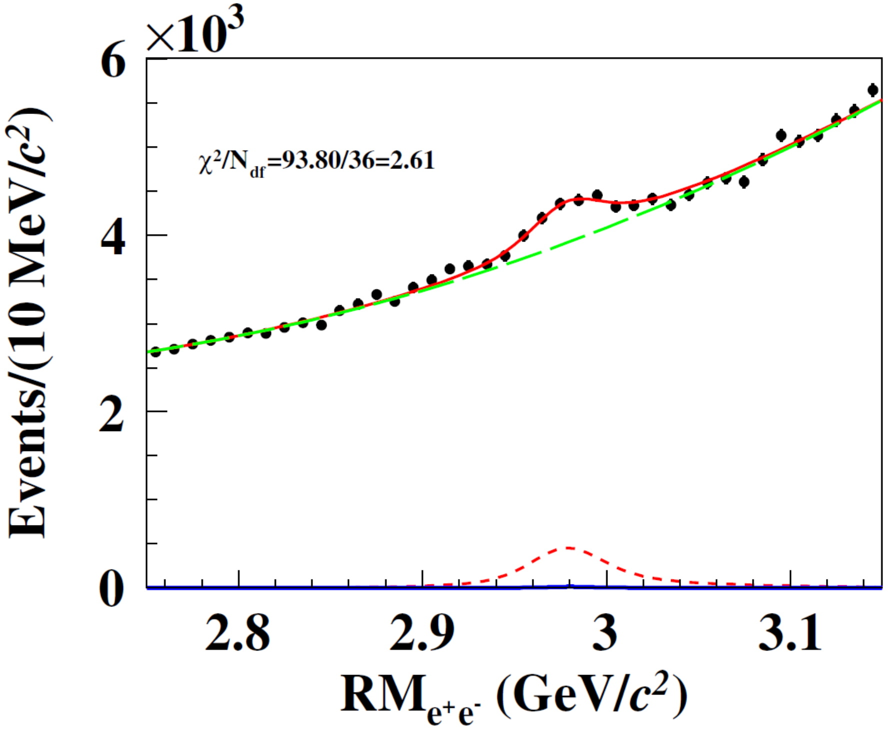
$$F_{\psi(3686)\eta_c}(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

- VMD is effective for most EM Dalitz decays except $\omega \to \mu^+\mu^-\pi^0$ [Phys. Lett. B 677, 260 (2009), Phys. Lett. B 757, 437 (2016)]
- Using $\psi(3686) \to e^+e^-\eta_c$ to extract the absolute branching fractions of η_c

Analysis Method and Result



Using $(448.1 \pm 2.9) \times 10^6$ $\psi(3686)$ events @ $\sqrt{s}$ = 3.686 GeV



- Branching fraction: $\mathcal{B}(\psi(3686) \to e^+e^-\eta_c) = (3.77 \pm 0.40_{\text{stat.}} \pm 0.18_{\text{syst.}}) \times 10^{-5}$
- $R \equiv \frac{\Gamma(\psi(3686) \to e^+e^-\eta_c)}{\Gamma(\psi(3686) \to \gamma\eta_c)} = (1.11 \pm 0.21) \times 10^{-2}$ [taking the average of $\mathcal{B}(\psi(3686) \to \gamma\eta_c)$ from PDG as input]

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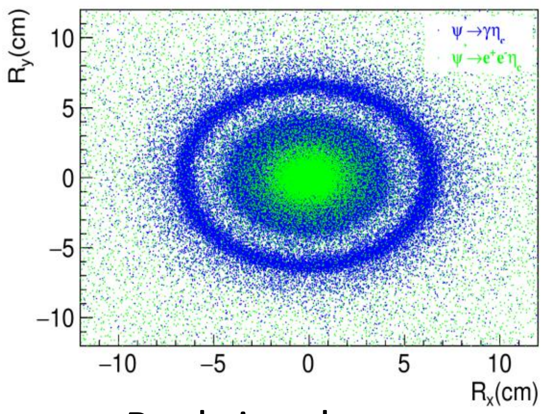
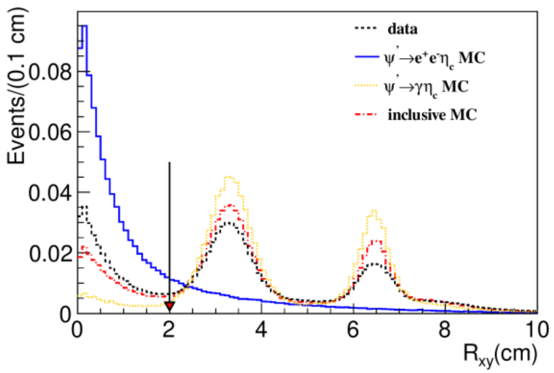
Method to Measure the BF with Considering Interference

- Using $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events @ $\sqrt{s} = 3.686$ GeV
- Using e^+e^- from photon conversion at material to reconstruct $\psi(3686) \to \gamma\eta_c$; using the vertex of e^+e^- to distinguish $\psi(3686) \to e^+e^-\eta_c$ and $\psi(3686) \to \gamma\eta_c$
- Simultaneously determine the branching fractions of $\psi(3686) \to e^+e^-\eta_c$ and $\psi(3686) \to \gamma\eta_c$ with considering the interference effect





Background

Real signal

$$\boxed{\frac{N^{tot}_{\psi(3686)} \cdot Br_{e^+e^-\eta_c}}{N^{MC}_{e^+e^-\eta_c}} \cdot N^{bkg}_{e^+e^-\eta_c}} + \boxed{N^{rec}_{\gamma\eta_c}} = N^{fit}_{\gamma\eta_c}$$

$$\frac{N^{tot}_{\psi(3686)} \cdot Br_{\gamma\eta_c}}{N^{MC}_{\gamma\eta_c}} \cdot N^{bkg}_{\gamma\eta_c} + N^{rec}_{e^+e^-\eta_c} = N^{fit}_{e^+e^-\eta_c}$$

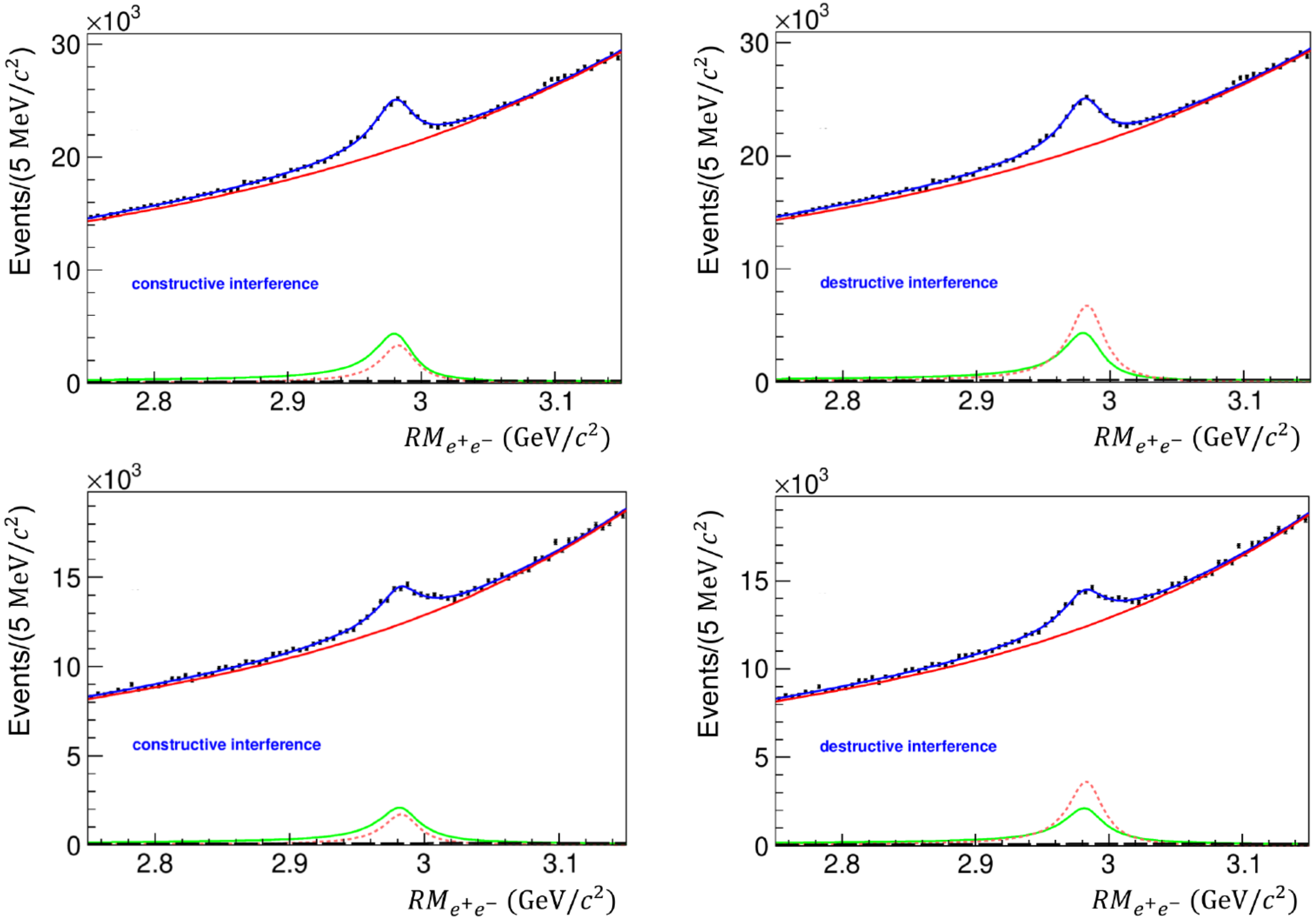
$$Br_{\gamma\eta_c} = \frac{N^{rec}_{\gamma\eta_c}}{\varepsilon_{\gamma\eta_c} \cdot N^{tot}_{\psi(3686)}}, \varepsilon_{\gamma\eta_c} = \frac{N^{suv}_{\gamma\eta_c}}{N^{MC}_{\gamma\eta_c}}$$

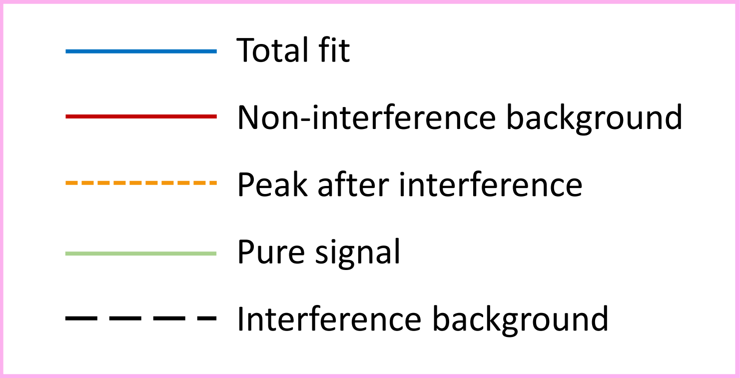
$$Br_{e^+e^-\eta_c} = \frac{N^{rec}_{e^+e^-\eta_c}}{\varepsilon_{e^+e^-\eta_c} \cdot N^{tot}_{\psi(3686)}}, \varepsilon_{e^+e^-\eta_c} = \frac{N^{suv}_{e^+e^-\eta_c}}{N^{MC}_{e^+e^-\eta_c}}$$

$$Br_{\gamma\eta_c} = \frac{N^{MC}_{\gamma\eta_c}(N^{fit}_{e^+e^-\eta_c} \cdot N^{bkg}_{e^+e^-\eta_c} - N^{suv}_{e^+e^-\eta_c} \cdot N^{fit}_{\gamma\eta_c})}{N^{tot}_{\psi(3686)}(N^{bkg}_{\gamma\eta_c} \cdot N^{bkg}_{e^+e^-\eta_c} - N^{suv}_{e^+e^-\eta_c} \cdot N^{suv}_{\gamma\eta_c})}$$

$$Br_{e^+e^-\eta_c} = \frac{N^{MC}_{e^+e^-\eta_c}(N^{fit}_{\gamma\eta_c} \cdot N^{bkg}_{\gamma\eta_c} - N^{suv}_{\gamma\eta_c} \cdot N^{fit}_{e^+e^-\eta_c})}{N^{tot}_{\psi(3686)}(N^{bkg}_{e^+e^-\eta_c} \cdot N^{bkg}_{\gamma\eta_c} - N^{suv}_{\gamma\eta_c} \cdot N^{suv}_{e^+e^-\eta_c})}$$

Signal Fit





$\psi(3686) \to \gamma\eta_c$

$\psi(3686) \to e^+e^-\eta_c$

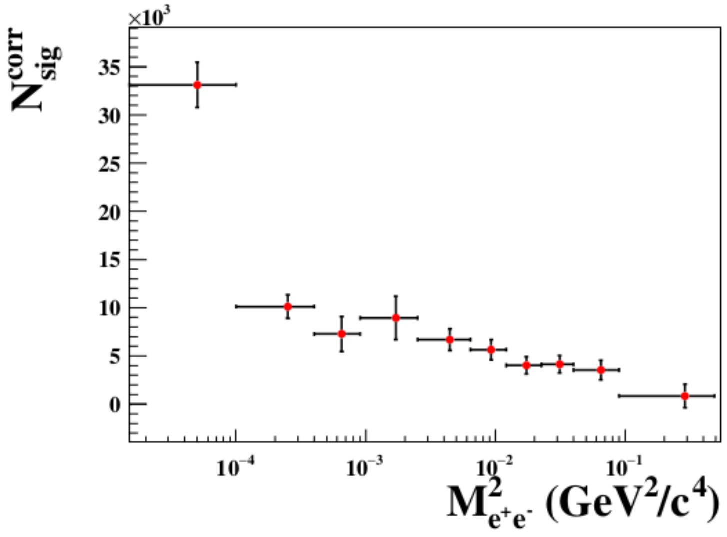
Branching Fraction

Parameters	Value	
	Constructive interference	Destructive interference
$N^{tot}_{\psi(3686)}$	2.708×10^9	
$N^{\mathrm{MC}}_{\gamma\eta_c}$	1×10^7	
$N^{\mathrm{MC}}_{e^+e^-\eta_c}$	1×10^6	
$N^{\mathrm{fit}}_{\gamma\eta_c}$	33554 ± 604	68295 ± 1170
$N^{\mathrm{fit}}_{e^+e^-\eta_c}$	17241 ± 785	36477 ± 3333
$N^{\mathrm{bkg}}_{\gamma\eta_c}$	682 ± 59	
$N^{\mathrm{bkg}}_{e^+e^-\eta_c}$	13991 ± 153	
$N^{\mathrm{suv}}_{\gamma\eta_c}$	37513 ± 284	
$N^{\mathrm{suv}}_{e^+e^-\eta_c}$	197229 ± 694	
$\mathcal{B}(\psi(3686) \to \gamma\eta_c)$	$(3.19 \pm 0.06_{\mathrm{stat.}} \pm 0.23_{syst.}) \times 10^{-3}$	$(6.48 \pm 0.12_{\mathrm{stat.}} \pm 0.95_{\mathrm{syst.}}) \times 10^{-3}$
$\mathcal{B}(\psi(3686) \to e^+e^-\eta_c)$	$(3.12 \pm 0.15_{\mathrm{stat.}} \pm 0.32_{\mathrm{syst.}}) \times 10^{-5}$	$(6.61 \pm 0.70_{\mathrm{stat.}} \pm 0.37_{\mathrm{syst.}}) \times 10^{-5}$
$R \equiv \frac{\Gamma(\psi(3686) \to e^+e^-\eta_c)}{\Gamma(\psi(3686) \to \gamma\eta_c)}$	$(9.7 \pm 1.3) \times 10^{-3}$	$(10.2 \pm 1.9) \times 10^{-3}$

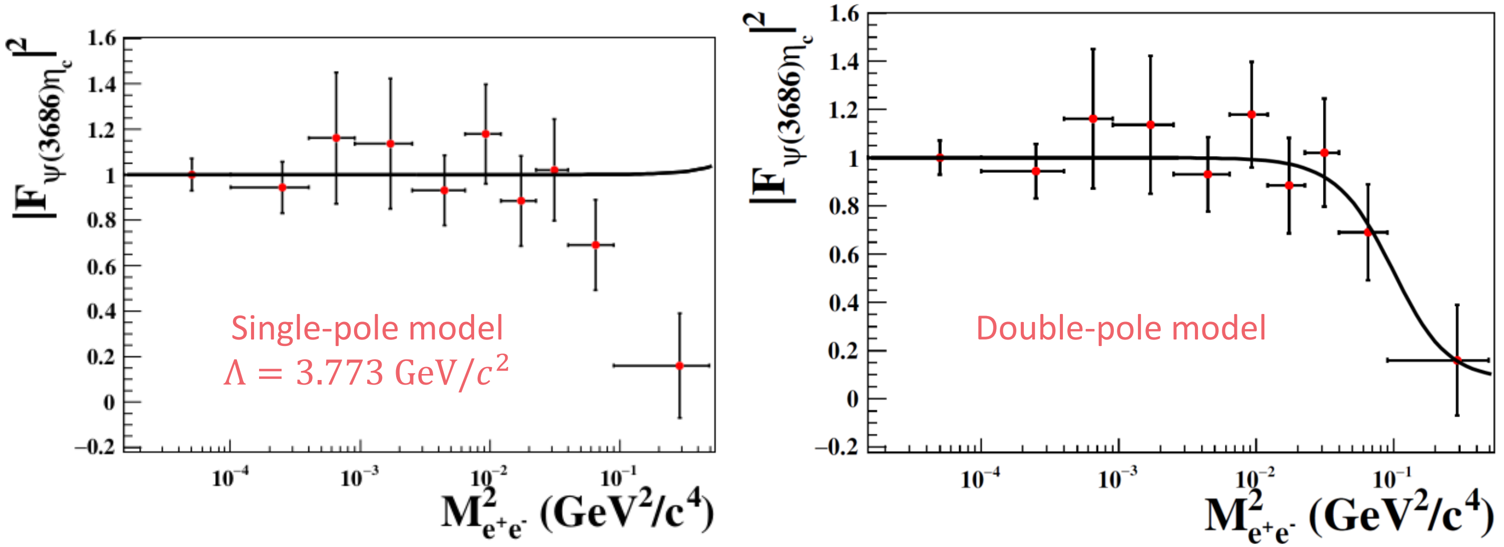
This analysis is being reviewed: https://docbes3.ihep.ac.cn/cgi-bin/DocDB/ShowDocument?docid=1240

Form Factor

- Measured TFF is not completely consistent with the VMD model under the single-pole approximation: $F_{\psi(3686)\eta_c}(q^2) = \frac{1}{1-q^2/\Lambda^2}$
- Double-pole model ($F_{\psi(3686)\eta_c}(q^2) = \frac{A}{1-q^2/\Lambda_1^2} + \frac{1-A}{1-q^2/\Lambda_2^2}$) can be used in the fit, while the result is not physical ($\Lambda_1 = (0.13 \pm 0.10)\ \mathrm{GeV}/c^2$, $\Lambda_2 = (27.3 \pm 62.3)\ \mathrm{GeV}/c^2$)
- Need further checking and discussion



Signal yield after correction using efficiency



Measured TFF

02

Study of η_c Decay

Physics Background

- ✓ As the singlet of S-wave and the lightest charmonium, η_c decays via the annihilation of charm and anti-charm quarks
- ✓ η_c has two main decay mechanism: strong decay via two gluons or EM decay via two photons, no tree-level decay

Strong decay of η_c:

- Test the 12% rule between ground-state charmonium and corresponding first radial excitation [Chin. Phys. C 46, no.7, 071001 (2022)]
- Potential mixing among η, η', η_c; glueballs are also included in some models [Phys. Rev. D 84, 034003 (2011), Phys. Rev. D 85, 034002 (2012), Phys. Rev. D 97, no.9, 096002 (2018), Phys. Lett. B 827, 136960 (2022)]
- Study intermediate resonances

  No need to consider the spin polarization due to the pseudoscalar nature of η_c, so that the PWA can be performed directly from η_c
- Due to complex non-perturbative effects, the calculations of the BFs of η_c decays are scarce and unreliable
- In history, η_c decays are usually measured via the radiative decays of vector charmonium

  Large uncertainty of the BFs of the radiative decays

  Unable to measure the absolute branching fractions

  Significant interference with background processes

Avoiding the interference, $\psi(3686) \to \pi^0 h_c, h_c \to \gamma\eta_c$ is an ideal decay channel to measure the absolute branching fractions of η_c

Physics Background

$\eta_c \to \gamma\gamma$:

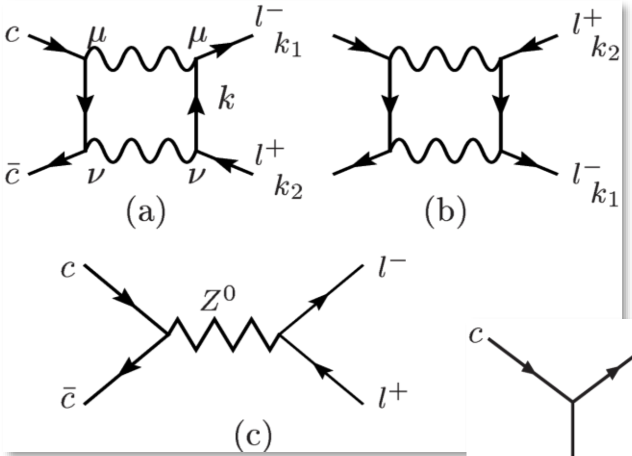
- The simplest decay; can be calculated by QCD
- Test the wave function from NRQCD calculation
- Benchmark for theoretical calculations
- More than 3σ between the latest LQCD calculation and PDG
  - ✓ PDG (Two-photon): $\Gamma_{\eta_c} = 5.1 \pm 0.4$ keV
  - ✓ LQCD: $\Gamma_{\eta_c} = 6.788 \pm 0.045_{\text{fit}} \pm 0.041_{\text{syst.}}$ keV [Phys. Rev. D 108, no.1, 014513 (2023)]
- The latest result from BESIII ($J/\psi \to \gamma\eta_c$): $\Gamma(\eta_c \to \gamma\gamma) = (11.30 \pm 0.56_{\text{stat.}} \pm 0.66_{\text{syst.}} \pm 1.14_{\text{ref.}})$ keV [Phys. Rev. Lett. 134, 181901 (2025)]
  - ✓ Large uncertainty
  - ✓ Interference effect
  - ✓ Larger than the PDG and latest LQCD calculation
- Absolute branching fraction has never been measured
- $R \equiv \frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(\eta_c \to \gamma\gamma)}$ cancels the non-perturbative uncertainty, predicted by theory to be$3/4$ [Phys. Lett. B 519, 212-218 (2001)]

Works	Theoretical Models	$\Gamma(\eta_c \to \gamma\gamma)/(\text{keV})$
E. S. Ackleh et al. (1992)	Potential Model	4.8
M. R. Ahmady et al. (1994)	Potential Model	11.8 ± 0.8
C. R. Münz et al. (1996)	DS&BS equation	3.5 ± 0.4
H. W. Huang et al. (1997)	DS&BS equation	$6-7$
A. Czarnecki et al. (2001)	NRQCD	7.01
N. Fabiano et al. (2002)	NRQCD	7.6 ± 1.5
D. Ebert et al. (2003)	Potential Model	5.5
C. W. Hwang et al. (2007)	Potential Model	$5.43-9.30$
C. S. Kim et al. (2005)	Potential Model	7.14 ± 0.95
J. P. Lansberg et al. (2006)	Heavy quark spin symmetry	$7.5-10$
J. J. Dudek et al. (2006)	LQCD	$2.65 \pm 0.26 \pm 0.80 \pm 0.53$
M. Z. Yang (2009)	Sum rule + pQCD	$6.49^{+0.74}_{-0.54}$
J. T. Laverty et al. (2009)	DS&BS equation	5.09
H. K. Guo et al. (2011)	NRQCD	$6.61^{+2.77}_{-2.83}$
T. Chen et al. (2020)	LQCD	1.122 ± 0.014
J. Chen et al. (2017)	DS&BS equation	$6.32-6.39$
R. Li et al. (2019)	Soft gluon factorization	$5.02 \pm 0.13 \pm 0.38$
Y. Chen et al. (2020)	LQCD	$1.62(19)/1.51(17)$
C. Lin et al. (2020)	LQCD	$3.93 \pm 0.09 \pm 0.43$
Y. Meng et al. (2021)	LQCD	$6.57 \pm 0.15 \pm 0.08$
B. Colquhoun et al. (2023)	LQCD	$6.788(45)(41)$

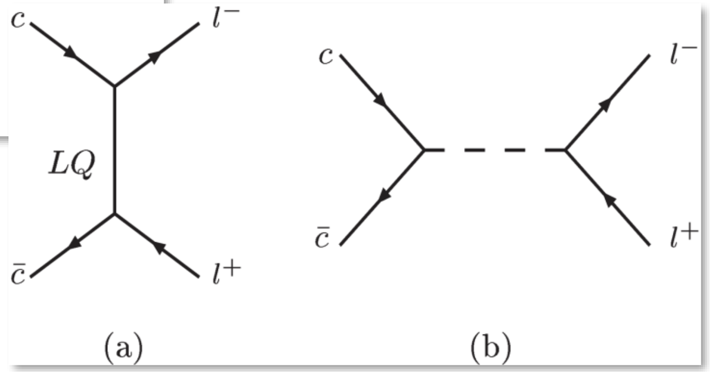
Physics Background

$\eta_c \to \ell^+\ell^-$:

- The lowest contribution in the SM is one-loop diagram, suppressed by α^2 compared with $\eta_c \to \gamma\gamma$
- The tree-level weak decay via Z^0 has little contribution due to the Breit-Wigner form of the propagator.
- Due to the helicity suppression, the decay width of $\eta_c \to e^+e^-$ is smaller than $\eta_c \to \mu^+\mu^-$ by 4 orders of magnitude
- Potential enhancement by new physics models: leptoquark, light pseudoscalar Higgs boson next-to-minimal supersymmetric Standard Model

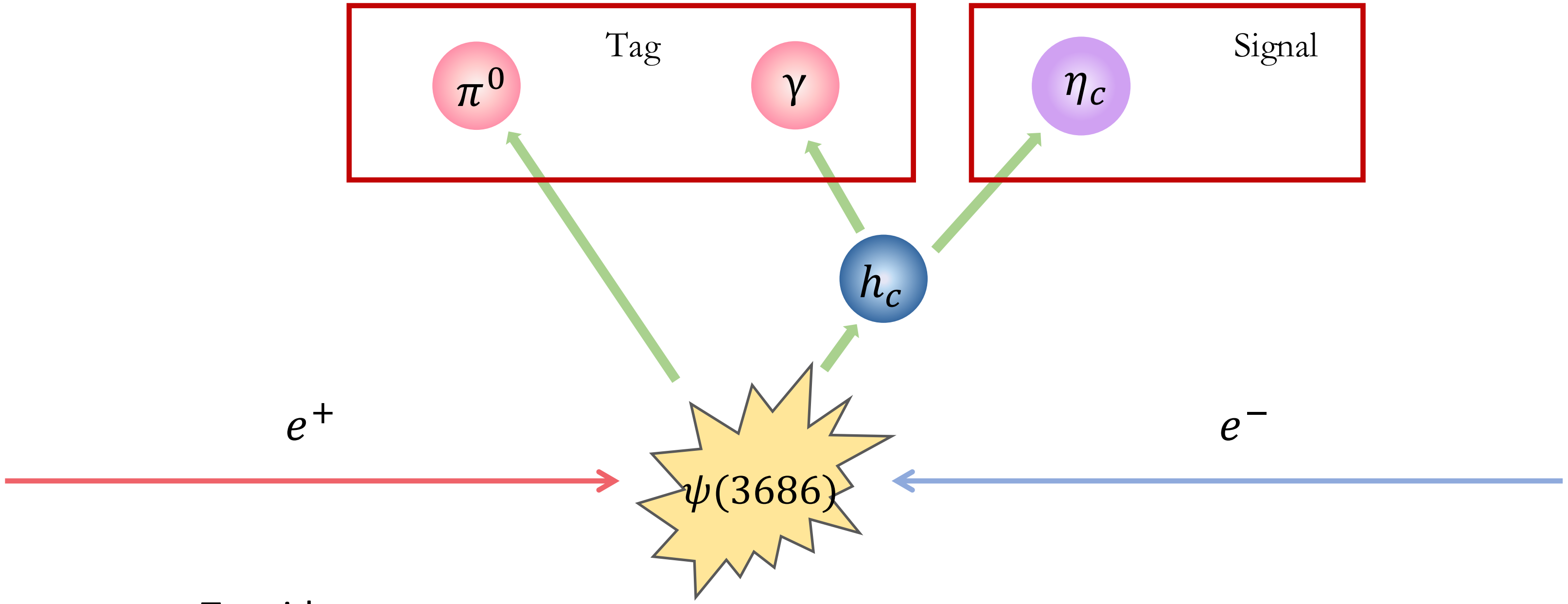


Phys. Rev. D 79, 074026 (2009)



Theoretical Works	$\mathcal{B}(\eta_c \to e^+e^-)$	$\mathcal{B}(\eta_c \to \mu^+\mu^-)$	Backup
L. Bergström (1982)	–	1.9×10^{-6}	
M. Z. Yang (2009)	$4.77^{+0.77}_{-0.66} \times 10^{-13}$	$6.41^{+1.04}_{-0.89} \times 10^{-9}$	Only include EM contribution
	$4.74^{+0.77}_{-0.66} \times 10^{-13}$	$6.39^{+1.03}_{-0.89} \times 10^{-9}$	Include weak contribution
Y. Jia (2009)	$(2.17 \pm 0.17) \times 10^{-13}$	$(3.02 \pm 0.24) \times 10^{-9}$	Taking $\mathcal{B}(\eta_c \to \gamma\gamma)$ from PDG as input
L. Tang (2012)	–	$6.39^{+1.03}_{-0.89} \times 10^{-9}$	
N. Kivel et al. (2016)	2.5×10^{-13}	0.74×10^{-9}	

Analysis Method



- Since the width of h_c is small and the background components are clear, the π^0 recoil mass spectrum (invariant mass spectrum of h_c) after tagging the γ is used to obtain the yield in both Tag and Signal side
  - ✓ $\gamma-$tagged h_c yield $\approx \eta_c$ yield
  - ✓ Estimate an item of systematic uncertainty to consider the potential non $-\,\eta_c$ background

Using $(2712.4 \pm 14.3) \times 10^6$ $\psi(3686)$ events @ $\sqrt{s} = 3.686$ GeV

- Tag side:

  Fit the recoil mass spectrum of π^0 to obtain the inclusive yield of η_c: $N_{\eta_c} = \frac{N_{\eta_c}^{\text{tag}}}{\varepsilon_{\eta_c}^{\text{tag}}}$

- Signal side:

  Fit the invariant mass spectrum of all reconstructed final particles from h_c to obtain exclusive yield of η_c: $N_X = \frac{N_X^{\text{sig}}}{\varepsilon_X^{\text{sig}}}$

✓ Branching fraction：

$$B(\eta_c \to X) = \frac{N_X}{N_{\eta_c}}$$

BF of the Strong Decay of η_c and Resonance Parameters of h_c

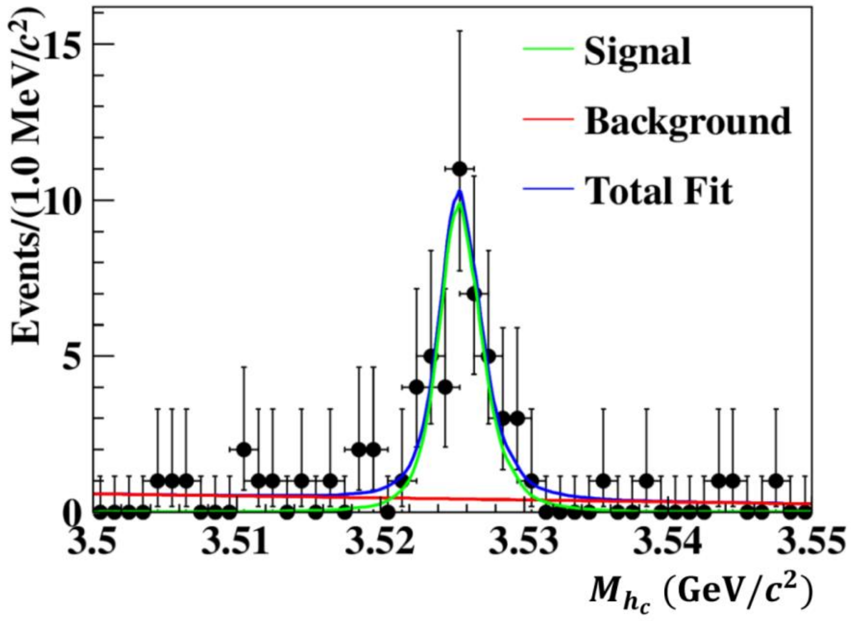
One order of magnitude better than the PDG precision

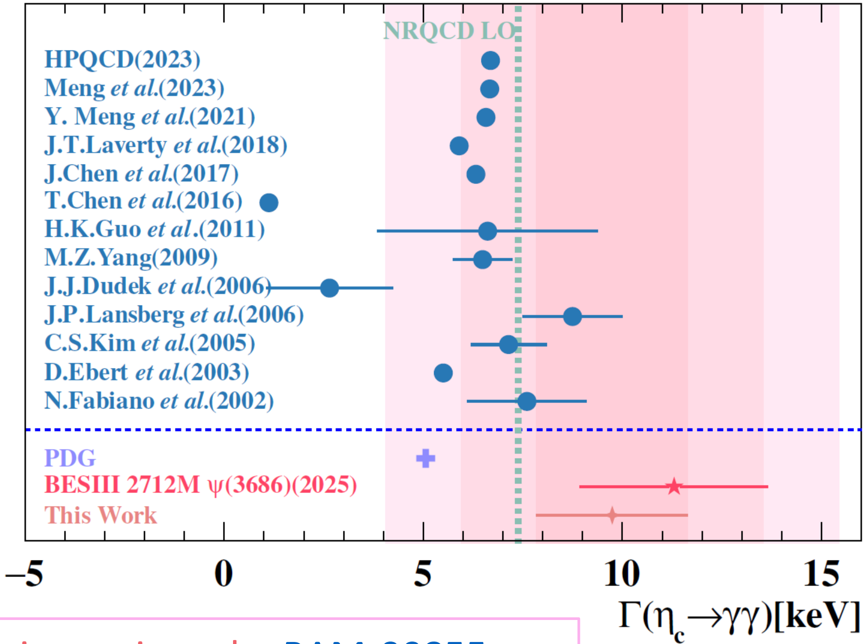
This Work				PDG	
$\Gamma_{h_c} = 0.878 \pm 0.063 \pm 0.023$ MeV				$\Gamma_{h_c} = 0.78 \pm 0.28$ MeV	
$M_{h_c} = 3525.340 \pm 0.025 \pm 0.010$ MeV$/c^2$				$M_{h_c} = 3525.37 \pm 0.14$ MeV$/c^2$	
η_c Decay Channel	χ^2/N_{df}	$N^{sig}_{X_i}$	$\varepsilon^{sig}_{X_i}(\%)$	$\mathcal{B}(\eta_c \to \text{hadronic})[\times 10^{-2}]$ (This work)	$\mathcal{B}(\eta_c \to \text{hadronic})[\times 10^{-2}]$ (PDG)
$\eta_c \to K_S^0 K^\pm \pi^\mp$	1.04	961 ± 33	3.6	$2.13 \pm 0.08 \pm 0.08$	2.4 ± 0.2
$\eta_c \to K^+ K^- \pi^0$	1.23	696 ± 29	5.2	$1.09 \pm 0.05 \pm 0.06$	1.2 ± 0.16
$\eta_c \to K^+ K^- \eta$	0.57	96 ± 11	1.2	$0.63 \pm 0.07 \pm 0.04$	0.68 ± 0.11
$\eta_c \to \pi^+ \pi^- \eta$	0.60	319 ± 22	1.4	$1.80 \pm 0.13 \pm 0.06$	1.7 ± 0.6
$\eta_c \to \pi^+ \pi^- \pi^+ \pi^- \eta$	0.93	325 ± 22	0.8	$3.39 \pm 0.24 \pm 0.24$	4.4 ± 1.6
$\eta_c \to K^+ K^- \pi^+ \pi^- \pi^0$	0.63	707 ± 31	1.7	$3.28 \pm 0.15 \pm 0.21$	3.5 ± 0.6
$\eta_c \to K_S^0 K^\pm \pi^\mp \pi^\pm \pi^\mp$	1.16	415 ± 22	1.5	$2.28 \pm 0.13 \pm 0.12$	2.8 ± 1.3
$\eta_c \to \pi^+ \pi^- \pi^0 \pi^0$	0.57	970 ± 41	3.1	$2.51 \pm 0.11 \pm 0.13$	4.7 ± 1.4
$\eta_c \to \pi^+ \pi^- \pi^+ \pi^- \pi^0 \pi^0$	1.05	1665 ± 55	0.9	$14.27 \pm 0.51 \pm 0.50$	15.8 ± 2.3
$\eta_c \to \pi^+ \pi^- \pi^+ \pi^- \pi^+ \pi^-$	1.10	684 ± 32	3.3	$1.69 \pm 0.08 \pm 0.05$	1.7 ± 0.4
$\eta_c \to K^+ K^- \pi^+ \pi^-$	0.57	503 ± 26	5.0	$0.82 \pm 0.04 \pm 0.03$	0.66 ± 0.11
$\eta_c \to K^+ K^- \pi^+ \pi^- \pi^+ \pi^-$	1.11	168 ± 14	1.6	$0.84 \pm 0.07 \pm 0.06$	0.75 ± 0.24
$\eta_c \to \pi^+ \pi^- \pi^+ \pi^-$	1.13	1088 ± 38	4.6	$1.93 \pm 0.07 \pm 0.05$	0.91 ± 0.12
$\eta_c \to p\bar{p}$	0.88	165 ± 14	9.7	$0.137 \pm 0.012 \pm 0.006$	0.144 ± 0.014
$\eta_c \to p\bar{p}\pi^0$	1.80	144 ± 16	4.3	$0.27 \pm 0.03 \pm 0.02$	0.36 ± 0.15
$\eta_c \to p\bar{p}\pi^+\pi^-$	0.96	305 ± 21	4.5	$0.55 \pm 0.04 \pm 0.03$	0.53 ± 0.21

This analysis is being reviewed：BAM-00855

Branching Fraction of $\eta_c \to \gamma\gamma$

- $\text{Br} = \frac{N^{\text{sig}}_{\gamma\gamma}}{N^{\text{tag}}_{\eta_c}} == (3.04 \pm 0.48_{\text{stat.}} \pm 0.11_{\text{syst.}}) \times 10^{-4}$
- **Taking** $\Gamma_{\eta_c} = (30.5 \pm 0.5)\ \text{MeV}/c^2$, $\Gamma_{\eta_c \to \gamma\gamma} = (9.27 \pm 1.46_{\text{stat.}} \pm 0.34_{\text{syst.}})\ \text{keV}$
- Taking $\Gamma_{J/\psi \to e^+e^-} = (5.53 \pm 0.10)\ \text{keV}$, $R \equiv \frac{\Gamma(J/\psi \to e^+e^-)}{\Gamma(\eta_c \to \gamma\gamma)} = 0.60 \pm 0.10$
- The most precise direct measurement of the branching fraction of $\eta_c \to \gamma\gamma$ so far, consistent with the latest measurement from BESIII using $J/\psi \to \gamma\eta_c$
- No interference effect
- Large deviation from the other measurements from two-photon processes
- Consistent with the latest LQCD calculation (HPQCD 2023) within 2σ





This work is being reviewed: BAM-00855

Upper Limit of the BF of $\eta_c \to \ell^+\ell^-$

- Using inclusive MC sample (Full blind):
  - Events left after selection:

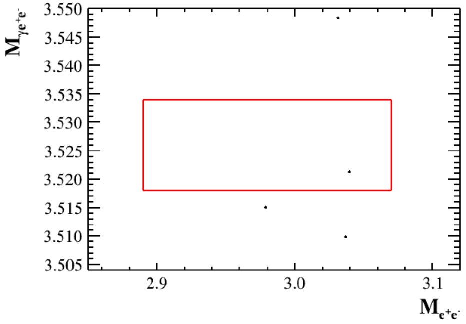
$$\eta_c \to e^+e^-:\ 1$$
$$\eta_c \to \mu^+\mu^-:\ 4$$

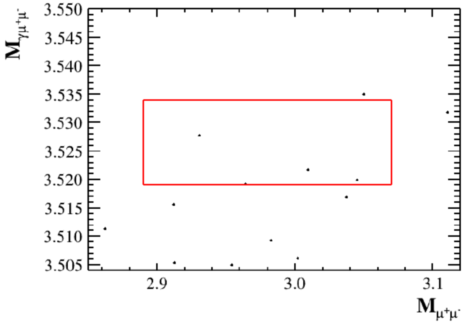
  - Upper limit of the BF:

$$B(\eta_c \to e^+e^-) = \boxed{\frac{N^{\text{sig}}_{e^+e^-}}{N^{\text{tag}}_{\eta_c}} < 2.6\times10^{-5}}$$

$$B(\eta_c \to \mu^+\mu^-) = \boxed{\frac{N^{\text{sig}}_{\mu^+\mu^-}}{N^{\text{tag}}_{\eta_c}} < 4.2\times10^{-5}}$$

4 orders of magnitude from the SM prediction





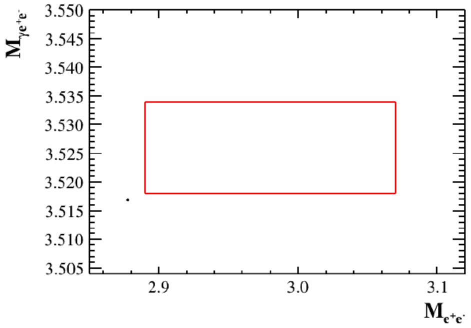
- Using semi-blind sample:
  - Events left after selection:

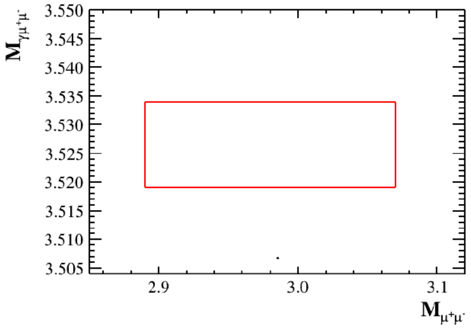
$$\eta_c \to e^+e^-:\ 0$$
$$\eta_c \to \mu^+\mu^-:\ 0$$

  - Upper limit of the BF:

$$B(\eta_c \to e^+e^-) = \frac{N^{\text{sig}}_{e^+e^-}}{N^{\text{tag}}_{\eta_c}} < 1.5\times10^{-4}$$

$$B(\eta_c \to \mu^+\mu^-) = \frac{N^{\text{sig}}_{\mu^+\mu^-}}{N^{\text{tag}}_{\eta_c}} < 1.6\times10^{-4}$$





This work is being reviewed: BAM-00836

03

Study of Hyperon-Nucleon Scattering

Physics Background

Nature 467, 1081-1083 (2010)
Science 340, 6131 (2013)
Phys. Rev. Lett. 121, no.16, 161101 (2018)

Astro observation has discovered large-mass neutron stars

Conflict

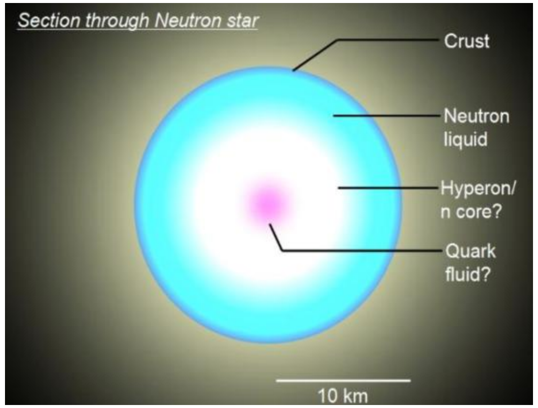
Pauli exclusion principle
Strong interactions between nucleons

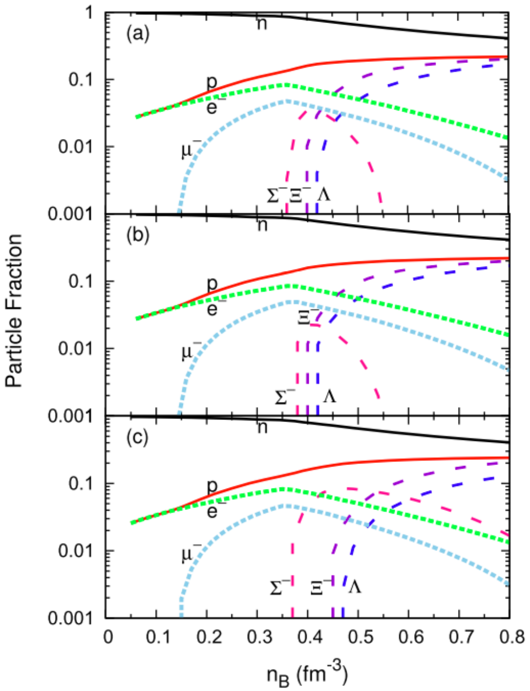
Extremely dense matter inside the neutron star → Number of nucleons in a quantum system increases dramatically → Chemical potential of baryons increases → Hyperons are created from nucleons by weak interaction → Soften equation of state → Unable to support neutron stars whose masses are more than 2 times of solar mass

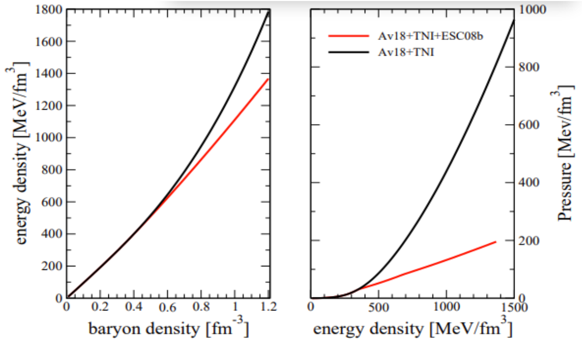
Phys. Lett. B 747 (2015) 43-47

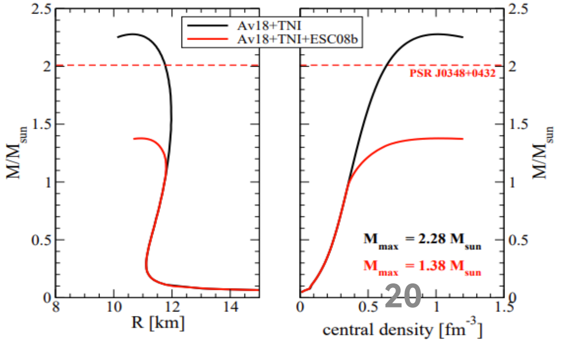
JPS Conf. Proc. 17, 101002 (2017)

Hyperon Puzzle









Physics Background

Key to solve the hyperon puzzle: hyperon-related two-body & three-body interaction

Experiment

- Scattering experiment: Most direct, unable to measure three-body interaction

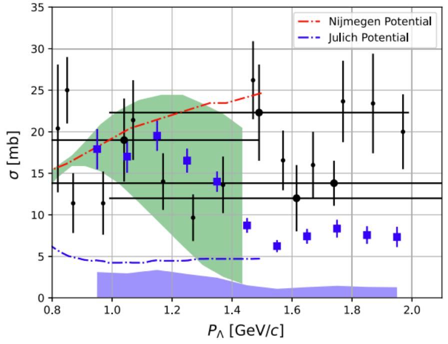
  NN scattering has been measured for many times [Ann. Rev. Nucl. Part. Sci. 10, 291-352 (1960)]

  YN scattering results are scarce and most are old

  YY scattering has little results

- Bound state (Hyper nucleus)
- Correlation function

Indirect measurem ent



Theory

- NN scattering theory is mature
- YN scattering has multiple models to describe, lacking experimental constraint

  Jülich or Nijmegen meson exchange model [Phys. Rev. C 72, 044005 (2005), Prog. Theor. Phys. Suppl. 185, 14-71 (2010)]

  Chiral effective field theory [Nucl. Phys. A 779, 244-266 (2006)]

  Low-momentum model [Phys. Rev. C 73, 011001 (2006)]

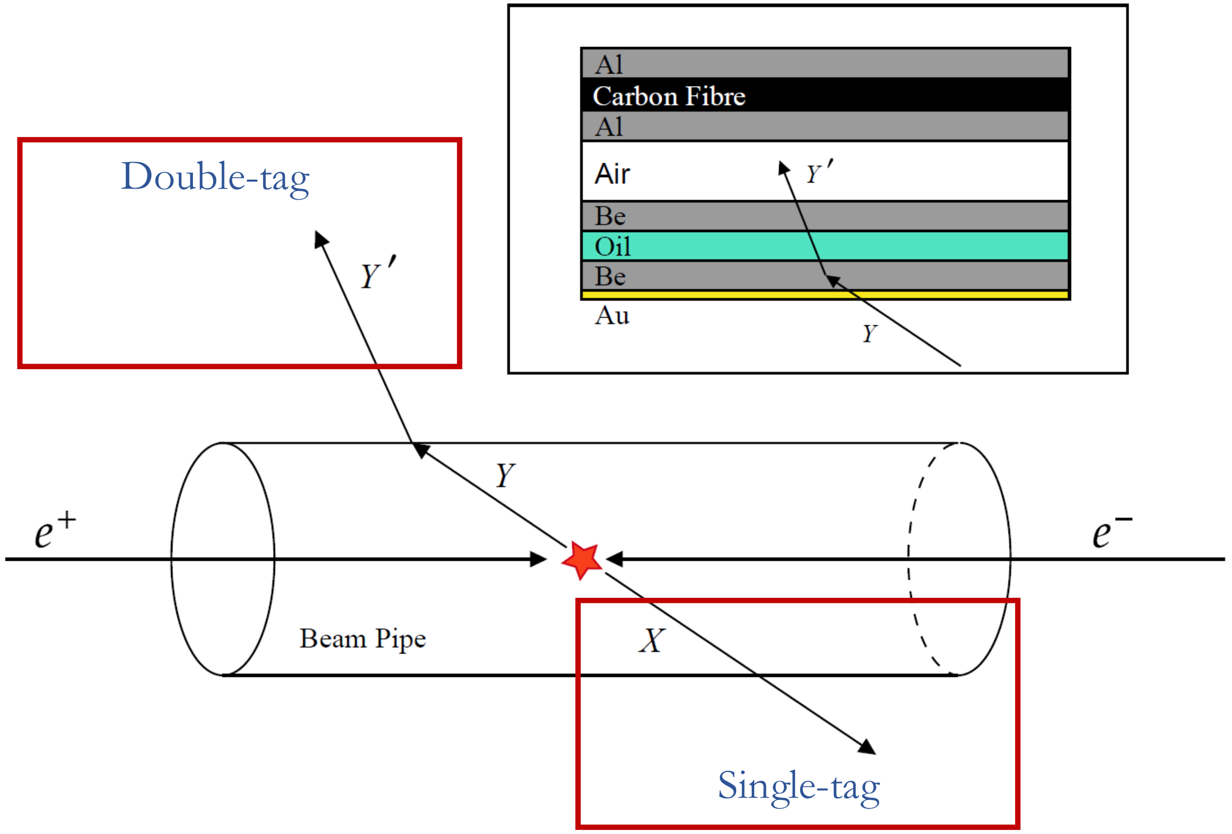
  Methods based on quark model [Prog. Part. Nucl. Phys. 58, 439-520 (2007)]

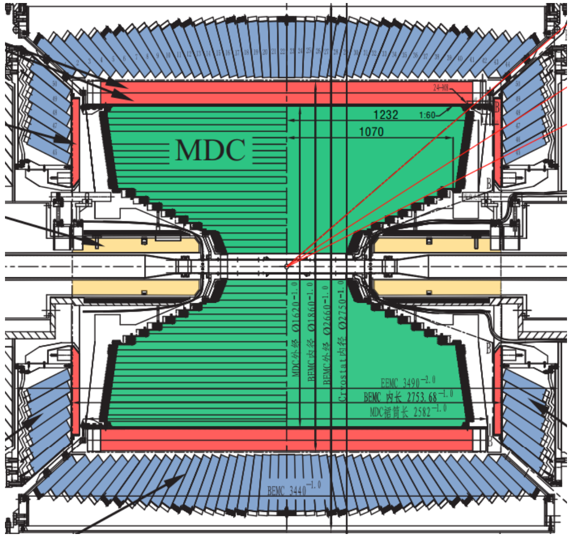
  ……

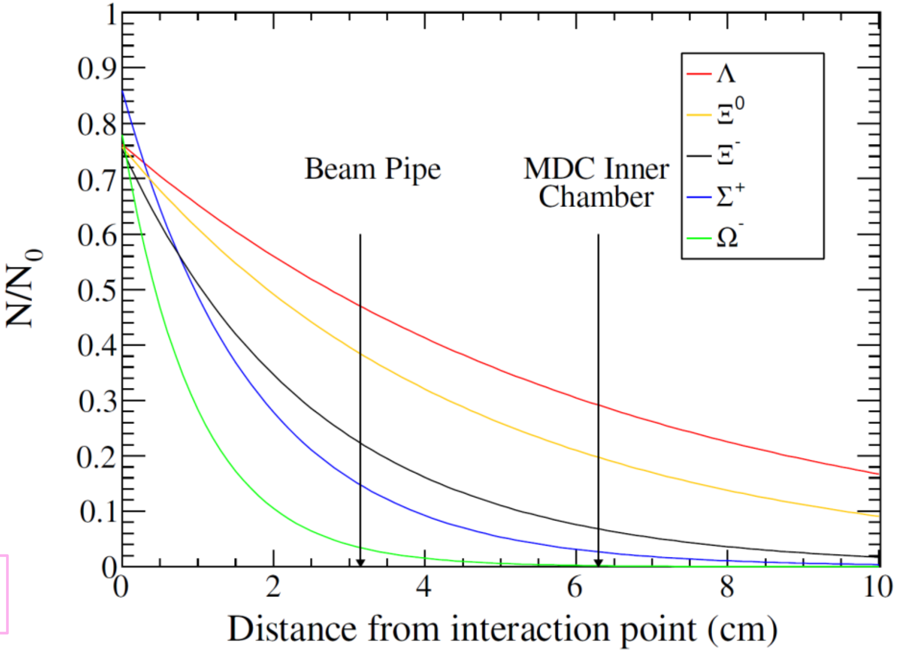
- Theory is not complete for YY and three-body scattering [Phys. Rev. C 62, 035801 (2000), Eur. Phys. J. A 56, no.6, 175 (2020)]

More experimental measurements of YN, YY scattering are needed

Analysis Method







Published at CPC： Chin. Phys. C 48, no.7, 073003 (2024)

Analysis Method

$$J/\psi,\ \psi(2S) \rightarrow \begin{cases} pK^-\bar{\Lambda} \\ \Lambda\bar{\Lambda} \\ \Sigma^+\bar{\Sigma}^- \\ \Xi^-\bar{\Xi}^+ \\ \Omega^-\bar{\Omega}^+ \end{cases} \Rightarrow$$

$$\Lambda + p \rightarrow \begin{cases} \boxed{\Sigma^+ n} \\ K^+\Lambda\Lambda \\ K^+\Xi^- p \end{cases}$$

This work

$$\Lambda + n \rightarrow \Sigma^- p$$

$$\Sigma^- + p \rightarrow \Sigma^0 n,\ \Lambda n$$

$$\Sigma^+ + n \rightarrow \Sigma^0 p,\ \Lambda p$$

$$\Xi^- + p \rightarrow \Xi^0 n,\ \Lambda\Lambda$$

$$\Xi^0 + n \rightarrow \Lambda\Lambda$$

Hyperon beam

Possible inelastic scattering

Analysis Method

Using $(10087 \pm 44) \times 10^6\ J/\psi$ events @ $\sqrt{s} = 3.097$ GeV

Double-tag yield:

$$N_{\rm DT} = \mathcal{L}_Y \cdot \sigma(YA \to Y'A') \cdot \mathcal{B}(Y') \cdot \varepsilon_{\rm sig}$$

Luminosity of Λ beam:

Average track length in material

$$\mathcal{L}_Y = \boxed{\sum_j^7} \mathcal{L}_Y^j = N_{\rm ST} \cdot \boxed{N_A \cdot \sum_j^7 \frac{\rho_T^j}{M^j}} \cdot \boxed{l^j} \cdot \boxed{\mathcal{R}_\sigma^j}$$

Ratio of the cross sections with different target material

Sum of the contributions of all the layers

Cross section:

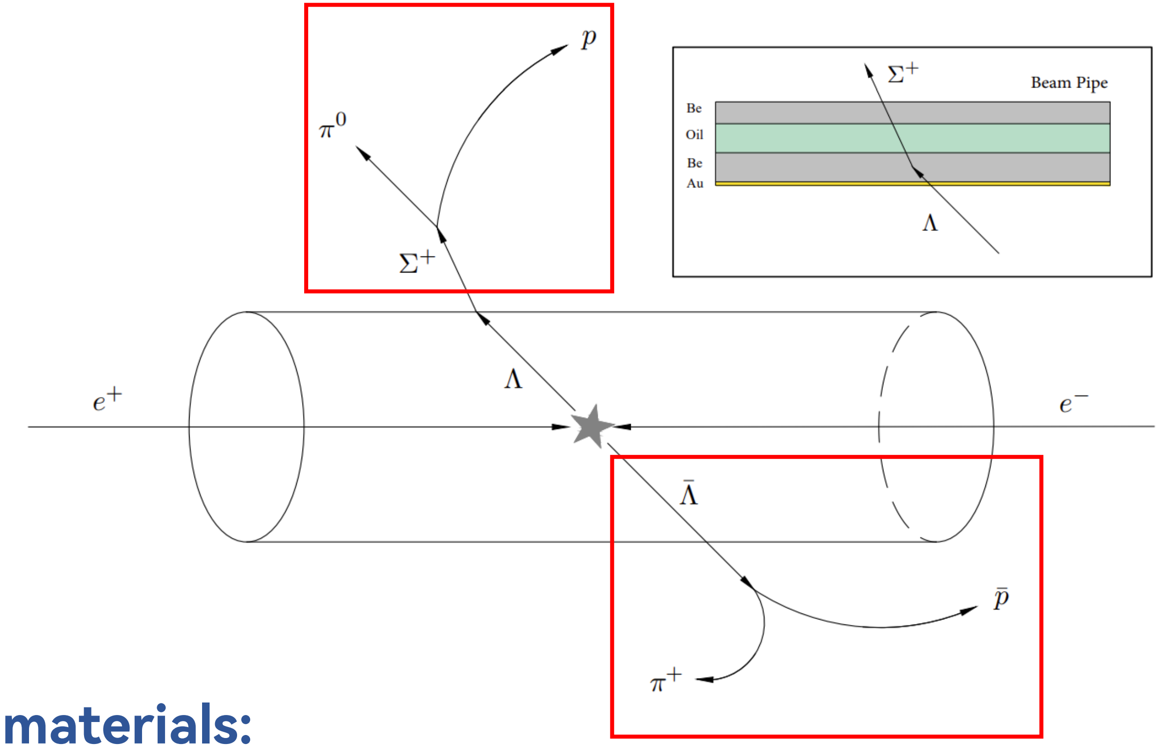
$$\sigma(YA \to Y'A') = \frac{N_{\rm DT}}{\varepsilon_{\rm sig} \cdot \mathcal{L}_Y} \cdot \frac{1}{\mathcal{B}(Y')}$$

Ratio of the cross section with different materials:

Assum surface reaction→proportional to the proton number in the nucleus surface

$$\mathcal{R}_\sigma \propto N_{\rm eff} = A^{\frac{2}{3}} \times \frac{N}{A} = \frac{N}{A^{\frac{1}{3}}}$$

Double-tag

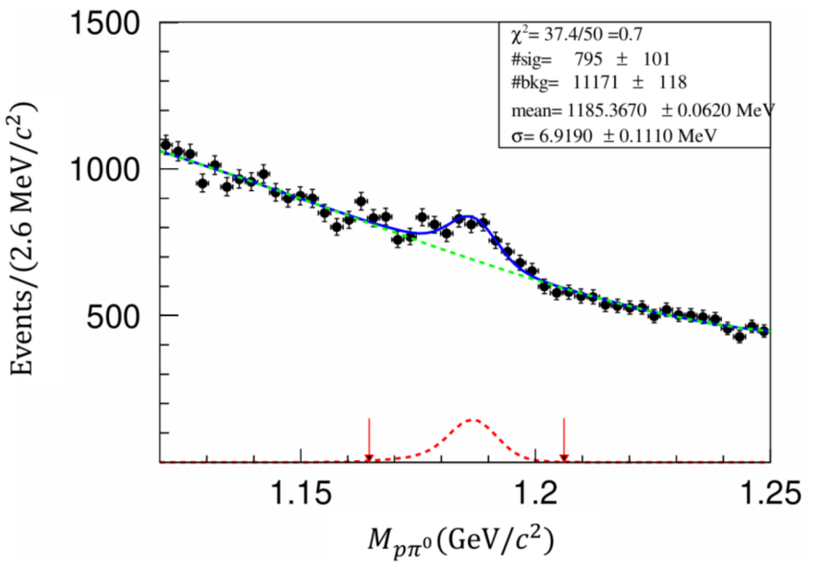


Single-tag

Cross Section of $\Lambda p \rightarrow \Sigma^+ n$

Published at PRC： Phys. Rev. C 109 (2024) 5, L052201

- **Fit $M_{p\pi^0}$ spectrum to obtain the yield**
- $N_{\mathrm{DT}} = 795 \pm 101$
- $\varepsilon_{\mathrm{sig}} = 24.32\%$



- **Calculation of effective luminosity**

$$\mathcal{L}_Y = \sum_j^7 \mathcal{L}_Y^j = N_{\mathrm{ST}} \cdot N_A \cdot \sum_j^7 \frac{\rho_T^j \cdot l^j}{M^j} \cdot \mathcal{R}_\sigma^j$$

$$l^j = \frac{\sum_i^{N_{\mathrm{ST}}^{\mathrm{MC}}} l^{ij}}{N_{\mathrm{ST}}^{\mathrm{MC}}}$$

$$\mathcal{L}_Y = N_{\mathrm{ST}} \cdot \frac{N_A}{N_{\mathrm{ST}}^{\mathrm{MC}}} \cdot \sum_j^7 \sum_i^{N_{\mathrm{ST}}^{\mathrm{MC}}} \frac{\rho_T^j \cdot l^{ij}}{M^j} \cdot \mathcal{R}_\sigma^j$$

$$\boxed{\mathcal{L}_\Lambda / N_{\mathrm{ST}} = 23.59 \times 10^{21}\ \mathrm{cm}^{-2}}$$

- **Total cross section**

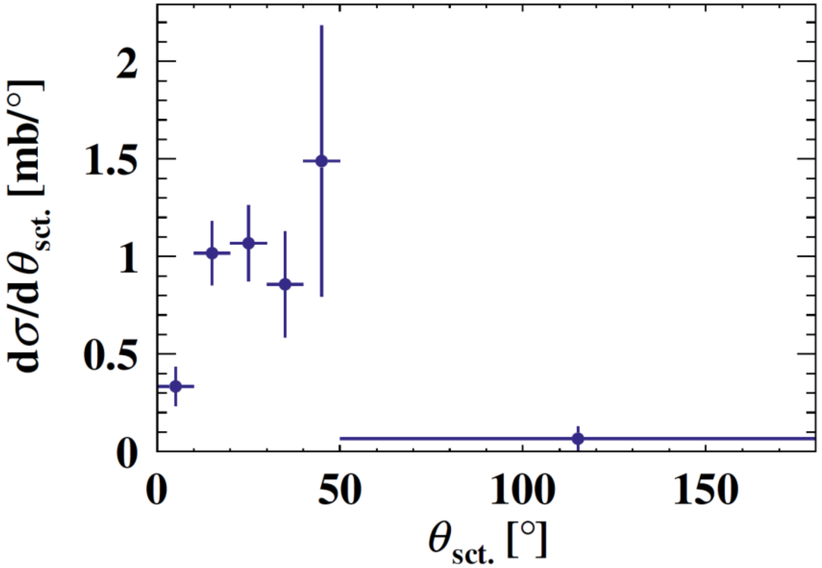
Parameters	Value
N_{ST}	7207565 ± 3741
N_{DT}	795 ± 101
$\varepsilon_{\mathrm{sig}}$	24.32%
$\mathcal{L}_\Lambda / N_{\mathrm{ST}}$	$23.59 \pm 10^{21}\ \mathrm{cm}^{-2}$
$\mathcal{B}(\Sigma^+ \rightarrow p\pi^0)$	$(51.57 \pm 0.30)\%$
$\sigma(\Lambda + {}^9\mathrm{Be} \rightarrow \Sigma^+ + X)$	$(37.3 \pm 4.7_{\mathrm{stat.}} \pm 3.5_{\mathrm{syst.}})$ mb

Differential Cross Section

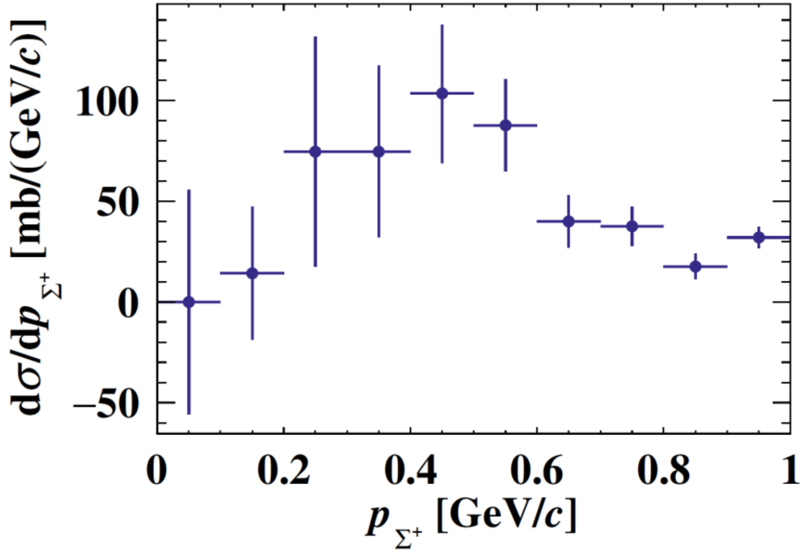
- Calculation method

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = \frac{M}{N_A \cdot \rho_T \cdot l} \cdot \frac{N_{\mathrm{DT}}(x)}{\varepsilon_{\mathrm{sig}}(x) \cdot N_{\mathrm{ST}} \cdot \mathrm{d}x} \cdot \frac{1}{\mathcal{B}(\Sigma^+ \to p\pi^0)}$$

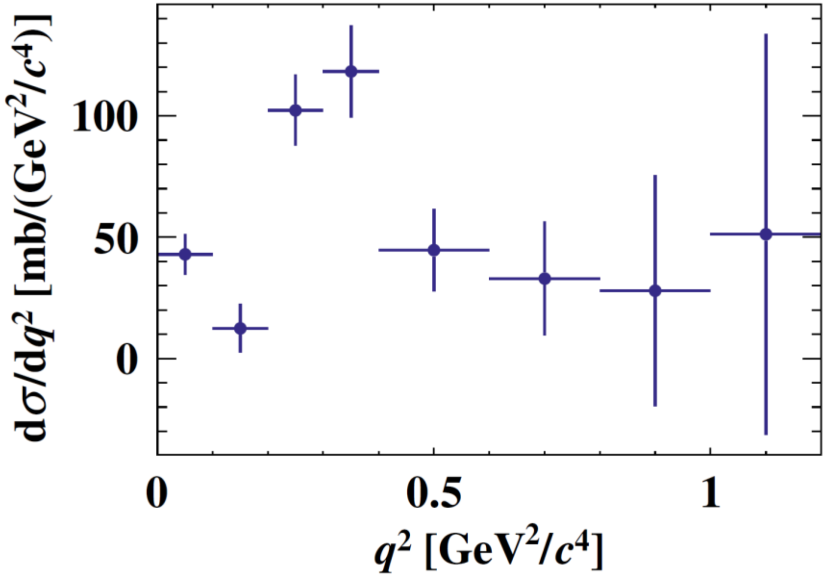
- $\theta_{sct.}$-dependent ($\theta_{sct.}$ is the angle between the momentum of incident Λ and the Σ^+)



- p_{Σ^+}-dependent (p_{Σ^+} is the momentum of Σ^+)



- q^2-dependent ($q^2 = (p_\Lambda - p_{\Sigma^+})^2$)



Prospect at STCF

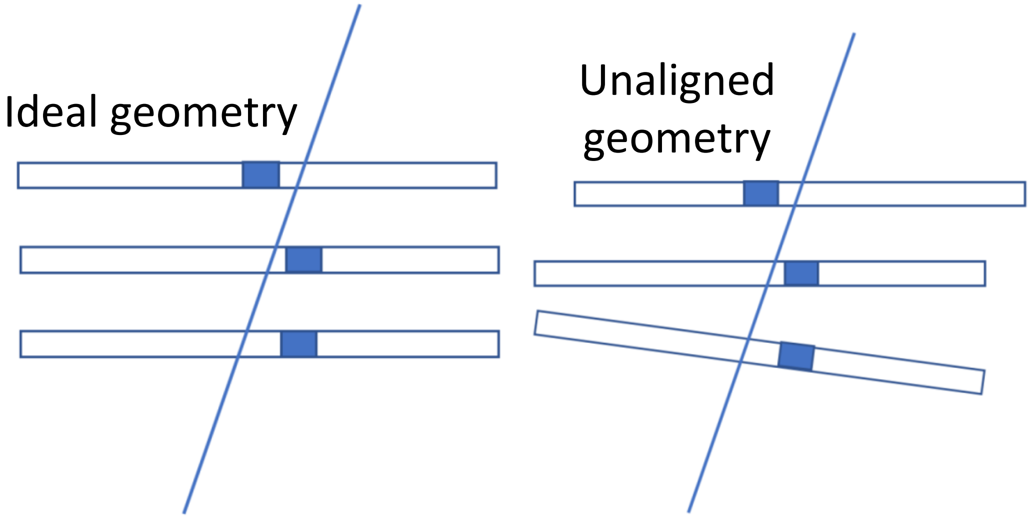
超子	$c\tau$ (cm)	衰变道	$\mathcal{B}_{\text{decay}}$ ($\times 10^{-3}$)	p_{max} (MeV/c)	n_{BP}^{Y} (BESIII: $\times 10^{5}$; STCF: $\times 10^{8}$)	$\mathcal{B}_{\text{tag}}$ (%)	$\mathcal{L}_Y/N_{\text{ST}}$($10^{21}\cdot \text{cm}^{-2}$)	预期事例数 (STCF情况下$\times 10^{3}$)
$\boldsymbol{\Lambda}$	7.89	$J/\psi \to \Lambda\bar{\Lambda}$	1.89 ± 0.09	1074	26	64	23.59	5290
$\boldsymbol{\Sigma^{+}}$	2.40	$J/\psi \to \Sigma^{+}\bar{\Sigma}^{-}$	1.07 ± 0.04	992	4	52	4.83	537
$\boldsymbol{\Xi^{0}}$	8.71	$J/\psi \to \Xi^{0}\bar{\Xi}^{0}$	1.17 ± 0.04	818	7	64	15.81	2368
$\boldsymbol{\Xi^{-}}$	4.91	$J/\psi \to \Xi^{-}\bar{\Xi}^{+}$	0.97 ± 0.08	807	3	64	7.44	924
$\boldsymbol{\Omega^{-}}$	2.46	$\psi(3686) \to \Omega^{-}\bar{\Omega}^{+}$	0.056 ± 0.003	774	0.05	43	2.61	3

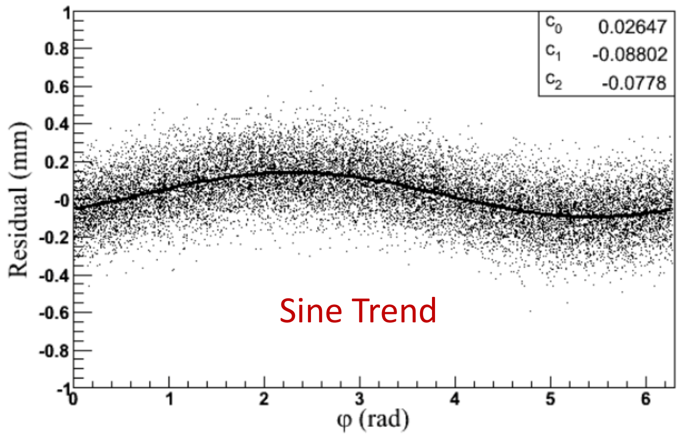
04

Development of the Joint Alignment Algorithm for BESIII Tracking System

Using fit residual to align: insufficient precision

Research Background





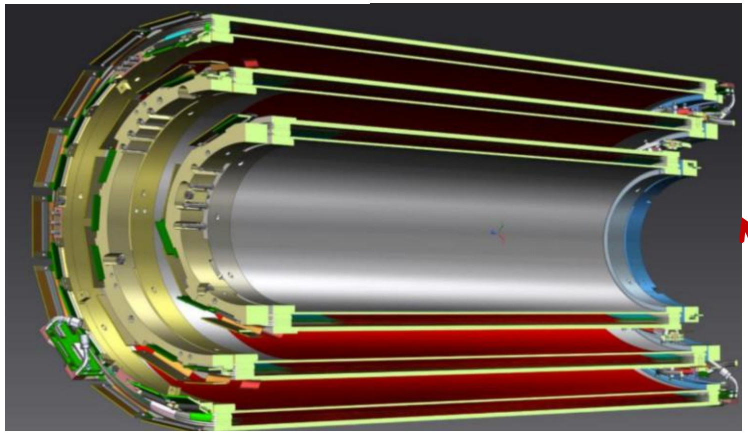
Fit residual with respect to ϕ in the case of transverse translation

MDC measurement: drift distance

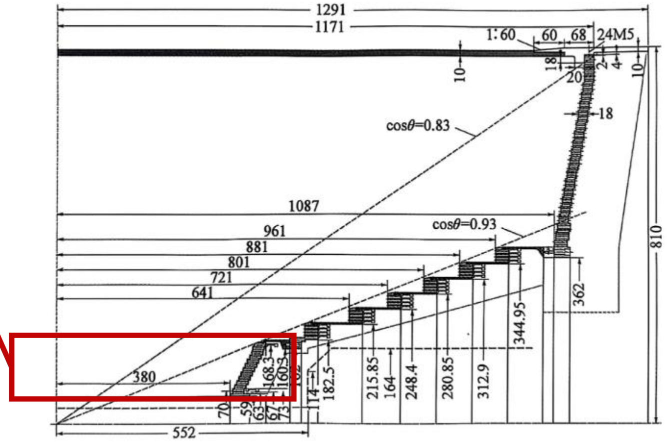
CGEM measurement： readout from x and v strip

difficulty

The derivatives of the measurements over the fit parameters cannot be solved analytically



CGEM



MDC

Nucl. Instrum. Meth. A 824, 515-517 (2016)
PoS EPS-HEP2021, 766 (2022)

Alignment Method: Millepede II

arXiv: hep-ex/0208021 [hep-ex]
Nucl. Instrum. Meth. A 566, 5-13 (2006)

$$y = f(\mathbf{x}; \mathbf{a})$$

$$r_i = y_i - f(\mathbf{x}_i; \mathbf{a}_\ell) \cong \mathbf{d}_i^{\mathrm{T}} \Delta\mathbf{a}$$

$$\mathbf{C} = \sum_{i=1}^{m} w_i \mathbf{d}_i \mathbf{d}_i^{\mathrm{T}}$$

$$\mathbf{b} = \sum_{i=1}^{m} w_i r_i \mathbf{d}_i$$

$$\mathbf{C}\Delta\mathbf{a} = \mathbf{b}$$

Decide the parameter equation of tracks → Express the measurements in the one-order linear approximation → Express the residual → Minimum the weighted residual sum of squares → Solve the normal equation

$$y_i \cong f(\mathbf{x}_i; \mathbf{a}_\ell) + \sum_{j=1}^{n} d_j \Delta a_j$$

$$d_j = \left.\frac{\partial f(\mathbf{x})}{\partial a_j}\right|_{\mathbf{x}=\mathbf{x}_i}$$

$$S = \sum_{i=1}^{m} \boxed{w_i} r_i^2$$

$$\boxed{w_i = \frac{1}{\sigma_i^2}}$$

Alignment parameters: global parameters

$$y_i \cong f(\mathbf{x}_i; \boxed{\mathbf{a}^{\mathrm{global}}}, \boxed{\mathbf{a}^{\mathrm{local}}}) + (\mathbf{d}_i^{\mathrm{global}})^{\mathrm{T}} \Delta\mathbf{a}^{\mathrm{global}} + (\mathbf{d}_i^{\mathrm{local}})^{\mathrm{T}} \mathbf{a}^{\mathrm{local}}$$

Track parameters: local parameters

Simultaneously fit the alignment parameters using all tracks

Alignment Method

Special structure

$$\left(\begin{array}{c||c|c|c}\sum_{k=1}^{\nu}\mathbf{C}_k^{\mathrm{global}} & \cdots & \mathbf{H}_k & \cdots \\ \hline\hline \vdots & \ddots & 0 & 0 \\ \hline \mathbf{H}_k^{\mathrm{T}} & 0 & \mathbf{C}_k^{\mathrm{local}} & 0 \\ \hline \vdots & 0 & 0 & \ddots \end{array}\right) \times \left(\begin{array}{c}\Delta\mathbf{a}^{\mathrm{global}} \\ \hline\hline \vdots \\ \hline \Delta\mathbf{a}_k^{\mathrm{local}} \\ \hline \vdots\end{array}\right) = \left(\begin{array}{c}\sum_{k=1}^{\nu}\mathbf{b}_k^{\mathrm{global}} \\ \hline\hline \vdots \\ \hline \mathbf{b}_k^{\mathrm{local}} \\ \hline \vdots\end{array}\right)$$

$$\mathbf{C} = \left(\begin{array}{c|c}\mathbf{C}_{11} & \mathbf{C}_{12} \\ \hline \mathbf{C}_{21} & \mathbf{C}_{22}\end{array}\right) \quad \xleftrightarrow[\mathbf{CB}=\mathbf{1}]{\mathbf{B}\equiv\mathbf{C}^{-1}} \quad \mathbf{B} = \left(\begin{array}{c|c}\mathbf{B}_{11} & \mathbf{B}_{12} \\ \hline \mathbf{B}_{21} & \mathbf{B}_{22}\end{array}\right)$$

$$\left(\begin{array}{c}\Delta\mathbf{a}_1 \\ \hline \Delta\mathbf{a}_2\end{array}\right) = \left(\begin{array}{c|c}\mathbf{B}_{11} & \mathbf{B}_{12} \\ \hline \mathbf{B}_{21} & \mathbf{B}_{22}\end{array}\right) \times \left(\begin{array}{c}\mathbf{b}_1 \\ \hline \mathbf{b}_2\end{array}\right)$$

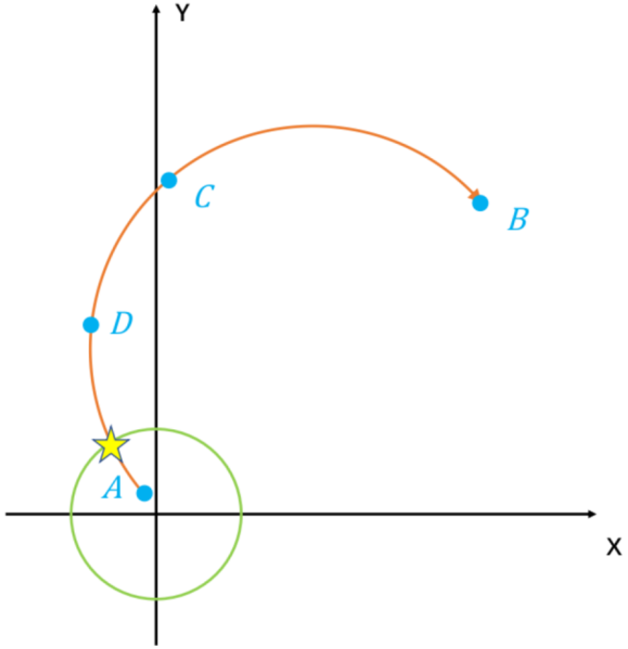
$$\mathbf{B}_{11} = (\mathbf{C}_{11} - \mathbf{C}_{12}\mathbf{C}_{22}^{-1}\mathbf{C}_{21})^{-1}$$
$$\mathbf{B}_{12} = -\mathbf{B}_{11}\mathbf{C}_{12}\mathbf{C}_{22}^{-1}$$
$$\mathbf{B}_{21} = -\mathbf{C}_{22}^{-1}\mathbf{C}_{21}\mathbf{B}_{11}$$
$$\mathbf{B}_{22} = \mathbf{C}_{22}^{-1} + \mathbf{C}_{22}^{-1}\mathbf{C}_{21}\mathbf{B}_{11}\mathbf{C}_{12}\mathbf{C}_{22}^{-1}$$

$$\Delta\mathbf{a}^{\mathrm{global}} = (\mathbf{C}')^{-1}\mathbf{b}$$
$$\mathbf{C}' = \sum_{k=1}^{\nu}\mathbf{C}_k^{\mathrm{global}} - \sum_{k=1}^{\nu}\mathbf{H}_k\mathbf{C}_k^{\mathrm{local}}\mathbf{H}_k^{\mathrm{T}}$$
$$\mathbf{b}' = \sum_{k=1}^{\nu}\mathbf{b}_k^{\mathrm{global}} - \sum_{k=1}^{\nu}\mathbf{H}_k((\mathbf{C}_k^{\mathrm{local}})^{-1}\mathbf{b}_k^{\mathrm{local}})$$

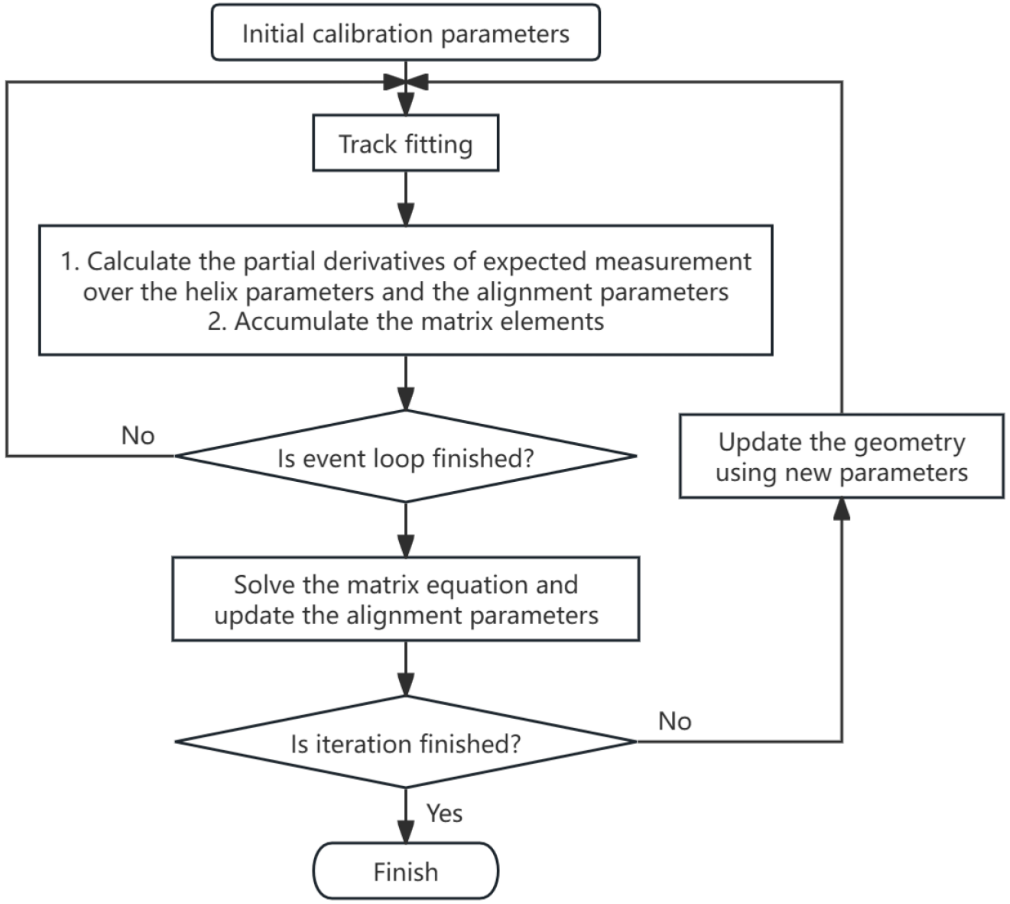
Solving the global parameters without solving local parameters

Algorithm Development

- Solving the intersection between the helix and unaligned detector by numerical method
- Construct spline function, solving the derivative of measurements over the global and local parameters
- Algorithm development has been finished; verification is being processed



Algorithm flow:



05 Summary

Summary

EM transition $\psi(3686) \to \eta_c$

- Discover $\psi(3686) \to e^+e^-\eta_c$ and measure the BF
- Measure the BF of $\psi(3686) \to \gamma\eta_c$ and $\psi(3686) \to e^+e^-\eta_c$ with considering the interference for the first time, reaching the best precision so far
- Measured the TFF of $\psi(3686) \to e^+e^-\eta_c$ for the first time, not completely consistent with VMD

Study of η_c decay

- Measured the BF of 16 channels of η_c decays with the best precision and obtained the mass and width of h_c
- Measured the absolute branching fraction of $\eta_c \to \gamma\gamma$ for the first time, reaching the best precision
- Set the upper limit of the BF of $\eta_c \to l^+l^-$ for the first time

Study of hyperon-nucleon scattering

- Provide the novel method to measure the hyperon-nucleon scattering at positron-electron colliders
- Measured the cross section of $\Lambda + {}^9\mathrm{Be} \to \Sigma^+ + \mathrm{X}$ for the first time at BESIII
- Obtained the differential cross section for the first time
- The differential cross section, the momentum-dependent and spin-dependent cross section can be studied further at STCF

Development of the joint alignment algorithm for BESIII tracking system

- Developed the joint alignment algorithm for CGEM and MDC
- Calculate the intersection between helix and unaligned geometry, and the derivative of the intersection over track parameters and the alignment parameters
- Realize the unaligned CGEM in the simulation
- Further validation is needed

Thank you !