ϕ and J/ψ Production in Proton-Proton Scattering

Based on ArXiv: 2511.08095

Di Ben

In collaborate with: Bing-Song Zou

Department of Physics and Center for High Energy Physics
Tsinghua University

Nov. 30, 2025 at HHaS

Contents

HIAF

	加速器	磁钢度(Tm)	典型粒子	能量(GeV/u)	束流强度	
HIAF	BRing-N	34	$^{238}U^{35+}$	0.80	$1\text{-}2\times10^{11}$ ppp	常温 booster
			$^{238}U^{76+}$	2.45	$0.5\text{-}1\times10^{11}$ ppp	
			p	9.30	5×10^{13} ppp	
	SRing	15	$^{238}U^{92+}$	1.10	$1\text{-}5\times10^{11}$ ppp	常温储存环 实验谱仪
CiADS	CiADS-I	-	p	0.50	5 mA	CW

Zhi-Yu Sun, Report of CNUF, 2023.

HIAF-U

	加速器	磁钢度(Tm)	典型粒子	能量(GeV/u)	束流强度	
HIAF-U	BRing-S	86	$^{238}U^{35+}$	2.95	2×10^{12} ppp	超导 booster
			$^{238}U^{76+}$	7.30	1×10^{12} ppp	
			$^{238}U^{92+}$	9.10	1×10^{12} ppp	
			p	25.0	4×10^{14} ppp	
	MRing	45	$^{238}U^{92+}$	4.40	2×10^{12} ppp	交叉/并束碰撞
EicC	eRing	16.7	e	50.0	4.5×10^{13} ppp	80%极化
	pRing	86	p	25.0	4.0×10^{14} ppp	70%极化
ISOL	CiADS-II	-	p	2.00	5-10 mA	CW

Zhi-Yu Sun, Report of CNUF (2023).

$$E_{beam} = 9.3\text{ GeV} \quad\rightarrow\quad \sqrt{s} \sim 4.4\text{ GeV}, \quad pp\phi \text{ threshold} \sim 2.9\text{ GeV}.$$

$$E_{beam} = 25.\text{ GeV} \quad\rightarrow\quad \sqrt{s} \sim 7.0\text{ GeV}, \quad ppJ/\psi \text{ threshold} \sim 5.0\text{ GeV}.$$

Proton-Proton Scattering

Tsinghua University

Nucleon Excitations

Near threshold experiments of $pp \rightarrow pp\phi$, $pp \rightarrow pK\Lambda$, $pp \rightarrow pK\Sigma$ ……

$s\bar{s}$ **pair** excited

- $R_{\phi/\omega} \sim 8 \times R_{OZI}$ M. Hartmann et al., PRL 97 (2006)
- Internally in nucleon

Introduce $N^*(1535)$ in $pp \rightarrow pp\phi$ to explain the experimental data near threshold.

Ju-Jun Xie et al., PRC 77 (2008).

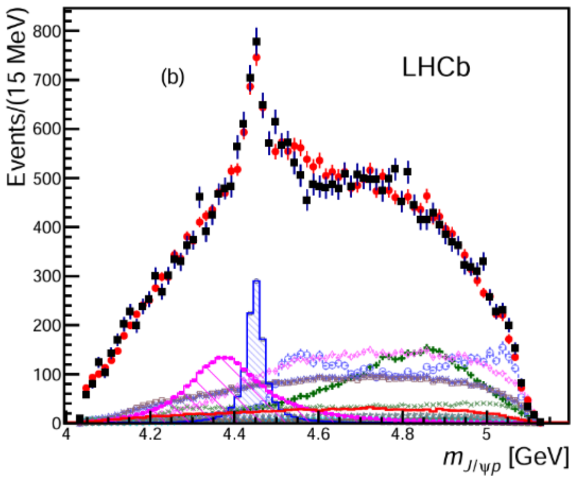
For J/ψ case, $c\bar{c}$ pair needed.

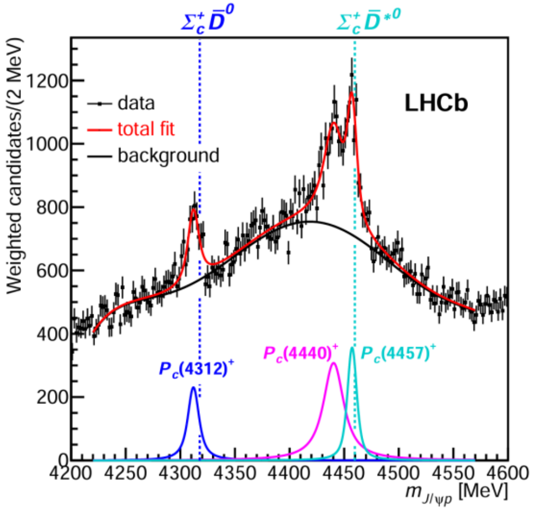
Hadronic Molecular States

LHCb: P_c states

R. Aaij et al. (LHCb Collaboration), PRL 115 (2015).

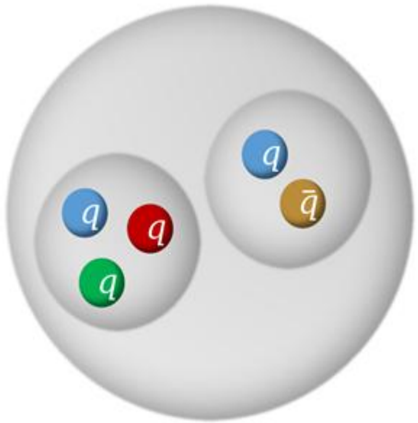
R. Aaij et al. (LHCb Collaboration), PRL 122 (2019).





In hadronic molecular picture: $\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$ including $c\bar{c}$ pair.

Jia-Jun Wu et al., PRL 105 (2010), Meng-Lin Du et al., PRL 124 (2020).



Analogous $c\bar{c}$ to $s\bar{s}$ pair: $K\Sigma^*$, $K^*\Sigma$. Jun He, PRD 95 (2017).

Nucleon excitations naturally contains a pair of $s\bar{s}$ ($N_{s\bar{s}}$ or P_s) or $c\bar{c}$ (P_c).

Aim

Can be observed? → Production cross section

Where to observe? → Distribution of the final state particles

What to observe? → Polarization Observables

For $pp \to pp\phi$:

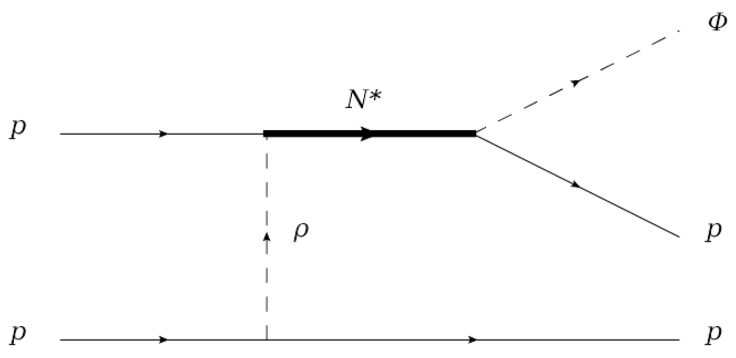
Threshold ~ 2.9 GeV, involving $N_{s\bar{s}}$ (P_s) states.

$E_{beam} = 9.3$ GeV → $\sqrt{s}$ ~ 4.4 GeV → ~1.5 GeV above.

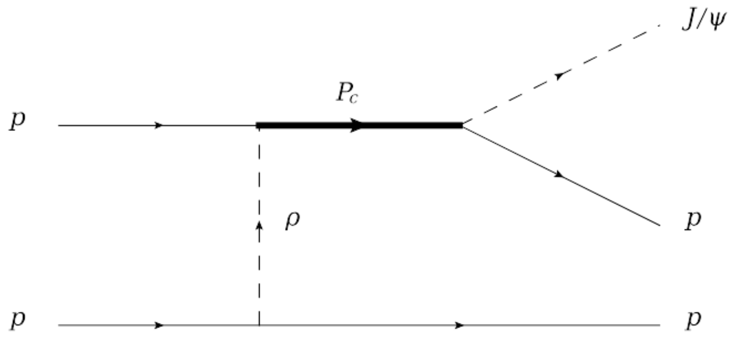
For $pp \to ppJ/\psi$:

Threshold ~ 5.0 GeV, involving P_c states.

$E_{beam} = 25.$ GeV → $\sqrt{s}$ ~ 7.0 GeV → ~2.0 GeV above.



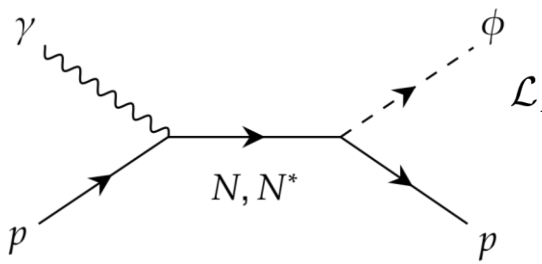
(a) ϕ production



(b) J/ψ production

Contents

Photoproduction: $\gamma p \to p\phi$



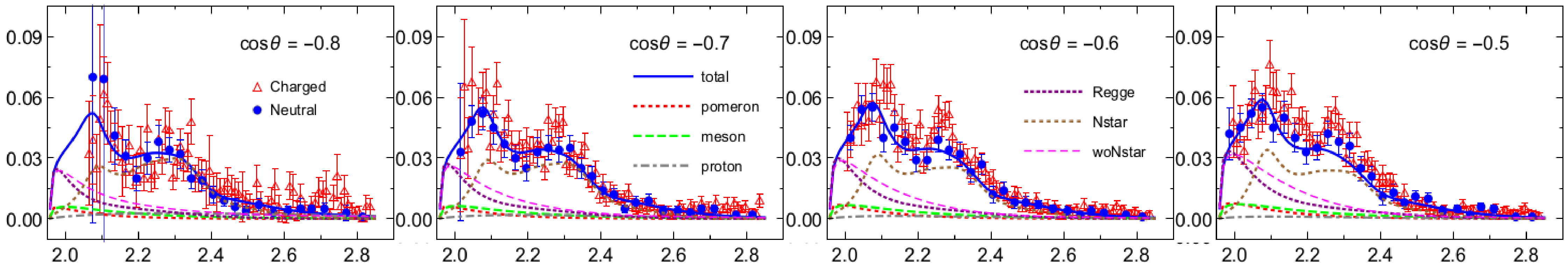
$$\mathcal{L}_{RNV}(\tfrac{3}{2}^{\pm}) = \bar{R}_\mu \left[\frac{ig_1}{2M_N}\Gamma_\nu^{(\pm)} N \pm \frac{g_2}{(2M_N)^2}\Gamma^{(\pm)}\partial_\nu N \mp \frac{g_3}{(2M_N)^2}\Gamma^{(\pm)} N \partial_\nu \right] V^{\mu\nu},$$

other constants			
g_σ	0.540 ± 0.029	$\Gamma_{N_2^*}$ (GeV)	0.23 ± 0.04
g_{f_1}	0.86 ± 0.17	g_1'	2.5 ± 0.5
g_{f_2}	0.25 ± 0.04	g_2'	-2.0 ± 0.6
$\Gamma_{N_1^*}$ (GeV)	0.099 ± 0.011	g_3'	2.5 ± 0.6
g_1	0.0395 ± 0.0024	h_2'	-0.90 ± 0.05
g_2	0.095 ± 0.007		
g_3	0.1937 ± 0.0034		
h_2	-9.5 ± 0.5		

$\gamma p \to p\phi$: Shu-Ming Wu et al., PRC 108 (2023)

$N_{s\bar{s}}$ (P_s) states: $N^*(2080)3/2^-$ and $N^*(2270)3/2^-$

Ratios of coupling constants and **total width** can be extracted.



Decay Behaviors of $N_{s\bar{s}}$ (P_s)

Tsinghua University

Ratios of couplings

$+$

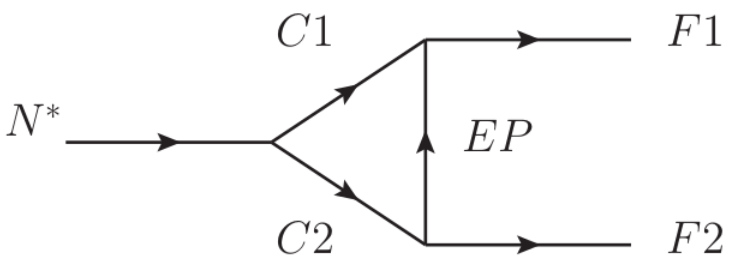
Total width

$+$

Decay Ratios

$\downarrow$

Determined couplings



$N(2270)$ as $K^*\Sigma^*$ molecule $\rightarrow$

Mode	Widths (MeV) $J^P = 3/2^-$		$J^P = 1/2^-$
	$N(1875)$ $K\Sigma^*$	$N(2080)$ $K^*\Sigma$	$N(2080)$ $K^*\Sigma$
$N\sigma(500)$	2.6	0.05	0.3
πN	2.8	0.2	22.7
ρN	2.3	3.8	6.1
ωp	[illegible]	[illegible]	18.2
$K\Sigma$	0.03	1.4	9.1
$K\Lambda$	0.7	3.7	19.3
ηp	0.6	0.4	1.8
$\pi\Delta$	201.4	82.6	46.9
$K^*\Lambda$	-	2.4	7.9
ϕp	-	19.2	27.0
$K^*\Sigma$	-	[illegible]	[illegible]
$K\Lambda(1520)$	-	0.1	1.3
$K\Lambda(1405)$	-	8.0	8.8
$K\pi\Lambda$	10.1	-	-
$K\pi\Sigma$	-	41.3	46.1
Total	228.2	181.7	216.8

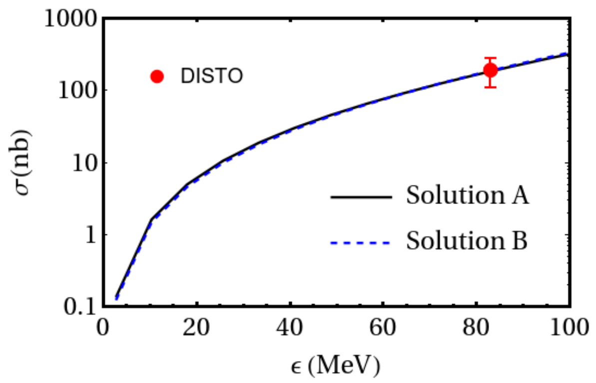
Yong-Hui Lin et al., NPA 980 (2018)

FS	Γ(MeV)			Γ_i/Γ(%)		
(J^P)	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^-$	$3/2^-$	$5/2^-$
$K\Sigma$	29.35	6.67	2.02	11.85	1.82	2.56
$K\Lambda$	93.60	25.15	13.37	37.80	6.88	16.95
$K\Sigma^*$	9.90	45.67	13.42	4.00	12.50	17.02
$K^*\Sigma$	2.13	14.32	1.74	0.86	3.91	2.21
$K^*\Lambda$	24.68	194.66	18.94	9.97	53.26	24.01

FS	Γ(MeV)			Γ_i/Γ(%)		
(J^P)	$1/2^-$	$3/2^-$	$5/2^-$	$1/2^-$	$3/2^-$	$5/2^-$
πN	16.98	2.35	1.55	6.86	0.64	1.97
$\pi\Delta$	10.93	40.32	12.69	4.41	11.03	16.08
ηN	2.51	2.24	3.10	1.01	0.61	3.93
ρN	23.06	11.08	3.46	9.31	3.03	4.38
ωN	7.25	4.51	1.68	2.93	1.23	2.13
ϕN	26.94	18.49	6.90	10.88	5.06	8.74

Di Ben et al., PRC 112 (2025)

Near Threshold: DISTO



$$S_{3/2}(q) = \frac{i}{\not{q} - M_R + i\Gamma_R/2}\left(\tilde{g}_{\mu\nu} + \frac{1}{3}\tilde{\gamma}_\mu\tilde{\gamma}_\nu\right) \quad \tilde{g}_{\mu\nu} = -g_{\mu\nu} + \frac{q_\mu q_\nu}{M_R^2},$$

$$D_{\mu\nu}(q) = \frac{-i(g_{\mu\nu} - q_\mu q_\nu/M_\rho^2)}{q^2 - M_\rho^2 + i\epsilon} \quad \tilde{\gamma} = \gamma^\nu \tilde{g}_{\mu\nu} = -\gamma_\mu + \frac{q_\mu \not{q}}{M_R^2}$$

	Vertex	g_1	g_2	g_3
Determined	$N(2080) \to \phi p$	0.50	1.21	2.46
	$N(2270) \to \phi p$	0.42	-0.34	0.42
Solution A	$N(2080) \to \rho p$	0.21	-0.20	0.21
	$N(2270) \to \rho p$	0.30	-0.28	0.30
Solution B	$N(2080) \to \rho p$	0.15	-0.31	0.13
	$N(2270) \to \rho p$	0.20	-0.40	0.17

$$f_\rho(l^2) = \left(\frac{\Lambda_\rho^2 - M_\rho^2}{\Lambda_\rho^2 - l^2}\right)^2 \quad f_N(q^2) = \left(\frac{\Lambda_N^4}{\Lambda_N^4 + (q^2 - M_N^2)^2}\right)^2$$

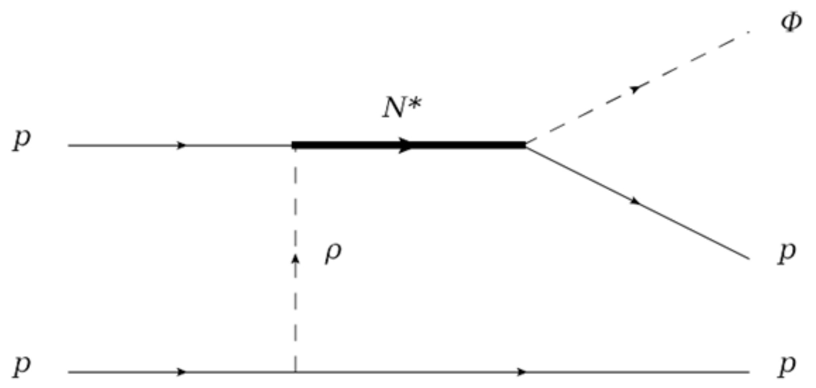
$\Lambda_\rho = 1.3$ GeV

$\Lambda_N = 1.5$ GeV

$g_{NN\rho} = 3.25$

$\kappa_\rho = 6.1$

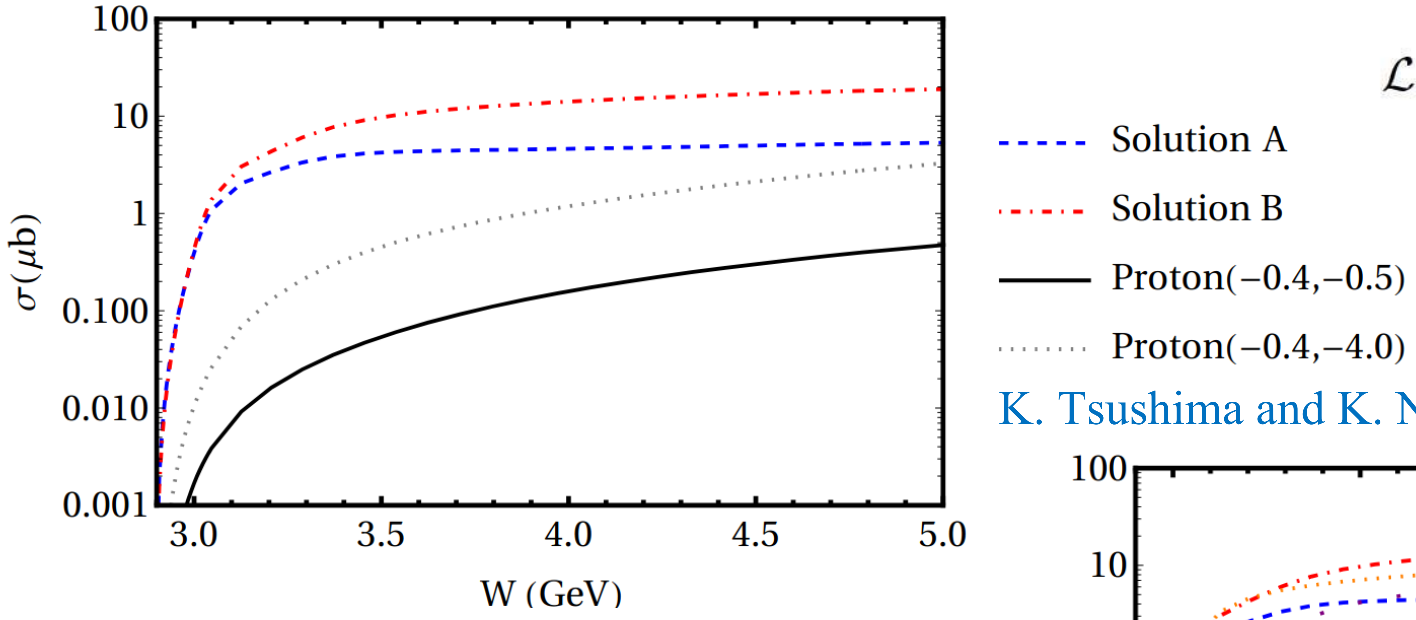
$$\mathcal{L}_{NN\rho} = -g_{NN\rho}\bar{N}(\gamma_\mu - \frac{\kappa_\rho}{2M_N}\sigma_{\mu\nu}\partial^\nu)\rho^\mu N$$



(a) ϕ production

R. Koch, ZPC 59 (1985), D. Ronchen et al., EPJA 49 (2013)

Cross Sections

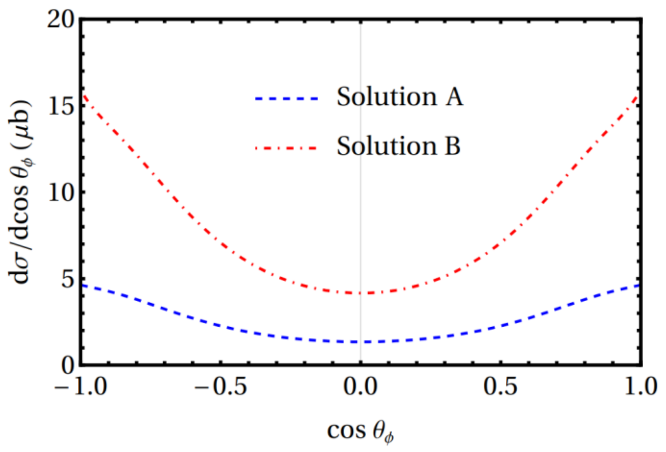


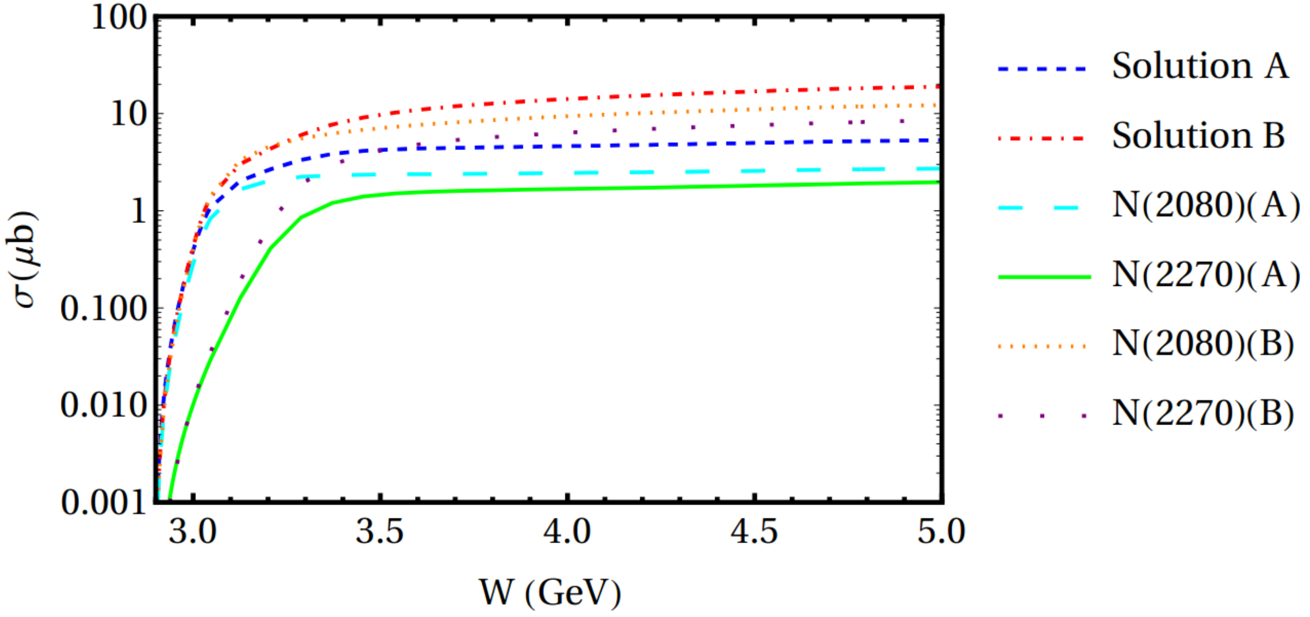
$$\mathcal{L}_{NN\phi} = -g_{NN\phi}\bar{N}(\gamma_\mu - \frac{\kappa_\phi}{2M_N}\sigma_{\mu\nu}\partial^\nu)\phi^\mu N$$

Molecules 5 / 20 μb

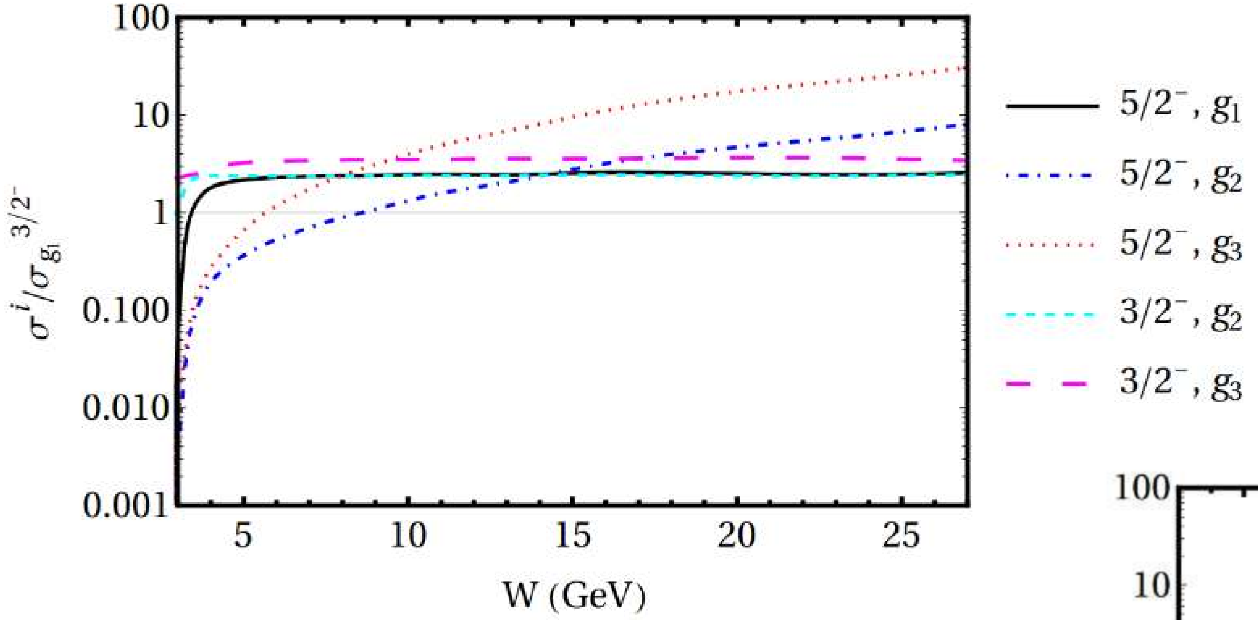
Proton 0.5 / 3 μb

K. Tsushima and K. Nakayama, PRC 68 (2003).





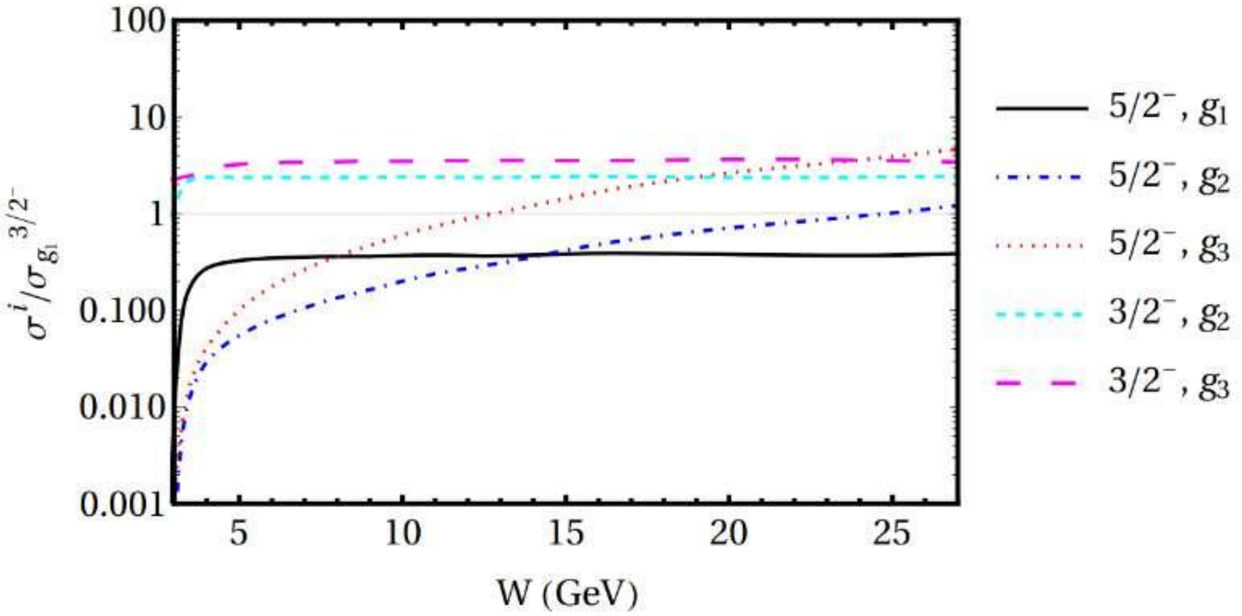
Higher Spin Effects



$$\mathcal{L}_{RNV}^{5/2^-} = +\frac{g_1}{(2M_N)^2}\bar{R}_{\mu\alpha}\gamma_\nu\gamma_5(\partial^\alpha V^{\mu\nu})N - i\frac{g_2}{(2M_N)^3}\bar{R}_{\mu\alpha}\gamma_5(\partial^\alpha V^{\mu\nu})\partial_\nu N + i\frac{g_3}{(2M_N)^3}\bar{R}_{\mu\alpha}\gamma_5(\partial^\alpha\partial_\nu V^{\mu\nu})N + h.c..$$

States with higher orbital angular momenta (L) are more likely to be observed.

Initial state	Γ(MeV)
$N^*(2270)1/2^-$	247.61
$N^*(2270)3/2^-$	365.52
$N^*(2270)5/2^-$	78.89



Di Ben et al., PRC 112 (2025)

Spin Observables & Cascade Decay

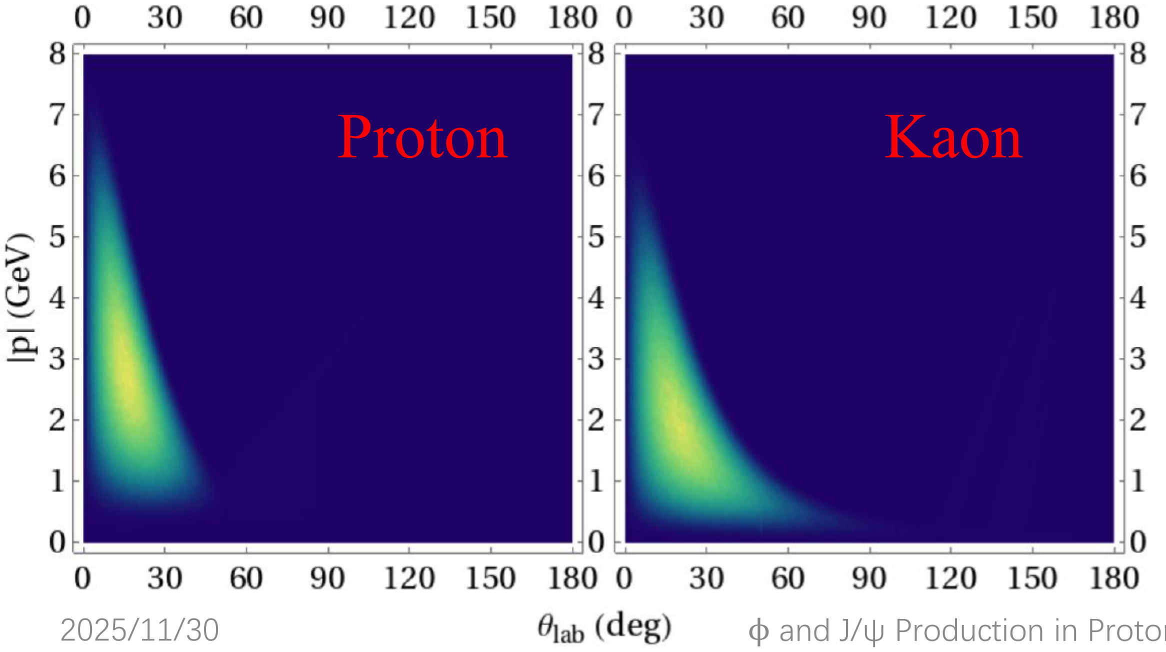
$$\rho_{\lambda_V \lambda'_V}(W,\theta) = \frac{\sum_\lambda T_{\lambda_V \lambda}(W,\theta) T^*_{\lambda'_V \lambda}(W,\theta)}{\sum_{\lambda_V \lambda} |T_{\lambda_V \lambda}(W,\theta)|^2}.$$

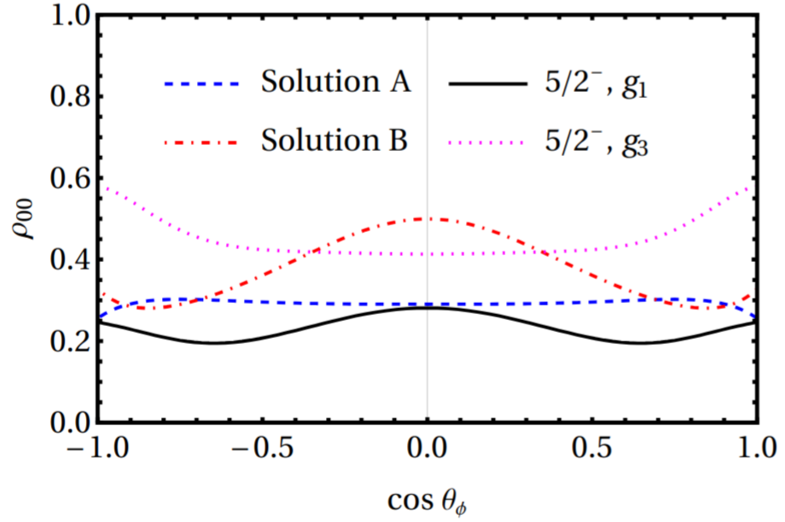
$$\mathcal{W}^{K^+K^-}(cos\Theta) = \frac{3}{4}(1-\rho_{00})(1+B^{K^+K^-}\cos^2\Theta)$$

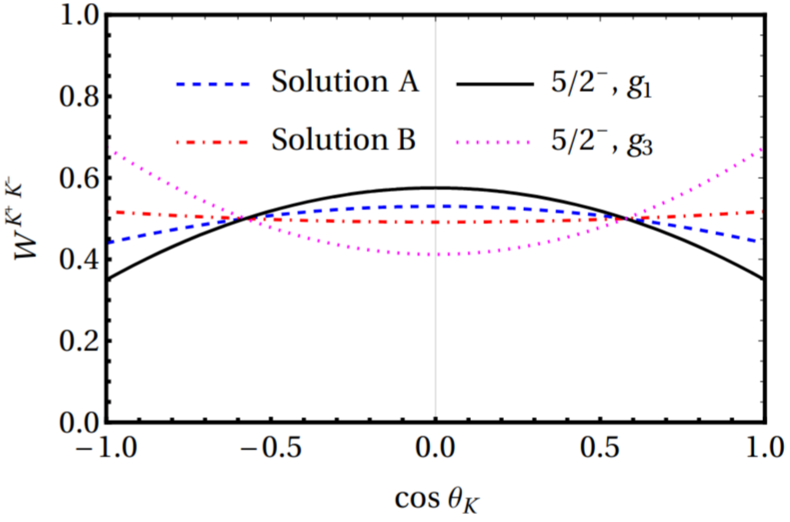
Decay anisotropy:

$$B^{K^+K^-} = -\frac{1-3\rho_{00}}{1-\rho_{00}}.$$

A. I. Titov et al., PRC 59 (1999)







STAR: Global Spin Alignment ρ_{00}

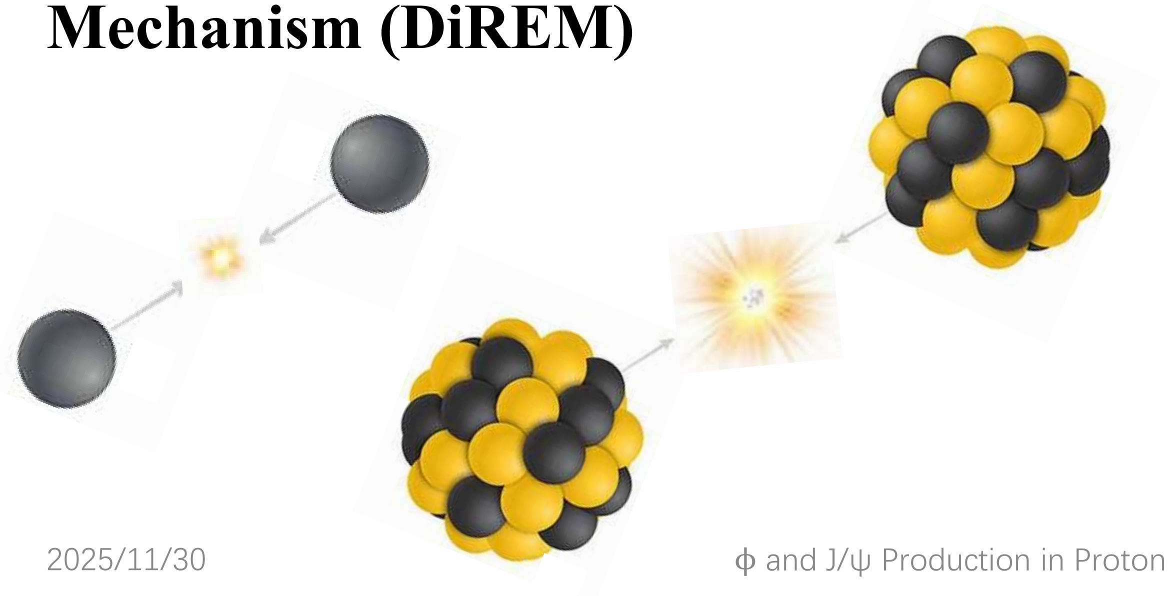
M. S. Abdallah et al. [STAR], Nature 614 (2023).

Averaged $\sqrt{s_{NN}}$ between 11 ~ 62 GeV:

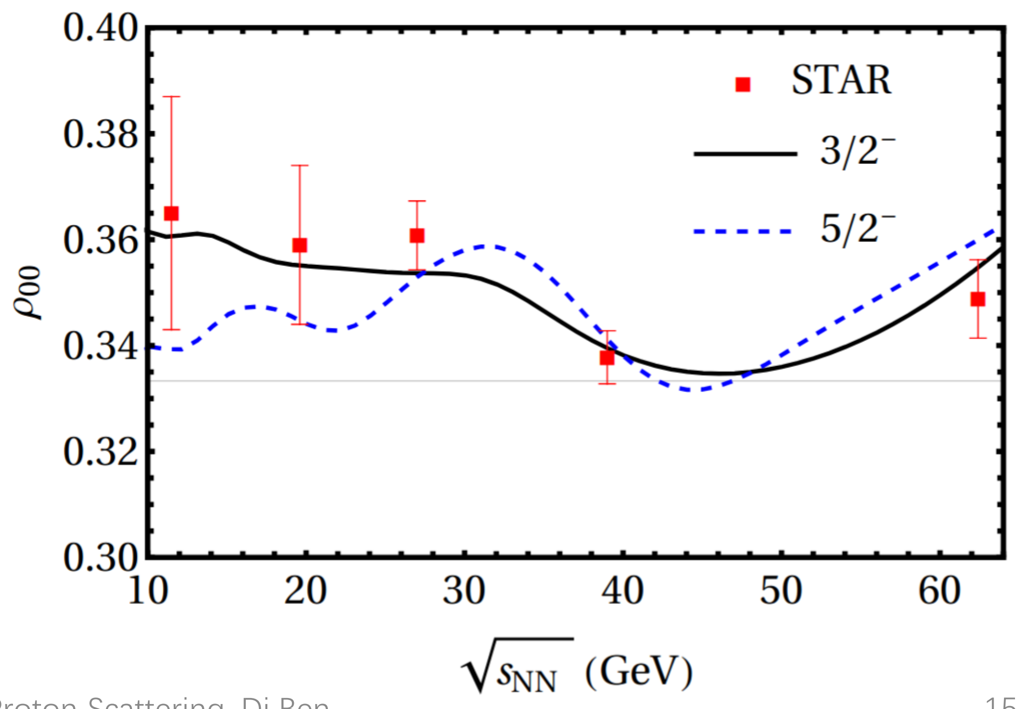
$$\rho_{00} = 0.3512 \pm 0.0017(stat.) \pm 0.0017(syst.)$$

Above 1/3 with 7.4σ

Deeply-Internal Resonances Excitation Mechanism (DiREM)



J^P	Parameter	Value ± Error
$3/2^-$	g_2/g_1	-0.19 ± 0.16
$(\chi^2 = 0.69)$	g_3/g_1	1.24 ± 0.04
$5/2^-$	g_2/g_1	-1.24 ± 0.16
$(\chi^2 = 2.16)$	g_3/g_1	3.45 ± 0.70



Contents

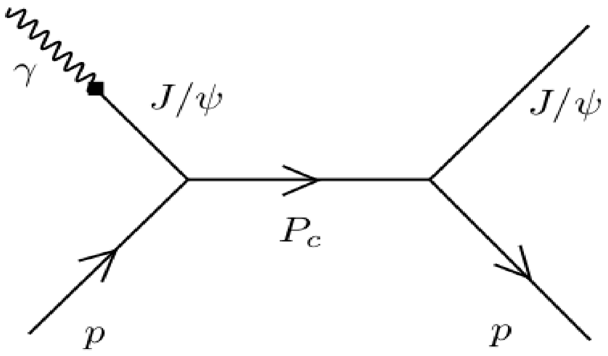
Photoproduction: $\gamma p \to pJ/\psi$

$\boldsymbol{\gamma p \to pJ/\psi}$ **:** Ming-Xiao Duan et al., arXiv: 2409.10364

Coupling constants of P_c states can be restricted

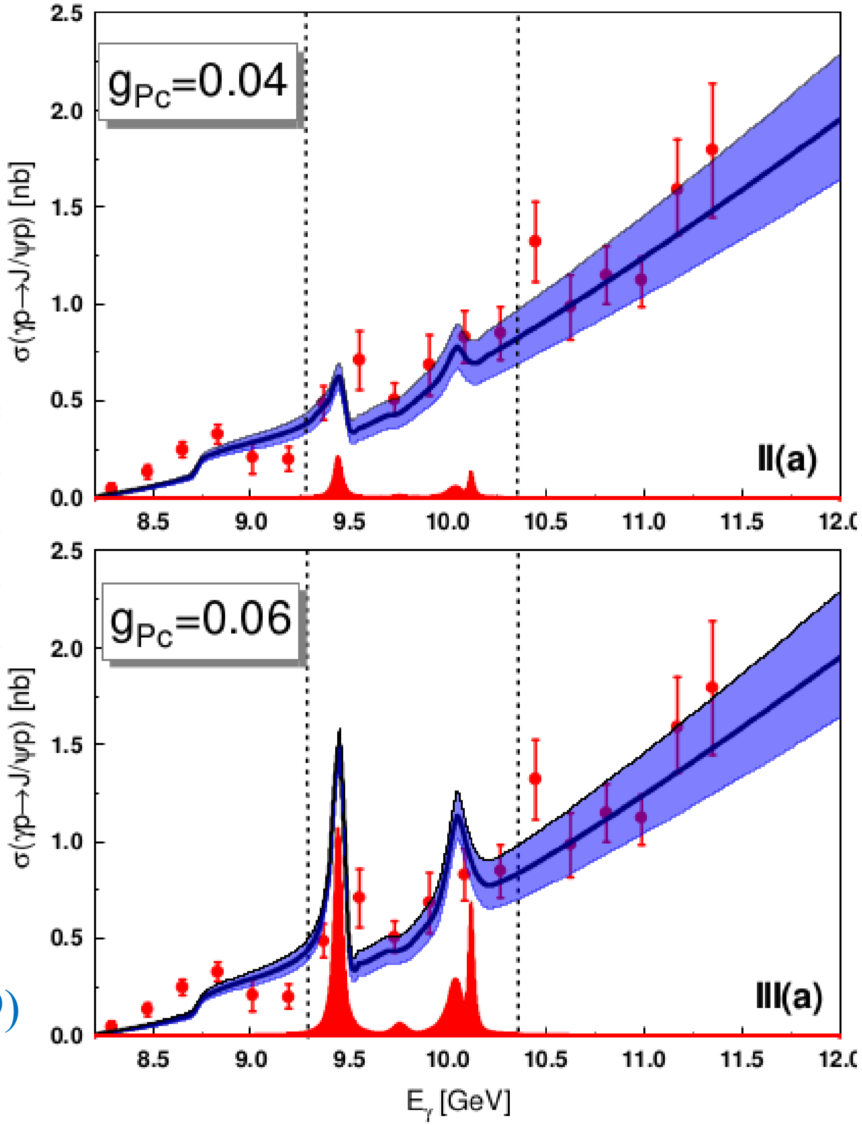
$$\mathcal{L}_{P_c(1/2^-)Vp} = g_{P_c(1/2^-)} \bar{N}\gamma_5\gamma_\rho \left(-g^{\rho\mu} + \frac{p^\rho p^\mu}{M_{P_c}^2}\right) P_c V_\mu,$$

$$\mathcal{L}_{P_c(3/2^-)Vp} = g_{P_c(3/2^-)} \bar{N} P_c^\mu V_\mu$$



	Widths (MeV) with (f_2, f_3)			
	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$		
	$P_c(4376)$	$P_c(4500)$	$P_c(4511)$	$P_c(4523)$
Mode	$\frac{3}{2}^-$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$
$\bar{D}^*\Lambda_c$	21.6	6.4	16.7	3.1
$J/\psi p$	0.7	36.7	4.4	0.2
$\bar{D}\Lambda_c$	~0	2.0	0.09	0.7
πN	0.6	49.9	6.0	0.5
$\chi_{c0}p$	0.1	4.7	0.5	~0
$\eta_c p$	~0	13.5	0.1	0.04
ρN	0.2	11.6	0.6	0.1
ωp	0.8	44.0	2.3	0.4

Yong-Hui Lin and Bing-Song Zou, PRD 100 (2019)



Scattering: $pp \to pP_c \to ppJ/\psi$

State	Molecule	J^P[26]	M_{P_c}(MeV)	Γ_{P_c}(MeV)
$P_c(4312)$	$\bar{D}\Sigma_c$	$1/2^-$	4311.9[25]	9.8[25]
$P_c(4380)$	$\bar{D}\Sigma_c^*$	$3/2^-$	4372.2 [26]	9.6 [26]
$P_c(4440)$	$\bar{D}^*\Sigma_c$	$1/2^-$	4440.3[25]	20.6[25]
$P_c(4457)$	$\bar{D}^*\Sigma_c$	$3/2^-$	4457.3[25]	6.4[25]
$P_c(4500)$	$\bar{D}^*\Sigma_c^*$	$1/2^-$	4502.7 [26]	28 [26]
$P_c(4511)$	$\bar{D}^*\Sigma_c^*$	$3/2^-$	4510.5 [26]	14.4[26]

[25] S. Navas et al. [PDG], PRD 110 (2024).
[26] Jia-Ming Xie et al., EPJC 82 (2022).
[27] M. Guidal et al., NPA 627 (1997).

$$\mathcal{D}_{\mu\nu}(s,t) = D_{\mu\nu}(t) \cdot \left(\frac{s}{s_0}\right)^{\alpha(t)-1} \frac{\pi\alpha'}{\sin[\pi\alpha(t)]} \frac{\mathcal{S} + e^{-i\pi\alpha(t)}}{2},$$

where:

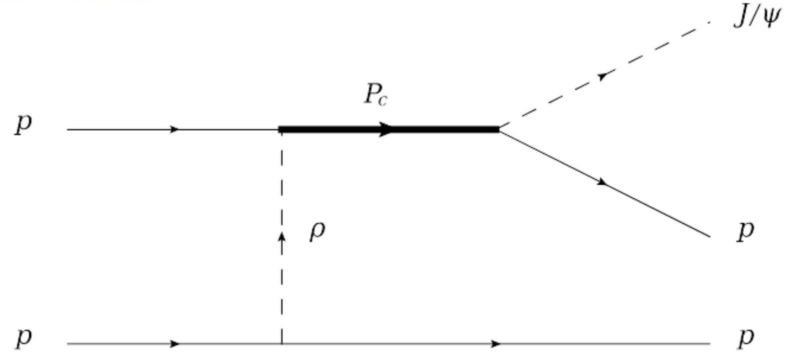
$$D_{\mu\nu}(t) = \frac{-i(g_{\mu\nu} - q_\mu q_\nu / M_\rho^2)}{\Gamma(\alpha(t))}.$$

And the Regge trajectory of ρ meson is given by [27]:

$$\alpha(t) = \alpha_0 + \alpha' t = 0.55 + 0.8t$$

Here $\mathcal{S}$ represents the signature factor, which for ρ mesons is $\mathcal{S} = +1$.

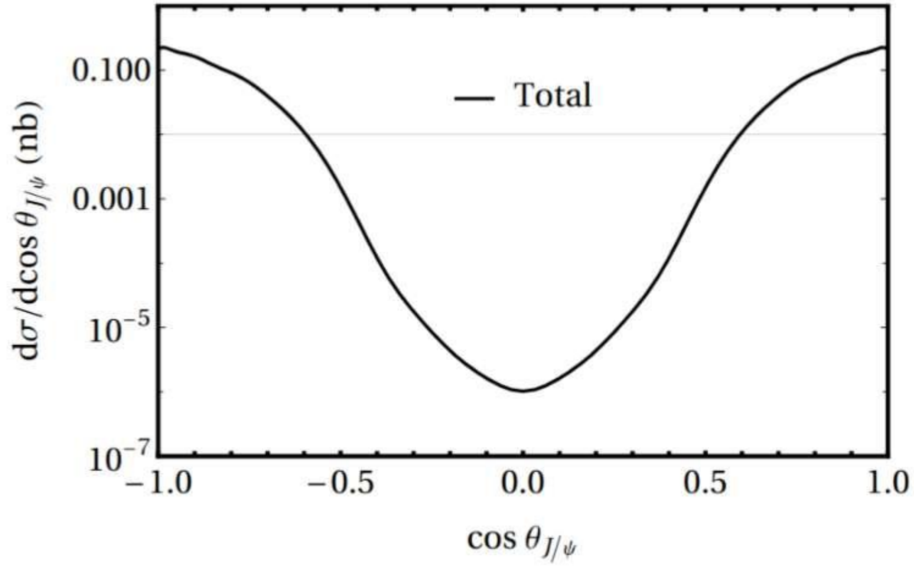
$$\boldsymbol{g_{P_c}(V = J/\psi) = 0.05, g_{P_c}(V = \rho) = 0.01}$$

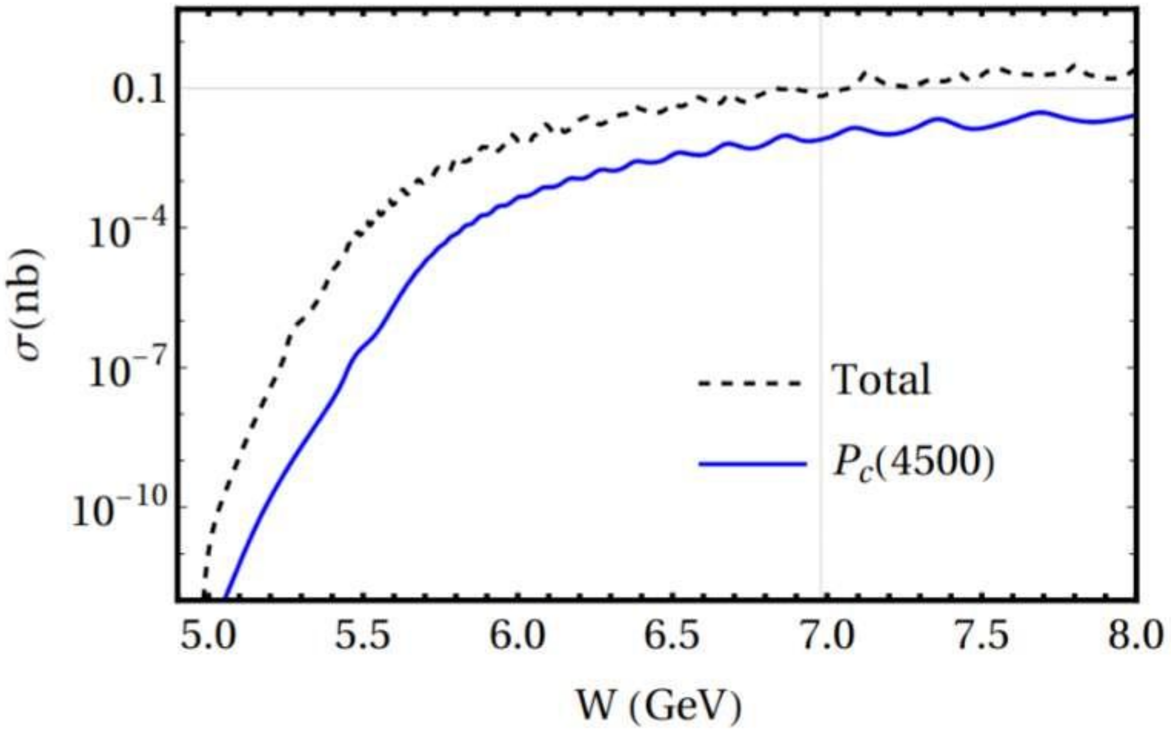


(b) J/ψ production

Production of J/ψ

J/ψ production at HIAF-U: 0.1 nb





Predominantly produced along the beam direction in CM frame.

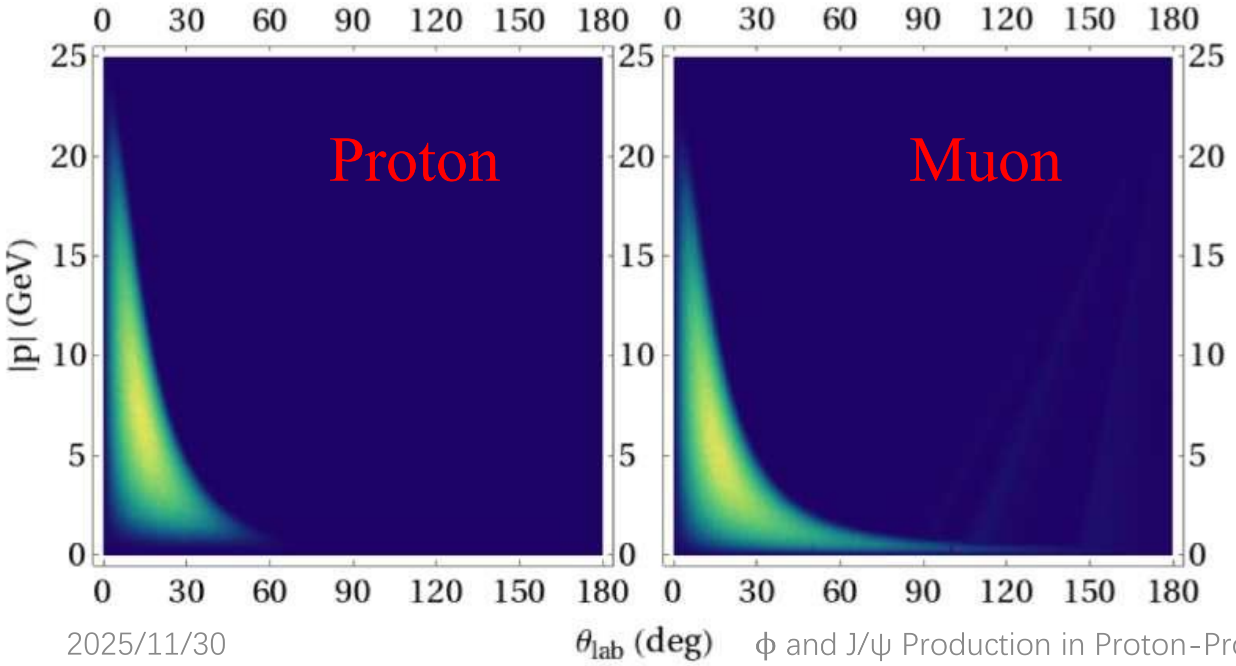
Predictions of J/ψ

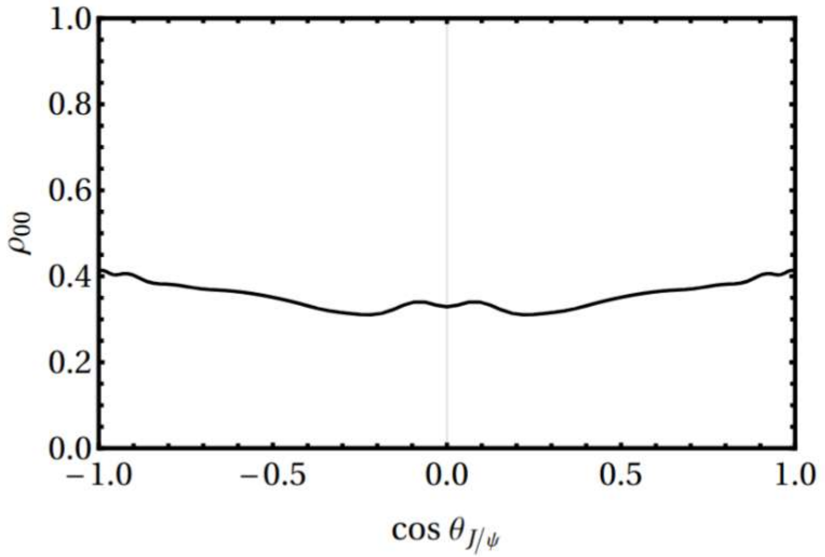
$$\mathcal{W}^{\mu^+\mu^-}(cos\Theta) = \frac{3}{8}(1+\rho_{00})(1+B^{\mu^+\mu^-}\cos^2\Theta),$$

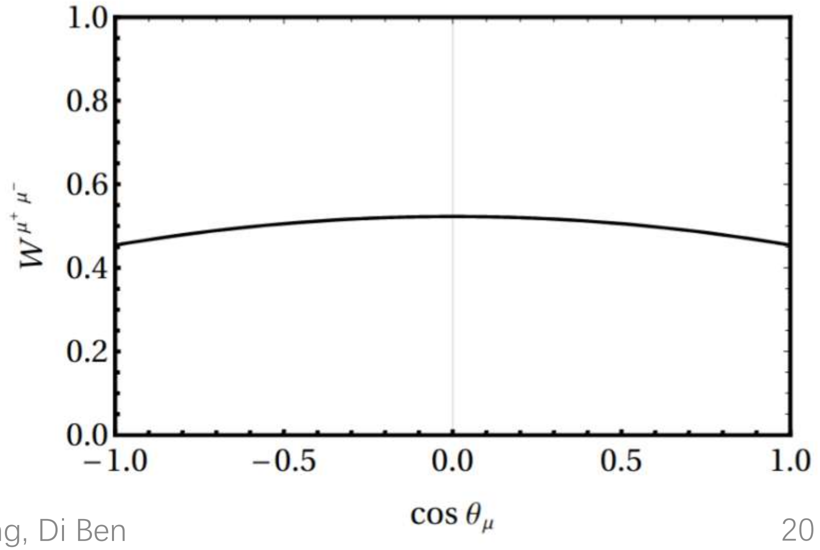
where $B^{\mu^+\mu^-}$ is given by:

A. I. Titov et al., PRC 59 (1999)

$$B^{\mu^+\mu^-} = \frac{1-3\rho_{00}}{1+\rho_{00}}.$$







Contents

Summary

Tsinghua University

- ✓ Production cross section of ϕ and J/ψ mesons at HIAF and HIAF-U reaches 10 μb and 0.1 nb, respectively.
- ✓ States with higher orbital angular momenta (L) are more likely to be observed at sufficiently high energies.
- ✓ Deeply-Internal Resonances Excitation Mechanism (DiREM) can well reproduce the global spin alignment of ϕ.
- ✓ Spin observables and cascade decay properties are provided as the model predictions.
- ✓ Final state particle distribution are provided as the guidance for future experiments at HIAF and HIAF-U.

Thank you very much!