Heavy quark production: spectroscopy and proton mass

Xu CAO

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

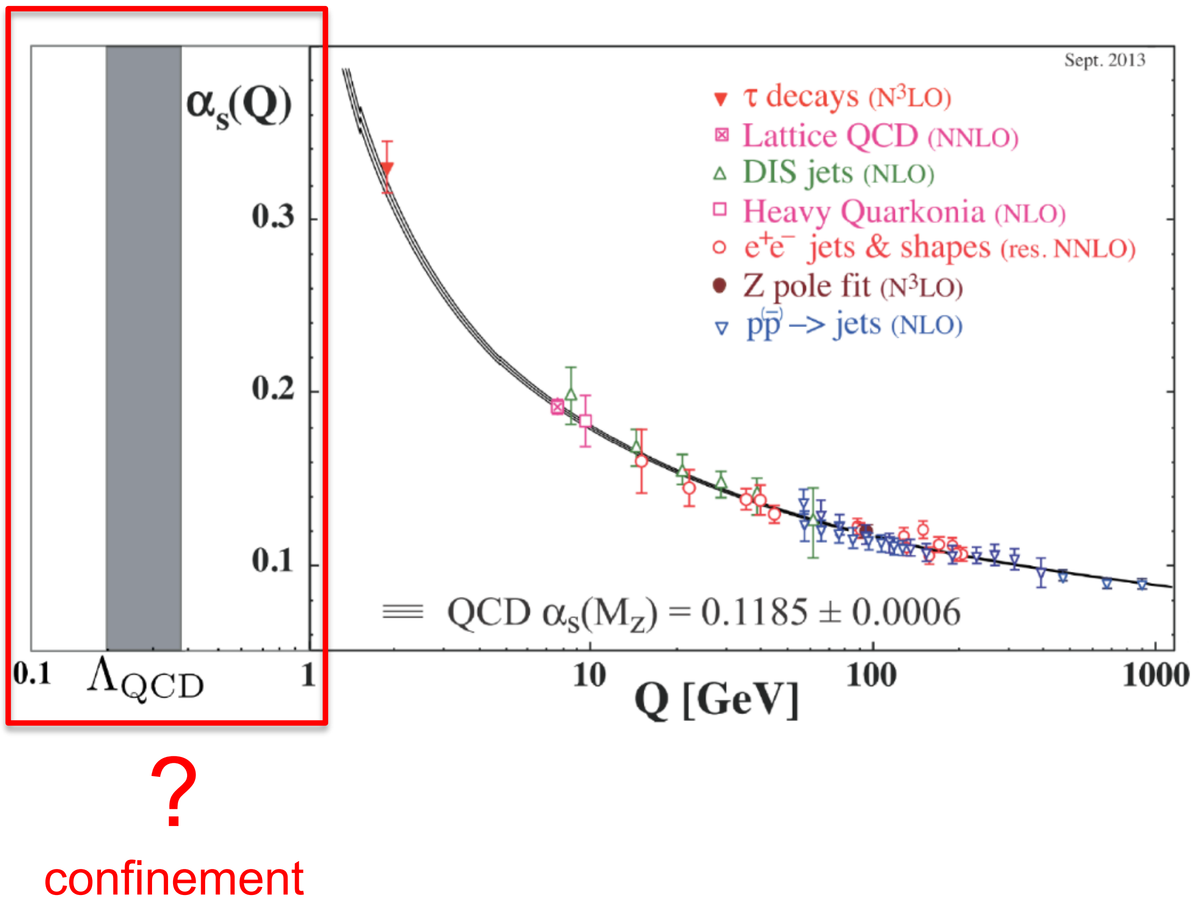
The 11th Workshop on Hadron physics
in China and Opportunities Worldwide
Tianjin, August 23 - 28, 2019

Introduction

Low-energy QCD: a big challenge

- Mysteries in hadron spectroscopy

  Hadron: a composite object constituted from quarks and gluon.

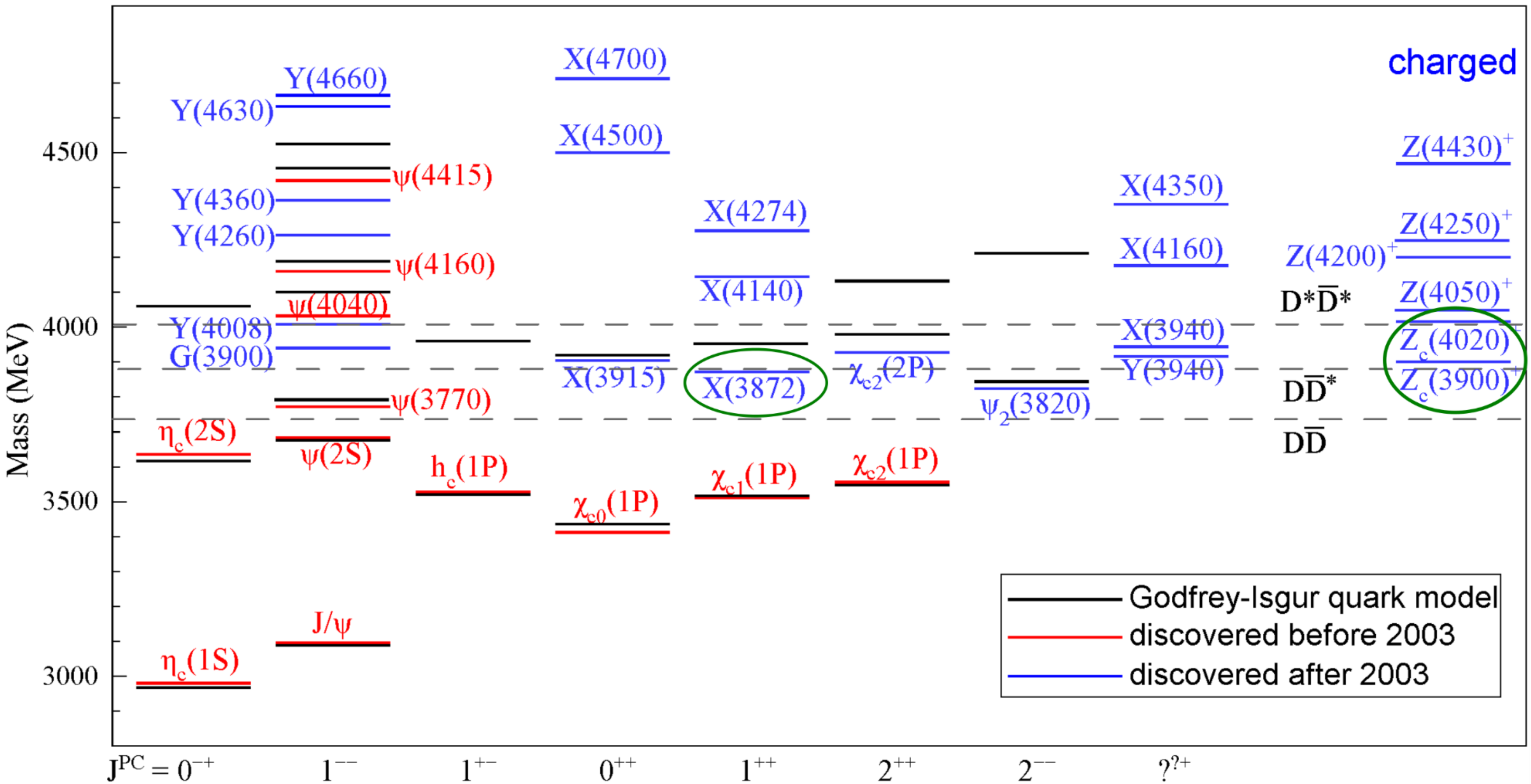


Introduction

Low-energy QCD: mesons

- Charmonium and XYZ spectroscopy:

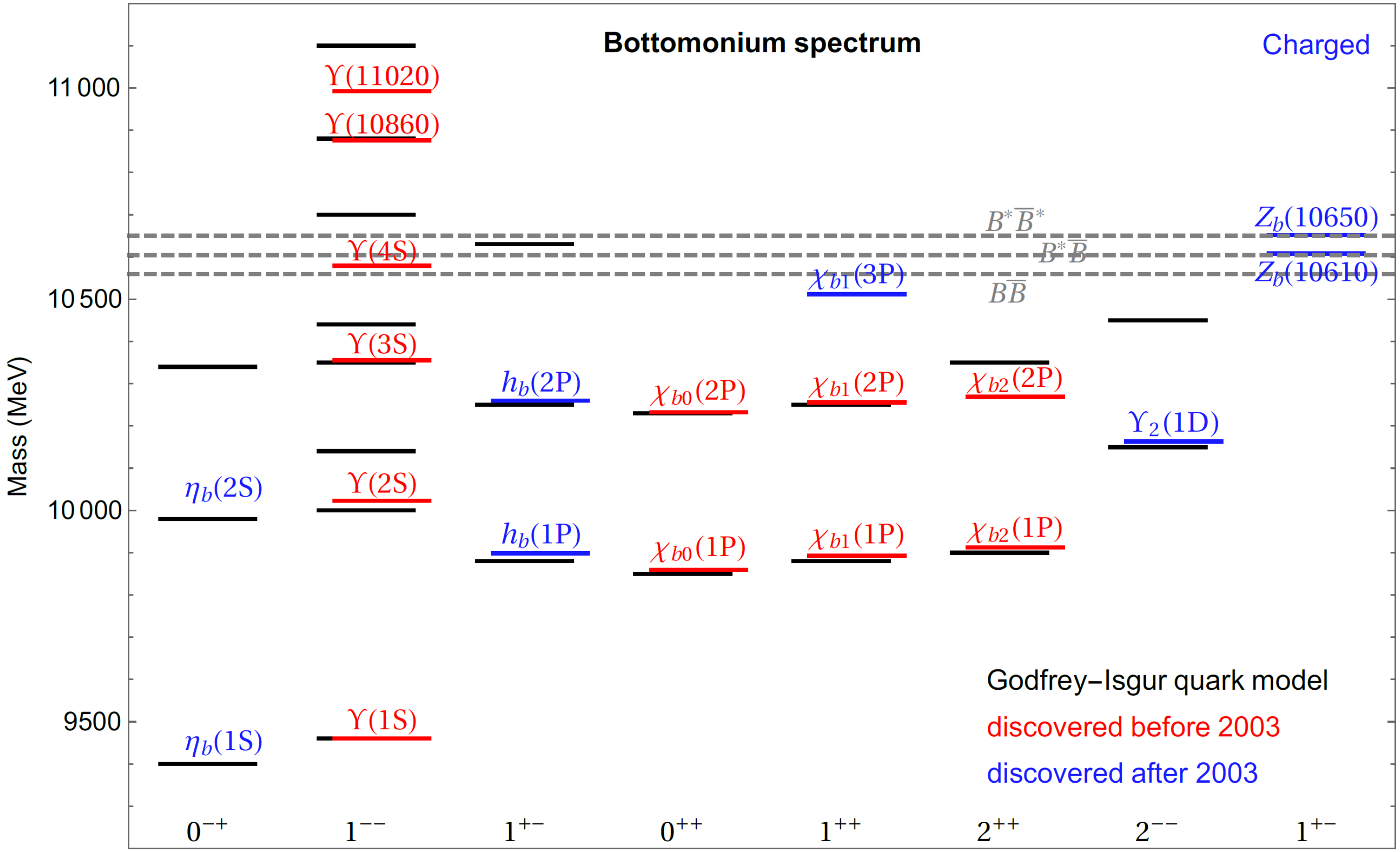
  Some states are very close to two-body S-wave thresholds



Introduction

Low-energy QCD: mesons

- Bottomonium and analogues of the XYZ spectroscopy: much less states observed. Only two Zb in bottomonium region

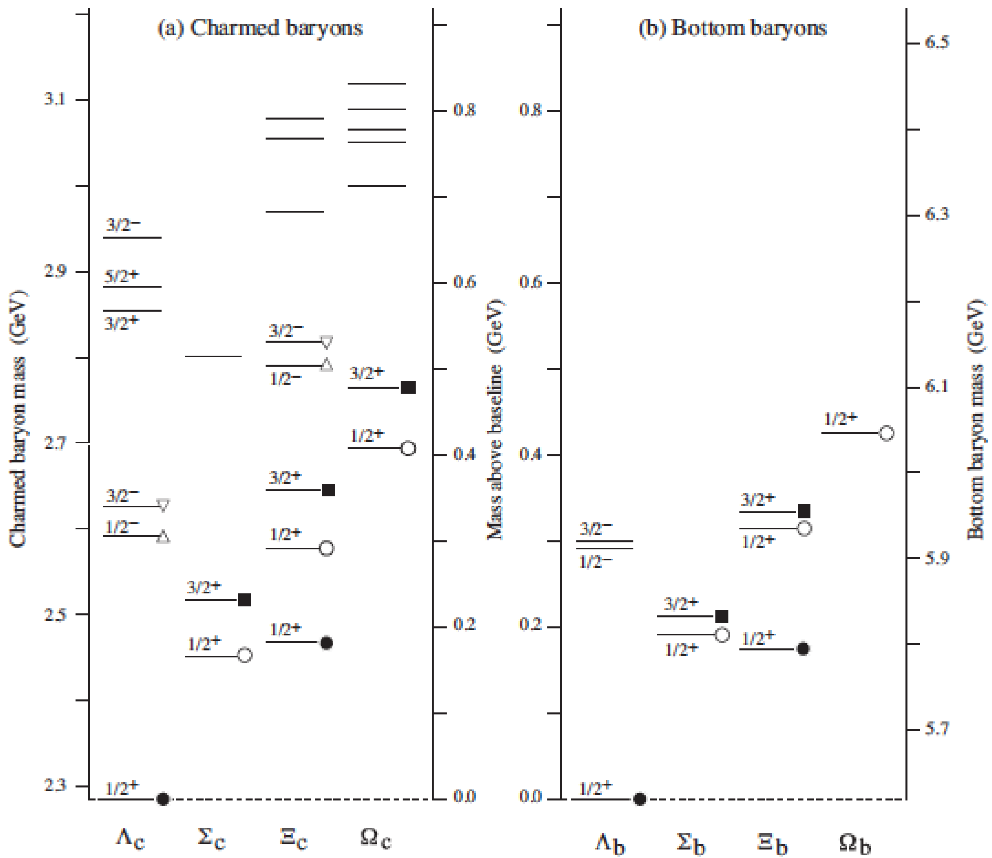


F.K.Guo, C.Hanhart, U.Meissner, Q.Wang, Q.Zhao, B.S.Zou, Rev.Mod.Phys.90(2018)015004

Introduction

Low-energy QCD: baryons

- 24
- 9



Assiciation production

- 7

Bottom meson

B(5280), B*(5325), B_1(5721), B_2(5747), B_J(5732), B_J(5840), B_J(5970)

- 5

Bottom strange meson

B_s(5367), B^*_s(5415), B_{s1}(5830), B_{s2}(5840), B_{sJ}(5850)

Introduction

Low-energy QCD: Exotica

- Exotic baryons P_c : Bingsong ZOU & Liming ZHANG's talks

LHCb

state	Mass [MeV]	Width [MeV]	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$0.53 \pm 0.16^{+0.15}_{-0.13}$

$$\mathcal{R}\,[\%] = \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

$$\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.2^{+0.6}_{-0.5}) \times 10^{-4}$$

$$10^{-3} > \mathcal{B}(\Lambda_b \to P_c^+ K^-)$$

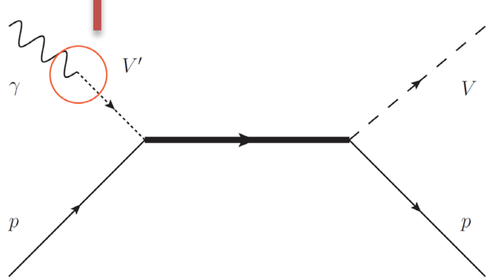
independent of J^P

X. C., Jian-ping Dai, 1904.06015

$$\frac{1}{FF^2(Q^2=0)} * \text{Several}\,\% > \mathcal{B}(P_c^+ \to J/\psi p) > 0.05\%$$

Differential or polarized cross section?

$\sigma_r \propto \mathcal{B}^2(P_c \to Vp)$ *non-determined form factor



$$\gamma p \to J/\psi p$$

Free of triangle singularity

Alexander SOMOV's talk

(null Pc results of GlueX)

Introduction

Low-energy QCD: Exotica

- Bottom analogues of the P_c states: P_b

Any theory explaining XYZ/ P_c states would predict similar states with bottom quarks.
e.g., hadronic molecular model:

P_b	Mass M (GeV)	Width Γ(MeV)	$\Gamma(P_b \to \Upsilon(1S)p)$	$\mathcal{B}(P_b \to \Upsilon(1S)p)$
J. J. Wu et al. [23]	11.10	1.33	0.51	0.38
Karliner&Rosner [27, 32]	11.14	$39^{\ddagger}$ or 61 †	—	$0.1^{\ddagger}$
Huang et al. [28, 29]	11.09 - 11.14✠	7.0	4.4	0.63
Lin et al. [26]	—	30-300	—	0.0003-0.0013
Yang et al. [31]	11.14	—	—	—
Xiao et al. [24]	10.96-11.022	2-110	—	—
Shen et al. [25]	11.120	25	—	—

Pb's mass is quite consistent within models (Guided by Heavy Quark Symmetry?)

- Other Zb states are expected! e.g. X.C. CPC39(2015)041002

		$I^G(J^{PC})$	RE($\sqrt{s}$)/MeV	IM($\sqrt{s}$)/MeV
$B^*\bar{B}^*$	VV	$0^+(0^{++})$	10650.2±1.9	11±7
		$0^-(1^{+-})$	10471.1±42.3	1±1
			10650.2±1.5	127±16
		$0^+(2^{++})$	10650.2±1.7	13±8
		$1^-(0^{++})$	10650.2±1.6	7±5
		$1^+(1^{+-})$	10650.2$^{(a)}$	5±4
		$1^-(2^{++})$	10650.2±1.6	7±3
$B^*\bar{B}$	VP	$1^+(1^{+-})$	10604.2$^{(b)}$	−6±4
		$1^-(1^{++})$	—	—
		$0^+(1^{++})$	10604.2±1.7	−95±17
			10781.0±1.3	−118±12
		$0^-(1^{+-})$	10781.7±1.3	−2±1
$B\bar{B}$	PP	$0^+(0^{++})$	10732.8±1.6	−6±4
		$1^-(0^{++})$	10558.0±1.1	−7±4

PRD80(2009)114007; 89(2004)034016
Photoproduction by t-channel vector exchange

$$\sigma_{Zc} \lesssim 10 \ \text{nb}$$

Naïve expectation:

$$\sigma_{Zb} = \sigma_{Zc} \frac{s_c (k_c^\gamma f_{\eta_c})^2}{s_b (k_b^\gamma f_{\eta_b})^2} \lesssim 0.5 \ \text{nb},$$

Introduction

Low-energy QCD: Merits

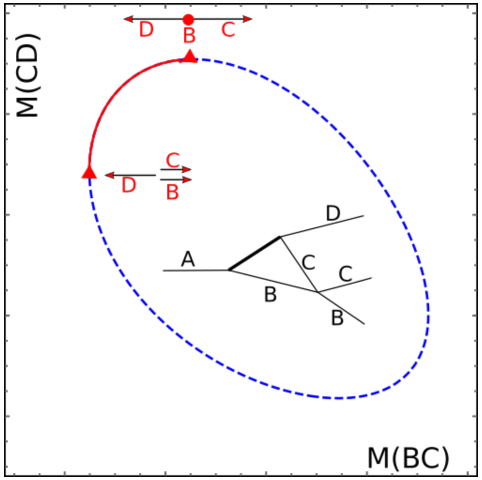
- EicC: **√s ~ 15 ~ 20 GeV, 2~4x10[33]/sec /cm[2]**
- Polarized (3.5 GeV 80%) e + (20 GeV 70%) p

1. larger cross section compared to e+e- collision
2. smaller background compared to pp and $p\bar{p}$ collisions
3. Especially, the polarized EicC can well pin down the quantum numbers
4. Flexiable mass
   - Masses limited to

$$B \to K\, X \quad M_B - M_K \approx 4.8 \text{ GeV}$$

$$\Lambda_b \to K\, P_c \quad M_{\Lambda_b} - M_K \approx 5.1 \text{ GeV}$$

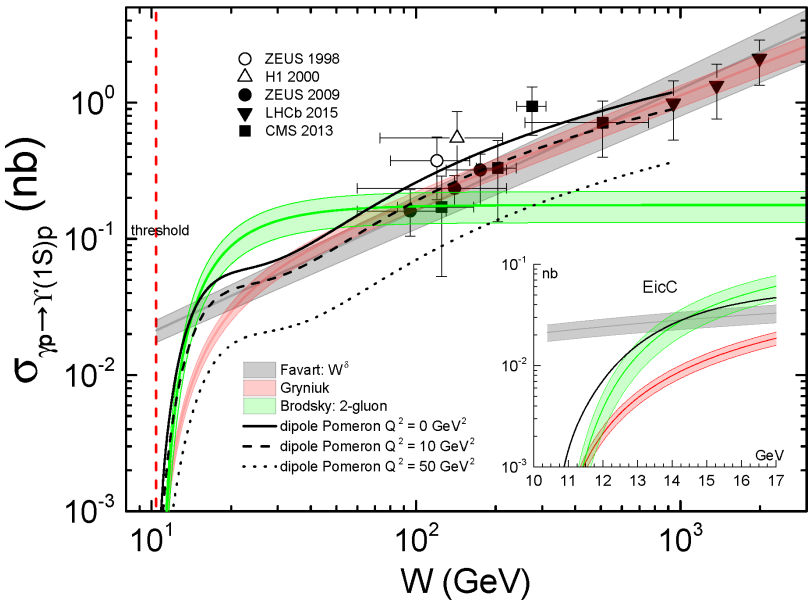
5. No triangle sigularity



Heavy Flavor@EicC

➢ EicC: privilege for heavy flavor physics:

- We know little about hidden bottom photo-&electro-production!



For W=15-20 GeV,

- Photoproduction: $\sigma(\gamma p \to \Upsilon p) \sim O\left(10^{-2}\ \text{nb}\right)$ (no resonant enhancement considered), $\sigma\left(\gamma p \to b\bar{b}X\right)$ is about two orders higher
- Electroproduction: roughly two orders of magnitude (α) smaller, $\sim O(0.1\ pb)$
- For an integrated EicC luminosity of 50 fb^{-1}, no. of Υ is $\sim O(10^4)$

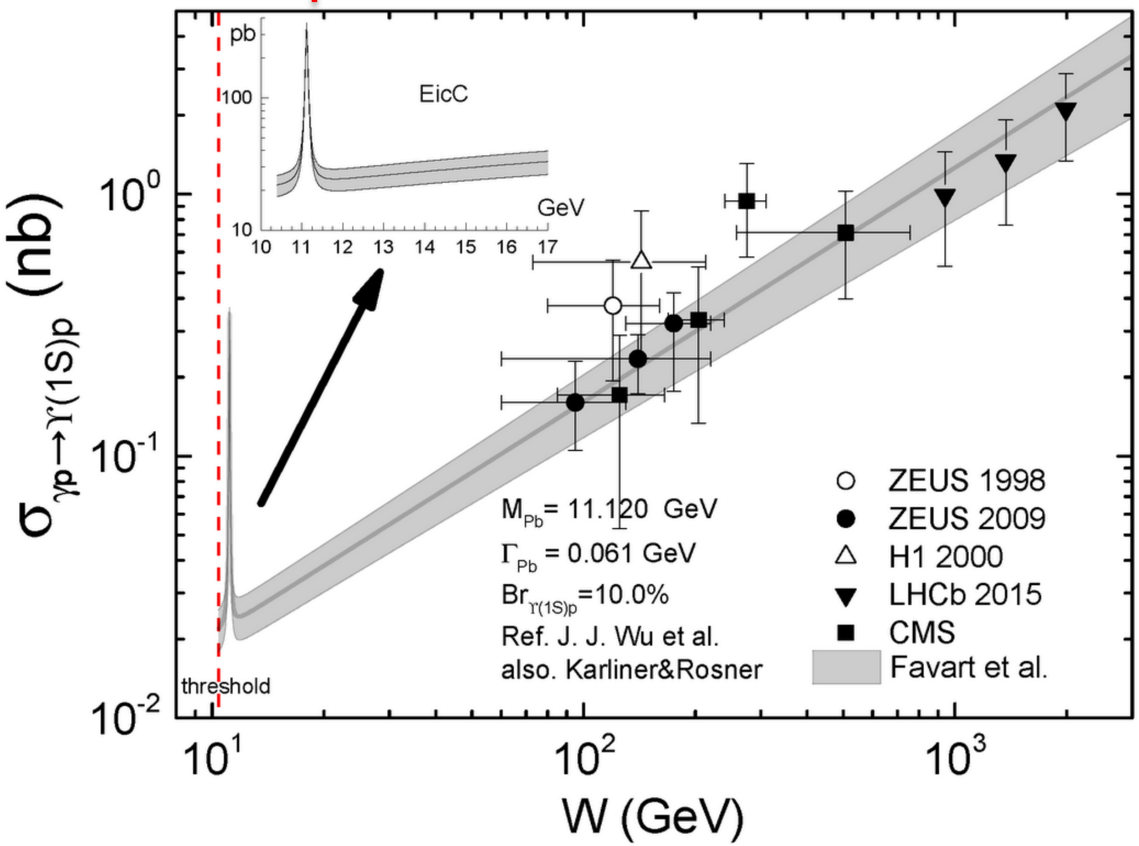
Heavy Flavor@EicC

- EicC-I has unique advantage to search for Penta-quark P_b

no. of P_b electroproduction is $\sim O(10^5)$ under 50 fb^{-1}

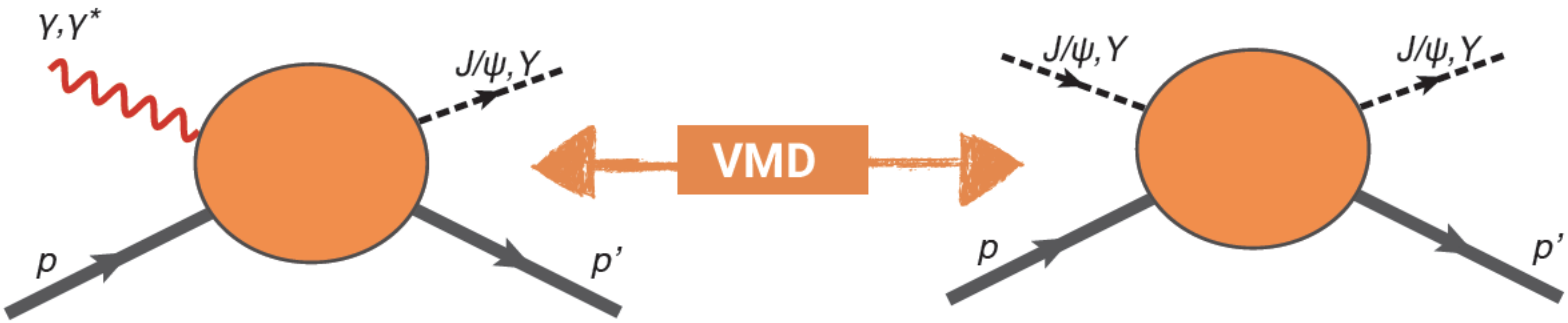
~ several 0.1nb @ P_b peak. Most optimistic?

$$\sigma \propto \mathcal{B}^2(P_b \to \Upsilon p) \times \mathcal{F}^2(Q^2)$$



Heavy Flavor@EicC

- Another topic: proton mass and trace anomaly



$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0)=\frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

- ***$M_{\psi p}$*'s Imaginary part:** related to the total cross section
- ***$M_{\psi p}$*'s Real part: contains conformal (trace) anomaly (→ 1-b)**

  Dominate the near threshold region

see S. JOOSTEN & Y. HATTA & Yi-Bo Yang's talks on Aug. 25

Heavy Flavor@EicC

- Another topic: proton mass and trace anomaly

Merits of Upsilon photoproduction

- Multi-pole expansion in OPE converges more fast because much larger mass

$$\lambda/\epsilon_0 \ll 1 \text{ with } \epsilon_0 = m_Q(3\alpha_s/4)^2,\ \lambda = \frac{s - M_\psi^2 - M_h^2}{2M_\psi}$$

(Kharzeev arxiv:9601029, 9807383)

- Uncertainties of quark mass and strong coupling are smaller:

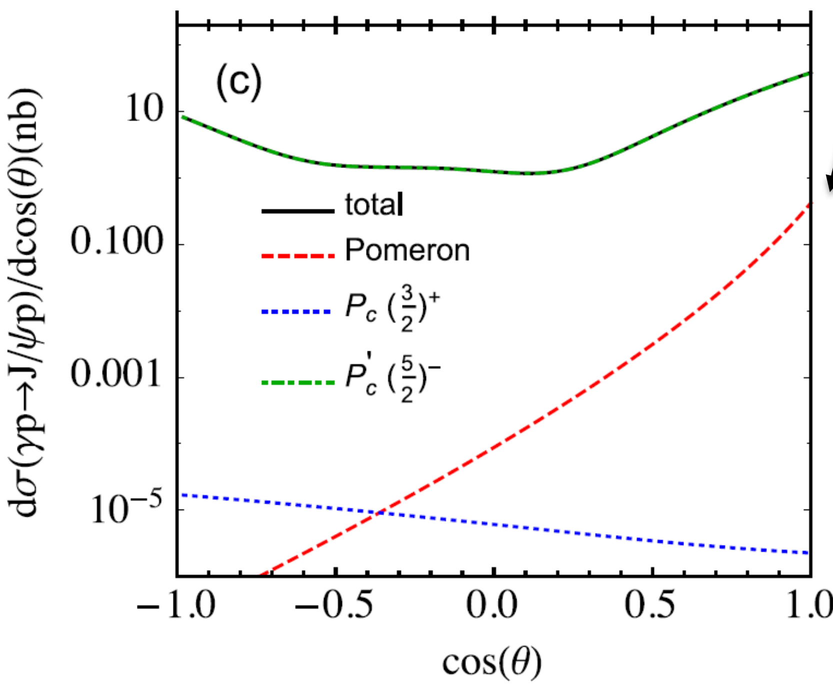
$$\frac{\Delta m_q}{m_q} \simeq \begin{cases} 2.5\% & \text{for } J/\psi \\ 1.0\% & \text{for } \Upsilon \end{cases}$$

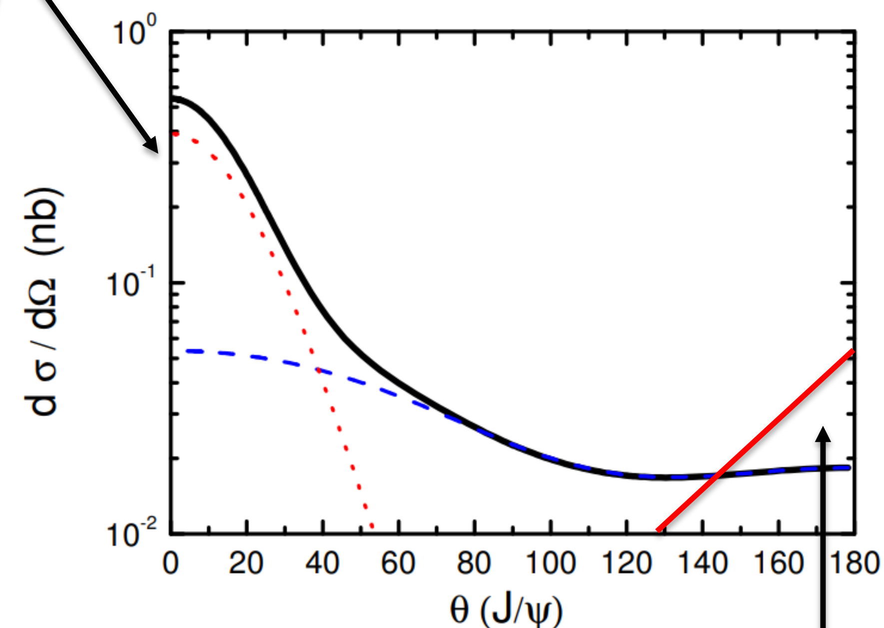
$$\frac{\Delta \alpha_s}{\alpha_s} \simeq \begin{cases} 7.8\% & \text{for } J/\psi \\ 3.7\% & \text{for } \Upsilon \end{cases}$$

Heavy Flavor@EicC

QIAN WANG, XIAO-HAI LIU, QIANG ZHAO, PRD.92(2015)034022

t-channel: trace anomaly





u-channel

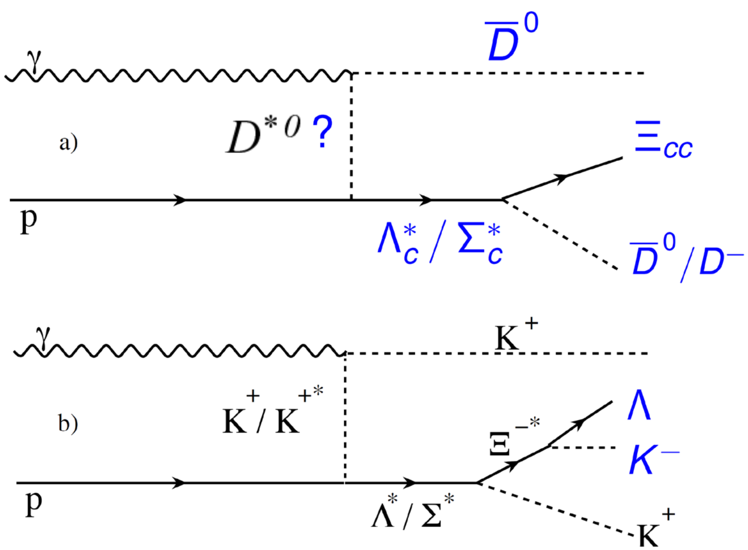
Jia-Jun Wu, T.-S. H. Lee, Bing-Song Zou, 1906.05375

Heavy Flavor@EicC

- Open-charm final states:

$B(P_c \to \Lambda_c \bar{D}^{(*)})$ is expected to be one order of magnitude larger than $B(P_c \to J/\psi p)$

See, e.g., Y.-H. Lin et al., PRD95(2017)114017



$\gamma p \to K^+ (K^+ \Xi^{-*}) \to K^+ (p \pi^- K^-) K^+$

S-channel P_c production
+ background:

Similar in bottom sector:
open-bottom final states
$P_b \to \Lambda_b \bar{B}^{(*)}$

Overall Normalization?

Heavy Flavor@EicC

Jia-Jun Wu, T.-S. H. Lee, Bing-Song Zou, 1906.05375

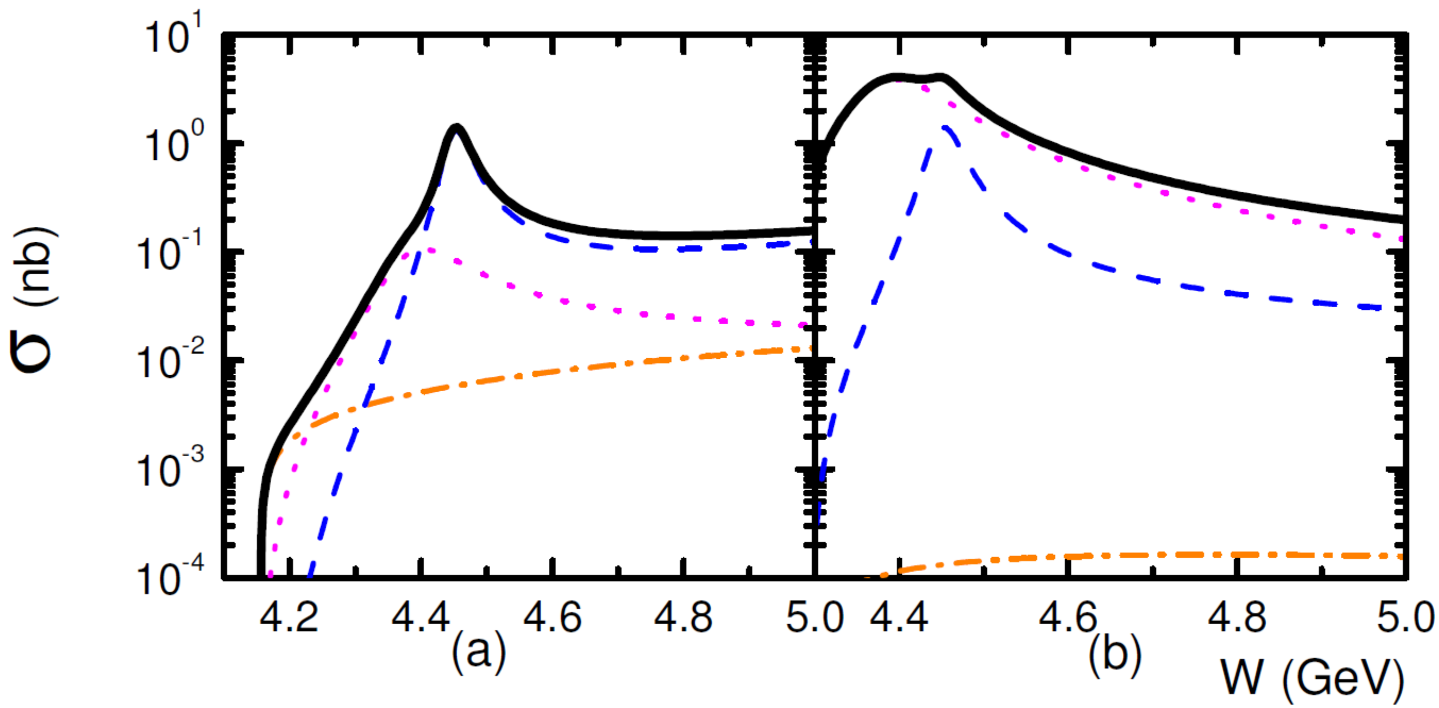


FIG. 10: The total cross sections of $\gamma p \to \bar{D}^0 \Lambda_c^+$(a) and $\gamma p \to \bar{D}^{*0} \Lambda_c^+$(b) with the invariant mass of γp. The pink dotted, blue dashed, orange dotted-dashed lines are the contribution purely from the $N^*_{c\bar{c}(\frac{3}{2}^-)}$, $N^*_{c\bar{c}(\frac{5}{2}^+)}$, and the background with $\Lambda = 0.55$ GeV, respectively. The black solid thick lines are for the coherent summation of all contributions with background $\Lambda = 0.55$ GeV

Heavy Flavor@EicC

- Naïve estimation of Open-bottom channels:

H1@HERA: consistent with pQCD calculation

$$\sigma(ep \to b\bar{b}X) = 19.5 \pm 9.3 \pm 3.7 \pm 1.8 nb \qquad \sqrt{s} = 318 GeV$$
$$\sigma(ep \to eb\bar{b}X) = 14.8 \pm 1.3 \pm 3.0 nb \qquad \sqrt{s} = 318 GeV$$

$$\sigma(\gamma p \to b\bar{b}X) = 310 \pm 150 \pm 60 \pm 40 nb \qquad < W >= 168 GeV$$
$$\sigma(\gamma p \to b\bar{b}X) = 206 \pm 19 \pm 46 nb \qquad < W >= 180 GeV$$

Resulting into:

$$R_b = \frac{\sigma(\gamma p \to b\bar{b}X)}{\sigma(\gamma p \to \Upsilon p)} \sim 50 - 400$$

at high energies. By considering the charm sector at W ~ 20 GeV

$$R_c = \frac{\sigma(\gamma p \to c\bar{c}X)}{\sigma(\gamma p \to J/\psi p)} \simeq 30 \sim 60$$

more open-bottom hadrons B and Λ_b (but with low detection efficiency)

How to reconstruct them efficiently from weak decays?

Heavy Flavor@EicC

courtesy of Xiaojun Yao@Duke

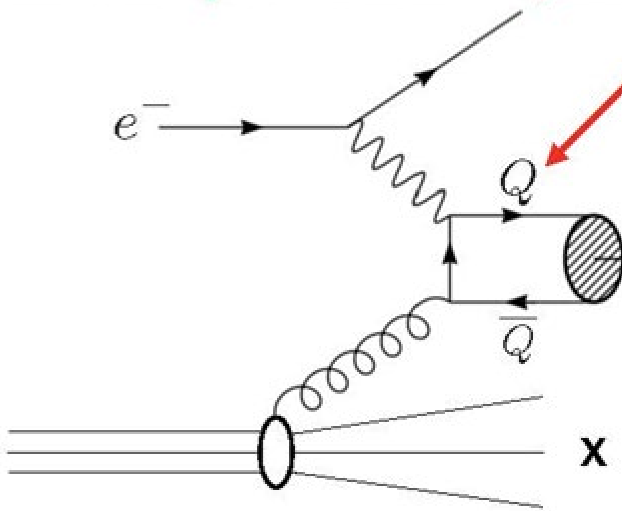
NRQCD factorization

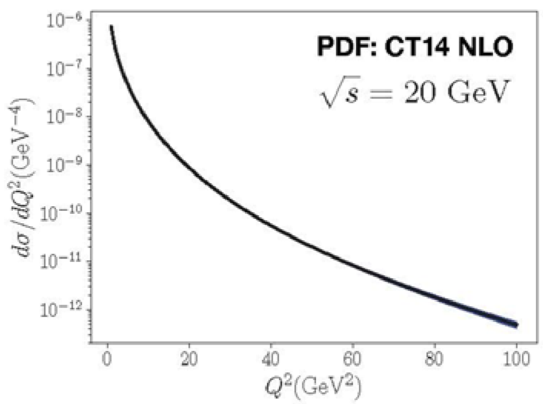
$$d\sigma(e^- + p \to H + X) = \sum_n d\sigma(e^- + p \to Q\overline{Q}(n) + X)\langle \mathcal{O}^H(n)\rangle$$

Short-distance production of heavy quark pair (calculable)

Long-distance matrix element: coalescence into quarkonium (fit)

LO octet production



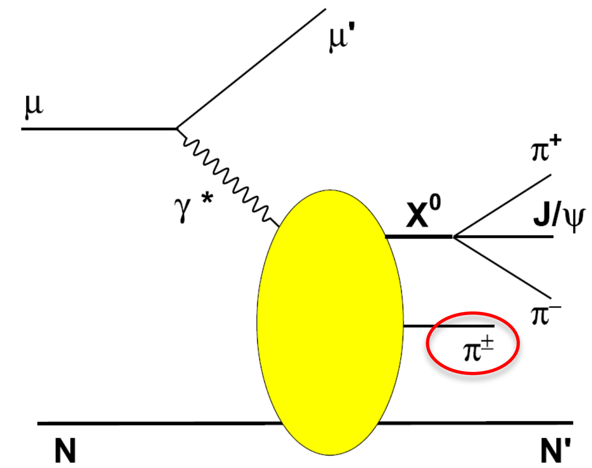


no. of $X(3872)$ is $\sim O(10^3 - 10^4)$ under 50 fb^{-1}

CM energy	10 GeV	15 GeV	20 GeV
Cross section	0.04 pb	0.13 pb	0.26 pb

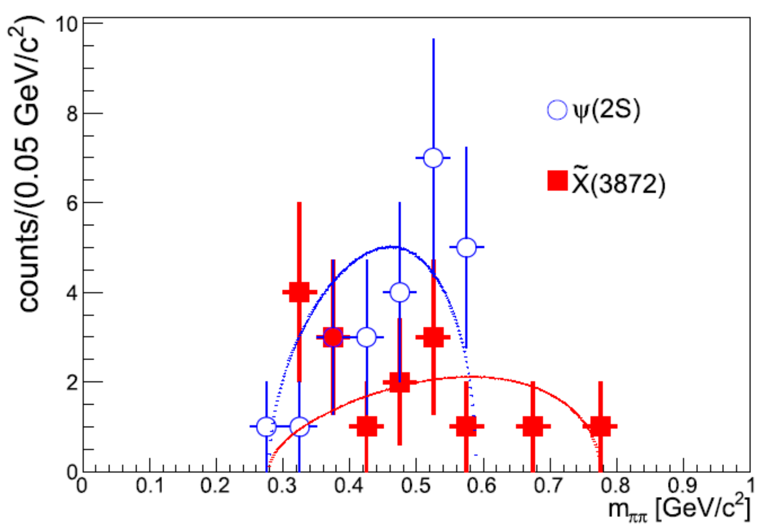
Heavy Flavor@EicC

PLB783(2018)334@COMPASS $4.1\ \sigma$

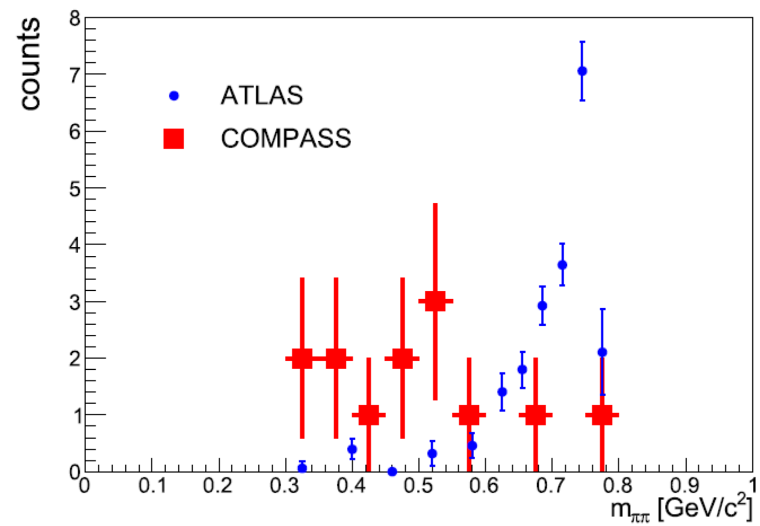


$$\sigma_{\gamma N\to\tilde{X}(3872)\pi N'}\times\mathcal{B}_{\tilde{X}(3872)\to J/\psi\pi\pi}=71\pm28(\mathrm{stat})\pm39(\mathrm{syst})\ \mathrm{pb}.$$

Benchmark channel@EicC: Zb(10610,10650)?
NRQCD does NOT work!



(a)



(b)

JHEP01(2017) 117@ ATLAS

Summary&Outlook

EicC energies covers bottom sector

- Virtual/real photon, polarization measurernents to have more probes to the internal structure and quantum nurnbers of exotic candidate.
- Theoretical estimates/simulation of production rate?
- As a factory of bottom baryons?

EicC's urgent goal

- Define a list of benchmark reactions for efficiency, resolution, and particle-ID studies

gamma p -> Upsilon p + pions

gamma p -> Zb p + pions

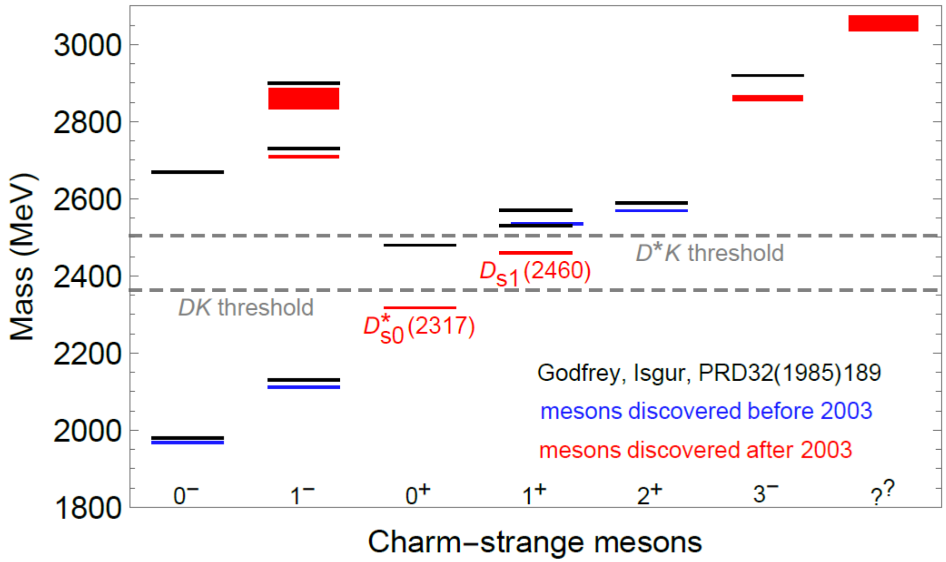
……

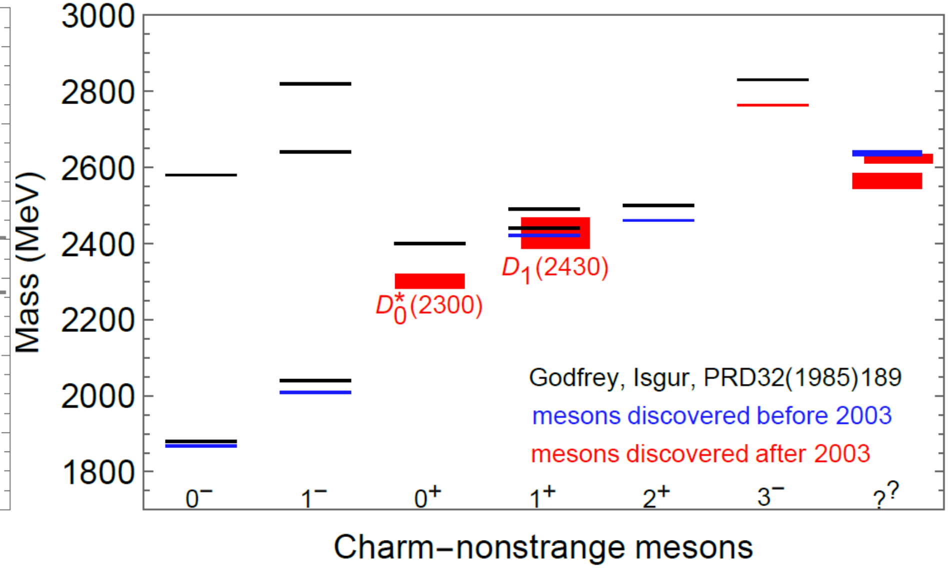
Heavily indebted to:

Feng-Kun Guo, Zhi Yang, Jia-Jun Wu, Ju-Jun Xie, Bing-Song Zou, Qiang Zhao ……

Thank You !

Charmed mesons





Bottomed mesons

B(5280), B*(5325), B_1(5721), B_2(5747), B_J(5732), B_J(5840), B_J(5970)

B_s(5367), B^*_s(5415), B_{s1}(5830), B_{s2}(5840), B_{sJ}(5850)

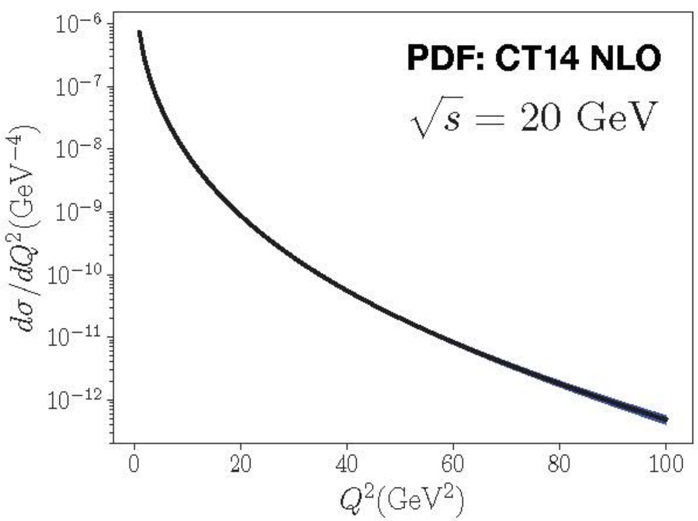
Xiaojun Yao@Duke

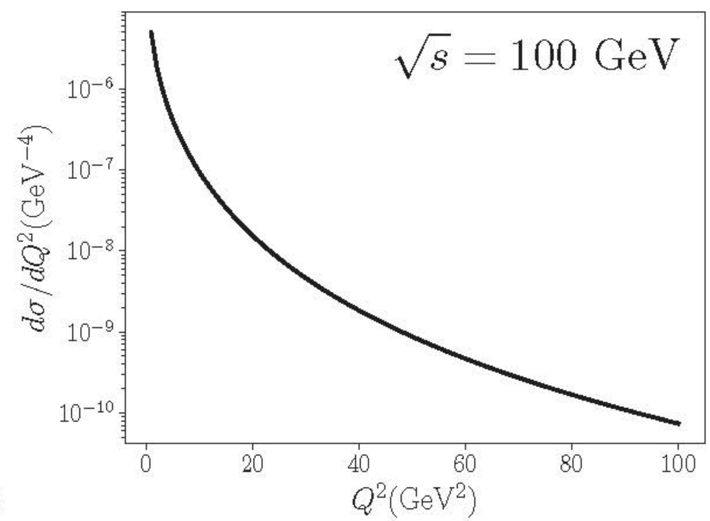
Quarkonium Cross Section

NRQCD factorization

$$\sigma(e+p\to e+\psi+X)=\int\frac{dQ^2}{Q^2}\int dy\int dx\, f_{g/p}(x)\,\delta(xys-(2m_c)^2-Q^2)$$
$$\times\frac{2\alpha_s(\mu^2)\alpha^2e_c^2\pi^2}{m_c(Q^2+(2m_c)^2)}\left\{\frac{1+(1-y)^2}{y}\left[\langle\mathcal{O}_8^\psi(^1S_0)\rangle+\frac{3Q^2+7(2m_c)^2}{Q^2+(2m_c)^2}\frac{\langle\mathcal{O}_8^\psi(^3P_0)\rangle}{m_c^2}\right]\right.$$
$$\left.-y\frac{8(2m_c)^2Q^2}{(Q^2+(2m_c)^2)^2}\frac{\langle\mathcal{O}_8^\psi(^3P_0)\rangle}{m_c^2}\right\},$$

S.Fleming and T.Mehen PRD 57, 1846 (1998)





5

Heavy Flavor@EicC

R. Molina, C. W. Xiao, E. Oset, PRC86(2012)014604

J/psi produced in nuclei: Role of the Fermi motion?

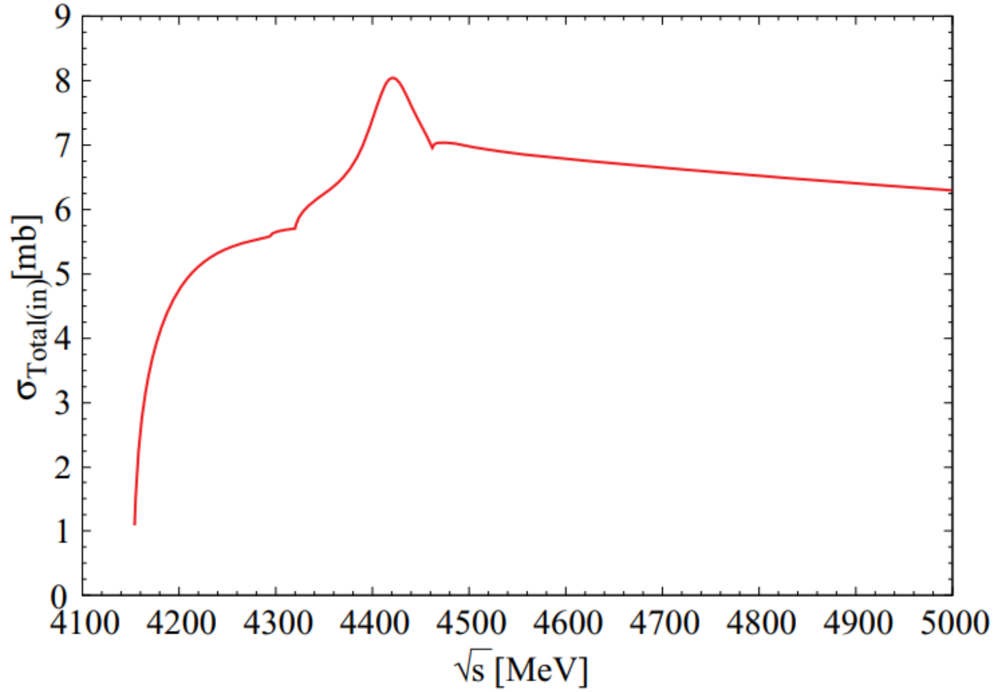


FIG. 6. (Color online) Total inelastic cross section of $J/\psi N$.