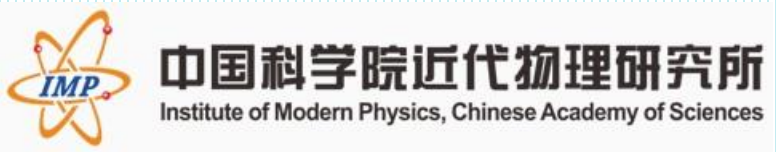
Photo- and electro-production of exotic states

from light quarks to charm then to bottom

曹　须



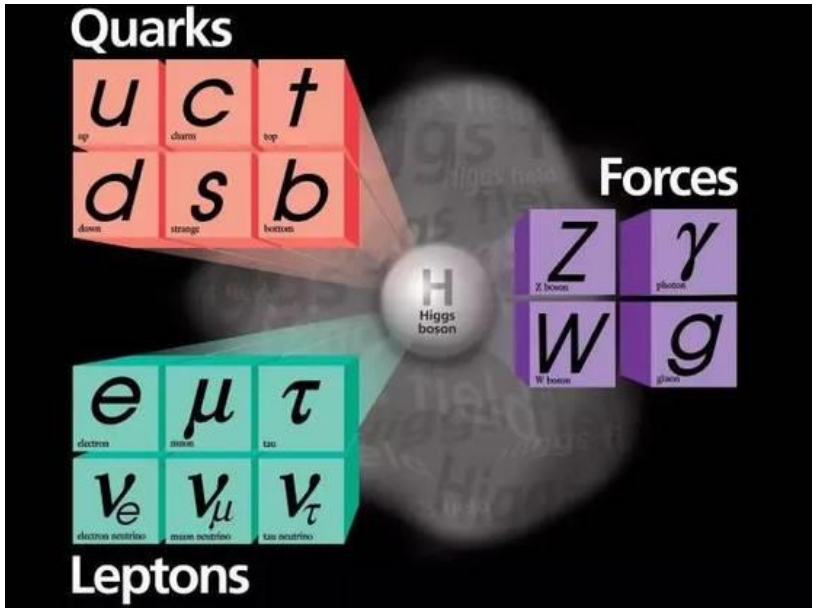
第二届强子与重味物理理论与实验联合研讨会
兰州大学，2021年3月25~28日

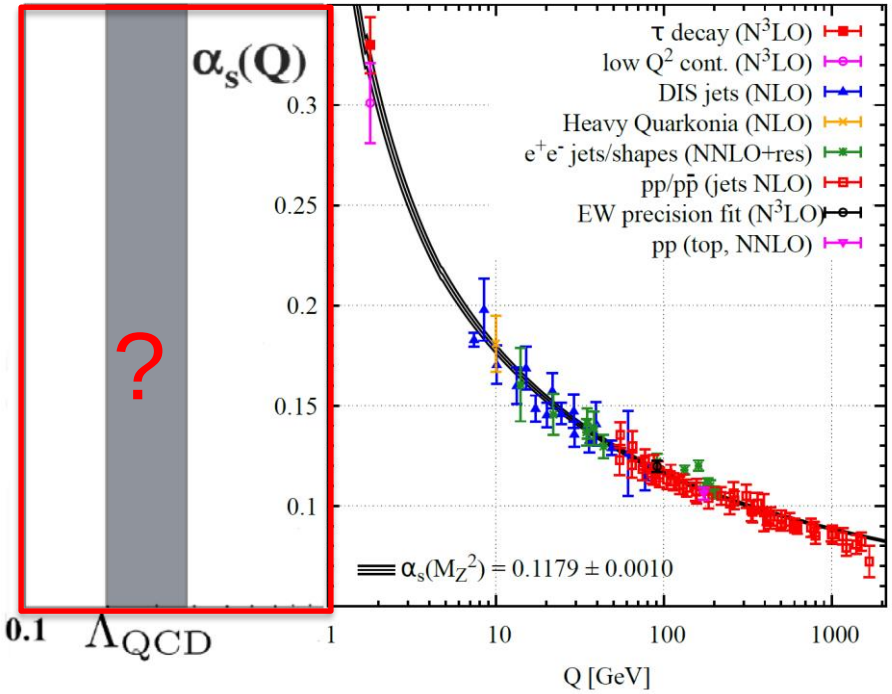
Introduction

Low-energy QCD: a big challenge

- Mysteries in hadron spectroscopy

  Hadron: a composite object constituted from quarks and gluon.

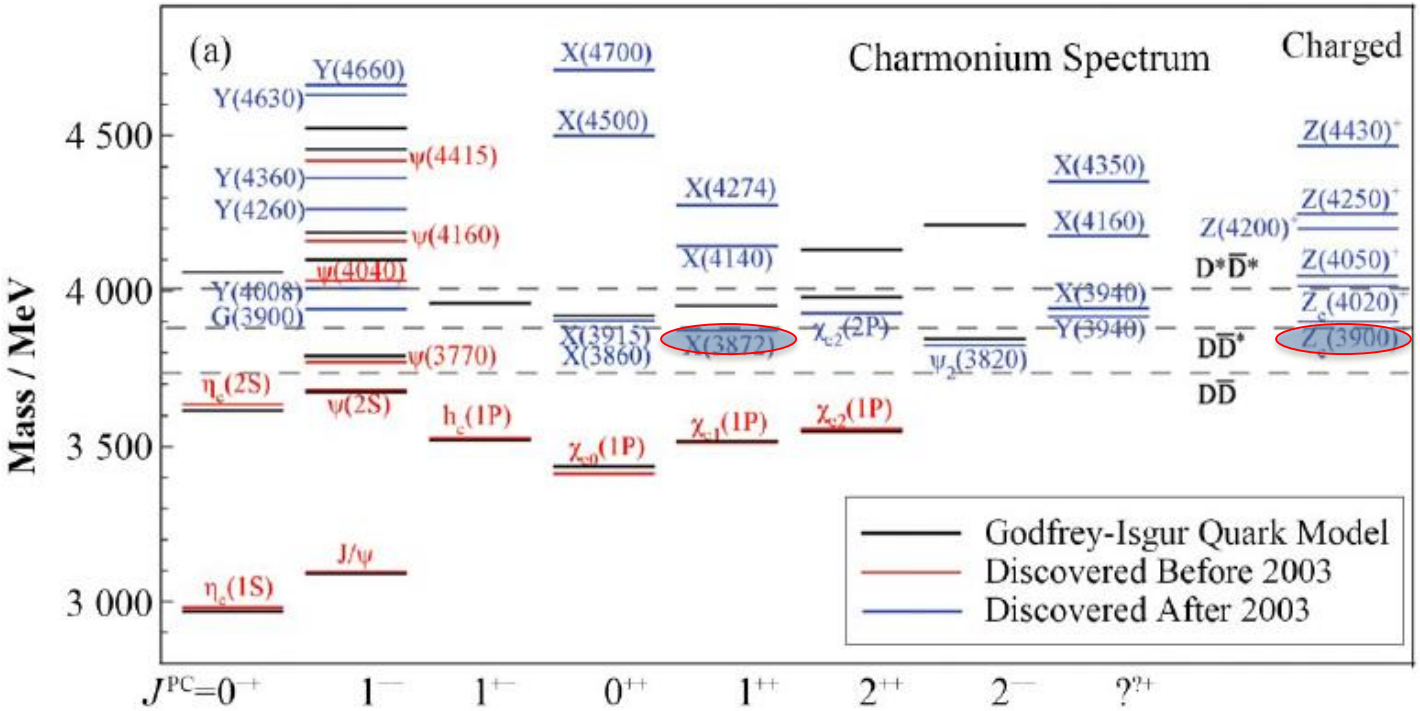




Introduction

- Charmonium and XYZ spectroscopy:

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

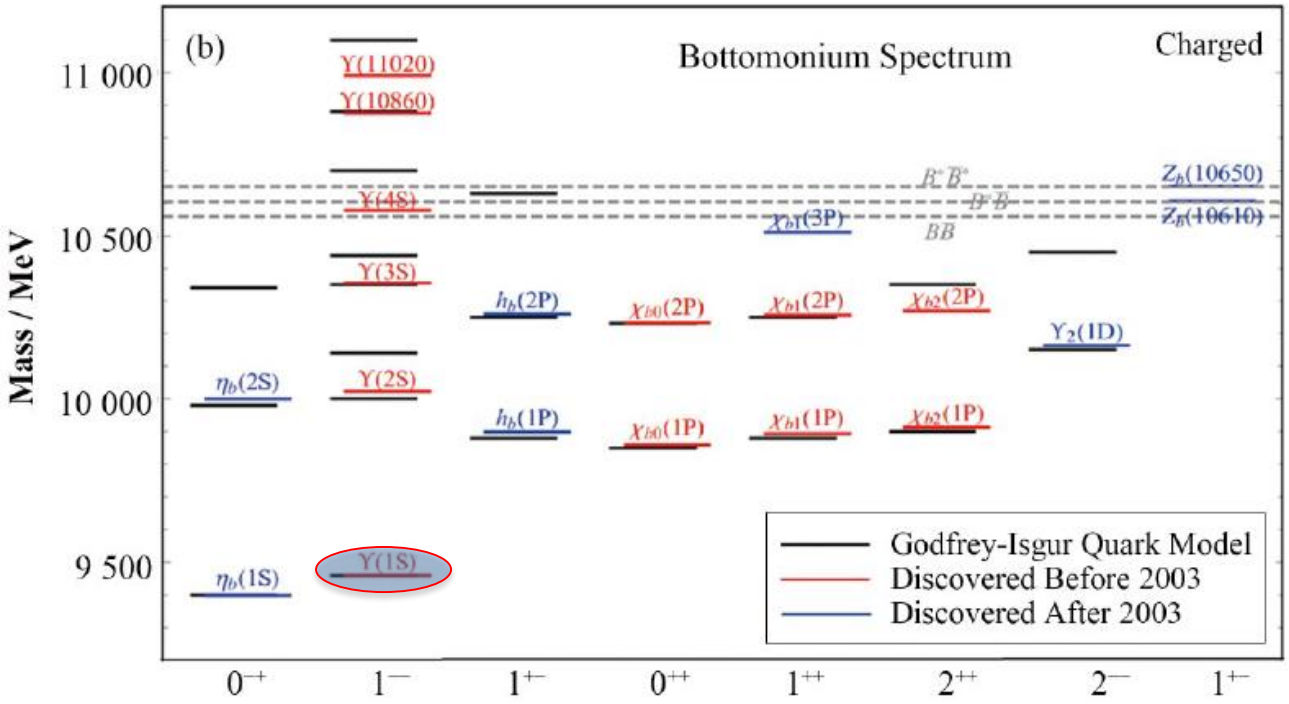


courtesy of F.K.Guo

Introduction

- Bottomonium and XYZ-like spectroscopy:

  much less states observed. Only two Z_b in bottomonium region

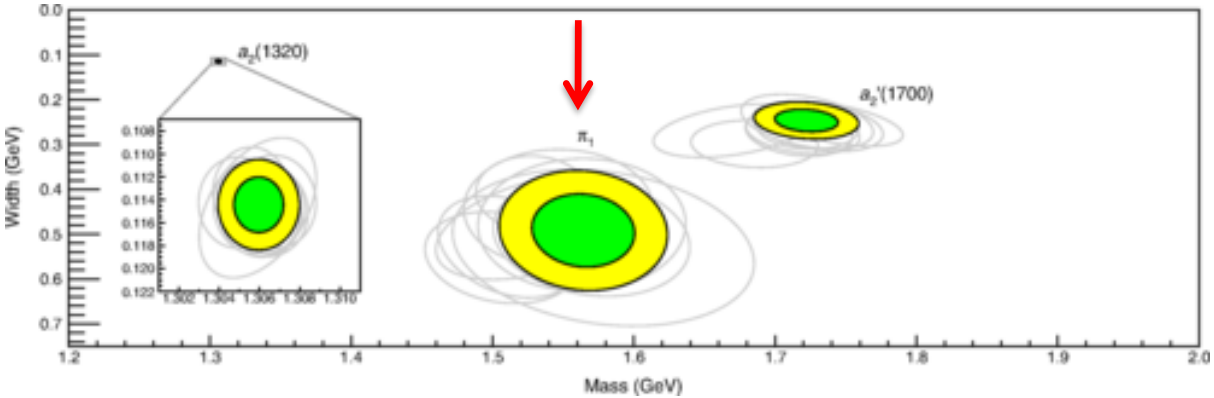


courtesy of F.K.Guo

Introduction

- Meson spectroscopy in light quark sector
- The only exotic J^P state: $\pi_1(1600)$ 1^{+-}: coupling to both $\eta^{(\prime)}\pi$

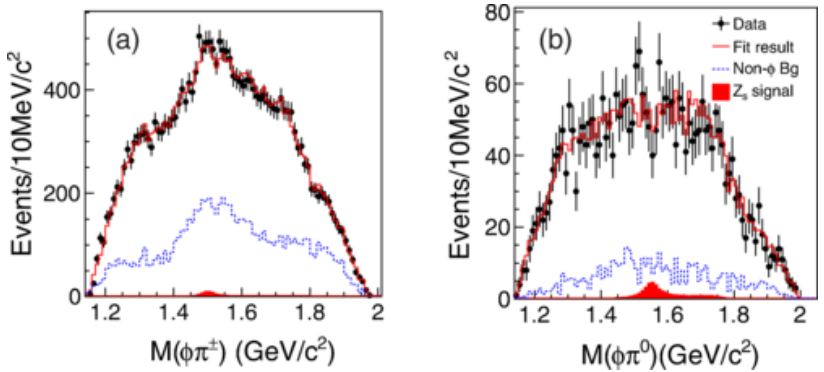
PRL122, 042002 (2019)



- NO charged Z_s :

  e.g.BESIII $e^+e^- \to \phi\pi\pi$

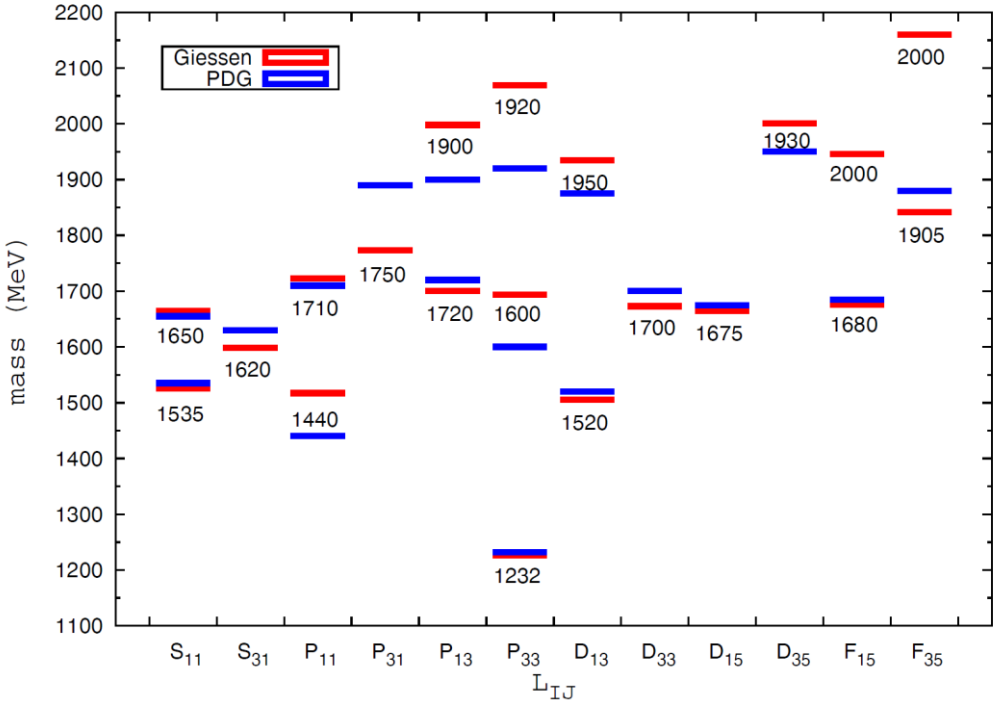
  PRD 99(2019)011101



Introduction

- Baryon spectroscopy: H. Lenske, M. Dhar, T. Gaitanos, X.C, PPNP 98(2018)119
- N^* & Δ^*: excitation of internal freedom:
- wide > 100 MeV with coupling to πN, ηN, ρN, σN, ωN, γN…

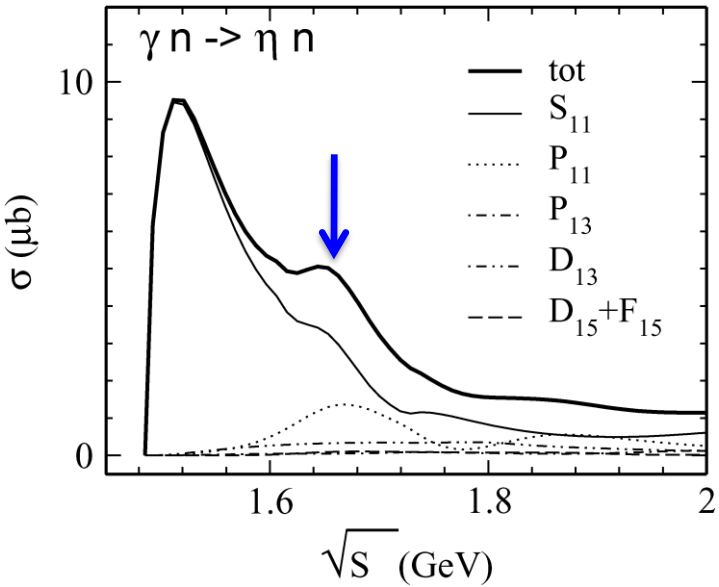
Narrow state makes sense!



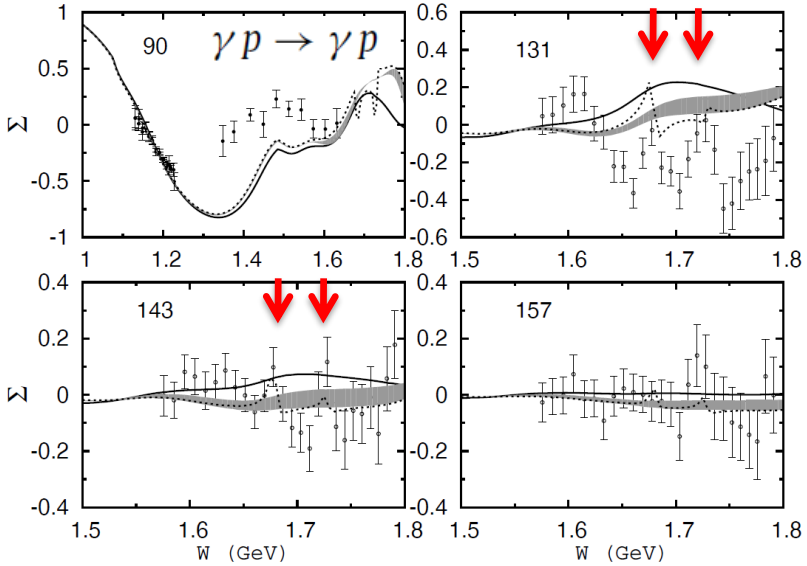
Introduction

- No evidence of Pentaquark P_s ($uuds\bar{s}$):

Shklyar et al. PLB650(2007)172



X. C., H. Lenske, PLB772(2017)274



- Alternation I: interference in the $1/2^-$ wave - S11(1535) and S11(1650) ---Bonn-Gatchina & chiral quark model(X.H.Zhong)
- Alternation II: strangeness threshold openings ---Doring & Nakayama

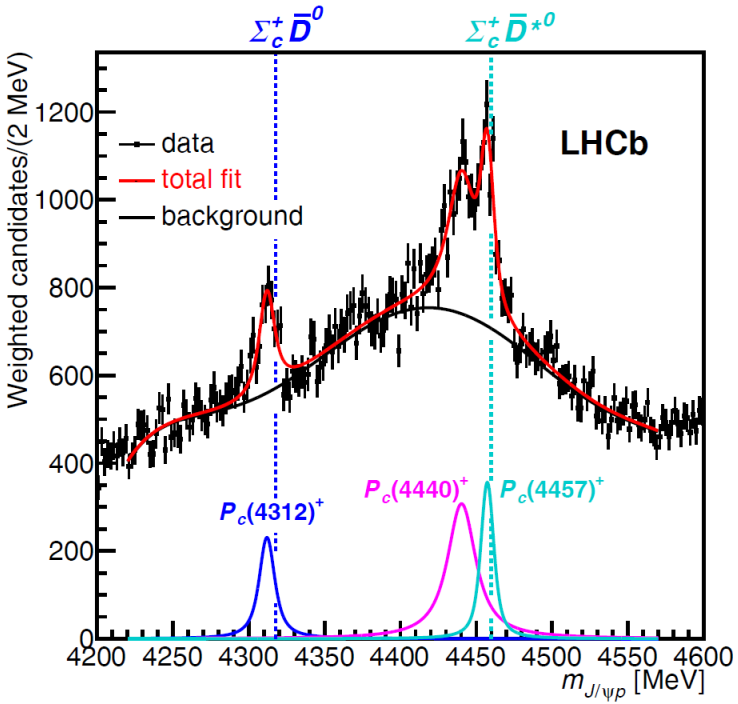
The significance of exotic N* is little (~1σ)

Introduction

- Evidence of Pentaquark $P_c(uudc\bar{c})$

LHCb,PRL115(2015)072001;122(2019)222001

$\Lambda_b^0 \rightarrow J/\psi\ p\ K^-$



$P_b(uudb\bar{b})$

Partners of P_c at bottom sector

?

Under heavy quark flavor symmetry

P_b are surely there,

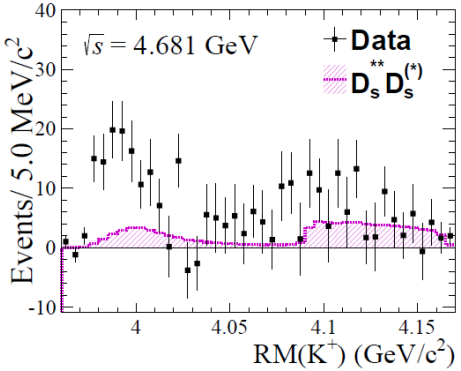
but cannot be produced through the decay of heavier baryons!!!

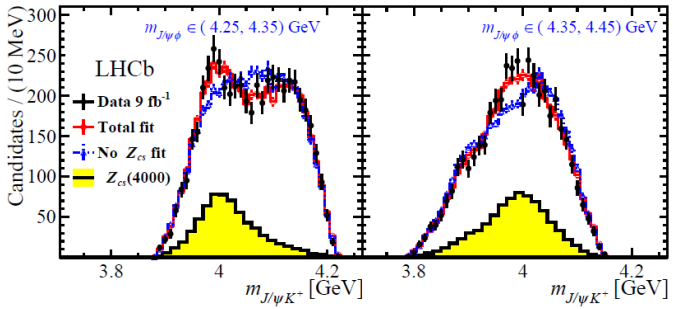
P_b	Mass M (GeV)	Width Γ(MeV)
J. J. Wu et al. [61]	11.10	1.33
Karliner&Rosner [42, 63]	11.14	39‡ or 61†
Huang et al. [85, 86]	11.09 - 11.14✠	7.0
Lin et al. [87]	—	30-300
Yang et al. [88]	11.14	—
Xiao et al. [62]	10.96-11.022	2-110
Shen et al. [89]	11.120	25
Gutsche et al. [90]	11.125	—

Introduction

- Evidence of Z_{cs} ($c\bar{c}s\bar{q}$)

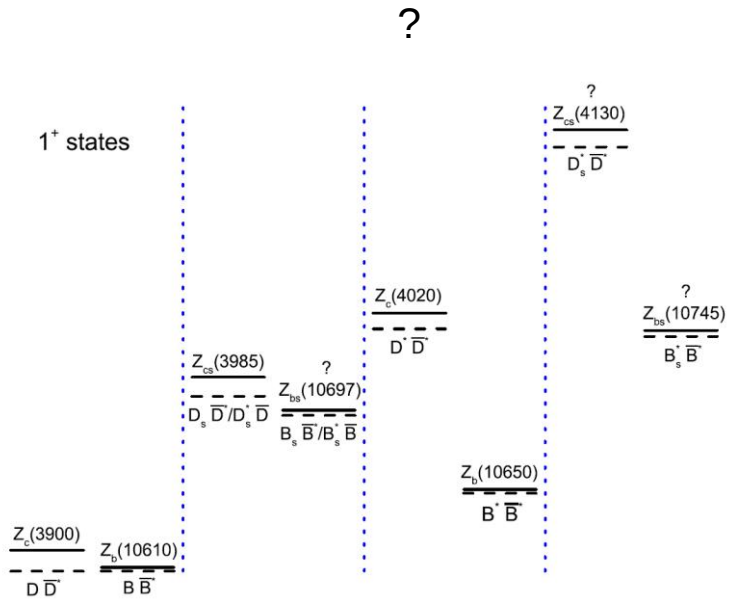
BESIII, 2011.07855; LHCb, 2103.01803





Z_{bs} ($b\bar{b}s\bar{q}$)

Partners of Z_{cs} at bottom sector



Z. Yang, X.C., F-K. Guo, J. Nieves, M. P. Valderrama, 2011.08725

X. C., J.-P. Dai, Z. Yang, EPJC (2021) 81:184

Introduction

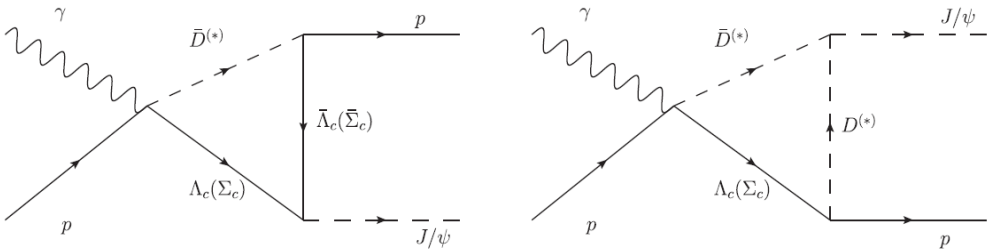
➢ Merits of ep collisions

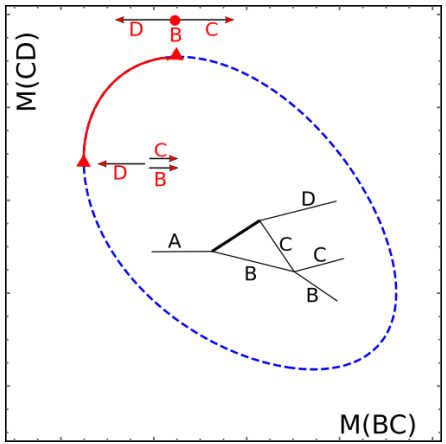
1. Larger cross section compared to e^+e^- collision
2. Smaller background compared to pp and $p\bar{p}$ collisions
3. Polarized beams: pin down the quantum numbers J^P
4. Flexible mass

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

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

5. No triangle sigularity





Schematic Design of EicC

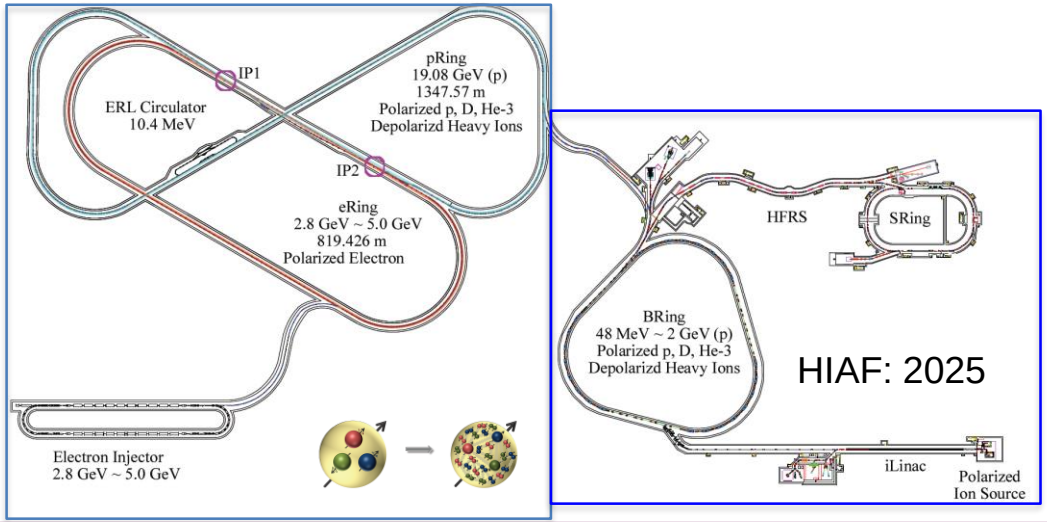
Electron-Ion Collider in China

white paper: 2102.09222, Front. Phys. to appear

核技术, 43(2): 020001 (2020)

中国科学: 物理学力学天文学, 50: 112005 (2020)

- **Energy:**
  - electron + proton: 3.5 GeV × 20 GeV
  - electron + ^{3}He: 3.5 GeV × 40 GeV (nucleus)
- **Luminosity:**
  - Instantaneous Lumi: 2 x 10^{33} cm^{-2} s^{-1}
  - Integrated Lumi for simulation = 50 fb^{-1}
- **Polarization:**
  - electron: 80% L
  - proton: 70% L&T
  - ^{3}He: 70% L&T
- **Phase space coverage**
  - **$4x10^{-3} < x < \sim 0.1$**
  - **$\sqrt{s} \sim 16.7$ GeV**



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EIC-US: 2103.05419; 1708.01527; 1410.8831

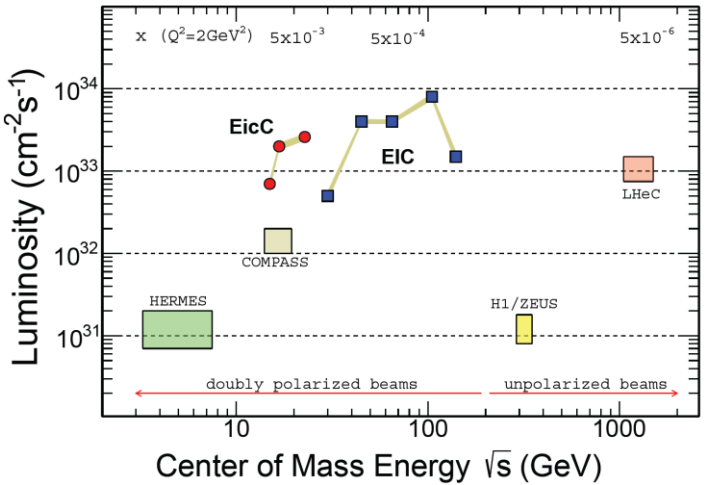


Photo- & electro-production

➢ Formalism

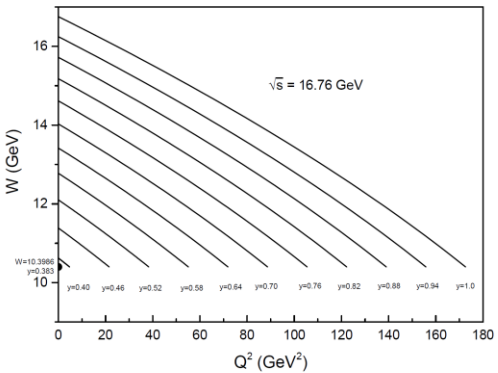
Q^2 dependence

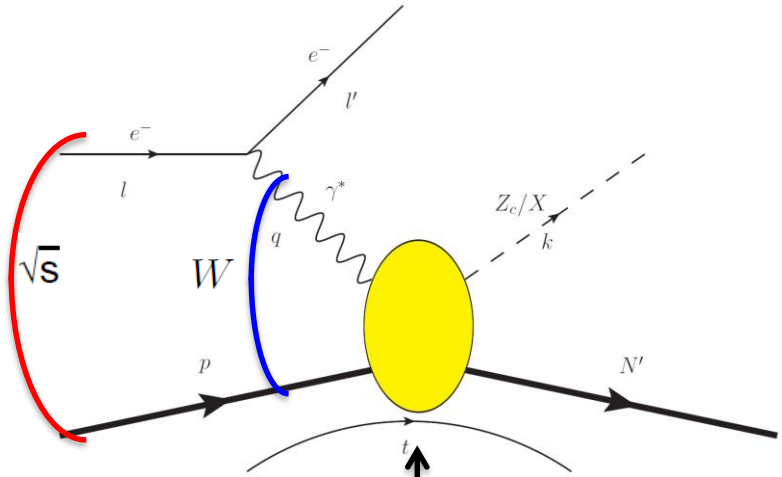
$$\frac{\mathrm{d}\sigma_{ep\to eVp}}{\mathrm{d}Q^2\mathrm{d}y\mathrm{d}t} = \Gamma_T(1+\epsilon R_L)D\frac{\mathrm{d}\sigma_{\gamma p\to Vp}}{\mathrm{d}t}$$

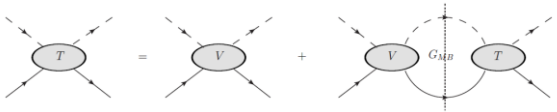
Photon flux ~ Q^{-2}

$\mathrm{d}W$

$$W^2 = y(s-M_N^2)+M_N^2-Q^2$$







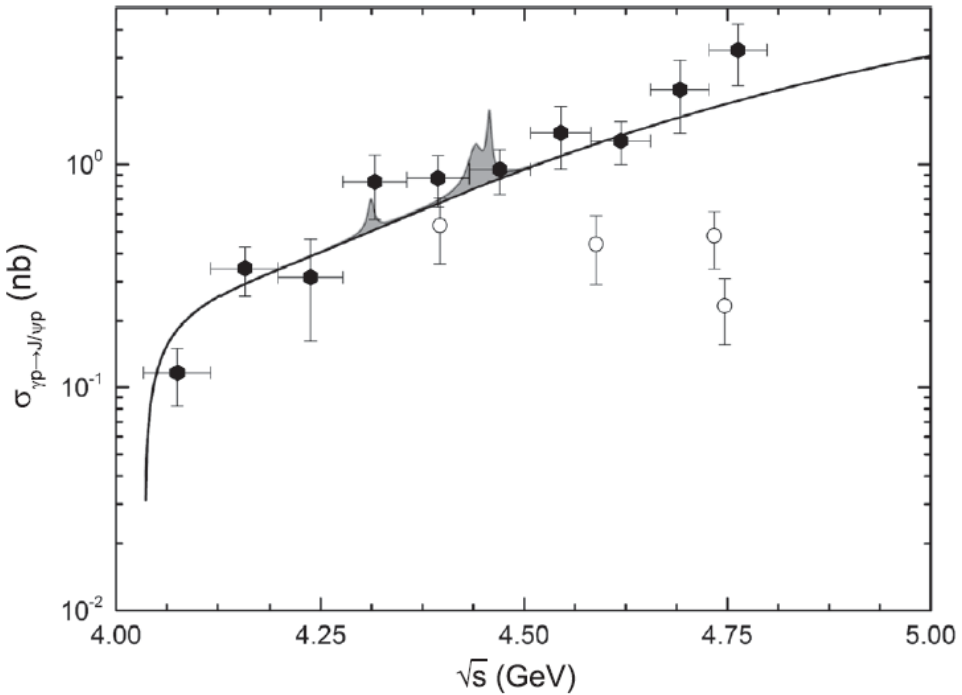
Input: P_b & P_c

Z & Pomeron ~ $e^{-b\,t(y,Q2)}$

Photo- & electro-production

- Photoproduction of P_c

X. C.&J.-P. Dai, PRD100(2019)054033



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

LHCb

$$5\% > \mathcal{B}(P_c^+ \to J/\psi p) > 0.5\% \sim 0.05\%$$

Photo- & electro-production

- Photoproduction of P_b

X. C.& F-K Guo &Y-T Liang, *et al.*, PRD101(2020)074010

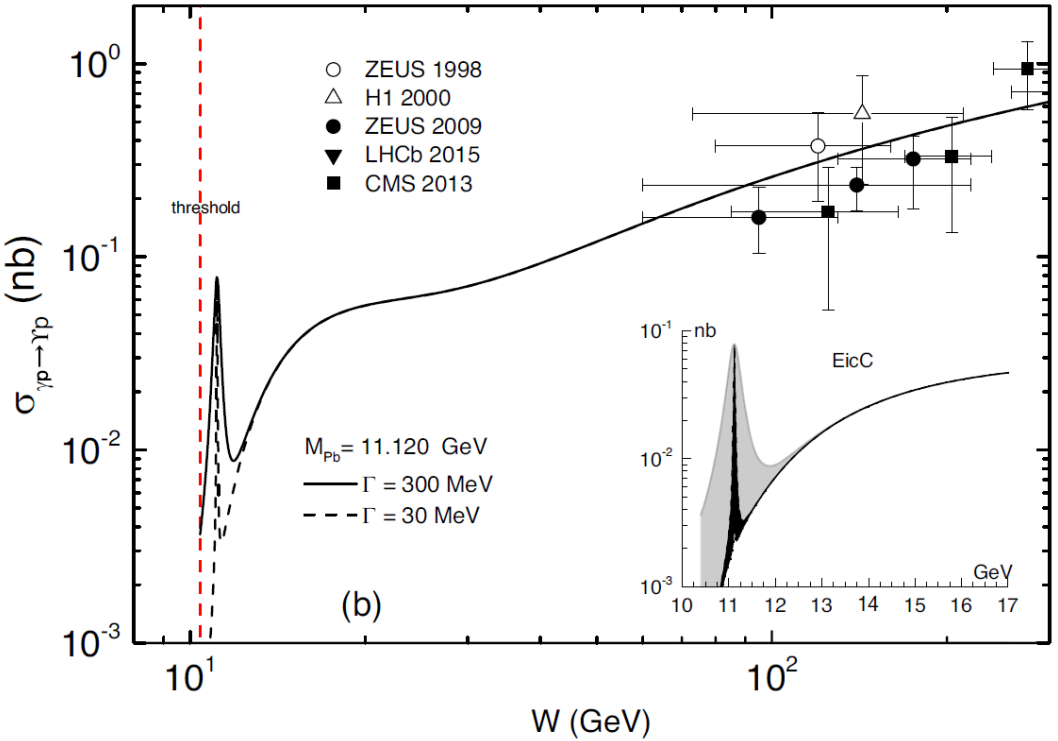


Photo- & electro-production

➢ Photoproduction of $Z_c(3900)$

X. C. in preparation, see also Q. Y. Lin & X. Liu & H. S. Xu, PRD88(2013)114009

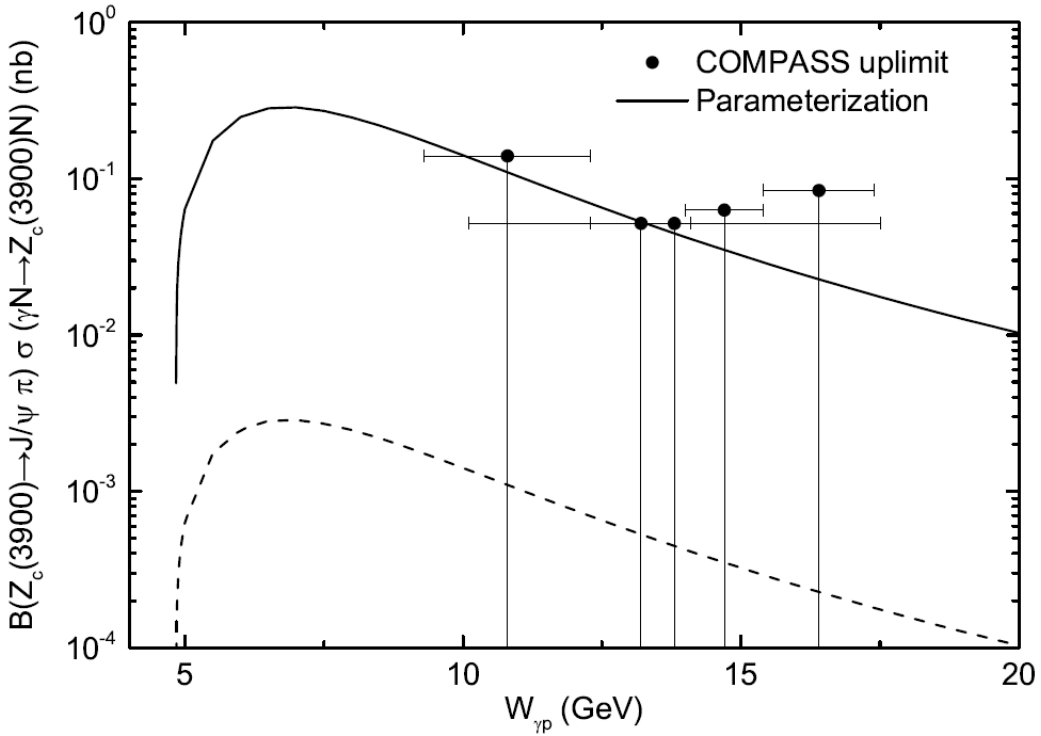
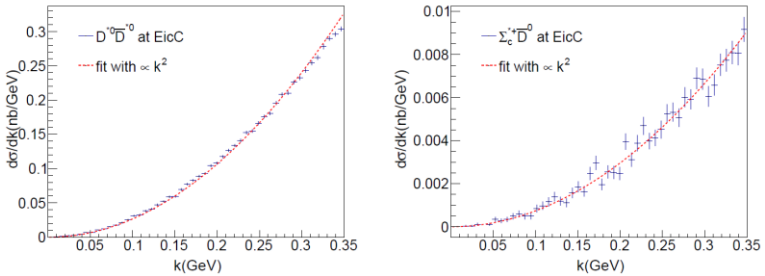


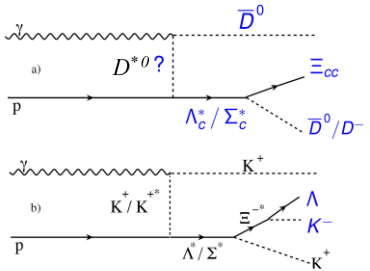
Photo- & electro-production

➢ Electroproduction@EicC

- Semi-inclusive production



- Open charm/bottom channels



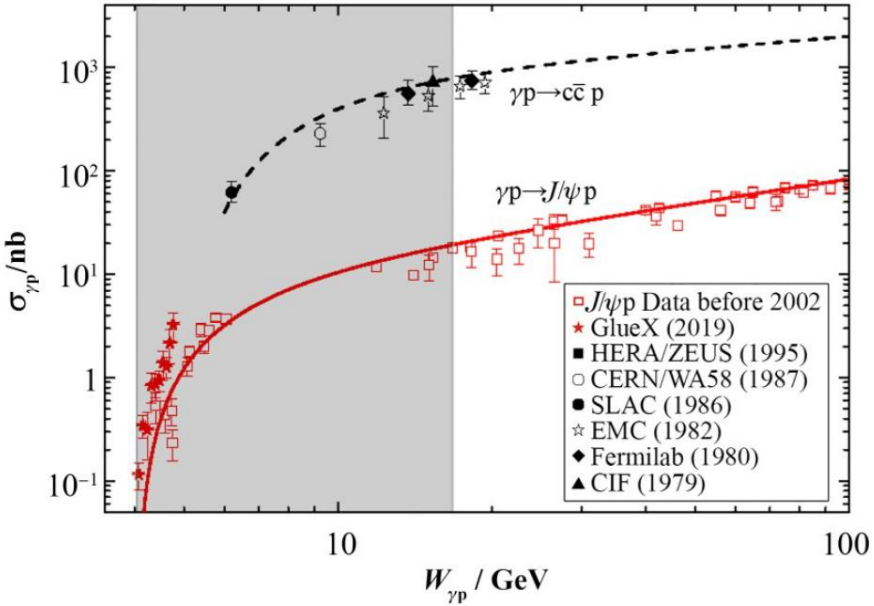
$\gamma p \to K^+(K^+\Xi^{-*}) \to K^+(p\pi^- K^-)K^+$

Exotic states	Production, decay processes	Detection efficiency	Expected events
$P_c(4312)$	$ep \to eP_c(4312)$ $P_c(4312) \to pJ/\psi$ $J/\psi \to l^+l^-$	~30%	15~1 450
$P_c(4440)$	$ep \to eP_c(4440)$ $P_c(4440) \to pJ/\psi$ $J/\psi \to l^+l^-$	~30%	20~2 200
$P_c(4457)$	$ep \to eP_c(4457)$ $P_c(4457) \to pJ/\psi$ $J/\psi \to l^+l^-$	~30%	10~650
$P_b(narrow)$	$ep \to eP_b(\text{narrow})$ $P_b(\text{narrow}) \to p\Upsilon$ $\Upsilon \to l^+l^-$	~30%	0~20
$P_b(wide)$	$ep \to eP_b(\text{wide})$ $P_b(\text{wide}) \to p\Upsilon$ $\Upsilon \to l^+l^-$	~30%	0~200
$X(3872)$	$ep \to eX(3872)p$ $X(3872) \to \pi^+\pi^- J/\psi$ $J/\psi \to l^+l^-$	~50%	0~90
$Z_c^+(3900)$	$ep \to eZ_c^+(3900)n$ $Z_c^+(3900) \to \pi^+ J/\psi$ $J/\psi \to l^+l^-$	~60%	90~9 300

Photo- & electro-production

➢ Electroproduction

- ➢ Decay to hidden OR open channel? $P_{b/c}$ MUST make a choice if they are real resonances!
- ➢ Open channels are expected to be large, though a calculation of each channel is tough.



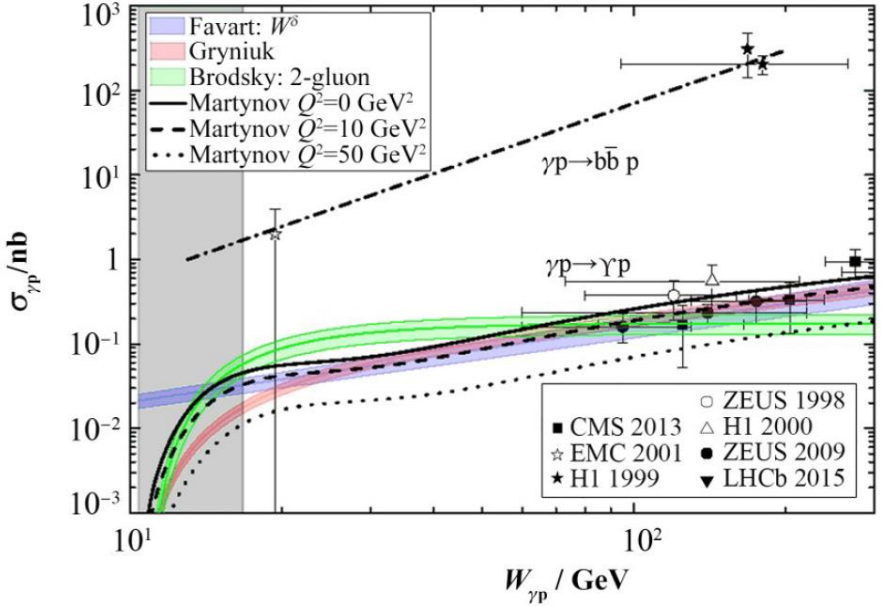
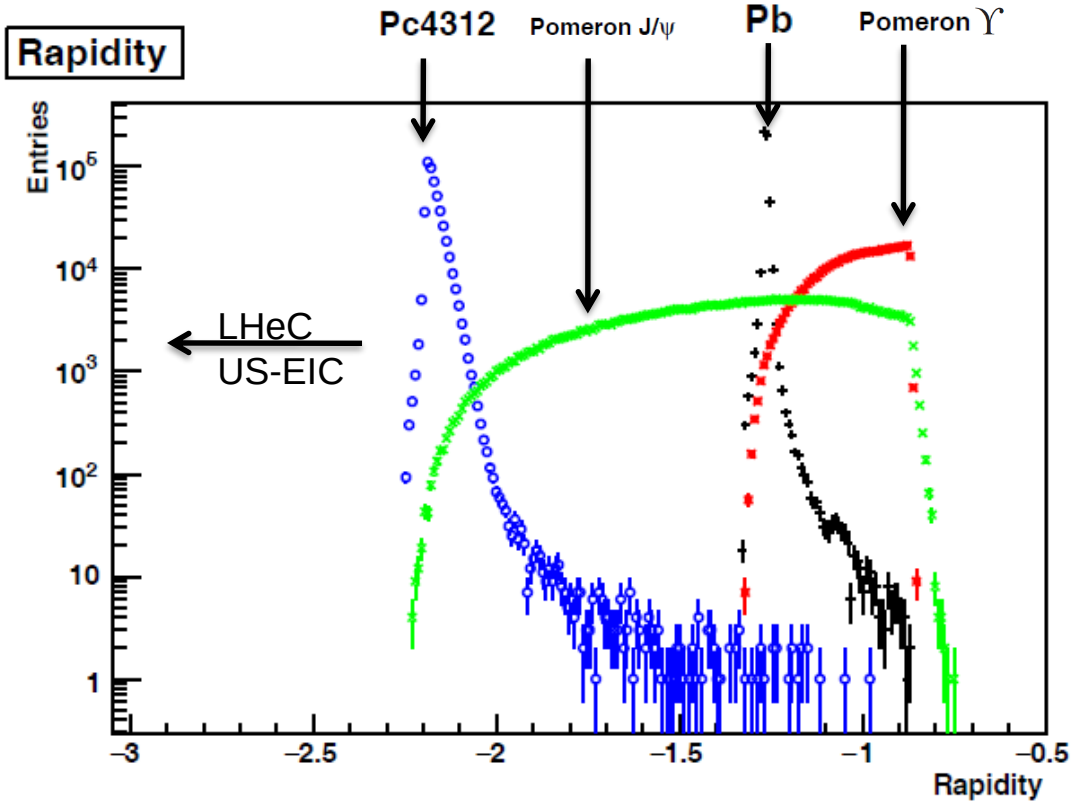


Photo- & electro-production

- Electroproduction

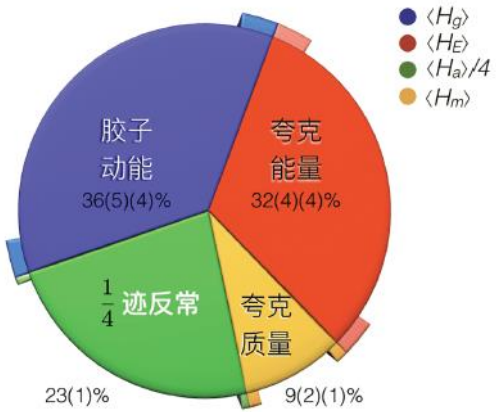


Proper Kinematical cuts enlarge Pc/background ratio
Z. Yang, X. C., Y-T Liang, J-J Wu, Chin. Phys. C44,084102(2020)

Photo- & electro-production

➢ Beyond exotica

➢ A topic concerning about many issues: P_b is only one of them



$$\gamma p \to \Upsilon p \qquad \frac{\Delta m_Q}{m_Q} \simeq \begin{cases} 2.5\% \\ 1.0\% \end{cases}, \qquad \frac{\Delta \alpha_s}{\alpha_s} \simeq \begin{cases} 7.8\% & \text{for } J/\psi \\ 3.7\% & \text{for } \Upsilon \end{cases}$$

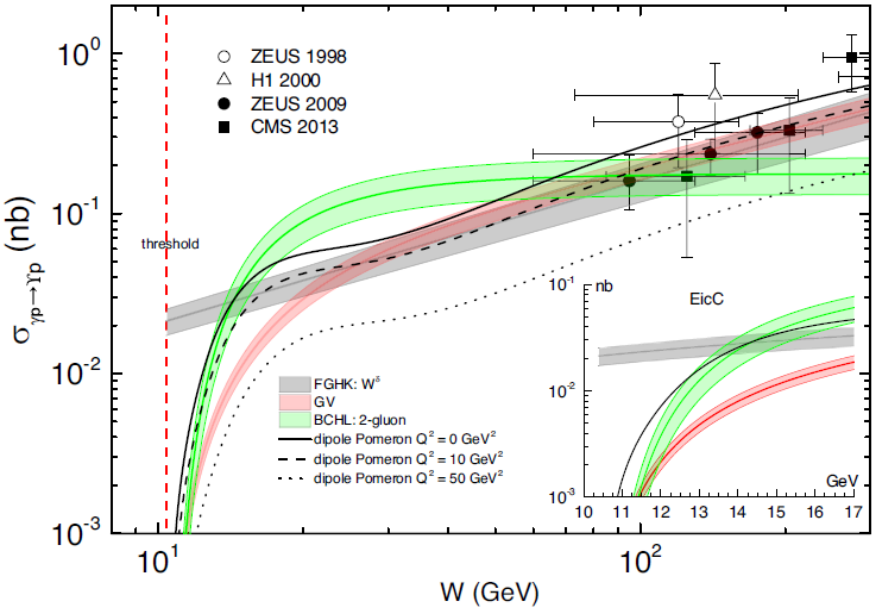
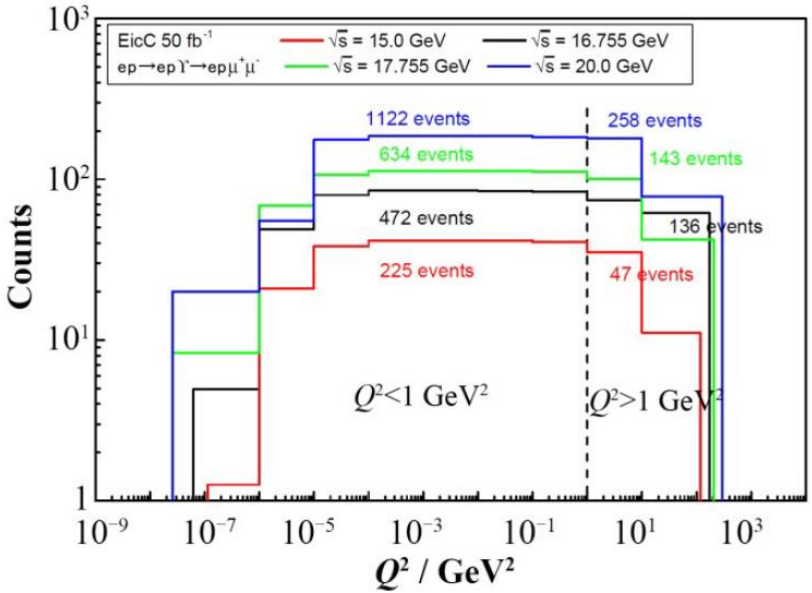


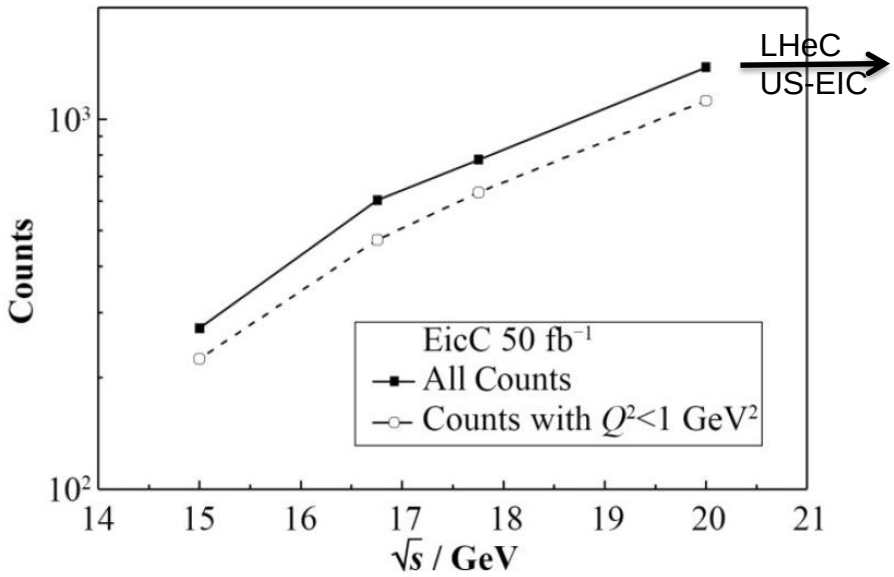
Photo- & electro-production

➢ Beyond exotica

- A topic concerning about many issues: P_b is only one of them

$$ep \rightarrow ep\Upsilon$$





Summary

- **Photo- & Electroproduction**
  - Narrow exotic states from light quarks to charm then to bottom is special!
  - To study & disentangle nature of hadrons in charm & bottom region
  - Hint for the puzzle of NO narrow states in light quark sector?
- **EicC & EIC-US**
  - A perfect platform for Photo- & Electroproduction
  - Strange states: Z_{cs} need more luminosity
- … indebted to many discussions with EicC collaborations … …

Thanks

Backup

- B decay

$B^+(\times 10^{-3})$		$B^0(\times 10^{-3})$	
K^+J/ψ	1.010±0.028	K^0J/ψ	0.873±0.032
$K^+\eta_c$	1.09±0.09	$K^0\eta_c$	0.79±0.12
$K^+\chi_{c0}$	0.149±0.015	$K^0\chi_{c0}$	0.111±0.024
$K^+X(3872)$	$0.19\pm0.06^{\dagger}$	$K^0X(3872)$	$0.11^{+0.05\dagger}_{-0.04}$
$K^+Z_c(3900)$	$?^{\ddagger}$	$K^{\pm}Z_c(3900)^{\mp}$	$?^{\ddagger}$
$\to \eta_c\pi^+\pi^-$	<0.047	$\to J/\psi\pi^{\mp}$	<0.0009
$K^+Z_c(4430)$	$?^{\S}$	$K^{\pm}Z_c(4430)^{\mp}$	$?^{\S}$
$\to J/\psi\pi^+$	<0.015	$\to J/\psi\pi^{\mp}$	$0.0054^{+0.0040}_{-0.0012}$
$\to \psi(2S)\pi^+$	<0.047	$\to \psi(2S)\pi^{\mp}$	$0.060^{+0.030}_{-0.024}$

Backup

➢ Electroproduction@EicC

Nuclear Techniques (*in Chinese*), 2020,43(2): 020001
see also X. C.& F-K Guo &Y-T Liang, *et al.,* PRD101(2020)074010

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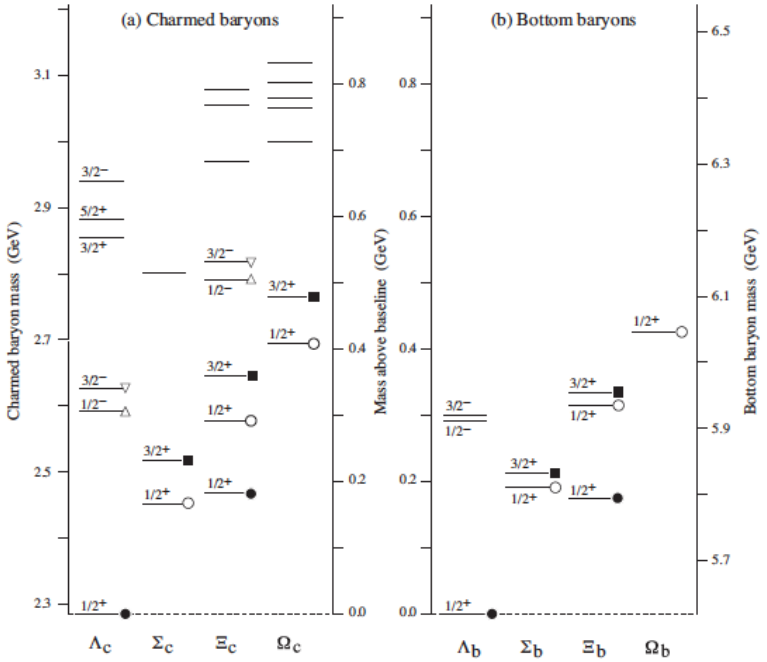
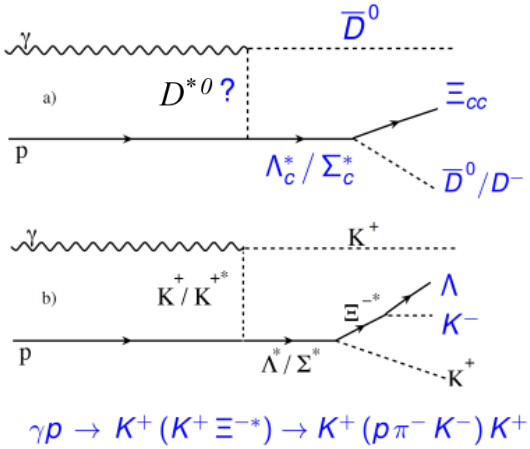
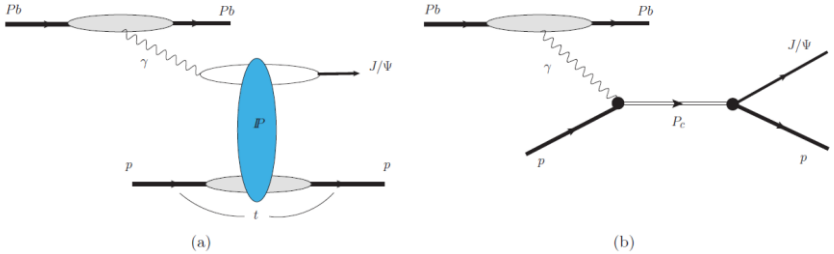




A coupled-channel calculation would make sense…

Backup

- Photoproduction of pentaquark states at the LHC & RHIC
- Goncalves&Jaime, PLB(2020)



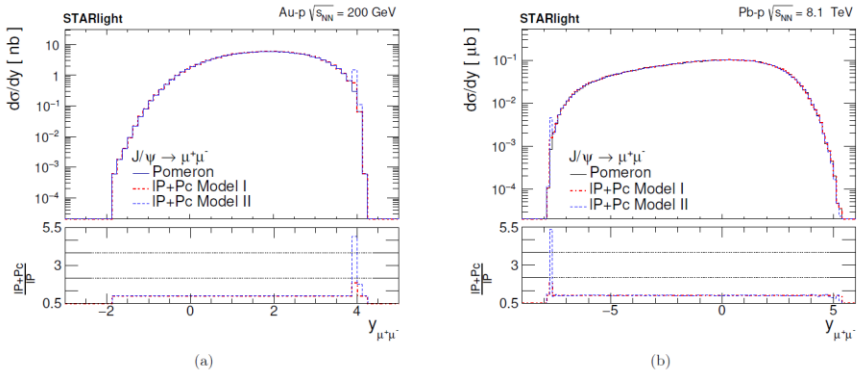


FIG. 3: Rapidity distribution for the J/Ψ photoproduction in (a) pAu collisions at RHIC and (b) pPb collisions at LHC in the collider mode.

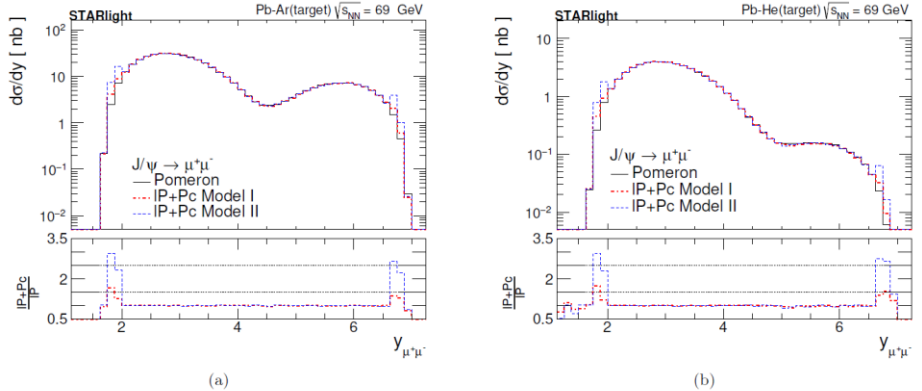


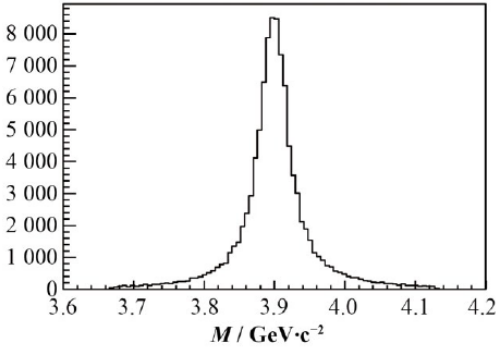
FIG. 5: Rapidity distribution for the J/Ψ photoproduction in (a) $Pb\,Ar$ and (b) $Pb\,He$ fixed – target collisions at LHC.

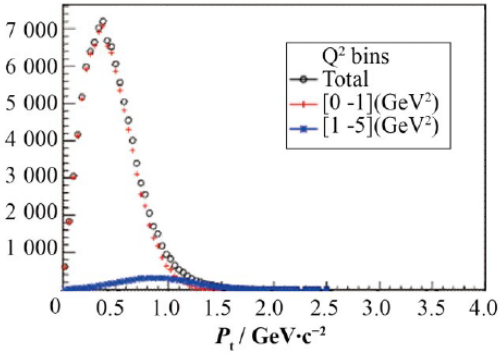
Backup

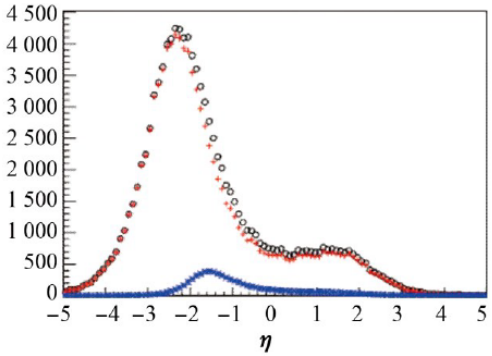
➢ Electroproduction@EicC

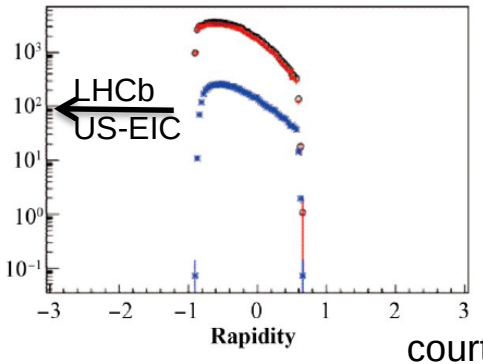
Nuclear Techniques (*in Chinese*), 2020,43(2): 020001

- A typical t-channel process for XYZ mesons
- $Z_c(3900)$





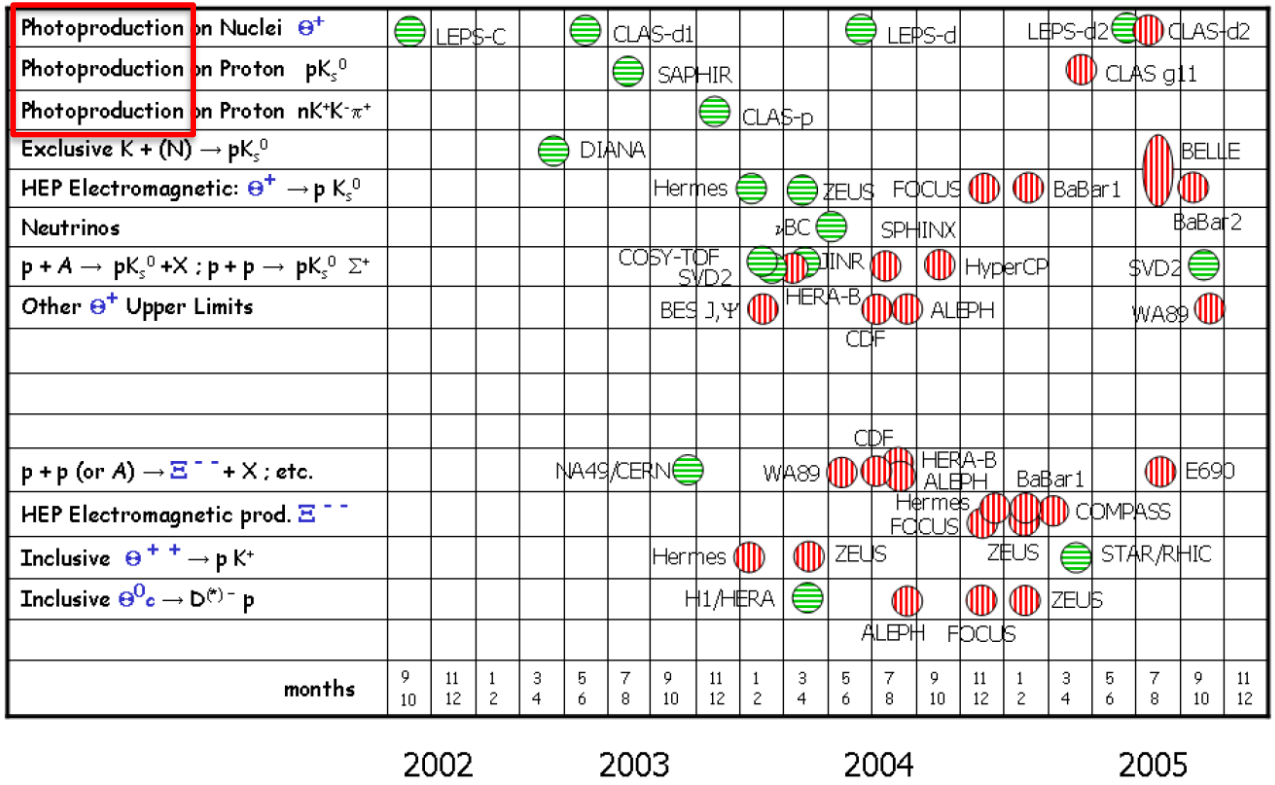




courtesy of Y.T.Liang

Backup

- Rise and Fall of Pentaquark Θ^+ (1540) ($uudd\bar{s}$): Schumacher, nucl-ex/0512042



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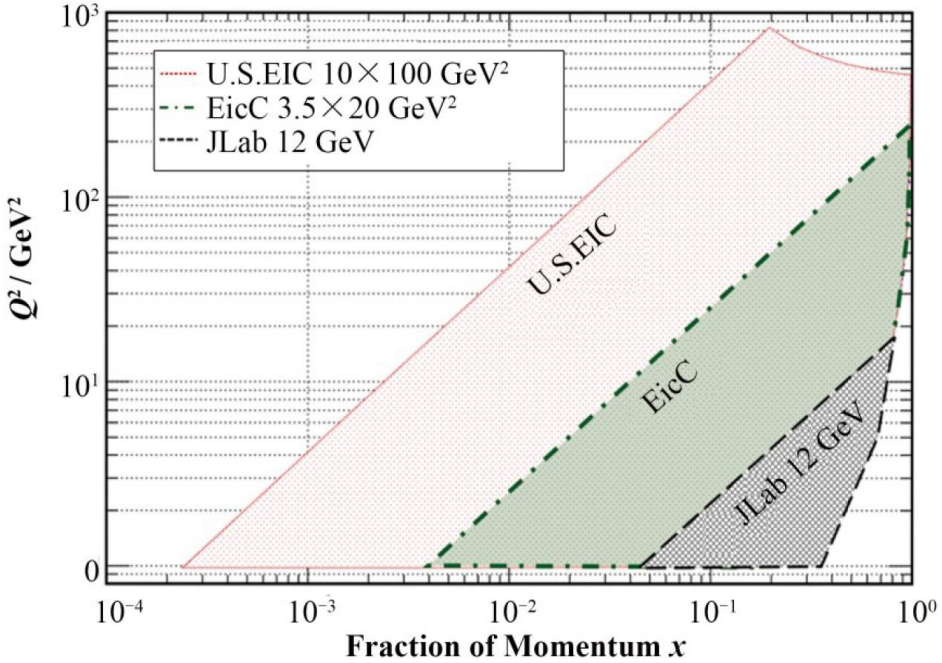
U.S.EIC 10×100 GeV²
EicC 3.5×20 GeV²
JLab 12 GeV
U.S.EIC
EicC
JLab 12 GeV
Q² / GeV²
Fraction of Momentum x
10³
10²
10¹
0
10⁻⁴
10⁻³
10⁻²
10⁻¹
10⁰

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