Spectroscopy: overview and theory

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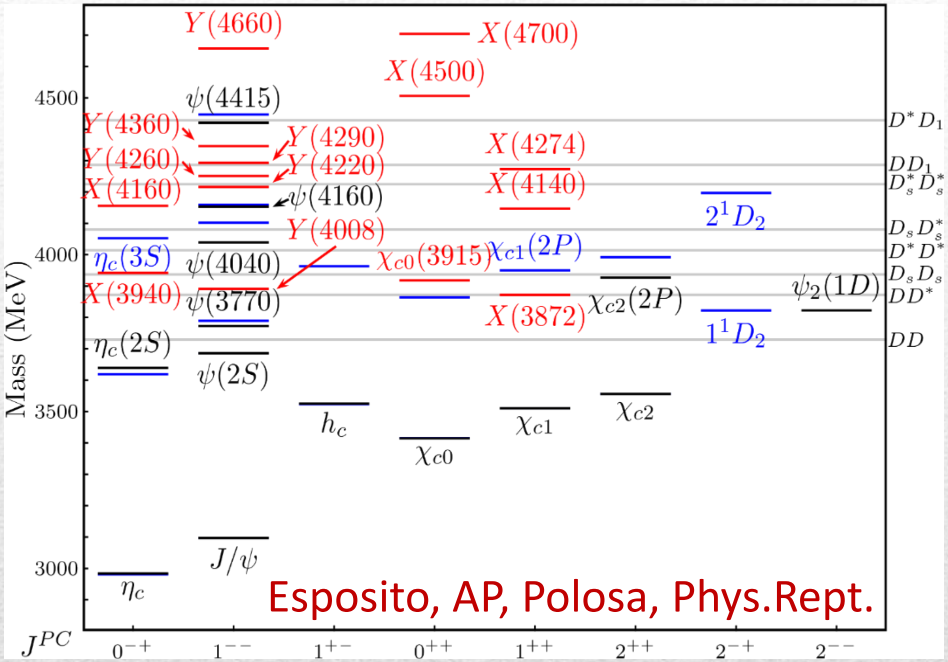
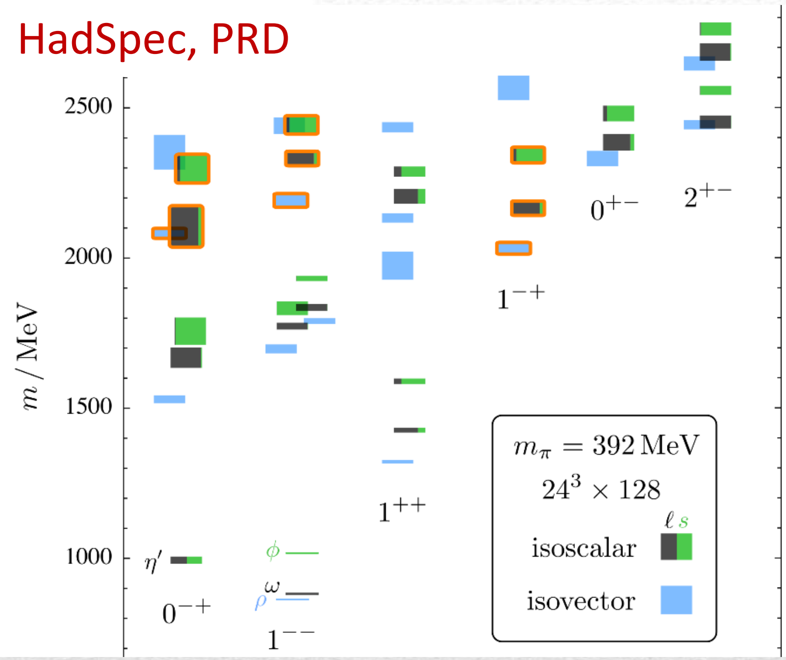
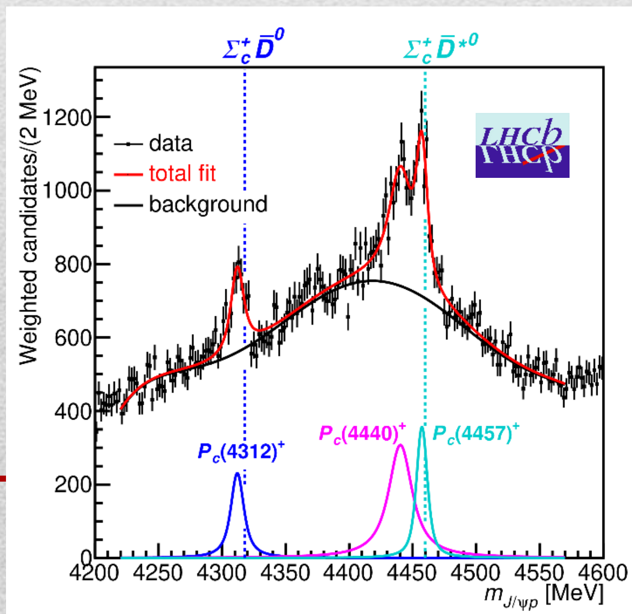
Temple University, March 19th, 2020

QCD spectrum



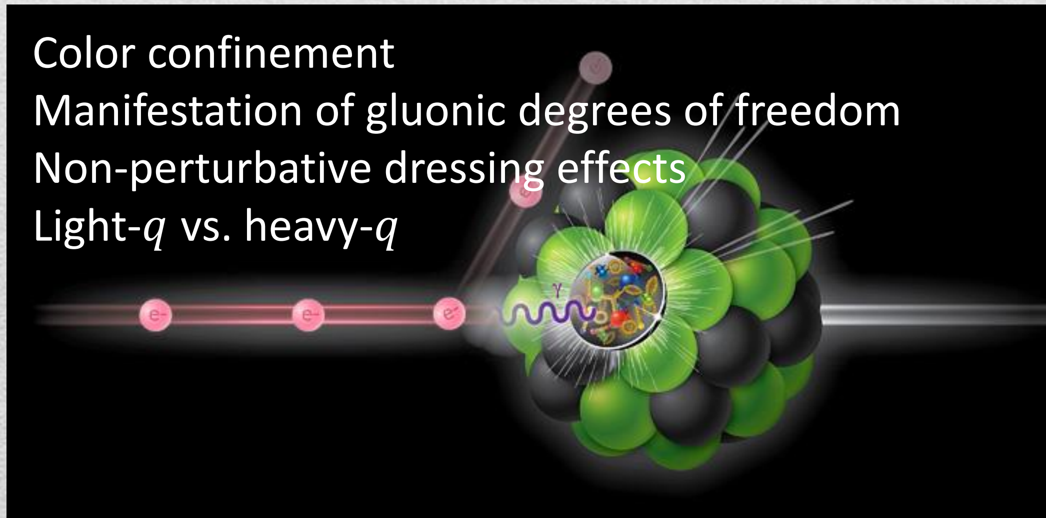




The spectrum of hadron excitations is incredibly rich

Several new observations beyond the minimal quark content

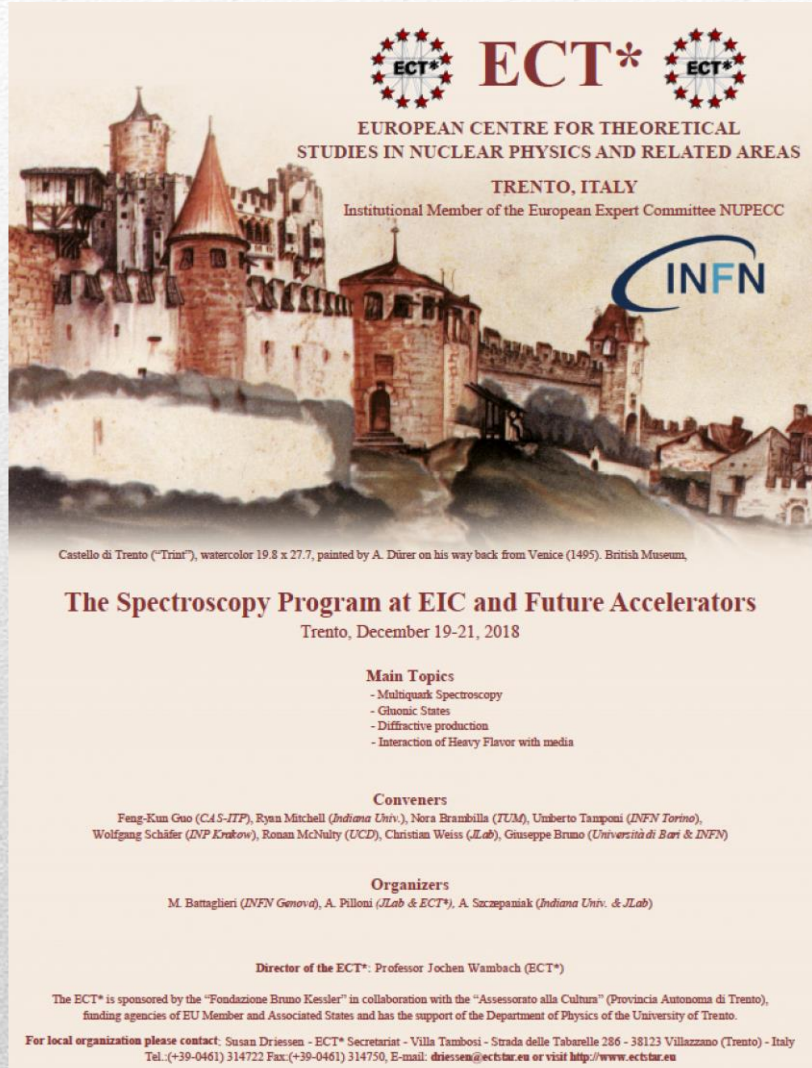
Hadron Spectroscopy at EIC



«The Electron Ion Collider will act like an enormous microscope»

We want to use it to study «human-size» hadrons!

Building the EIC spectroscopy community



Goals

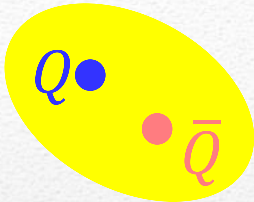
- Demonstrate a strong physics case for a hadron spectroscopy program at EIC (to be part of the next EIC physics book)
- Study the impact on EIC design (machine and detectors)

Working groups

- Multiquark & Gluonic states
  conveners: F.K. Guo, R. Mitchell
- Diffractive production
  conveners: W. Schafer, R. McNulty
- Heavy flavor in media
  conveners: C. Weiss, G. Bruno

Quarkonium orthodoxy & exotic

Esposito, AP, Polosa, Phys.Rept. 668



$$V(r) = -\frac{C_F \alpha_s}{r} + \sigma r$$

(Cornell potential)

Effective theories

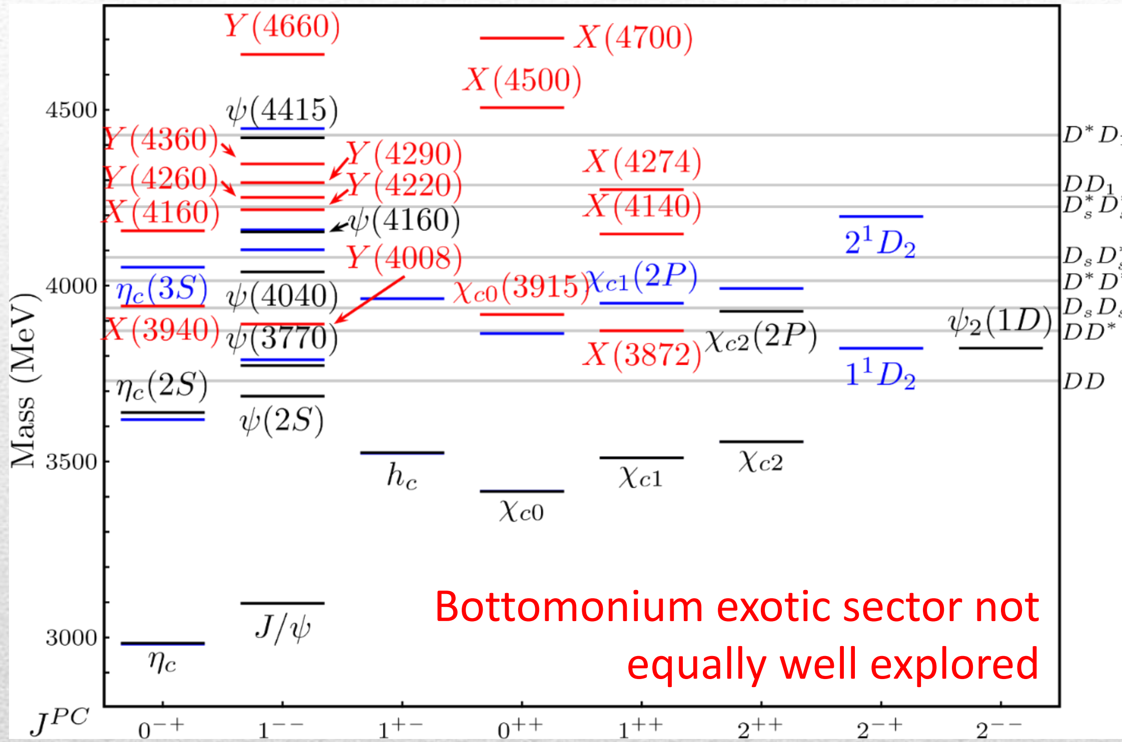
(HQET, NRQCD, pNRQCD...)

approximate heavy quark spin symmetry (HQSS)

Integrate out heavy DOF

↓

spectrum, decay & production rates

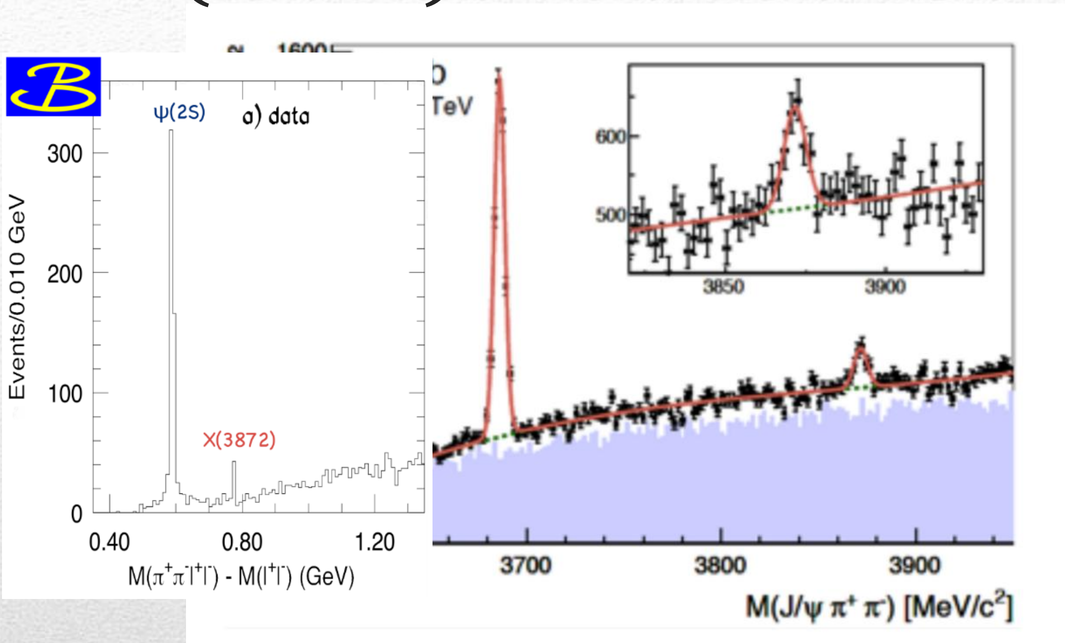


Bottomonium exotic sector not equally well explored

A host of unexpected resonances have appeared

Hardly reconciled with usual charmonium interpretation

$X(3872)$



- Discovered in
  $B \to K\, X \to K\, J/\psi\, \pi\pi$
- Quantum numbers 1^{++}
- Very close to DD^* threshold
- Too narrow for an above-treshold charmonium
- Isospin violation too big
  $\frac{\Gamma(X\to J/\psi\ \ \omega)}{\Gamma(X\to J/\psi\ \ \rho)} \sim 0.8 \pm 0.3$
- Mass prediction not compatible with $\chi_{c1}(2P)$

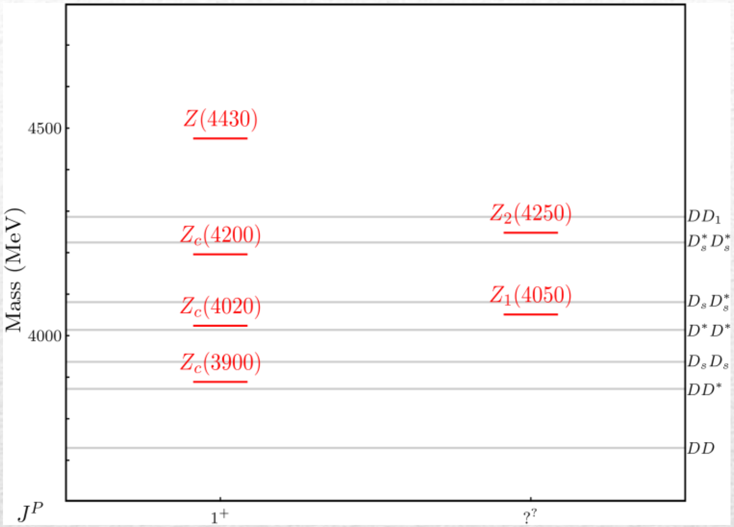
Sizeable prompt production at hadron colliders, $\sim$ 5% of $\psi(2S)$

$\sigma_{PR} \times B(X \to J/\psi\pi\pi) =$
$(1.06 \pm 0.11 \pm 0.15)$ nb @CMS

$M = 3871.68 \pm 0.17$ MeV
$M_X - M_{DD^*} = -3 \pm 192$ keV
$\Gamma < 1.2$ MeV @90%

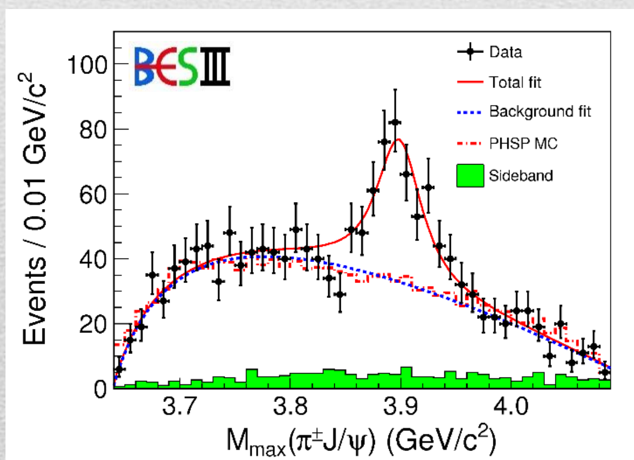
Charged Z states: $Z_c(3900), Z_c'(4020)$

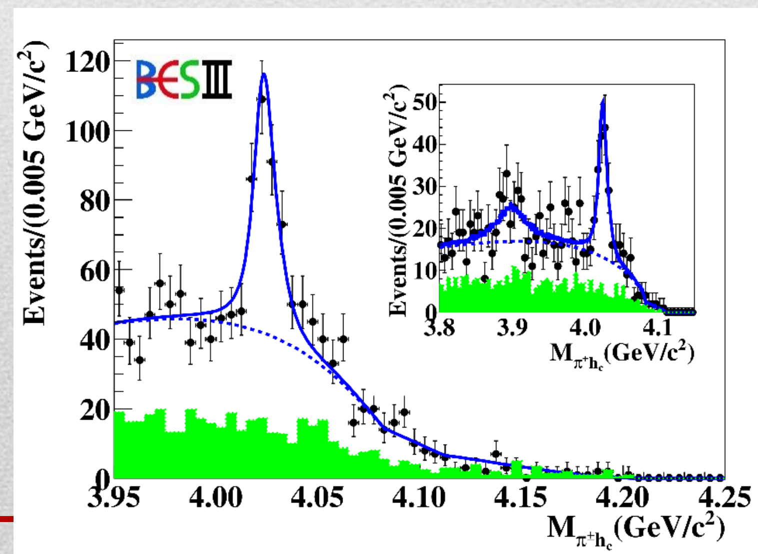
Charged quarkonium-like resonances have been found, **4q needed**



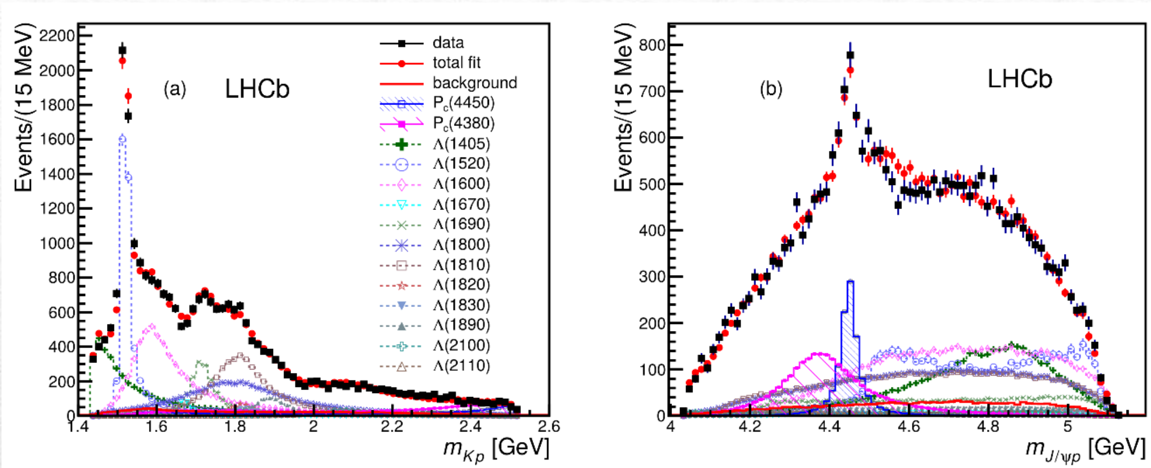
Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

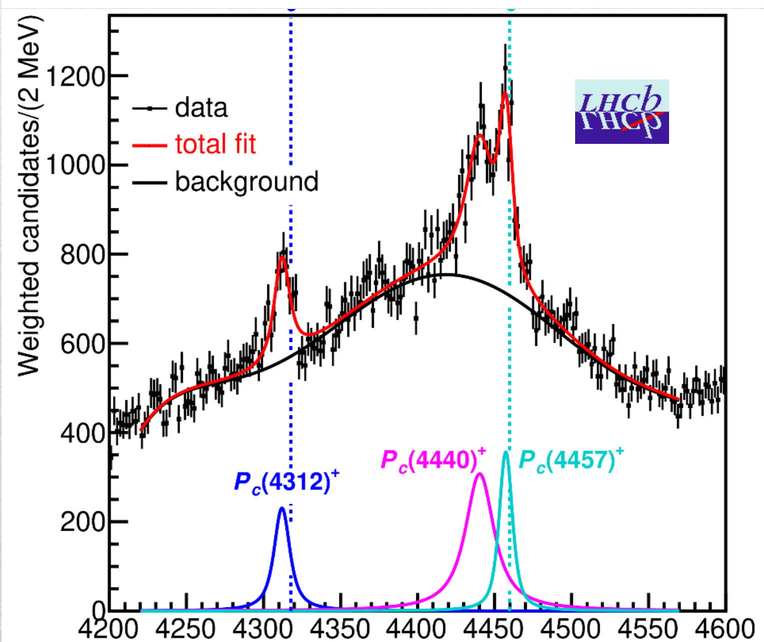
$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV
$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV





Pentaquarks!





LHCb, PRL 115, 072001
LHCb, PRL 117, 082003

Two states seen in $\Lambda_b \to (J/\psi\, p)\, K^-$,
evidence in $\Lambda_b \to (J/\psi\, p)\, \pi^-$

$$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$$
$$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$$
$$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$$
$$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$$

Quantum numbers

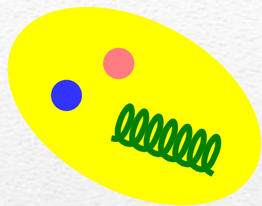
$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

LHCb, PRL 122, 222001

Higher statistics analysis revealed a two-peak structure of the narrow state,
plus a new lighter one
Quantum numbers still unknown

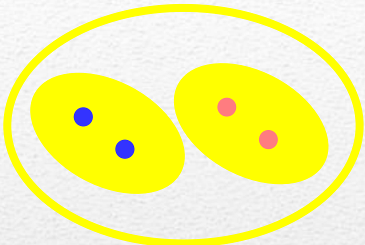
Models

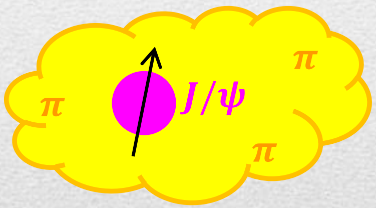
Compact



Hybrids
Containing gluonic degrees of freedom

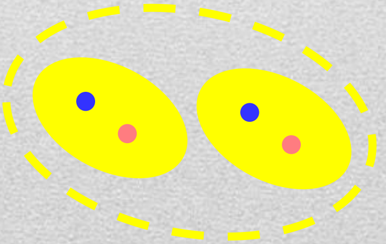
Multiquark
Several (cluster) of valence quarks





Hadroquarkonium
Heavy core interacting with a light cloud via Van der Waals forces

Rescattering effects
Structures generated by cross-channel rescattering, very process-dependent



Molecule
Bound or virtual state generated by long-range exchange forces

Extended

What at the EIC?

- High energy in the CoM, possibility to study heavy flavors charm sector well explored, little is known for the bottom sector
  - Meson(-like) spectroscopy: $X_{b,c}$, $Z_{b,c}$
  - Baryon(-like) spectroscopy: $P_{b,c}$
- Coupling to (virtual) photons can provide more information about their nature
- Interaction of exotic with nuclear media can complement the study in AA and pA

Need for cross section estimates of signal + irreducible background

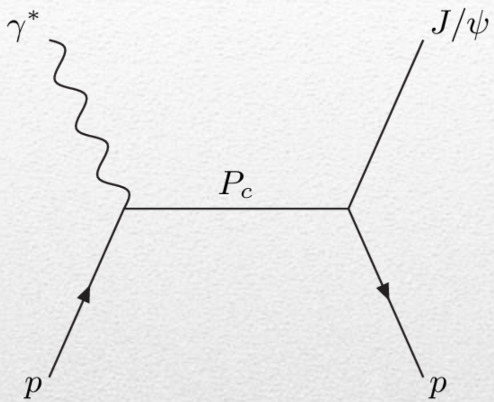
Reactions to be studied for the YR

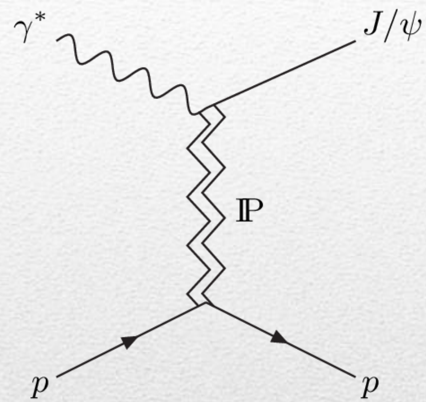
- Exclusive P_c photoproduction: C. Fanelli, A. Hiller Blin, D. Winney,
- Exclusive $X, \tilde{X}, Z$ photoproduction: M. Albaladejo
- Diffractive semi-inclusive ph.production: V. Mathieu, A. Szczepaniak
- Semi-inclusive X production: AP, X. Yao

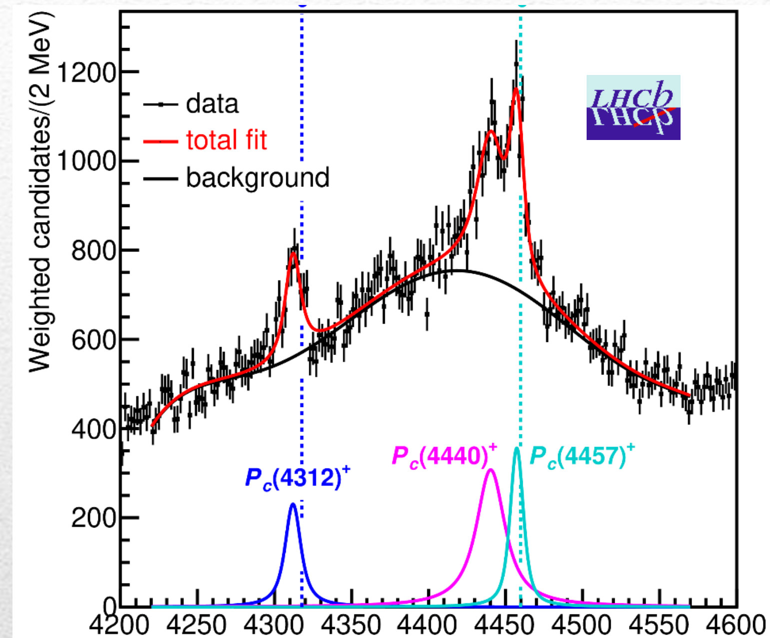
- (study of the scalar exotics in $\gamma\gamma$ fusion)
- (production of hybrids and doubly heavy)

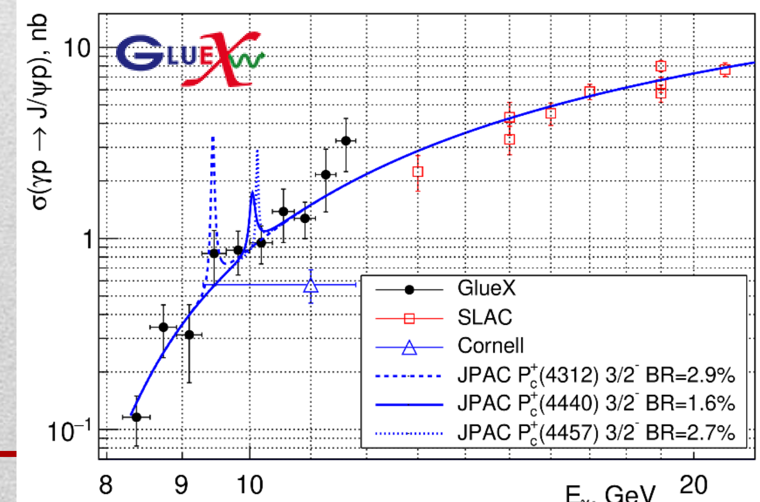
- all to be extended to the $b\bar{b}$ sector
- Partial overlap with Exclusive and Diffractive WG

Exclusive P_c photoproduction





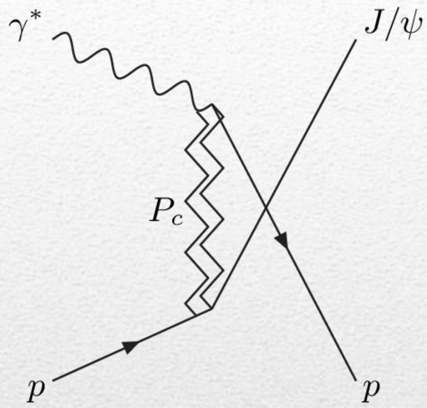


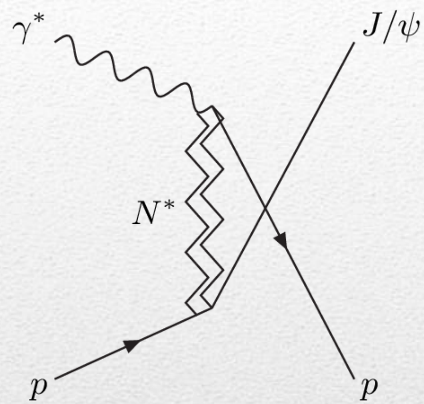


At Jlab12 measurements of direct P_c production are being performed

Using VMD, $\mathrm{BR}(P_c \to J/\psi\, p) \sim 1\%$

Exclusive P_c photoproduction





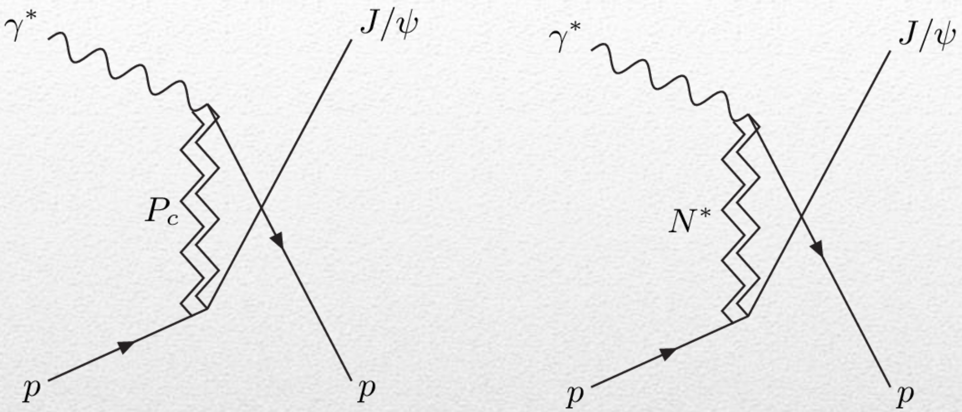
$$\sim s^{\alpha(u)}$$

At EIC energies the direct production is negligible, backward region dominated by u-channel P_c exchange

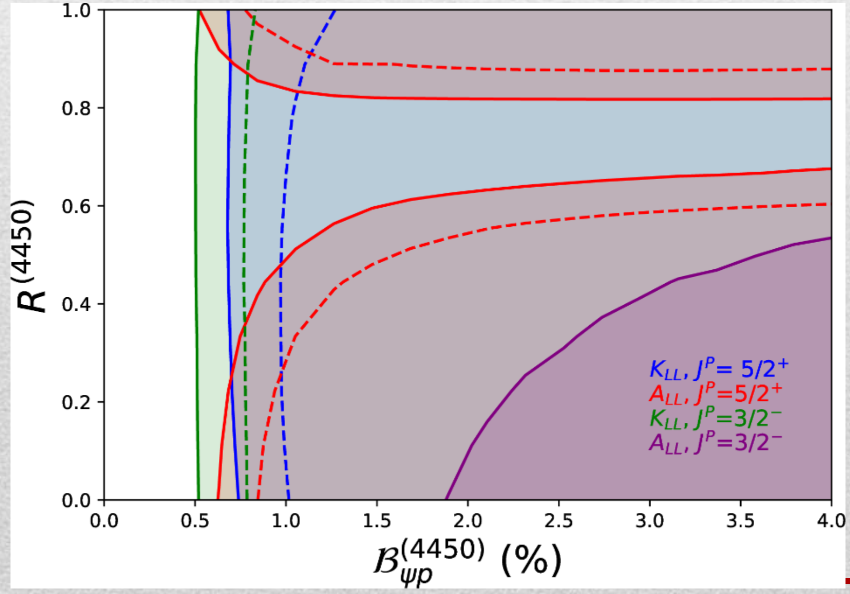
Main bkg is due to ordinary N^* exchanges
OZI suppressed

All couplings are known or related to the GlueX BR estimate

Polarized P_c photoproduction



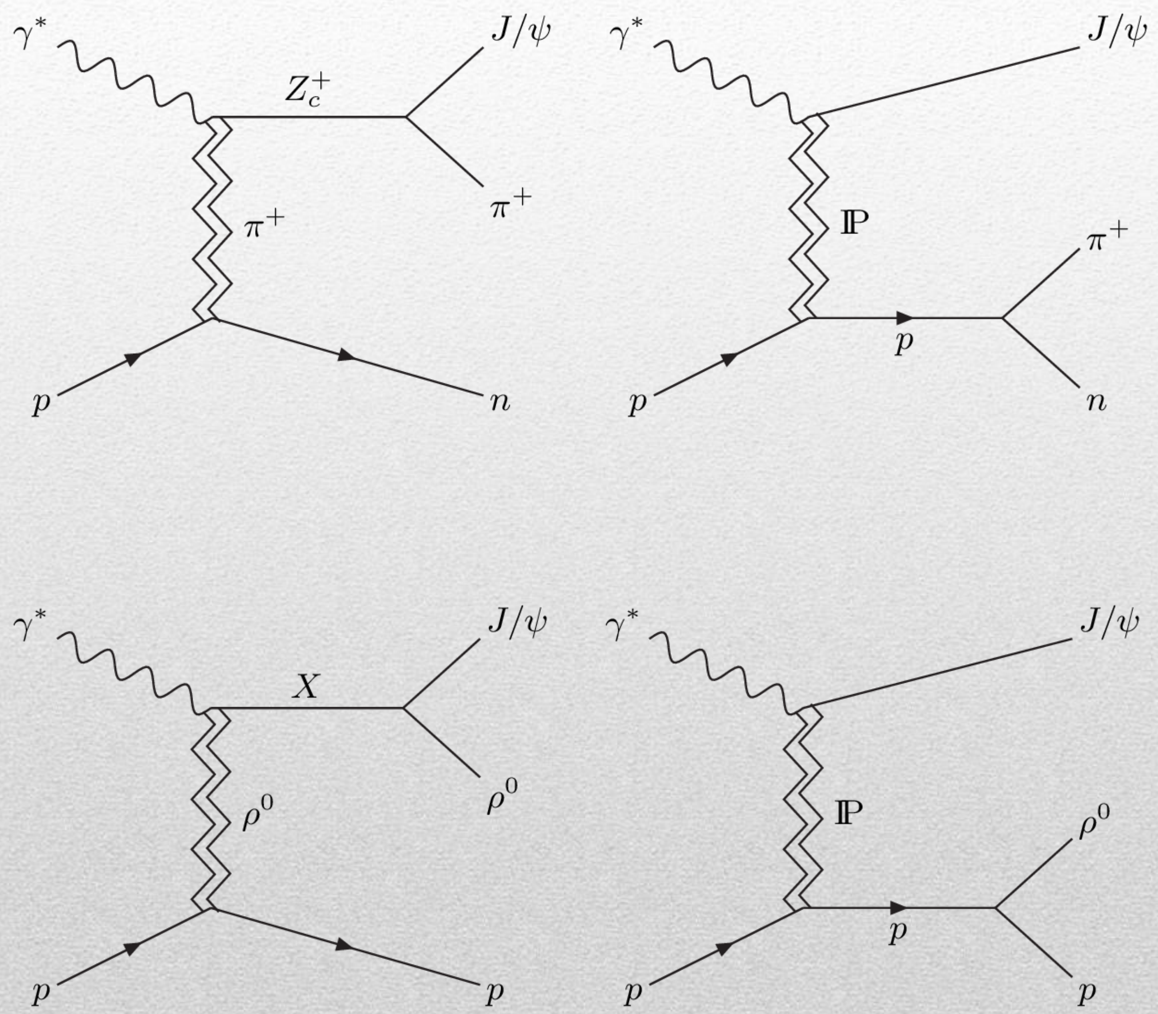
$\sim s^{\alpha(u)}$



Sensitivity of Polarization observables
to 5q parameters at SBS
Easily extended for the EIC

D. Winney, C. Fanelli,
AP *et al.* (JPAC), PRD100, 034019

Exclusive X, Z_c photoproduction



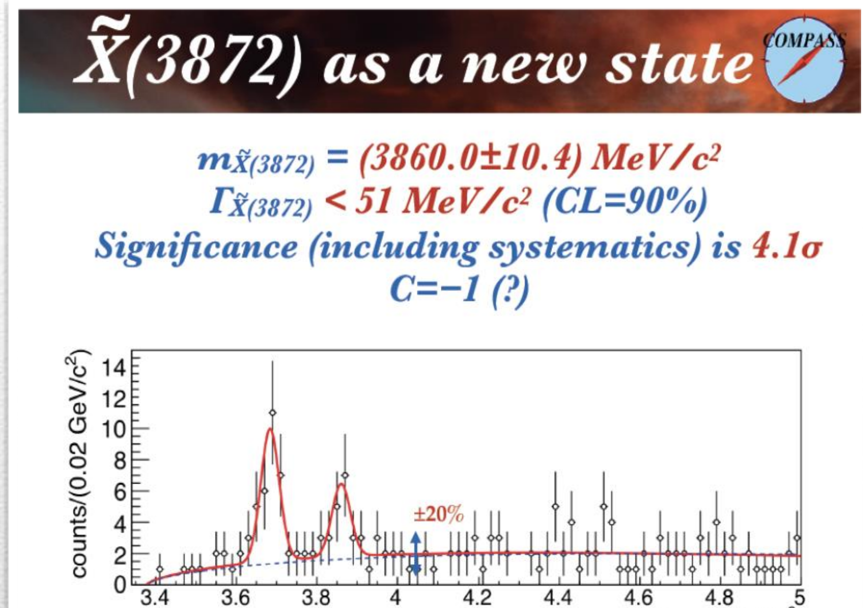
Z_c^+ production has been studied in the literature

Lin, Liu, Xu PRD88, 114009

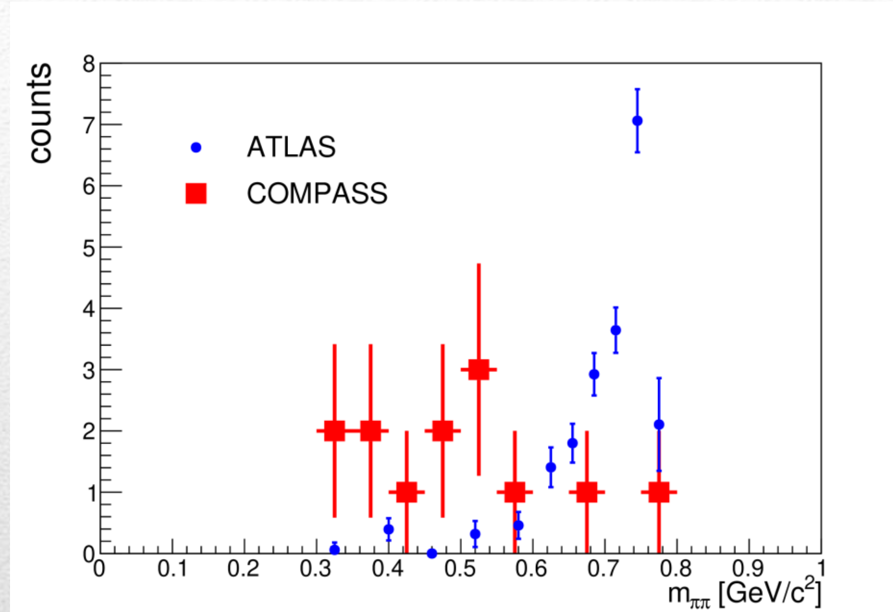
VMD + saturation of the width by measured decay modes provide rigid prediction

Vector meson exchange is well known, and leads to rigid prediction for the X

Another $\tilde{X}$?



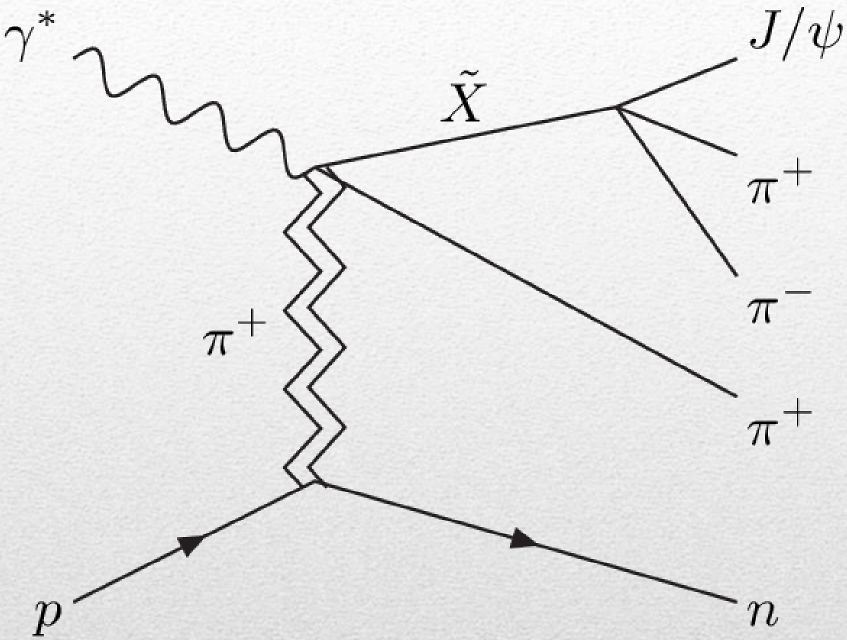
A. Guskov

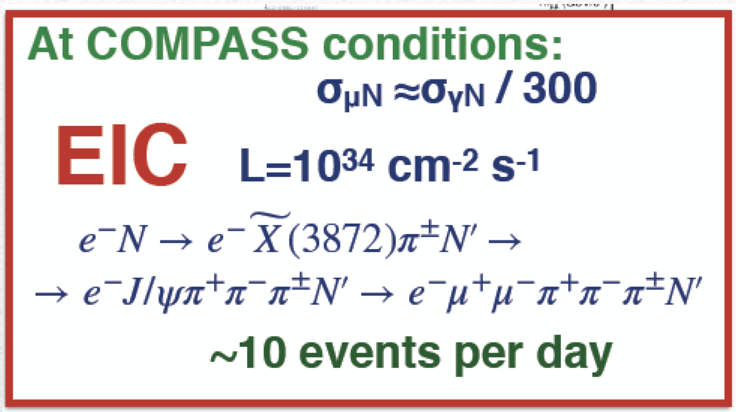


COMPASS claimed the existence of a state degenerate with the $X(3872)$, but with $C = 1$

Large photoproduction cross section

Another $\tilde{X}$?





A. Guskov

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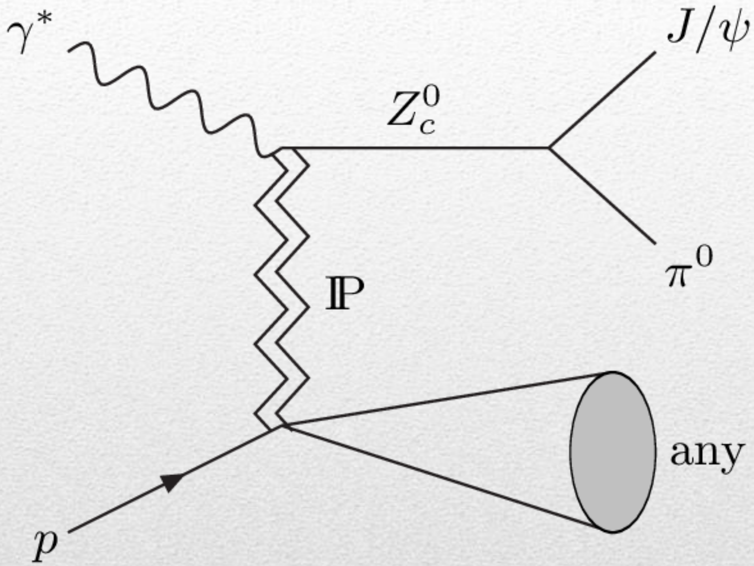
Large photoproduction cross section

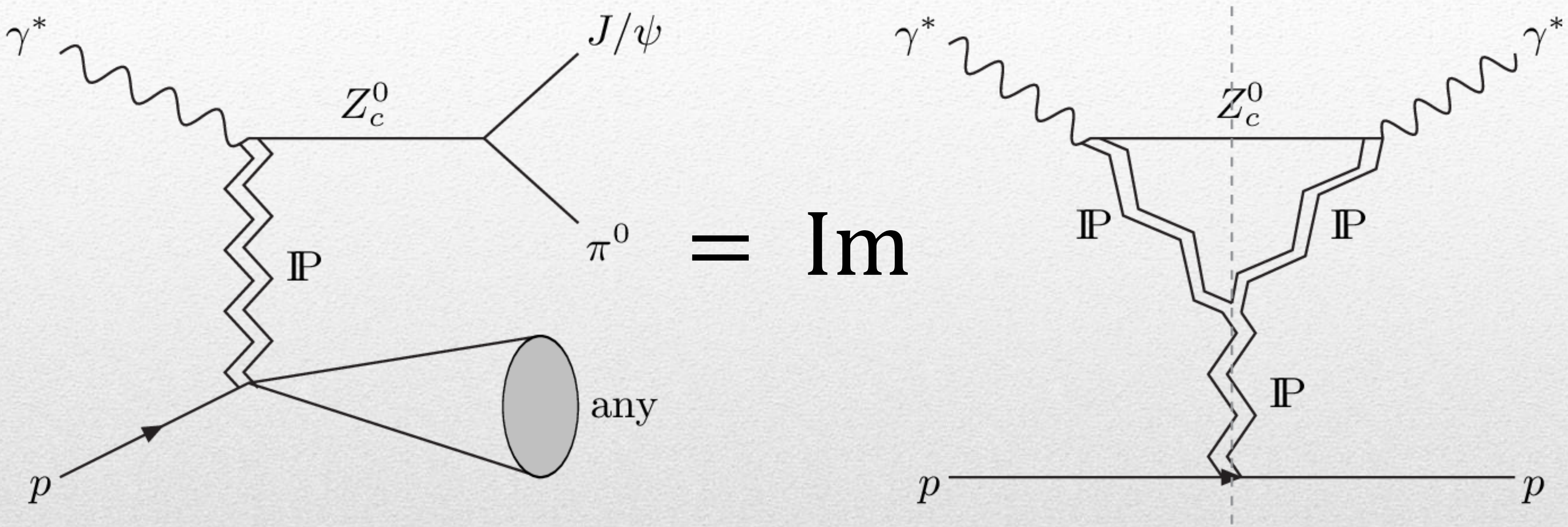
Diffractive semi-inclusive Z_c ph.



Large rapidity gap

If the target fragments are separated from the beam ones, one can invoke Regge factorization

Diffractive semi-inclusive Z_c ph.



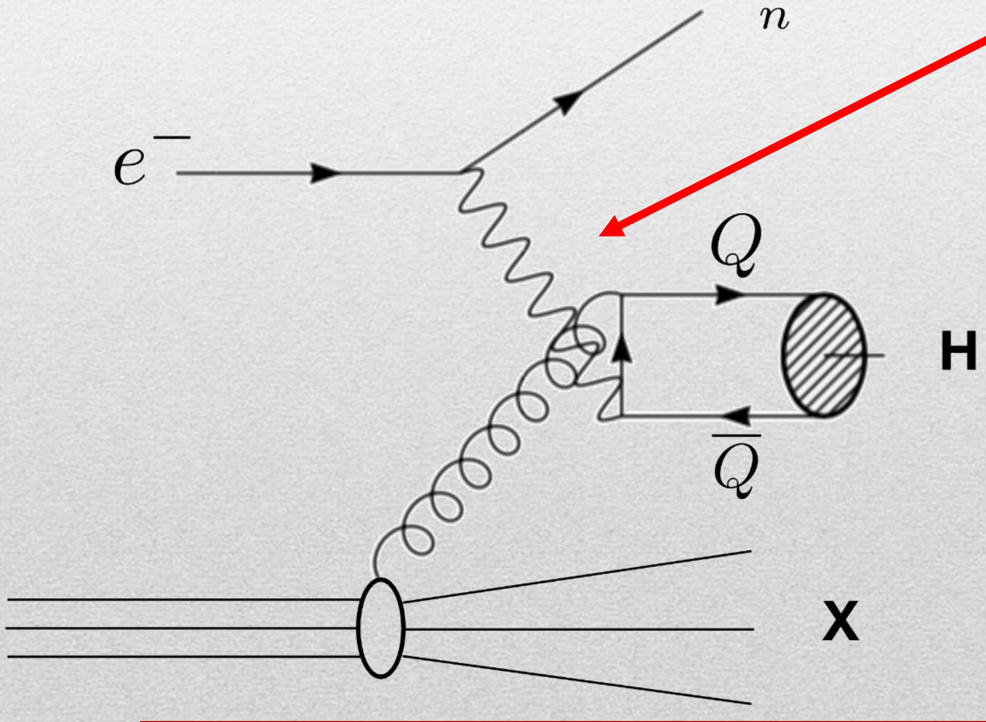
If the target fragments are separated from the beam ones, one can invoke Regge factorization

Quark-Regge duality allows to replace the intermediate hadrons with a Pomeron exchange
Triple Pomeron vertex well known
Model needed for $Z_c^0\gamma\mathbb{P}$ coupling

Semi-inclusive X production

For large Q^2 one can invoke NRQCD factorization
to describe quarkonium(-like) production

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



Perturbative partonic
matrix element, calculable

Nonperturbative transition
matrix element $Q\bar{Q} \to H$
fitted from data

Semi-inclusive X production

One can assume the same NRQCD factorization for exotics, independent of their internal structure

$$\sigma[X(3872)] = \sum_n \hat{\sigma}[c\bar{c}_n] \, \langle \mathcal{O}_n^X \rangle$$

$$\mathrm{Br}[X \to J/\psi\pi^+\pi^-] \left(\langle \mathcal{O}_8^X(^3S_1) \rangle + 0.159 \, \langle \mathcal{O}_8^X(^1S_0) \rangle + 0.085 \, \langle \mathcal{O}_1^X(^1S_0) \rangle \right.$$
$$\left. + 0.00024 \, \langle \mathcal{O}_1^X(^3S_1) \rangle \right) = (2.7 \pm 0.6) \times 10^{-4} \text{ GeV}^3$$

Artoisenet and Braaten, PRD81, 114018 from Tevatron data

If one consider the first term only, it leads to

$$\mathrm{Br}[X \to J/\psi\pi^+\pi^-]\sigma(X(3872), Q^2 > 1 \text{ GeV}) \approx 2.6 \text{ pb} \qquad \sqrt{s} = 100 \text{ GeV}$$

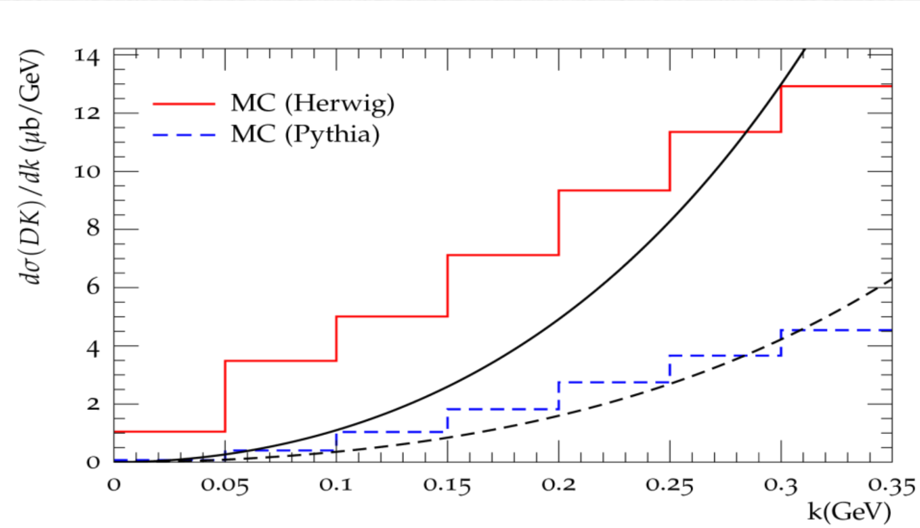
Production of other exotics

Other cross sections have been estimated, generally quite large

Guo et al. EPJC74, 9, 3063
Guo et al. CTP, 61, 354

	$Z_b(10610)$	$Z_b(10650)$	$Z_c(3900)$	$Z_c(4020)$
Tevatron	0.26(0.47)	0.06(0.17)	11(13)	1.7(2.0)
LHC 7	4.8(8.0)	1.2(3.0)	187(211)	29(31)
LHCb 7	0.76(1.3)	0.18(0.47)	33(39)	5.5(5.8)
LHC 8	5.9(9.5)	1.4(3.5)	220(240)	34(36)
LHCb 8	0.9(1.4)	0.22(0.56)	40(48)	6.3(6.9)
LHC 14	11(17)	2.6(6.5)	382(423)	61(63)
LHCb 14	1.9(3.0)	0.52(1.2)	84(88)	14(14)

X_b	$E_{X_b} = 24$ MeV($\Lambda = 0.5$ GeV)	$E_{X_b} = 66$ MeV($\Lambda = 1$ GeV)
Tevatron	0.08(0.18)	0.61(1.4)
LHC 7	1.5(3.1)	12(23)
LHCb 7	0.25(0.49)	1.9(3.7)
LHC 8	1.8(3.6)	14(27)
LHCb 8	0.3(0.62)	2.2(4.7)
LHC 14	3.2(6.8)	24(51)
LHCb 14	0.65(1.3)	4.9(9.7)



Estimates can be given using MC generators, using coalescence model and assuming a molecular nature for the exotics

Summary

- Exclusive P_c photoproduction: C. Fanelli, A. Hiller Blin, D. Winney,
- Exclusive $X, \tilde{X}, Z$ photoproduction: M. Albaladejo
- Diffractive semi-inclusive ph.production: V. Mathieu, A. Szczepaniak
- Semi-inclusive X production: AP, X. Yao

BACKUP

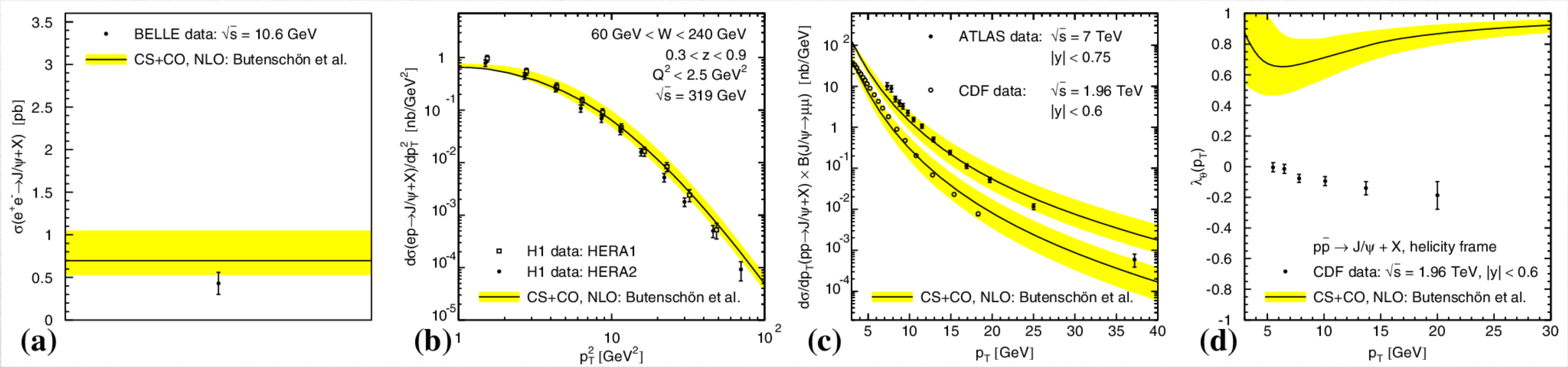
Multiscale system

Systematically integrate out the heavy scale, $m_Q \gg \Lambda_{QCD}$

$$m_Q \gg m_Q v \gg m_Q v^2$$

Full QCD ⟶ NRQCD ⟶ pNRQCD

$m_b \sim 5$ GeV, $m_c \sim 1.5$ GeV
$v_b^2 \sim 0.1, v_c^2 \sim 0.3$



Factorization (to be proved) of universal LDMEs

Good description of many production channels, some known puzzles (polarizations)

Comparison: EIC vs. others

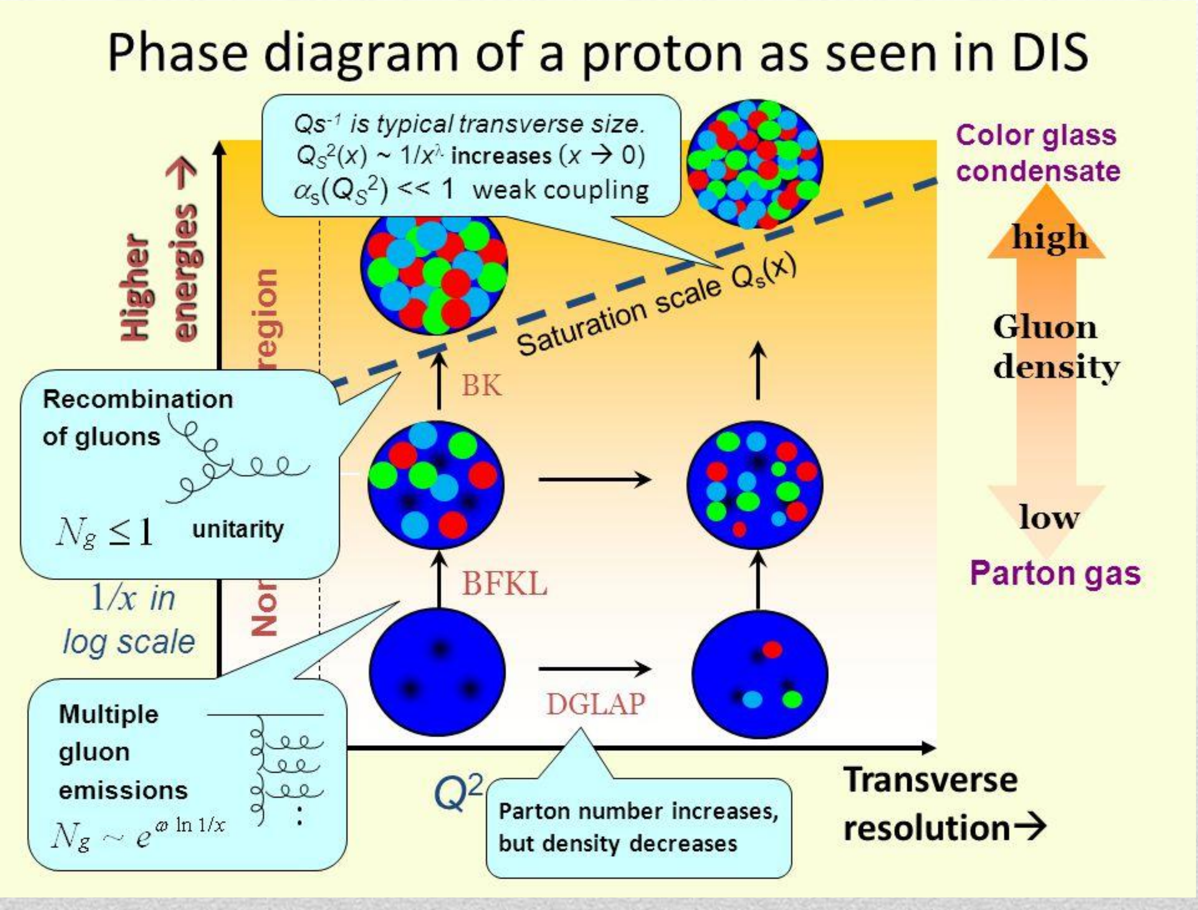
Too late (?) for charm physics ✘

Flexibility in the production mechanism ✓
Flexibility in energy (no Λ_b) ✓
Less clean environment ✘

Same luminosity ✓
Lower cross sections ✘
Better efficiencies for neutrals (?) ✓

Polarized electron & ion beams ✓

Hybrid production

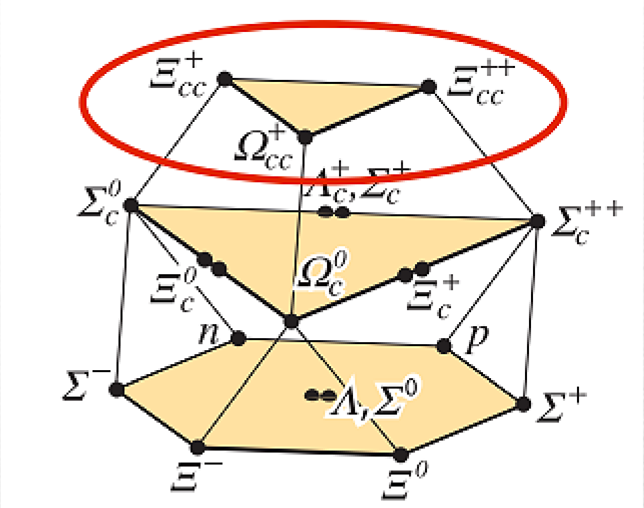


Suprisingly, no calculation for heavy hybrid production has been carried out so far

The only example for B decays is Petrov et al. PRD58, 034013

Room for improvement and inclusion of the large number of gluons at small x

Doubly heavy



Lots of attention recently on tetraquark and baryons with two heavy quarks, driven by LHCb and lattice results

Quigg and Eicthen, PRL119, 202002
Esposito, AP et al. PRD88, 054029
Karliner and Rosner, PRD90, 094007
Karliner and Rosner, PRL119, 202001
Francis et al. PRL118, 142001

MC code available, GENXICC2.0, which implements the heavy diquark in Pythia
NRQCD approach in e^+e^- collisions in Chen et al. JHEP1412, 018

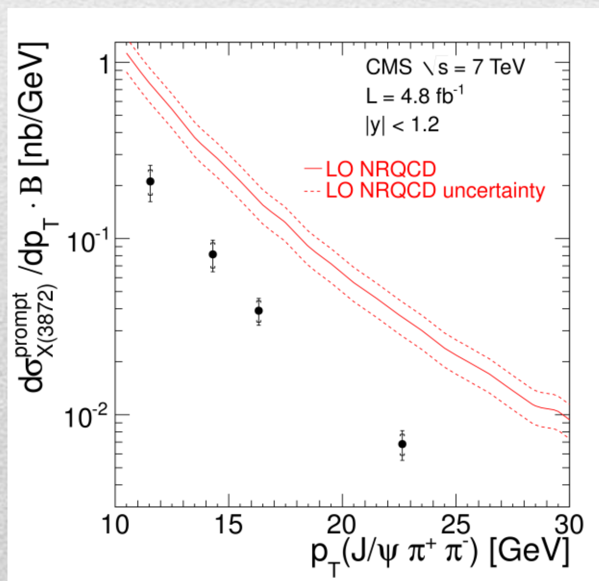
$X(3872)$

Large prompt production at hadron colliders

$\sigma_B/\sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\%$

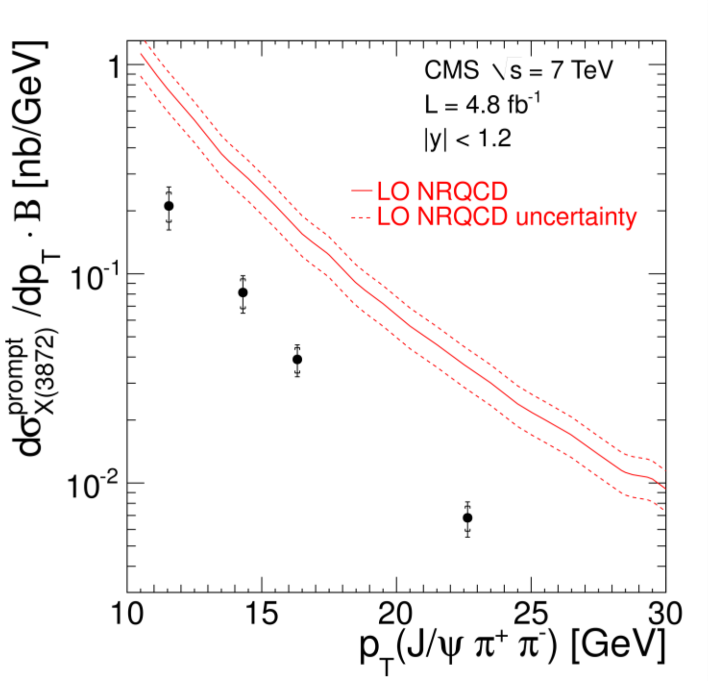
$\sigma_{PR} \times B(X \to J/\psi\pi\pi)$
$= (1.06 \pm 0.11 \pm 0.15)$ nb

CMS, JHEP 1304, 154



B decay mode	X decay mode	product branching fraction ($\times 10^5$)		B_{fit}	R_{fit}
K^+X	$X \to \pi\pi J/\psi$	$\mathbf{0.86 \pm 0.08}$	(BABAR,[26] Belle[25])	$0.081^{+0.019}_{-0.031}$	1
		$0.84 \pm 0.15 \pm 0.07$	BABAR[26]		
		$0.86 \pm 0.08 \pm 0.05$	Belle[25]		
K^0X	$X \to \pi\pi J/\psi$	$\mathbf{0.41 \pm 0.11}$	(BABAR,[26] Belle[25])		
		$0.35 \pm 0.19 \pm 0.04$	BABAR[26]		
		$0.43 \pm 0.12 \pm 0.04$	Belle[25]		
$(K^+\pi^-)_{NR}X$	$X \to \pi\pi J/\psi$	$0.81 \pm 0.20^{+0.11}_{-0.14}$	Belle[106]		
$K^{*0}X$	$X \to \pi\pi J/\psi$	< 0.34, 90% C.L.	Belle[106]		
KX	$X \to \omega J/\psi$	$R = 0.8 \pm 0.3$	BABAR[33]	$0.061^{+0.024}_{-0.036}$	$0.77^{+0.28}_{-0.32}$
K^+X		$0.6 \pm 0.2 \pm 0.1$	BABAR[33]		
K^0X		$0.6 \pm 0.3 \pm 0.1$	BABAR[33]		
KX	$X \to \pi\pi\pi^0 J/\psi$	$R = 1.0 \pm 0.4 \pm 0.3$	Belle[32]		
K^+X	$X \to D^{*0}\bar{D}^0$	$\mathbf{8.5 \pm 2.6}$	(BABAR,[38] Belle[37])	$0.614^{+0.166}_{-0.074}$	$8.2^{+2.3}_{-2.8}$
		$16.7 \pm 3.6 \pm 4.7$	BABAR[38]		
		$7.7 \pm 1.6 \pm 1.0$	Belle[37]		
K^0X	$X \to D^{*0}\bar{D}^0$	$\mathbf{12 \pm 4}$	(BABAR,[38] Belle[37])		
		$22 \pm 10 \pm 4$	BABAR[38]		
		$9.7 \pm 4.6 \pm 1.3$	Belle[37]		
K^+X	$X \to \gamma J/\psi$	$\mathbf{0.202 \pm 0.038}$	(BABAR,[35] Belle[34])	$0.019^{+0.005}_{-0.009}$	$0.24^{+0.05}_{-0.06}$
K^+X		$0.28 \pm 0.08 \pm 0.01$	BABAR[35]		
		$0.178^{+0.048}_{-0.044} \pm 0.012$	Belle[34]		
K^0X		$0.26 \pm 0.18 \pm 0.02$	BABAR[35]		
		$0.124^{+0.076}_{-0.061} \pm 0.011$	Belle[34]		
K^+X	$X \to \gamma\psi(2S)$	$\mathbf{0.44 \pm 0.12}$	BABAR[35]	$0.04^{+0.015}_{-0.020}$	$0.51^{+0.13}_{-0.17}$
K^+X		$0.95 \pm 0.27 \pm 0.06$	BABAR[35]		
		$0.083^{+0.198}_{-0.183} \pm 0.044$	Belle[34]		
		$R' = 2.46 \pm 0.64 \pm 0.29$	LHCb[36]		
K^0X		$1.14 \pm 0.55 \pm 0.10$	BABAR[35]		
		$0.112^{+0.357}_{-0.290} \pm 0.057$	Belle[34]		
K^+X	$X \to \gamma\chi_{c1}$	$< 9.6 \times 10^{-3}$	Belle[23]	$< 1.0 \times 10^{-3}$	< 0.014
K^+X	$X \to \gamma\chi_{c2}$	< 0.016	Belle[23]	$< 1.7 \times 10^{-3}$	< 0.024
KX	$X \to \gamma\gamma$	$< 4.5 \times 10^{-3}$	Belle[111]	$< 4.7 \times 10^{-4}$	$< 6.6 \times 10^{-3}$
KX	$X \to \eta J/\psi$	< 1.05	BABAR[112]	< 0.11	< 1.55
K^+X	$X \to p\bar{p}$	$< 9.6 \times 10^{-4}$	LHCb[110]	$< 1.6 \times 10^{-4}$	$< 2.2 \times 10^{-3}$

Prompt production of $X(3872)$



CMS, JHEP 1304 (2013) 154

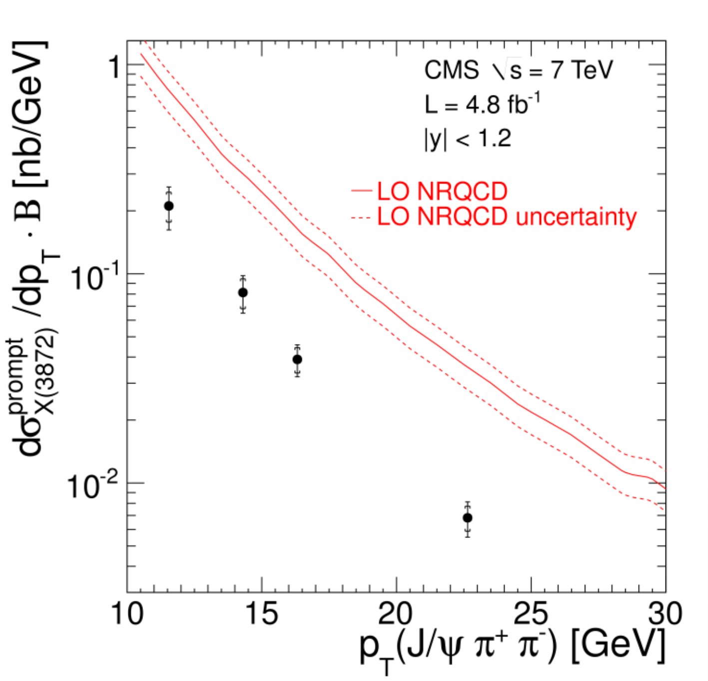
The question is:

«Are large prompt production cross sections at hadron colliders compatible with a loosely bound molecule interpretation?»

$M = 3871.69 \pm 0.17$ MeV
$E_B = M_{DD^*} - M_X = 10 \pm 200$ keV (PDG)
$\Gamma < 1.2$ MeV @90%

The width of the D^* and of the $X(3872)$ are neglected, according to Weinberg's spirit
The $X(3872)$ is considered a (stable) bound state of (stable) $\bar{D}^0 D^{*0}$

Prompt production of $X(3872)$



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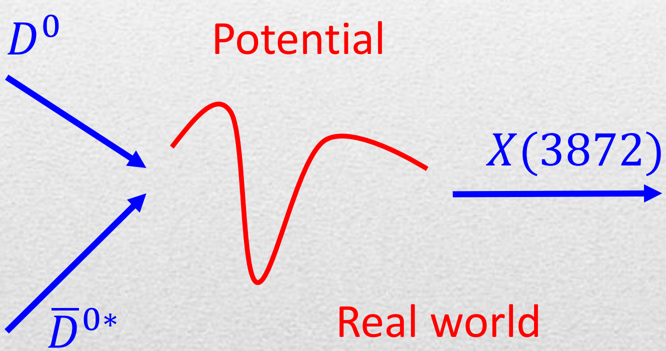
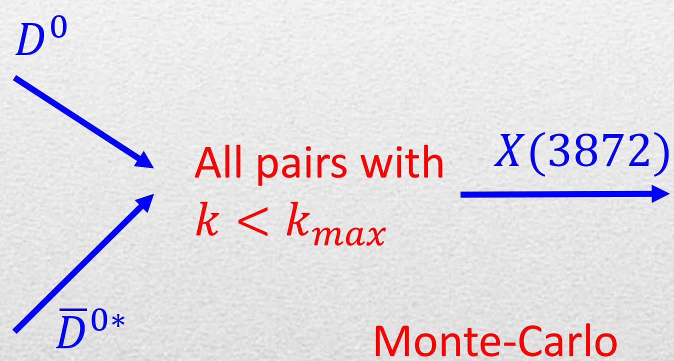
$$k_B = \sqrt{2\mu E_B} \sim 20 \text{ MeV}, \qquad R = \frac{1}{k_B} \sim 10 \text{ fm}$$

Hadronic molecules with MC simulations

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

Q. What is a molecule in MC? **A.** «Coalescence» model





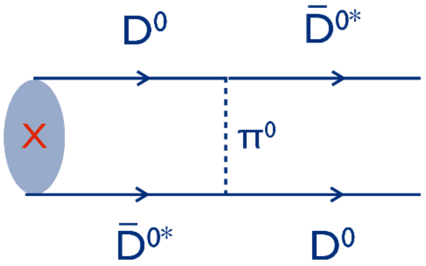
$$\sigma\big(p\bar{p} \to X(3872)\big) \sim \int d^3k \; |\langle X|D\overline{D}^*\rangle\langle D\overline{D}^*|p\bar{p}\rangle|^2 < \int_{k<k_{max}} d^3k \; |\langle D\overline{D}^*|p\bar{p}\rangle|^2$$

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

Estimating k_{max}

The choice of k_{max} is crucial. By phase space argument, the cross section scales as k_{max}^3, small changes have huge impacts on the results

D mesons interact via π^0-exchange:



$$\frac{\hbar^2}{2\mu r_0^2} - \frac{g^2}{4\pi}\frac{e^{-m_\pi r_0}}{r_0} = |E_B| \simeq 0.25\ \text{MeV}$$

using the fact that $g^2/4\pi \sim 10$ we find a characteristic size

(1) $r_0 \simeq 8\ \text{fm} \quad \Rightarrow \quad \Delta k \sim 1/2r_0 \simeq 20\ \text{MeV}$

(uncertainty principle)

(2) $k_0 = \dfrac{\sqrt{\lambda(m_X^2, m_D^2, m_{D^*}^2)}}{2m_X} \simeq 30\ \text{MeV}$

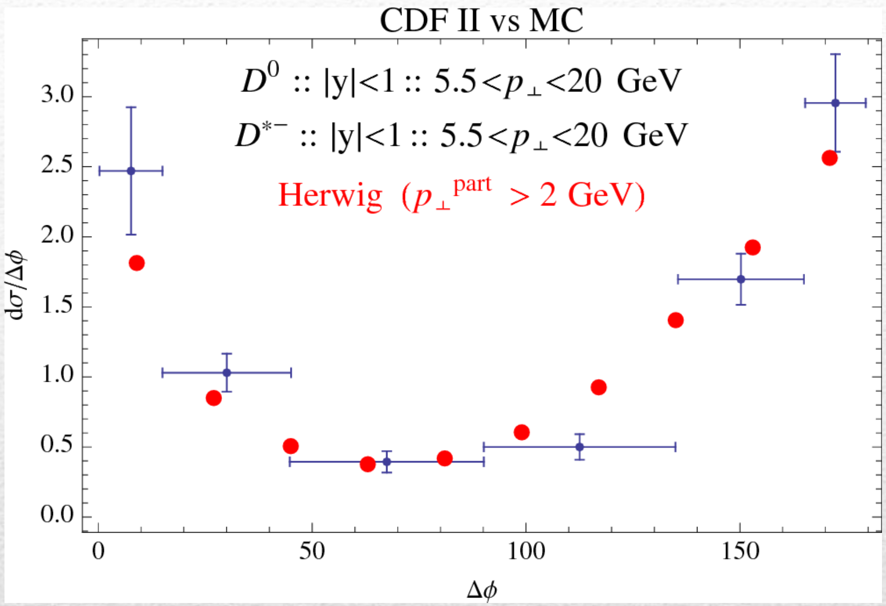
C. Sabelli (2009)

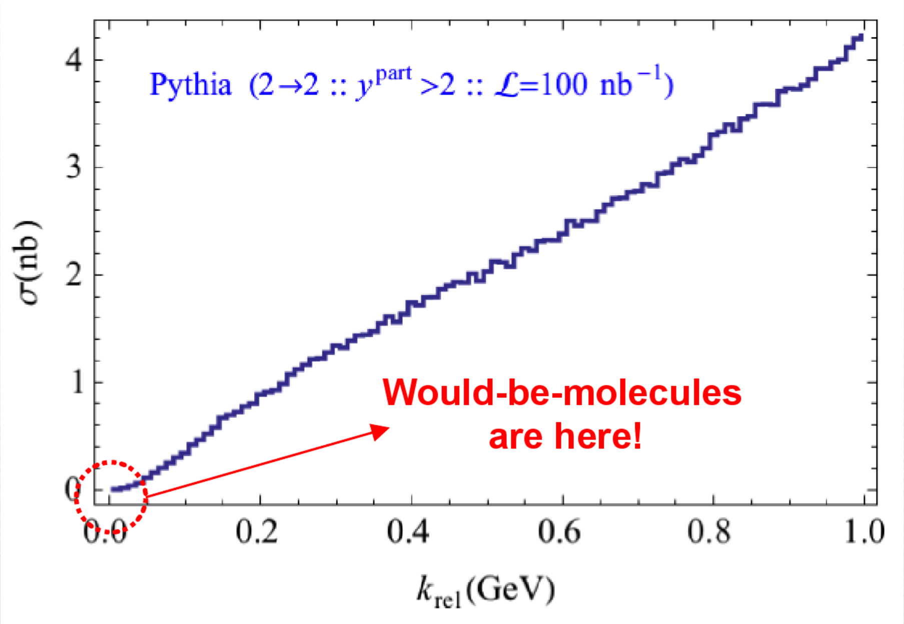
Alternative, one can model the binding potential.

For example, a simple square well with this corresponds to:

$$\sqrt{\langle k^2 \rangle} \approx 50\ \text{MeV}, \quad \sqrt{\langle r^2 \rangle} \approx 10\ \text{fm}$$

2009 Results





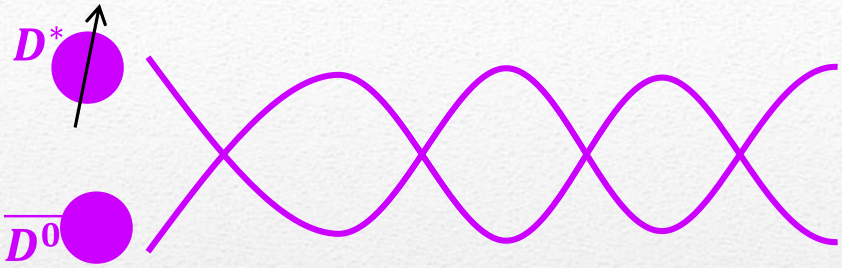
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

We get $\sigma(p\bar{p} \to DD^* | k < k_{max}) \approx 0.1$ nb @$\sqrt{s} = 1.96$ TeV

Experimentally $\sigma(p\bar{p} \to X(3872)) \approx 30 - 70$ nb!!!

Bignamini, Grinstein, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

Estimating k_{max} -- Part II



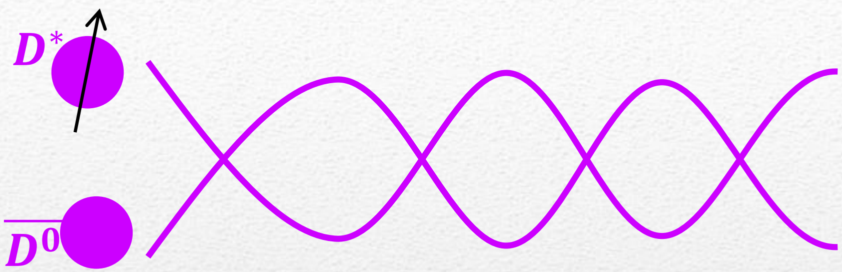
A solution can be Final State Interactions (rescattering of DD^*)
Artoisenet and Braaten, PRD81, 114018

$$\mathcal{M} = -N A_{prod}^{on} \cdot \frac{e^{i\delta} \sin \delta}{k a_{NN}}$$

Watson-Migdal model for FSI, the on-shell elastic scattering matrix multiplies the production amplitude

$$\sigma\big(p\bar{p} \to X(3872)\big) \to \sigma(p\bar{p} \to DD^* | k < k_{max}) \times \frac{6\pi\sqrt{2\mu\, E_B}}{k_{max}}$$

Estimating k_{max} -- Part II



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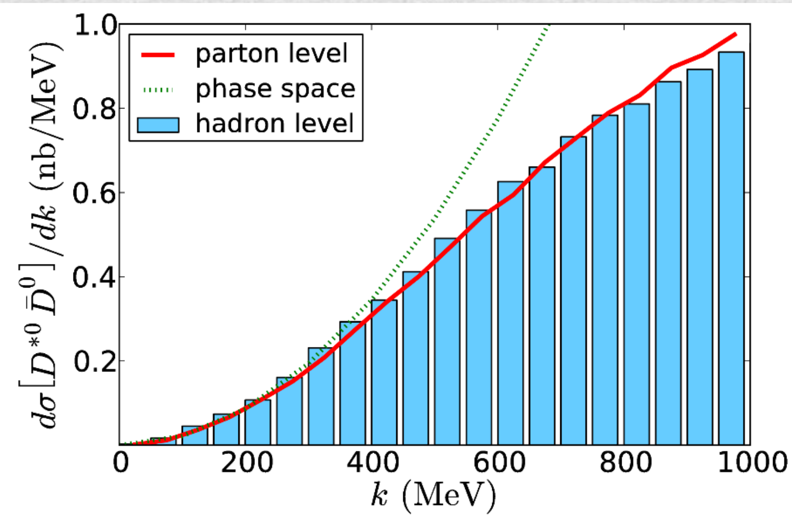
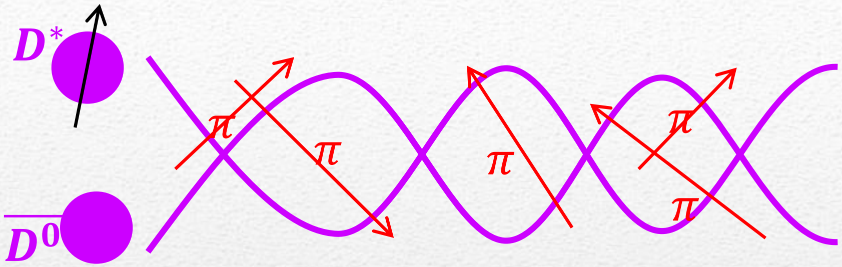


To take into account the rescattering correctly, one needs to integrate up to the scale of the mediator,

$$\sigma_{FSI}(p\bar{p} \to DD^*|k < 2m_\pi) \approx 23 \text{ nb}$$
$$\sigma(p\bar{p} \to DD^*|k < 5m_\pi) \approx 230 \text{ nb}$$

Estimating k_{max} -- Part III & IV



Watson-Migdal approach requires the DD^* to recoil onto some debrys. The theorem is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound, the D and D^* only talk with each other

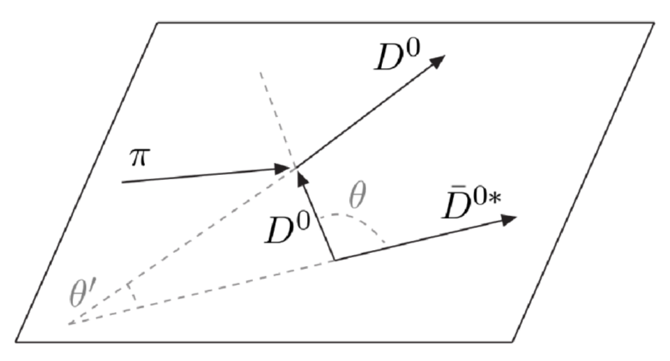
Artoisenet and Braaten, PRD83, 014019

What is the role of 2-body unitarity in a 100-body high energy collision?

A new mechanism?

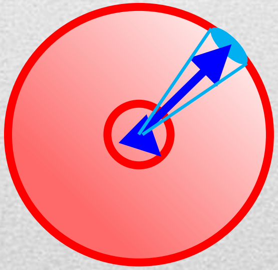
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the DD^* pairs

Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

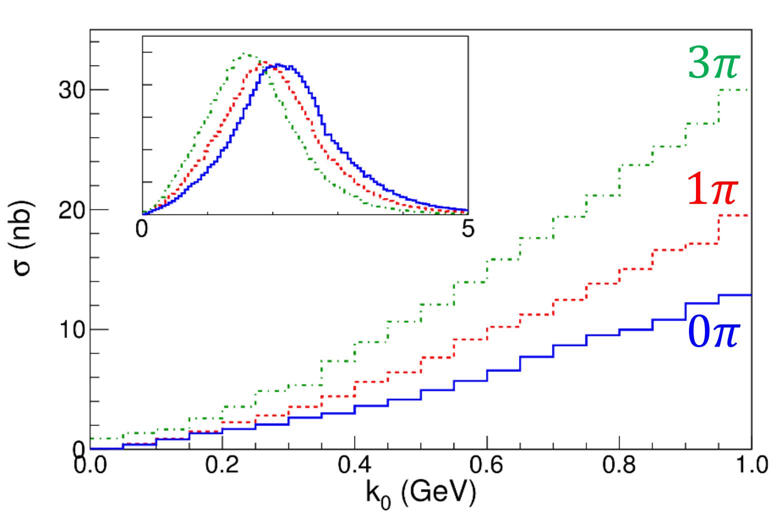


The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100\text{ keV}$



By comparing hadronization times of heavy and light mesons, we estimate up to ~ 3 collisions can occur before the heavy pair to fly apart



We get $\sigma\left(p\bar{p} \to X(3872)\right) \sim 5\text{ nb}$, still not sufficient to explain all the experimental cross section

Estimating k_{max} -- Part V

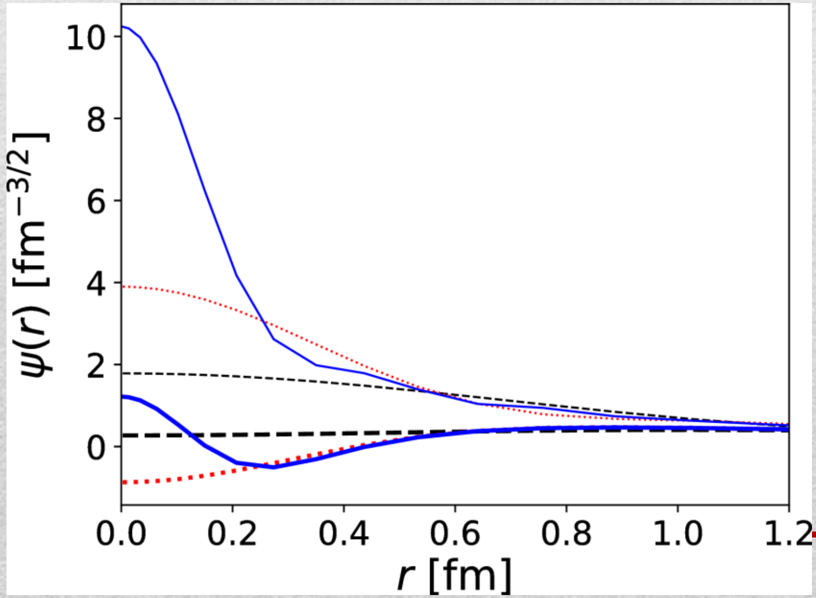
$$\sigma(\bar{p}p \to X) \sim \left|\int d^3\mathbf{k}\langle X|D^0\bar{D}^{*0}(\mathbf{k})\rangle\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle\right|^2$$
$$\simeq \left|\int_{\mathcal{R}} d^3\mathbf{k}\langle X|D^0\bar{D}^{*0}(\mathbf{k})\rangle\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle\right|^2$$
$$\leq \int_{\mathcal{R}} d^3\mathbf{k}\,|\Psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k}\,\left|\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle\right|^2$$
$$\leq \int_{\mathcal{R}} d^3\mathbf{k}\,\left|\langle D^0\bar{D}^{*0}(\mathbf{k})|\bar{p}p\rangle\right|^2$$

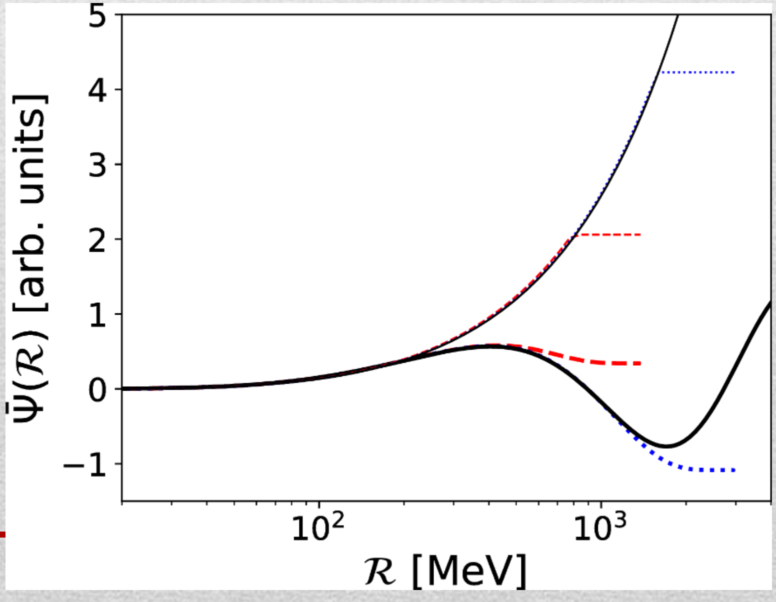
The estimate of the k_{max} has been brought back

Albaladejo *et al.* arXiv:1709.09101

The essence of the argument is that one has to look at the integral of the wave function

$$\int_R d^3\mathbf{k}\,\psi(\mathbf{k})$$





Estimating k_{max} -- Part VI

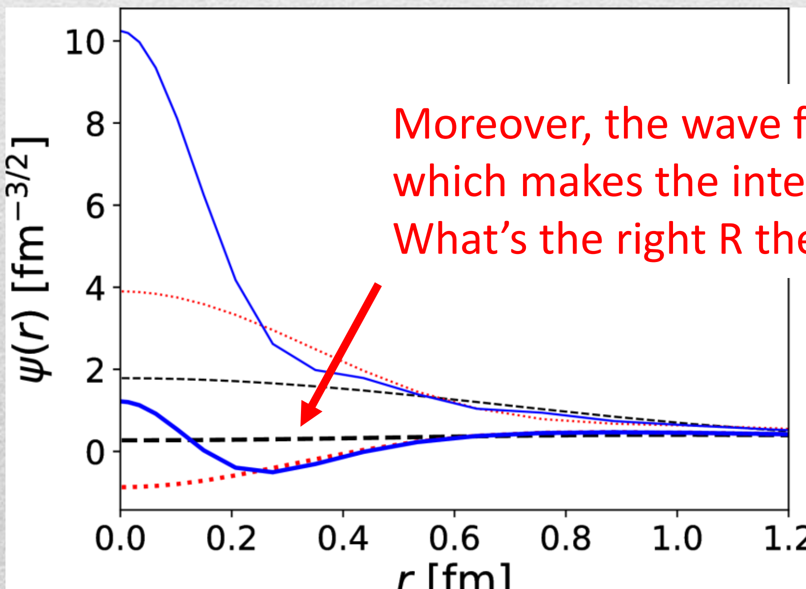
However, the integral of the wave function may not be well defined.
For example, if one considers the wave function in the scattering length approximation,

Esposito, AP *et al.* arXiv:1709.09631

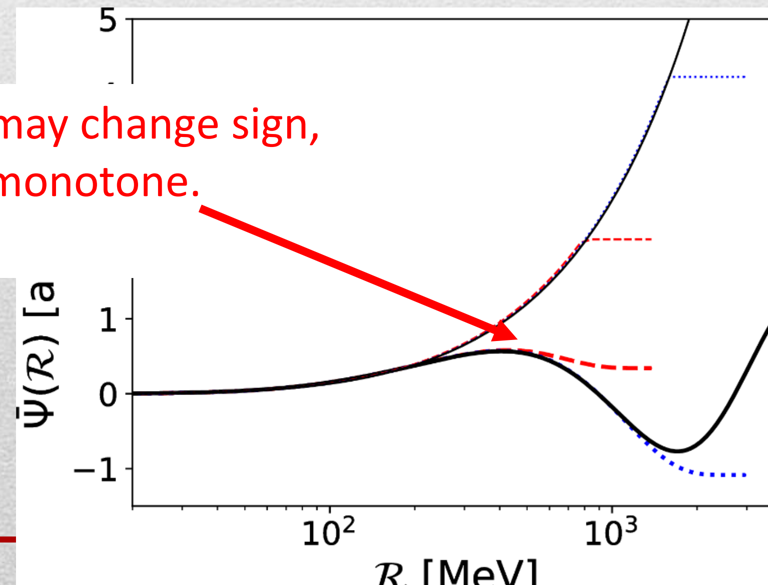
$$\psi(\mathbf{k}) = \frac{1}{\pi}\frac{a^{3/2}}{a^2k^2+1}$$ it's not integrable

A physical value should rather be based on expectation values which involve $|\psi(\mathbf{k})|^2$

For example, an estimate using the virial theorem gives $k \sim 100$ MeV for the deuteron



Moreover, the wave function may change sign,
which makes the integral nonmonotone.
What's the right R then?



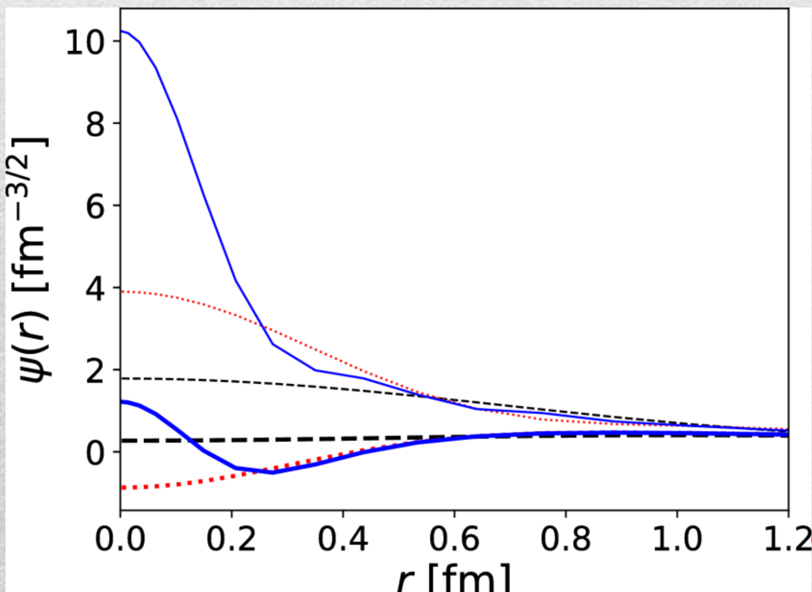
Estimating k_{max} -- Part VI

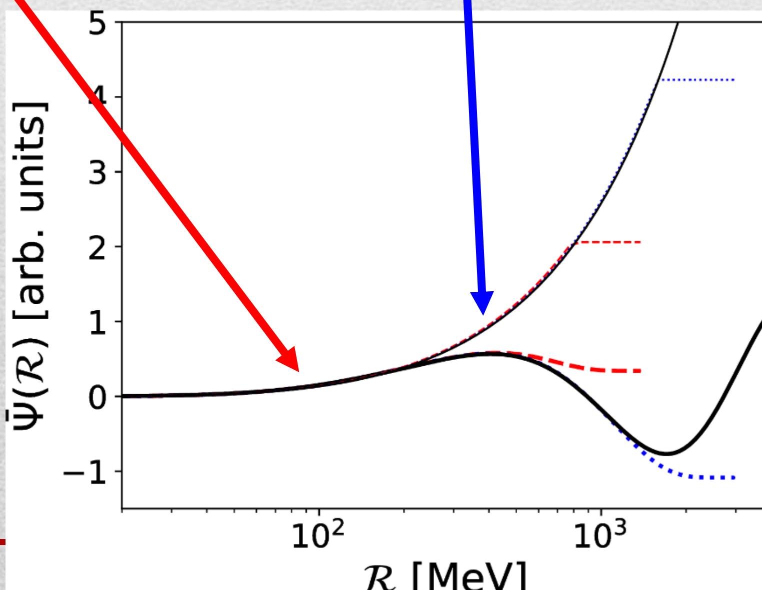
An accurate calculation using several deuteron *S*-wave functions available on the market (for example https://www.phy.anl.gov/theory/research/av18/deut.wfk) give

$$\int_R d^3\mathbf{k}\,|\psi(\mathbf{k})|^2 = 90\% \text{ for } k_{max} = 110 \text{ MeV}$$

This also show that this region is well controlled by pion exchange - universal

This is not!





Light nuclei at ALICE

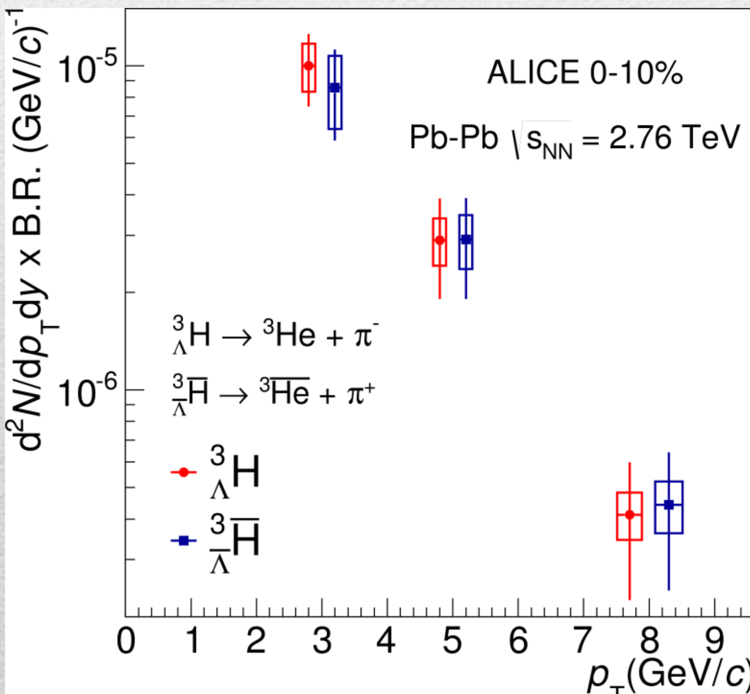
In 2015, ALICE published data on production of light nuclei in Pb-Pb and *pp* collisions

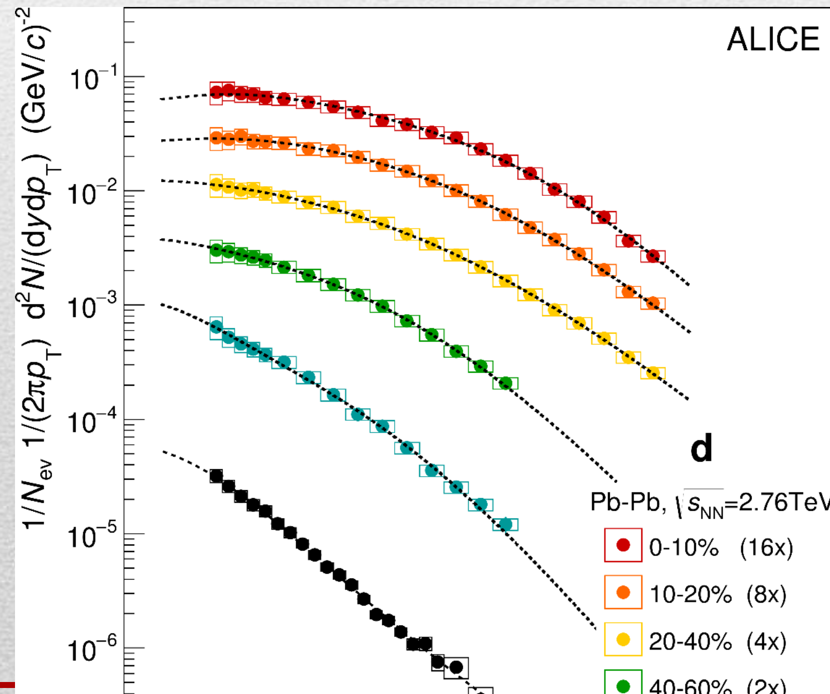
These might provide a benchmark for $X(3872)$ production

Hypertriton
arXiv:1506.08453

Helium-3
arXiv:1506.08951

Deuteron
arXiv:1506.08951



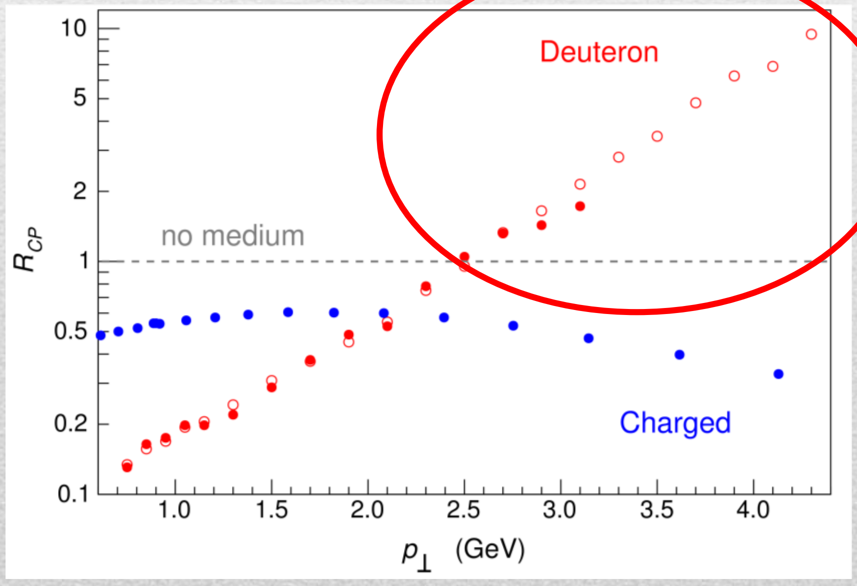


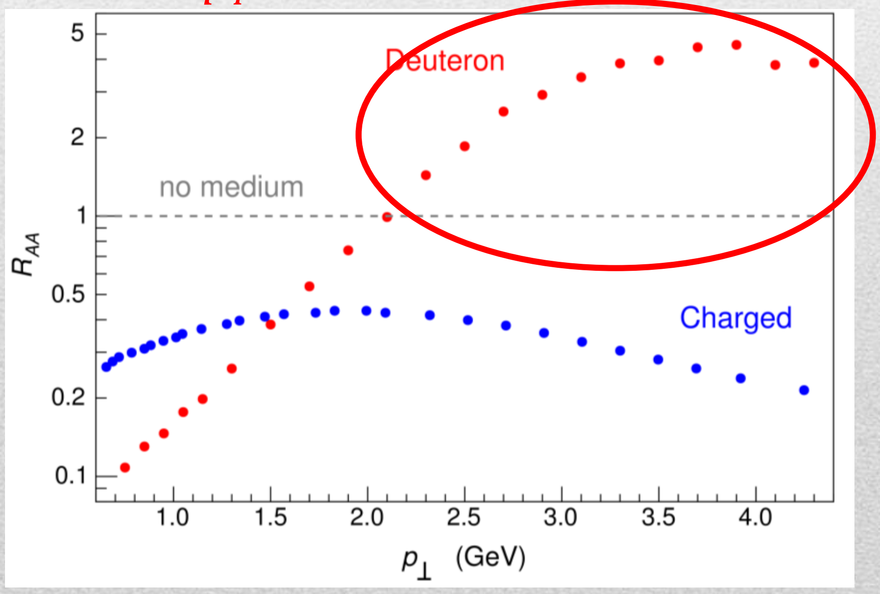
Nuclear modification factors

We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different $\sqrt{s}$)

$$R_{CP} = \frac{N_{coll}^{P}\left(\frac{dN}{dp_T}\right)_{C}}{N_{coll}^{C}\left(\frac{dN}{dp_T}\right)_{P}} \qquad R_{AA} = \frac{\left(\frac{dN}{dp_T}\right)_{\text{Pb}-\text{Pb}}}{N_{coll}\left(\frac{dN}{dp_T}\right)_{pp}}$$

Larger than 1 at $p_T > 2.5$ GeV

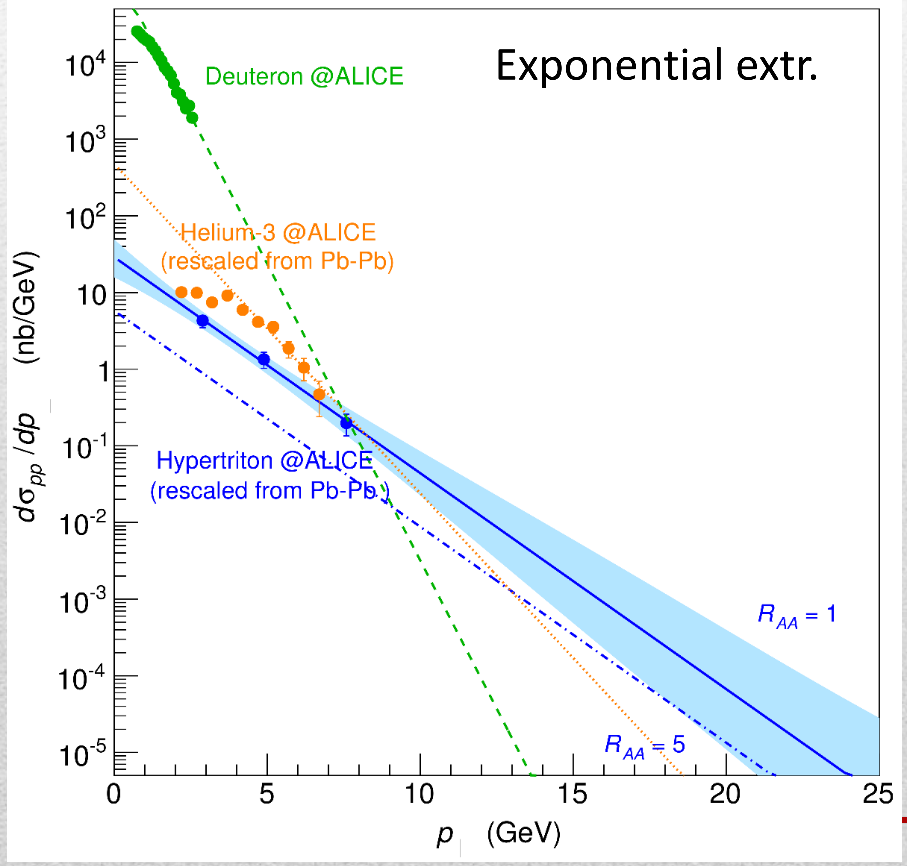


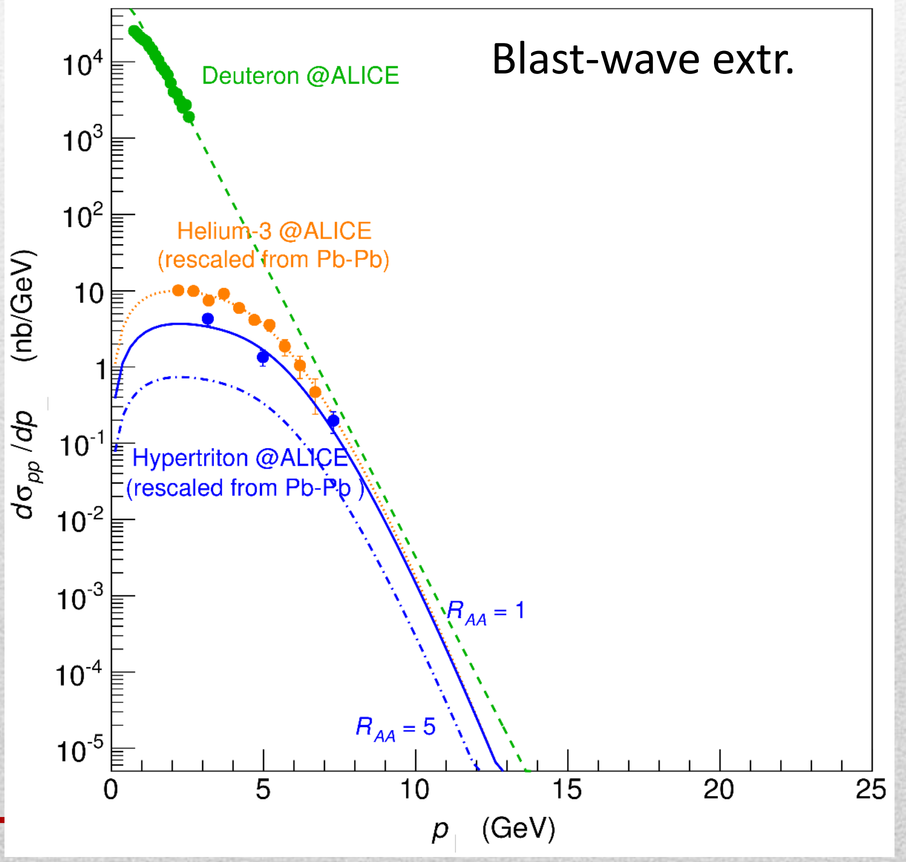


Light nuclei at ALICE

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp



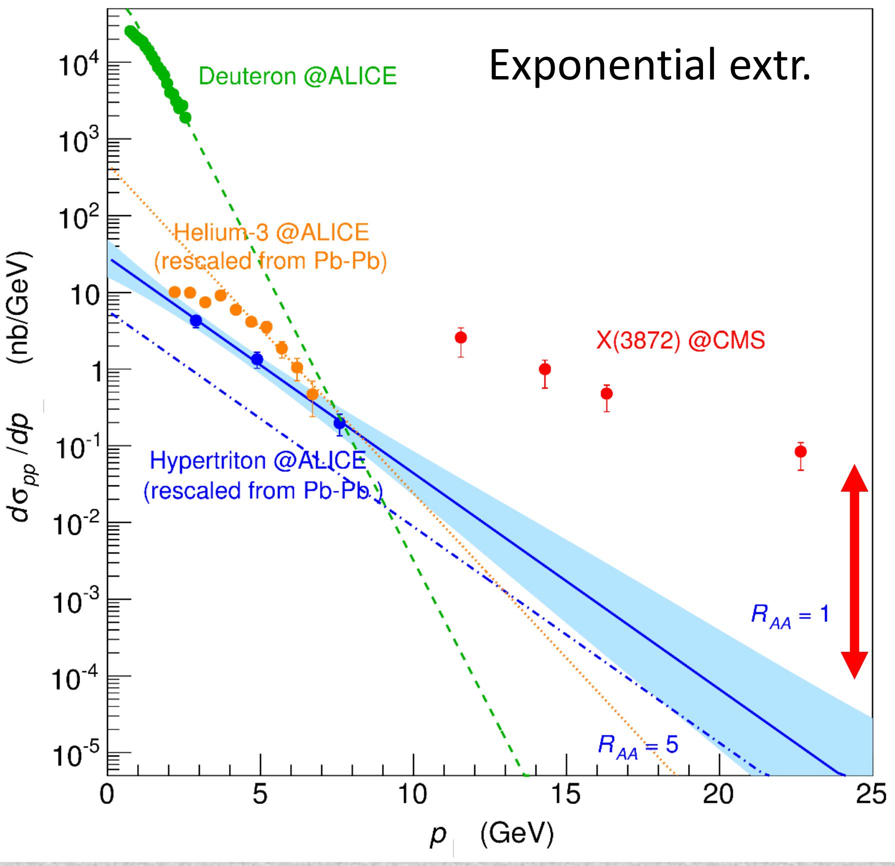


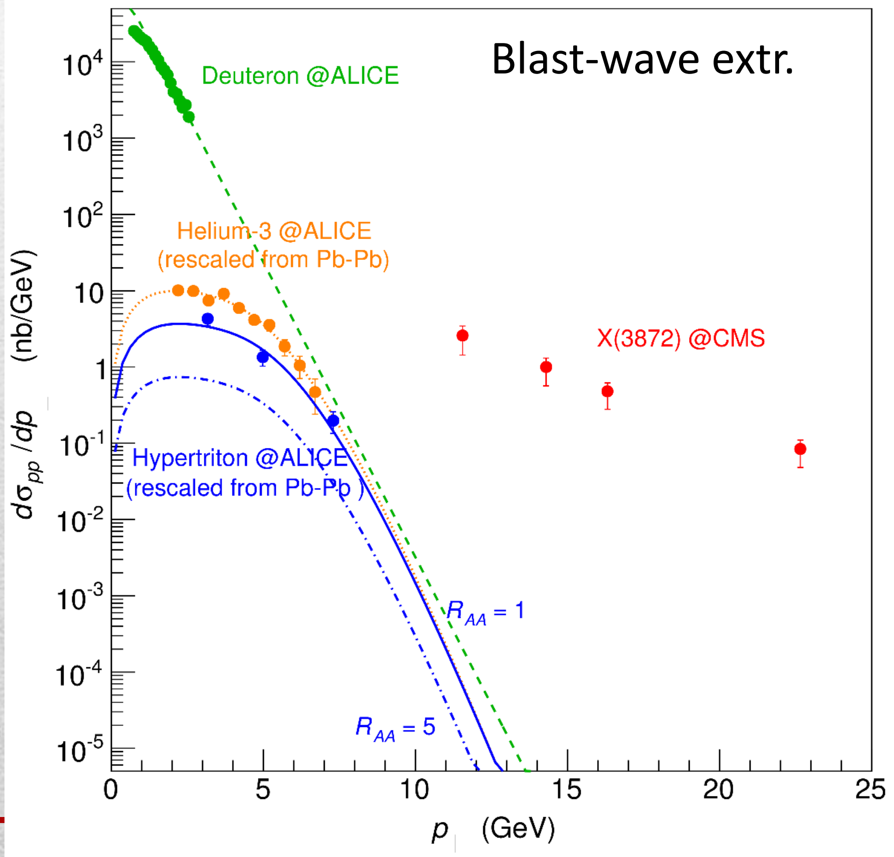
Light nuclei at ALICE vs. $X(3872)$

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp

The $X(3872)$ is way larger than the extrapolated cross section





Light nuclei at ALICE vs. $X(3872)$

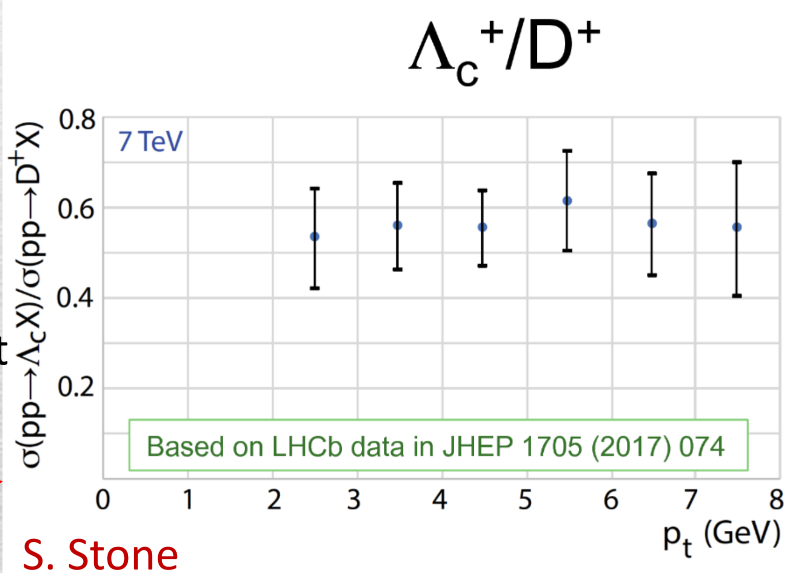
If the production is long-distance dominated, that's pretty much it.

If it's short-distance dominated, one can think on an effect related to the number of quarks involved, in the spirit of constituent counting rules

Brodsky and Lebed, PRD91, 114025
Guo et al., CPC41, 053108
Voloshin, PRD94, 074042
Wang, CPC42, 043103

However, it is not easy to make sense of constituent counting rules in inclusive reactions, where you cannot track the energy carried by each quark

They seem to spectacularly fail



S. Stone

Production of $Y(4260)$ and $P_c(4450)$

Given the new lineshape by BESIII, we need to rethink the binding energy of the $Y(4260)$

J. Nys and AP, to appear

	Constituents	**Bind. Energy**	**Bind. Mom.**	**Mediator**
$X(3872)$	$\bar{D}^0 D^{*0}$	$\sim$100 keV	$\sim$50 MeV	1π ($\sim$300 MeV)
$Y(4260)$	$\bar{D} D_1$	$\sim$70 MeV	$\sim$400 MeV	2π ($\sim$600 MeV)
$P_c(4450)$	$\bar{D}^* \Sigma_c$	$\sim$10 MeV	$\sim$150 MeV	1π ($\sim$300 MeV)

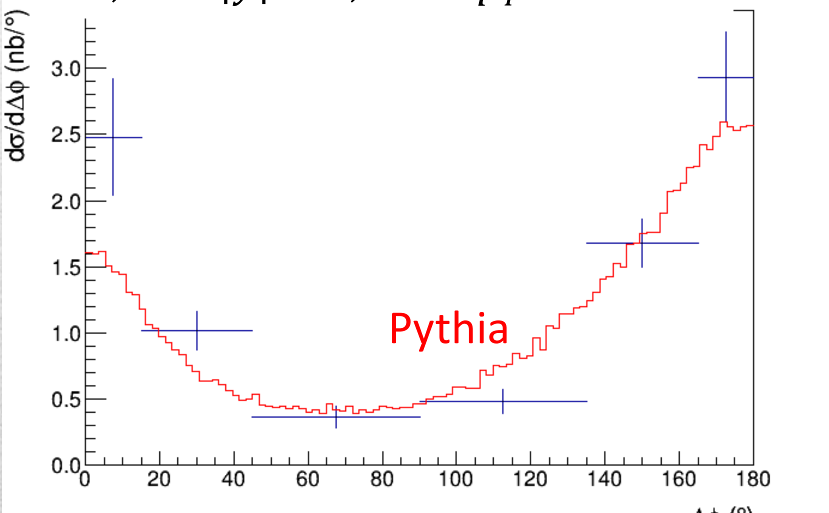
If the states are purely hadron molecule, all the properties depend on the position of the pole with respect to threshold – all the features are universal

Production of $Y(4260)$ and $P_c(4450)$

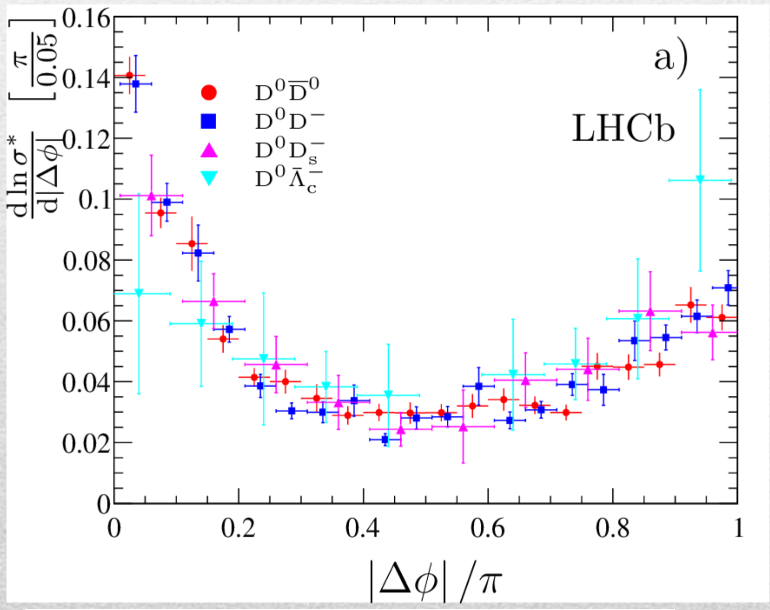
We can use Pythia to simulate the production of event, and calculate the relative production of $Y(4260)$ and $P_c(4450)$ with respect to the $X(3872)$ J. Nys and AP, to appear

We tune our MC on charm pair production

CDF data, $\sqrt{s} = 1.96$ TeV
D^0, D^{*-}: $|y| < 1, 5.5 < p_T < 20$ GeV



For baryons we can double check with LHCb data



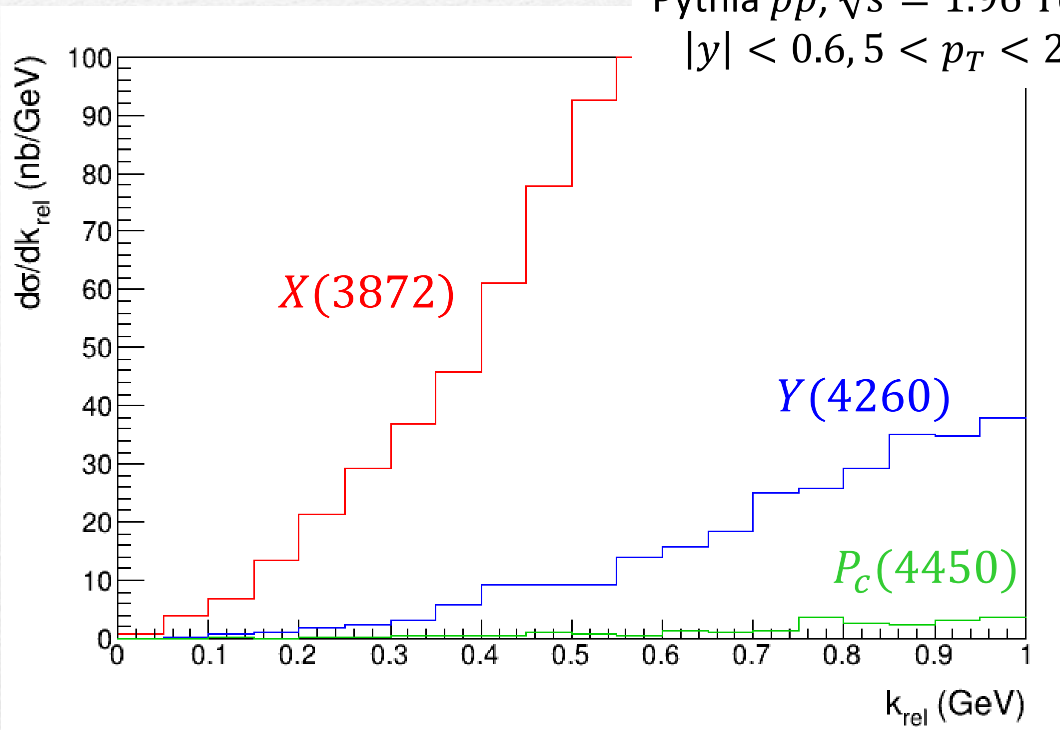
LHCb, $\sqrt{s} = 7$ TeV, JHEP 1206, 141
all: $2 < y < 4, 3 < p_T < 12$ GeV

Production of $Y(4260)$ and $P_c(4450)$

Naively, the fragmentation function of the D_1 is 1/10 of the D^*, but the cross section scales as k_{max}^3

J. Nys and AP, to appear

Pythia $p\bar{p}$, $\sqrt{s} = 1.96$ TeV
$|y| < 0.6, 5 < p_T < 20$ GeV



	No FSI	With FSI
$Y(4260)/X$	23	0.75
$P_c(4450)$/X	1.0	0.01

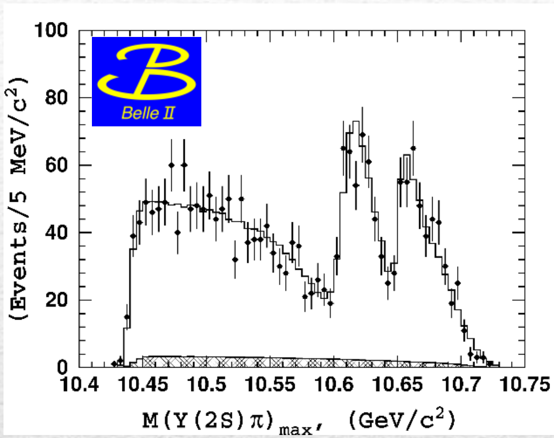
The production of $Y(4260)$
is expected to be at worse comparable
with the $X(3872)$

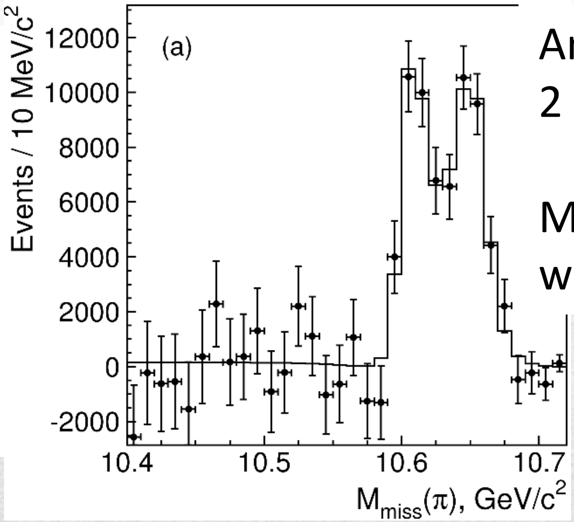
Conclusions

- An Electron Ion Collider is going to be a challenge from any point of view
- The spectroscopy program requires an intense effort from the theory side, to exploit all the unique features of the new machine
- The working group just started working, some estimates are on the way. We need people and ideas!
- We aim to have a workshop in December, and to wrap up the white book in ~ 1 year from now

Thank you

Charged Z states: $Z_b(10610), Z'_b(10650)$





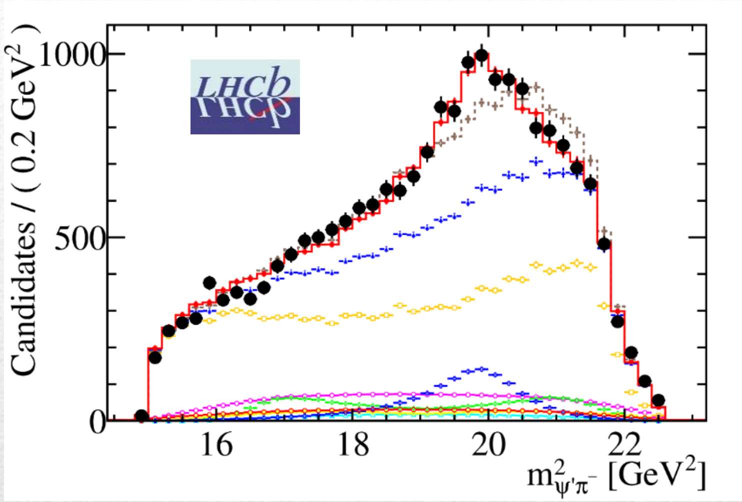
Anomalous dipion width in $\Upsilon(5S)$,
2 orders of magnitude larger than $\Upsilon(nS)$

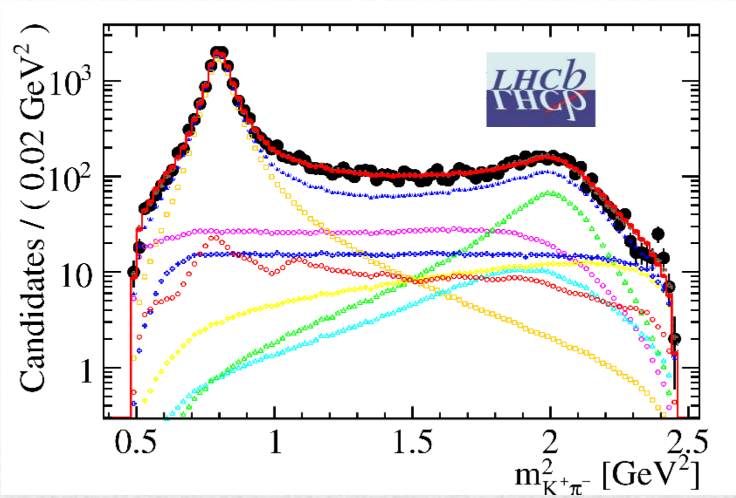
Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$
which violates HQSS

2 twin resonances!

$\Upsilon(5S) \to Z_b(10610)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to (BB^*)^+\pi^-$
$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV
$\Upsilon(5S) \to Z'_b(10650)^+\pi^- \to \Upsilon(nS)\,\pi^+\pi^-, h_b(nP)\,\pi^+\pi^-$
and $\to \bar{B}^{*0}B^{*+}\pi^-$
$M = 10652.2 \pm 1.5$ MeV, $\Gamma = 11.5 \pm 2.2$ MeV

Charged Z states: $Z(4430)$

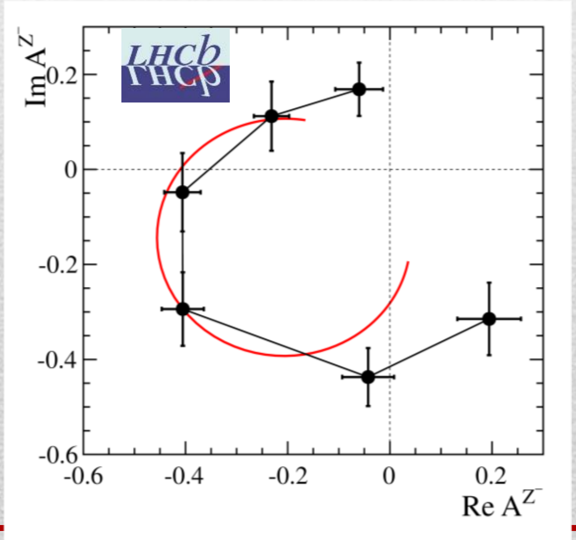




$$Z(4430)^+ \to \psi(2S)\,\pi^+$$
$$I^G J^{PC} = 1^+ 1^{+-}$$

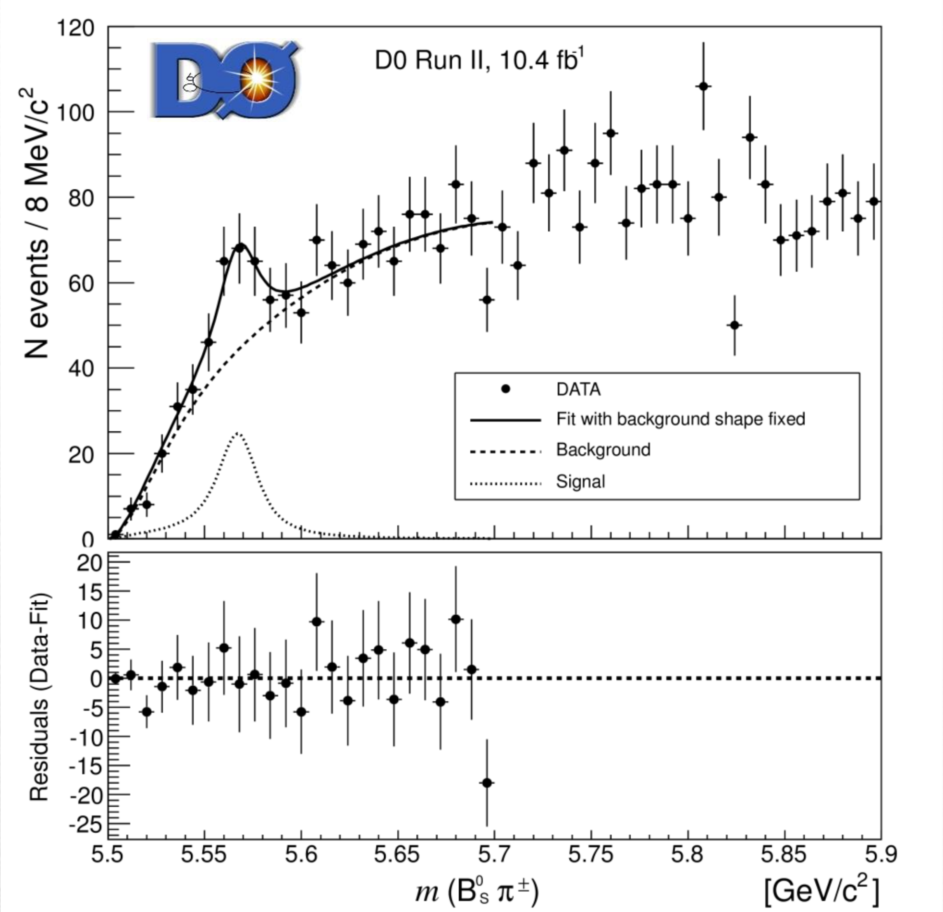
$$M = 4475 \pm 7^{+15}_{-25}\text{ MeV}$$
$$\Gamma = 172 \pm 13^{+37}_{-34}\text{MeV}$$

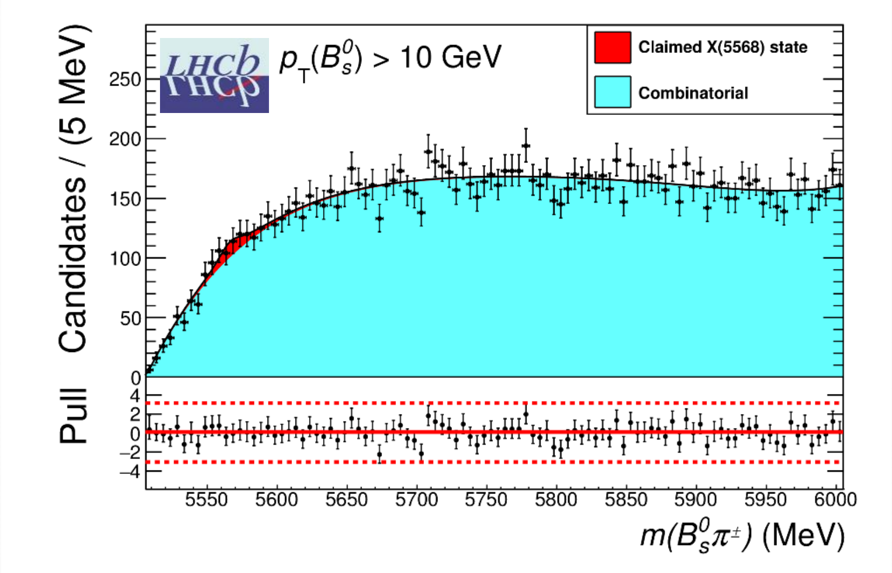
Far from open charm thresholds



If the amplitude is a free complex number, in each bin of $m^2_{\psi'\pi^-}$, the resonant behaviour appears as well

Flavored $X(5568)$





- A flavored state seen in $B_s^0\,\pi$ invariant mass by D0 (both $B_s^0 \to J/\psi\,\phi$ and $\to D_s\mu\nu$),
- not confermed by LHCb or CMS
- (different kinematics? Compare differential distributions)

Controversy to be solved

Joint Physics Analysis Center

- Joint effort between theorists and experimentalists to work together to make the best use of the next generation of very precise data taken at JLab and in the world
- Created in 2013 by JLab & IU agreement
- It is engaged in education of further generations of hadron physics practitioners

Effective Field Theories
Analyticity+Unitarity
Dispersion Relations
Regge Theory

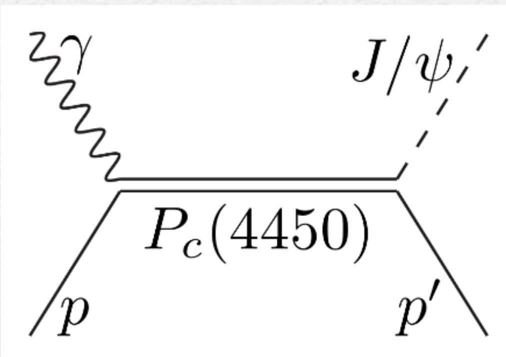
Experiments
CLAS, GlueX, BESIII, COMPASS,
LHCb, BaBar, Belle II, KLOE, MAMI
Lattice

Fundamental parameters
Resonances, exotic states

Insight on QCD dynamics

P_c photoproduction

To exclude any rescattering mechanism, we propose to search the $P_c(4450)$ state in photoproduction.



$$\langle \lambda_\psi \lambda_{p'} | \, T_r \, | \lambda_\gamma \lambda_p \rangle = \frac{\overbrace{\boxed{\langle \lambda_\psi \lambda_{p'} | \, T_{\mathrm{dec}} \, | \lambda_R \rangle}}^{\text{Hadronic vertex}} \overbrace{\boxed{\langle \lambda_R | \, T^\dagger_{\mathrm{em}} \, | \lambda_\gamma \lambda_p \rangle}}^{\text{EM vertex}}}{M_r^2 - W^2 - i\Gamma_r M_r}$$

Hadronic part

- 3 independent helicity couplings,
  → approx. equal, $g_{\lambda_\psi, \lambda_{p'}} \sim g$
- g extracted from total width and (unknown) branching ratio

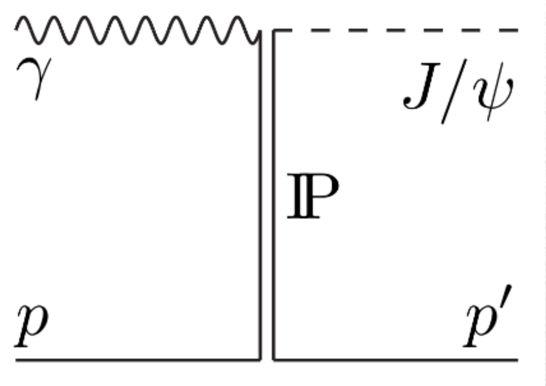
Vector meson dominance relates the radiative width to the hadronic width

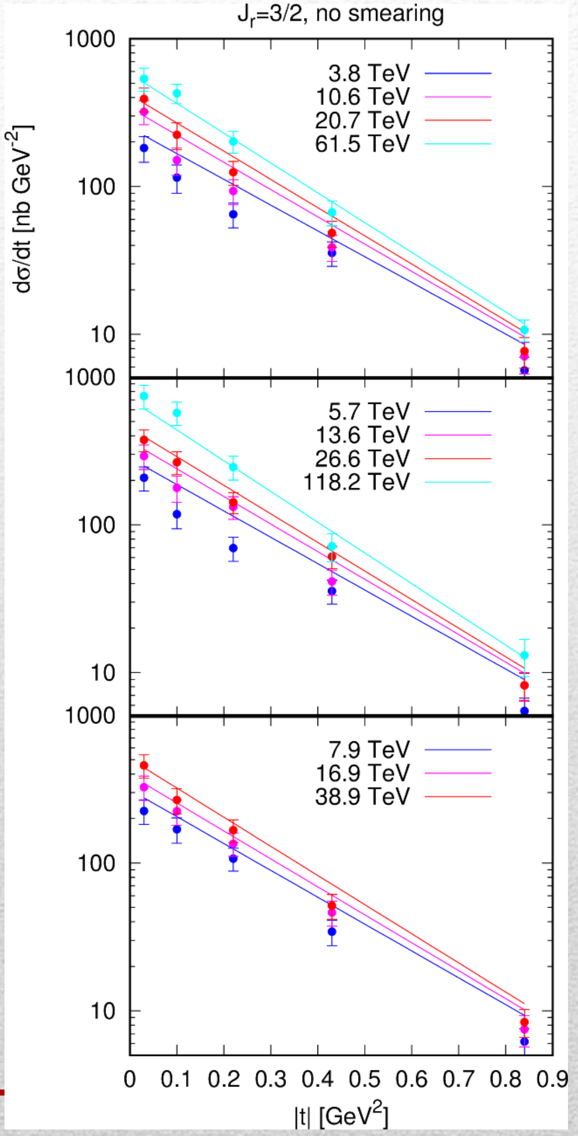
$$\Gamma_\gamma = 4\pi\alpha \, \Gamma_{\psi p} \left(\frac{f_\psi}{M_\psi} \right)^2 \left(\frac{\bar{p}_i}{\bar{p}_f} \right)^{2\ell+1} \times \frac{4}{6}$$

Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Background parameterization

The background is described via an Effective Pomeron, whose parameters are fitted to high energy data from Hera





$$\langle \lambda_\psi \lambda_{p'} | T_P | \lambda_\gamma \lambda_p \rangle = iA \left(\frac{s - s_t}{s_0} \right)^{\alpha(t)} e^{b_0 (t - t_{\min})} \delta_{\lambda_p \lambda_{p'}} \delta_{\lambda_\psi \lambda_\gamma}$$

Asymptotic + Effective threshold

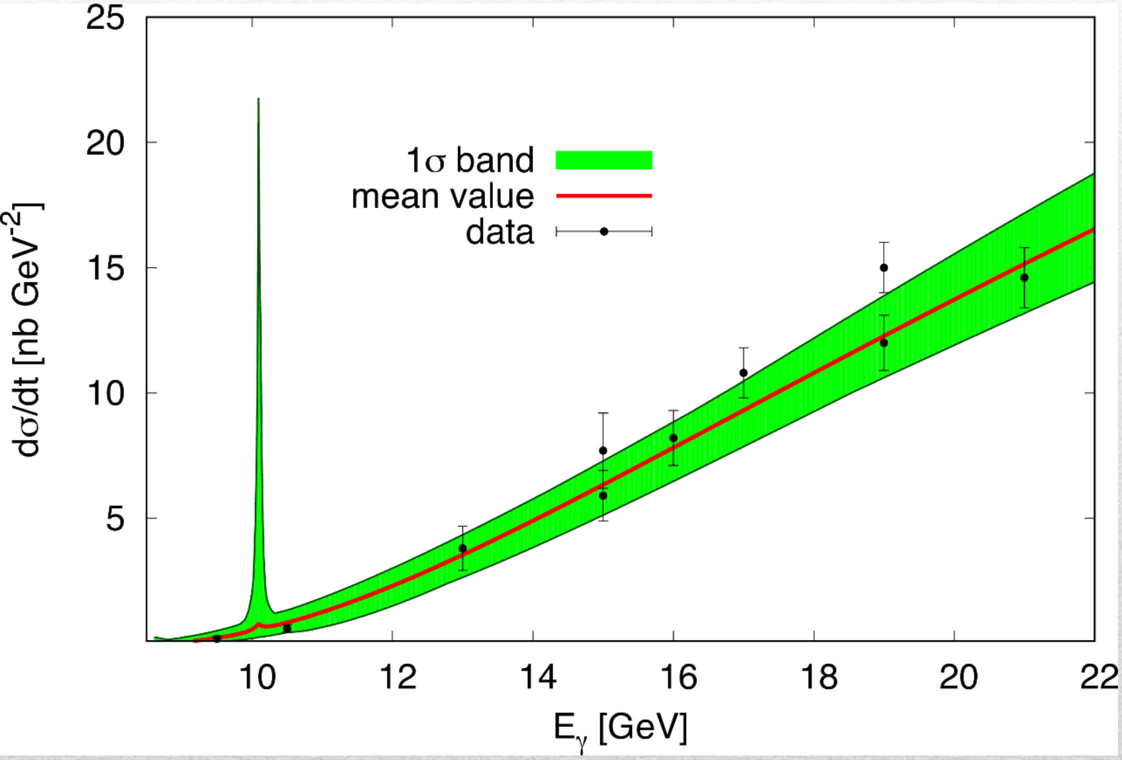
Helicity conservation

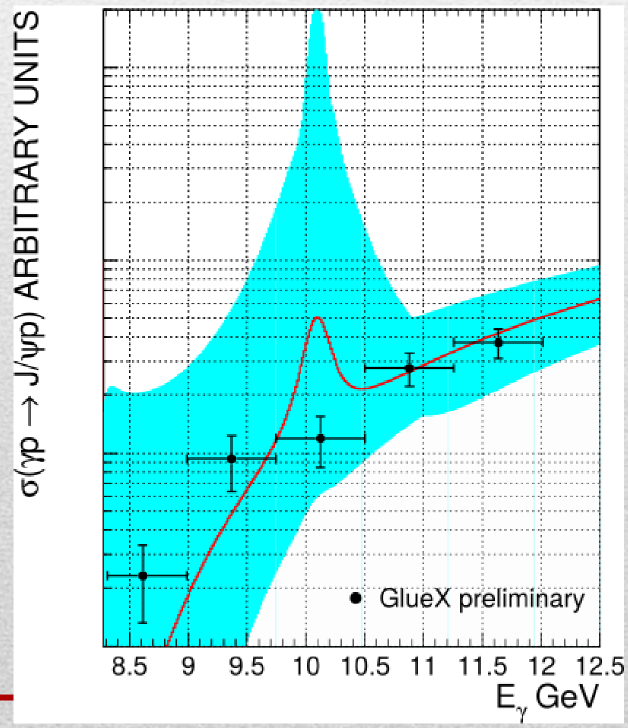
Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

Pentaquark photoproduction

$J^P = (3/2)^-$

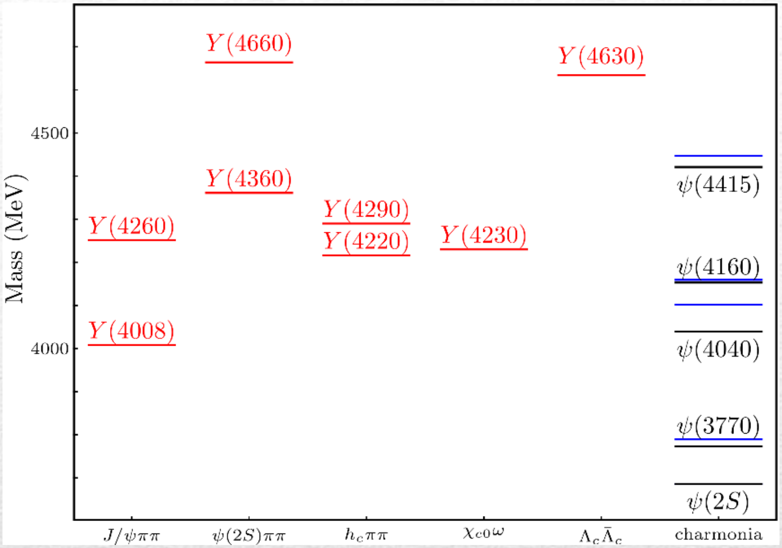
σ_s (MeV)	0	60
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$
$\mathcal{B}_{\psi p}$ (95% CL)	≤ 29 %	≤ 30 %





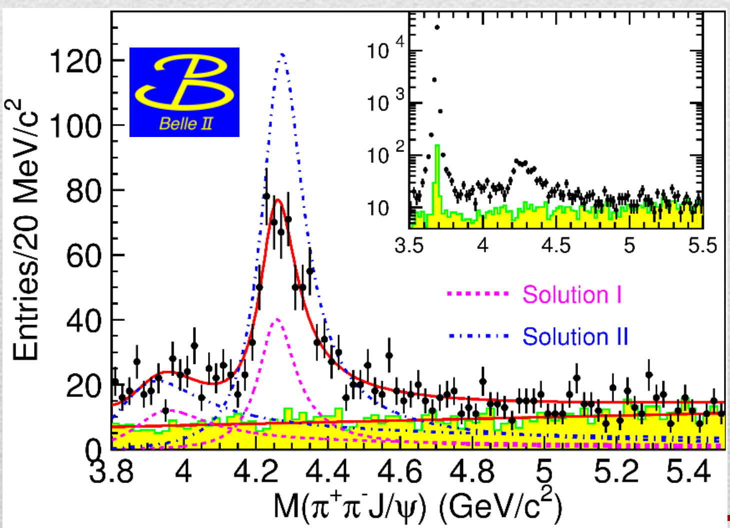
Hiller Blin, AP *et al.* (JPAC), PRD94, 034002

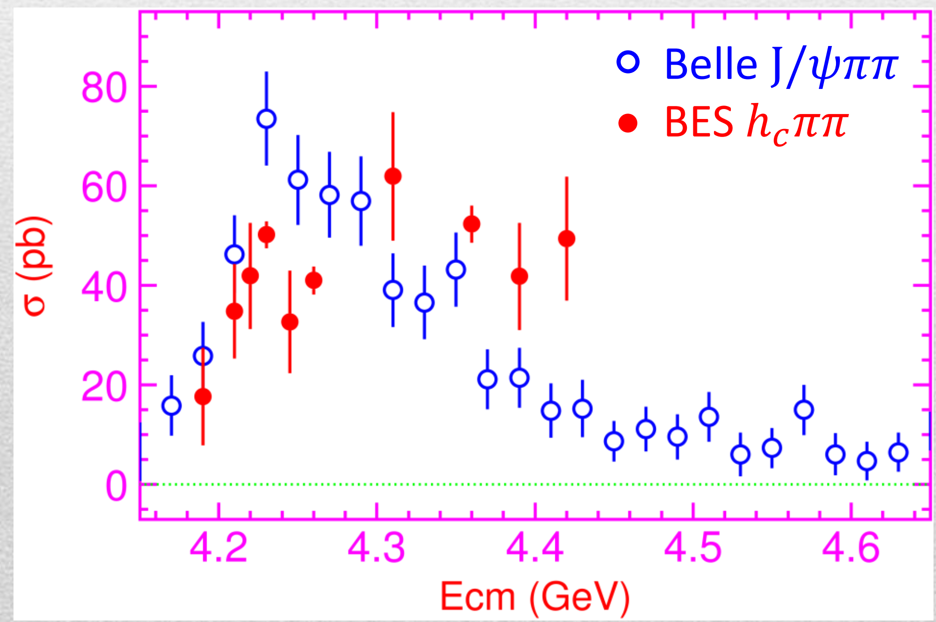
Vector Y states



Lots of unexpected $J^{PC} = 1^{--}$ states
found in ISR/direct production (and nowhere else!)
Seen in few final states,
mostly $J/\psi\ \pi\pi$ and $\psi(2S)\ \pi\pi$

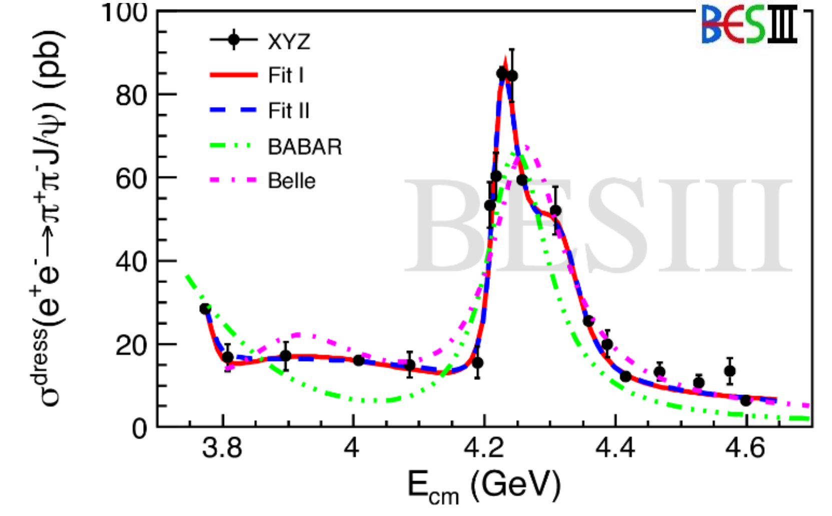
Not seen decaying into open charm pairs
Large HQSS violation





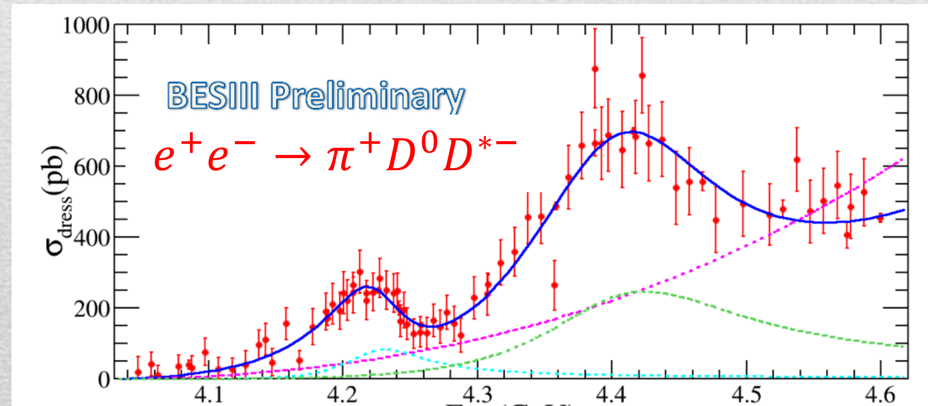
Vector Y states in BESIII

BESIII, PRL118, 092001 (2017) $e^+e^- \to J/\psi\,\pi\pi$



BESIII, PRL118, 092002 (2017)

Parameters	Solution I	Solution II
$\Gamma_{e^+e^-}\mathcal{B}[\psi(3770)\to\pi^+\pi^-J/\psi]$		0.5 ± 0.1 (0
$\Gamma_{e^+e^-}\mathcal{B}(R_1\to\pi^+\pi^-J/\psi)$	$8.8^{+1.5}_{-2.2}\,(\cdots)$	$6.8^{+1.1}_{-1.5}\,(\cdots)$
$\Gamma_{e^+e^-}\mathcal{B}(R_2\to\pi^+\pi^-J/\psi)$	$13.3\pm1.4\,(12.0\pm1.0)$	$9.2\pm0.7\,(8.9\pm0.6)$
$\Gamma_{e^+e^-}\mathcal{B}(R_3\to\pi^+\pi^-J/\psi)$	$21.1\pm3.9\,(17.9\pm3.3)$	$1.7^{+0.8}_{-0.6}\,(1.1^{+0.5}_{-0.4})$
ϕ_1	$-58\pm11\,(-33\pm8)$	$-116^{+9}_{-10}\,(-81^{+7}_{-8})$
ϕ_2	$-156\pm5\,(-132\pm3)$	$68\pm24\,(107\pm20)$



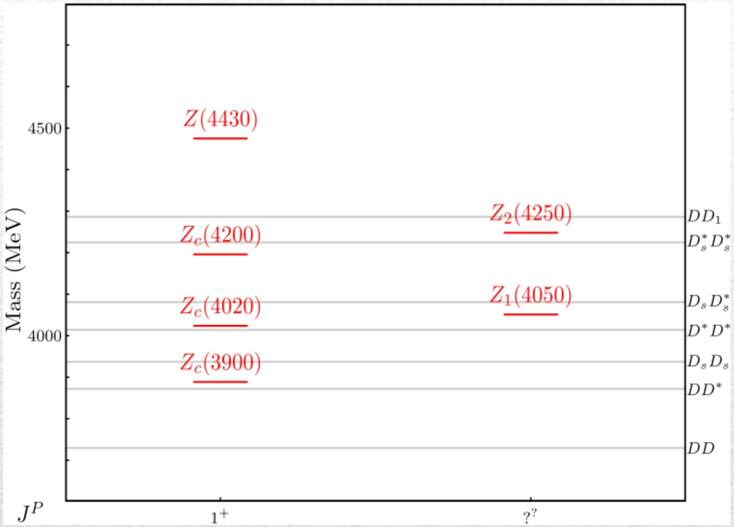
Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

$M(Y(4220)) = (4224.8\pm5.6\pm4.0)$ MeV/c^2, $\Gamma(Y(4220)) = (72.3\pm9.1\pm0.9)$ MeV.
$M(Y(4390)) = (4400.1\pm9.3\pm2.1)$ MeV/c^2, $\Gamma(Y(4220)) = (181.7\pm16.9\pm7.4)$ MeV.

New BESIII data show a peculiar lineshape for the $Y(4260)$
The state appear lighter and narrower, compatible with the ones in $h_c\pi\pi$ and $\chi_{c0}\omega$
A broader old-fashioned $Y(4260)$ is appearing in $\bar{D}D^*\pi$, maybe indicating a $\bar{D}D_1$ dominance

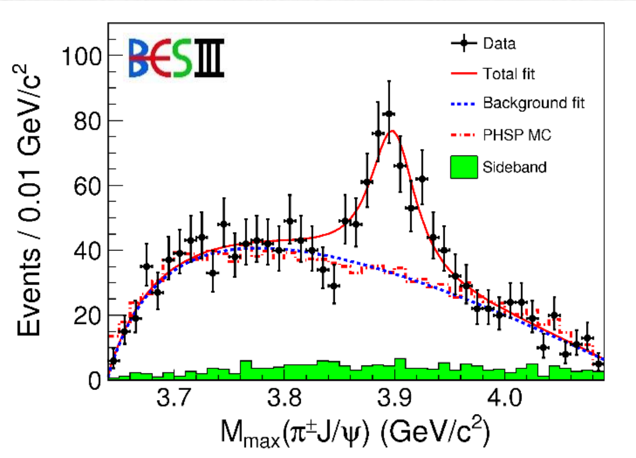
Charged Z states: $Z_c(3900), Z_c'(4020)$

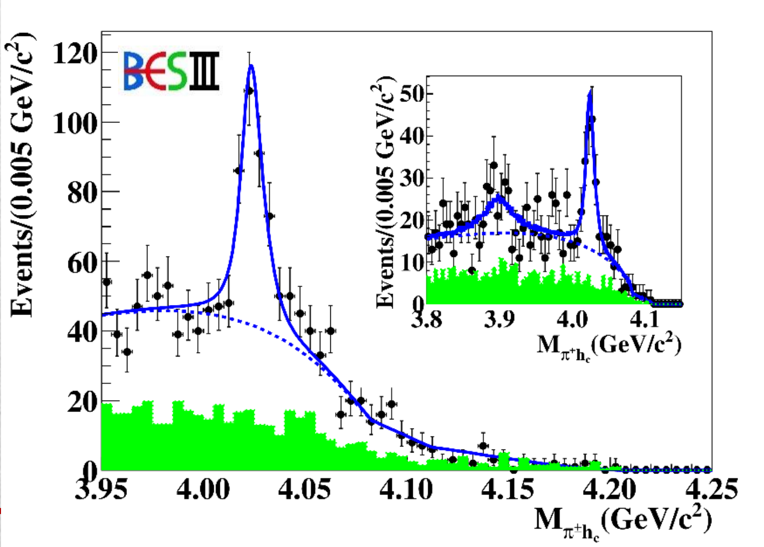
Charged quarkonium-like resonances have been found, **4q needed**



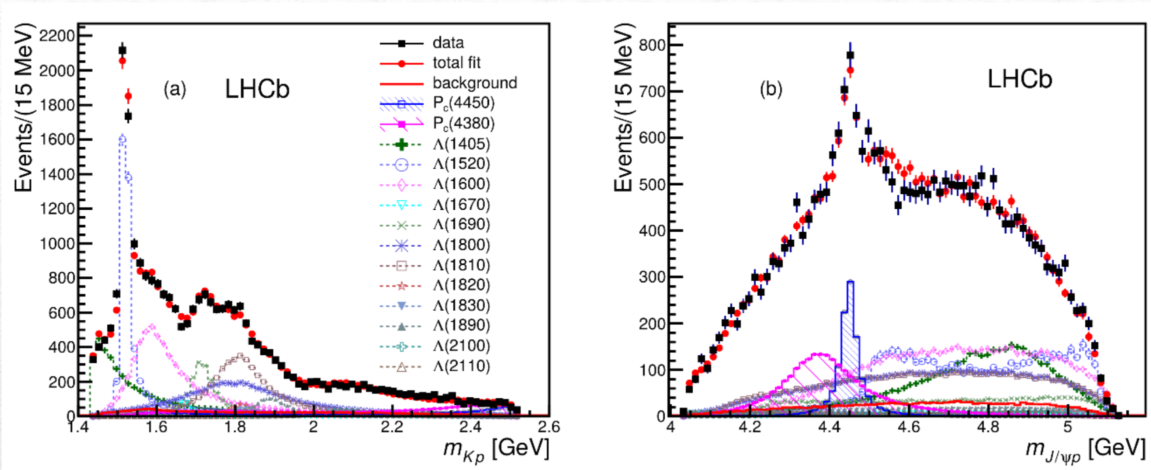
Two states $J^{PC} = 1^{+-}$ appear
slightly above $D^{(*)}D^*$ thresholds

$e^+e^- \to Z_c(3900)^+\pi^- \to J/\psi\,\pi^+\pi^-$ and $\to (DD^*)^+\pi^-$
$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV
$e^+e^- \to Z_c'(4020)^+\pi^- \to h_c\,\pi^+\pi^-$ and $\to \bar{D}^{*0}D^{*+}\pi^-$
$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV





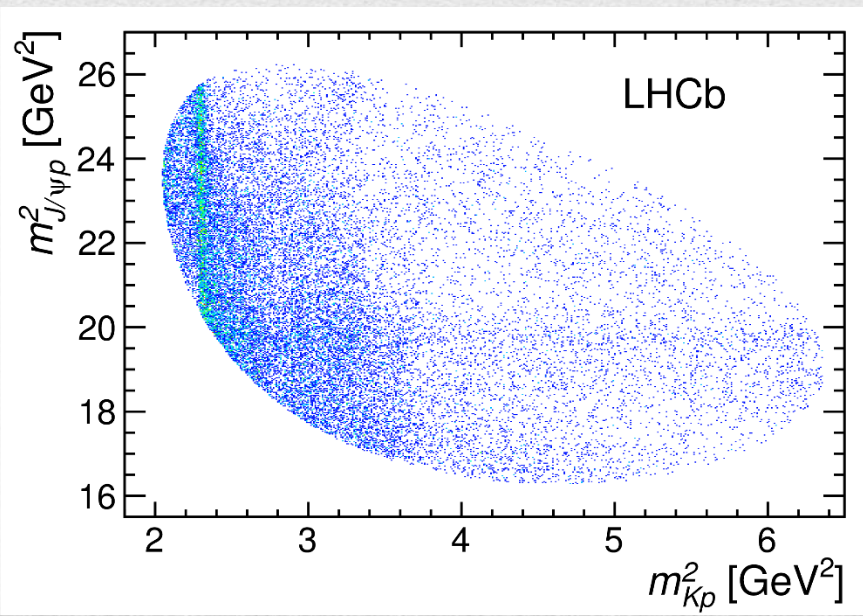
Pentaquarks!



LHCb, PRL 115, 072001
LHCb, PRL 117, 082003

Two states seen in $\Lambda_b \to (J/\psi\, p)\, K^-$, evidence in $\Lambda_b \to (J/\psi\, p)\, \pi^-$

$M_1 = 4380 \pm 8 \pm 29$ MeV
$\Gamma_1 = 205 \pm 18 \pm 86$ MeV
$M_2 = 4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma_2 = 39 \pm 5 \pm 19$ MeV



Quantum numbers

$$J^P = \left(\frac{3}{2}^-, \frac{5}{2}^+\right) \text{ or } \left(\frac{3}{2}^+, \frac{5}{2}^-\right) \text{ or } \left(\frac{5}{2}^+, \frac{3}{2}^-\right)$$

Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by Λ^* (model dependence?)

No obvious threshold nearby

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle [23] (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [24,25] (>10), *BABAR* [26] (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi)$ ...	CDF [27,28] (11.6), D0 [29] (5.2)
				$pp \to (\pi^+\pi^- J/\psi)$ ...	LHCb [30,31] (np)
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [32] (4.3), *BABAR* [33] (4.0)
				$B \to K(\gamma J/\psi)$	Belle [34] (5.5), *BABAR* [35] (3.5)
					LHCb [36] (> 10)
				$B \to K(\gamma\,\psi(2S))$	*BABAR* [35] (3.6), Belle [34] (0.2)
					LHCb [36] (4.4)
				$B \to K(D\bar{D}^*)$	Belle [37] (6.4), *BABAR* [38] (4.9)
$Z_c(3900)^+$	3888.7 ± 3.4	35 ± 7	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [39] (np)
				$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [40] (8), Belle [41] (5.2)
					CLEO data [42] (>5)
$Z_c(4020)^+$	4023.9 ± 2.4	10 ± 6	1^{+-}	$Y(4260) \to \pi^-(\pi^+ h_c)$	BES III [43] (8.9)
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [44] (10)
$Y(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(\omega J/\psi)$	Belle [45] (8), *BABAR* [33,46] (19)
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [47] (7.7), *BABAR* [48] (7.6)
$Z(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [49] (5.3), *BABAR* [50] (5.8)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [51,52] (6)
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [41,53] (7.4)
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [54] (5.0), *BABAR* [55] (1.1)
$Y(4140)$	4145.6 ± 3.6	14.3 ± 5.9	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [56,57] (5.0), Belle [58] (1.9),
					LHCb [59] (1.4), CMS [60] (>5)
					DØ [61] (3.1)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [52] (5.5)
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [62] (7.2)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$Y(4220)$	4196^{+35}_{-30}	39 ± 32	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data [63,64] (4.5)
$Y(4230)$	4230 ± 8	38 ± 12	1^{--}	$e^+e^- \to (\chi_{c0}\omega)$	BES III [65] (>9)
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [54] (5.0), *BABAR* [55] (2.0)
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	*BABAR* [66,67] (8), CLEO [68,69] (11)
					Belle [41,53] (15), BES III [40] (np)
				$e^+e^- \to (f_0(980) J/\psi)$	*BABAR* [67] (np), Belle [41] (np)
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [40] (8), Belle [41] (5.2)
				$e^+e^- \to (\gamma\, X(3872))$	BES III [70] (5.3)
$Y(4290)$	4293 ± 9	222 ± 67	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data [63,64] (np)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [58] (3.2)
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [71] (8), *BABAR* [72] (np)
$Z(4430)^+$	4478 ± 17	180 ± 31	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [73,74] (6.4), *BABAR* [75] (2.4)
					LHCb [76] (13.9)
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [62] (4.0)
$Y(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [77] (8.2)
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [71] (5.8), *BABAR* [72] (5)
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi(\pi\Upsilon(nS))$	Belle [78,79] (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle [78] (16)
				$\Upsilon(5S) \to \pi^-(B\bar{B}^*)^+$	Belle [80] (8)
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^-(\pi^+\Upsilon(nS))$	Belle [78] (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle [78] (16)
				$\Upsilon(5S) \to \pi^-(B^*\bar{B}^*)^+$	Belle [80] (6.8)

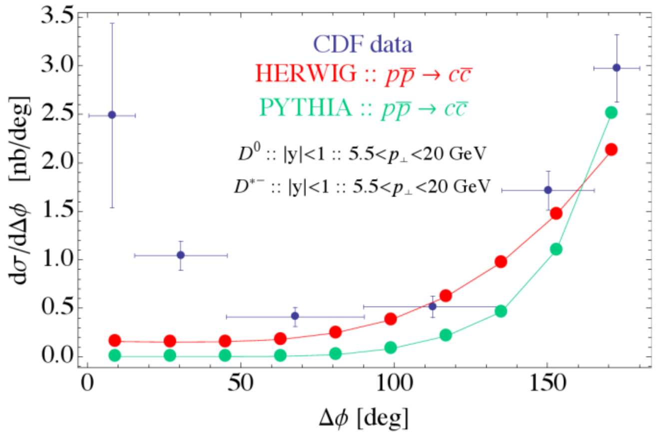
Esposito, AP, Polosa, Phys.Rept. 668
Guerrieri, AP, Piccinini, Polosa, IJMPA 30, 1530002

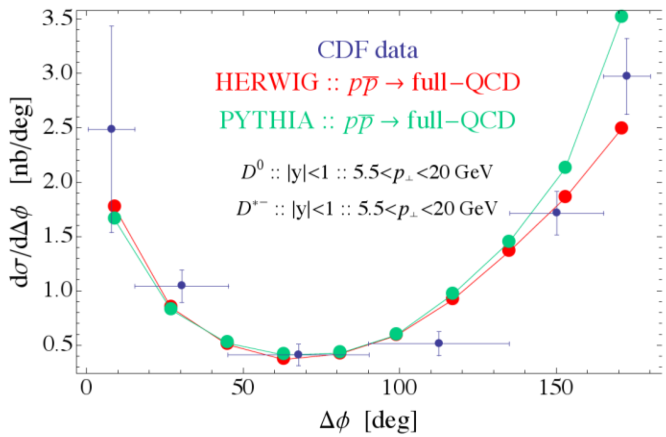
Tuning of MC

Monte Carlo simulations

A. Esposito

- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:





The c-cbar run understimate the low angles (low-k_0) region!

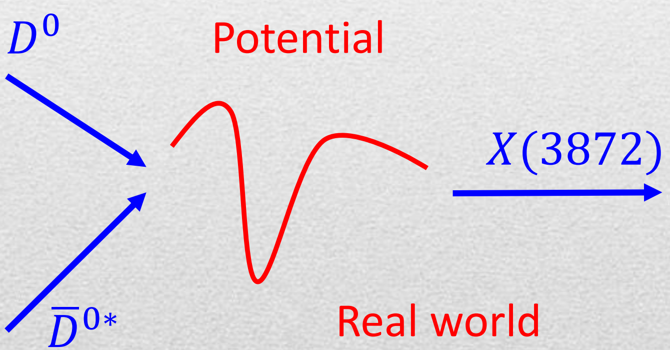
Such distributions of charm mesons are available at Tevatron
No distribution has been published (yet) at LHC

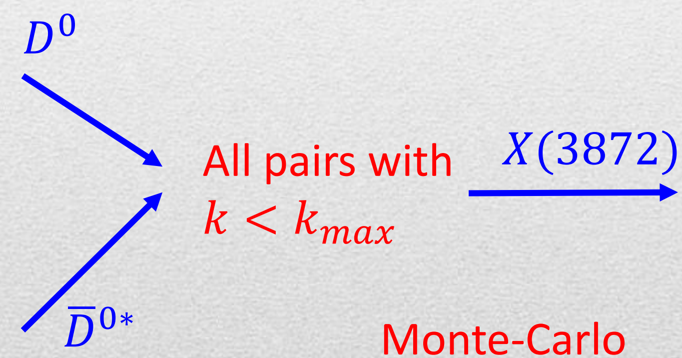
Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\bar{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?)

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

Q. What is a molecule in MC? **A.** «Coalescence» model





$$\sigma\big(p\bar{p} \to X(3872)\big) \sim \int d^3k \; |\langle X|D\bar{D}^*\rangle\langle D\bar{D}^*|p\bar{p}\rangle|^2 < \int_{k<k_{max}} d^3k \; |\langle D\bar{D}^*|p\bar{p}\rangle|^2$$

This should provide an upper bound for the cross section

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001
Kadastic, Raidan, Strumia PLB683 (2010) 248

Estimating k_{max}

The binding energy is $E_B \approx -0.16 \pm 0.31\ \text{MeV}$: very small!
In a simple square well model this corresponds to:

$$\sqrt{\langle k^2 \rangle} \approx 50\ \text{MeV}, \sqrt{\langle r^2 \rangle} \approx 10\ \text{fm}$$

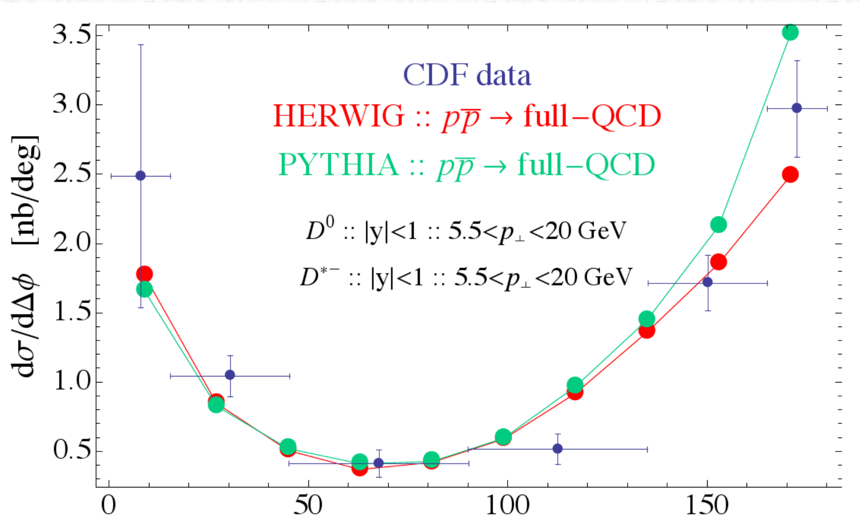
$$\left(\begin{array}{c} \text{binding energy reported in Kamal Seth's talk is } E_B \approx -0.013 \pm 0.192\ \text{MeV:} \\ \sqrt{\langle k^2 \rangle} \approx 30\ \text{MeV}, \sqrt{\langle r^2 \rangle} \approx 30\ \text{fm} \end{array} \right)$$

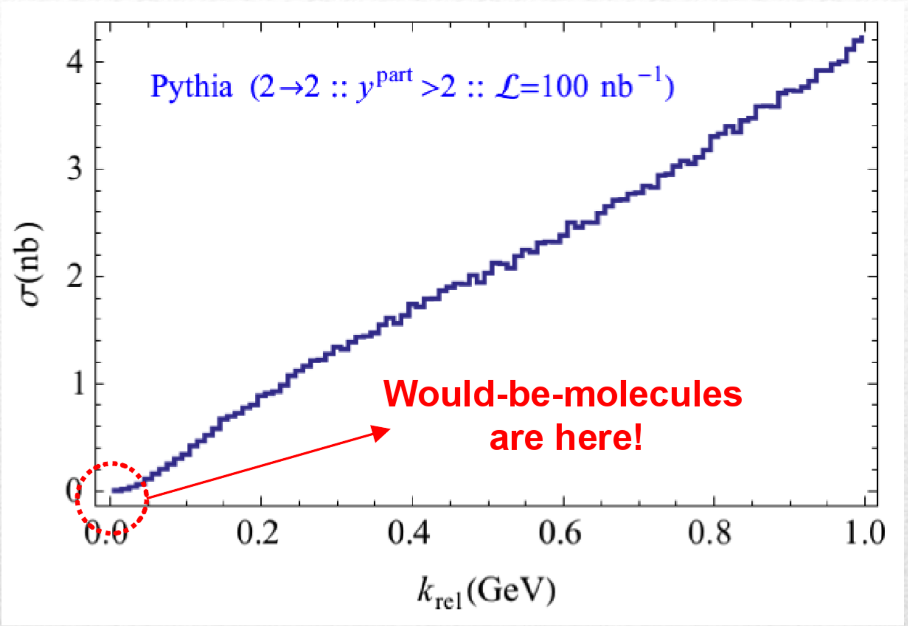
to compare with deuteron: $E_B = -2.2\ \text{MeV}$

$$\sqrt{\langle k^2 \rangle} \approx 80\ \text{MeV}, \sqrt{\langle r^2 \rangle} \approx 4\ \text{fm}$$

We assume $k_{max} \sim \sqrt{\langle k^2 \rangle} \approx 50\ \text{MeV}$, some other choices are commented later

2009 results





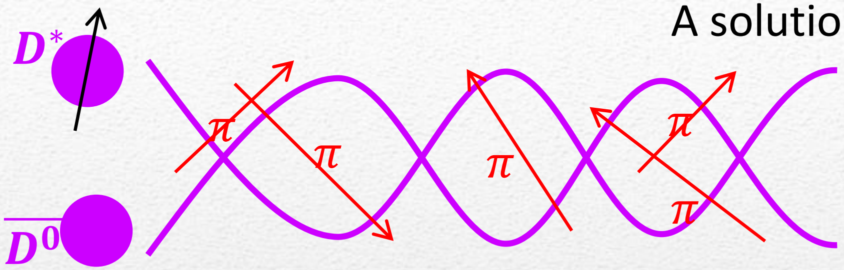
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$

We get $\sigma(p\bar{p} \to DD^* | k < k_{max}) \approx 0.1\text{ nb} @\sqrt{s} = 1.96\text{ TeV}$

Experimentally $\sigma(p\bar{p} \to X(3872)) \approx 30 - 70\text{ nb!!!}$

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

Estimating k_{max}



A solution can be FSI (rescattering of DD^*) , which allow k_{max} to be as large as $5m_\pi \sim 700$ MeV

$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230$ nb

Artoisenet and Braaten, PRD81, 114018

However, the applicability of Watson theorem is challenged by the presence of pions that interfere with DD^* propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten, PRD83, 014019

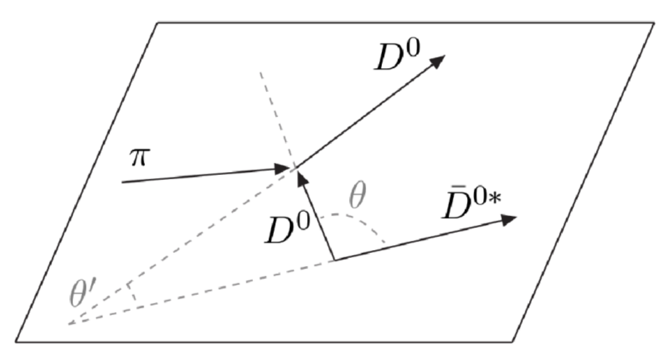
Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354 use $E_{max} = M_X + \Gamma_X$ for above-threshold unstable states

With different choices, 2 orders of magnitude uncertainty, limits on predictive power

A new mechanism?

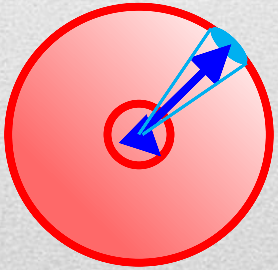
In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the pairs DD^*

Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

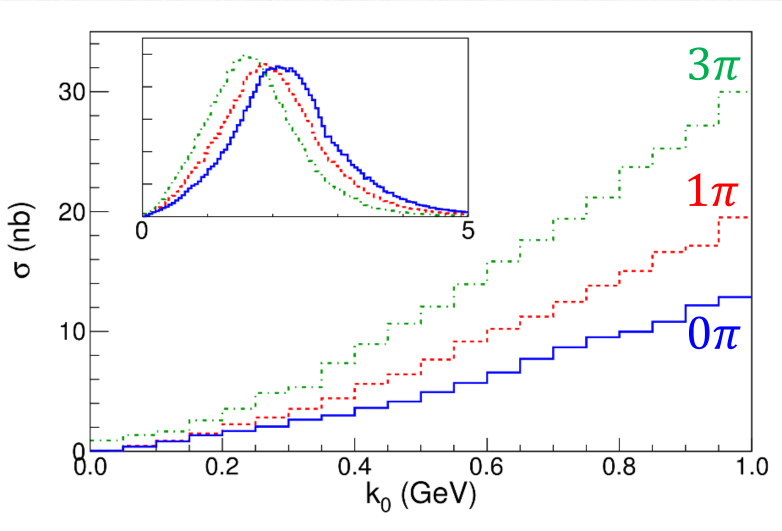


The mechanism also implies: D mesons actually "pushed" inside the potential well (the classical 3-body problem!)

$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100\ \mathrm{keV}$



By comparing hadronization times of heavy and light mesons, we estimate up to ~ 3 collisions can occur before the heavy pair to fly apart



We get $\sigma\left(p\bar{p} \to X(3872)\right) \sim 5\ \mathrm{nb}$, still not sufficient to explain all the experimental cross section