Production of tetraquarks at LHC

Incontro sulla fisica con ioni pesanti a LHC

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In collaboration with
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ALICE

INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

X(3872) ?

Discovered by Belle in 2003 and confirmed by Babar, CDF, D0, Bes III

Seen also by CMS and LHCb

Golden channel

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Production mechanisms

$$B \to K\, X(3872)$$
$$Y(4260) \to \gamma X(3872)$$
$$pp \to X(3872) + \text{all}$$
$$p\bar{p} \to X(3872) + \text{all}$$

Other decay modes

$$X(3872) \to \omega J/\psi$$
$$X(3872) \to D^{*0}\bar{D}^0$$
$$X(3872) \to \gamma J/\psi$$
$$X(3872) \to \gamma\psi(2S)$$

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FIND IT

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FIND IT

What about production in Pb-Pb or p-Pb?

$$\sigma(P_bP_b \to X(3872))$$

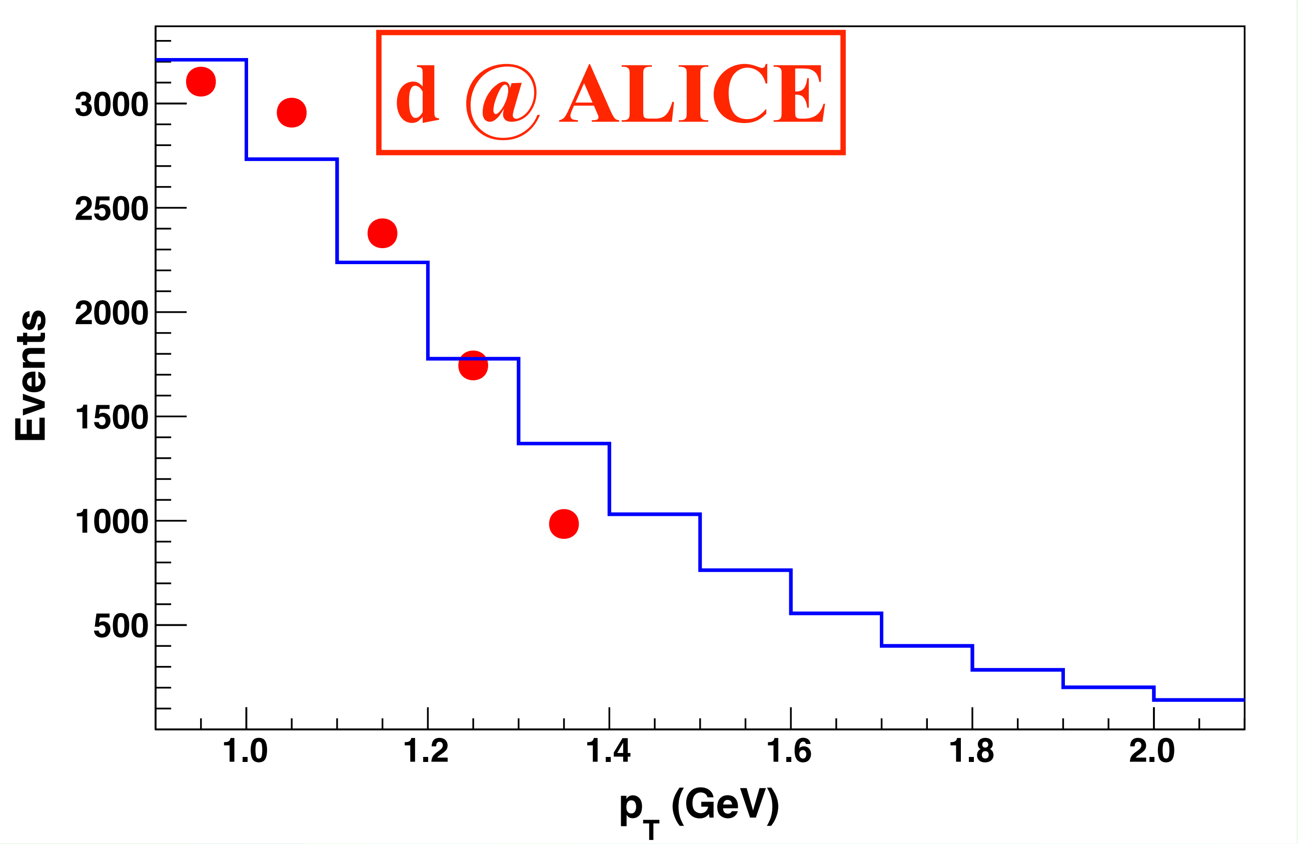
$$\sigma(pP_b \to X(3872))$$

X(3872) vs deuteron

If X(3872) is a molecule like deuteron, we expect to compare production cross-sections

We use antideuteron ALICE data and MC simulations to extrapolate at high p_T

Sharma et al (ALICE) Acta Phys Polon Supp 5, 605 (2012)



ALG, Piccinini, Pilloni, Polosa PRD 90, 034003

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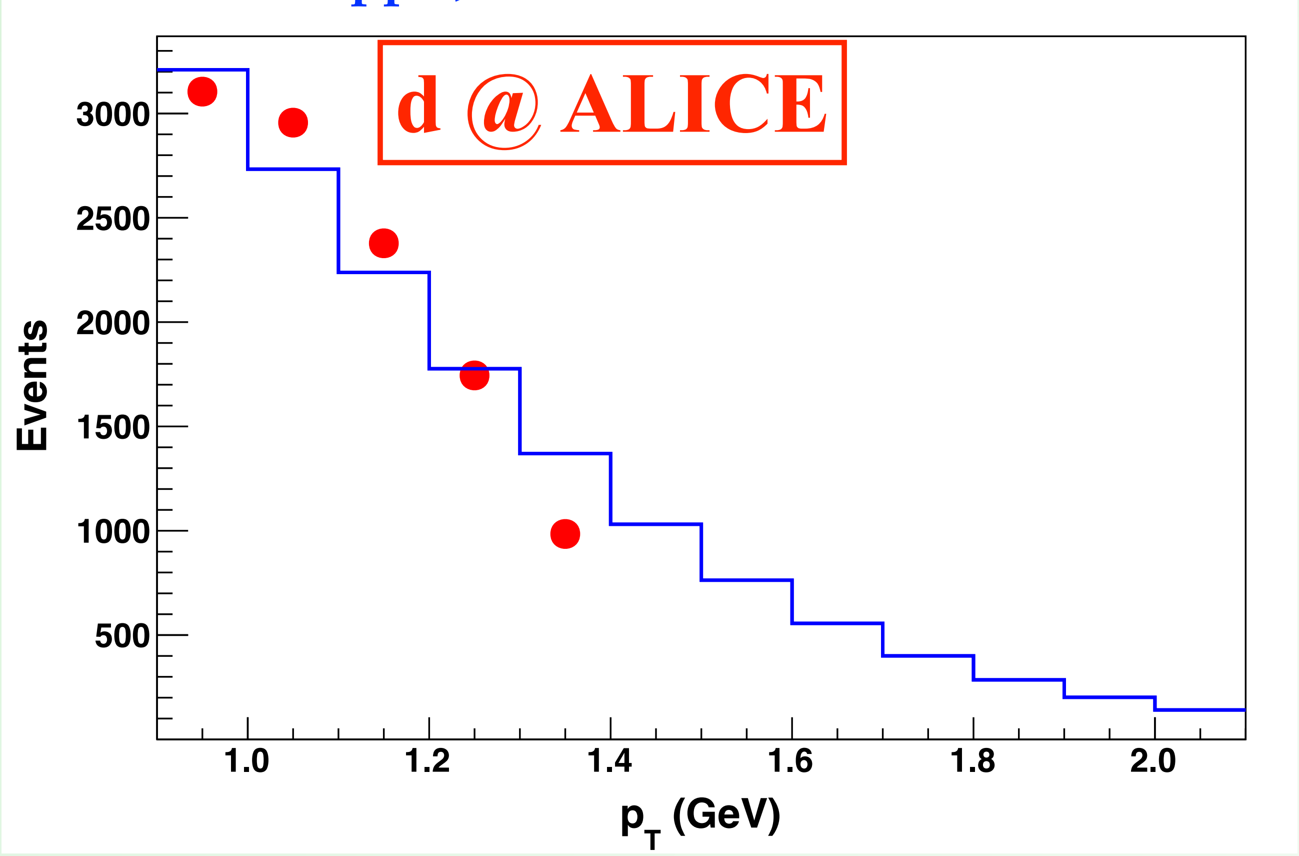
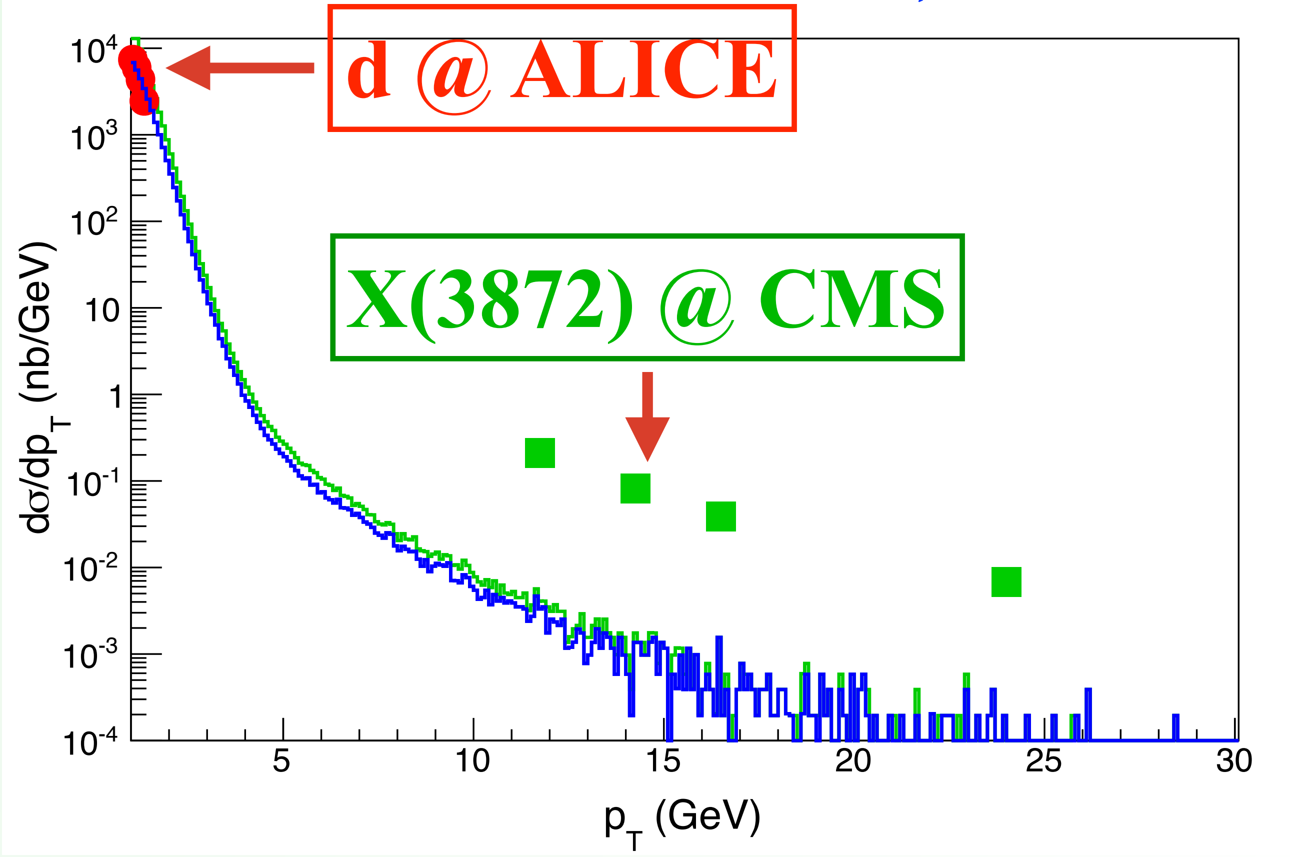


ALG, Piccinini, Pilloni, Polosa PRD 90, 034003

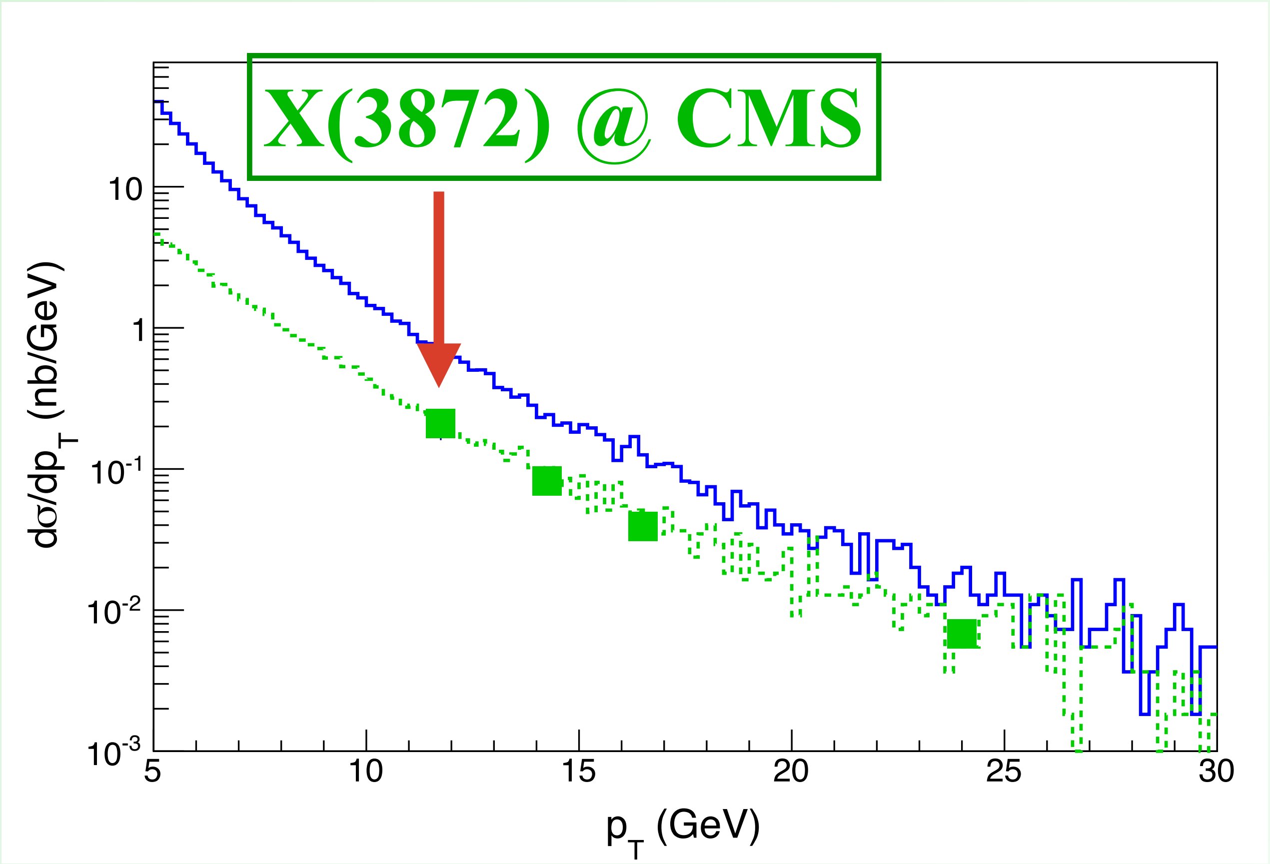


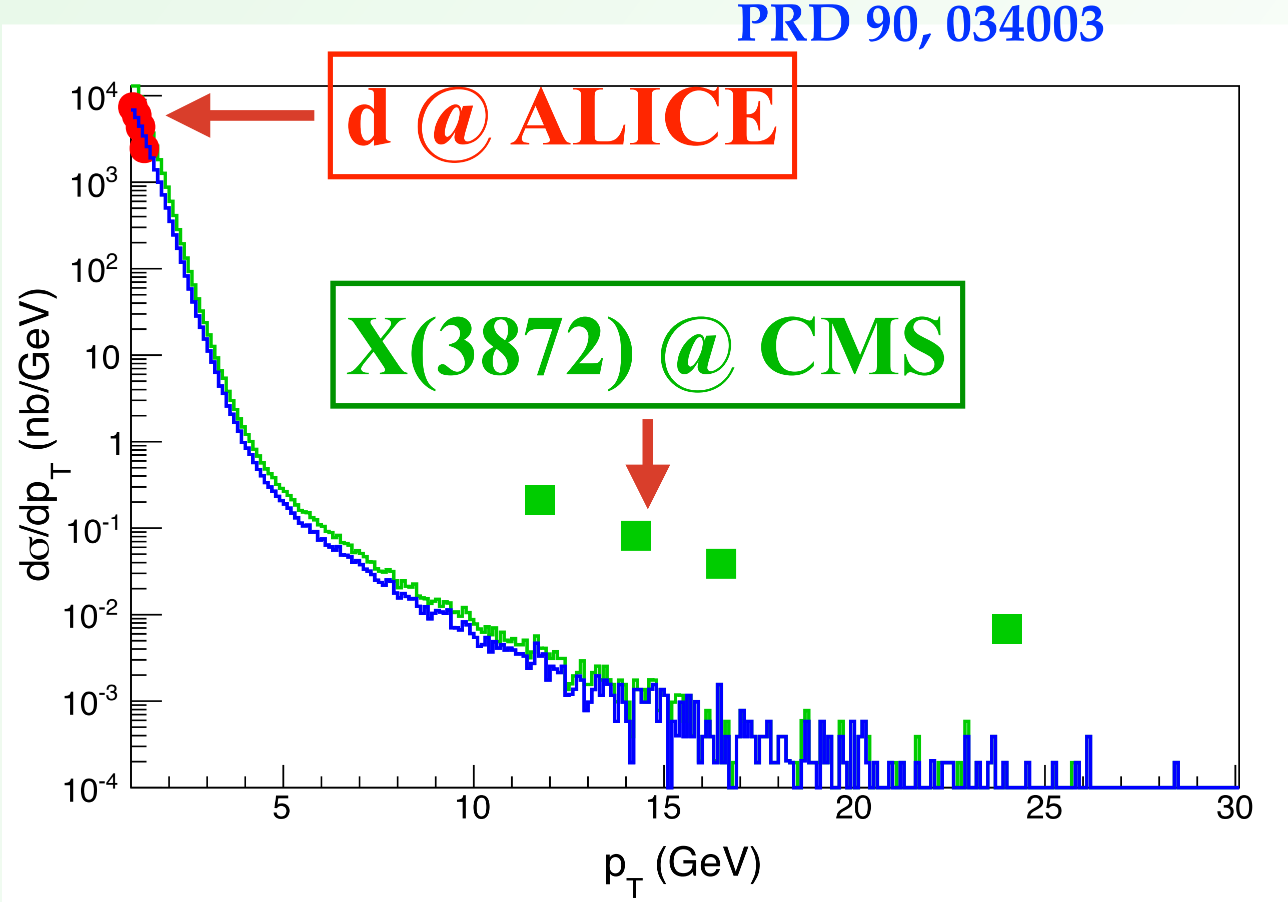
X(3872) vs deuteron

Going backwards by normalizing to CMS X(3872) data

The prediction for antideuteron is much larger than what expected by data

ALG, Piccinini, Pilloni, Polosa
PRD 90, 034003





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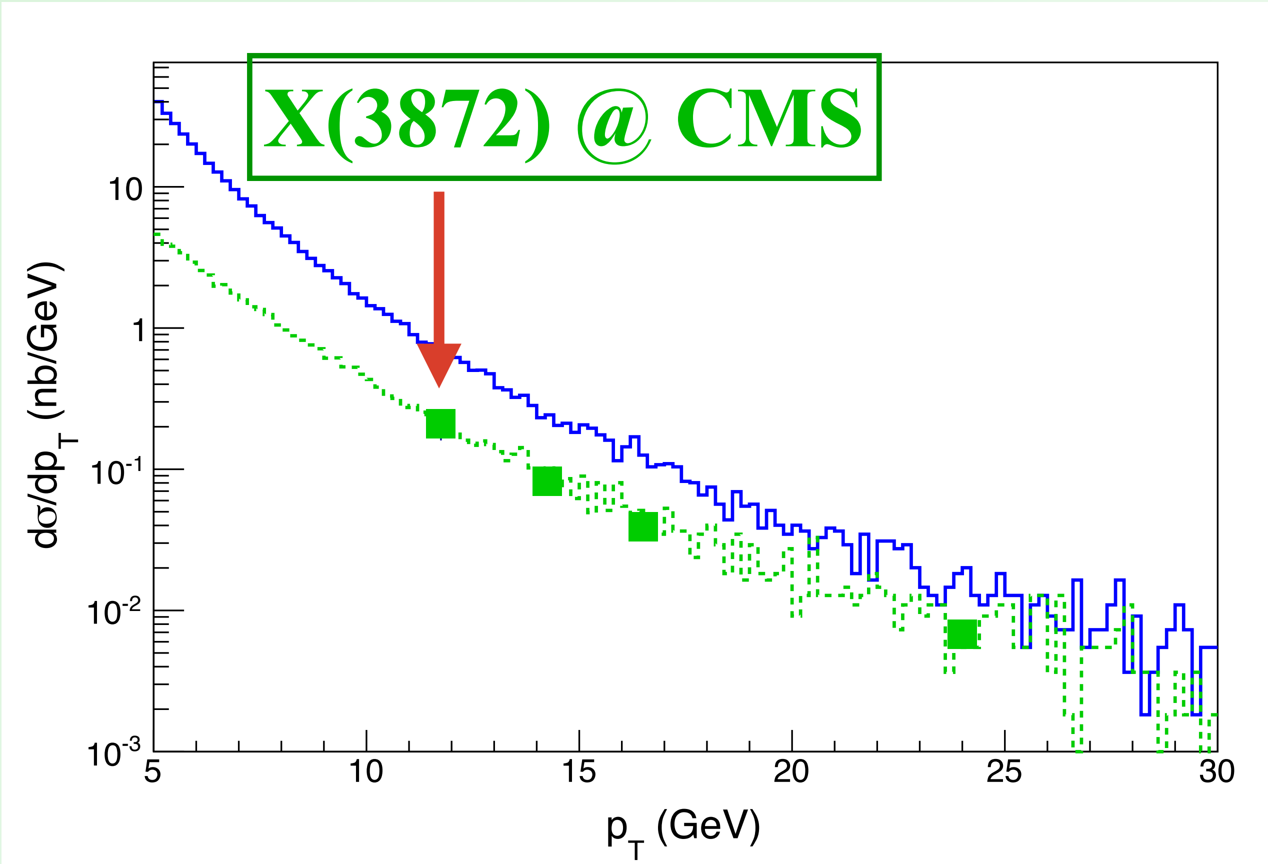
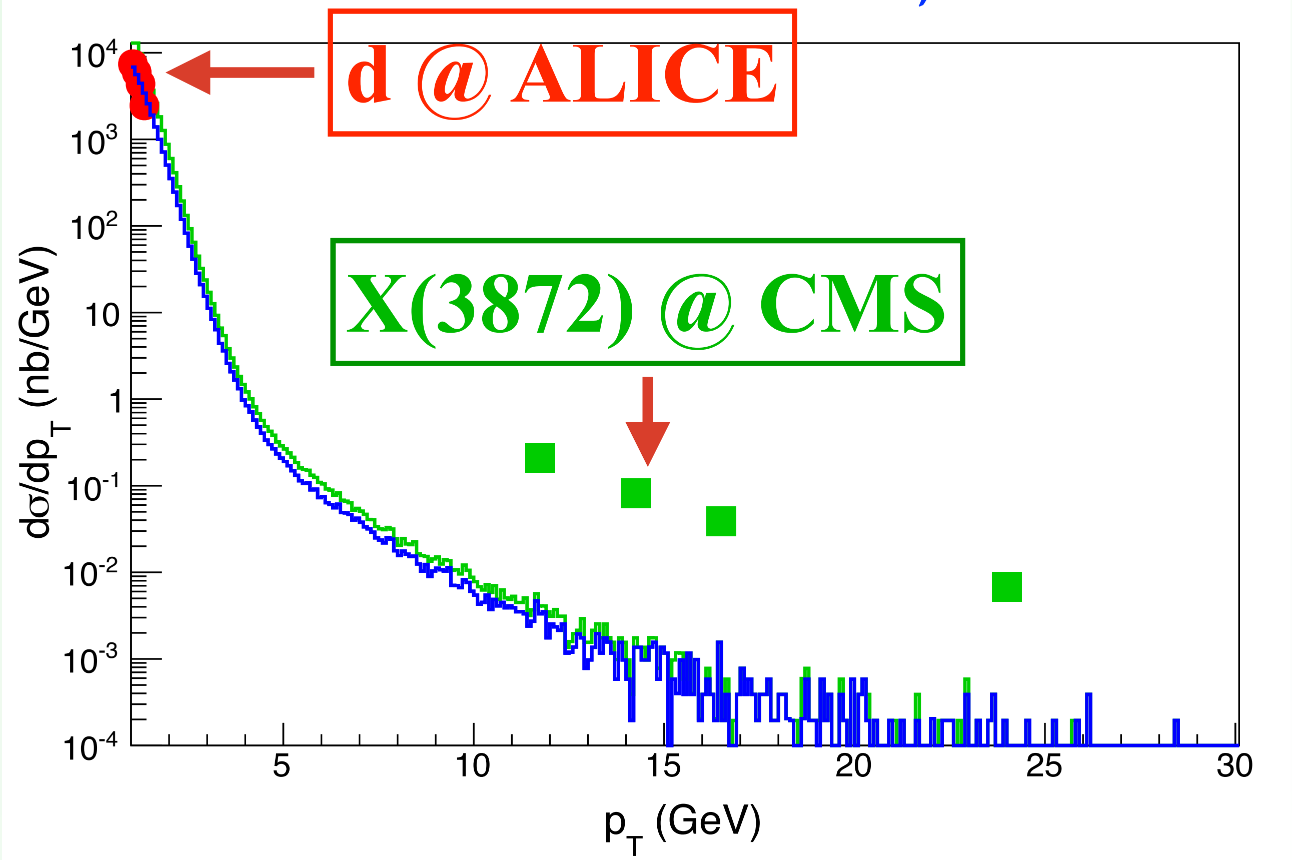
1) **ALICE data are preliminary**
2) **MC is not reliable in the region** $p_T \sim 1\,\text{GeV}$
3) **Dependence on hadronization model**
4) **Different fragmentation functions**

ALG, Piccinini, Pilloni, Polosa
PRD 90, 034003



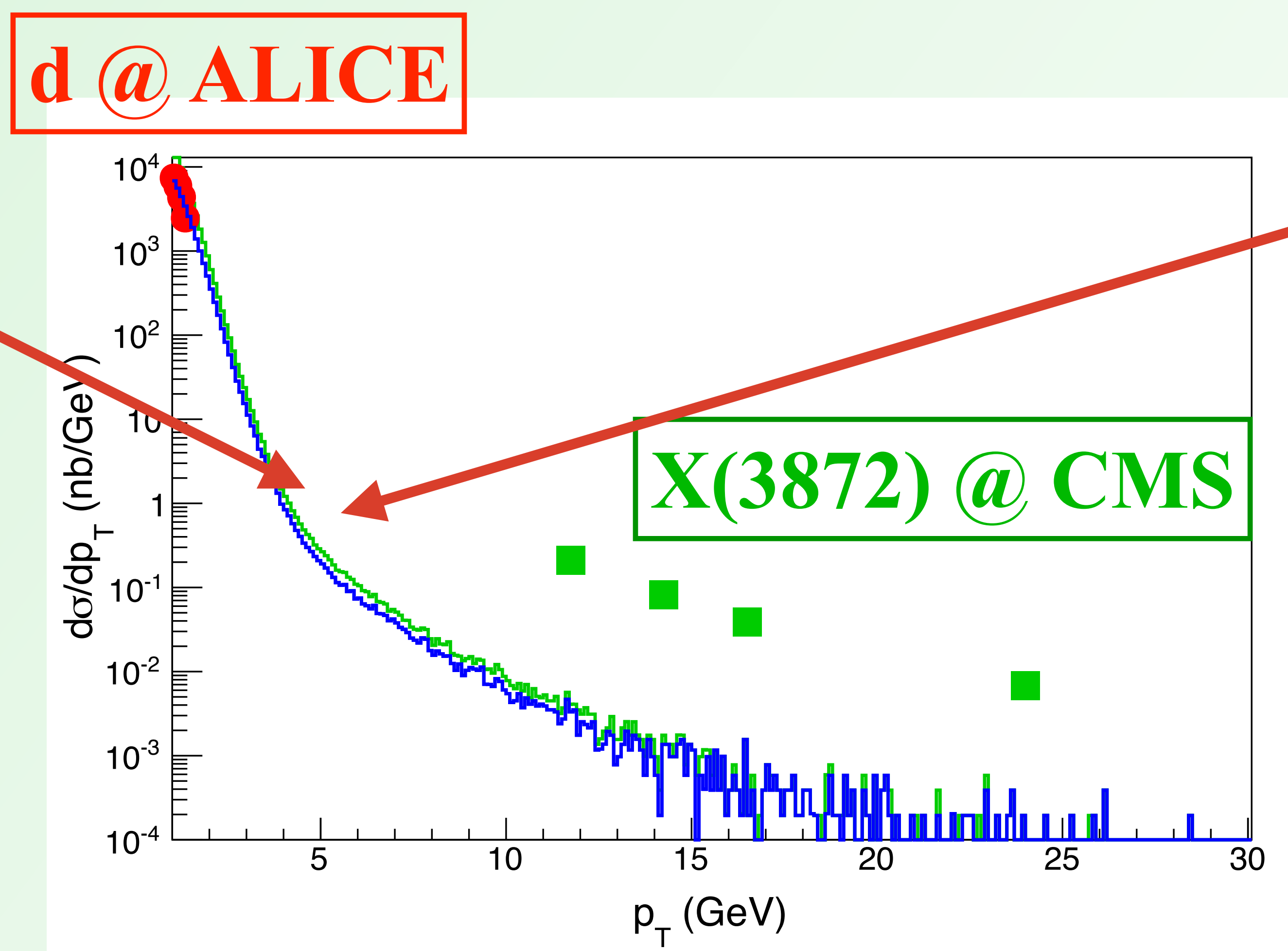


X(3872) vs deuteron

DON'T TRUST ME, WE NEED DATA!

Deuteron at higher p_T

X at lower p_T



The queen of the exotics

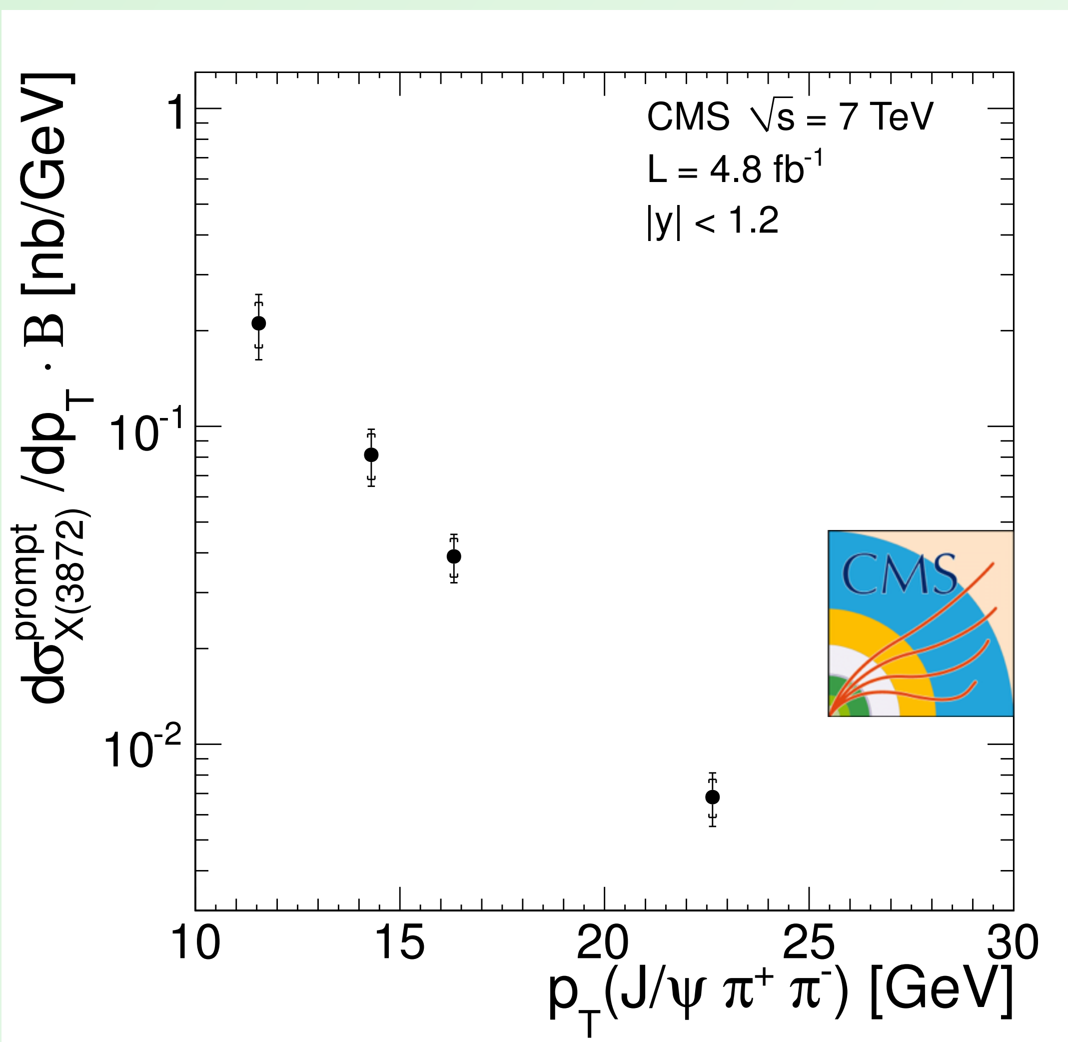
$$M = (3871.69 \pm 0.17)\mathrm{MeV}$$

$$\Gamma < 1.2\mathrm{MeV}$$

$$J^{PC} = 1^{++}$$

Large inclusive prompt production cross section

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



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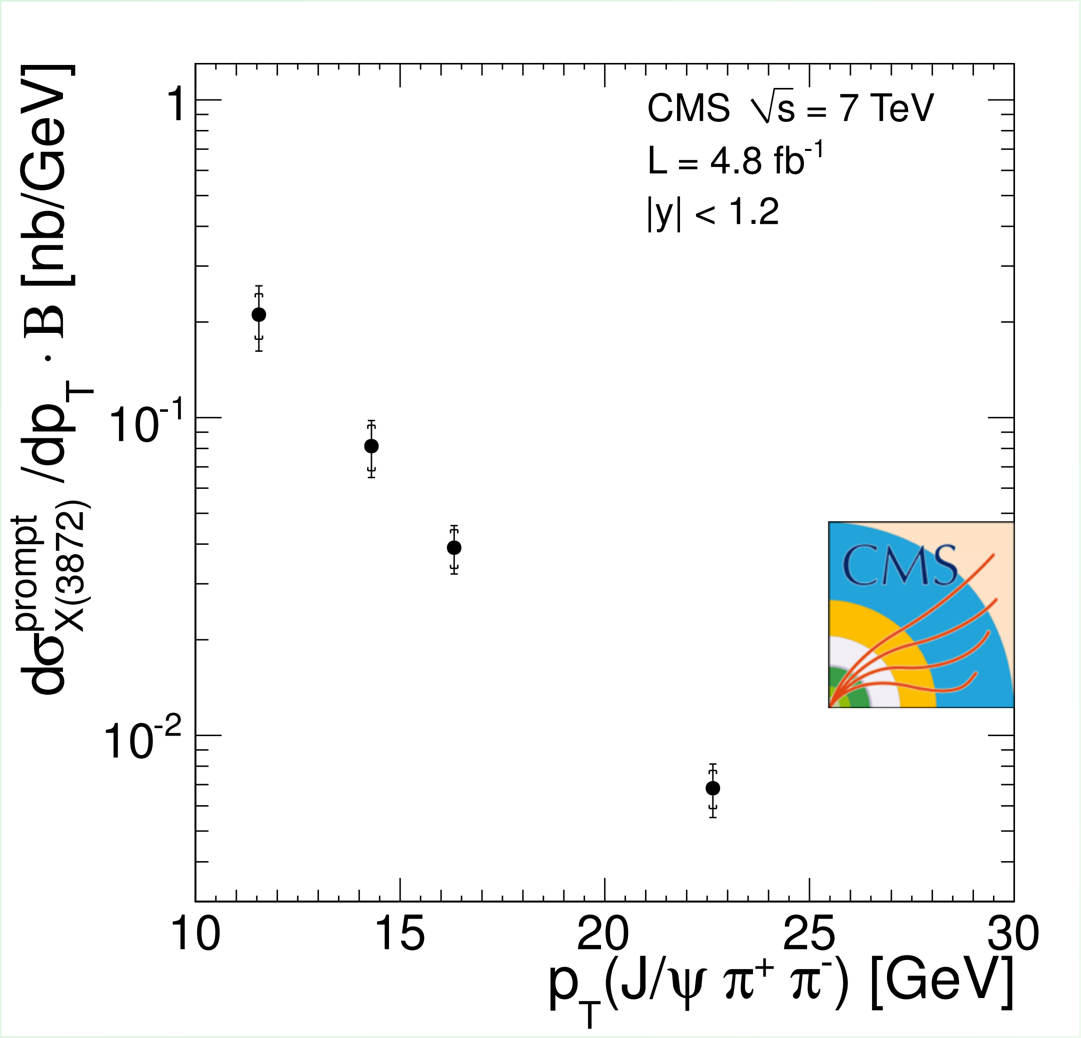

(Discovery decay mode)

$$X(3872) \to J/\psi\pi^+\pi^-$$

Pion couple dominated by the I=1 component

Huge isospin-breaking

$$\frac{\Gamma(X(3872) \to J/\psi\omega)}{\Gamma(X(3872) \to J/\psi\pi^+\pi^-)} = 0.8 \pm 0.3$$

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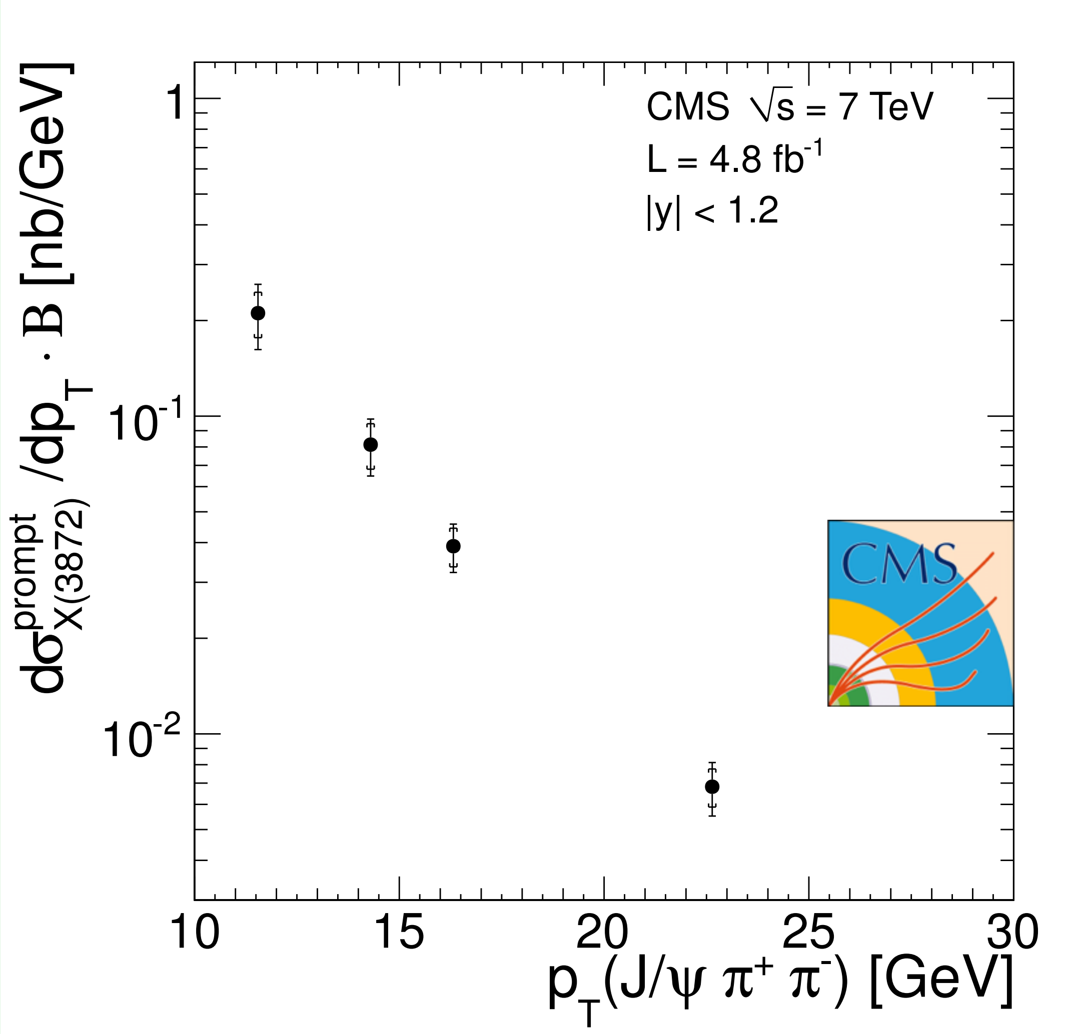


Extremely small binding energy

$$\varepsilon = m_X - m_D - m_{D^*} \lesssim 0$$

Better estimate up to now

$$\varepsilon = -3 \pm 192\,\text{keV}$$

$$\sigma_{\Delta m} = 21\,\text{keV}$$

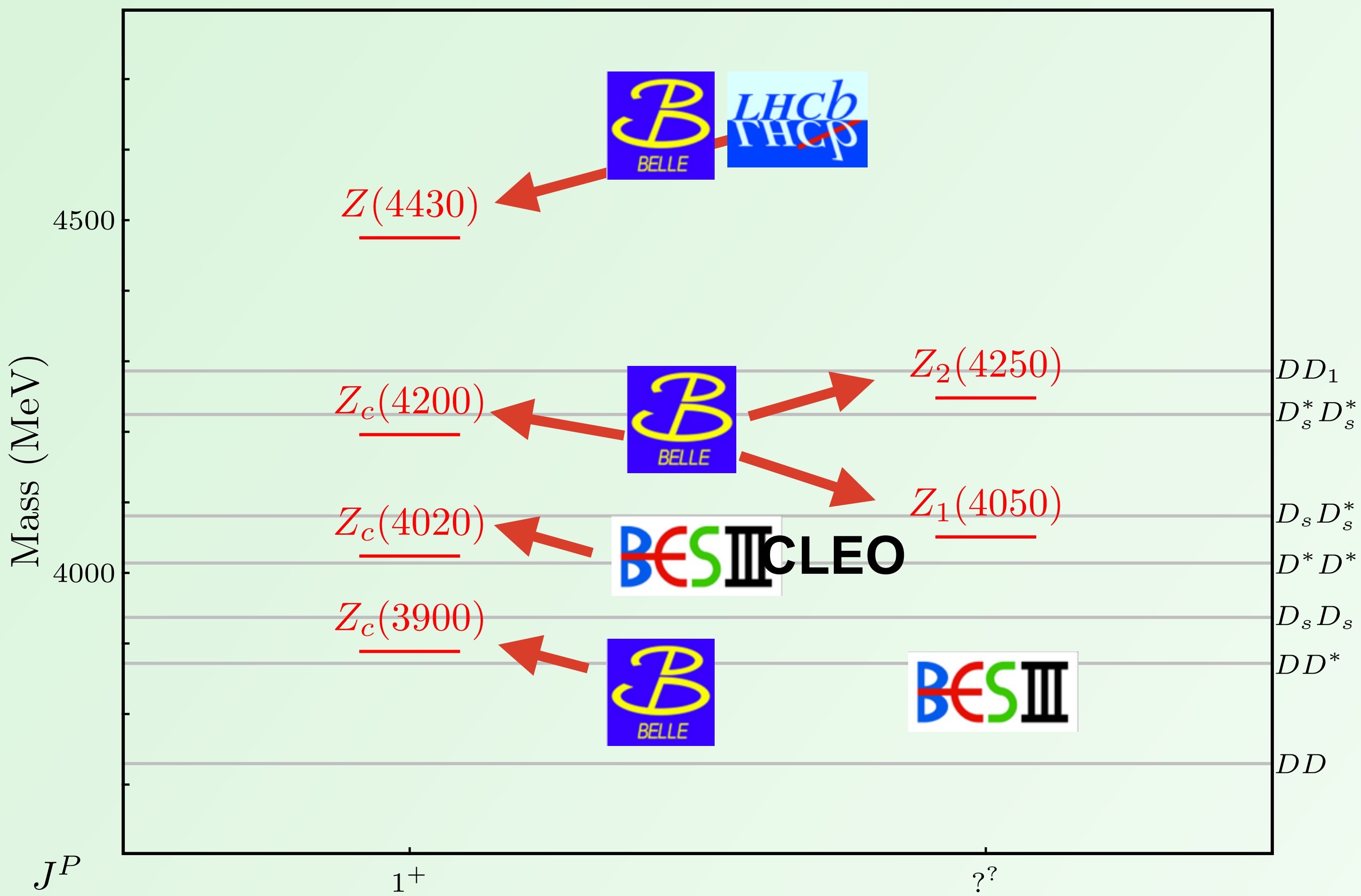
$$\sigma_{m(D^0)} = 44\,\text{keV}$$

Tomaradze *et al*, PRD 91 (2015) 1, 011102

Exotic fauna

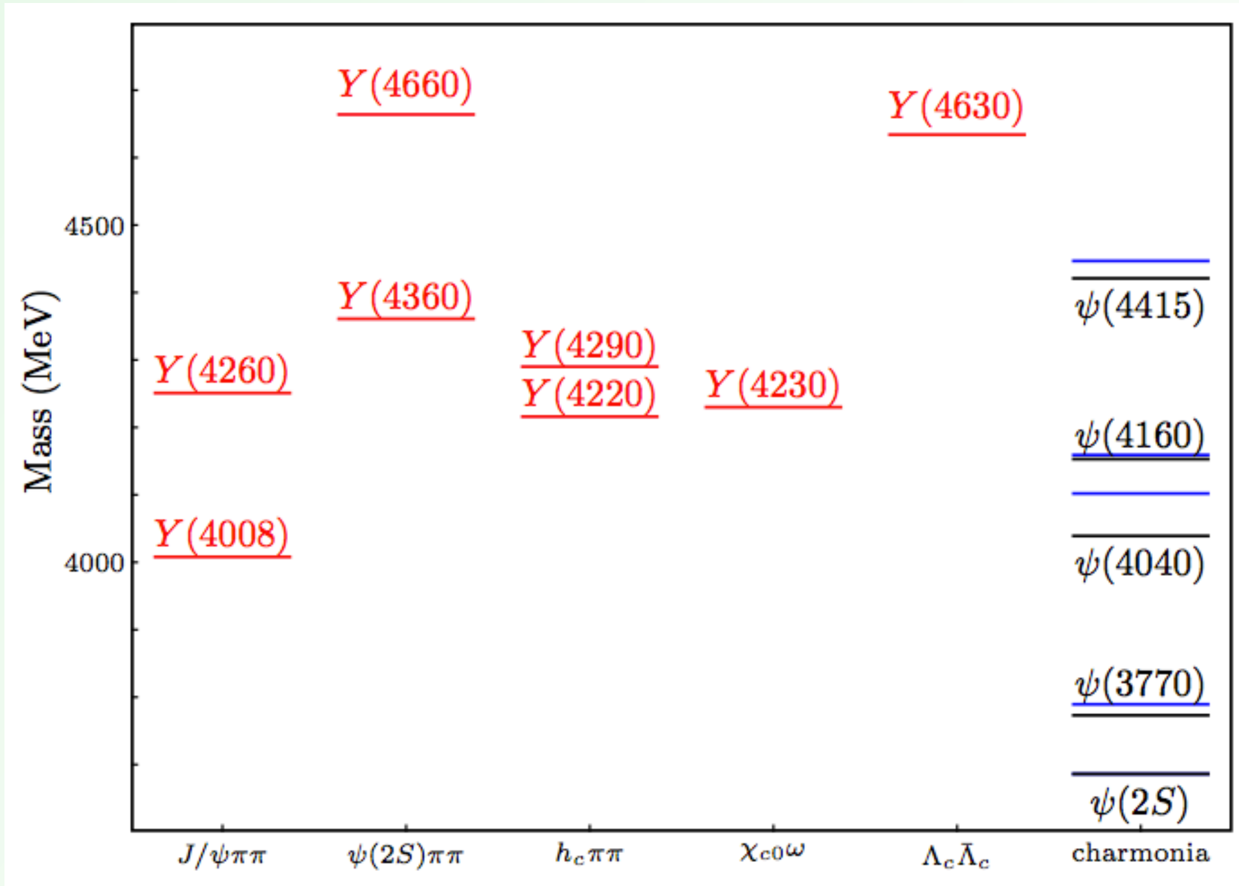
Z charged resonances

4Q MATTER



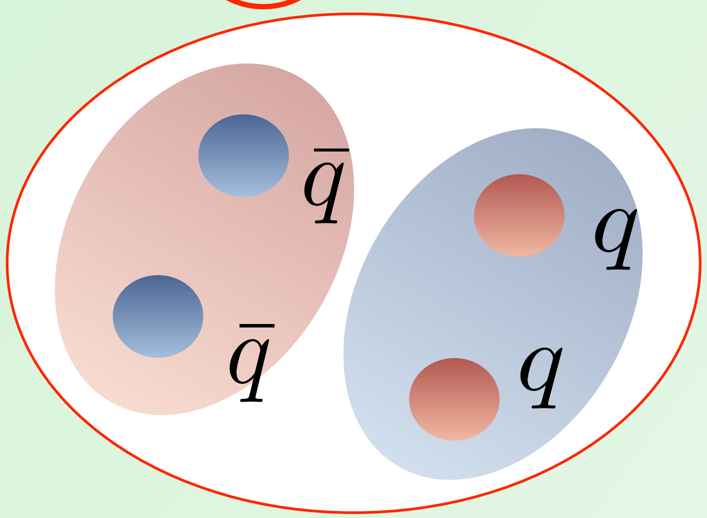
Y vector resonances

Do not fit with the charmonium spectrum



Diquark-antidiquark model

$$\bar{\mathbf{3}} \otimes \bar{\mathbf{3}} = \mathbf{3} \oplus \mathbf{6}$$



$$\mathbf{3} \otimes \mathbf{3} = \bar{\mathbf{3}} \oplus \bar{\mathbf{6}}$$

Maiani, Piccinini, Polosa, Riquer
PRD71 014028

$$H = \sum_{dq} m_{dq} - 2 \sum_{i \neq j, a} k_{ij} \vec{S}_i \vec{S}_j \frac{\lambda_i^a}{2} \frac{\lambda_j^a}{2}$$

color-spin hamiltonian

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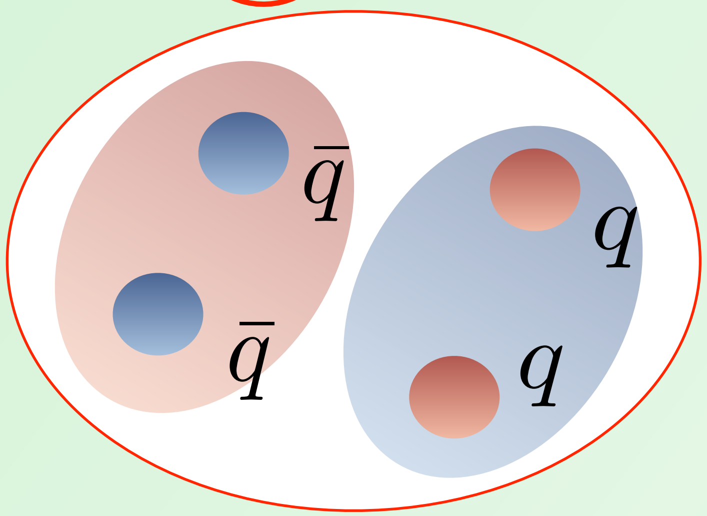

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Z spectrum understood as S-wave tetraquarks
+ radial excitations (Z(4430))

J^{PC}	$cq\,\bar{c}\bar{q}$	$c\bar{c}\,q\bar{q}$	Resonance Assig.	Decays
0^{++}	$\lvert 0,0\rangle$	$1/2\lvert 0,0\rangle + \sqrt{3}/2\lvert 1,1\rangle_0$	$X_0(\sim 3770\text{ MeV})$	η_c, J/ψ + light mesons
0^{++}	$\lvert 1,1\rangle_0$	$\sqrt{3}/2\lvert 0,0\rangle - 1/2\lvert 1,1\rangle_0$	$X_0'(\sim 4000\text{ MeV})$	η_c, J/ψ + light mesons
1^{++}	$1/\sqrt{2}(\lvert 1,0\rangle + \lvert 0,1\rangle)$	$\lvert 1,1\rangle_1$	$X_1 = X(3872)$	$J/\psi + \rho/\omega$, DD^*
1^{+-}	$1/\sqrt{2}(\lvert 1,0\rangle - \lvert 0,1\rangle)$	$1/\sqrt{2}(\lvert 1,0\rangle - \lvert 0,1\rangle)$	$Z = Z(3900)$	$J/\psi + \pi$, $h_c/\eta_c + \pi/\rho$
1^{+-}	$\lvert 1,1\rangle_1$	$1/\sqrt{2}(\lvert 1,0\rangle + \lvert 0,1\rangle)$	$Z' = Z(4020)$	$J/\psi + \pi$, $h_c/\eta_c + \pi/\rho$
2^{++}	$\lvert 1,1\rangle_2$	$\lvert 1,1\rangle_2$	$X_2(\sim 4000\text{ MeV})$	J/ψ + light mesons

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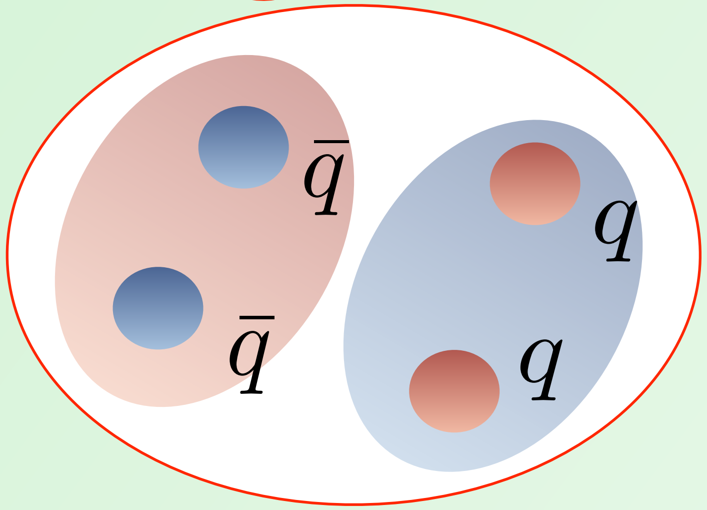

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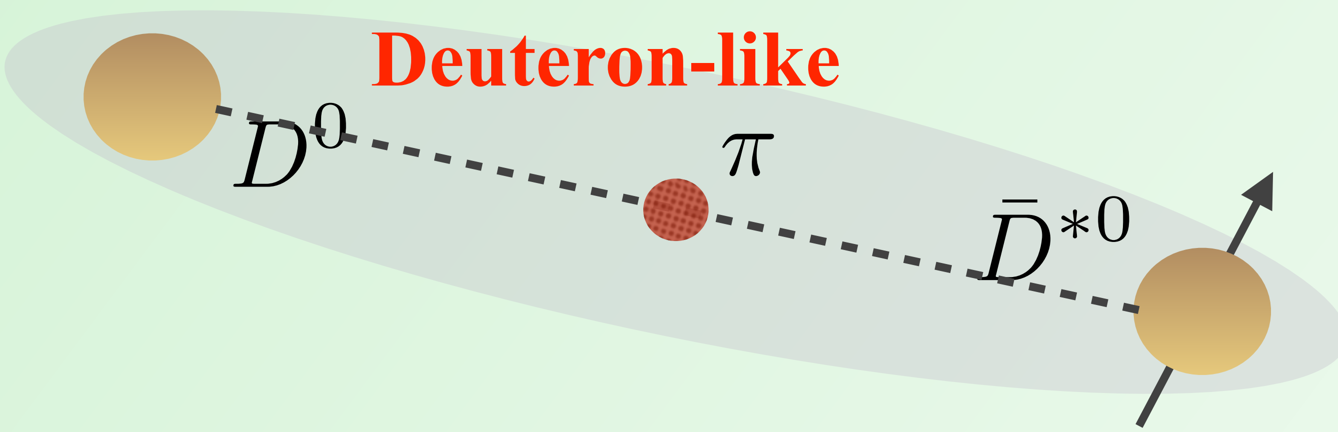
color-spin hamiltonian

Y spectrum understood as P-wave tetraquarks + radial escitation

State	$P(S_{c\bar{c}} = 1) : P(S_{c\bar{c}} = 0)$	Assignment	Radiative Decay
Y_1	3:1	$Y(4008)$	$\gamma + X_0$
Y_2	1:0	$Y(4260)$	$\gamma + X$
Y_3	1:3	$Y(4290)/Y(4220)$	$\gamma + X_0'$
Y_4	1:0	$Y(4630)$	$\gamma + X_2$

Molecule



Tornqvist, Z. Phys. C61, 525
Braaten and Kusunoki, PRD 69 074005
Swanson, Phys. Rept. 429, 243-305

$$X(3872) \sim D^0\bar{D}^{*0}$$

$$Z_c(3900) \sim D^0\bar{D}^{*}+$$

$$Z_c'(4020) \sim D^{*0}\bar{D}^{*+}$$

$$Y(4260) \sim D\bar{D}_1$$

Interaction mediated by exchange of light mesons

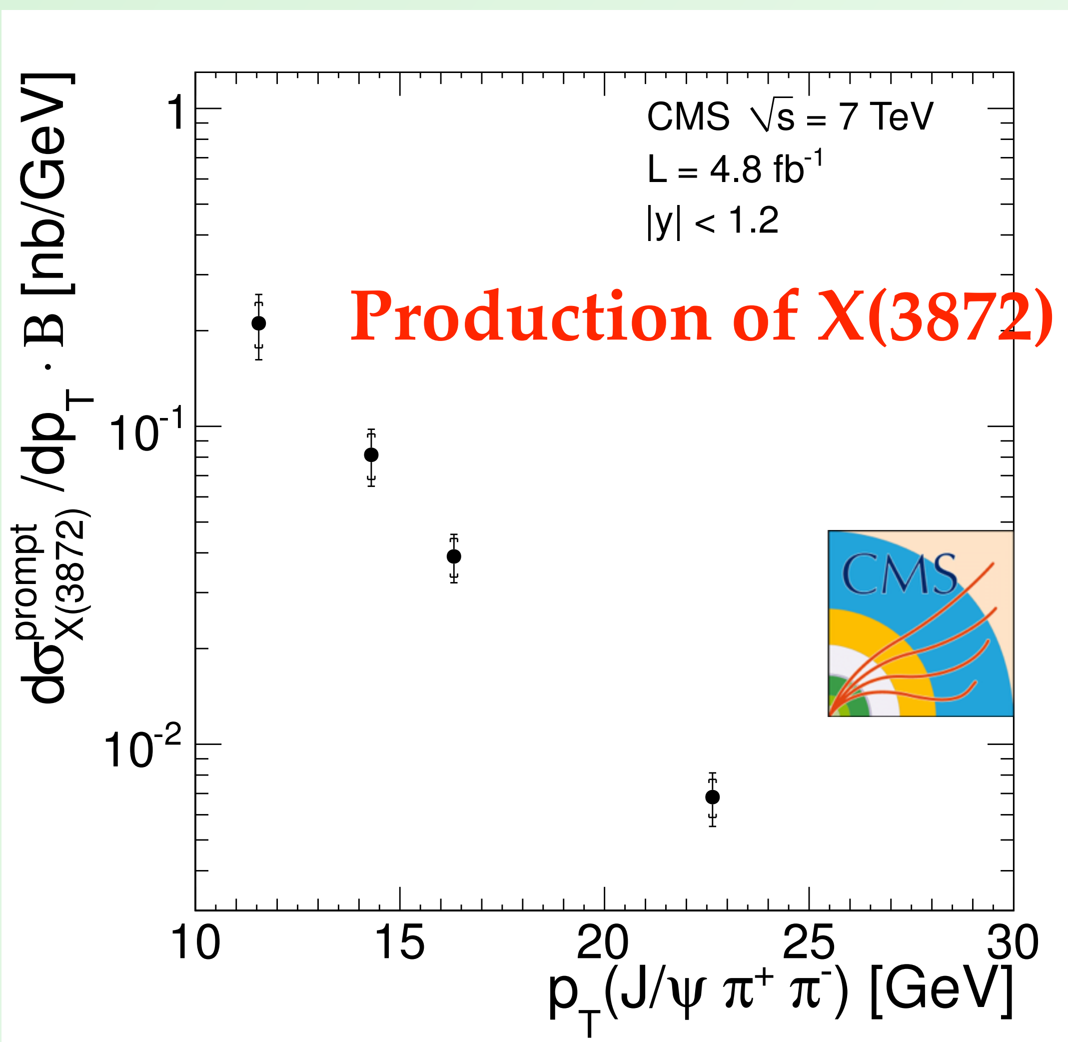
- **Model independent relations: compositeness (Weinberg's theorem)**
- **Decay patterns in the constituents and X(3872) isospin violation**
- **No predictions!!! If near-threshold states, then molecule**
- **Binding energies vary from -70 to -0.1 MeV, or even positive!**

Prompt production of X(3872)

Molecule challenged:
loosely bound molecules in a very high energy collisions?

$$E_{X(3872)} = (-0.003 \pm 192)\,\mathrm{MeV}$$ **binding energy of X(3872)**

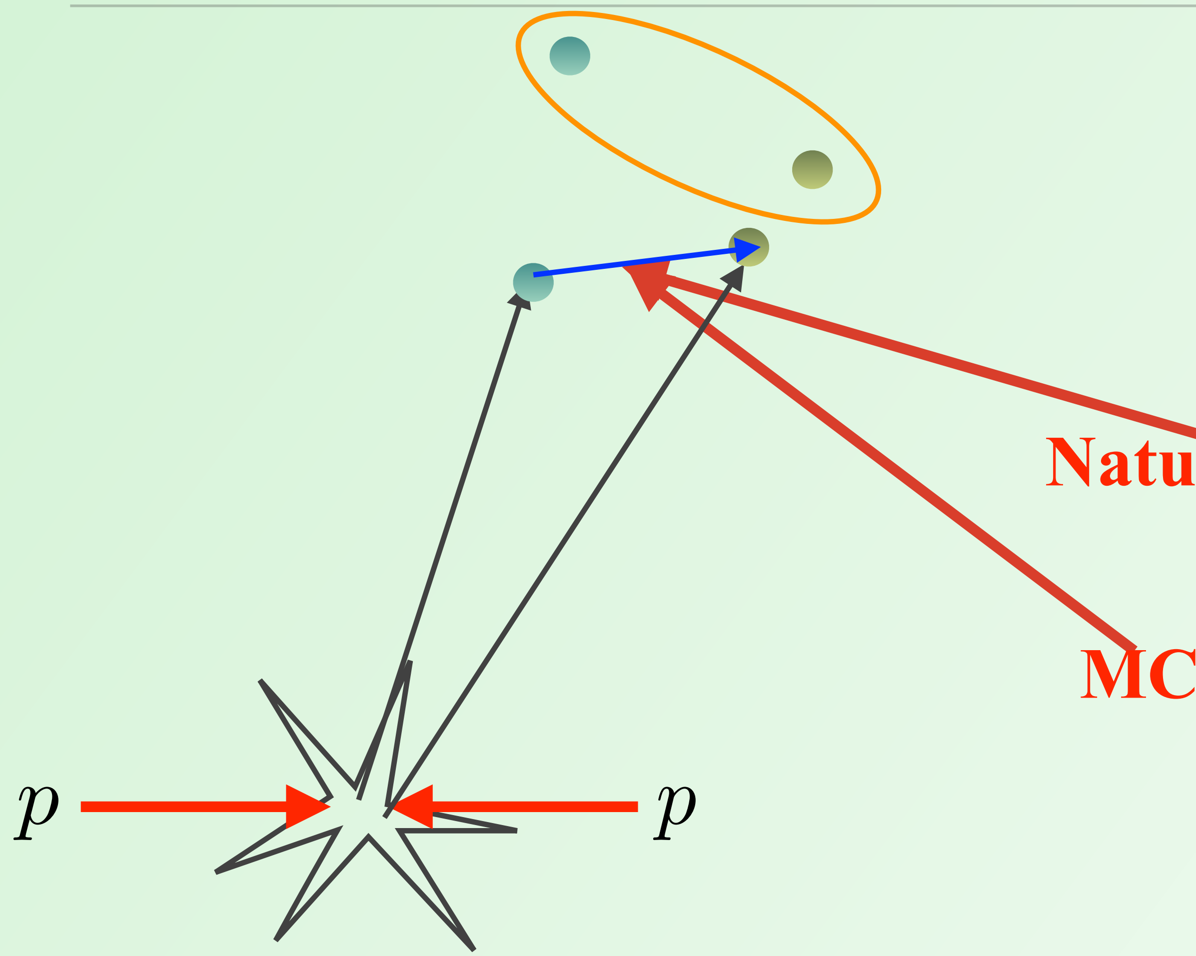
$$E_d = (-2.2245 \pm 0.0002)\,\mathrm{MeV}$$ **binding energy deuteron**



Production of X(3872) at LHC

We aim to evaluate prompt production cross sections at hadron colliders via MC simulations!

Molecules in MC simulations



Nature: dynamics generates an attractive potential

MC simulations: “coalescence” model

All pairs with $k_{rel} < k_{max}$

$$\sigma_{prod} \sim \int d^3k |\langle pp|DD^*\rangle\langle DD^*|X\rangle|^2 < \int_{k<k_{max}} d^3k |\langle pp|DD^*\rangle|^2$$

Bignamini, Grinstein, Piccinini, Polosa, Sabelli PRL103 (2009) 248

Upper bound for the production cross section

It is worth to notice the critical role of k_{max}

2009 results

In a simple square well model and using the X(3872) binding energy:

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

To compare with deuteron

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

We assume

$$k_{max} \sim \sqrt{\langle k^2 \rangle} \approx 50\,\mathrm{MeV}$$

2009 results

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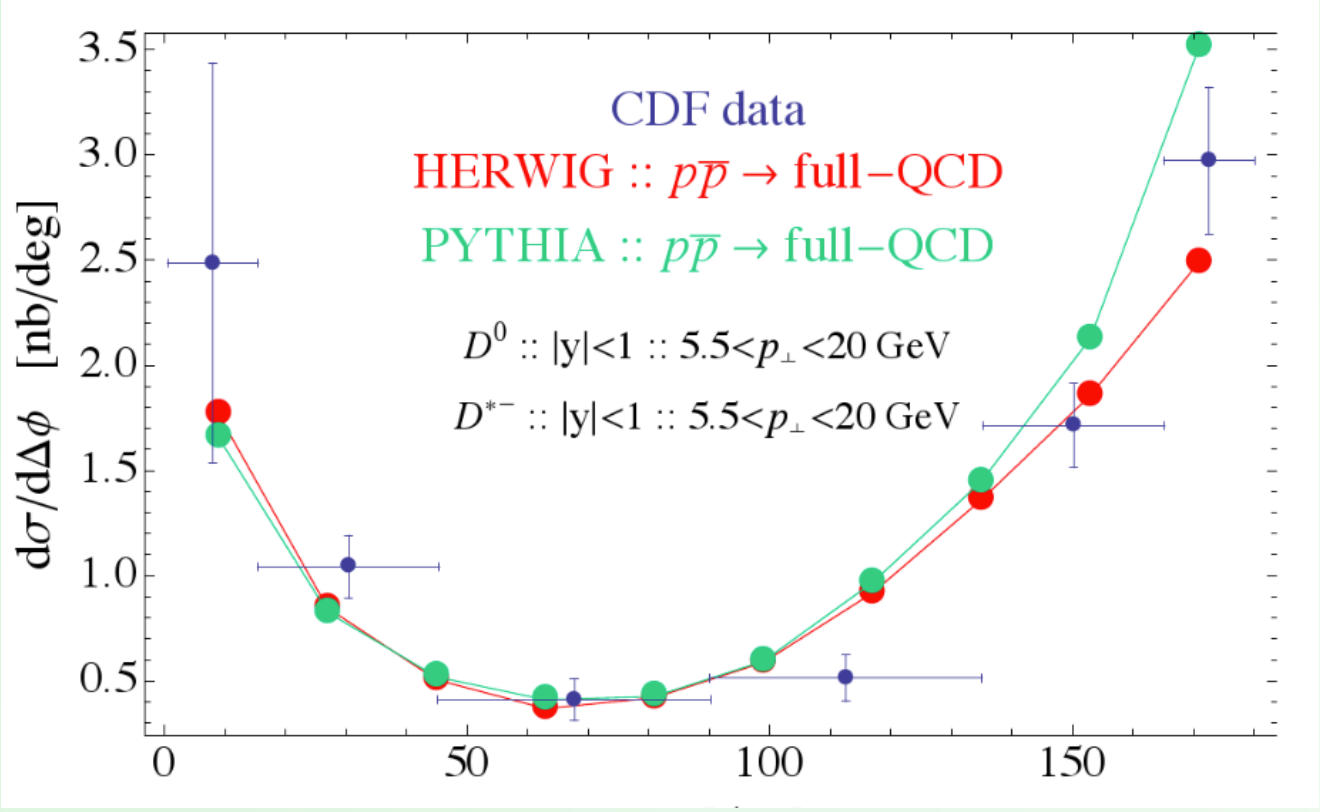
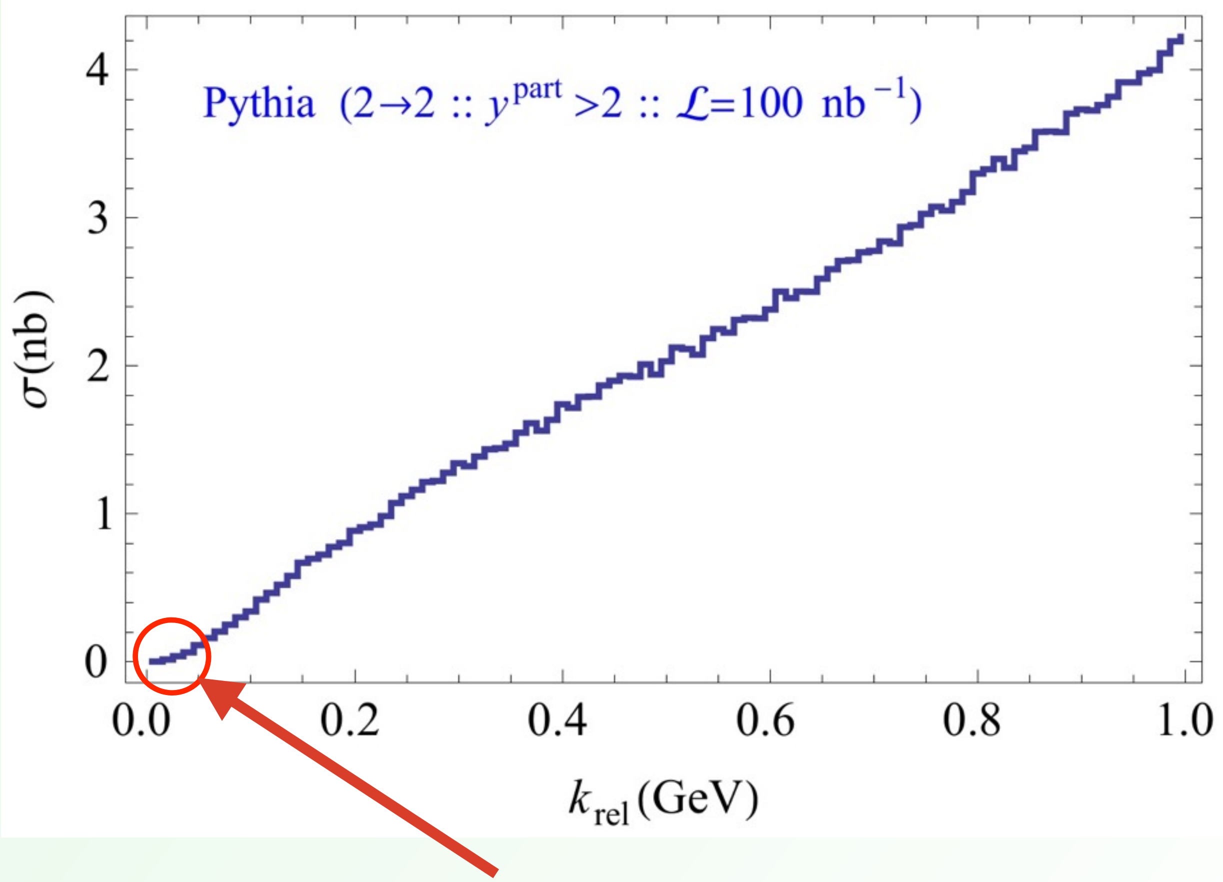


Tuning MC to reproduce CDF distribution

$$\frac{d\sigma}{d\Delta\phi}(p\bar{p} \to D^0 D^{*-})$$



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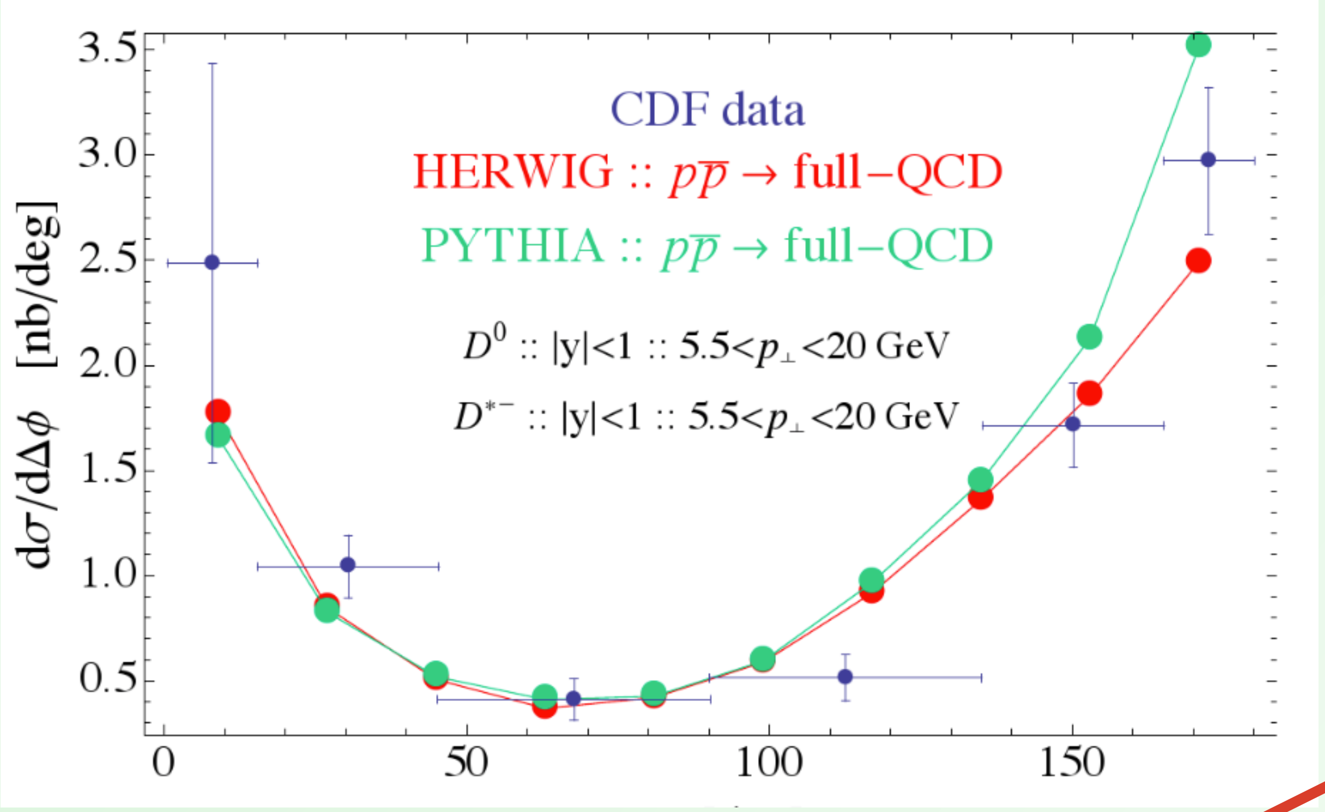

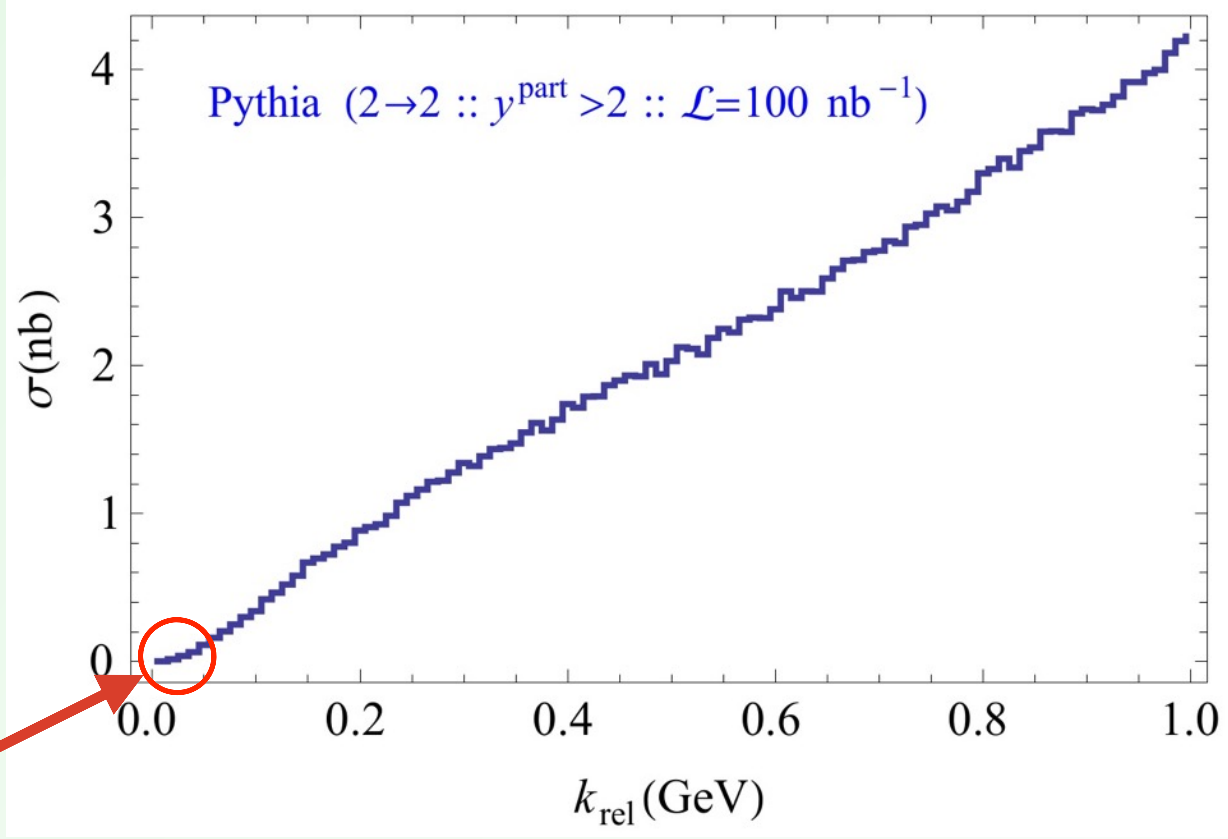

$$\sigma(p\bar{p} \to DD^*|k < k_{max}) = 0.1\mathrm{nb} \text{ at } \sqrt{s} = 1.96\,\mathrm{TeV}$$

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

Bignamini, Grinstein, Piccinini, Polosa, Sabelli PRL 103 (2009) 248

Final state interactions

A solution can be final state interactions (rescattering of DD*) allowing

$$k_{max} \sim 5\, m_\pi \sim \ 700\,\mathrm{MeV}$$

$$\sigma(p\bar{p} \to DD^*|k < k_{max}) \approx 230\,\mathrm{nb} > \sigma_{exp}(p\bar{p} \to X(3872))$$

Artoisenet and Braaten PRD81 (2010) 114018

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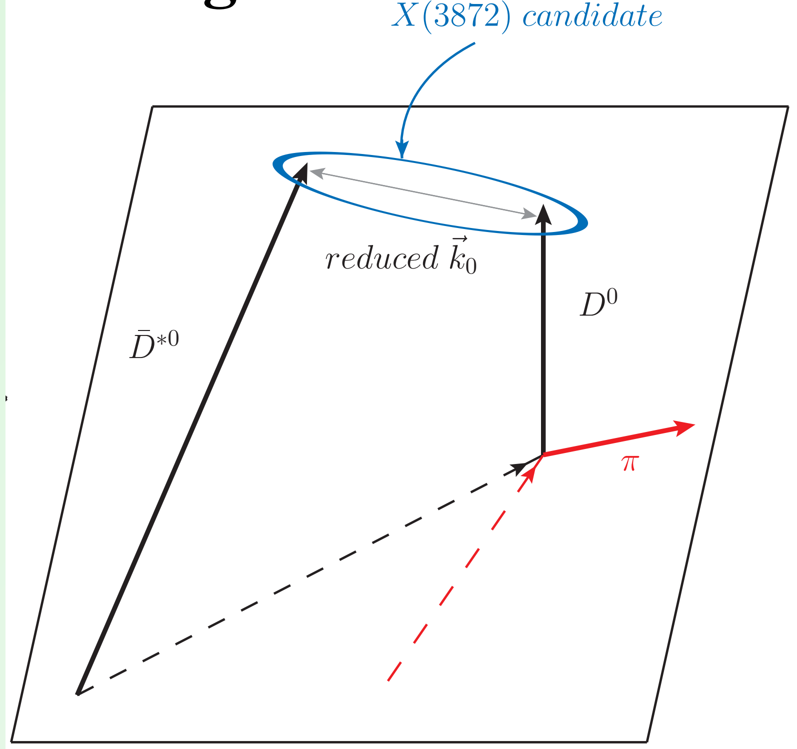
Artoisenet and Braaten PRD81 (2010) 114018

Parametrizing final state interactions with a billiard-like model



Plane $\pi - D$ rescattering

Esposito, Piccinini, Pilloni, Polosa JMP 4, 1569

ALG, Piccinini, Pilloni, Polosa PRD90, 034003

Using pions produced during the hadronization process

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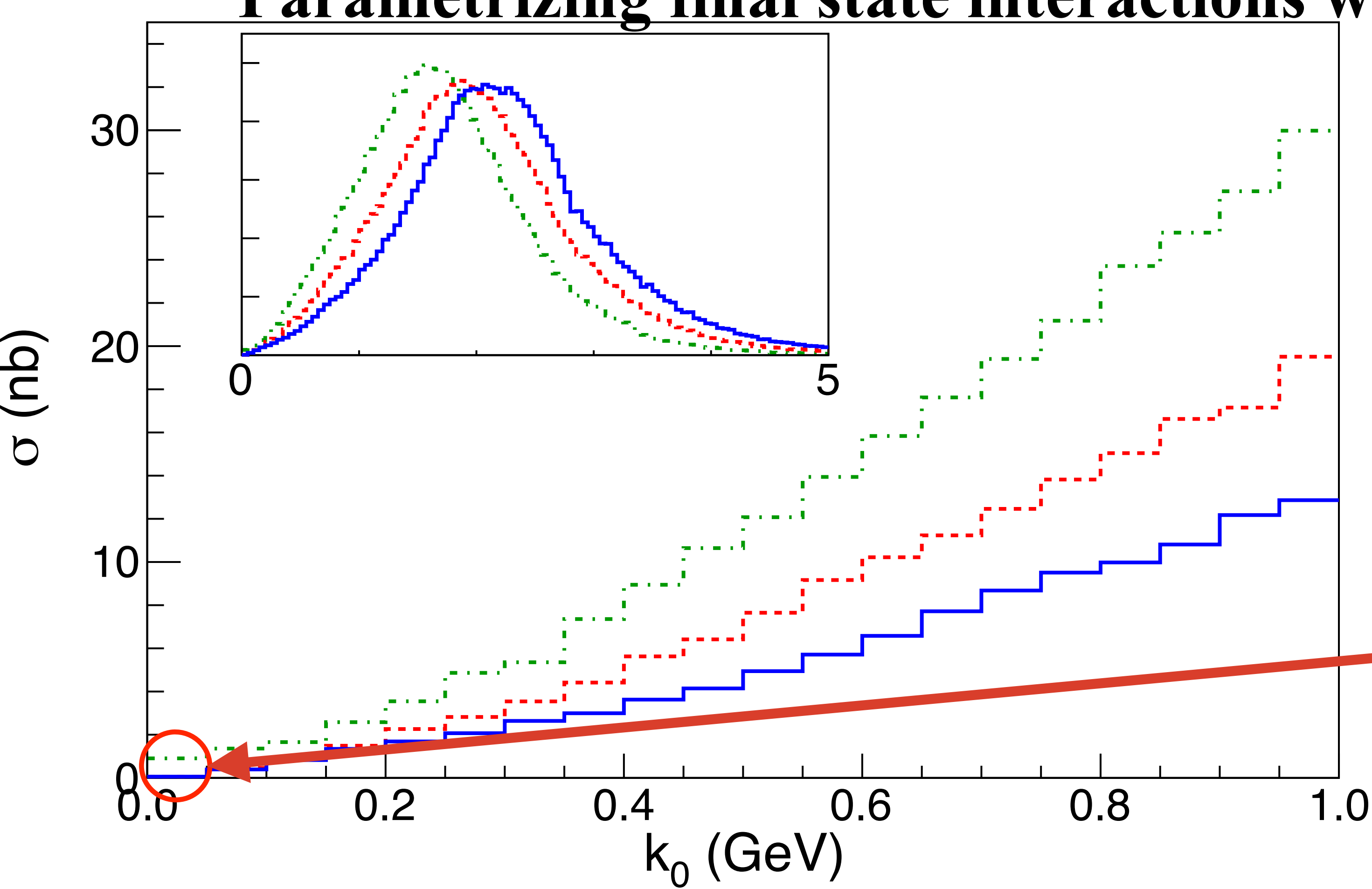


Esposito, Piccinini, Pilloni, Polosa JMP 4, 1569

ALG, Piccinini, Pilloni, Polosa PRD90, 034003

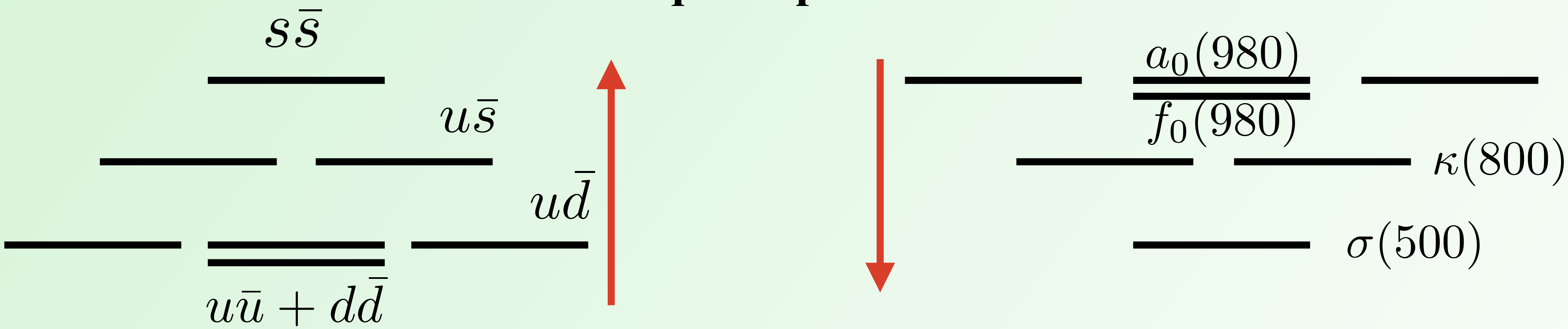
Using pions produced during the hadronization process

$$\sigma(p\bar{p} \to X(3872)) \sim 5\ nb$$

Still not sufficient

Light scalar tetraquarks in QGP

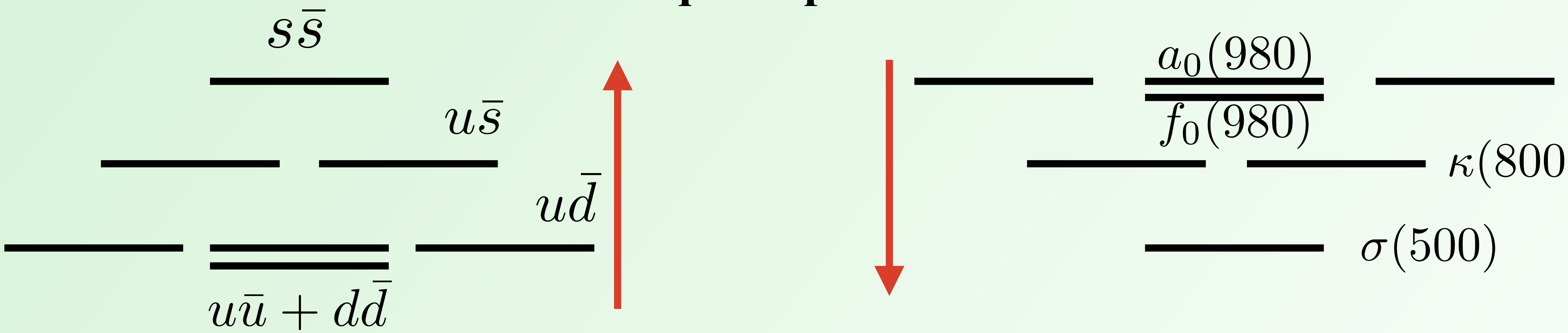
Inversion of the spectrum well explained in the tetraquark picture



Light scalar S-wave mesons **Light scalar P-wave mesons**

Light scalar tetraquarks in QGP

Inversion of the spectrum well explained in the tetraquark picture

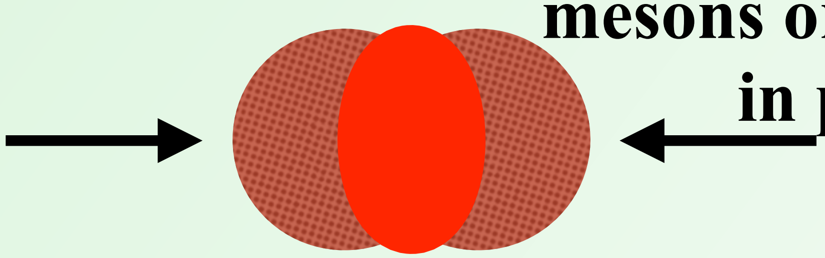


Light scalar S-wave mesons

Light scalar P-wave mesons

Hadronization at low p_t

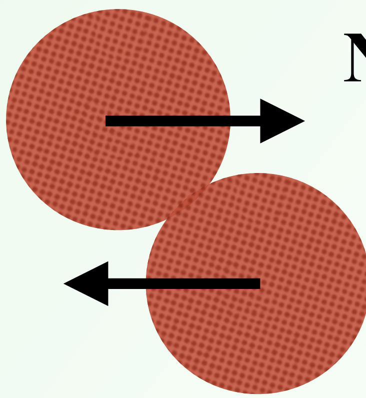
Recombination



Similar production of mesons or tetraquarks in plasma

Hadronization at high p_t

Parton fragmentation

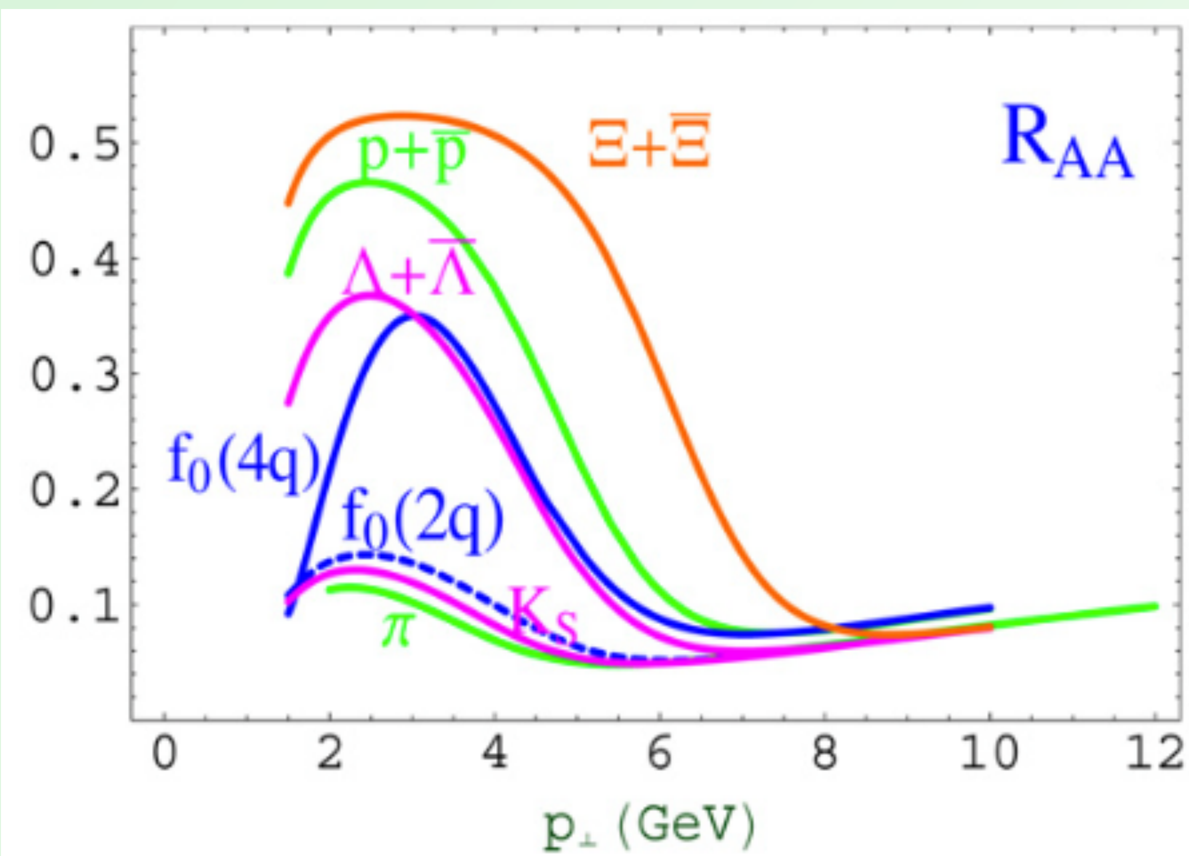


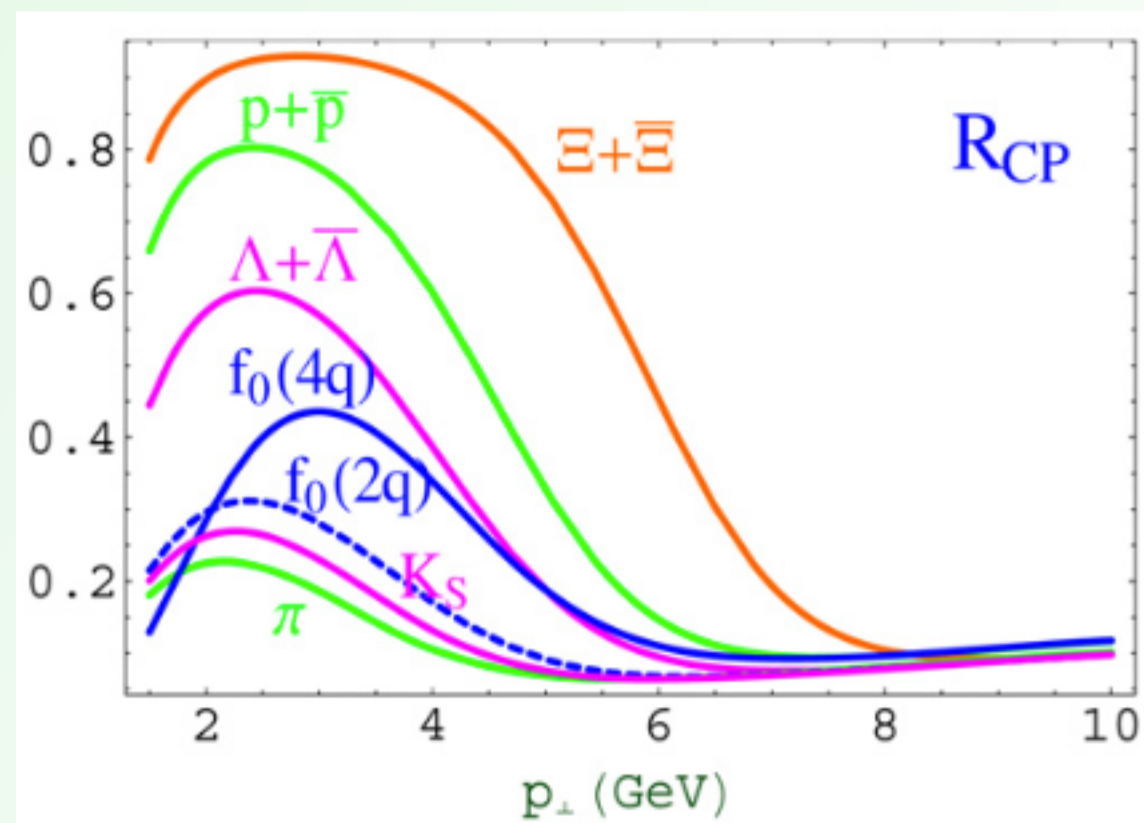
No plasma: difference in production of hadrons with different quarks number

Nuclear modification factors

$$R_{AA} = \frac{d^2 N_{Pb+Pb(p)}(b=0)/dP_t^2}{N_{coll(b=0)} d^2 N_{p+p}(b)/dP_t^2} \qquad R_{CP} = \frac{N_{coll(b)} d^2 N_{Pb+Pb(p)}(b=0)/dP_t^2}{N_{coll(b=0)} d^2 N_{Pb+Pb(p)}(b)/dP_t^2}$$

Sensitive to the number of valence quarks inside the hadron





Maiani, Polosa, Riquer, Salgado PLB 645 (2007)

$$f_0(980)(2q) \quad vs \quad f_0(980)(4q)$$

Conclusions

- **Measure of the X(3872) cross section at ALICE in p-p, p-Pb and Pb-Pb**
- **Production of X(3872) at LOW p_t**
- **Production of antideuteron at HIGH p_t**
- **Nuclear modification factors for the $f_0(980)$**
- **Prompt invariant mass spectrum of**

$$J/\psi\,\pi^{\pm}\pi^{\mp}$$

$$J/\psi\,\pi^{\pm}$$

$$\psi(2S)\,\pi^{\pm}\pi^{\mp}$$

$$\psi(2S)\,\pi^{\pm}$$

Why not?

Backup slides