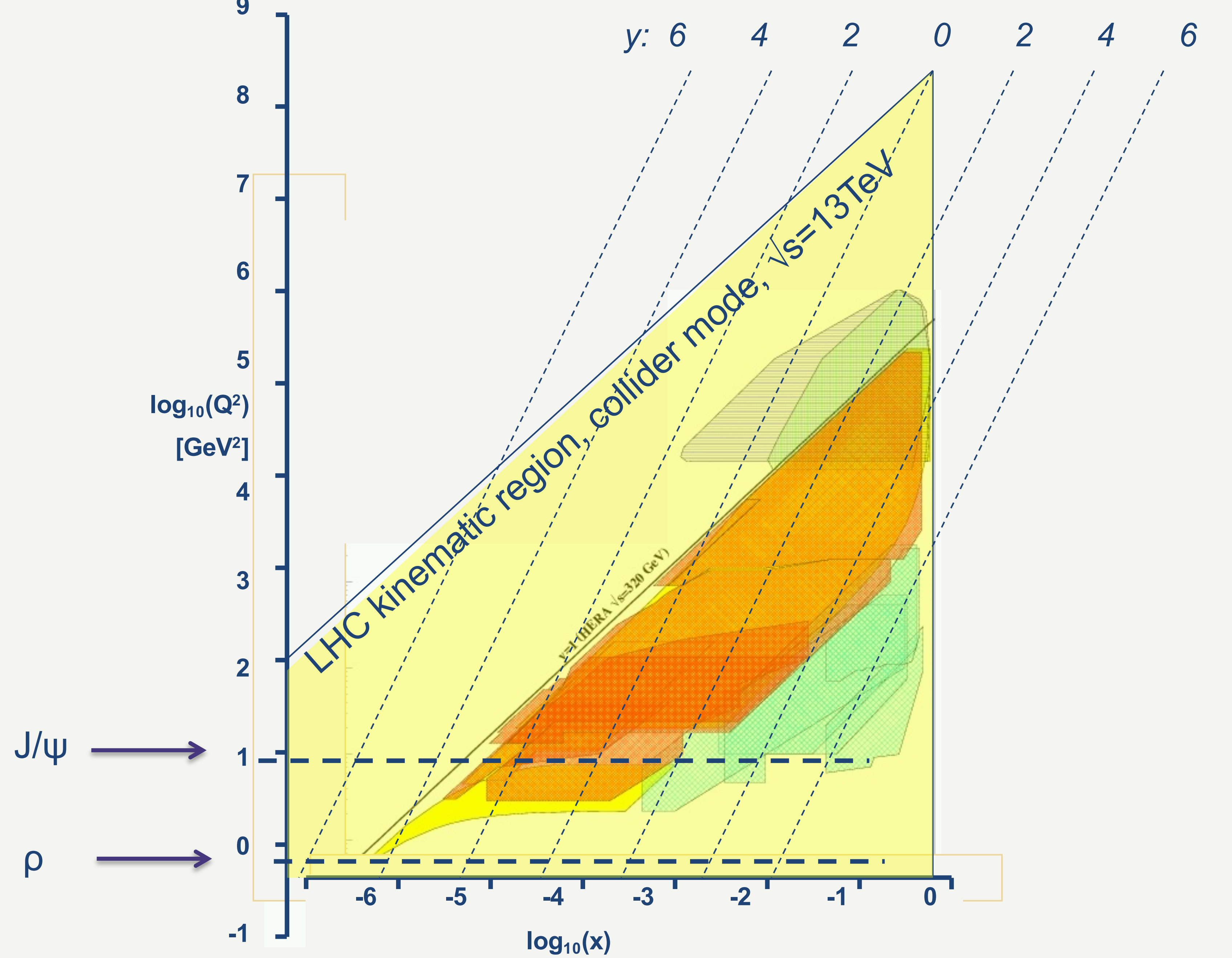
Tetraquarks in Central Exclusive Production

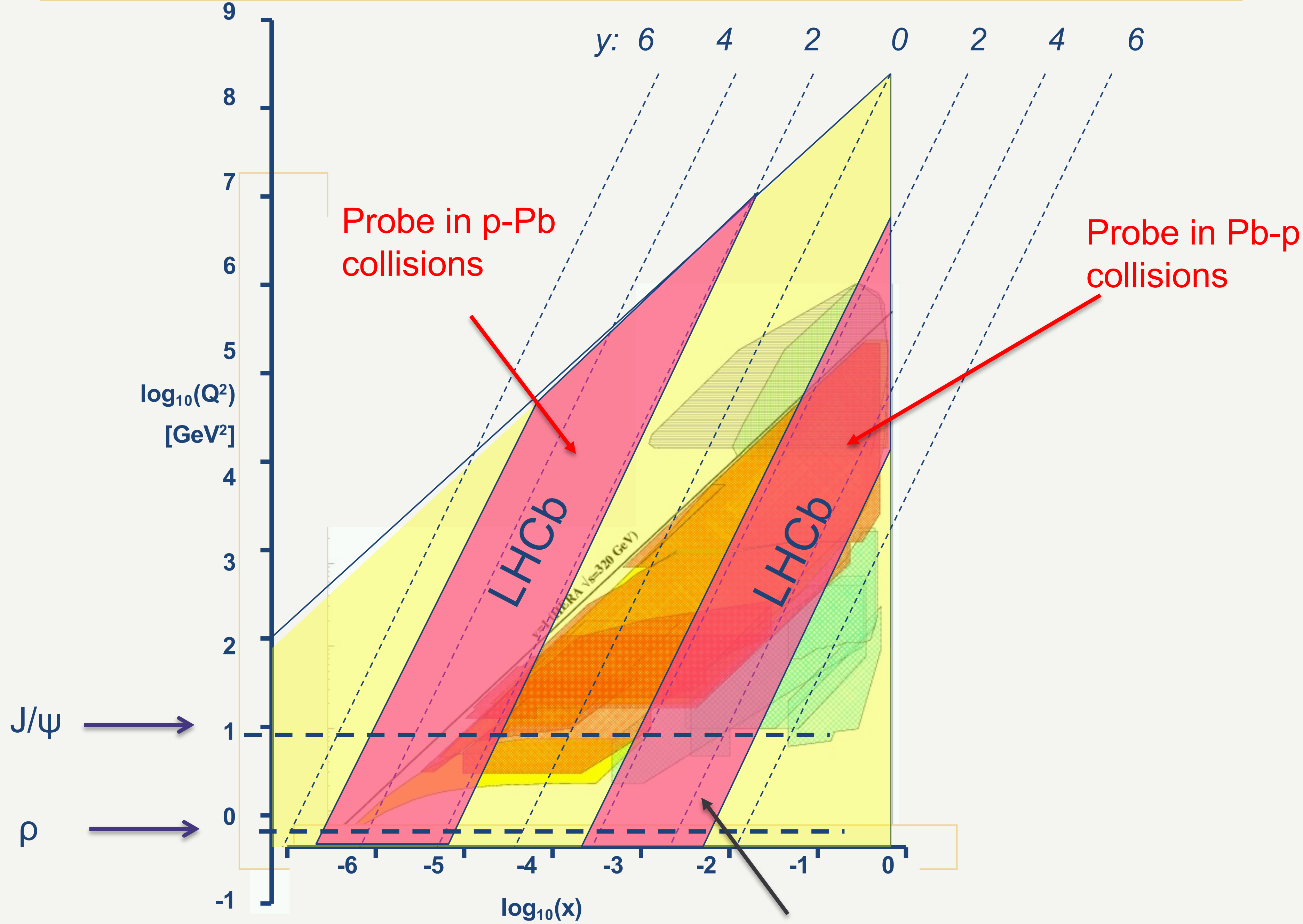
Ronan McNulty

Diffraction and Gluon Saturation at the LHC and EIC
Trento 10-14 June 2024

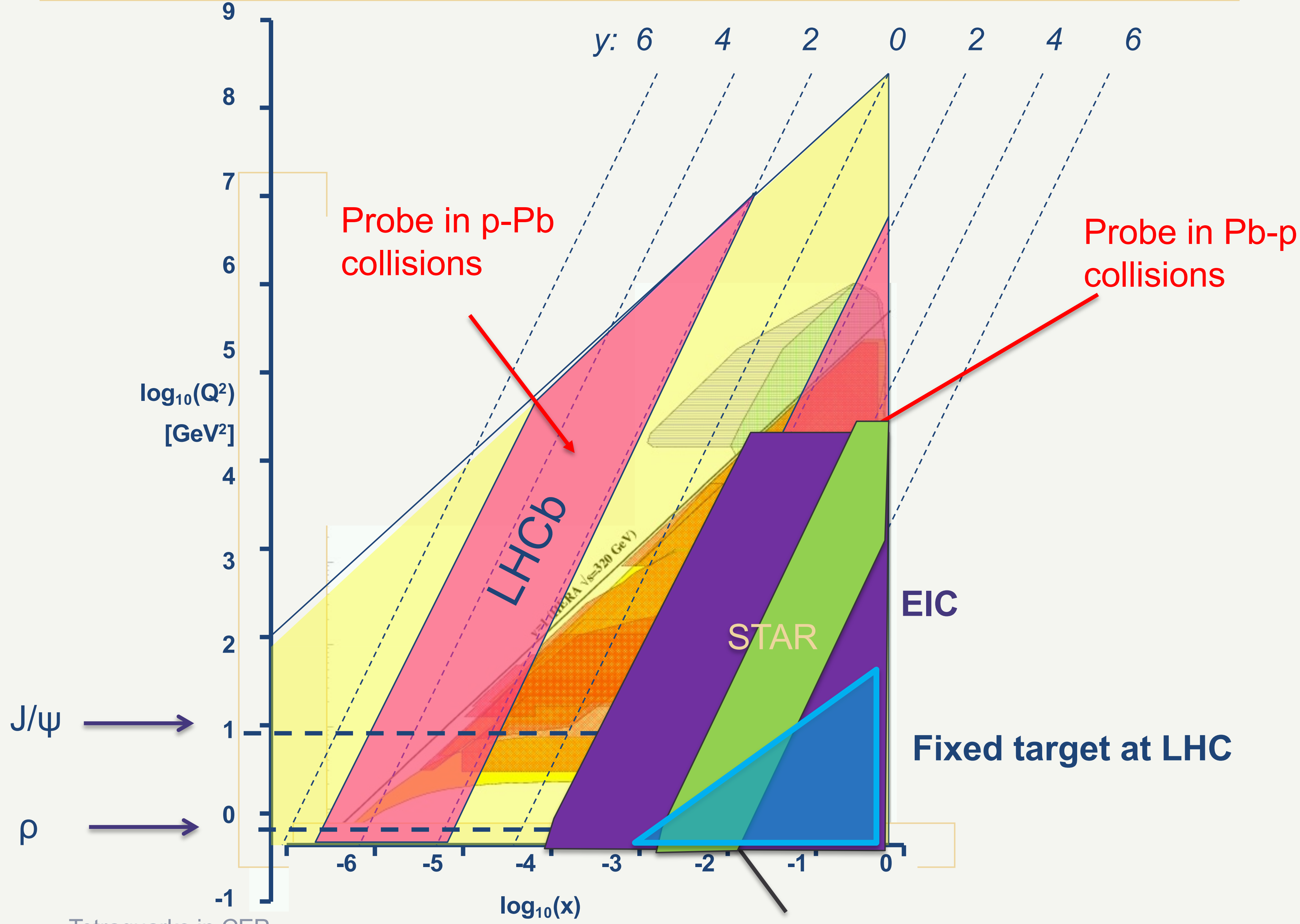
Synergies between eh and hh



Synergies between eh and hh



Synergies between eh and hh



Motivation for CEP

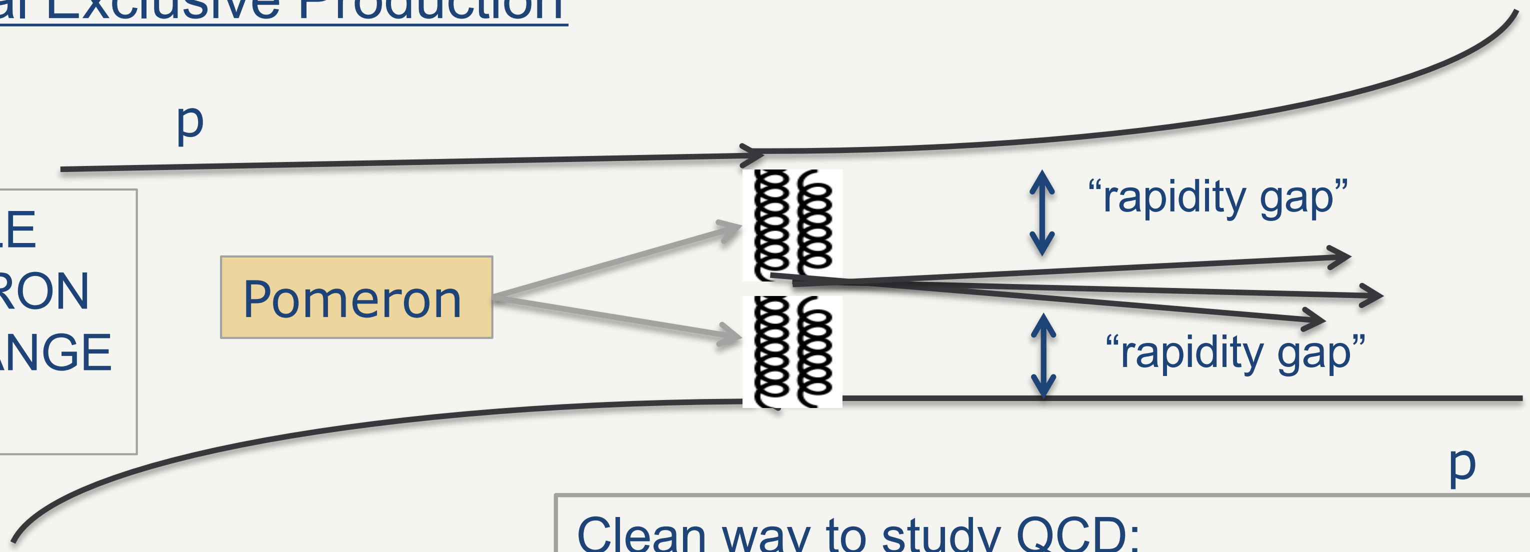
- Much to understand about QCD
  - perturbative / non-perturbative regime
  - proton and nuclear structure (PDFs GPDs)
  - saturation
  - quark model bound states (ρ, ρ', f_0,$f_{2....}$)
  - beyond the naïve quark model (hybrids, **<u>tetraquarks</u>**, glueballs)
  - colourless propagators: pomerons and odderons

- Can be addressed in diffractive DIS.

Physics of the Vacuum

Central Exclusive Production

DOUBLE POMERON EXCHANGE (DPE)



Clean way to study QCD:
- structure of projectiles
- nature of colour-free propagators
- structure of what is produced out of vacuum

$\sigma_{elastic} \approx 40mb$

$\sigma_{diffractive} \approx 10mb$

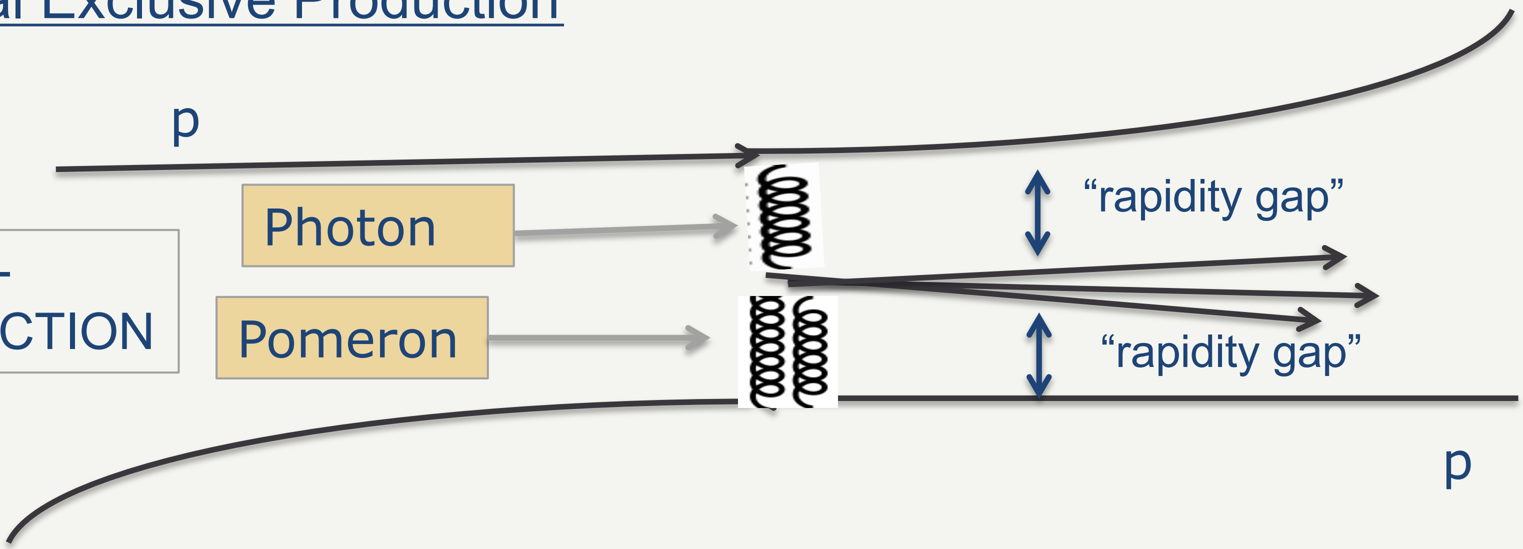
$\sigma_{inelastic} \approx 60mb$

100 μb

Physics of the Vacuum

<u>Central Exclusive Production</u>

PHOTO-
PRODUCTION



$\sigma_{elastic} \approx 40mb$

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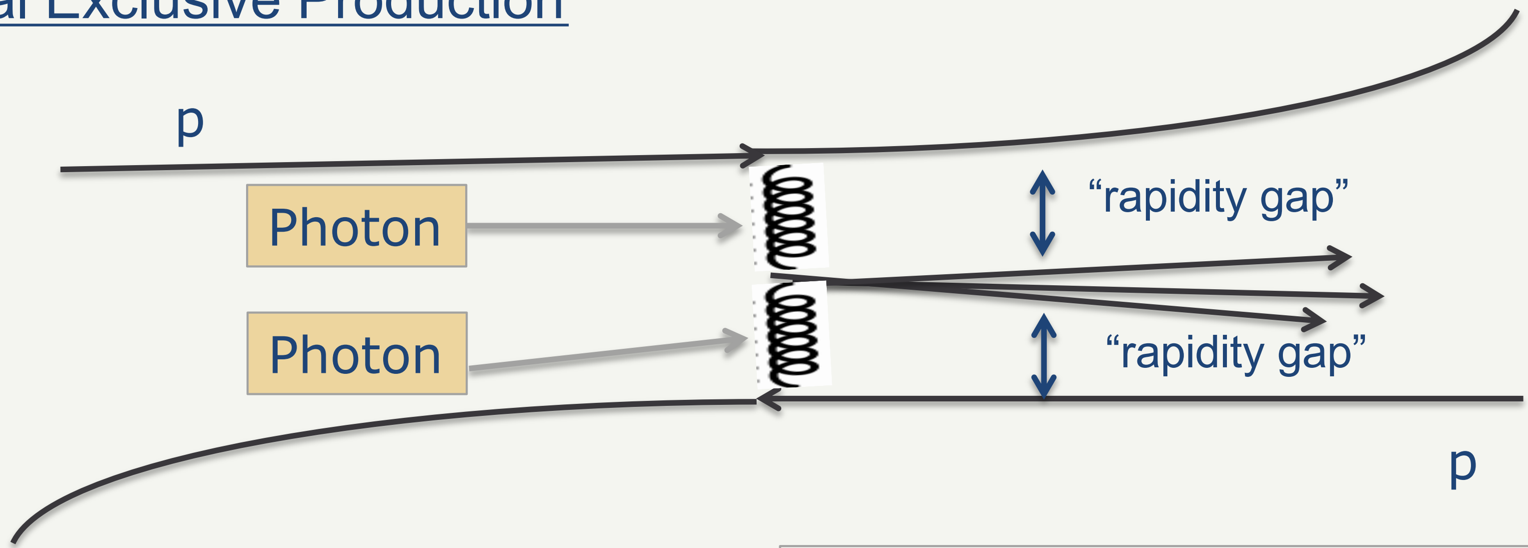
100 μb

Physics of the Vacuum

Central Exclusive Production

QED



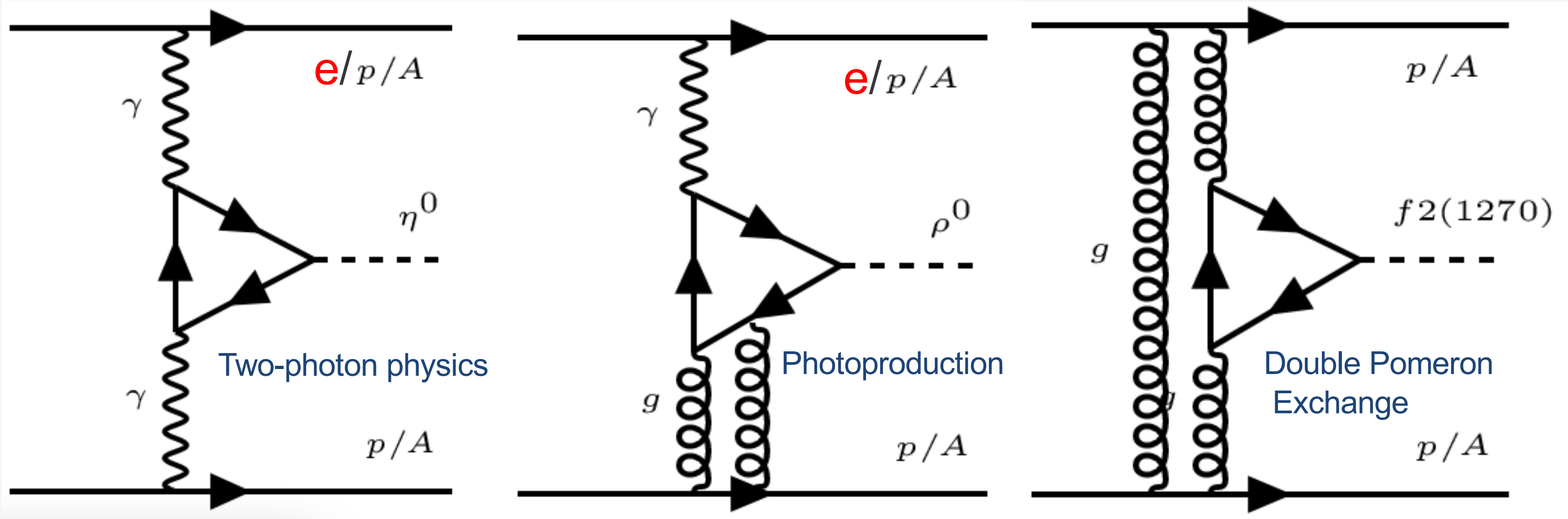
CEP is characterised by a rapidity gap all the way to the proton

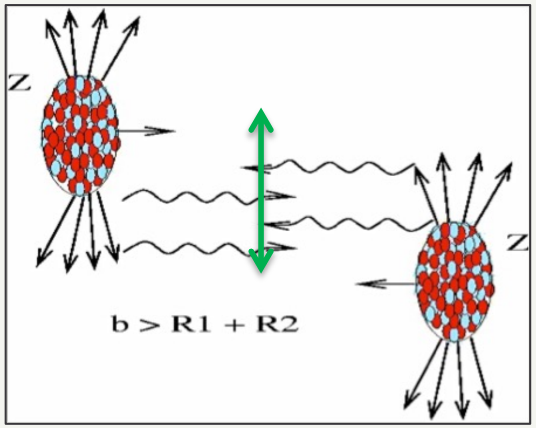
Detect as large a gap as possible...

$\sigma_{elastic} \approx 40$mb
$\sigma_{diffractive} \approx 10$mb
$\sigma_{inelastic} \approx 60$mb

100 pb

Colourless propagators





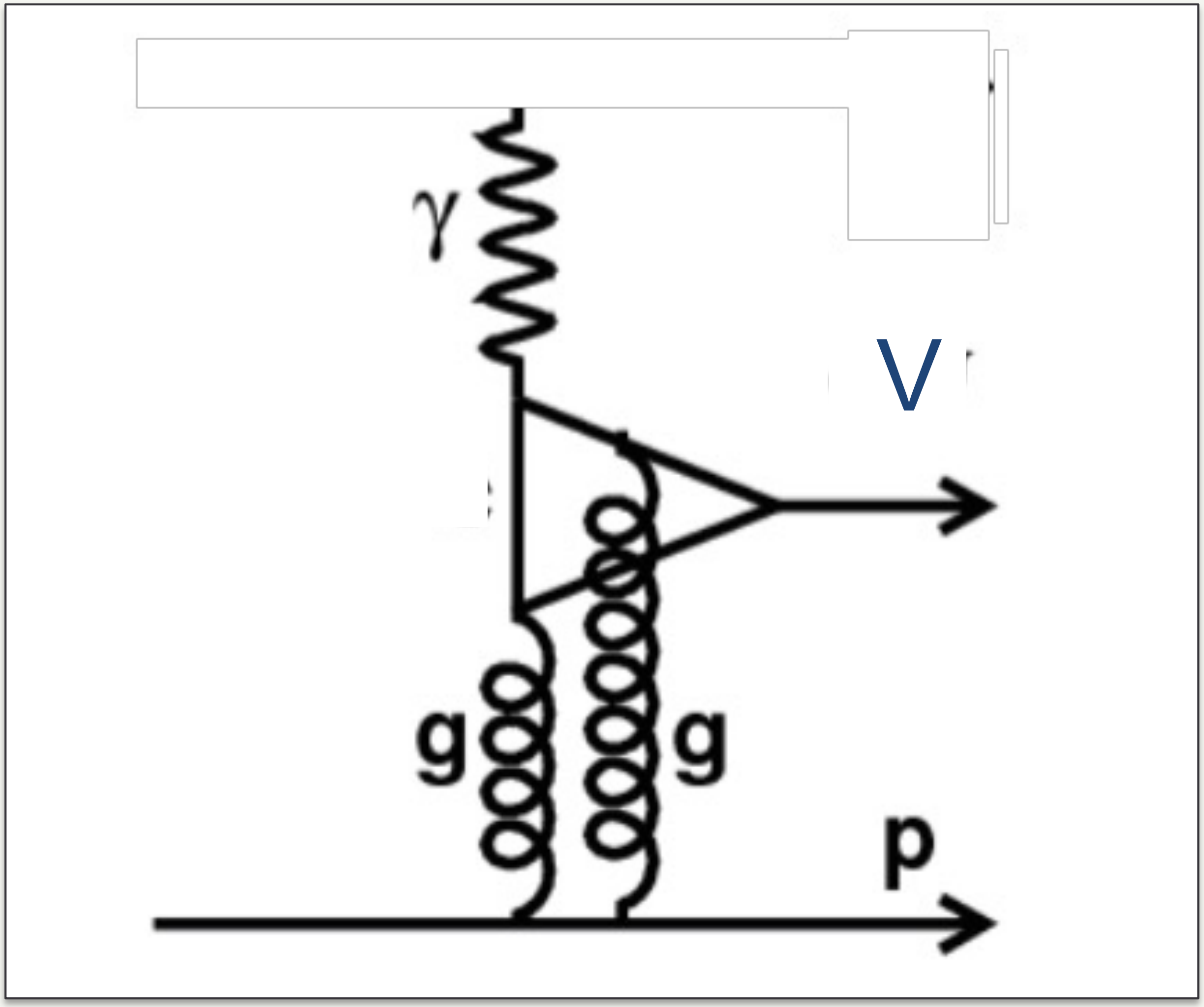
Tetraquarks in CEP

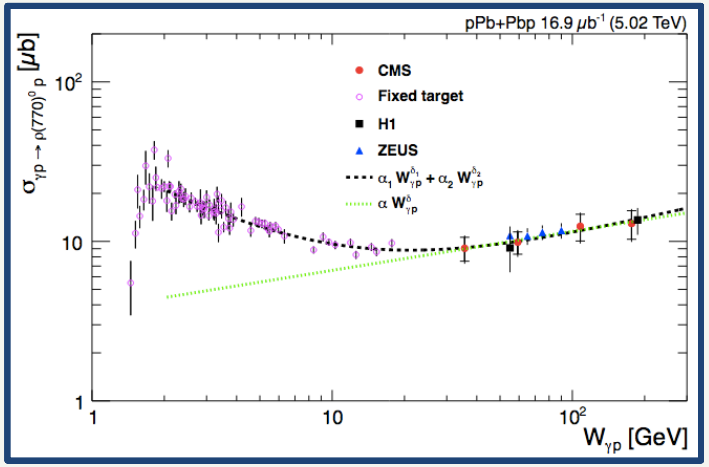
Hadron colliders:
Generally, to ensure no (colourful) QCD interaction, $d>R_1+R_2$ (1.5 - 6 fm).

Large impact parameter ↔ Small p_T

Electron-hadron collider:
~70% of total cross-section is diffractive

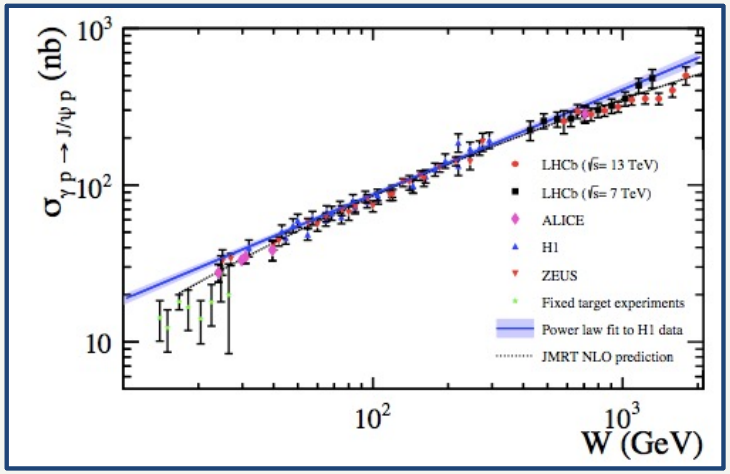
Photoproduction



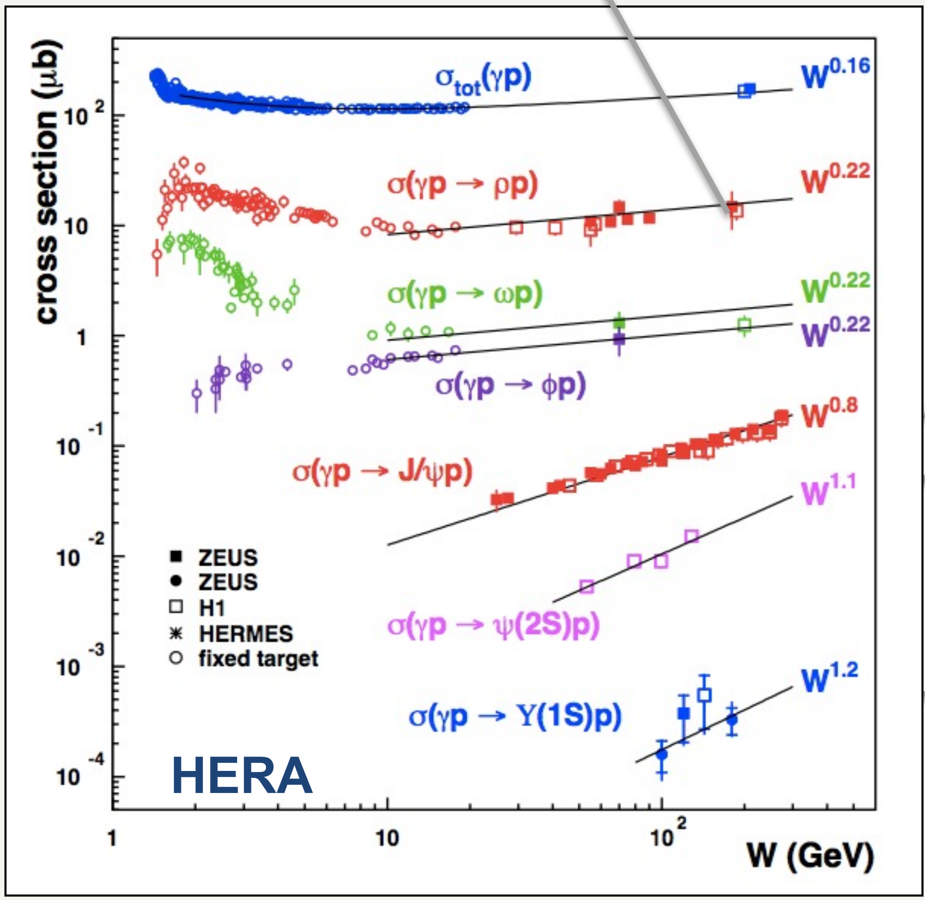


CMS (pPb) ALICE (XeXe, PbPb)

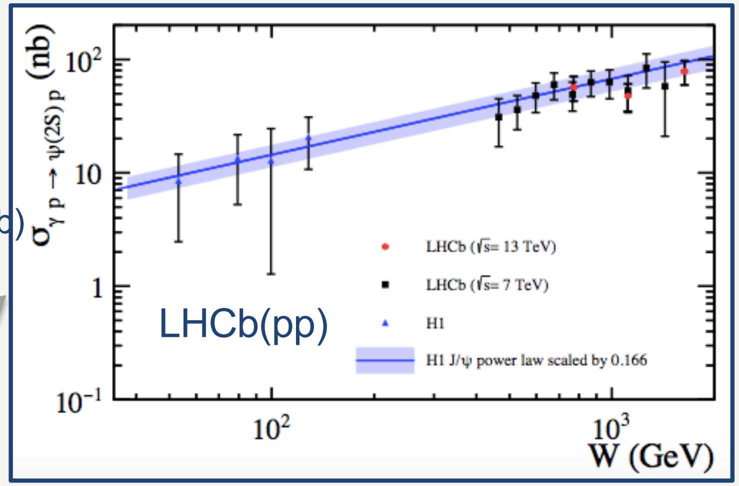
ALICE (pPb, PbPb)
LHCb (pp, PbPb)



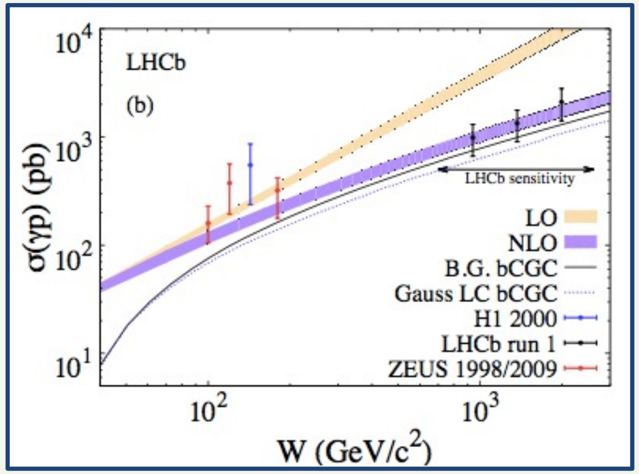
Central region
$W_{LHC} \sim W_{HERA}$
Forward
$W_{LHC} >> W_{HERA}$



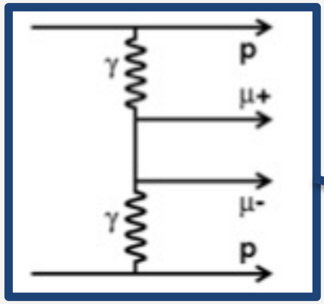
LHCb
(pp, PbPb)



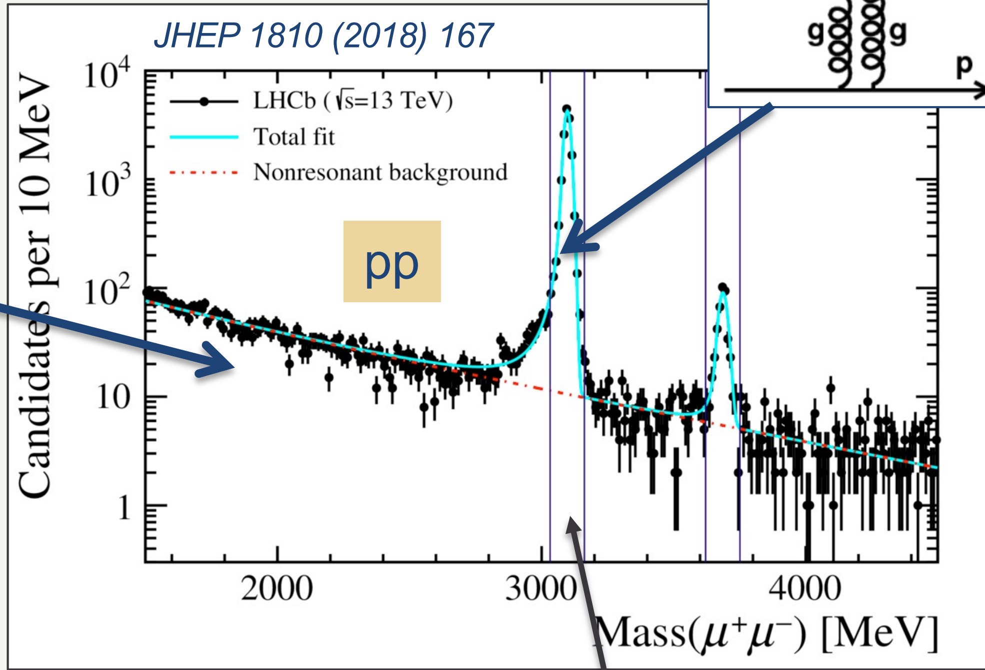
LHCb (pp)
CMS (pPb)

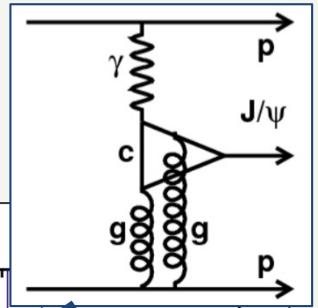


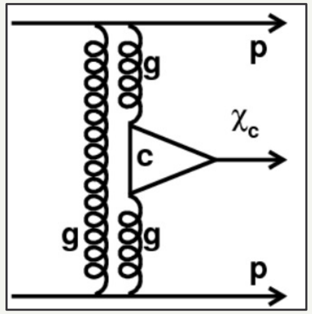
Dimuons in p(Pb)p(Pb) collisions



$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV (enhanced in PbPb)



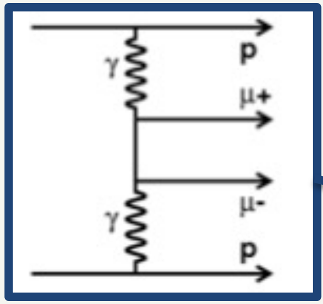




Feed-down (not present in pA)

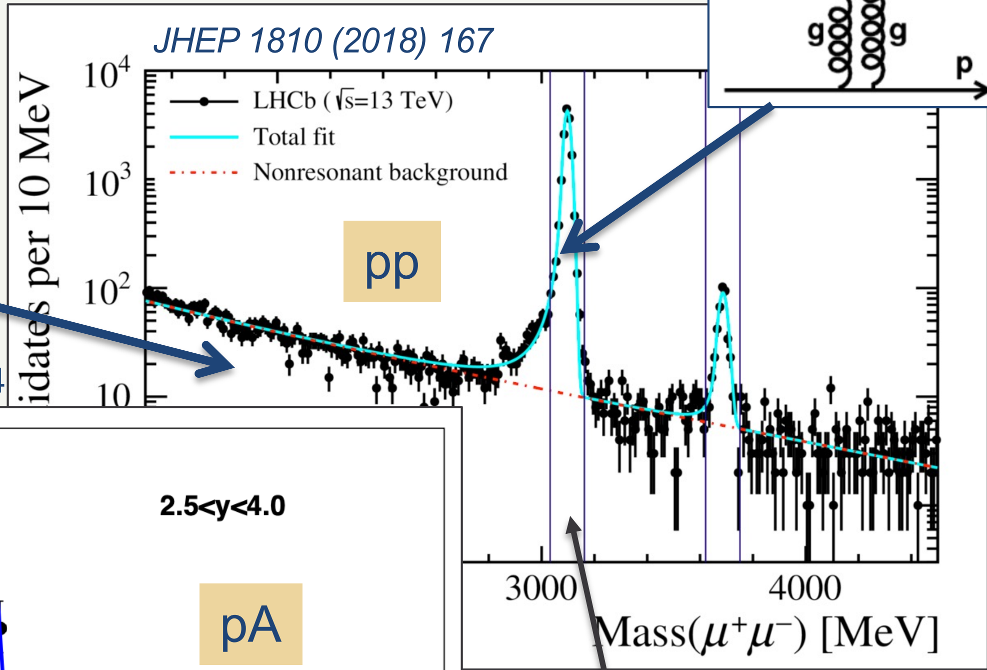
$\chi_c \longrightarrow J/\psi + \gamma$

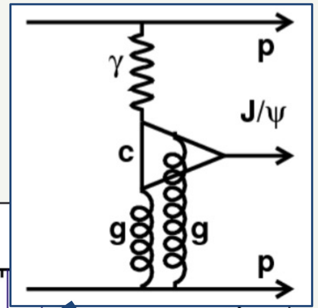
Dimuons in p(Pb)p(Pb) collisions



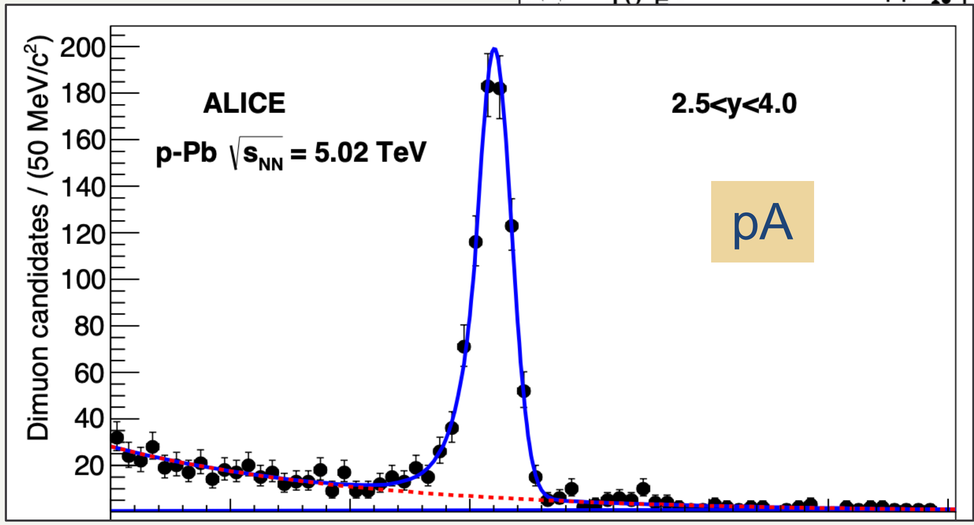
$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV (enhanced in PbPb)

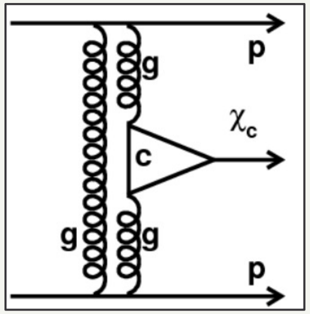
JHEP 1810 (2018) 167





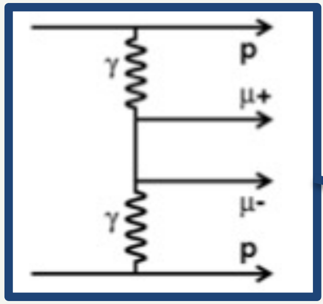
Phys.Rev.Lett. 113 (2014) 23, 232504



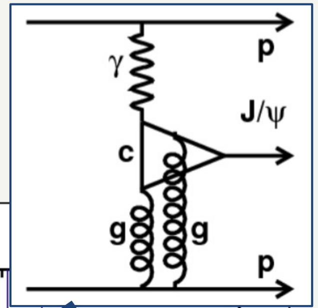


Feed-down (not present in pA)

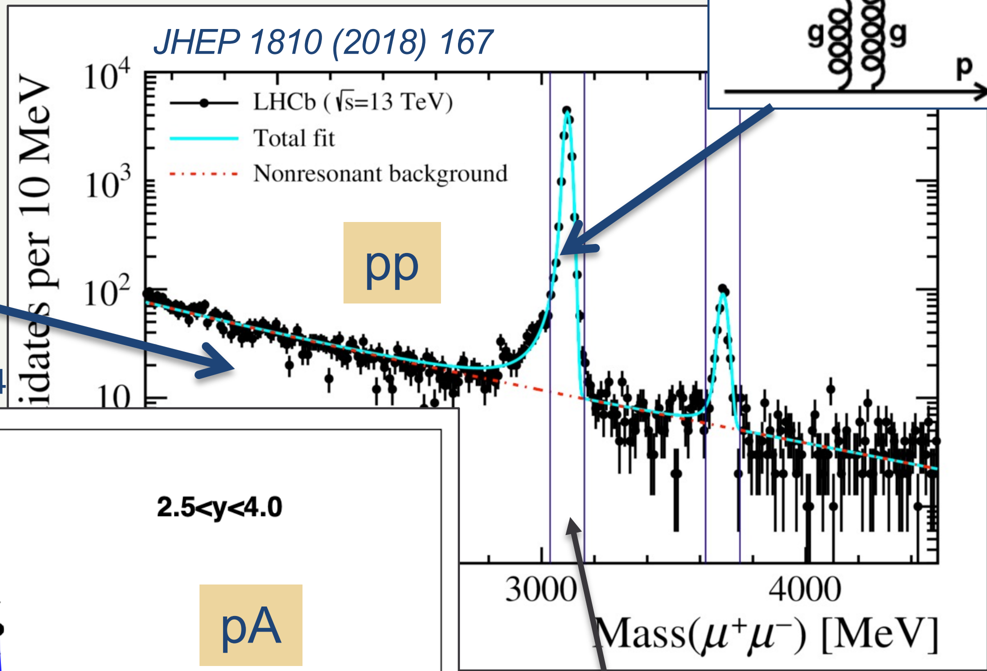
Dimuons in p(Pb)p(Pb) collisions



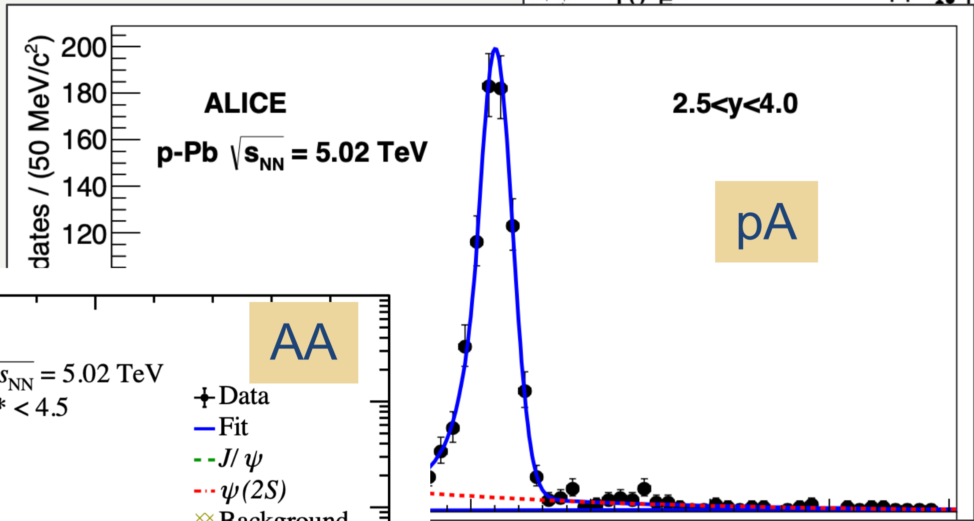
$\gamma\gamma$ events continue to detection threshold at ~ 600 MeV (enhanced in PbPb)



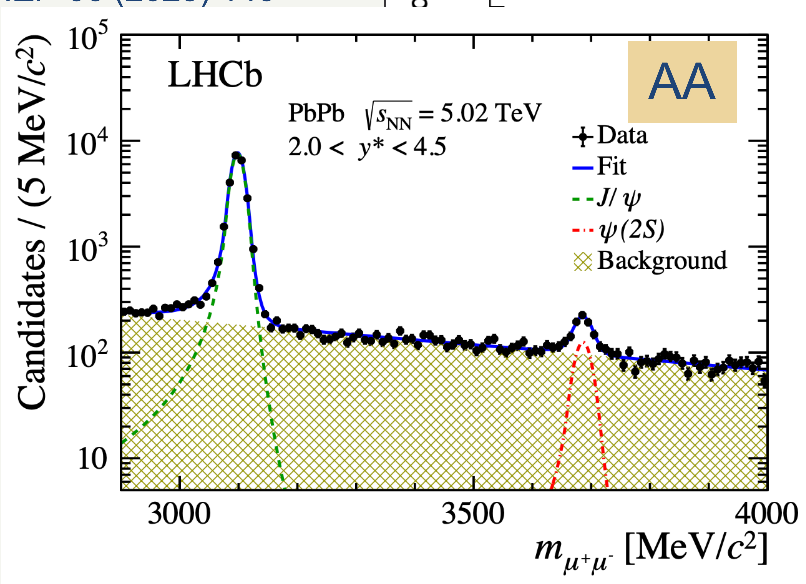
JHEP 1810 (2018) 167

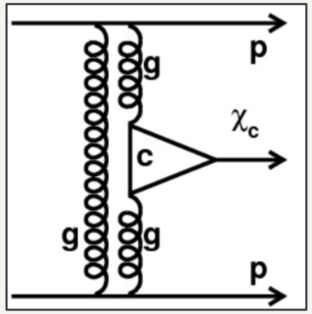


Phys.Rev.Lett. 113 (2014) 23, 232504

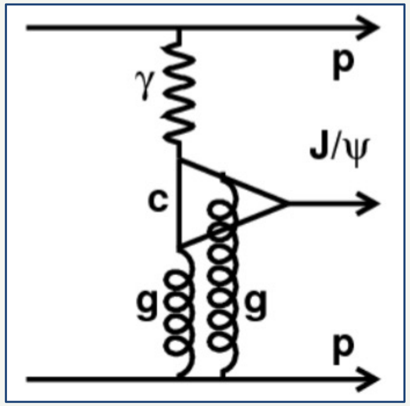


JHEP 06 (2023) 146





Feed-down (not present in pA)



Implications: GPDs and PDF

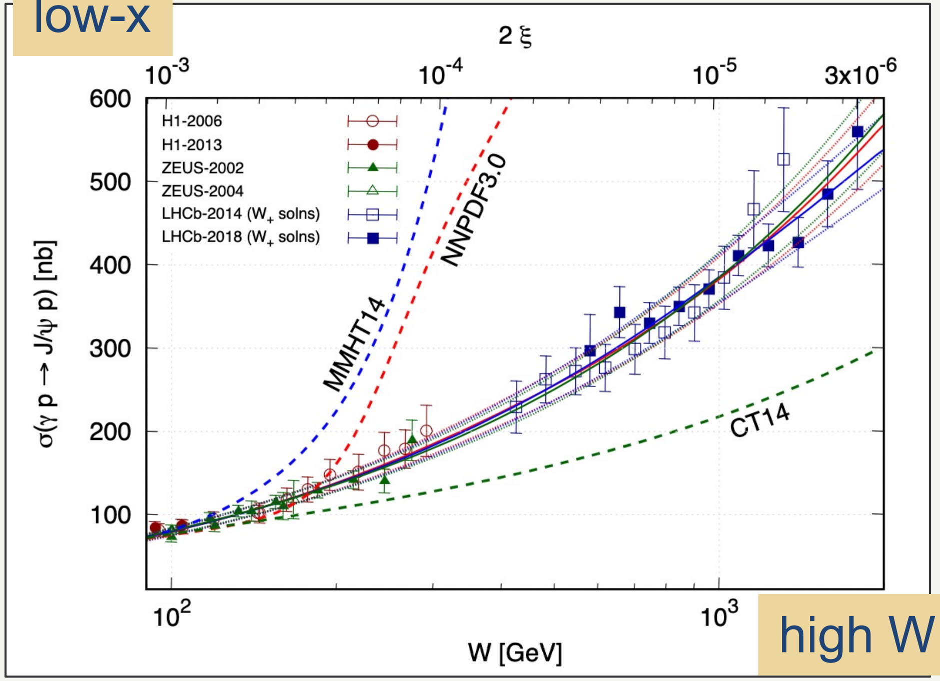
Ryskin, Z. Phys. C 57 (1993) 89

$$\frac{d\sigma}{dt}(\gamma^* p \to J/\psi\, p)\Big|_{t=0} = \frac{\Gamma_{ee} M^3_{J/\psi} \pi^3}{48\alpha} \left[\frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x,\bar{Q}^2)\right]^2 \left(1+\frac{Q^2}{M^2_{J/\psi}}\right)$$

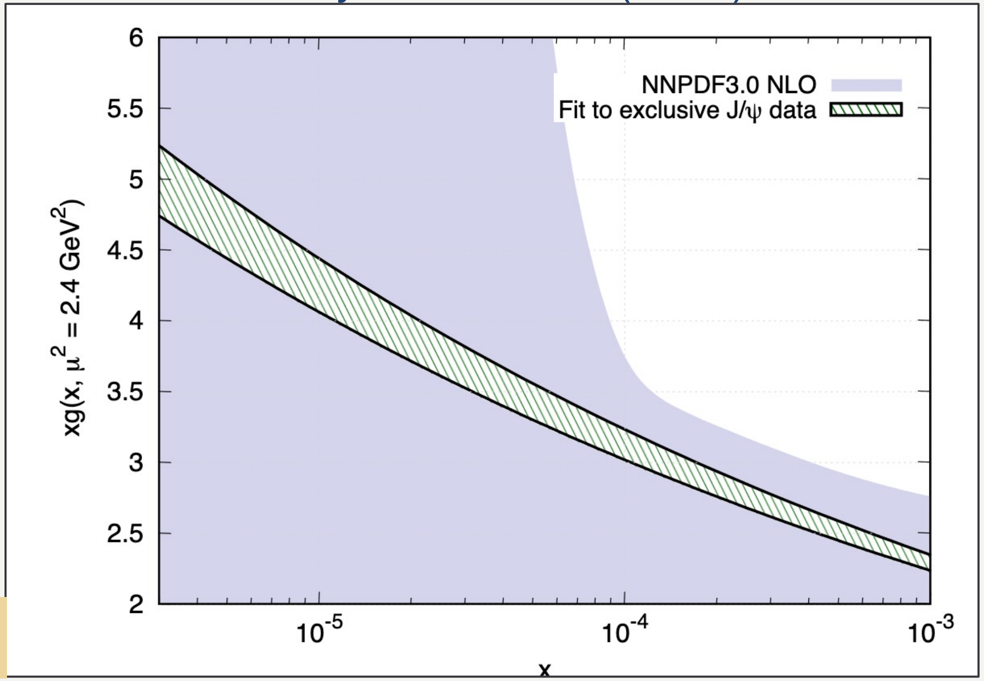
Flett, Martin, Ryskin, Teubner. Phys.Rev.D 102 (2020) 114021

Flett, Jones, Martin, Ryskin, Teubner. Phys.Rev.D 101 (2020) 9, 094011

low-x



high W



makes use of Shuvaev transform to relate GPDs and PDFs

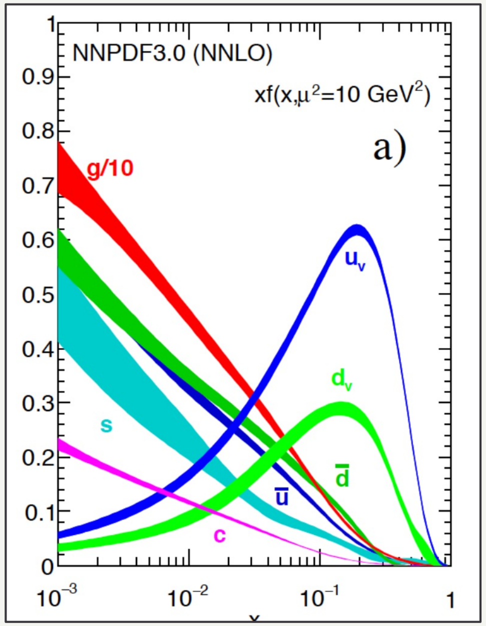
$$H_q(X,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds}{y(s)\sqrt{1-y(s)x'}}\right] \frac{d}{dx'}\left(\frac{q(x')}{|x'|}\right),$$

$$H_g(X,\xi) = \int_{-1}^{1} dx' \left[\frac{2}{\pi}\mathrm{Im}\int_0^1 \frac{ds\,(X+\xi(1-2s))}{y(s)\sqrt{1-y(s)x'}}\right] \frac{d}{dx'}\left(\frac{g(x')}{|x'|}\right),$$

where the transform kernel,

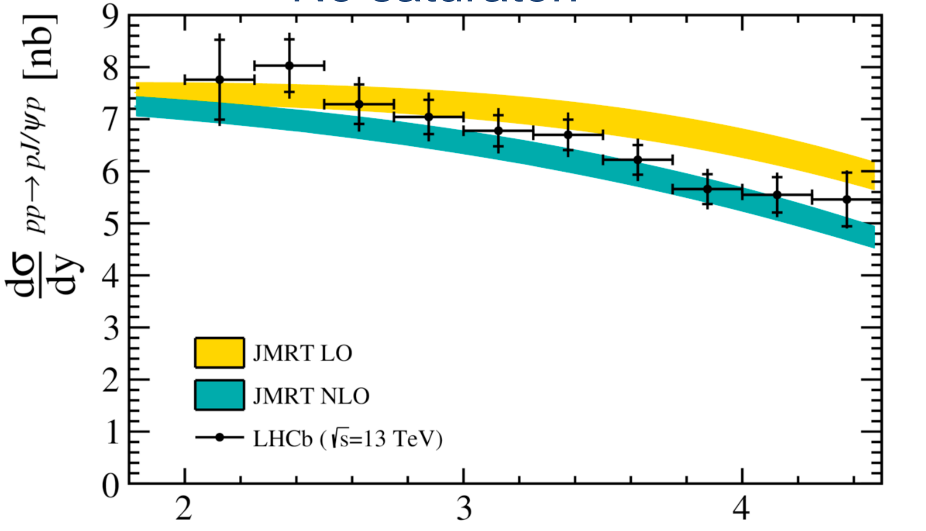
$$y(s) = \frac{4s(1-s)}{(X+\xi(1-2s))}.$$

Implications: Saturation



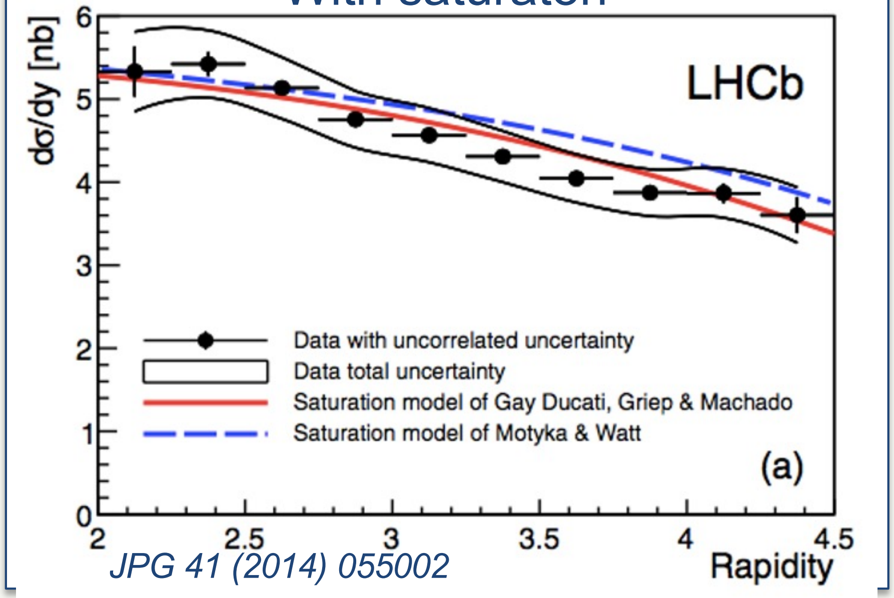
Saturation effects become visible at low-x.
Onset of saturation expected to scale with nucleon density ~ $A^{1/3}$ so
may be easier to see in nuclear collisions

No saturaton



JHEP 1810 (2018) 167

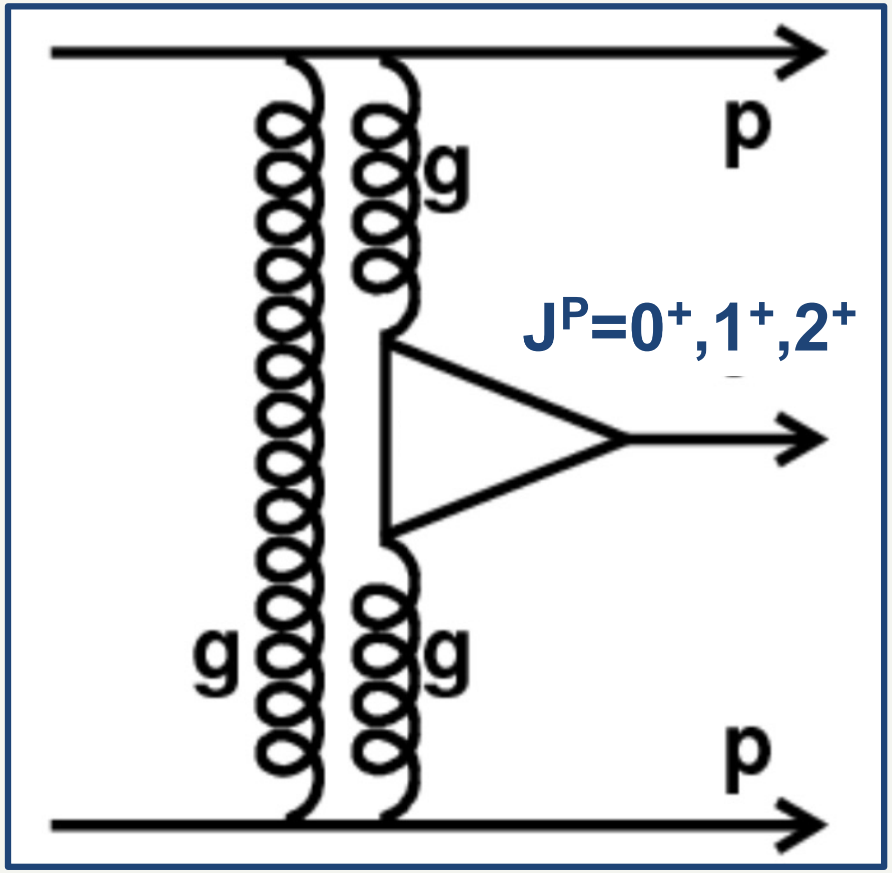
With saturaton



JPG 41 (2014) 055002

Saturation is not inconsistent with the data, but is also not required.

Double Pomeron Exchange

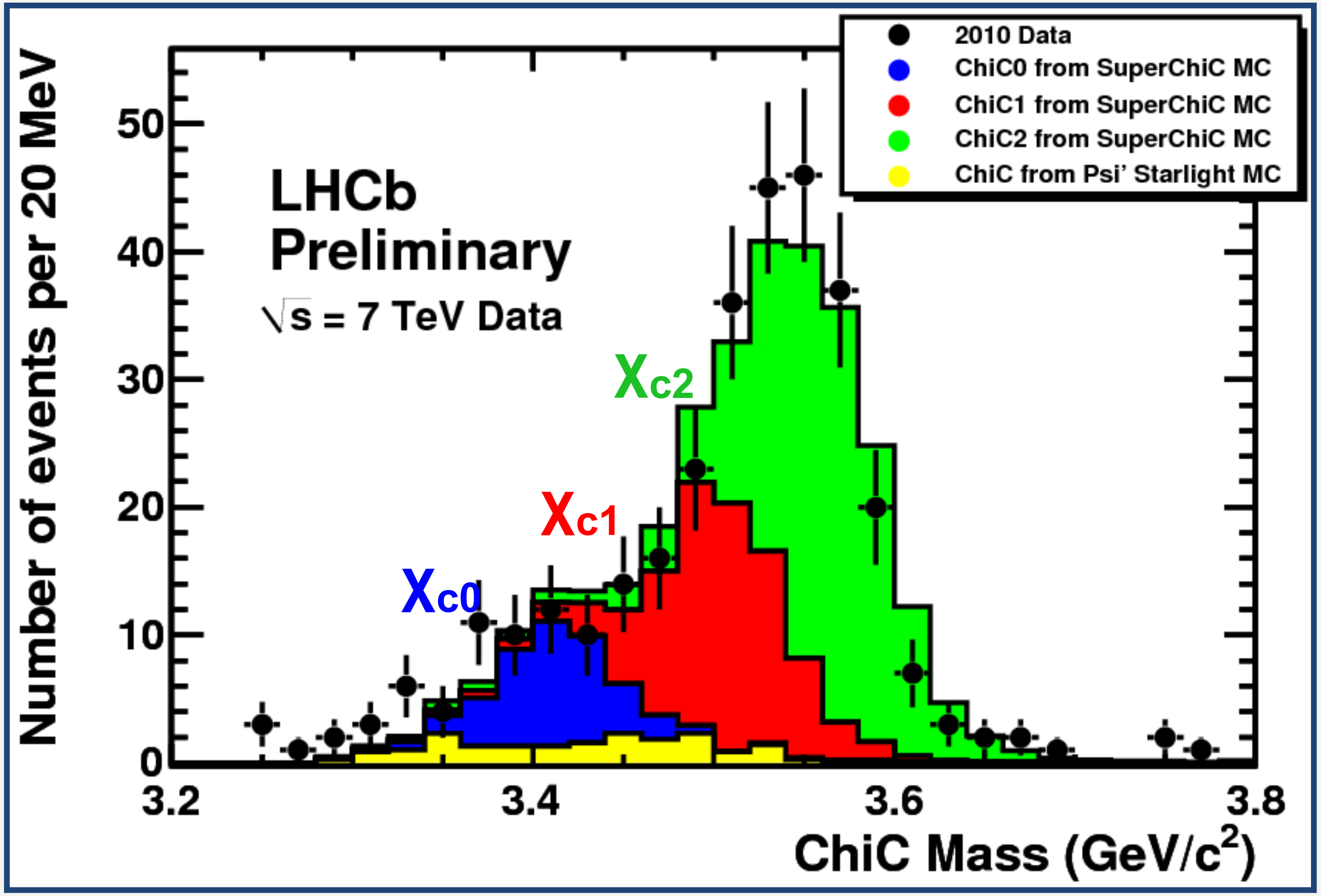


Understanding colourless strong interactions is fundamental

Also simple environment for spectroscopy, in particular, glueballs

Charmonium production

LHCb-CONF-2011-022



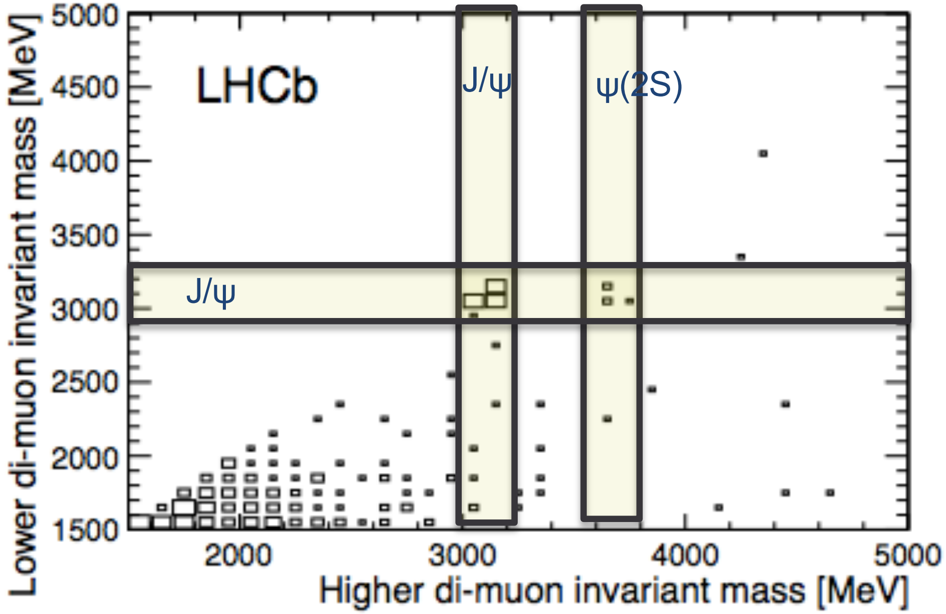
Can only be produced in DPE

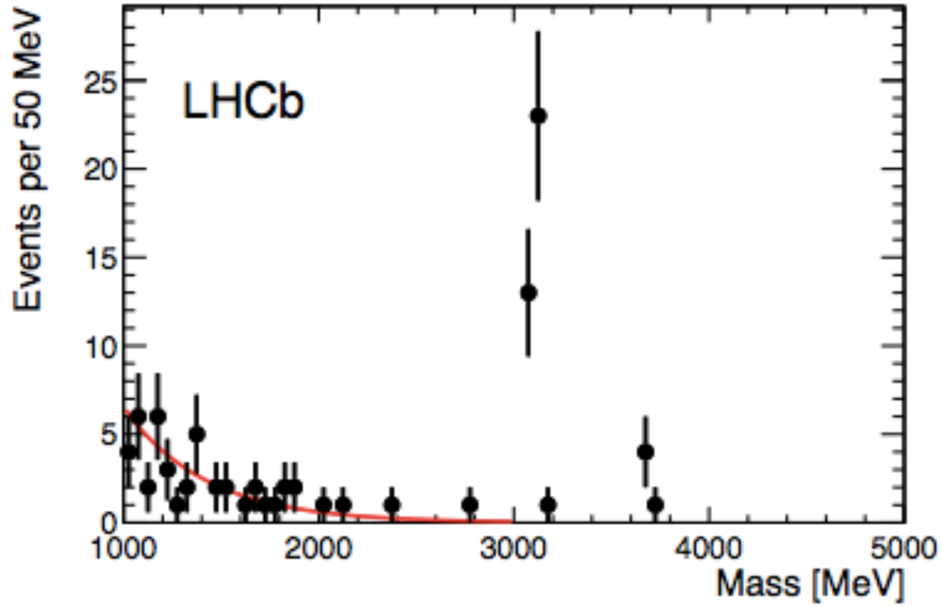
Difficult to separate peaks: work ongoing with photon conversions

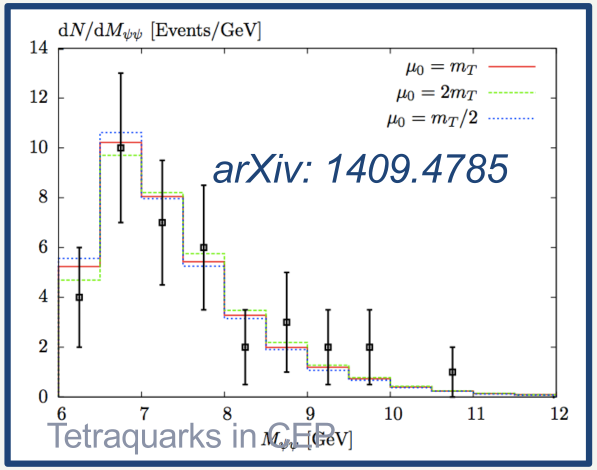
J/ψJ/ψ: search for exotica

JPG 41 (2014) 115002

$$\begin{aligned}
\sigma^{J/\psi\, J/\psi} &= 58 \pm 10(\text{stat}) \pm 6(\text{syst})\ \text{pb},\\
\sigma^{J/\psi\, \psi(2S)} &= 63^{+27}_{-18}(\text{stat}) \pm 10(\text{syst})\ \text{pb},\\
\sigma^{\psi(2S)\psi(2S)} &< 237\ \text{pb},\\
\sigma^{\chi_{c0}\chi_{c0}} &< 69\ \text{nb},\\
\sigma^{\chi_{c1}\chi_{c1}} &< 45\ \text{pb},\\
\sigma^{\chi_{c2}\chi_{c2}} &< 141\ \text{pb},
\end{aligned}$$







LHCb estimate exclusive cross-section. **58+-12 pb**
Harland-Lang, Khoze, Ryskin: **2-7 pb**

$$\sigma^{J/\psi J/\psi}\ :\ \sigma^{J/\psi\psi(2S)}\ :\ \sigma^{\psi(2S)\psi(2S)} = 1\ :\ 0.40\ :\ 0.044$$

J/ψJ/ψ: search for exotica

JPG 41 (2014) 115002

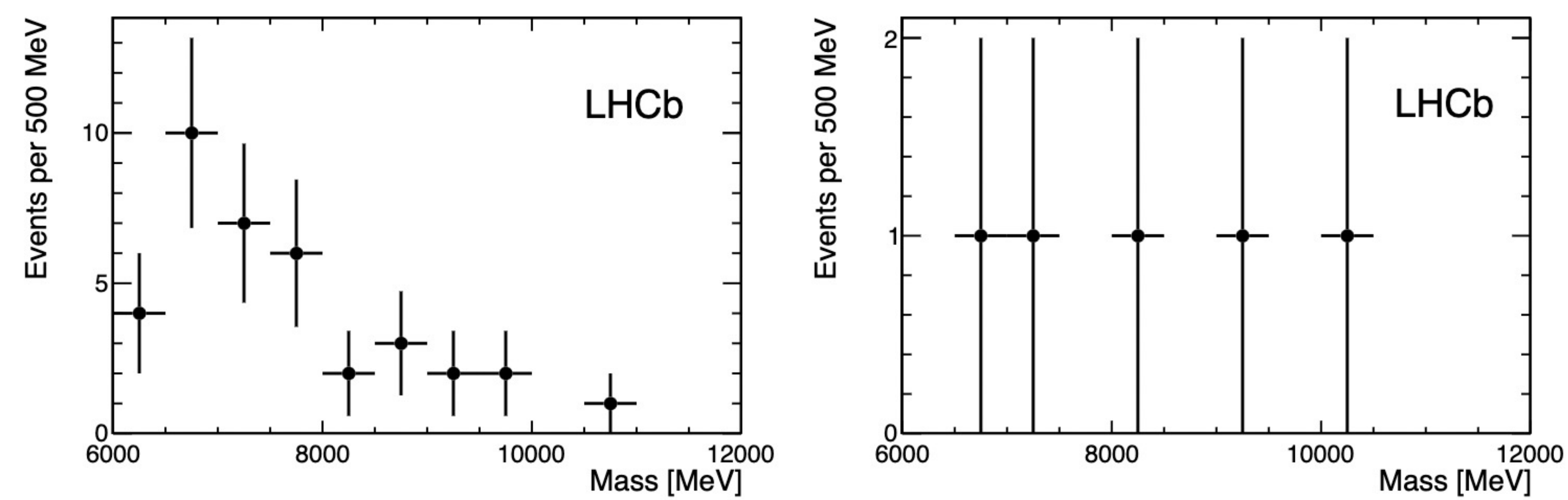
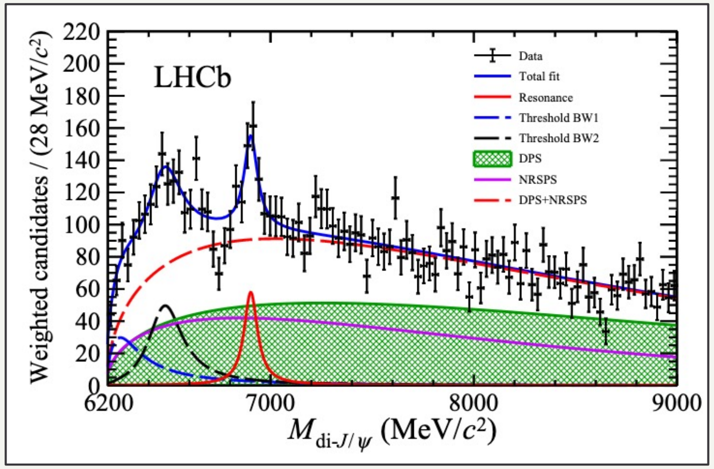


Figure 3: Invariant mass of the four-muon system in (left) $J/\psi\, J/\psi$ and (right) $J/\psi\, \psi(2S)$ events.

Sci.Bull. 65 (2020) 23, 1983-1993



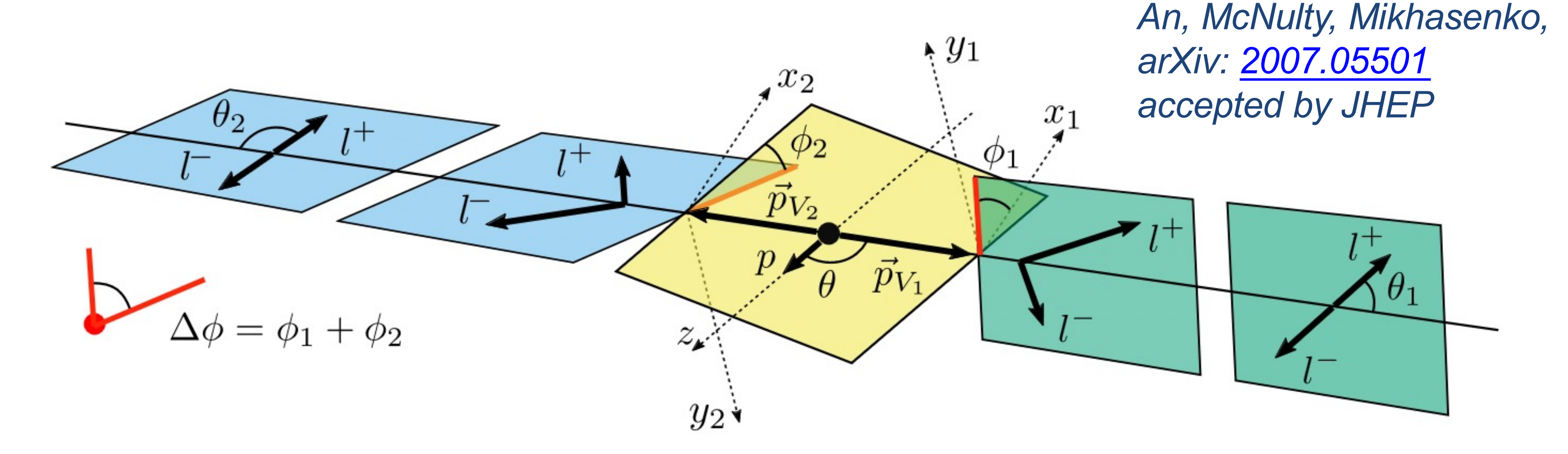
Tetraquarks in CEP

Today from **inclusive** measurements we know there is significant structure and tetraquark candidates

Diffractive measurements are cleaner and help identify quantum numbers

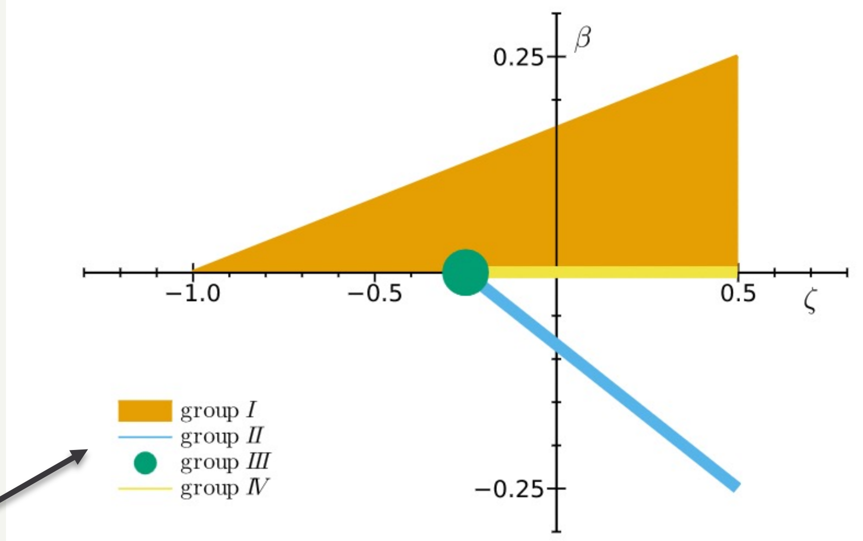
How to find J^P of resonances

An, McNulty, Mikhasenko,
arXiv: [2007.05501](2007.05501)
accepted by JHEP



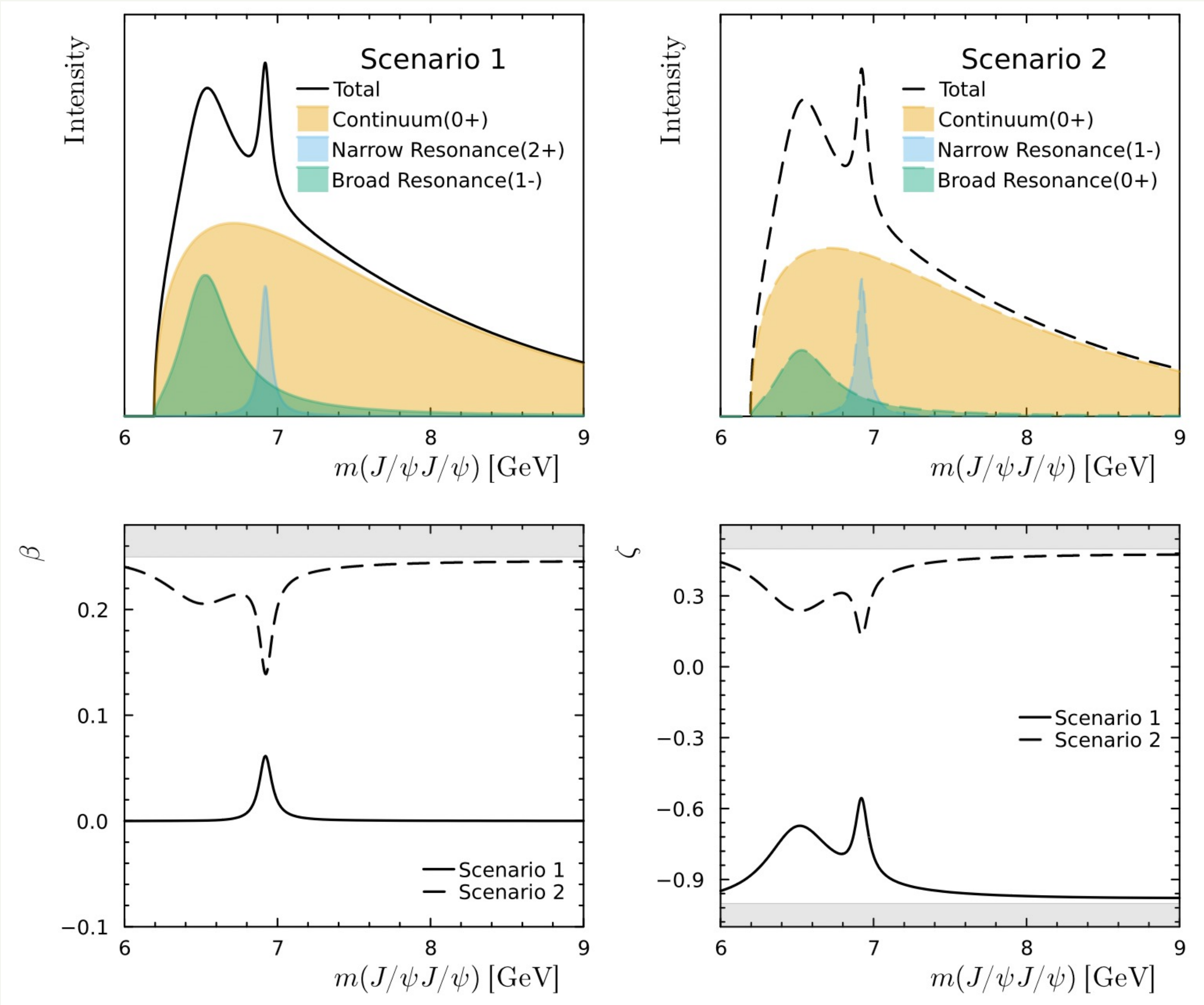
$$I(\Delta\phi) = 1 + \beta\cos(2\Delta\phi).$$

$$I(\cos\theta_i) = 1 + \zeta\,\frac{3\cos^2\theta_i - 1}{2}.$$



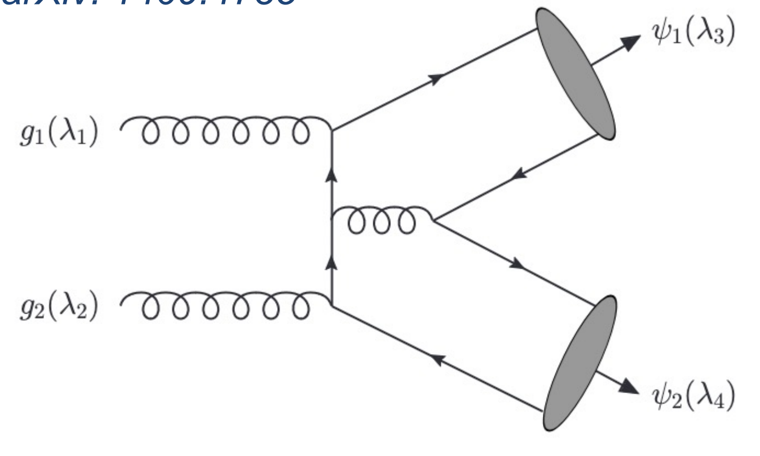
J=even/odd
P=+/-

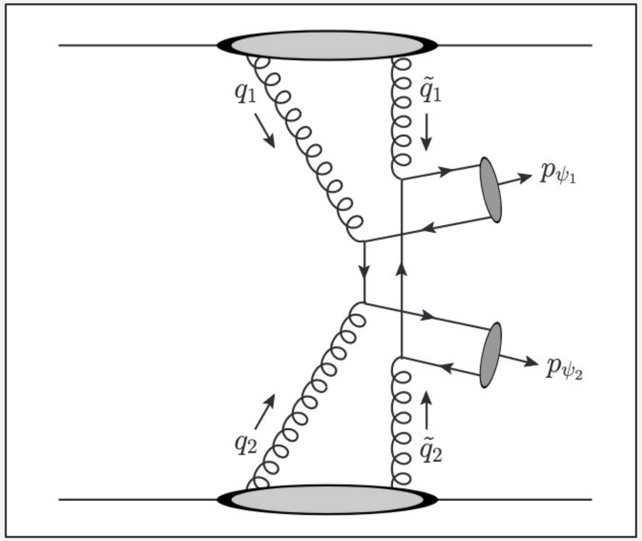
How angular distributions help...



Production for continuum

arXiv: 1409.4785





What is production mechanism for tetraquark states ?

Can molecular states be produced in CEP?

Can tightly bound 4-quark states be produced in CEP?

$c\bar{c}c\bar{c}$. v $c\bar{c}s\bar{s}$

Molecular picture inconsistent with CEP

arXiv:1305.0527

A Mechanism for Hadron Molecule Production in $p\bar{p}(p)$ Collisions

A Esposito*, F Piccinini†, A Pilloni* and AD Polosa*

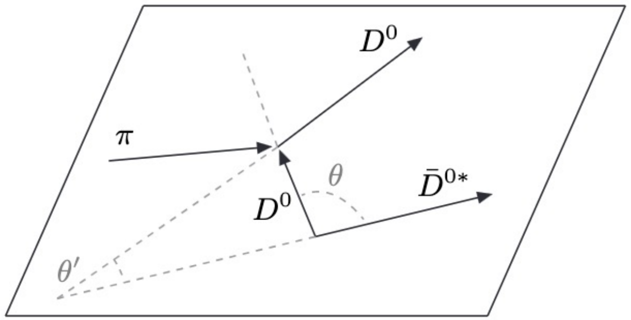
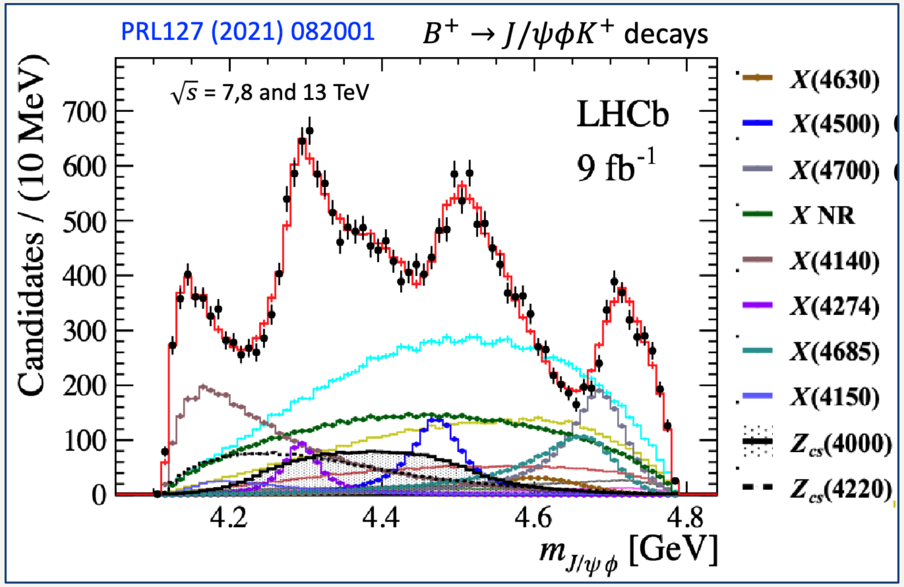


FIG. 1: The elastic scattering of a D^0 (or D^{*0}) with a pion among those produced in hadronization could reduce the relative momentum $\boldsymbol{k}_0$ in the centre of mass of the $D^0\bar{D}^{0*}$ pair.

In our view the X could rather be the meson-molecule analogue of the stable deuterium.

Given the large number of pions produced in the neighbourhood of the open charm meson pairs in momentum phase space, it is plausible that some of those pions could scatter elastically on the D^0 or D^{*0} component of the would-be-molecule changing the relative momentum in the centre of mass of the pair, $\boldsymbol{k}_0$, towards lower values - see Fig. 1. We can assume the initial total energy $\mathcal{E}$ of the pair to be positive. However, if $k_0 = |\boldsymbol{k}_0|$

J/ψ+ϕ: search for exotica



Structure seen in **inclusive** production of J/ψ+ϕ.

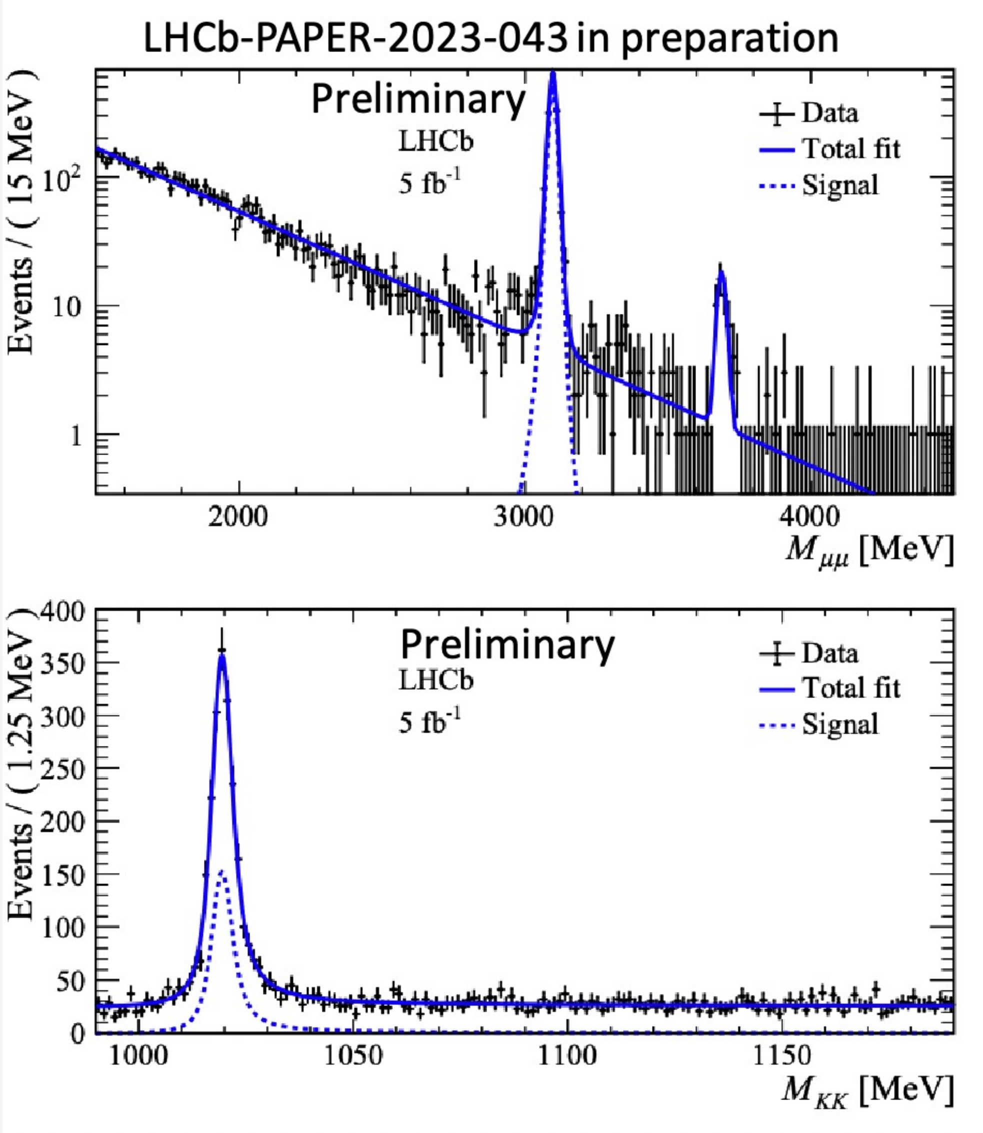
Can these structure be seen in central **exclusive** production?

- Cleaner environment
- Insight into production mechanism

Central exclusive production

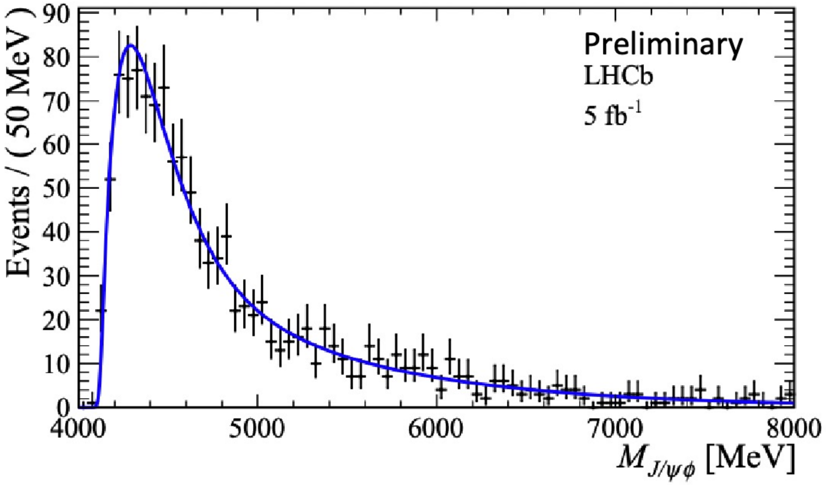
Search for events with precisely four tracks

2 muons + 2 identified kaons

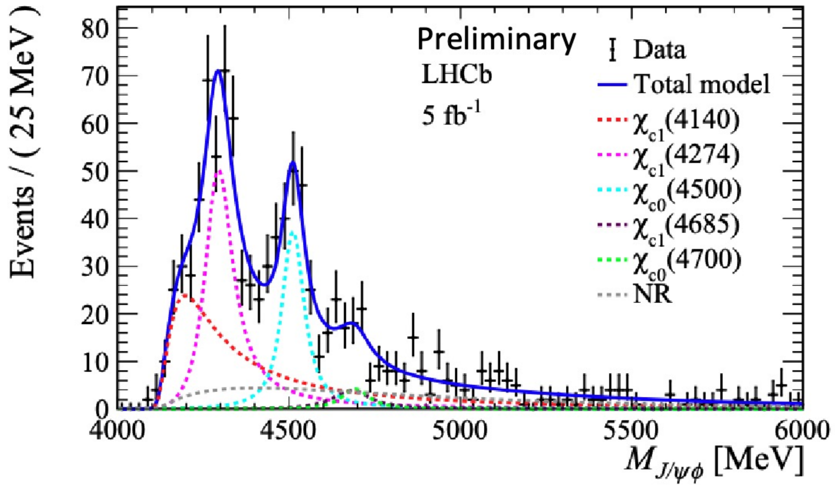


4-track invariant mass

Side-band: > 4 tracks in the event

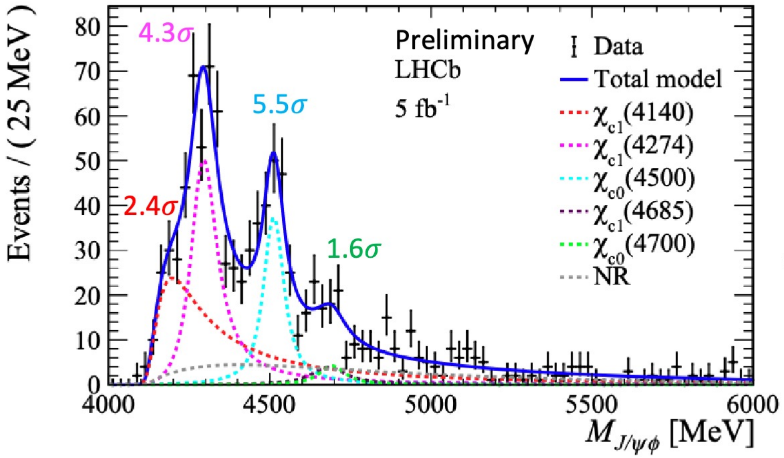


4 tracks in the event



LHCb-PAPER-2023-043 in preparation

(on arXiv next week)



$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.85 \pm 0.16 \pm 0.30)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.77^{+0.14}_{-0.13} \pm 0.18)\,\text{pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.44^{+0.09}_{-0.08} \pm 0.07)\,\text{pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,\text{pb},$$
$$\sigma_{NR} \times \mathcal{B}_{\rm eff}^{NR} = (0.46^{+0.25}_{-0.19}\,{}^{+0.21}_{-0.22})\,\text{pb},$$

Summary of cross-sections

Production rate for these exotic states is not particularly small

Process	Final state	Cross-section
Photoproduction	$p + J/\psi + p$	7nb
Double pomeron exchange	$p + J/\psi + \chi_{c2} + p$	2nb
	$p + J/\psi + \phi + p$	90pb
	$p + J/\psi + J/\psi + p$	60 pb

How are these produced?

Conclusions

- Tetraquark states are seen in central exclusive diffractive events
- Cross-sections have not yet been calculated theoretically
- CEP can shed light on the nature of these states: tightly bound, molecules or even glueballs.