A personal selection of recent UPC measurements related to saturation

Guillermo Contreras
Czech Technical University in Prague

Key questions we are interested in

What can we learn about the structure of hadrons at high energies with the LHC?

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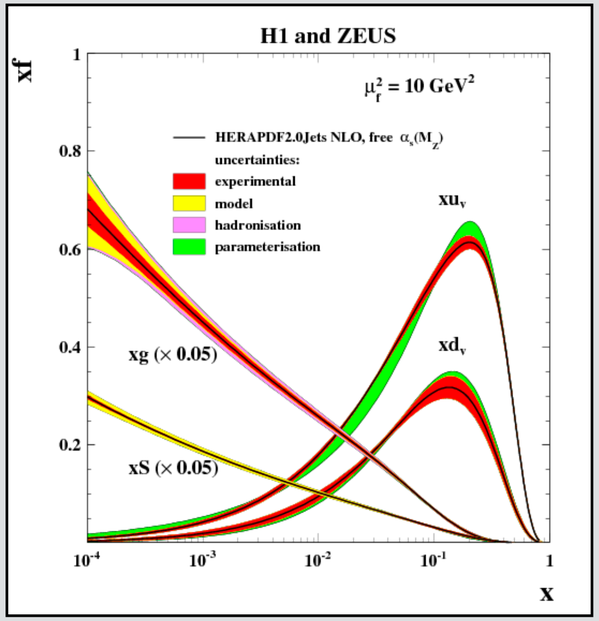
Measurements at HERA imply that, when seen with a high-energy probe, nucleons are made mainly of gluons



H1 and Zeus, EPCJ 75 (2015) 580

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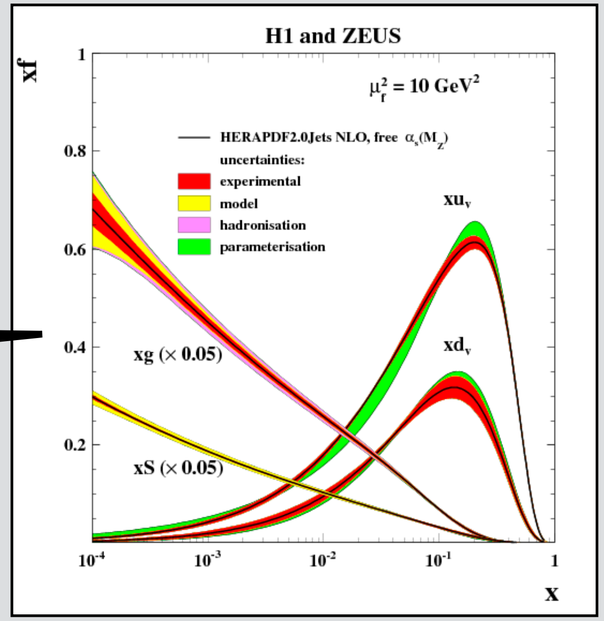

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How does the gluon structure of nucleons change with energy at high energies?

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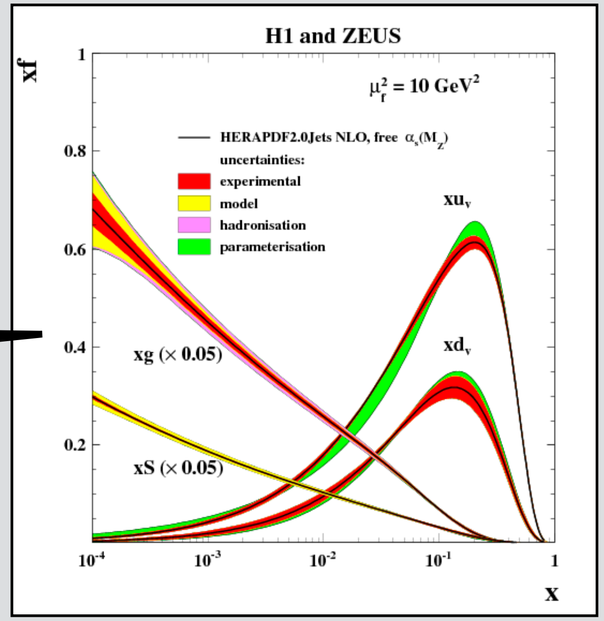

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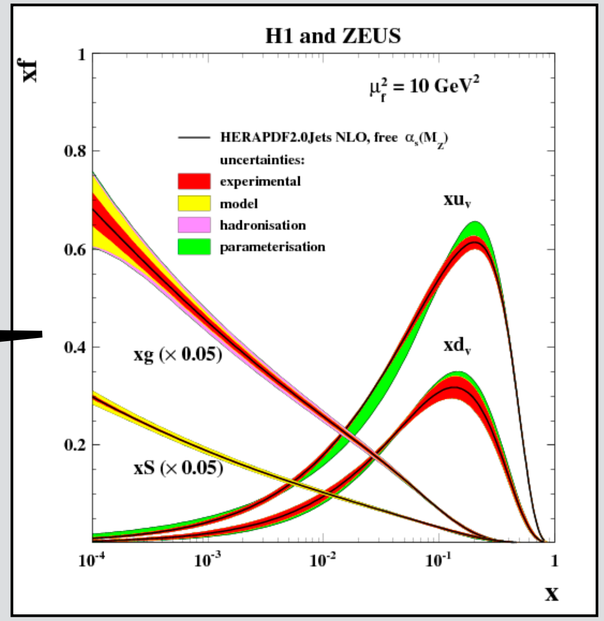

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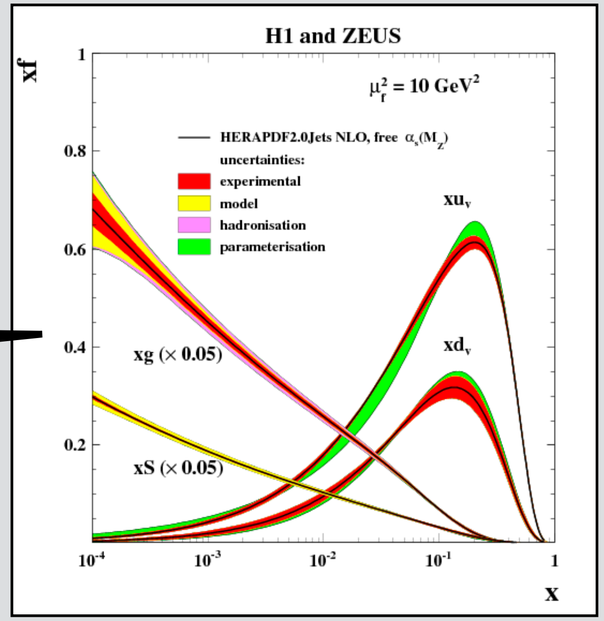

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What can we learn about the structure of hadrons at high energies with the LHC?

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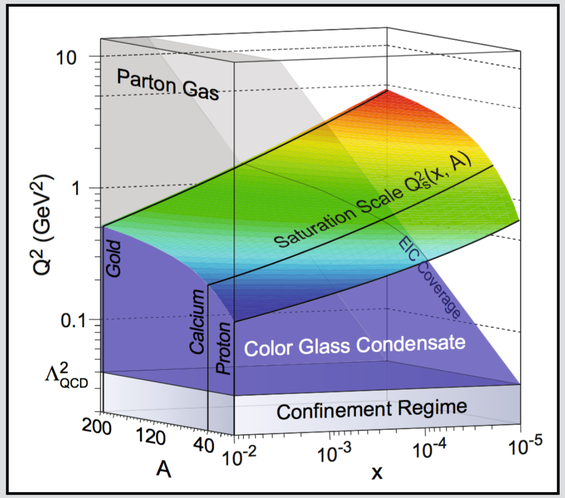
Saturation is expected to set in earlier in heavy nuclei



Accardi et al, EPJA 52 (2016) 268

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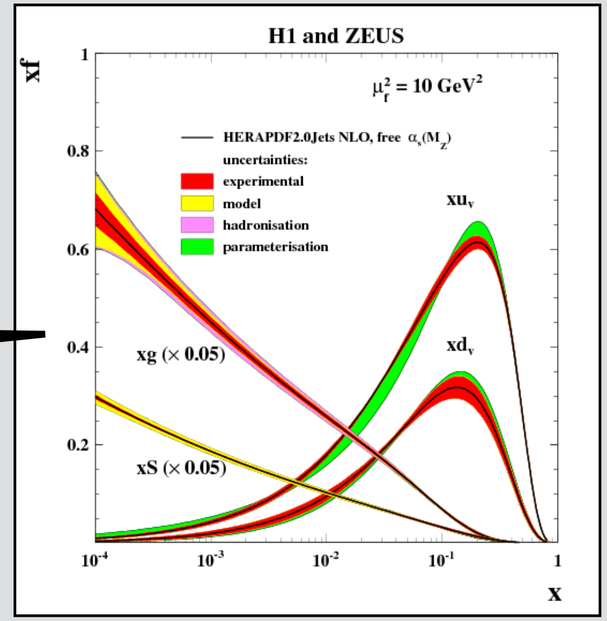

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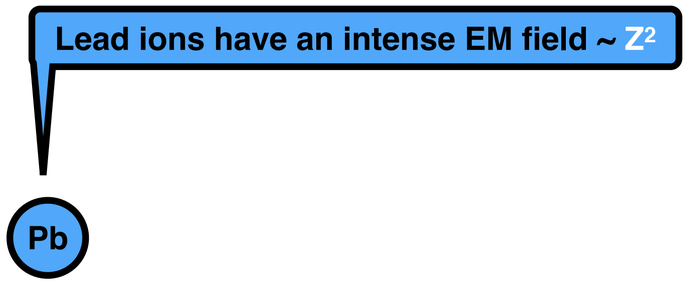
Photons at the LHC to understand QCD



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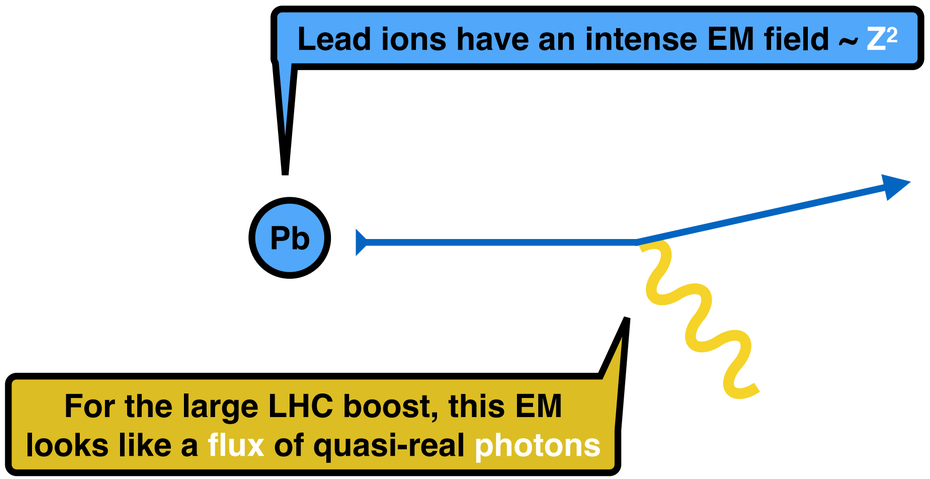

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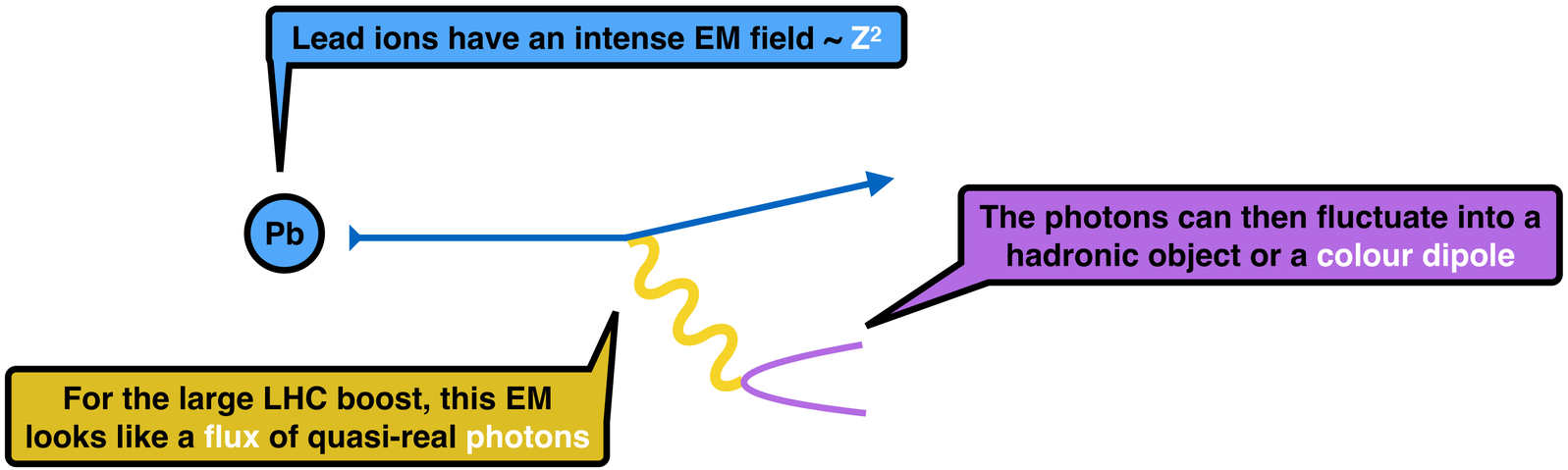

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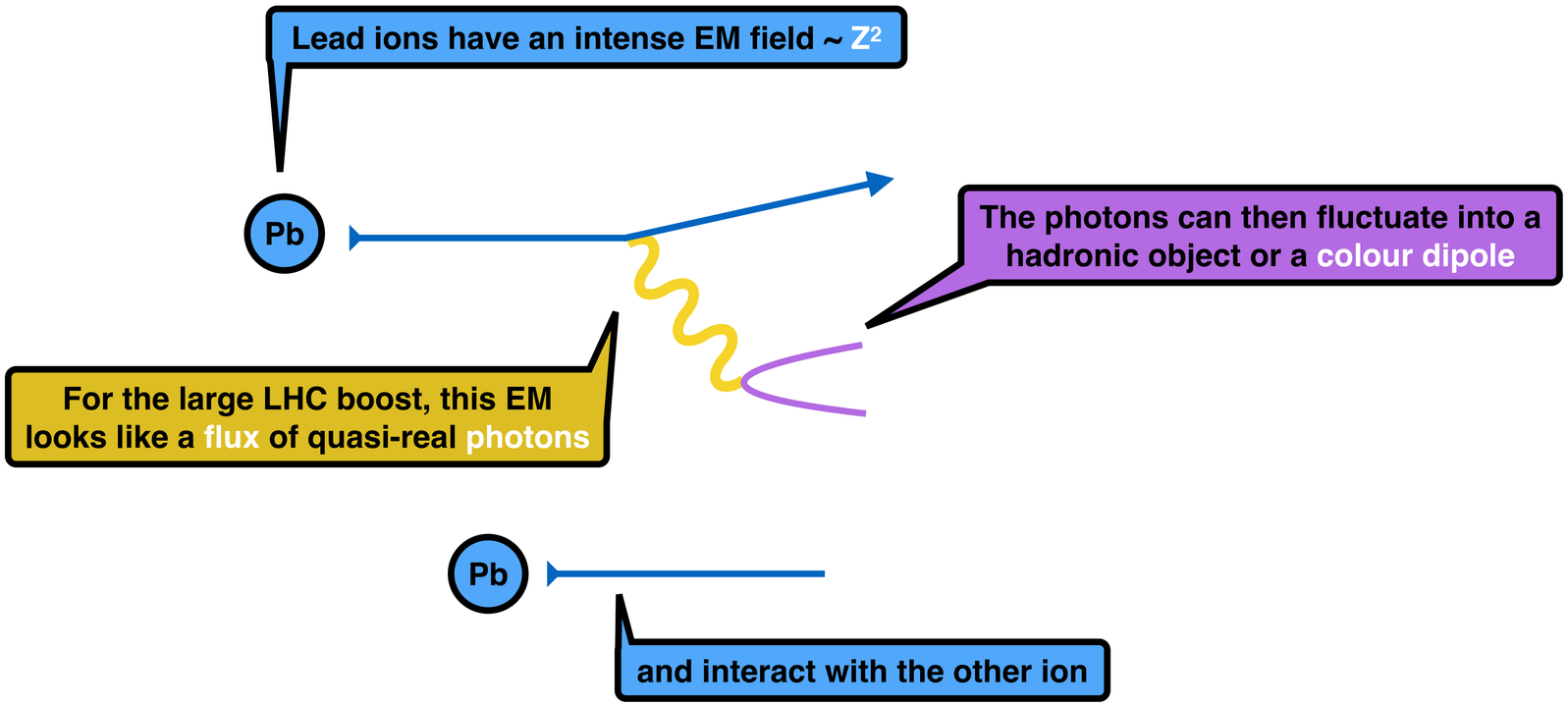

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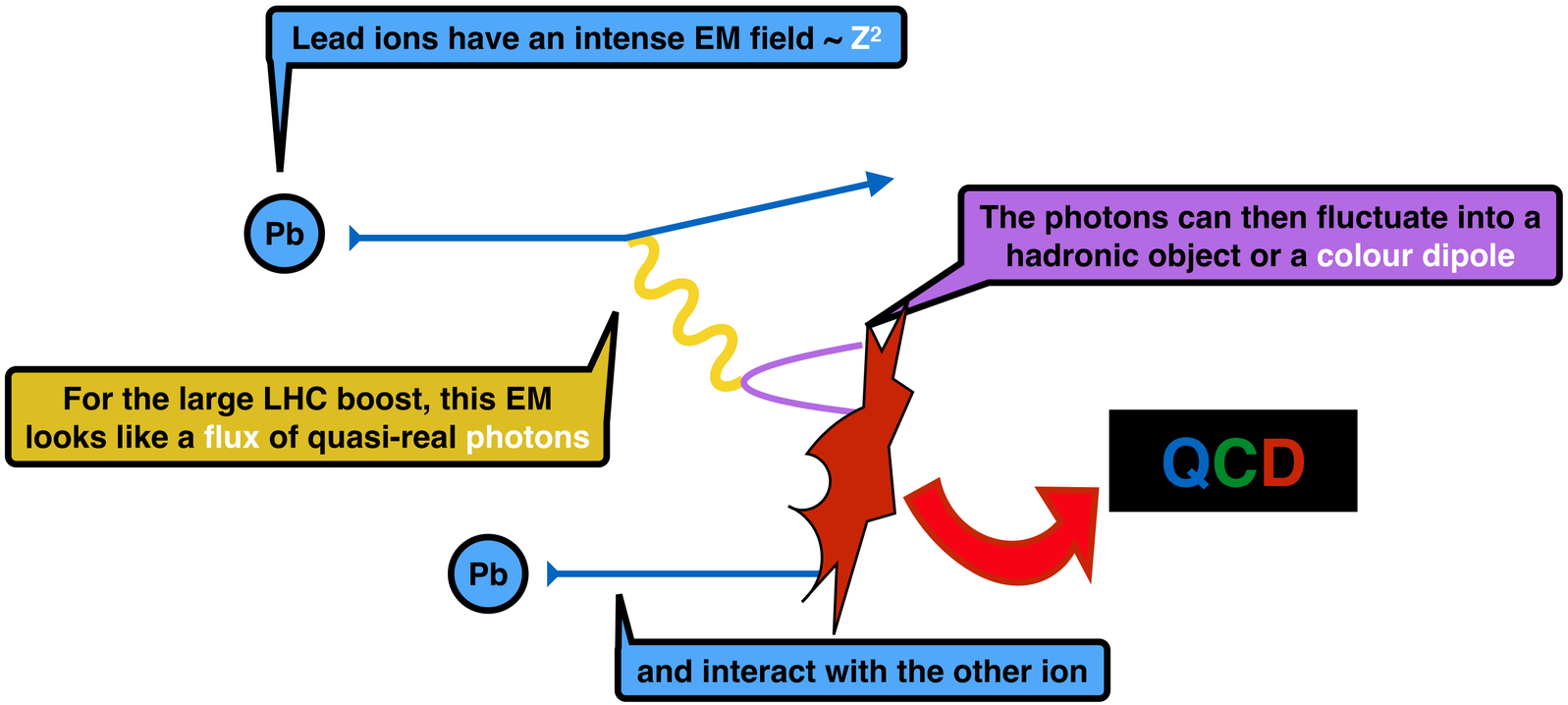

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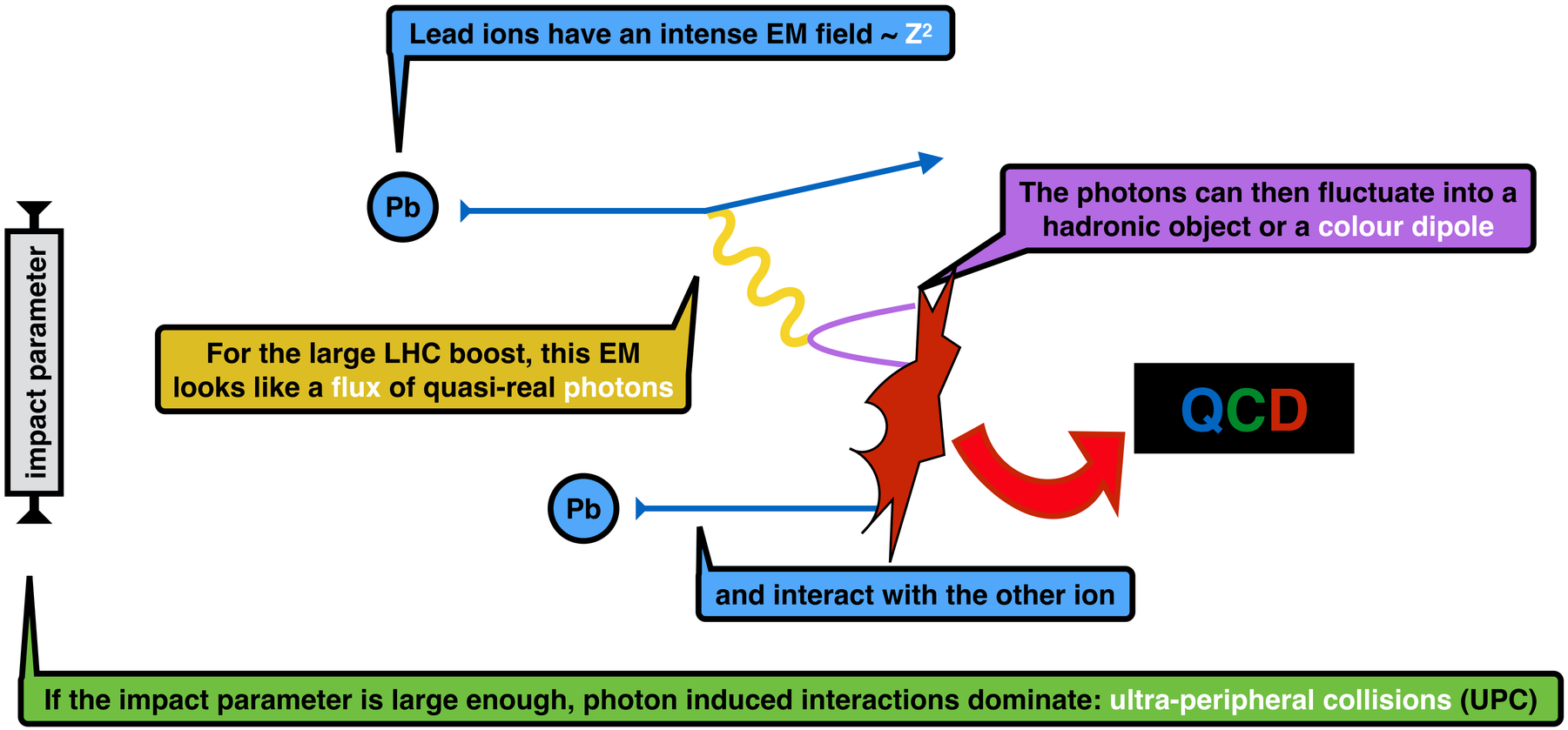

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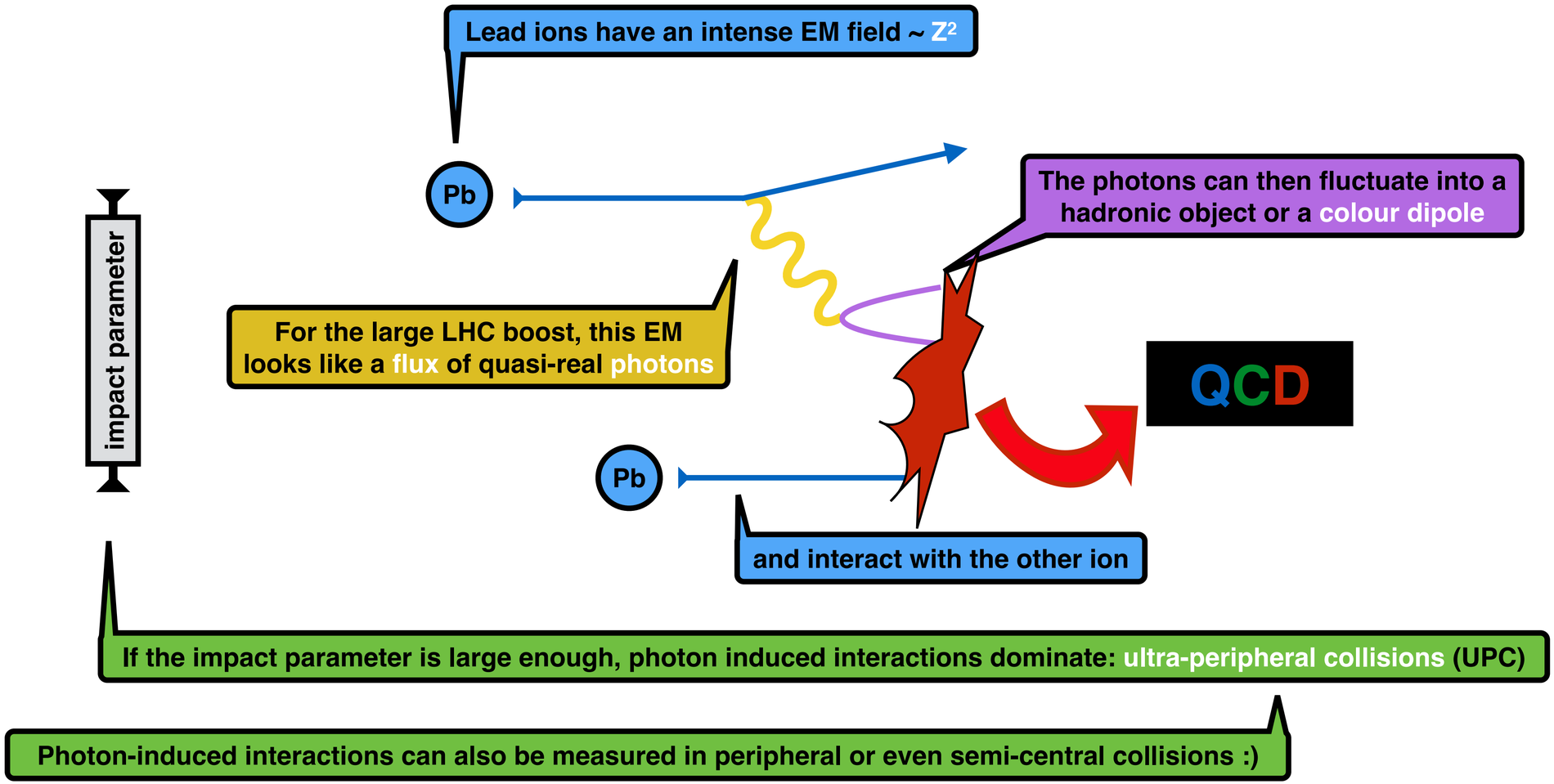
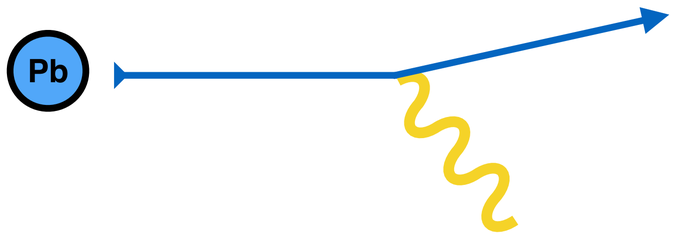


... specially in the context of electromagnetic dissociation (EMD) ...

How well do we understand the photon flux?



Photon flux of a point charge

Form factor

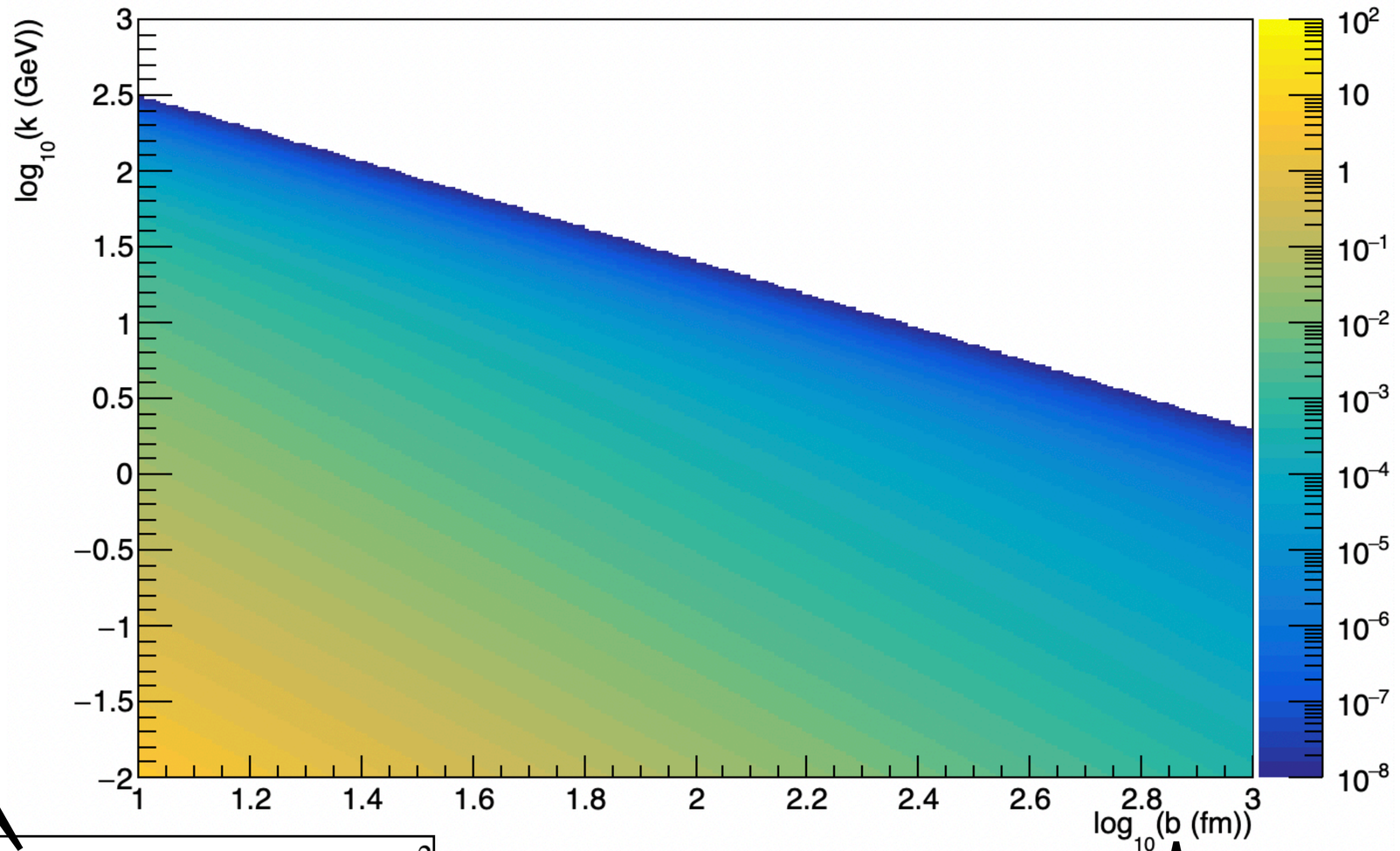
Electric charge

$$n(k,\vec{b}) = \frac{Z^2\alpha}{\pi^2 k}\left|\int_0^\infty dk_\perp k_\perp^2 \frac{F(k_\perp^2+(k/\gamma)^2}{k_\perp^2+(k/\gamma)^2} J_1(bk_\perp)\right|^2$$

Photon flux of a point charge

Using LHC boost and relevant LHC ranges for k and b

N(k,b)



Photon energy

Impact parameter

Form factor

Electric charge

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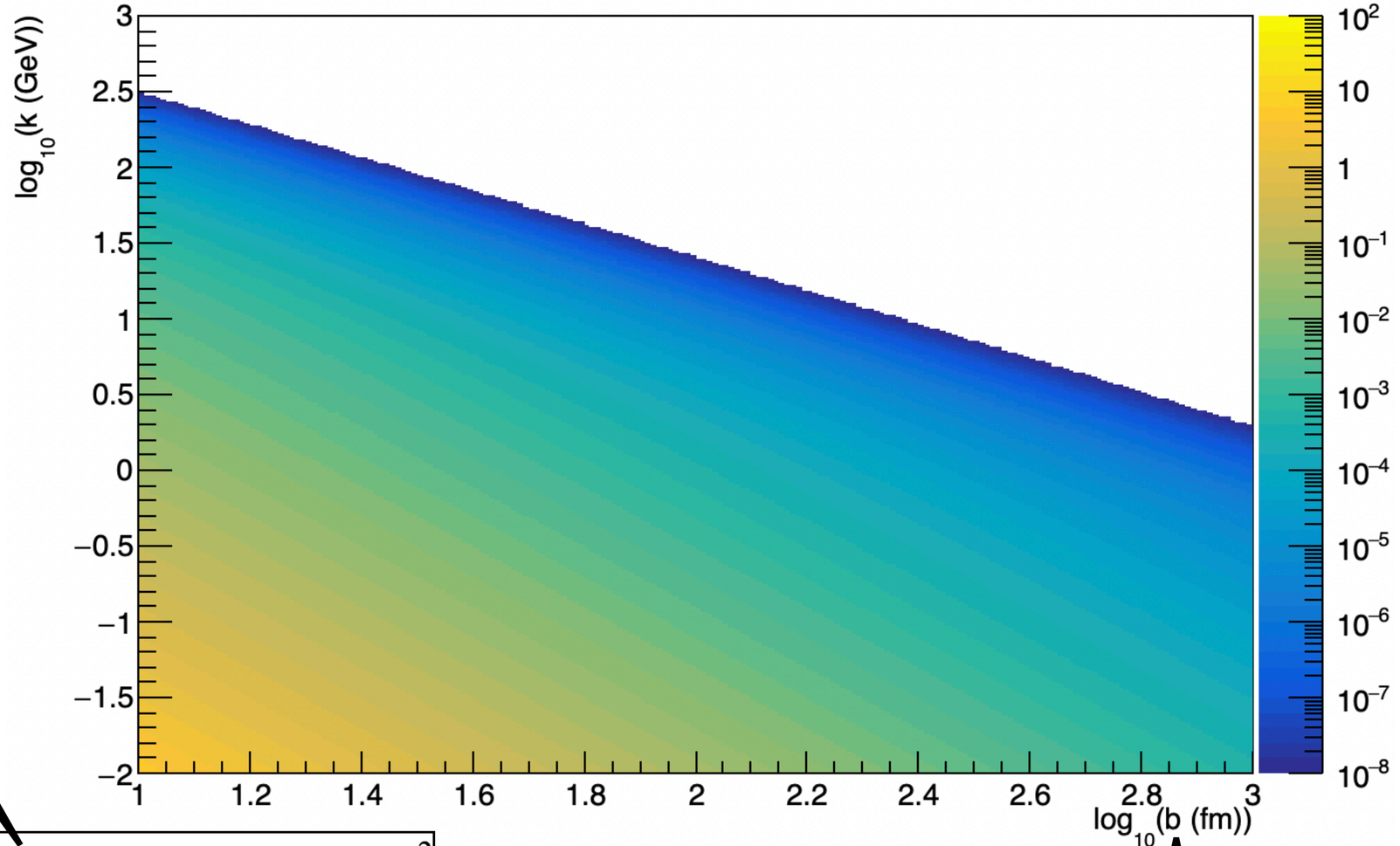

Photon energy

10 orders of magnitude

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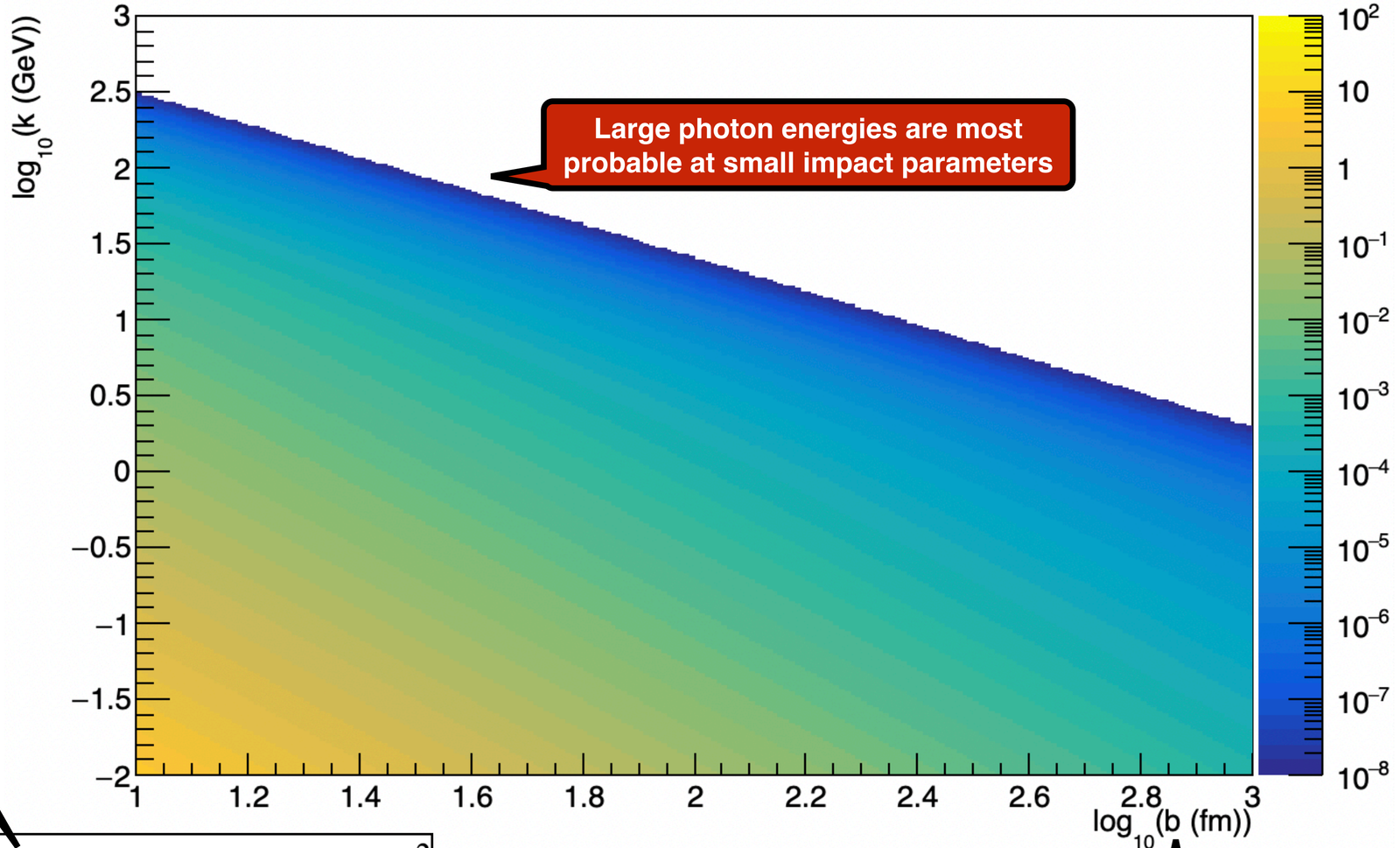

Photon energy

Large photon energies are most probable at small impact parameters

10 orders of magnitude

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Impact parameter

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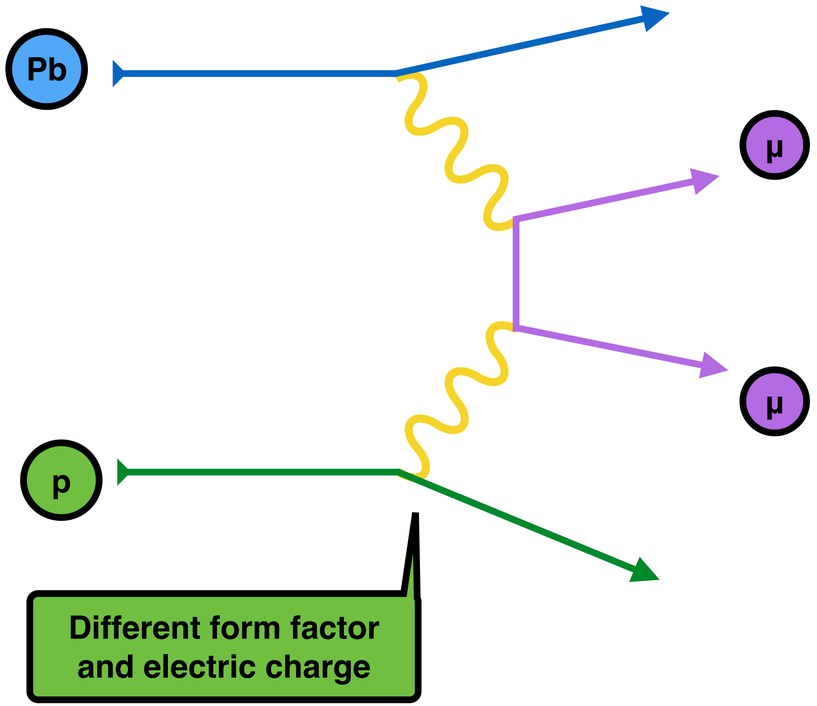
Muon pair production in p-Pb UPC



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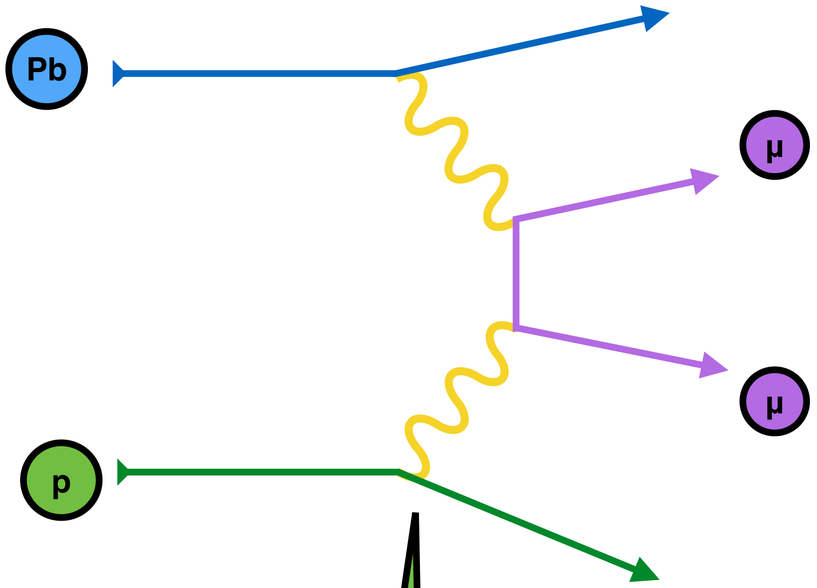
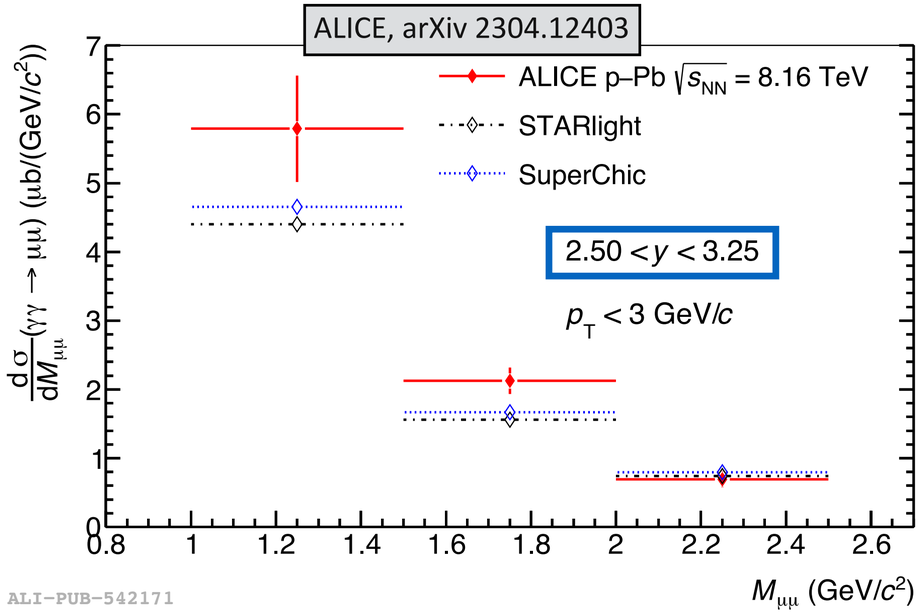
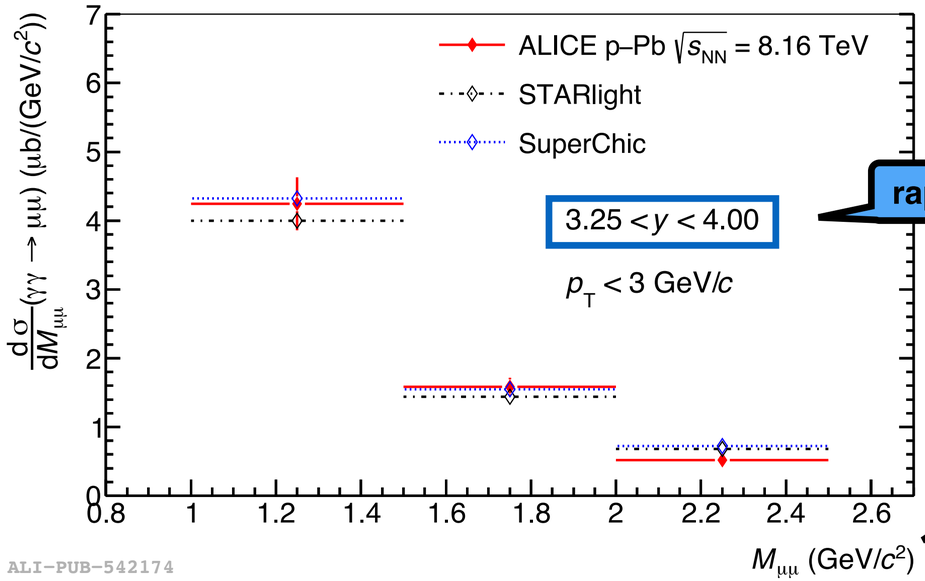


Different form factor and electric charge





Cross section

rapidity range

μμ mass

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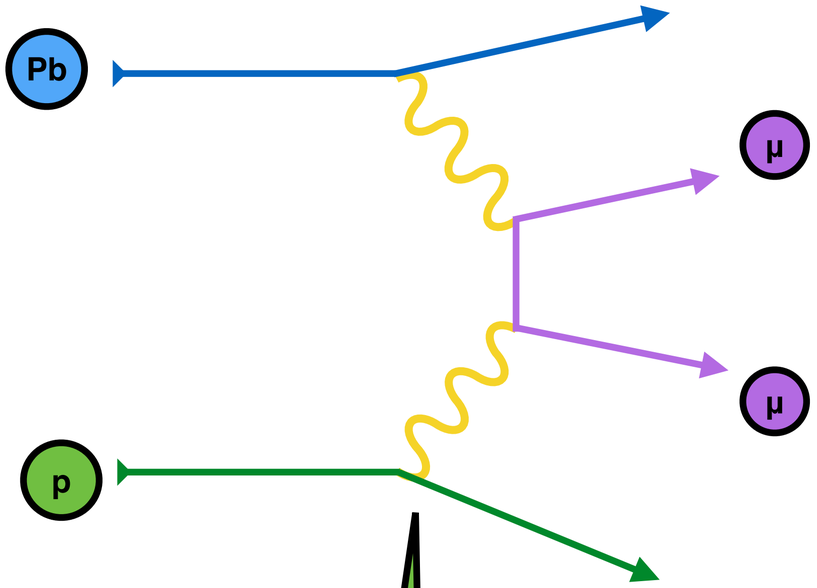
Muon pair production in p-Pb UPC



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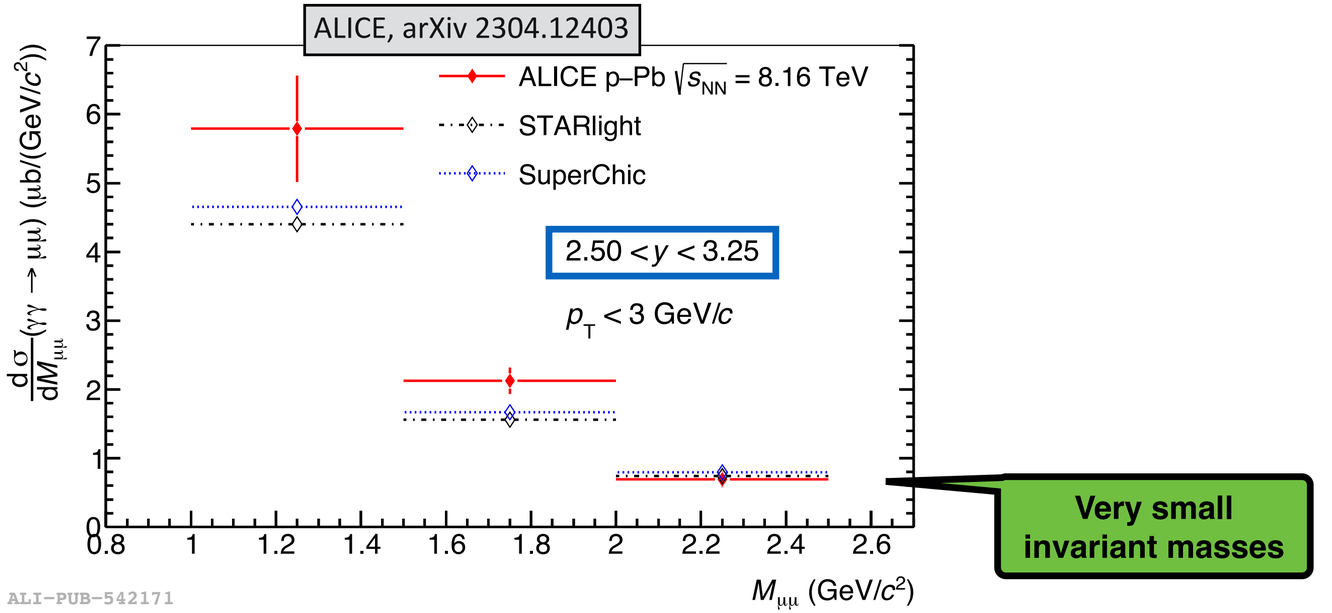
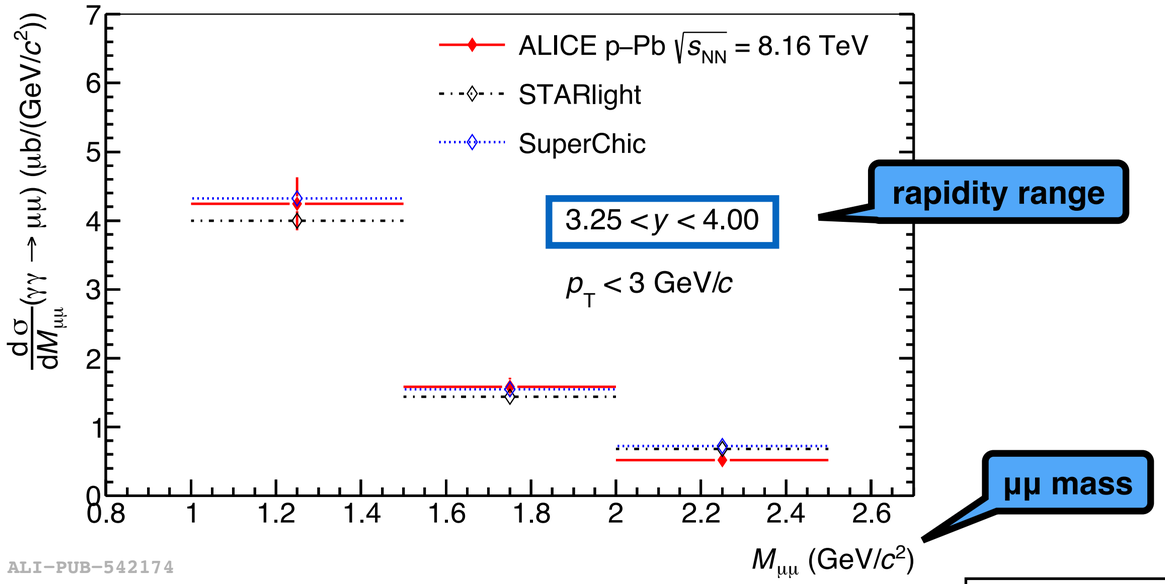


Very small invariant masses

Cross section



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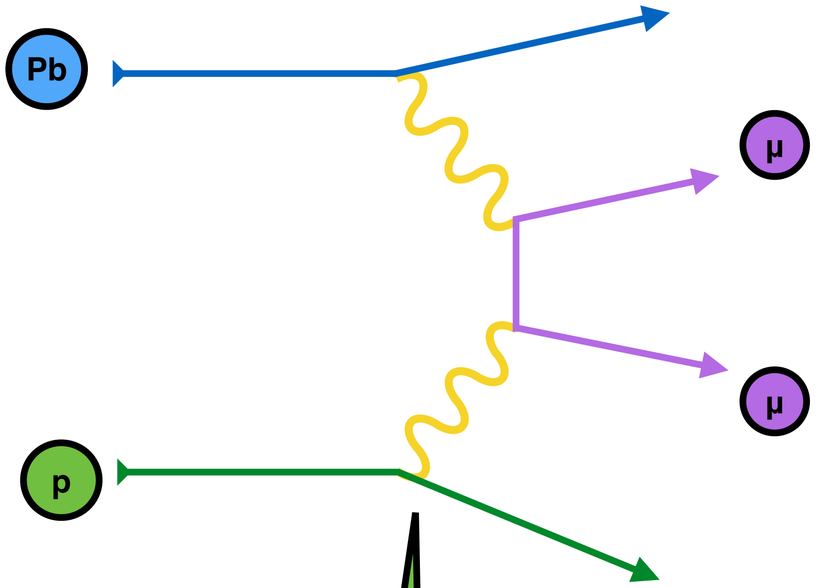

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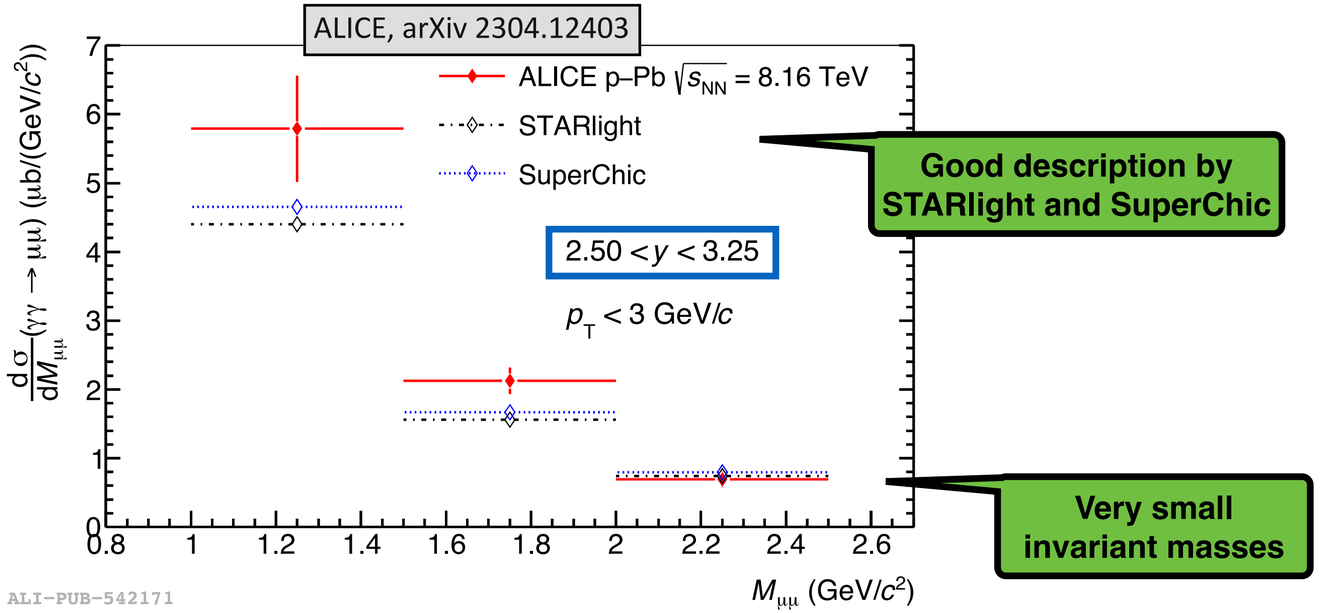
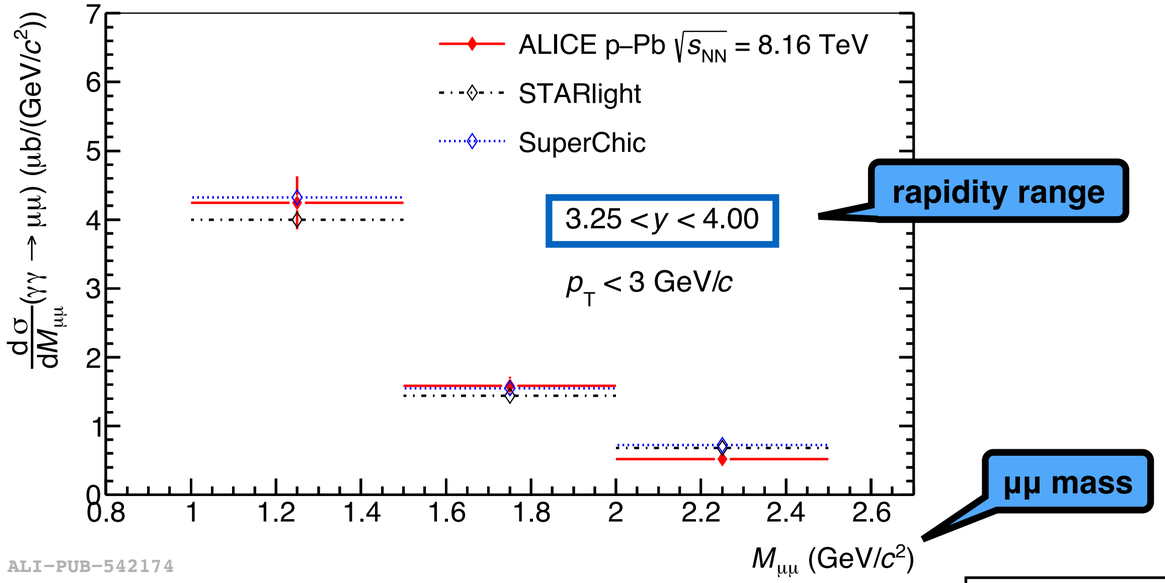


Good description by STARlight and SuperChic

Very small invariant masses

Cross section



rapidity range

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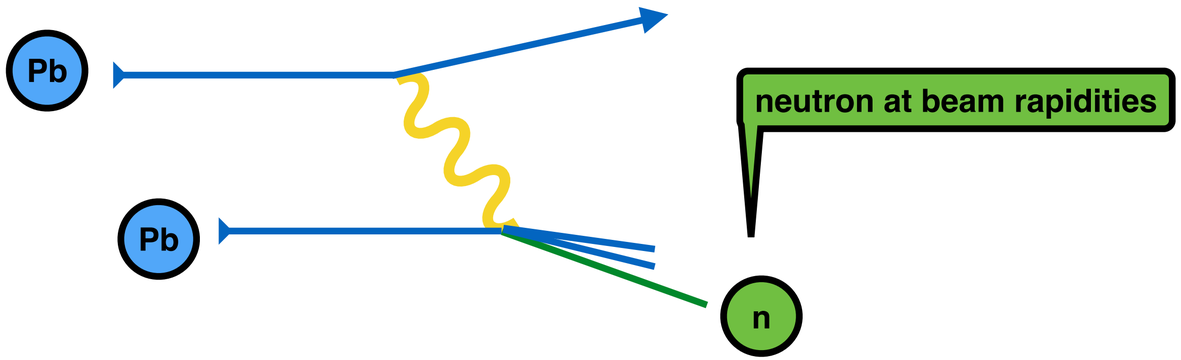
Electromagnetic dissociation (EMD)



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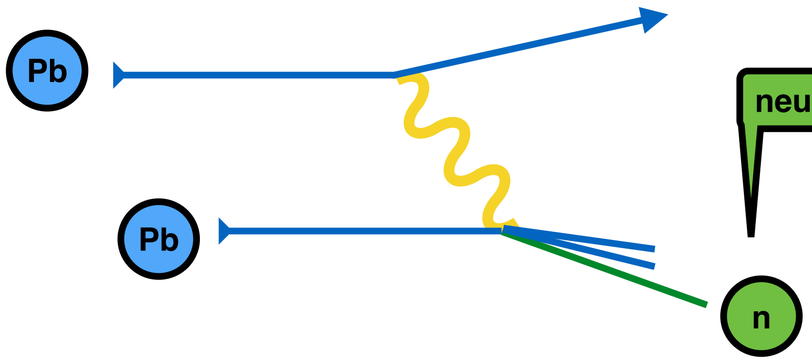
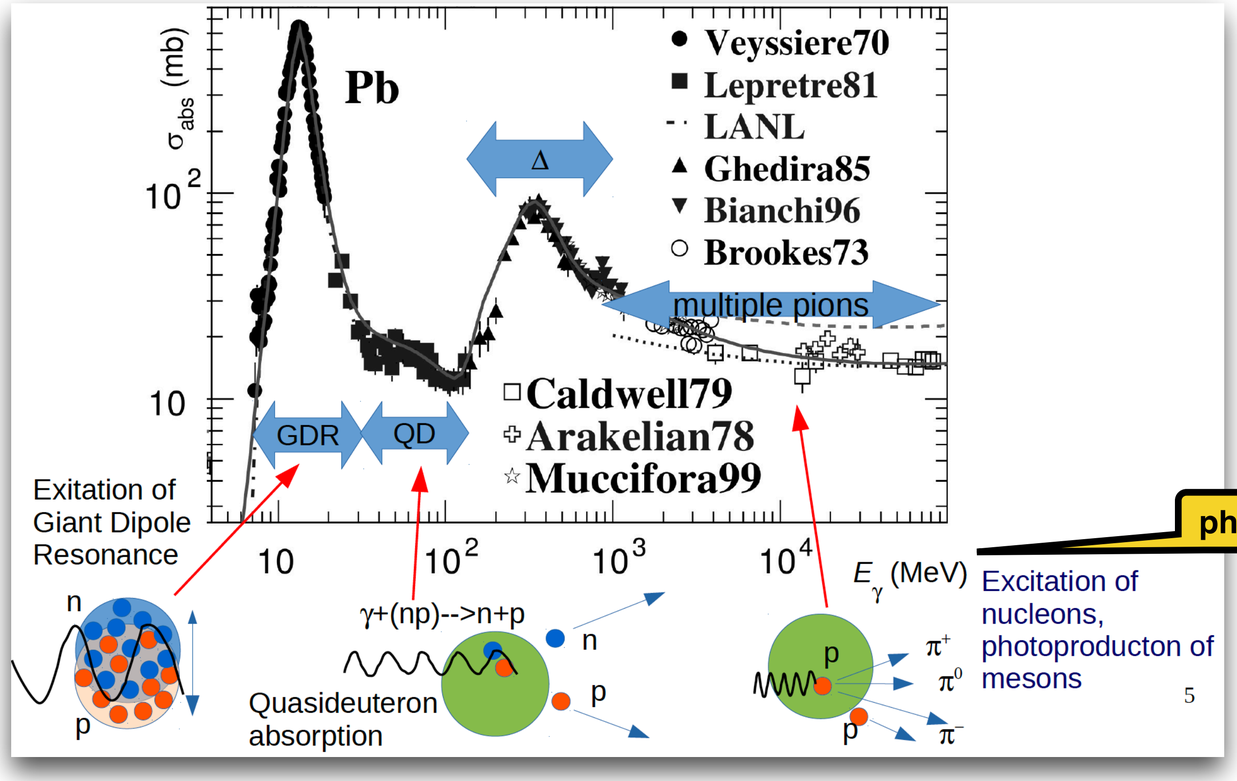


neutron at beam rapidities

Slide from Igor Pshenichnov



photon energy

5

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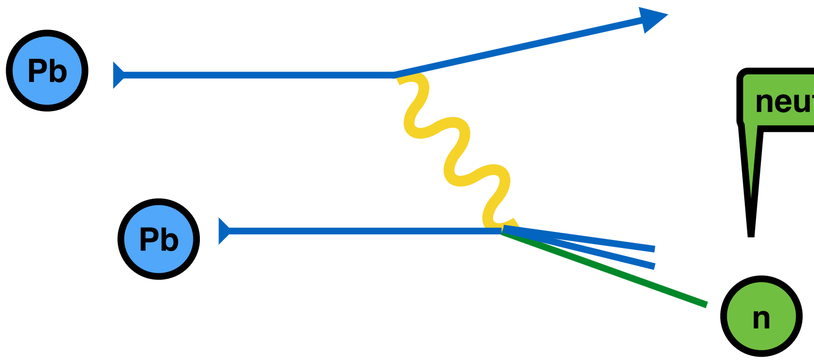

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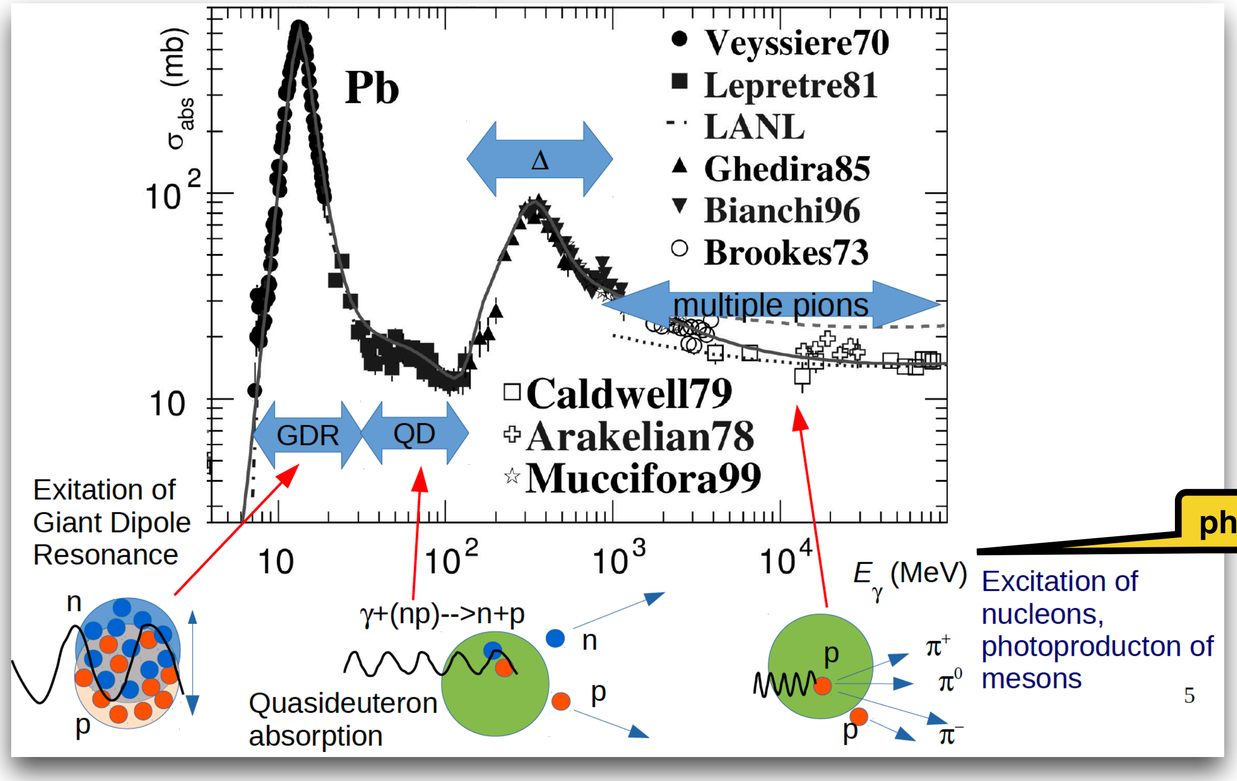

10+ MeVs needed to excite the GDP

photon energy

5

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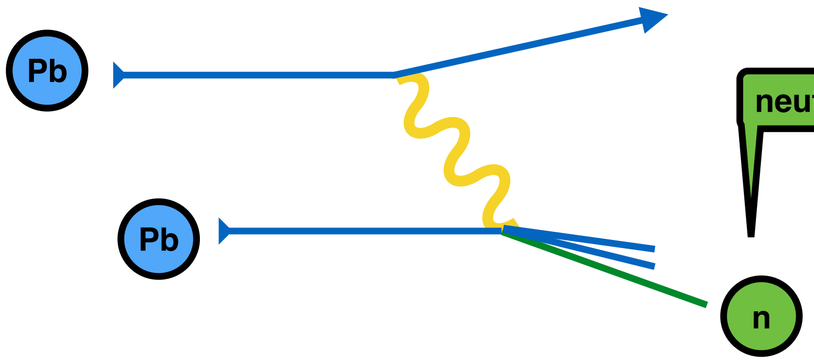

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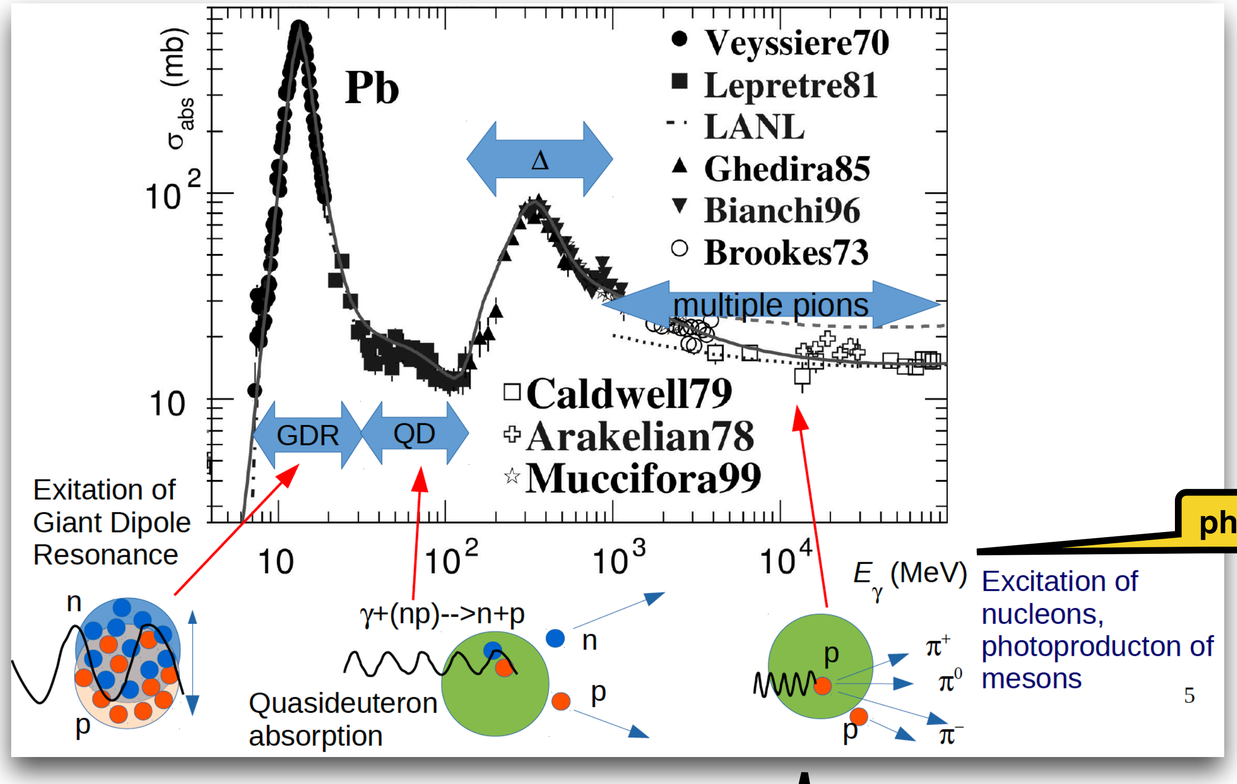


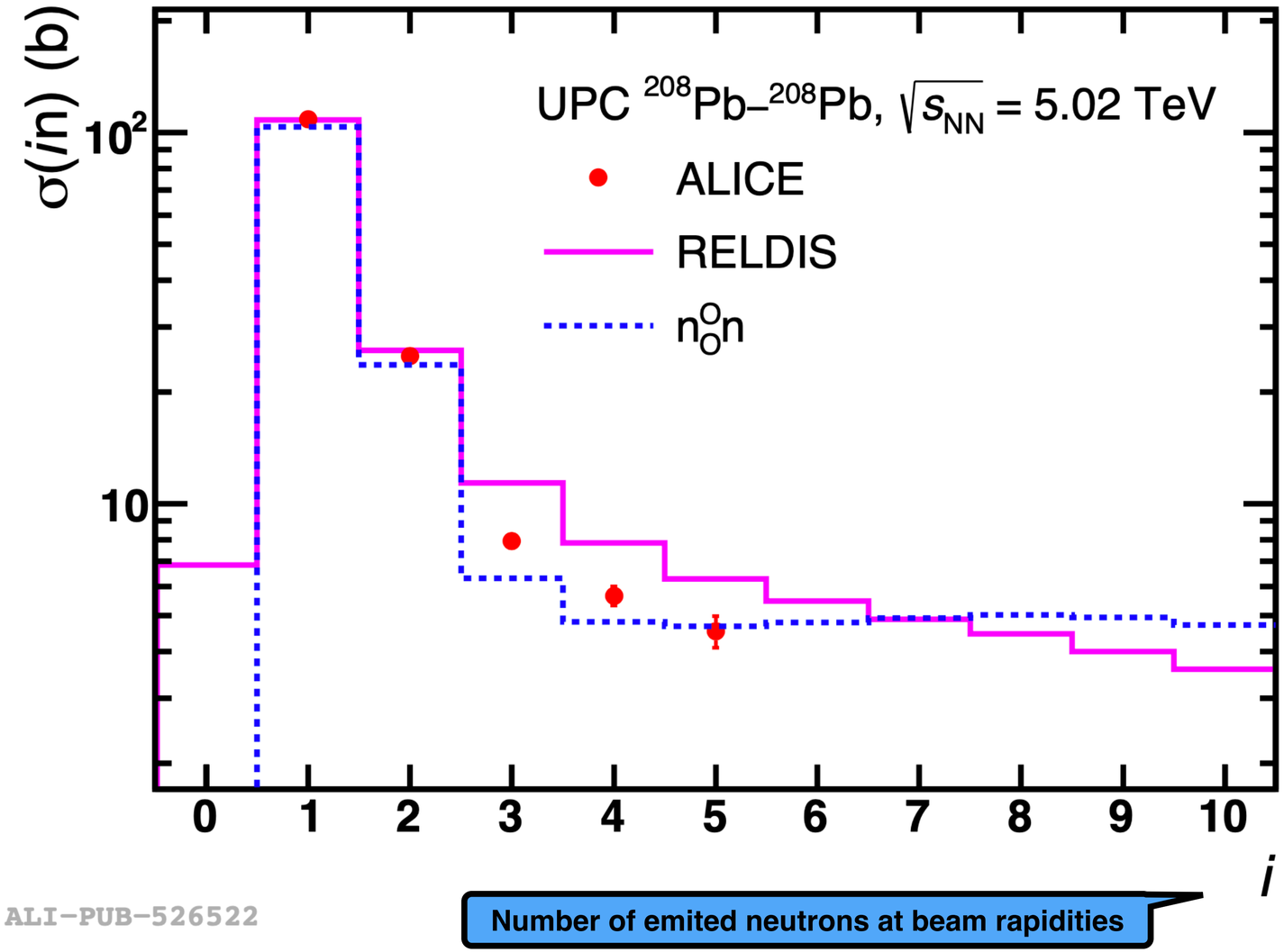
10+ MeVs needed to excite the GDP

photon energy

At larger photon energies, charged particles are produced

Measurement of EMD as a function of the number of neutrons

ALICE, 2304.12403



Cross section

Number of emited neutrons at beam rapidities

Measurement of EMD as a function of the number of neutrons

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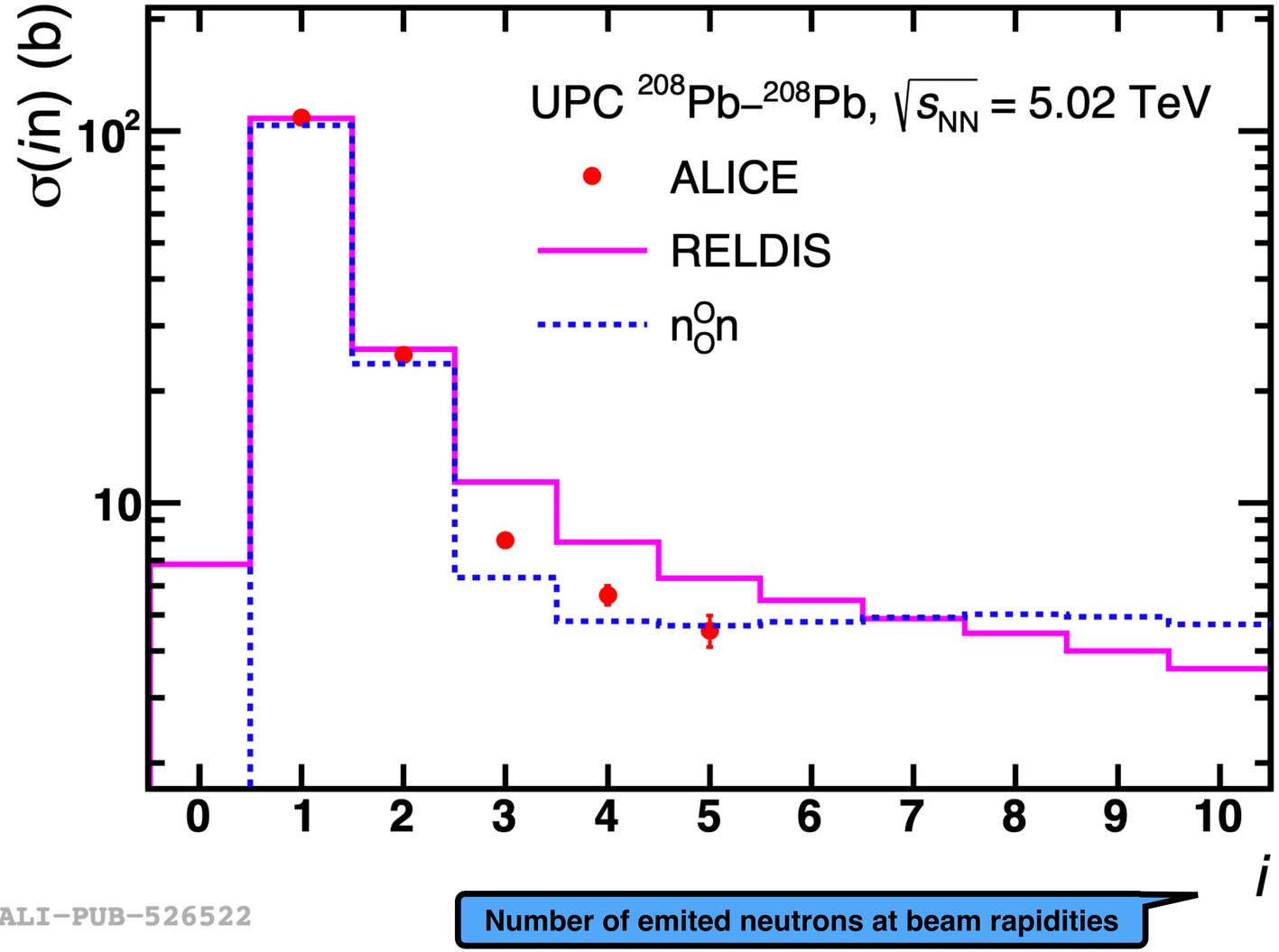

Huge cross section

Cross section

Number of emited neutrons at beam rapidities

ALI-PUB-526522

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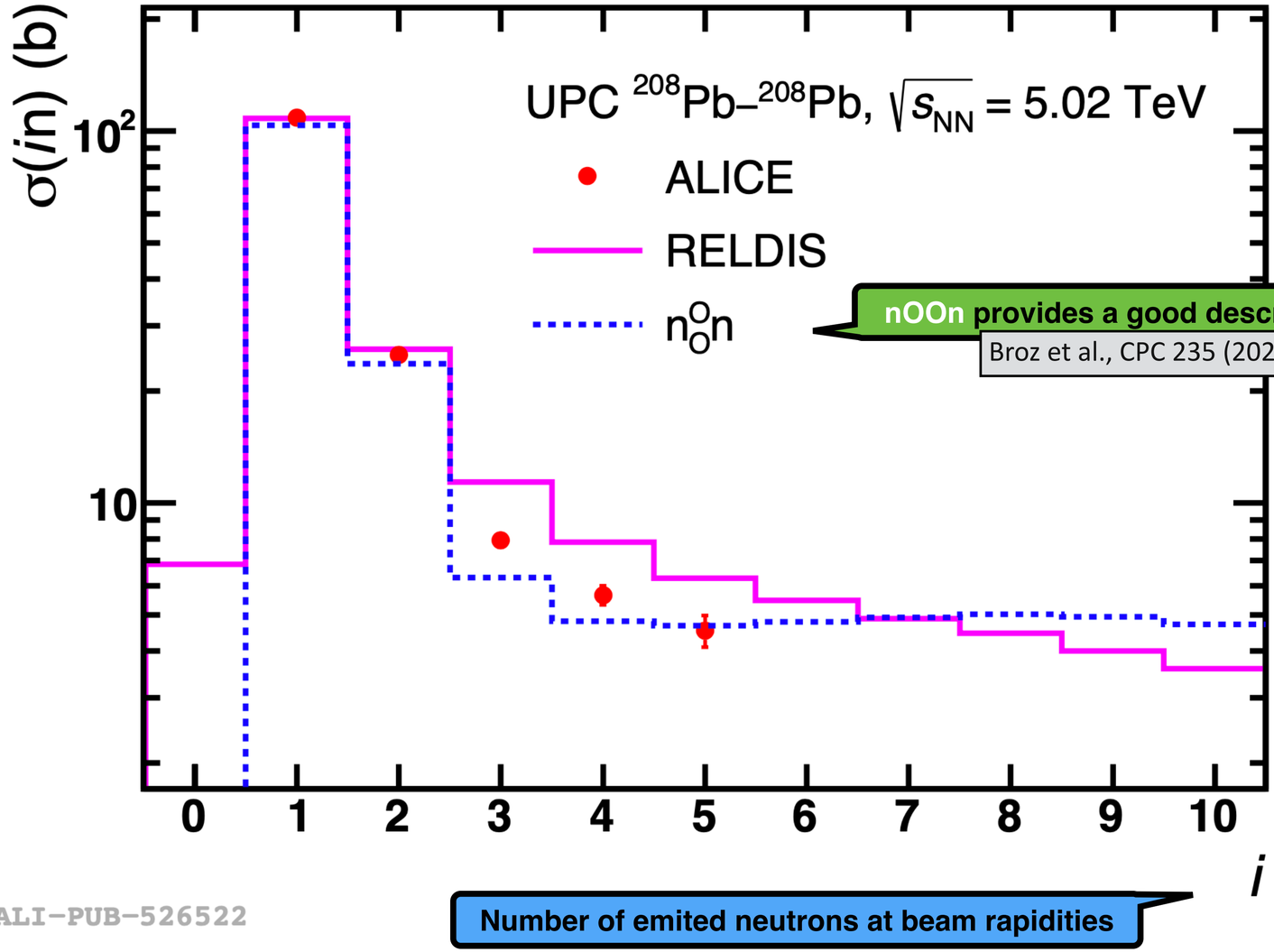
ALICE, 2304.12403



Huge cross section

Cross section

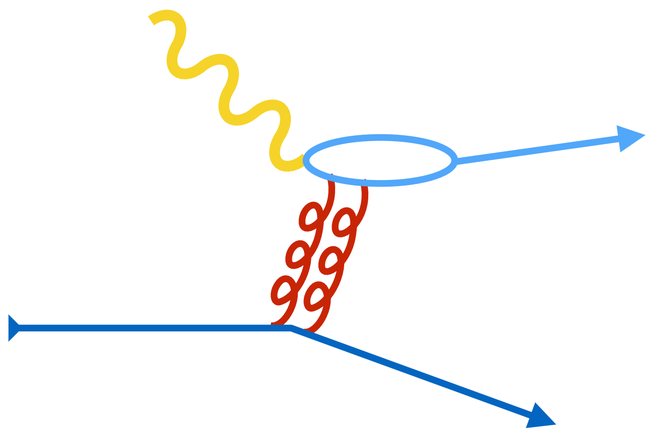
nOOn provides a good description of data

Broz et al., CPC 235 (2020) 107181

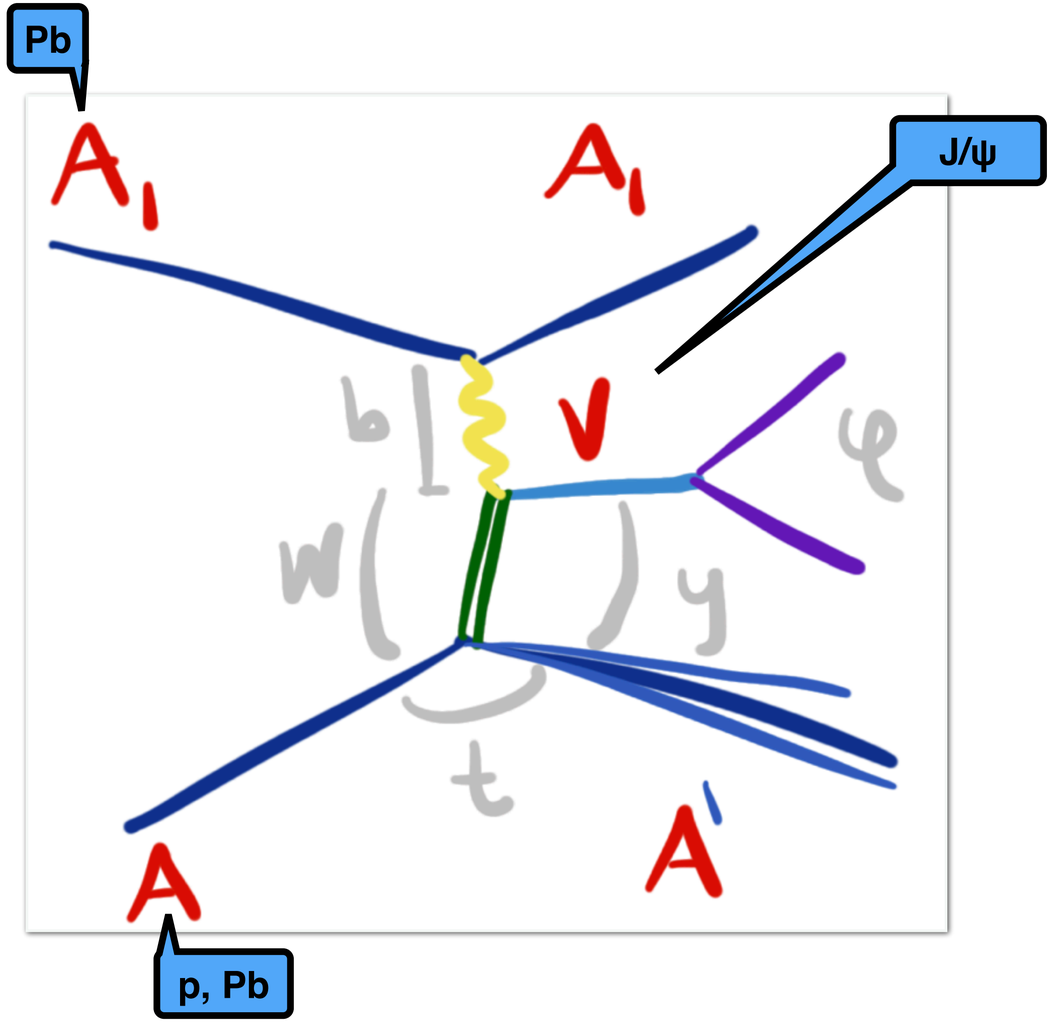
ALI-PUB-526522

Number of emited neutrons at beam rapidities

Diffractive vector meson photoproduction



Diffractive J/ψ photoproduction in UPC



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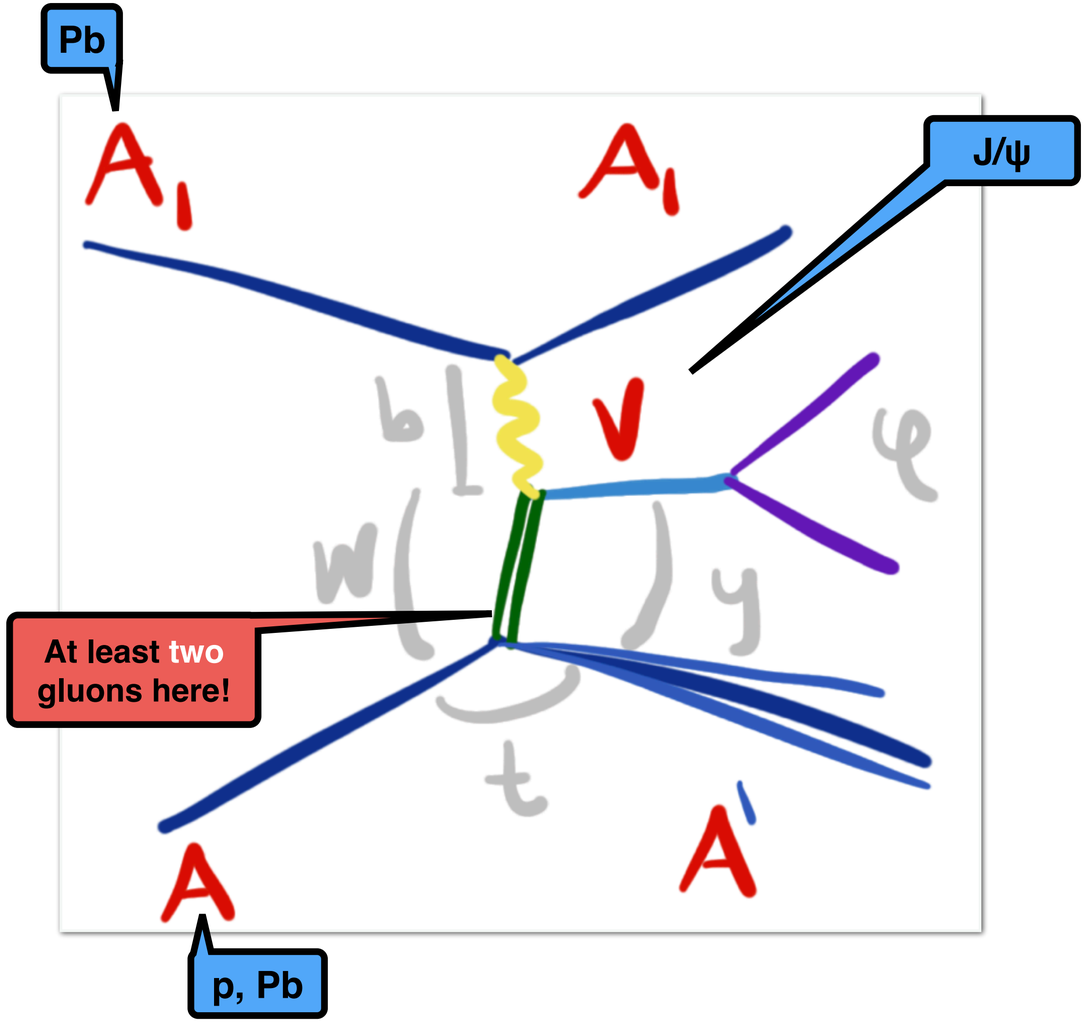

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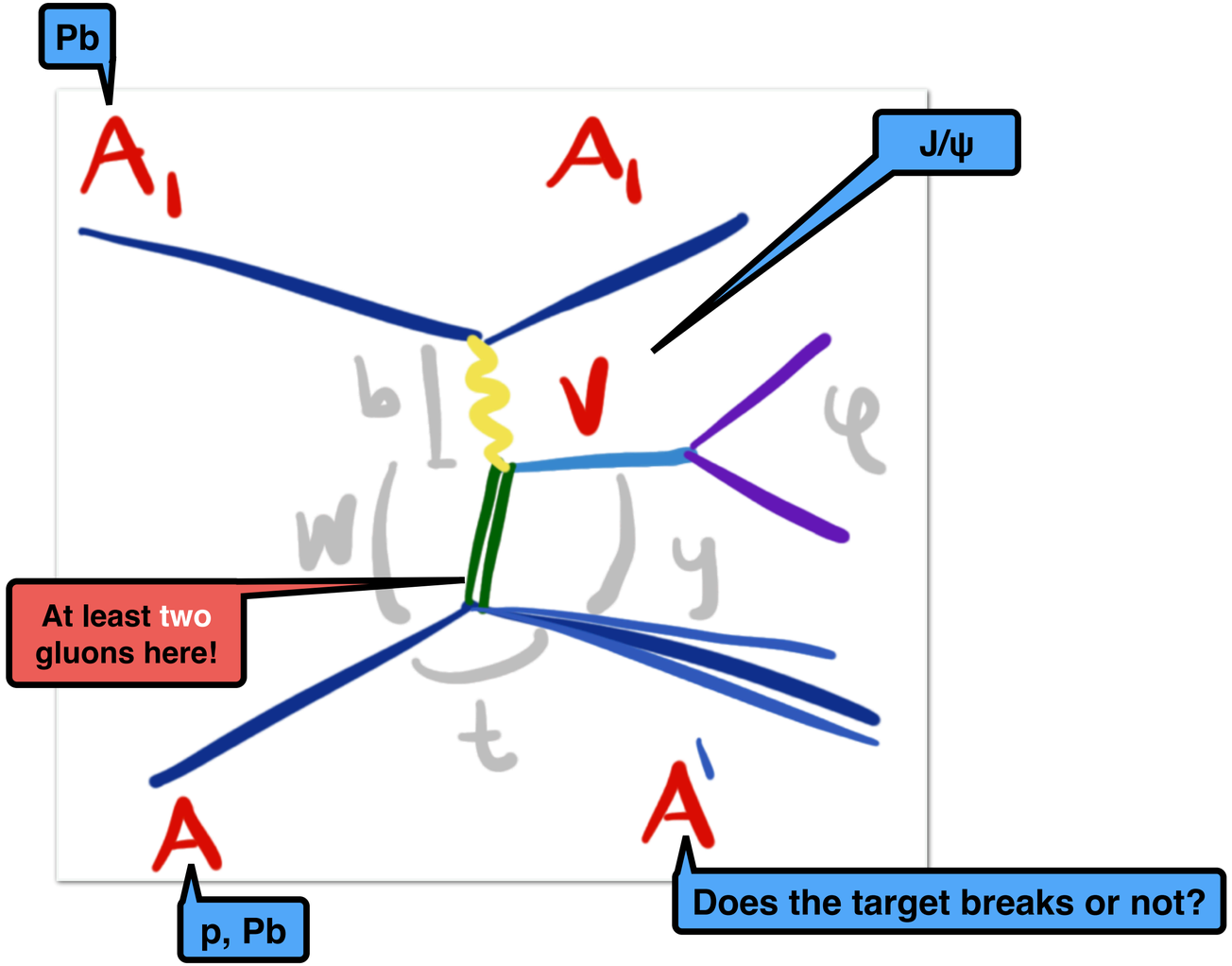

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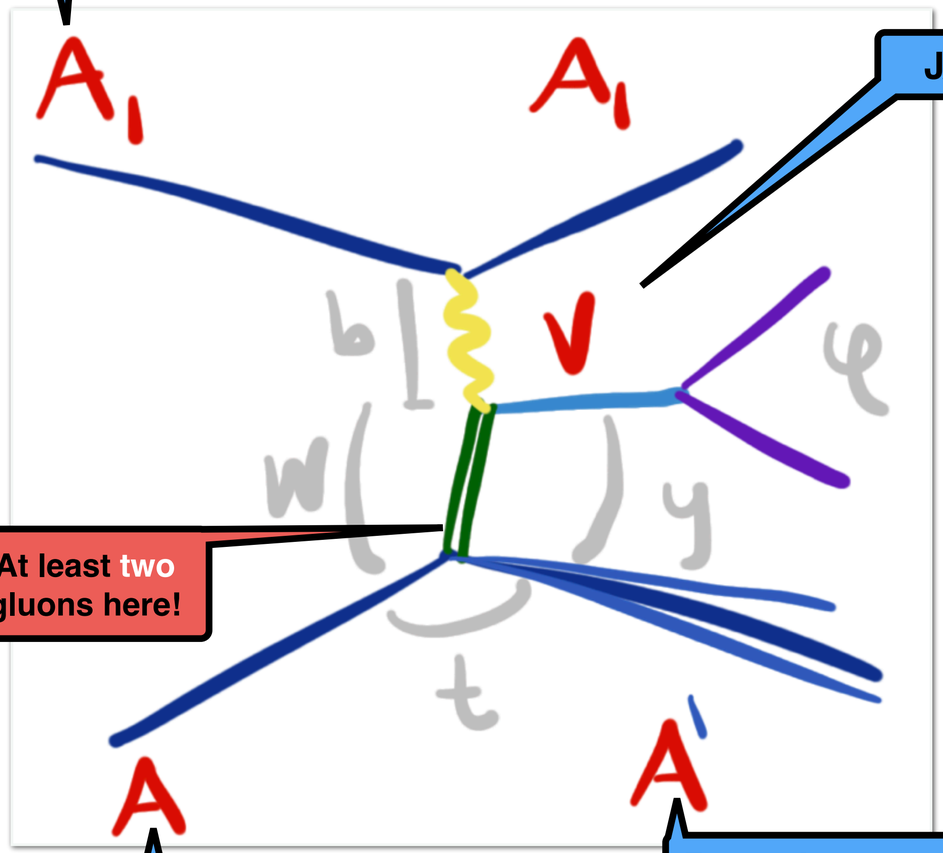

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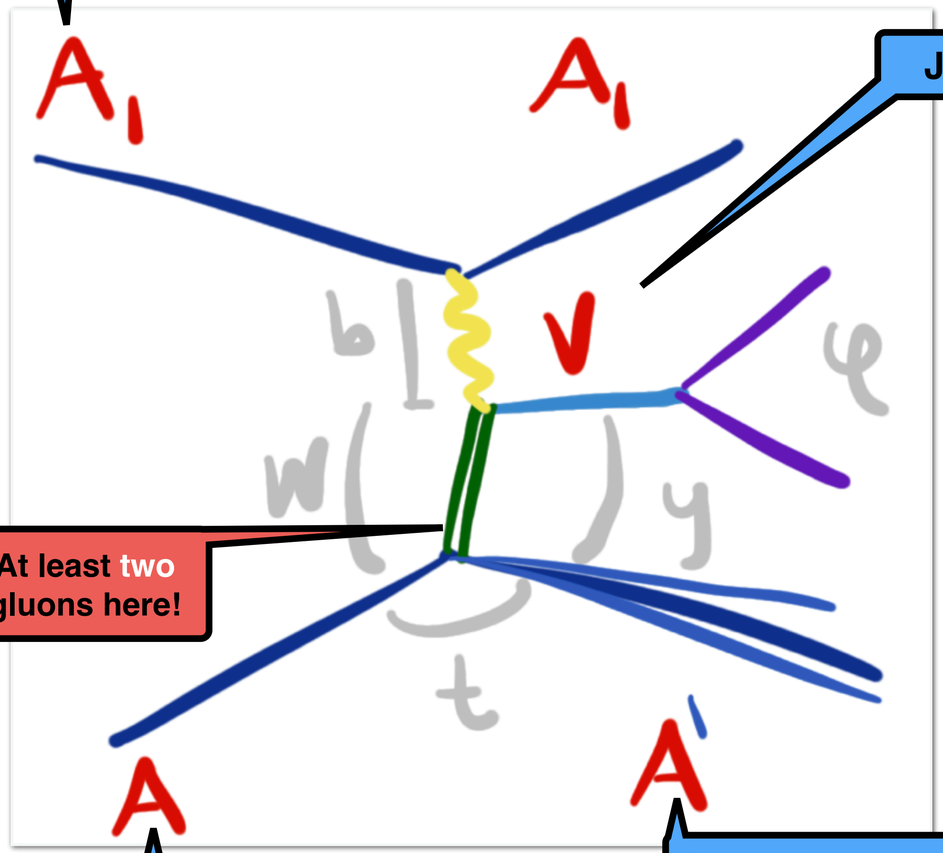

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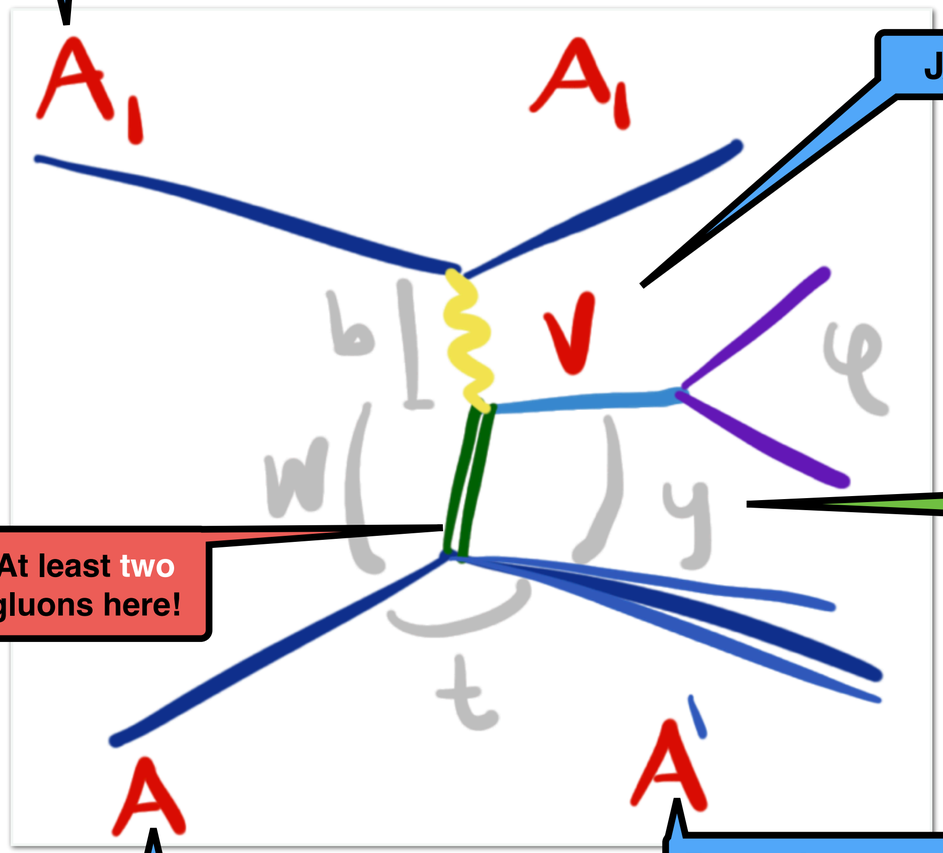


Pb

J/ψ

$$x = \frac{m}{\sqrt{s}} e^{-y} = \frac{m^2}{W^2}$$

Kinematics: vector meson rapidity => energy (Bjorken-x) evolution

At least two gluons here!

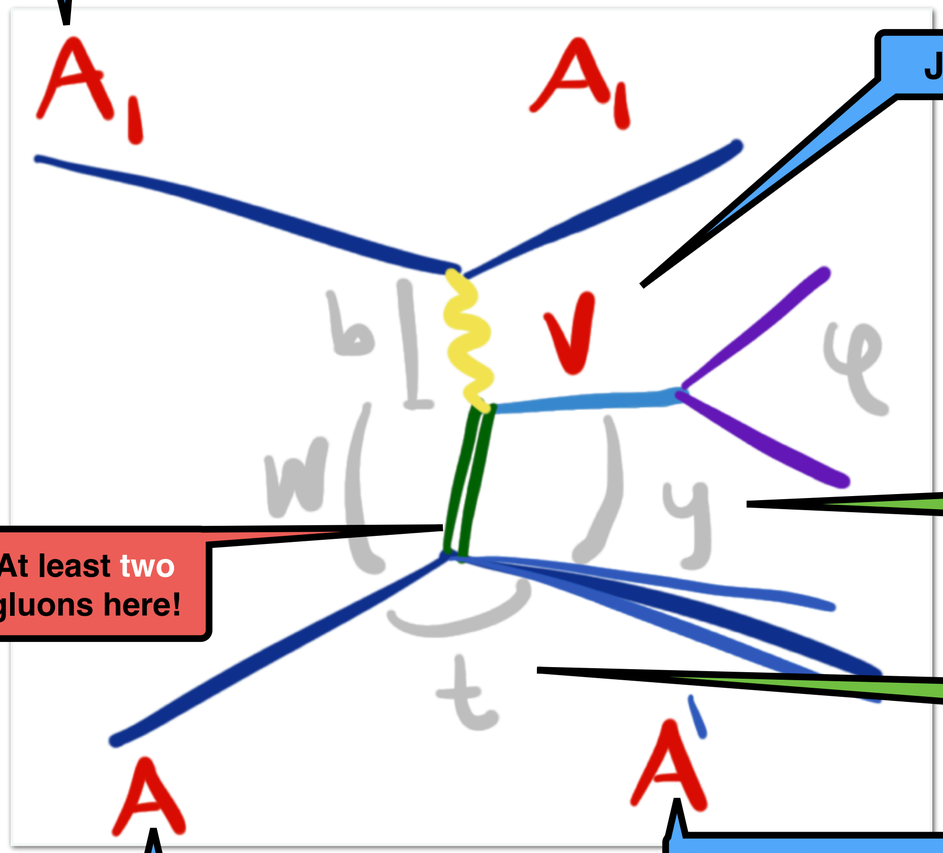
p, Pb

Does the target breaks or not?

proton: dissociative or exclusive production

nucleus: incoherent or coherent production

Diffractive J/ψ photoproduction in UPC



Pb

J/ψ

$$x = \frac{m}{\sqrt{s}} e^{-y} = \frac{m^2}{W^2}$$

Kinematics: vector meson rapidity => energy (Bjorken-x) evolution

At least two gluons here!

Kinematics: Mandelstam t => transverse structure of the target

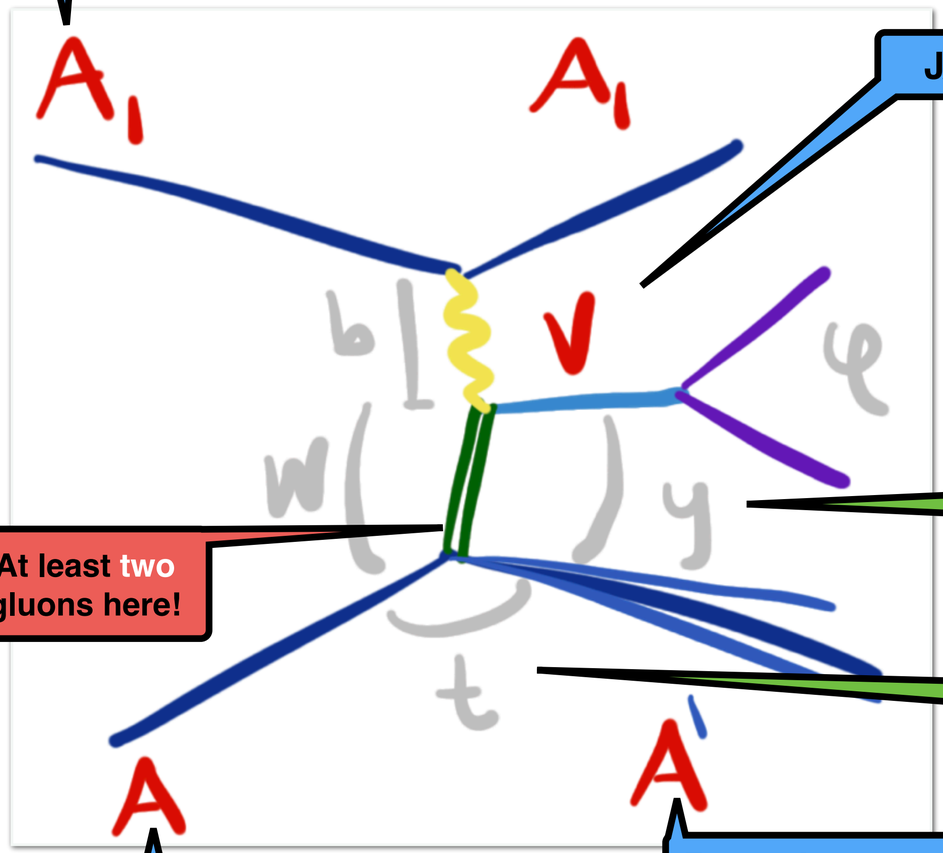
p, Pb

Does the target breaks or not?

proton: dissociative or exclusive production

nucleus: incoherent or coherent production

Diffractive J/ψ photoproduction in UPC



$$x = \frac{m}{\sqrt{s}} e^{-y} = \frac{m^2}{W^2}$$

Kinematics: vector meson rapidity => energy (Bjorken-x) evolution

At least two gluons here!

Kinematics: Mandelstam t => transverse structure of the target

$$|t| \approx p_{\perp}^2$$

Transverse momentum of the vector meson

Does the target breaks or not?

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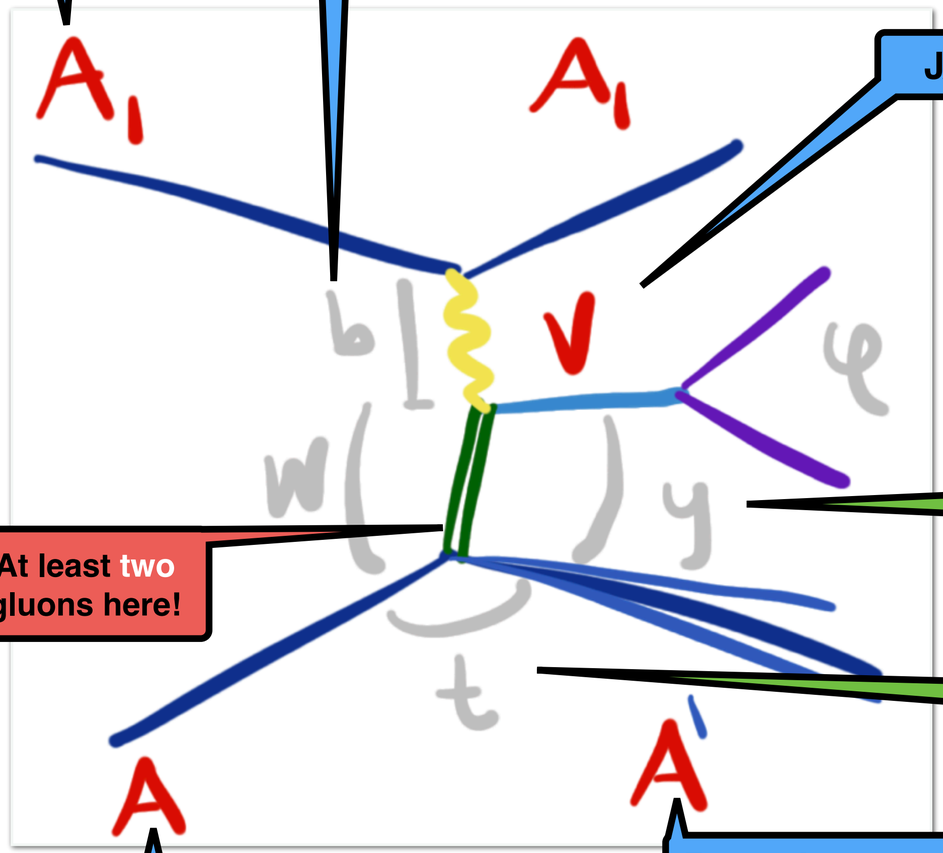

Pb

For coherent production, different impact parameters (for the photon emission): peripheral, several ultra-peripheral ranges

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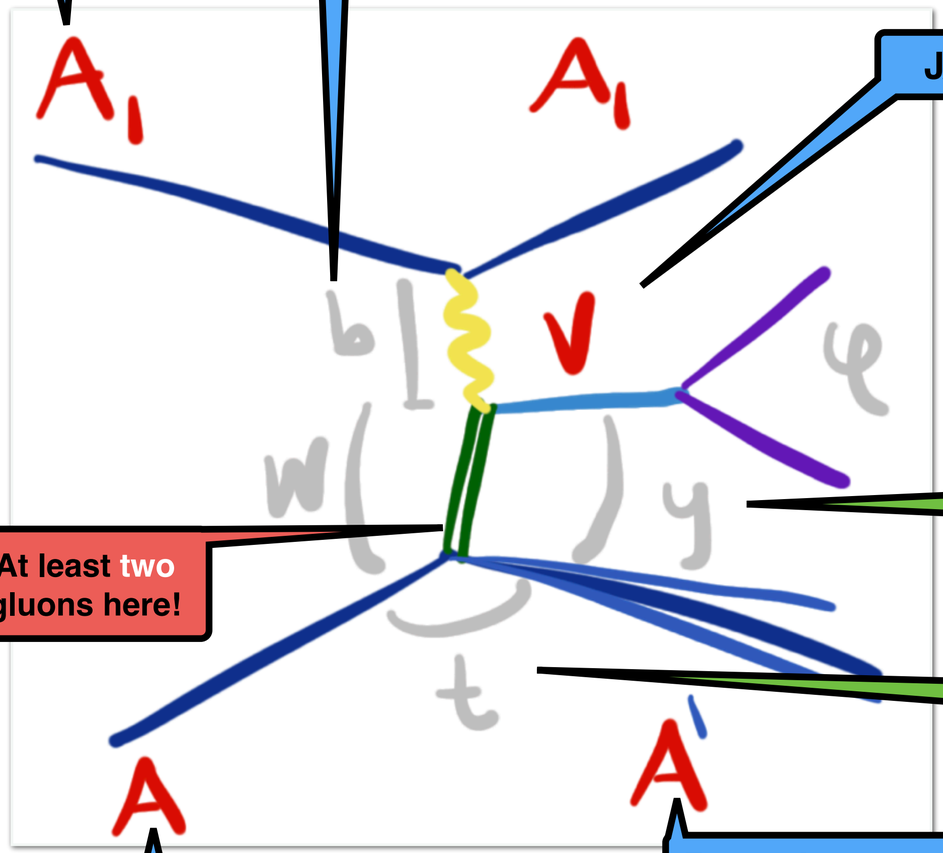

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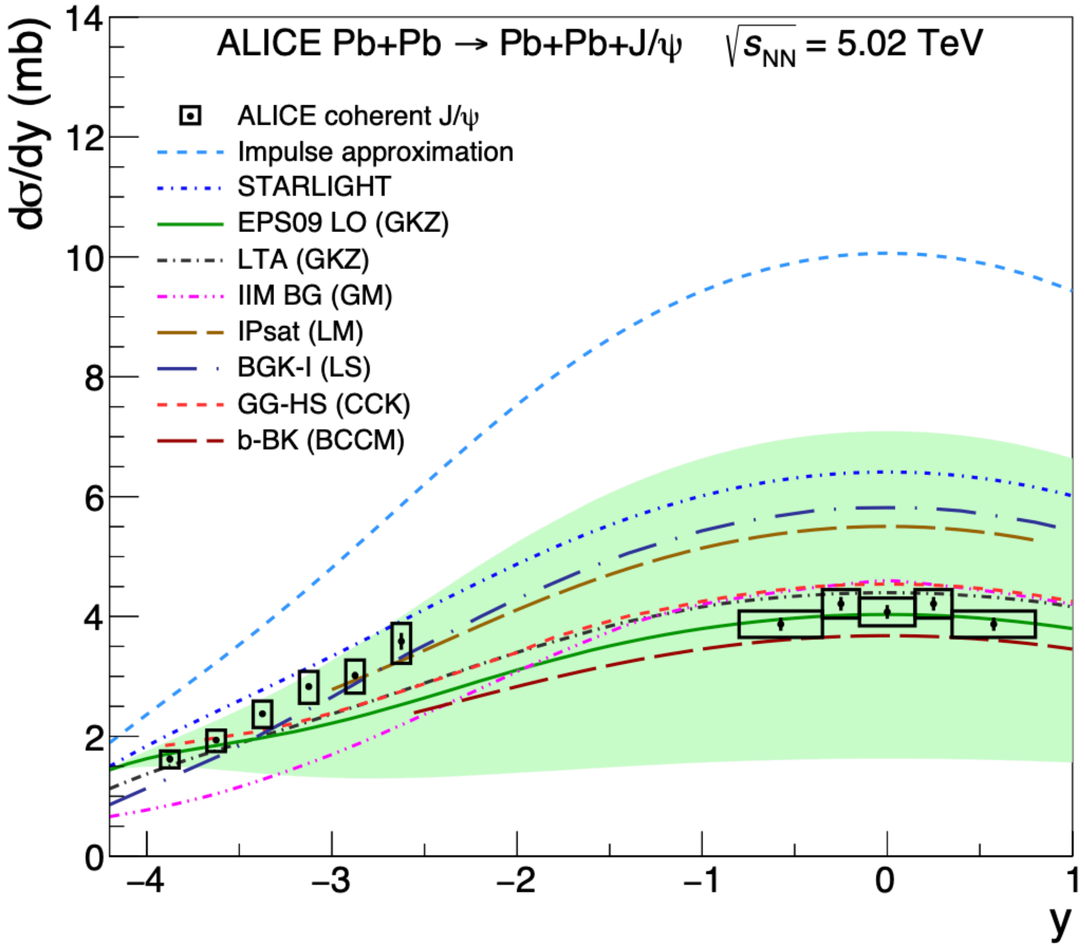
Coherent J/ψ production in Pb-Pb UPC
Bjorken-*x* dependence

Rapidity dependence

ALICE, EPJC (2021) 81, 712



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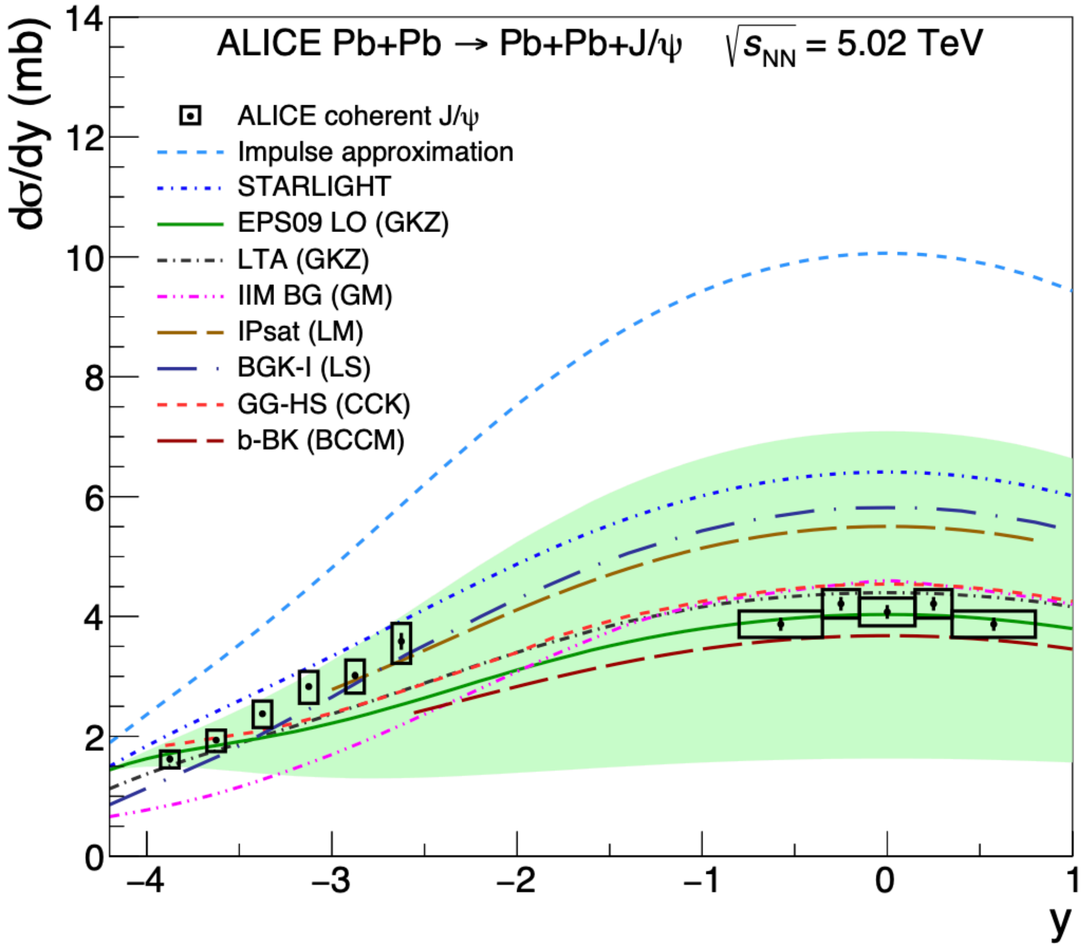

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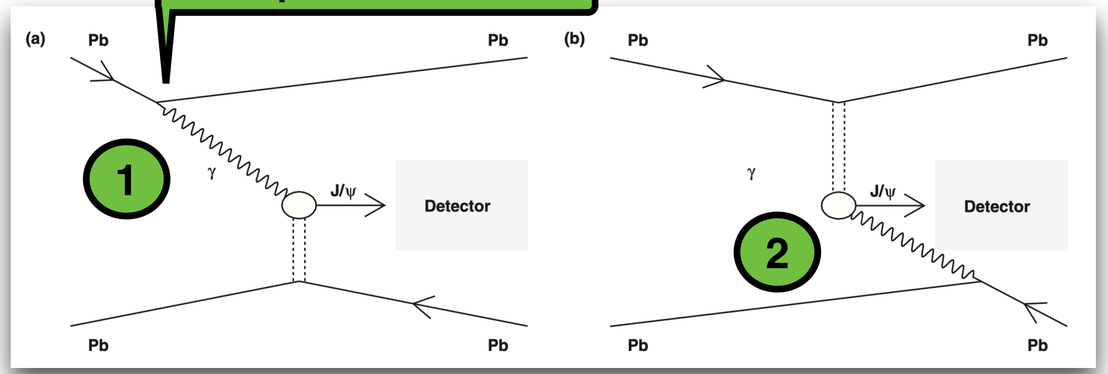
Two photon sources



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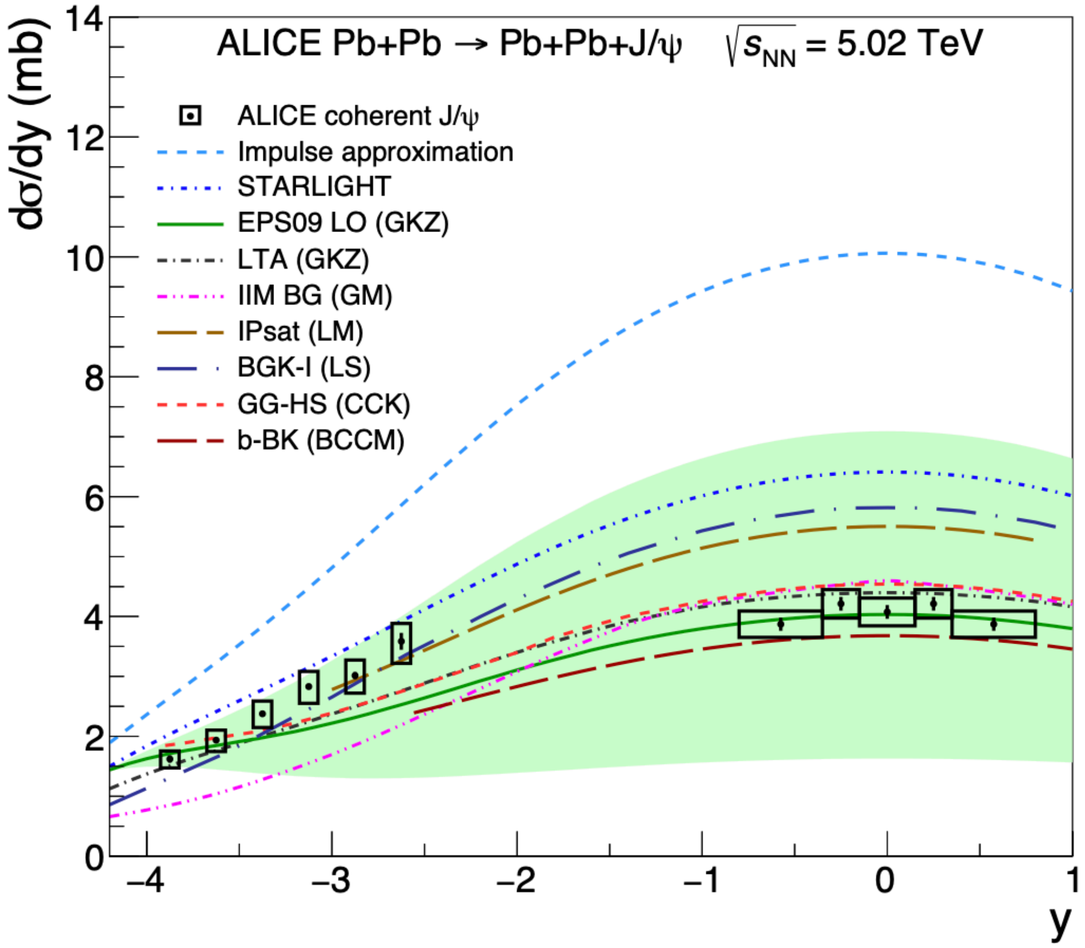

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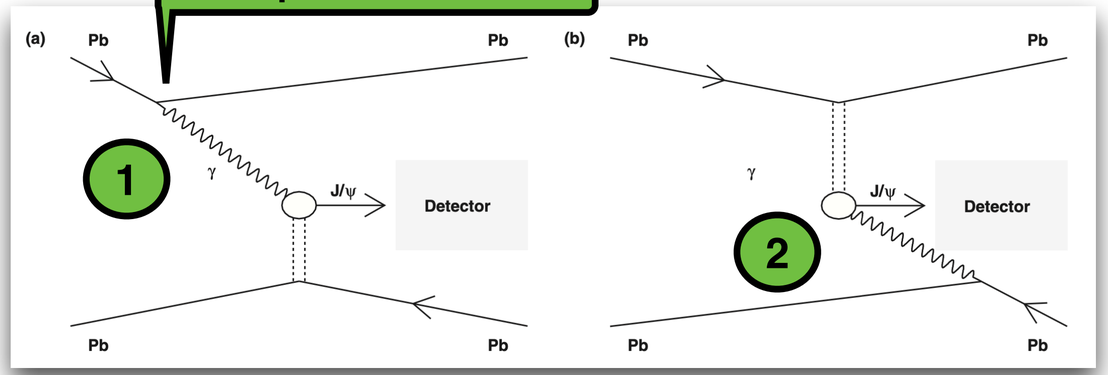

What we measure

What we want (1)

What we want (2)

$$\frac{d\sigma_{\mathrm{PbPb}}}{dy} = n_\gamma(y;\{b\})\sigma_{\gamma\mathrm{Pb}}(y) + n_\gamma(-y;\{b\})\sigma_{\gamma\mathrm{Pb}}(-y)$$

Photonuclear cross sections at two rapidities, i.e. Bjorken-x

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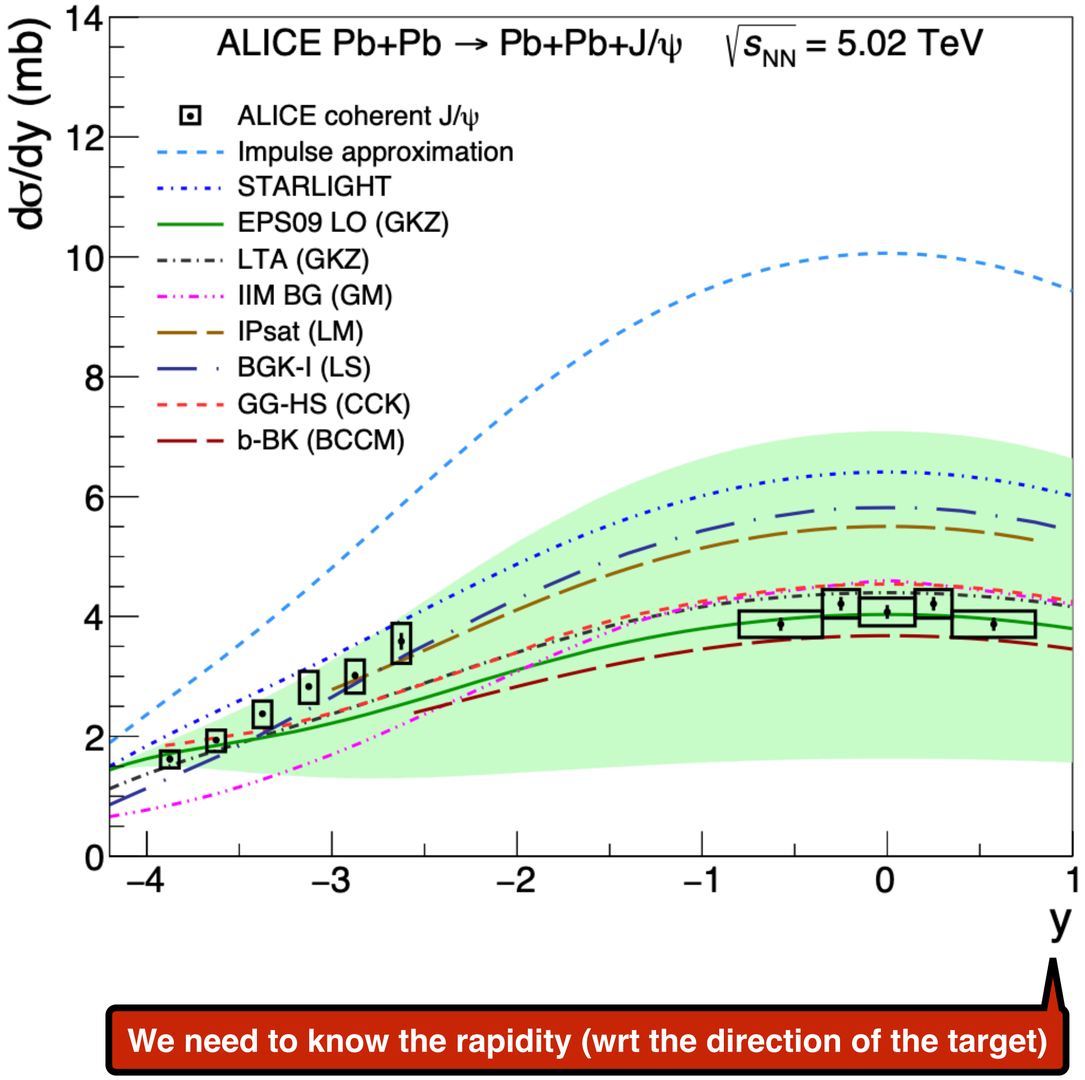

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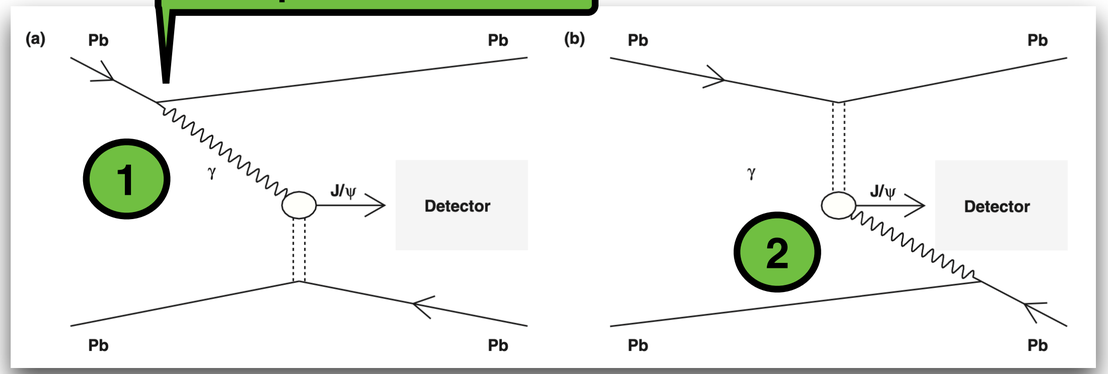

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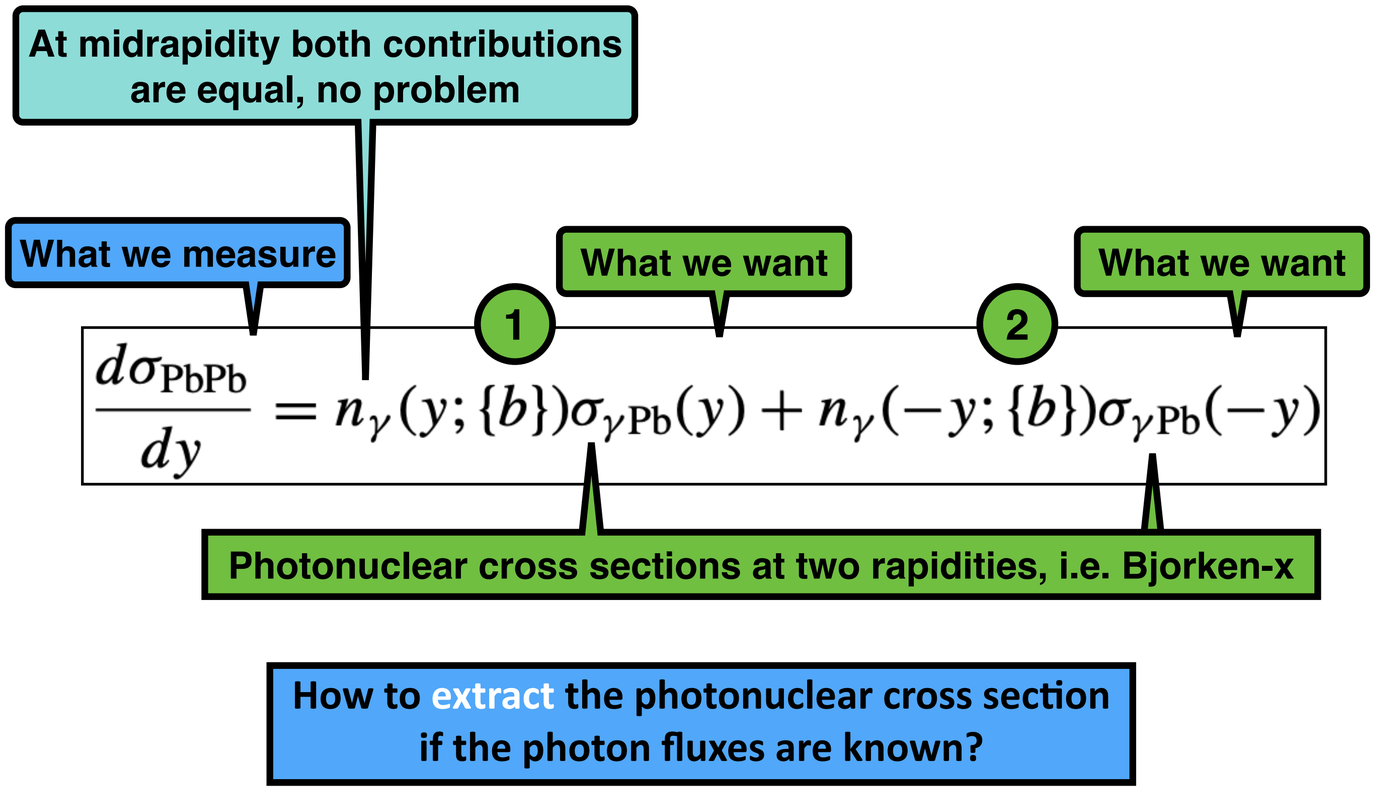
Guillermo Contreras, CTU in Prague

Ambiguity problem: first solutions applied to LHC Run 1 data



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At forward rapidities (2) **dominates (95% of the cross section)**

Guzey et al, Phys.Lett. B726 (2013) 290-295

At midrapidity both contributions are equal, no problem

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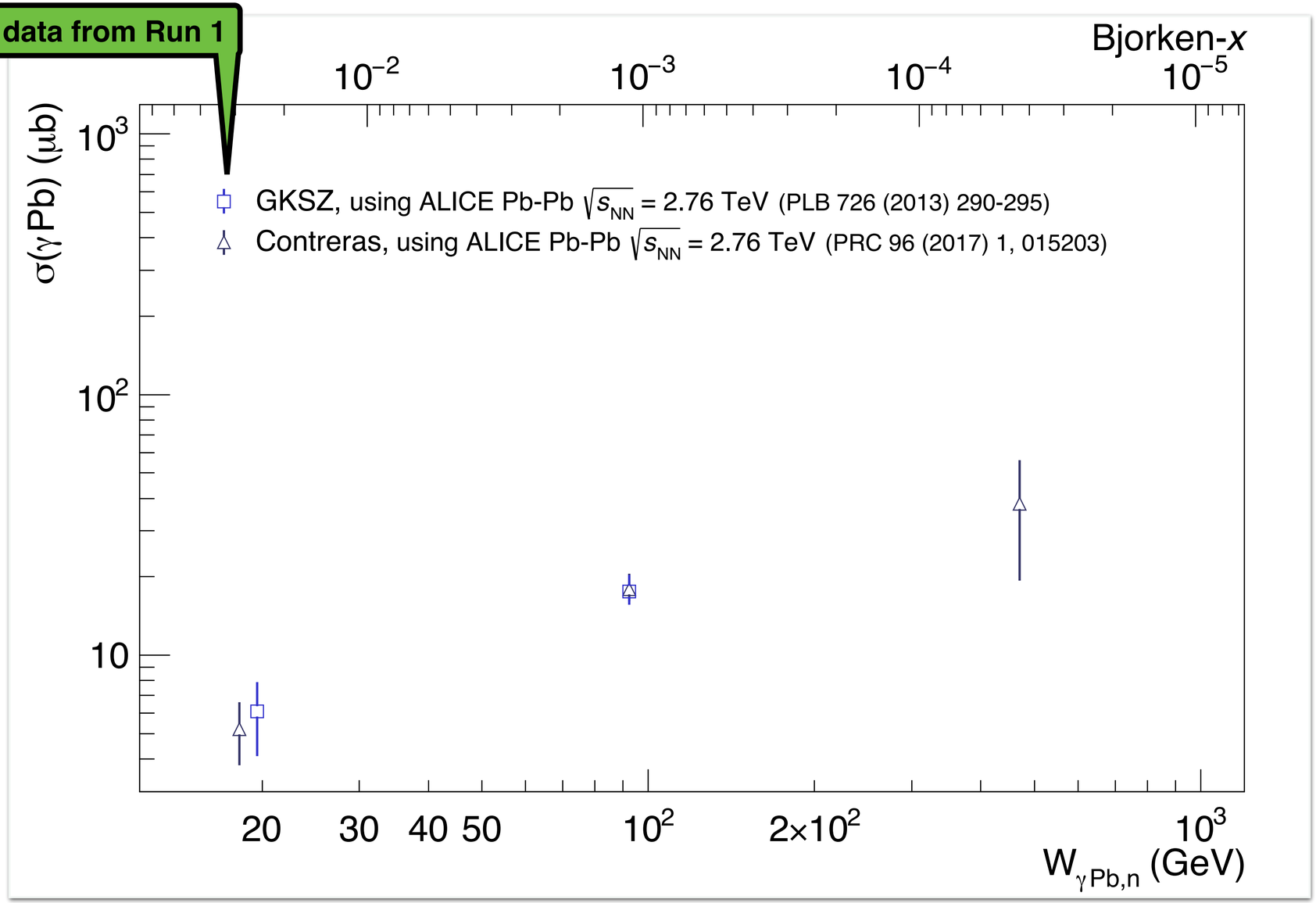
For example, use peripheral and ultra peripheral collisions

JGC, PRC **96**, 015203 (2017)

Energy/Bjorken-x dependence of coherent production from Run 1

Analyses using ALICE data from Run 1



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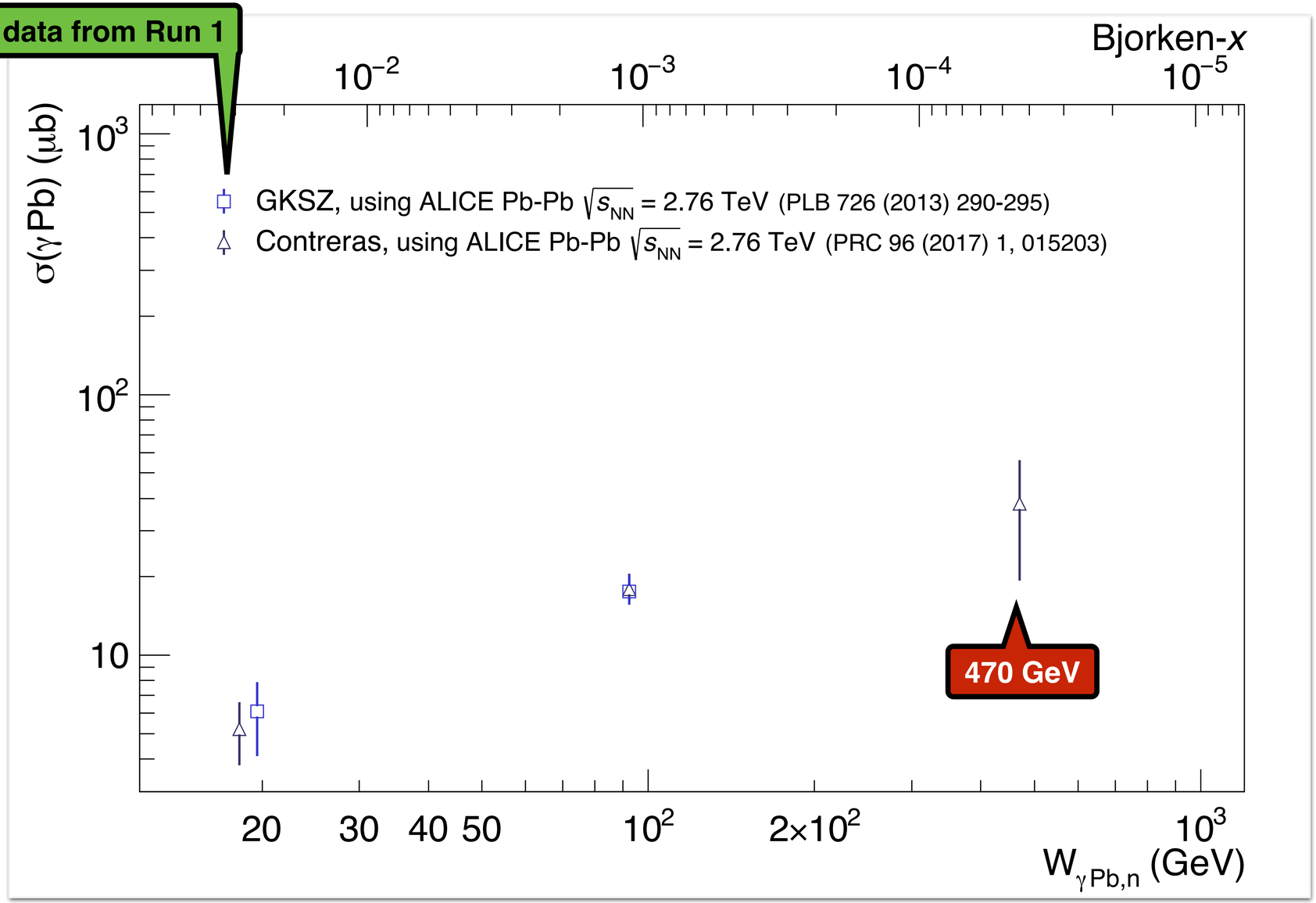
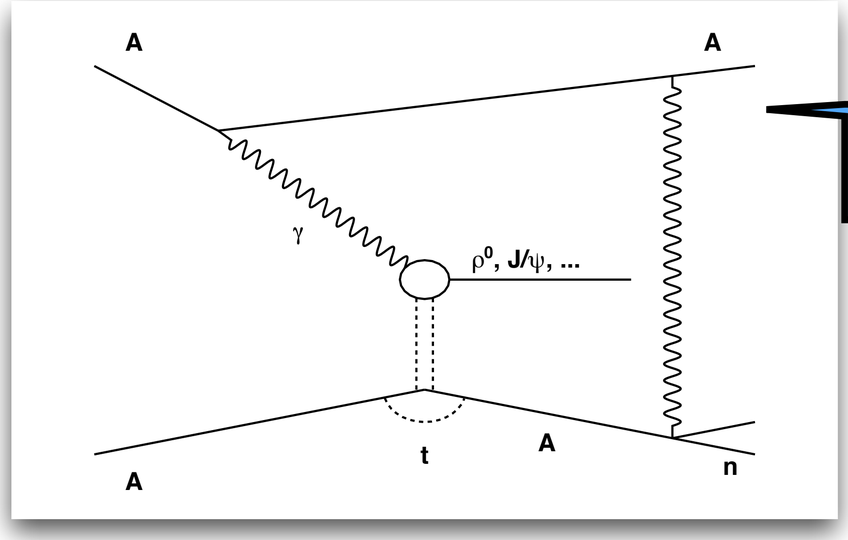


Ambiguity problem: use EMD

Guzey, Strikman, Zhalov, EPJ C74 (2014) 2942



Independent interaction

Electromagnetic dissociation of nuclei

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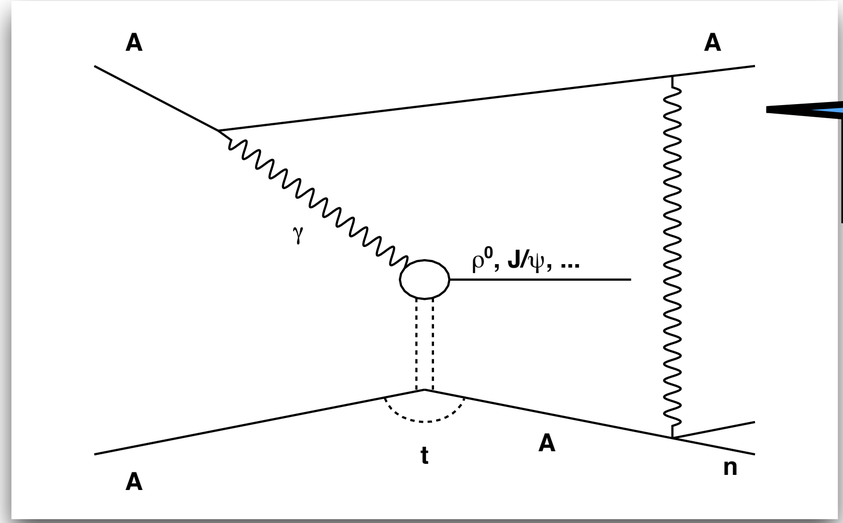

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In order to dissociate the nucleon, the second photon needs to be energetic
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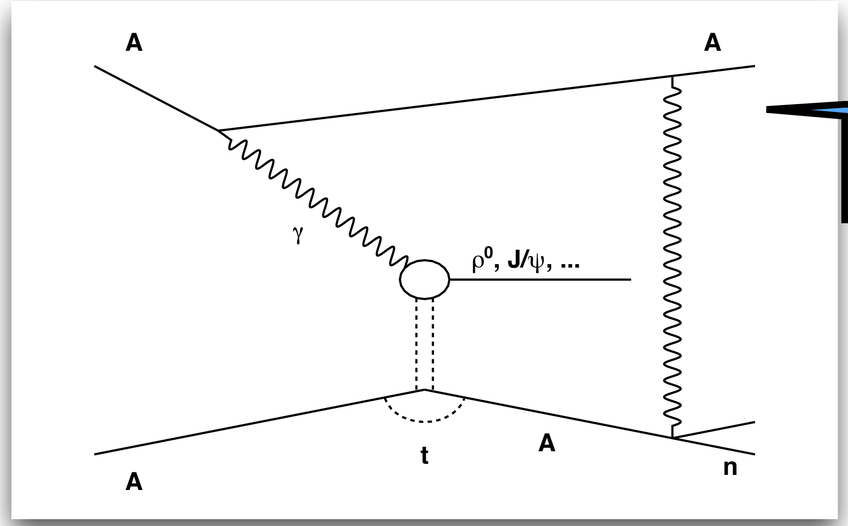

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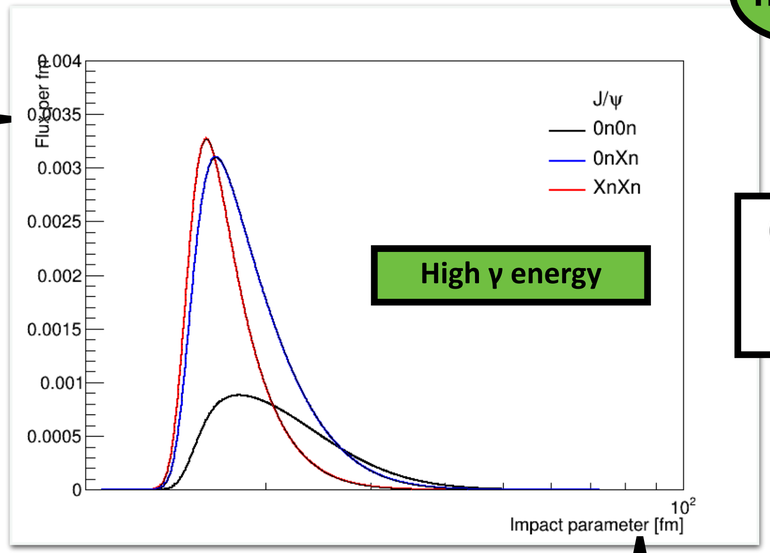
nOOn **Photon fluxes at fwd rapidity:**

Broz et al., CPC 235 (2020) 107181

Flux



Impact parameter

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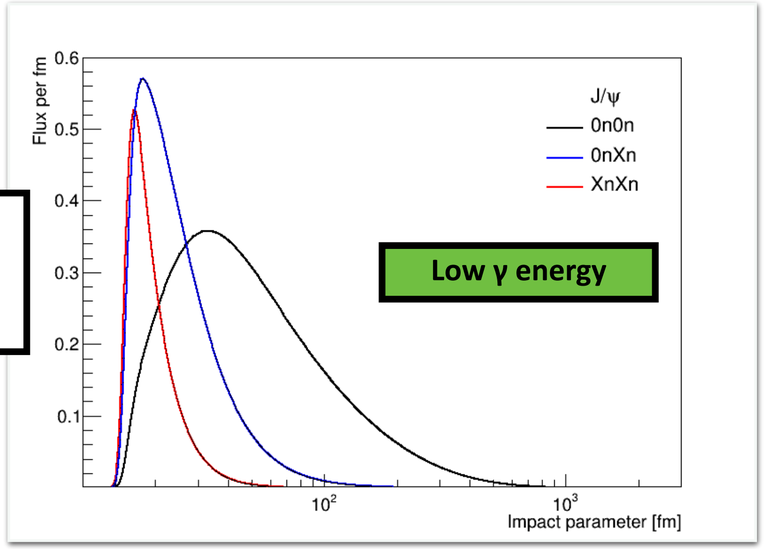
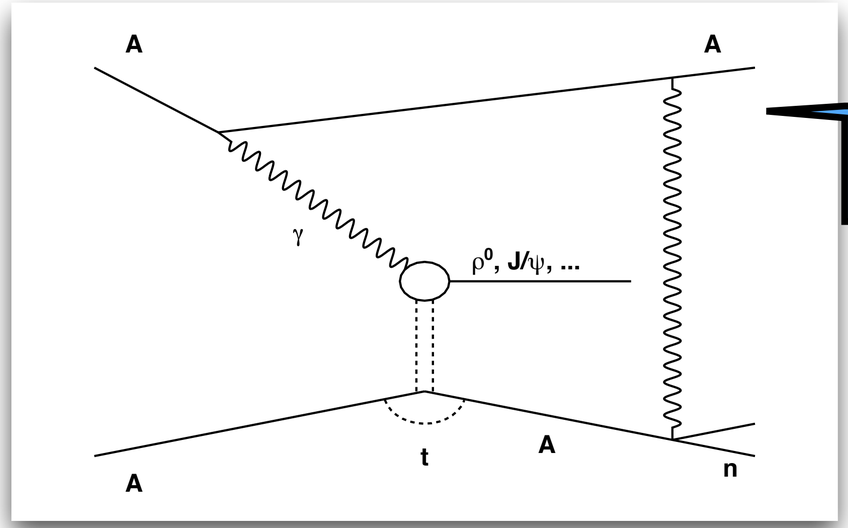


EMD as seen by zero-degree calorimeters



Independent interaction

neutrons are emitted along the beamline

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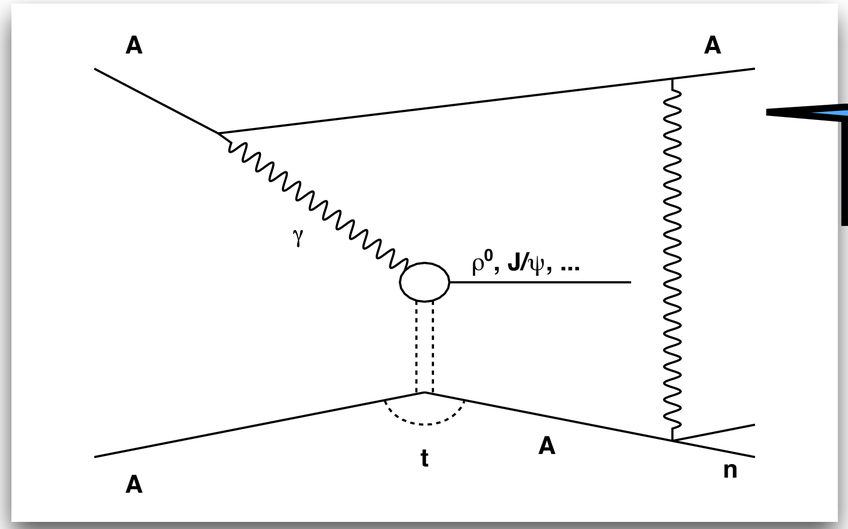

Independent interaction

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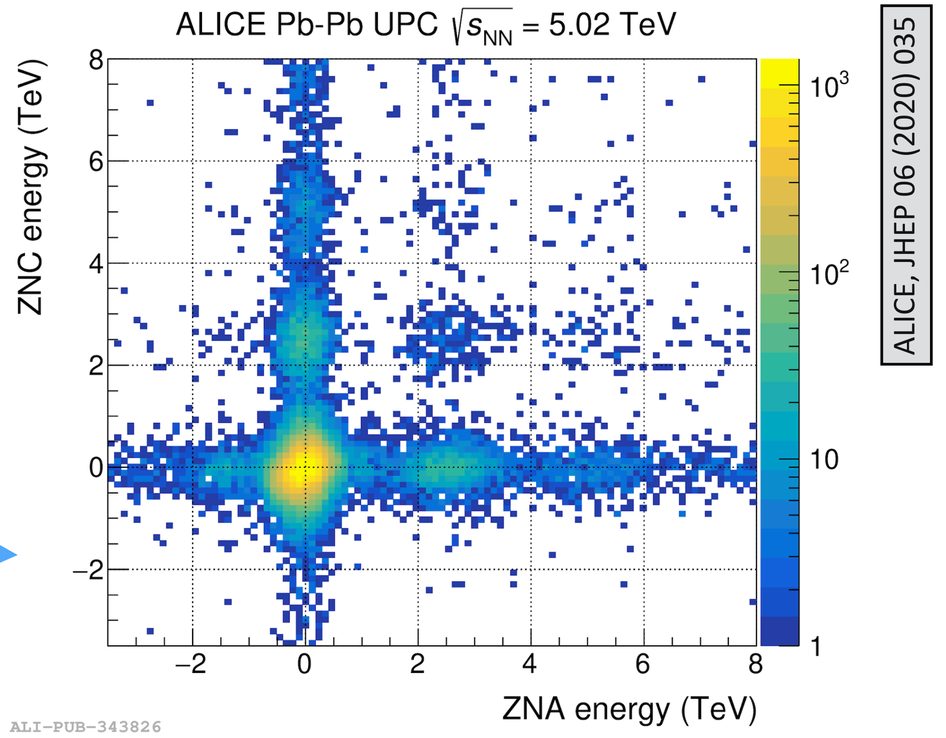

ALICE, JHEP 06 (2020) 035

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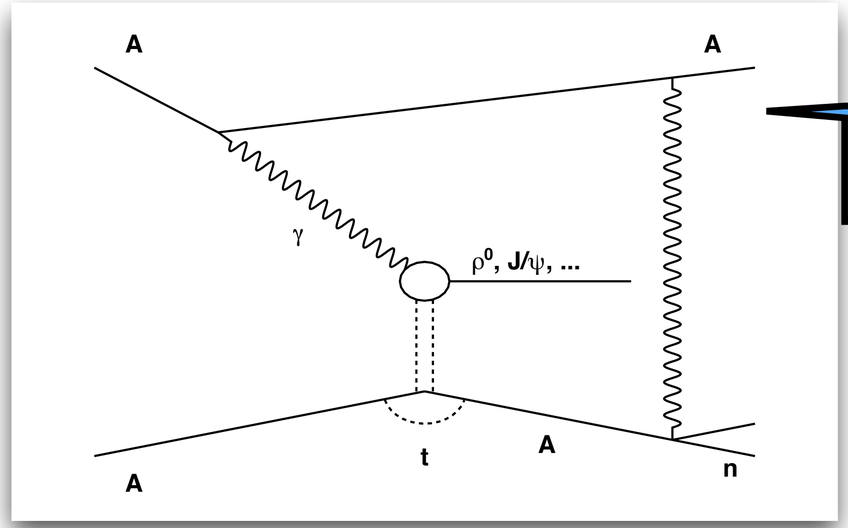

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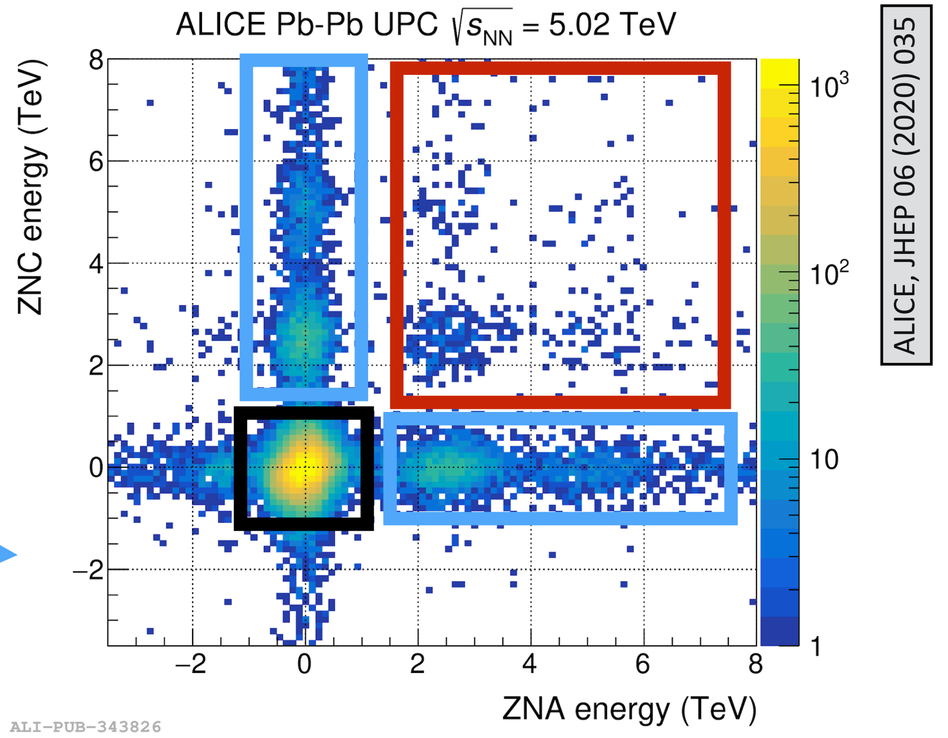

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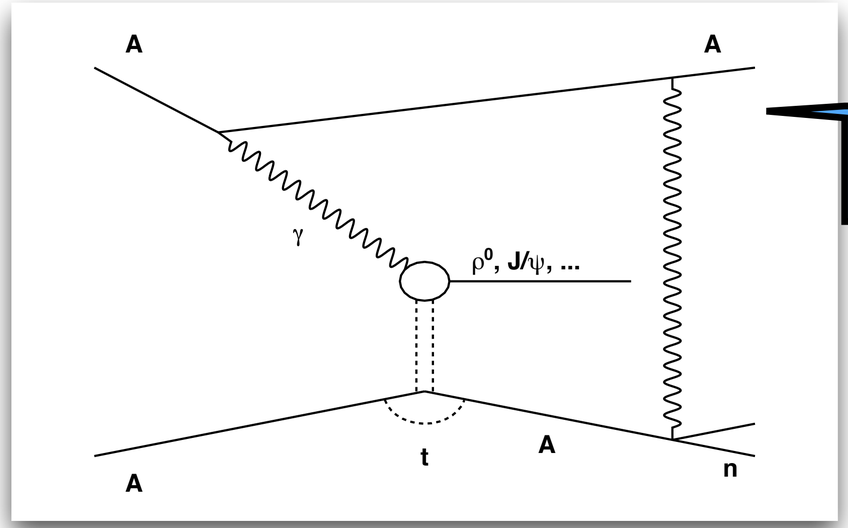

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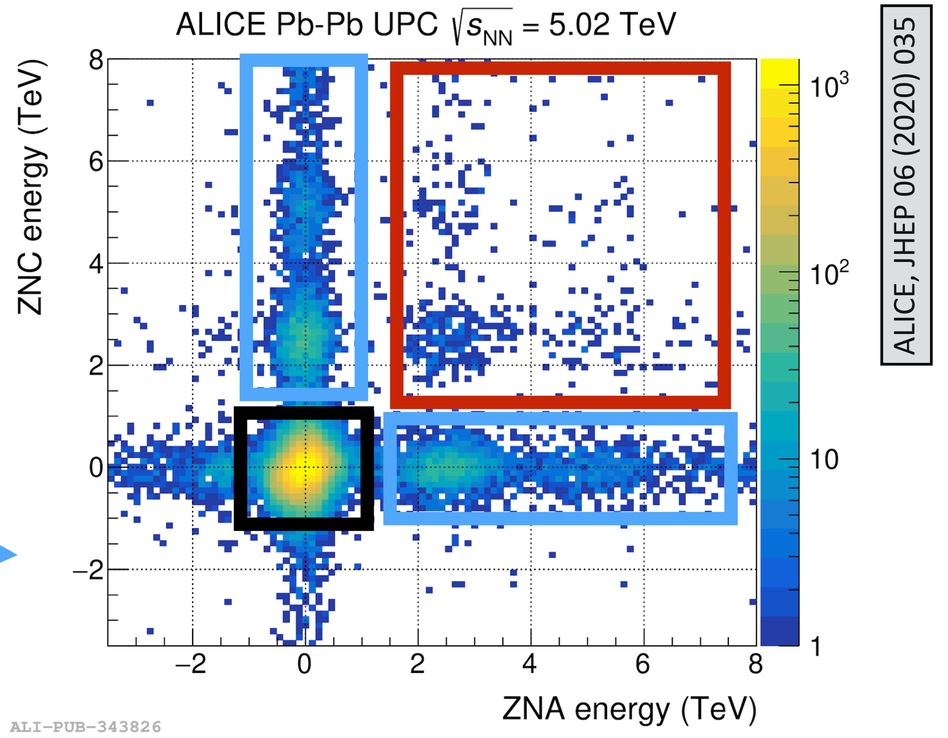

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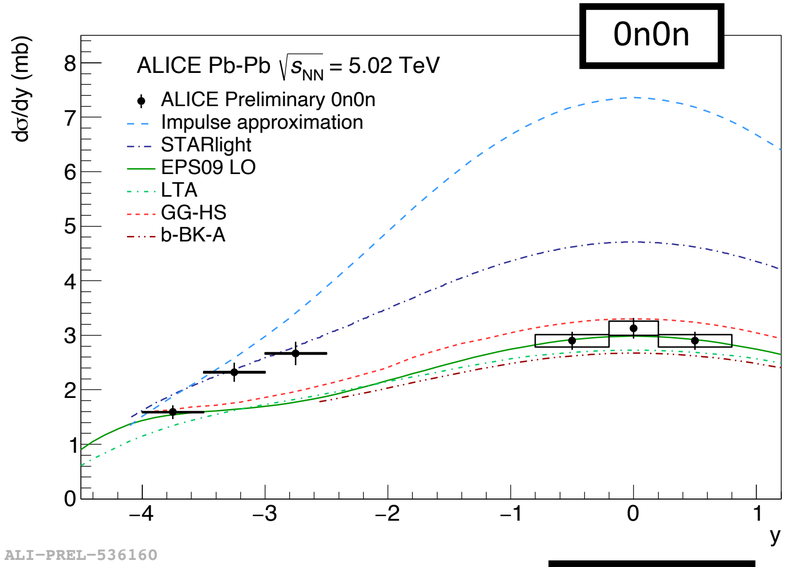
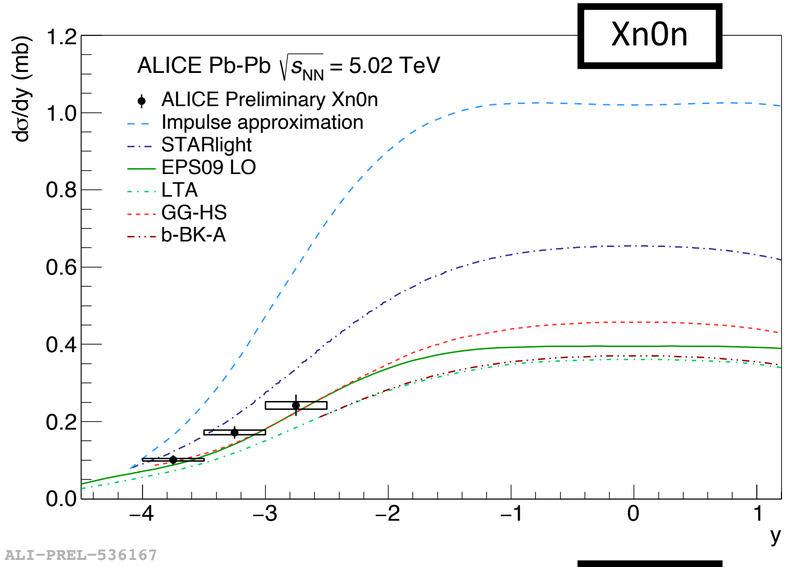
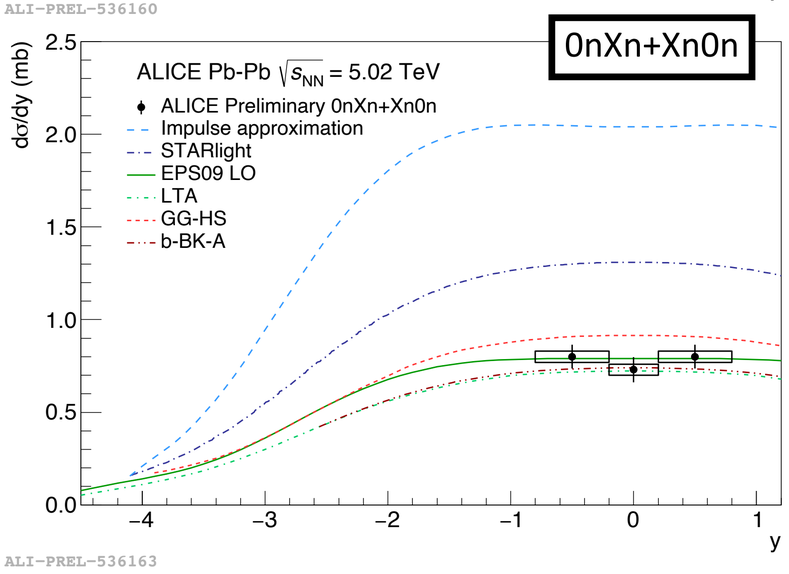
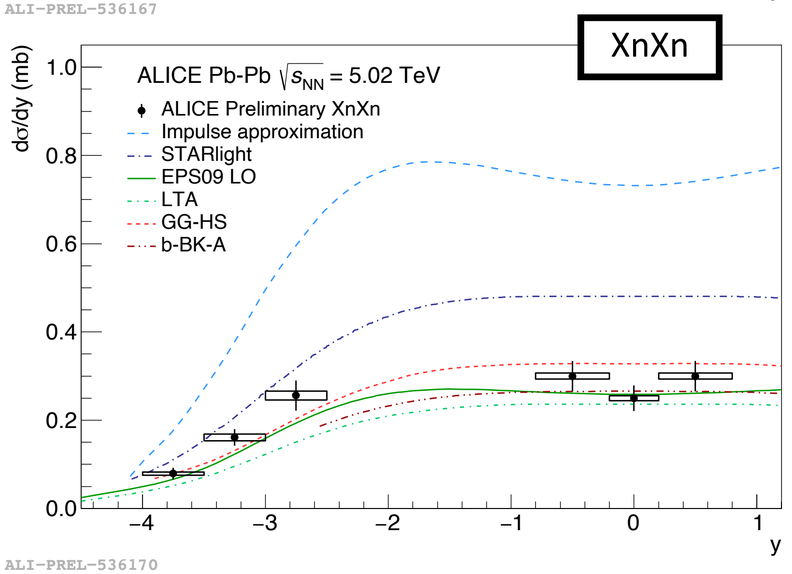
LHC Run 2: rapidity dependence of J/ψ coherent production in EMD classes

ALICE









Guillermo Contreras, CTU in Prague

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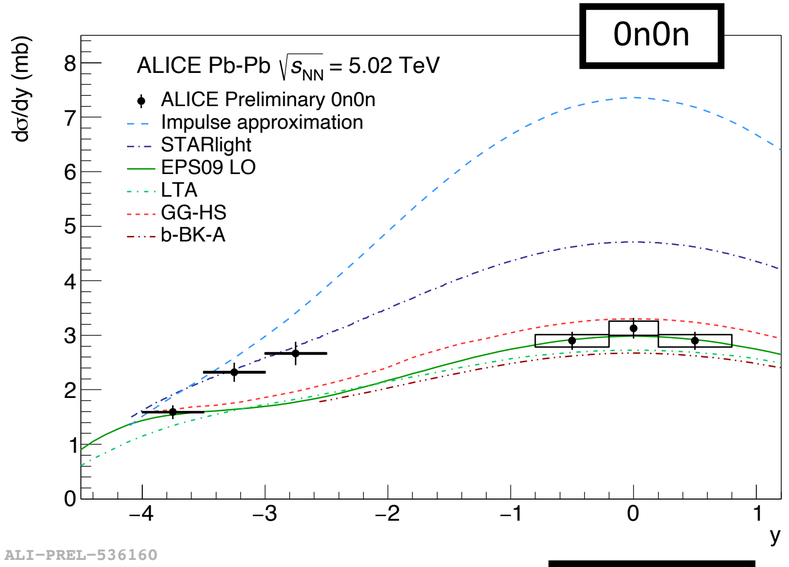

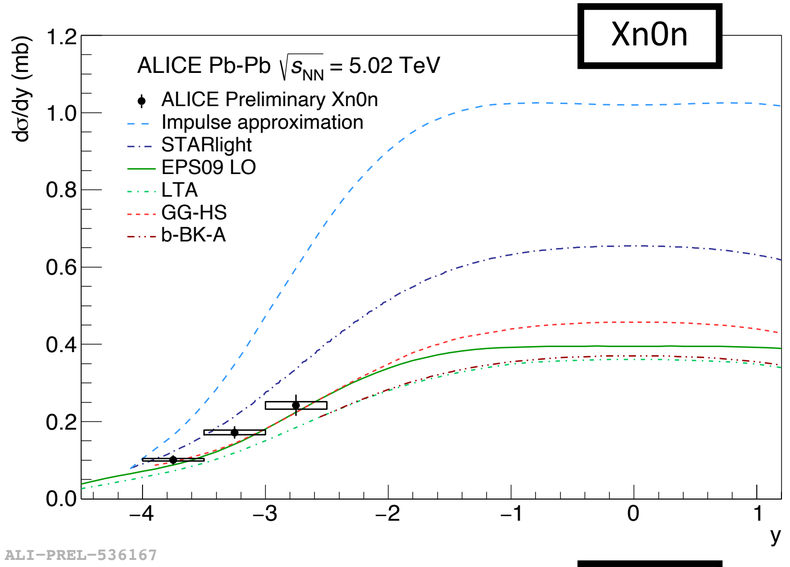

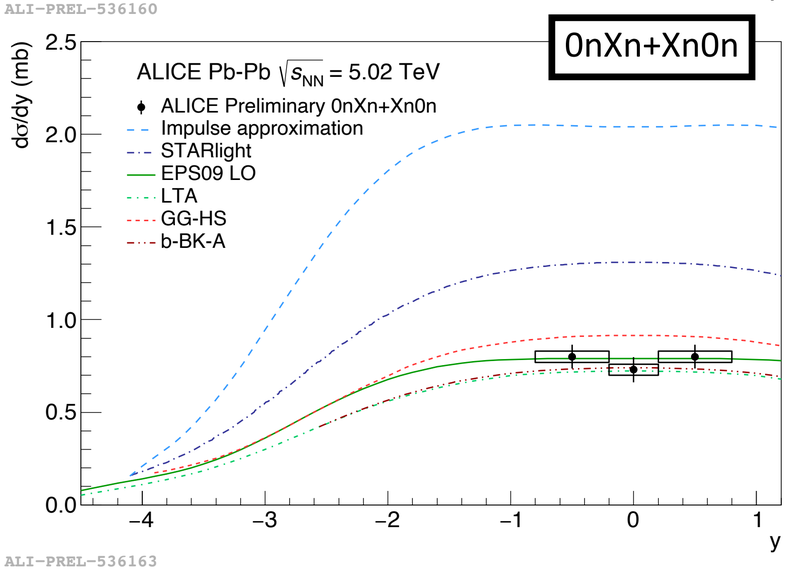

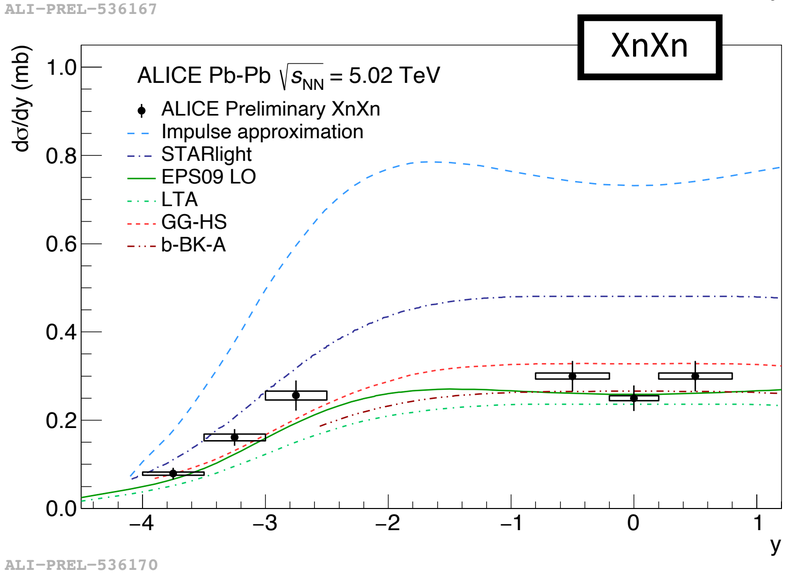

Several UPC measurements for each rapidity range → We can extract the photonuclear cross sections!

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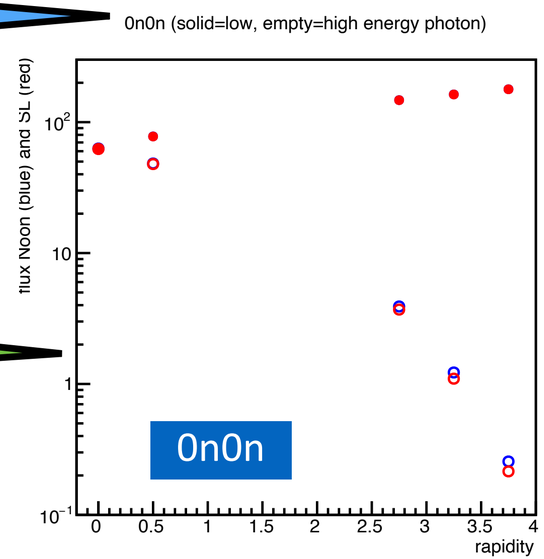
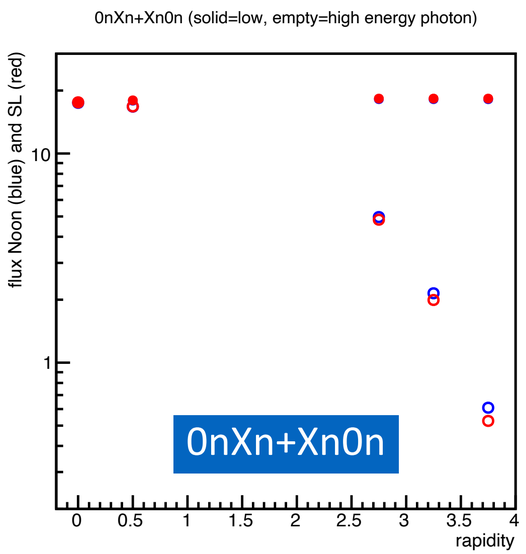
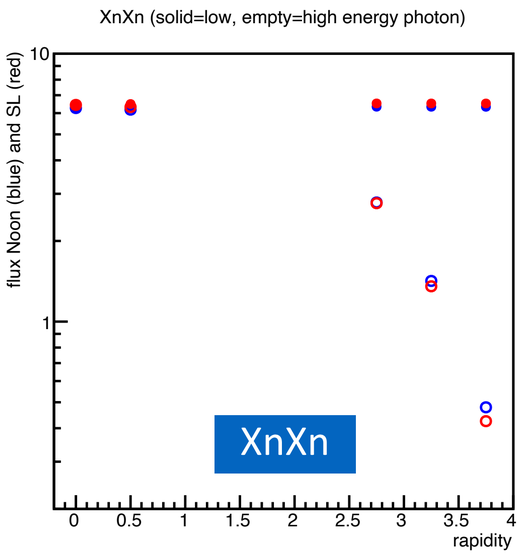
Warning: how well do we understand the photon flux?

low/high energy photon (solid/empty)

Flux:
nOOn (blue), STARlight (red)







rapidity

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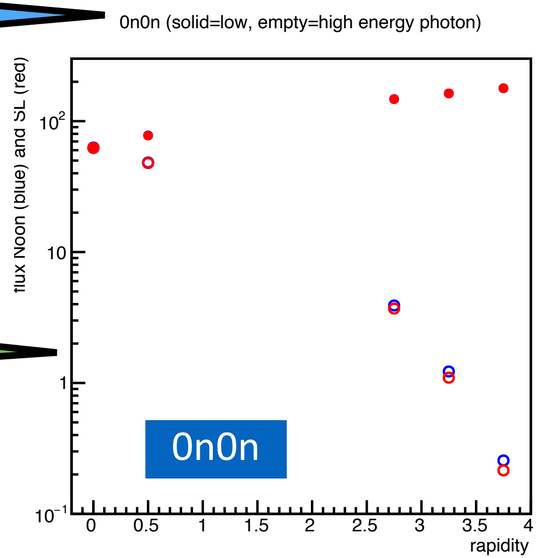
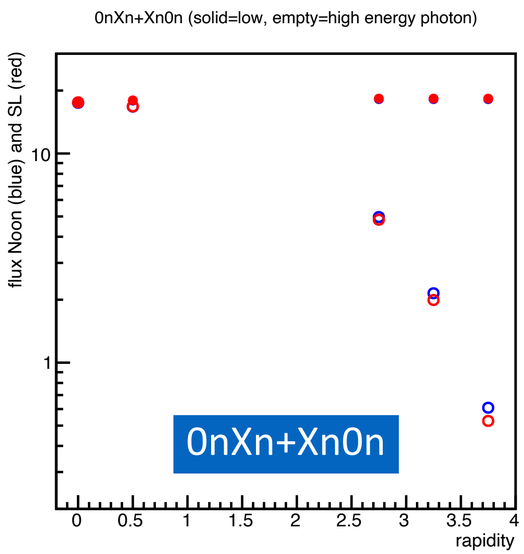
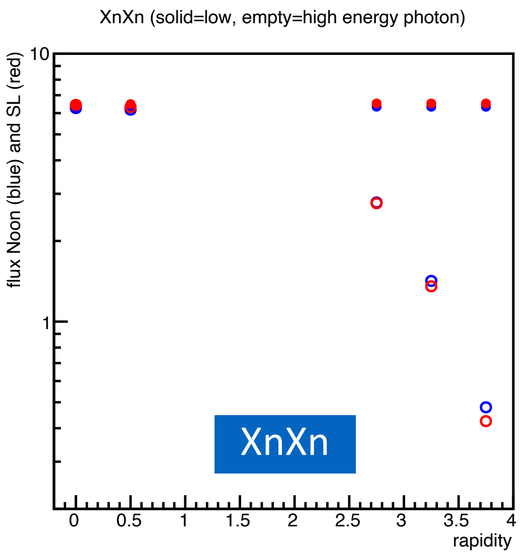
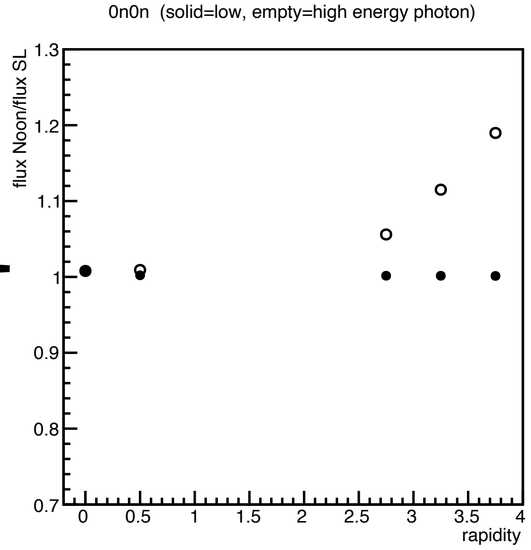


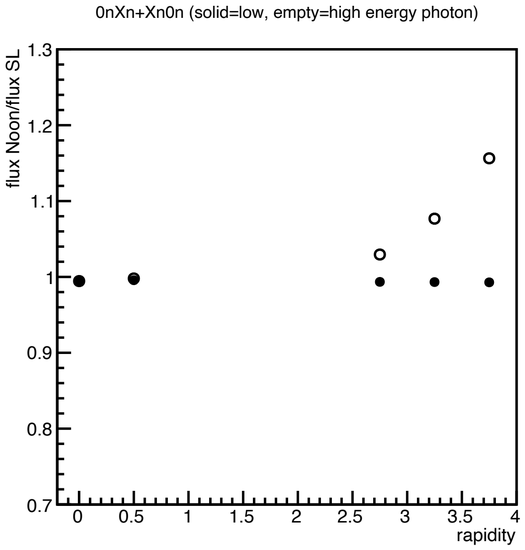


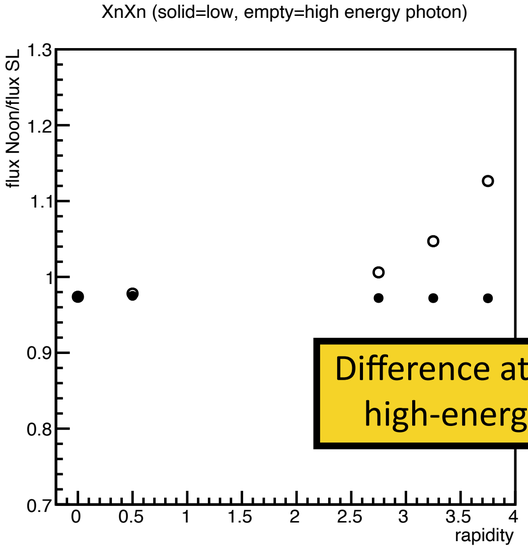


rapidity

Ratio of fluxes: nOOn to STARlight



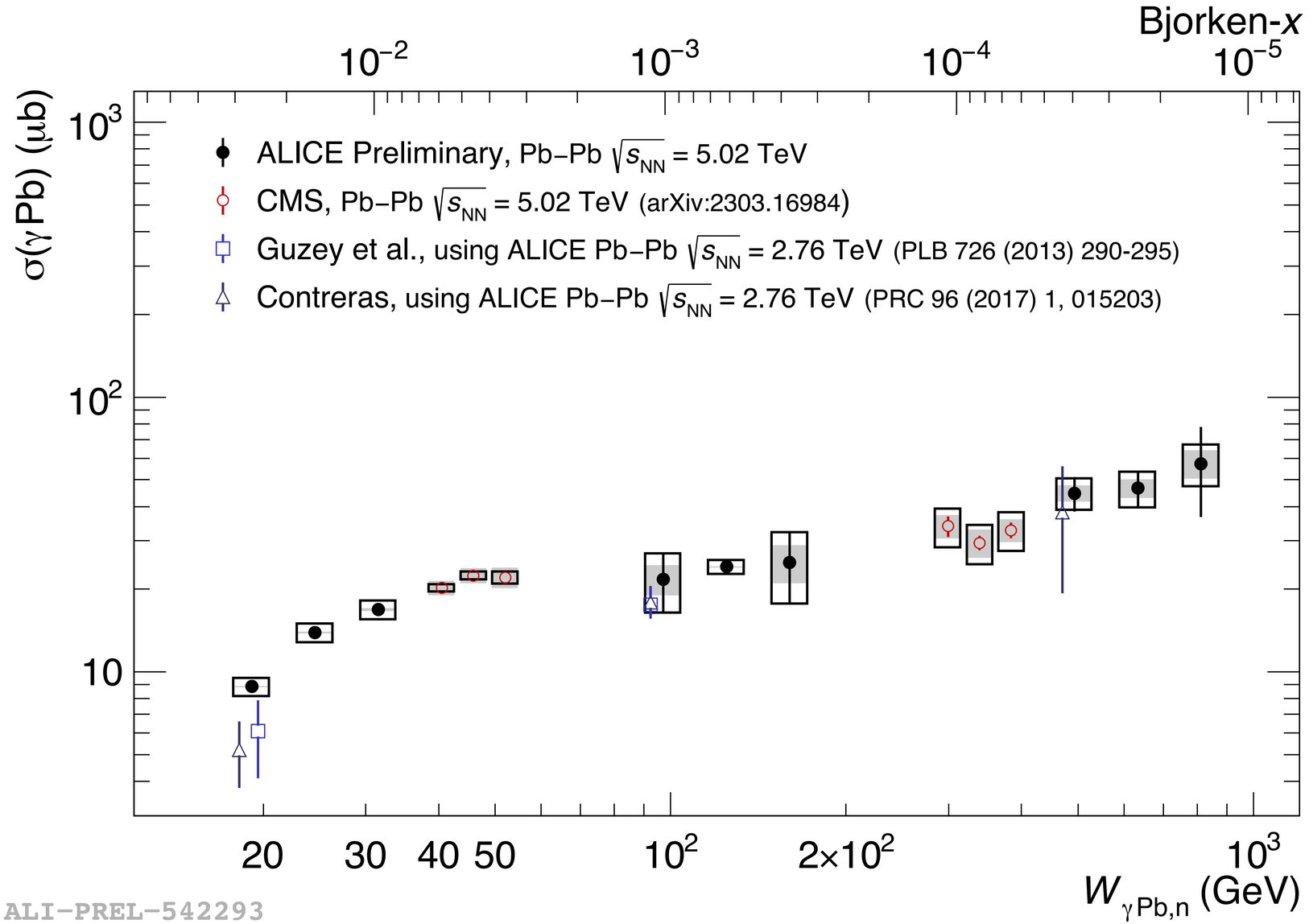




Difference at large rapidity for high-energy photon fluxes

Guillermo Contreras, CTU in Prague

Energy/Bjorken-x dependence of coherent production from Run 2



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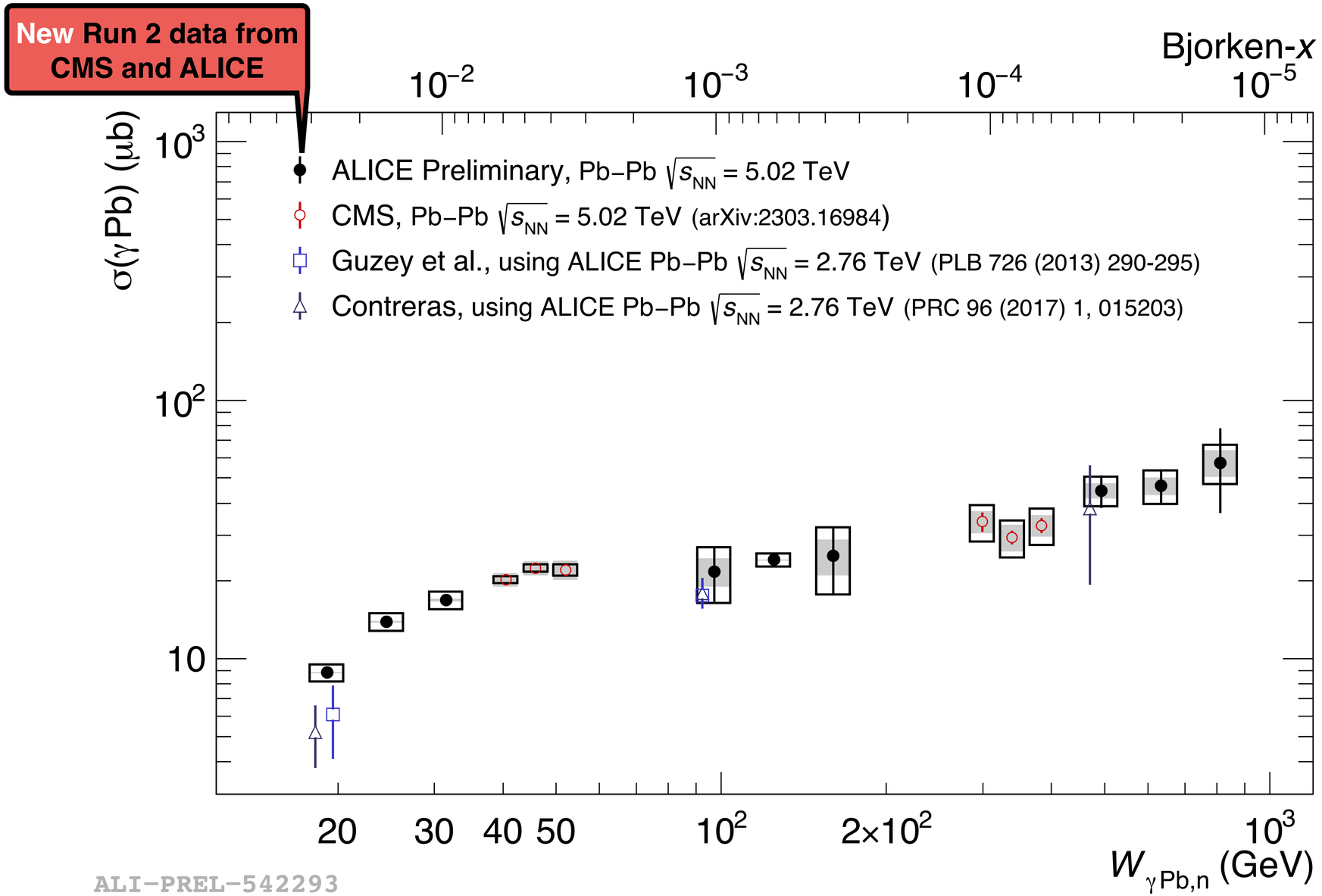

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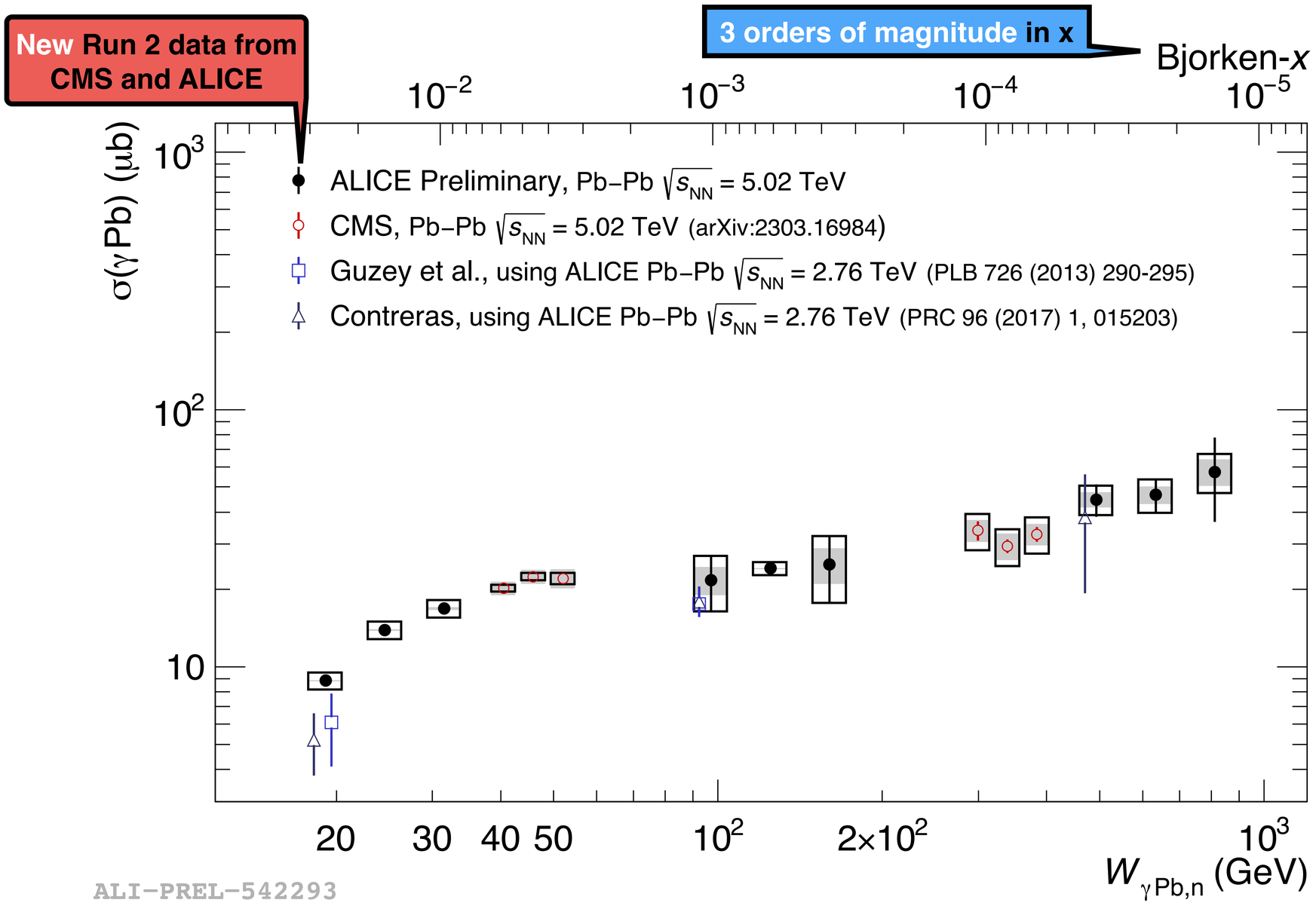

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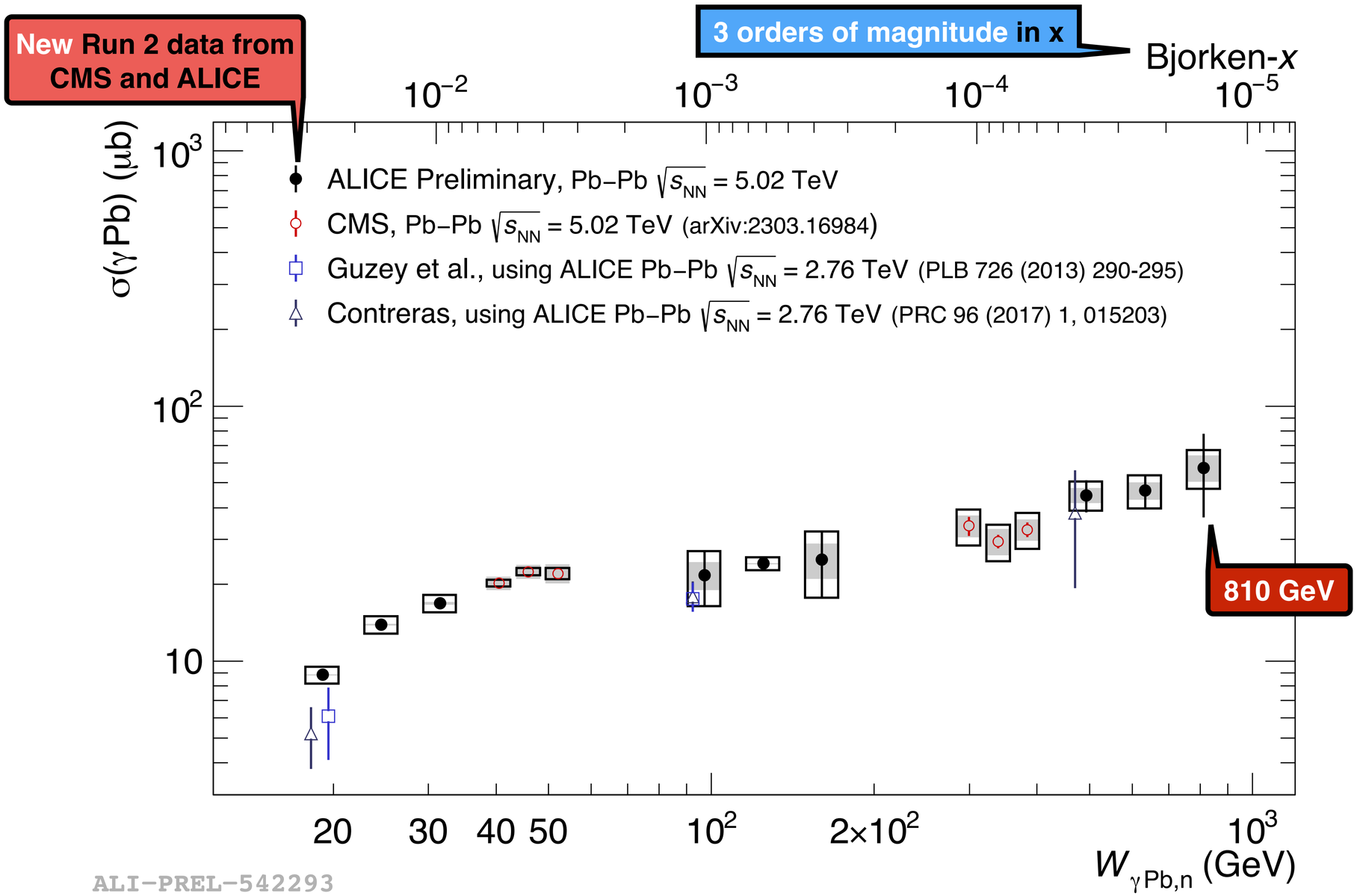

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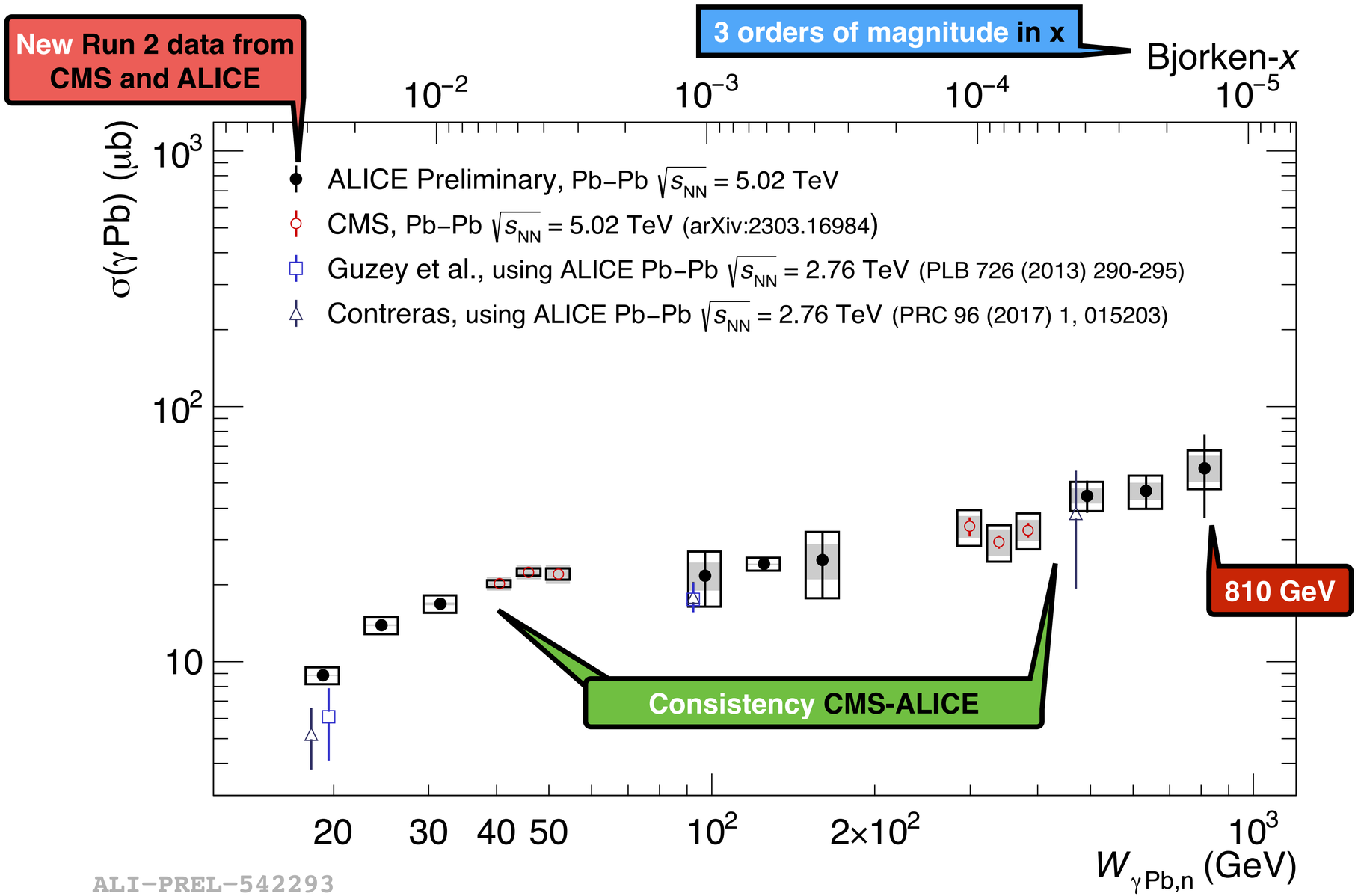

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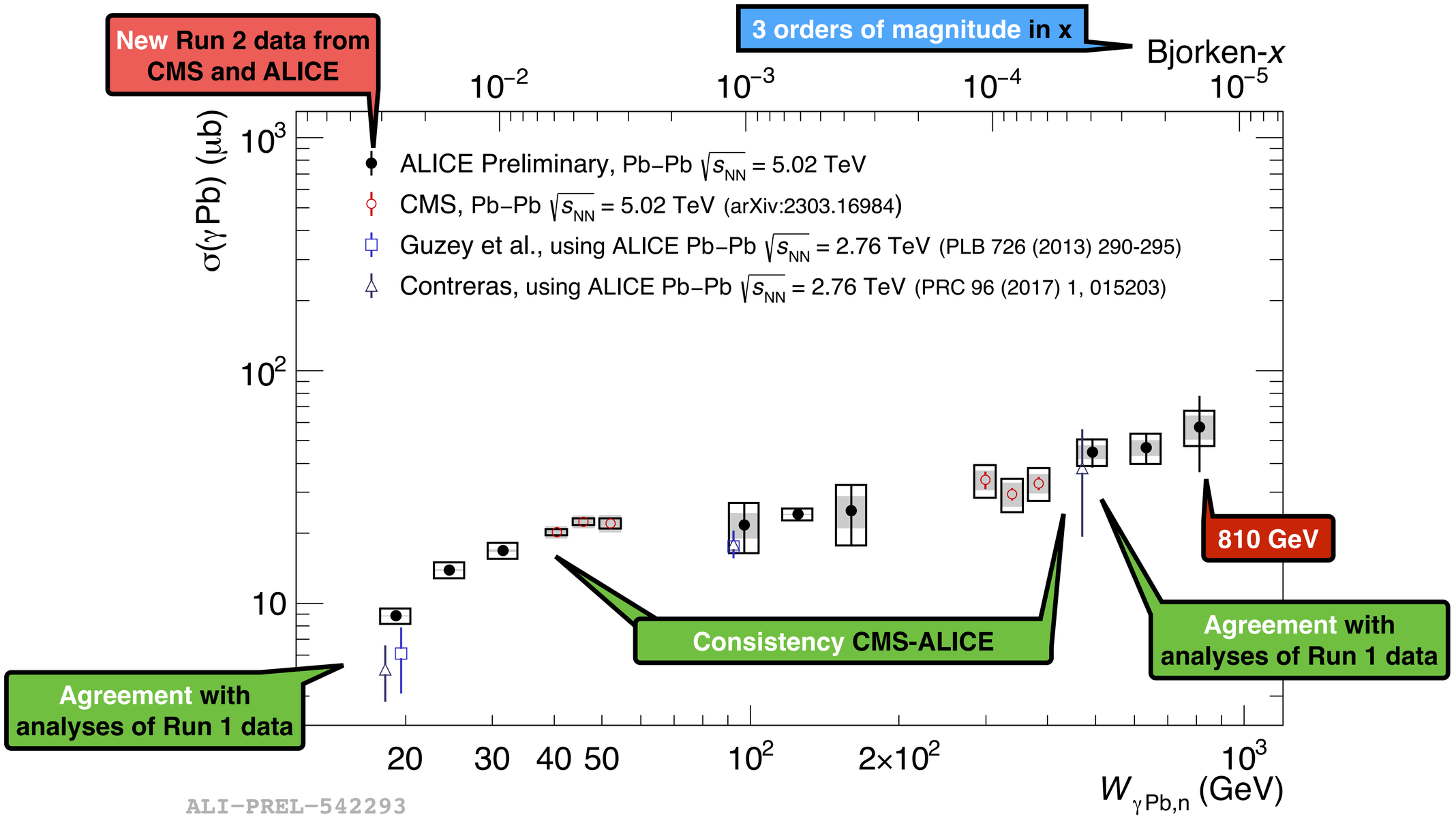
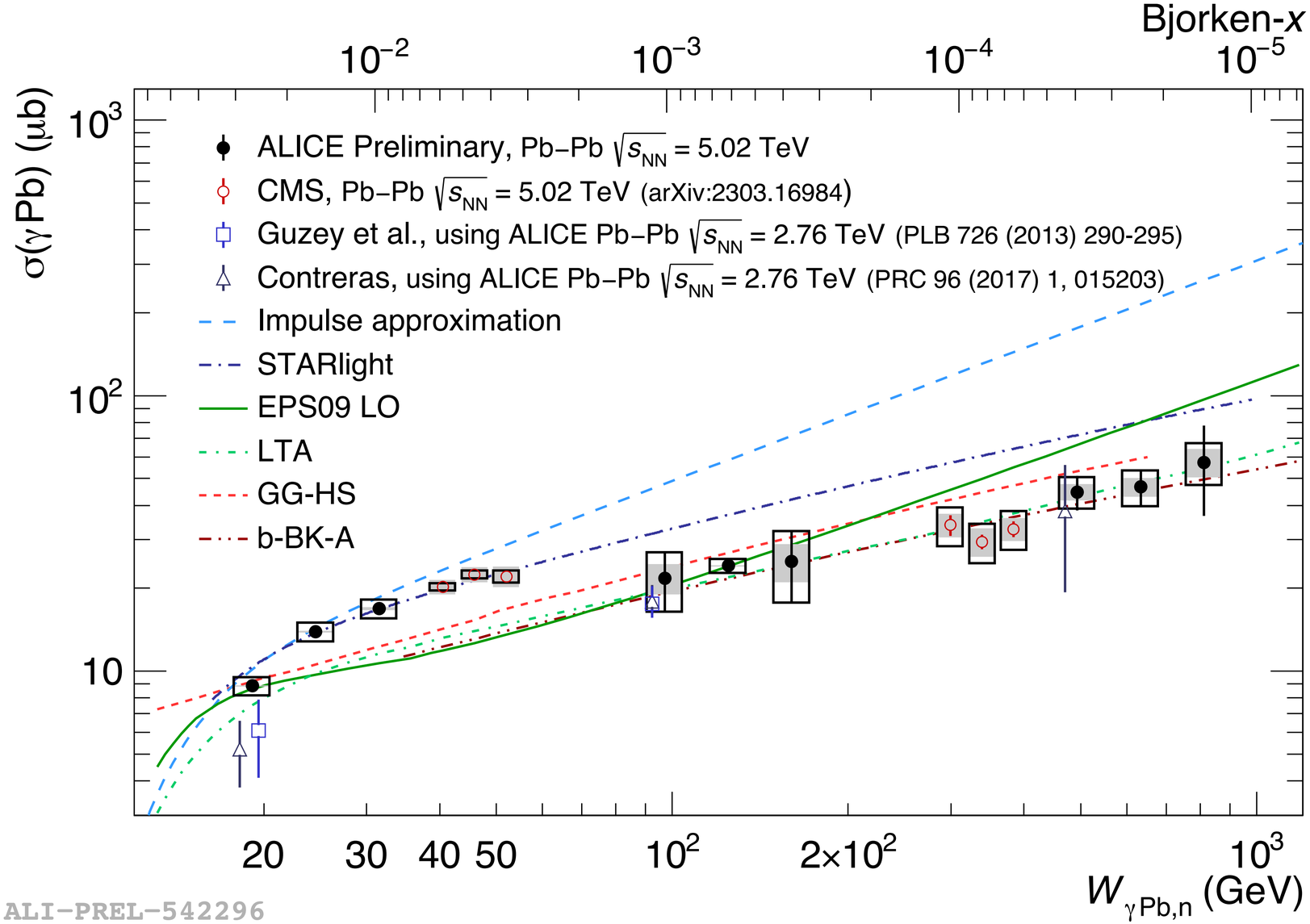


Energy/Bjorken-x dependence of coherent production from Run 2: Models



ALI-PREL-542296

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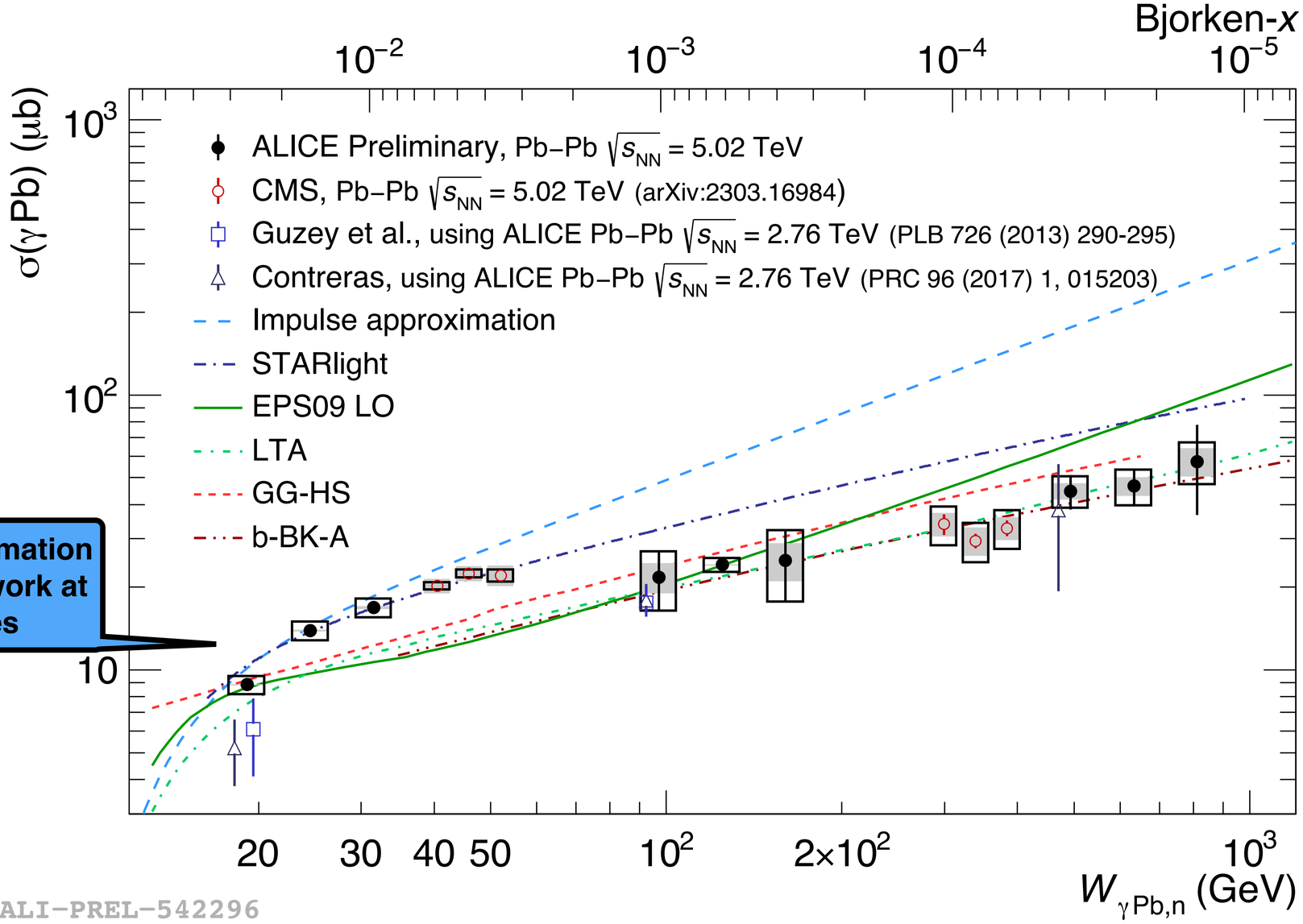

Impulse approximation and STARlight work at low energies

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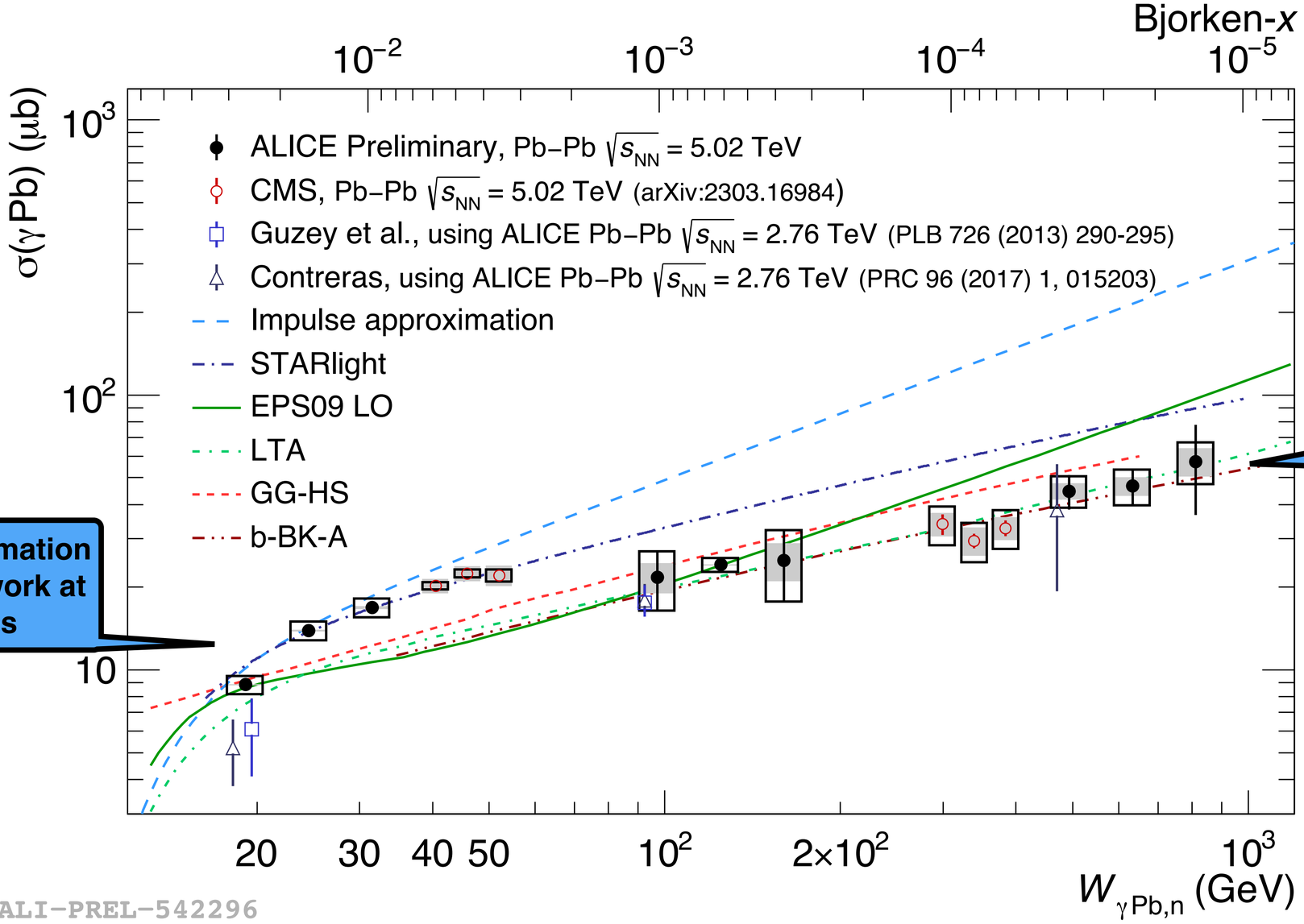

Impulse approximation and STARlight work at low energies

LTA and colour dipole based models (b-BK-A, GG-HS) work at high energies

Warning: impulse approximation

Nuclear suppression factor (shadowing)

$$S_{\mathrm{Pb}} = \sqrt{\frac{\sigma_{\gamma\mathrm{Pb}}}{\sigma^{\mathrm{IA}}_{\gamma\mathrm{Pb}}}}$$

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The impulse approximation is normally obtained using γp data

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Rapidity range	STARlight (μb)	GKSZ (μb)
$3.5 < y < 4$	13	10
$3 < y < 3.5$	18	14
$2.5 < y < 3$	22	19
$0.2 < y < 0.8$	49	48
$-0.2 < y < 0.2$	58	58
$-0.8 < y < -0.2$	68	71
$-3 < y < -2.5$	142	176
$-3.5 < y < -3$	167	215
$-4 < y < -3.5$	196	262

Guzey et al, PLB726 (2013) 290

Employing different experimental data sets, may produce different answers

Energy/Bjorken-x dependence of coherent production from Run 2: Shadowing

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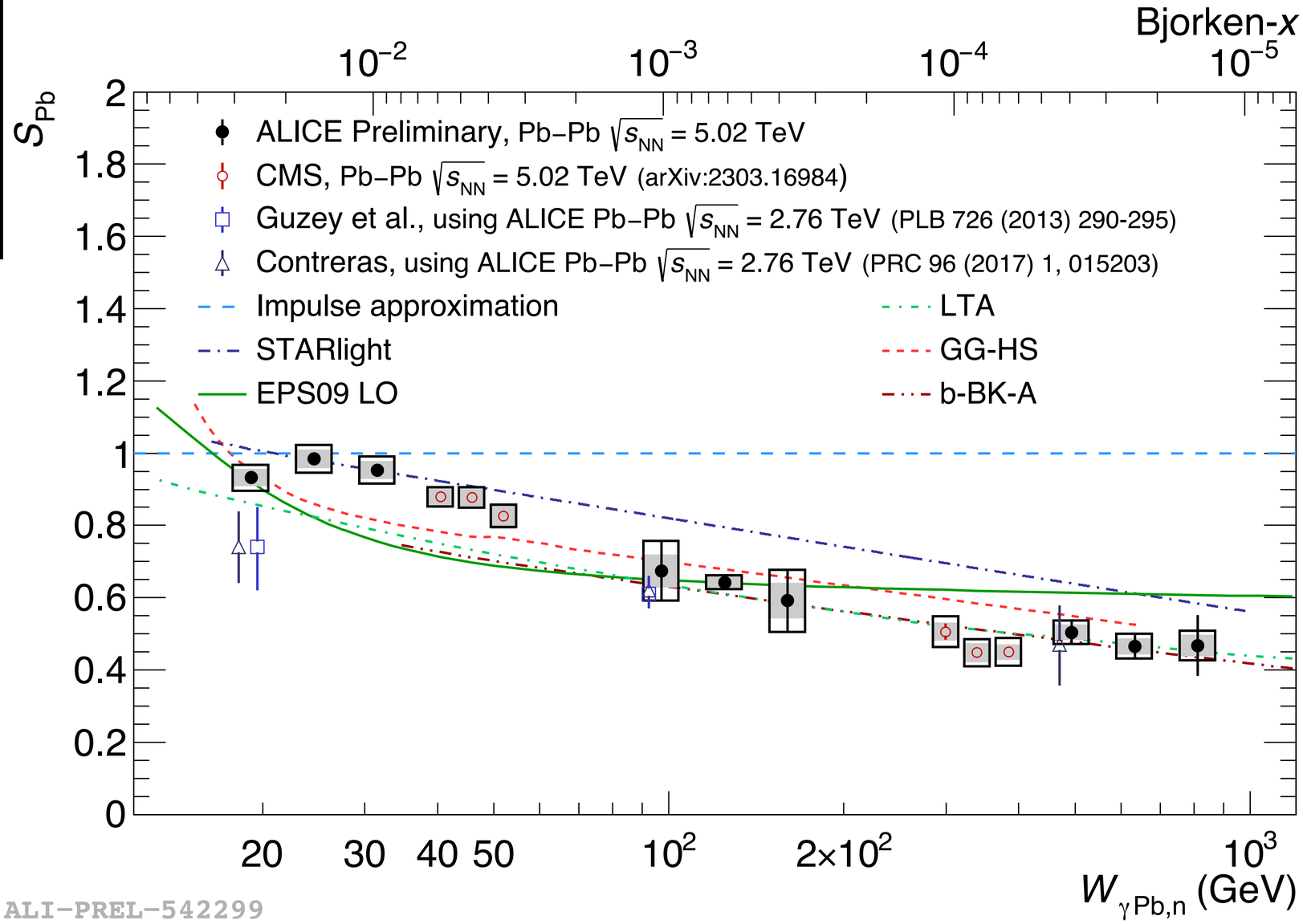

ALI-PREL-542299

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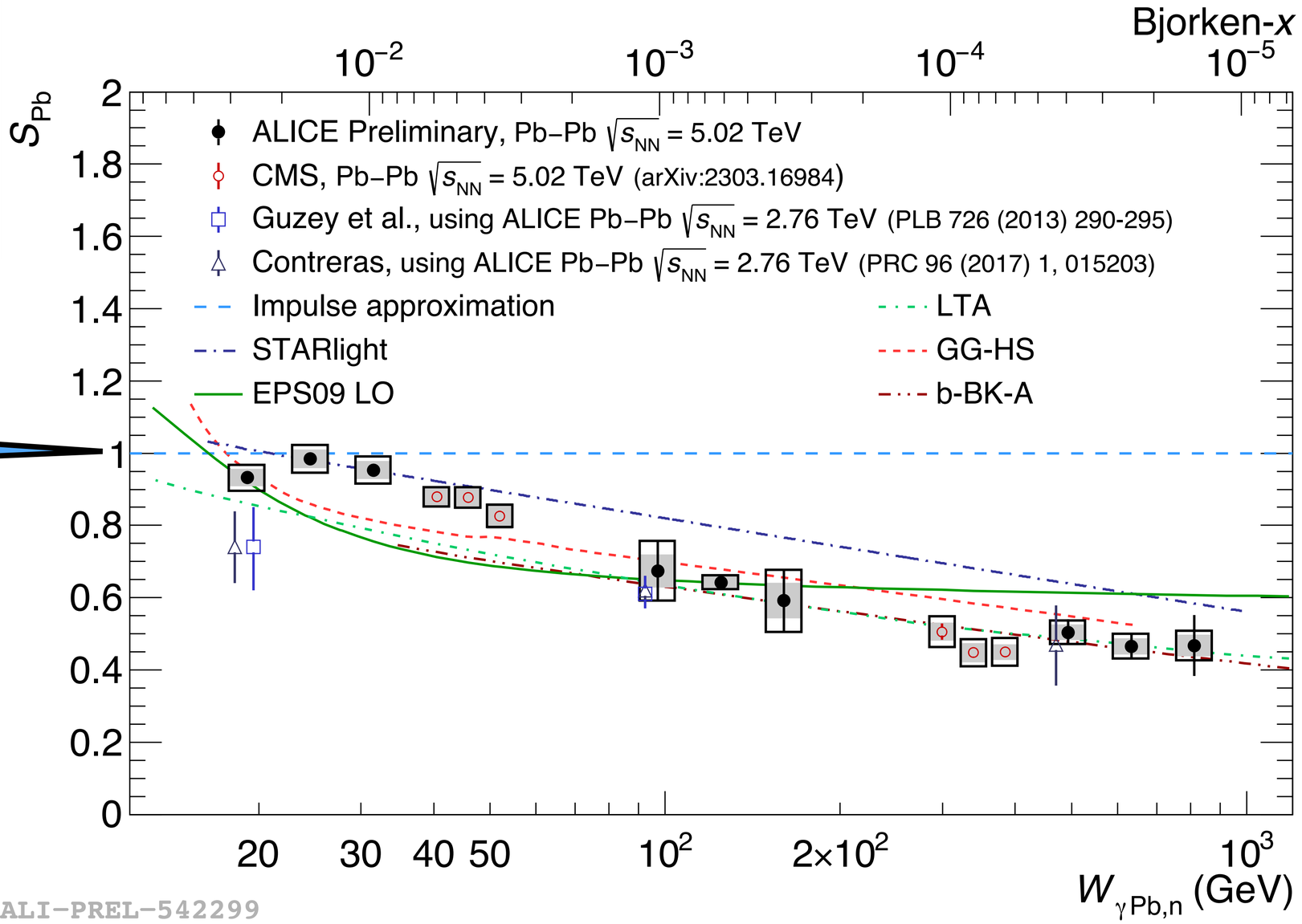
No shadowing at low energies?



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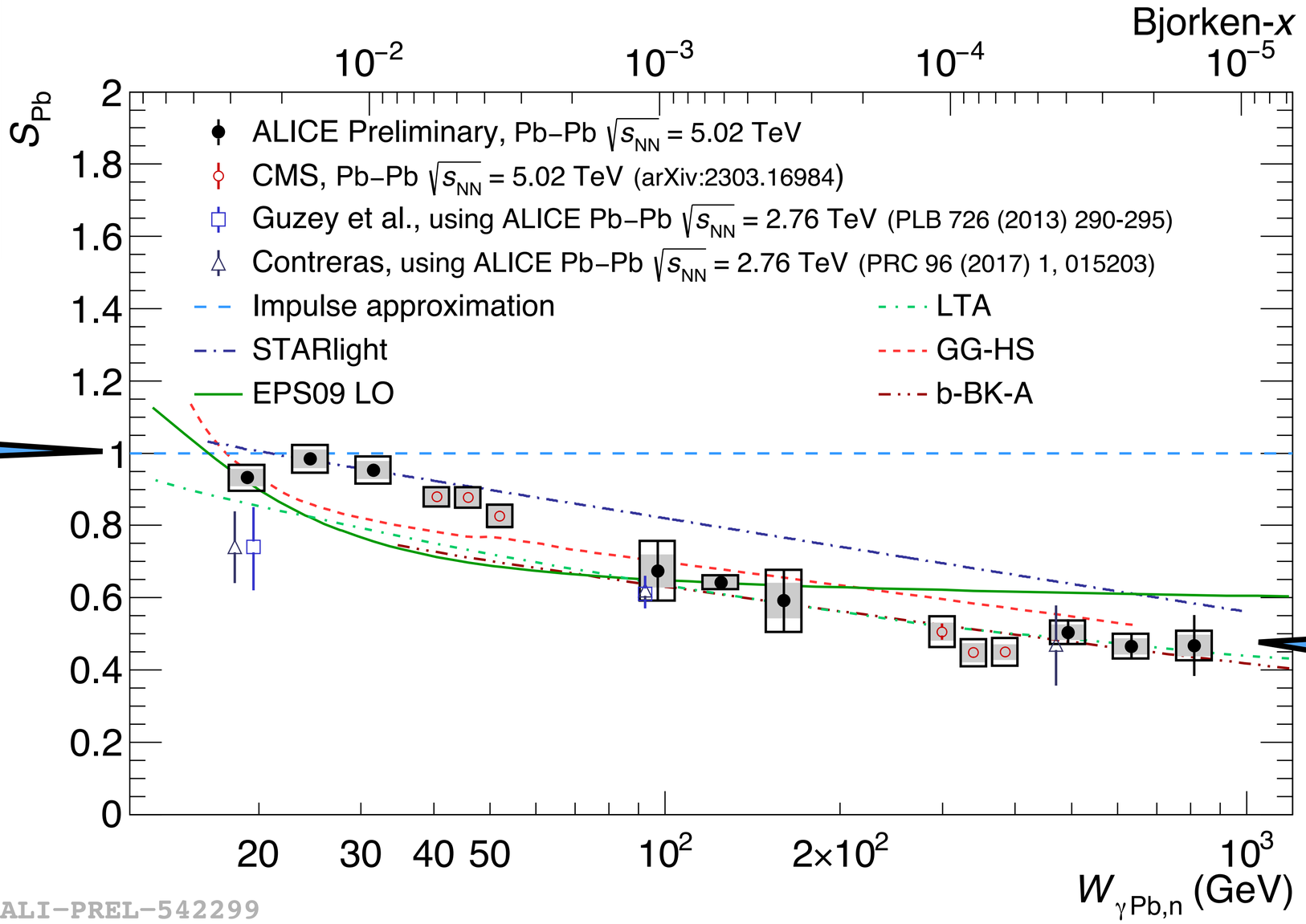

No shadowing at low energies?

Flattening of shadowing at high energies?

ALI-PREL-542299

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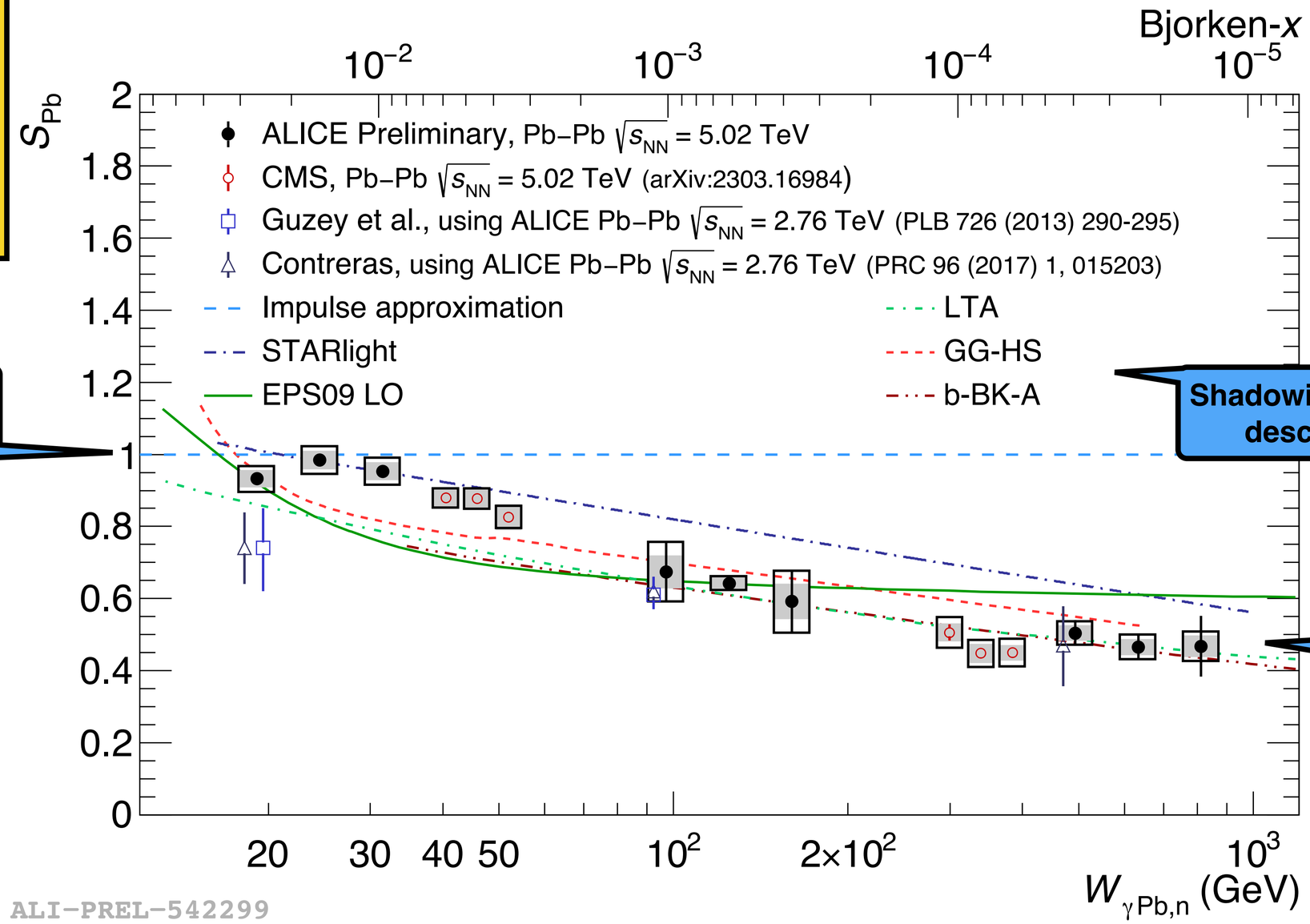

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Shadowing and saturation models describe data equally well.

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ALI-PREL-542299

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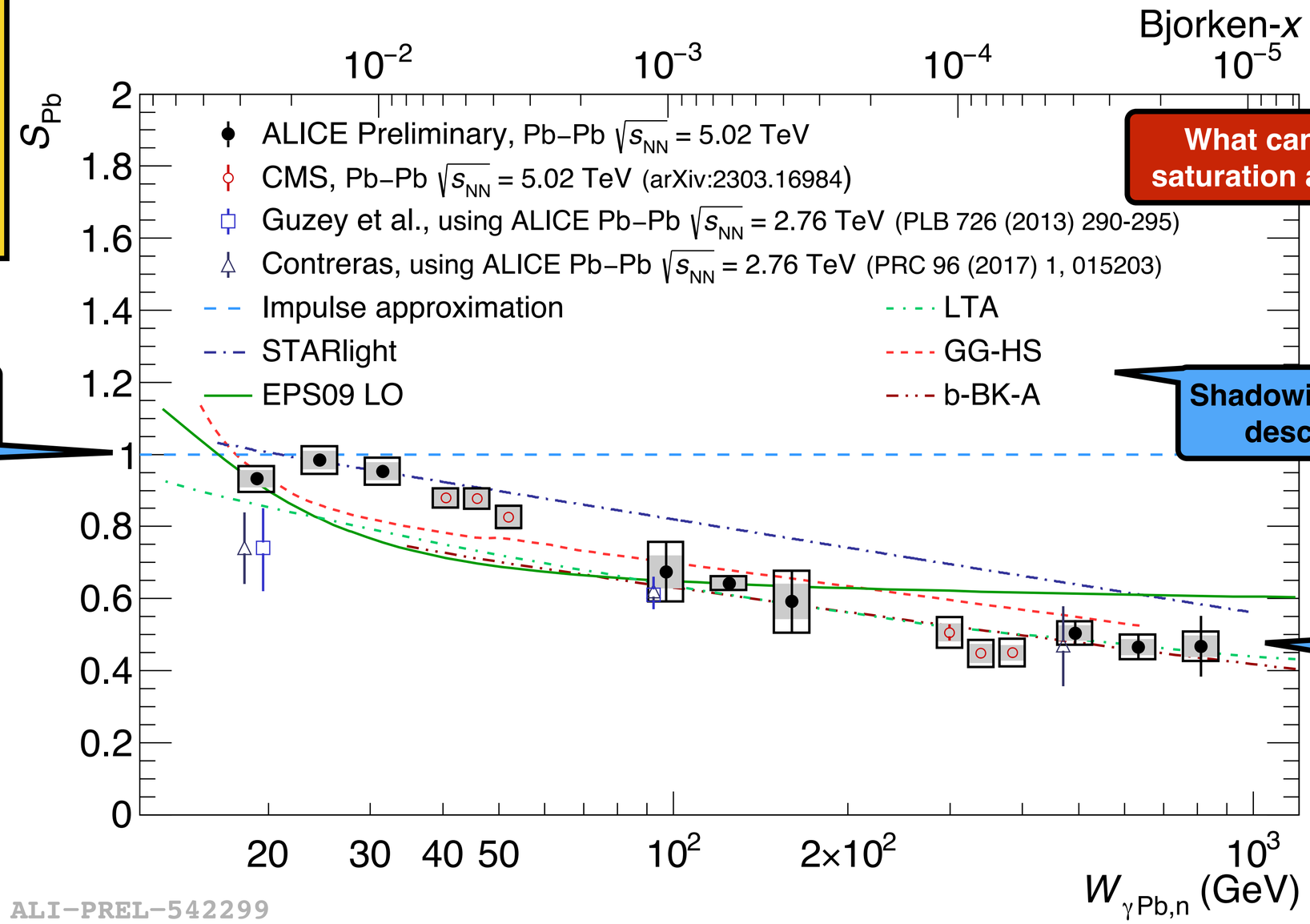

What can we do to disentangle saturation and shadowing models?

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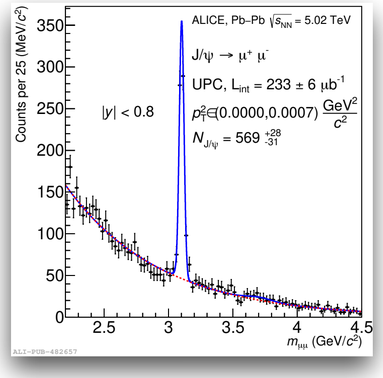
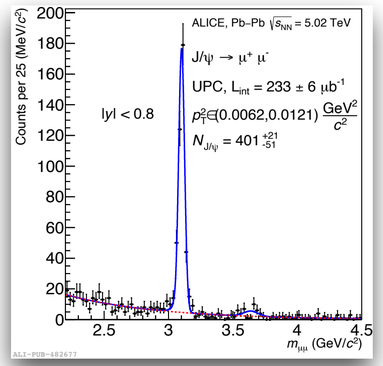
ALI-PREL-542299

J/ψ photonuclear production in Pb-Pb UPC
Mandelstam-*t* dependence

γPb collisions: Mandelstam-t dependence of coherent production

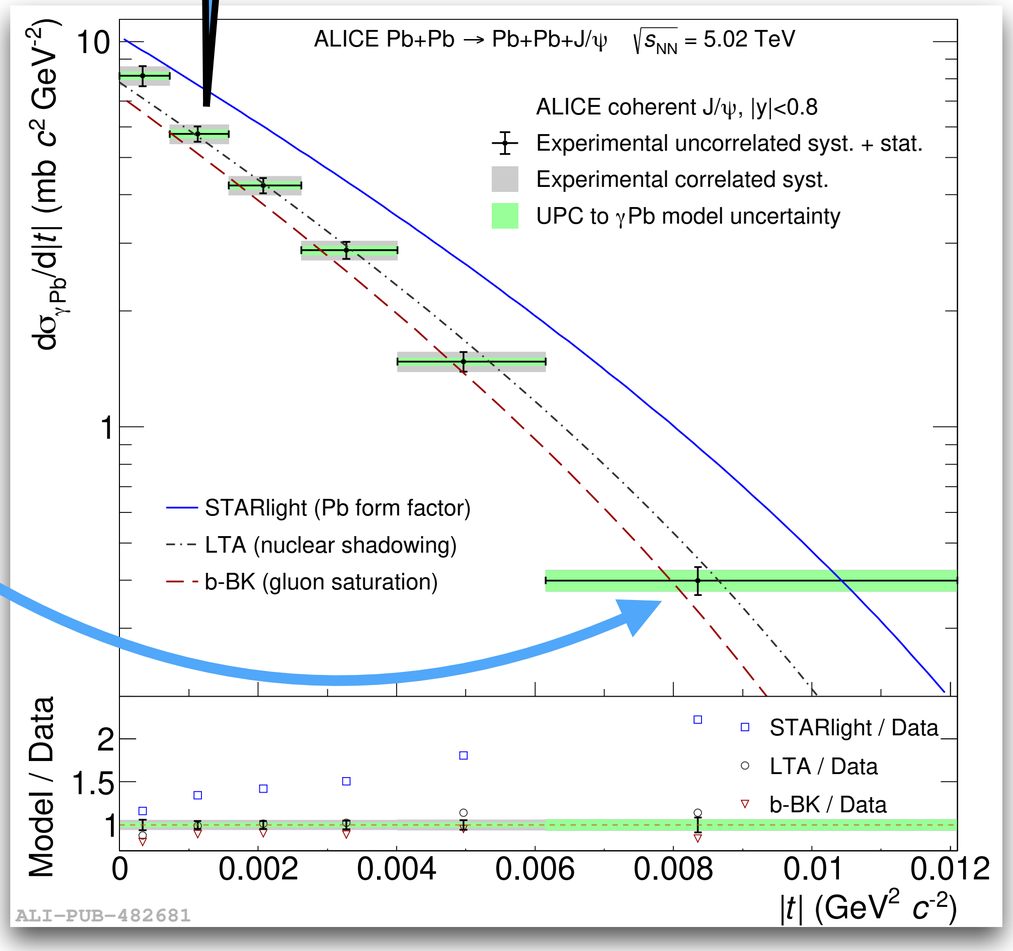
ALICE, PLB 817(2021) 136280





Very clear signals

HERA-like precision!



Guillermo Contreras, CTU in Prague

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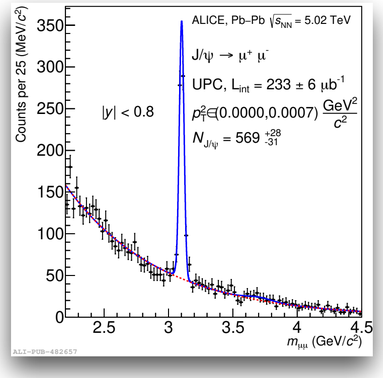

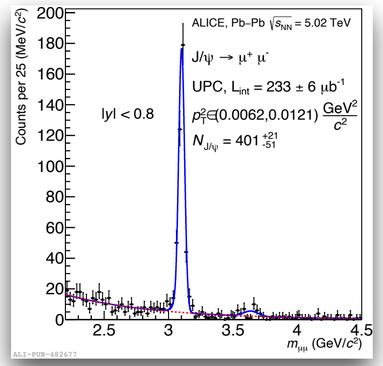

ALICE, PLB 817(2021) 136280

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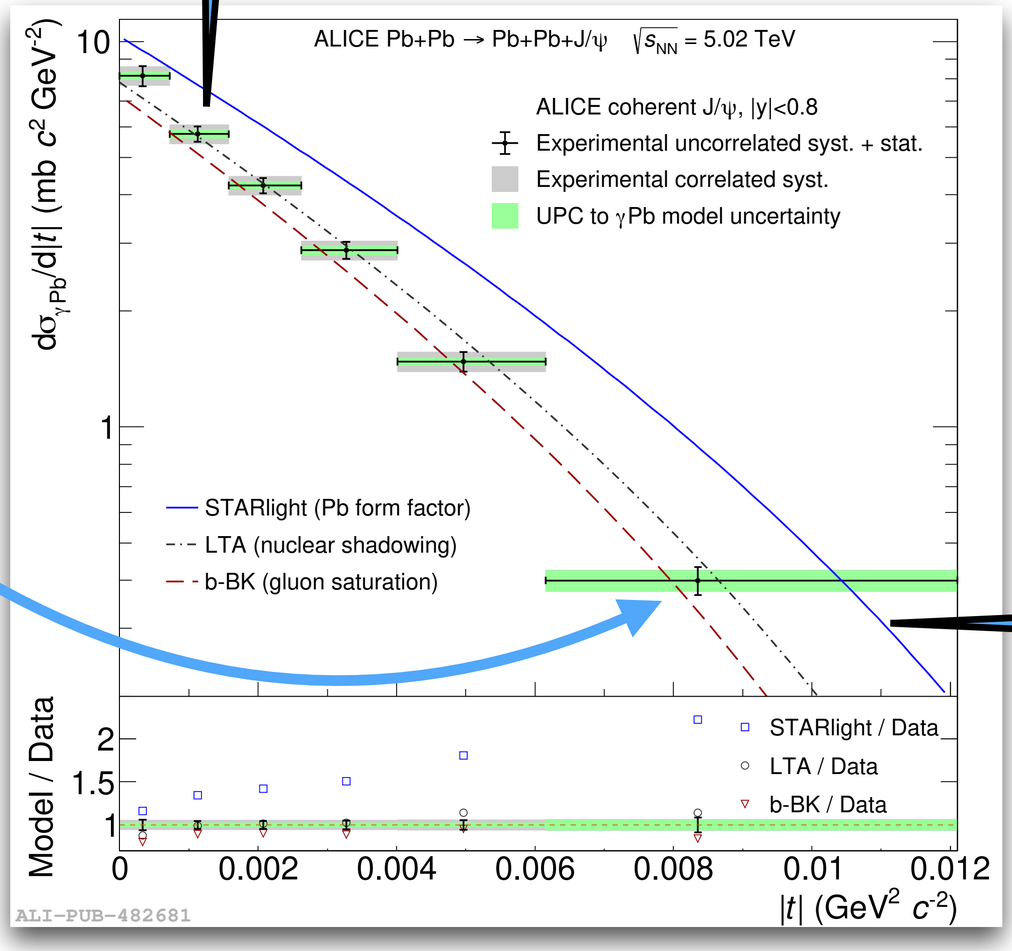

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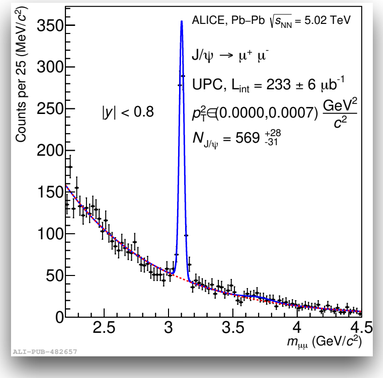
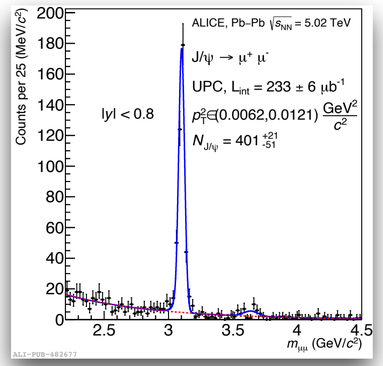
ALICE, PLB 817(2021) 136280





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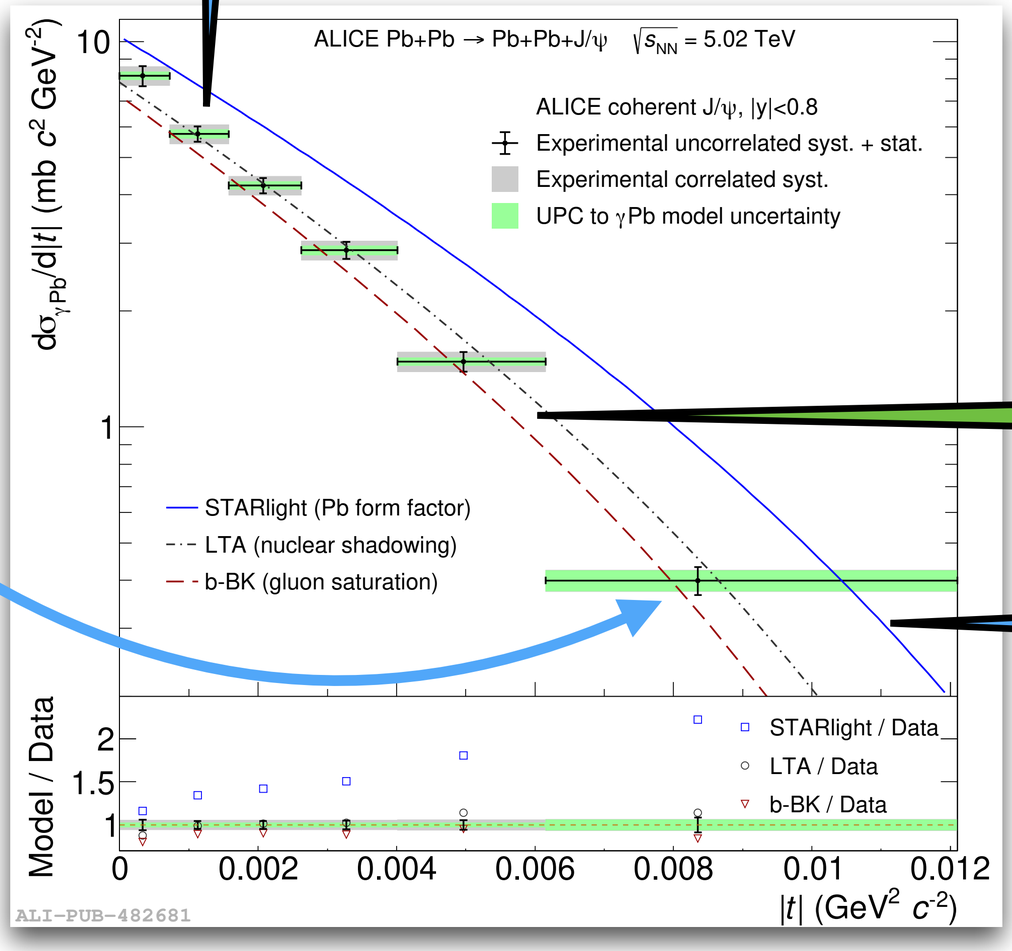

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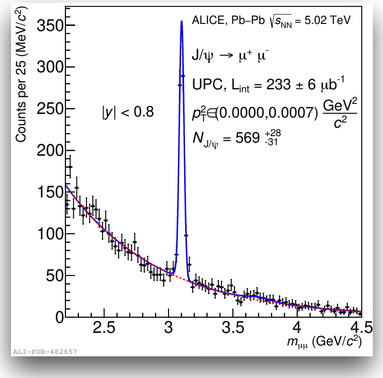
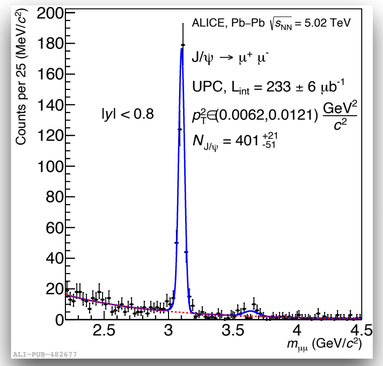
ALICE, PLB 817(2021) 136280





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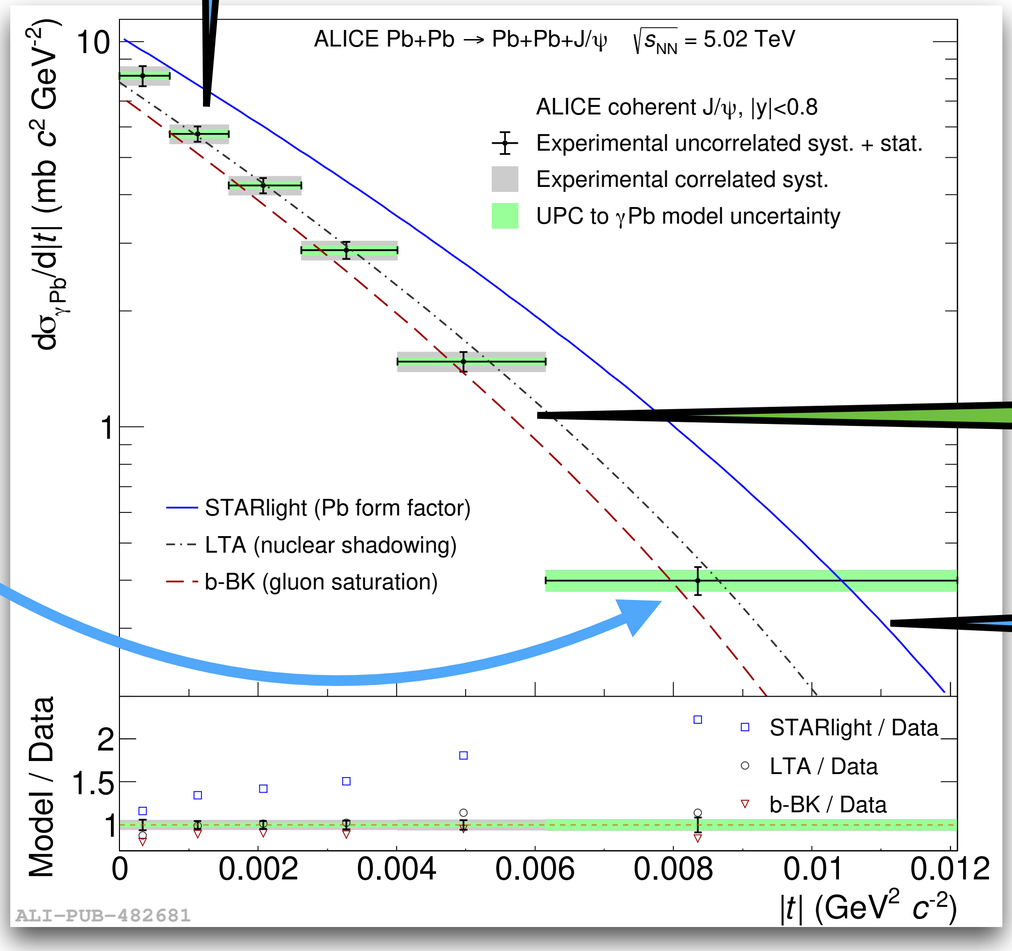

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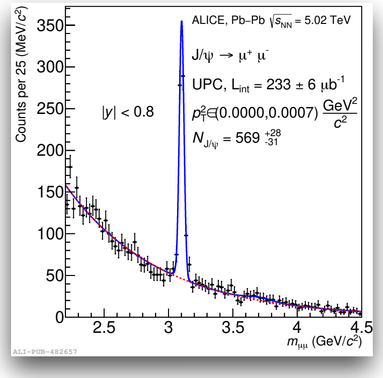

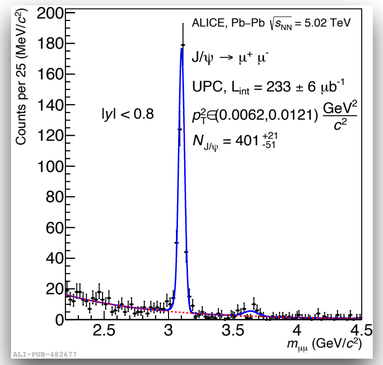

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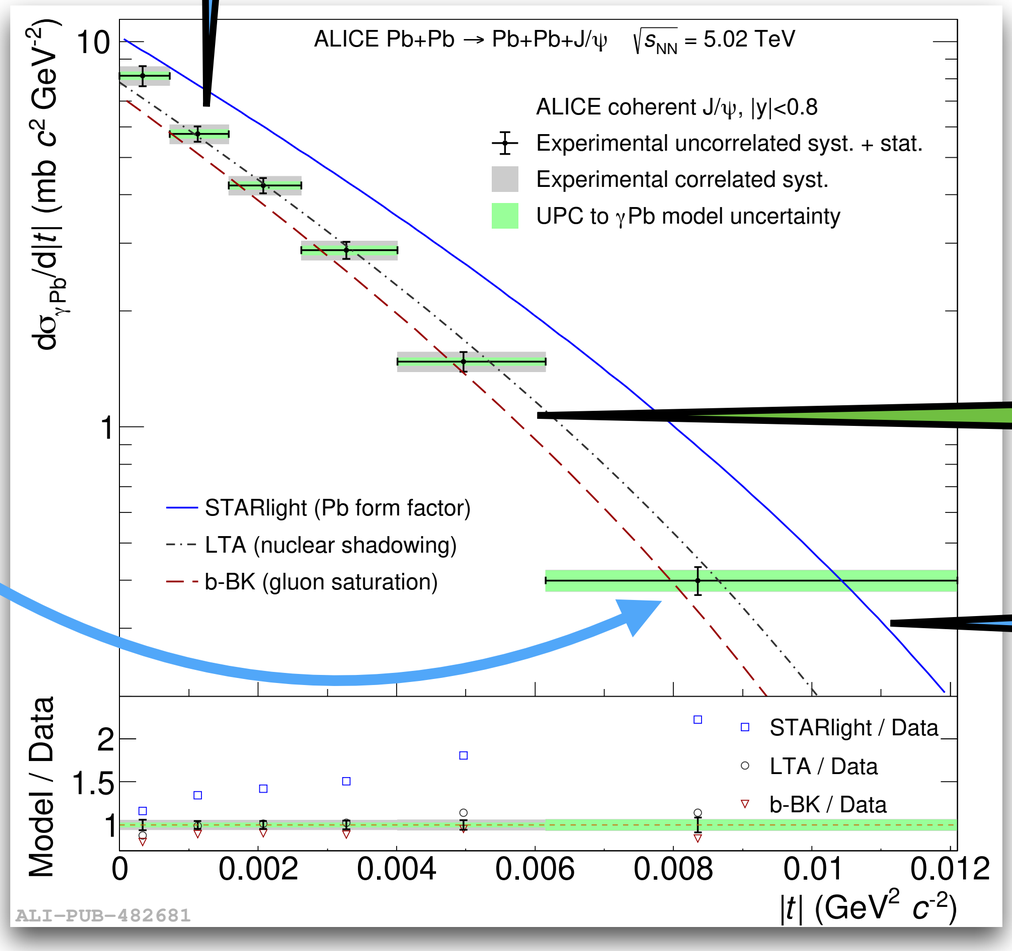

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Dynamic QCD effects seem to make the t-distribution steeper ... do nuclei grow with energy?

Guillermo Contreras, CTU in Prague

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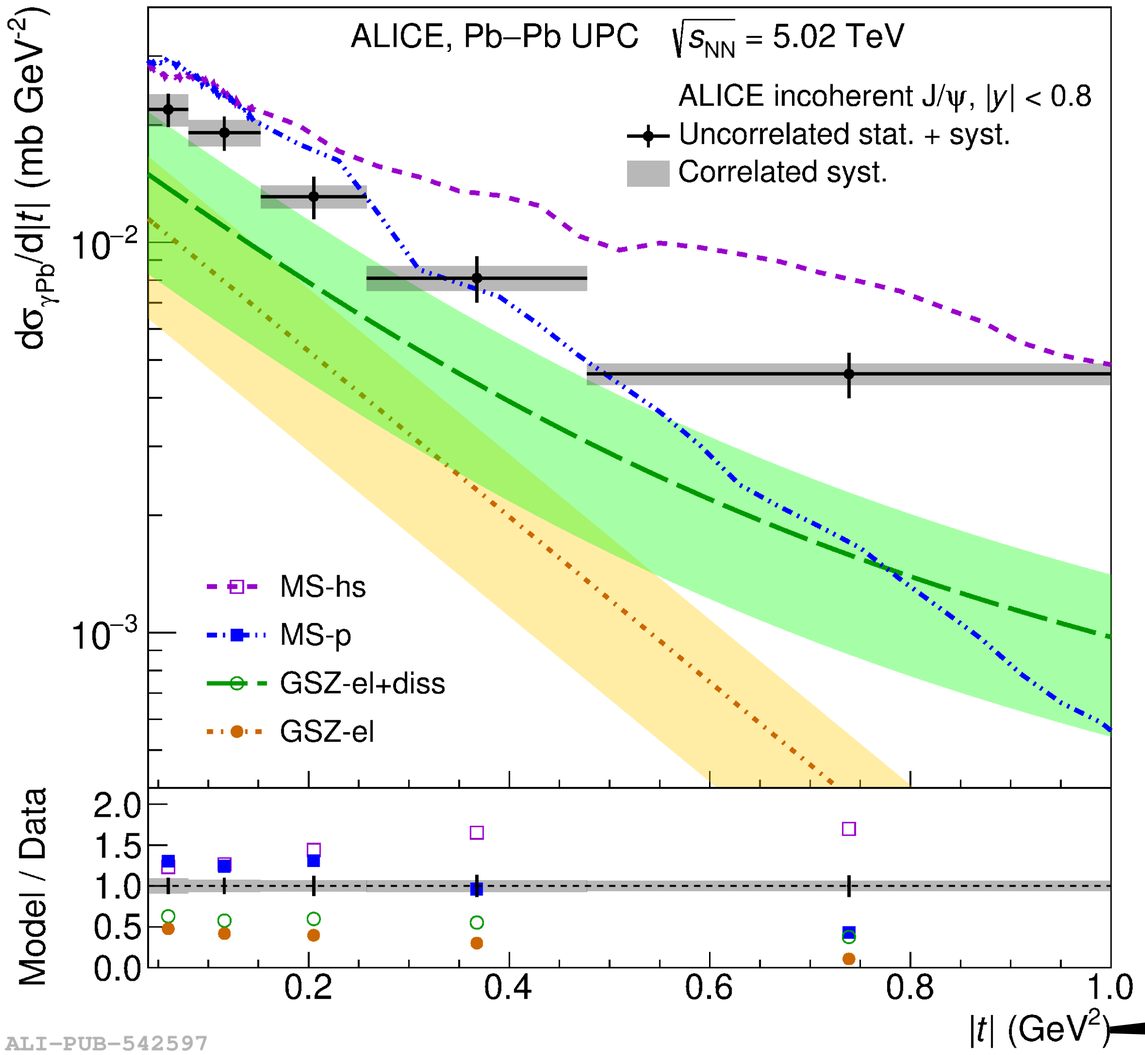

ltl related to the size of the target: effect of smaller structures appears at lager ltl

ALICE, arXiv 2305.06169

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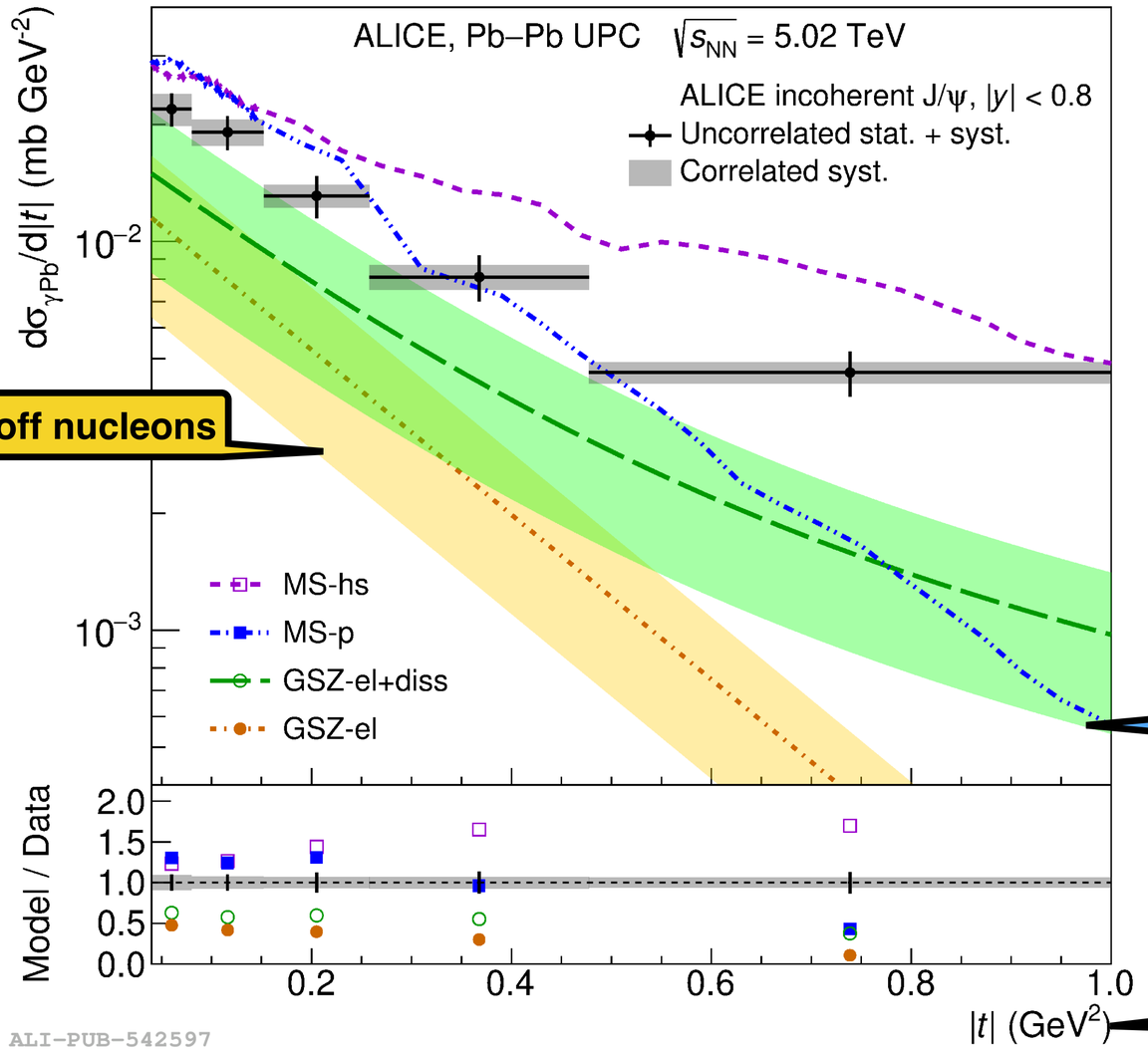

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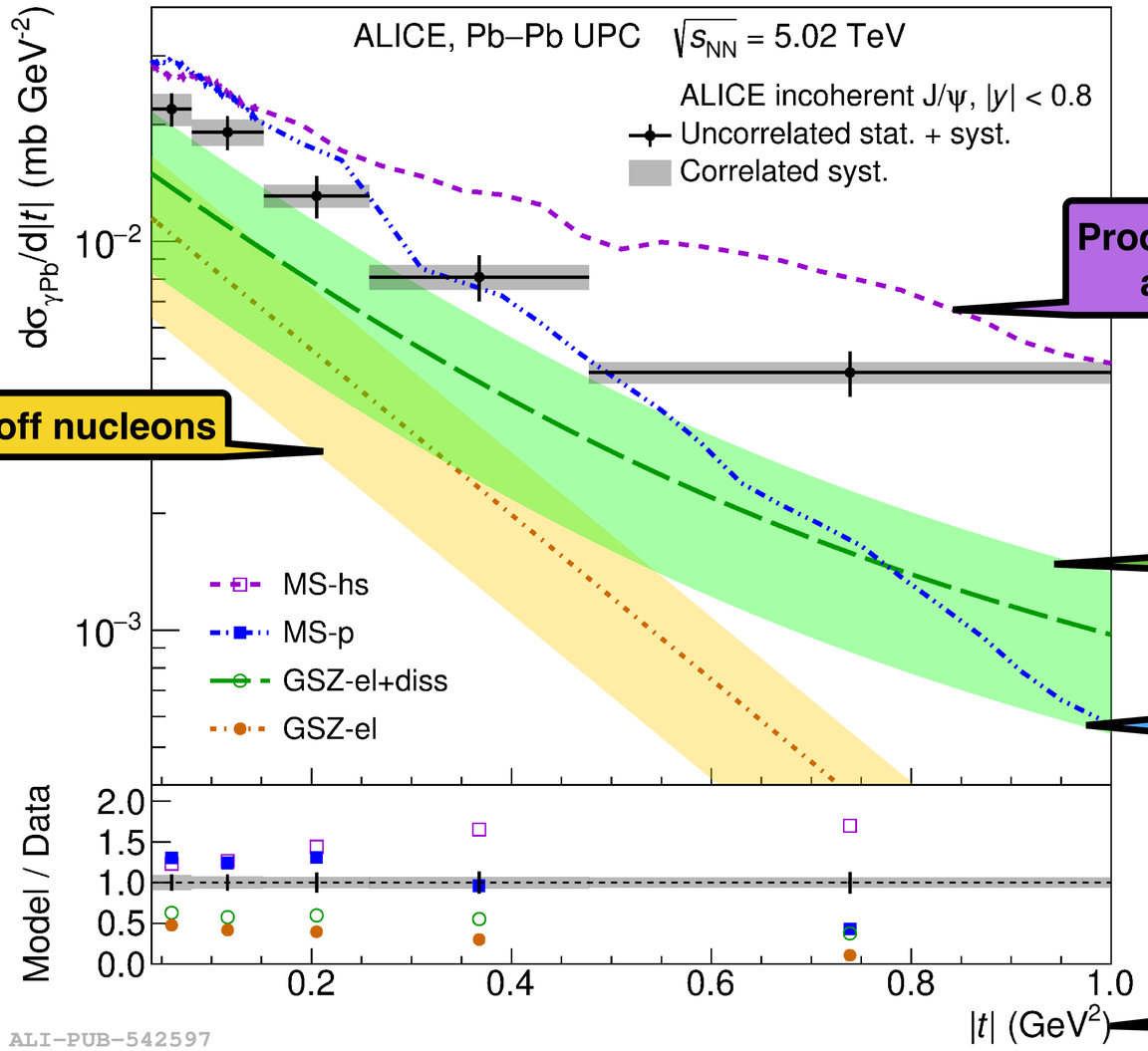

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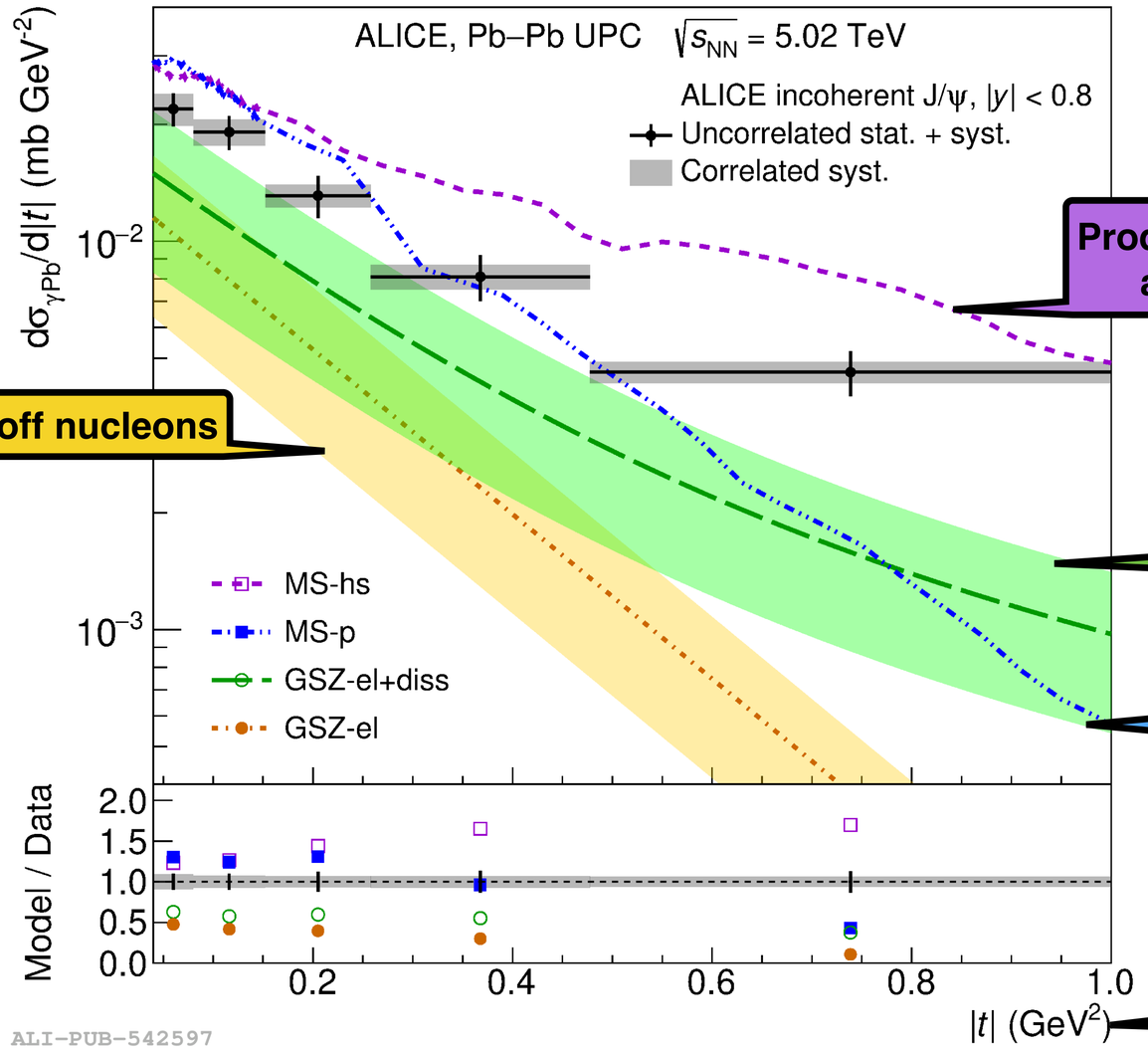

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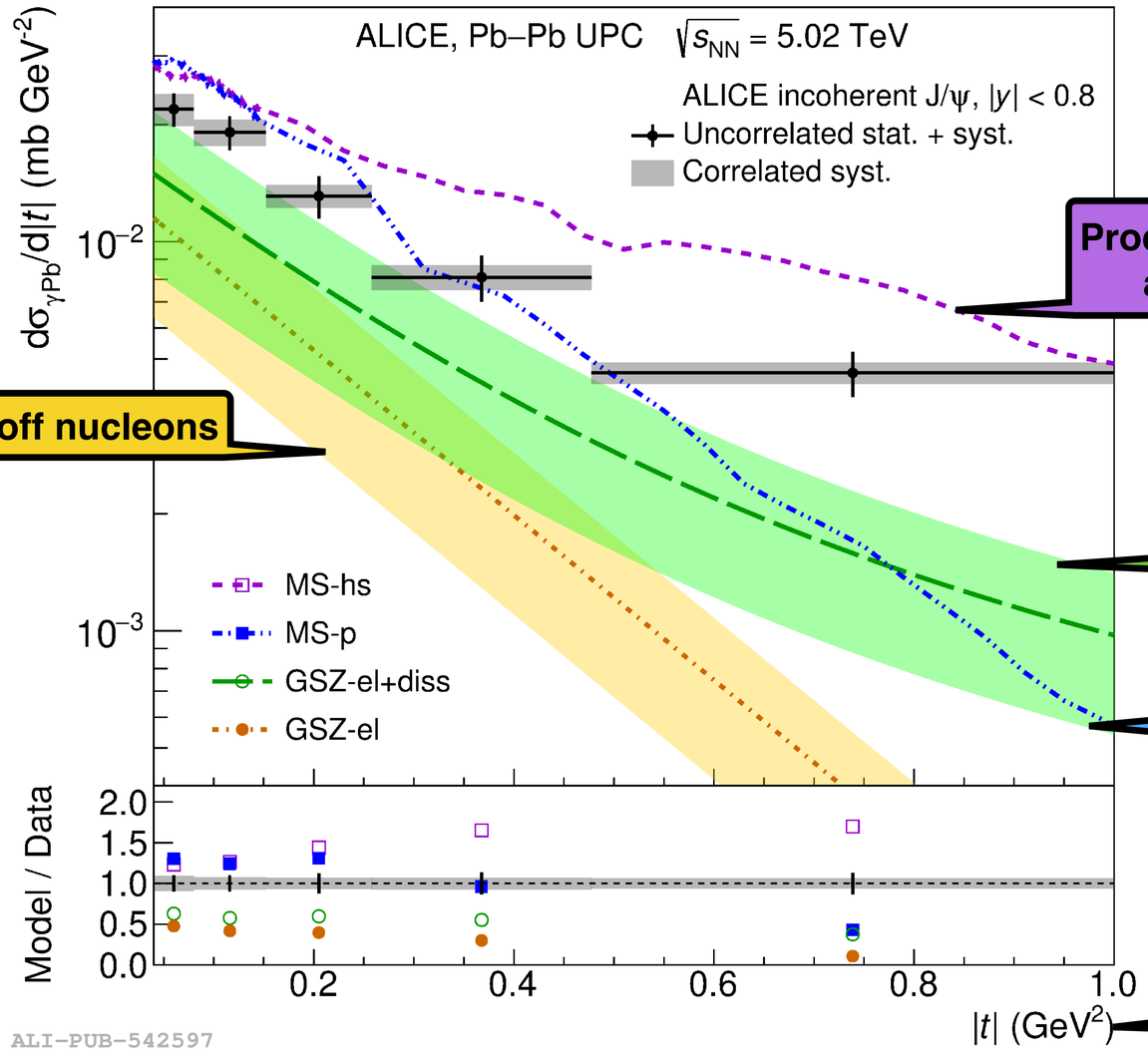

Production off nucleons and off hot spots

Larger ltl is sensitive to quantum fluctuations of the colour field at sub-nucleon size scales

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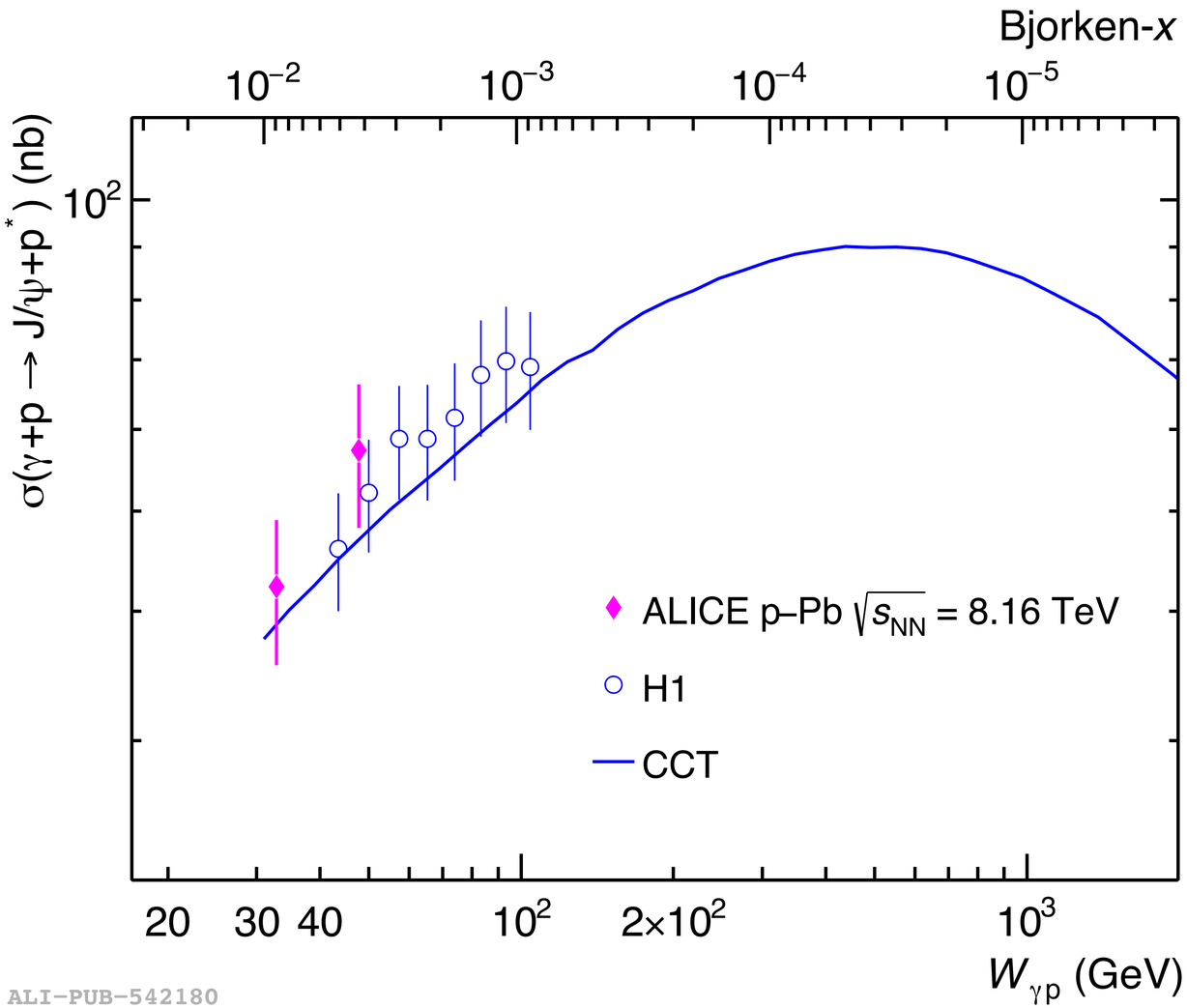

ALI-PUB-542180

ALICE, arXiv 2304.12403

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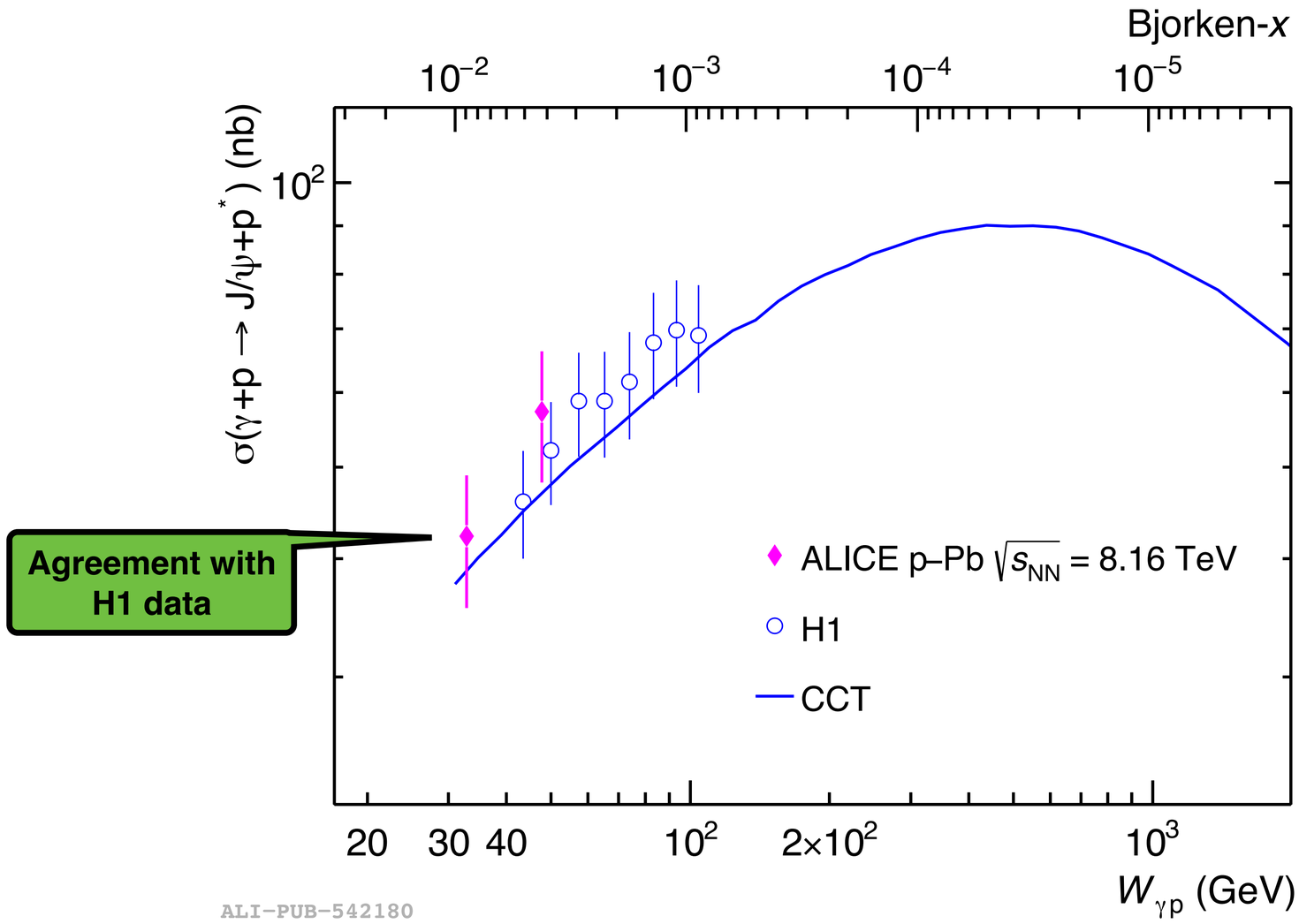

Agreement with H1 data

ALICE, arXiv 2304.12403

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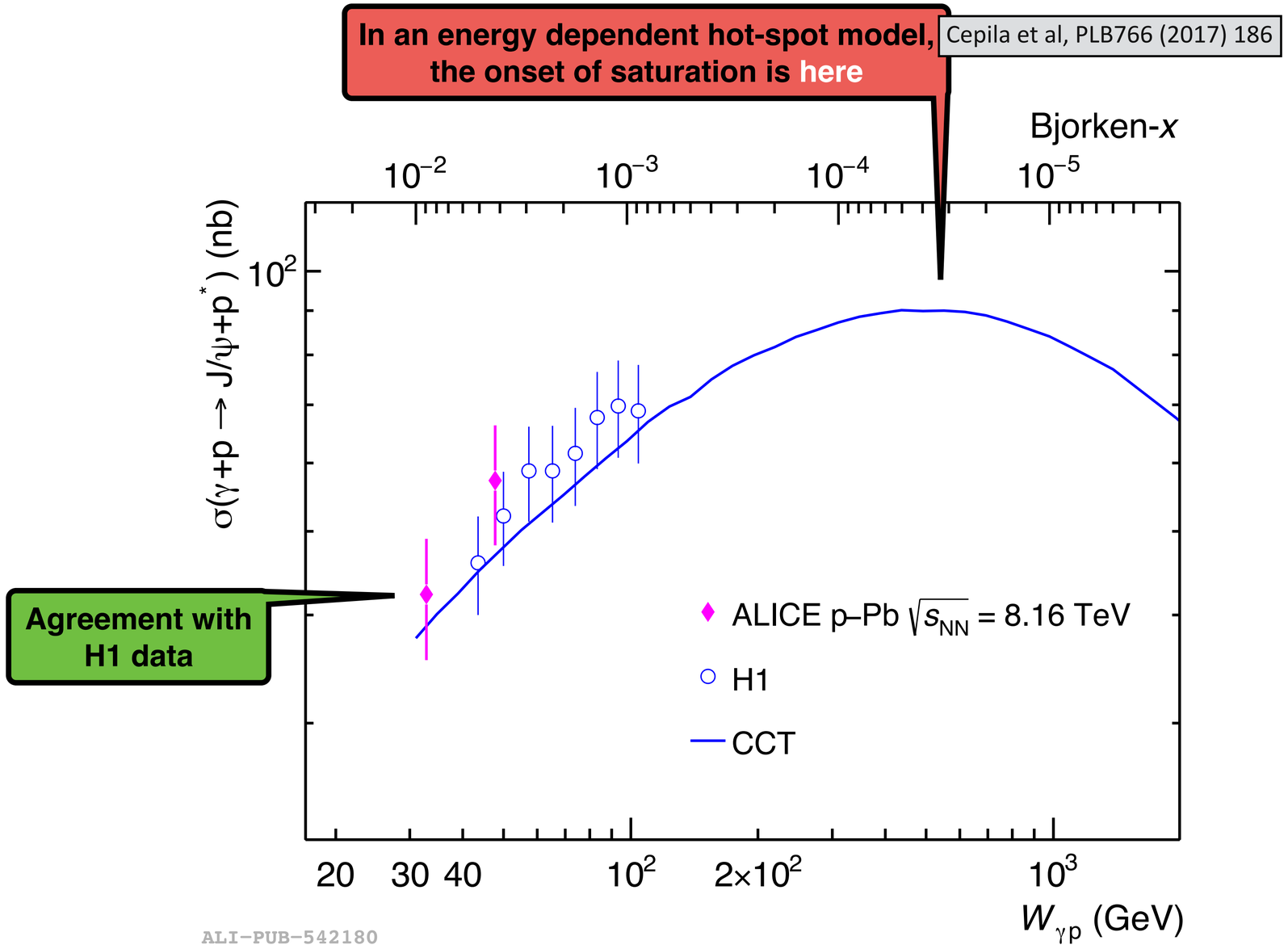

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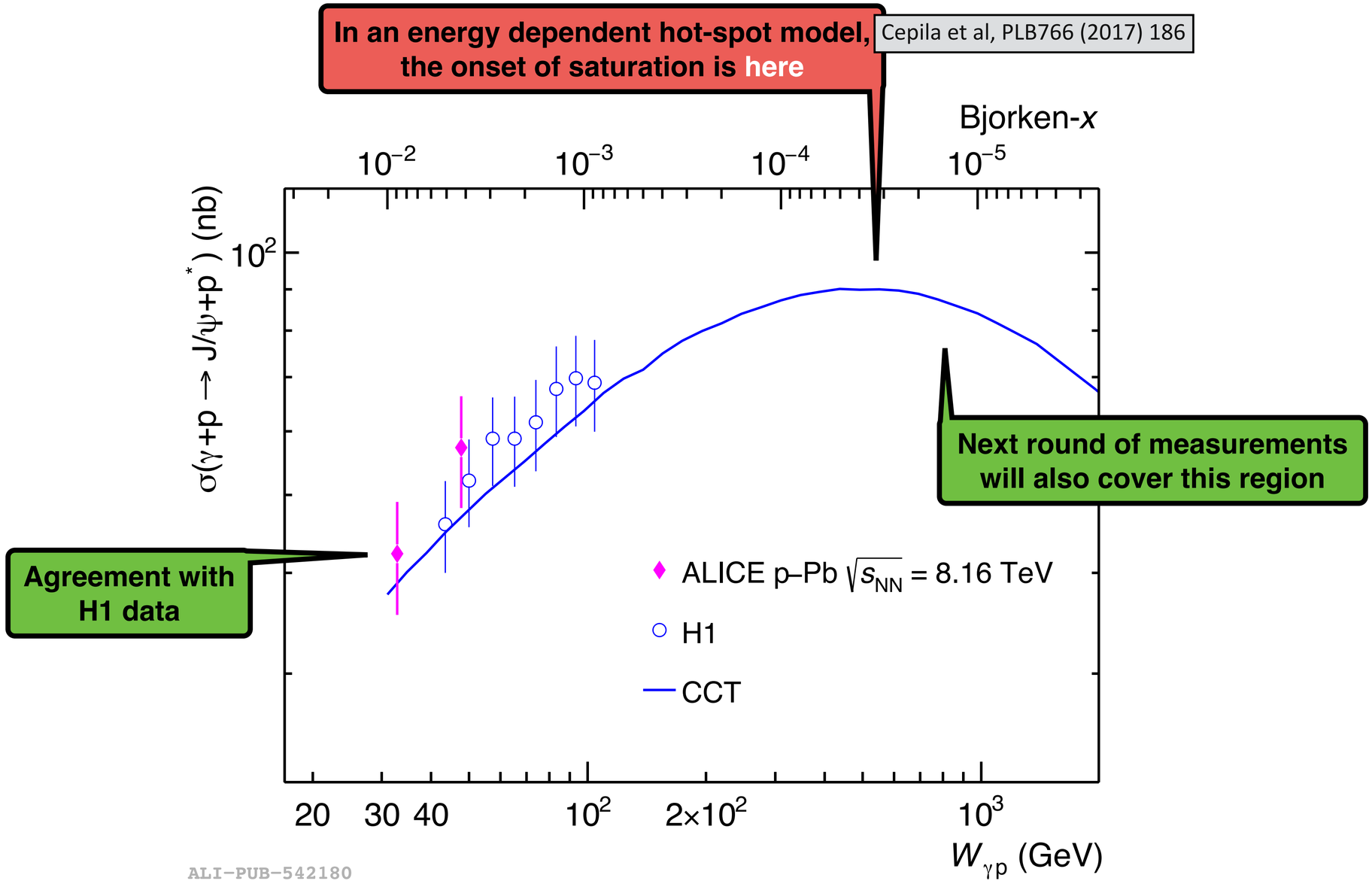

ALICE, arXiv 2304.12403

A brief look at the future

Expectations for Run 3+4 at the LHC

Current measurements were done with few thousand of J/ψ candidates from LHC Run 2 data

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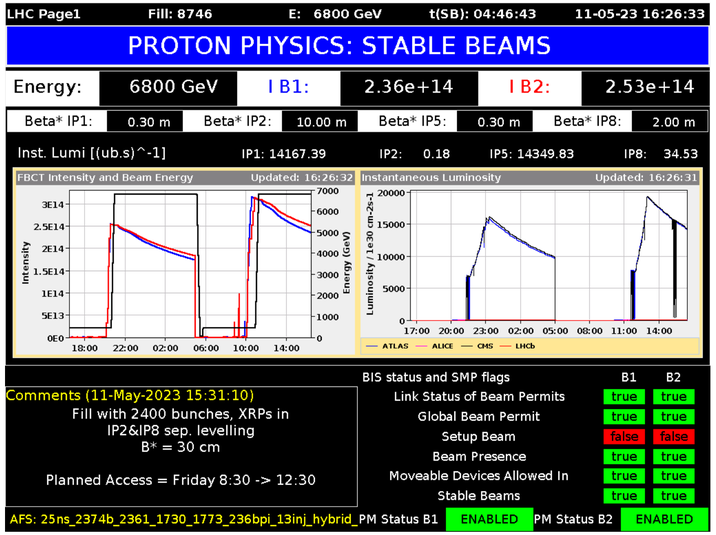

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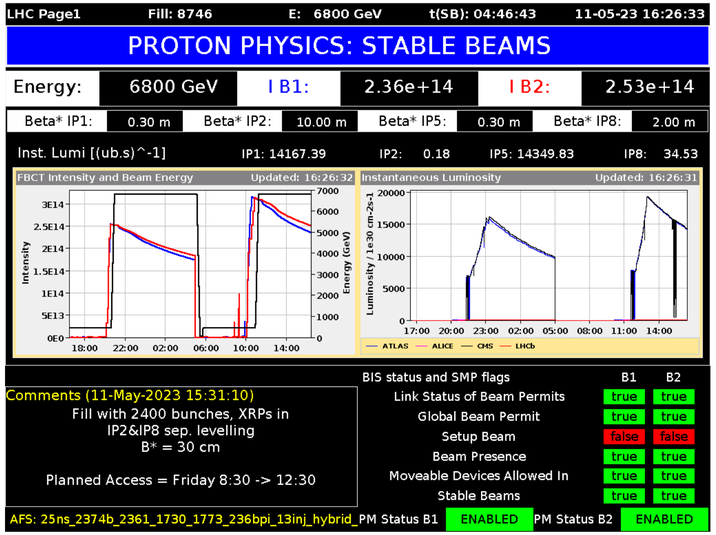

Pb-Pb UPCs: projections for 13 1/nb in the LHC Run 3 and 4

		PbPb				
Meson	σ	All Total	|y|<0.9 Total	|y|<2.4 Total	2.5<|y|<4 Total l	2<|y|<5 Total
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to \mathrm{K}^+\mathrm{K}^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$\mathrm{J}/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2\mathrm{S}) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$\Upsilon(1\mathrm{S}) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

Acceptances

Millions of J/ψ expected In Run 3+4

Citron et al, CERN Yellow Rep.Monogr. 7 (2019) 1159-1410

Summary and outlook

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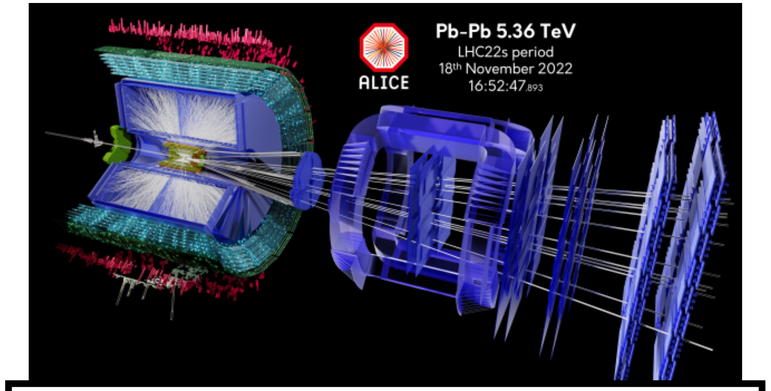
Large Pb-Pb data sample this year
Oxygen-Oxygen and proton-Oxygen collisions for 2024
Later on p-Pb (γp) collisions
....



Event from the 2022 data taking period

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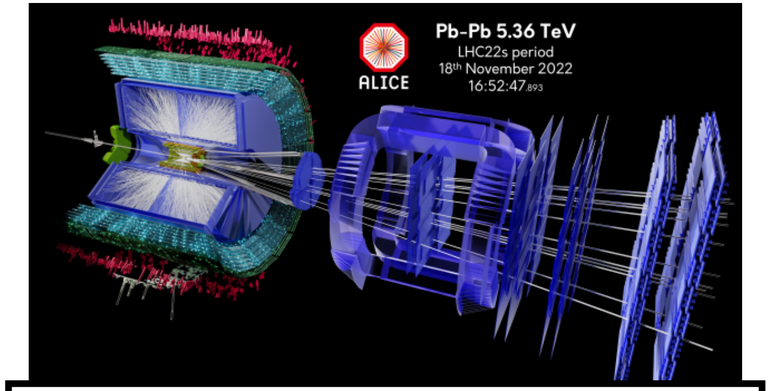
The LHC Run 3 has started!
Large Pb-Pb data sample this year
Oxygen-Oxygen and proton-Oxygen collisions for 2024
Later on p-Pb (γp) collisions
....



Event from the 2022 data taking period

Outlook

A bright future for photoproduction studies at the LHC with Run 3+4 data!