Exclusive and inclusive photonuclear interactions at the LHC

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Related Subjects

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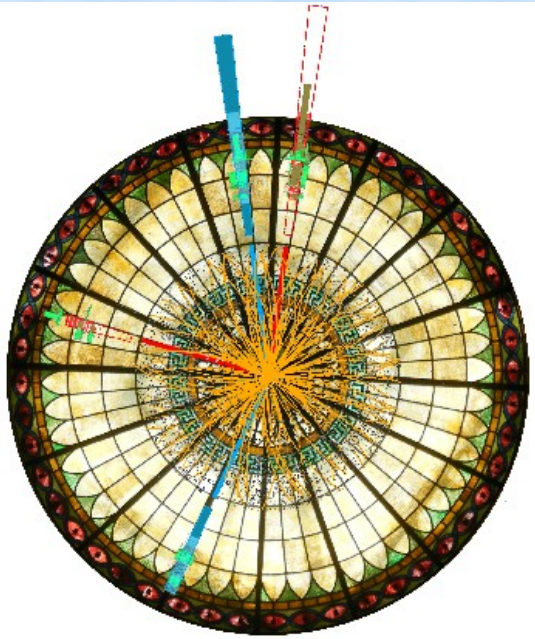
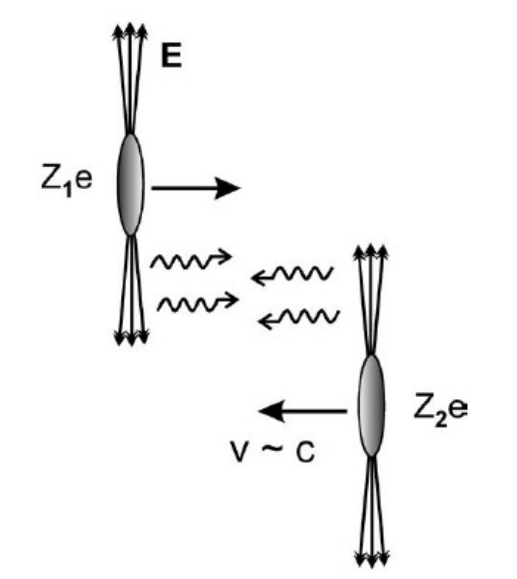


Photoproduction in ultra-peripheral collisions



The EM field of a relativistic heavy ion or proton corresponds to an equivalent flux of photons.

The photon flux scales as Z^2, so heavy ions are particularly good photon sources.

Photonuclear/photon-hadron interactions may occur in collisions ultra-peripheral collisons ($b>2R$).

Photon spectrum extends to γ/R (with R ≈ 7 fm for heavy ions).

Photon-induced interactions in eA vs. in pA or AA

- Energy reach very favorable in UPC:

LHC: $W_{\gamma N} \leq 500$ GeV for γA (Pb-Pb collisions)

$W_{\gamma N} \leq 1500$ GeV for γp (p-Pb collisions)

MEIC: $W_{\gamma N} \sim$ 15-70 GeV

eRHIC: $W_{\gamma N} \sim$ 50-100 GeV

LHeC: $W_{\gamma N} \sim$ 1300 GeV (γp); 800 GeV (γA) [E_e = 60 GeV]

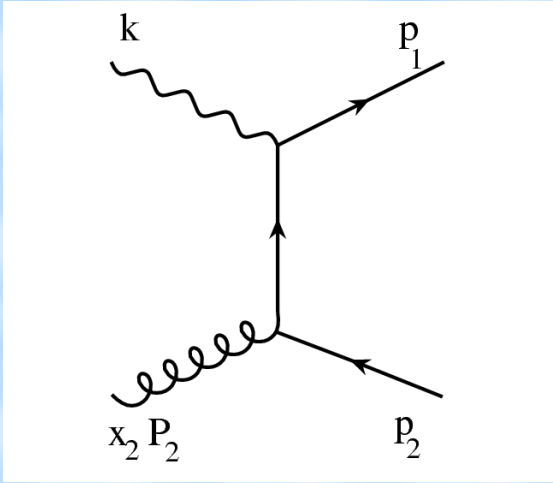
- UPC restricted to photoproduction ($Q^2 \approx 0$) because of the Form Factor.

Photon-induced interactions in eA vs. in pA or AA

- Experimental focus so far on *exclusive* processes (vector mesons, and some $\gamma\gamma \rightarrow$ X).

- But this is no fundamental limitation. Cross sections for many *inclusive* reactions are huge.

- Example: Photoproduction of charm, Pb+Pb $\rightarrow$ Pb+ccbar+X through photon-gluon fusion, cross section $\sigma \approx 1$ b! (Klein, Nystrand, Vogt, Phys. Rev. C 66 (2002) 044906).

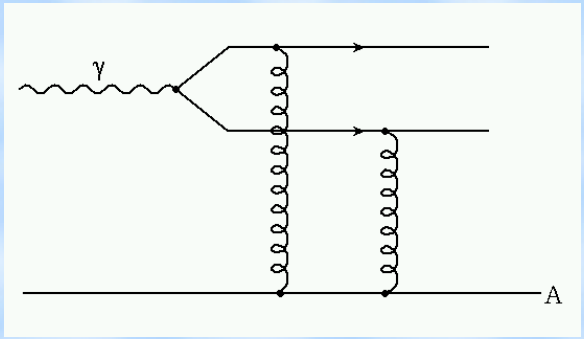


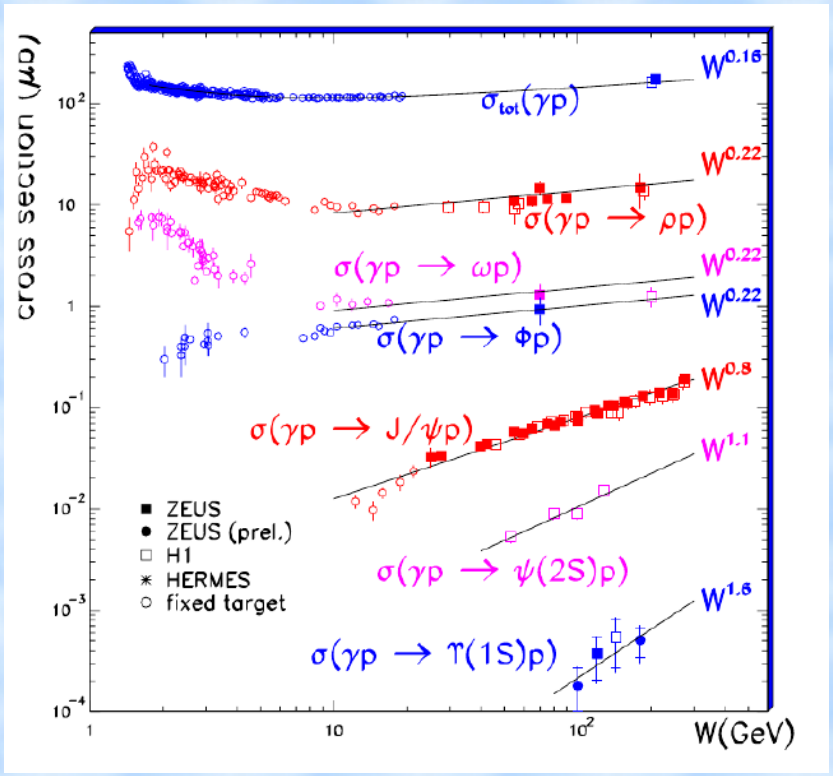
Exclusive heavy vector meson production

Exclusive photoproduction γ+p → V+p calculable from pQCD for heavy vector mesons, at LO:

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

Ryskin 1993





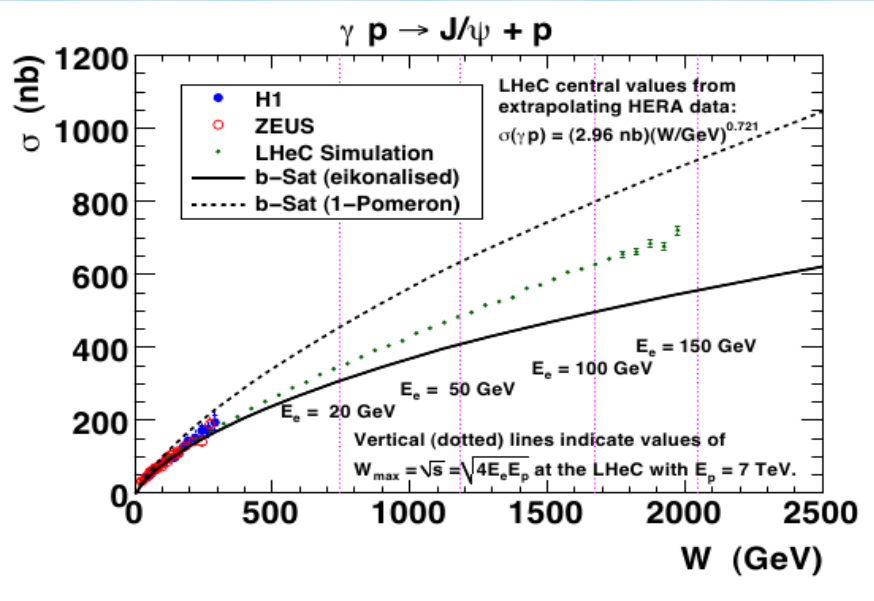
- The connection to the gluon distribution with a scale $(M_V/2)^2$ explains the rapid increase of the γ+p → J/ψ+p cross section, ∝ $W^{0.8}$.

- Normalization off by a factor ~2-3 supposedly due to higher order terms.

- Increase in cross section considerably slower for the light (ρ,ω) vector mesons, ∝ $W^{0.22}$.

Exclusive heavy vector meson production

Exclusive J/ψ production proposed as a key measurement at a future EIC and the LHeC e-p collider (arXiv:1206.2913):



"Due to the extremely clean final states produced, the relatively low effective x-values ($x_{eff} \sim (Q^2 + m^2)/(Q^2 + W^2)$) and scales ($Q^2 \sim (Q^2 + m^2)/4$) accessed [356, 390], and the experimental possibility of varying both W and t over wide ranges, J/ψ photoproduction ($Q^2 \to 0$) may offer the cleanest available signature to study the transition between the dilute and dense regimes of small-x partons."

Exclusive vector meson production in A+A collisions

- Very high rates and cross sections for exclusive vector meson production in A+A collisions at RHIC and LHC.

- A photon from the EM field of one of the nuclei interacts with the other nucleus and produces a vector meson.

- First calculation of this process performed 15 years ago:

PHYSICAL REVIEW C, VOLUME 60, 014903

Exclusive vector meson production in relativistic heavy ion collisions

Spencer R. Klein and Joakim Nystrand
Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 8 February 1999; published 16 June 1999)

The production rates are large enough that heavy ion colliders could be used as vector meson factories. The ϕ and J/ψ production rates at LHC are comparable to those at existing or planned meson factories based on e^+e^- annihilation.

Exclusive vector meson production in A+A collisions

- The cross section $d\sigma(A+A \rightarrow A+A+V)/dy$ is the product of the photonuclear cross section and the photon flux:

$$\frac{d\sigma}{dy} = \omega_1 \frac{dn_\gamma}{d\omega_1} \sigma_{\gamma A \rightarrow VA}(\omega_1) + \omega_2 \frac{dn_\gamma}{d\omega_2} \sigma_{\gamma A \rightarrow VA}(\omega_2)$$

- The photon energy, ω, is given by the vector meson rapidity:

$$\omega_{1,2} = \frac{1}{2} M_V e^{\pm y}$$

- Away from y=0 there is a two-fold ambiguity in ω for symmetric systems.

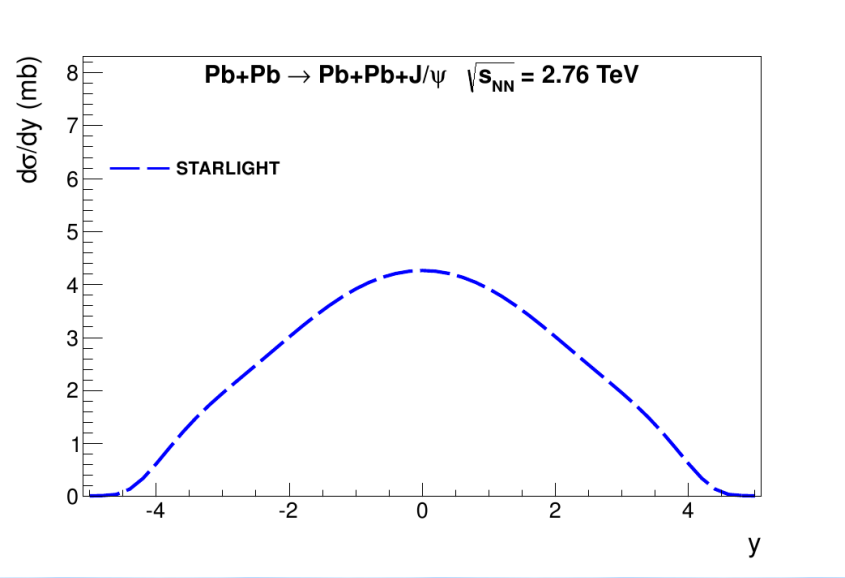
Exclusive vector meson production in A+A collisions

Summary of calculation by Klein, Nystrand 1999:

- Photon flux: Weizsäcker-Williams spectrum calculated in impact parameter space.

- Photonuclear cross section: γ-p from data scaled to γ-A using a Glauber model.

- Implemented in the STARLIGHT Monte Carlo event generator (http://starlight.hepforge.org/).



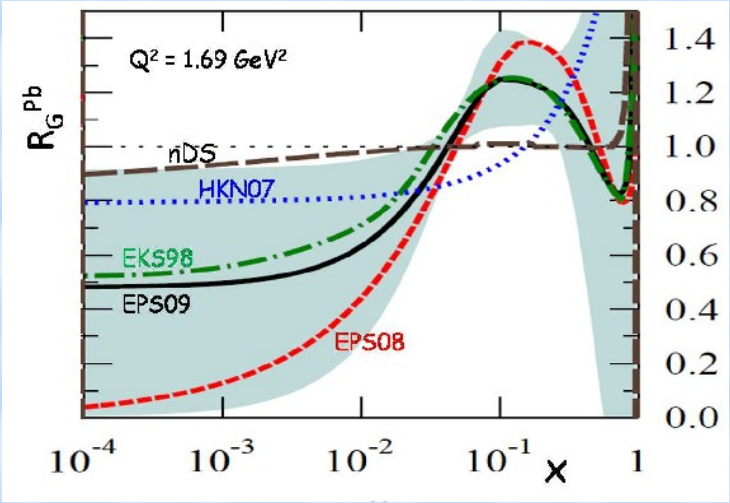
Note: Calculation identical to 1999 paper, only difference is $\sqrt{s}$ = 5.5 → 2.76 TeV.

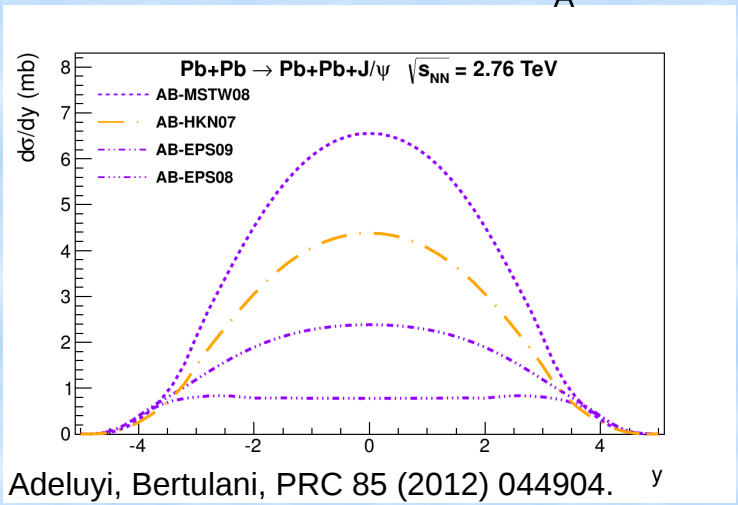
Nuclear gluon distribution and the photoproduction cross section

The proportionality $d\sigma/dt \propto [g(x,Q^2)]^2$ factorizes through the whole calculation leading to $d\sigma/dy \propto [g(x,Q^2)]^2$.

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = \frac{\alpha_s^2 \Gamma_{ee}}{3\alpha M_V^5} 16\pi^3 [xg(x, \frac{M_V^2}{4})]^2$$

Uncertainty in nuclear gluon distribution translates into different cross section for photoproduction of J/ψ at mid-rapidity ($d\sigma/dy \propto [g_A(x,Q^2)]^2$).





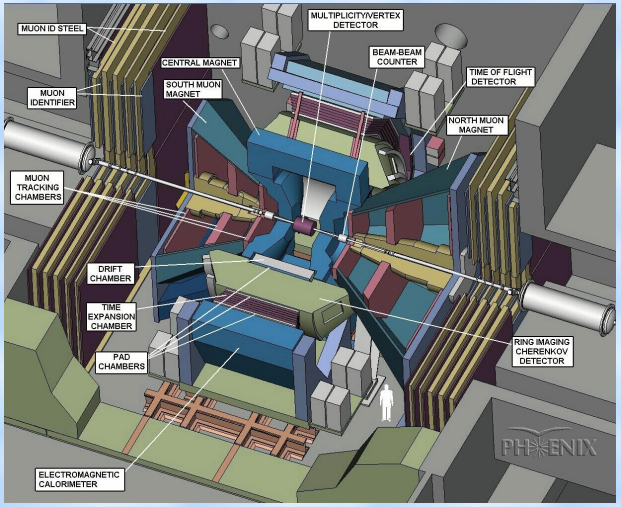
Adeluyi, Bertulani, PRC 85 (2012) 044904.

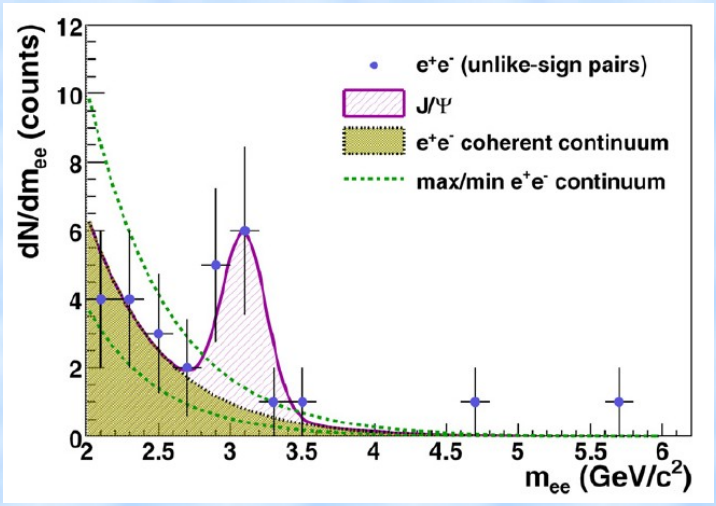
$R_G = g_A(x,Q^2)/[A \cdot g_p(x,Q^2)]$

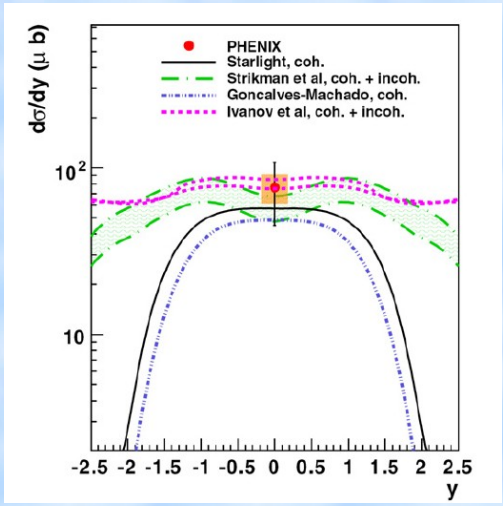
Results on exclusive J/ψ production

First result on exclusive photoproduction of J/ψ in heavy-ion collisions by PHENIX (Phys. Lett. B 679 (2009) 321).

The electrons were identified in the central tracking arm ($|\eta|<0.35$, $\Delta\varphi=2x90^{o}$). The trigger required a signal in one of the ZDCs.







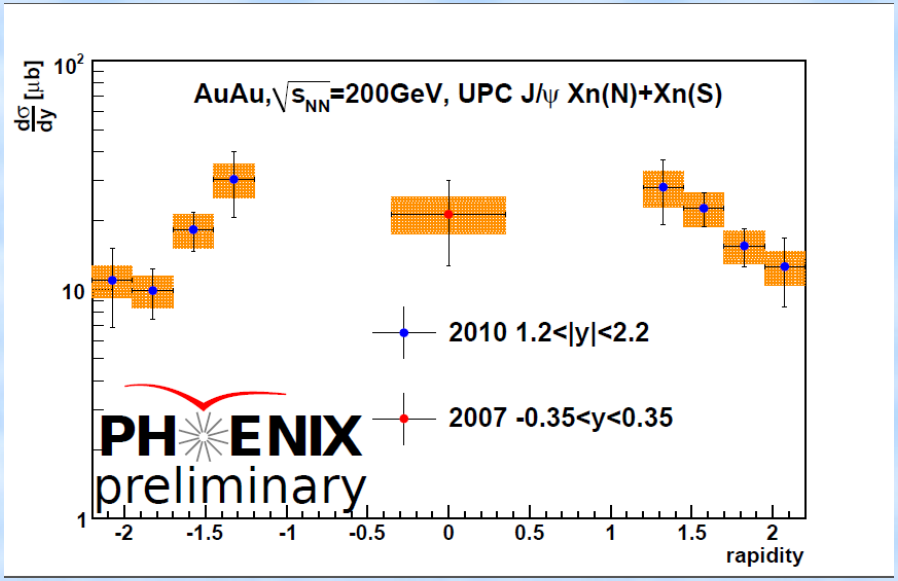
Measured $d\sigma(y=0)/dy = 76 \pm 33$ (stat.) ± 11 (syst) μb, requiring at least of of the nuclei to break up because of exchange of an additional photon.

Includes both coherent and incoherent photoproduction.

Result in agreement with models, but too little statistics to draw any conclusions regarding shadowing (around $x \sim 10^{-2}$).

Results on exclusive J/ψ production

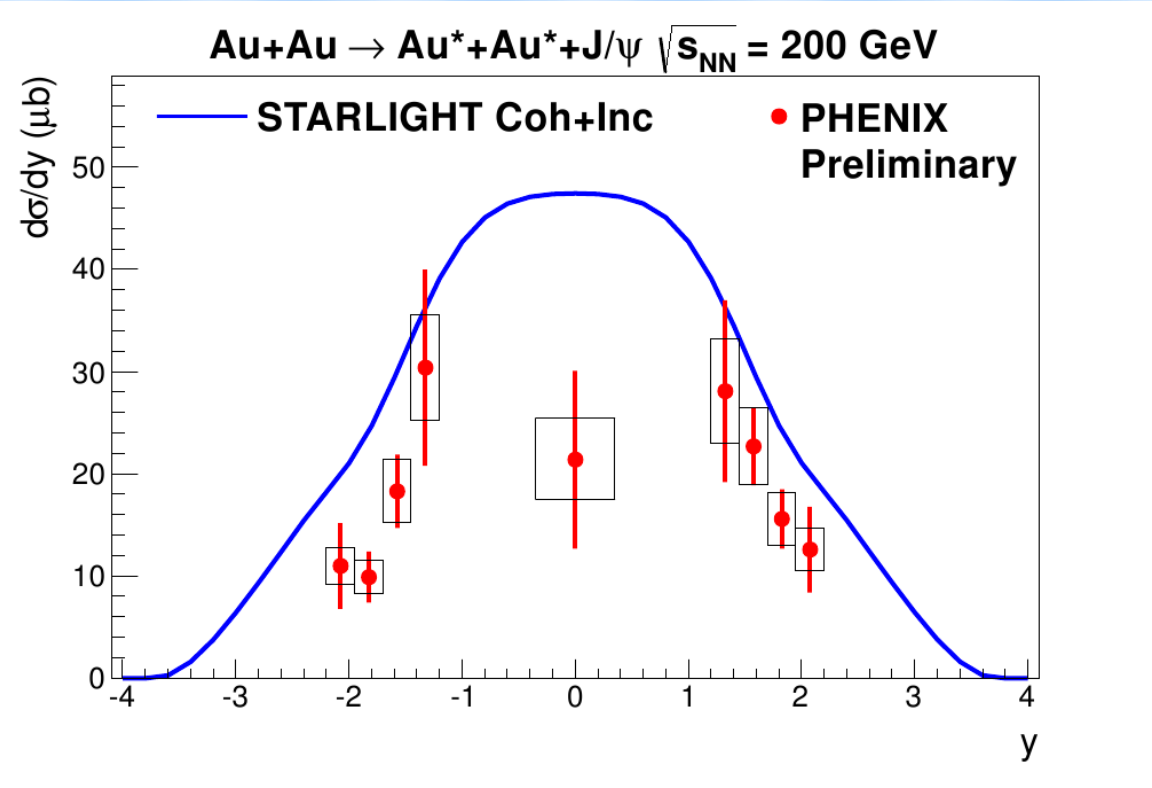
Updated preliminary results with better statistics from 2007 and 2010 (Mickey Chiu, Workshop on photon-induced collisions at the LHC 2014):



- Includes also results from PHENIX muon arm (1.2 < |y| < 2.2).

- Requires that both nuclei break up. This can happen through the exchange of multiple photons in a single event, even for coherent production.

Results on exclusive J/ψ production



STARLIGHT includes only hadronic effects (no gluon shadowing).

Incoherent calculation not available at the time of the PHENIX paper.

Klein, Nystrand, Phys. Rev. C 60 (1999) 014903.

- Both nuclei break up.

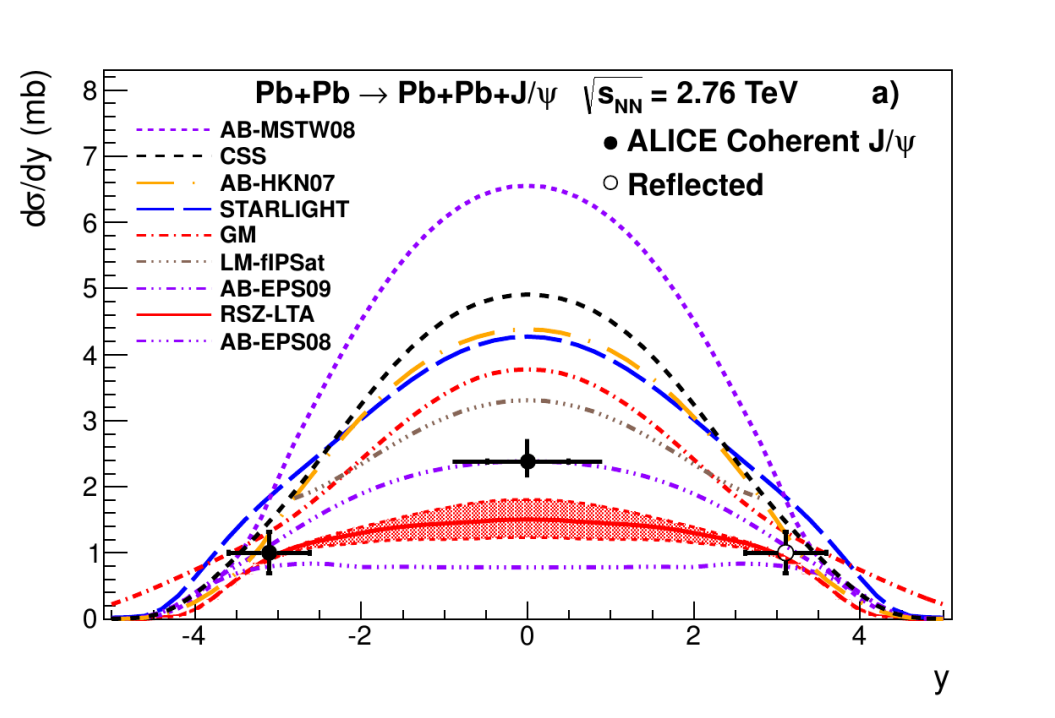
- Enhances the relative contribution from incoherent interactions.

- PHENIX result 2.7σ below STARLIGHT at y=0.

Results on exclusive J/ψ production

Recent measurement by ALICE at LHC with higher precision

Strong suppresion of the cross section at midrapidity ($x \sim 10^{-3}$) compared with Impulse Approximation and STARLIGHT calculation.

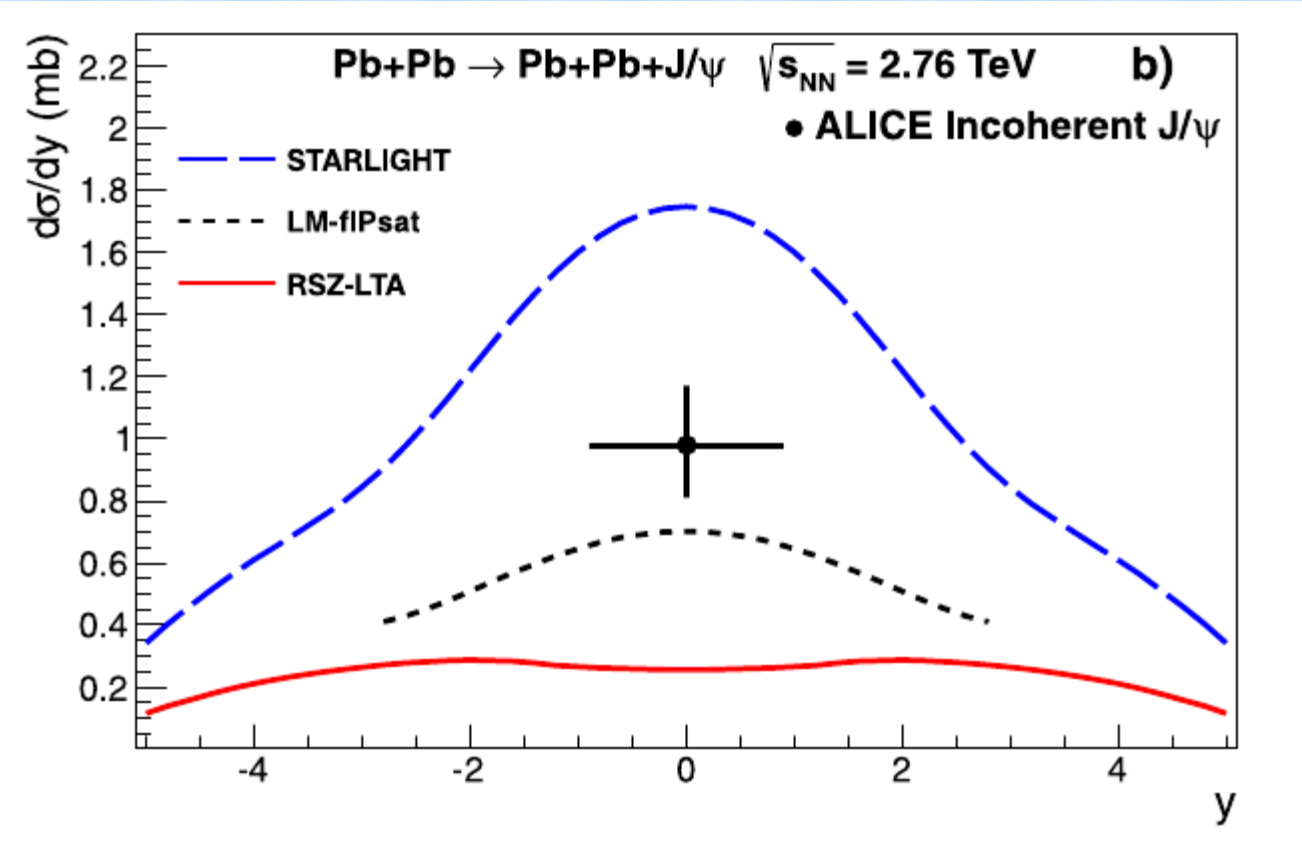


Result consistent with models which include gluon shadowing according to the EPS09 parameterization (AB-EPS09, RSZ-LTA).

ALICE Collaboration, Phys. Lett. B 718 (2013) 1273 (Muon arm), EPJC 73 (2013) 2617 (Central Barrel).

Results on exclusive J/ψ production

Fewer predictions for incoherent production. Experimental result between the two extreme predictions (STARLIGHT, RSZ-LTA).



ALICE Collaboration, EPJC 73 (2013) 2617.

Results on exclusive J/ψ production

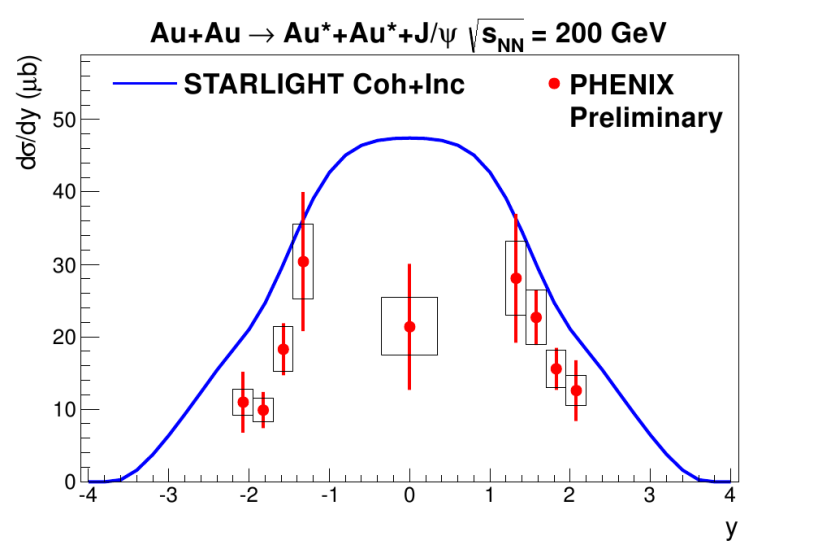
More details on the results from ALICE in the talk by Jaroslav Adam, including results on $\psi(2S)$.

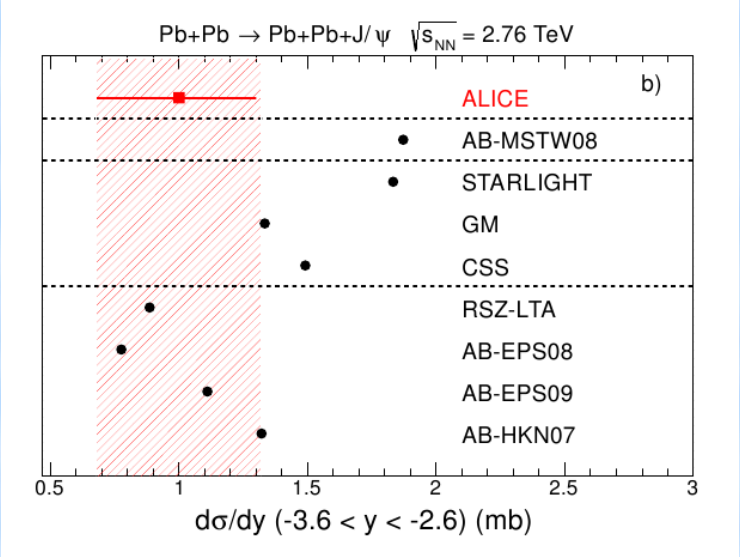
Results on exclusive J/ψ production

It turns out that a J/ψ at y=0 at RHIC ($\sqrt{s_{NN}}$ = 200 GeV) corresponds to about the same Bjorken x as a J/ψ at y=3 at the LHC ($\sqrt{s_{NN}}$ = 2.76 TeV).

One would thus expect the same reduction in the cross section due to shadowing in both cases.

Phys. Lett. B 718 (2013)1293.





Ratio STARLIGHT/data

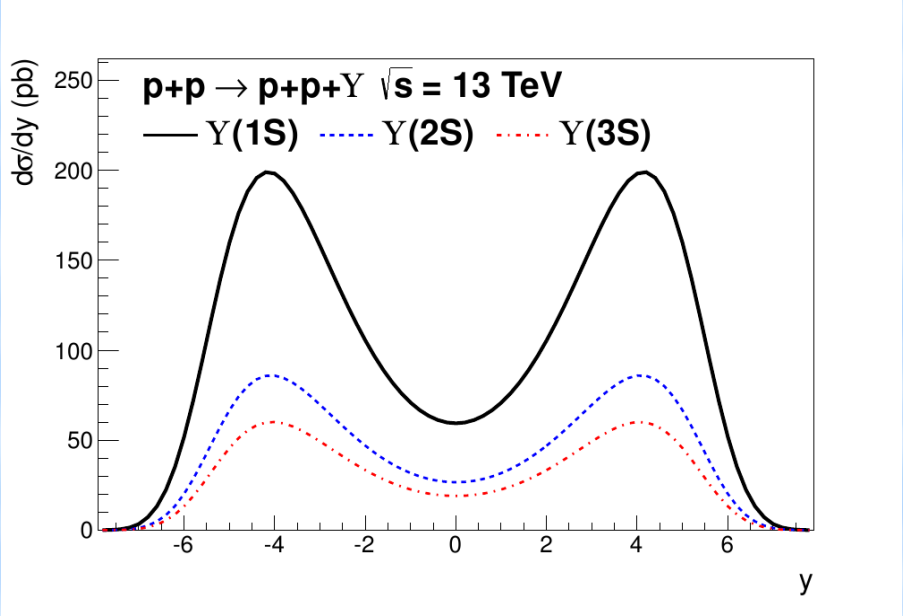
PHENIX (y=0): 2.2 ALICE (y=3.1): 1.7

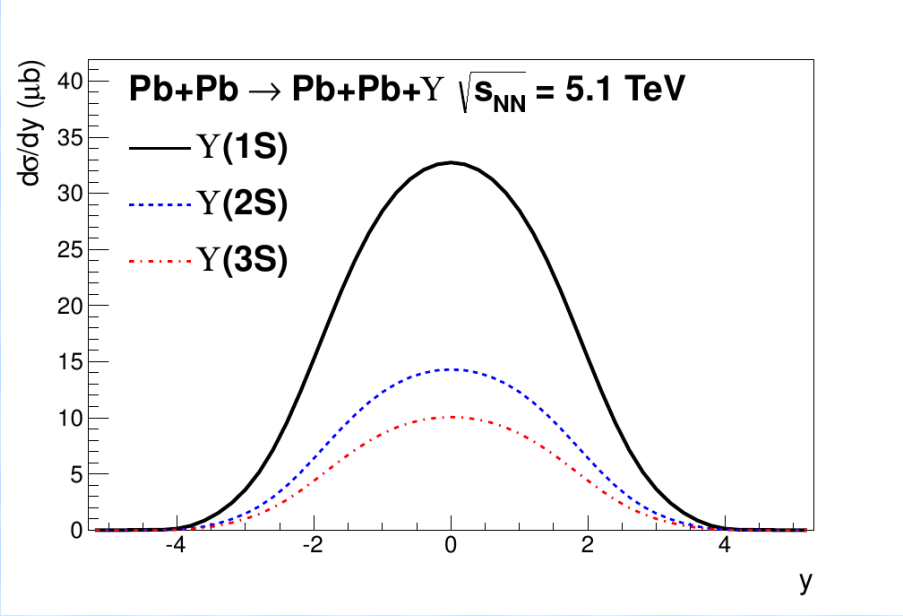
⇒ OK considering the errors.

Outlook heavy vector mesons

Υ(1S,2S,3S) might be within reach in p-p, p-Pb and Pb-Pb collisions during LHC Run 2.

STARLIGHT predictions:





- $\sigma(\gamma+p\rightarrow\Upsilon(1S)+p)$ from ZEUS and H1 data. QCD inspired power law $\sigma \propto W^{1.7}$ assumed.
- Cross section Υ(2S), Υ(3S) calculated from the dilepton coupling $\Gamma_{\Upsilon\rightarrow e+e-}$.
- Hadronic nuclear effects small ($\approx$10%).

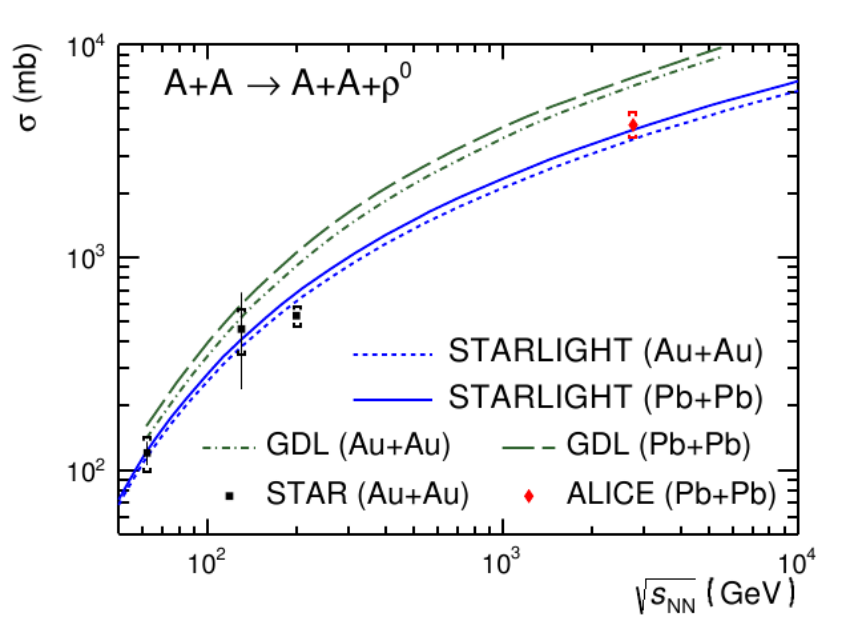
S.R. Klein, J. Nystrand, PRL 92 (2004) 142003.

Exclusive production of light vector mesons (ρ^0)

Measurements by STAR in Au+Au → Au+Au+π^++π^- interactions at $\sqrt{s_{NN}}$ = 62, 130, and 200 GeV (Phys. Rev. Lett. 89 (2002) 272302; Phys. Rev. C 77 (2008) 034910; Phys. Rev. C 85 (2012) 014910).

Recent preliminary results from ALICE in Pb+Pb → Pb+Pb+π^++π^- interactions at $\sqrt{s_{NN}}$ = 2.76 TeV (arxiv:1403.09177).

Measurement at mid-rapidity extrapolated from models to give total cross section (≈10% uncertainty between different models).



Total σ(Pb+Pb → Pb+Pb+ρ^0) = 4.2 ±0.1 (stat.) ±0.6 (syst.) b at $\sqrt{s}$ = 2.76 TeV!

About a factor of 2 below a Glauber calculation in black disk limit GDL (V. Rebyakova, M. Strikman, M. Zhalov, Phys. Lett. B 537 (2002) 51), in agreement with STARLIGHT (S.R. Klein, J. Nystrand, Phys. Rev. C 60 (1999) 014903).

Two-photon production of pseudoscalar and tensor mesons

In the very early days of UPC (before RHIC), much focus on $\gamma\gamma \rightarrow$ single meson:

Baur, Ferreira Filho, Nucl. Phys. A 518 (1990) 786; Vidovic, Greiner, Soff, Phys. Rev. C 47 (1993) 2288; J. Phys. G 21 (1995) 545; Baur, Hencken, Trautmann, J. Phys. G 24 (1998) 1657; Chikin, Korotkih, Kryukov, Sarycheva, Pshenichnov, Bondorf, Michustin, Eur. Phys. J A 8 (2000) 537; Roldao, Natale, Phys. Rev C 61 (2000) 064907; Bertulani, Natale, Nucl. Phys. A 703 (2002) 861; Baltz, Gorbunov, Klein, Nystrand, Phys. Rev. C 80 (2009) 044902.

No measurements until now. Too much background from photonuclear processes (vector mesons).

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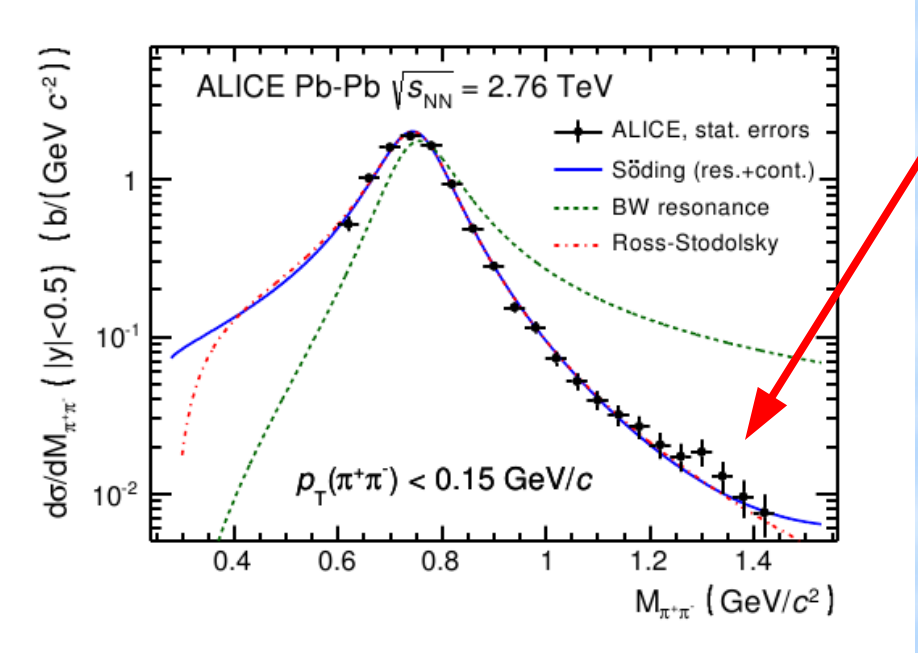


A signal for $f_2(1270) \rightarrow \pi^+\pi^-$ with statistical significance of 4^{+2}_{-1}.

ALICE arxiv:1403.09177

Two-photon production of pseudoscalar and tensor mesons

For two-photon production one has

$d\sigma(Pb+Pb \rightarrow Pb+Pb+f_2)/dy = n(\omega_1)\, n(\omega_2)\, \sigma_{\gamma\gamma\rightarrow f2}$

where $n(\omega)$ are the photon spectra and the two photon cross section is given by

$$\sigma_{\gamma\gamma}(W) = 8\pi(2J+1)\frac{\Gamma_{\gamma\gamma}\Gamma}{(W^2-m_R^2)^2+\Gamma^2 m_R^2} \approx 8\pi^2(2J+1)\frac{\Gamma_{\gamma\gamma}}{2m_R^2}\delta(W-m_R)$$

This means that

$d\sigma(Pb+Pb \rightarrow Pb+Pb+f_2)/dy \propto \Gamma_{\gamma\gamma}$

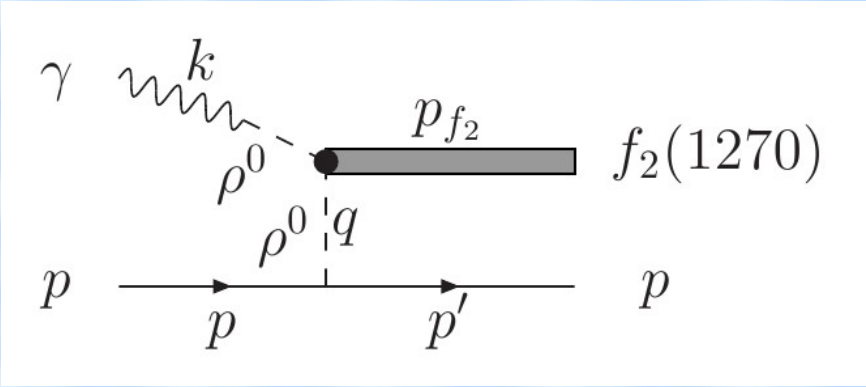
where $\Gamma_{\gamma\gamma}$ depends on the structure of the meson and in principle can be calculated from models.

Two-photon production of pseudoscalar and tensor mesons

However, since this is at a hadron collider, other processes might contribute.

For example, the CLAS collaboration at J-Lab has found evidence of both $f_0(980)$ and $f_2(1270)$ in data on $\gamma p \to \pi^+\pi^- p$ (Phys. Rev. D 80 (2009) 072005).

This has recently (J.J. Xie, E. Oser, arxiv:1412.3234) been explained by hadronic processes like



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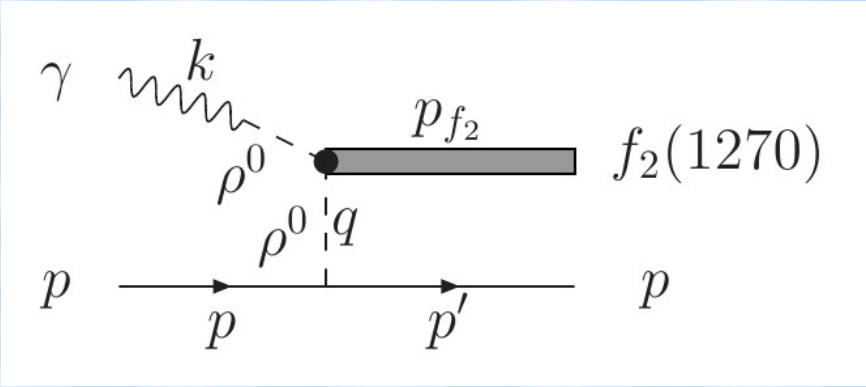

Measuring $\sigma(Pb+Pb \to Pb+Pb+f_2)$ one could thus detect or set limits for such couplings to nuclear targets.

Non-exclusive particle production in UPC

The $\sigma(\gamma+A\rightarrow V+A)$ is only a small part of the total $\sigma(\gamma+A\rightarrow X)$.

The photon spectrum at the LHC extends from $\sim$0 to several 100 TeV in the rest frame of the target nucleus.

A whole range of photonuclear reactions are possible.

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A whole range of photonuclear reactions are possible.

Photons at the high end of the spectrum can produce particles around midrapidity.

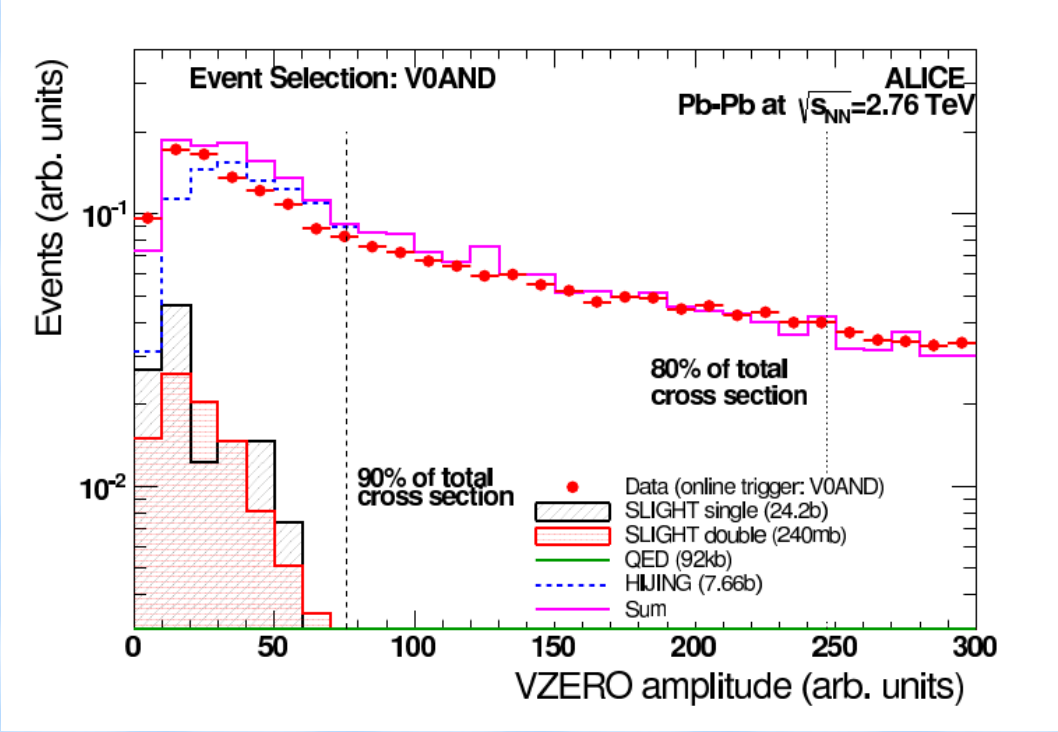
Cross section for having at least one charged particle from photoproduction within $|\eta| < 1.0$ is 4.5 b in Pb+Pb at $\sqrt{s}_{NN} = 2.76$ TeV (O.Djuvsland, J.Nystrand, Phys. Rev. C 83 (2011) 041901).

This is based on a simulation using DPMJET interfaced to the photon spectrum in STARLIGHT.

Non-exclusive particle production in UPC

This produces a background to hadronic interactions in the most peripheral bins.

ALICE Collaboration, Phys. Rev. C 88 (2013) 044909



Measure of multiplicity →

—— Hijing, hadronic only

—— Hijing + STARLIGHT + QED

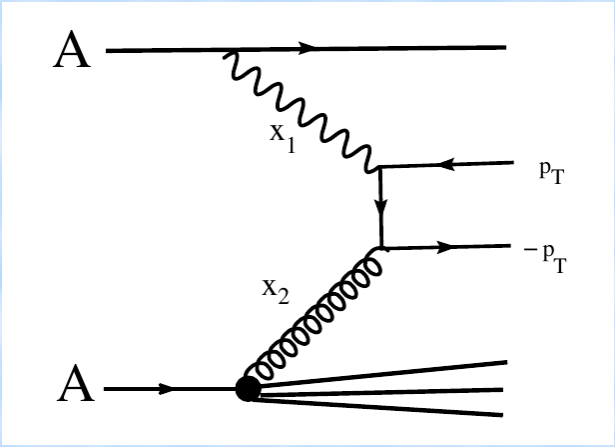
Non-exclusive particle production in UPC

But these interaction can also be an interesting signal!

For example:

- Photonuclear jet production (Strikman, Vogt, White, PRL 96 (2006) 082001) probes the nuclear parton distributions.

- Photoproduction of heavy quarks (Baron, Baur, Phys. Rev. C 48 (1993) 199; Greiner, Vidovic, Hofmann, Schäfer, Soff, Phys. Rev. C 51 (1995) 911; Klein, Nystrand, Vogt, Phys. Rev. C 66 (2002) 044906) probes in particular the nuclear gluon distributions.



Events are characterized by a ~ 9 units wide rapidty gap ($-9 \leq y \leq 0$) on the side of the photon emitting nucleus.

Non-exclusive particle production in UPC

Not many Monte Carlo models for high energy γ+A interactions.

But DPMJET (R. Engel, J. Ranft, S. Roesler, Phys. Rev. D 55 (1997) 6957; 57 (1998) 2889) can handle them.

Can be run interfaced to STARLIGHT (http://starlight.hepforge.org)

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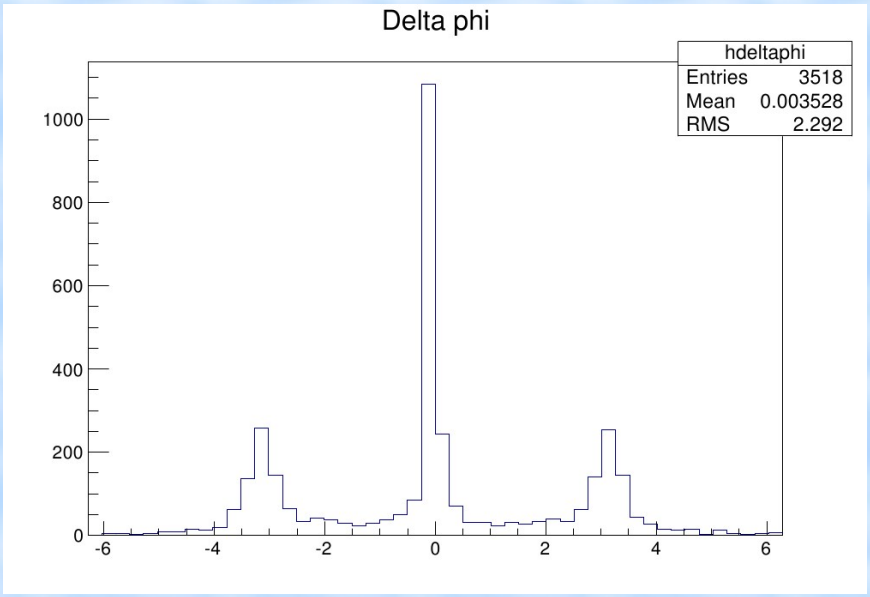
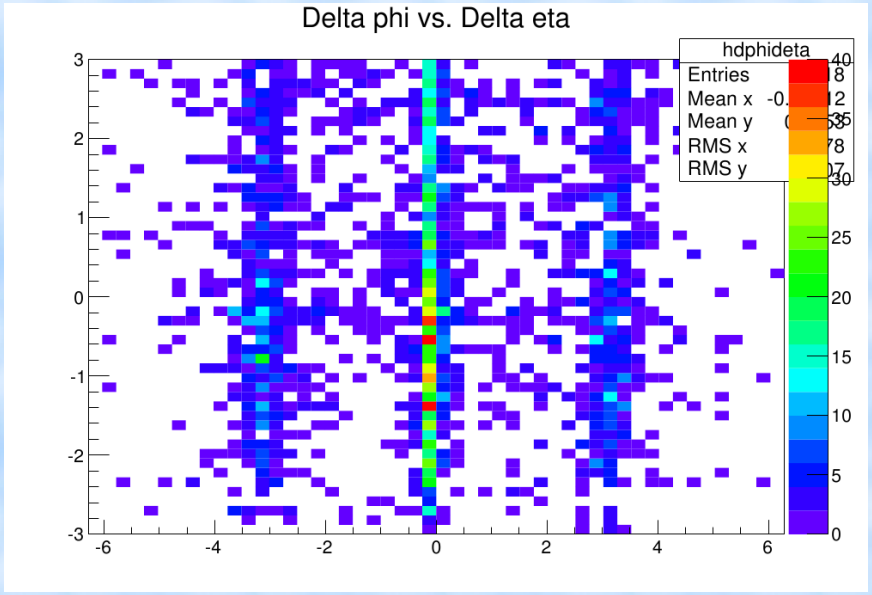
Examples of photonuclear jetproduction with DPMJET in Pb+Pb at $\sqrt{s_{NN}}$ = 5 TeV. p_T(trigger) > 4.0 GeV, p_T(associated) > 1.5 GeV:





Peak yield at y ~ 2-3. ⇒ Should work very well for Atlas, CMS.

Conclusions

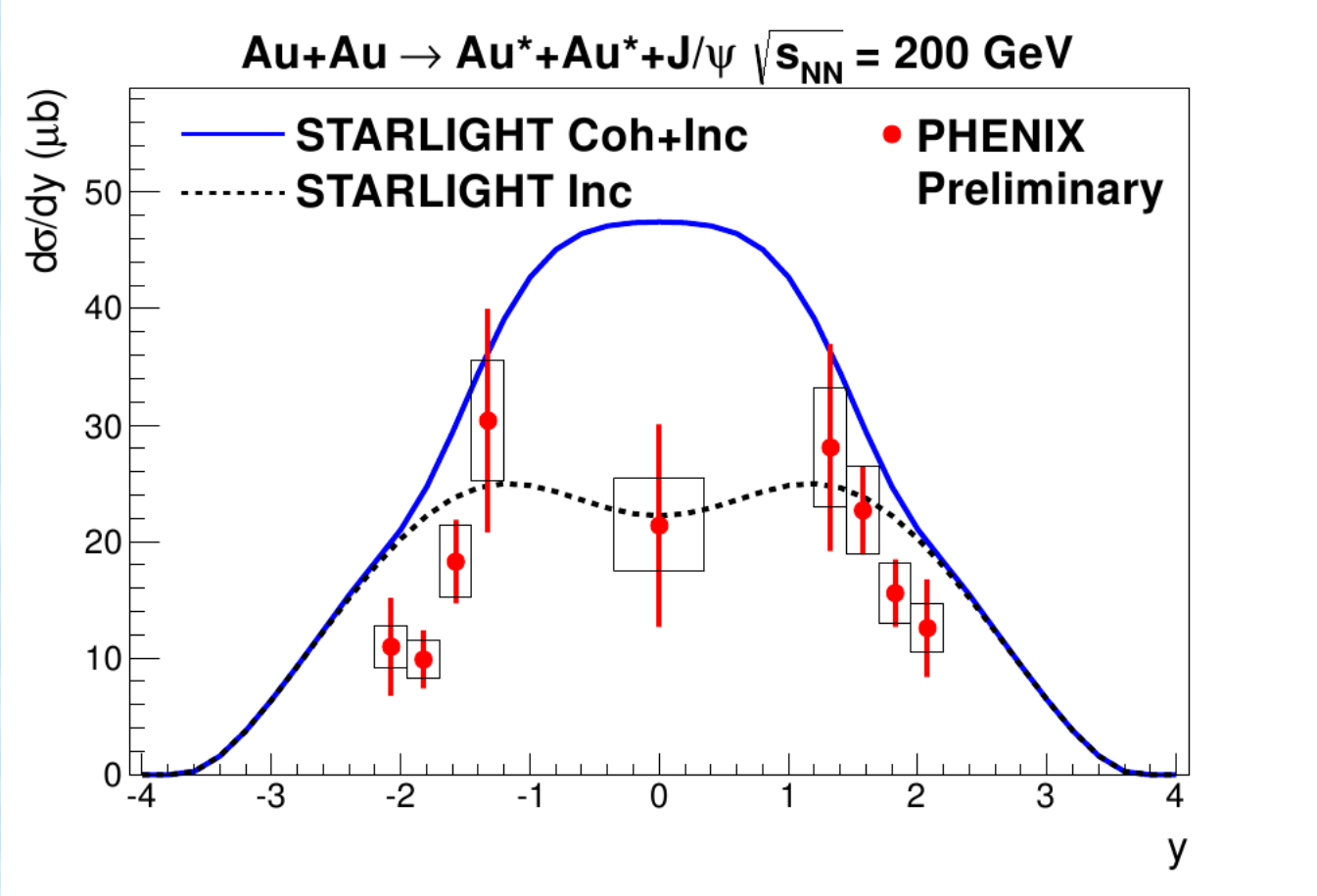
- First two heavy-ion runs at LHC have produced a multitude of results on ultra-peripheral collisions, most of them from ALICE.

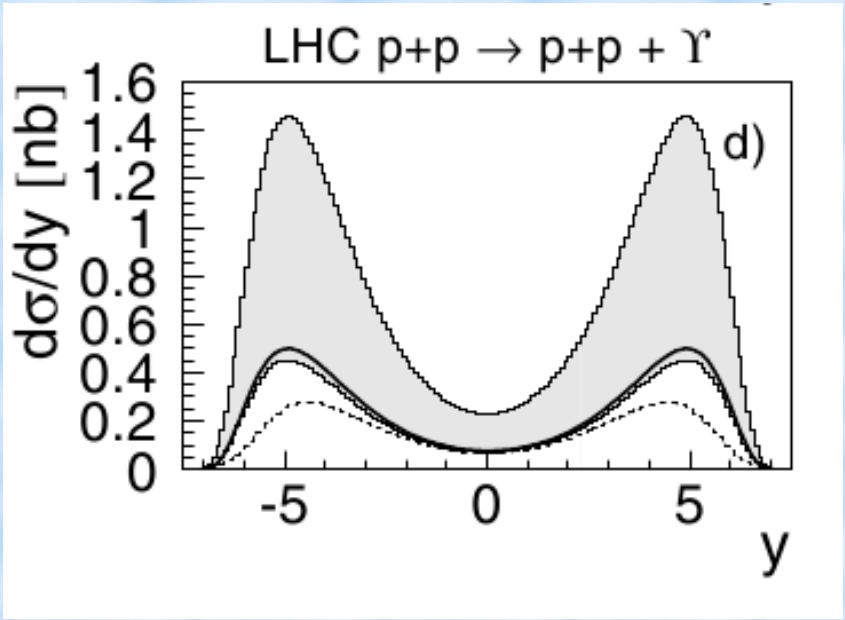
- There is more to do with vector mesons. Remeasuring the J/ψ at 5 TeV will reduce the Bjorken-x probed by factor 2. ψ(2S)and Υ with high statistics will provide new insights.

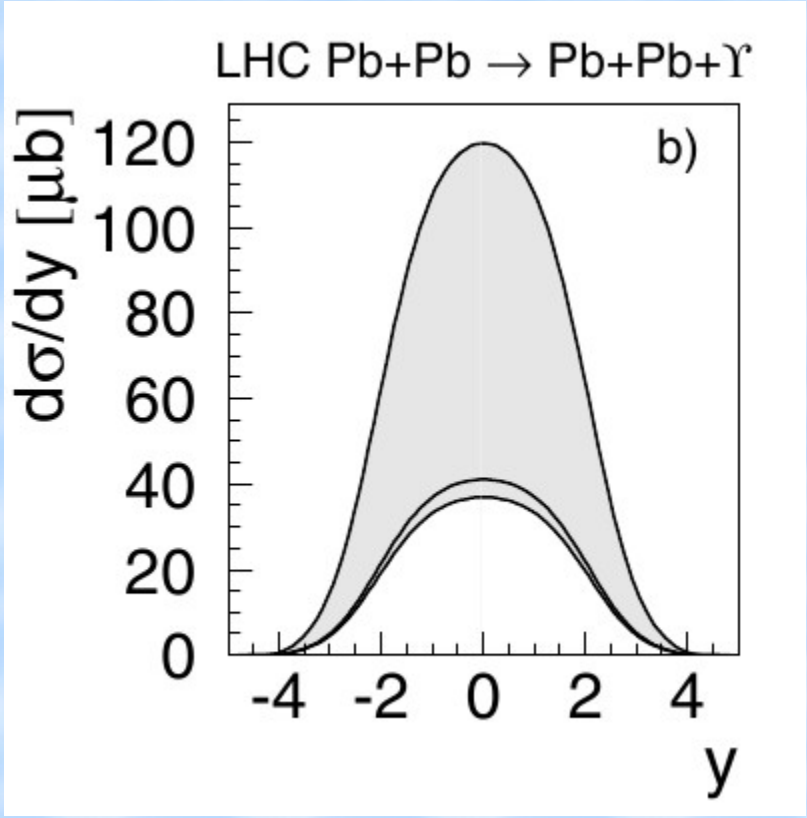
- Two-photon interactions may attract more attention, with the challenges/ opportunities provided by hadronic beams.

- Hopefully, also photonuclear γ+parton interactions will attract more interest.

Backup


Au+Au → Au*+Au*+J/ψ $\sqrt{s_{NN}}$ = 200 GeV
STARLIGHT Coh+Inc
STARLIGHT Inc
PHENIX
Preliminary
dσ/dy (μb)
0
10
20
30
40
50
-4
-3
-2
-1
0
1
2
3
4
y





S.R. Klein, J. Nystrand, PRL 92 (2004) 142003.

Results on exclusive J/ψ production

A note on the sensitivity to the scale:

Following Adeluyi, Bertulani, but starting from $d\sigma/dy$ from STARLIGHT without nuclear effects and multiplying it by $[R_G(x,\mu^2)]^2$.

Use scale $\mu^2 = M_V^2$ as default and $\mu^2 = (M_V/2)^2$ and $\mu^2 = (2M_V)^2$ as extreme limits.

This gives (at y=0 $\Leftrightarrow$ x = $1.1 \cdot 10^{-3}$):

HKN07:	$d\sigma/dy$ = 4.7 μb	(4.3 – 5.0 μb)
EPS09:	$d\sigma/dy$ = 2.9 μb	(2.1 – 3.3 μb)
EPS08:	$d\sigma/dy$ = 2.5 μb	(0.8 – 3.5 μb)

ALICE Result: $d\sigma/dy$ = 2.38 +0.34/-0.24 (stat+sys) μb

EPS08 has a very strong dependence of the scale, but the separation between EPS09 and HKN07 is clear and HKN07 is inconsistent with ALICE data.