BROOKHAVEN NATIONAL LABORATORY

Hard Probe 2020

STAR

J/psi photoproduction off deuteron in d+Au UPC at STAR

Kong Tu
on behalf of STAR Collaboration
BNL

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Center for Frontiers in Nuclear Science

Photoproduction of J/psi

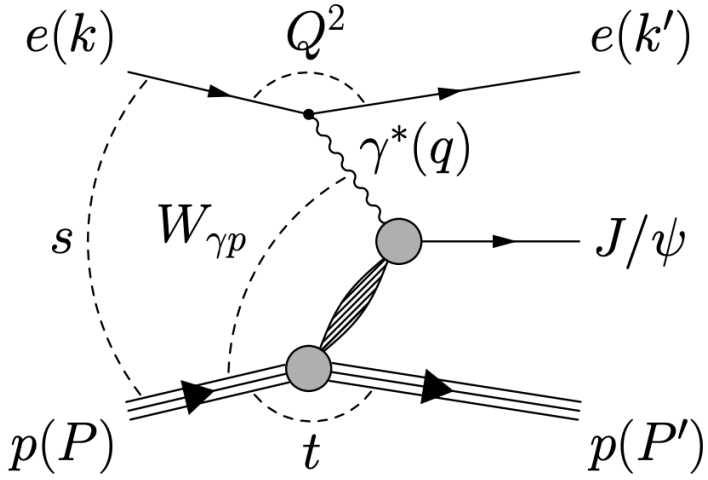
Cross section of J/psi meson in photoproduction, with a ***hard scale*** imposed by its mass, is sensitive to the gluon density at the LO

$$\left.\frac{d\sigma}{dt}\left(\gamma^* p \to \psi p\right)\right|_0 = \frac{\Gamma_{ee}\, M_\psi^3\, \pi^3}{48\alpha}\, \frac{\alpha_S(\overline{Q}^2)^2}{\overline{Q}^8} \left[xg(x,\overline{Q}^2)\right]^2 \left(1+\frac{Q^2}{M_\psi^2}\right)$$

It's a power probe to study the gluon density and its distributions inside nucleons and nucleus, physics applications:

- Gluon spatial distributions
- Gluon shadowing effects
- Gluon saturations
- Origin of mass, D-term
- Short-Range Correlations
- …

e+p=e'+J/psi+p'



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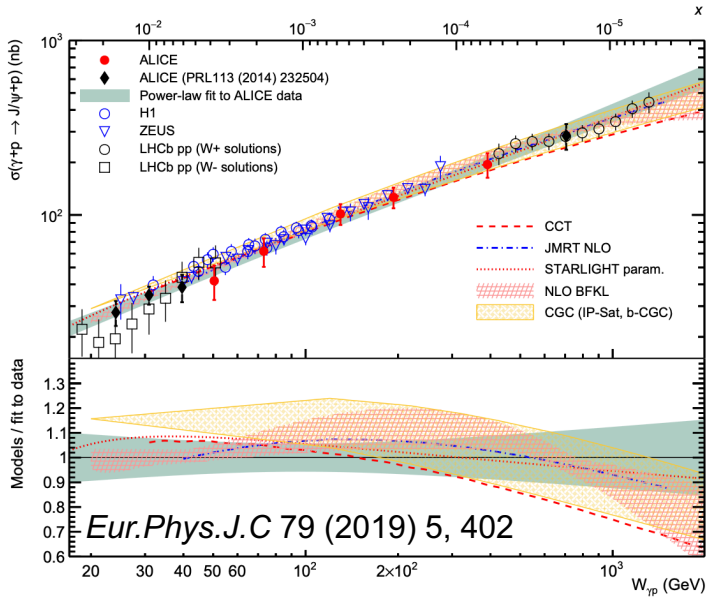
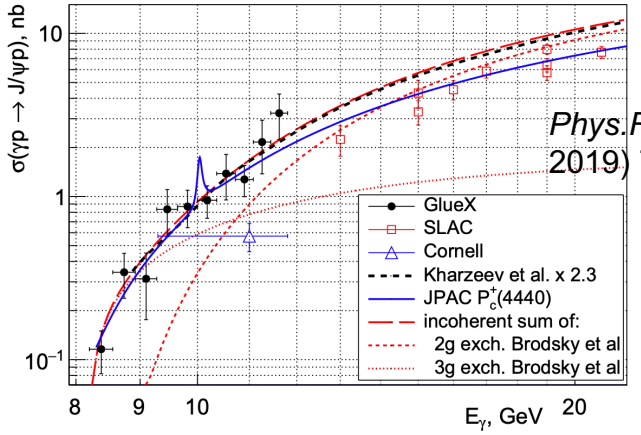
Low energy elastic J/psi was measured by SLAC, Cornell, and GlueX recently.

Proton

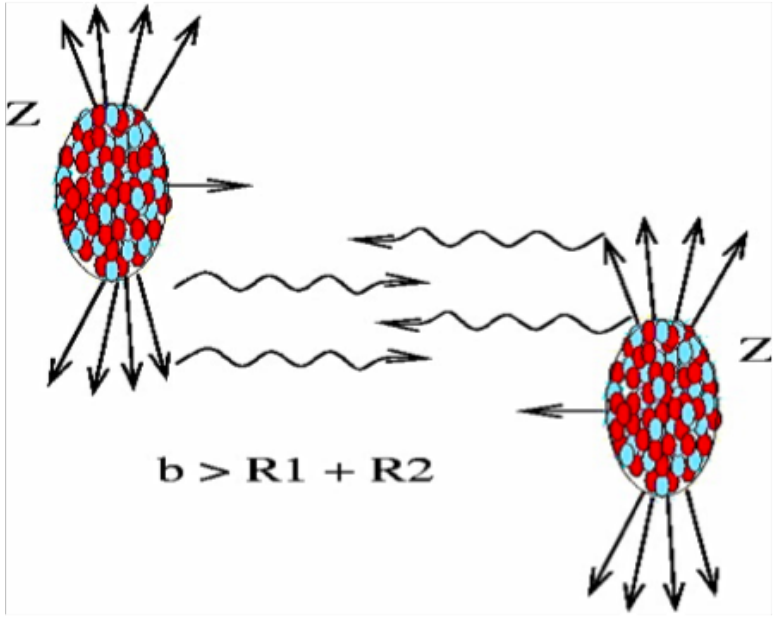
High energy elastic J/psi was measured at HERA (H1, ZEUS) and LHC off protons.





Phys.Rev.Lett. 123 (2019) 7, 072001

Photoproduction of J/psi in HEAVY NUCLEUS



Ultra-peripheral collisions of heavy ions

- Impact parameter b > 2R
- High energy quasi-real photons
- Huge enhancement of the photon flux comparing to electron-proton

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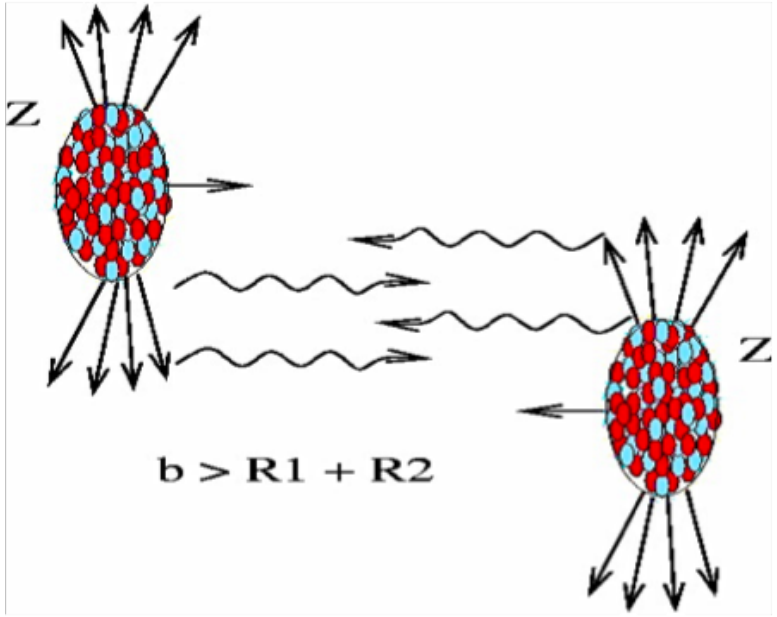

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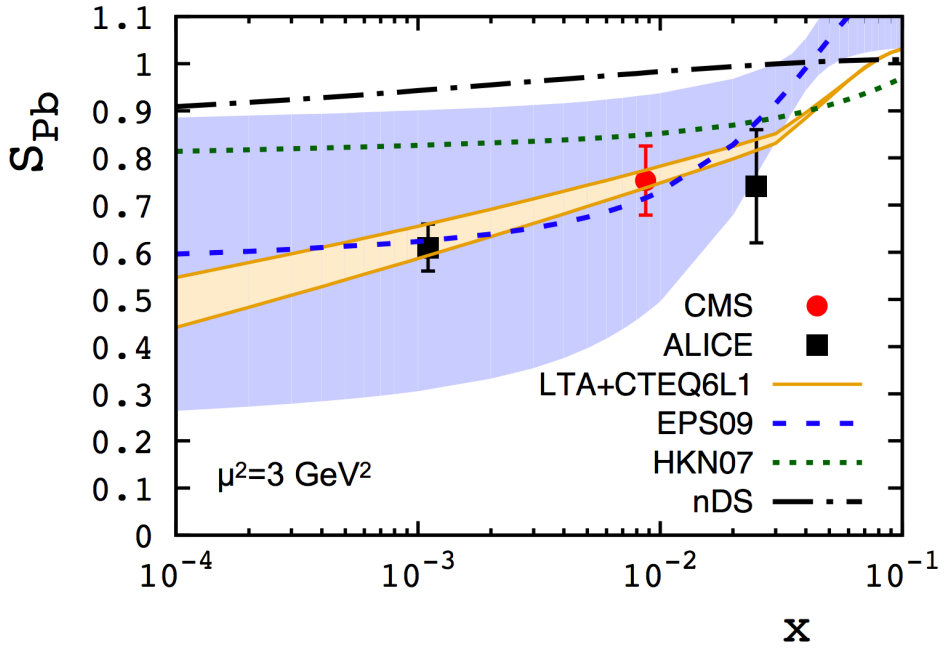
Gluon shadowing? Nuclear effects?



Leading Twist Approximation (LTA) describes the Ultra-peripheral collisions (UPC) data at the LHC very well

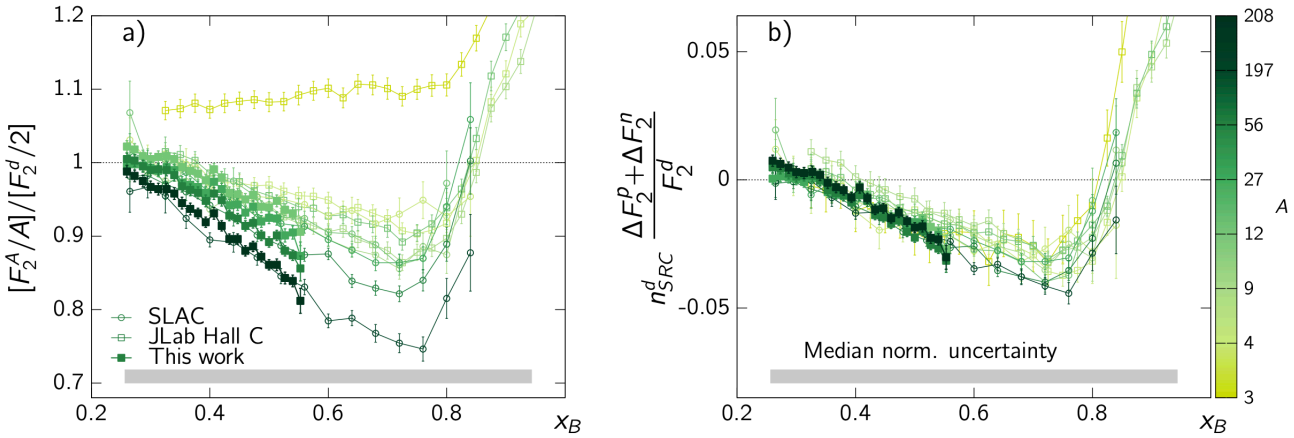
LTA: Guzey, Zhalov JHEP 1310 (2013) 207
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

Photoproduction of J/psi in LIGHT NUCLEUS

Big questions

- Why nucleus is nucleus instead of a few free nucleons sitting together?
- Where does nuclear effect come from?
- How can we find out?

Recent experiments point to local density with extreme configurations, at least for high x region, e.g., valence quarks. (***Nature 566, 354 (2019)***)



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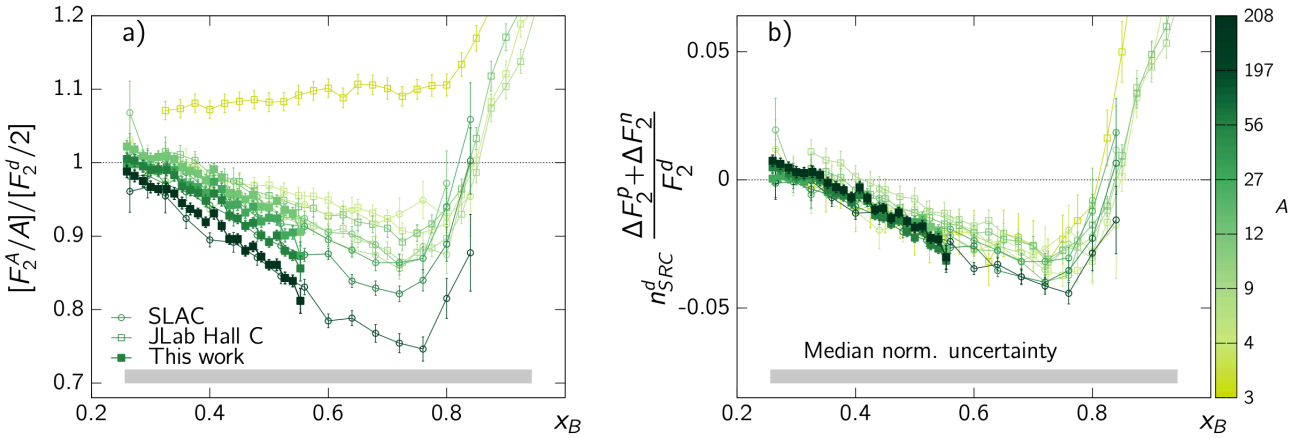
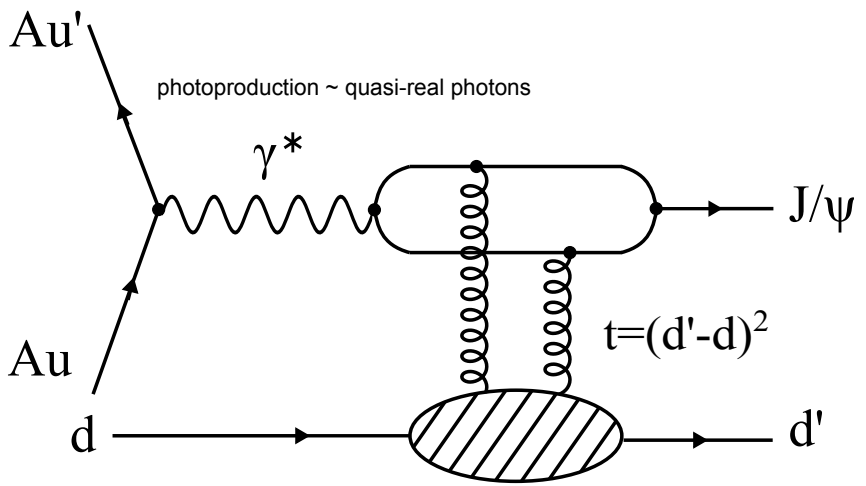


New ideas - deuteron

Study the simplest and lightest nuclei

- More proton-like or nuclei-like?
- Possible to control its configurations at the initial state?

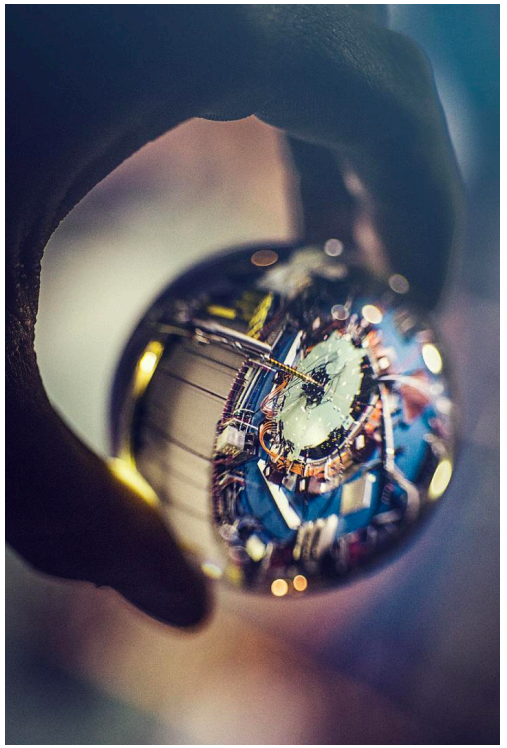
UPC dAu collisions at RHIC can be a perfect testing ground



STAR data

- Deuteron-gold collisions at 200 GeV recorded at STAR, with ~ 93 nb^{-1}
- Ultra-peripheral triggers were used during 2016 data taking, with J/psi vector meson targeted (i.e., topological requirement)
- J/psi → ee pair are reconstructed using TPC for |y| < 1.0
- Zero Degree Calorimeter (ZDC) was used to detect neutrons from deuteron breakup, providing additional info about the physics process.

STAR 20 years



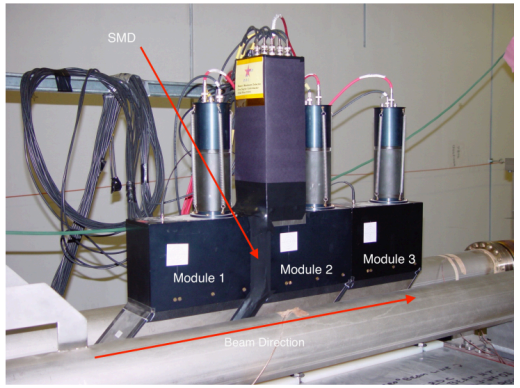


Fig. 2. ZDC modules installed on RHIC-STAR experiment.

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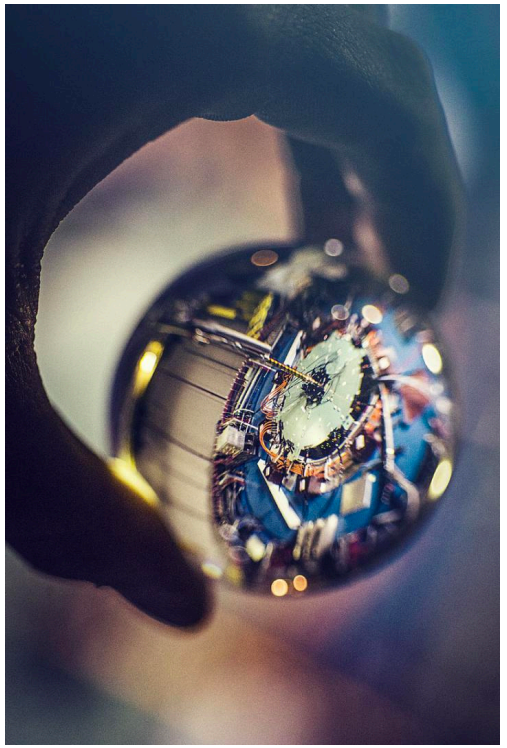
- Au + d → J/psi + Au' + X
  - X = d' (coherent) or X = d', d' → p'+n' (coherent + Coulomb)
  - X = p'+n' (elastic nucleon)
  - X = p'+X or n'+X (nucleon dissoc.)

STAR 20 years



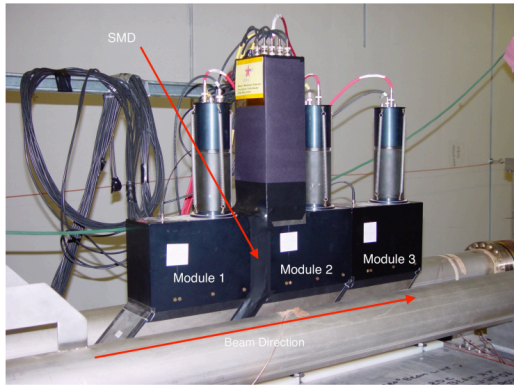


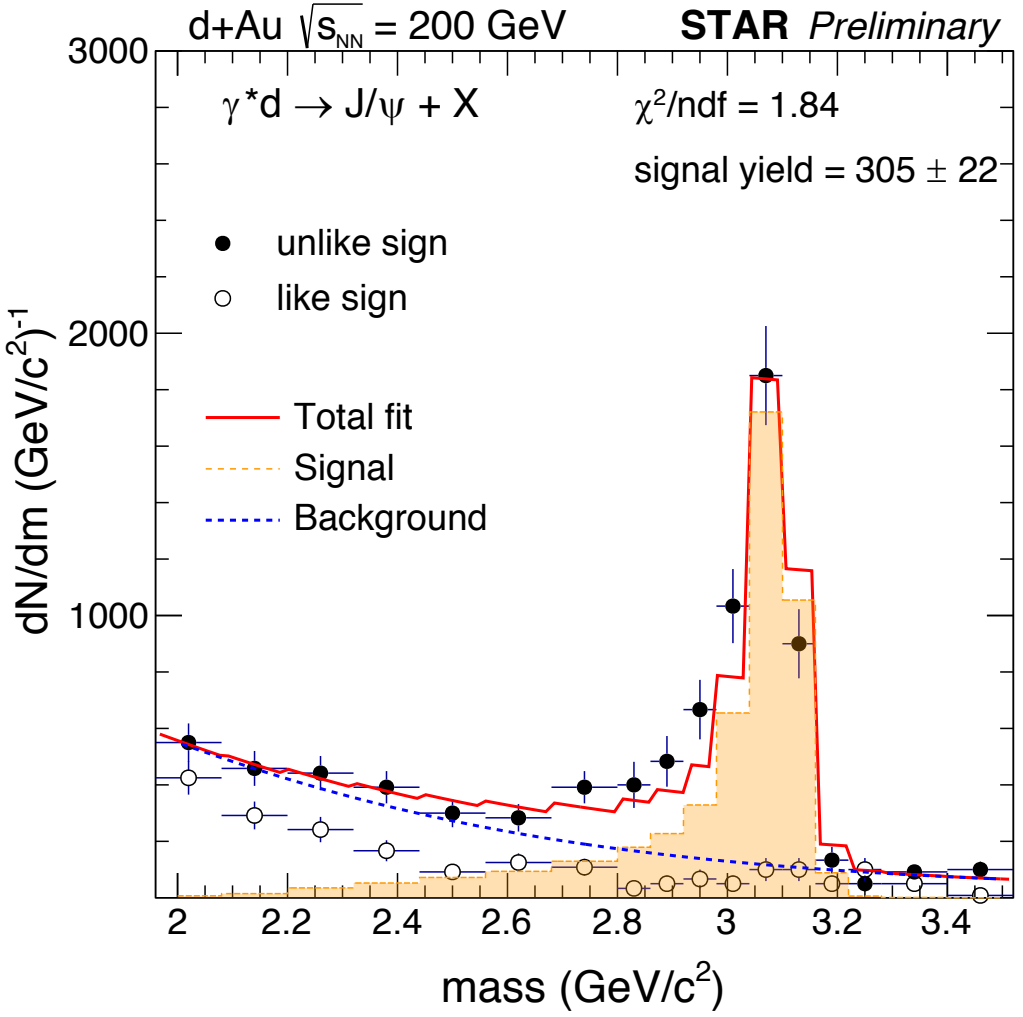
Fig. 2. ZDC modules installed on RHIC-STAR experiment.

J/psi in UPC dAu @ 200 GeV

- Clear signal, roughly 300 J/psi are reconstructed.
- Signal function based on STARlight J/psi mass signal after STAR GEANT simulations.
- Background function:

$$(x - A)e^{B(x-A)(x-C)+Cx^3}$$

- Difference between bkg and like-sign is due to photon-photon→ee (QED background)



Analysis technique

Energy

$$W^2_{\gamma^* p} = 4E_{\mathrm{p}}k$$

Photon energy determined by J/psi rapidity

$$k = \frac{1}{2} M_{J/\psi} e^{-y_{\mathrm{J}}}$$

- 100 GeV/nucleon at RHIC
- <W> ~ 25 GeV

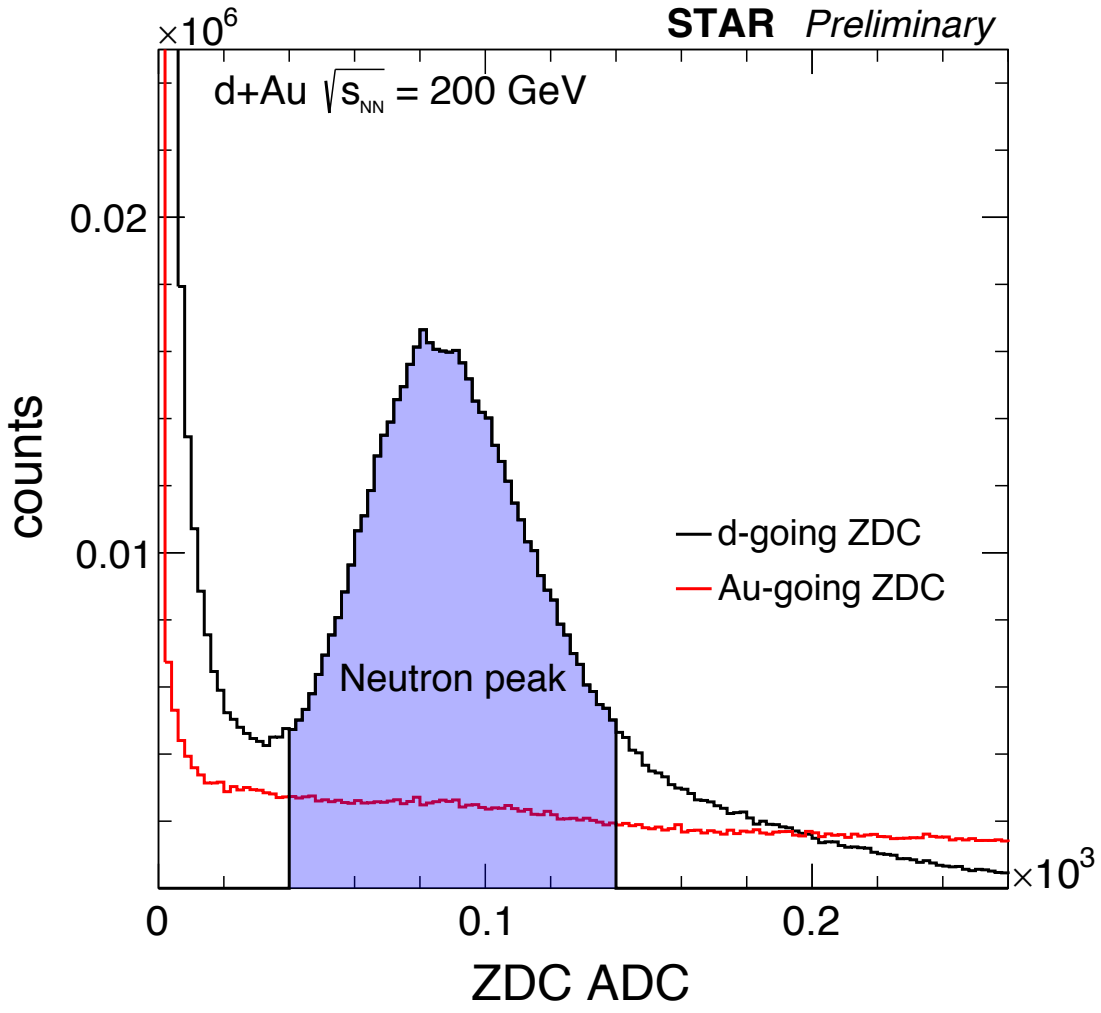
- Differential cross section in photon-deuteron system is:

$$\frac{d\sigma}{dtdy} = \frac{1}{\Phi_{T,\gamma}\, L_{int} \times Br(ee) \times \Delta t_i \times (A \times \epsilon) \times \epsilon_{trig} \times \Delta y} \frac{N^{obs}_{i,t,pt,y}}{}$$

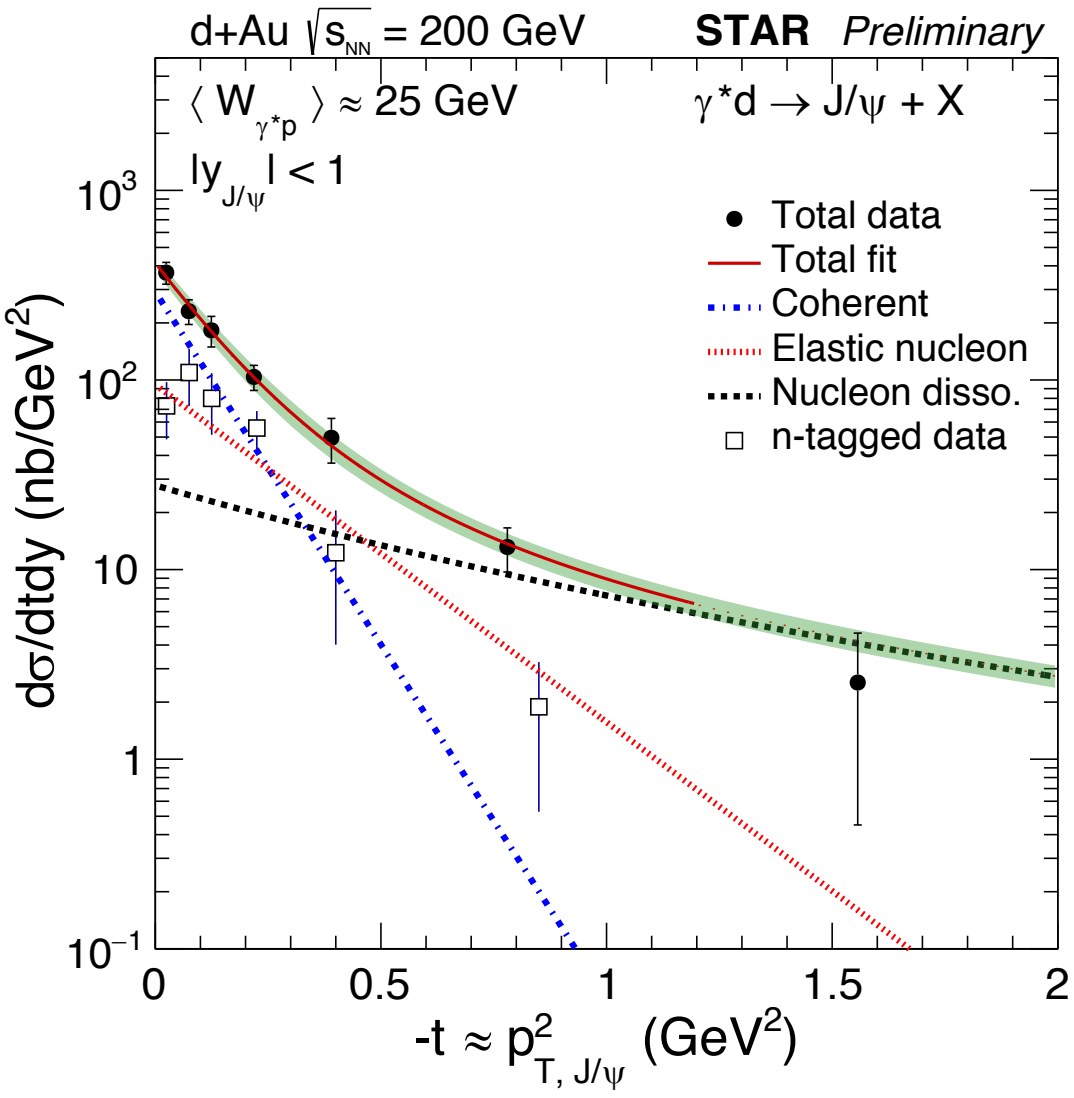
- ***t*** is the momentum transfer, $\Phi_{T,\gamma}$ is the transversely polarized photon flux.
- In UPC, t ~ p_T^2 is used instead since $Q^2 \sim 0$
- Integrating over ***t*** to obtain the cross section for each W → σ(W)

Neutrons in UPC dAu

- The UPC trigger used in analysis is unbiased with respect to the ZDC
- ZDC for d- and Au-going directions can be used to look for neutrons
- Neutrons in d-going direction came from deuteron breakup
  a) coherent + coulomb
  b) incoherent
  (Without neutron, however, doesn't mean coherent.)
- Au-going side has no neutron, stay intact!



Results



Only statistical uncertainty is shown, green band is 1-sigma fit error

What is plotting

- Total data – no selections on final-state of the deuteron breakups, only J/psi at mid-rapidity with no other activity
- n-tagged data – total data + requirement of neutron at d-going ZDC.

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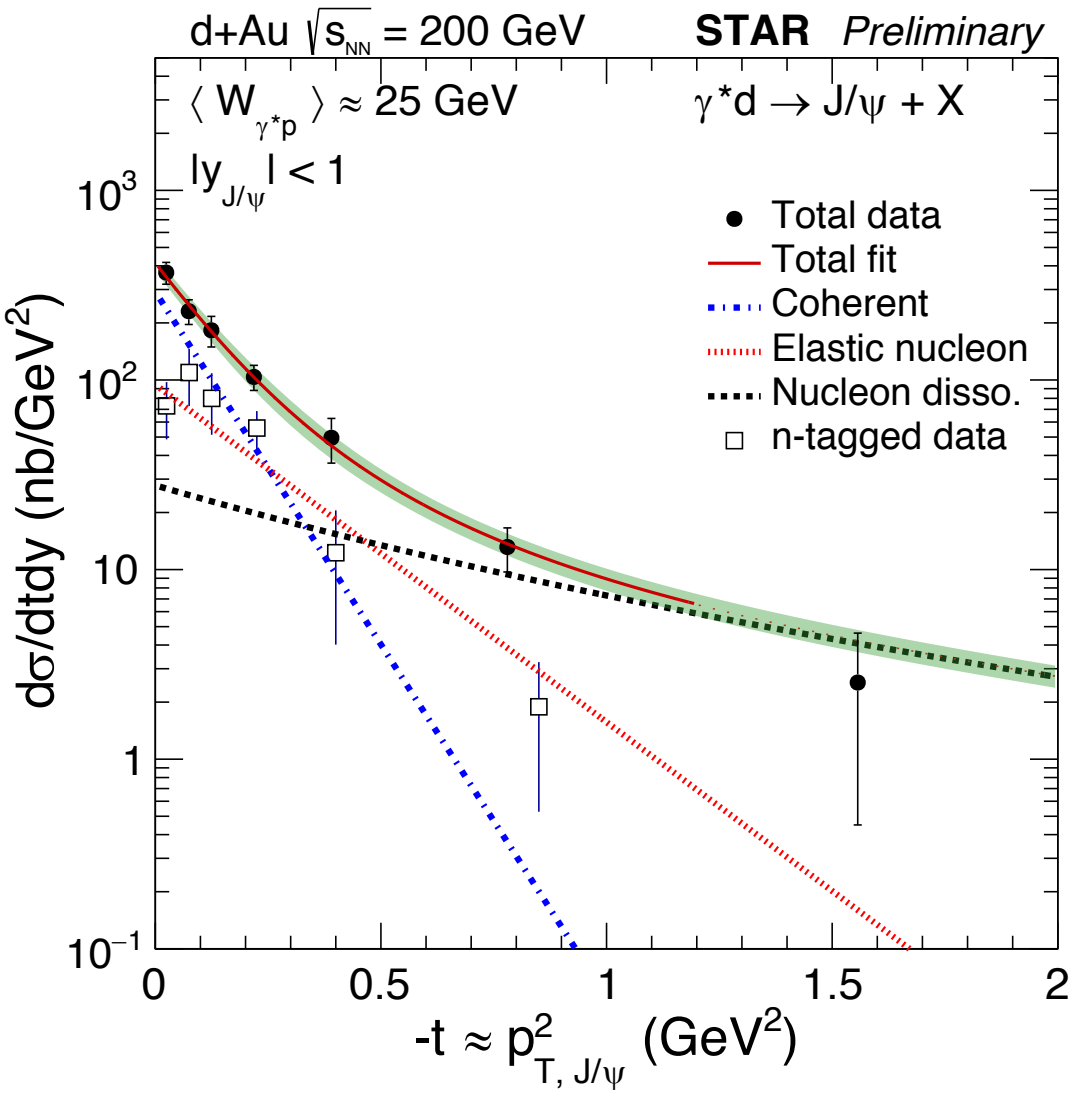

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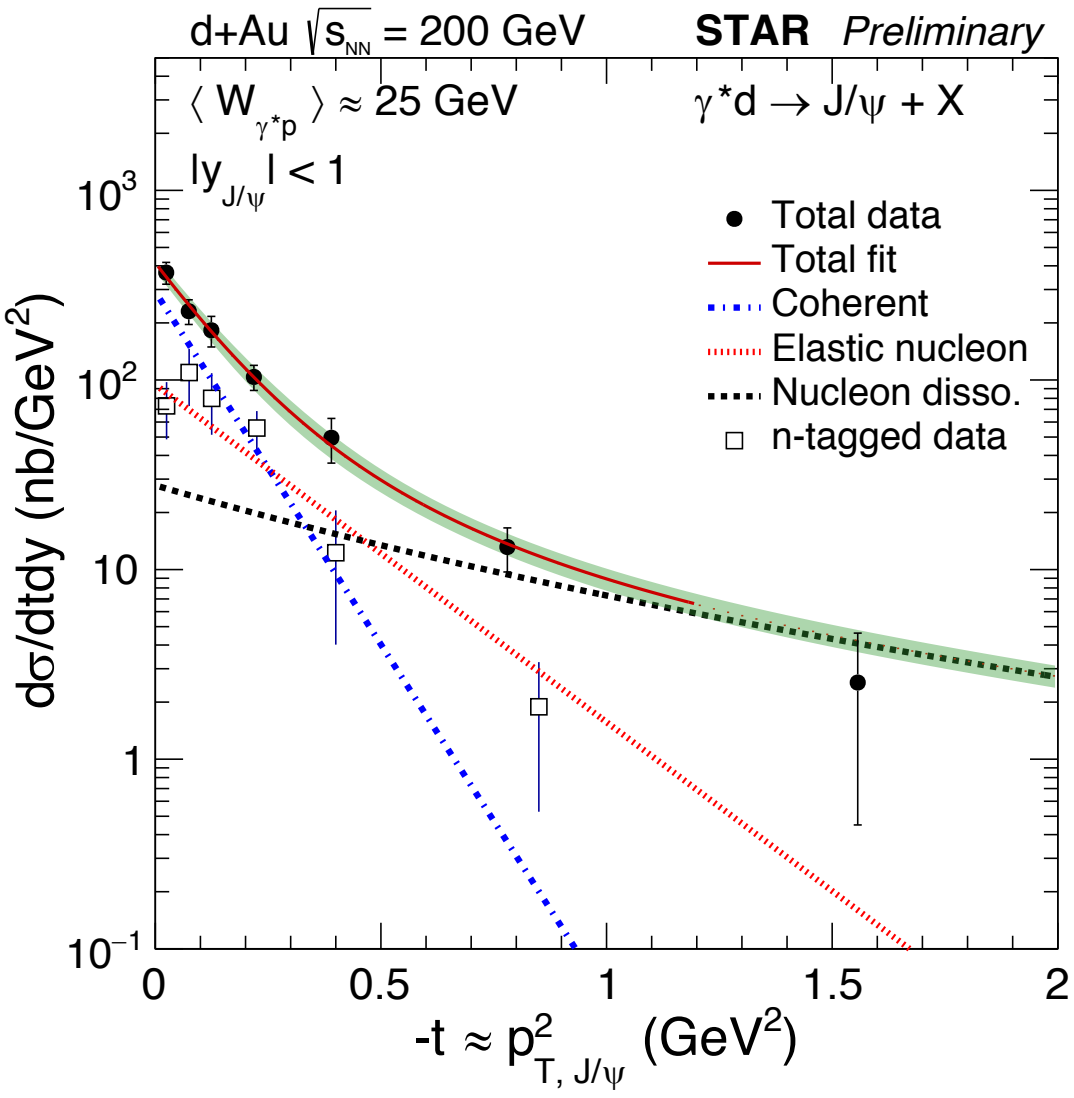
- Total fit has three components:
  1) Coherent contribution, assuming an exponential function
  2) Elastic nucleon (H1 proton data as shape)
  3) Nucleon dissociative (H1 proton data as shape)

  (ref. *Eur.Phys.J.C* 73 (2013) 6, 2466)

- Fit range t = (0, 1.2) GeV^2

Results



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What is plotting

Caveat:

- Incoherent diffractive contributions should go to 0 for t ~ 0 GeV^2. H1 data used as templates are not ideal.

Solution:

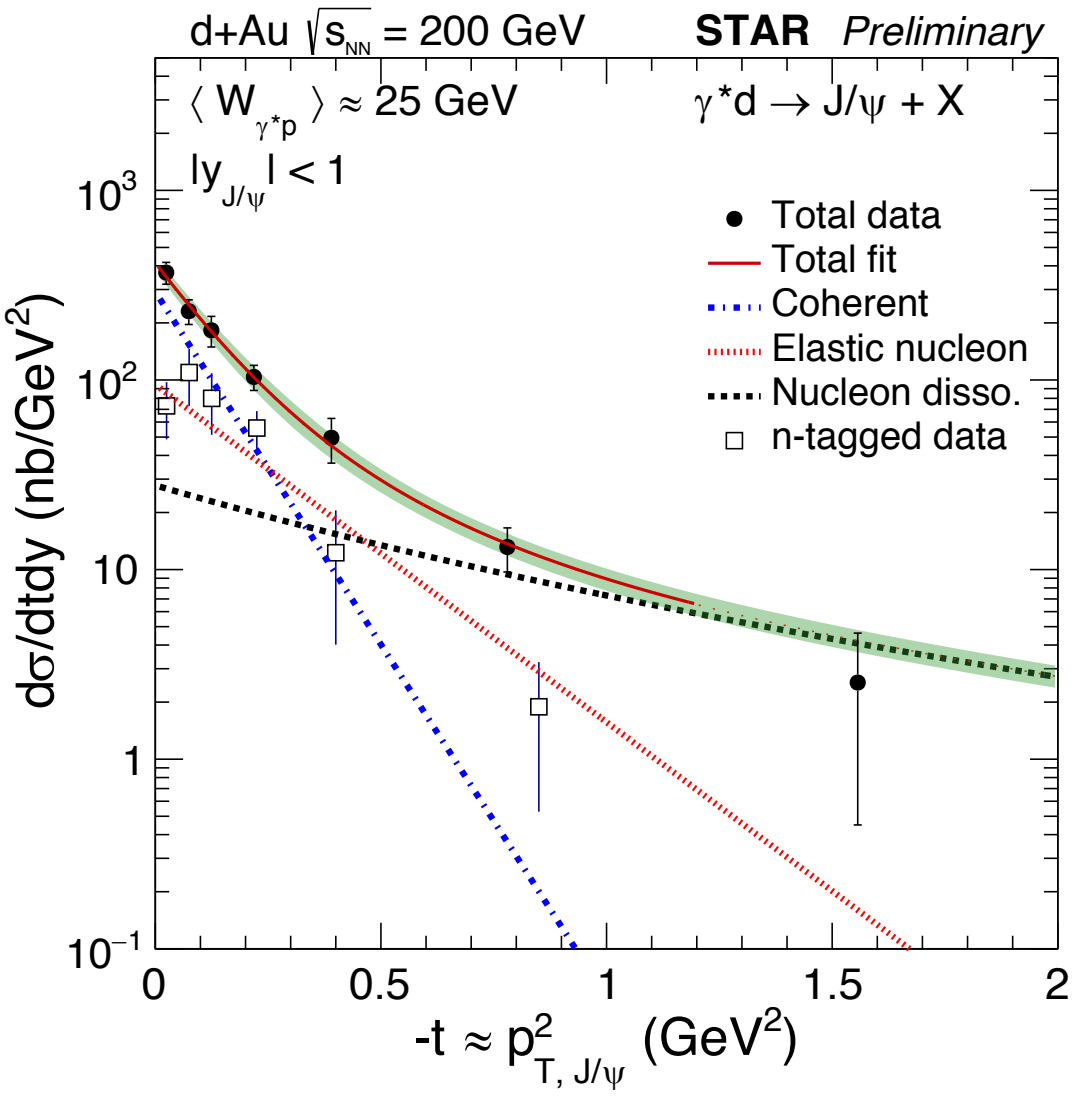
- Fit without the first bin (t > 0.05) is checked, with similar results obtained. Used it as systematic uncertainty.

Neutron tagged data:

- First look at J/psi photoproduction with neutron tagging.
- Limited statistics, but under expectation

Results

Proton charged radius ~ 0.8 fm, deuteron charged radius 1.8 fm



Cross sections:

- $t < 1.2$ GeV^2
- Total cross section = 73 $\pm$ 9 (stat.) $\pm$ 11(sys.) nb
- Coherent = 34 $\pm$ 6 (stat.) $\pm$ 5 (sys.) nb
- Coherent slope para. = -8.5 $\pm$ 1.2 (stat.) $\pm$ 1.5 (sys.) GeV^{-2}
- Coherent $d\sigma/dt$ @ t = 0, 300 $\pm$ 40 (stat.) $\pm$ 45 (sys.) nb/GeV^2

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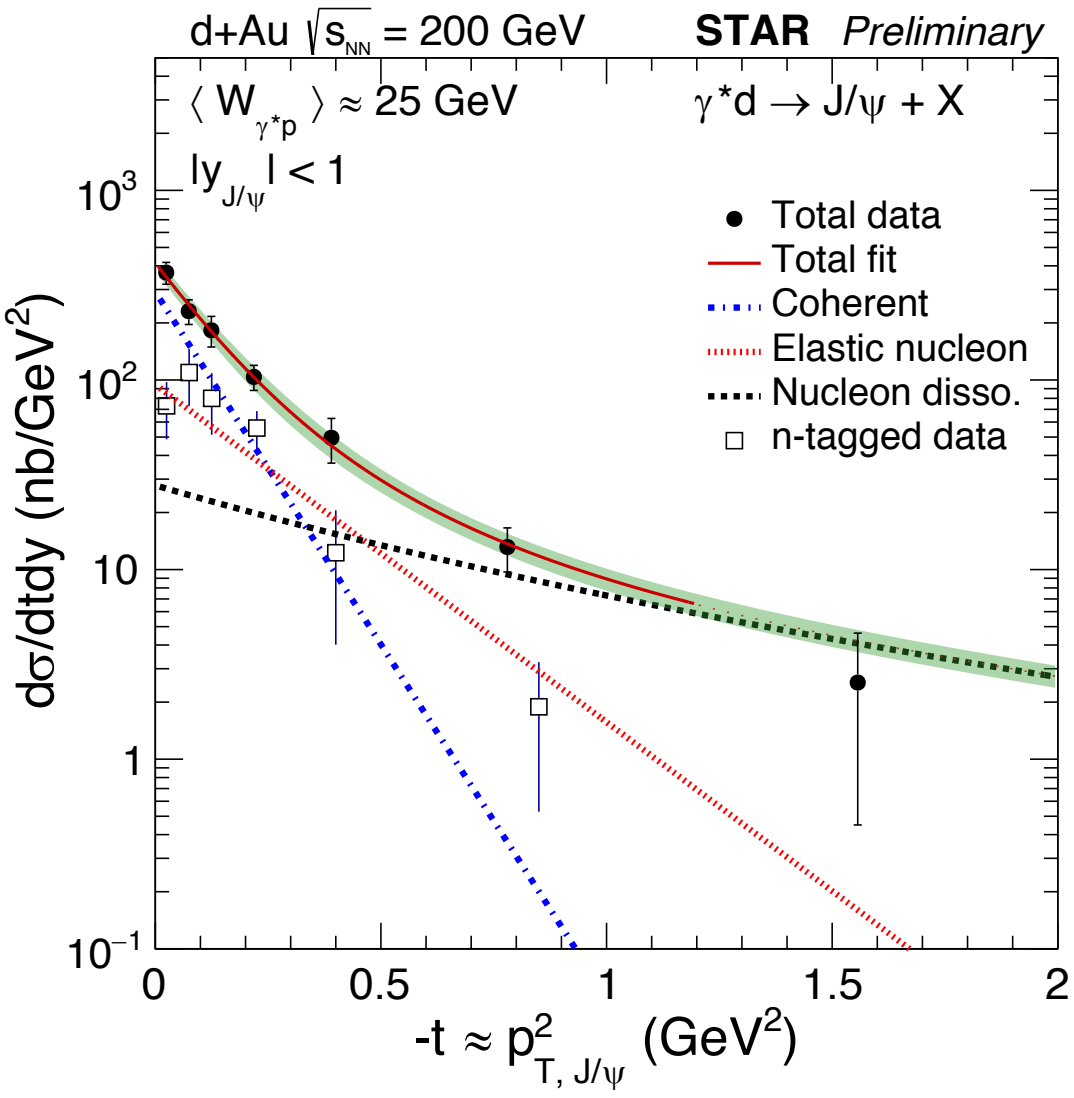

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- Coherent slope para. = -8.5 ± 1.2 (stat.) ± 1.5 (sys.) GeV^{-2}
- Coherent $d\sigma/dt$ @ t = 0, 300 ± 40 (stat.) ± 45 (sys.) nb/GeV^2

J/psi photoproductions off protons:

- $t < 1.2$ GeV^2 @ <W> = 55 GeV
- Coherent slope para. = -4.3 ± 0.2GeV^{-2}
- Coherent $d\sigma/dt$ @ t = 213 ± 18 nb/GeV^2

(ref. *Eur.Phys.J.C* 73 (2013) 6, 2466)

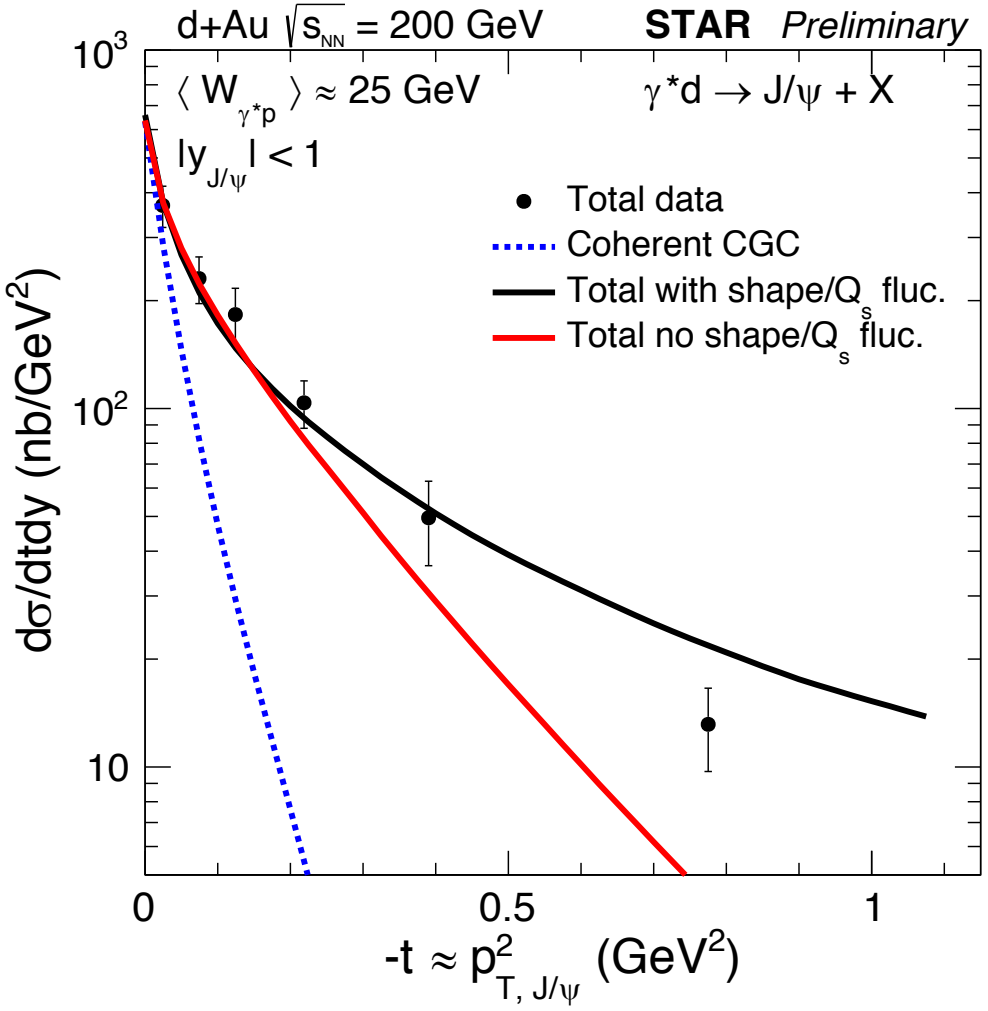
Supports coh. slope ~ size of the target ?

Only statistical uncertainty is shown, green band is 1-sigma fit error

Comparison with theory

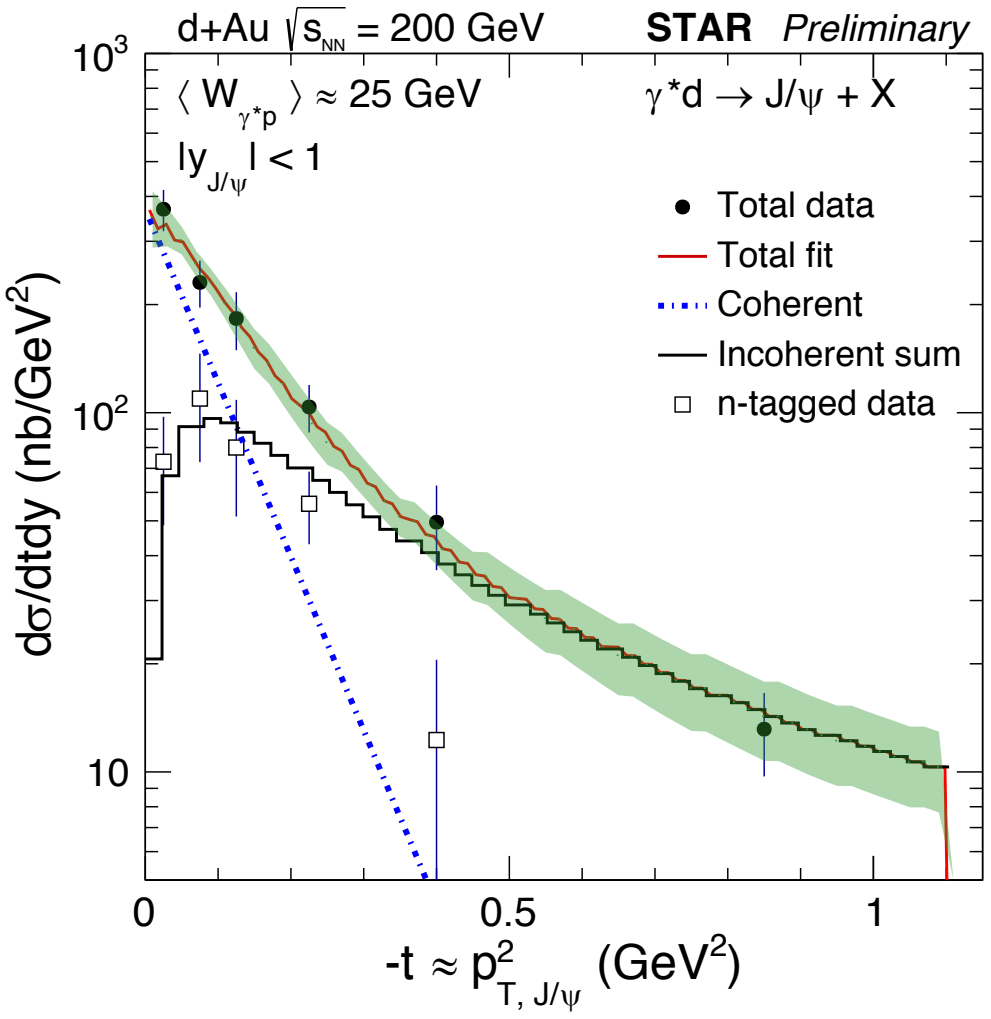
- CGC – calculations with J/psi off protons at HERA indicated importance of gluon fluctuations of the protons (*Phys.Rev.Lett.* 117 (2016) 5)
- Same calculations, thanks to the authors, has just been made for UPC J/psi measurement off deuteron.
- Both with and without fluctuations of incoherent contributions are compared with data. Favors fluctuations!
- However, coherent suggests a much steeper slope ~ -28 GeV^{-2} → Huge deuteron?
- Encourage more data for low t to narrow down what the slope is -- very challenging.

Mäntysaari and Schenke (new prediction 2020)



Curves are NOT fits. Only overlay

Alternative fit with CGC incoherent as template



Fit range (0,1.2) GeV^2

- Total data – the same data as previous slides
- Total fit has two components:
  - Coherent contributions, free exponential fit functions (same)
  - Incoherent sum, are templates from CGC theory calculations, includes both elastic nucleon and nucleon dissociative contributions

Take-away:

- Total cross sections are similar
- Coherent slope ~ **-11 $\pm$ 4 GeV^{-2}** > -28 **GeV^{-2}**

(Mean value becomes steeper, but still consistent with default method within uncertainty.)

Gluon source distributions

Caveat:

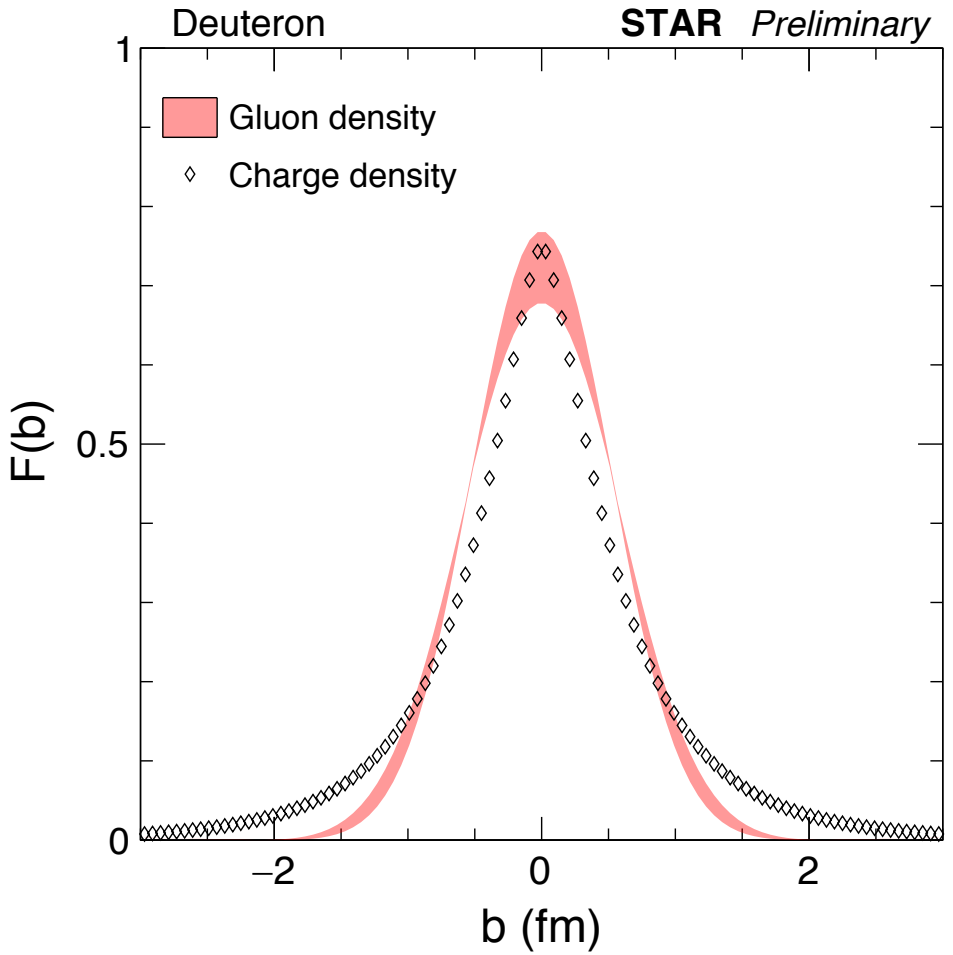
1. Only the exponential function with a slope parameter is used for Fourier transformations ~ -8.5 GeV^{-2}

2. Only statistical uncertainty is applied. No correlated error or systematic uncertainty

3. Charge density is from Hulthen distributions

Hint:

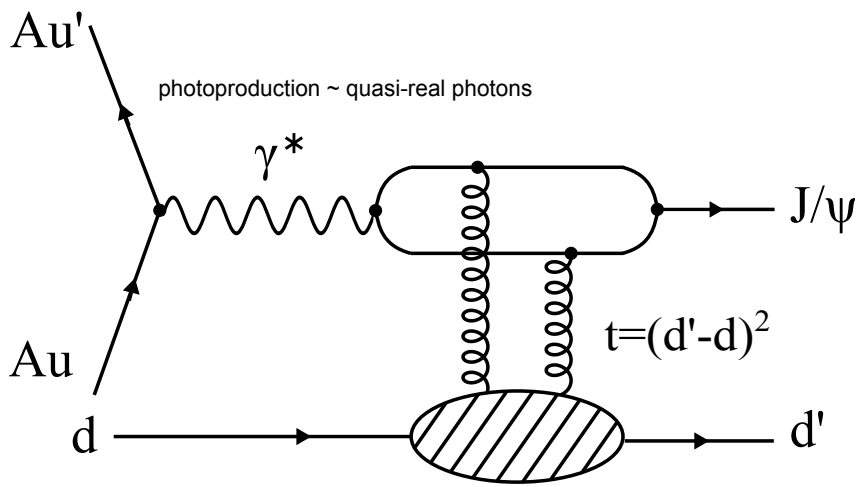
Gluon source distribution tends to be wider than the charge distribution



Ref: Talk by M. Diehl for Fourier transformations: http://www.int.washington.edu/talks/WorkShops/int_10_3/People/Diehl_M/Diehl1.pdf

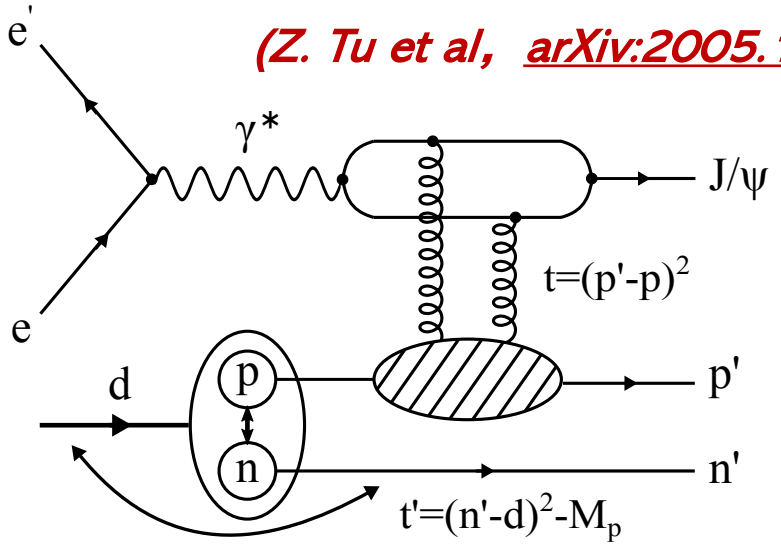
Summary

- First measurement of J/psi meson in photoproduction off deuteron.
- No ZDC trigger bias and tagging neutron spectator is practically possible to gain insights of underlying physics process
- Measurements are sensitive to the deuteron wavefunc. and gluon dist. of deuteron.
- Similar process can be done at the Electron-Ion Collider, with spectator tagging capability to access the extreme deuteron configurations
- STAR data is a great baseline measurement. *Looking forward to the future!*



STAR @ RHIC

(Z. Tu et al, arXiv:2005.14706)



EIC

Backups

Fit range (0.05, 1.2) GeV^2