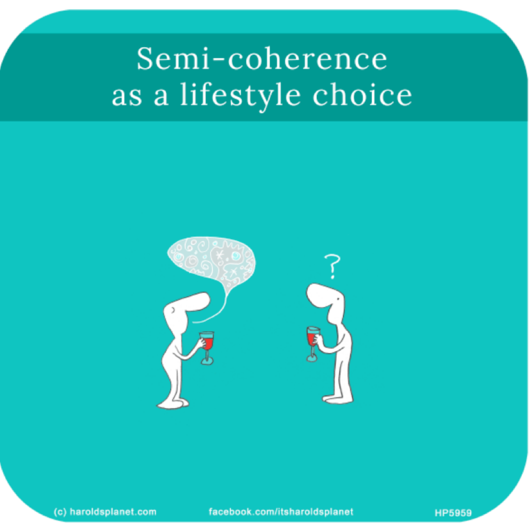
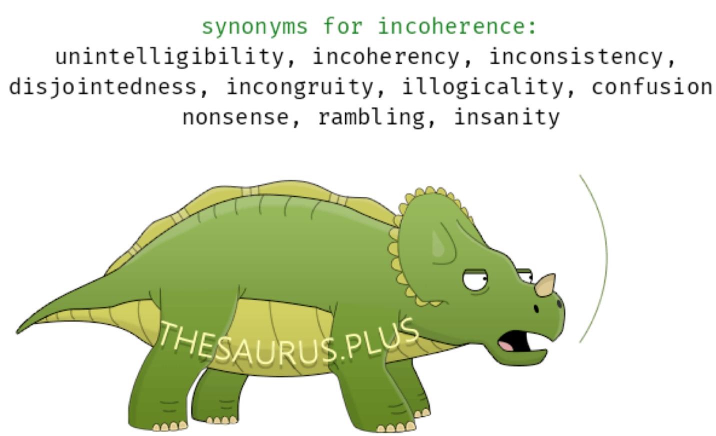
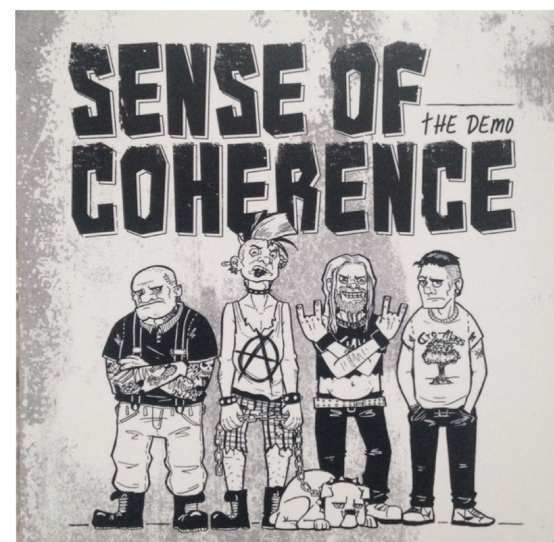
ρ^0 production in UPCs: current and future target fragmentation studies

Spencer Klein,
LBNL

- ρ^0 production with nuclear breakup
  - Factorization, and what it means
- ρ^0 & ρ' (& some J/ψ): what we know
- Future prospects

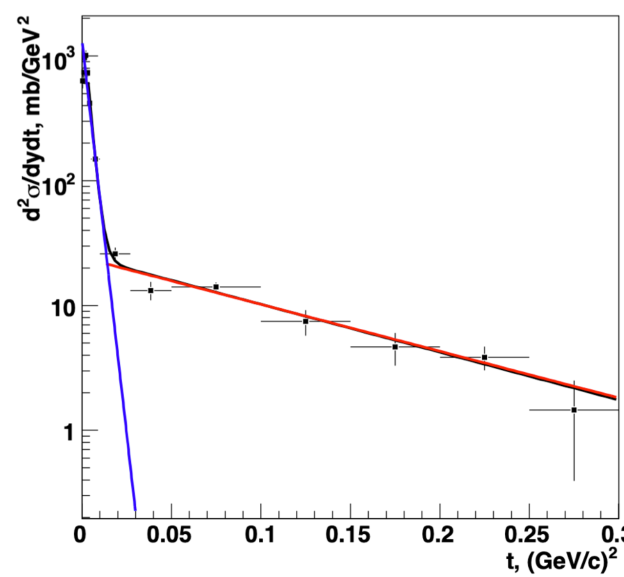






The ρ^0 seen in STAR

- 2002: 1^{st} ρ^0 photoproduction measurement
  - Main trigger requires neutrons in both ZDCs
    - "Topological" trigger did not require ZDCs, but efficiency was hard to evaluate
  - Few hundred events; proof of principle
  - ρ^0 + direct pp
  - 130 GeV AuAu Cross-section matched Glauber calculation
- 2008 ρ^0 production in 200 GeV AuAu
  - Separated coherent and incoherent components
    - Different $d\sigma/dt$ spectra
    - Incoherent visible at large t
  - s-channel helicity conservation holds
- 2010: 62.4 GeV cross-section
  - Matched Glauber calculation



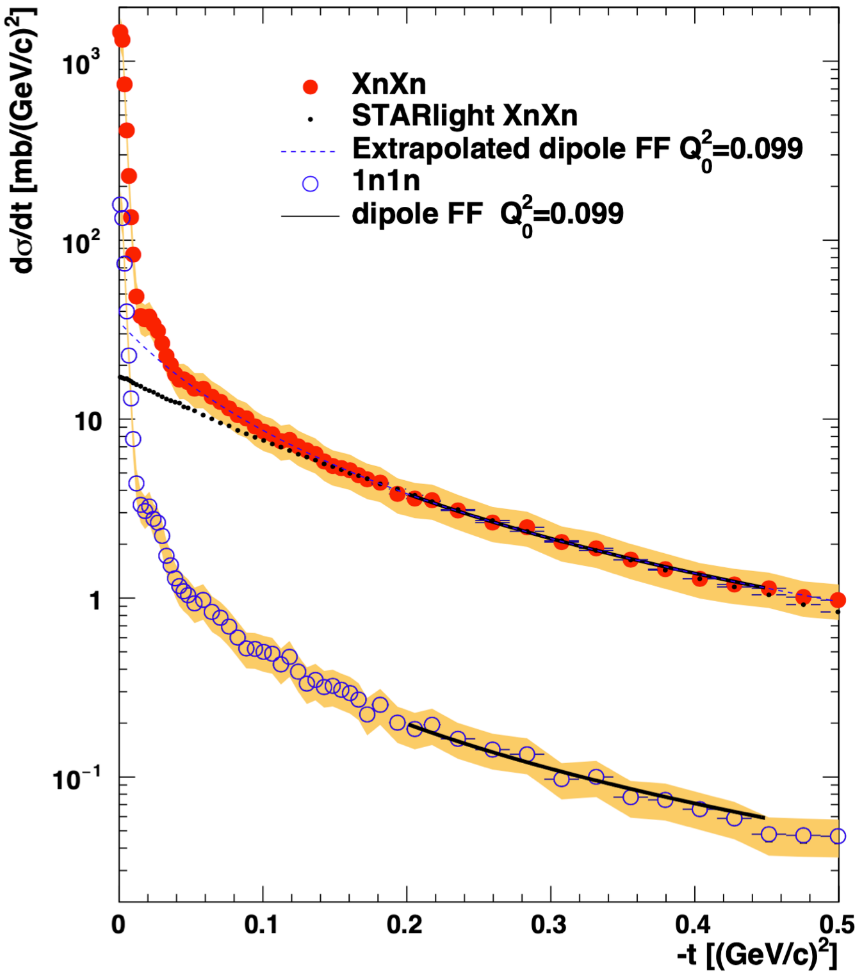
STAR, Phys. Rev. **C77**, 034910 (2008)

Incoherent ρ^0 in the 2017 STAR analysis

- 294,000 'exclusive' $\pi^+\pi^-$ with $p_T < 100$ MeV/c
- Exp(-bt) is no longer an adequate for the incoherent component
- A dipole form factor is a good fit

$$\frac{d\sigma}{dt} = \frac{A/Q_0^2}{(1+|t|/Q_0^2)^2}$$

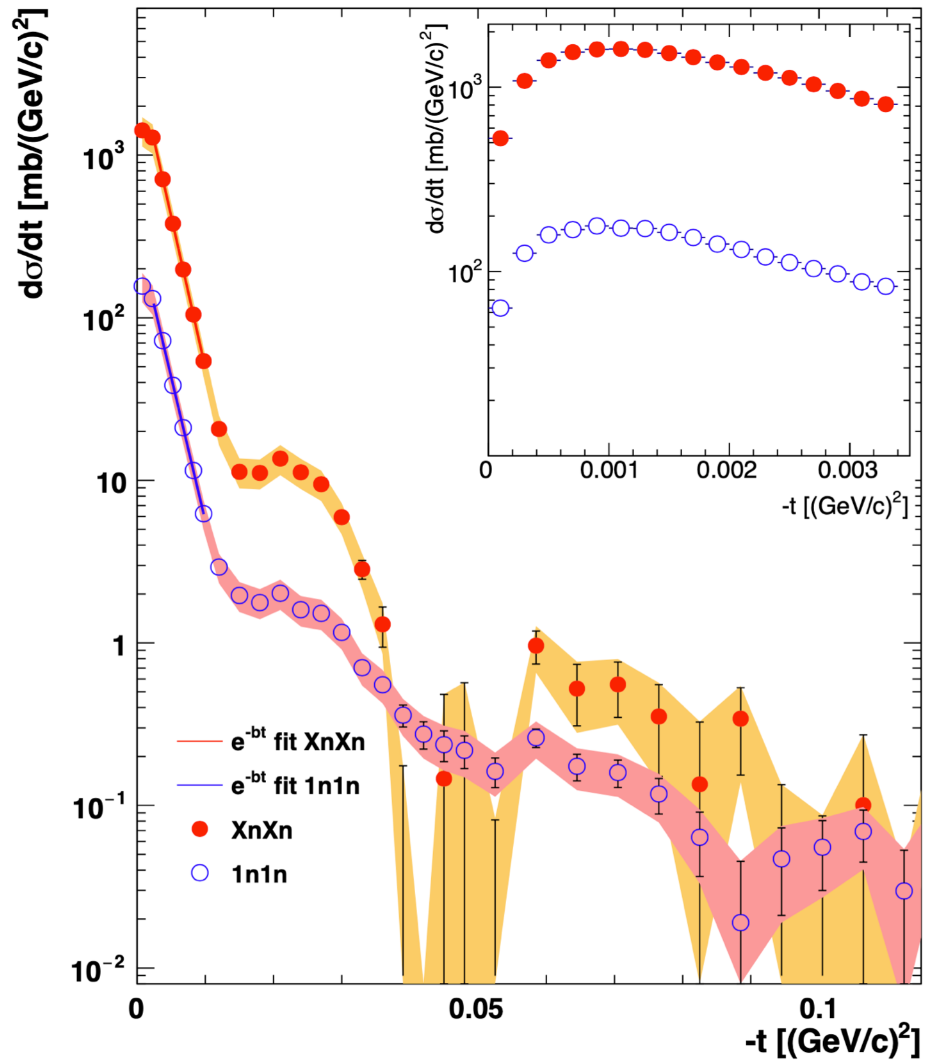
  - 0.2 GeV² < t < 0.45 GeV²
  - Matches expectation for recoil from a single nucleon
  - $Q_0^2 = 0.099$ (GeV/c)²
  - Is single-nucleon recoil appropriate at low t?
    - Nucleon emission energetically impossible
    - Photon emission is via shell model states
  - We don't know what to expect at low t



STAR: PR **C96**, 054904 (2017)

Coherent ρ^0 in the 2017 STAR analysis

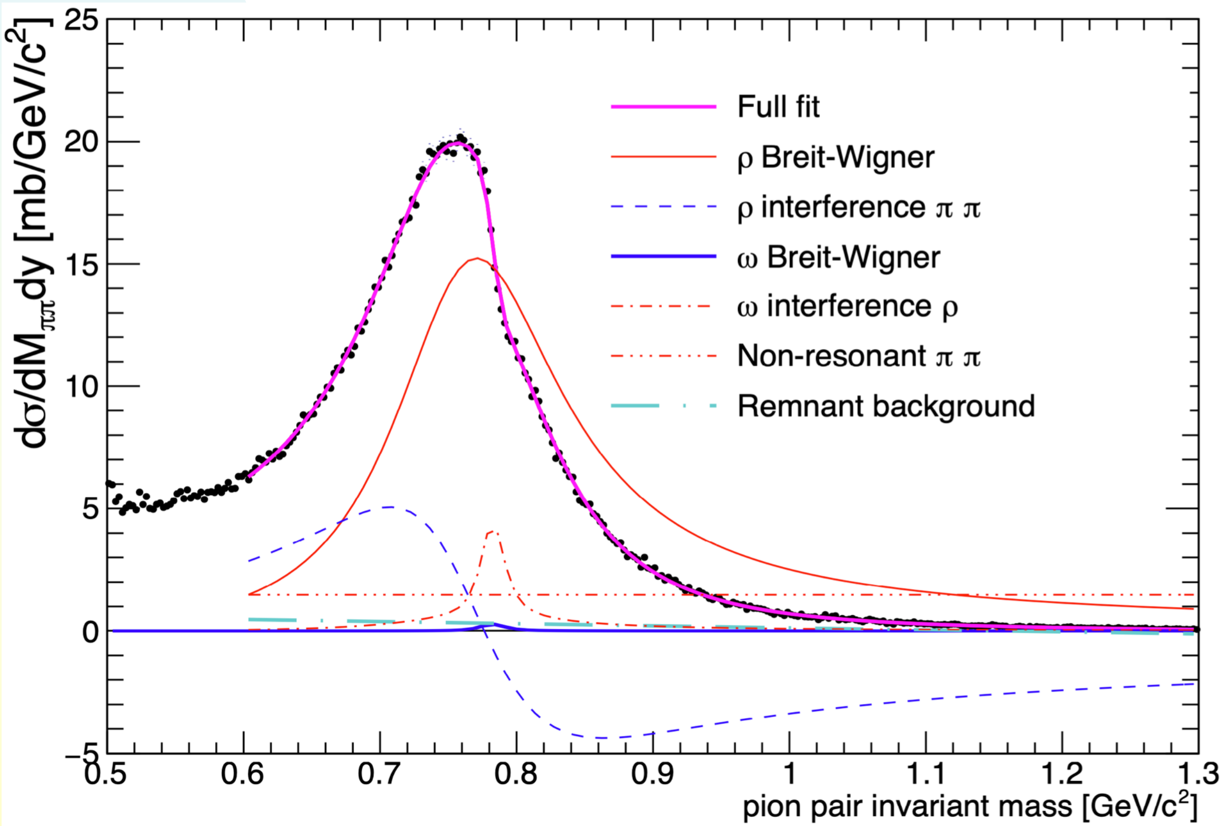
- Found by subtracting the incoherent ρ^0 fit, extrapolated down to zero
  - Energy conservation requires extrapolation to fail as t-> 0
- Several diffractive minima are visible
- Spectrum is the convolution of the photon p_T, Pomeron p_T and detector resolution
  - 2-d vectors
  - Photon p_T and Pomeron p_T directions are correlated due to the bi-directional interference



STAR: PR **C96**, 054904 (2017); H. Xing et al., JHEP **10**, 064 (2020)

The 2017 STAR mass spectrum

- Mass spectra fit by ρ^0 + direct $\pi\pi$ + $\omega \to \pi\pi$
  - All of these states should be $J^{PC}=1^{--}$, so they interfere
  - ω required for acceptable fit
  - Ratios & phase angle consistent with low-energy fixed-target studies
    - Pomeron exchange @ high energies; meson exchange at lower

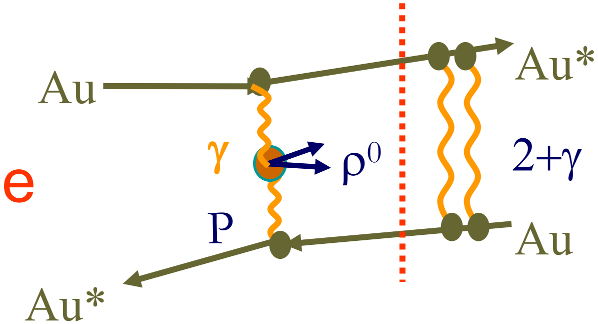


STAR: PR **C96**, 054904 (2017)

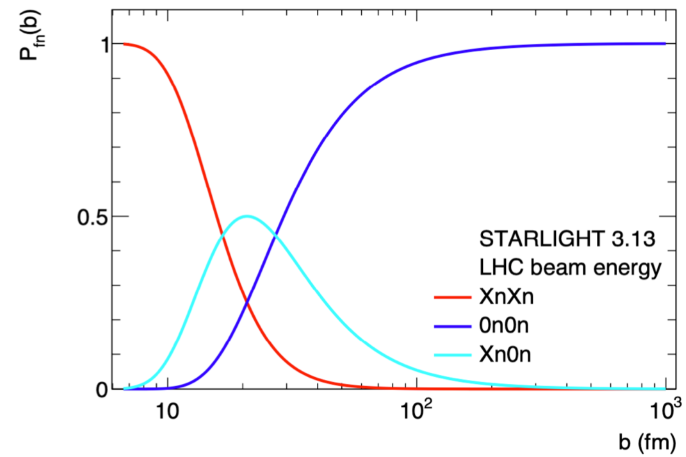
Why do we observe coherent production here?

- This is NOT exclusive production
- STAR requires neutrons in both zero degree calorimeter in its trigger
  - Reaction is $AuAu \rightarrow Au^* Au^* \pi^+ \pi^-$
- Two definitions of coherence:
  - Add amplitudes with a phase factor
    - $\sigma_{coherent} = | \Sigma_i A_i \exp(ikx)|^2$
    - AA->A*A* V (ρ, ρ', J/ψ) still exhibits coherence as long as $\exp(ikx) \sim 1$, i. e. $p_T <$ hbar/b
      - Also requires longitudal coherence -> small momentum transfer
  - Initial and Final nuclear states are the same
    - $\sigma_{coherent} = |\langle A|V|A \rangle|^2$; target must remain in ground state
    - Required in Good-Walker Paradigm
- UPC data points to first explanation
  - Can be explained by multi-photon exchange, but this does not solve the overall problem.

Multiphoton exchange



- Ideally study events with ρ^0 and nothing else
- However, for lead $Z\alpha$ ~ 0.6
  - Probability of an additional photon depends on b; can be large
    - Single or mutual dissociation
    - P(b) ~ $1/b^2$
      - Biases impact parameter distributions

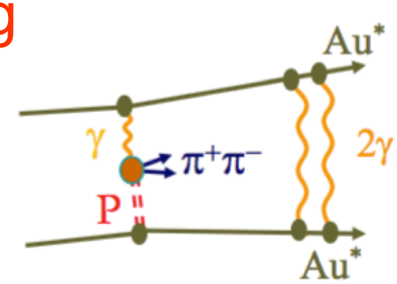


- We need to account for these photons
  - n emission from Giant Dipole Resonance
  - n and p from higher resonances
  - Forward π^+ from Δ^+ and higher excitations
- Experimentally
  - ρ^0 w/ neutrons in ZDC are normally treated as subclasses of events
    - Different impact parameter distributions
  - Forward π^+ can fill-in expected rapidity gaps, and may cause events to be vetoed; this must be corrected

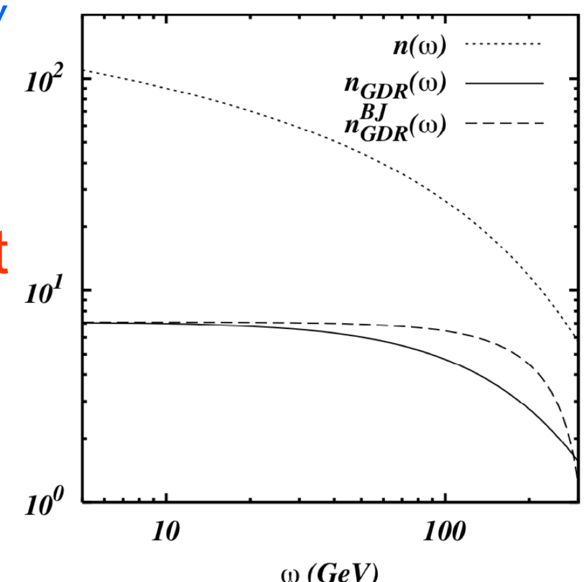
A. J. Baltz *et al.*, PRL **89**, 102301 (2002); SK & P. Steinberg, Ann. Rev. Nucl. Part. Sci. **70**, 323 (2020)

Factorization

- Factorization assumes each photon does one thing
- Photons are emitted independently
  - True for 'low-energy' photons
- Calculate σ in impact-parameter space
  - Unitarity corrections needed for Coulomb excitation
- Photon distributions scale as $1/b^2$
  - <b> drops as # of photons rises
    - For 2 photons, $\sigma \sim 1/b^4$, for 3 photons $1/b^6$
  - Photon energy spectrum hardens with more γ
    - Some tunability
- Photons are linearly polarized along \vec{b}
- STAR has limited data w/o ZDC requirement
  - Agrees with predictions from factorization



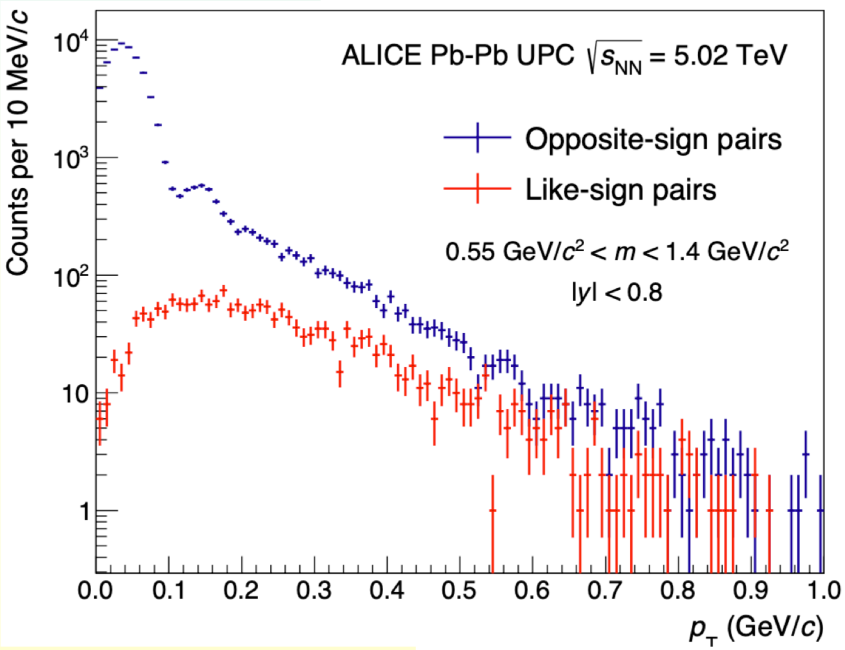
$$\sigma = \int d^2 b P_1(b) P_2(b) \ldots$$



S. N. Gupta, Phys.Rev. **99**, 1015 (1955)
G. Baur et al., Nucl. Phys. **A729**, 787 (2003)

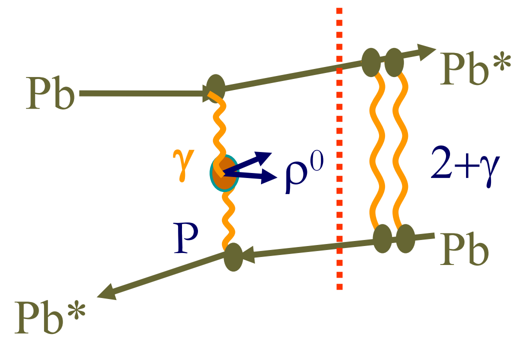
ALICE ρ^0 analysis for PbPb at 5.02 TeV

- Triggers on events with two tracks in TPC + ITS
  - No ZDCs in trigger
- Like-sign background subtracted
- Incoherent production subtracted using template from STARlight
- Diffrctive minima visible.

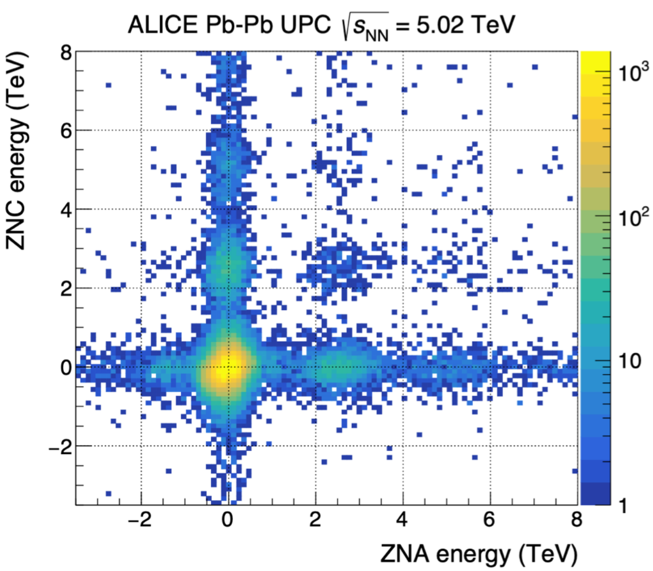


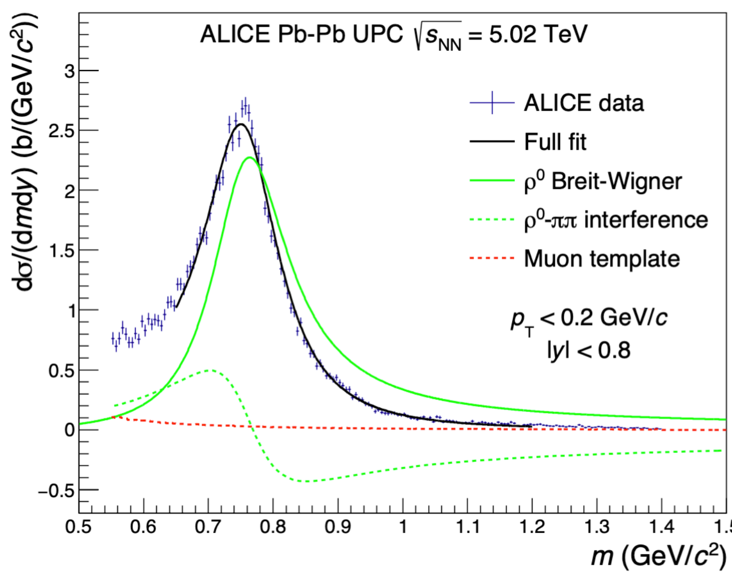
ALICE, JHEP **06**, 035 (2020)

ALICE cross-sections for neutrons with ρ^0



- ρ^0 + direct $\pi^+\pi^-$ with p_T < 200 MeV/c
- Multiple models for ρ^0 photoproduction
- Multiple factorization calculations
- Categorize ρ^0 + direct $\pi\pi$ events by number of neutrons
  - 1n peak from Giant Dipole Resonance is prominent
  - 0n0n, 0nXn and XnXn

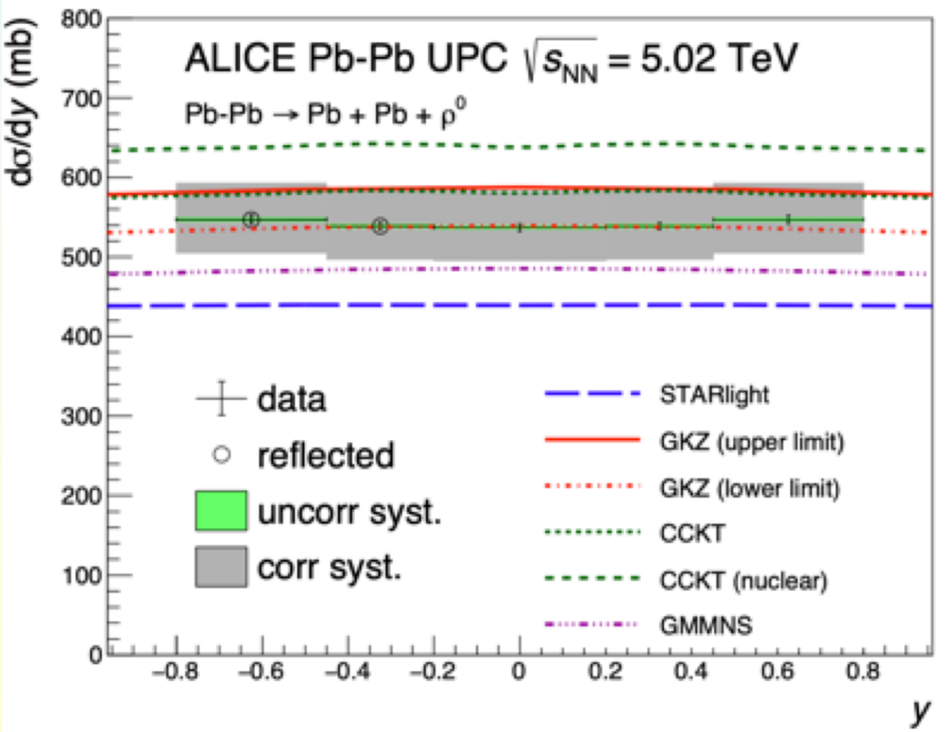




ALICE, JHEP **06**, 035 (2020)

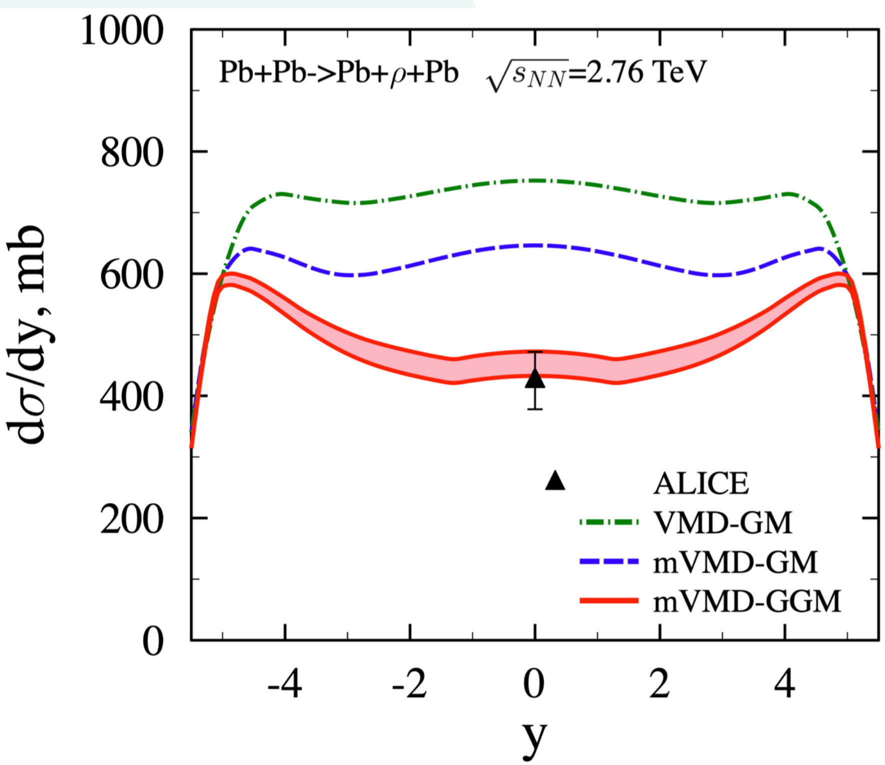
Total ρ^0 cross-section

- $d\sigma/dy$ ~ 550 mb and Δy ~ 10 -> σ_{tot} ~ 5.5 barns
  - Comparable to the hadronic cross-section in PbPb
- Multiple predictions – Glauber calculations, dipole models
  - GKZ model is a Glauber-Gribov model, whereby the dipole may fluctuate to heavier intermediate states as it travels through the target



Coherent photoproduction in the Glauber model

- In the Glauber model, dipoles in a heavy nucleus may multiple scatter (interact many times), but the dipole does not change as it travels through the nucleus. Can also allow other on-mass-shell vector mesons.
- In the Glauber Gribov model, the dipole may take on excited virtual intermediate states as it travels through the nucleus.

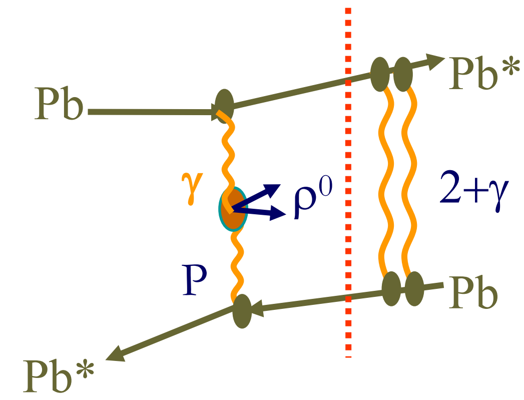


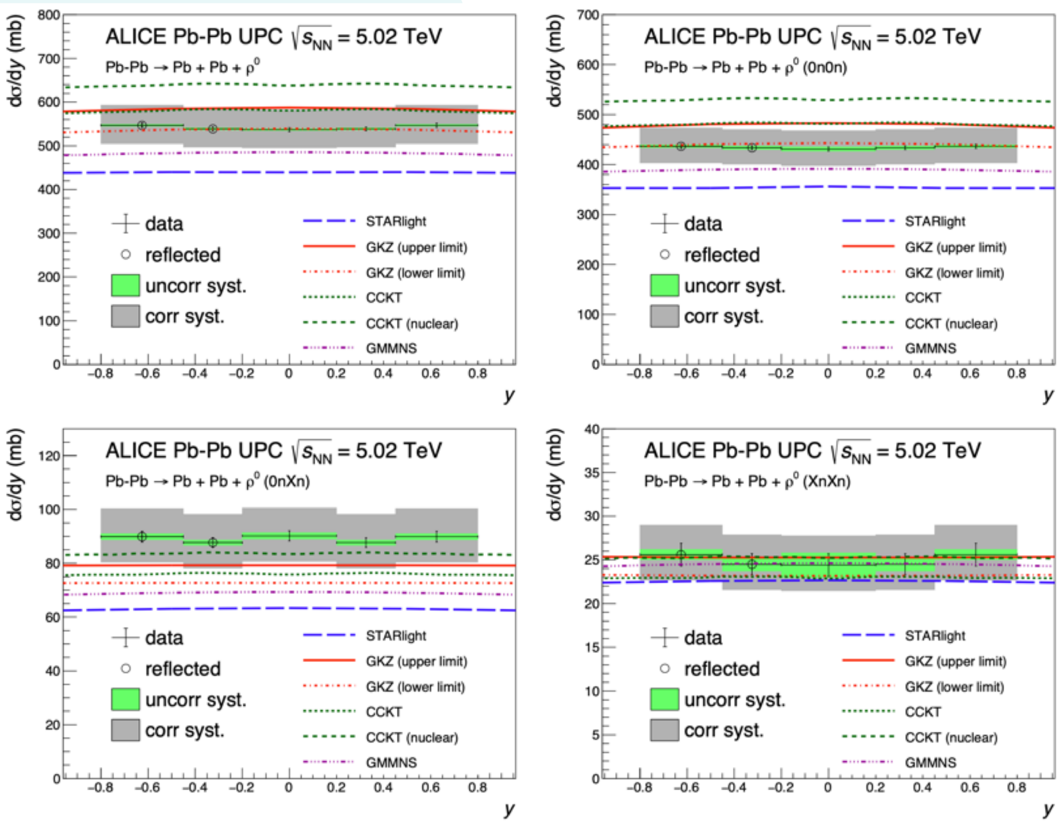
Glauber VMD
Glauber w/ Generalized VMD
Glauber-Gribov

L. Frankfurt, V. Guzey and M. Strikman, Phys. Lett. B752, 51 (2016)

ALICE cross-sections for neutrons with ρ^0

- ρ^0 + direct $\pi^+\pi^-$ with p_T < 200 MeV/c
- Factorization Calculations
  - STARlight – parameterized γA->A* data
  - N00N – different approach to unitarity
    - Used in CCKT curves below
  - General, but not complete agreement





ALICE, JHEP **06**, 035 (2020)
SK et al., Comput. Phys. Comm. **212**, 258 (2017)
M. Broz et al., Comput. Phys. Comm. **253**, 10781 (2020)

The Good-Walker Paradigm

- Coherent photoproduction probes the average nuclear distribution
- Incoherent photoproduction is sensitive to event-by-event changes in the nuclear configuration Ω (positions of nucleons, gluon hot spots, etc).

$$\frac{\mathrm{d}\sigma_{\mathrm{tot}}}{\mathrm{d}t} = \frac{1}{16\pi}\left\langle \left|A(K,\Omega)\right|^2 \right\rangle$$

Total cross-sections (Ω) average over cross-section (|Amplitude|^2)

$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$

Coherent cross-sections average over amplitudes (Ω)

$$\frac{\mathrm{d}\sigma_{\mathrm{inc}}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle \left|A(K,\Omega)\right|^2 \right\rangle - \left| \langle A(K,\Omega)\rangle \right|^2 \right)$$

Incoherent is difference

Ω is nuclear configuration; K is kinematic factors

This formalism relies on $\sigma_{coherent} = |\langle A|V|A\rangle|^2$;
target must remain unexcited

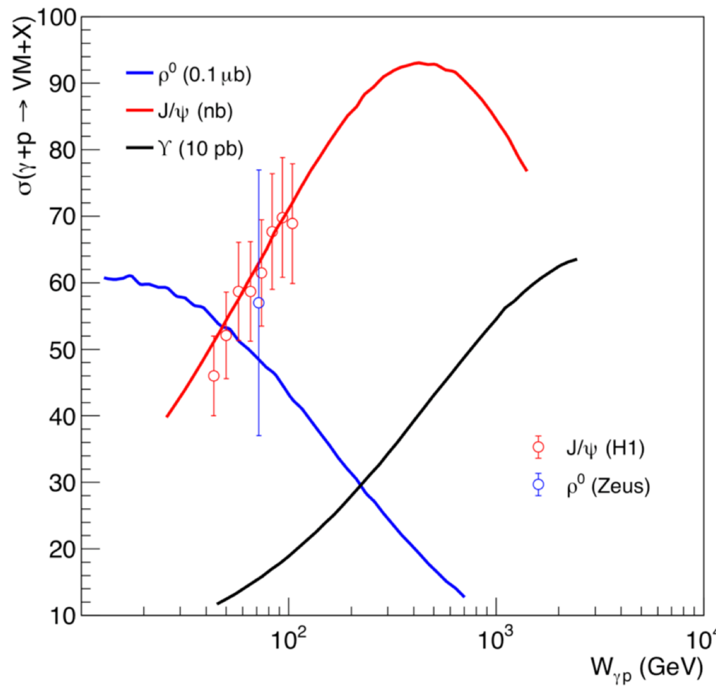
M. Good & D. Walker, Phys. Rev. 120, 1857 (1960); S. K. & H. Mantysaari, Nature Rev. Phys. **1**, 662 (2019)

What is the problem?

- STAR and ALICE data show that the presence of nuclear breakup does not preclude coherent emission.
  - As measured by momentum transfer from target
- Even for low-charge emitters like electrons, there is likely a problem
- Excitation leading to photon emission can be very soft, and also very hard to see
  - ^{197}Au has a 77 keV excited state with a 1.9 ns lifetime
  - How does such a soft excitation change the kinematics of vector meson production, at a much higher energy scale
  - The struck nucleus can also emit bremsstrahlung photons, down to arbitrarily low energy
    - Cross section is small, but so what?
- Good-Walker must be adjusted to preserve coherent interactions in the presence of soft emission.
  - It is likely that the time scale (hbar/energy) plays a role, but the dividing line is unclear.

Incoherent and coherent production and the black disk limit

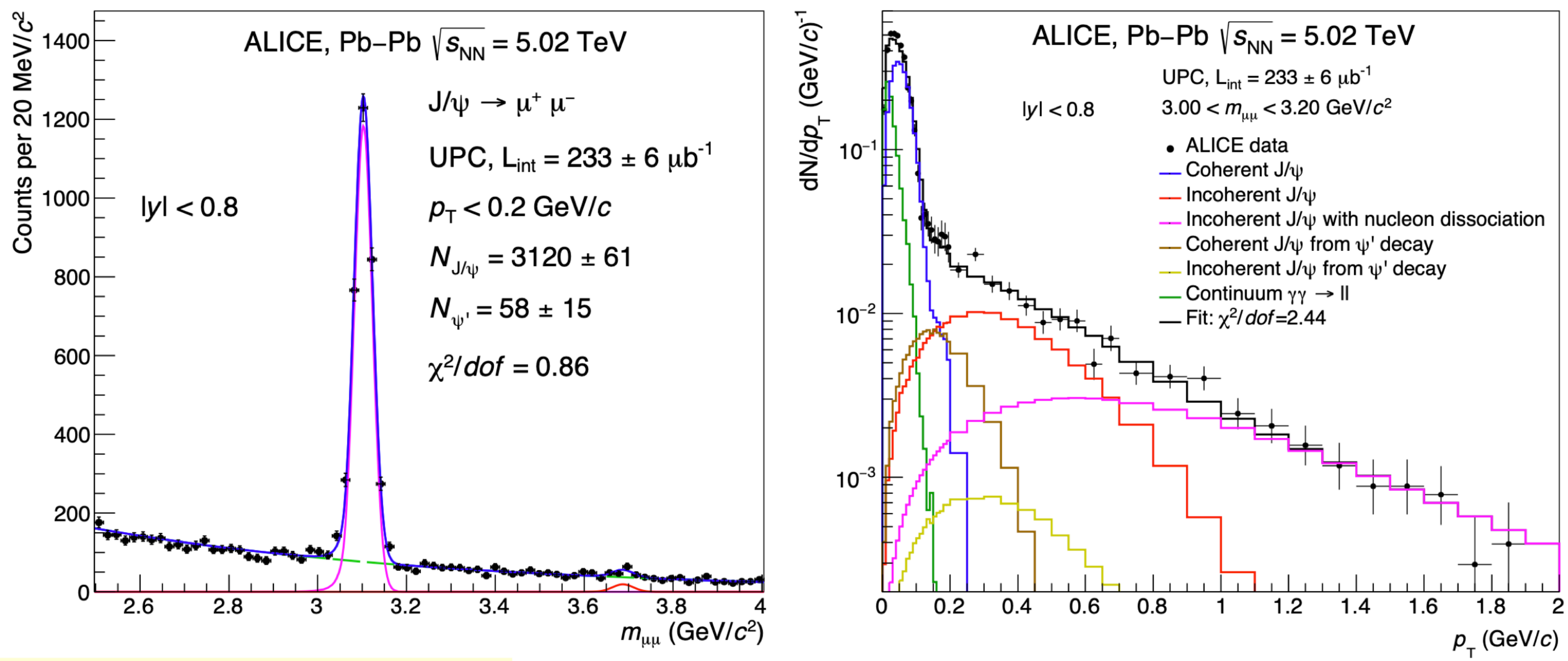
- Higher photon energies -> lower Bjorken-x
  - Lower x values -> more gluons, more hotspots
  - The fraction of the proton or ion surface covered with hot spots rises
- The ‘black disk limit;’ the nucleus acts like an absorptive disk
- Black disks don’t fluctuate
  - Incoherent production should disappear.
- High-mass final states require more energetic (larger x) gluons,
  - Slower to disappear
- Extension to nuclei model dependent
  - Black disk limit -> no incoherent production -> no target fragmentation
  - Modifications likely as limit approaches



J. Cepila et al., Nucl. Phys. B934, 330 (2018)

ALICE J/ψ photoproduction

- J/ψ, ψ' in ALICE central
- Coherent and incoherent production separated via p_T spectra
  - Neutrons in ZDC not yet used
  - Protons in proton calorimeters could also be probed

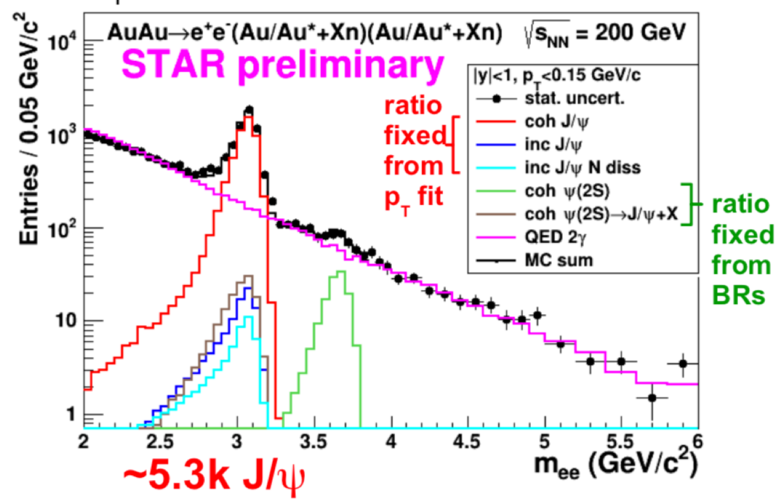


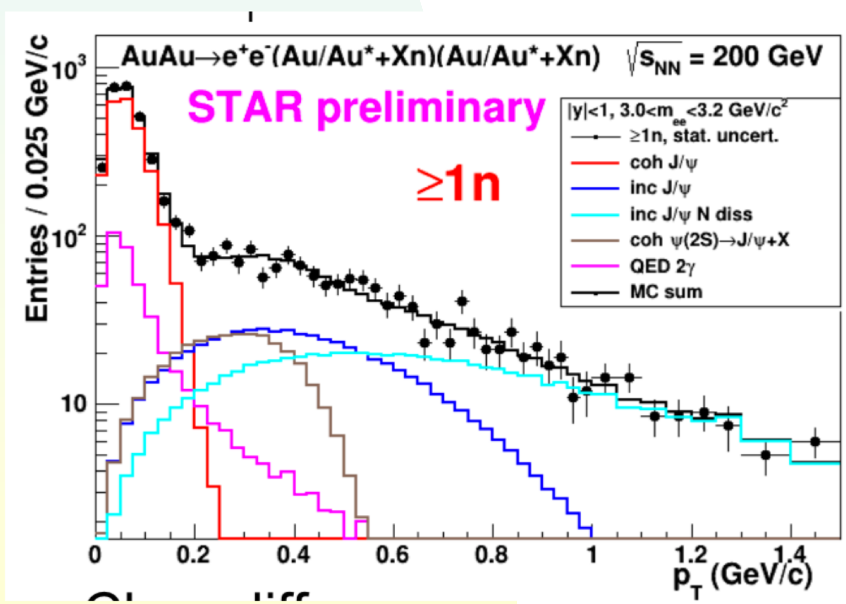
ALICE, Eur. Phys. J **C81**, 712 (2021)

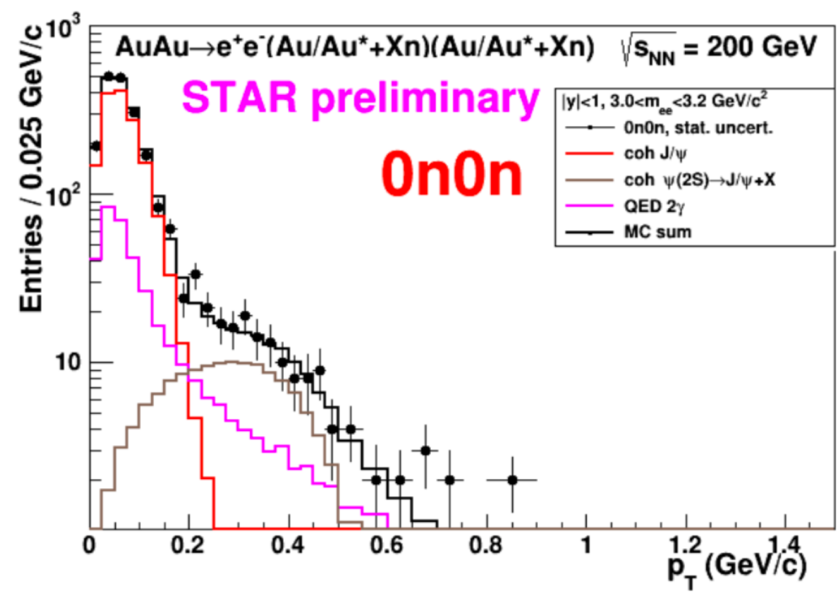
STAR J/ψ photoproduction

- J/ψ -> ee with calorimeter based trigger; no ZDCs required
- J/ψ p_T spectra separated by ZDC neutron content
- Events with neutrons have a larger high p_T tail, consistent with more incoherent production

- p_T < 0.15 GeV/c:





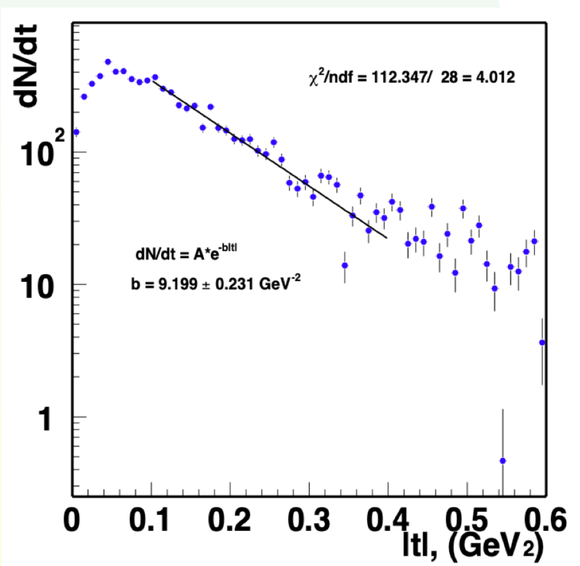


W. Schmidke [STAR], DPF 2019

ρ^0 and J/ψ photoproduction in dAu at RHIC

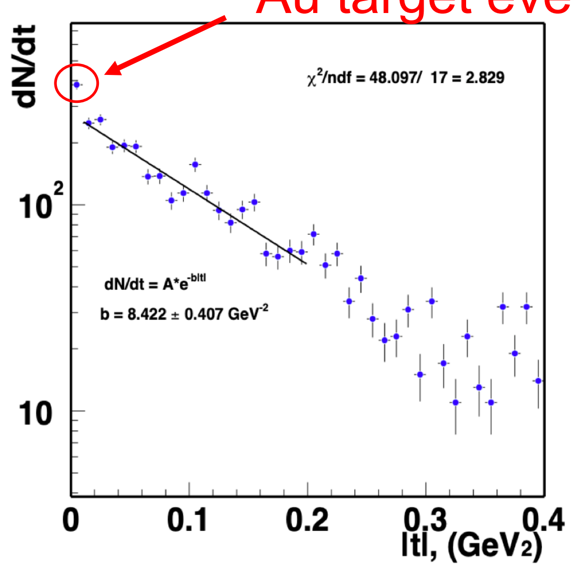
- J/ψ – see talk by Kong Tu on Friday
- Photon almost always comes from Au
- Deuteron coherent enhancement is modest
- STAR data with ‘topological’ & topological + ZDC triggers
- Neutron tagged deuteron breakup
- Slopes of dN/dt are quite similar?

Neutron tagged

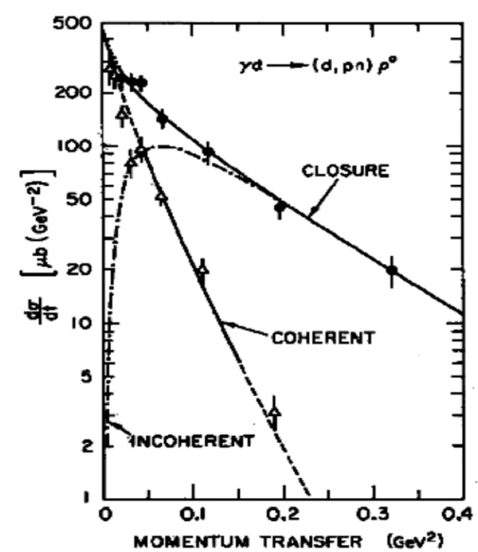


No neutron

Au target events?



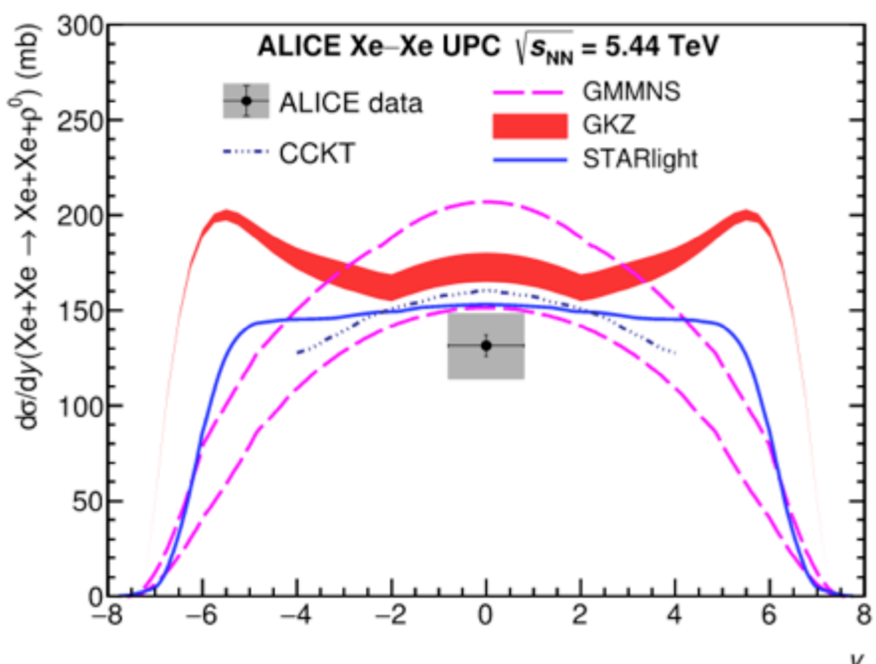
Theory

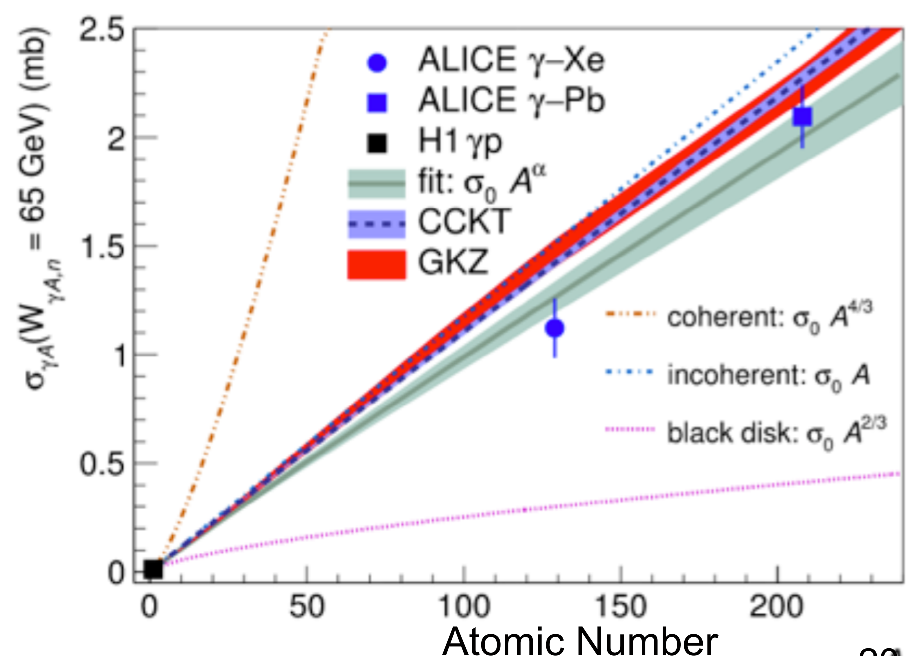


S. Timoshenko for STAR, arXiv:nucl-ex/0501010

ρ^0 photoproduction in XeXe collisions

- From a 6-hour XeXe run in 2017
- Trigger, analysis similar to PbPb
- Cross-section consistent with Glauber calculations
- From p, Xe, Pb, $\sigma \sim A^{0.96 \pm 0.02}$
  - Significant shadowing; $\sigma \sim A^{4/3}$ in absence of shadowing
- Limited luminosity; neutrons not studied

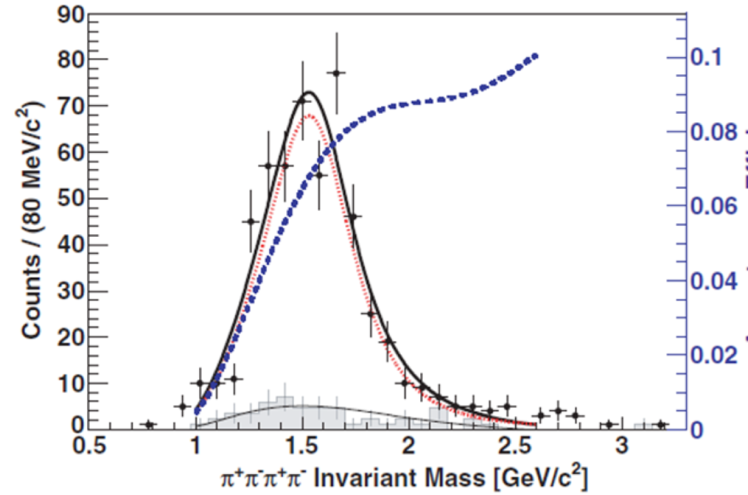


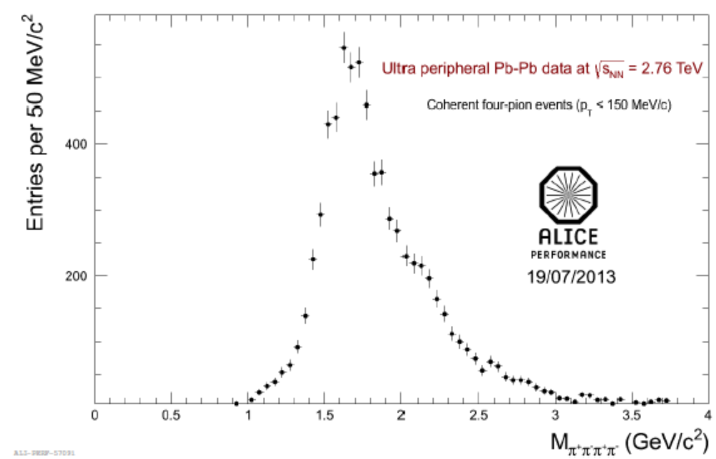


ALICE, Phys. Lett. **B820**, 136481 (2021)

Excited ρ and $\pi\pi\pi\pi$ final states

- Seen by STAR and ALICE
- Expected to be mixture of ρ'(1450) & ρ' (1700)
  - These two states can interfere, and predominantly decay to $\pi\pi\pi\pi$
- $M_{\pi\pi\pi\pi}$ ~ 1540 MeV
- Γ ~ 670 MeV
- Significant decays to $\rho^0\pi\pi$
- Consistent with expected mixture of ρ'(1450) & ρ' (1700)

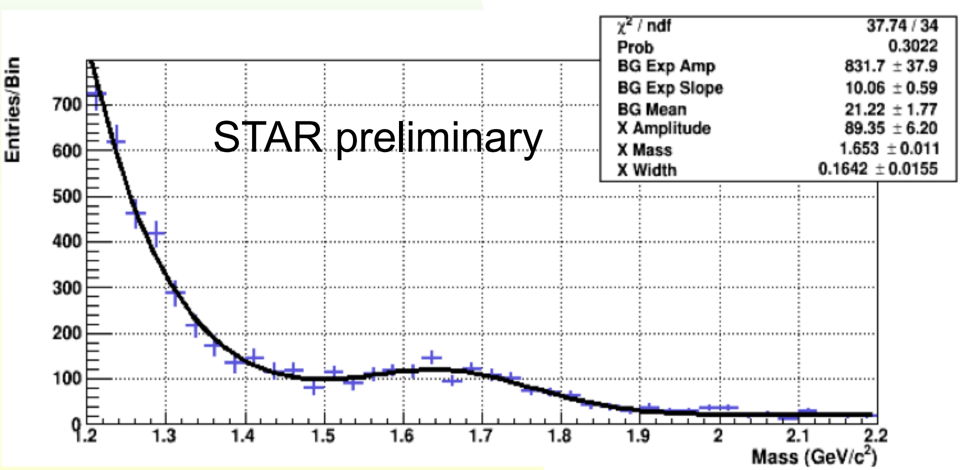


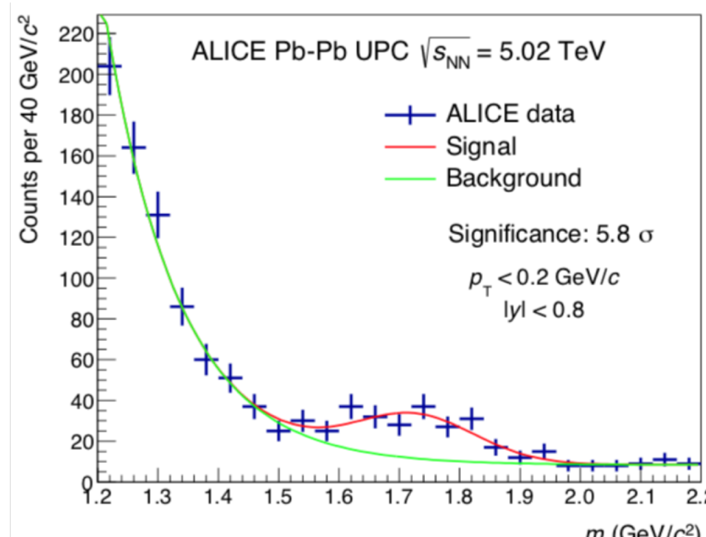


STAR: PRC81, 044901 (2010) ALICE: C. Mayer, 2014 CERN UPC wkshp

$\rho' \to \pi\pi$?

- STAR and ALICE see a heavy $\pi\pi$ state
  - STAR: M_X = 1653 ± 10 MeV, $\Gamma(X)$=164 ± 15 MeV (stat. only)
  - ALICE: M_X = 1725 ± 17 MeV, $\Gamma(X)$=143 ± 21MeV
- Width inconsistent with ρ' (1700) [M=1720 MeV, Γ=250 MeV]
- ρ' branching ratio to pp is small
- Mass, width and abundance may be consistent with ρ_3(1690)
  - consistent w/ Br($\rho_3 \to \pi^+\pi^-$) & previous $\gamma p \to \rho_3 \to \eta\pi^+\pi^-$ data
    - Spin 3 allowed through in-medium wave function modifications?





STAR: DIS2016, ALICE: arXiv:2002.10879

What can we learn about target fragmentation?

- Two highly correlated signatures of incoherent production
  - Harder p_T spectrum
    - Quantitative measurements require separation of coherent component
      - Usually, look at high p_T where coherent component is small
  - Neutron (and presumably proton and photon) emission
    - Background from nuclear breakup via extra photon exchange
- Extra photon exchange can also produce forward particles
  - It can be avoided by low-z emitters
  - pA collisions or oxygen
- In pA collisions, photon-from-gold dominates vector meson production
  - For photon-from-gold, $p_{TVM} \sim hbar/R_p$
  - For photon-from-proton, $p_{TVM} \sim hbar/R_A$
  - Can they be separated well enough?
    - All papers so far have focused on proton (or d) target

Looking Ahead

- At RHIC, the sPHENIX countinous readout DAQ will allow enormous samples of UPC data to be collected, including pA
  - Is there interest and manpower
- At the LHC, ALICE has new TPC endcaps and a continuous readout DAQ.
  - Large UPC samples are expected in Run 3 and Run 4
  - 2 & 4-prong final states, high mass ρ^0 states, helicity studies etc.

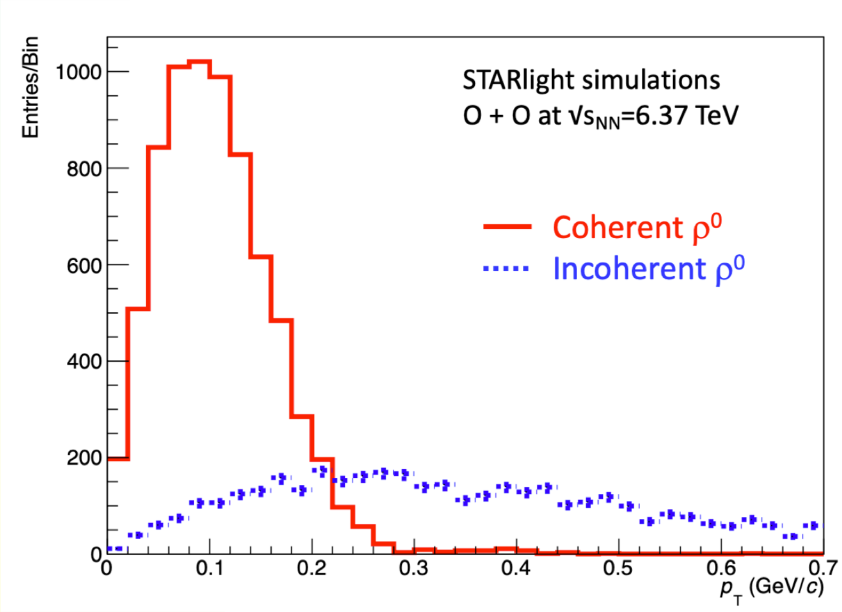
ALICE Central barrel

			PbPb				
Meson	σ	All Total	Central 1 Total	Central 2 Total	Forward 1 Total 1	Forward 2 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
$\phi \to K^+K^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$J/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2S) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$Y(1S) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

Z. Citron et al., arXiv:1812.06772

Oxygen-Oxygen running

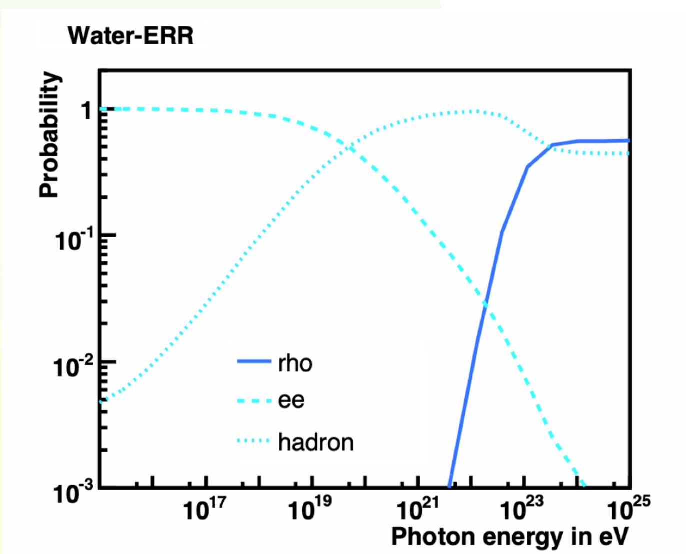
- A short (1 nb^{-1}?) oxygen-oxygen run has been proposed for Run 3
- First all-t measurement of incoherent photoproduction on nuclei at collider energies?
  - Z = 8, additional photon flux is reduced ~ 100 times
  - ^{16}Oxygen is doubly magic, so not easy to dissociate
  - Incoherent:coherent ratio is larger
  - Unlike Pb, neutrons may be associated with incoherent processes

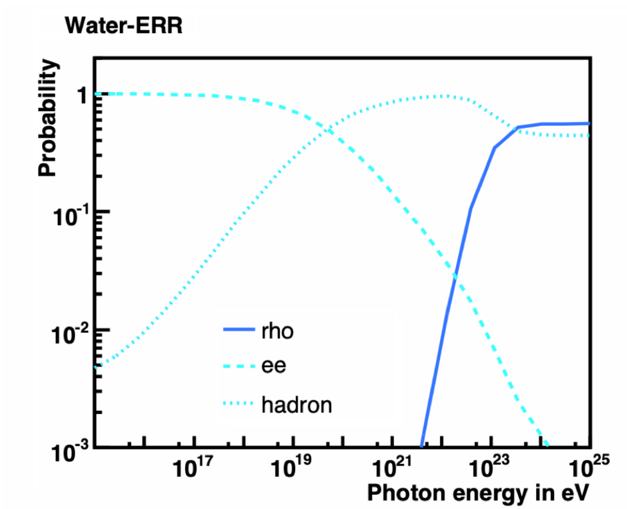


ALICE public note: https://cds.cern.ch/record/2765973/files/ALICE_PN_ProjectionShortOxygenRun.pdf

ρ^0 photoproduction in the very large A limit

- At high enough energy (above 10^{23} eV) photons will interact coherently with bulk matter to produce ρ^0 + direct $\pi\pi$
  - Coherent interactions with multiple nuclei
- The LPM effect suppresses pair production, so this is the dominant interaction
- The formation length L_f=2 hbar k/M_V^2 becomes comparable to the interaction length
- $\sigma \sim N_{targets}^2$, but $N_{targets}$ depends on L_f, so the term cross section loses meaning





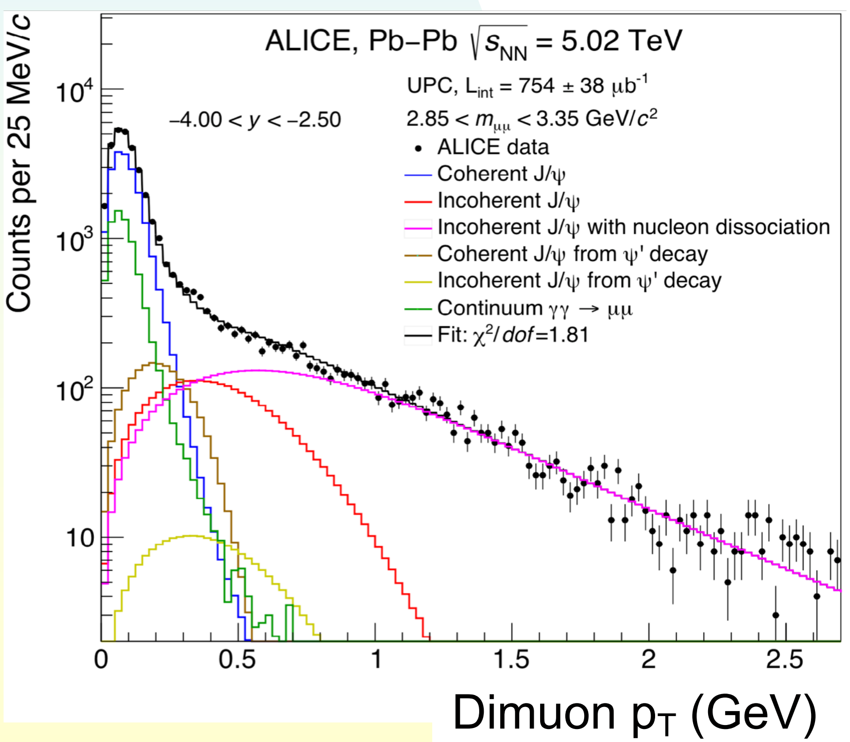
SK and E. Couderc, PRL 103, 062504 (2009)

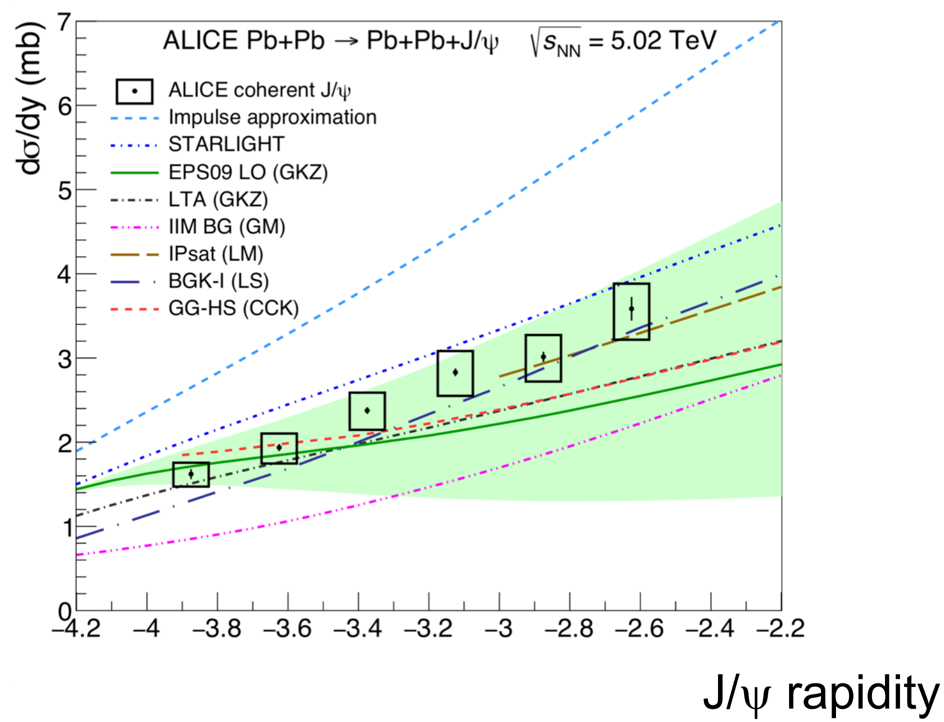
Conclusions

- Coherent and incoherent photoproduction of vector mesons are an important channel for probing the average nuclear configuration and gluonic/hadronic hot spots respectively.
- The conventional Good-Walker paradigm may need modification to account for accompanying soft interactions.
  - This is also a big issue for the EIC.
- Current experiments can detect neutron emission (and, for ALICE proton emission) accompanying vector meson production
  - Because of extra photon exchange, the nucleon emission data cannot be cleanly related to heavy=ion target fragmentation
  - Deuteron targets can be studied, but that work is at an early stage.
  - Proton targets can also be studied.
- Looking ahead, the planned LHC oxygen-oxygen run may offer the opportunities to study fragmentation of a light/medium ion.

ALICE PbPb-> J/ψ at $\sqrt{s_{NN}}$=5.02 GeV

- p_T spectrum measured out to 2.5 GeV/c
  - Coherent (Pb), incoherent (single N) & nucleon dissociation seen
- $\sigma_{coherent}$ indicates shadowing ~ 0.8
  - Consistent with/slightly above EPS09 (&EPPS16) fits to worlds data
    - Smaller errors
- Consistent with leading twist approximation (LTA) & other models



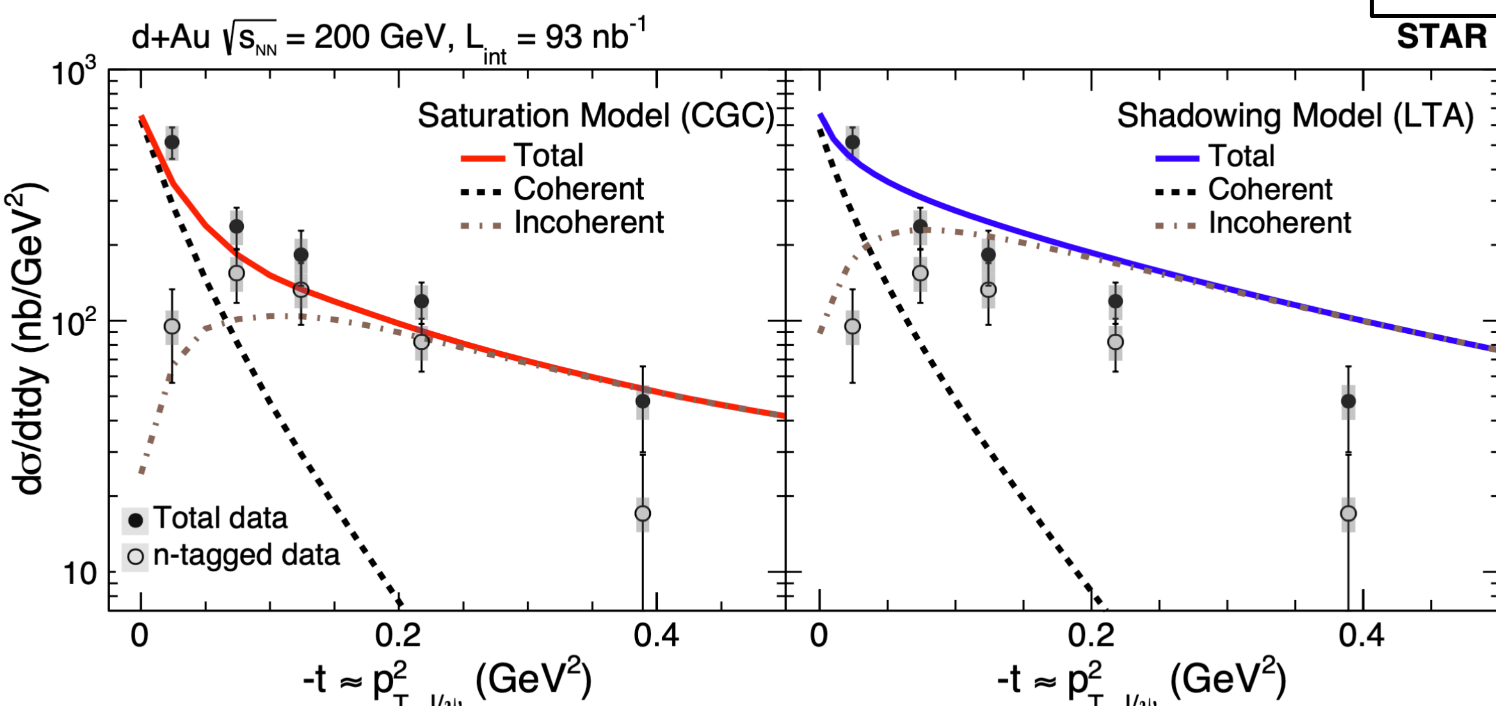


ALICE: Phys. Lett., 134926 (2019)

Photoproduction in dAu collisions in STAR

- Gold is usually photon emitter; deuteron is usually target
  - Deuteron coherent enhancement is modest
- Trigger on calorimeter clusters; no ZDC in trigger
- Tag deuteron breakup (incoherent prod) w/ ZDC
  - For large J/ψ p_T, if the neutron were struck, it would miss the ZDC
    - Can tag events where the proton (only?) was stuck
- Neutron/Noneutron larger at large p_T

See Kong Tu's talk on Friday



STAR, arXiv:2109.07625