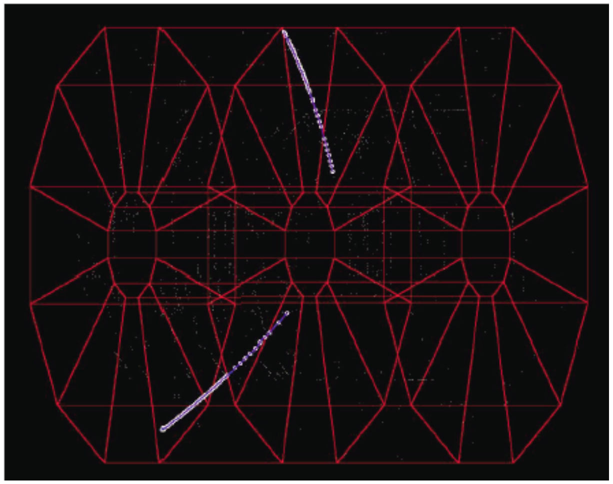
Ultra-peripheral collisions and hadronic structure

Spencer Klein, LBNL

- Introduction: Why UPCs?
- QED: dilepton production
- The structure of heavy nuclei
- Toward nucleon parton distributions at low x
- Gluon shadowing w/ nuclear targets
- Conclusions



Some experimental emphasis; experiment-agnostic

Why ultra-peripheral collisions (UPCs)?

- UPCs are electromagnetic interactions of heavy ions/protons.
- Useful to study nuclear structure, search for new physics, and study meson spectroscopy
- They are the energy frontier for electromagnetic probes
  - Maximum CM energy $W_{\gamma p}$ ~ 3 TeV for pp at the LHC
    - ~ 10 times higher in energy than HERA
  - Probe parton distributions in proton and heavy-ions down to
    - Bjorken-x down to a few 10^{-6} at moderate Q^2
- Electromagnetic probes have $\alpha_{EM} \sim 1/137$, so are less affected by multiple interactions than hadronic interactions
  - "Precision" measurements,
  - Exclusive interactions
- Two-photon physics & couplings at the energy frontier
  - New particle searches (axions), $\gamma\gamma \to W^+W^-$, etc.

Ultra-peripheral collisions (UPCs)

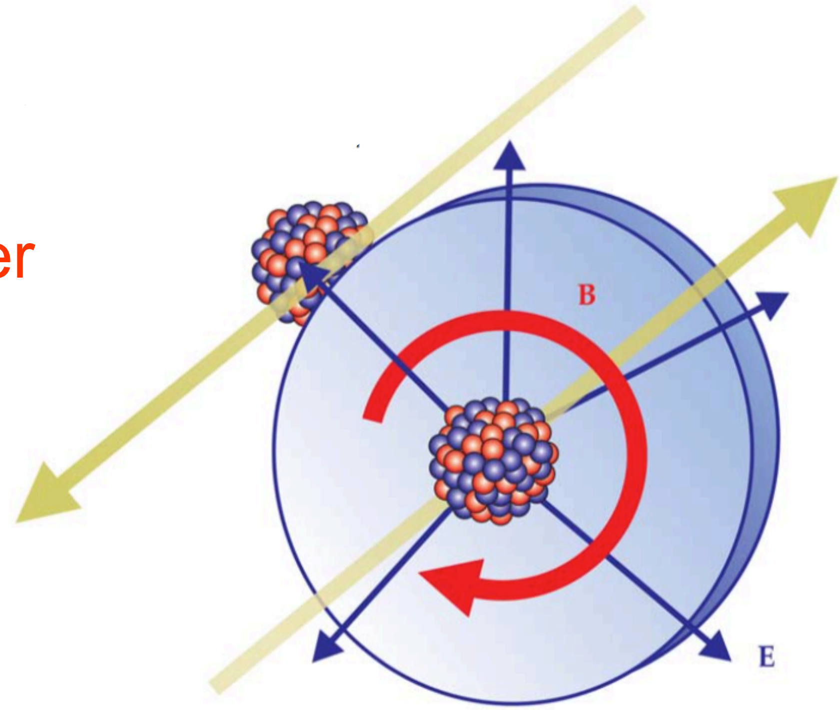
- Heavy nuclei carry strong electric and magnetic fields
  - Fields are perpendicular -> treat as nearly-real virtual photons
    - $E_{max} = \gamma hc/b$
  - Photonuclear interactions
  - Two-photon interactions
- Visible when $b >\sim 2R_A$, so there are no hadronic interactions;
  - STAR & ALICE also see photon interactions in peripheral nuclear collisions

Energy	**AuAu RHIC**	**pp RHIC**	**PbPb LHC**	**pp LHC**
Photon energy (target frame)	0.6 TeV	~12 TeV	500 TeV	~5,000 TeV
CM Energy $W_{\gamma p}$	24 GeV	~80 GeV	700 GeV	~3,000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~100 GeV	200 GeV	~1,400 GeV

*LHC at full energy $\sqrt{s}$=14 TeV/5.6 TeV

Photons from nuclei

- Crossed E and B fields -> photons
  - Usually, neglect photon virtuality
- Photon energy spectrum is the Fourier transform of E(M) field, as seen at impact parameter b
  - Equivalent photon approximation – massless photons
    - Usually OK
  - Photon wavelength > width of EM 'pancake'
  - $k_{max} \sim \gamma hc/b$
    - $N(k,b) \sim 1/b^2$
    - Most energetic photons are near $b \sim R_A$
- Photon flux inside nucleus drops off rapidly, per Gauss' law



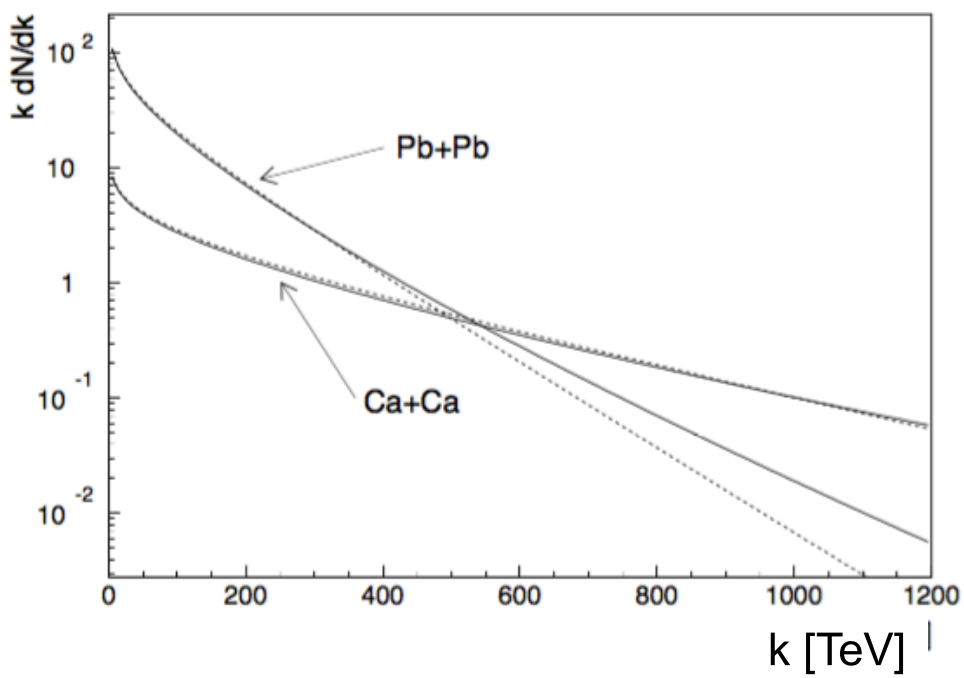
$$n(k,b) = \frac{d^3N}{dkd^2b} = \frac{Z^2\alpha}{\pi^2 kb^2} x^2 K_1^2(x)$$

$x = bk/\gamma$.

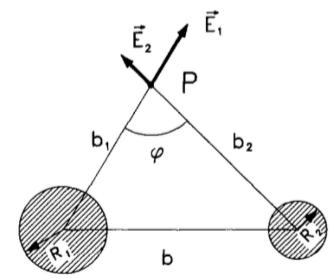
Photon energy spectrum

- "k_{max}" = γ hbar c /R_A
  - Lighter nuclei -> higher photon energies
  - Cutoff is gentle – 'cutoff' is an overstatement
- kdN/dk ~ 1/k
- Z^2 flux enhancement partially cancelled out by higher luminosities

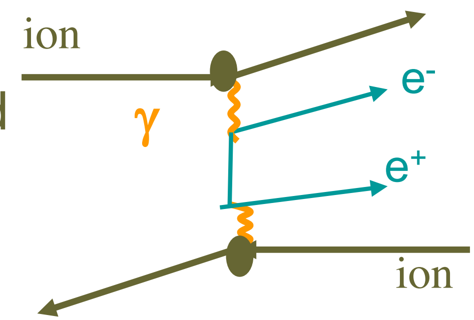
LHC photon energy spectrum in the target frame



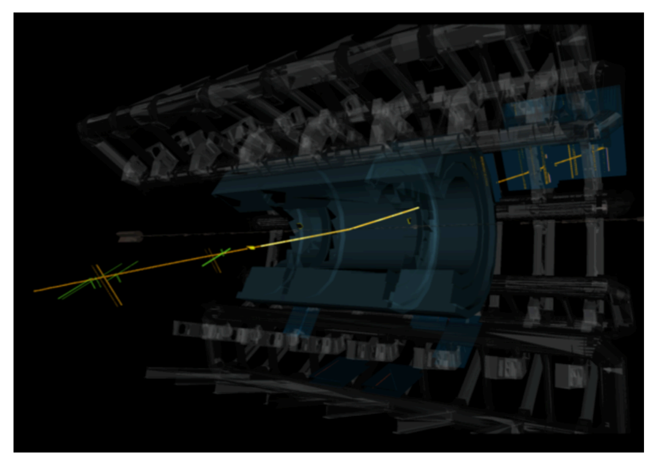
Two photon collisions



- Two photon fields collide
  - 3 transverse positions: 2 nuclei+ interaction point
  - $\sigma \sim \int d\phi \int b_1 db_1 \int b_2 db_2 \, N_{\gamma 1}(b_1) N_{\gamma 2}(b_2) \sigma(\gamma_1\gamma_2 \text{->} F)$
- Copious production of dileptons
  - σ ~ 200,000 barns with lead at the LHC
    - Mostly near threshold, with lepton $p_T \sim m_e$, produced at small angles to the beampipe
    - Significant background in vertex detectors
  - Special case: bound-free pair production
    - Electron bound to nucleus



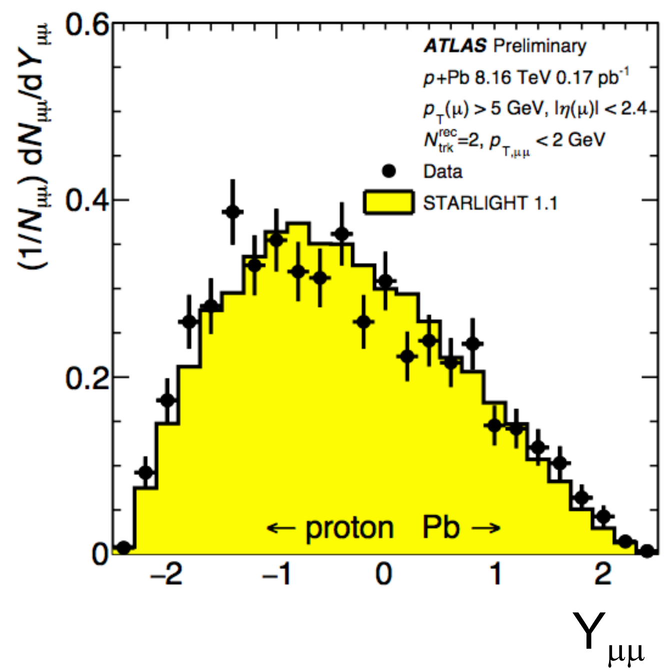
- γγ-> Higgs
  - Small cross-section, but maybe Run 3 or 4
- γγ -> new physics
- Meson spectroscopy

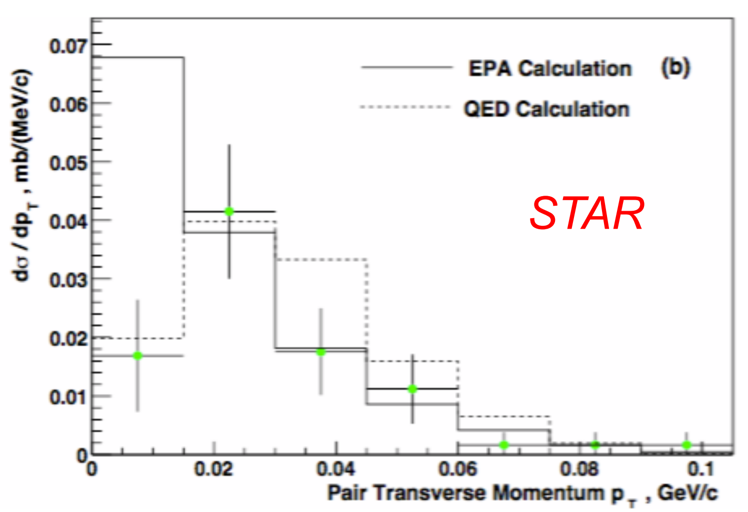


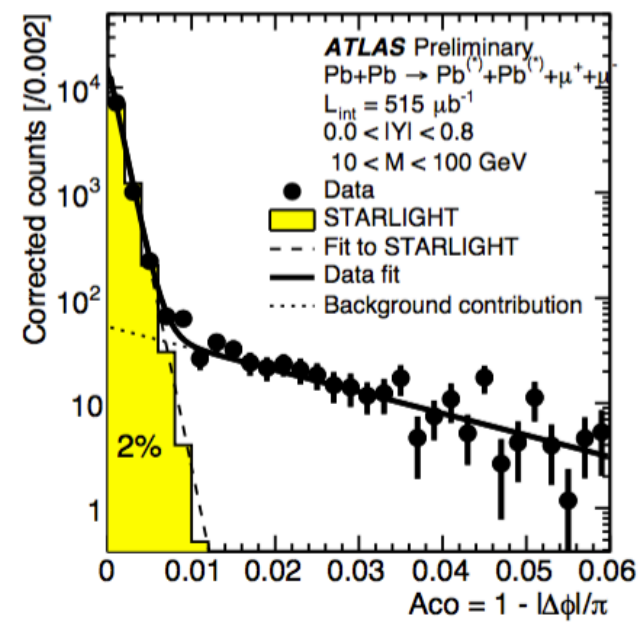
$M_{\mu\mu}$=173 GeV dimuon UPC in ATLAS

γγ -> Dileptons

- ALICE, ATLAS & STAR data is in good agreement with lowest order QED
  - STARlight Monte Carlo
  - $Z\alpha \sim 0.6$, so perturbation theory might fail
- STAR sees failure at low pair p_T due to equivalent photon approximation
- ATLAS sees acoplanarity tail – higher order correction, incoherent photons or background?



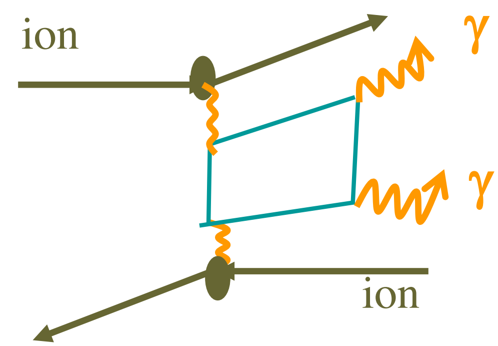


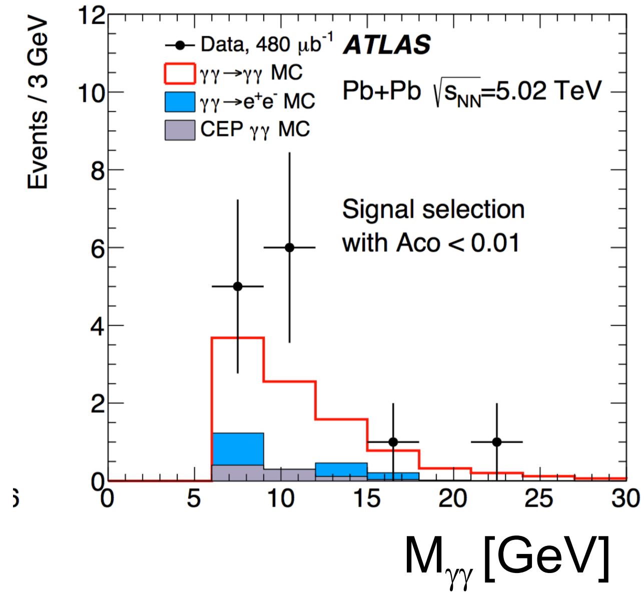


STAR; Phys. Rev. C70, 031902 (2004); M. Dyndal, Quark Matter 2017

γγ -> γγ

- Light-by-light scattering
  - Not possible classically
- Proceeds via a ‘box’ diagram
  - Small cross-section
- The ‘box’ gets contributions from all charged particles
  - Standard model and beyond-SM
  - Sensitive to new physics
- ATLAS sees 13 events, vs. a background of 2.5 ± 0.7
- Limited precision, but already used by Ellis et al. to set limits on anomalous couplings

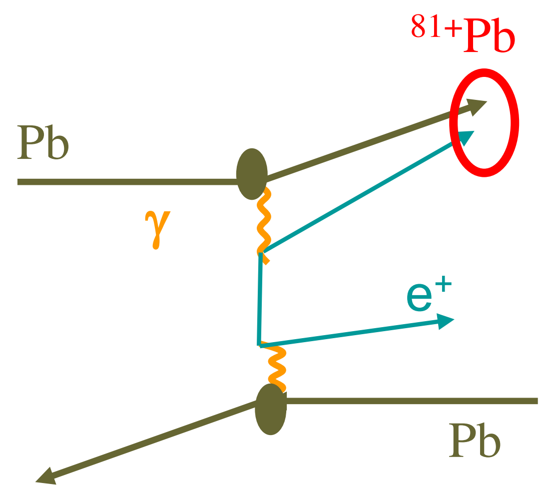


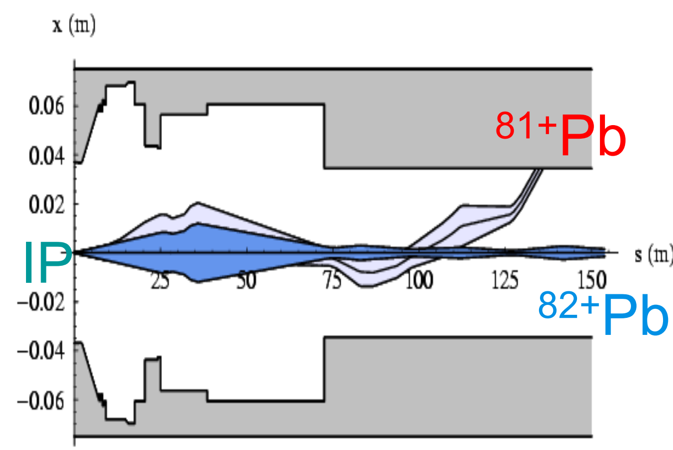


ATLAS: arXiv:1702.01625
J. Ellis *et al.*, PRL 118, 261802 (2017)

UPCs and LHC luminosity

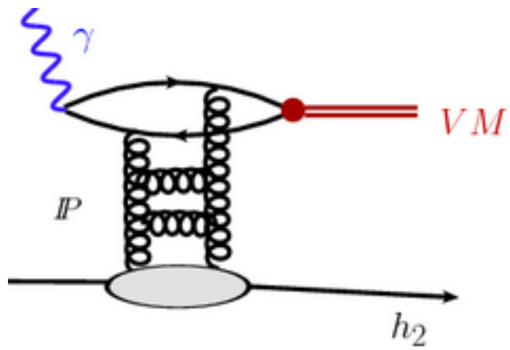
- σ[PbPb($\gamma\gamma$) -> (Pbe^-) Pb e^+] ~ 280 b @ LHC
- Single-electron lead has charge:mass ratio reduced by 1/82
- The (Pbe^-) beam strikes the beampipe 135 m downstream from the magnet
  - At $L = 10^{27}/cm^2/s$, the beam deposits 23 Watts
- LHC magnet quench from BFPP demonstrated!
  - $L_{max}=2.3*10^{27}/cm^2/s$
- Luminosity limit for LHC & potentially fcc
  - Some mitigation possible by orbit bumps.





SK [NIM, 2000], J. Jowett *et al.*, IPAC 2016

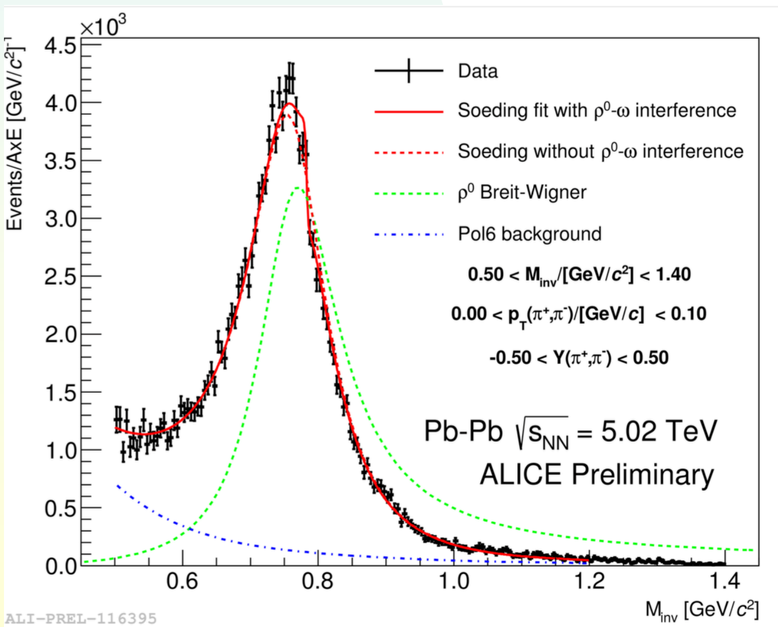
Vector Meson photoproduction

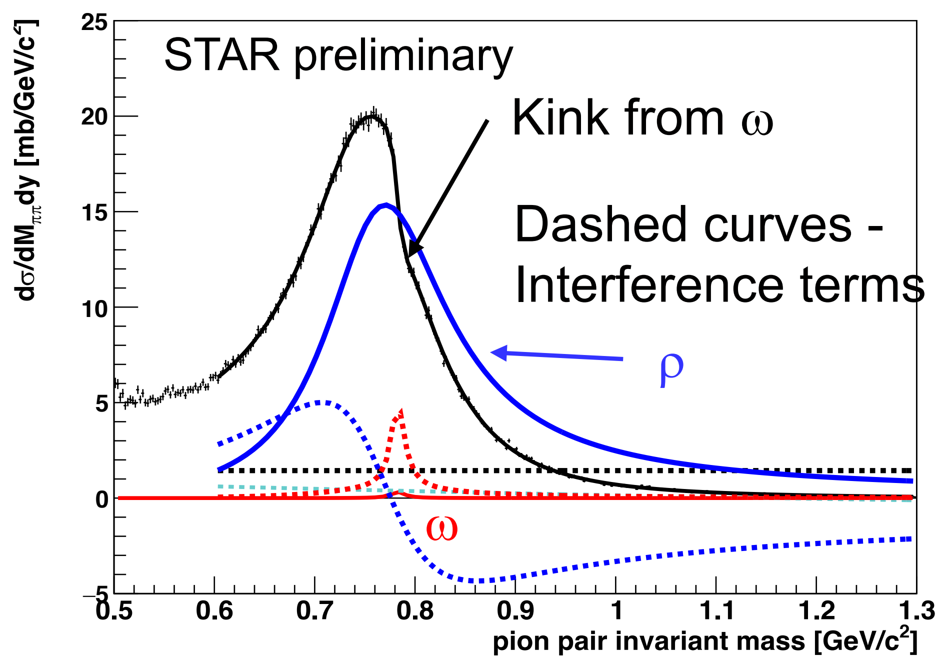


- Process has large cross-sections
- Produced via colorless 'Pomeron exchange'
  - Require >=2 gluon exchange for color neutrality
    - Gluon ladder
- Light meson production usually treated via vector meson dominance model
  - ρ, direct $\pi^+\pi^-$, ω, ρ' observed at RHIC &/or LHC
- Heavy meson production treated with pQCD
  - J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ seen at LHC
- Rapidity maps into photon energy
  - $k = M_V/2\exp(\pm y)$
    - Twofold ambiguity – which nucleus emitted the photon?
  - Cross-section is convolution of bi-directional photon flux with $\sigma(\gamma A)$
    - Photon flux is understood to < 10%

ρ^0 *mass spectrum*

- 294,000 exclusive $\pi^+\pi^-$ with p_T < 100 MeV/c seen by STAR
- Mass spectra fit by ρ^0 + direct $\pi\pi$ + ω->$\pi\pi$
  - ω required for acceptable fit
  - Masses, amplitude ratios & phase angle consistent with low-energy fixed-target studies
    - Pomeron exchange @ high energies; meson exchange at lower



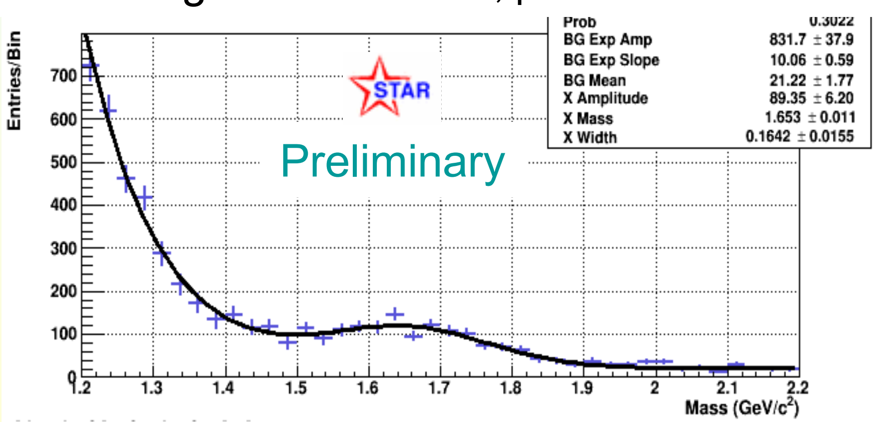


D. Horak [ALICE], QM17; SK [STAR] , DIS2016

Higher mass states

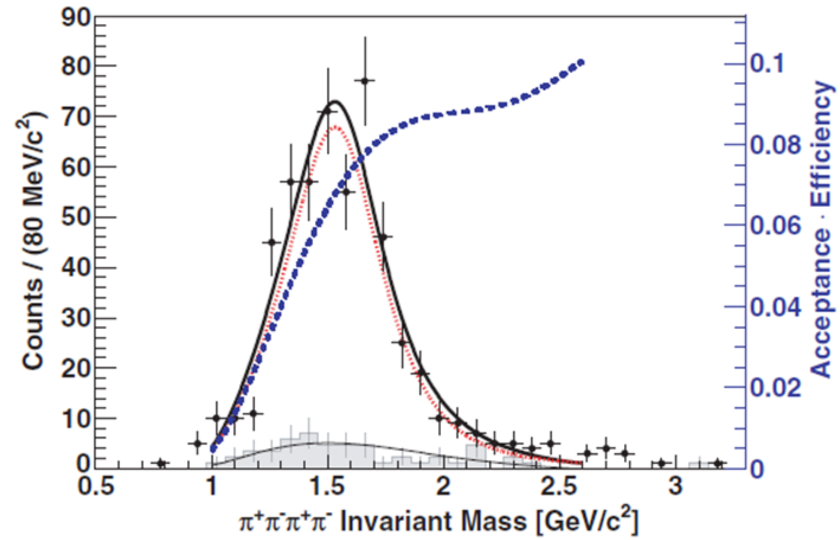
- Expect higher mass ρ' states
  - Radial excitations of the ρ, etc.
    - Like 2s,3s in hydrogen
    - Decays to ππ, ππππ, etc.
  - Possible high-spin excitations
    - Like 2p,3d, etc. in hydrogen
- Meson spectroscopy in UPCs
  - Production ~ to σ_{VA} (elastic)

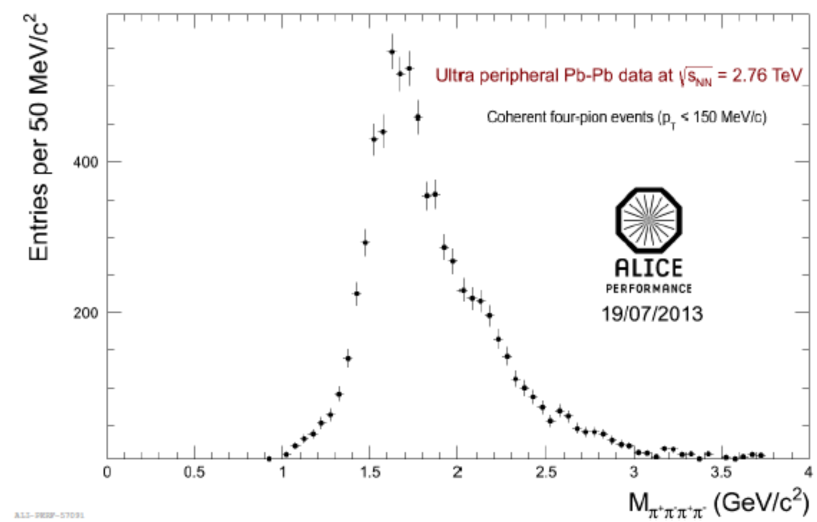
STAR high mass ππ SK, presented at DIS2016



Extra resonance required for a good fit
Consistent with $\rho_3(1690)$

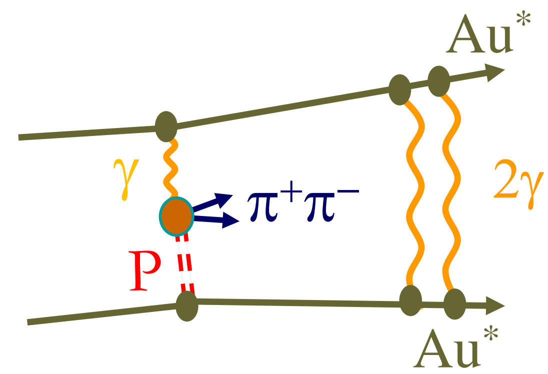
STAR ππππ mass
PRC81, 044901 (2010)





ALICE ππππ mass
C. Mayer, 2014 CERN UPC wkshp

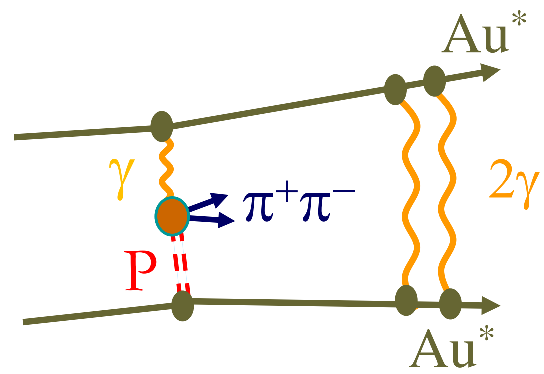
Incoherent production: coherence vs. incoherence

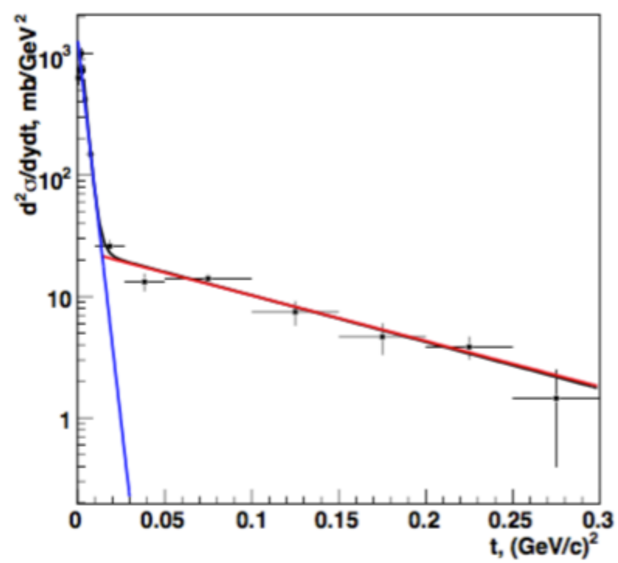


- Coherence in quantum mechanics:
  - Common picture: Final state == initial state
    - Then, add amplitudes
- Slightly looser condition: indistinguishable final states
  - Example: vector meson production on a nuclear target
    - Amp = $\Sigma_i A_i \exp(ikx_i)$
      - i nucleons at positions x_i
  - Happens whether nucleons are bound or not
    - E. g.: ρ^0 photoproduction with mutual Coulomb excitation
      - STAR showed that nuclear excitation does not destroy coherent addition of amplitudes, even though the nuclei break up
        - In QED, emission of low-energy photons is independent
        - Nucleon positions do not change much during the reaction
  - Coherence requires only a definite phase relationship
- Muddies separation of coherent & incoherent production

Separating coherent & incoherent

- ρ^0 + mutual Coulomb excitation
- $d\sigma/dt$ fit by two exponentials
  - Cut out very small t (interference) region
  - Slope 1 $b_1 = 388 \pm 24/GeV^2$
  - Slope 2 $b_2 = 8.8 \pm 1.0/GeV^2$
- Slope determined by size of target
  - p_T * size ~ hbar c
    - Details depend on assumed shape
  - More accurately, radius ~ $\pi/2$ hbar c $\sqrt{b}$
    - $Radius_1$ ~ 6.1 fm ~ R_{Au}
    - $Radius_2$ ~ 0.9 fm ~ R_p
- Hard scattering centers within nucleus
- The nuclear density distribution is the Fourier transform of $d\sigma/dt$

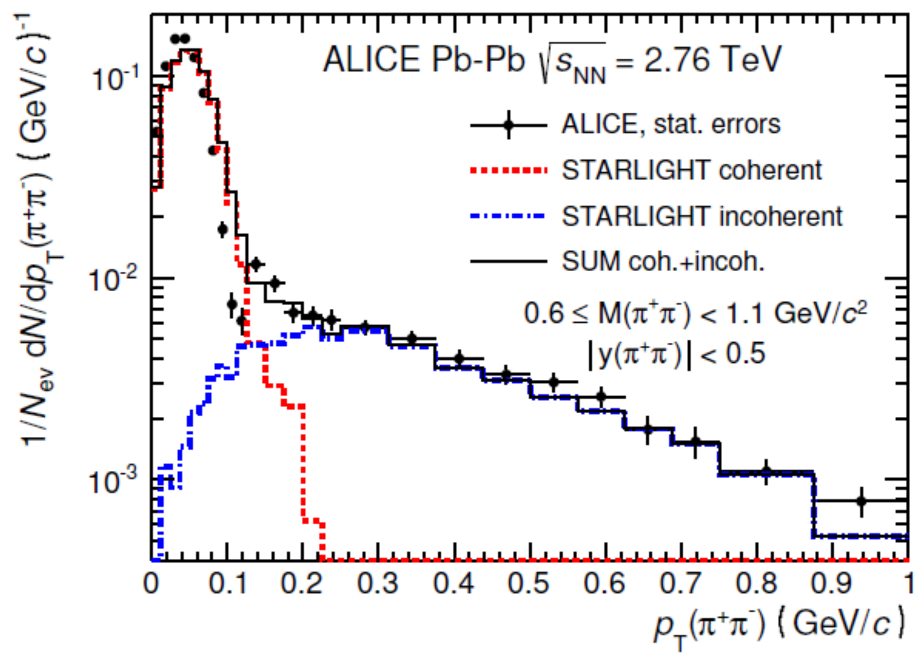


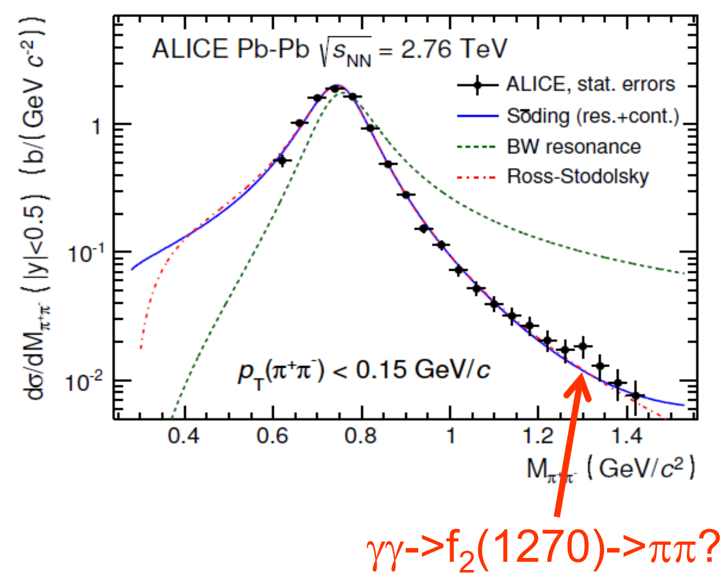


STAR, PRC77, 034910 (2008)

ALICE ρ^0 p_T spectrum

- Trigger on charged particles (neutrons not required)
- p_T spectrum shows coherent peak $p_T < \sim 100$ MeV/c and incoherent tail due to scattering from individual protons
  - Dip at p_T=120 MeV/c not understood
- Mass peak consistent with ρ^0, with possible hint of $\gamma\gamma \to f_2(1270) \to \pi\pi$





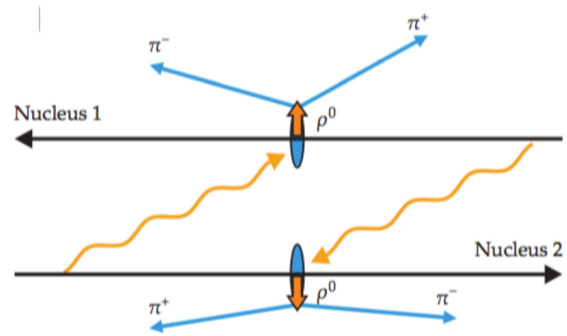
ALICE, JHEP **1509**, 095 (2015) & J. Adam, presented at DIS 2016

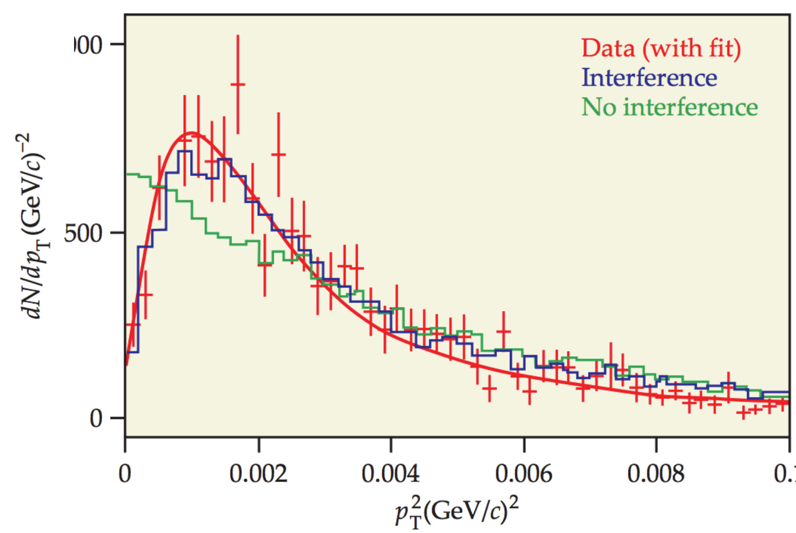
Extreme coherence: ρ^0 interferometry

- 2 nuclei -> 2 indistinguishable ρ^0 sources
  - Add amplitudes
- Typical separation 20-40 fm
  - Propagator exp(ikb)
- Moving from nucleus 1 to nucleus 2 is a parity transform
  - Vector mesons are negative parity -> subtract amplitudes

$$\sigma \propto |A_1 - A_2 \exp(i\mathbf{p}_T \cdot \mathbf{b})/\hbar)|^2$$

  - A_1,A_2 are amplitudes
  - For pbar p, it is a CP transform
    - Add amplitudes
- σ suppressed for $p_T <$ <|b|>
- Example of Einstein-Podolsky-Rosen paradox





STAR data + fit

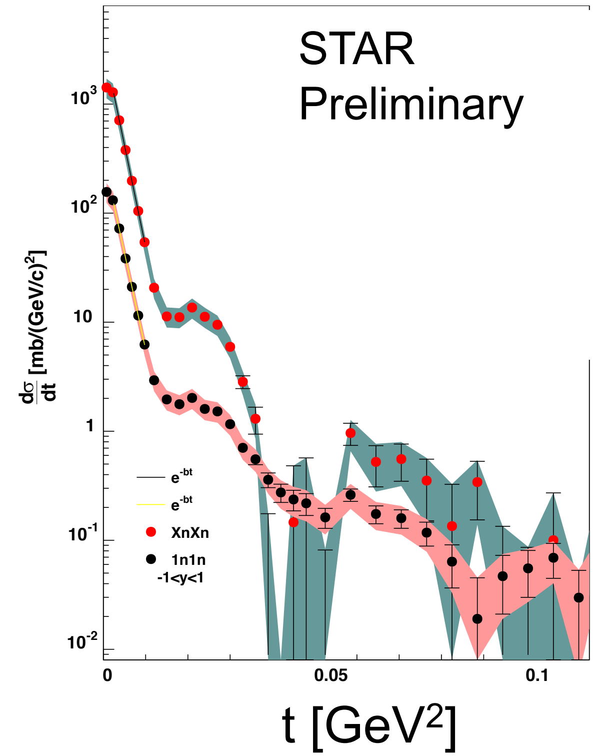
SK, Joakim Nystrand, PRL **84,** 2330 (2000) & Phys. Lett. A308, 323 (2003);
STAR PRL 102, 112301 (2009)

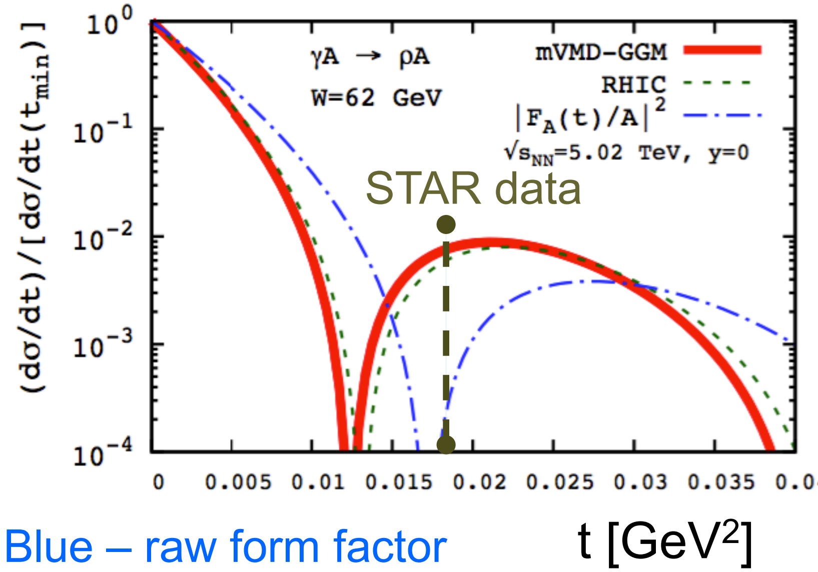
Imaging the nucleus

- STAR has measured ρ^0 $d\sigma/dt$

$$\left.\frac{d\sigma}{dt}\right|_{\text{Coherent}} = \left.\frac{d\sigma}{dt}\right|_{\text{Total}} - \left.\frac{d\sigma}{dt}\right|_{\text{Incoherent}}$$

  - Incoherent determined at large |t|
- 2 diffraction minima observed
  - 1^{st} dip at t= 0.018 GeV^2
- Mimima positions depend on locations of interaction sites
  - Nuclear shadowing decreases the # c interactions in the nuclear interior,
    - Larger mean radius
    - Shadowing explained cross-section
    - Calculated dip at t=0.012 GeV^2
      - Data matches 'no-shadowing' position better
  - Dip partly washed out by photon p_T





Blue – raw form factor

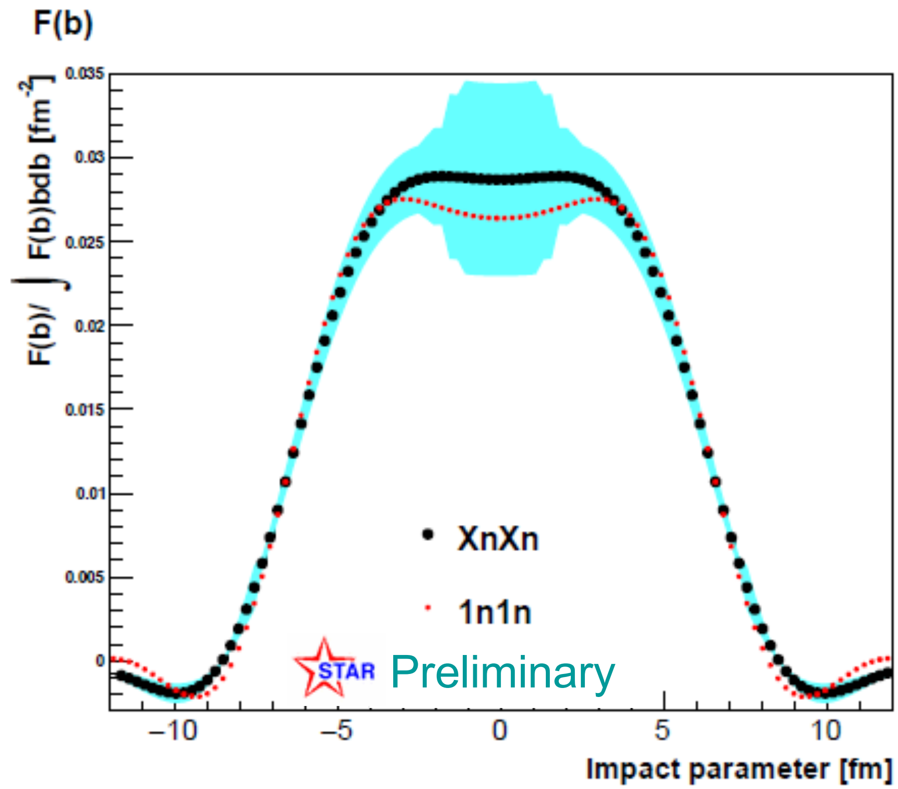
Red – w/ shadowing

STAR, arXiv:1502.03376; Guzey, Strikman & Zhalov, arXiv:1611.05471

"Imaging" the nucleus

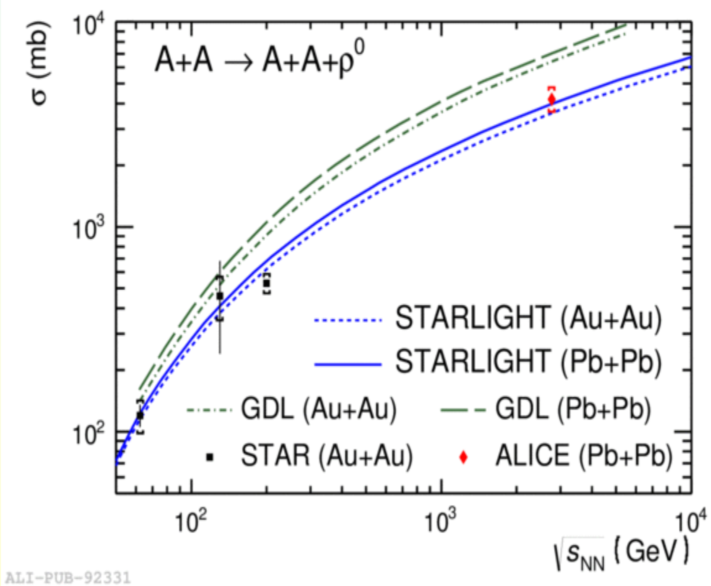
- Target (gluons?) density is the Fourier transform of $d\sigma/dt$
  - $|t|_{max} = 0.06$ GeV^2
- 2-d Fourier (Hanckel) tranform
  - Targets, integrated over z
  - 2-d avoids 2-fold ambiguity
- Blue band shows effect of varying $|t|_{max}$ from 0.05 - 0.09 GeV^2
  - Variation at small |b| may be due to windowing (finite t range)
- Negative wings at large |b| are likely from interference
- FWHM=2*(6.17±0.12 fm) [stat. error only]

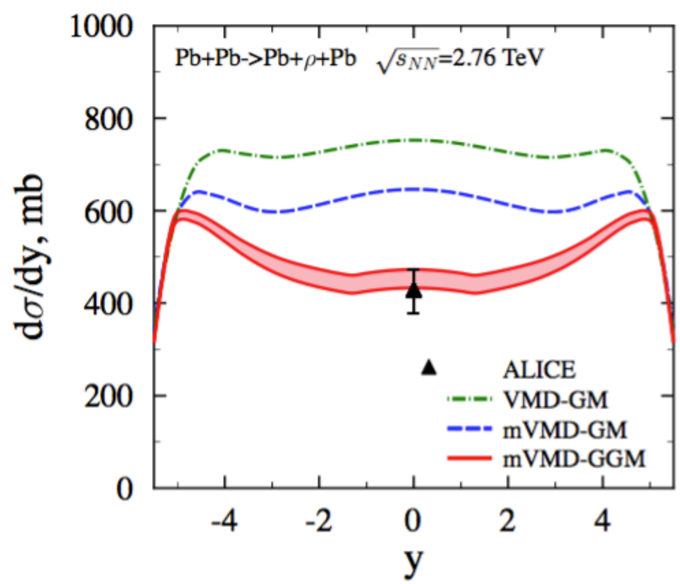
$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T \, p_T \, J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}$$



ρ^0 coherent cross-section

- Coherent photoproduction cross-section from 62.4 GeV to 2.9 TeV
  - σ below colored dipole model & generalized VDM model
    - With quantum Glauber calculation
  - σ in agreement with classical Glauber model ala STARlight
    - Theorists are not happy!
- New model adds nuclear shadowing to quantum Glauber model and finds agreement with σ data (but not dip position)

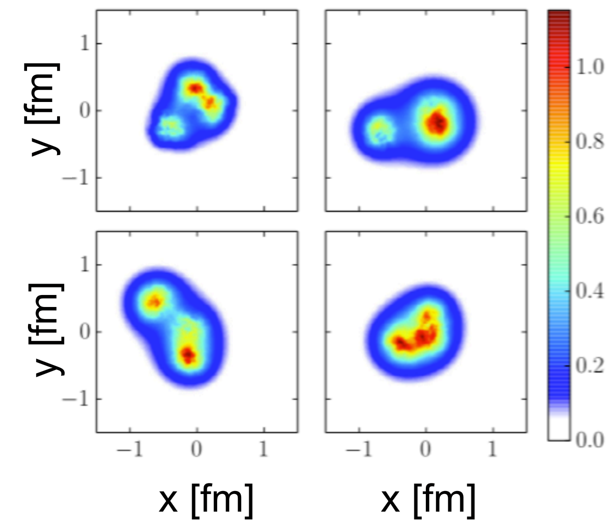


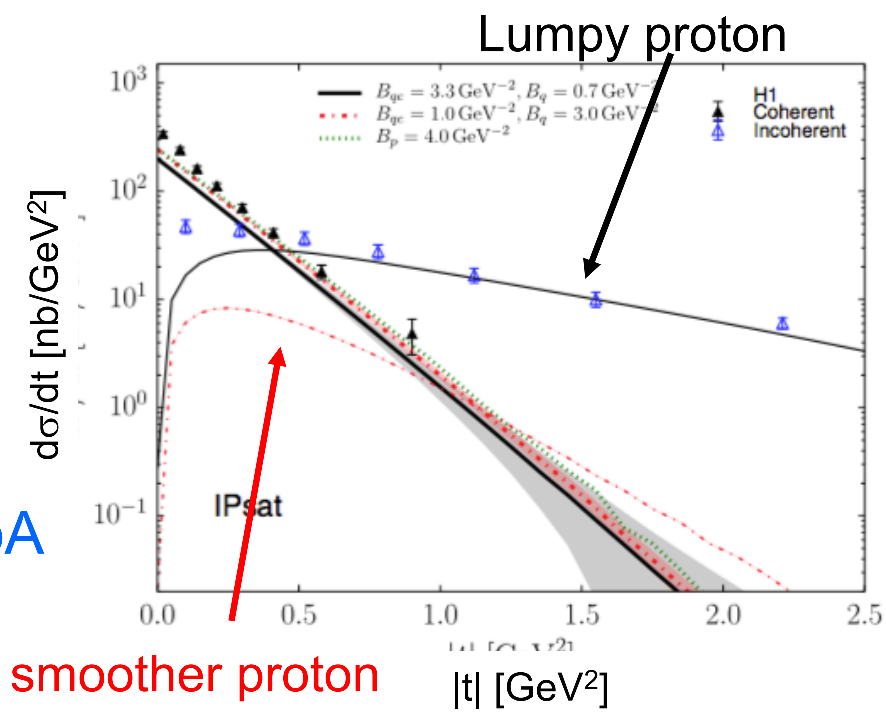


D. Horak [ALICE], QM17; L. Frankfurt et al., Phys. Lett. B752, 51 (2017)

Incoherent VM photoproduction

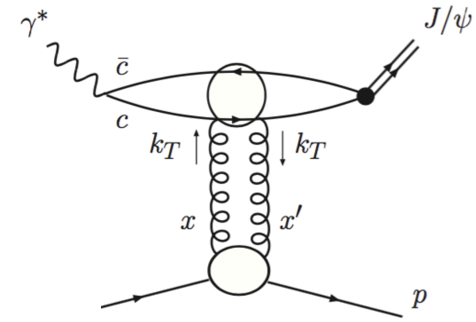
- Probes event-by-event fluctuations in the nuclear configuration
  - Quark/gluon transverse positions
- Walker-Good (QM) formalism:
  - $d\sigma/dt_{total} \sim <|Amp(K,\Omega)|^2>_\Omega$
    - Ω = nuclear configurations
      - positions of nucleons (gluons)
    - K = kinematic factors: x, Q^2, t,…
  - $d\sigma/dt_{Coherent} \sim |<Amp(K,\Omega)>_\Omega|^2$
  - $d\sigma/dt_{Incoherent} = d\sigma/dt_{total} - d\sigma/dt_{Coherent}$
- HERA data on $\gamma^*p \to J/\psi\, p$ indicates protons are quite lumpy/stringy
  - Reproduces most v_2 & v_3 results in pA
- High energy limit: lumps dominate incoherent production drops





Mäntysaari & Schenke PRD 94, 034042 (2016); J. Cepila *et al.*, PLB766, 186 (2017)

VM photoproduction in pQCD



- In 2-gluon model, leading order pQCD

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

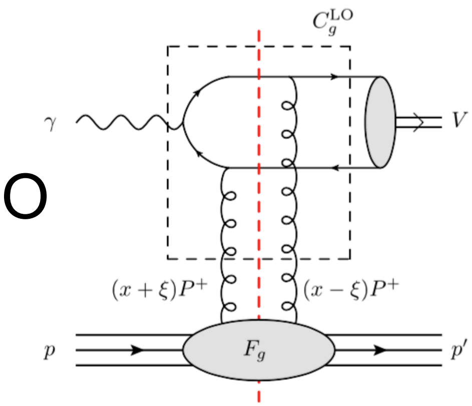
- With $\bar{Q}^2 = (Q^2 + M^2_{J/\psi})/4, \qquad x = (Q^2 + M^2_{J/\psi})/(W^2 + Q^2)$
  - Vector meson mass provides hard scale
- Some caveats
  - pQCD factorization does not strictly hold
    - Two gluons have different x values (with x' ≪ x ≪ 1)
      - Use generalized (skewed) gluon distributions – smallish correction.
      - Can do exactly with Shuvaev transform
  - Photon is not pure $q\bar{q}$ dipole
  - Choice of scale μ
  - "Absorptive corrections" for pp akin to $b > R_A + R_b$

Jones, Martin, Ryskin and Teubner ("JMRT"), JHEP 1311, 085 (2013); and others

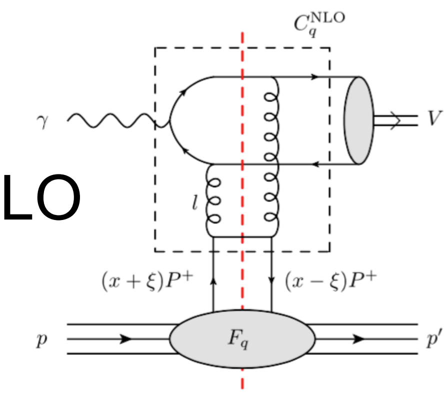
VM photoproduction at NLO

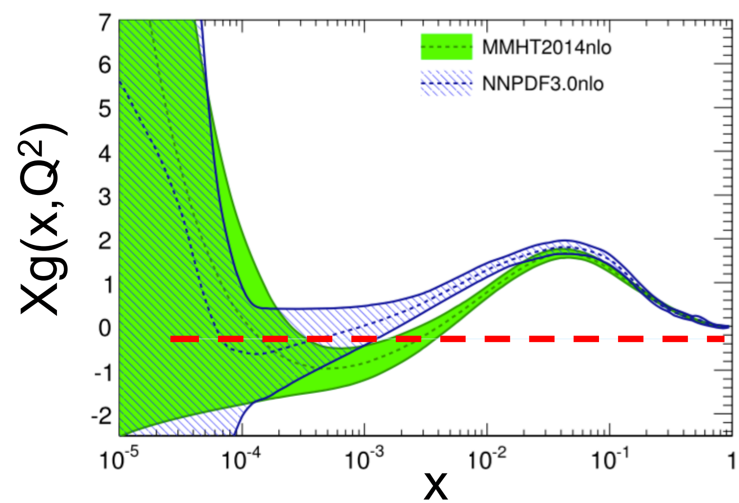
- NLO 'correction' larger than LO amplitude & opposite sign
  - "Standard" parton distributions have too few low-x, low-Q^2 gluons, suppressing the LO term
    - More gluons would increase the LO term
- High sensitivity to scale
  - Reduce by picking LO scale $\mu_F = m_{VM}/2$
    - Reduces overall scale problem
  - $\sigma(\gamma p \rightarrow \Upsilon p)$ variation with scale is ~ ± 15 to $\pm 25\%$
- NNLO terms need to be checked
  - With higher gluon density, probably OK
- Use in structure function determination?

LO



NLO



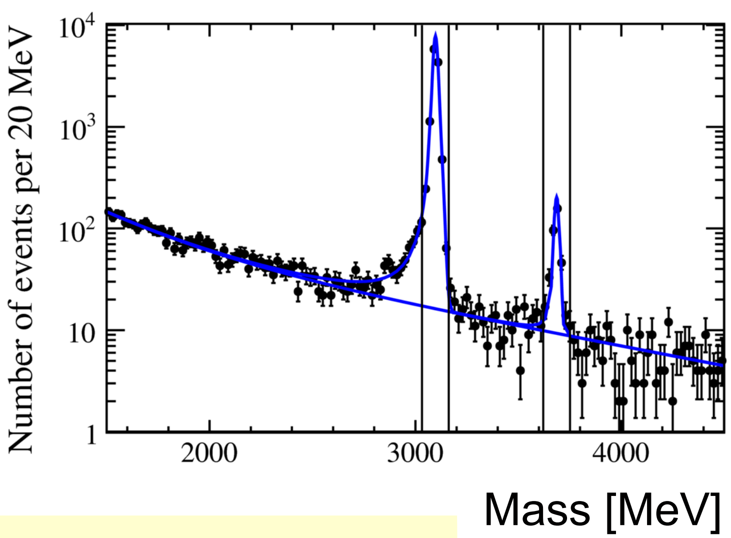


JMRT, J. Phys.G. **43**, 035002 (2016); Eur. Phys. J.76, 633 (2016)

Gluon distribution @ Q^2=1.21 GeV^2

$\gamma p \to Q\bar{Q}$ with proton targets in pp & pA

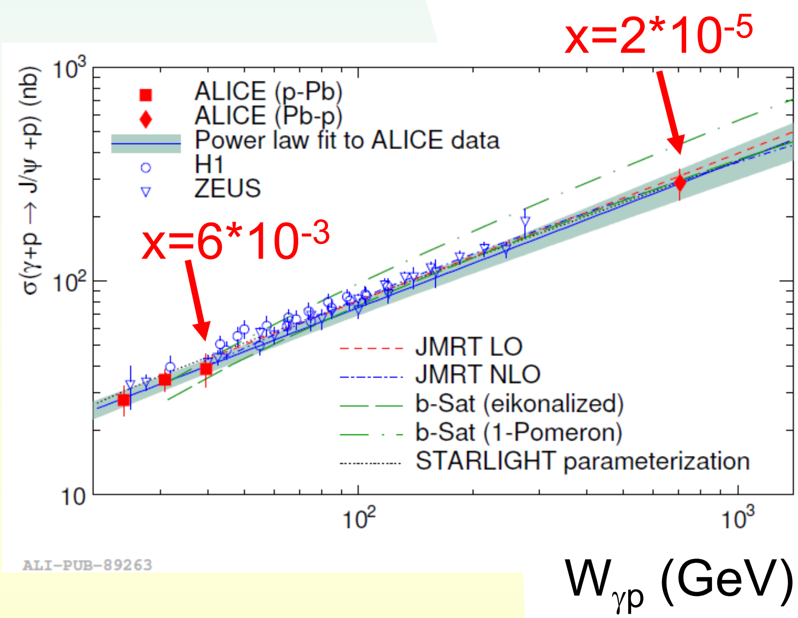
- High statistics data extends HERA $\gamma p \to J/\psi\, p$ studies to higher energies
  - Access gluon distributions down to 10^{-6} at $Q^2 \sim m_{quark}^2$
- Avoiding the two-fold ambiguity: $k = M_V/2 \exp(\pm y)$
  - Ambiguity disappears at y=0 (solutions are degenerate) or large |y|, where the low-k solution dominates.
  - Estimate lower-k solution and correct
  - In pA, most of the photons come from the heavy nucleus
    - Kinematic differences between γp & γA give further discrimination

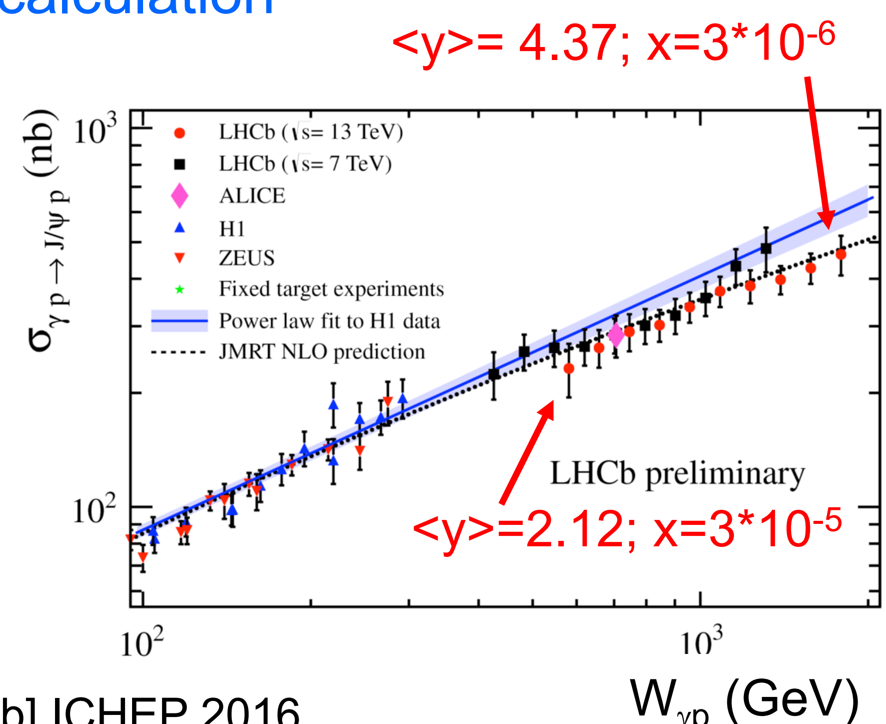


R. McNulty [LHCb] ICHEP 2016

$\sigma(\gamma p \to J/\psi\ p)$

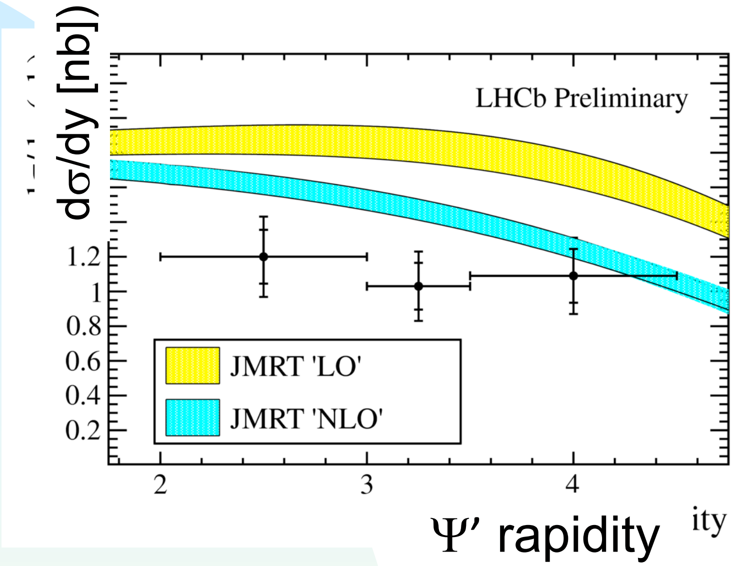
- Data up to $W_{\gamma p}$= 1.5 TeV -5 times the HERA maximum
- ALICE sees good pA agreement with HERA data
- LHCb 13 TeV-beam data somewhat below 7 TeV data?
  - LHCb bootstraps from HERA range to avoid 2-fold ambiguity
- NLO calculation predicts a small down-turn from power law prediction at energies above ~ 300 GeV
  - 13 TeV data agrees well with NLO calculation

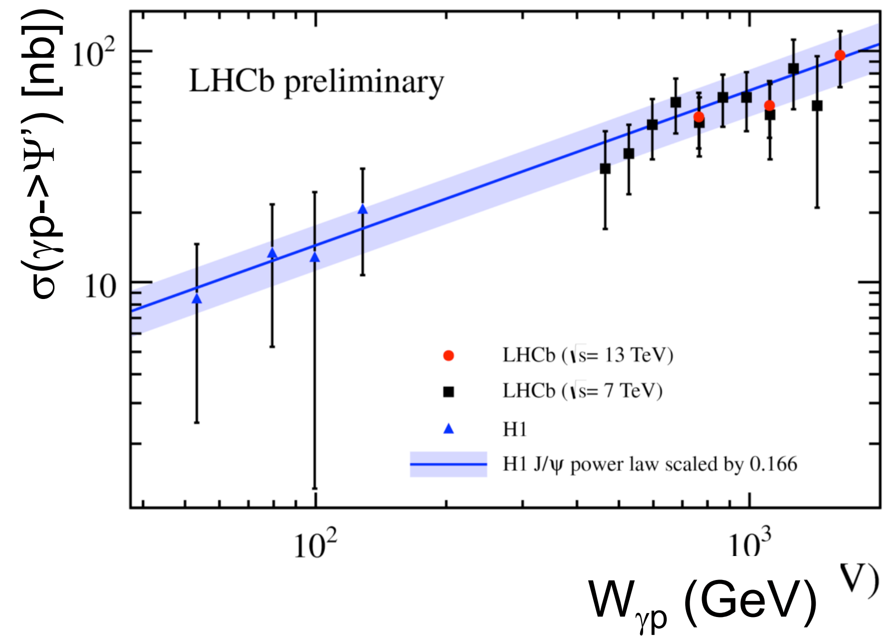




J. Adams [ALICE], DIS 2016; R. McNulty [LHCb] ICHEP 2016

ψ’ photoproduction on proton targets





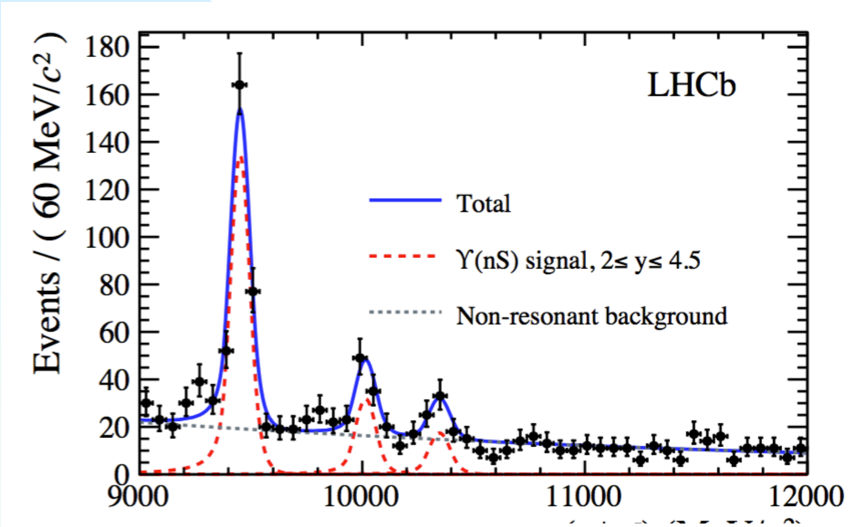
Good fit to power law
Data is a bit below the NLO pQCD

As with J/ψ, LHCb data quality is more precise than HERA & extends to higher energy

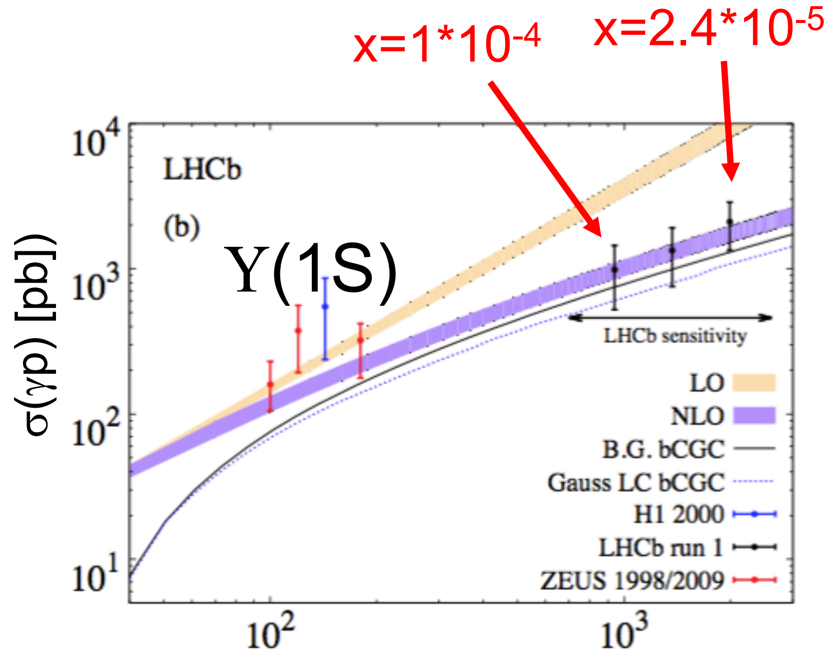
R. McNulty [LHCb] ICHEP 2016

$\gamma p \to \Upsilon p$

Forward dimuons with LHCb



$M_{\mu\mu}$ (MeV)



$W_{\gamma p}$ (GeV)

Υ(1S), Υ(2S) & Υ(3S) resolved

Good agreement with NLO calculation (Q^2 ~ 25 GeV^2)

Higher Q^2-> less sensitivity to some theoretical uncertainties

Same calculations match J/Ψ & Y data, at different Q^2

No evidence for saturation at low Q^2

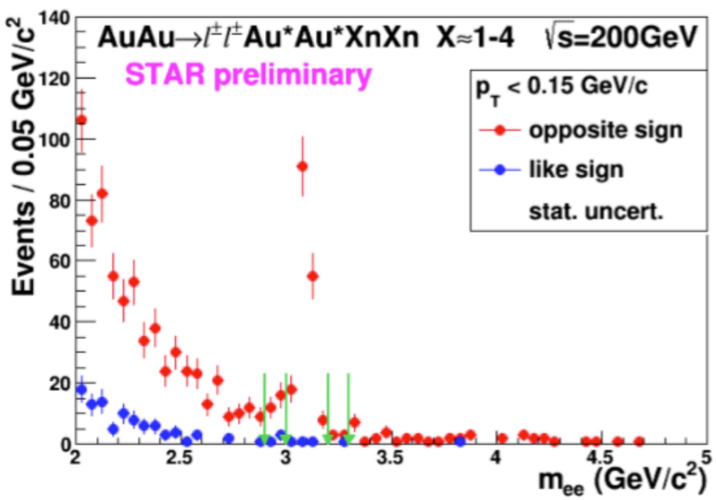
R. McNulty [LHCb] ICHEP 2016

Heavy quarkonium photoproduction on ion targets

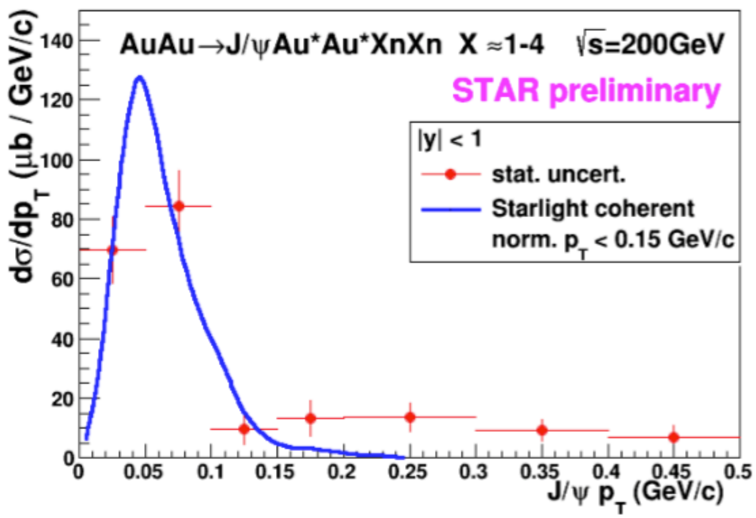
- Best data for nuclear gluon distributions for $x<10^{-3}$
  - No HERA data for A>1 nuclei
  - $Q^2 = (M_{VM}/2)^2$
- Measure/calculate suppression relative to proton targets
  - Many theoretical uncertainties cancel
- Impulse approximation calculation sometimes used as reference
  - Replaces missing proton data at correct $\sqrt{s}$
  - Account for higher order corrections by tie-in to HERA data
- Shadowing is expected, because a single $q\bar{q}$ dipole may interact with multiple nucleons in a heavy target
  - "Leading twist" shadowing

J/ψ in AuAu at RHIC

Coherent & incoherent J/ψ Photoproduction
Bjorken-x ~ 0.015
$\gamma\gamma \rightarrow e^+e^-$ also observed



M_{ee} (GeV)

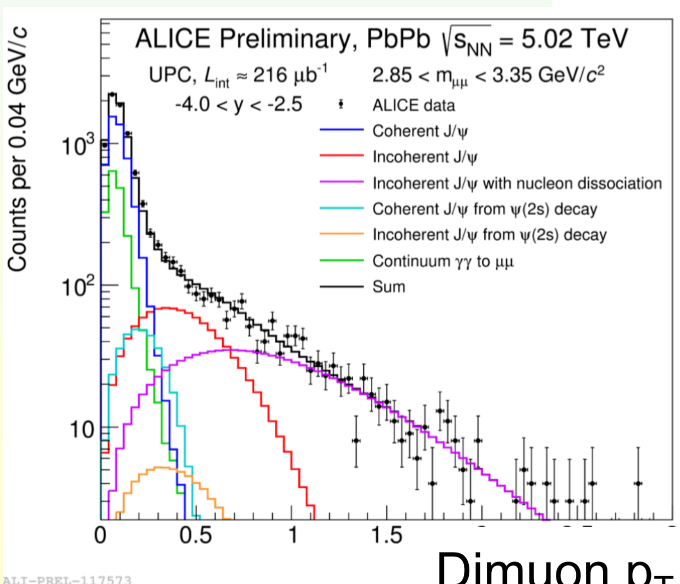


J/ψ p_T (GeV)

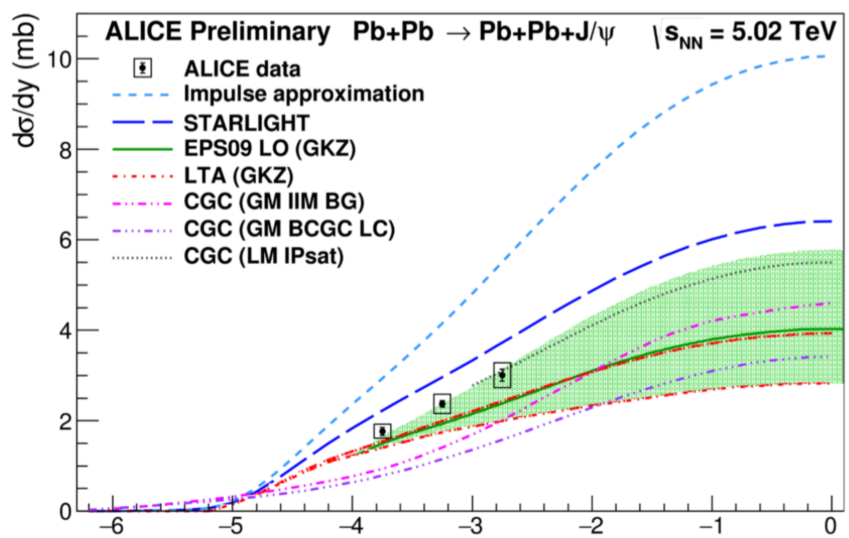
W. Schmidke [STAR], DIS 2016

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
- $\sigma_{coherent}$ is ~ 40% of impulse approximation prediction
  - 75% of STARlight (Glauber calc; no gluon shadowing)
  - Consistent with EPS09 model
  - Consistent with leading twist approximation
- Also: J/ψ in pPb @ 8 GeV, $J/\psi \rightarrow p\bar{p}$, ψ'-> $J/\psi\ \pi^+\pi^-$



Dimuon p_T (GeV)

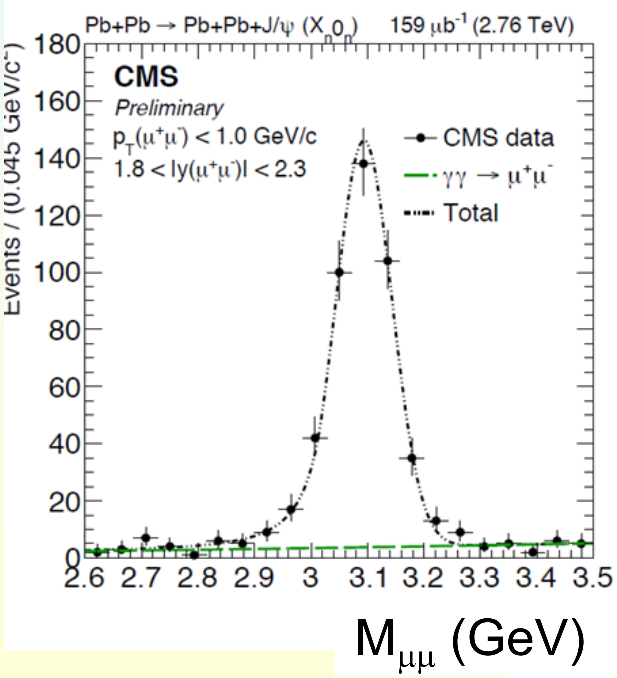


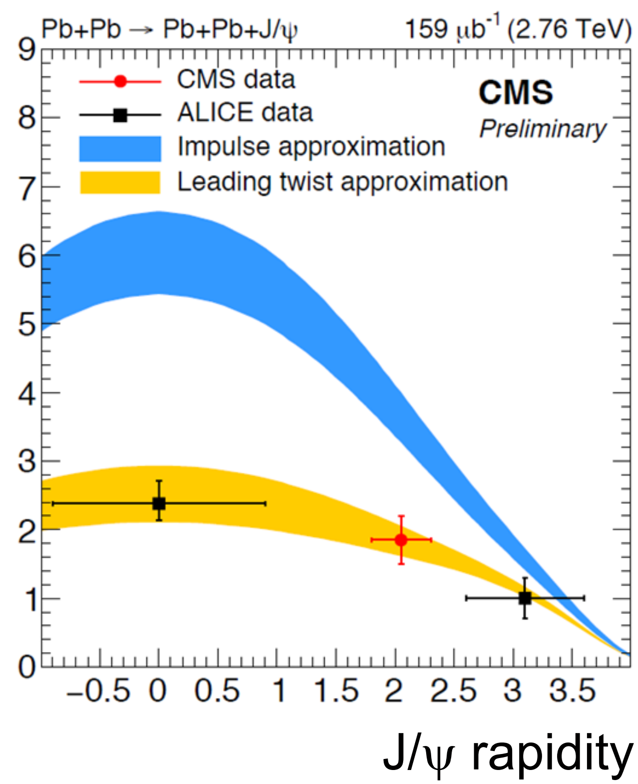
E. Kryshen [ALICE], QM17

J/ψ rapidity

PbPb-> J/ψ in CMS at $\sqrt{s_{NN}}$= 2.76 GeV

- $\mu^+\mu^-$ at |y| = 2.05
- Cross-section is ~ 40% of impulse approximation
  - Moderate nuclear shadowing
  - Consistent with leading twist calculation



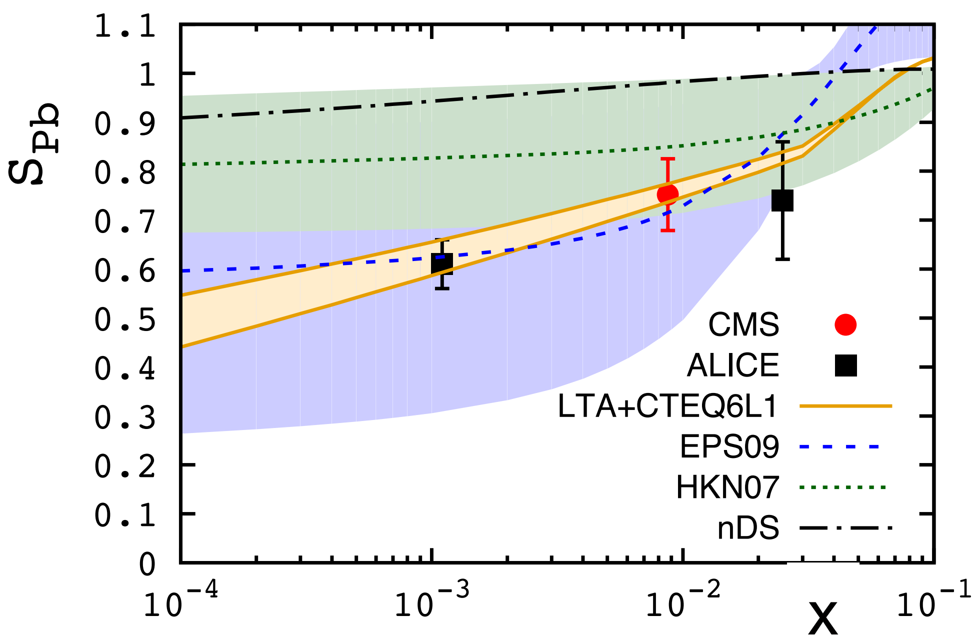


D. Tapai Takaki [CMS], QM17

Nuclear Shadowing

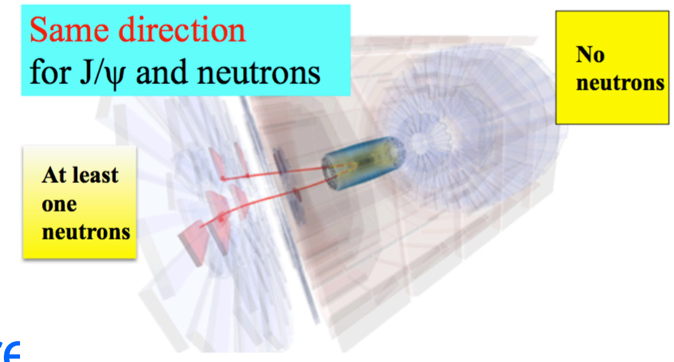
- Compare ALICE & CMS data with PDF shadowing models
  - Use impulse approximation for proton reference
    - Normalize to HERA data to correct for higher order terms
    - 6 different parton distributions
- Consistent w/ 2012 leading twist approximation calculation
  - Except for MNRT07 parameterization
- More shadowing than HKN07 parameterization
- EPS09 parameterization fits data well
  - Error bars should shrink
    - Also true w/ EPPS'16
- No need for exotica e. g.
  - Colored glass condensate
  - Hard saturation cutoff

V. Guzey & M. Zhalov, JHEP 1310, 207 (2013)
Frankfurt Guzey & Strikman, Phys. Rept. 512, 255 (2012) updated by V. Guzey & M. Strikman.



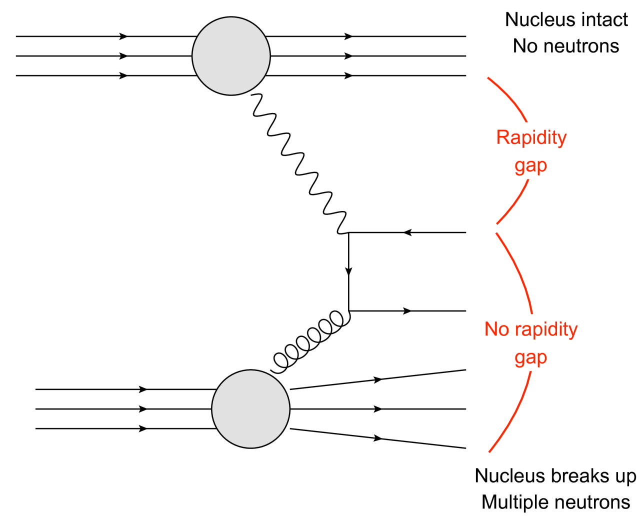
Back to coherence….

- Photon energy $k=M_V/2 \exp(\pm y)$
  - $k > M_V/2$ -> J/ψ follows photon direction
  - $k< M_V/2$ -> J/ψ opposes photon direction
- In incoherent production, target fragmentation neutrons go in opposite direction from photon
- Neutrons from Coulomb excitation in coherent or incoherent production are evenly distributed
- Neutron flux vs. hemisphere probes energy dependence of $\sigma_{incoherent}/\sigma_{coherent}$
- CMS observes more neutrons in opposite hemisphere
  - Incoherent production is suppressed (compare coherent) at high photon energies
    - Probes gluons with low Bjorken-x in target
    - Possible sign of saturation

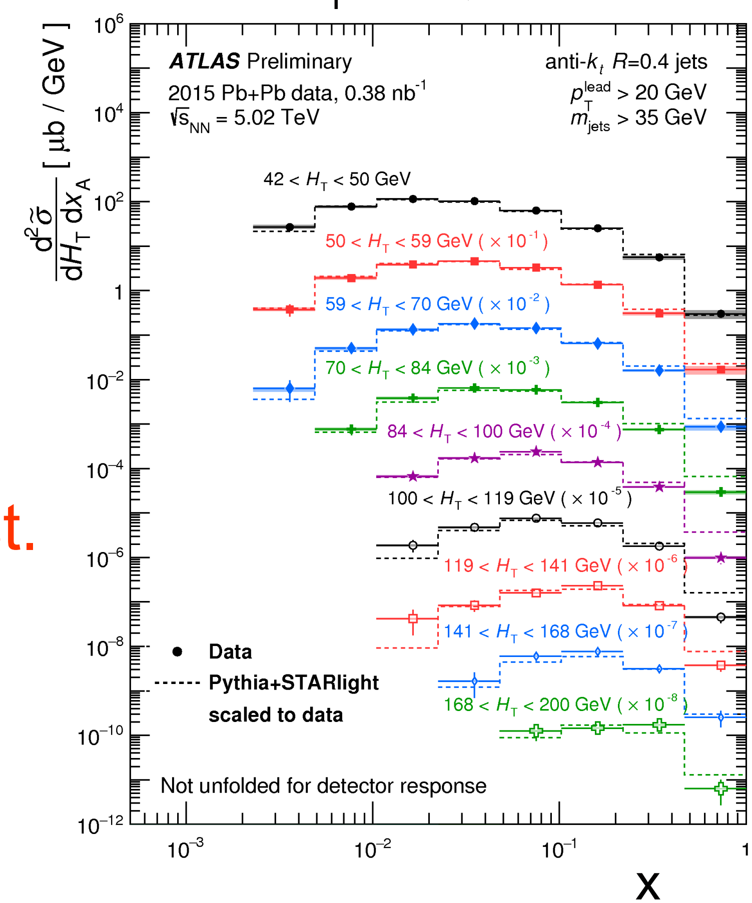


Photoproduction of dijets

- Single gluon exchange
  - theoretically clean
  - One rapidity gap
- x depends on dijet mass & rapidity
  - $10^{-2} < x < 1$
- Jet masses give Q^2
  - $1600\ \text{GeV}^2 < Q^2 < 40{,}000\ \text{GeV}^2$
- Data vs. STARlight/PYTHIA hybrid
  - Some differences
    - Detector?
    - Nuclear modifications to pdfs?
- Unfolding in progress, to probe gluon dist.
- Room to expand kinematic reach



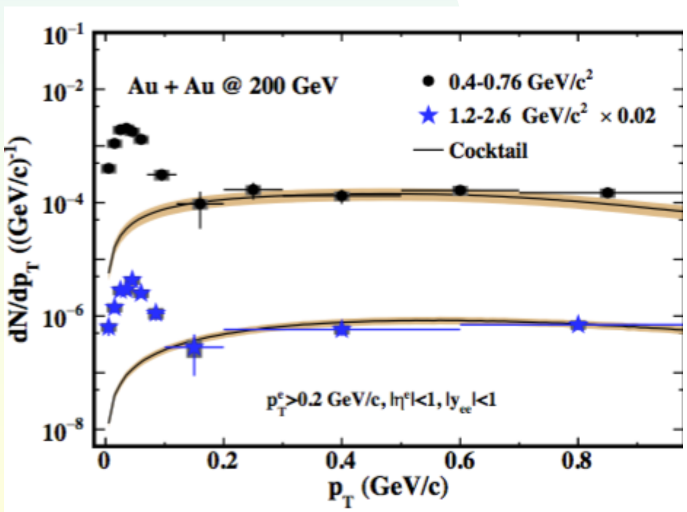
$H_T \sim 2Q$

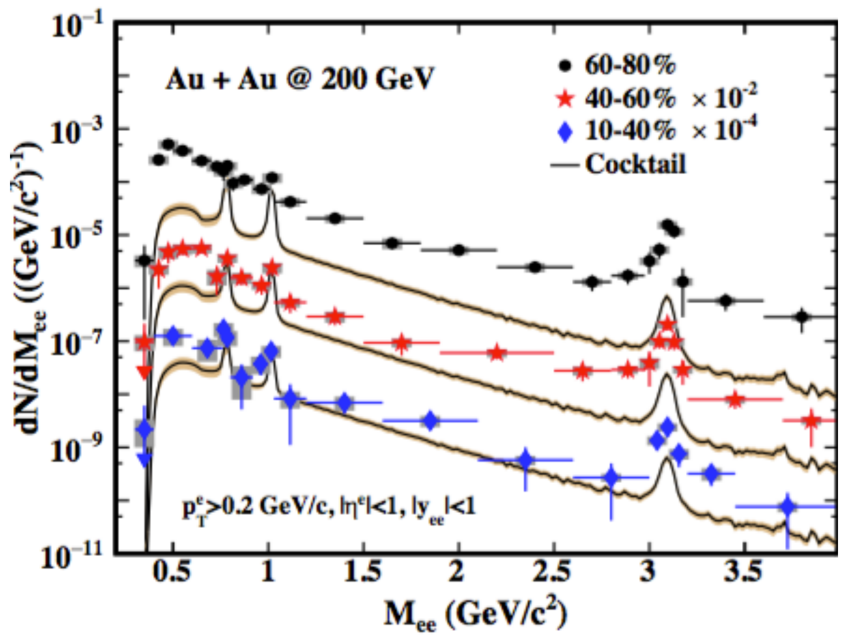


A. Angerami [ATLAS], QM17

Photonic reactions in peripheral collisions

- ALICE & STAR see an excess of lepton pairs with $p_T < 100$ MeV/c
  - Excess is significant - "$R_{AA} \sim 7$"
  - STAR – continuum + J/ψ at midrapidity
  - ALICE – forward J/ψ only
- "Big Mystery…"

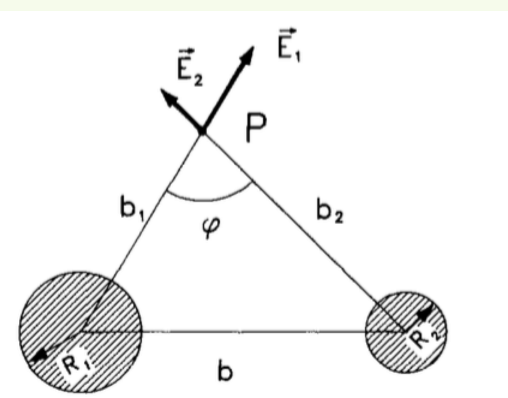


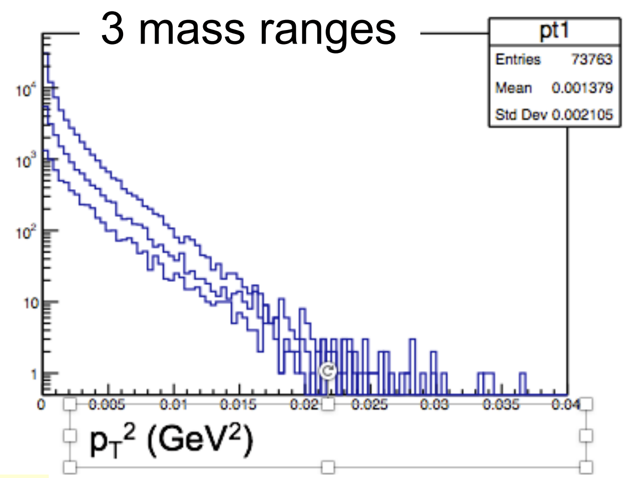


Z. Zhou [ALICE]; W. Zha [STAR], QM17; S. Yang [STAR], QM17

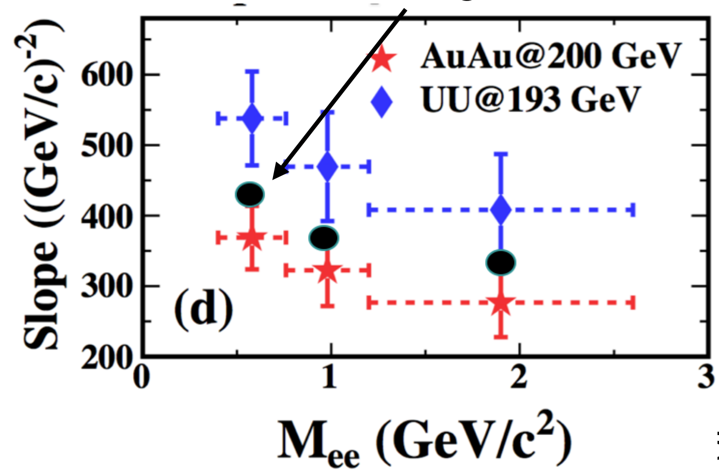
γγ -> ee in peripheral collisions

- Photonic reactions do not disappear when $b < 2R_A$
- Continuum $\gamma\gamma \to l^+l^-$ + photoproduced J/ψ
- Two-photon production is usually outside nucleus
  - Calculate rate, etc. in STARlight with constraints on |b|
  - **Preliminary:** kinematics, seem consistent with STAR excess
    - Rate comparison in progress
  - Fit p_T^2 spectrum: $dN/dp_T^2 \sim \exp(-bp_T^2)$
    - b's are consistent with STAR data in 3 mass ranges





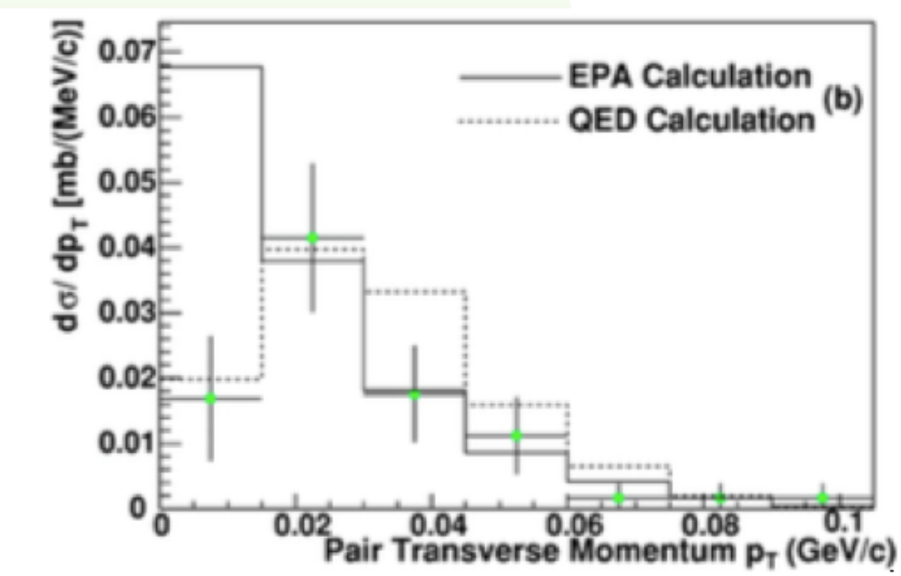
Black circles are STARlight for AuAu

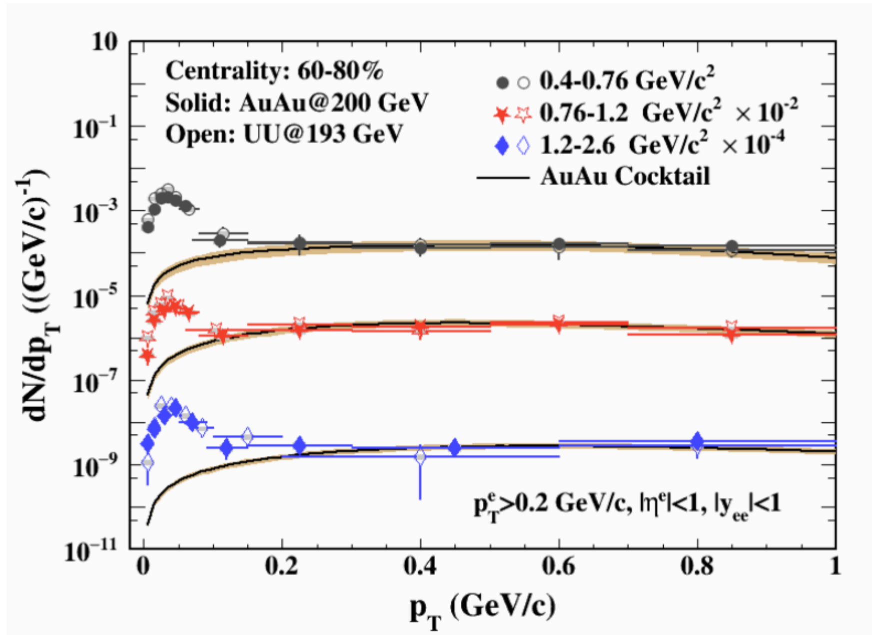


S. Yang [STAR], QM17; SK, paper in progress

The low p_T drop

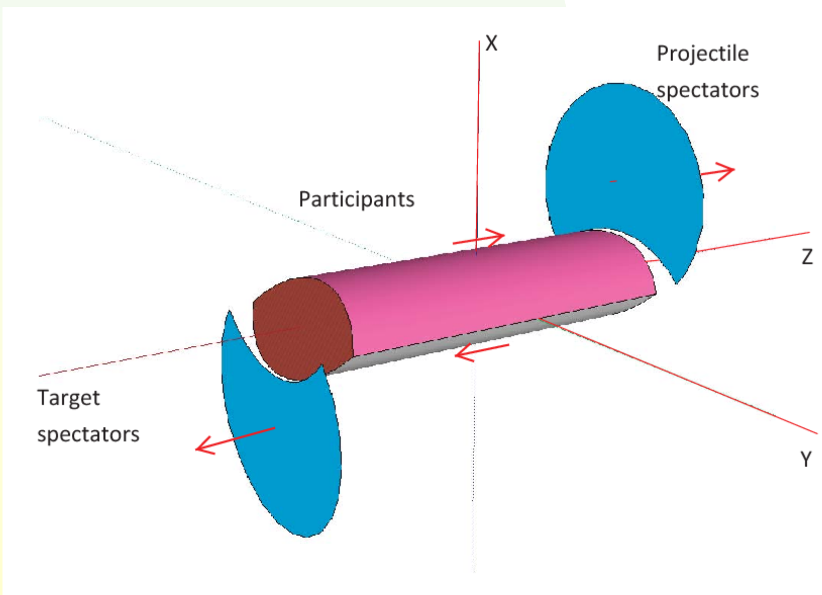
- The STAR p_{Tee} spectrum drops for p_{Tee} < 40 MeV/c
  - Looks similar to interference dip in vector meson photoproduction, but cause is different
  - Equivalent (real) photon approximation fails at low γ p_T
  - Q^2 ~< $(hbar/R_A)^2$
- A full QED calculation reproduces the p_T spectrum in UPCs
  - Dip width should scale with photon energy, i. e. with M_{ee}
    - Scaling STAR UPC result by minimum M_{ee} (from 140 MeV/c^2 to 400 MeV/c^2) -> p_T peak @ 75 MeV/c – pretty close

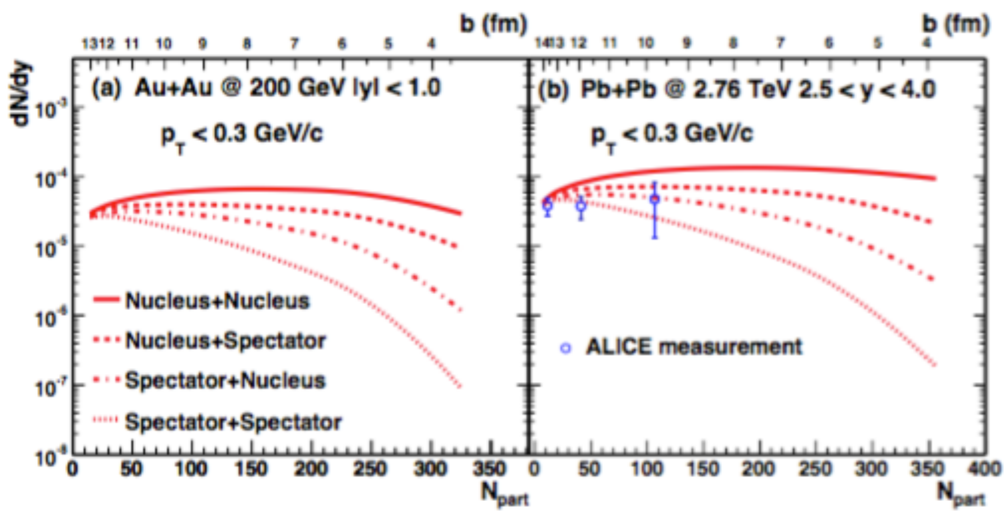




Photoproduced J/ψ in PCs

- Calculations for different assumptions of photon emitter & target coherence: entire nucleus, or spectator region
  - Photons are emitted before collision, at a typical time $t=k/\gamma$
    - Think retarded time, ala Jackson
  - Re. target (participant nucleons) the photon flux is lower (Gauss' law), there is destructive interference, and the nucleons may lose energy via hadronic interactions before the photonic interaction
    - Small contribution to cross-section
- Cross-sections consistent with photoproduction expectations

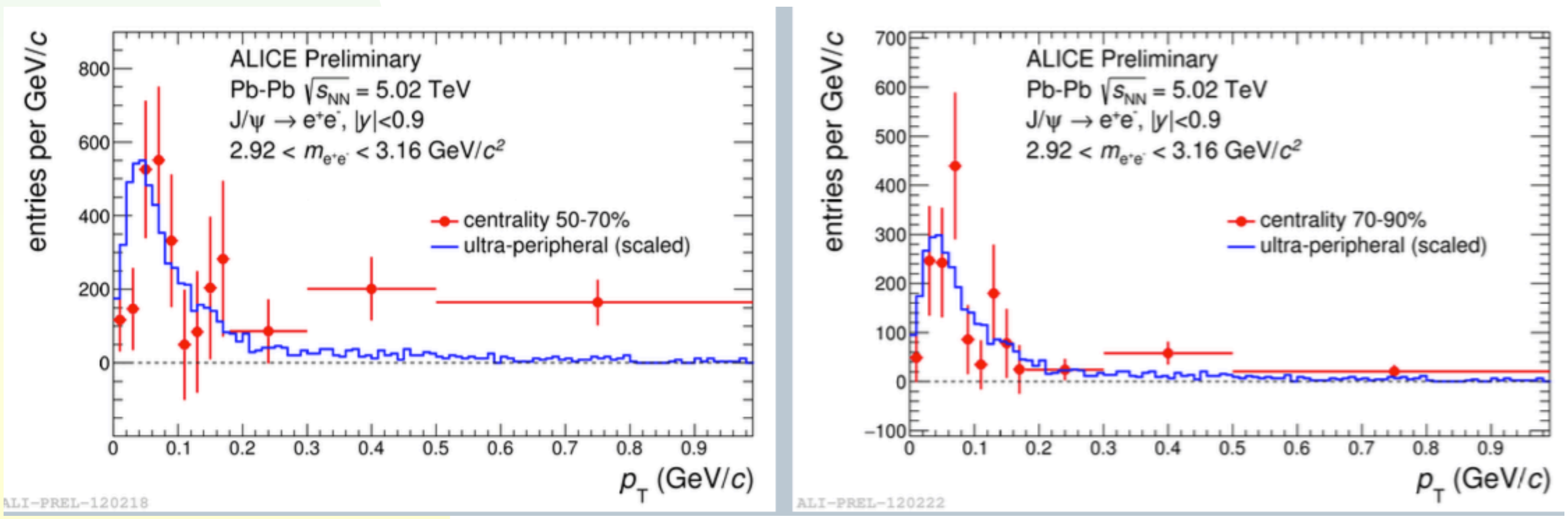




W. Zha et al. (SK), arXiv:1705.01460

p_T spectrum for $\gamma A \to J/\psi$ in PCs

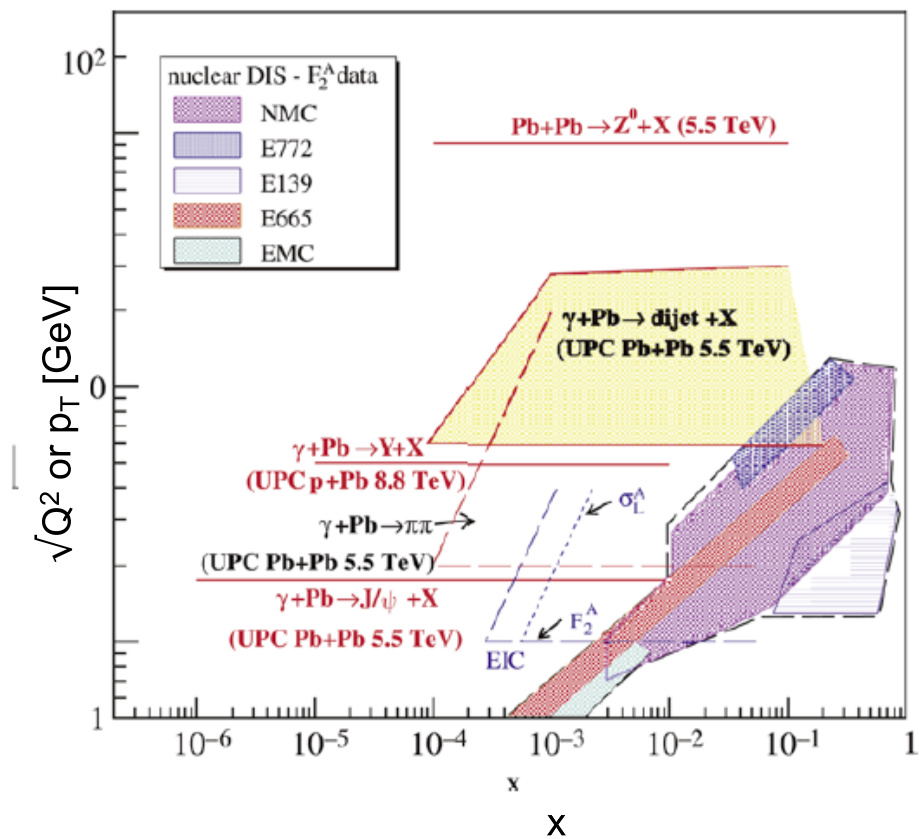
- p_T spectrum is consistent with UPC J/ψ photoproduction data
  - Drop at low p_T due to interference between two directions
    - System is smaller (|b| is smaller), so interference extends to higher p_T than for UPCs
- Spectator-only target has a different matter distribution than full nucleus target.
  - Different p_T spectrum + some azimuthal anisotropy
    - Sensitive to event plane?



Z. Zhou [ALICE], QM17

Looking ahead

- More vector meson photoproduction data
  - Incorporation into gluon distributions
- More open jets and charm
  - Experimentally harder, but theoretically cleaner
- J/ψ tomography
- γ on polarized protons at RHIC
  - $\gamma + p\uparrow \to J/\psi + p\uparrow$ probes parton distribution-E
    - pp and pA collisions
    - Roman pots detect scattered protons to measure $\vec{t}$ directly.
- UPCs at the fcc can reach down to Bjorken-x ~10^{-7}
- Connects to precision data from EIC



D. D'Enterria, QM17; A. J. Baltz *et al.*, Phys. Rept. 458 (2008) 1

Conclusions

- Ultra-peripheral collisions are the energy frontier for electromagnetic & electroweak interactions.
- Electromagnetic dilepton production can be used to test strong field QED, search for new physics, and quench LHC magnets.
- Light vector meson photoproduction has been used to observe diffraction patterns from gold nuclei.
  - Determine the hadronic size and shape of the gold nucleus.
- The high-quality quarkonium photoproduction data is consistent with next to leading order QCD.
  - Proton-target data meshes smoothly with lower-energy HERA results.
  - Lead-target data demonstrates moderate shadowing, consistent with leading order twist.
    - There is no need for a colored glass condensate to explain the data.
- Expect an explosion of UPC data using more diverse probes, including dijet production and open charm.

Backup