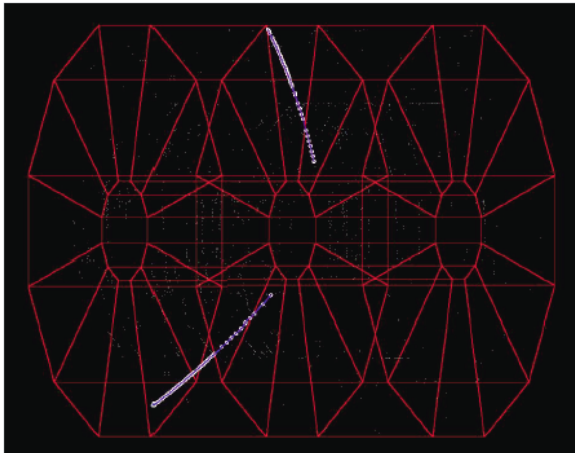
Ultra-peripheral collisions and hadronic structure

Spencer Klein, LBNL



Why UPCs?

QED: dilepton production

The structure of heavy nuclei

Toward nucleon parton distributions at low x

Gluon shadowing w/ nuclear targets

Conclusions

Focus on new results (past ~ year)!

Many more new results than I can cover

Some experimental preference

Apologies to authors that I neglect

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	~3000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~100 GeV	200 GeV	~1400 GeV

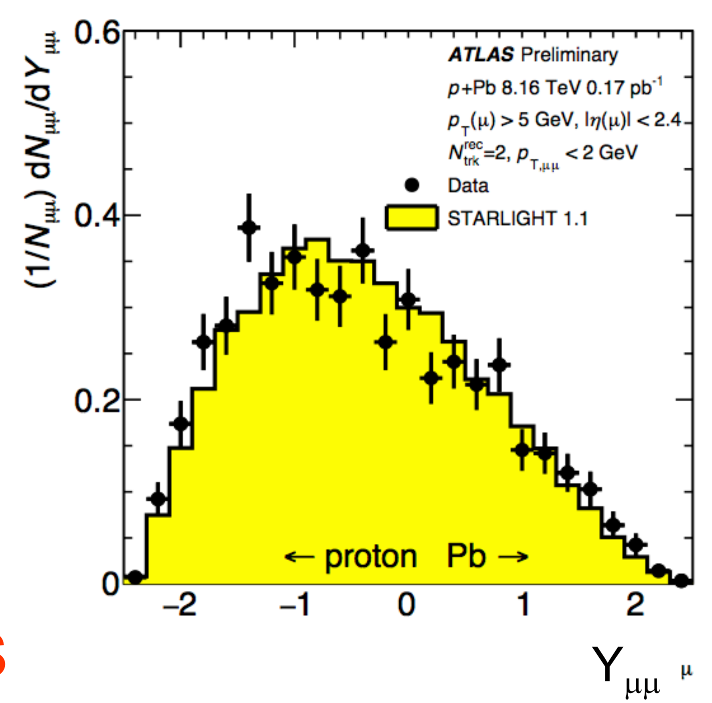
*LHC at full energy $\sqrt{s}$=14 TeV/5.6 TeV

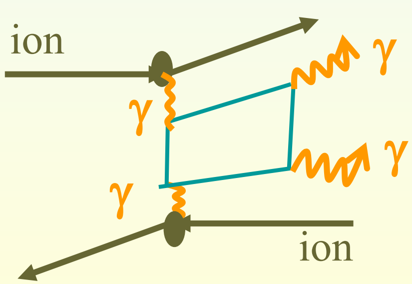
Why UPCs?

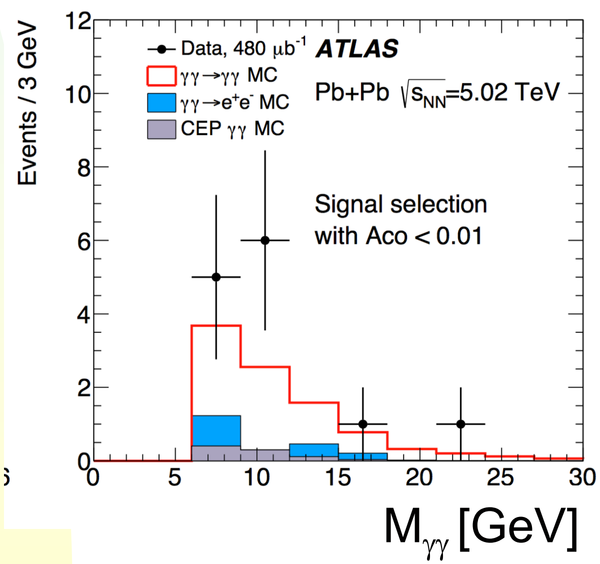
- The energy frontier for electromagnetic probes
  - Maximum CM energy $W_{\gamma p}$ ~ 3 TeV for pp at the LHC
    - ~ 10 times higher in energy than HERA
  - Probe parton distributions in proton and heavy-ions down to
    - Bjorken-x down to a few 10^{-6} at moderate Q^2
- Electromagnetic probes have α_{EM} ~ 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), $\gamma\gamma \rightarrow W^+W^-$, etc.

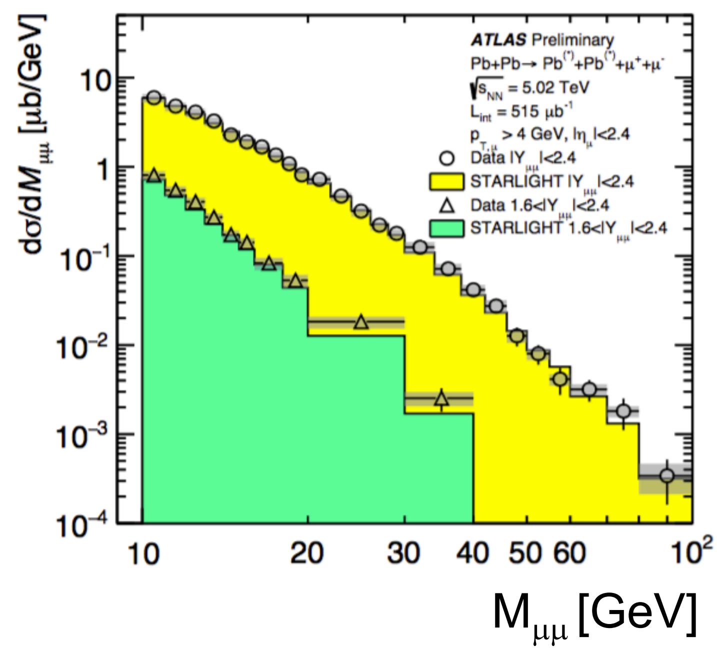
γγ -> Dileptons

- Large samples from ALICE, ATLAS & STAR
- Data is in excellent agreement with lowest order QED
  - STARlight Monte Carlo
  - $Z\alpha \sim 0.6$, so perturbation theory might fail
- Light-by-light scattering seen by ATLAS
  - Sensitive to new particles





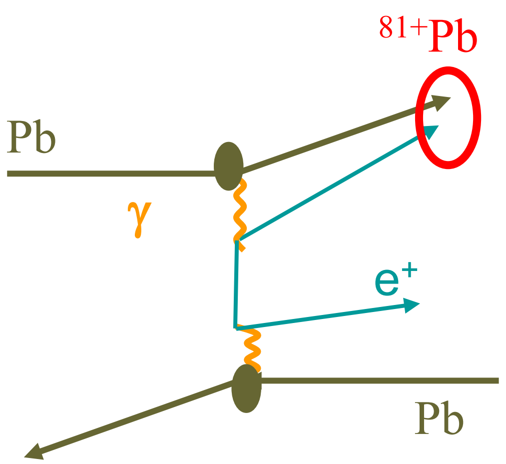


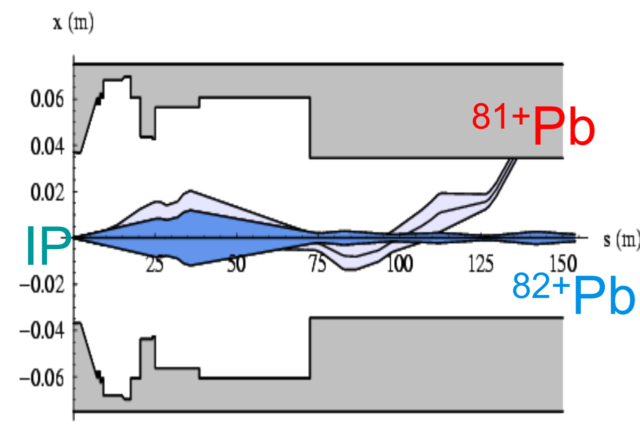


ATLAS: arXiv:1702.01625; M. Dyndal, this conference

UPCs and LHC luminosity

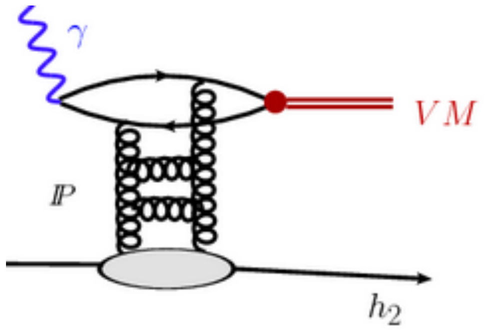
- σ[PbPb($\gamma\gamma$) -> (Pbe$^-$) Pb e$^+$] ~ 280 b @ LHC
- Single-electron lead has charge:mass ratio reduced by 1/82
- The (Pbe$^-$) beam strikes the beampipe 135 m downstream from the magnet
  - At $L = 10^{27}$/cm^2/s, the beam deposits 23 Watts
- LHC magnet quench from BFPP demonstrated!
  -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





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

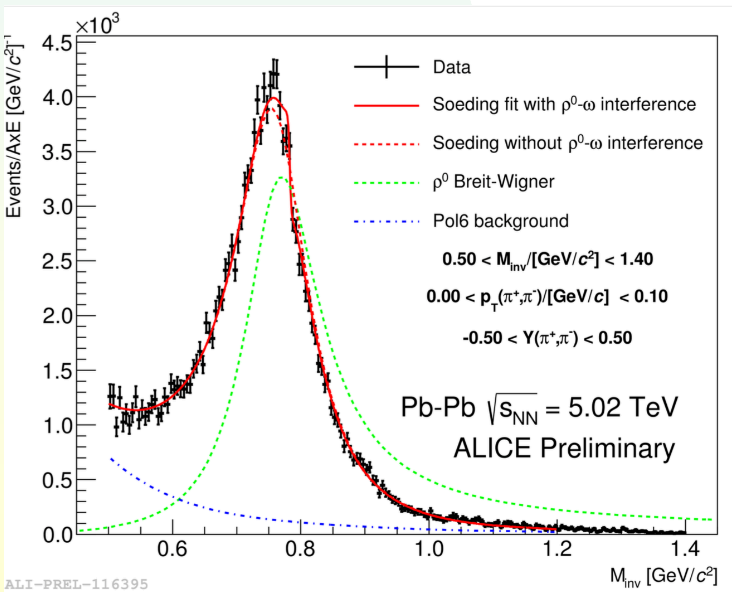
Vector Meson photoproduction

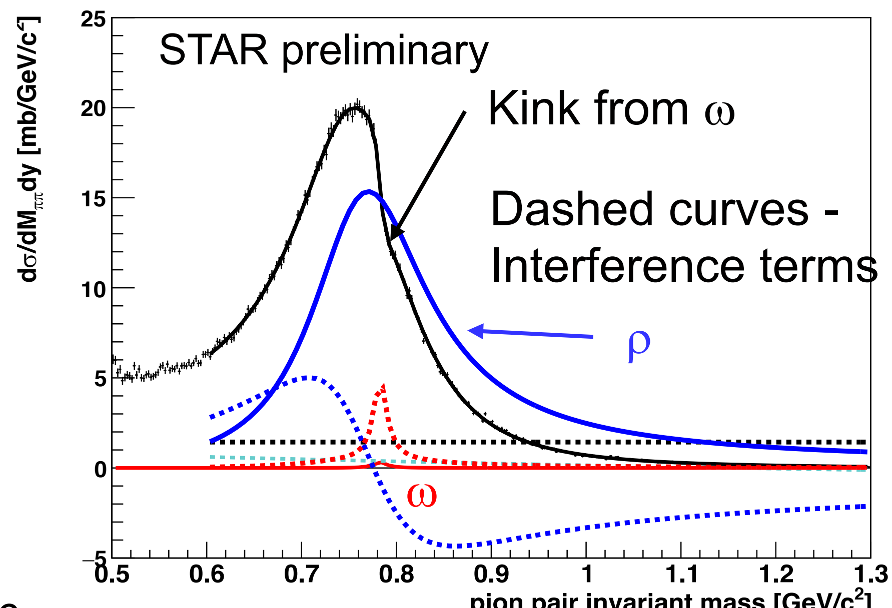


- Process has large cross-sections
- Produced via colorless ‘Pomeron exchange’
  - Require >=2 gluon exchange for color neutrality
    - Gluon ladder
- Light meson production usually treated via vector meson dominance model
  - ρ, direct $\pi^+\pi^-$, ω, ρ' observed at RHIC
- Heavy meson production treated 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 photoproduction

- 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
  - Ratios & phase angle consistent with low-energy fixed-target studies
    - Pomeron exchange @ high energies; meson exchange at lower
- STAR also sees a high mass state M = 1653 MeV, Γ=164 MeV
    - $\rho_3(1690)$?

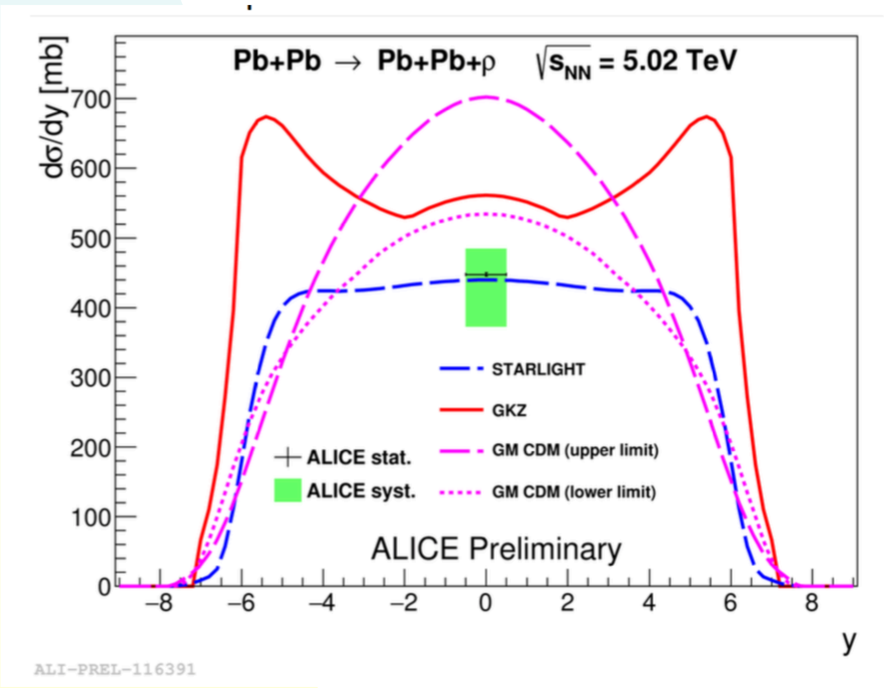




D. Horak [ALICE], QM17; SK [STAR] , DIS2016

ALICE ρ^0 cross-section

- Coherent cross-section found for |y|<0.5
  - σ below colored dipole model
  - σ below generalized VDM model
    - With nuclear shadowing correction
  - σ in agreement with STARlight

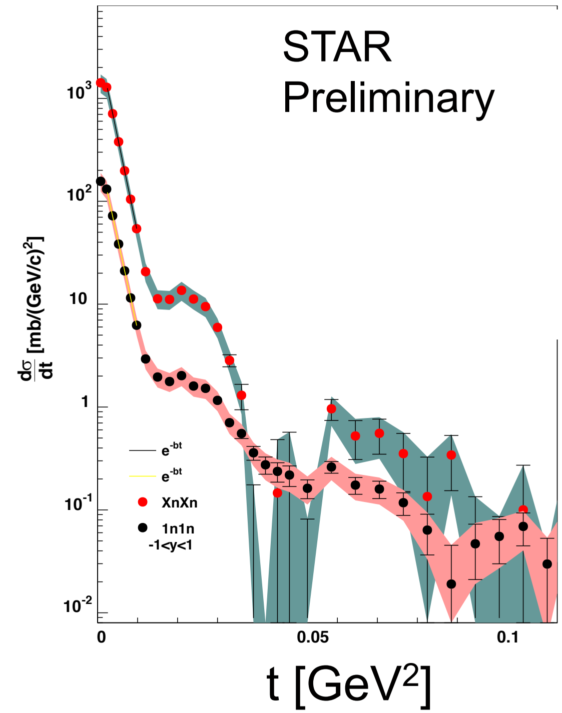


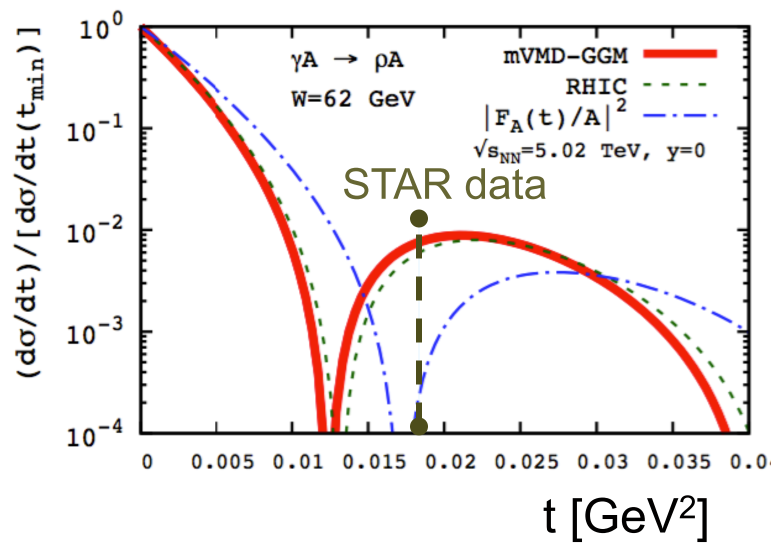
Imaging the nucleus

- 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 distribution of interaction sites
  - Nuclear shadowing decreases the # of 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



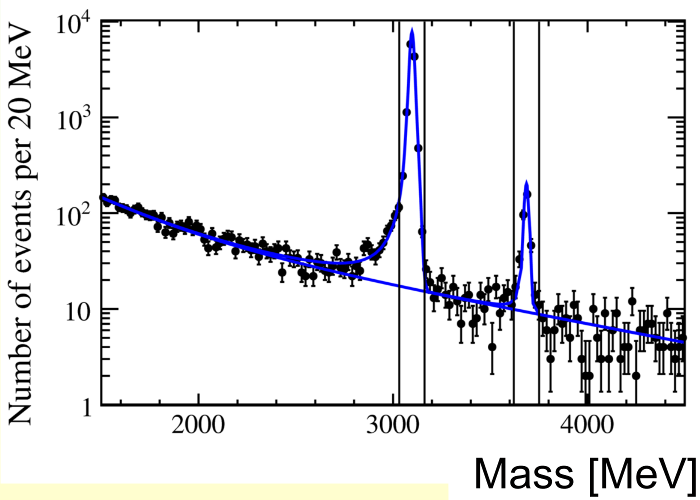


Blue – raw form factor
Red – w/ shadowing

SK [STAR], DIS2016
Guzey, Strikman & Zhalov, arXiv:1611.05471

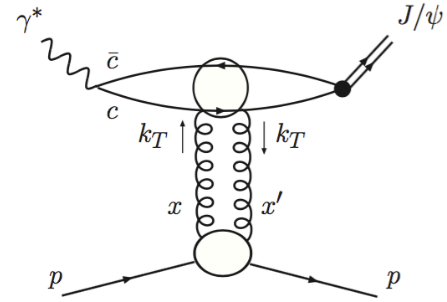
$\gamma p \to Q\bar{Q}$ in pp and pA

- High statistics data
  - Extend HERA $\gamma p \to J/\psi$ p studies to higher energies
  - Access gluon distributions down to 10^{-6} at $Q^2 \sim m_{quark}^2$
- In pp & AA there is 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

VM photoproduction in pQCD



- In 2-gluon model, leading order pQCD

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

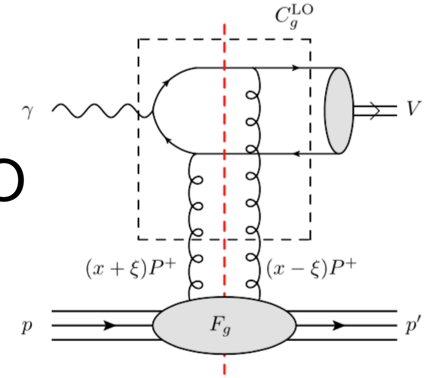
- With $\bar{Q}^2 = (Q^2 + M^2_{J/\psi})/4, \qquad x = (Q^2 + M^2_{J/\psi})/(W^2 + Q^2)$
  - Vector meson mass provides hard scale
- Some caveats
  - pQCD factorization does not strictly hold
    - Two gluons have different x values (with x' ≪ x ≪ 1)
      - Use generalized (skewed) gluon distributions – 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

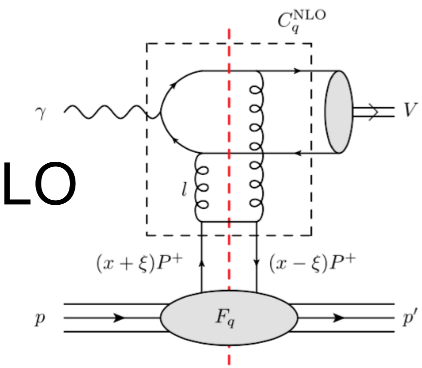
VM photoproduction at NLO

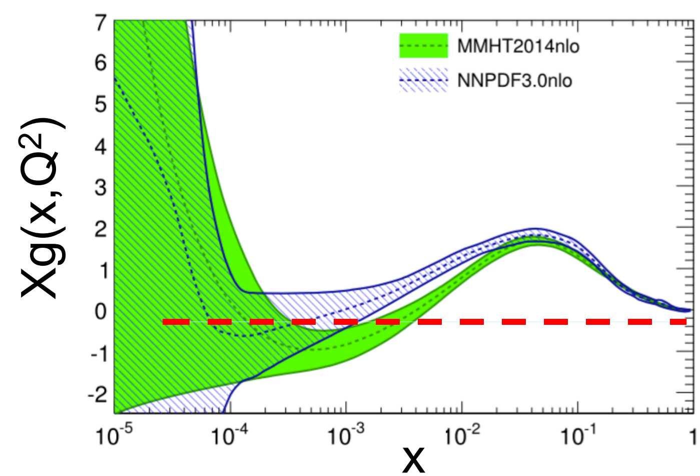
- NLO ’correction’ larger than LO amplitude & opposite sign
  - “Standard” parton distributions have too few low-x, low-Q^2 gluons, suppressing the LO term
    - More gluons would increase the LO term
- High sensitivity to scale
  - Reduce by picking LO scale $\mu_F = m_{VM}/2$
    - Reduces overall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

LO



NLO



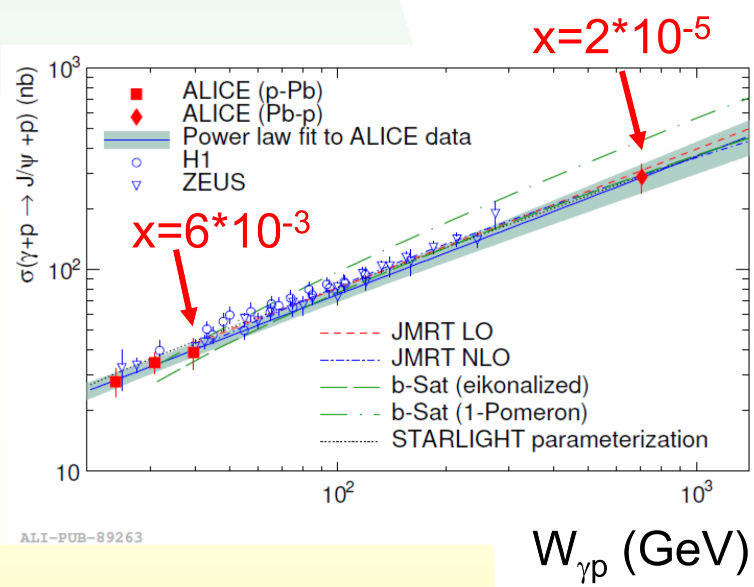


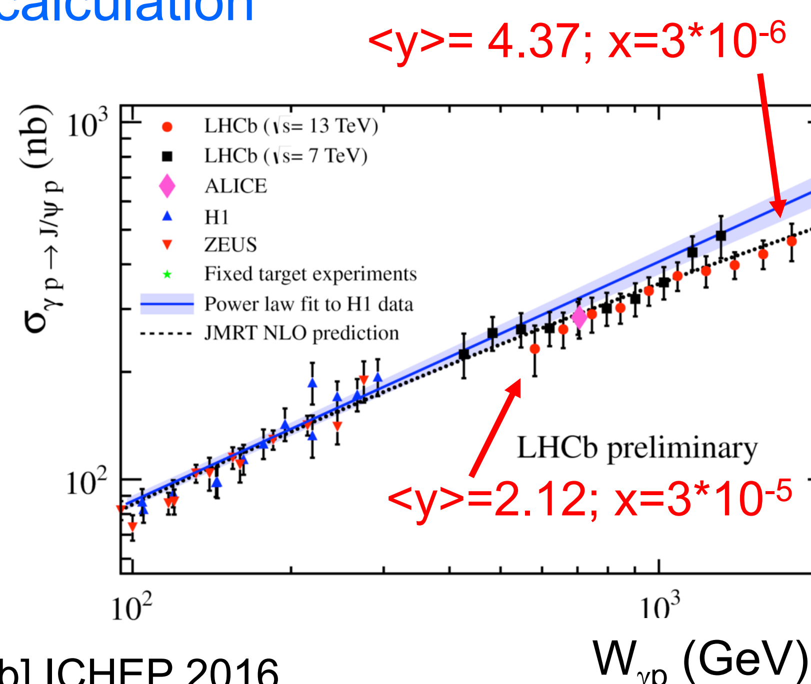
Gluon distribution @ Q^2=1.21 GeV^2

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

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

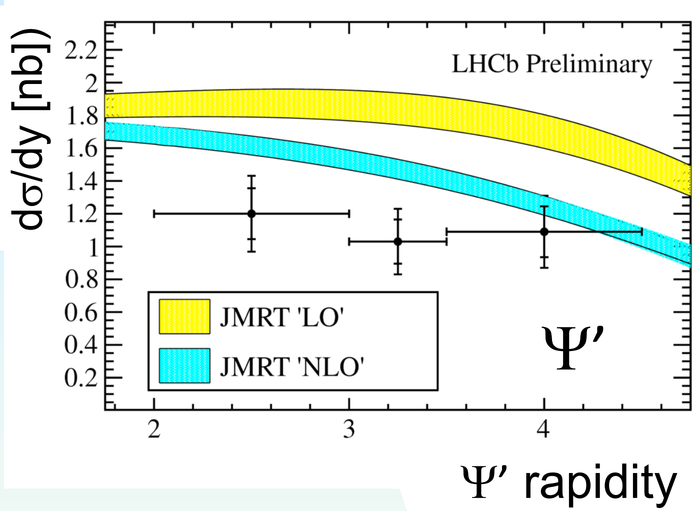
- Data up to $W_{\gamma p}$= 1.5 TeV -5 times the HERA maximum
- ALICE sees good pA agreement with HERA data
- LHCb 13 TeV-beam data somewhat below 7 TeV data?
  - LHCb uses bootstraps from HERA range for 2-fold ambiguity
- NLO calculation predicts a small down-turn from power law prediction at energies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

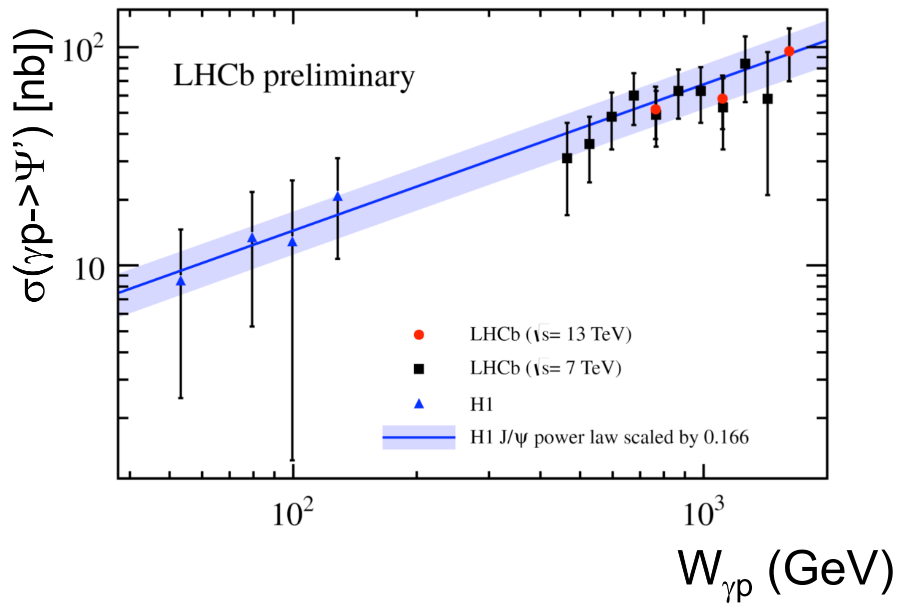




J. Adams [ALICE], DIS 2016; R. McNulty [LHCb] ICHEP 2016

ψ' photoproduction on proton targets





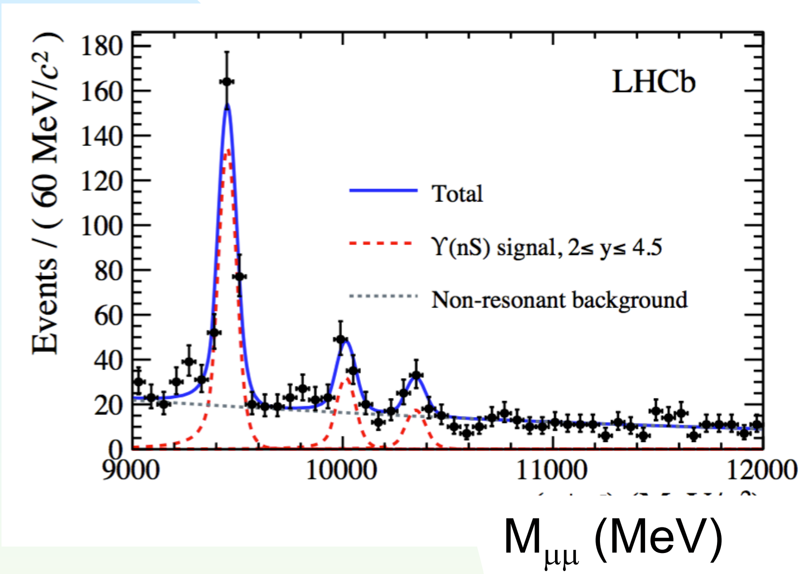
Good fit to power law
Data is a bit below the NLO pQCD

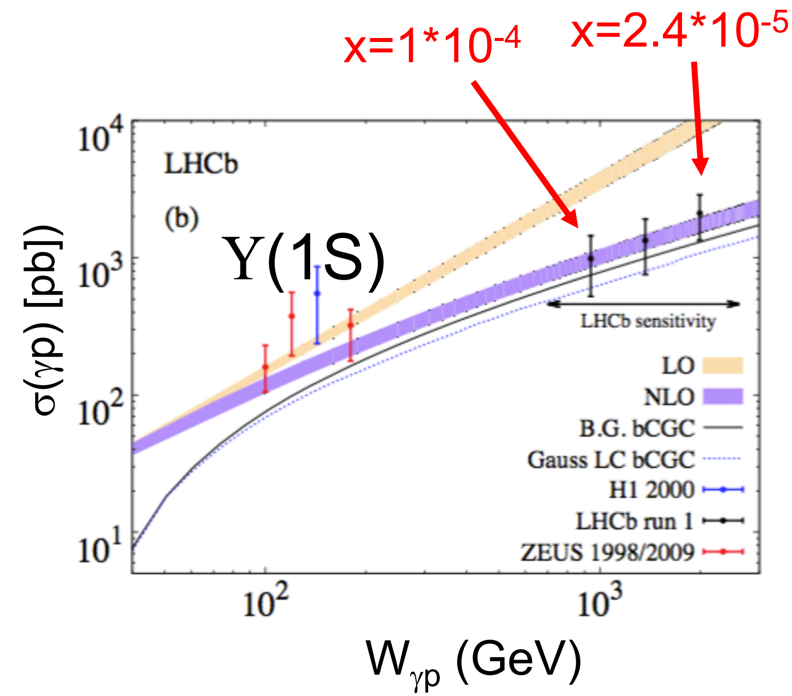
As with J/ψ, LHCb data quality is more precise than HERA & extends to higher energy

R. McNulty [LHCb] ICHEP 2016

γp->Υp

Forward dimuons with LHCb





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 & Υ data, at different Q^2

No evidence for saturation at low Q^2

Heavy quarkonium photoproduction on ion targets

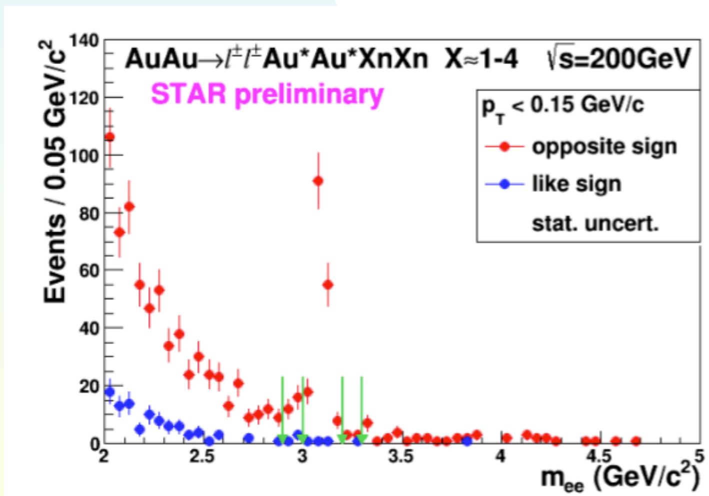
- Best data for nuclear gluon distributions for $x<10^{-3}$
  - $Q^2 = (M_{VM}/2)^2$
- Measure/calculate suppression relative to proton targets
  - Many theoretical uncertainties cancel
- Impulse approximation calculation sometimes used as reference
  - Replaces missing proton data at correct $\sqrt{s}$
  - 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

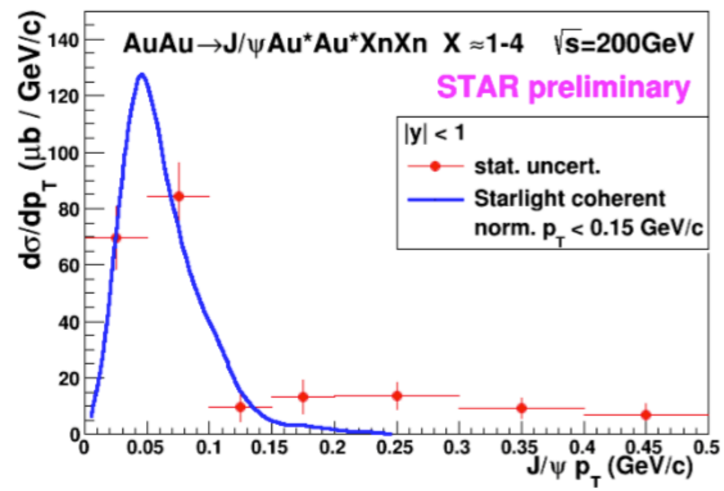
Coherent & incoherent J/ψ Photoproduction

Bjorken-x ~ 0.015

γγ->e^+e^- observed



M_{ee} (GeV)

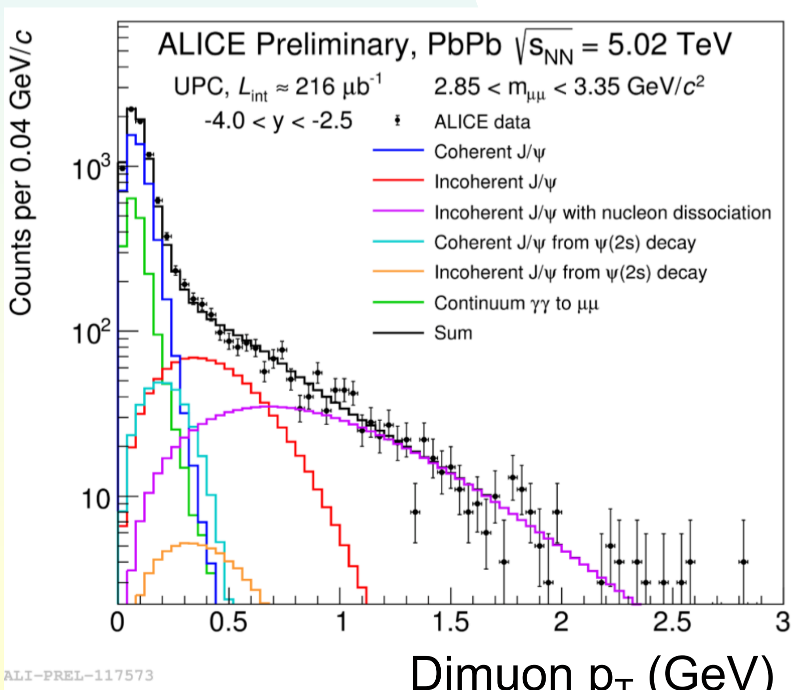


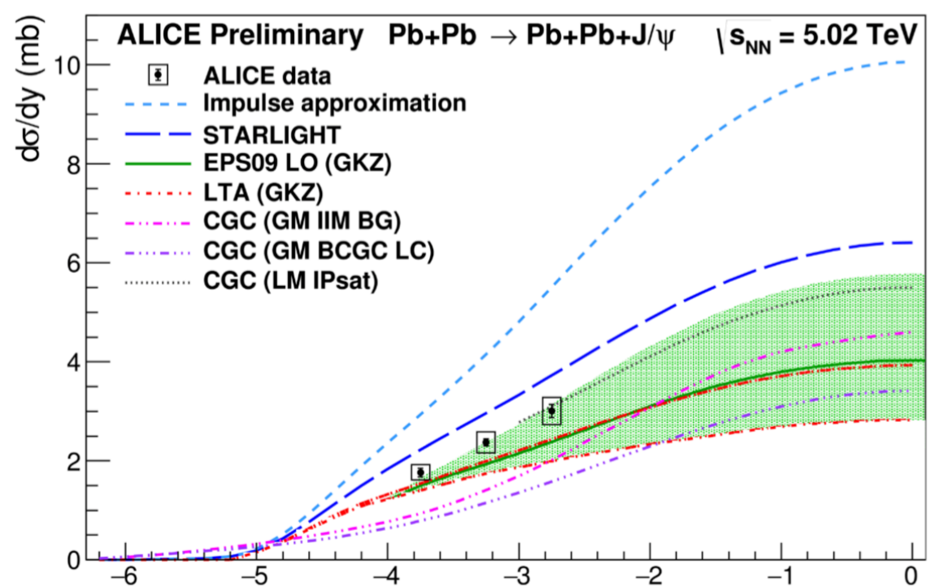
J/ψ p_T (GeV)

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
- $\sigma_{coherent}$ indicates gluon shadowing ~ 0.8
  - Consistent with EPS09 model
  - Consistent with leading twist approximation
- Also: J/ψ in pPb @ 8 GeV, $J/\psi \rightarrow p\bar{p}$, ψ'-> J/ψ $\pi^+\pi^-$

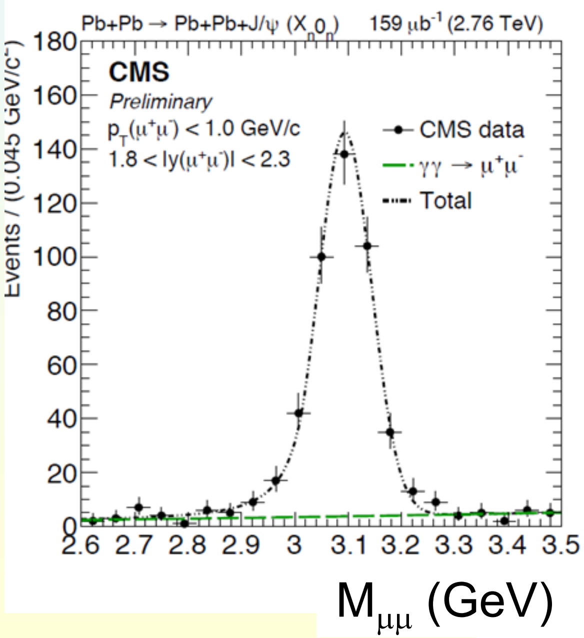


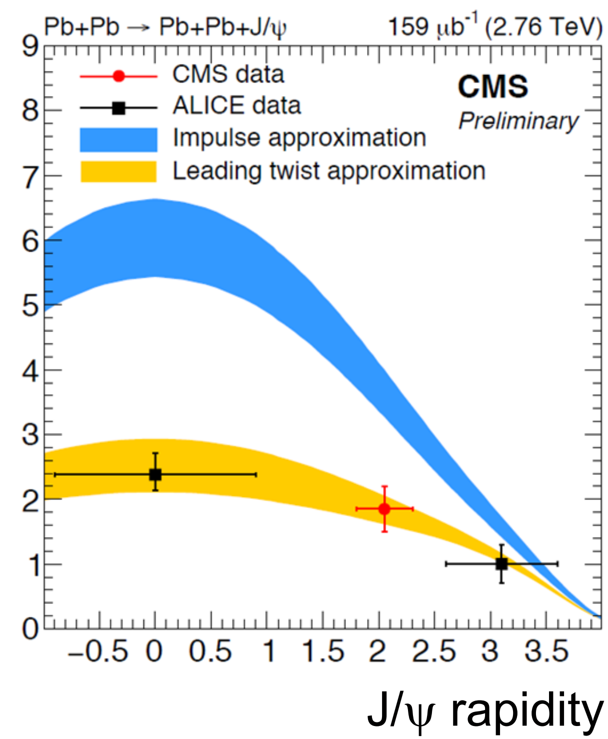


E. Kryshen [ALICE], QM17

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
- In incoherent photoproduction, J/ψ & neutrons go in same direction
  - Incoherent cross-section increases rapidly with photon energy?

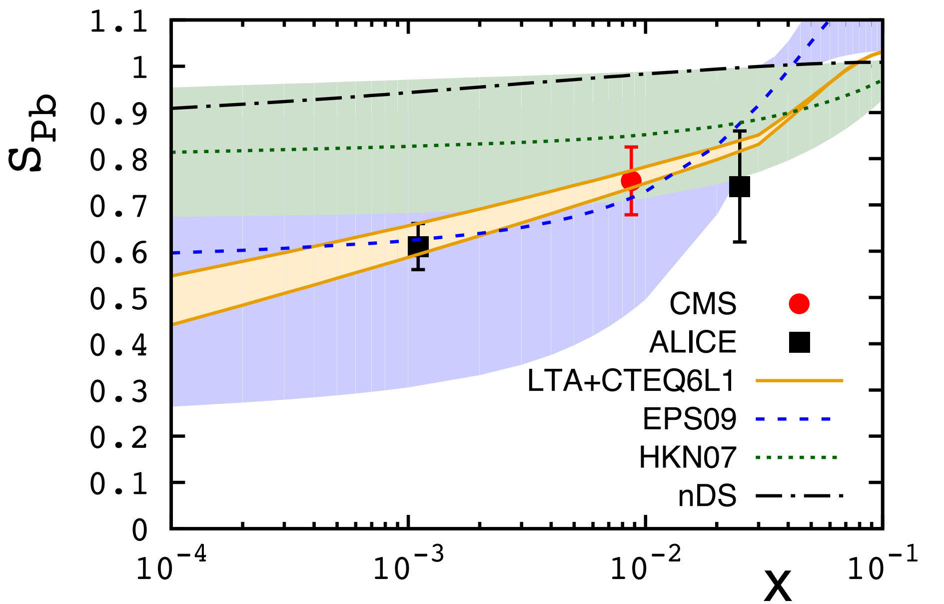




D. Tapai Takaki [CMS], QM17

Nuclear Shadowing

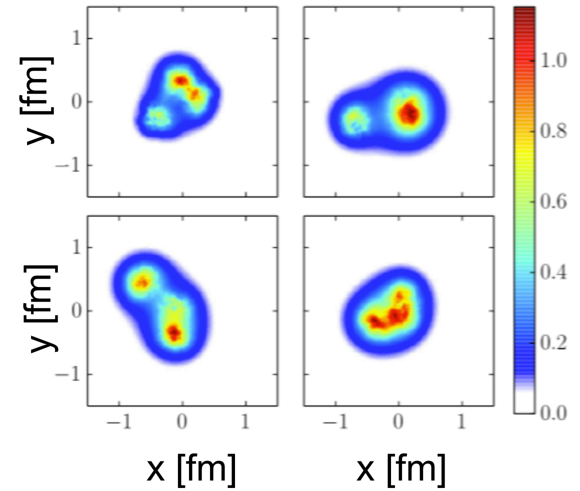
- Compare ALICE & CMS data with PDF shadowing models
  - Use impulse approximation for proton reference
    - Normalize to HERA data to correct for higher order terms
    - 6 different parton distributions
- Consistent w/ 2012 leading twist approximation calculation
  - Except for MNRT07 parameterization
- 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

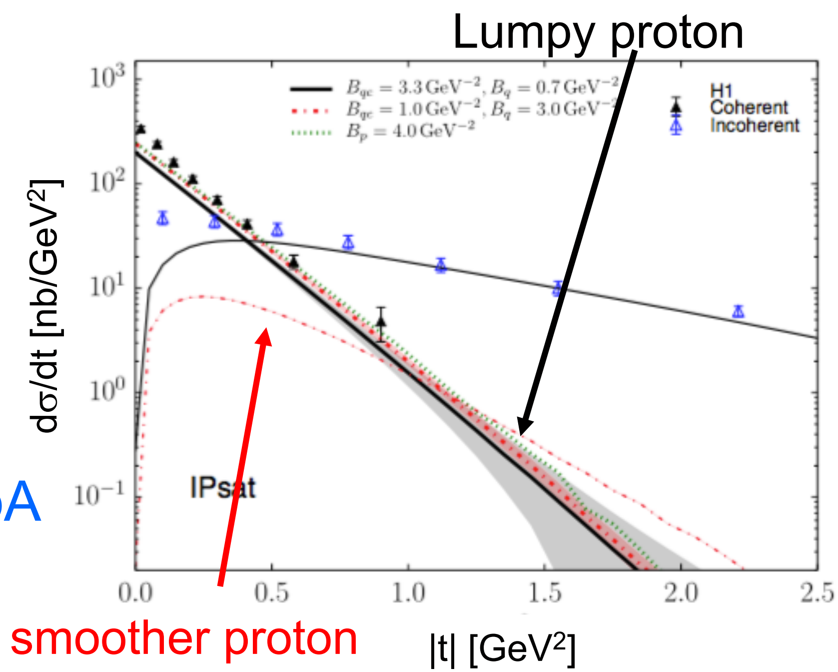


V. Guzey & M. Zhalov, JHEP 1310, 207 (2013)
Frankfurt Guzey & Strikman, Phys. Rept. 512, 255 (2012) updated by V. Guzey & M. Strikman.

Incoherent VM photoproduction

- Probes event-by-event fluctuations in the nuclear configuration
  - Quark/gluon transverse positions
- Walker-Good formalism:
  - $d\sigma/dt_{total} \sim \langle|Amp(K,\Omega)|^2\rangle_\Omega$
    - Ω = nuclear configurations
      - positions of nucleons (gluons)
    - K = kinematic factors: x, Q^2, t,…
  - $d\sigma/dt_{Coherent} \sim |\langle Amp(K,\Omega)\rangle_\Omega|^2$
  - $d\sigma/dt_{Incoherent} = d\sigma/dt_{total} - d\sigma/dt_{Coherent}$
- HERA data on $\gamma^* p \rightarrow J/\psi\, p$ indicates protons are quite lumpy/stringy
  - Reproduces most v_2 & v_3 results in pA
- AA data & calculations exist
  - Need comparisons

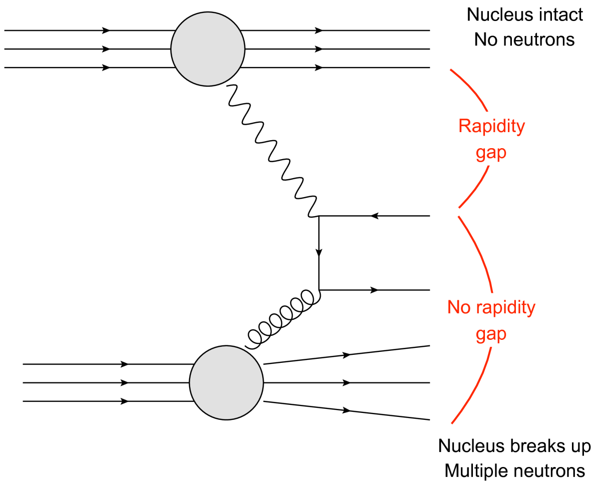




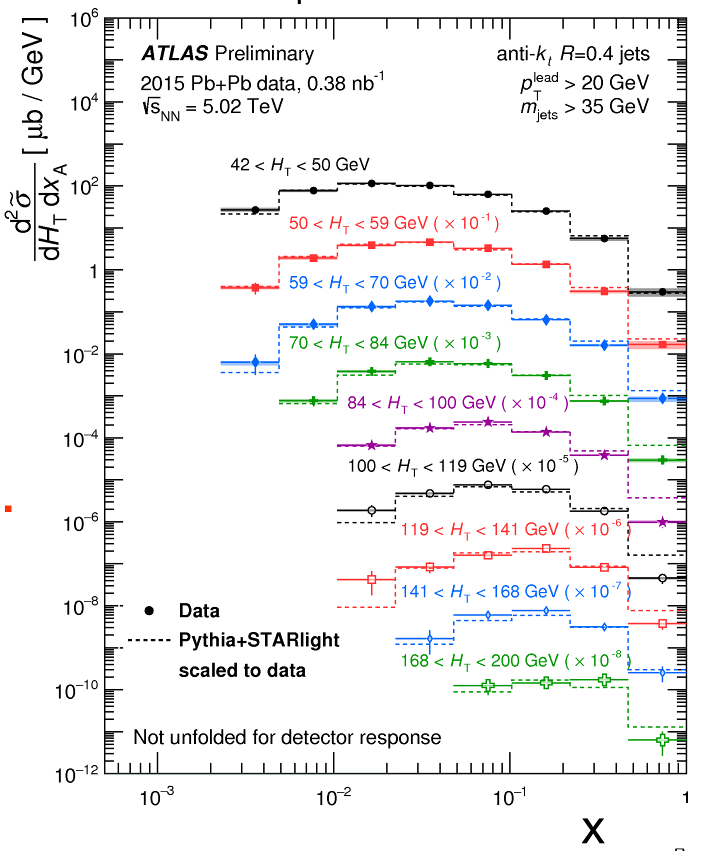
H. Mäntysaari, QM17; Mäntysaari & Schenke PRD 94, 034042 (2016)

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
  - $1600\ GeV^2 < Q^2 < 40{,}000\ GeV^2$
- Data vs. STARlight/PYTHIA hybrid
  - Some differences
    - Detector?
    - Nuclear modifications to pdfs?
- Unfolding in progress, to probe gluon dist.
- Room to expand kinematic reach



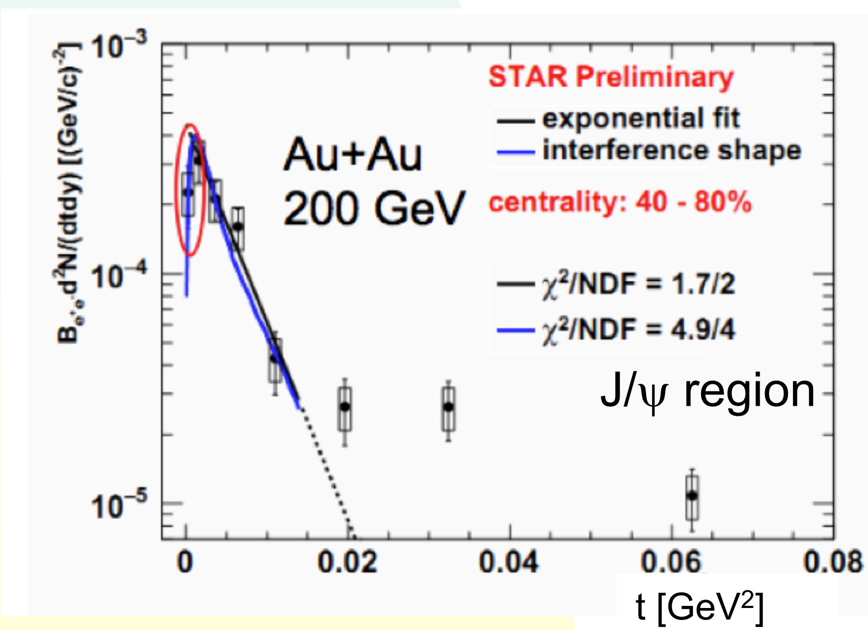
$H_T \sim 2Q$

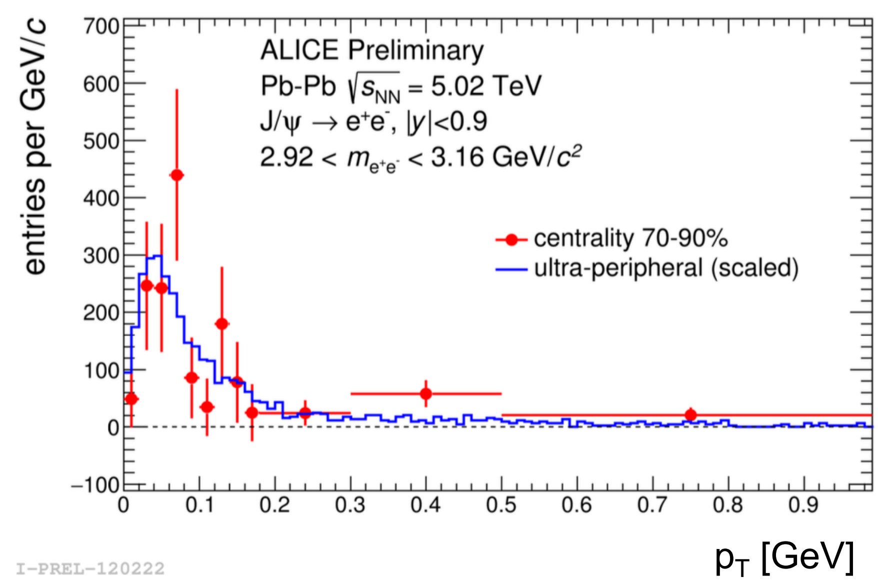


A. Angerami [ATLAS], QM17

UPCs in peripheral collisions

- Photon reactions do not disappear when $b < 2R_A$
  - Rates are reduced due to lower photon flux inside nucleus
  - Interference effects alter p_T spectrum
- Data shows an excess of lepton pairs with $p_T < 100$ MeV/c
  - Excess is significant - "$R_{AA} \sim 7$"
- Mix of photoproduced J/ψ + continuum l^+l^-

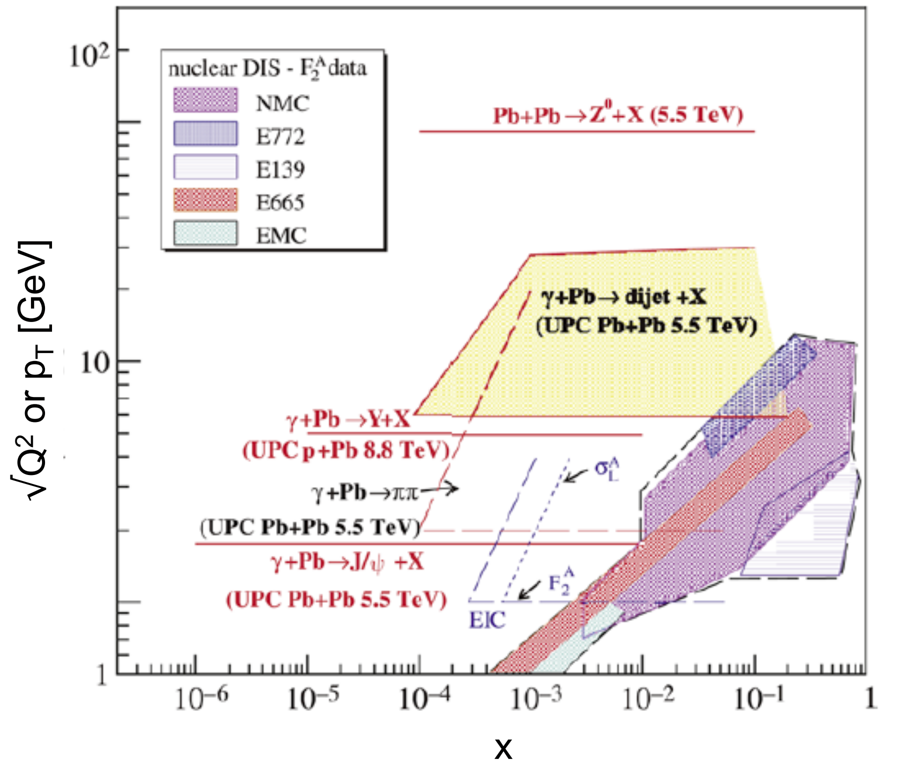




Z. Zhou [ALICE]; W. Zha [STAR], QM17; S. Yang [STAR], QM17

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
  - $\gamma + p\uparrow \rightarrow J/\psi + p\uparrow$ 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

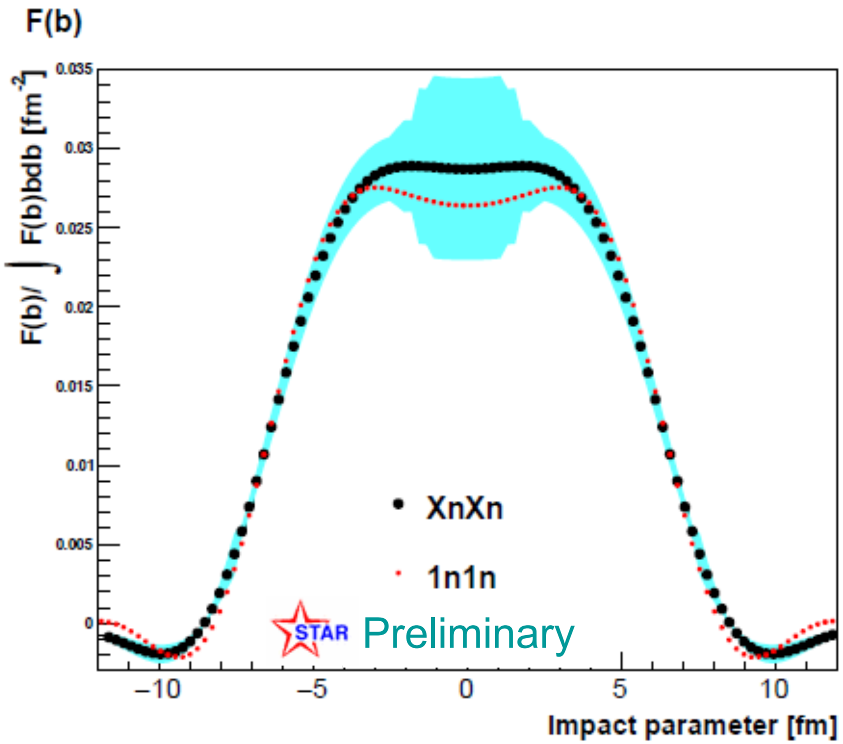
- Ultra-peripheral collisions are the energy frontier for electromagnetic & electroweak interactions.
- Electromagnetic dilepton production can be used to test strong field QED, search for new physics, and quench LHC magnets.
- Light vector meson photoproduction has been used to observe diffraction patterns 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

“Imaging” the nucleus

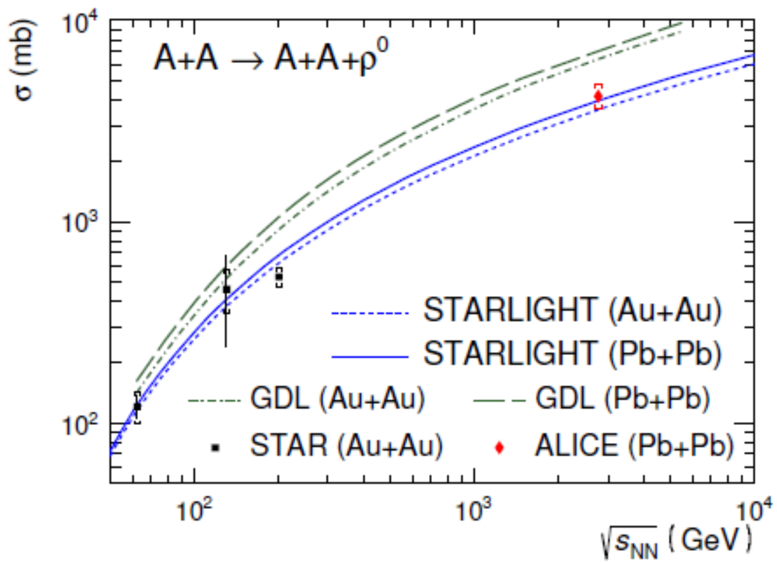
- Target (gluons?) density is the Fourier transform of $d\sigma/dt$
  - $|t|_{max} = 0.06\ \mathrm{GeV}^2$
- 2-d Fourier (Hanckel) tranform
  - Targets, integrated over z
  - 2-d avoids 2-fold ambiguity
- Blue band shows effect of varying $|t|_{max}$ from 0.05 - 0.09 GeV^2
  - Variation at small |b|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

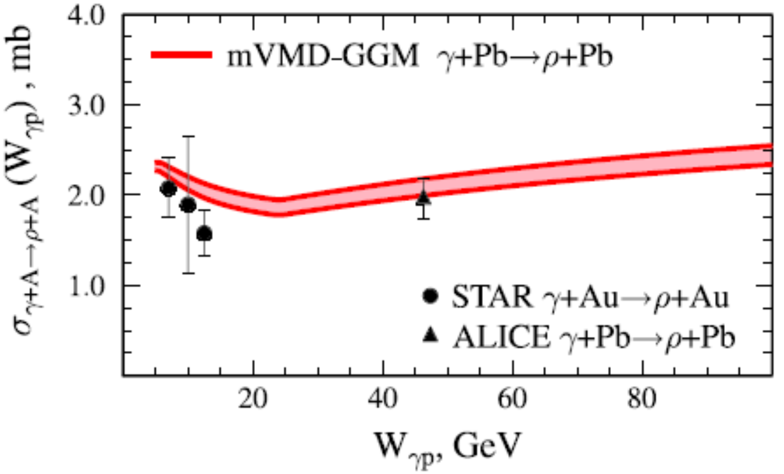
$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T\, J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$



ρ^0 cross-section

- Cross-section is convolution of Weizsacker-Williams photon flux with σ(γA->VA)
  - Calculate σ(γA->VA) with a Glauber calculation, using HERA data (or HERA data tied to first principles) as input
- ALICE & STAR cross-sections are half the predictions of a quantum Gribov-Glauber calculation ("GDL")
  - "Shadowing" from cross-section fluctuations
    - Higher mass qq -> smaller dipole size -> smaller σ

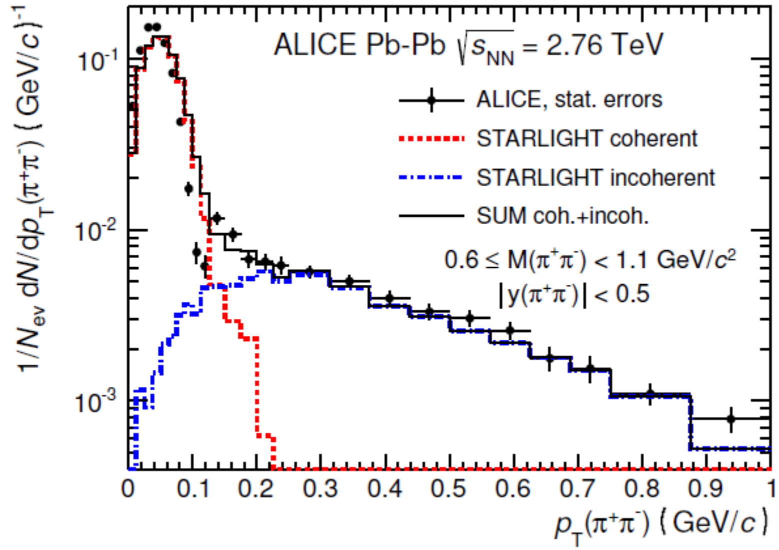


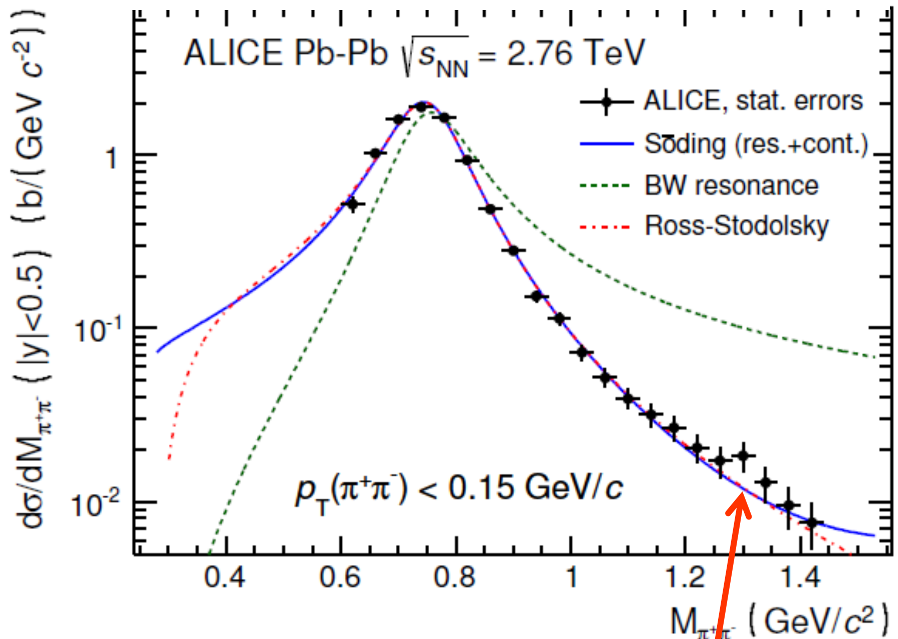


L. Frankfurt *et al.*, Phys.Lett. **B752** 51 (2016)

ALICE ρ^0

- Trigger on charged particles (neutrons not required)
- Coherent peak for p_T< ~ 100 MeV/c
- Dip at p_T=120 MeV/c not understood
- Mass peak consistent with ρ^0, with possible hint of $\gamma\gamma$->f_2(1270)->$\pi\pi$





ALICE, JHEP **1509**, 095 (2015) & J. Adams. Presented at DIS 2016