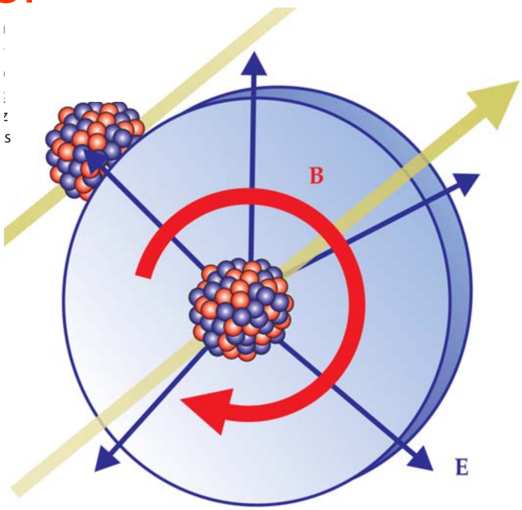
Ultra-peripheral collisions: the energy frontier for photon physics

Spencer R. Klein, LBNL

- UPCs: a tool to study the photon energy frontier
- QED: dilepton production
- Low-x partons in protons and nuclei
- Beyond the Standard Model: axions and such
- γp and γA as 'small systems'
- A peek forward and some conclusions

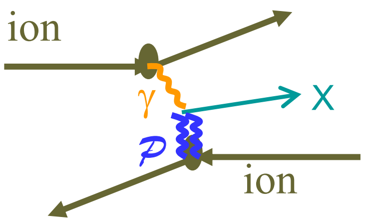


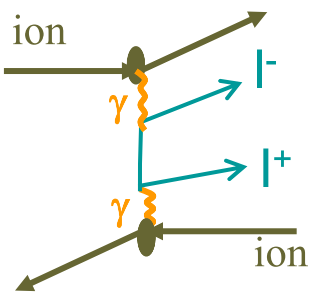
See also the talk Monday by Ashik Ikbal Sheikh

Way too many recent results to cover
Focus on experiment
Apologies to authors that I neglect

Ultra-peripheral collisions (UPCs)

- Heavy nuclei carry strong electric and magnetic fields
  - Lorentz contracted E and B fields are perpendicular -> treat as nearly-real virtual photons
    - $E_{max} = \gamma hc/b$
- Photonuclear interactions and two-photon interactions
  - Most visible when b>~2R_A, so there are no hadronic interactions;
    - Also seen in hadronic heavy-ion 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

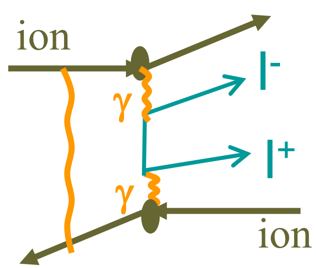
*LHC at full energy √s=14 TeV/5.6 TeV

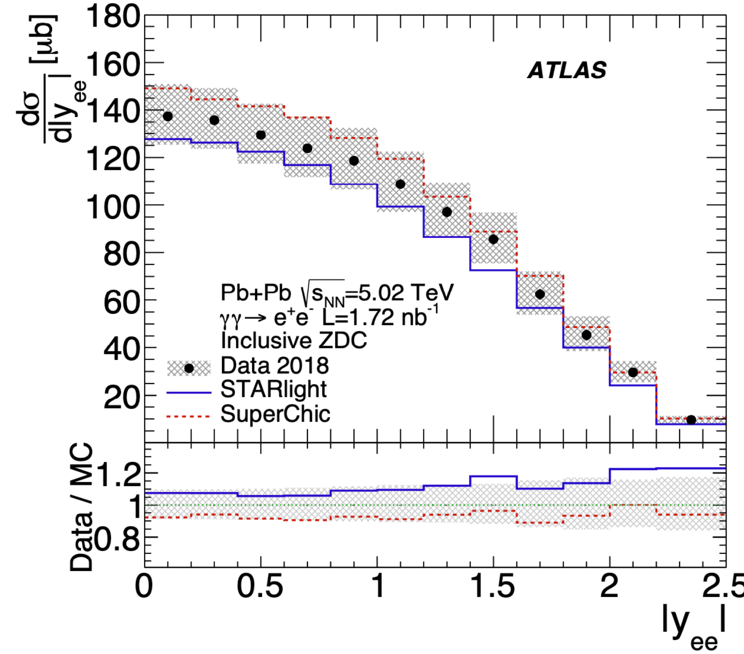
Why UPCs?

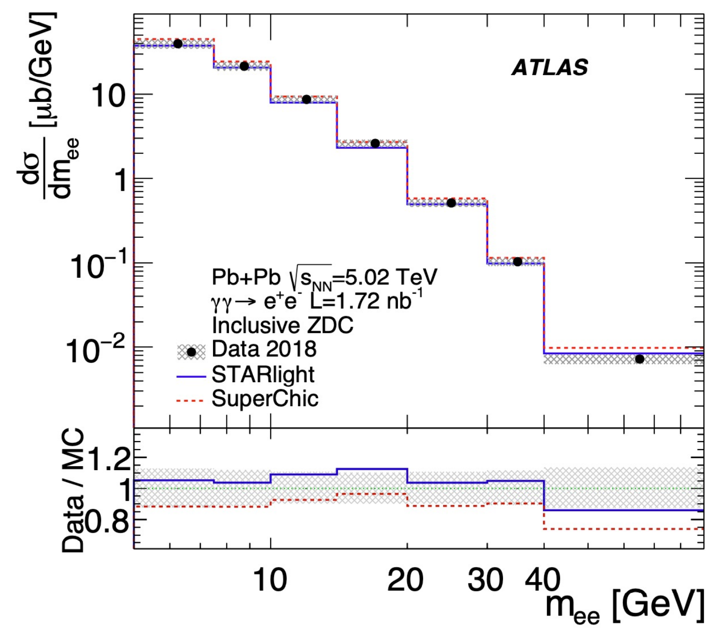
- A technique to study reactions involving photons at the energy frontier
  - Maximum CM energy $W_{\gamma p}$ ~ 3 TeV for pp at the LHC
    - ~ 10 times higher in energy than HERA
  - Photonuclear Interactions
    - Nuclear structure at low-x
      - Bjorken-x down to a few 10^{-6} at moderate Q^2
      - Exclusive interactions access transverse distribution of partons and event-by-event fluctuations
  - Two-photon interactions
    - Dilepton production, $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to \gamma\gamma$
      - Tau anomalous magnetic moment from $\gamma\gamma \to \tau^+\tau^-$
    - New particle searches (axions), etc.
- α_{EM} ~ 1/137, so reactions are cleaner than in hadroproduction
  - "Precision" measurements with 5-10% uncertainties

$\gamma\gamma$ -> Dileptons

- Results from ALICE, ATLAS & STAR
  - e^+e^- $\mu^+\mu^-$ and $\tau^+\tau^-$
- Data agrees with lowest order QED
  - STARlight & SuperChic Monte Carlos
    - SuperChic includes interactions inside the two nuclei
      - But still with $b>2R_A$
    - Data is between 2 predictions
    - No need for higher order corrections to cross-section, although $Z\alpha \sim 0.6$
      - Exception – Final state radiation causes acoplanar events
- Calculations account for additional photon exchange
  - Nuclear excitation…



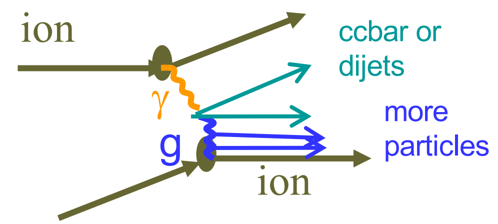




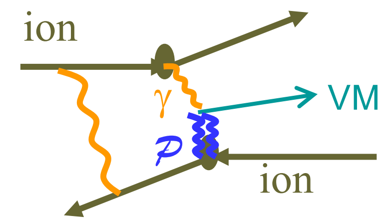
ATLAS: M. Dyndal, at ICHEP 2024

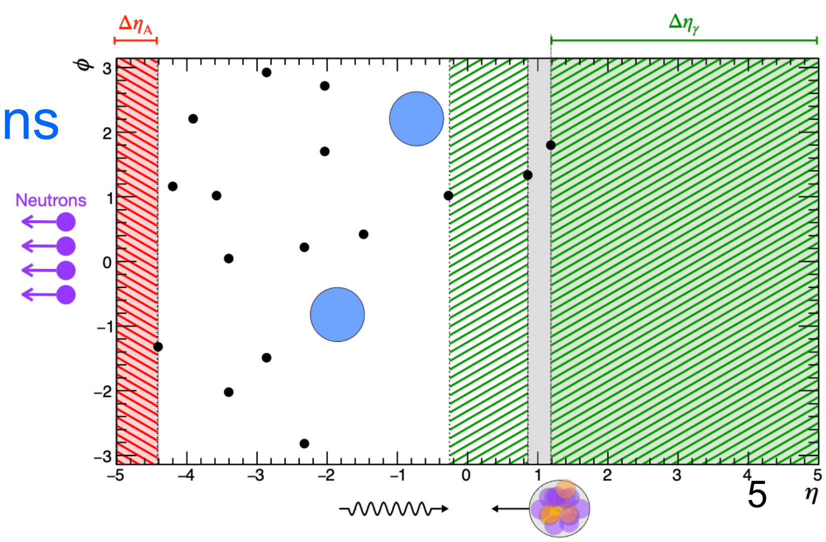
Probing nuclear structure at low-x

- Single-gluon interactions (at LO):
  - γ + g -> open charm or dijets
    - Theoretically clean
    - Many experimental details
      - Direct vs. resolved contribution



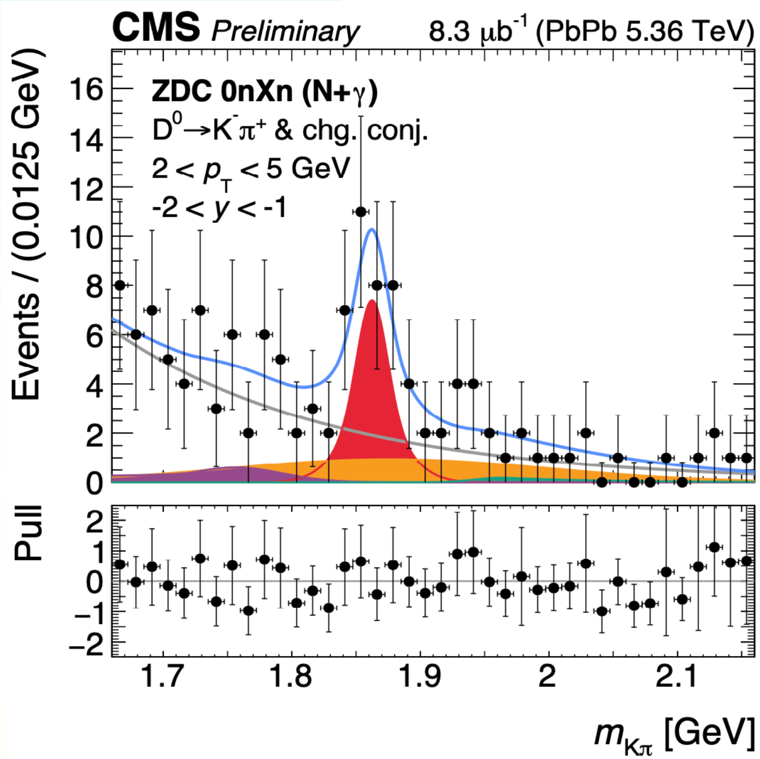
- Vector meson photoproduction
  - Exclusive J/ψ–> ll etc. is experimentally easy
    - Compare gluon densities in p and A, so theoretical uncertainties cancel
  - Coherent vector mesons probe transverse distribution of target partons
  - Incoherent production probes event-by-event fluctuations
- Additional photon exchange adds complications

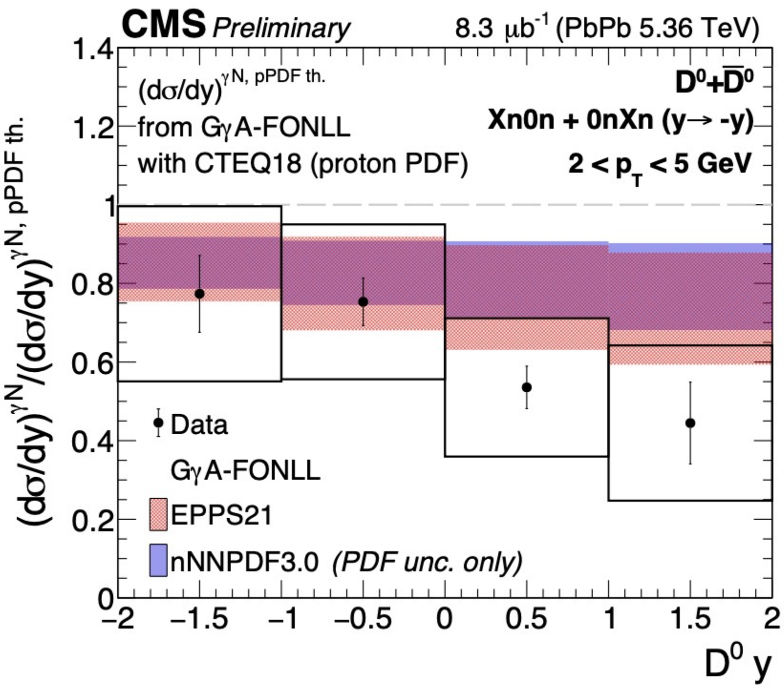




Probing nuclear structure at low x

- Probes gluons at low Bjorken-x
  - $x \sim M_{xx}/2\gamma m_p \exp(y)$ and $Q^2 \sim (M_{xx})^2$
    - Charm quark mass gives hard scale
- CMS D^0 cross sections are ~ below CTEQ18 FONLL calculations, but ~ below/consistent with + ePPS21 nPF & nNNPDF 3.0 +FONLL

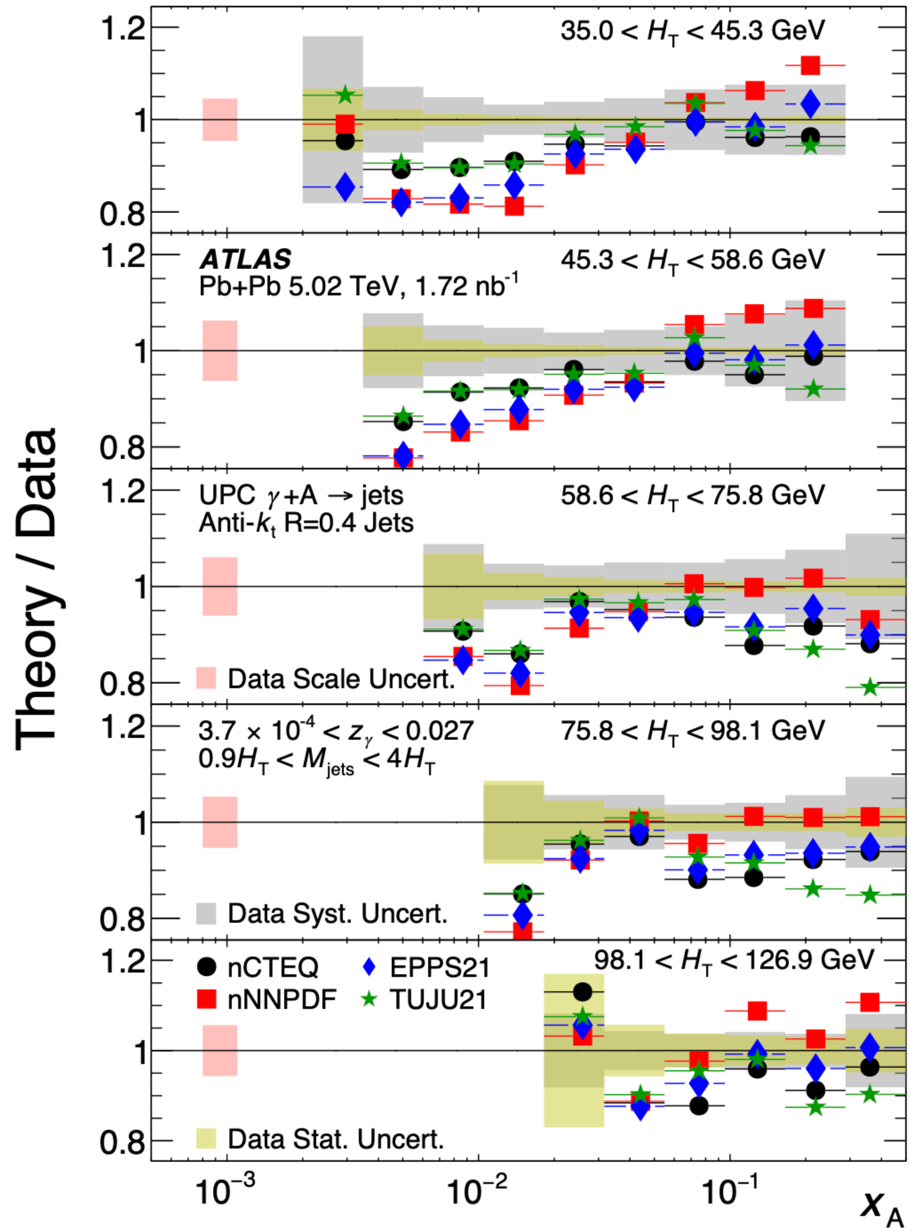




CMS-PAS-HIN-25-002

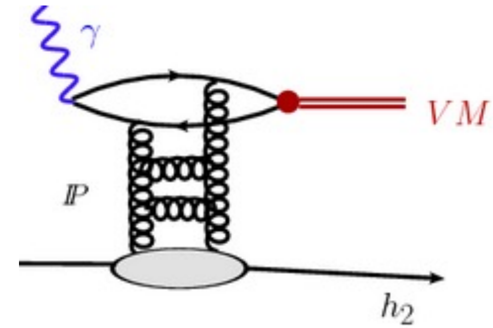
Gluon distributions from ATLAS dijets

- Dijets with H_T> 35 GeV
  - Scalar jet momentum sum
- Explicit corrections for additional photon exchange
- Unfolding to get 3-d spectra
  - Y_{jets}, M_{jj} , H_T
  - ~ 5% systematic uncertainties
- $5*10^{-3} < x < \sim 0.5$
- Compared with nCTEQ, nNNPDf, EPPS21 and TUJU21
  - Models are generally a bit below the data at small x



ATLAS: PRD **111,** 052006 (2025)

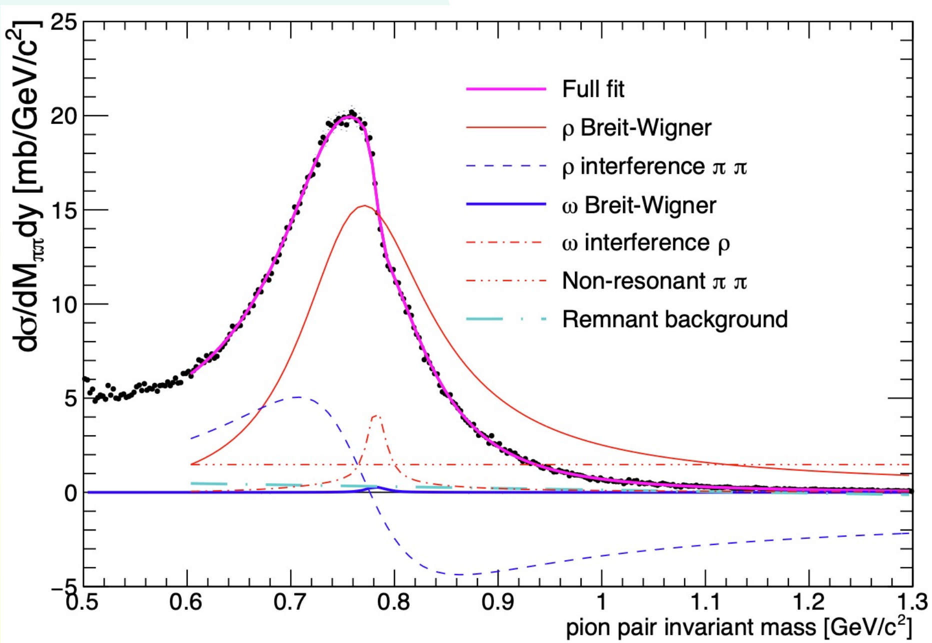
Vector Meson photoproduction

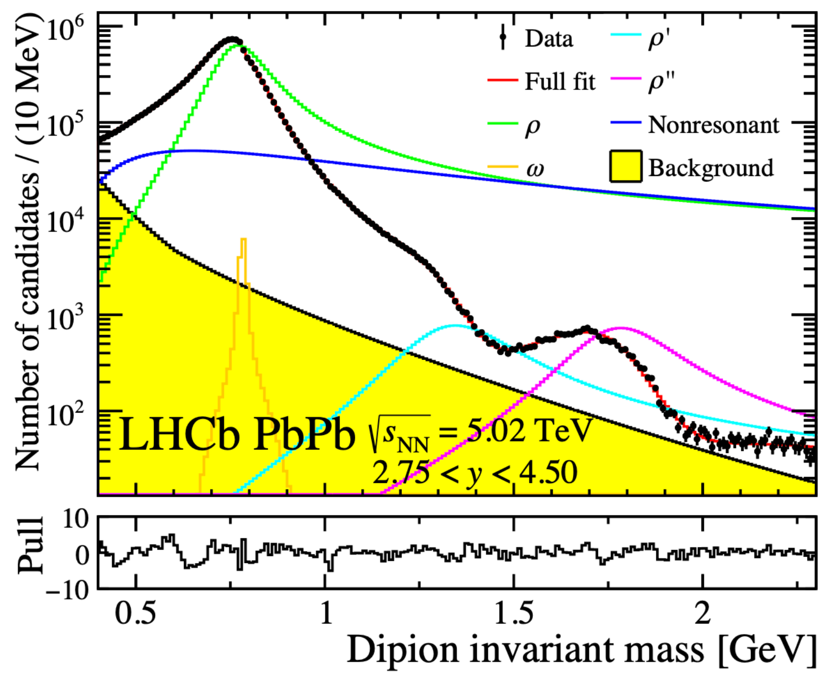


- Large cross-sections
  - Probe gluon distributions and fluctuations
- Produced via colorless 'Pomeron exchange'
  - Require >=2 gluon exchange for color neutrality
    - Gluon ladder
- Light meson production usually treated via vector meson dominance model
  - ρ, direct $\pi^+\pi^-$, ω, ρ' observed at RHIC & LHC
- Heavy meson production treated with pQCD
  - J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$
- 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 $\sigma(\gamma A)$

ρ^0 photoproduction

- High precision mass spectra: 294K (20M) exclusive $\pi^+\pi^-$ from STAR (LHCb)
- Mass spectra fit by ρ^0 + direct $\pi\pi$ + ω->$\pi\pi$ + high mass state
  - M = 1653 MeV, Γ=164 MeV - Consistent with ρ_3(1690)?
  - LHCb also sees intermediate mass resonance
- On tape (on tap?): >10 M event samples from multiple expts.

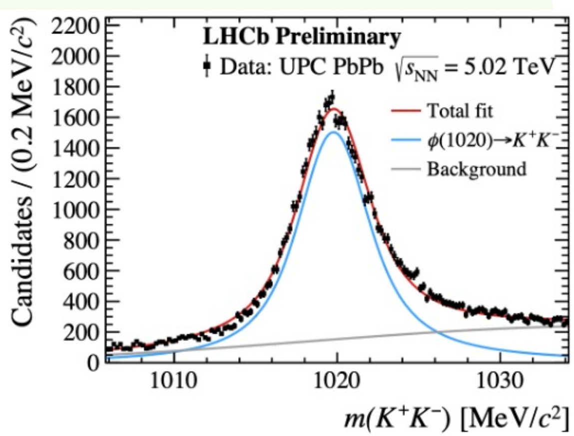


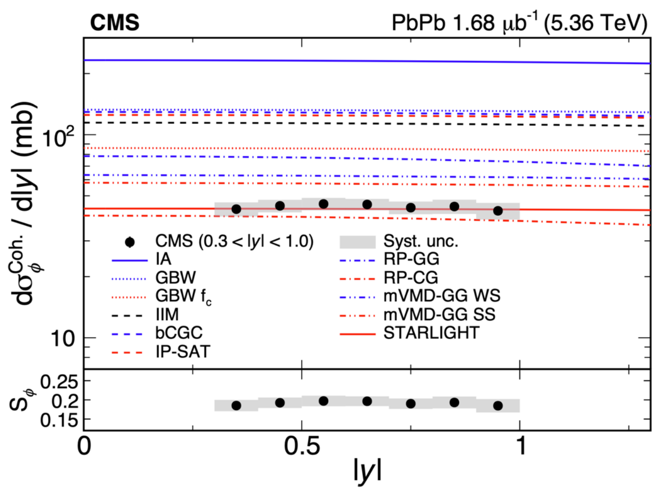


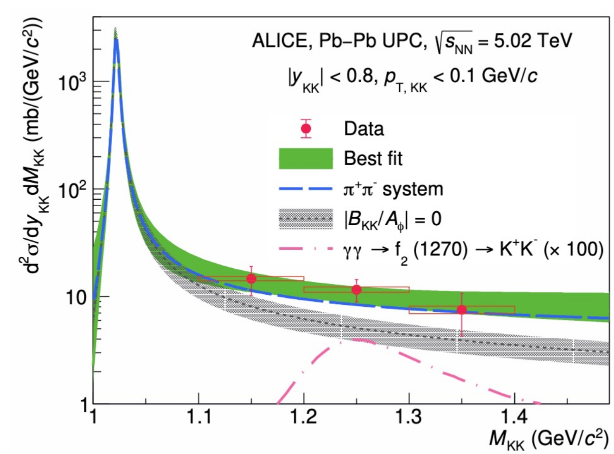
STAR, Phys. Rev. C 96, 054904 (2017); LHCb, arXiv:2506.06250

ϕ photoproduction

- The ϕ has an intermediate mass
  - Highlighted in Electron-Ion Collider planning
  - $Q^2 \sim M^2$, so the ϕ should exhibit more saturation than the J/ψ
- $K^\pm$ from $\phi \to K^+K^-$ have p ~ 130 MeV/c
  - β~0.2 -> Large dE/dx and quick stopping -> challenging
- Cross-section compatible with Glauber calculations
  - Accounts for nucleon positions & multiple γN interactions
- Direct K^+K^- also seen, ϕ: direct KK ratio similar to ρ: direct $\pi\pi$

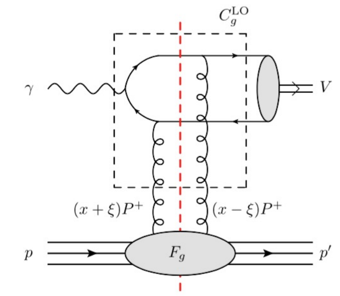


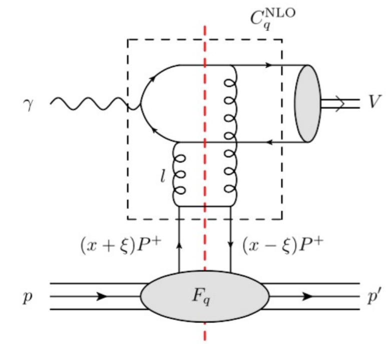




CMS, arXiv:2504.05193; LHCb-CONF-2024-006; ALICE: PRL 132, 222303 (2024)

VM photoproduction in pQCD

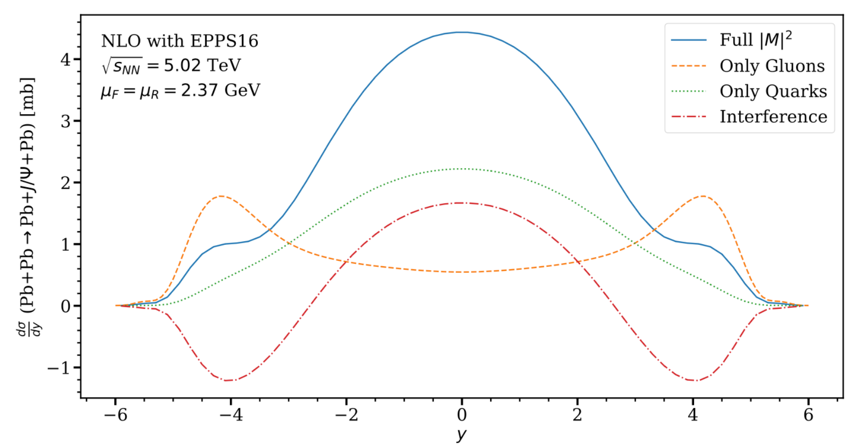




- Leading order pQCD, via 2 gluons

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

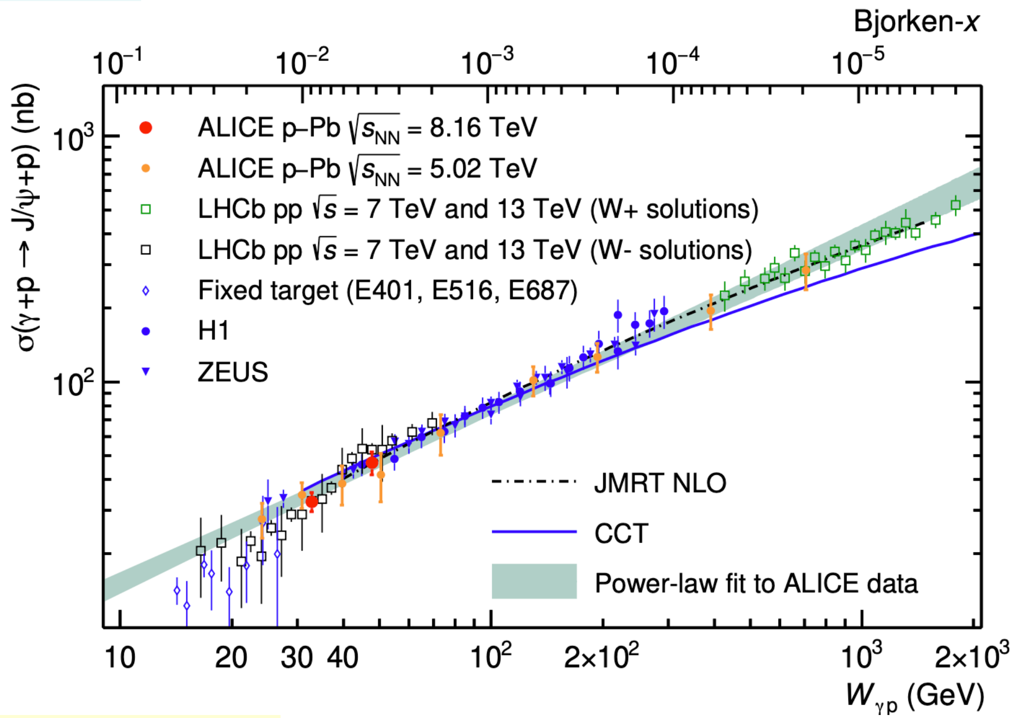
- With $\bar{Q}^2 = (Q^2 + M_{J/\psi}^2)/4, \qquad x = (Q^2 + M_{J/\psi}^2)/(W^2 + Q^2)$
  - Vector meson mass provides hard scale
- Some caveats
  - NLO 'correction' larger than LO amplitude & opposite sign
    - "Standard" parton distributions have too few low-x, low-Q^2 gluons, suppressing the LO term
    - More gluons would increase the LO term
  - Large contribution from quarks
  - High scale sensitivity
- Measure shadowing by comparing $\sigma(\gamma A)$ to $\sigma(\gamma p)$



K. Eskola et al., Phys., Rev. C **106**, 035202 (2022)

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

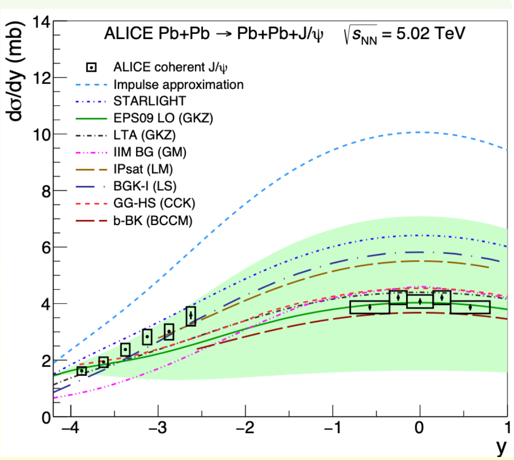
- Data up to $W_{\gamma p}$= 1.5 TeV -5 times the HERA maximum
  - Bjorken-x down to a few 10^{-6}
- Data follows a power law (w/ possible slight downturn
  - At Lowest Order, if $g(x) \sim x^{-\lambda}$, then $\sigma(\gamma p \to J/\psi\ p)$ is also a power law
    - No evidence for a kink from onset of saturation
    - At NLO, situation is more complicated

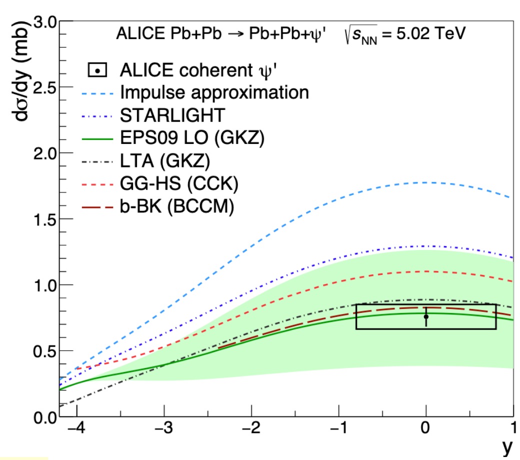


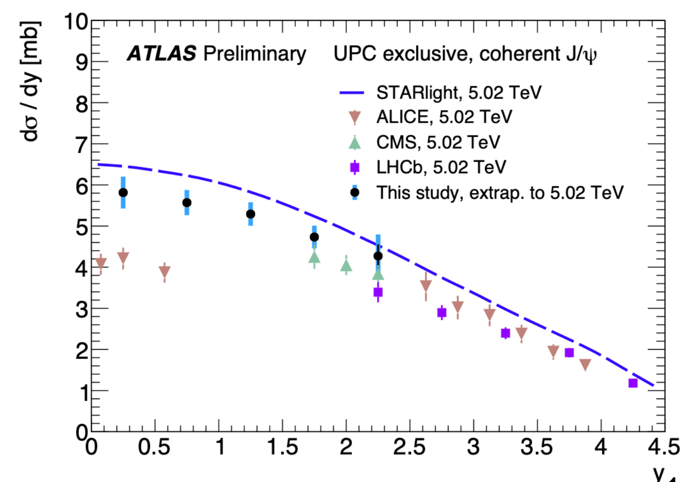
ALICE, PRD **108**, 112004 (2023)

J/ψ & ψ' photoproduction on lead

- Shadowing should be describable w/ pQCD
- Tension between ALICE & ATLAS @ midrapidity
  - Due to multiple interactions between an ion pair?
    - AA->AAeeJ/ψ
  - Tension between mid-rapidity and forward data
- ALICE sees a bit more shadowing than leading twist, while ATLAS sees pretty good agreement
- ALICE agrees with EPS09 parameterization
  - Can provide significant constraints



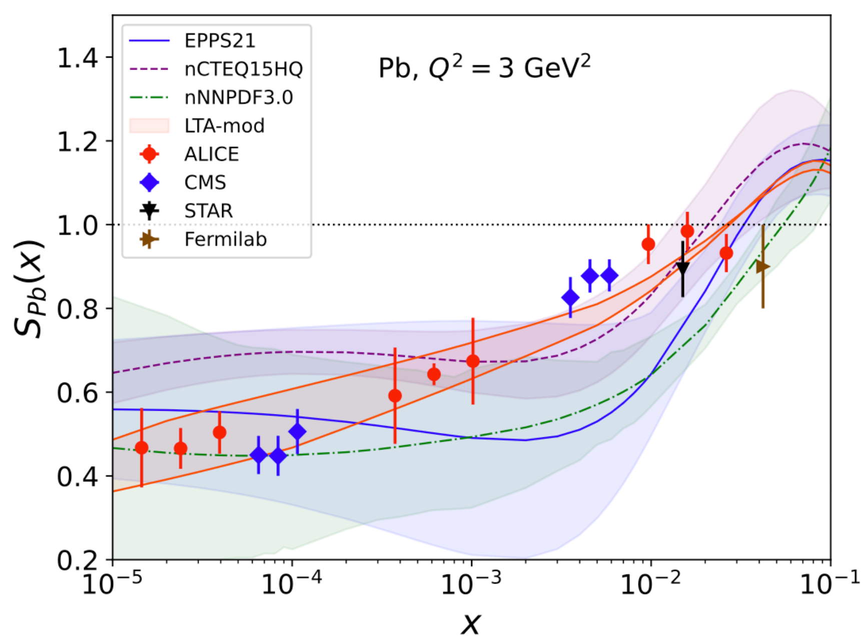




ALICE, Eur. Phys. J. **81**, 712 (2021); ATLAS-CONF-2025-003

Nuclear Shadowing

- Compare coherent photoproduction cross-sections on proton and ion targets
  - Many uncertainties cancel
- Data from ALICE, CMS, STAR and Fermilab (+LHCb for p)
- $S_{Pb}(x) < 1$ -> clear shadowing
- To LO, $S_{Pb}(x) \sim g(x)^2$
- Data is consistent with leading twist approximation



V. Guzey & M. Strikman,
PRC **110**, 045201 (2024)

x

Gluon spatial distribution and fluctuations

- The Good-Walker formalism links coherent and incoherent production to the average nuclear configuration and event-by-event fluctuations respectively
  - Configuration = position of nucleons, gluonic hot spots etc.
- Coherent: Nucleus remains in ground state
  - Impact parameter and p_T are conjugate variables. Fourier transform of $d\sigma/dt$ gives transverse distribution of (gluon) targets
- Incoherent = Total – coherent;
  - Square of sums minus sum of squares-> sensitive to fluctuations

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

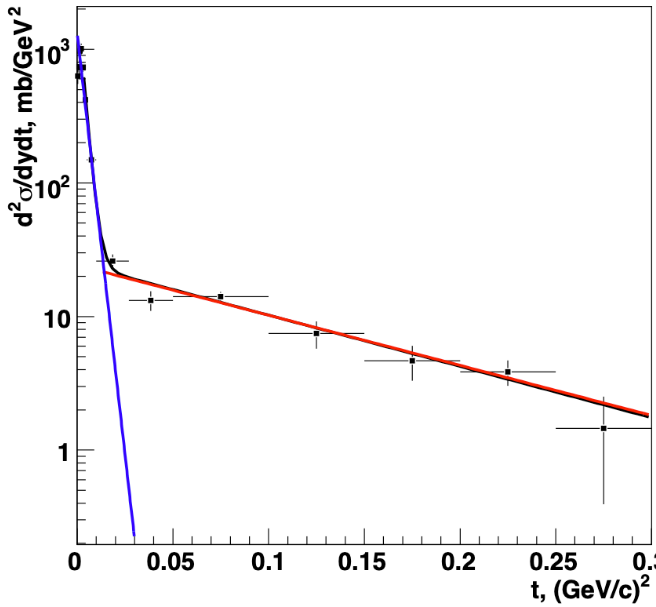
$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\langle A(K,\Omega)\rangle\right|^2$$ Average amplitudes (Ω)

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

Good and Walker, Phys. Rev. D **120**, 1857 (1960); Miettinen and Pumplin, Phys. Rev. D **18**, 1696 (1978)

Good-Walker caveats

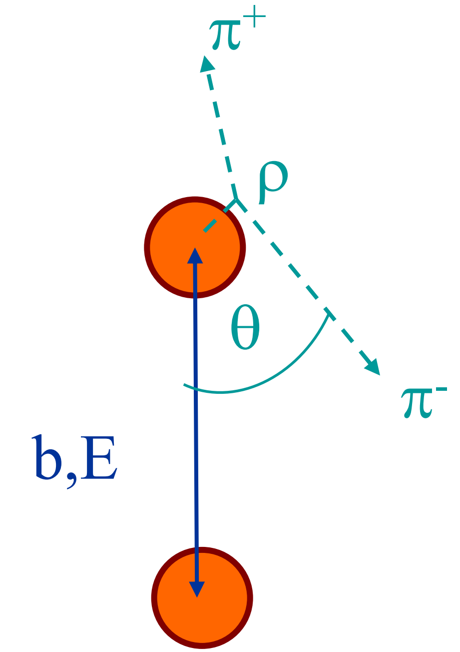
- The identification "Coherent -> Nucleus remains in ground state" fails in at least two cases
  - Photoproduction accompanied by nuclear excitation
  - Coherent photoproduction in peripheral collisions
- Photoproduction cross-sections are consistent with amplitude addition, despite the excitation/destruction.
- Excitation is exothermic. At low |t|, the energy transfer may be too small to excite a target.
  - Lead requires 2.6 MeV for excitation
  - Gold only needs 77 keV.
- They should have different low-|t| behavior. In contrast, at a partonic level, they are similar.



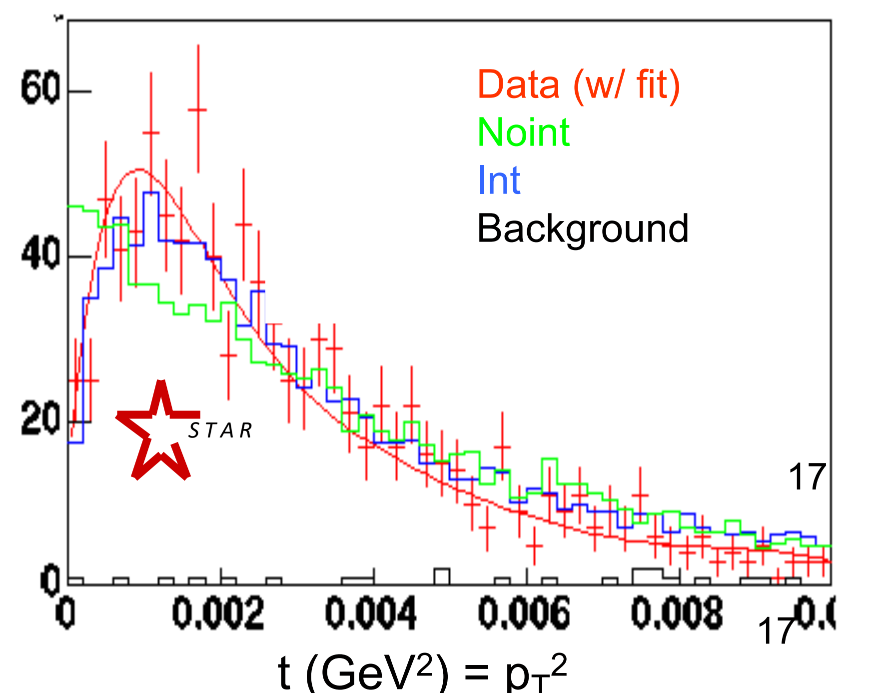
STAR, PRC **77**, 034910 (2008); SK, PRC **107**, 055203 (2023).

Coherent photoproduction p_T spectrum

- p_T distribution comes from nuclear form factor
  - $<p_T>$ ~~few hbar/R_A ~ 30 MeV/c for heavy nuclei
  - Small contribution from photon p_T
- Either nucleus can be photon emitter or target
  - Indistinguishable -> Add amplitudes
- $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
  - minus since ρ,ω,ϕ, J/ψ are $J^{PC} = 1^{--}$
    - + sign in pbar p collisions
- σ suppressed for $p_T < h/<b>$
- Effect is angle dependent
  - photon **linear** polarization follows b
  - $\pi^+\pi^-$ plane is near E field (b)
    - $P(\theta) \sim \cos^2(\theta)$
    - Interference largest when $p_\pi \parallel p_\rho$



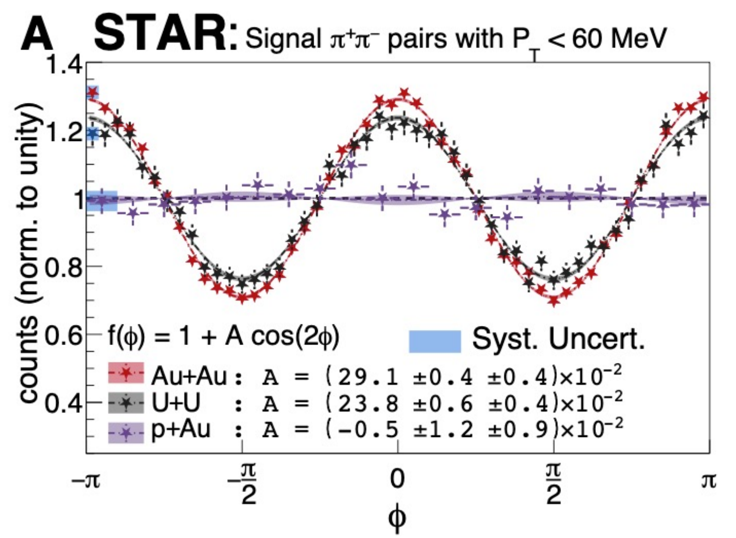
(transverse view)

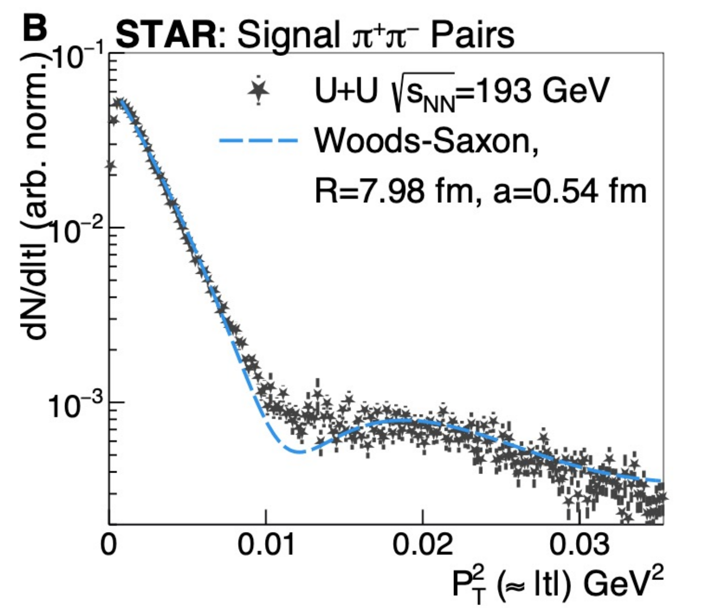


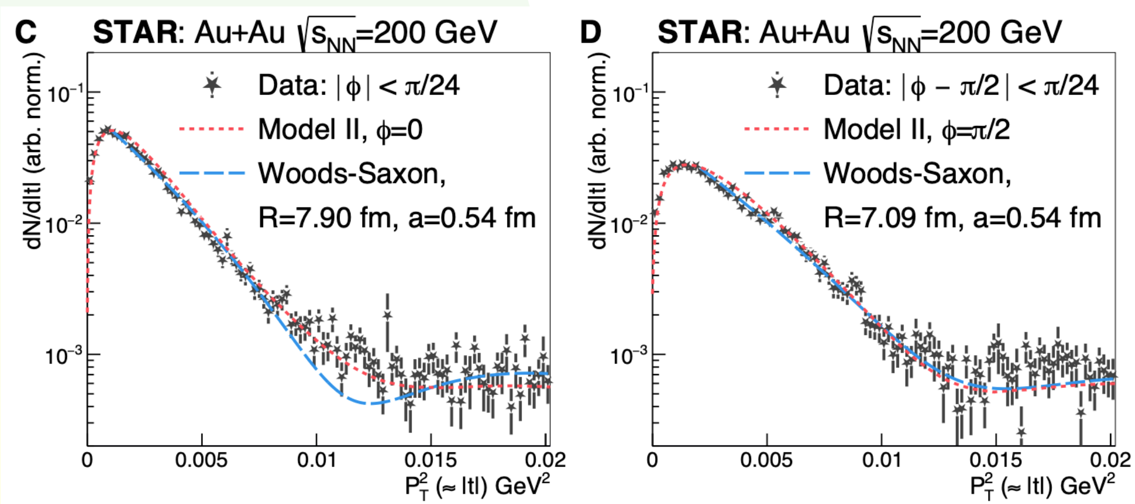
STAR, PRL **102**, 112301 (2009)

Tomographic measurement of radii

- Fit coherent $d\sigma(AA \rightarrow Aa\pi^+\pi^-)/dt$ with nuclear density distribution and Glauber calculation
  - Inclusion of interference in fit of $d\sigma/dt$ permits precision hadronic-radius measurements.
    - Expected angular modulation seen
  - $R(^{197}Au) = 6.53 \pm 0.06$ fm
  - $R(^{238}U) = 7.29 \pm 0.08$ fm



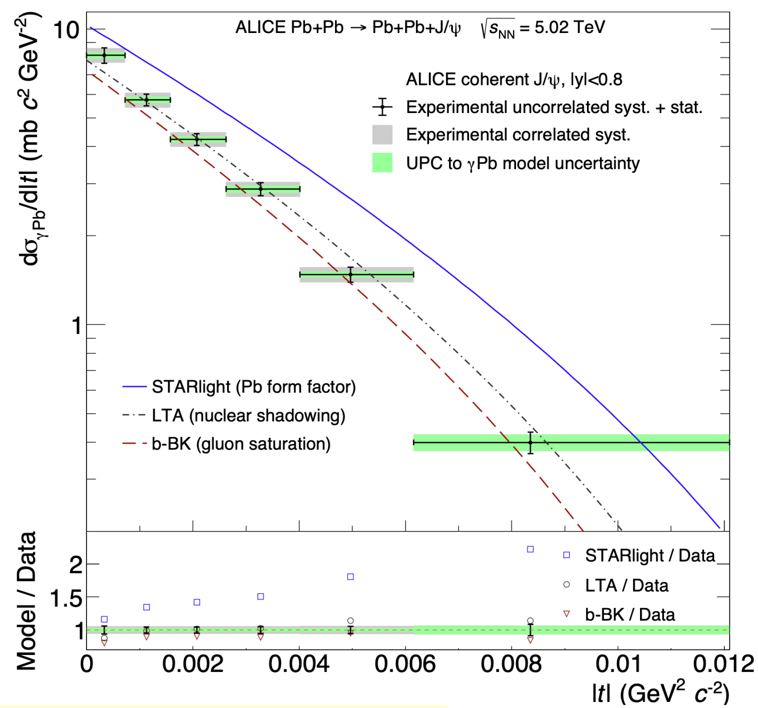




STAR, Science Adv.abq3903 (2022)

Nuclear shadowing & shape changes

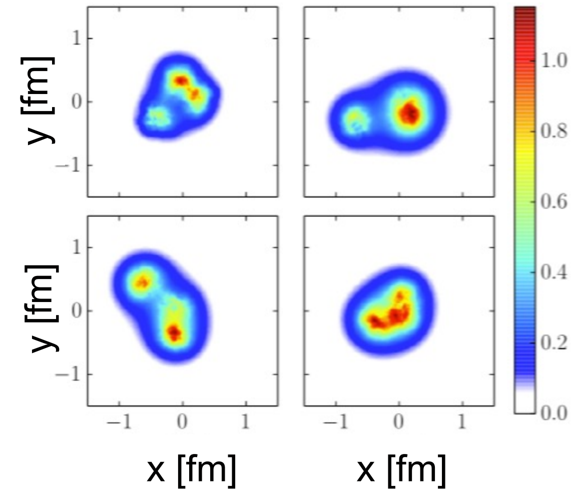
- ALICE has studied dσ/dt for coherent J/ψ photoproduction
  - J/ψ is heavy enough that pQCD should be applicable
- Shape is inconsistent with a Woods-Saxon distribution
- Effective size is smaller, consistent with predictions from leading twist approximation or a saturation model

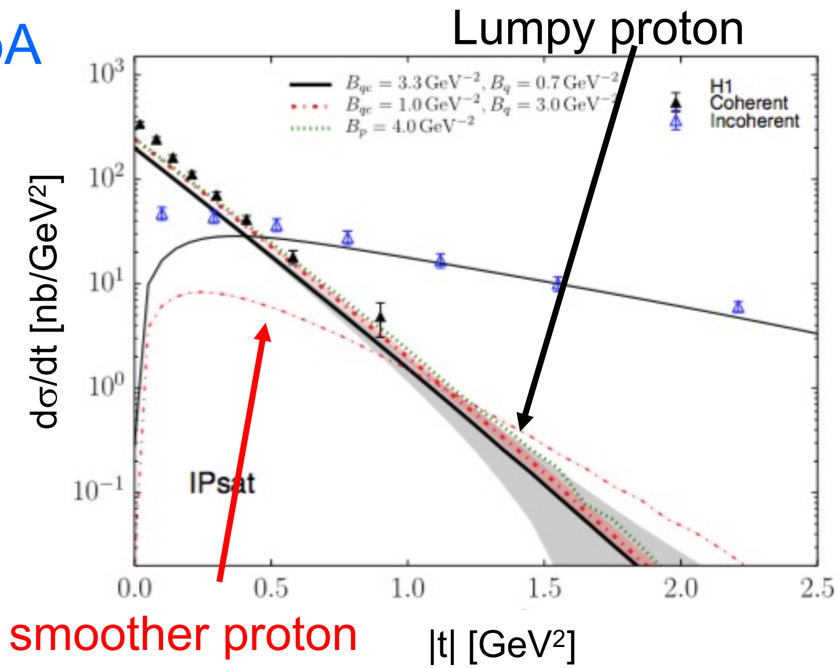


ALICE, PLB **817**, 136280 (2021)

Incoherent J/ψ photoproduction

- Probes event-by-event fluctuations in the nuclear configuration
  - Quark/gluon transverse positions
- Use Walker-Good formalism:
- HERA data on $\gamma^{*}p \rightarrow J/\psi\ p$ indicates protons are quite lumpy/stringy
  - Reproduces most v_2 & v_3 results in pA

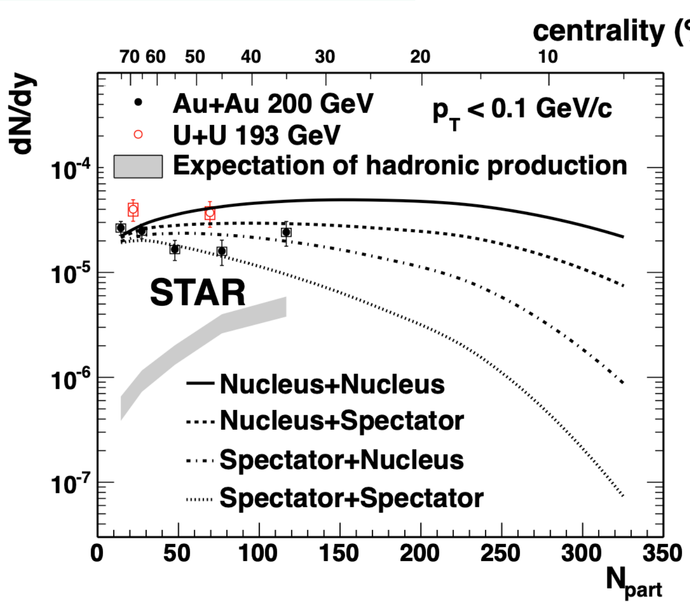


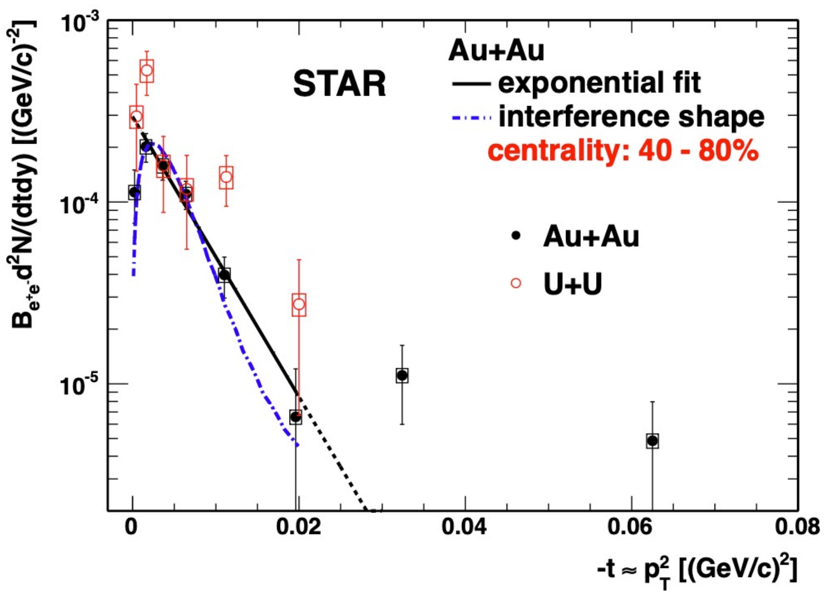


H. Mäntysaari, QM17; Mäntysaari & Schenke PRD 94, 034042 (2016)

UPCs in peripheral collisions

- Photonuclear and $\gamma\gamma$ reactions do not disappear when $b < 2R_A$
  - Rates are reduced due to lower photon flux inside nucleus
- How large is the target coherence region for J/ψ photoproduction?
  - All nucleons, or just spectators?
    - Data mildly supports non-participation of participants
      - Participants may lose energy before interacting, reducing σ
- Interference at larger p_T since b is small
- Apparent nuclear size unchanged (i. e. including participants?)

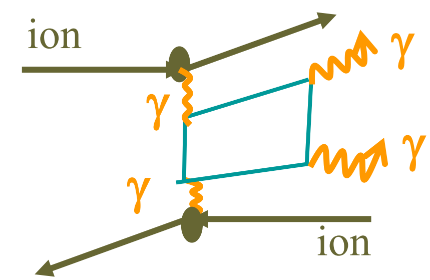


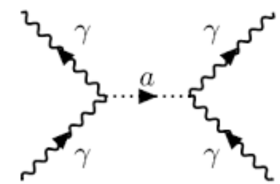


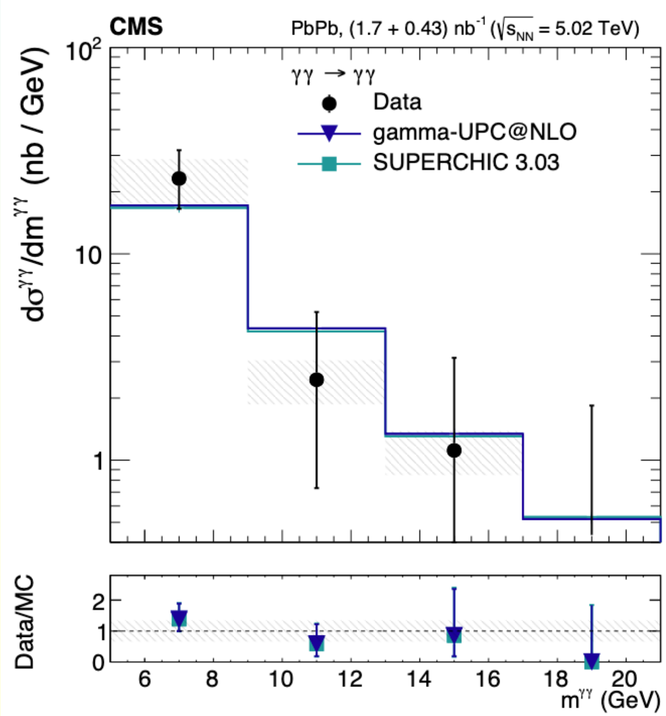
ALICE, arXiv:2409.11940; STAR, PRL 123, 132302 (2019)

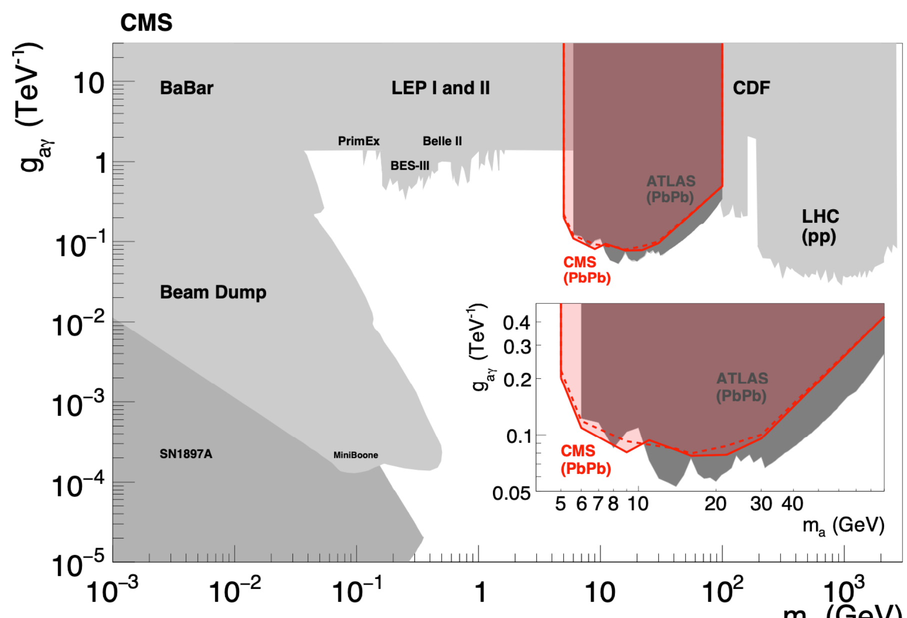
γγ->γγ and beyond the standard model

- Two main channels
  - Box diagram – all charged particles
    - Including BSM particles
    - Cross-section in agreement with Standard Model
  - Via axion-like particle resonance
    - Peak at $M_{\gamma\gamma}$ = Ma
    - Limits set by CMS and ATLAS





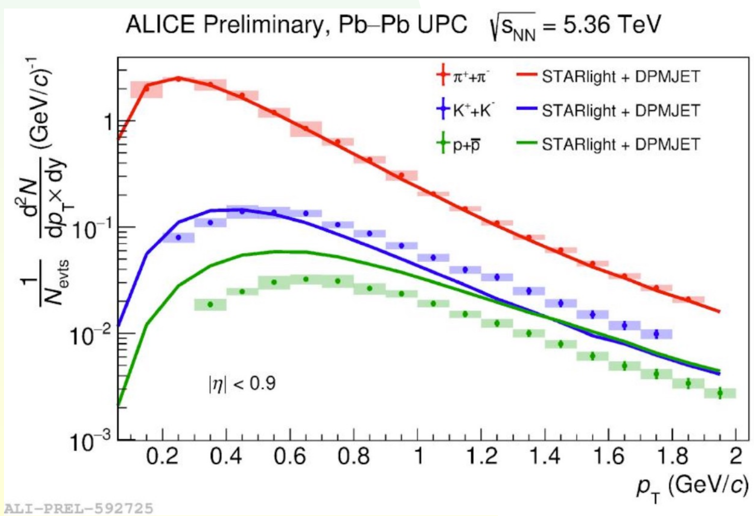


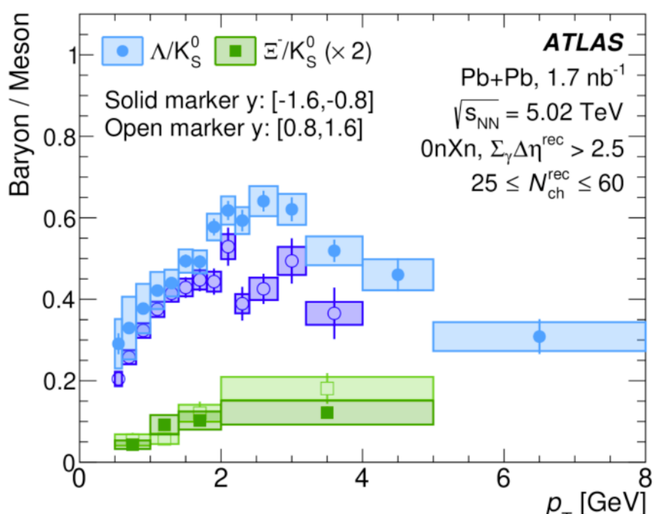


CMS, arXiv:2412.15413

γA Collisions as a small system

- QGP-like behavior has been observed in small systems where it was not expected: pA and high multiplicity pp
- γA collisions are another small system
- $\pi^{\pm}$ spectra agree with DPMJET simulations.
  - Some strangeness enhancement
- Baryon enhancement at intermediate p_T
- Similar to other small systems



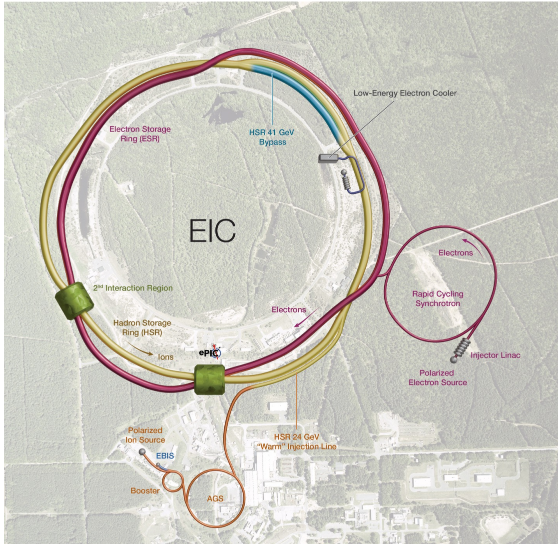


ALICE Quark Matter 2025, ATLAS arXiv:2503.08181

Looking ahead

- LHC Run 3 brings many detector upgrades
  - ALICE streaming DAQ eliminates trigger bottleneck
    - Light meson samples 100 times larger than currently analyzed
  - LHCb and the ALICE FoCal (LHC Run 4) will expand forward coverage and provide data down to $x < 10^{-5}$
- Expect solid (single-gluon) parton distributions down to $x<10^{-4-5}$
  - Over a wide range of Q^2 to map out saturation as $f(Q^2)$
- Vector meson studies will probe shape modifications due to shadowing, and probe partonic fluctuations
  - Key for saturation studies
- In ~ 2035, the new ALICE 3 detector will provide full coverage out to coverage to $|\eta|<4$ at low p_T
- Oxygen running at RHIC and LHC probes another intermediate-sized nuclei
- Longer term, the proposed fcc could reach Bjorken-x ~10^{-7}

UPCs & the Electron Ion Collider



- The Electron-Ion collider is an ep/eA collider being built at Brookhaven National Laboratory
- Both UPCs and the EIC use photons to probe protons/nuclei

	UPCs	Electron-Ion Collider
$W_{\gamma p}$ (max)	3 TeV	140 GeV
$W_{\gamma N}$ (max) Heavy Ion	700 GeV	100 GeV
Photon Q^2	Real only	Real + Virtual
Polarization	Linearly polarized photons	Electrons, protons, light ions
Ion targets	p, Pb, Au, Xe, O	Wide range of nuclei, including d, t, other light ions
Usage	1 month/yr at CERN	Dedicated, will run many nuclei

Complementary techniques: the EIC will offer far more precision, but UPCs have a larger reach in energy (or in Bjorken-x)

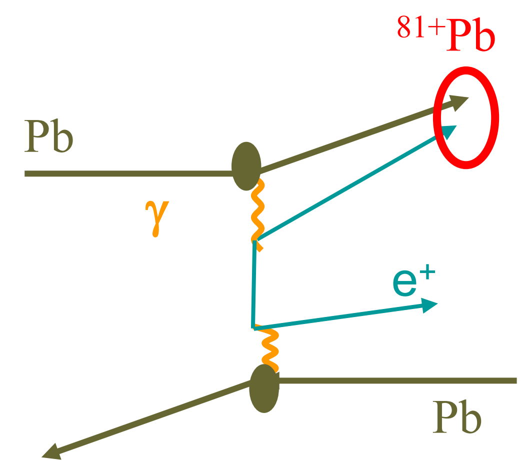
Conclusions

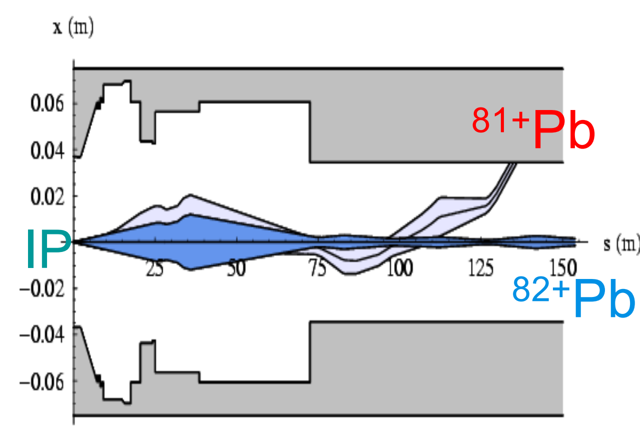
- UPCs are the energy frontier for electromagnetic interactions.
- Measurements of $\gamma\gamma$-> ll agree well with LO QED calculations, proving that UPCs can make precise measurements.
- Photoproduction of dijets and open charm probe gluon shadowing in heavy nuclei. Dijet data appears to be slightly below current nuclear parton distribution predictions.
- $\sigma(\gamma p \to J/\psi p)$ is close to a power-law, without clear evidence of saturation. Comparisons of coherent and incoherent J/ψ production prefer a lumpy proton over a smooth one.
- $\sigma(\gamma Pb \to J/\psi\ Pb)$ and $\sigma(\gamma Pb \to \psi'\ Pb)$ exhibit shadowing, at/below the leading-twist predictions.
- Light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) has been observed, and limits set on axion production.
- The small systems formed in γA interactions behave similarly to other systems with similar multiplicities.
- In the near future, we expect very large data sets for a variety of uses.

Backup

UPCs and LHC luminosity

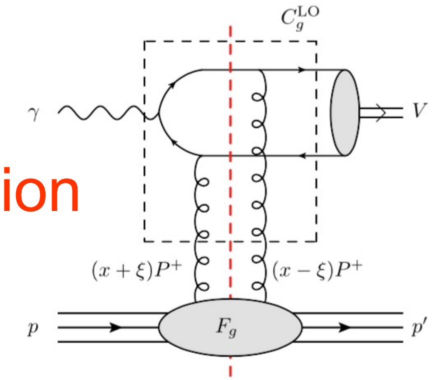
- σ[PbPb(γγ) -> (Pbe$^-$) Pb e$^+$] ~ 280 b @ LHC
- Single-electron lead has charge:mass ratio reduced by 1/82
- The (Pbe$^-$) beam strikes the beampipe 135 m downstream from the magnet
  - At L = 10^{27}/cm^2/s, the beam deposits 23 Watts
- LHC magnet quench from BFPP demonstrated!
  - $L_{max}=2.3*10^{27}$/cm^2/s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





J. Jowett *et al.*, IPAC 2016

The dipole approach



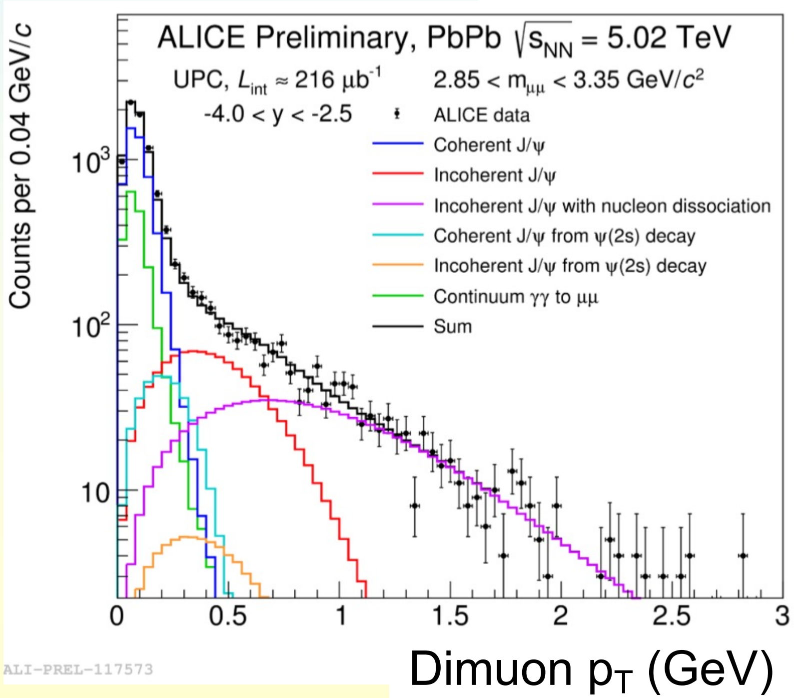
- Needed to incorporate transverse size into calculation
- Start with basics: $\sigma = |<\Psi_\gamma|M|\Psi_V>|^2$
- Treat the $q\bar{q}$ pair as a dipole with size r
  - Need VM and photon wave functions, matrix element as f(r)
  - $\sigma \sim r^2$; r scales with 1/Q, but relationship is not simple
  - Different matrix elements for different nuclear models
    - pQCD, shadowing, colored glass condensate, etc.

$$A(K,\Omega) = 2\mathrm{i}\int \mathrm{d}^2\mathbf{r}_T \frac{\mathrm{d}z}{4\pi} \mathrm{d}^2\mathbf{b}_T e^{-i\mathbf{b}_T\cdot\mathbf{k}_T/\hbar} \times \Psi^*(\mathbf{r}_T, z, Q^2)\Psi_V(\mathbf{r}_T, z, Q^2)N_\Omega(\mathbf{r}_T, \mathbf{b}_T)$$

- Dipole approach allows impact-parameter dependent calculations
  - Can calculate $d\sigma/dt$ for different nuclear conditions
    - Different effective target shapes at different x,Q^2

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 $\pi^+\pi^-$

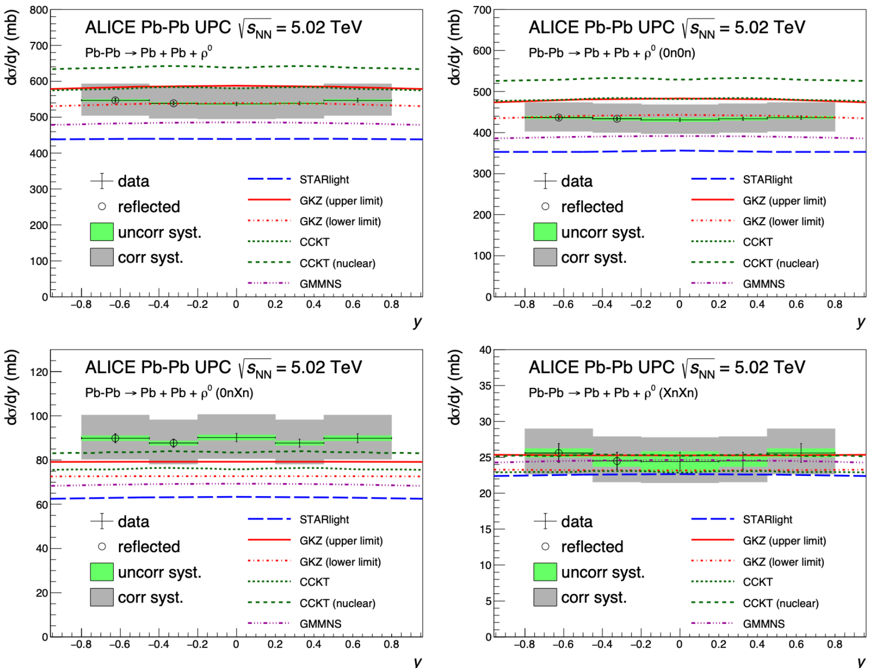


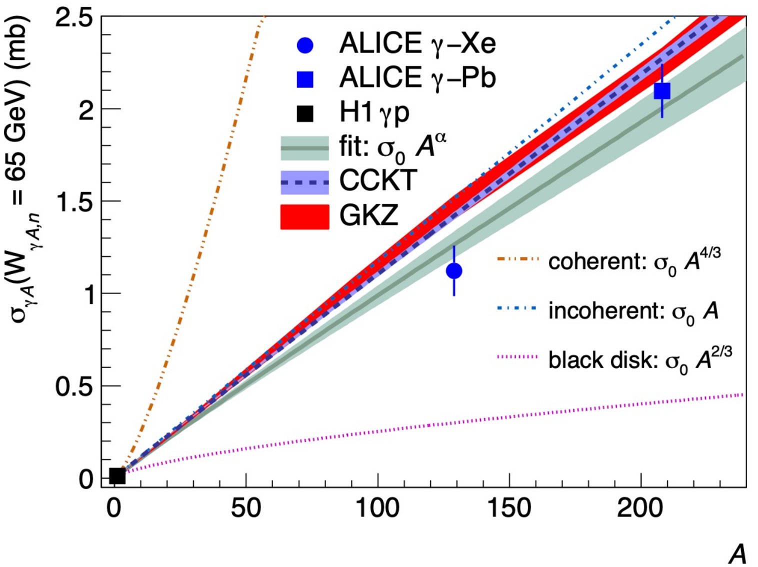
E. Kryshen [ALICE], QM17

J/ψ rapidity

ALICE coherent ρ^0 cross-section

- $|y|<0.5$
  - σ below colored dipole model
  - σ below generalized VDM model
    - With nuclear shadowing correction
  - σ in agreement with STARlight
- Consistent results for events with and without neutrons
  - Factorization works!
  - Photon emission is independent
- Xe data shows $\sigma \sim A^{0.96 \pm 0.02}$



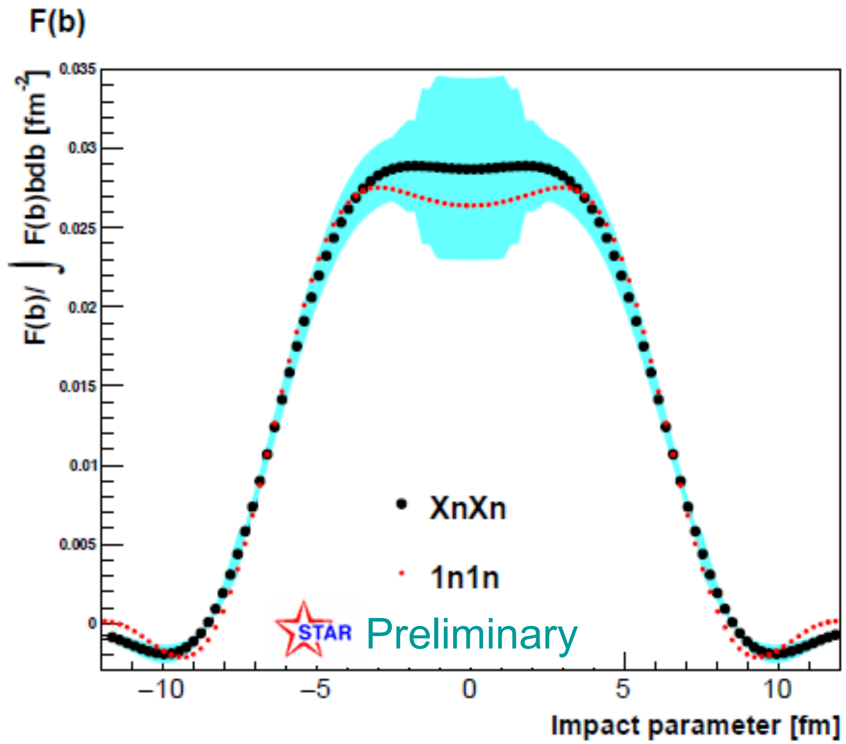


ALICE] **JHEP** 06 (2020) 035; Phys.Lett.B **820** (2021) 136

"Imaging" the nucleus

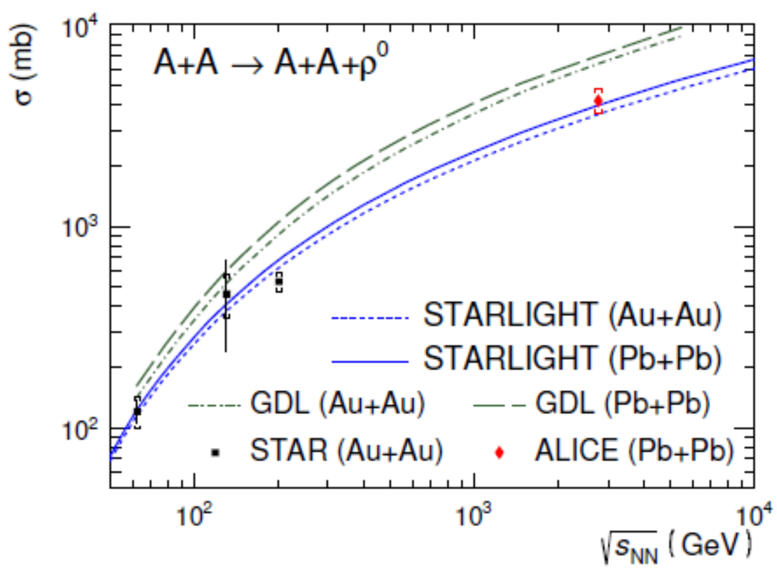
- Target (gluons?) density is the Fourier transform of $d\sigma/dt$
  - $|t|_{max} = 0.06\ GeV^2$
- 2-d Fourier (Hanckel) tranform
  - Targets, integrated over z
  - 2-d avoids 2-fold ambiguity
- Blue band shows effect of varying $|t|_{max}$ from 0.05 - 0.09 GeV^2
  - Variation at small |b| may be due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

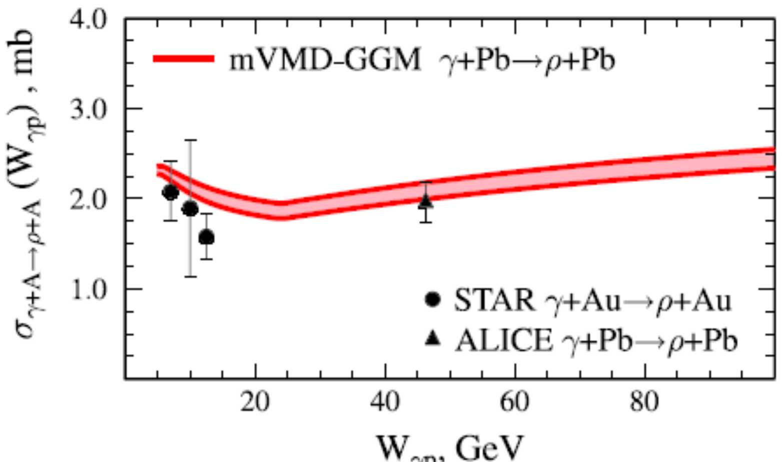
$$F(b) \propto \frac{1}{2\pi}\int_0^\infty dp_T\, p_T\, J_0(bp_T)\sqrt{\frac{d\sigma}{dt}}$$



ρ^0 cross-section

- Cross-section is convolution of Weizsacker-Williams photon flux with $\sigma(\gamma A \to VA)$
  - Calculate $\sigma(\gamma A \to VA)$ 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

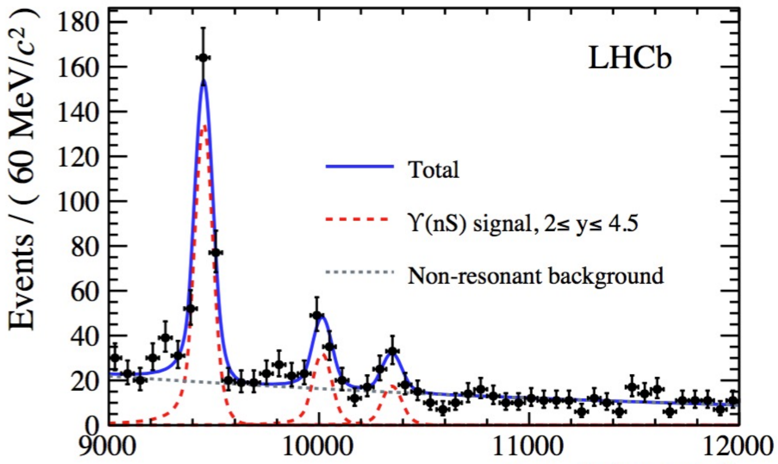




L. Frankfurt *et al.*, Phys.Lett. **B752** 51 (2016)

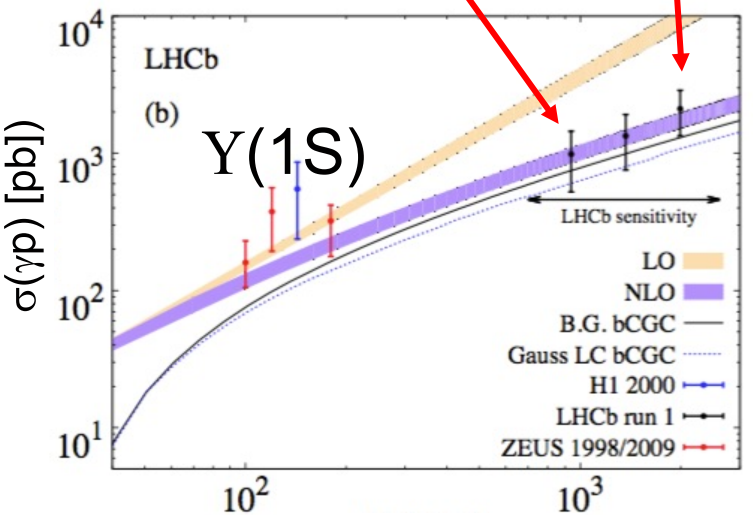
γp->Υp

Forward dimuons with LHCb



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

$x=1*10^{-4}$ $x=2.4*10^{-5}$



$W_{\gamma p}$ (GeV)

Υ(1S), Υ(2S) & Υ(3S) resolved

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

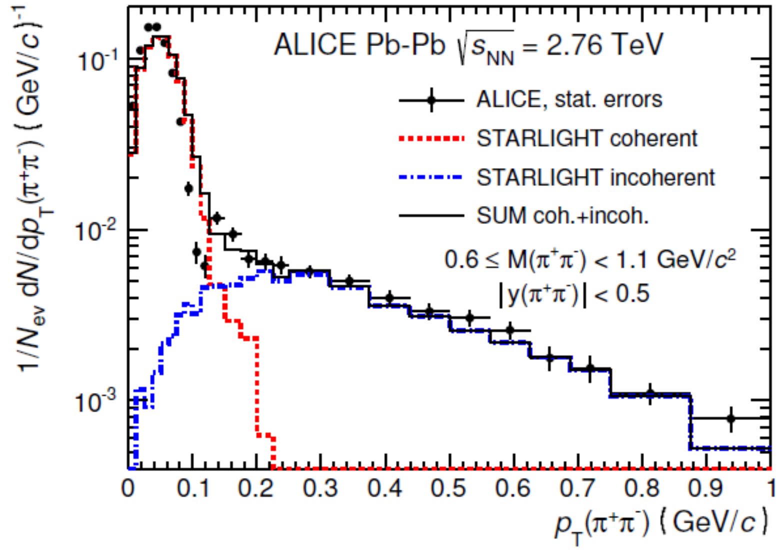
Higher Q^2-> less sensitivity to some theoretical uncertainties

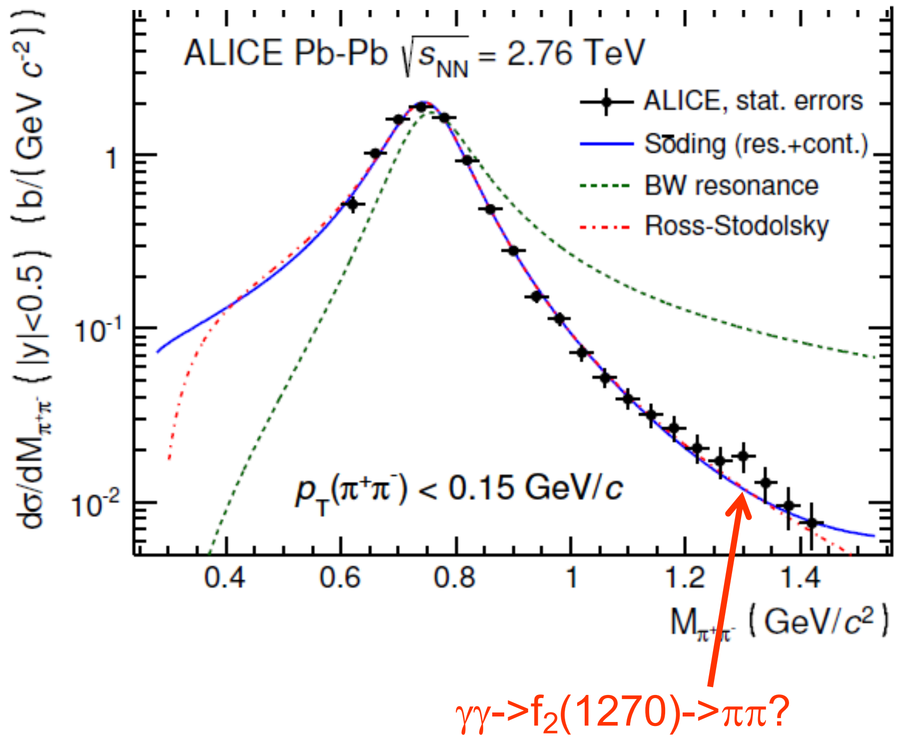
Same calculations match J/Ψ & Υ data, at different Q^2

No evidence for saturation at low Q^2

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