Imaging the gluons in a nucleus using high-energy photons

Spencer Klein, LBNL

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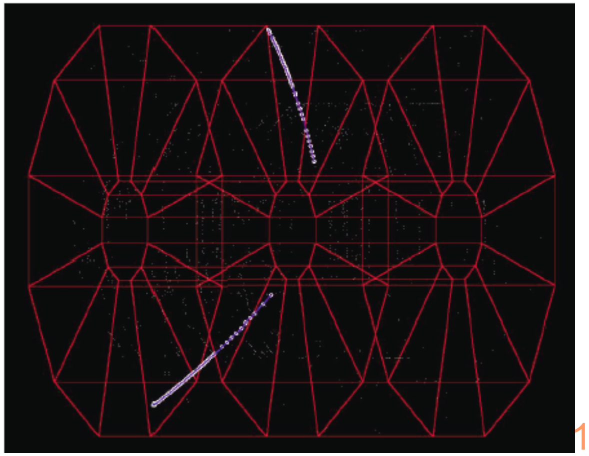
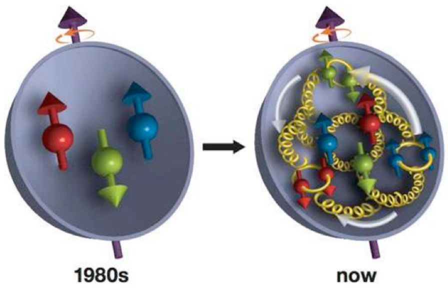
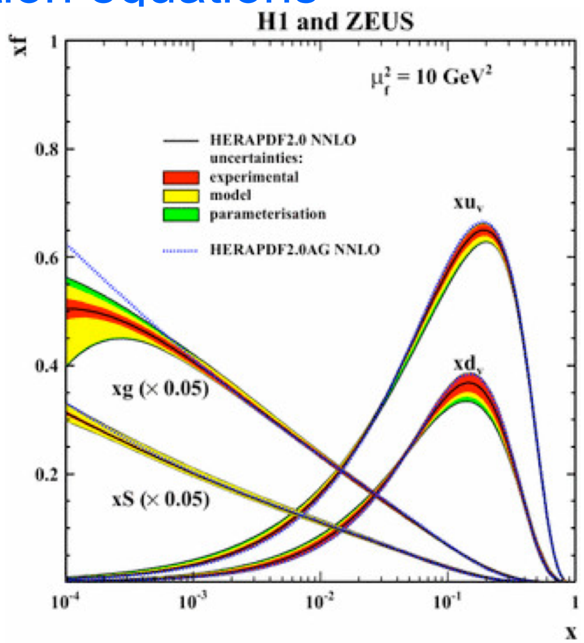
- Quarks and gluons in nuclear matter
- Photonic probes of nuclei
- Ultra-peripheral collisions at RHIC and the LHC
- Measuring gluon densities
- Imaging and gluon spatial distributions
- The Electron-Ion Collider
- Conclusions



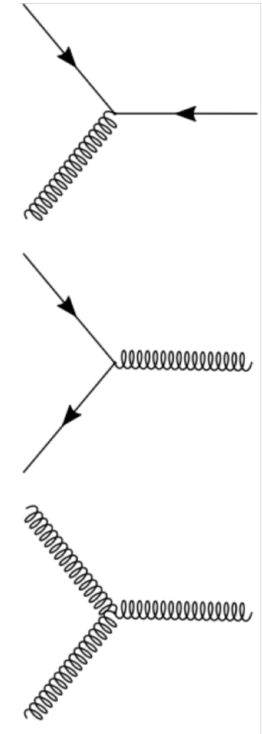
Quarks and gluons in protons

- Simple proton = 3 valence quarks
  - Surprisingly accurate – explains proton spin
- 3 valence quarks + gluons + sea quarks
- Parton distributions are quantified by
  - Bjorken-x: Fraction of proton energy carried by parton
    - In infinite energy frame
  - Q^2: Characteristic of probe – a measure of microscope power
- At lower x or higher Q^2, more partons are visible
  - Governed by evolution equations

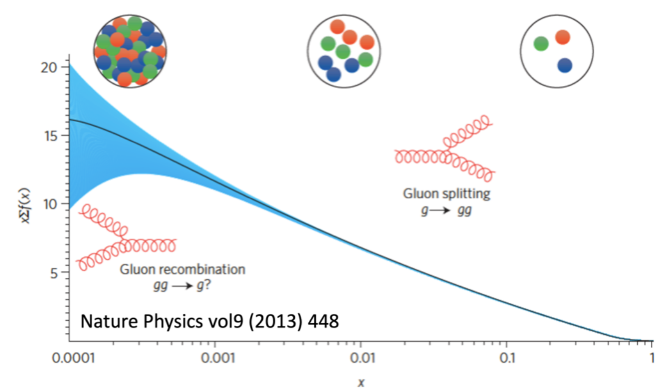




Quarks and gluons at high densities

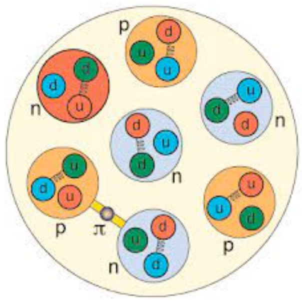


- Parton densities rise due to splitting
- At high densities, parton recombination is also possible
- At high enough densities, the rates of splitting and recombination will be equal
  - Equilibrium, known as saturation
- Other phenomena may be possible
  - Colored glass condensate – a classical gluon field
    - Originally predicted new phenomena, such as monojets in heavy-ion collisions
    - Now is mostly considered a calculational tool
- Understanding high-density partonic matter is a key goal of nuclear physics
  - “Cold nuclear matter”
  - Background to understanding signatures of the quark gluon plasma

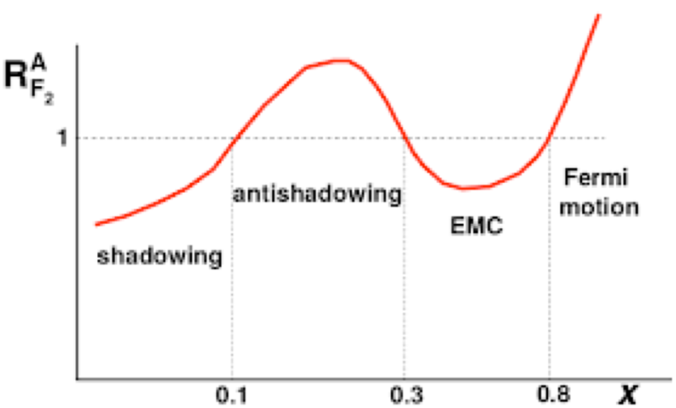


Quarks and gluons in nuclei

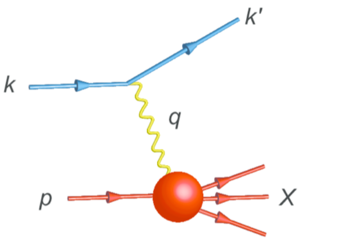
- Nucleons interact via π exchange
  - Nucleons may also interact via parton exchange
- Parton distributions are altered when an isolated nucleon is placed in a nucleus, adjacent to other nucleons
  - Quantified by changes in parton distributions



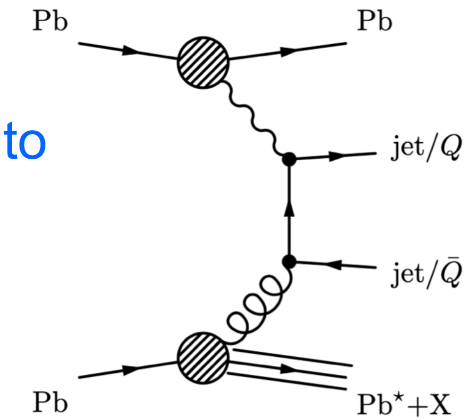
- Different phenomena in different Bjorken-x ranges
  - Fermi motion of nucleons in nuclei
  - "EMC effect," likely due to nucleon-nucleon correlations
  - Shadowing gluon recombination
  - Antishadowing – pileup
- With the higher density, nuclei are more likely to exhibit high-density phenomena, like saturation
  - Phenomena emerge at larger Bjorken-x
  - Increase is by "Oomph factor" ~ $A^{1/3}$ ~
    - 6 for gold/lead

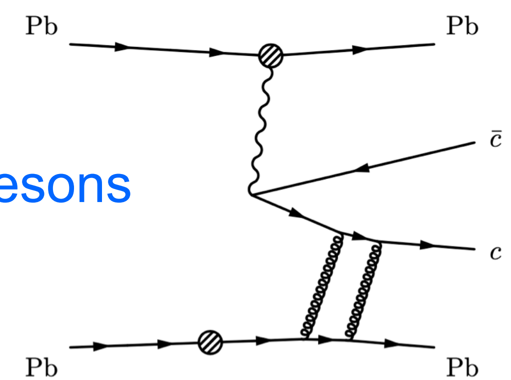


Measuring gluon distributions



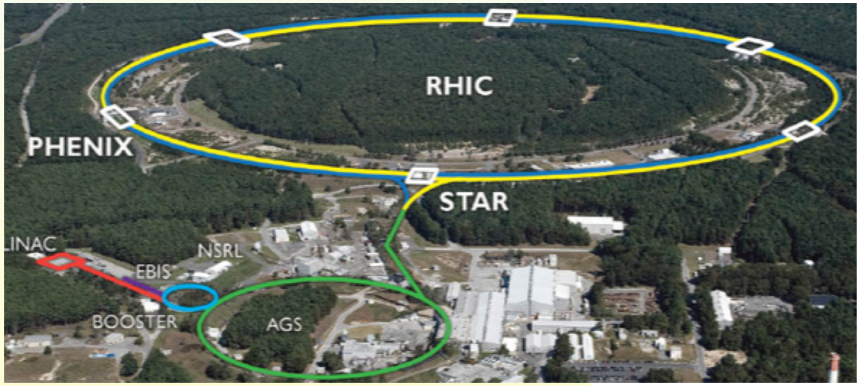
- In Deep Inelastic Scattering, an emits a virtual photon which interacts with the nucleus
  - Sensitive to quark distributions in nucleus
  - x and Q^2 determined from scattered electron
  - y = inelasticity=fraction of electron energy transferred to hadrons
- Gluons may be inferred from evolution of quark distributions
  - How does the quark density change with x or Q^2?
- Direct measurements are highly desirable
  - Reactions that proceed via gluons
  - Photoproduction of dijets, open charm, or vector mesons
    - Single gluon exchange, but experimentally harder
  - Photoproduction of vector mesons
    - Experimentally simple, but theoretical complications





Photoproduction in ultra-peripheral collisions

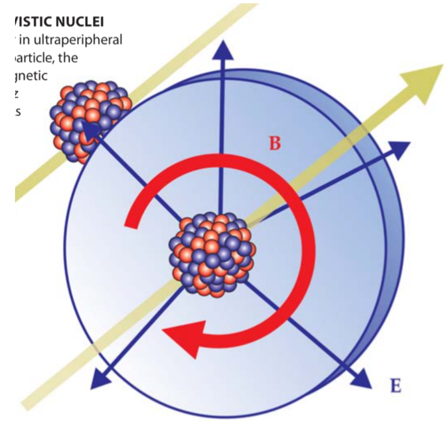
- Ultra-peripheral collisions (UPCs) occur when $b>\sim 2R_A$, so there are no hadronic interactions
  - Must account for $b>2R_A$ when computing photon-nucleus luminosity
- Photons are nearly real ($Q^2 \sim 0$)
  - Hard scale (Q^2) comes from final state
    - e. g. for J/ψ $Q^2 \sim (M_V/2)^2$
- Two-photon reactions are also studied (e. g. $\gamma\gamma \to e^+e^-$)
  - Physics + test of the photon flux calculations
- Electromagnetic interactions have also been seen accompanied by hadronic interactions



RHIC

The LHC

Photons from relativistic nuclei



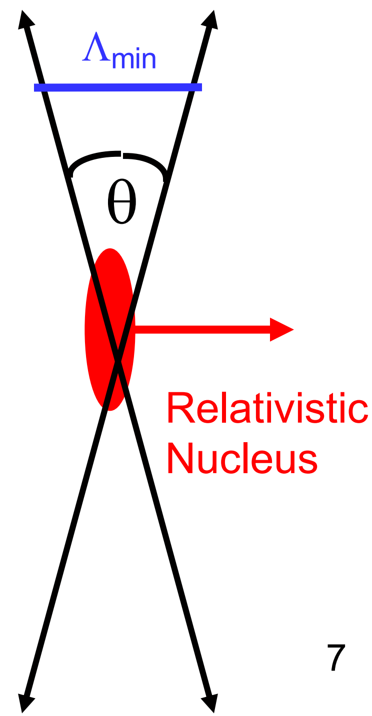
- Perpendicular E and B fields -> just like a photon field
  - Fourier transform E(x,b)-> E(k,b) and quantize
  - Equivalent photon approximation
- Pancaked E & M fields: opening angle $\theta=1/\gamma$
- $k_{max} = c/\lambda_{max} = \gamma$ hbar c/b

$$N(k,b) = \frac{Z^2\alpha k^2}{\pi^2\gamma^2\hbar^2\beta^2}\left(K_1^2(x) + \frac{K_0^2(x)}{\gamma^2}\right)$$

  - x=kb/γ hbar c
    - x<1: $N \sim K_1^2(x) \sim 1/x^2$
    - x > 1: N is exponentially suppressed
    - Note: $1/b^2$ dependence
- Integrate over d^2b: with $b>2R_A$ (no nuclear collision)

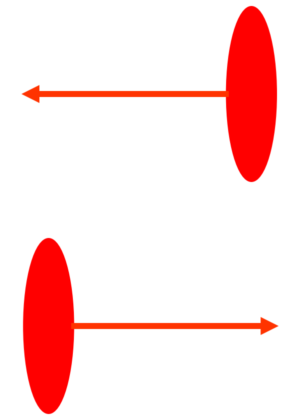
$$N(k) = \frac{Z^2\alpha k^2}{\pi^2\gamma^2\hbar^2\beta^2}\left(K_1^2(u) + \frac{K_0^2(u)}{\gamma^2}\right)$$

  - u= γ hbar c/2R_A



Fermi, Weizsacker, Williams…

UPC collision energies



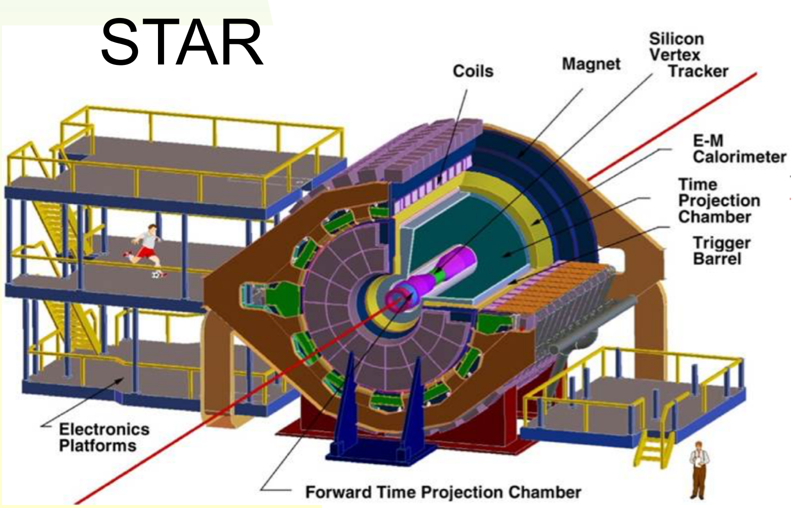
- Maximum energies depend on species
  - Energy/nucleon scales with charge/mass ratio
    - Energy/nucleon for Pb ~ $0.4 \cdot E_{proton}$
- Photon energy depends on hbar/R_A
  - Much higher energy with proton beams
- UPC cross-sections can scale as Z^4, Z^2A^2 to $Z^2A^{4/3}$
  - For lighter final states higher rates with heavy ions
- The LHC is the energy frontier for photons
  - Can reach down to Bjorken x ~ 10^{-6}

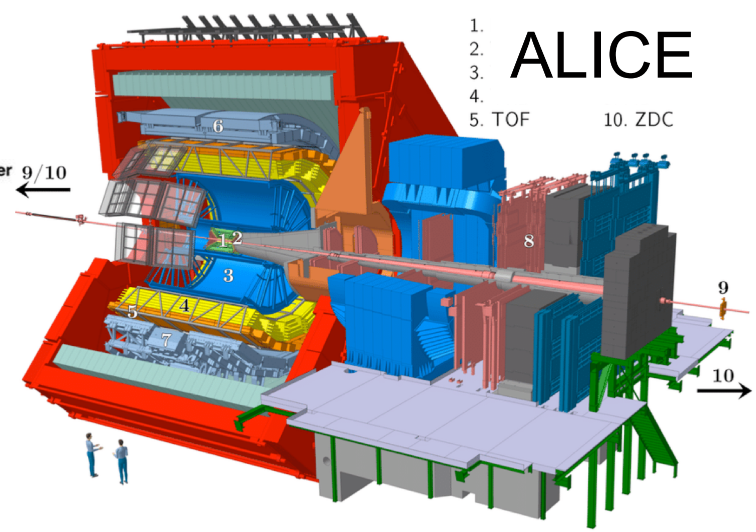
Energy	AuAu RHIC	pp RHIC	PbPb LHC	pp LHC
Photon energy (target frame)	0.6 TeV	~12 TeV	500 TeV	~5,000 TeV
CM Energy $W_{\gamma p}$	24 GeV	~80 GeV	700 GeV	~3000 GeV
Max $\gamma\gamma$ Energy	6 GeV	~100 GeV	200 GeV	~1400 GeV

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

Observing UPCs

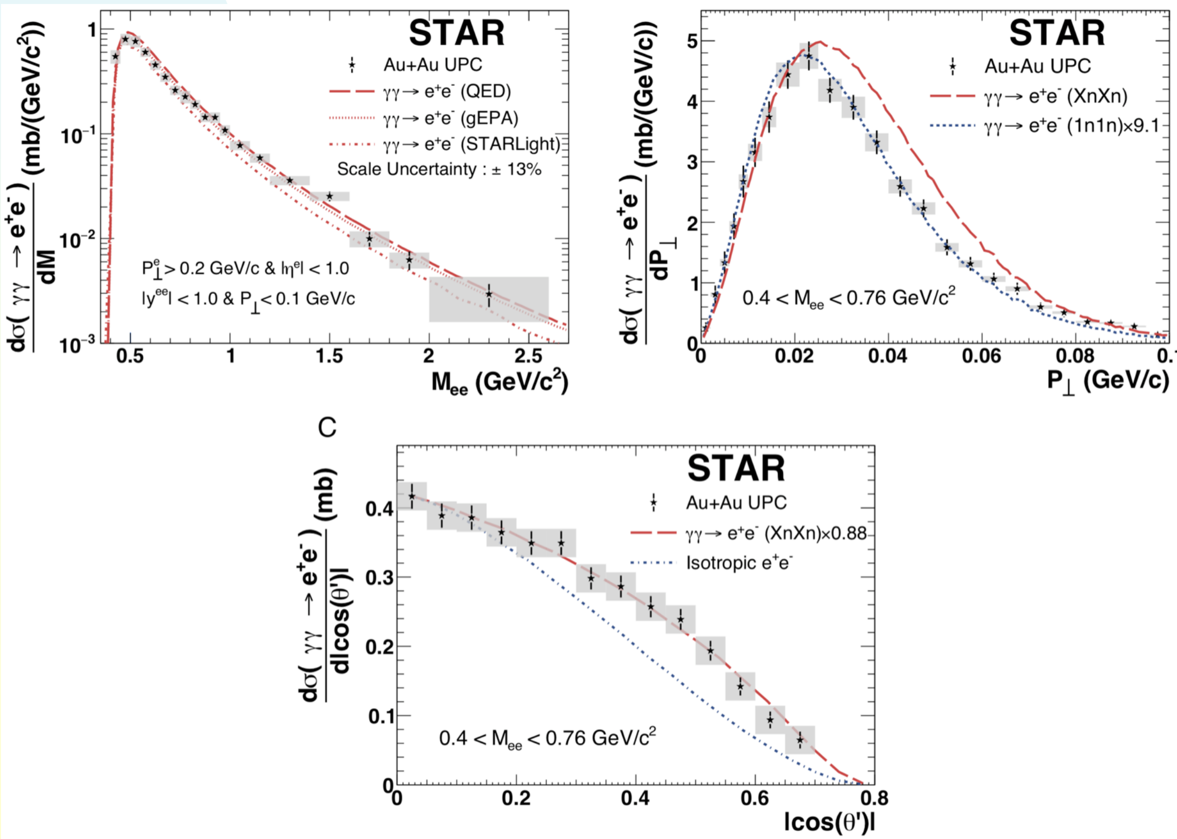
- Most studied UPC final states are simple: $J/\psi \rightarrow e^+e^-$, $\rho \rightarrow \pi^+\pi^-$, etc.
- Need to see these charged particles + ”Nothing else”
  - “Nothing else” requires large angular acceptance, plus coverage down to small-ish (~100 MeV/c) transverse momentum (p_T)
    - Hermeticity, down to low p_T
  - Constraint: $\Sigma p_T < 100$ MeV/c reduces backgrounds
- Triggering is one of the main challenges in UPCs
- The nuclei may also dissociate, via additional photon exchange
  - Need zero degree calorimeters to detect neutrons from breakup
- All 4 LHC detectors, plus STAR and PHENIX at RHIC have studied UPCs





STAR γγ->ee

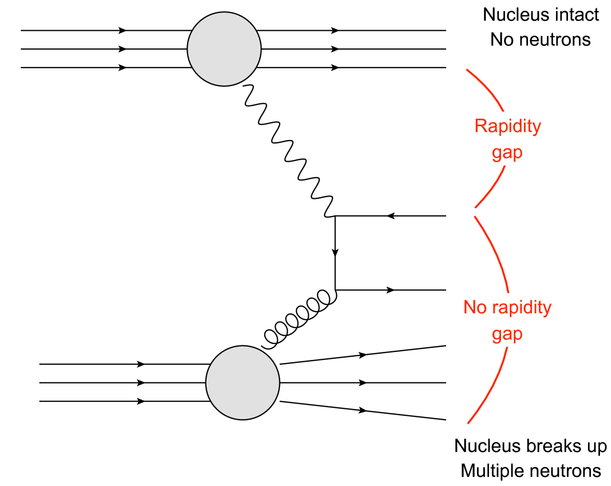
- Excellent test of equivalent photon paradigm
- Good agreement with STARlight Monte Carlo
  - STARlight == Monte Carlo w/ Equivalent Photon approx.
    - Photons are real, not virtual (no mass, but should not be important
- Except pair $\langle p_T \rangle$ is larger, likely due to limits and biasing of b



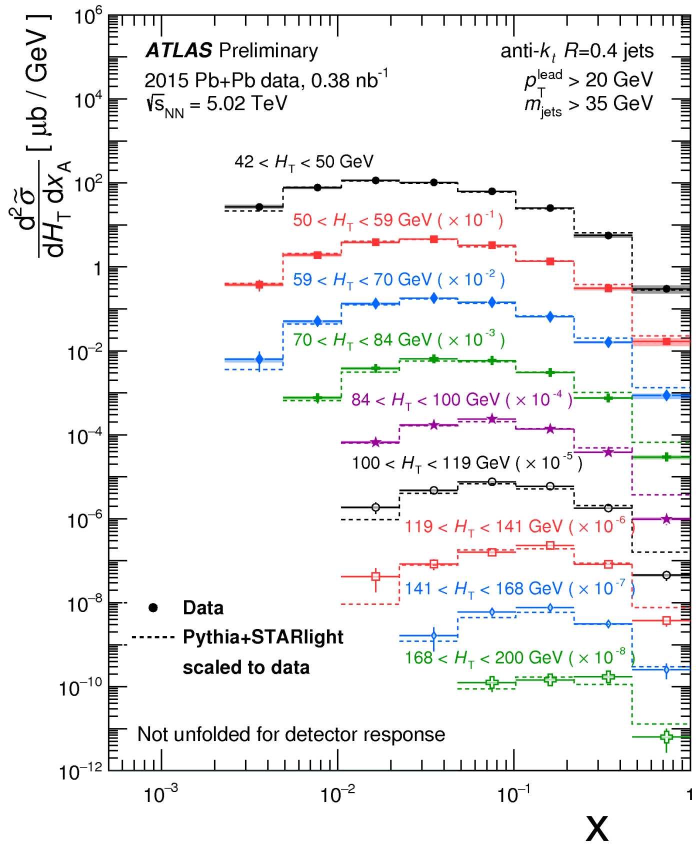
STAR, arXiv:1910.12400

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



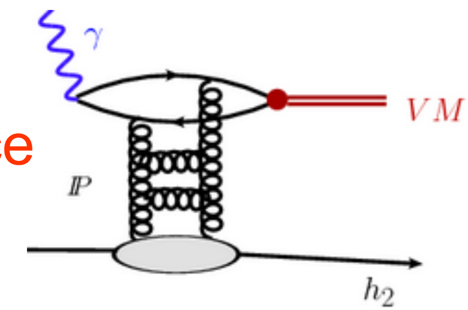
$H_T \sim 2Q$



A. Angerami [ATLAS], QM17

Exclusive vector meson photoproduction

- Occurs via colorless 'Pomeron exchange'
  - Require >=2 gluon exchange for color neutrality
    - Gluon ladder
- Light meson production via vector meson dominance
  - ρ, direct $\pi^+\pi^-$, ω, ρ'
- Heavy meson production treated with pQCD
  - J/ψ, ψ', $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$
- 3 targets, 3 coherence lengths and 3 p_T scales
  - Coherent: nucleus remains intact. $p_T < \sim hbar/R_A$ & $\sigma \sim A^2$
  - Incoherent: nucleus breaks up; protons remain intact. $p_T <\sim hbar/R_p$
  - Proton dissociation: struck proton breaks up. $p_T \sim \Lambda_{QCD} \sim 300$ MeV
- Rapidity maps into photon energy
  - $k = M_V/2\exp(\pm y)$
    - For coherent: twofold ambiguity – which nucleus emitted the photon?
  - Cross-section is sum of 2 directional cross-sections
  - γ + Odderon (3-gluon state) could lead to tensor mesons



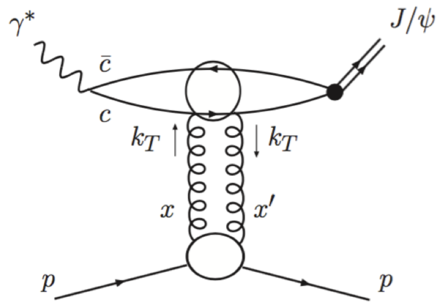
A/A*/Ax

V. Goncalves, Eur. Phys J C79, 408 (2019)

VM photoproduction in LO pQCD

- In 2-gluon model, leading order pQCD

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

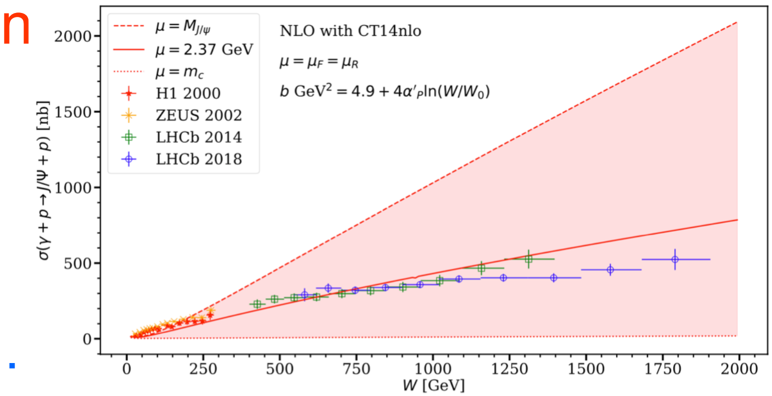


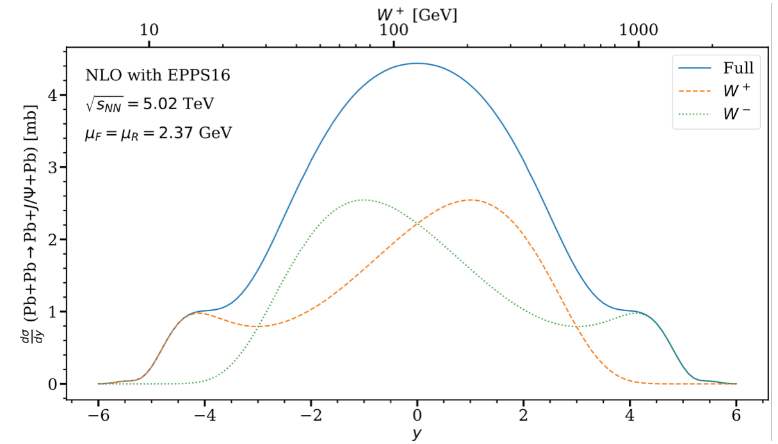
- With $\bar{Q}^2 = (Q^2 + M^2_{J/\psi})/4, \qquad x = (Q^2 + M^2_{J/\psi})/(W^2 + Q^2)$
  - Vector meson mass provides hard scale
- Some caveats
  - pQCD factorization does not strictly hold
    - Two gluons have different x values (with x' ≪ x ≪ 1)
      - Use generalized (skewed) gluon distributions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

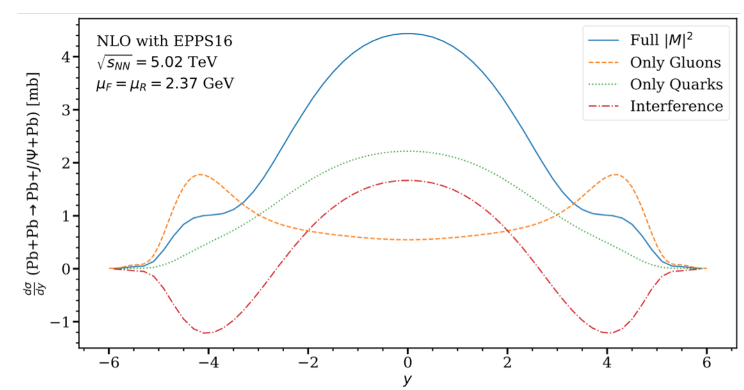
Jones, Martin, Ryskin and Teubner ("JMRT"), JHEP 1311, 085 (2013); and others

J/ψ photoproduction in NLO

- Some surprises in a new NLO calculation
- Very large scale uncertainty
  - Hope for reduction using some tricks
- σ_{NLO} ~55-70% below σ_{LO}
  - Previous LO calculations matched data…
- Multiple peaks in dσ/dy for UPCs
  - Note photon directional ambiguity
- NLO gluon contribution partly cancels LO gluon contribution
  - Quark contribution is important
- Different parton distribution fits give different results
  - Real part of gluon amplitude
- How well do uncertainties cancel when comparing proton and ion data?

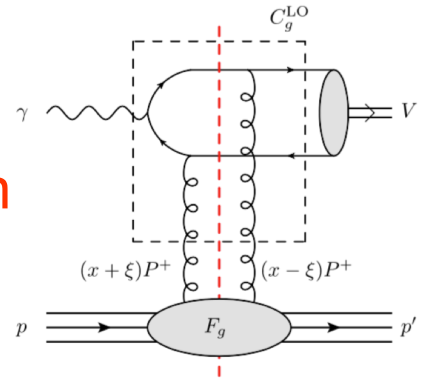






K. Eskola et al., arXiv:2203.11613

The dipole approach



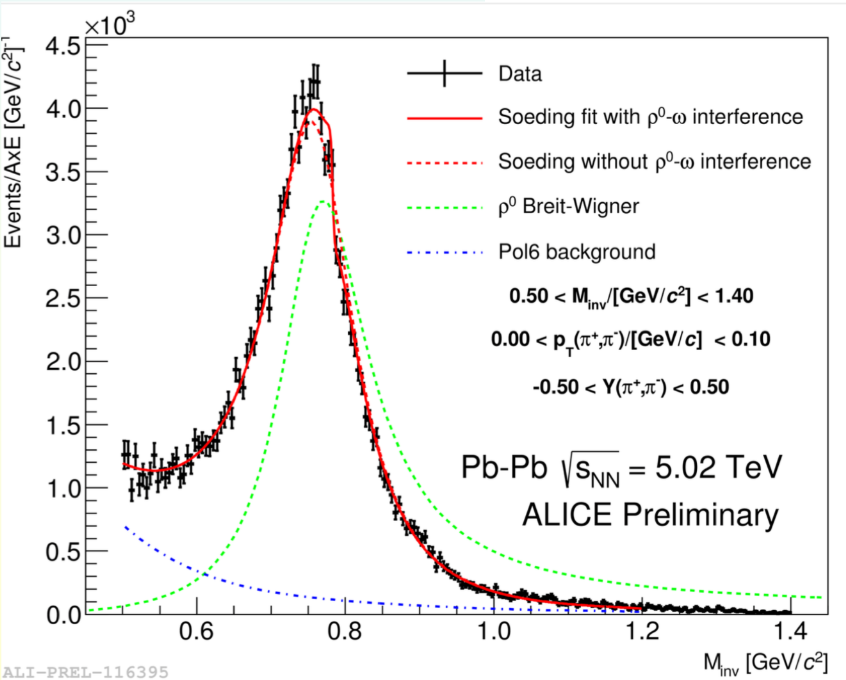
- Needed to incorporate transverse size into calculation
  - Important for nuclei
- Start with basics: $\sigma = |<\Psi_\gamma|M|\Psi_V>|^2$
- Treat the $\overline{q}q$ pair as a dipole with size r
  - Need VM and photon wave functions, matrix element as f(r)
  - $\sigma \sim r^2$; r scales with 1/Q,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

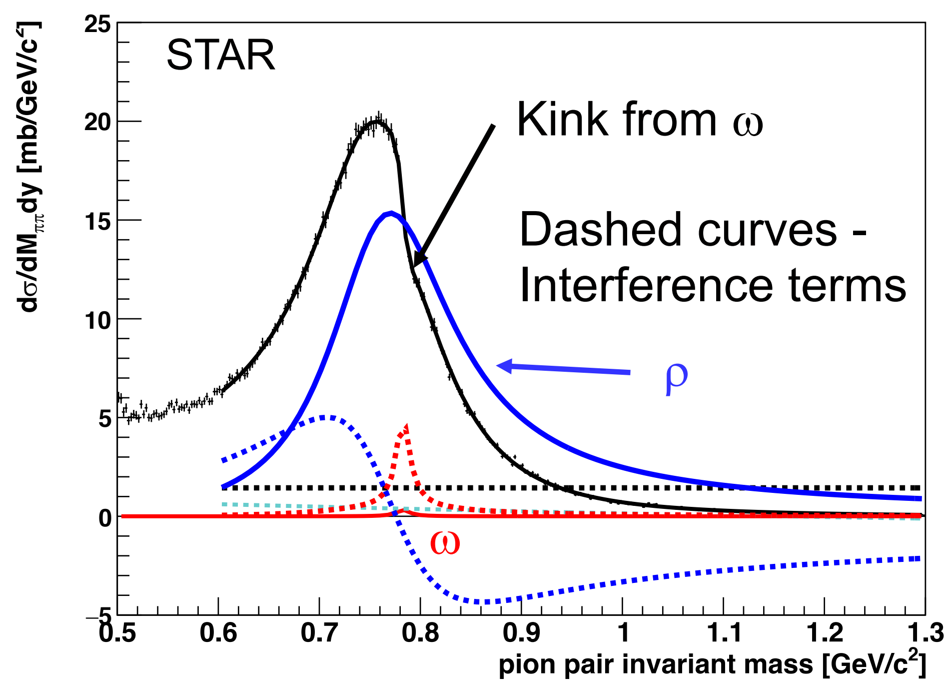
$$A(K,\Omega) = 2\mathrm{i} \int \mathrm{d}^2\mathbf{r}_T \frac{\mathrm{d}z}{4\pi} \mathrm{d}^2\mathbf{b}_T e^{-i\mathbf{b}_T\cdot\mathbf{k}_T/\hbar} \times \Psi^*(\mathbf{r}_T, z, Q^2)\Psi_V(\mathbf{r}_T, z, Q^2) N_\Omega(\mathbf{r}_T, \mathbf{b}_T)$$

- 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

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

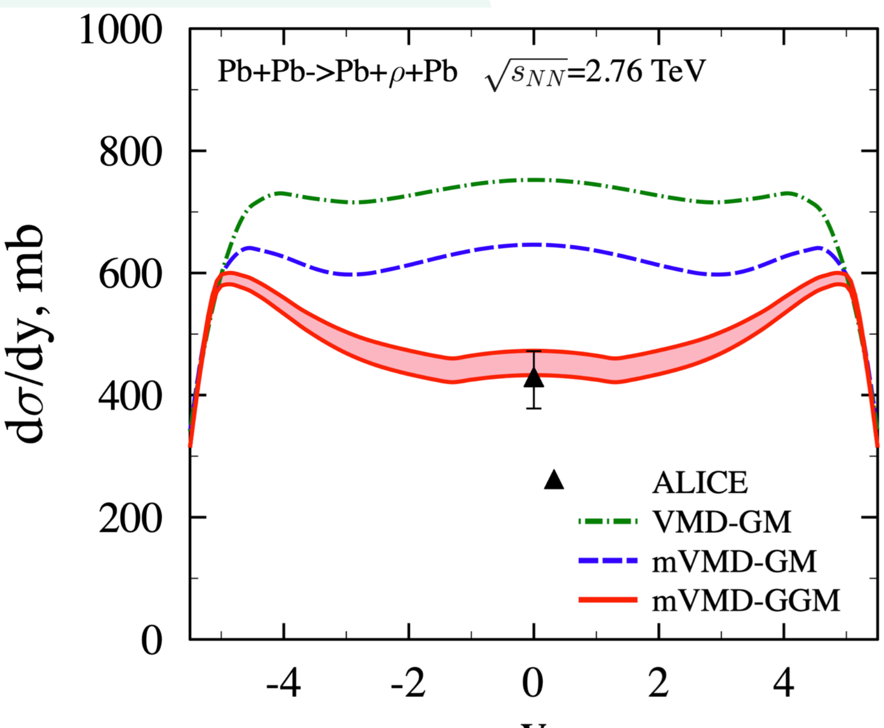




STAR: PR **C96**, 054904 (2017); ALICE: arXiv:2002.10879

Coherent ρ^0 photoproduction & 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.
  - Needed to explain the data

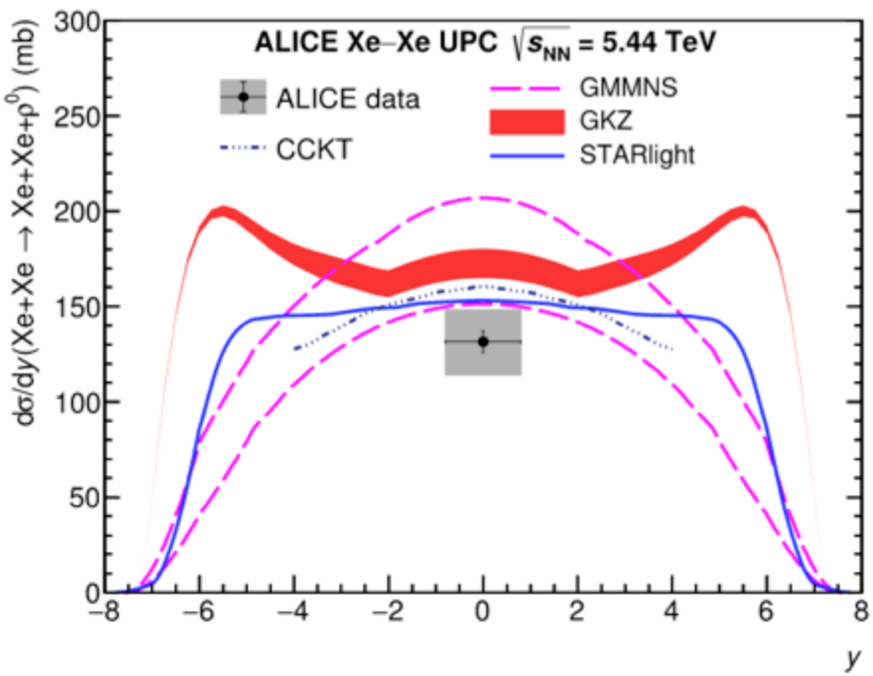


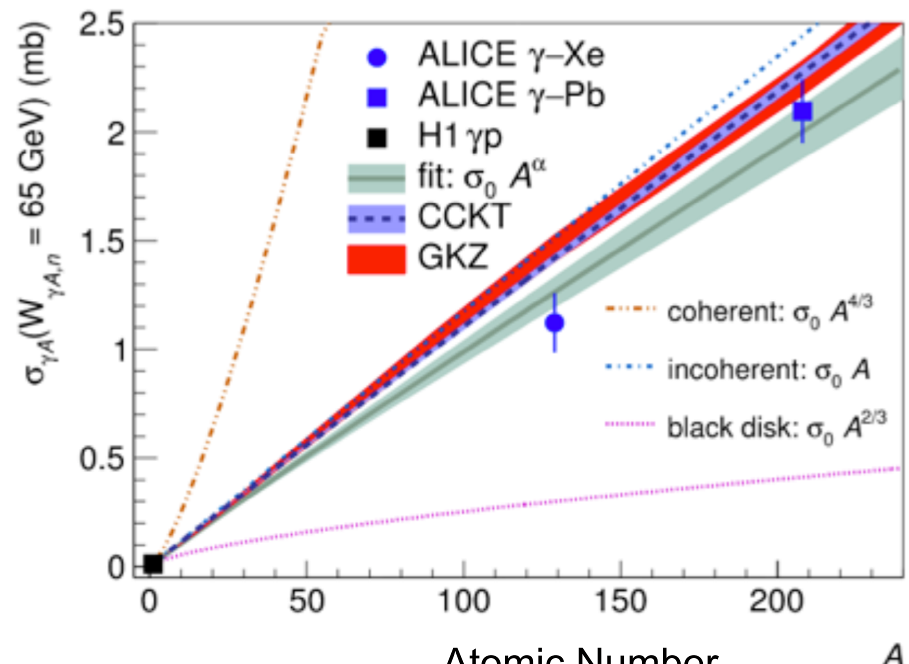
Glauber VMD
Glauber w/ Generalized VMD
Glauber-Gribov

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

ρ^0 photoproduction as a function of target

- From a 6-hour XeXe run in 2017
- Trigger, analysis similar to PbPb
- Cross-section consistent with Glauber-Gribov calculations
- From p, Xe, Pb, $\sigma \sim A^{0.96 \pm 0.02}$
  - Significant shadowing; $\sigma \sim A^{4/3}$ in absence of shadowing

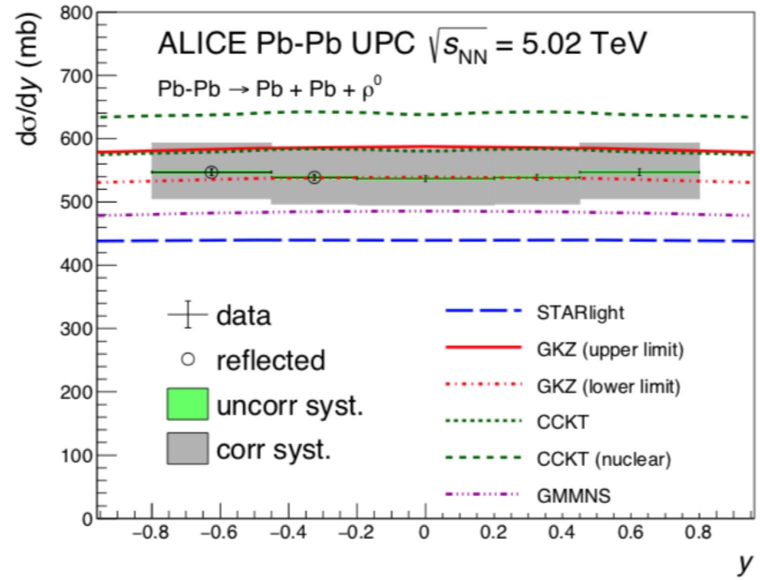


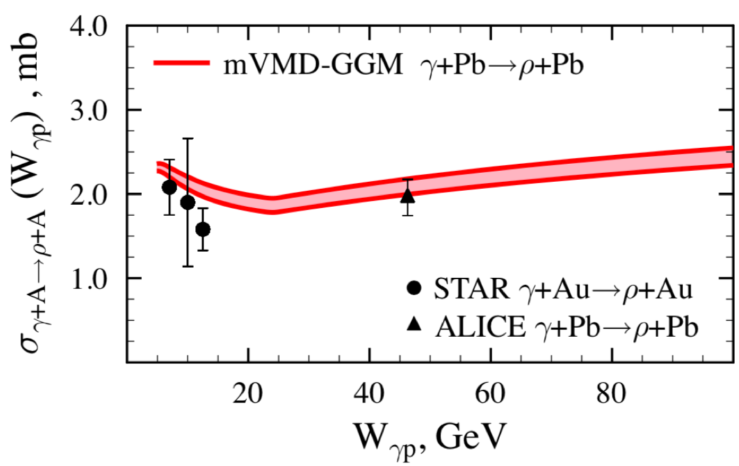


ALICE, Phys. Lett. **B820**, 136481 (2021)

ρ^0 cross-section

- M_ρ too low for pQCD
  - Use dipole or Glauber calculation, implicitly or explicitly tuned to HERA data instead
- $d\sigma/dy$ found for coherent photoproduction
  - Direct $\pi\pi$ removed
- σ above 'STARlight' prediction
  - i. e. below Glauber calculation
- σ in agreement with quantum Glauber model that includes a correction for high mass dipole fluctuations (inelastic diffraction)
  - Fluctuations matter





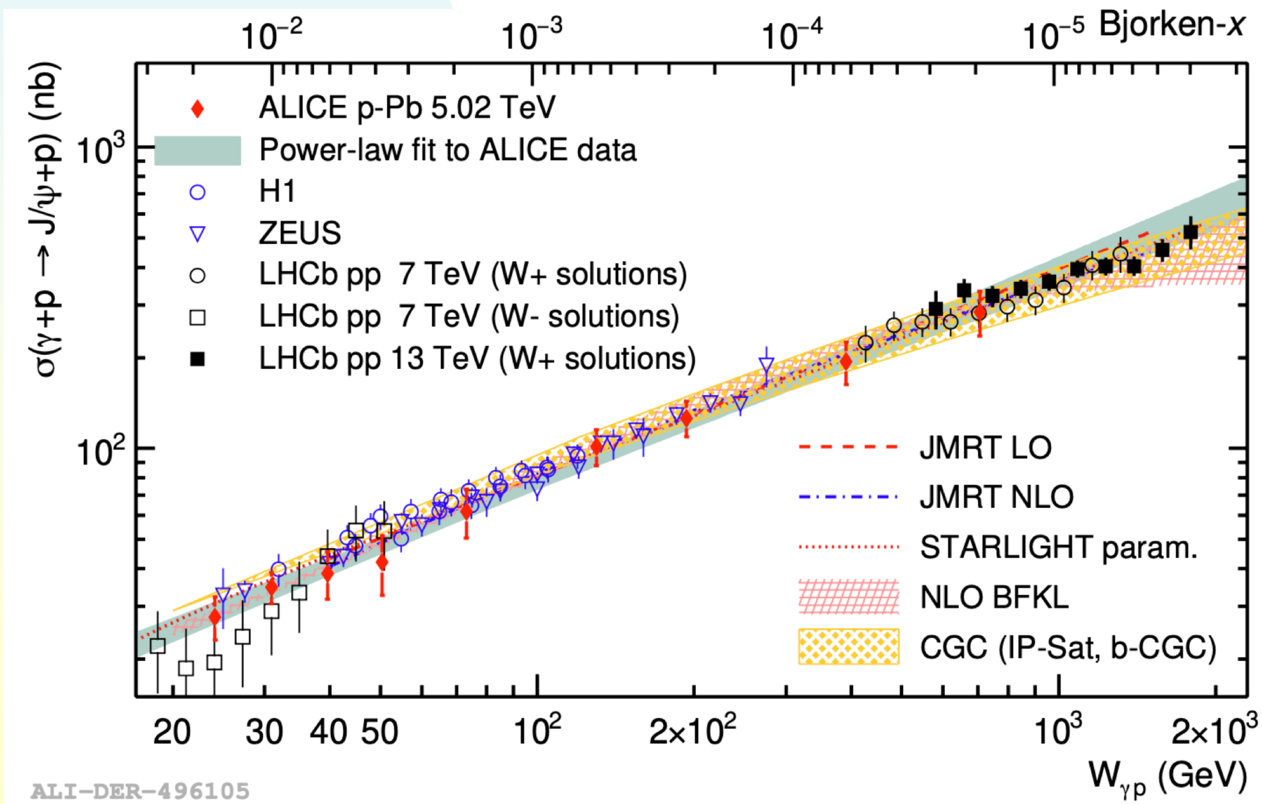
ALICE: arXiv:2002.10879; L. Frankfurt et al., Phys. Lett. B752, 51 (2016)

Heavy quarkonium photoproduction on ion targets

- There is no HERA data with ion targets, so we know little about parton distributions for $x<10^{-3}$
  - Some data from LHC pA/AA interactions
- Probe for nuclear gluon distributions for $x<10^{-3}$ at $Q^2 = (M_{VM}/2)^2$
- Usually measure/calculate suppression relative to proton targets
  - Many theoretical uncertainties cancel
- Impulse approximation calculation sometimes used as reference
  - Treats target as a collection of independent nucleons
  - Replaces missing proton data at correct $\sqrt{s}$
- Shadowing is expected, because a single $q\bar{q}$ dipole may interact with multiple nucleons in a heavy target
  - "Leading twist" shadowing - multiple scattering
    - Nuclear shadowing
  - Gluon shadowing would appear as an additional suppression

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

- Map rapidity to photon energy, with a 2-fold ambiguity $k = M_V/2 \exp(\pm y)$
- Data up to $W_{\gamma p}$ = 1.5 TeV - 5 times the HERA maximum
  - Fairly close to a power law, with possible slight downturn
    - Expected in lowest order as long as $g(x) \sim x^{-4\Lambda}$
- ALICE: In pA collisions, proton is usually target
- LHCb: 2-fold photon direction ambiguity; use HERA data to unfold



NLO calculation is older, only partial NLO

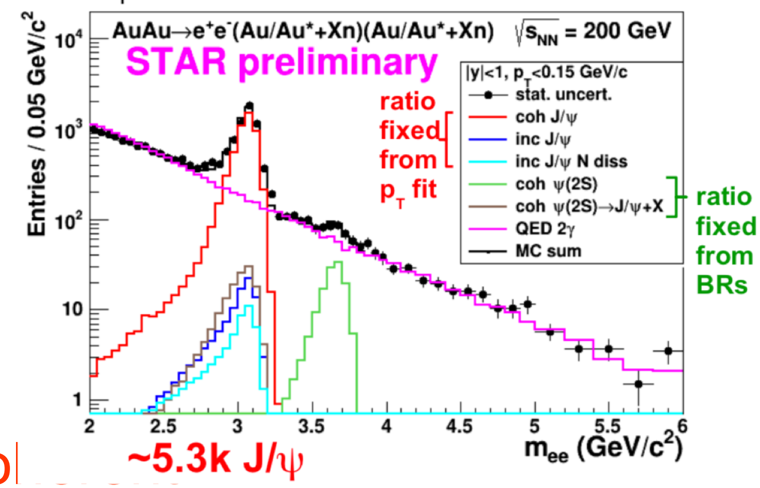
S. Ragoni for ALICE and LHCb, arXiv:2109.03066

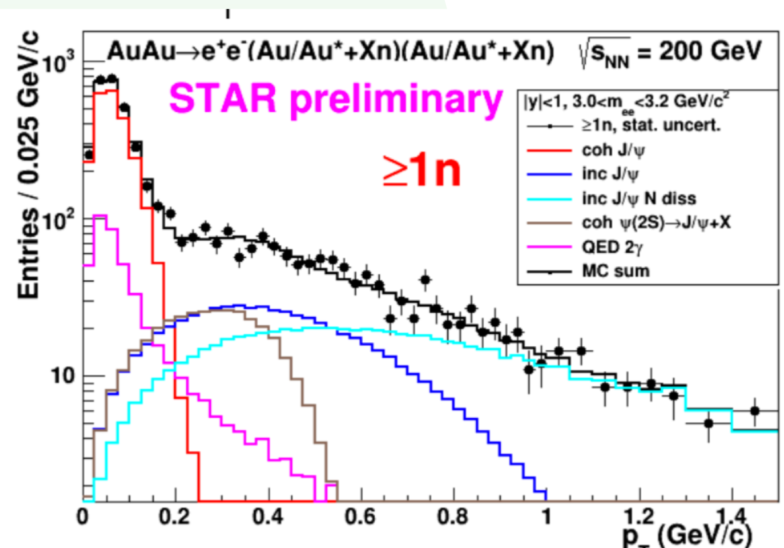
$W_{\gamma p}$ (GeV)

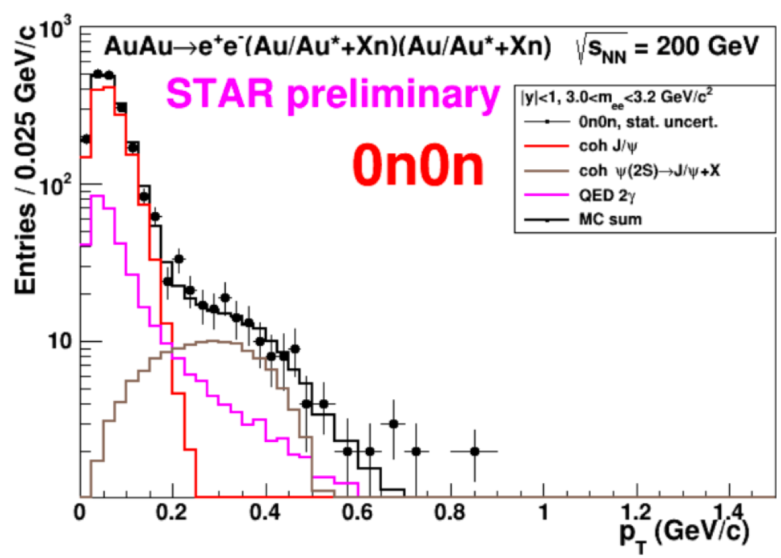
J/ψ photoproduction on gold at RHIC; x ~ 10^{-2}

- AuAu and polarized p-Au collisions
- Data with a calorimeter trigger
- J/ψ, ψ’ ->e^+e^- and γγ->e^+e^-
  - γγ->e^+e^- fraction larger than in pp/pA
  - Coherent & incoherent photoproduction
  - M_{ee}, p_{Tee} fit to mixture
- Events with neutrons are more likely inco

- p_T < 0.15 GeV/c:



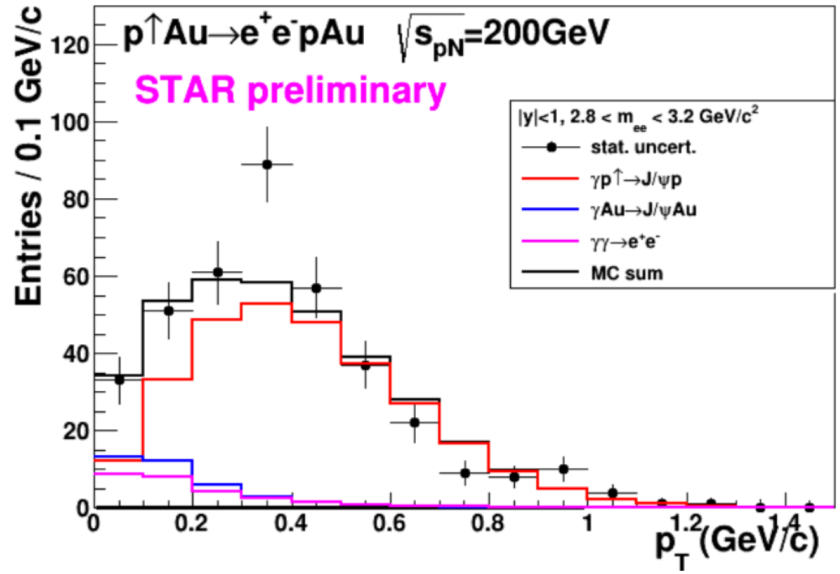


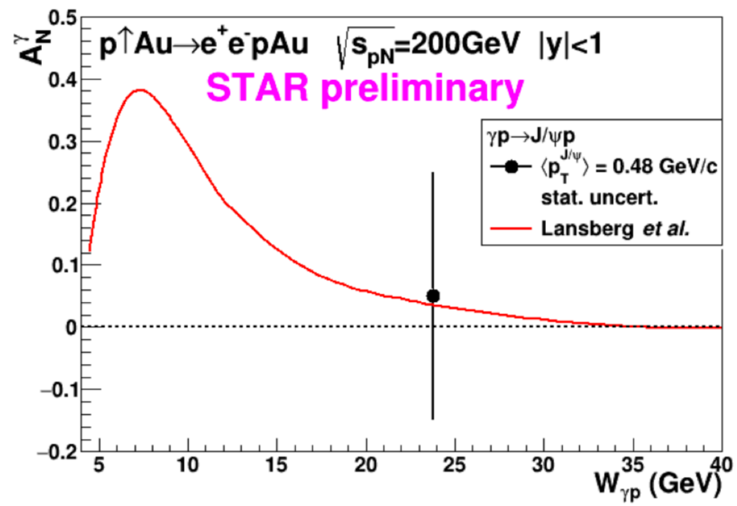


W. Schmidke [STAR], DPF 2019

Polarized J/ψ photoproduction at STAR

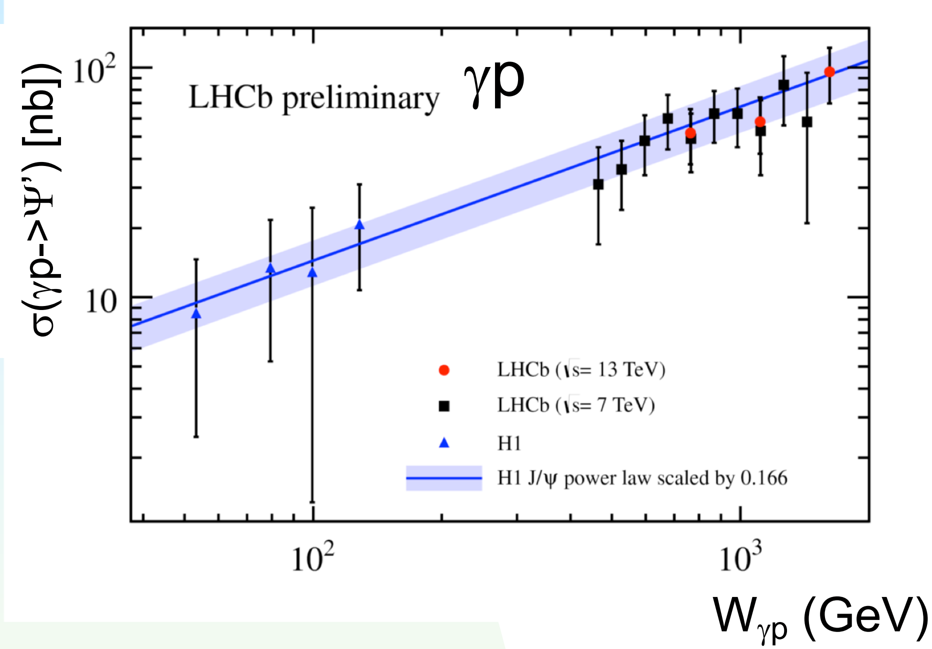
- Sensitive to polarized GPDs (generalized parton distributions), which probe the transverse position of partons with the nucleus
  - Is gluon polarization dependent on position within nucleus?
- From polarized p on Au collisions
  - Dominated by photon-from-gold
    - p_T cut improves separation
  - Polarized proton target
- Look at scattering asymmetries, which depends on $W_{\gamma p}$ and p_T
- 1st measurement; proof of principle

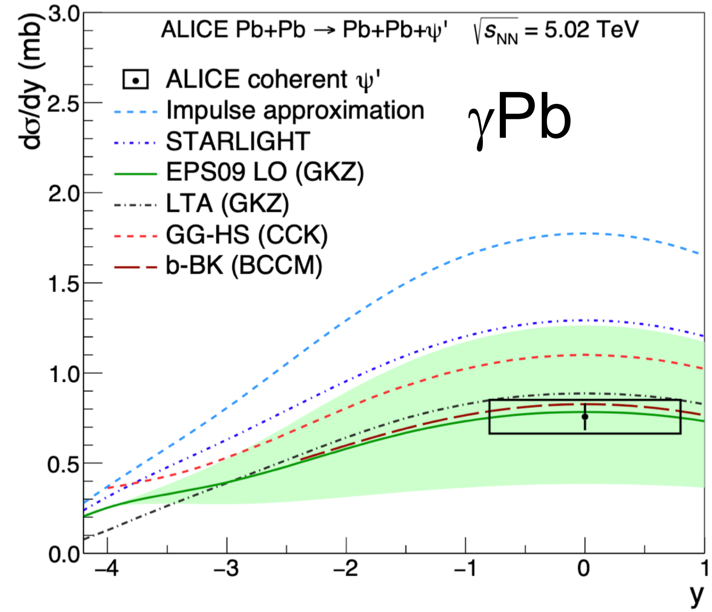




W. Schmidke [STAR], DPF 2019

ψ' photoproduction on proton & lead targets





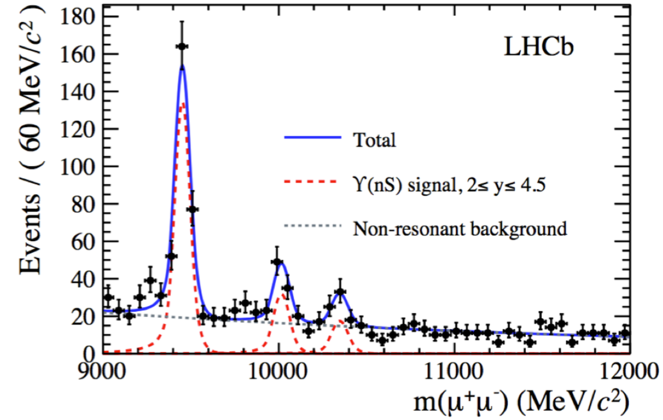
γp is a good fit to power law
Data is a bit below the partial NLO calculation
LHCb data quality is more precise than HERA & extends to higher energy

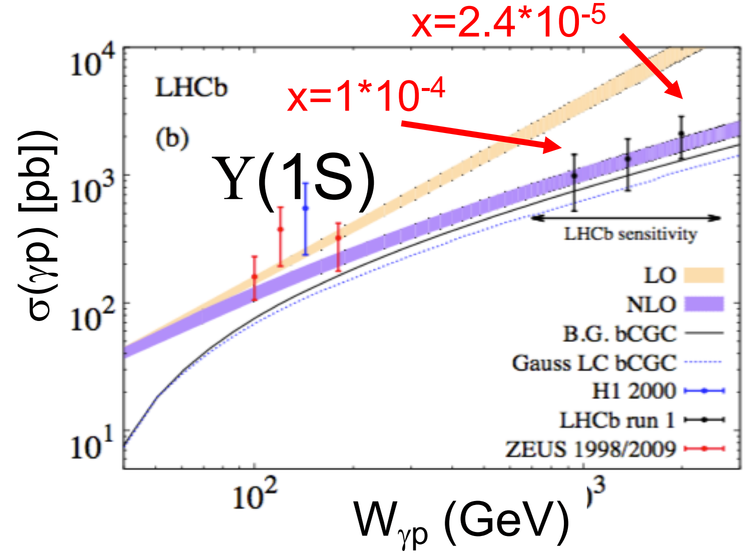
γA data shows moderate suppression, as the J/ψ

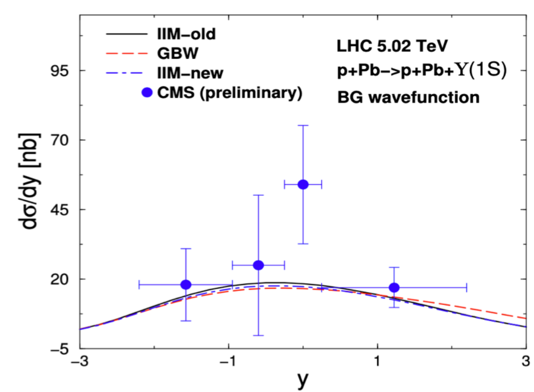
R. McNulty [LHCb] ICHEP 2016; ALICE, Eur. Phys. J. C81, 712 (2021)

γp->Υp

- Central (CMS) & forward (LHCb)
- Υ(1S), Υ(2S) & Υ(3S) resolved
- Agreement with partial NLO calculation (Q^2 ~ 25 GeV^2)
  - Same calculations match J/Ψ & Υ data, at different Q^2
  - Higher Q^2-> less sensitivity to some theoretical uncertainties
- Larger difference between LO and partial NLO calcs. than J/ψ
- No evidence for saturation at low Q^2



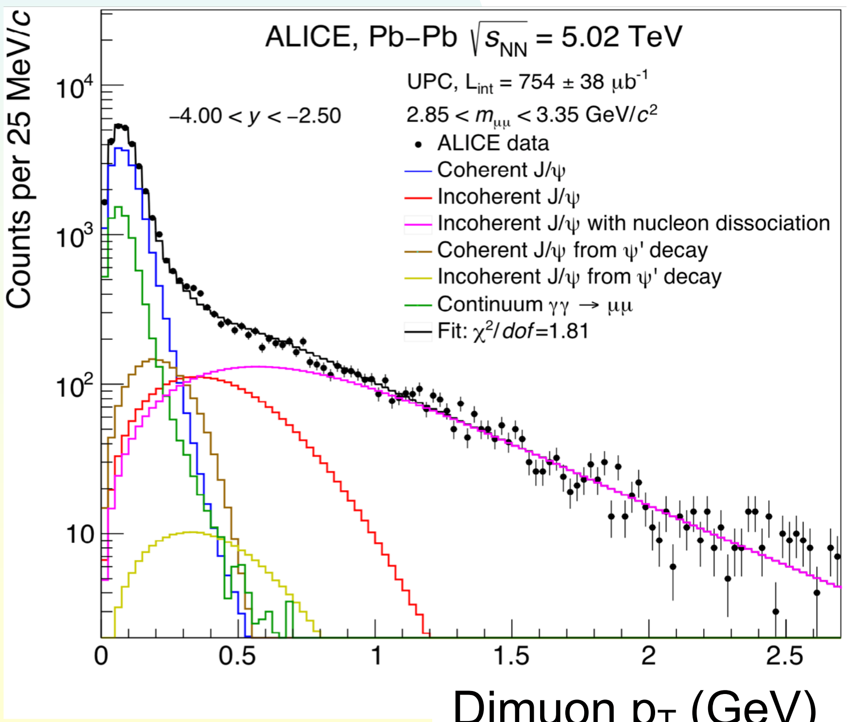


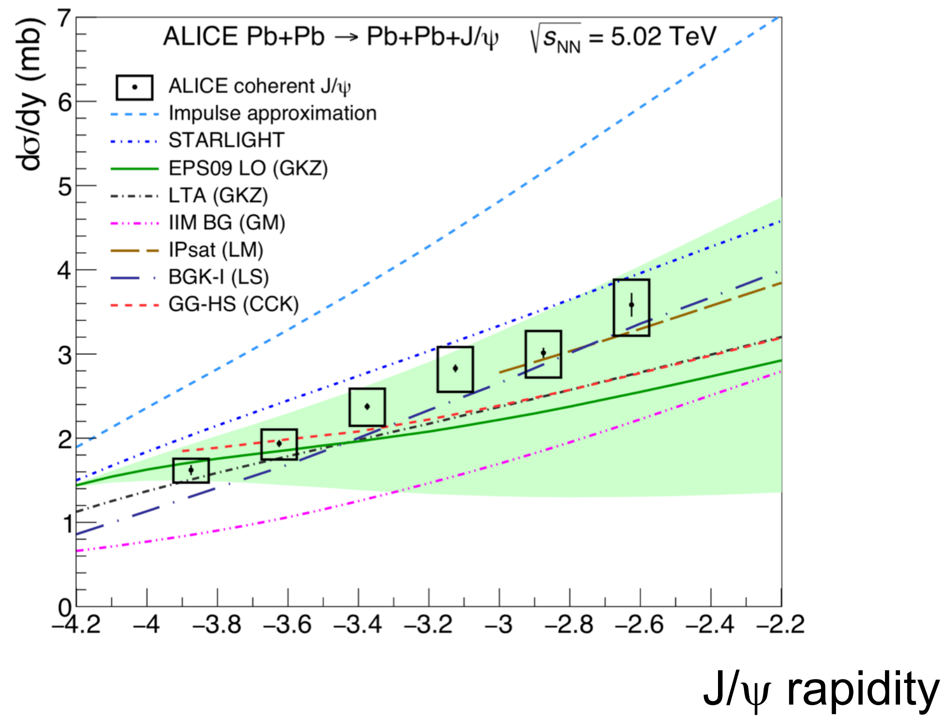


R. McNulty [LHCb] ICHEP 2016;
M. Machado & CMS, in ISMD2017

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

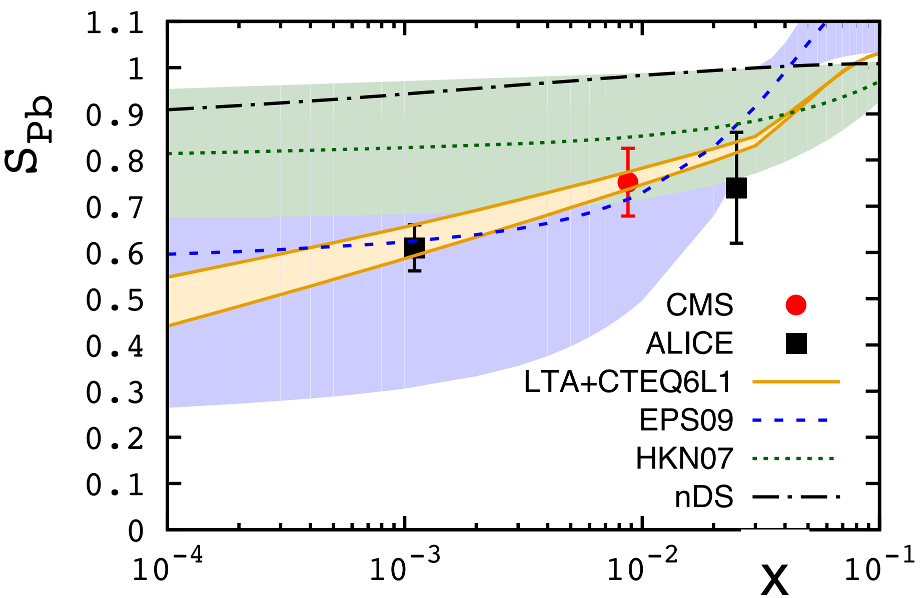




ALICE: Phys. Lett., 134926 (2019)

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.

Beyond gluon densities: to 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: Sum the amplitudes, then square -> average over different configurations
- Incoherent = Total – coherent; total: square, then sum cross-sections for different configurations

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

Mantysaari and Schenk, PRD **94**, 034042 (2016)

Good-Walker and transverse interaction profiles

- The coherent cross-section gives us access to the transverse spatial distribution of individual targets within the nucleus

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

Average amplitudes (Ω)

- We can also write $\sigma_{coherent} = |\Sigma_i A_i k \exp(ikb)|^2$
  - Usually work with $t= p_T^2+p_z^2 \sim p_T^2$
- Because of exponential $d\sigma/dp_T$ encodes information about the transverse locations of the interactions
  - without shadowing, this is the shape of the nucleus
- The two-dimensional Fourier transform of $d\sigma/dt$ gives F(b), the transverse distribution of targets

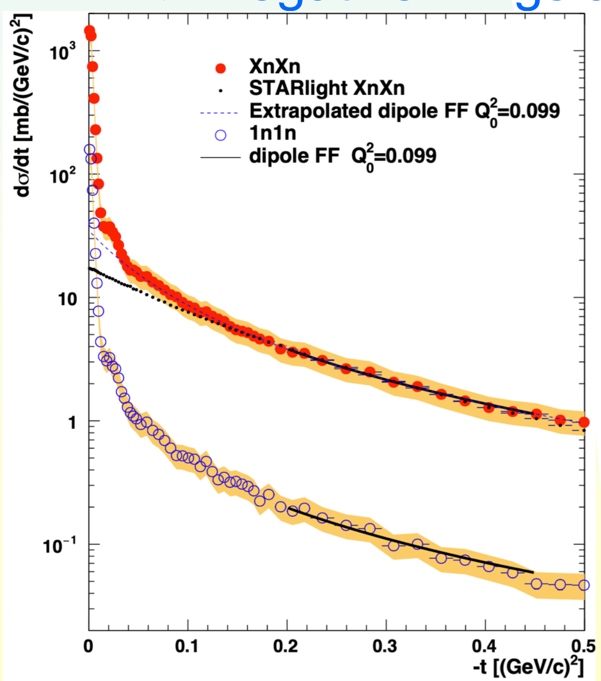
$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}$$

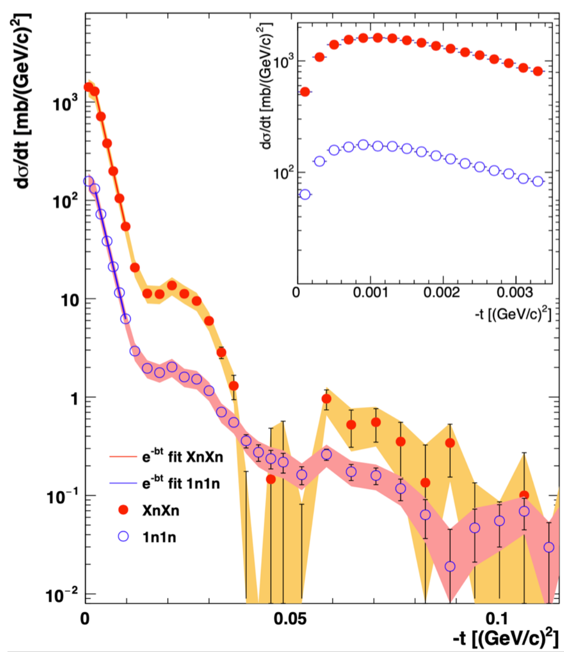
*flips sign after each diffractive minimum

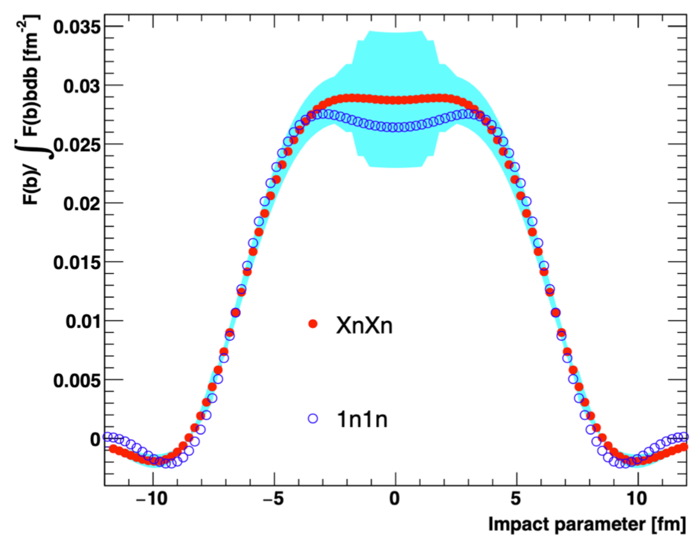
- Multiple serious caveats – range of integration/ windowing finding diffractive minima, subtracting out photon p_T etc.

The STAR ρ^0 analysis

- 384,000 dipion events
- Fit $d\sigma_{incoherent}/dt$ in region of large |t| with a dipole form factor, extrapolate and subtract, leaving $d\sigma_{coherent}/dt$
  - Diffractive minima are visible
- 2-d Fourier tranform
- 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

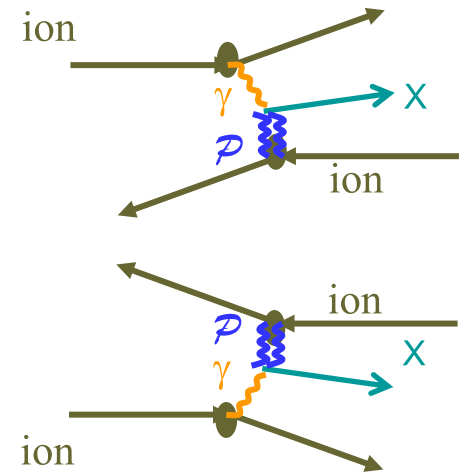






STAR, Phys. Rev. C**96**, 054904 (2017)

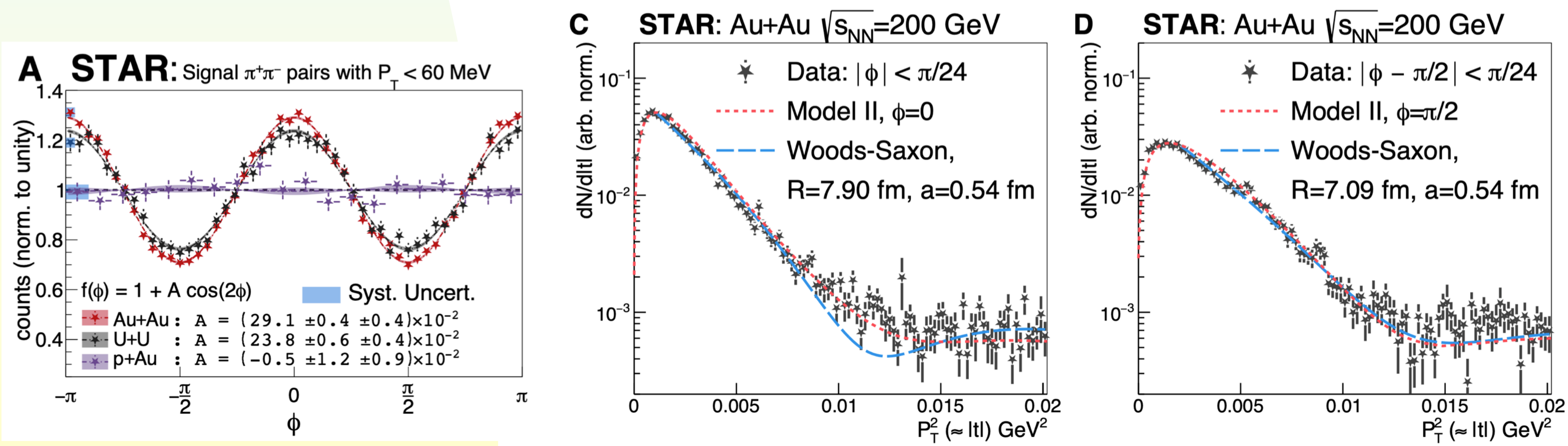
STAR fit to ρ^0 data



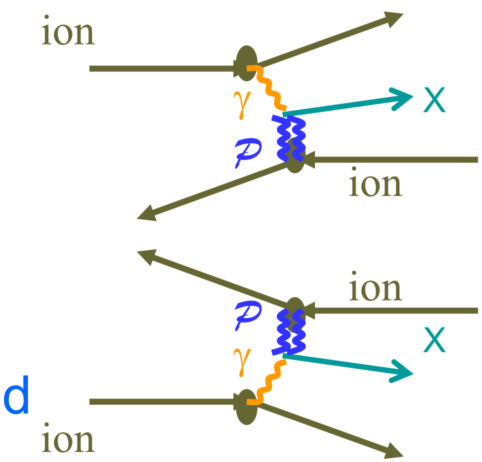
- Model includes photon p_T, ρ^0 scattering on target, and interference between the two γ directions
- Cross-section $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
  - The vector meson is linearly polarized along b
    - π^+ and π^- p_T preferentially follow b
  - $e^{ip\cdot b}$ gives a correlation between the ρ^0 p_T & pion p_T
    - -> an angular modulation in p_T
- Model fits data well
  - Hadronic radii (w/ neutron skin) R_{Au}= 6.62±0.03 fm & R_U = 7.29±0.08 fm

Precision UPC physics!

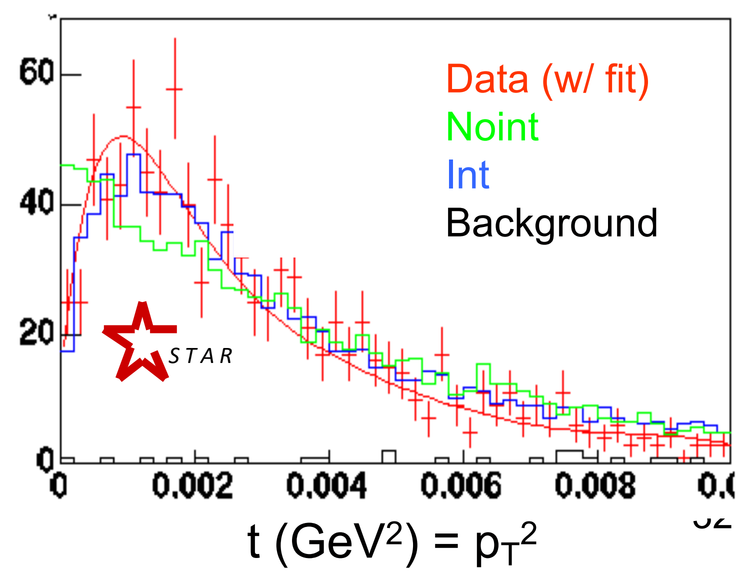
STAR, arXiv:2204.01625



Photoproduction & the directional ambiguity



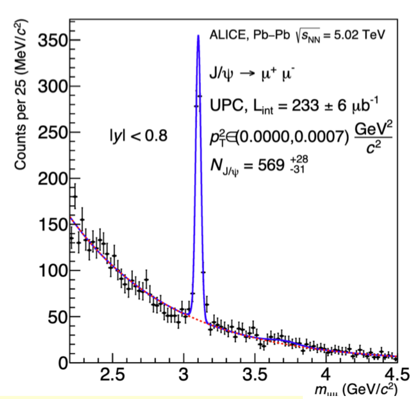
- Photoproduction can occur two ways
  - Either nucleus can emit a photon
- For coherent production (with no nuclear breakup) the two cases are indistinguishable
  - Except the photon & 'Pomeron' energies are swapped
- Add amplitudes for two directions: $\sigma \sim |A_1 - A_2 e^{ip\cdot b}|^2$
  - minus since $\rho, \omega, \phi, J/\psi$ are $J^{PC} = 1^{--}$
    - Plus sign in pbar p collisions
- σ suppressed for $p_T < h/\langle b \rangle$
  - $p_T < \sim 30$ MeV/c
- Measured by STAR – consistent with calculations

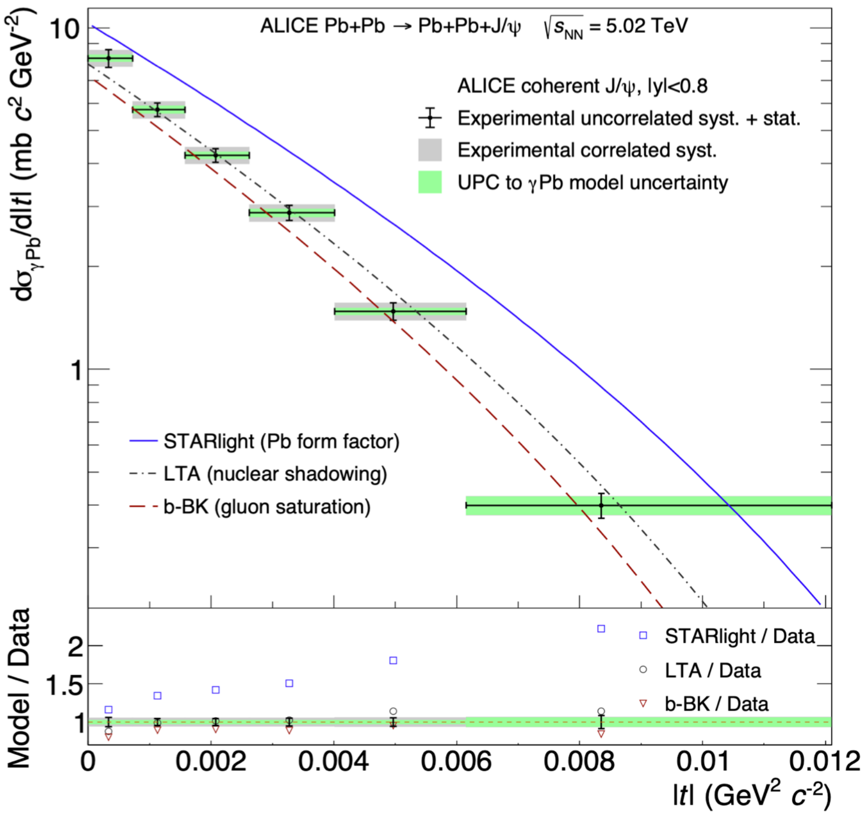


STAR: PRL 102, 112301 (2009)

ALICE: J/ψ on lead targets

- ALICE has measured the p_T spectrum for $J/_y$ photoproduction
- Resolution and photon pT removed via deconvolution
  - Photon p_T spectrum for $0 < b < \infty$
    - When b is restricted (e. g. $b>2R_A$), $<p_T>$ should increase
- p_T falls faster than expected from the Pb form factor
  - Effective nucleus is larger
- Consistent with leading twist approximation or a dipole model with gluon saturation





ALICE, Phys. Lett. B**817**, 136280 (2021)

Incoherent production and event-by-event fluctuations

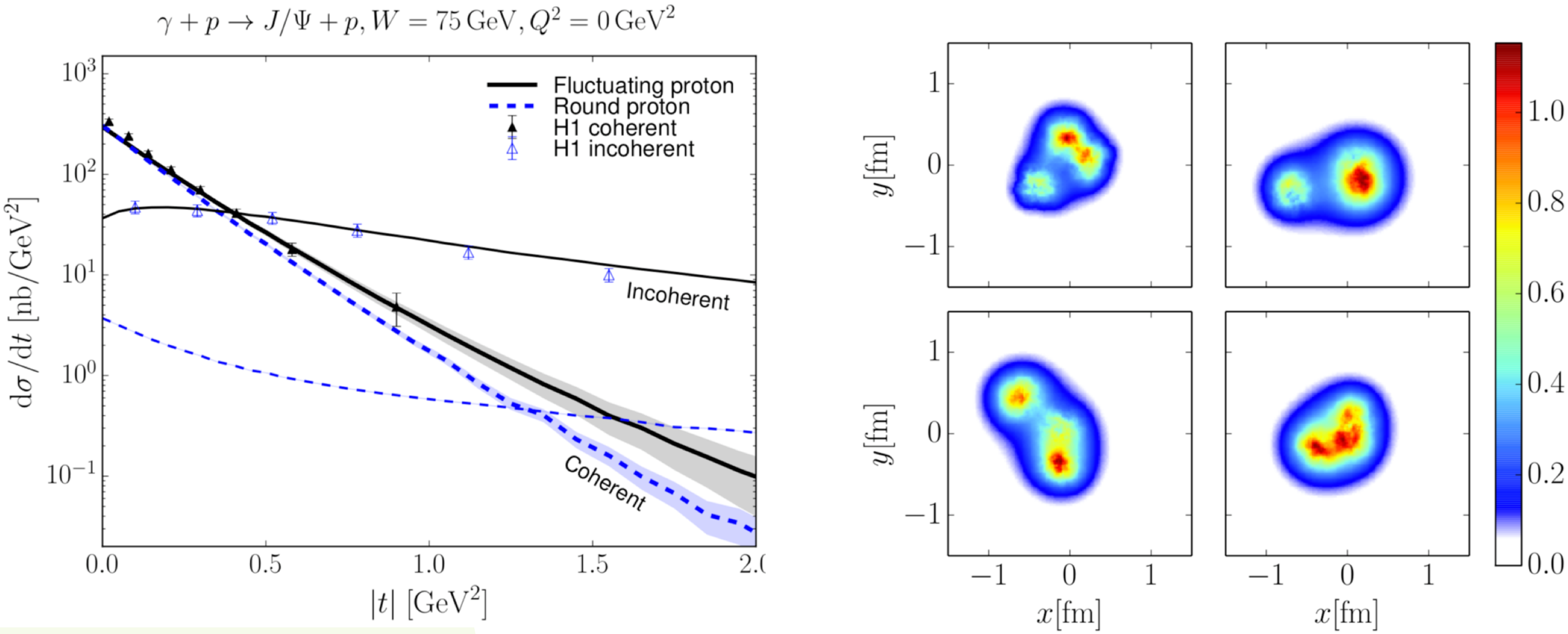
- The incoherent cross-section lets us measure the event-by-event fluctuations in the nuclear configuration, including the positions of individual nucleons, gluonic hot spots, etc.

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

- Probes the deviations from the mean.
- The connection between t and impact parameter is weaker than with coherent production, but this can be used to test models.

$\gamma^*p \to J/\psi$ at HERA and gluonic hot spots

- HERA data provides an application of the Good-Walker formalism

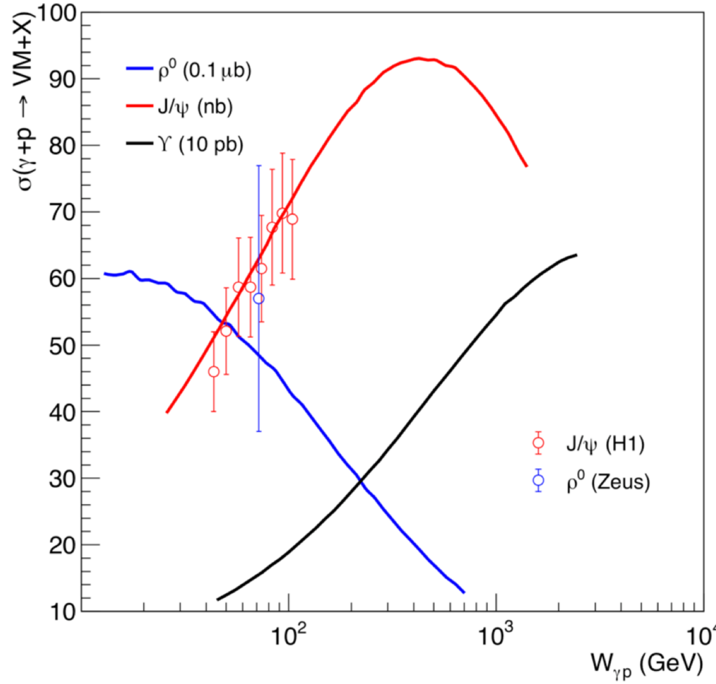


- The proton is far from smooth. It contains gluonic hot spots (or other fluctuations)
- The EIC will map this behavior in x, Q^2, and should apply it to nuclei

Mantysaari and Schenk, PRD **94**, 034042 (2016)

Strong saturation and the black disk limit

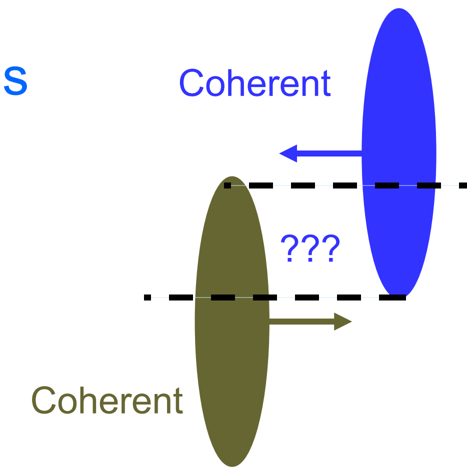
- Higher photon energies probe lower Bjorken-x values
  - Lower x values -> more gluons, more hotspots
  - The fraction of the proton or ion surface covered with hot spots rises
- Eventually, the whole surface is covered. This is the ‘black disk limit,’ when the nucleus acts like a totally absorptive disk
- Black disks don’t fluctuate, so incoherent photoproduction should disappear.
- High-mass final states require more energetic (larger x) gluons, so they will be slower to disappear
- Extension to nuclei model dependent

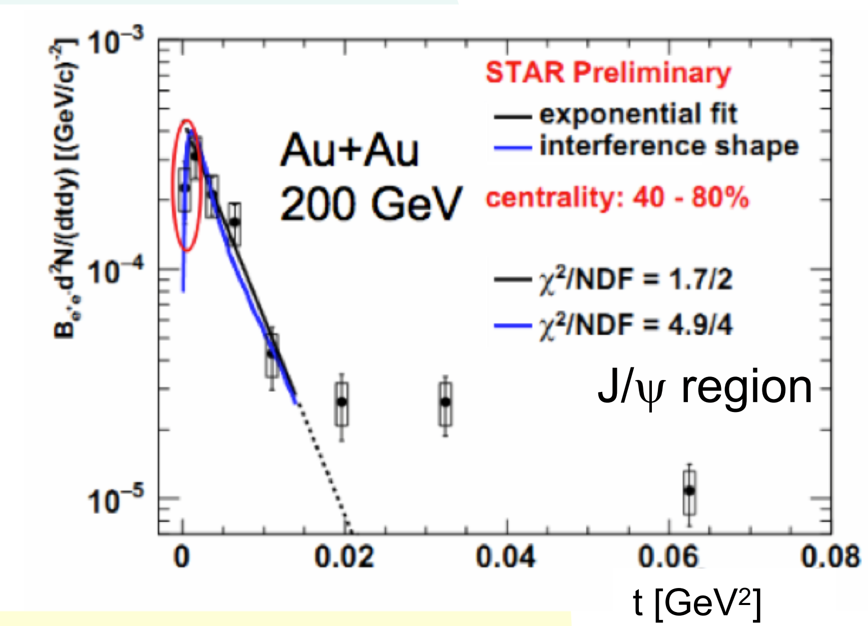


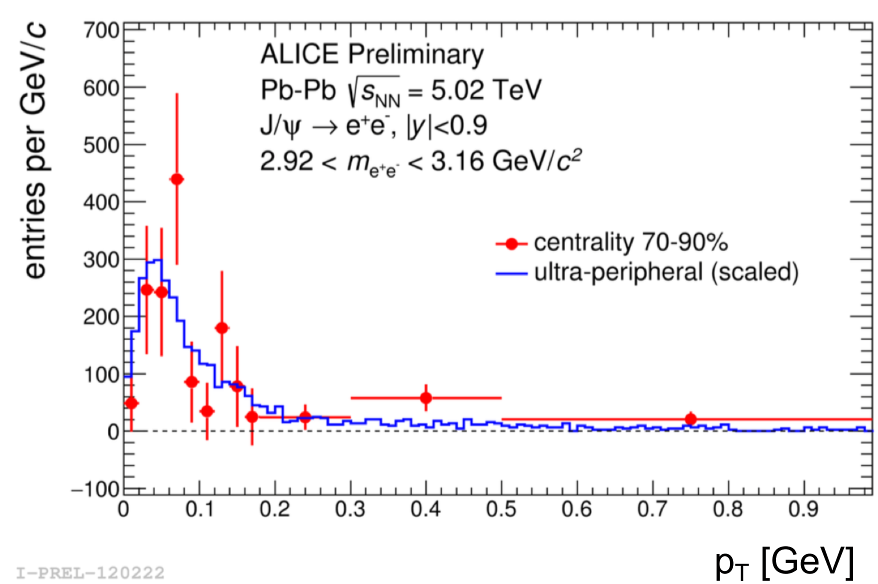
J. Cepila et al., Nucl. Phys. B934, 330 (2018)

UPCs in peripheral collisions

- Photon reactions do not disappear when $b < 2R_A$
  - Rates are lower due to lower photon flux inside nucleus
  - Coherence is reduced/eliminated
  - Hadronic interactions reduce target energy
- Data shows excess l^+l^- pairs with p_T < 100 MeV/c
  - Photoproduced J/ψ + continuum l^+l^-







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

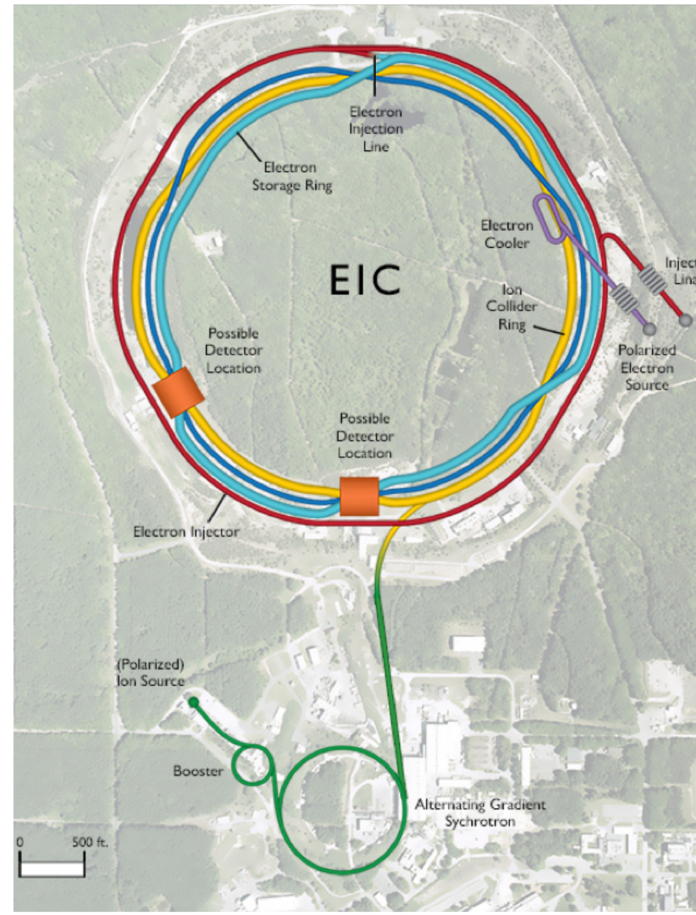
Looking ahead with UPCs

- LHC Runs 3 (starting now) and 4 will feature higher luminosity and improved detectors
  - ALICE will add a much-improved vertex detector (for open charm) and a streaming DAQ, eliminating the need for a trigger
    - Trigger is a huge bottleneck for UPCs
- A short oxygen-oxygen run is planned
  - Good species to measure incoherent photoproduction
- Precision vector meson photoproduction data
- More open dijets and charm
- J/ψ transverse distribution studies
- UPCs at a future CERN or Chinese 100 TeV hadron collider could reach down to Bjorken-x $\sim 10^{-7}$

x

The proposed U. S. electron-ion collider

- Add an 18 GeV electron ring to the RHIC complex
- Augmented ion ring
  - 275 GeV p, 110 GeV/n ions
  - Improve polarized source
- Coherent electron cooling to reduce emittance
- Very high luminosity ~ $10^{34}/cm^2/s$
  - Precision physics
- At least one detector
  - Full acceptance, with excellent forward and backward coverage
  - Collaboration forming now
- Completion in early 2030s

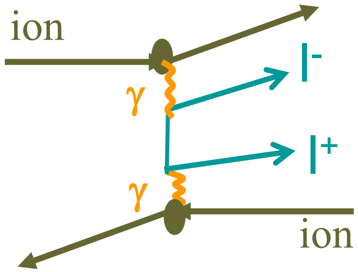


Conclusions

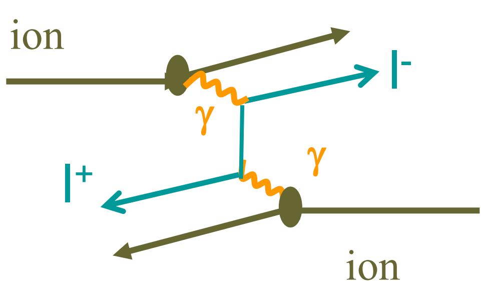
- Photoproduction is a key tool to study partons in dense nuclear environments
  - The LHC is the energy frontier, probing gluons down to Bjorken-x of 10^{-6}
- Photoproduction of open charm and dijets are theoretically fairly clean, but messy experimentally.
- Photoproduction of quarkonium is experimentally straightforward, with results on many mesons, including the ρ, ρ', J/ψ, ψ' and Υ
- $\sigma(\gamma p \to J/\psi\ p)$ is reasonably well described by a simple power law, as predicted if gluon distributions also follow a power law
- Light meson production on nuclei is well-described by the Glauber-Gribov paradigm that accounts for multiple dipole interactions.
- J/ψ photoproduction on lead shows a moderate suppression of the cross-section, consistent with the leading-twist model of shadowing, and with the favored regions of nuclear PDFs.
- Looking ahead, we expect much photoproduction data from LHC Run 3 and 4, and the future U. S. electron-ion collider.

Backup

$\gamma\gamma$-> dileptons

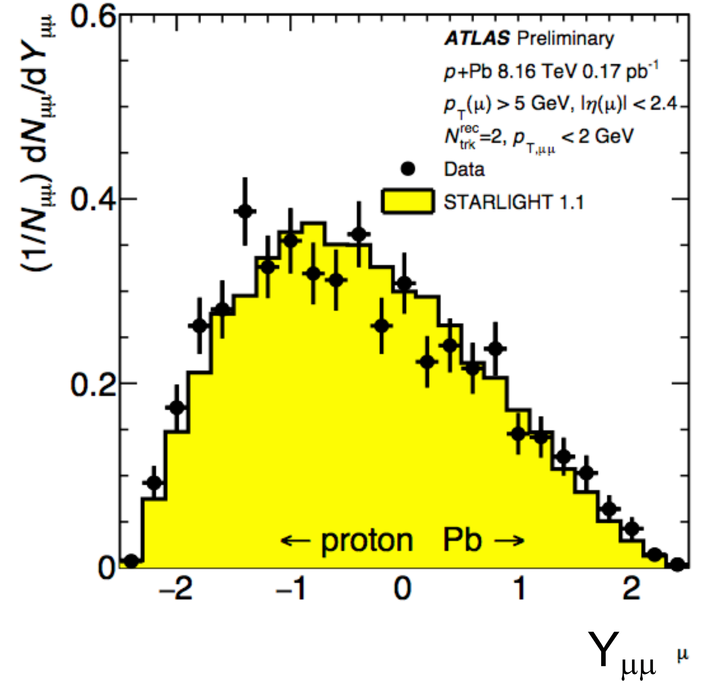


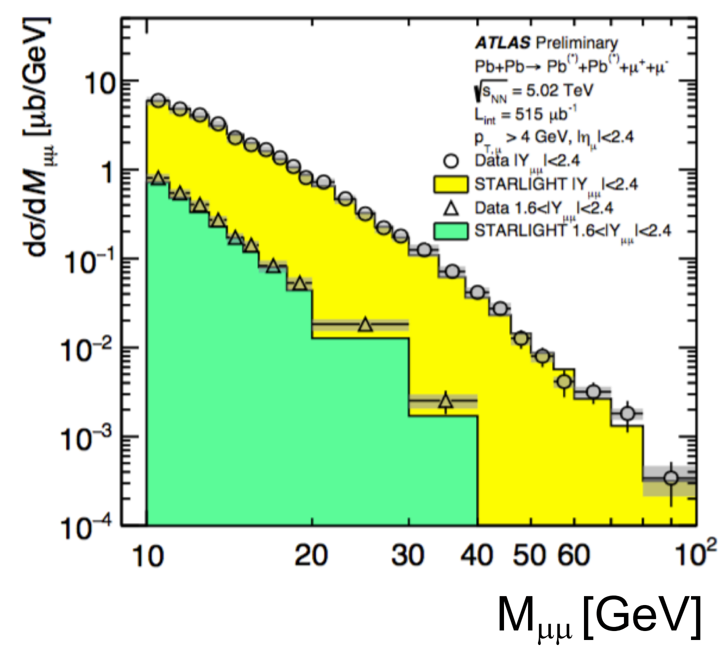
- Well described by LO QED
- Overlap of photon fluxes+ the Breit-Wheeler formula for $\gamma\gamma \rightarrow l^+l^-$
- σ is huge – 200,000 barns for PbPb at the LHC
  - Multiple pairs possible at smaller impact parameters
  - Production out to μm impact parameters for forward production
- Strong forward/backward topology
  - Most leptons go 'down beampipe'
    - Low detection efficiency (but cross-section is large)
- Lepton pair $p_T < \sim M_{ll}/\gamma$
  - Leptons are nearly back-to-back
- Studies from STAR, ATLAS, CMS, plus incidental measurements (background $J/\psi \rightarrow ll$) from CMS, ALICE



ATLAS $\gamma\gamma \to \mu^+\mu^-$

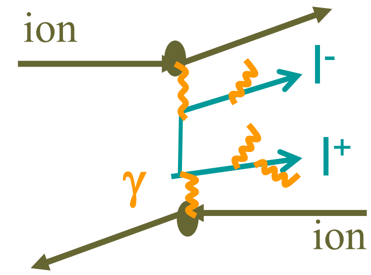
- Data is in excellent agreement with STARlight Monte Carlo
  - The STARlight Monte Carlo is a common benchmark
    - It uses real photons (Equiv. Photon approx.), but difference with full quantum electrodynamics calculation is very small
- Small differences at large rapidity and large pair mass
  - Possibly because STARlight does not include pair production inside nuclei



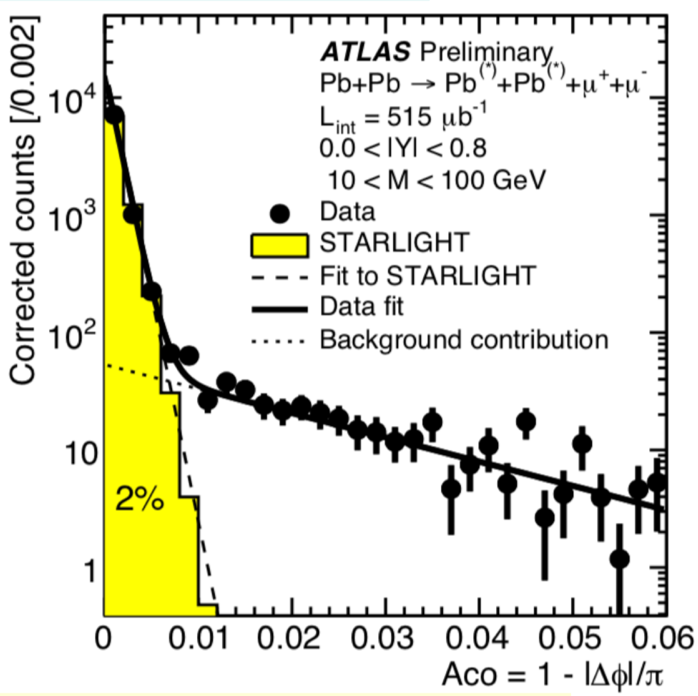


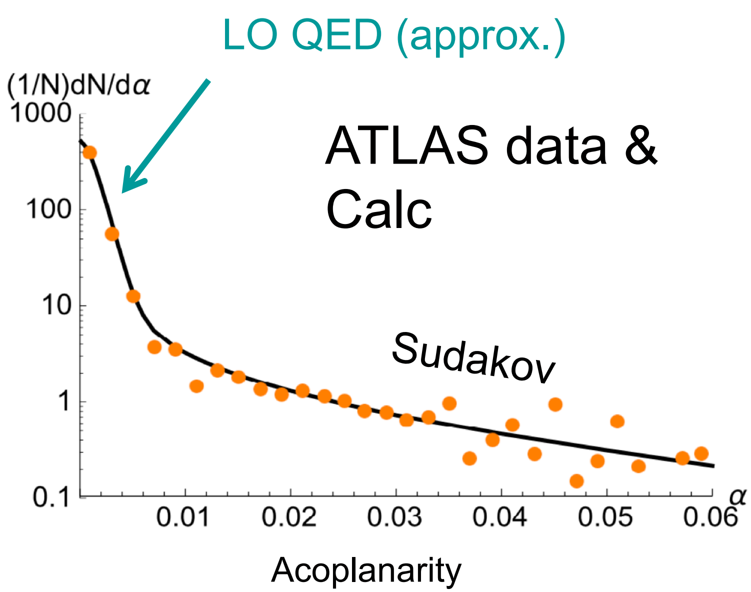
ATLAS-CONF-2016-025

Large p_T pairs



- Low pair p_T region well described by LO QED
- A tail at large acoplanarity/p_T is not well described by LO QED
- Compatible with higher order terms per a Sudakov resummation
  - Emission of many soft photons





ATLAS: Nucl.Phys. **A967**, 281 (2017); SK, A. Muller, B. W. Xiao and F. Yuan, Phys. Rev. D102, 094013 (2020)

Photon transverse momenta

- Normally, photons are plane waves
- Here, there is a transverse component. From the Poynting vector, we can write

$$n(\omega;\mathbf{b}) = \frac{1}{\pi\omega}\left|\mathbf{E}_\perp(\mathbf{b},\omega)\right|^2 = \frac{4Z^2\alpha}{\omega}\left|\int\frac{d^2k_\perp}{(2\pi)^2}\mathbf{k}_\perp\frac{F(\mathbf{k}_\perp^2+\omega^2/\gamma^2)}{\mathbf{k}_\perp^2+\omega^2/\gamma^2}e^{-i\mathbf{b}\cdot\mathbf{k}_\perp}\right|^2$$

- F(q) is the emitter form factor; q is the momentum transfer
  - F(q) ~ 1 for q<hbar/R_A
  - F(q) ~ 0 for q>hbar/R_A

  } Photon wavelength > nucleus?
- Can extract p_T spectrum for integral over all b

$$\frac{d^2N}{d^2k_T} = \frac{\alpha Z^2 F(k_T^2+k_z^2/\gamma^2)k_T^2}{\pi^2(k_T^2+k_z^2)^2}$$

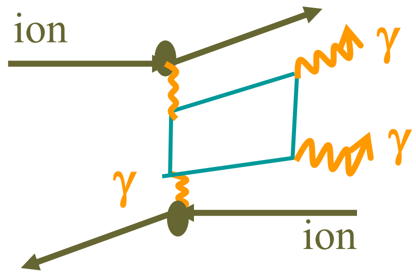
  - Photon p_T is small, ~ k/γ

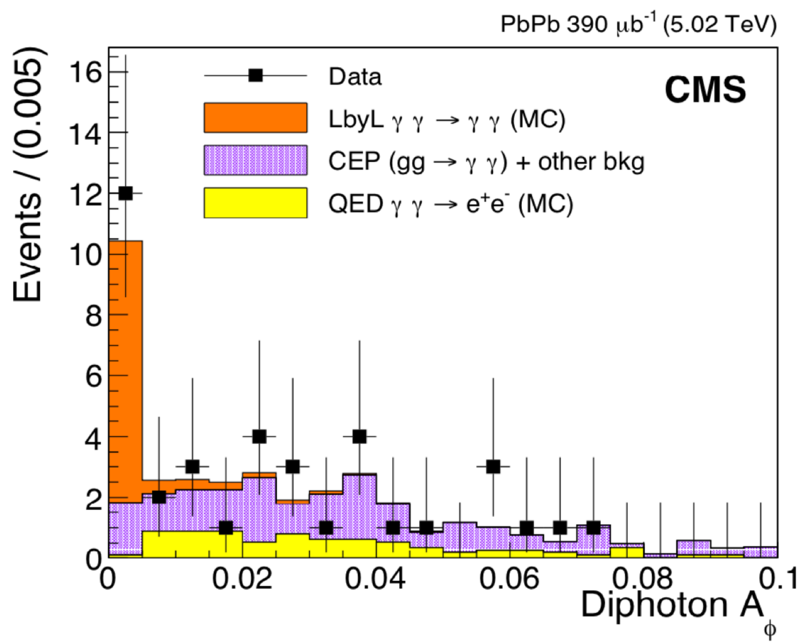
For b>2R_A, etc., b and k_T are conjugate variables -> pain
  - no direct answer, but <p_T^2> ~ 1/b^2

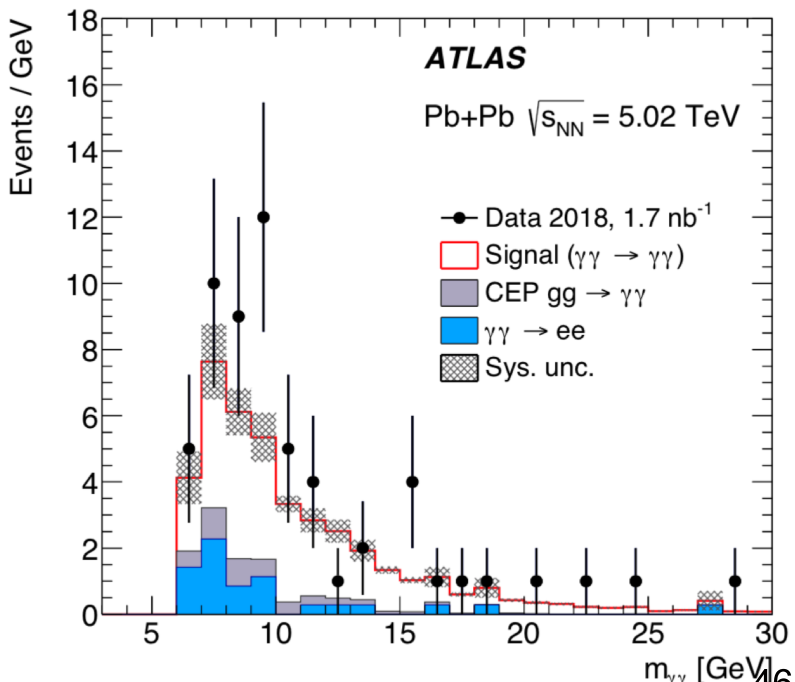
Vidovic et al., Phys. Rev. **C47**, 2308 (1993); Klein & Nystrand, PRL 84, 2330 (2000); Klein *et al*. (2020)

Light-by-light scattering

- Seen by ATLAS and CMS
- "Box diagram" is sensitive to new (beyond-standard-model) charged particles.
- Limits on axion-like particles

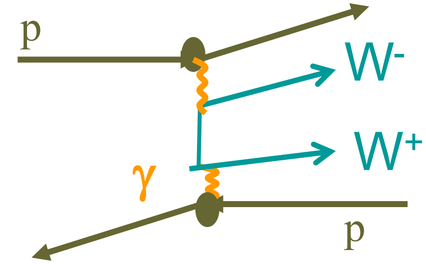




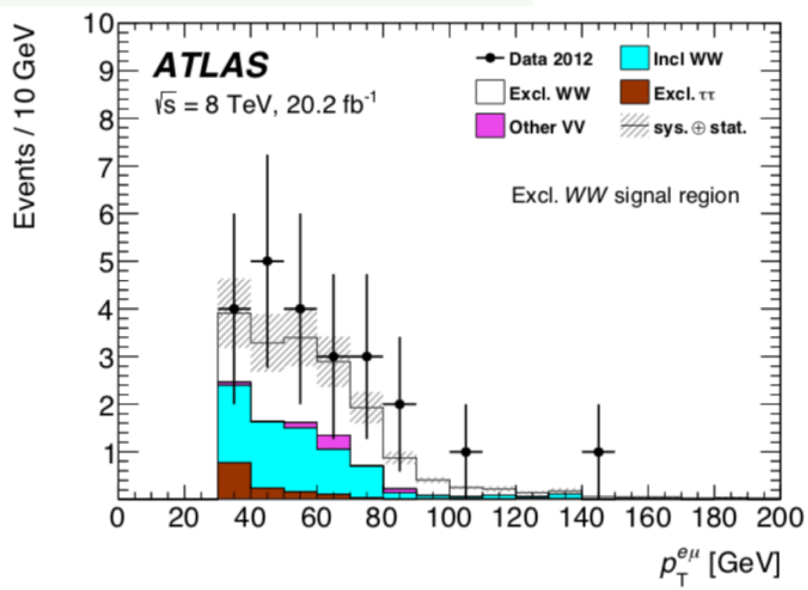


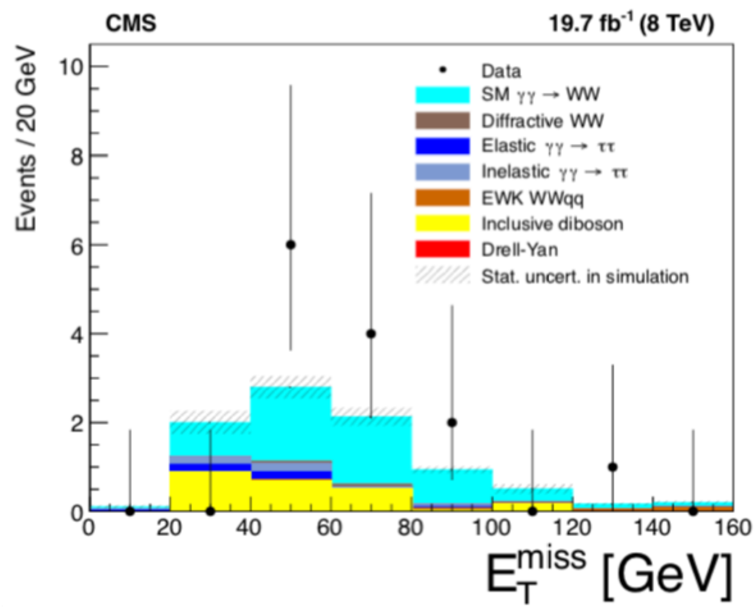
ATLAS: PRL **123**, 052001 (2019); CMS: PL **B797**, 134826 (2019)

γγ->W+W-



- Studied by ATLAS and CMS in pp collisions
  - pp allows higher final state masses
  - Some photon emission accompanied by proton dissociation
- W->lν -> missing energy & acoplanar leptons
  - Background rejection is tough
  - CMS saw 13 events; 5.3 ± 0.7 signal plus 3.9 ± 0.6 background expected
- 3.4σ evidence; compatible with Standard Model
  - Limits on non-standard quartic couplings set

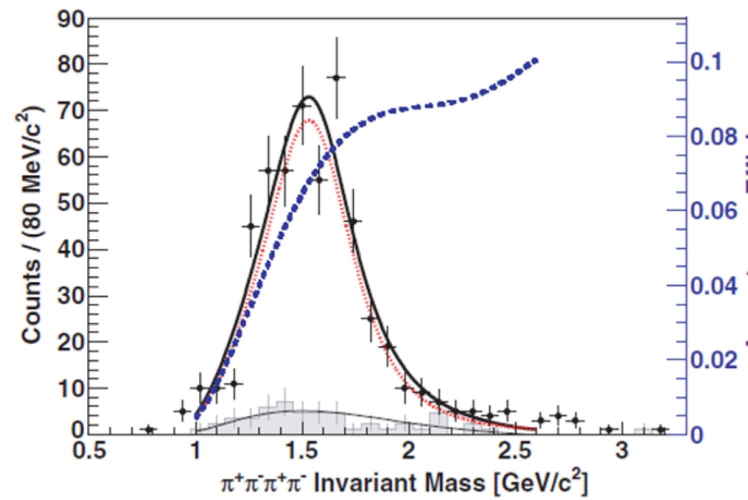


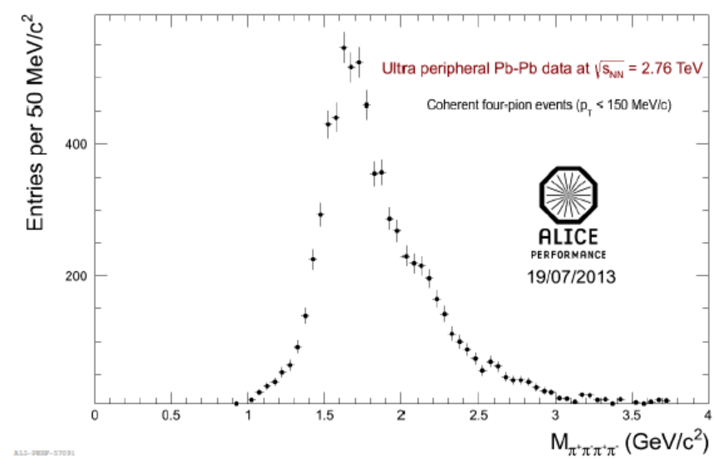


CMS: JHEP **1608**, 119 (2016)
ATLAS: PRD94, 032011 (2016).

Excited ρ and ππππ 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 ππππ
- $M_{\pi\pi\pi\pi}$ ~ 1540 MeV
- Γ ~ 670 MeV
- Significant decays to $\rho^0\pi\pi$
- Consistent with expected mixture of ρ'(1450) & ρ' (1700)

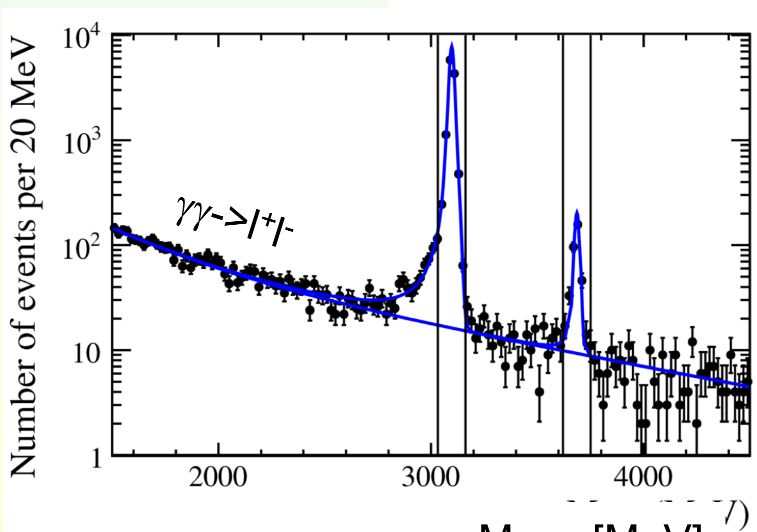




STAR: PRC81, 044901 (2010) ALICE: C. Mayer, 2014 CERN UPC wkshp

γp -> $Q\bar{Q}$ in pp and pA

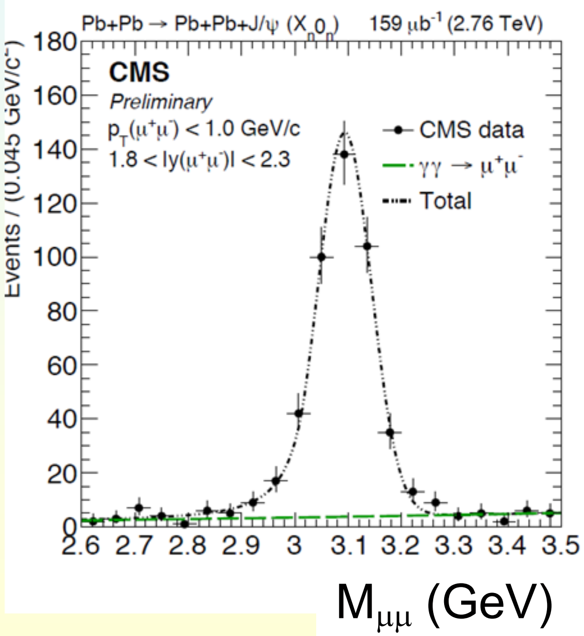
- High statistics data extends HERA σ(γp->J/ψ) to higher energies
  - Access gluon distributions down to 10^{-6} at $Q^2 \sim m_{quark}^2$
- In pp & AA there is the two-fold ambiguity: $k = M_V/2 \exp(\pm y)$
  - Ambiguity disappears at y=0 (solutions are degenerate) or large |y|, where the low-k solution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

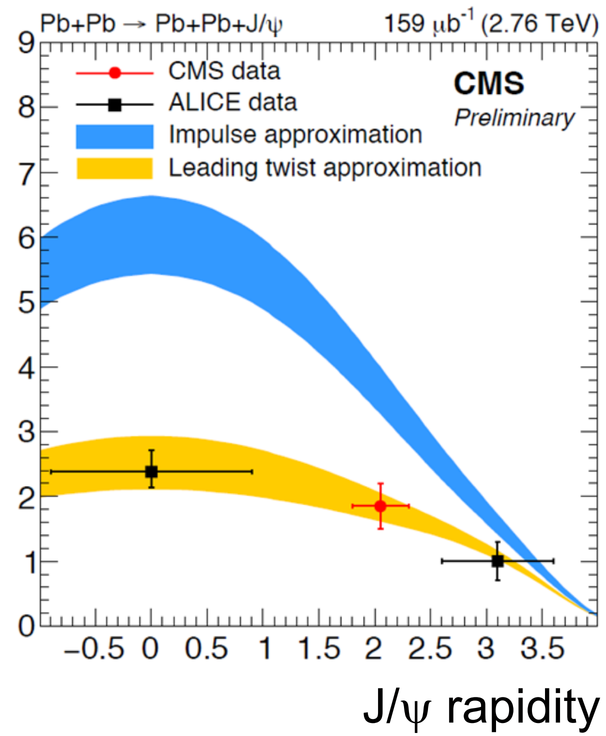


R. McNulty [LHCb] ICHEP 2016

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
  - Again, consistent with leading twist calculation

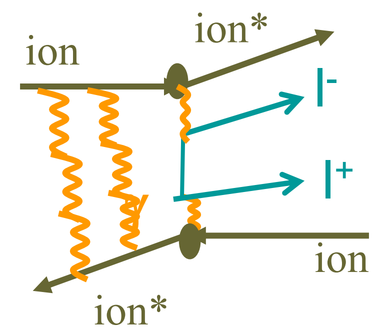


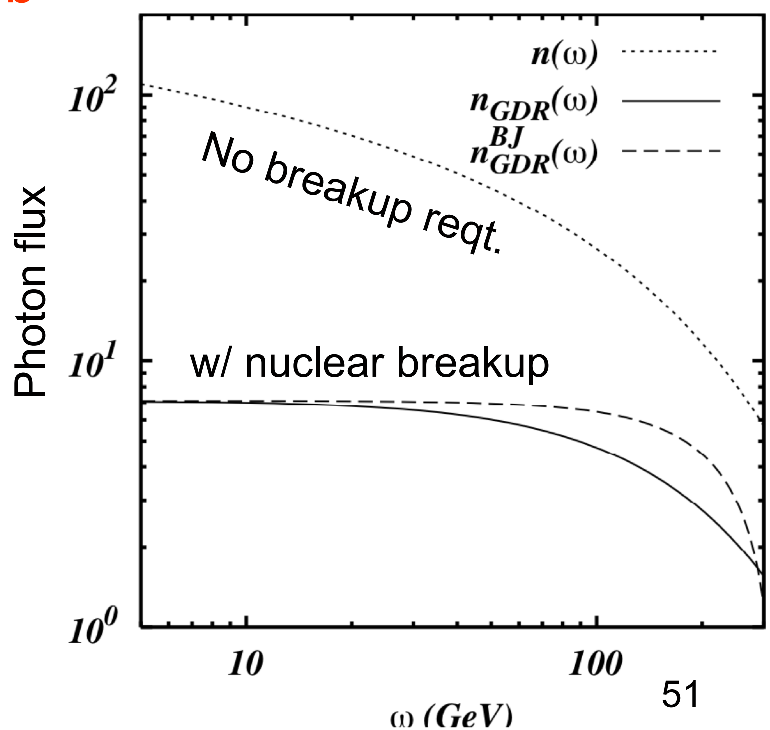


D. Tapai Takaki [CMS], QM17

Multi-photon exchange & impact-parameter 'engineering'

- Photon distributions scale as $1/b^2$
  - In multi-photon exchange <b> is smaller
    - For 2 photons, $\sigma \sim 1/b^4$, for 3 photons $1/b^6$
  - <b> drops and $\langle p_T \rangle$ rises with more photons
  - Due to kinematics '1 photon does one thing'
- Photons spectrum is harder with smaller b
  - Can tune photon spectrum
- STAR requires neutrons in their zero degree calorimeters to trigger
  - From nuclear breakup
- Can tune photon spectrum
  - Bidirectional ambiguity…
- Photon polarizations are also parallel

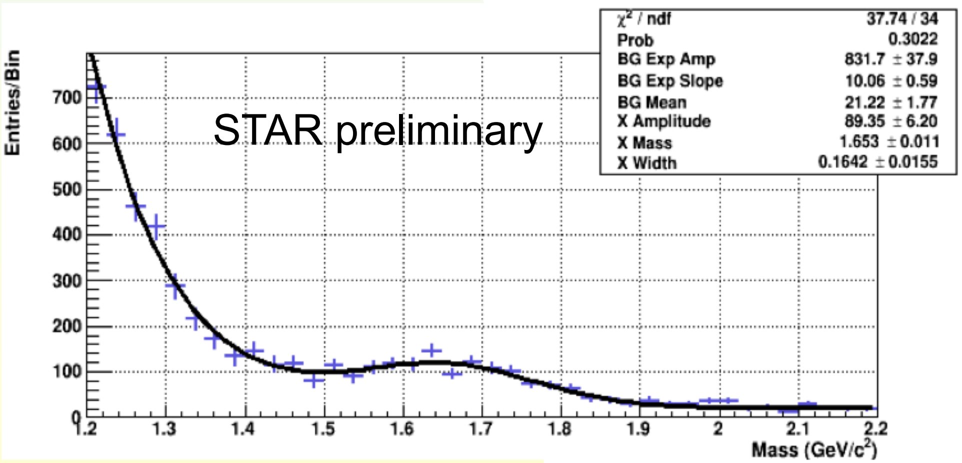


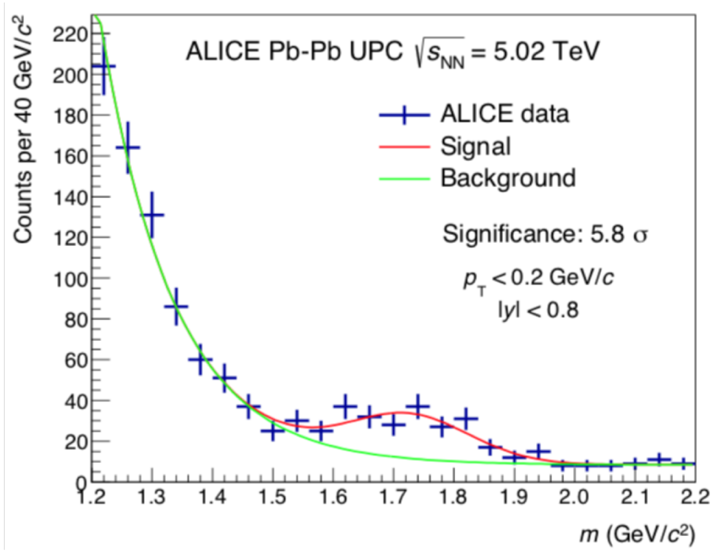


G. Baur *et al.,* Nucl. Phys. A&29, 787 (2003)

ρ' -> ππ?

- STAR and ALICE see a heavy ππ state
  - STAR: M_X = 1653 ± 10 MeV, Γ(X)=164 ± 15 MeV (stat. only)
  - ALICE: M_X = 1725 ± 17 MeV, Γ(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(ρ_3->$\pi^+\pi^-$) & previous γp-> ρ_3 -> $\eta\pi^+\pi^-$ data
    - Spin 3 allowed through in-medium wave function modifications?

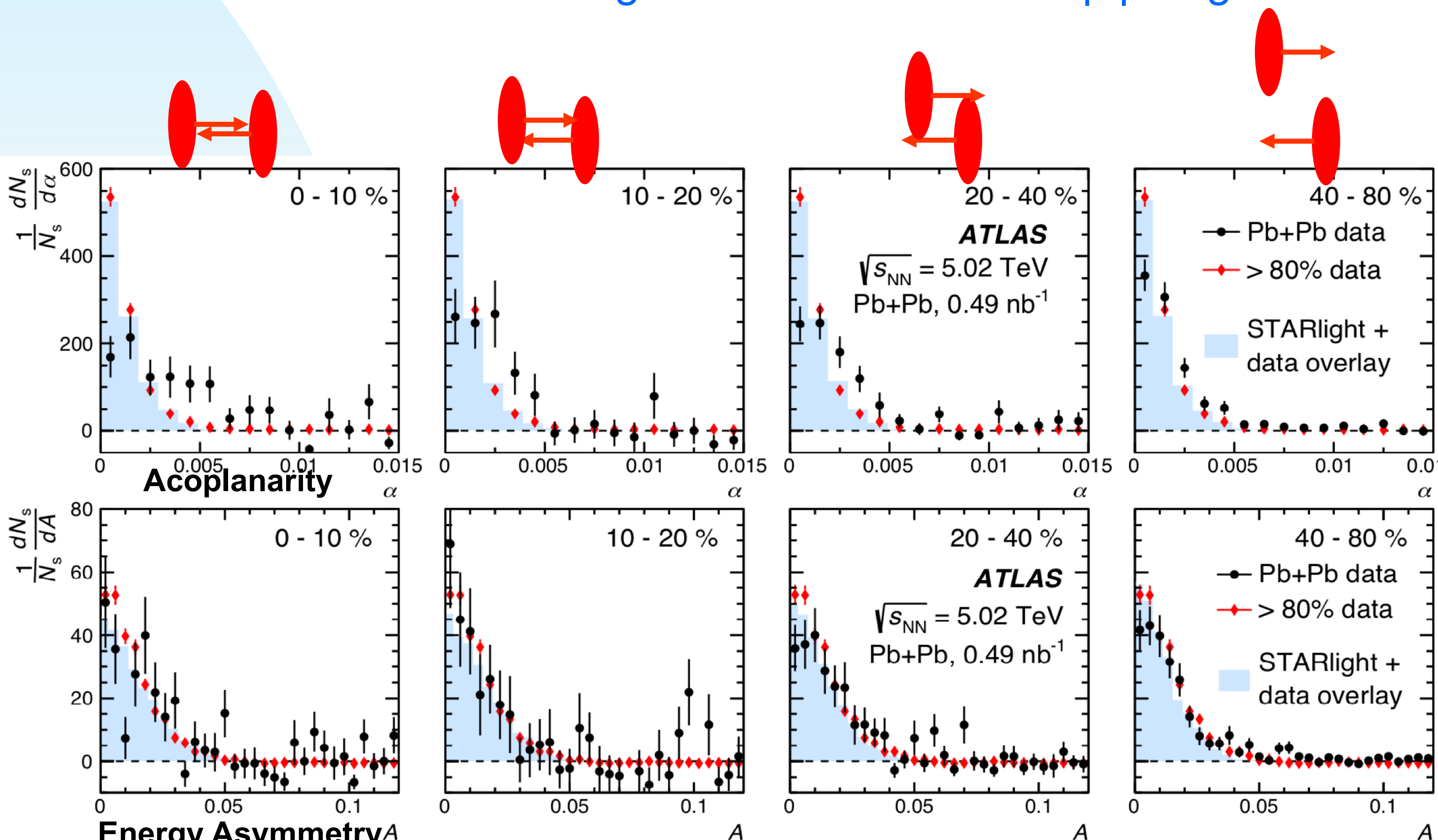




STAR: DIS2016, ALICE: arXiv:2002.10879

p_T spectra from UPCs to peripheral

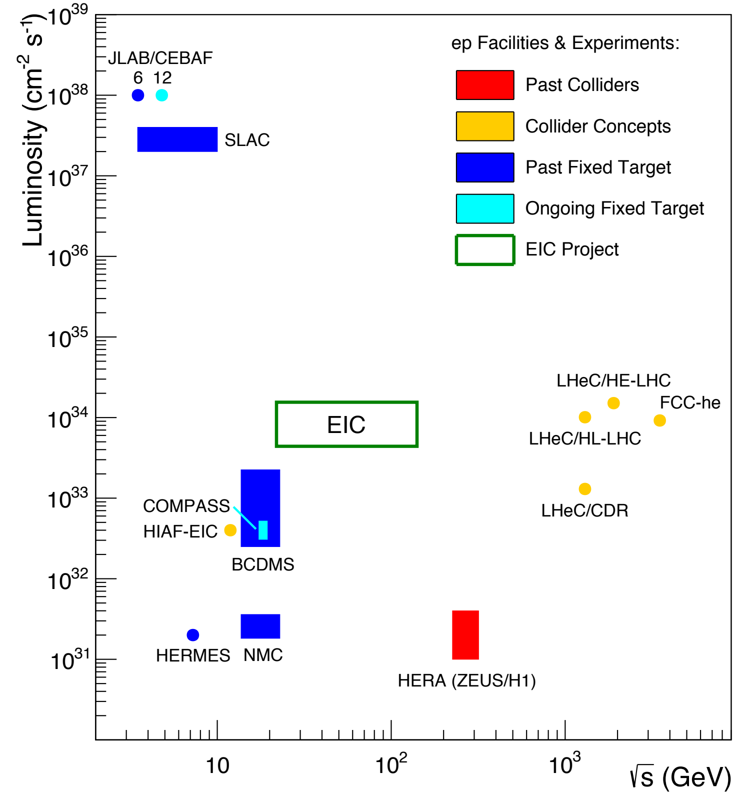
- ATLAS has studied $\gamma\gamma \rightarrow \mu^+\mu^-$ in hadronic collisions
- Acoplanarity (p_T) increases in more central collisions
  - Medium interactions? Magnetic field? Restricted |b| range

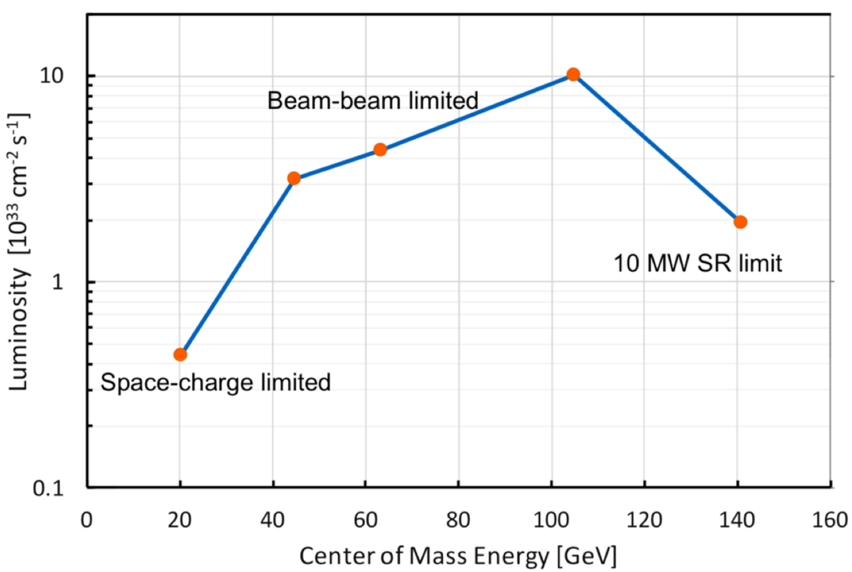


ATLAS: PRL **121**, 212301 (2018)

EIC luminosity

- Luminosity 1000 times HERA
  - High currents required
  - $I_{electron}$=2.5 A
    - Max. 9 (or 10) MW synchrotron radiation limits $I_{electron}$ at high energies
      - Cost of cooling
  - I_{hadron} =1.0 A
- For ion beams, luminosity/nucleon is roughly constant





Trade energy for luminosity?

Different physics topics may hav different optimal energies