Ultra-peripheral collisions measurements (high-energy photons in nuclear physics)

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Presented at the Town Meeting on Hot & Cold QCD
Sept. 23-25, 2022, MIT

What have we learned

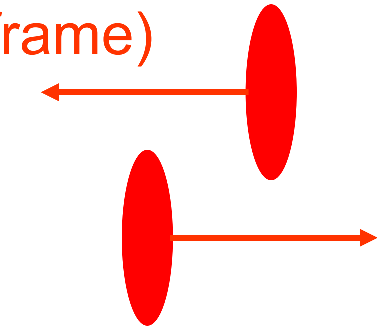
The next ~ 5 years

LHC Runs 5+ and the EIC era

This is a huge subject; I apologize to everyone whose nice results I do not have time to cover. The focus will be on hot and cold QCD, since it is the focus of this meeting.

UPCs: the photon energy frontier

- Energies up to 500 TeV (lab frame)/5,000 PeV (target frame)
- Gluons (mostly) in nuclei at low Bjorken –x
  - Reaching x <~10^{-6} over a range of Q^2
  - Gluon densities and transverse distributions
  - Baryon stopping in photoproduction, anisotropy etc.



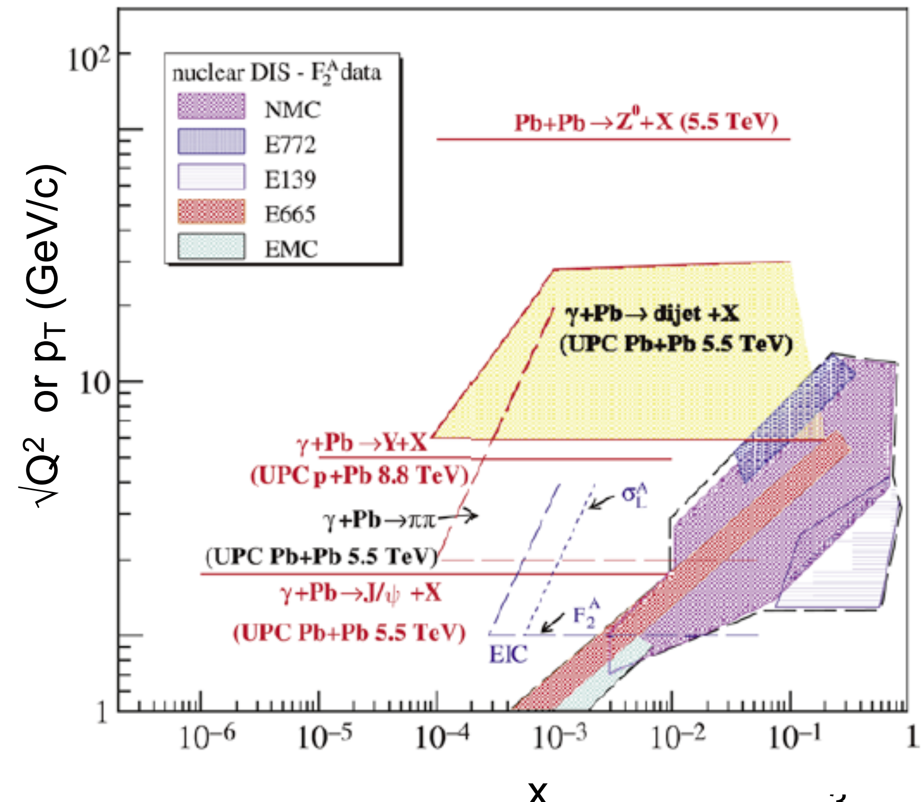
- Dilepton production (QED studies)
- Beyond standard model physics
  - Light-by-light scattering and axion-like particle searches
  - τ anomalous magnetic moment, magnetic monopoles etc.

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

Parton measurements: x and Q^2

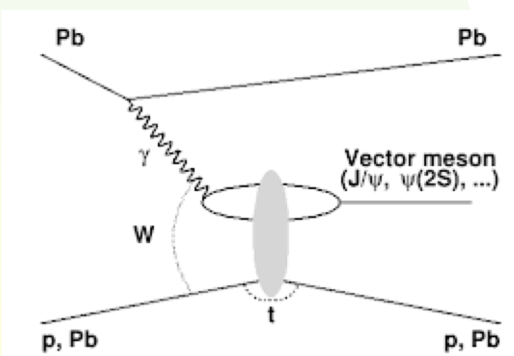
- Bjorken-x depends on final state mass and rapidity
  - For pp or AA, 2-fold photon directional ambiguity
    - $x=M_V/2\gamma M_p \exp(\pm y)$
    - Resolve ambiguity using VM accompanied by neutron emission or peripheral collisions, at a statistical cost
- Q^2 depends on probe
  - Vector meson: $Q^2 \sim (M_V/2)^2$
  - Dijets: $Q^2 \sim M_{jj}^2$
  - Open charm: $Q^2 \sim M_{cc}^2$
- 2008 predictions (right) ~ fulfilled
  - Except for Z^0
- Higher energy and far forward detectors can push downward in x
- RHIC can probe polarized protons

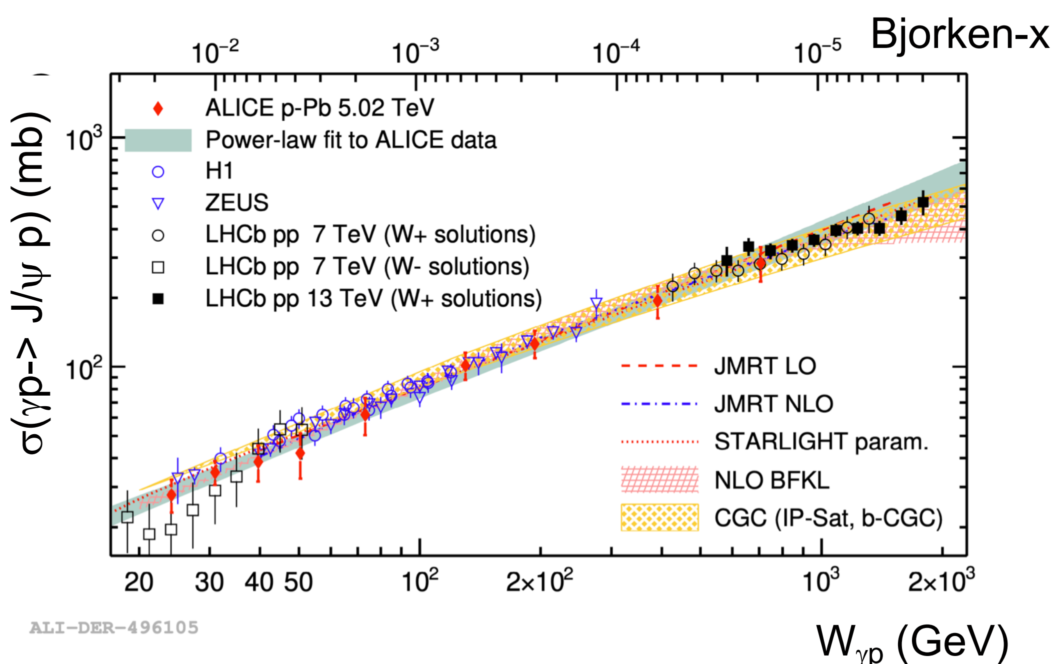


A. J. Baltz *et al.*, Phys. Rept. **458** (2008) 1

J/ψ photoproduction & gluon distributions in protons

- LHCb (in pp collisions) and ALICE (in pA collisions) data
- 2-gluon exchange -> $\sigma \sim g(x)^2$
  - Current data down to x ~ few 10^{-6} at $Q^2 \sim (M_{J/\psi}/2)^2$
- Consistent with a power law $\sigma \sim W_{\gamma p}^{\delta}$ (ALICE) or a slight downturn at high energies (LHCb)
  - At lowest order, the power law is equivalent to a power law for gluon density $xg(x) \sim x^{-\Delta}$
    - Shadowing should lead to a downturn
      - Visible at lower x?

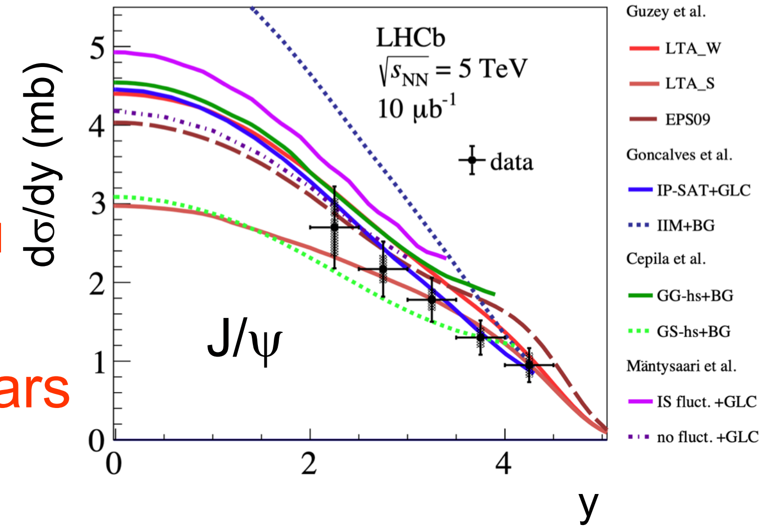


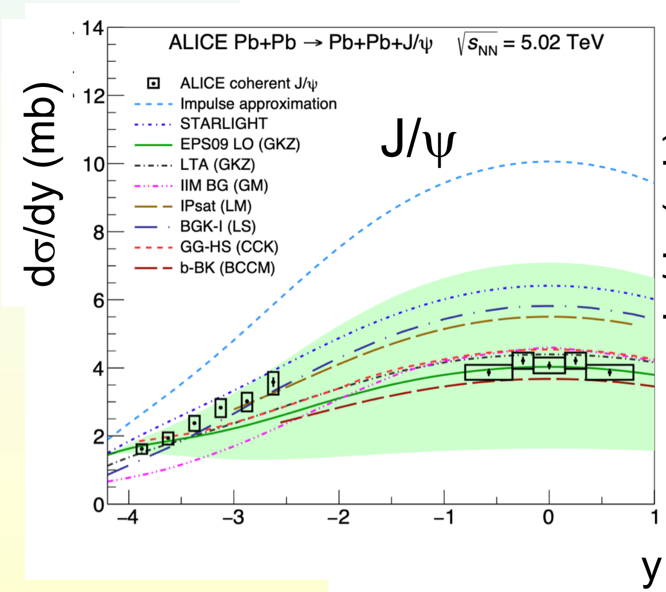


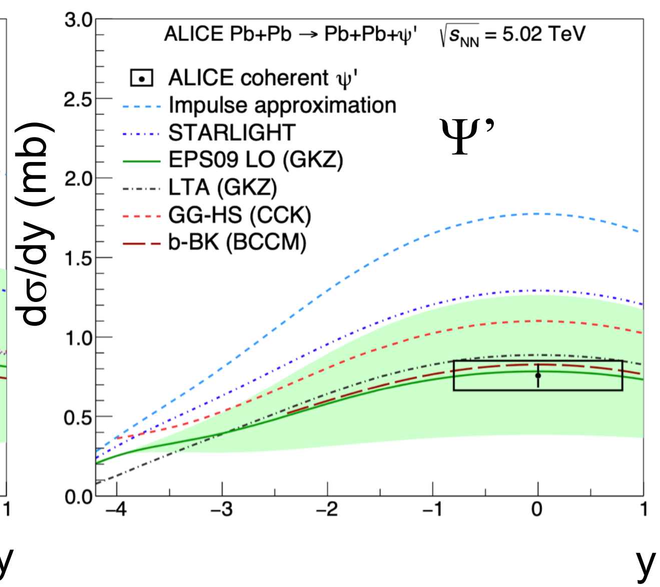
S. Ragoni, arXiv:2109.03066

Gluon shadowing in lead targets

- J/ψ and ψ' photoproduction
  - γp is implicit/explicit reference
- Moderate shadowing
- Consistent w/ leading twist approximation
- Near best-fit values of nuclear parton distribution but with much smaller error bars
- Consistent w/ many dipole model calcs.
  - Data on dσ/dt or studies with other mesons differentiate



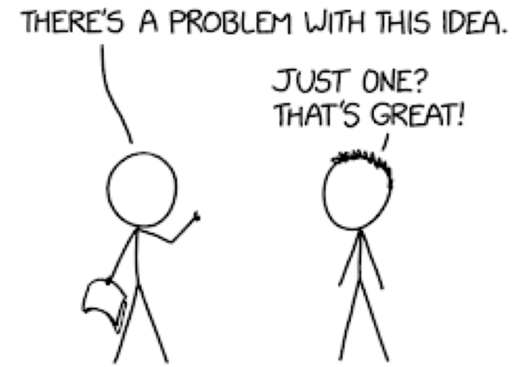


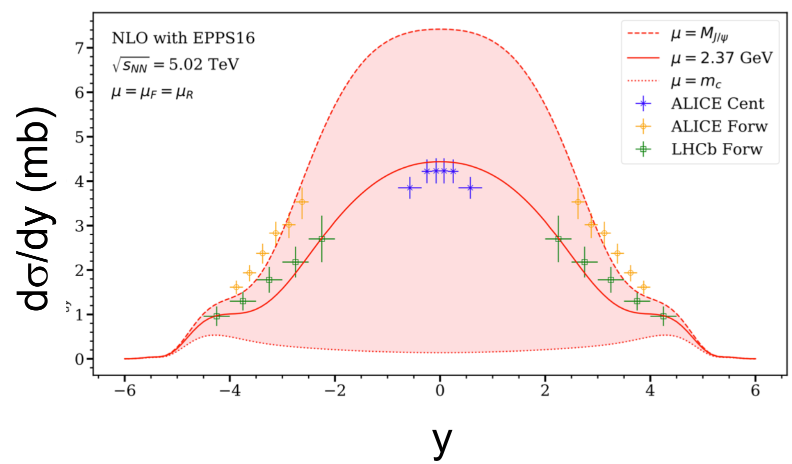


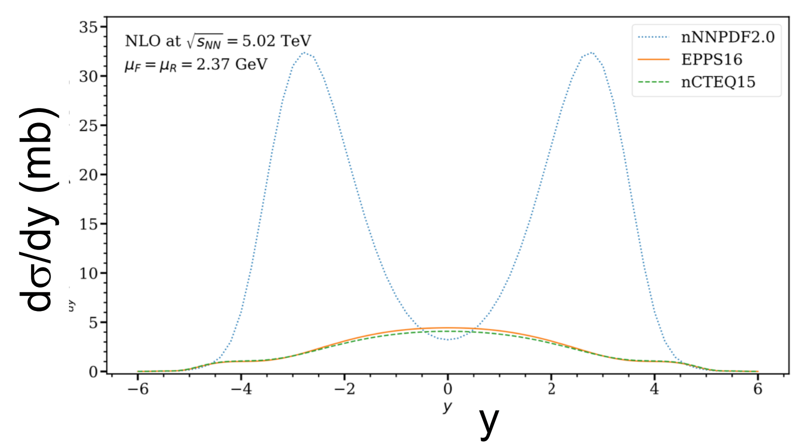
ALICE: Eur.Phys.J.C 81 (2021) 712; LHCb: JHEP 07 (2022) 117

Theoretical issues in vector meson photoproduction

- 2-gluon exchange is more complex than 1-gluon exchange
  - VMs really probe generalized (skewed) parton distributions
    - Shuvayev transform bridges the gap (with assumptions)
- A new next-to-leading order calculation brought many surprises, with large `corrections'
  - The quark contribution is significant
  - Large scale uncertainty
- These factors mostly cancel when comparing lead/gold and protons
- Despite these issues, vector mesons are an important probe of low-x gluons
  - Theoretical progress expected!







K. Eskola et al., arXiv:2203.11613; xkcd.com

Beyond gluon densities: 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)

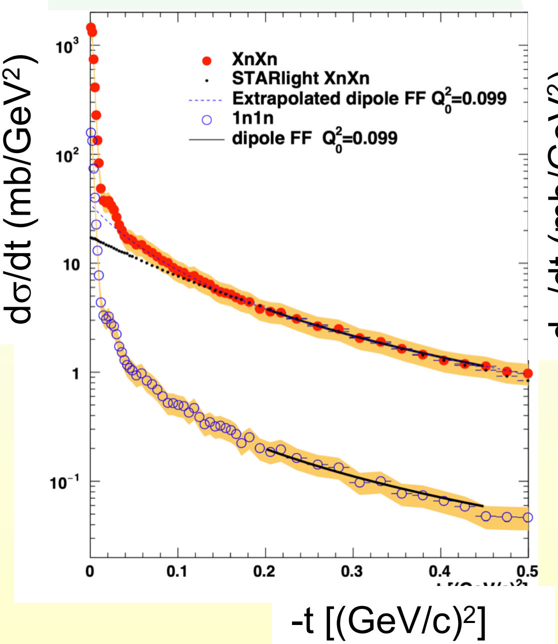
from dσ/dt to transverse profiles

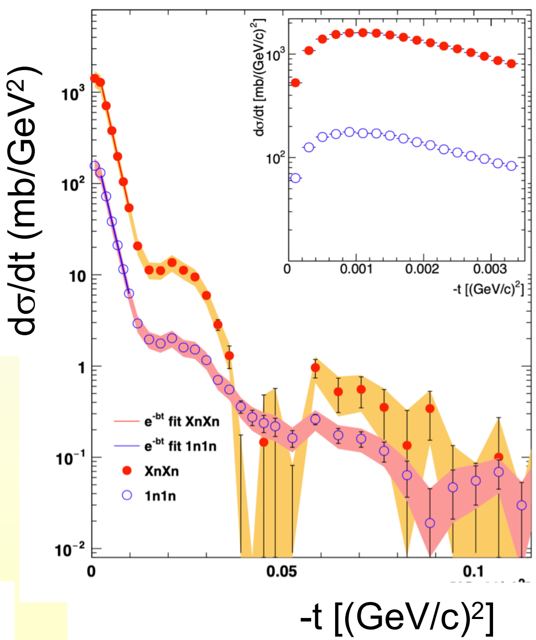
- $d\sigma/dp_T$ encodes the transverse distribution of interactions
  - The 2-d Fourier transform of $d\sigma/dt$ gives F(b)

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

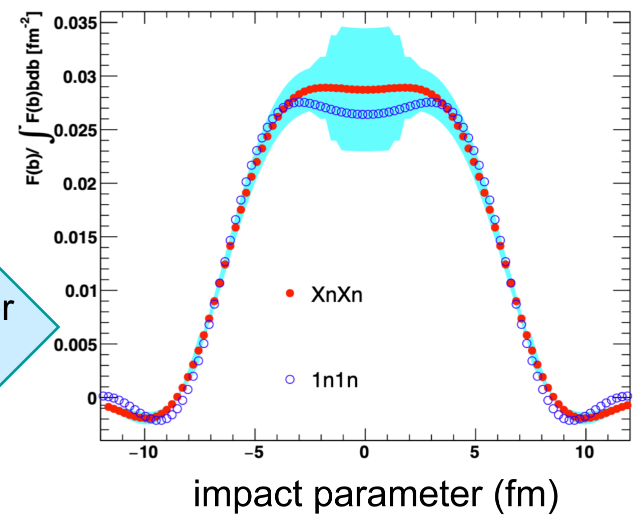
*flips sign after each diffractive minimum

- STAR fit $d\sigma_{incoherent}/dt$ for $\pi^+\pi^-$ at large |t| to a dipole form factor, extrapolated and subtracted, leaving $d\sigma_{coherent}/dt$
  - Large variation at small |b| is likely windowing (finite t range)
- Neglected photon p_T, bidirectional interference, & other factors, but this is a nice proof of principle





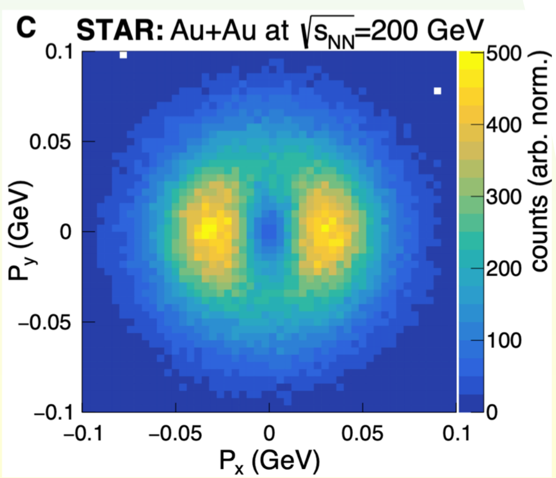
2d Fourier transform

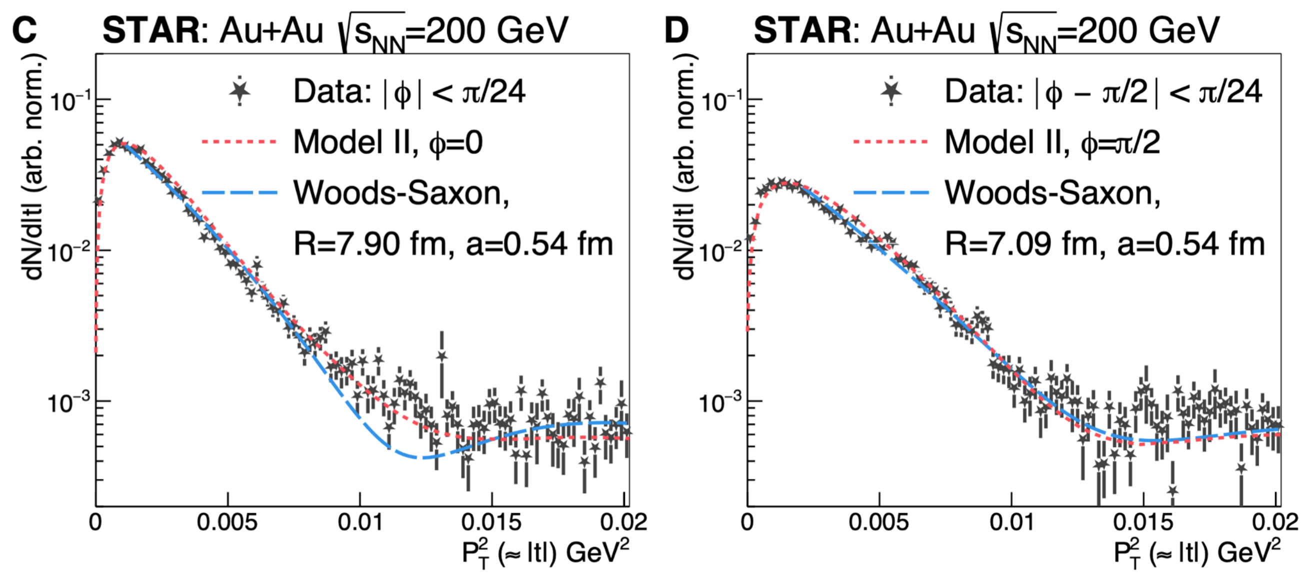


STAR, Phys. Rev. C**96**, 054904 (2017)

Fitting for the hadronic nuclear radius

- Fit $d\sigma/dt$ to a model, with a floating nuclear radius
  - Including interference between the two photon directions
    - -> angular correlation between ρ^0 p_T and pion daughter p_T
- Hadronic radius of ^{197}Au = 6.53 ± 0.03 (stat.) ± 0.05 (syst.) fm
  - -> Neutron skin thickness = 0.17 ± 0.03 (stat.) ± 0.08 (syst.) fm
- Hadronic radius of ^{238}U = 7.29 ± 0.06 (stat.) ± 0.05 (syst.) fm
  - -> Neutron skin thickness = 0.44 ± 0.05 (stat.) ± 0.08 (syst.) fm
- Precision measurements!

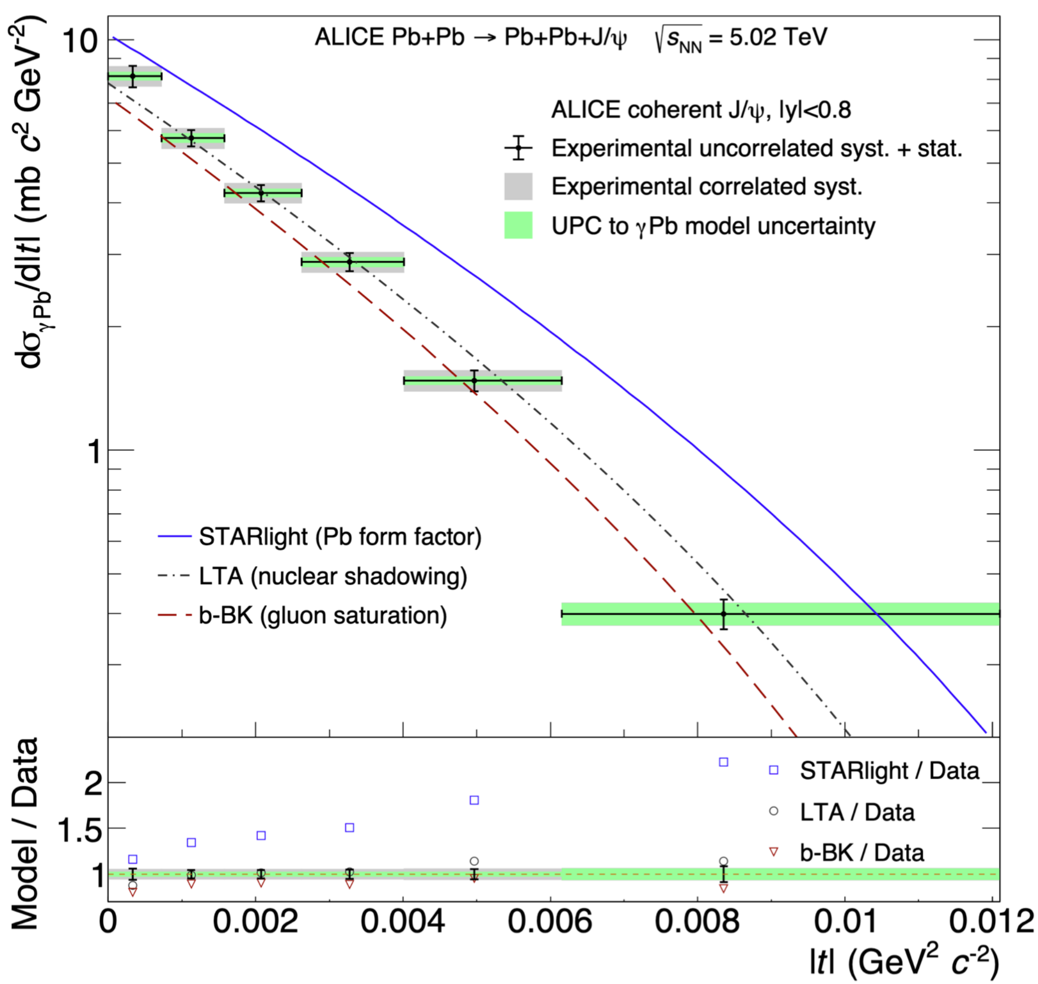




STAR, arXiv:2204.01625

dσ/dt for coherent J/ψ photoproduction

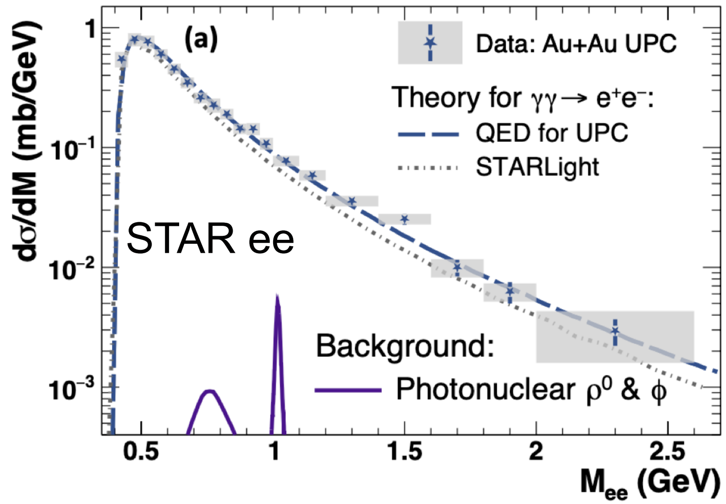
- Slope of dσ/dt measures effective target size
  - Multiple interactions in a target can lead to larger effective source sizes
- dσ/dt for coherent J/ψ falls off more steeply than the Woods-Saxon nuclear form factor
- Consistent with dipole-model calculations that include nuclear shadowing and/or gluon saturation
- $x \sim 5*10^{-4}$, $Q^2 \sim 2.25$ GeV^2

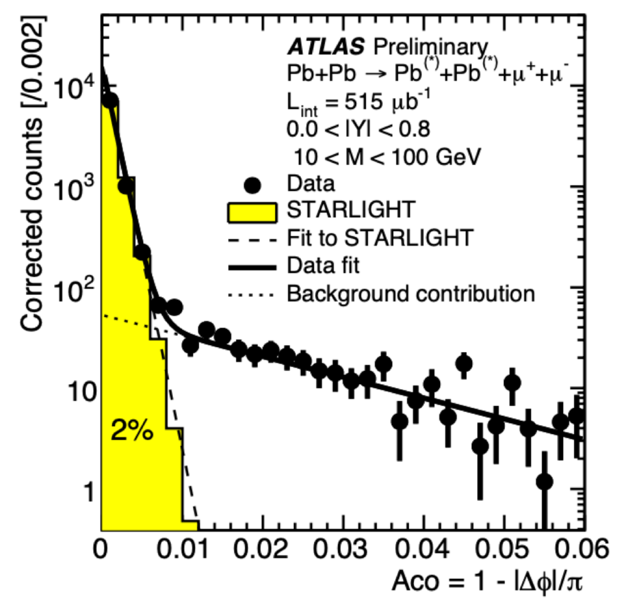


ALICE, Phys.Lett. B **817** (2021) 136280

γγ->dileptons

- High-statistics, precision measurements from STAR and ATLAS
- ”Observation of Breit-Wheeler scattering”
- Is lowest order QED good enough?
  - Coulomb corrections?
  - Is the ATLAS high-acoplanarity tail consistent with final state radiation?
    - Sudakov resumnation?
- important benchmark for testing/probing photon emission

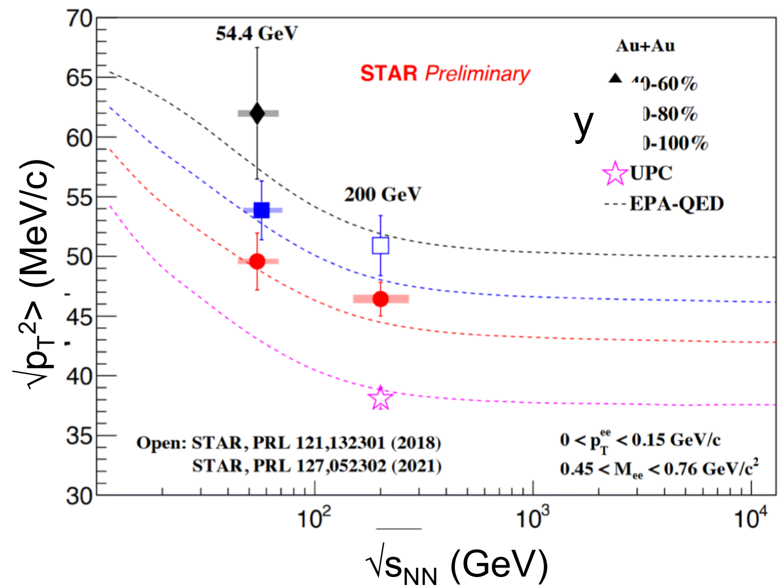




STAR, PRL 127, 052302 (2021); ATLA, S ATLAS-CONF-2016-025

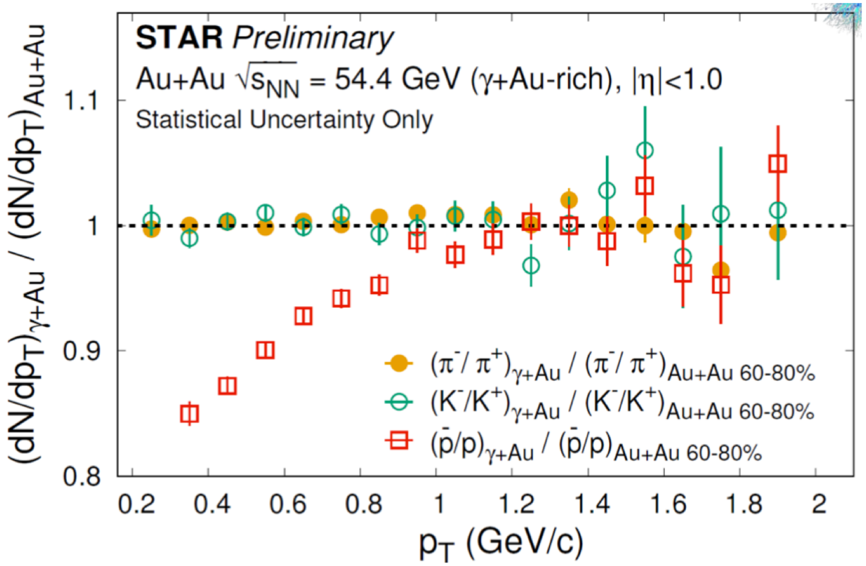
Photoproduction and γγ reactions in peripheral collisions

- Coherent J/ψ photoproduction and γγ->dileptons in peripheral collisions have been observed by STAR, ALICE, ATLAS & LHCb
- For γγ->ll, there is pair p_T broadening
  - b and p_T are conjugate; constraints on b -> larger $\langle p_T \rangle$
- Questions for J/ψ photoproduction,
  - Does the coherent target region include participants as well as spectators?
  - How do slow-moving long-lived J/ψ survive the expanding fireball?
- Coherent J/ψ production is an independent measure of the reaction plane.
  - Connection to hot QCD studies



γA/p reactions and baryon stopping

- In baryon junction models, baryon number is carried by a non-perturbative configuration: the baryon junction
- In these (and other?) models, baryon stopping can be explained by via the exchange of Reggeons which carry baryon number
- γA collisions are a simpler laboratory than AA
  - STAR measures the pbar:p ratio in γA collisions, and sees a drop at low p_T (compared to AA), consistent with baryon stopping
- Backward (u-channel) meson production at high energies
  - e. g. γp-> Vp,
    - proton at mid-rapidity,
    - V is far forward
  - STAR forward detector (?)or EIC



N. Lewis (STAR), RHIC/AGS Users meeting; J. D. Brandenburg et al., arXiv:2205.05685; D. Cebra et al., Phys. Rev. C 106, 015204 (2022)

The next 5 years

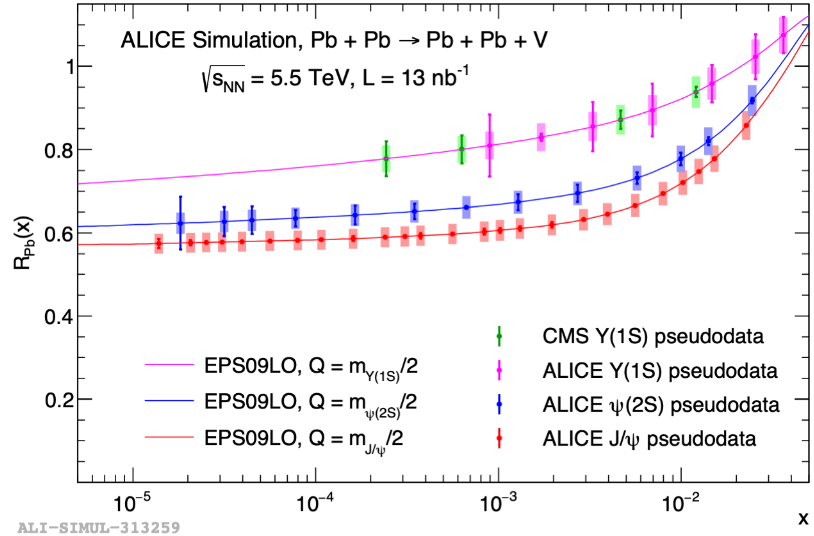
- LHC Runs 3 and 4 will provide a flood of new data
  - All experiments are undergoing significant upgrades
    - The ALICE streaming DAQ offers a huge improvement, by eliminating the main bottleneck for UPCs: the trigger
      - sPHENIX would have a similar advantage for UPCs
- Higher beam energies and more forward instrumentation reach down further in Bjorken-x
- Vastly improved statistics will allow much finer binning, rare decays, Υ states, searches for exotica etc.
-

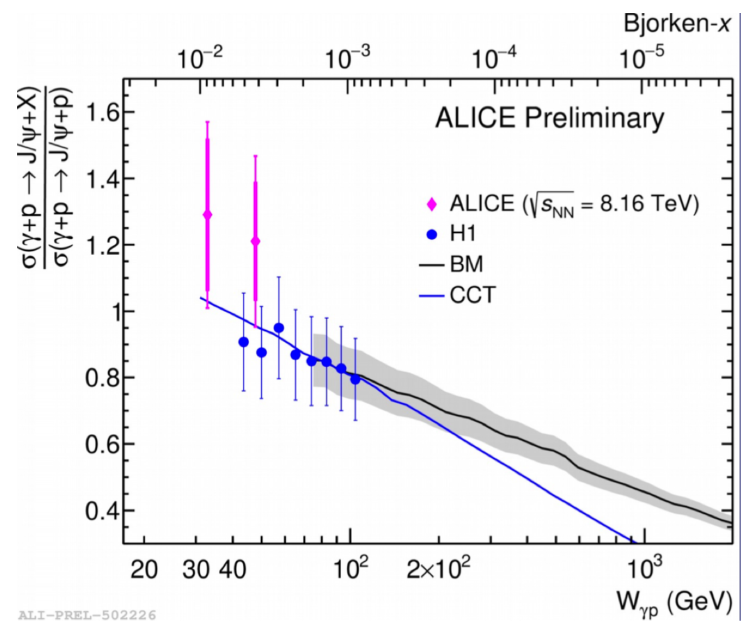
PbPb						
Meson	σ	All Total	~ALICE Central	~ATLAS/ CMS	~ALICE μ arm	~LHCb
$\rho \to \pi^+\pi^-$	5.2b	68 B	5.5 B	21B	4.9 B	13 B
$\rho' \to \pi^+\pi^-\pi^+\pi^-$	730 mb	9.5 B	210 M	2.5 B	190 M	1.2 B
$\phi \to \mathrm{K}^+\mathrm{K}^-$	0.22b	2.9 B	82 M	490 M	15 M	330 M
$\mathrm{J}/\psi \to \mu^+\mu^-$	1.0 mb	14 M	1.1 M	5.7 M	600 K	1.6 M
$\psi(2\mathrm{S}) \to \mu^+\mu^-$	30μb	400 K	35 K	180 K	19 K	47 K
$\Upsilon(1\mathrm{S}) \to \mu^+\mu^-$	2.0 μb	26 K	2.8 K	14 K	880	2.0 K

Z. Citron et al., arXiv:1812.06772

Vector mesons – the next 5 years

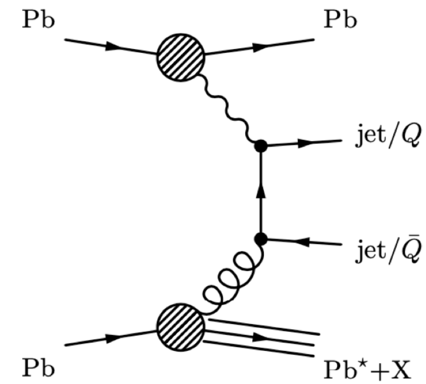
- Much improved measurements of cross-sections and dσ/dt for coherent and incoherent production of multiple vector mesons
  - Q^2 from vector meson masses
  - Radius measurements over a range of x and Q^2
  - Nuclear fluctuations, from geometric fluctuations and nuclear hot spots
    - 1st LHC data shown at right
- Better theory, especially regarding soft nuclear breakup
- A few more nuclei
  - Oxygen may allow the measurement of incoherent dσ/dt over the full t range



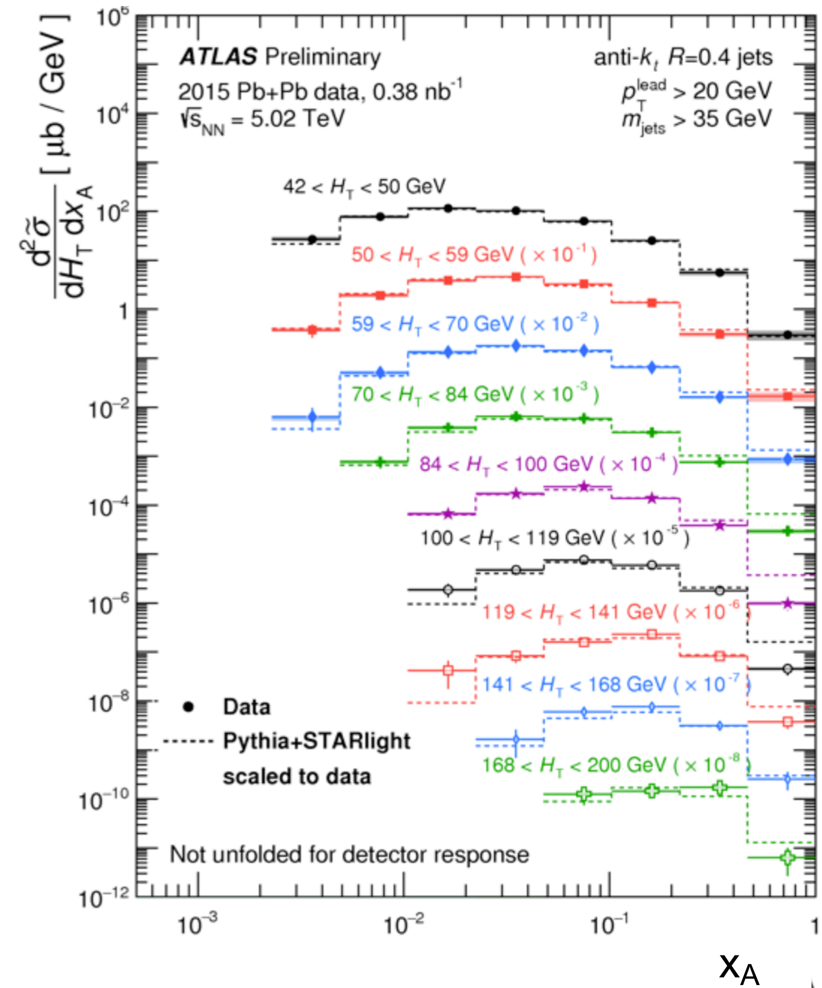


Z. Citron et al., arXiv:1812.06772 V. Pozdynakov (ALICE), Moriond 2022

Dijets and open charm



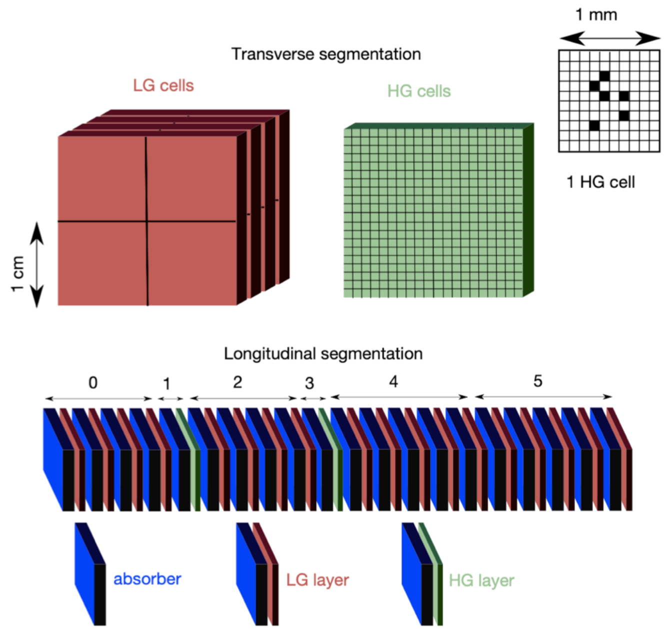
- Dijets and open charm are produced via single gluon exchange, so there is less theoretical uncertainty
- $Q^2 \sim M_{jj}^2$ or M_{cc}^2
- ATLAS preliminary dijet results (from QM2017) look promising, covering a wide range of x, Q^2
  - Also CMS results on asymmetries
- Open charm has high rates, and can reach lower x and Q^2 values than dijets
- Several experiments are pursuing dijets and/or open charm
  - Good progress expected over next 5 years

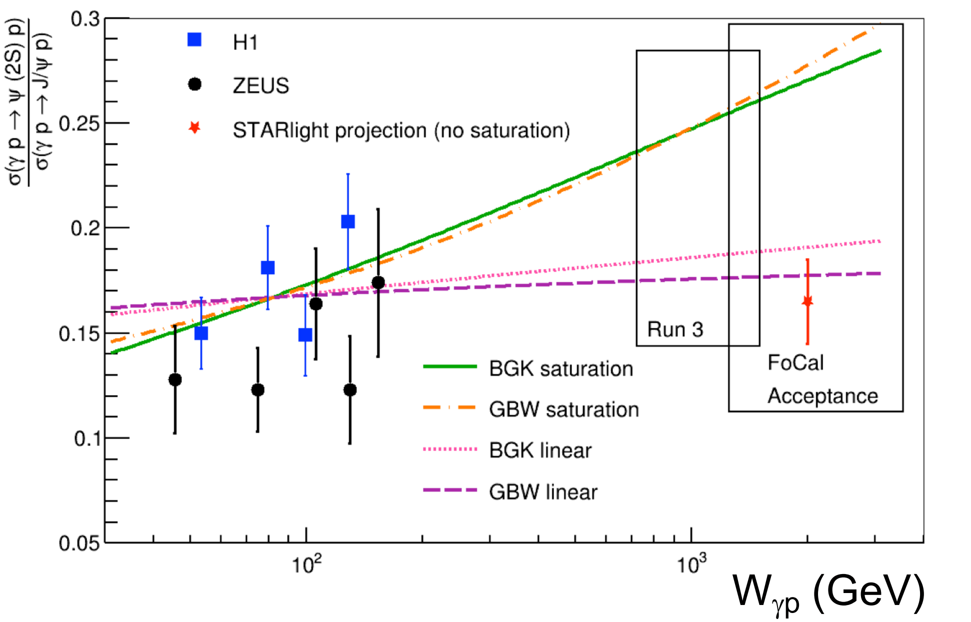


ATLAS, Quark Matter 2017

The ALICE FoCal

- A forward calorimeter to study low-x partons
  - ~ $2.3 < \eta < 5.8$
  - Highly segmented
- J/ψ and ψ' photoproduction
  - Larger $|\eta|$ -> Lower x
  - J/ψ reach below 10^{-6}
- The ψ':J/ψ ratio is sensitive to saturation models

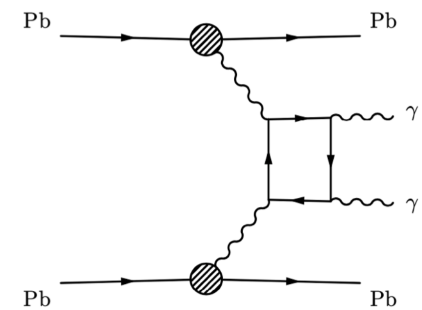


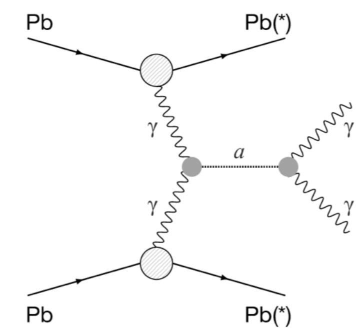


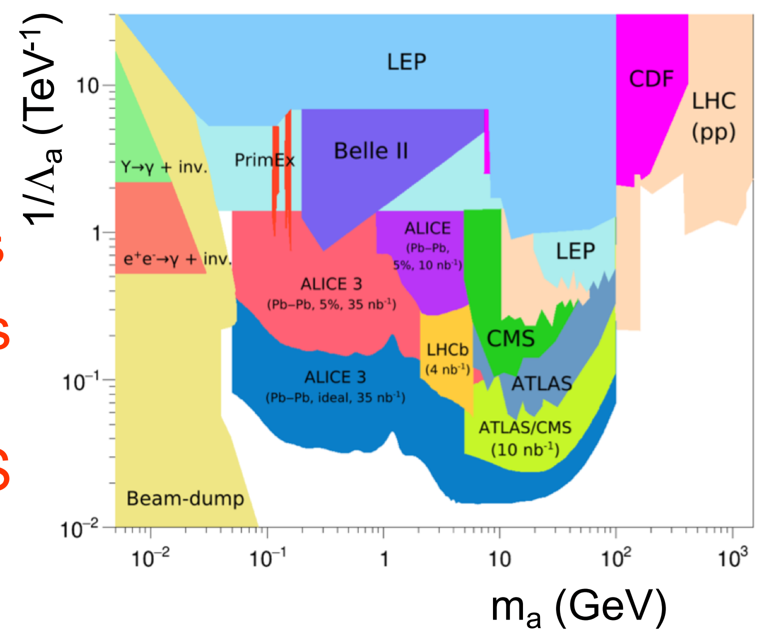
A. Bylinkin et al. "UPC measurements with FoCal", in preparation.

Light-by-light scattering

- Box diagram is sensitive to all charged particles, standard model and BSM
  - Seen by ATLAS and CMS
  - Cross-section will set limits on BSM processes
- An axion-like particle produces a peak in $M_{\gamma\gamma}$ at the axion mass
  - ATLAS and CMS have set 2-d limits: coupling and axion mass
- With higher luminosity, CMS and ATLAS will search for axions with lower couplings
- ALICE 3 (and maybe ALICE) will set limits on lighter ALPs, filling in the gap between fixed-target experiments and CMS/ATLAS



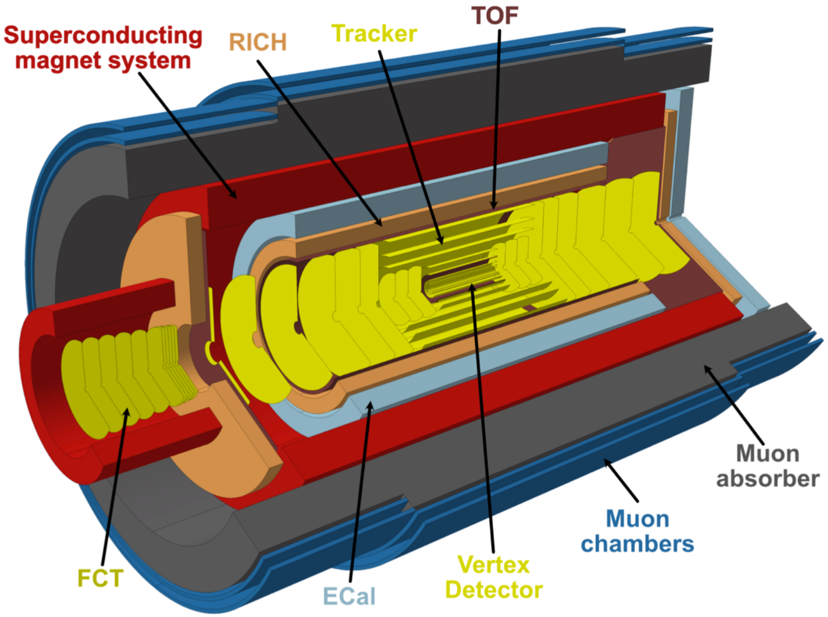


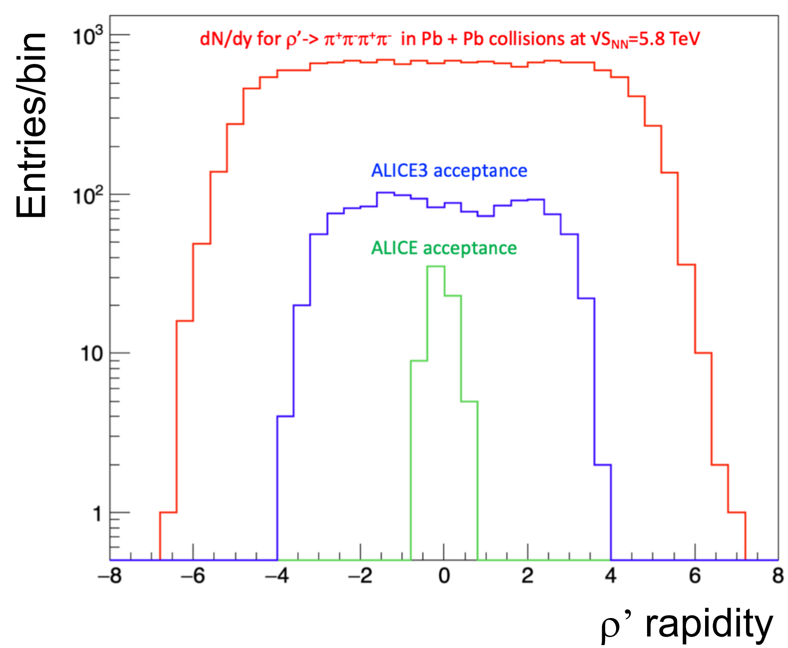


ATLAS JHEP 03 (2021) 243; D. D'Enterria (CMS) arXiv:1808.03524; ALICE 3 LoI

ALICE 3

- A large-acceptance general purpose heavy-ion detector
  - $-4 < \eta < 4$
  - Charged and neutral particles down to low p_T
  - PID
  - Low radius vertex detector
- Large acceptance more complex UPCs
  - Dijets, open charm, 4/6/+ prong events, final states with photons
  - $\rho' \to 4\pi$ acceptance is 19 times that of current ALICE
  - $d\sigma/dy$ over wide range
- Much improved background rejection
  - Key for $\gamma\gamma \to \gamma\gamma$ at low $M_{\gamma\gamma}$
- Installation for Run 5; data in ~ 2035

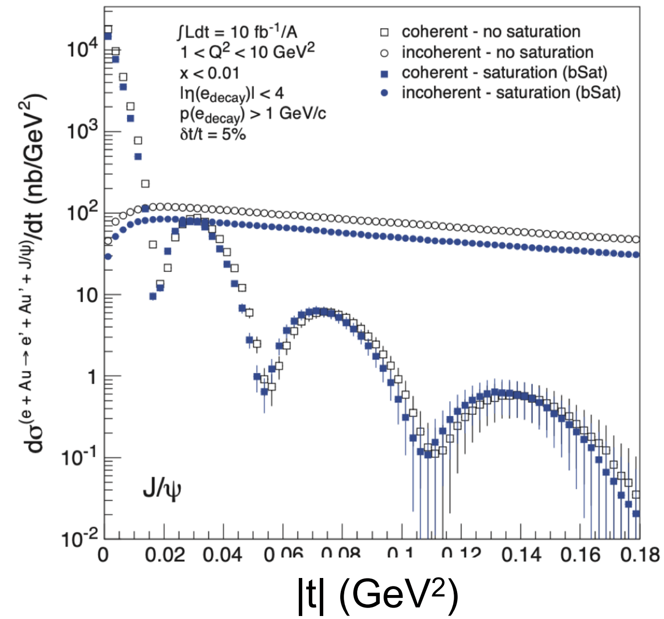


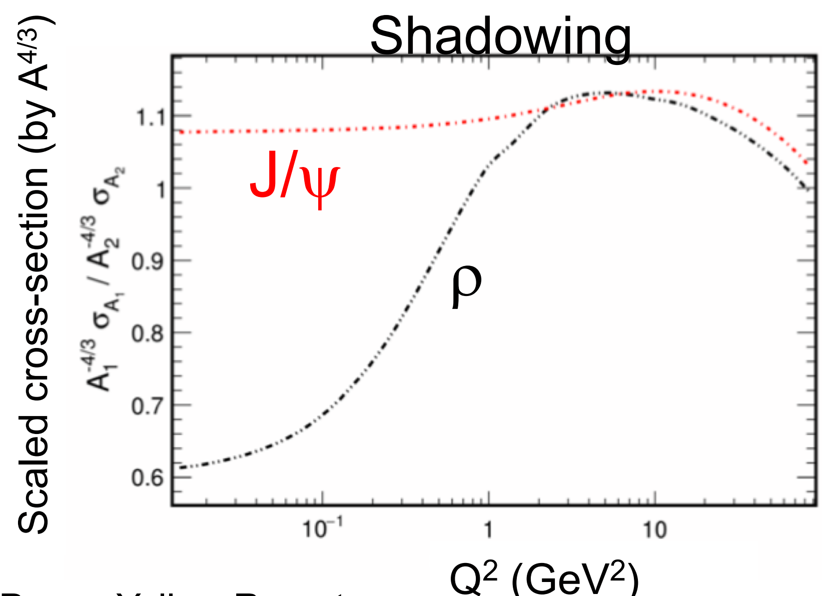


ALICE 3 LoI

The EIC (a UPC-centric perspective)

- Study vector meson photoproduction under diverse conditions
  - Systematic mapping of many different vector mesons w/ different wave functions
  - Wide range of photon Q^2
  - Good forward instrumentation to effectively separate coherent and incoherent production
    - Was the nucleus excited?
    - Map out transverse distribution of gluons in nuclei
- Multiple other probes of gluons:
  - Open charm
  - Dijets
  - Evolution of structure functions…





EIC White Paper, Yellow Report

UPCs in the EIC era

- The EIC will collect high-precision data on the production of a wide range of vector mesons at a wide range of Q^2
  - With excellent subsystems to detect the products of nuclear breakup, to separate coherent and incoherent production.
- Even during the EIC era, there is still a need for UPCs, to:
  - Probe partons down to the lowest Bjorken-x values
    - $x < 10^{-6}$ for protons
    - $x < 10^{-5}$ for nuclei
    - Precision shadowing measurements and test for saturation
  - Photoproduction of heavy hadrons
  - Study BSM physics
    - $\gamma\gamma \rightarrow \gamma\gamma$, BSM charged particles and limits on axion-like particles
    - $\gamma\gamma \rightarrow \tau^+\tau^-$ and the tau anomalous magnetic moment
  - $\gamma\gamma \rightarrow$ heavy exotic hadrons
- ALICE 3 will provide an enormous boost to UPC studies

Some things I do not have time to discuss….. UPCs are a technique that gives access to a very wide range of topics

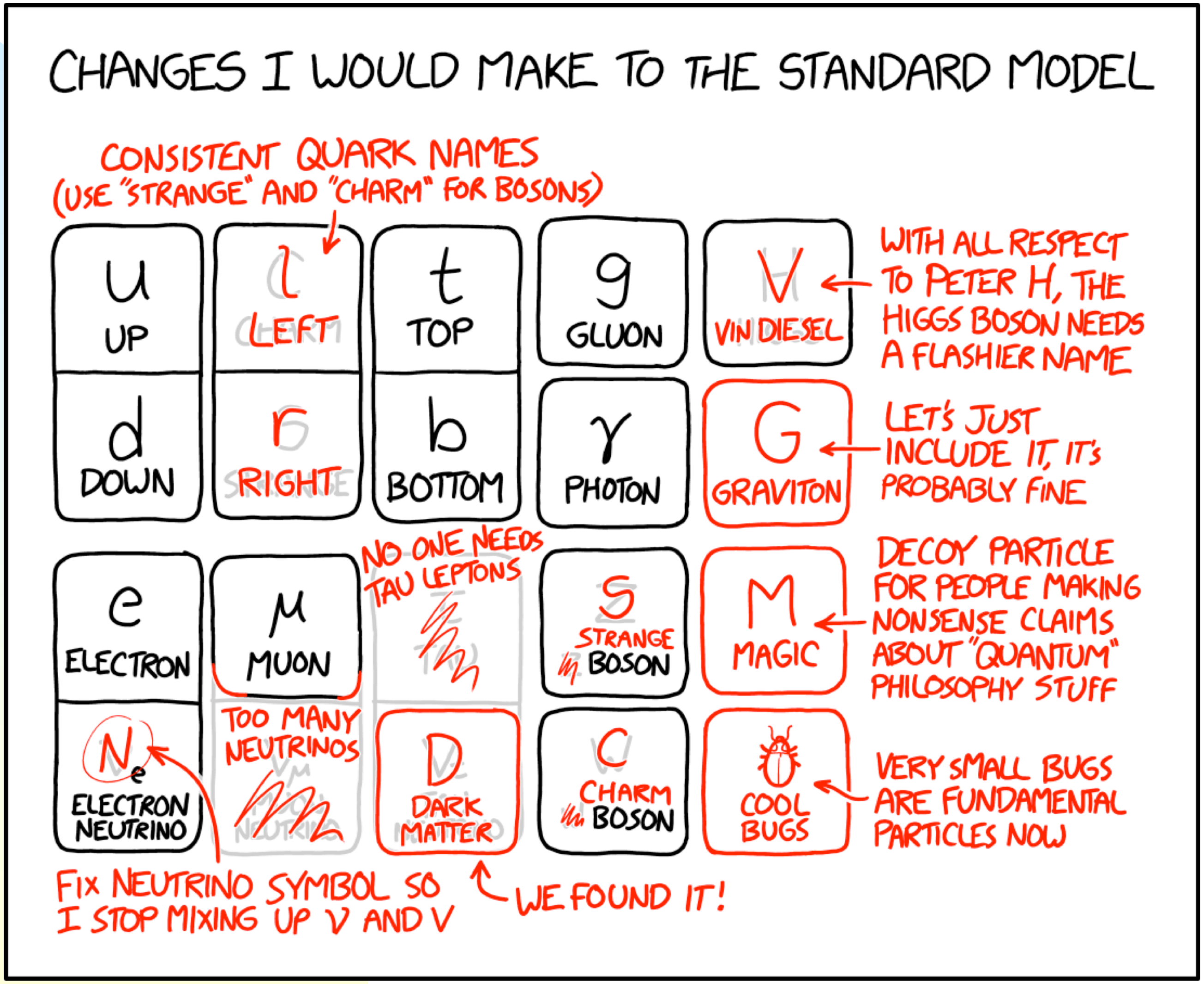
- Limits on an anomalous τ magnetic moment from $\gamma\gamma$ -> $\tau^+\tau^-$
- Measurements of azimuthal asymmetry in γA collisions (STAR and ATLAS)
- Other vector mesons (ϕ, ρ', Υ states)
- A-scaling of ρ photoproduction (ALICE: Xe and Pb)
- J/ψ photoproduction on deuteron targets (STAR)
- J/ψ production w/ proton dissociation on proton targets (ALICE)
- Coulomb excitation in UPCs (ALICE)
- A possible future small very-low-threshold (10 MeV?) ALICE forward calorimeter for testing Low's theorem, including in UPCs
- Use of interactions with Coulomb excitation for impact-parameter engineering

Conclusions and future prospects

- **UPCs probe low-x parton distributions, study baryon stopping in simple systems and probe BSM physics**
- In the next ~ 5 years, STAR and the LHC experiments will*:
  - Map the target distribution in nuclei, and better probe event-by-event fluctuations in nuclear configuration, at different x and Q^2
    - Multiple probes – vector mesons, dijets and open charm
  - Study baryon stopping and other aspects of 'general' γA collisions
  - Probe BSM physics via light-by-light scattering and set limits on axion-like particles
- The EIC and UPCs are complementary, respectively providing precision measurements for different photon Q^2 and probes of very-low x gluons. Both are needed.
- (My) UPC future priorities are:
  - Trigger bandwidth and resources to analyze data
  - New instrumentation, including FoCal and ALICE 3
    - FoCal reaches gluons with the lowest x values
    - ALICE 3 will have more than ten times better performance than ALICE 2

* I do not know of sPHENIX plans to study UPCs

And finally…



xkcd.com