J/ψ photoproduction and γγ-> ee in peripheral collisions

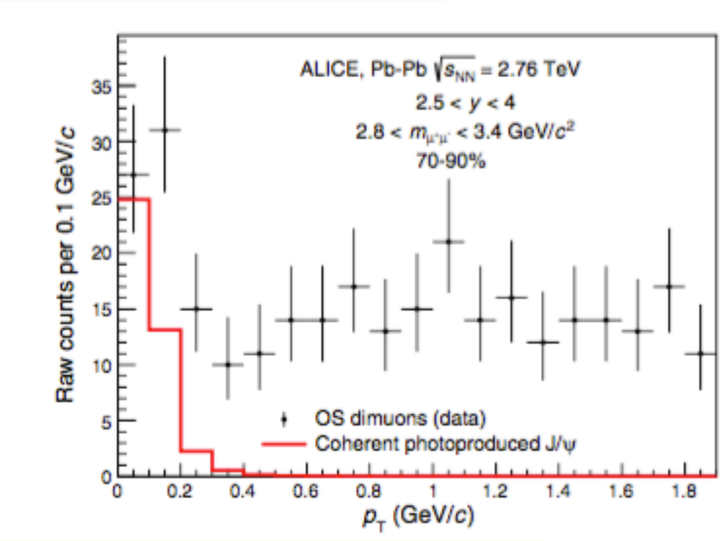
Spencer Klein, LBNL

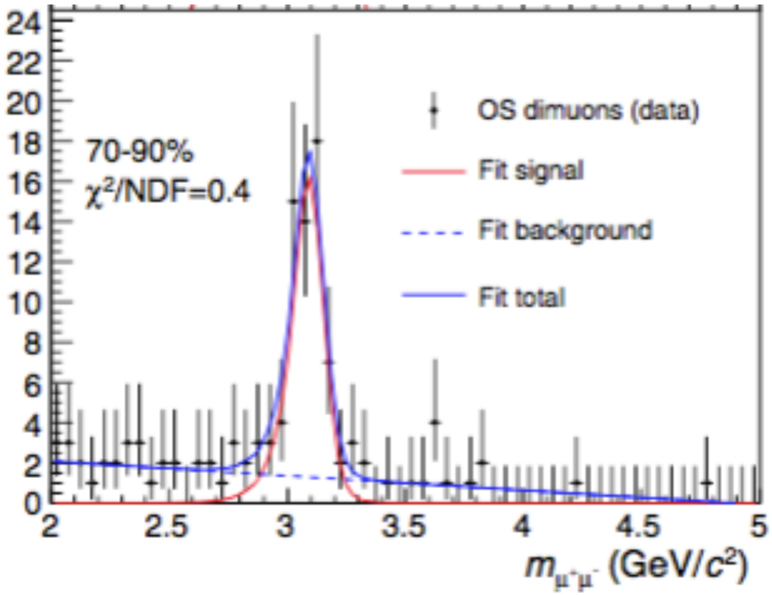
- The low p_T excess in peripheral collisions
- Coherent photons from heavy ions
- J/ψ photoproduction
- J/ψ photoproduction in peripheral collisions
- γγ -> ee
- γγ -> ee in peripheral collisions
- What can we learn about the hadronic medium
- Conclusions

presented at the LBNL Heavy flavor workshop, Oct. 30 – Nov. 1, 2017

ALICE J/ψ–> $\mu^+\mu^-$ excess

- J/ψ excess for pT < 100 MeV/c in peripheral collisions
  - Magnitude is significant 70-90% centrality larger R_{AA}
- Low p_T peak not expected for any hadronic mechanism
  - Consistent with coherent photoproduction
- Seen at forward rapidity, 2.5 y < 4

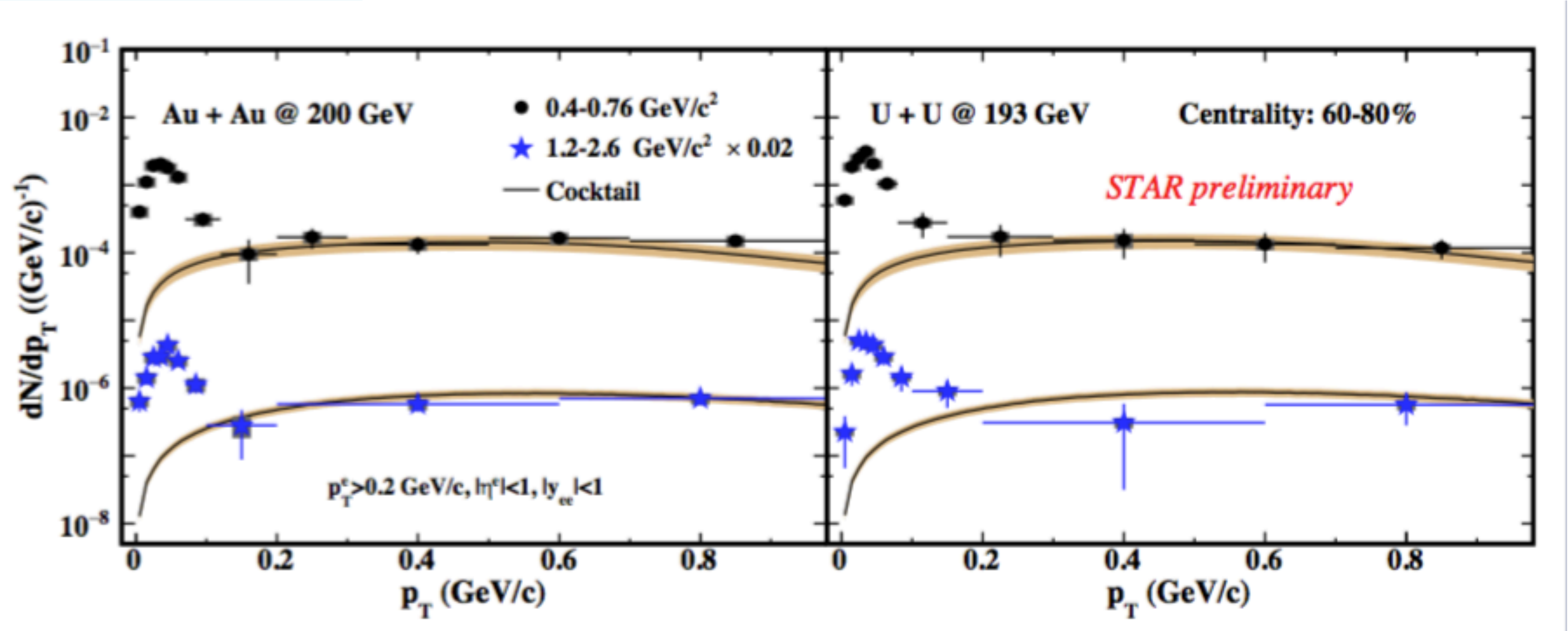




ALICE, PRL 116, 222301 (2016)

STAR low p_T e^+e^- excess in AuAu & UU

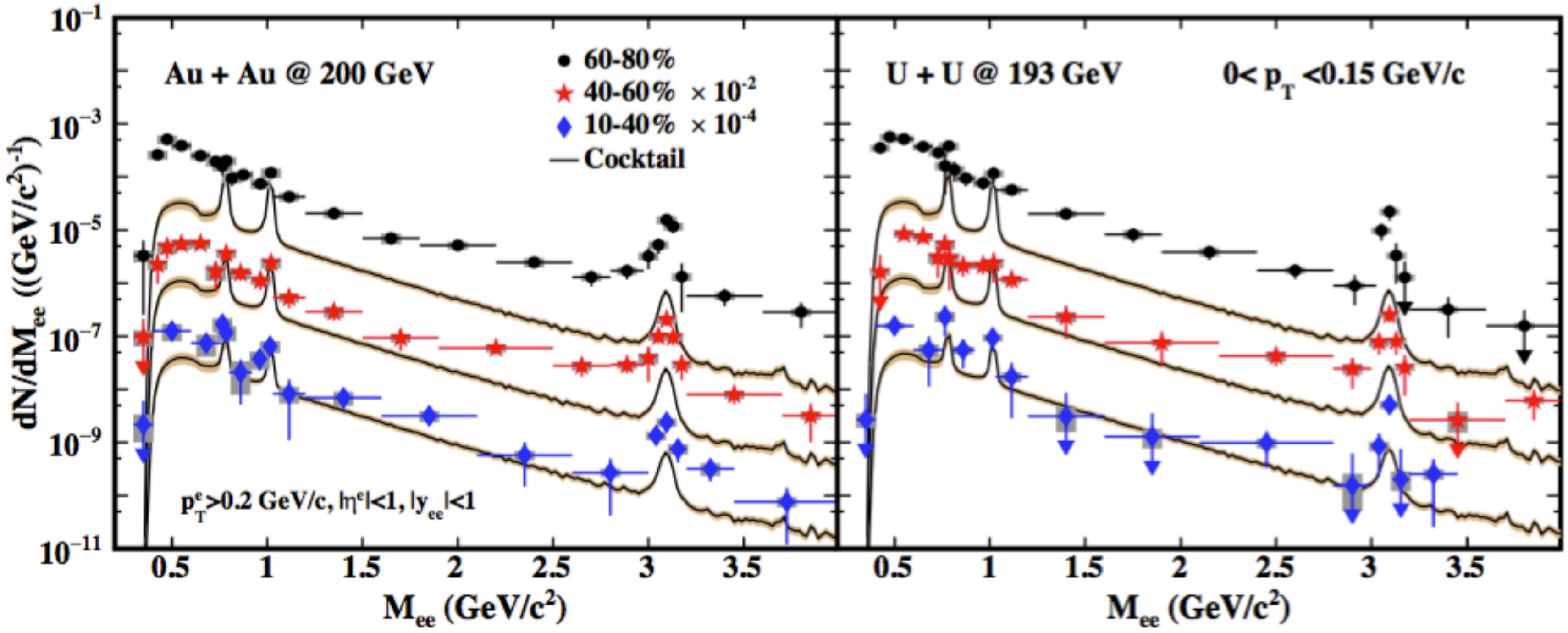
- Excess over hadronic cocktail for $p_T < 150$ MeV/c
- Excess is only for pT < 150 Mev/c
  - p_T spectrum similar to ALICE



S. Yang [STAR], QM17

STAR Au-Au + U-U mass spectra

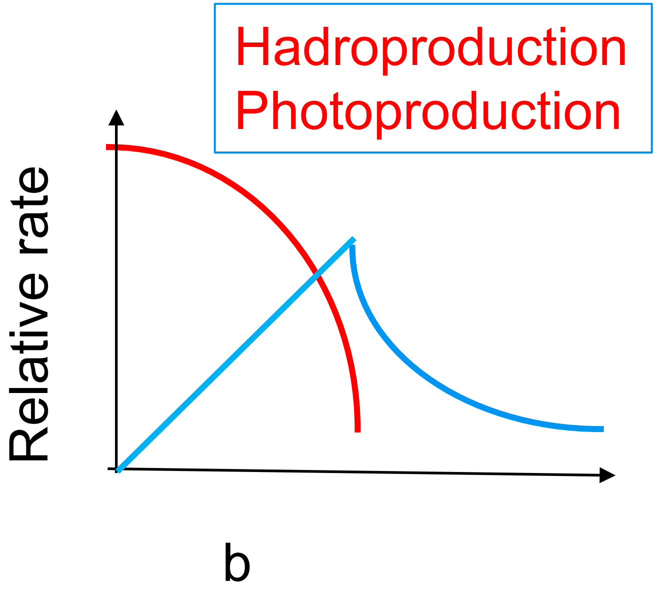
- J/ψ + e^+e^- continuum from 0.4 to 4 GeV/c
  - No clear φ, ω, ρ excess
  - Relative excess is largest in 60-80% centrality
    - Drops as impact parameter->0.

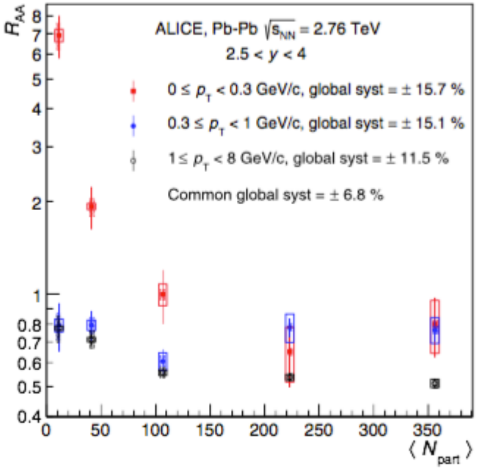


S. Yang, QM'17

R_{AA} for photonic interactions

- R_{AA} not optimum term
  - Different production mechanisms have different scaling
    - $\gamma\gamma$ -> ee scales as Z^4
    - γA -> J/ψ A scales as Z^2A^2
- Photon flux is highest around nuclear periphery
- Photoproduction is largest in the most peripheral collisions
  - Drops sharply with decreasing radii
  - Drops more slowly with increasing radii
  - $\gamma\gamma$-> ee has fairly little |b| dependence
- R_{AA} varies rapidly with centrality

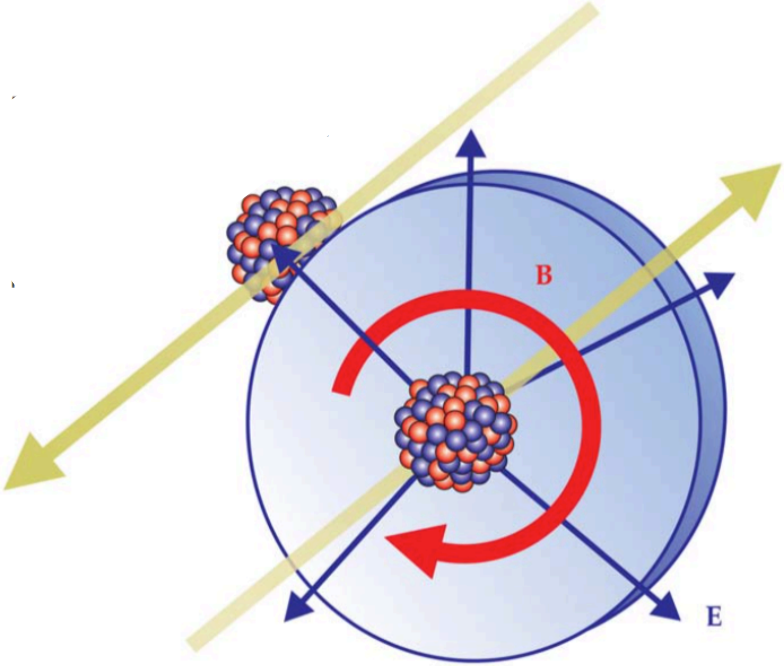




ALICE, PRL 116, 222301 (2016)

Photons from nuclei

- Crossed E and B fields -> photons
  - Usually, neglect photon virtuality
- Photon energy spectrum is the Fourier transform of E(M) field, as seen at impact parameter b
  - Photon wavelength > width of EM 'pancake'
  - $k_{max} \sim \gamma hc/b$
    - Most energetic photons are right near nucleus
- Soft threshold $k_{max} \sim \gamma hc/R_A$
- Photon flux drops off rapidly inside the nucleus
  - Gauss' Law

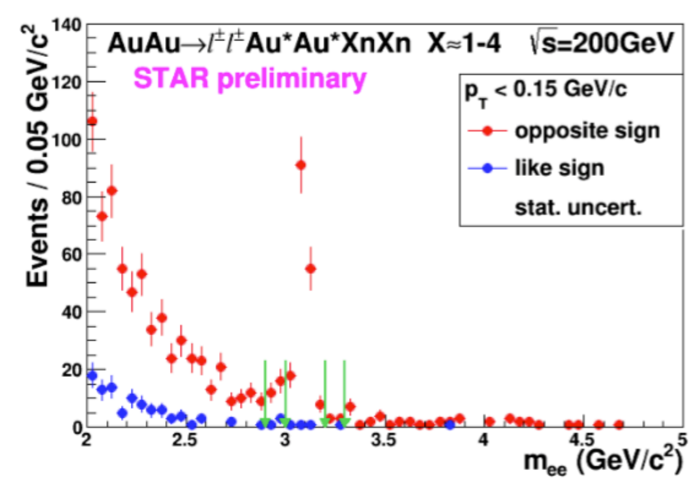


$$\boxed{n(k,b) = \frac{d^3N}{dkd^2b} = \frac{Z^2\alpha}{\pi^2 kb^2}x^2K_1^2(x)}$$

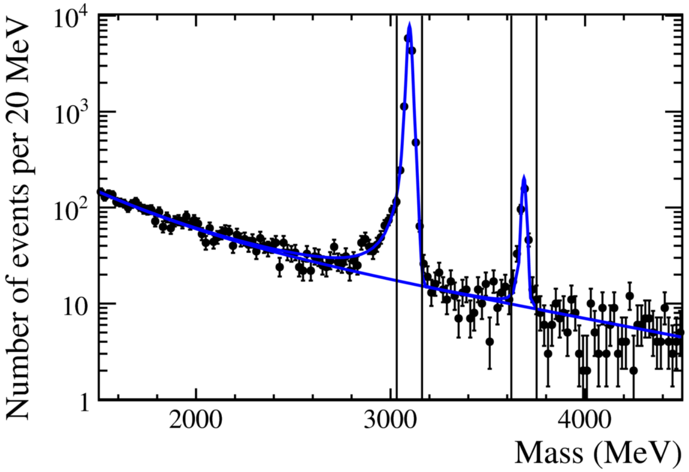
$x = bk/\gamma$.

J/ψ photoproduction in UPCs (b>2R_A)

- Convolute photon flux with $\sigma(\gamma A(p) \to J/\psi A(p))$
  - Subject to two-fold ambiguity in photon direction
    - $k = M_V/2 \exp(\pm y)$
- Proton target data from pp or pA (mostly p target)
- Heavy ion target data from AA
- Data from STAR, ALICE, CMS and LHCb



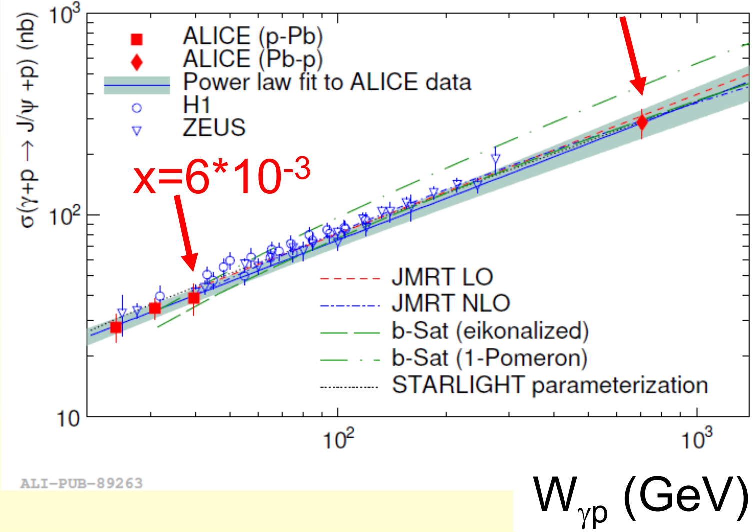
W. Schmidke [STAR], DIS 2016



R. McNulty [LHCb] ICHEP 2016

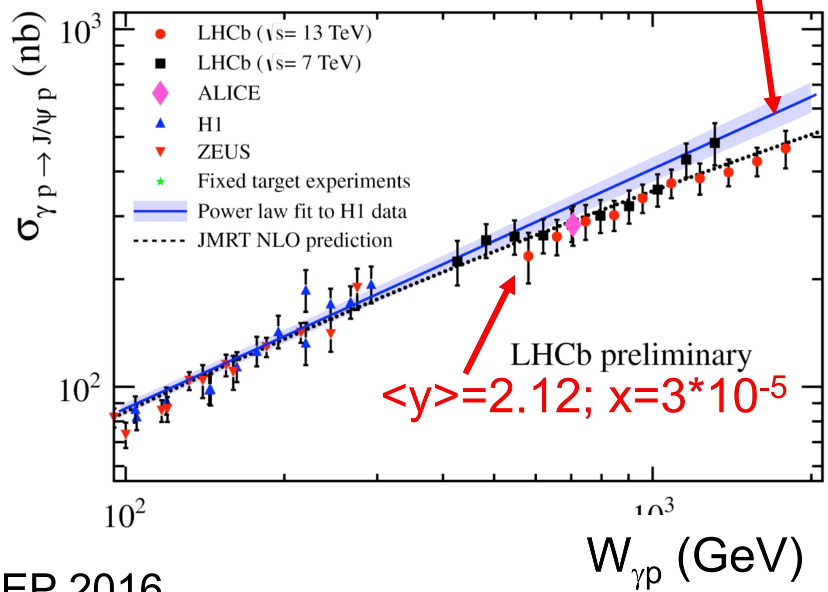
$\sigma(\gamma p \to J/\psi\ p)$ in pA and pp UPCs

- Data up to $W_{\gamma p}$= 1.5 TeV -5 times the HERA maximum
- ALICE & LHC-b see good pA agreement with HERA data
- LHCb 13 TeV-beam data somewhat below 7 TeV data?
  - LHCb uses bootstraps from HERA range for 2-fold ambiguity
  - 13 TeV data supports NLO contribution to cross-section
- J/ψ photoproduction is well understood here
  - Also ψ', Υ



$x=2*10^{-5}$

$x=6*10^{-3}$



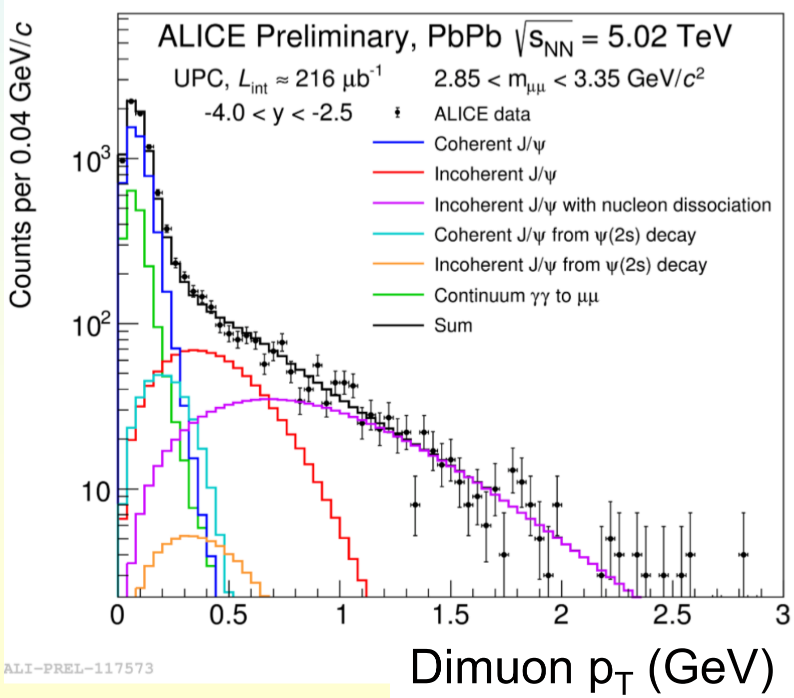
$\langle y \rangle$= 4.37; $x=3*10^{-6}$

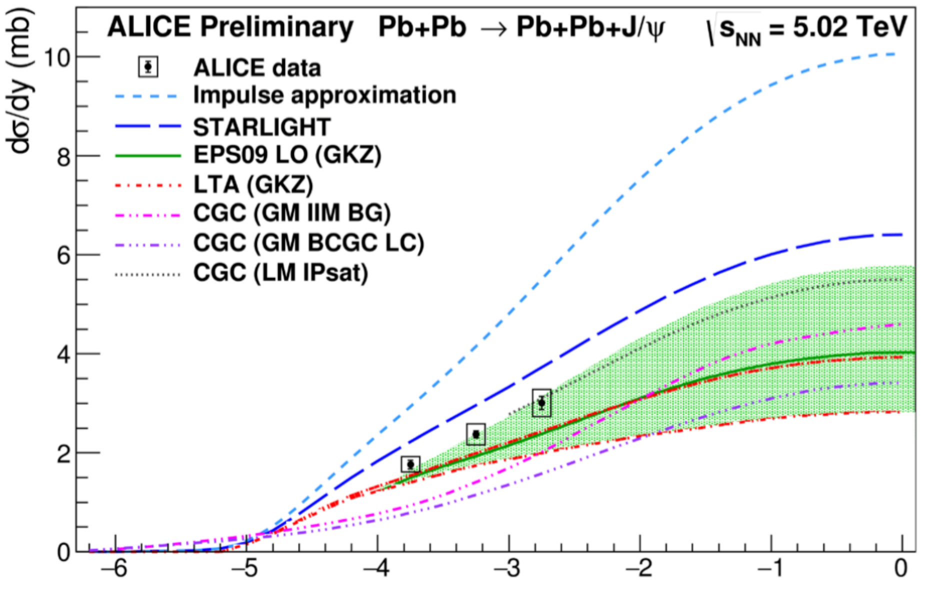
$\langle y \rangle$=2.12; $x=3*10^{-5}$

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

ALICE PbPb-> J/ψ at $\sqrt{s_{NN}}$=5.02 GeV

- p_T spectrum measured out to 2.5 GeV/c
  - Coherent (Pb), incoherent (single N) & nucleon dissociation seen
- $\sigma_{coherent}$ ~ 80% of ‘no shadowing’ expectation
  - Consistent with EPS09 model
  - Consistent with leading twist approximation
    - A $q\bar{q}$ dipole may interact with multiple nucleons in a heavy target

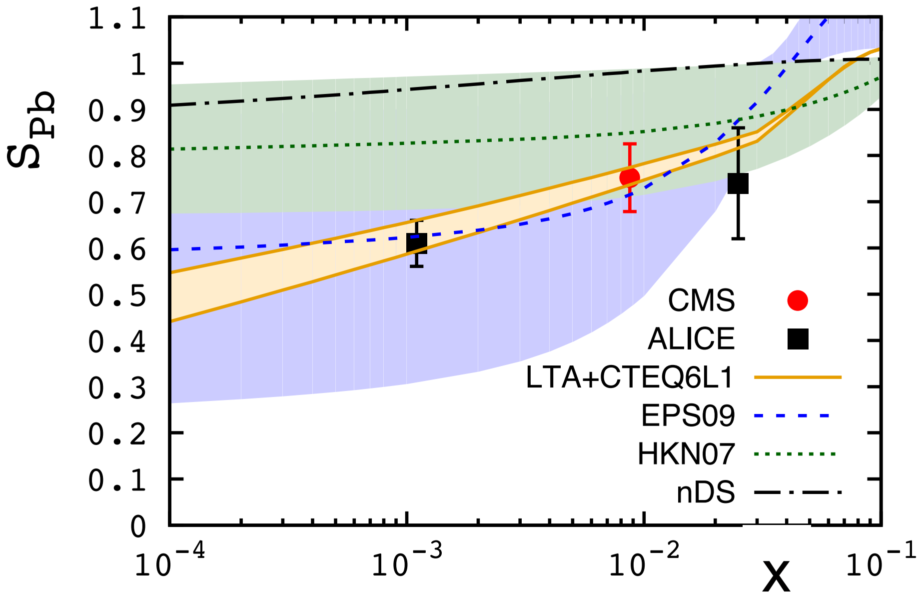




E. Kryshen [ALICE], QM17

Nuclear Shadowing

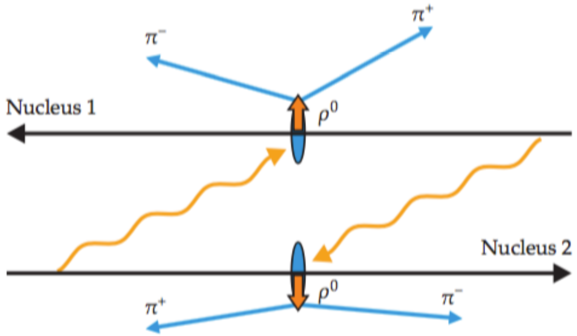
- Compare ALICE & CMS data with PDF shadowing models
  - Use impulse approximation for proton reference
    - Normalize to HERA data to correct for higher order terms
    - 6 different parton distributions
- Consistent w/ 2012 leading twist approximation calculation
  - Except for MNRT07 parameterization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



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

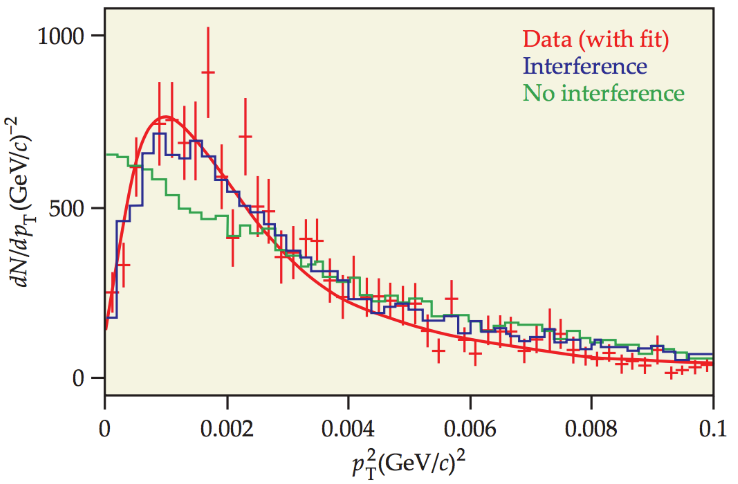
The p_T spectrum & interference

- p_T spectrum is set by the coherence conditions
  - The phase factor in $\sigma = |\Sigma_i A_i \exp(ikr_i)|^2$
  - Sum over target positions i
    - Coherence for momentum $kR_A < 1$
- Targets in both nuclei 2 nuclei
  - Nucleus 1 ↔ nucleus 2 is a parity transform
  - Vector mesons are negative parity -> subtract amplitudes



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

STAR ρ^0 data + fit

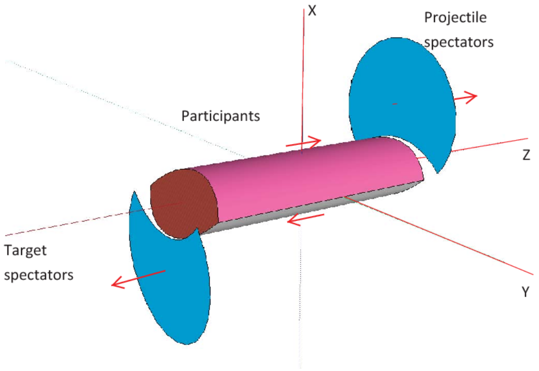


- σ suppressed for $p_T <$ <|b|>
  - In UPCs @ RHIC, <|b|> 20-50 fm
  - In PCs |b| is < 15 fm
- Example of Einstein-Podolsky-Rosen paradox

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

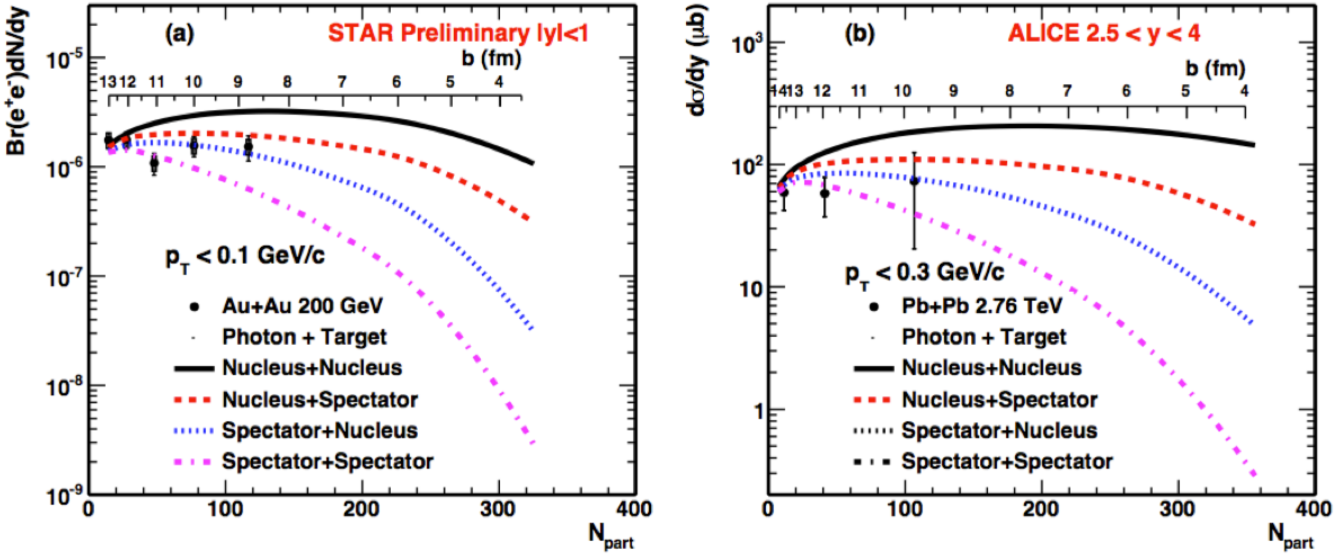
J/ψ Photoproduction cross-section in PCs

- σ depends coherence for photon emission and in the target
  - Entire target, or just spectator region?
- Photons are emitted before collision, at the retarded time t=k/γ
  - They come from the whole nucleus
- Participant nucleons may lose energy via hadronic interaction, before or after the photoproduction interaction
  - If they lose energy first, σ(γp->J/ψ p) drops
    - Time ordering matters –need to consider diagrams with both possibilites
- The photon flux on participant nucleons is lower (Gauss' law)
- The participants are at very small |b|, so destructive interference reduces the cross-section
  - Small contribution to cross-section



Calculations of σ

- Four possibilities:
  - photon emission from the whole nucleus or spectators only
  - Targets: whole nucleus, or just spectators
- Should bracket the actual cross-section
  - Photon emission from nucleus expected
- Predictions consistent with STAR & ALICE data
  - "Nucleus+Nucleus," " Spectator+Spectator" slightly disfavored

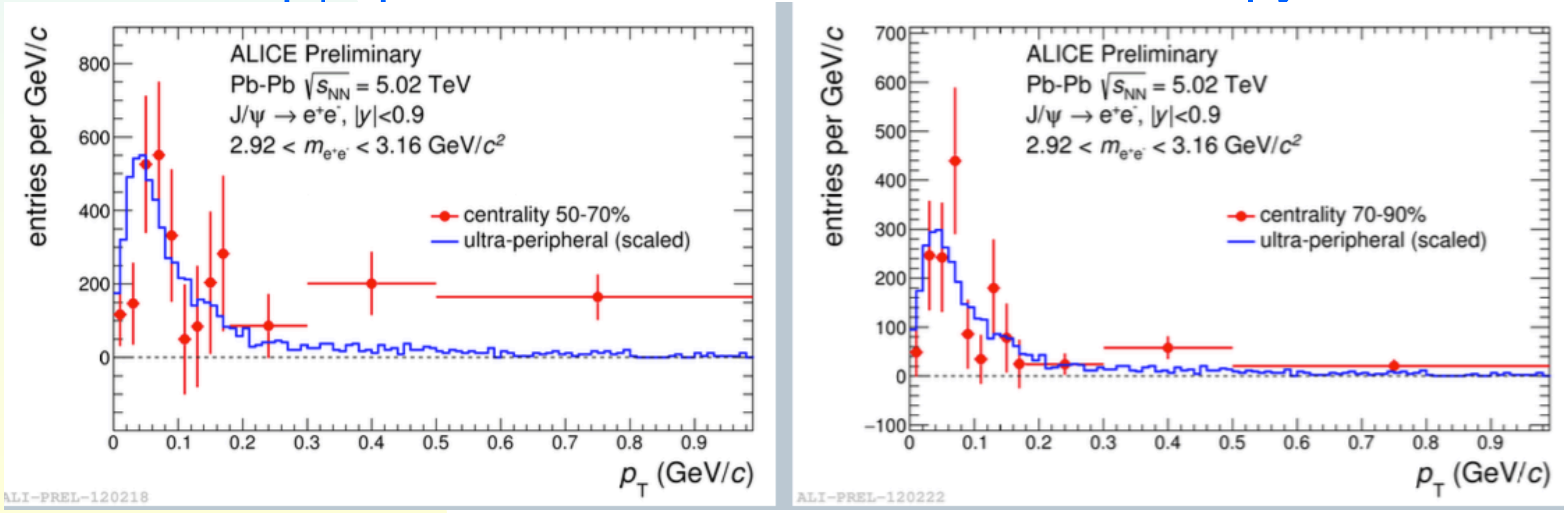


W. Zha et al. (SK),

arXiv:1705.01460

p_T spectrum for γA->J/ψ in PCs

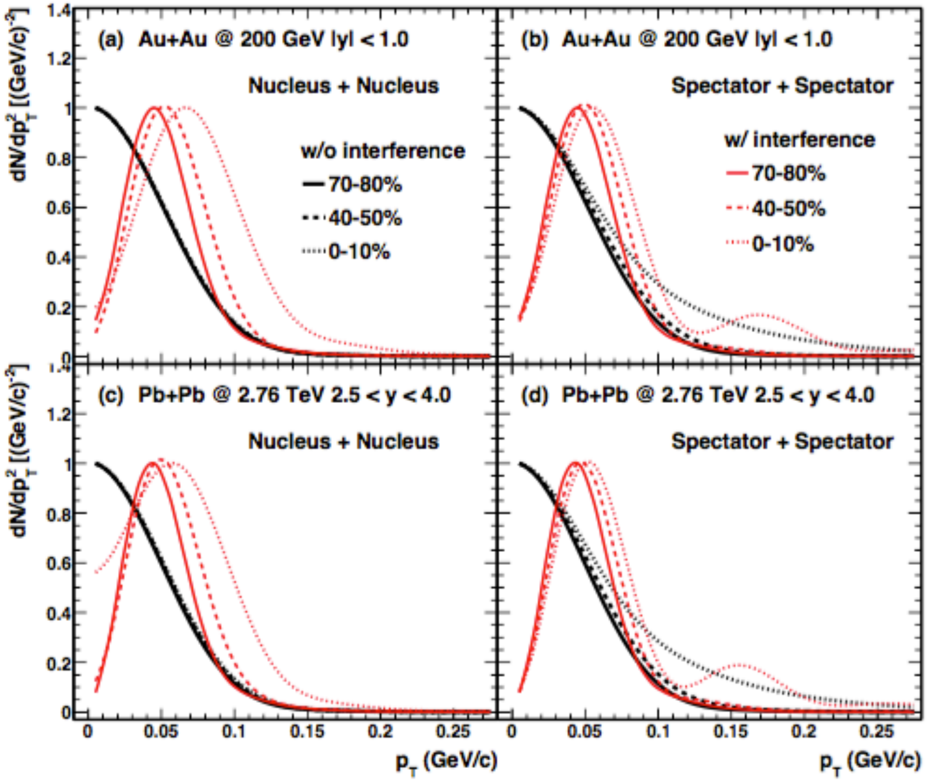
- Spectrum is consistent with UPC J/ψ photoproduction data
  - Drop at low p_T due to interference between two directions
    - |b| is smaller, so interference should extend to higher p_T than for UPCs
- Spectator-only target has a different matter distribution than full nucleus target.
  - Different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



Z. Zhou [ALICE], QM17

p_T spectrum - II

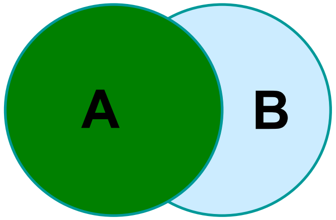
- p_T spectrum depends on size of the coherence region
- Interference depends on |b|
  - Extends to higher p_T for more central collisions
    - Could reduce total cross-section.



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

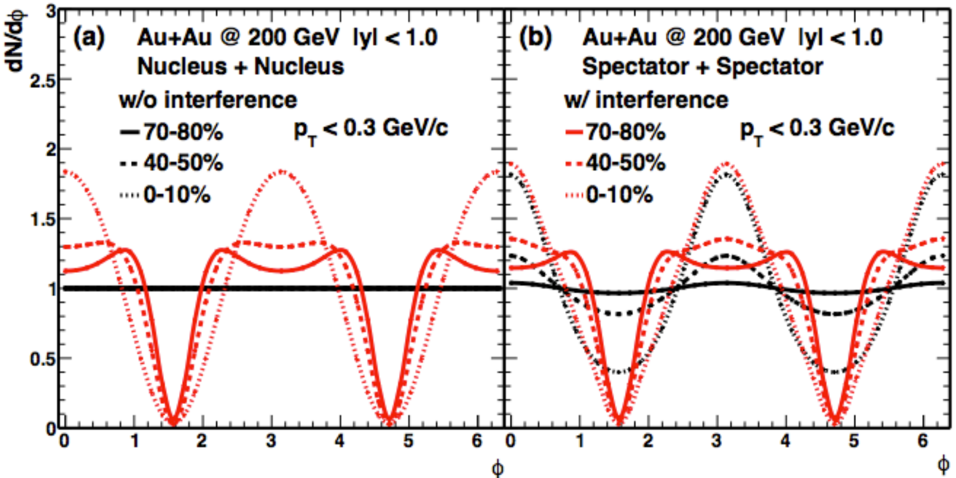
What can we learn about hadronic collisions (I)?

- Most of J/ψ photoproduction amplitude is from spectator region
  - Little direct probe of quark gluon plasma
- J/ψ p_T distribution is Fourier transform of coherent production region
  - I. e. region A minus region B
  - This region is asymmetric
- Some sensitivity to event plane
- Photoproduced J/ψ in spectator region may be destroyed by expanding fireball



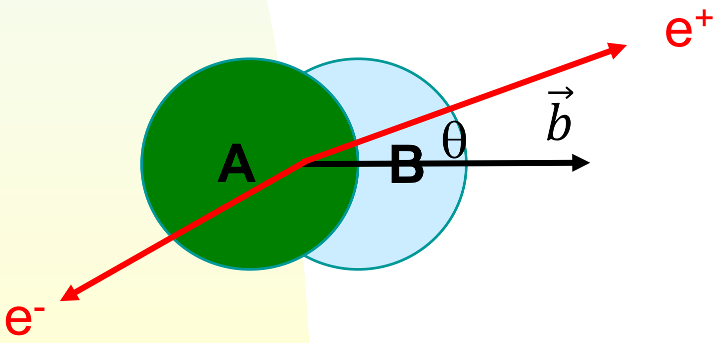
W. Zha et al. (SK), arXiv:1705.01460

Z. Xu (Pers. Comm.)

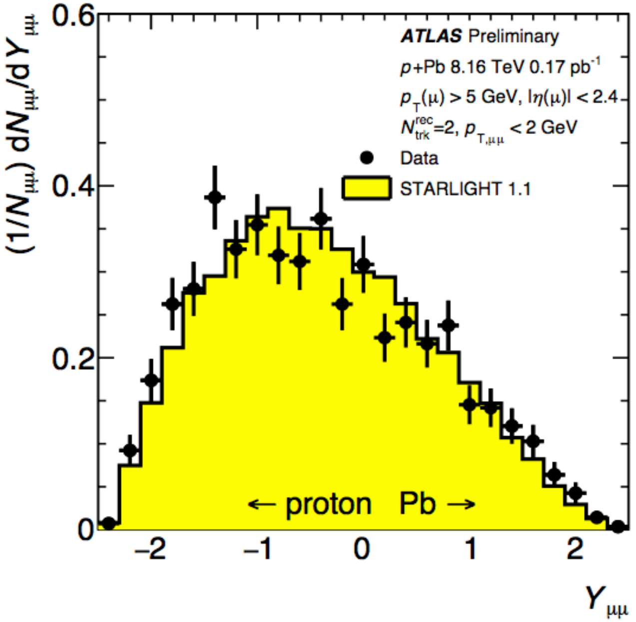


What can we learn about hadronic collisions (II)?

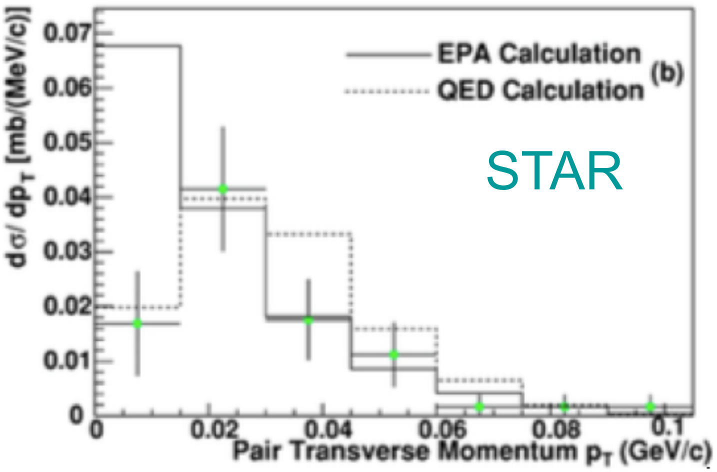
- J/ψ are linearly polarized following the photon polarization, which follows the impact parameter vector
    - Angular distribution of decay is also somewhat sensitive to impact parameter vector, but large statistics are needed
    - e^+e^- preferentially follow (as $\cos^2(\theta)$) the impact parameter vector
- Both of these approaches require far larger data sets than we currently have



$\gamma\gamma$-> ee in UPCs



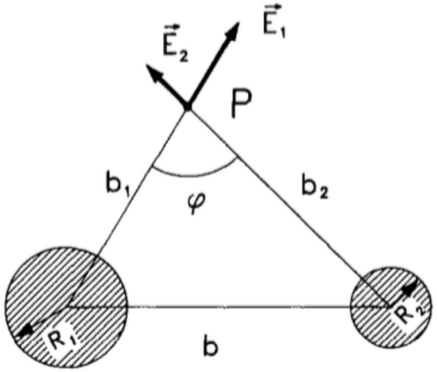
- Weizsacker-Williams virtual photon method for photon flux
  - Photons are treated as real
- Breit-Wheeler $\gamma\gamma$-> ee cross-section
  - Lowest order QED, for real photons
  - Heavily peaked in forward/backward direction
- Generally excellent agreement with data
  - Except: pair $d\sigma/dp_T$ at very low p_T
    - Discrepancy seen by STAR & ATLAS
    - Known problem w/ equivalent photon approach
    - Full lowest order QED calculation matches data
      - Provided by Kai Hencken



ATLAS: arXiv:1702.01625; STAR Phys. Rev. C70, 013902 (2004)

STARlight mods for peripheral collisions

- Three transverse positions
  - Nucleus 1
  - Nucleus 2
  - The two-photon impact point



- $\sigma \sim \int d\phi \int b_1 db_1 \int b_2 db_2\ N_{\gamma 1}(b_1) N_{\gamma 2}(b_2) \sigma(\gamma_1\gamma_2 \to P)$
  - Constraints: $b > R_1 + R_2$ and b_1, $b_2 > R_A$
    - The latter insures removes regions where the photon flux is greatly reduced, and ensures that the final state does not interact with the nucleus
  - For peripheral collisions, constraint becomes
    - $b_{max} > b > b_{min}$
    - Keep constraint b_1, $b_2 > R_A$
      - This does not matter much; most production occurs outside the nuclei
- A similar mod could be done for photonuclear interactions.

SK, in progress; G. Bauer & L. G. Ferreira Filho, Nucl. Phys. A518, 786 (1990)

Calculational considerations

- Uranium is not spherical, so focus on AuAu here
  - 10-40% centrality, 40-60% and 60-80%
- Convert centrality into impact parameters
  - Impact parameter is input to STARlight
  - Simple black-disk geometry with σ_{geom}=7.1b= ‘$\pi(2R_A)^2$
    - Implies R_A=7.5 fm, but, OK for now…
  - 80% centrality = 80% of collisions σ=0.8*7.1b = 5.6 b, etc.
- Most pairs are near threshold (M_{ee} ~ $2m_e$) and invisible to STAR, so the total cross-section is not relevant
  - Apply cuts to MC that match STAR cuts

Cross-section predictions

- σ_{hadr} is the fraction of the hadronic cross-section
- σ_{ee} (restr.) is with $M_{ee}>0.4$ GeV & $|y_{ee}|<1$
  - STAR acceptance for pairs
- σ_{ee} (visible) is σ_{ee} (restr.) with $|\eta_{ee}|<1$and $p_{Te} > 0.2$ GeV/c
  - STAR acceptance for individual leptons

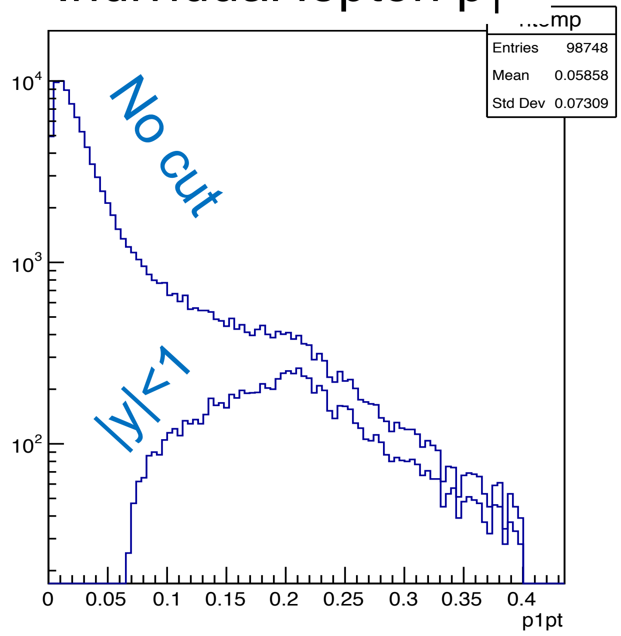
Centrality	**B-range**	σ_{hadr}	σ_{ee} **(restr.)**	**% w/ $|\eta_e|<1$ & $p_{Te} > 0.2$ GeV/c**	σ_{ee} **(visible) /σ_{hadr}**
60-80%	11.6-13.4 fm	1.42 b	3.8 mb	3.3%	$8.8*10^{-5}$
40-60%	9.4-11.6 fm	1.42 b	4.0 mb	3.3%	$9.3*10^{-5}$
10-40%	4.8-9.4 fm	2.13 b	6.4 mb	3.3%	$9.9*10^{-5}$

Little evolution with centrality. $\gamma\gamma$ kinematics do not change significantly between b=2.4 fm and b=6.7 fm. Biggest change is width of range, Δb

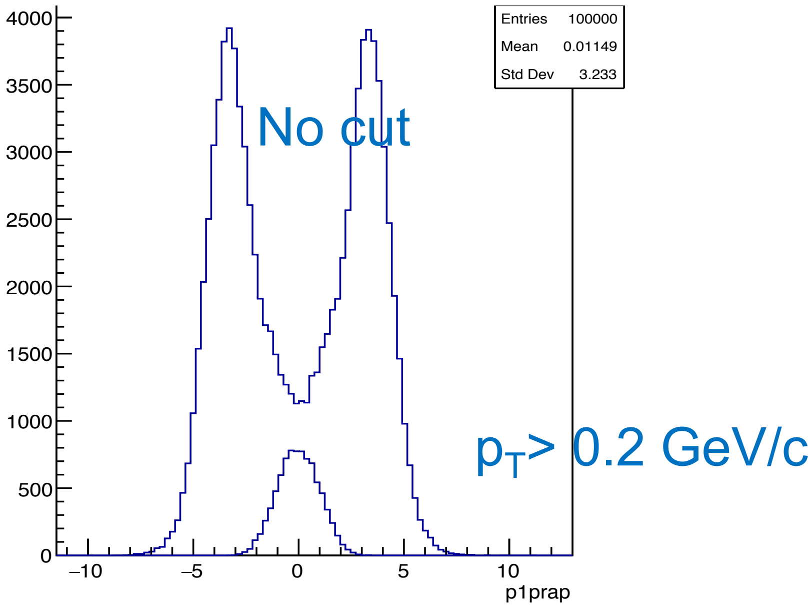
Individual track p_T & pseudorapidity

- Rapidity is heavily forward/backward peaked
  - Moderated by cut p_T track > 0.2 GeV/c
- p_T is peaked near 0
  - After cut $|y|<1$, $\langle p_T \rangle$ 0.2 GeV/c
- Very few leptons with p_T > 1 GeV/c → ALICE sees no continuum signal

Individual lepton p_T

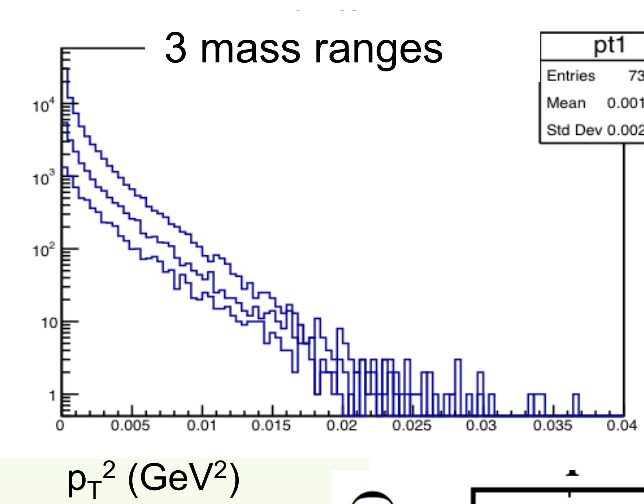


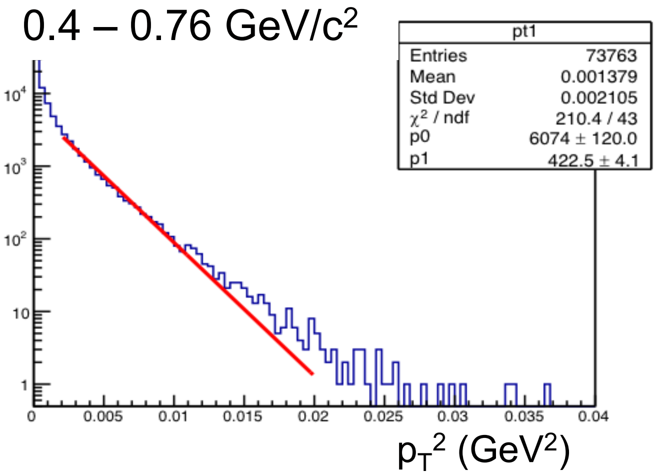
Individual lepton pseudorapidity

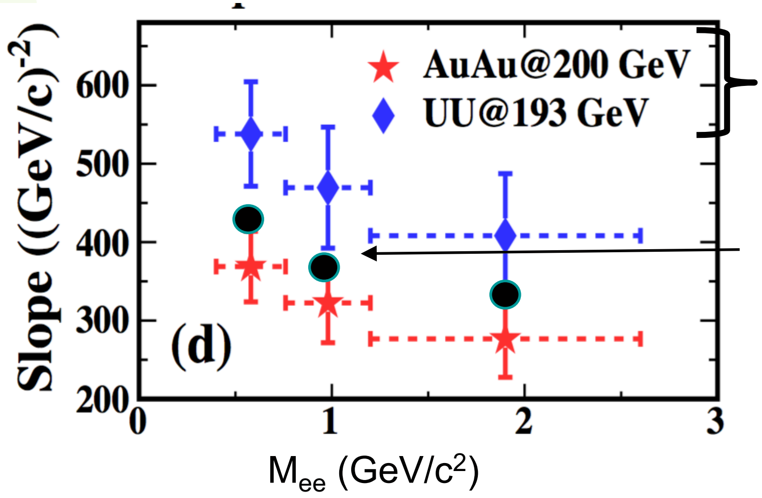


Pair p_T^2

- Histogram p_T^2 in 3 mass bins, ala STAR
  - Fit $0.002 < p_T^2 < 0.02$ $(\mathrm{GeV}/c)^2$ range to $dN/dp_T^2 = A \exp(-Bp_T^2)$
    - Not a good fit to the data, but follows STAR procedure
    - Same slope (B) trend as STAR data





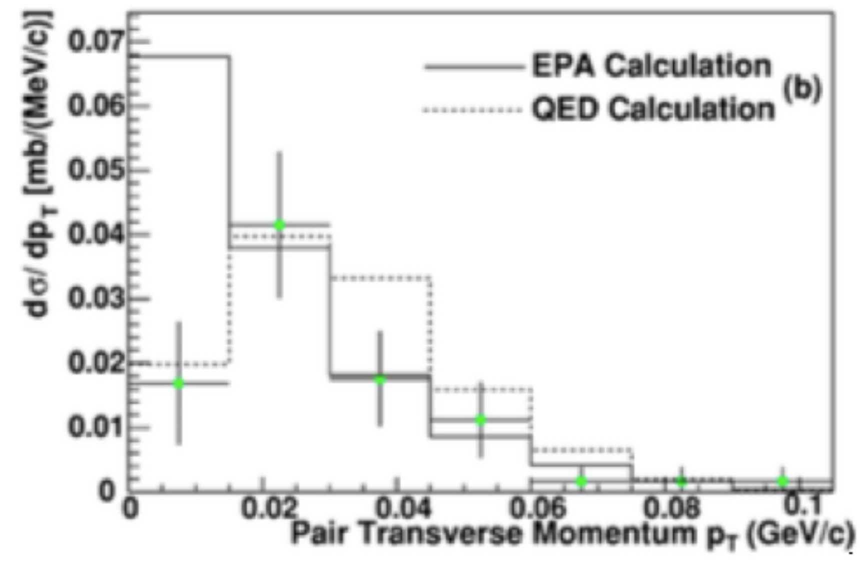


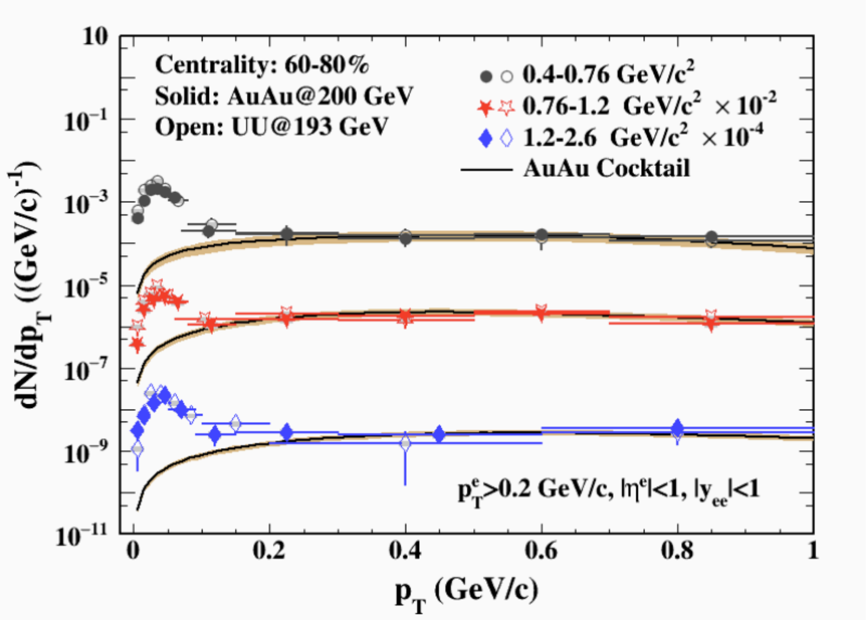
Preliminary STAR data

Fits to STARlight Distributions for AuAu

The low p_T drop

- The STAR p_{Tee} spectrum drops for p_{Tee} < 40 MeV/c
  - Looks similar to interference dip in vector meson photoproduction
- Photon emission with p_T < photon energy/ion Lorentz boost is suppressed
  - Dip width should scale with photon energy, i. e. with M_{ee}
    - Scaling from previous STAR result p_T peak @ 25 MeV -> p_T peak @ 75 MeV/c – reasonably close

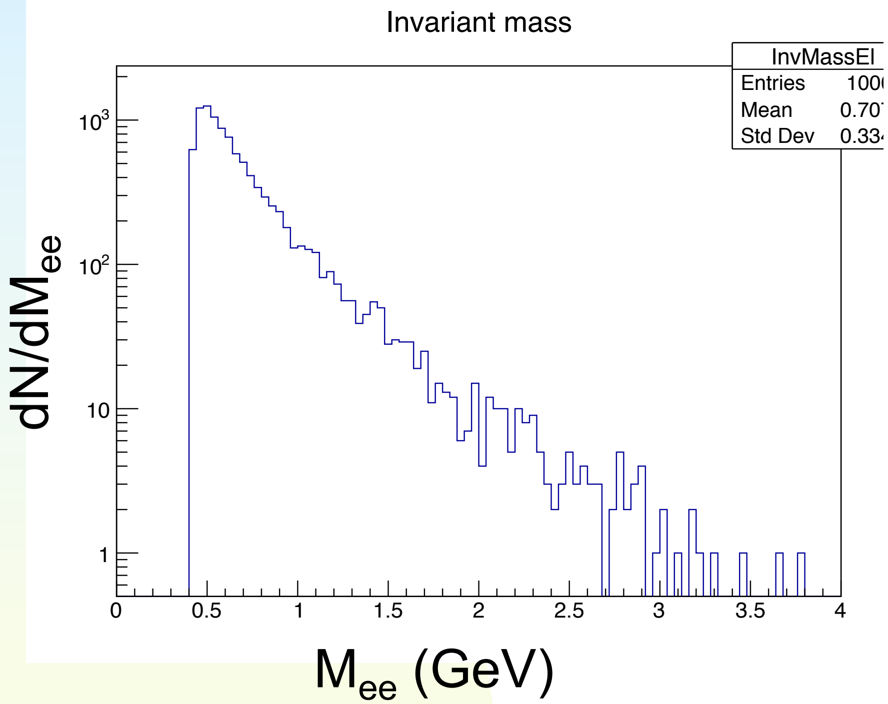




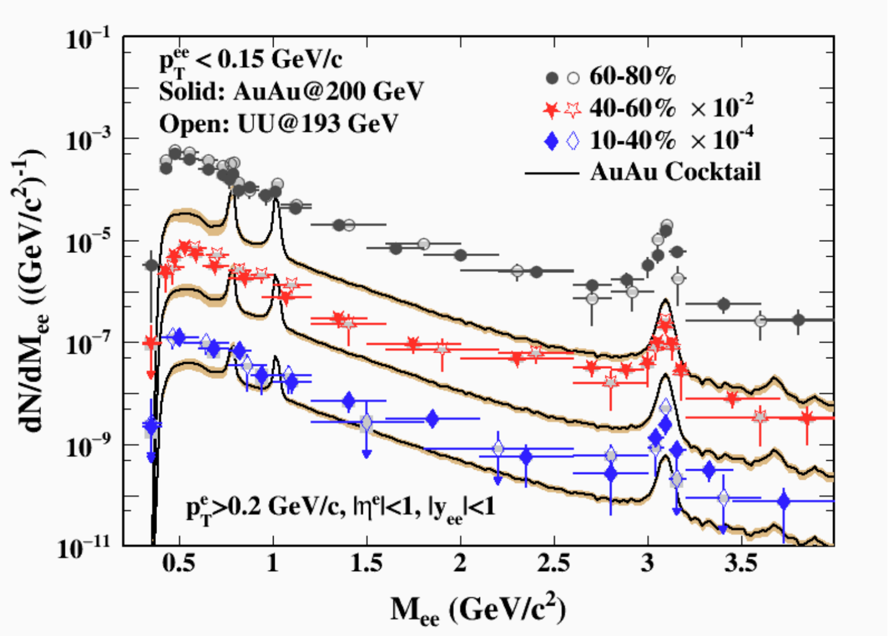
STAR: Phys. Rev. C70, 013902 (2004) & S. Yang, QM ‘17

M_{ee} spectrum

STARlight



STAR data



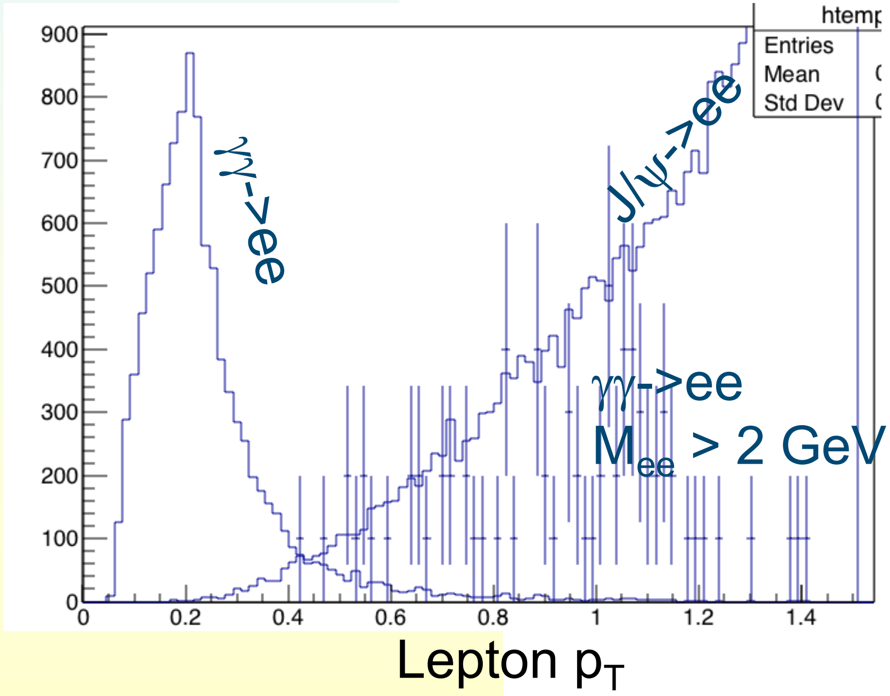
Low p_{Tee} paper did not make a fit to the mass spectrum & the right-hand plot is hard to read

Both decrease about a factor of 10 going from

M_{ee}=0.5 GeV to M_{ee}=1.0 GeV & from M_{ee}=1.0 GeV to M_{ee}=2.0 GeV

One diagnostic

- J/ψ (or $\rho/\omega/\phi$) -> ee and $\gamma\gamma$-> ee share many characteristics
  - Similar pair p_T spectra
  - Hard to distinguish rapidity distributions in central detectors
- The angular distribution of the final state l^+l^- is very different
  - -> Very different lepton spectra
  - With $p_{T\mu}$ > 1 GeV/c cut, ALICE sees J/ψ -> ee only



Lepton p_T w/ STAR cuts
STAR $\gamma\gamma$-> ee
STAR J/ψ -> ee
STAR $\gamma\gamma$->ee w/ M_{ee} > 2 GeV/c
J/ψ are in UPC, but this doesn't affect lepton spectra much

Arbitrary normalization

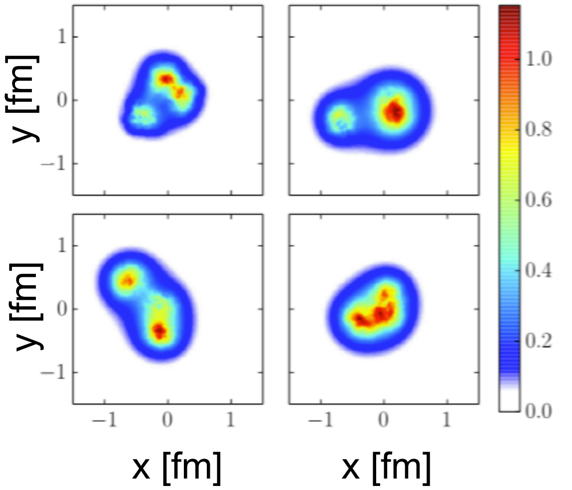
Conclusions

- STAR and ALICE have observed an excess of dilepton pairs with $p_T < \sim 100$ MeV/c in peripheral heavy ion collisions
  - STAR sees J/ψ + a mass continuum
  - ALICE sees only J/ψ
- The J/ψ production rate and kinematics are consistent with expectations from coherent photoproduction
- The STAR continuum is mostly consistent with two-photon production of electron pairs.
  - The kinematics are well matched to simulations of that process
- ALICE does not see continuum production because its analysis (due to forward muon spectrometer) requires $p_{T\mu} > 1$ GeV/c.
- J/ψ have some sensitivity to the event plane orientation. Large statistics are required to contribute useful information.

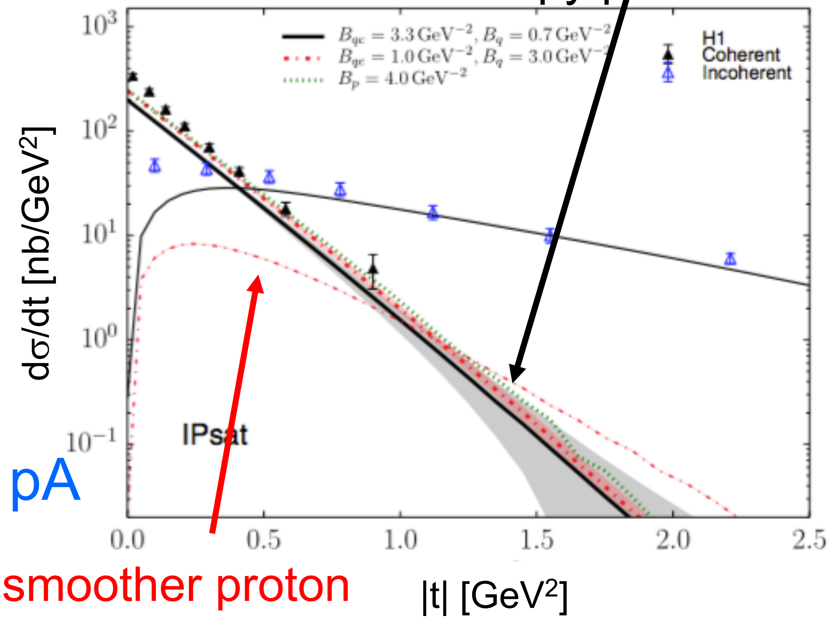
Backup

Incoherent VM photoproduction

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



Lumpy proton



smoother proton

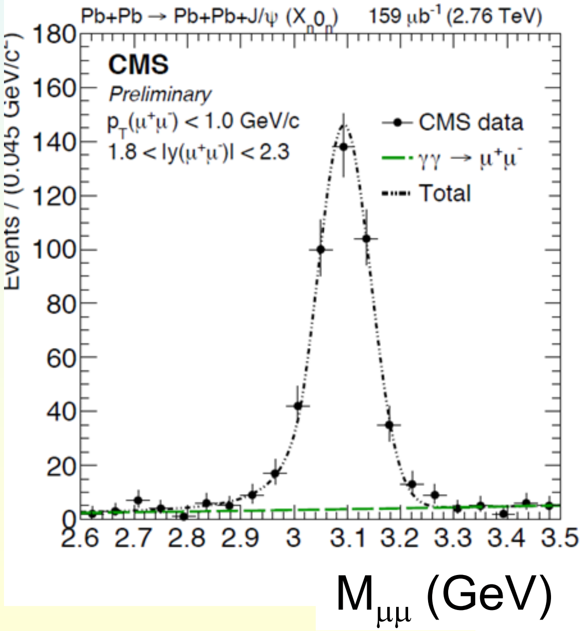
H. Mäntysaari, QM17; Mäntysaari & Schenke PRD 94, 034042 (2016)

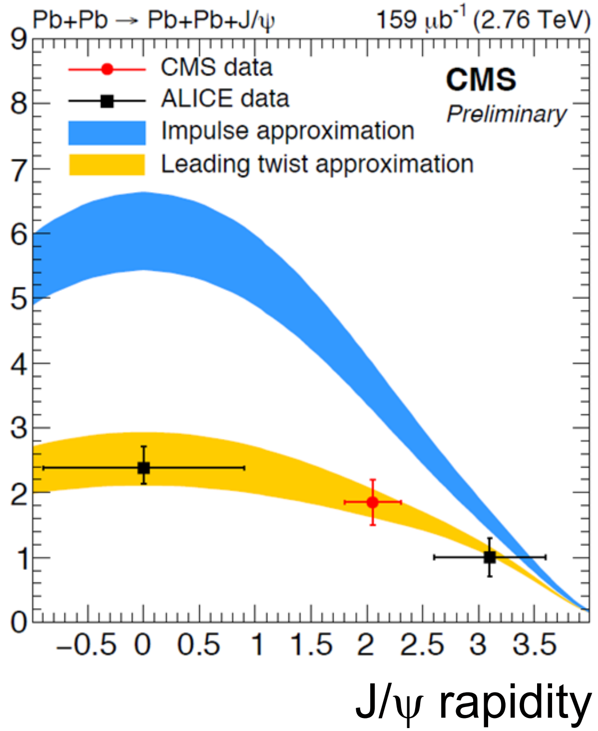
Cross-section Comparison

- STAR low p_T ee analysis used 720 million 0-80% centrality events
- σ for pairs with $|y_{ee}|<1$, Mee>0.4 = 3.8 mb (per pg. 6)
  - 456,000 pairs in AuAu sample
- ε(both leptons in acceptance) = 0.033
  - STARlight predicts 15,048 visible pairs in sample
- STAR finds about twice as many pairs as STARlight
  - Understanding this is a work in progress
    - Acceptance corrections??
      - Lepton p_T spectrum is very soft
    - Pair p_T spectrum?
    - Pair production within nuclei?

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

- $\mu^+\mu^-$ at |y| = 2.05
- Cross-section is ~ 40% of impulse approximation
  - Moderate nuclear shadowing
  - Consistent with leading twist calculation
- In incoherent photoproduction, J/ψ & neutrons go in same direction
  - Incoherent cross-section increases rapidly with photon energy?

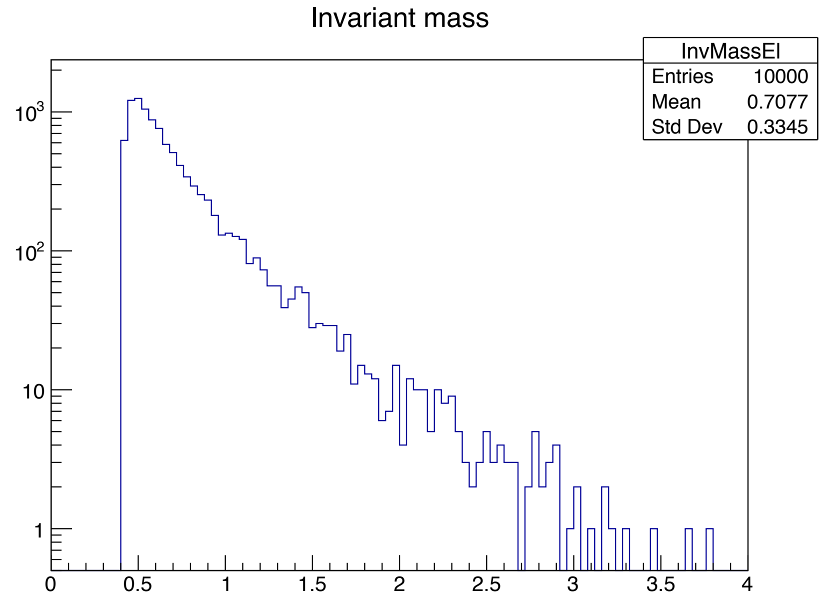




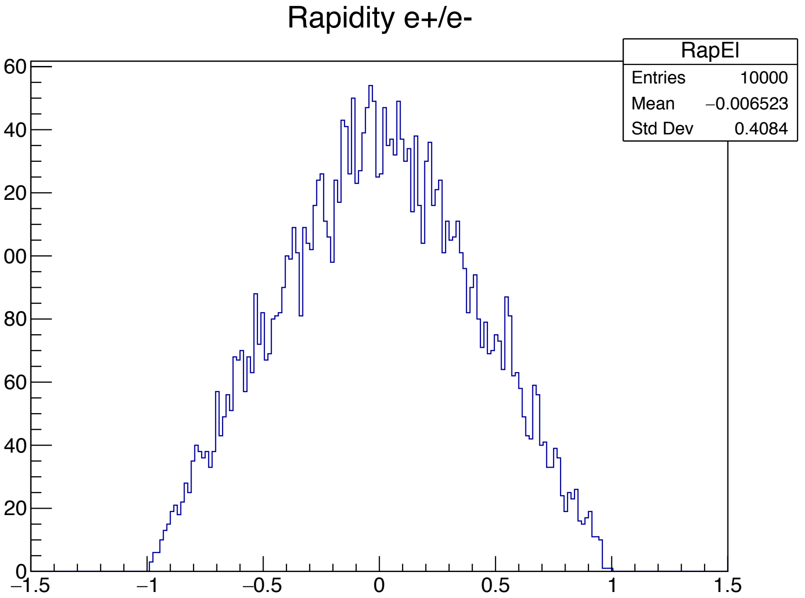
D. Tapai Takaki [CMS], QM17

Pair Kinematic Distributions

- For 60-80% centrality
  - Centrality doesn't matter much, so I will focus on 60-80% centrality, which has the best signal:noise ratio



Pair Mass (GeV)



Pair Rapidity