Using coherent dipion photoproduction to image gold nuclei

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Presented at DIS 2021

- Nuclear shadowing, $d\sigma_{coherent}/dt$ and the shape of the nucleus
- The STAR detector
- Extracting and fitting $d\sigma_{coherent}/dt$
- Concerns/limitations/systematic uncertainties
  - For UPCs and the EIC
- Conclusions

*Work done in collaboration with Ya-Ping Xie

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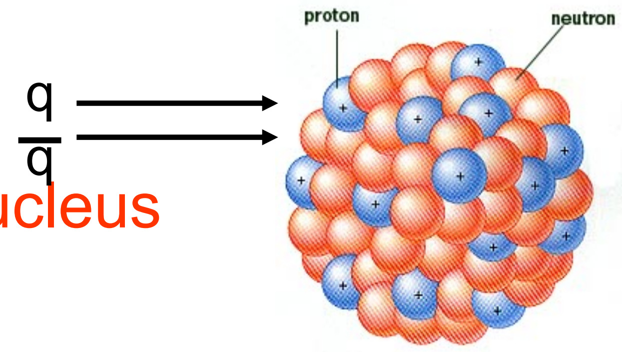
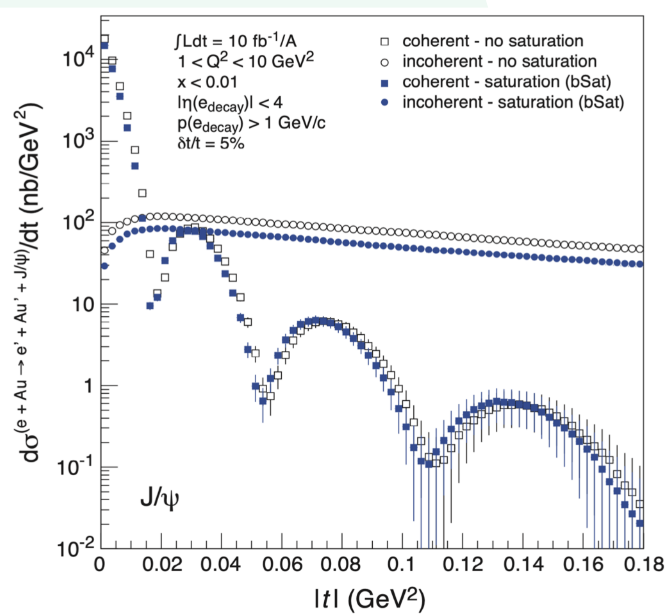
Nucleon shadowing of dipoles

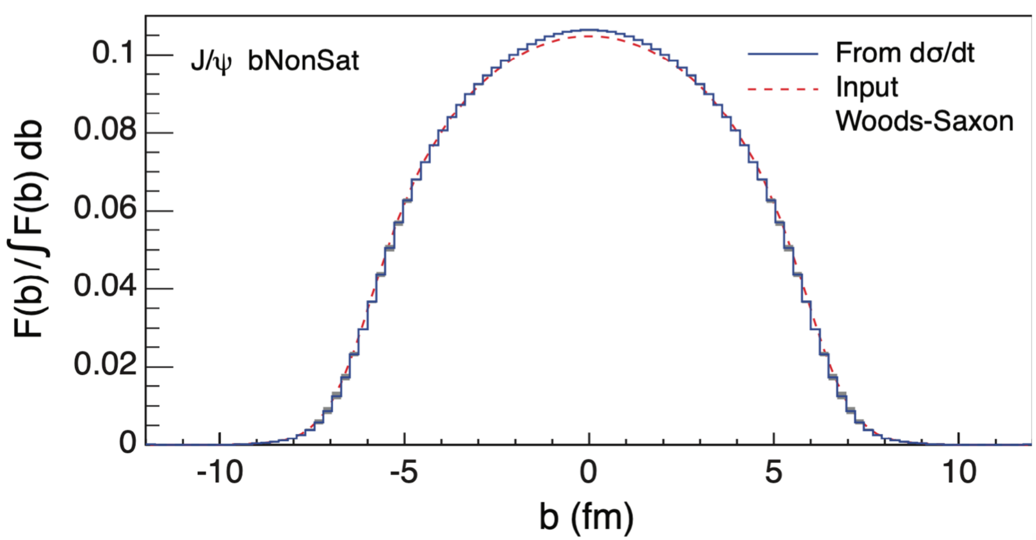
- A photon fluctuates to a $q\bar{q}$ dipole which scatters elastically from the nucleus, emerging as a ρ^0 or $\pi\pi$ or ω
  - $\rho^0 + \pi\pi$ photoproduction too low in Q^2 for pQCD
- Large dipoles (small $M_{\pi\pi}$) interact on the front of the nucleus
  - "Black disk limit"
  - Multiple interactions from one dipole
- Small dipoles (high $M_{\pi\pi}$) penetrate more deeply and see internal nucleons
  - Woods-Saxon distribution
- Shadowing changes effective shape of nucleus
  - Shadowing affects the shape of $d\sigma/dt$



Measurements of $d\sigma_{coherent}/dt$ and the interaction profile are key EIC measurements

- Highlighted in 2012 White Paper and 2021 Yellow Report
- Need to measure out to ~3rd diffractive minimum for an accurate transform
  - “Windowing” problem

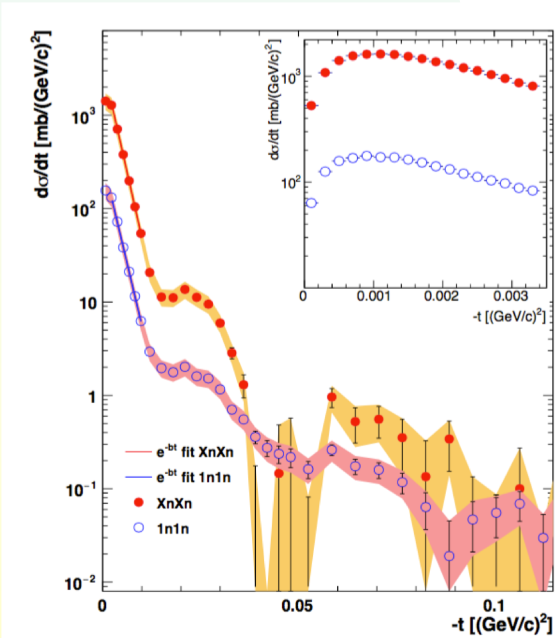


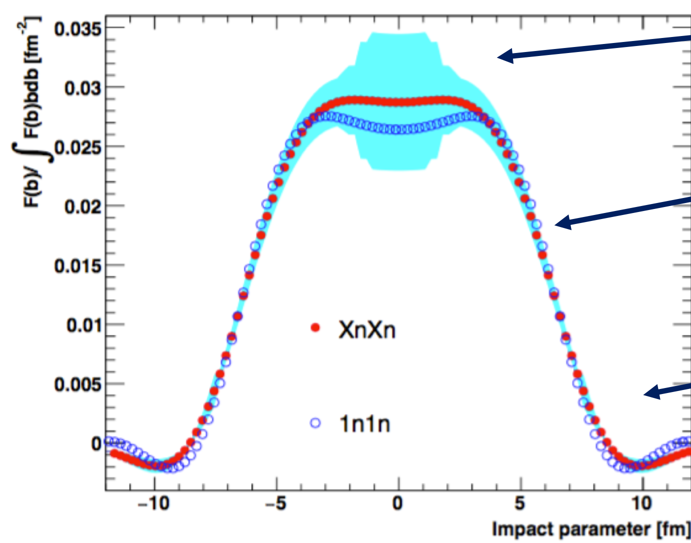


From the EIC White Paper and Yellow Report, arXiv:1212.1701 & 210305419

Previous STAR analysis

- 294,000 photoproduced $\pi\pi$ pairs (after tight cuts)
  - $M_{\pi\pi}$ spectrum well fit to ρ^0 + direct $\pi\pi$ + $\omega \to \pi\pi$ cocktail
- Could not measure out to large enough |t| for an accurate transformation
  - Large uncertainties at small b
- Today: try a simpler problem – fitting the data to a linear combination of the two limiting cases





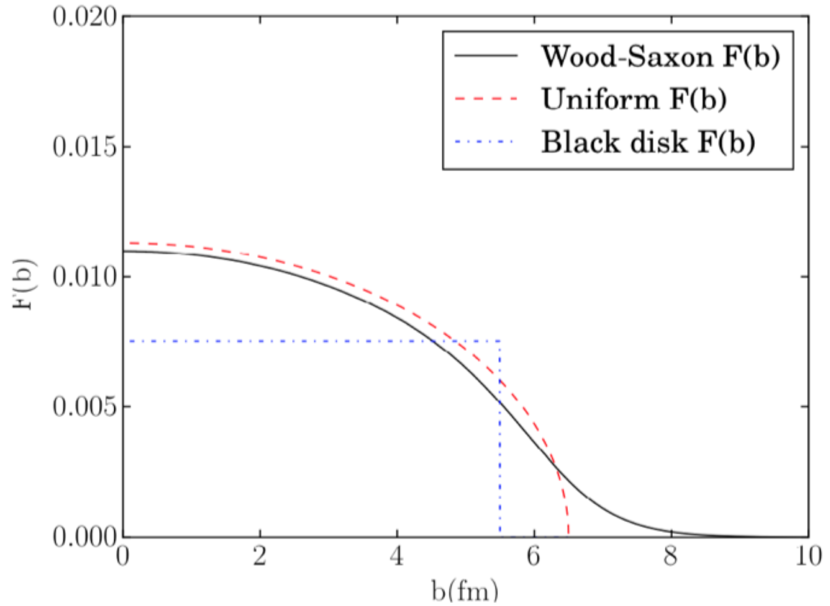
Large variation with t_{max} Windowing?

Sharp edges

Negative due to destructive interference

STAR, Phys. Rev. **C96**, 054904 (2017)

Two limits



- Small dipole
  - Interactions follow Woods-Saxon

$$\rho_A(s) = \frac{\rho_0}{1 + exp[(s - R_{WS})/d]}$$

    - R_{WS}=6.5 fm for protons
    - +0.25 fm for neutron skin
    - d=0.7 fm – represents skin thickness
- Large dipole
  - Interactions on front face of the nucleus
    - Multiple interactions, does not change the overall picture.
  - Nucleus is a black disk
    - Maximum radius not well defined.
    - Here take R_{BD}=8 fm – largest reasonable value
- Density ρ_0 set by normalization

From dσ/dt to nuclear density profiles

- For coherent production in low-density targets
  - $\sigma = |\Sigma_i A_i \exp(ipx_i)|^2$
    - A_i, x_i are nucleon interaction amplitudes and positions
      - The interaction sites differ for the low-$M_{\pi\pi}$ and high $M_{\pi\pi}$ cases
- $d\sigma/dp_T$ depends on the shape of the nucleons
  - $p_{||}$ is negligible here, and will be neglected
  - $t=p_T^2+p_{||}^2$
- Fourier transform of dσ/dt gives nuclear density profile

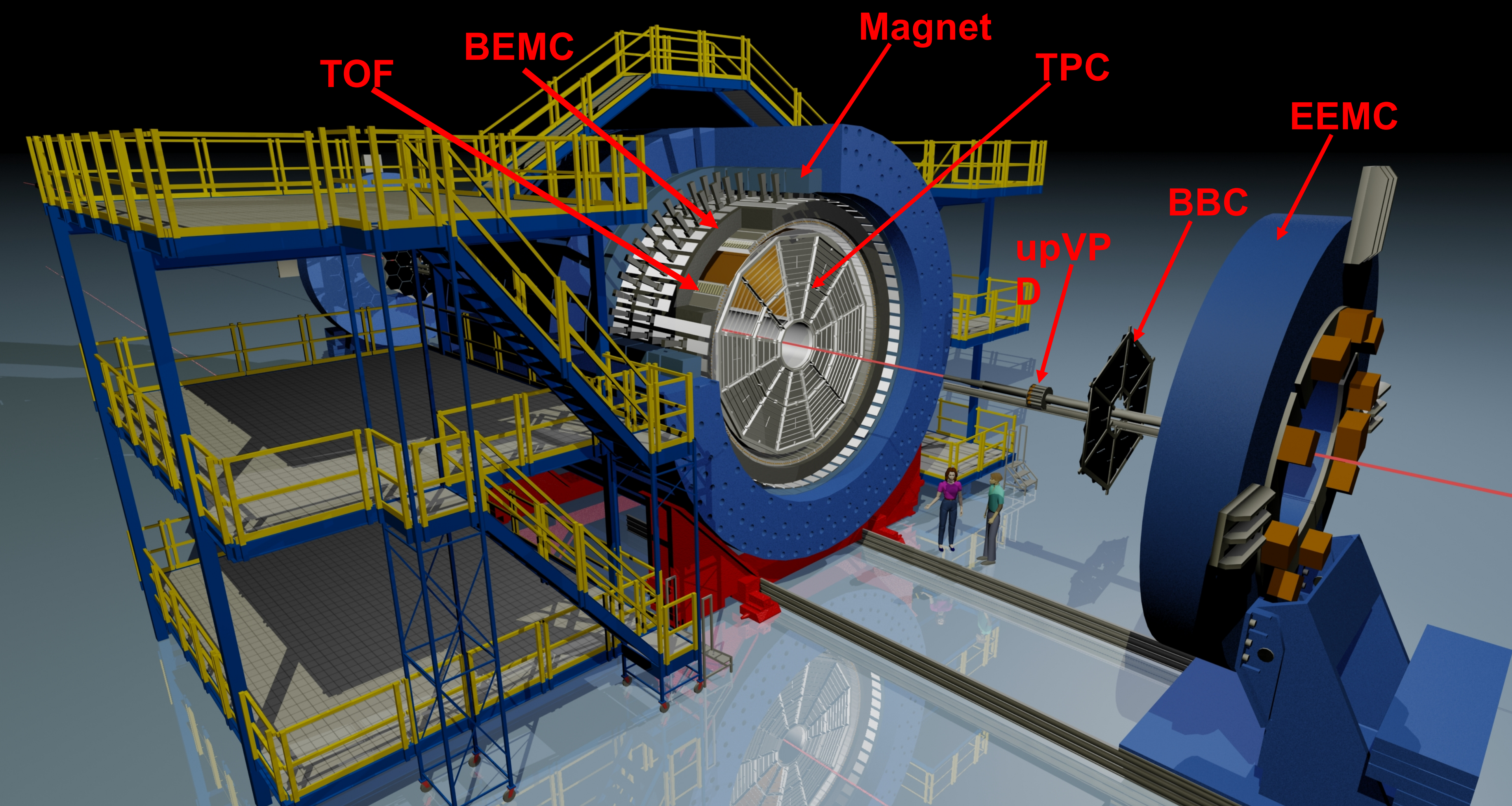
$$F(b) \propto \frac{1}{2\pi} \int_0^\infty dp_T p_T J_0(bp_T) \sqrt{\frac{d\sigma}{dt}}$$

* = flips sign after each minimum

  - In data, there is an upper limit to t -> windowing problems
- Gives the two-dimensional (traverse) distribution of interaction sites within the nuclear target

Toll & Ullrich, Phys. Rev. **C87**, 024913 (2013), STAR, Phys. Rev. **C96**, 054904 (2017)

The Solenoid Tracker At RHIC (STAR)



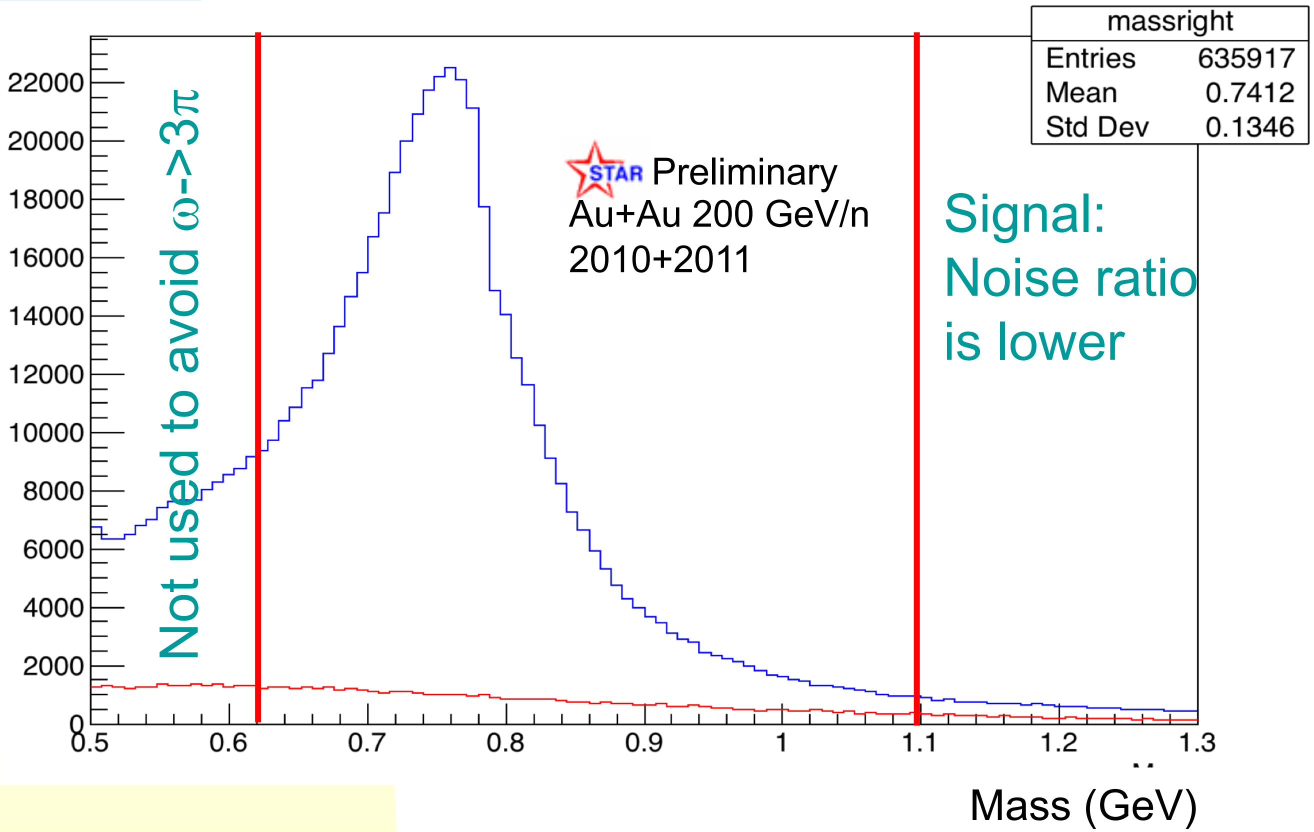
Detectors for |y|<1 – TPC, time-of-flight system, EM Calorimeter
Zero degree calorimeters at large $|\eta|$
Beam-Beam Counters veto events w/ charged particles in 2 < |y|<5

Analysis plan

- Use STAR Au+Au data from 2010+2011, with UPC trigger
  - 2-6 tracks in TPC + neutrons in both zero degree calorimeters
    - Neutrons are from mutual Coulomb dissociation
- Select clean $\pi\pi$ events w/ tight cuts
- Subtract background (like sign events)
- Fit $d\sigma/dt$ at high t to a dipole form factor to get $d\sigma_{incoherent}/dt$. Extrapolate to small |t| and subtract, leaving the coherent $d\sigma/dt$.
- Fit $d\sigma_{coherent}/dt$ to linear combination of two cocktails that represent the Woods-Saxon and black disk extremes
  - Woods-Saxon distribution
  - Black Disk
- Each cocktail is the quadrature sum of:
  - Photon p_T
  - Pomeron p_T
    - Larger nuclear radius because of neutron shell
  - Experimental resolution

The ππ mass spectrum

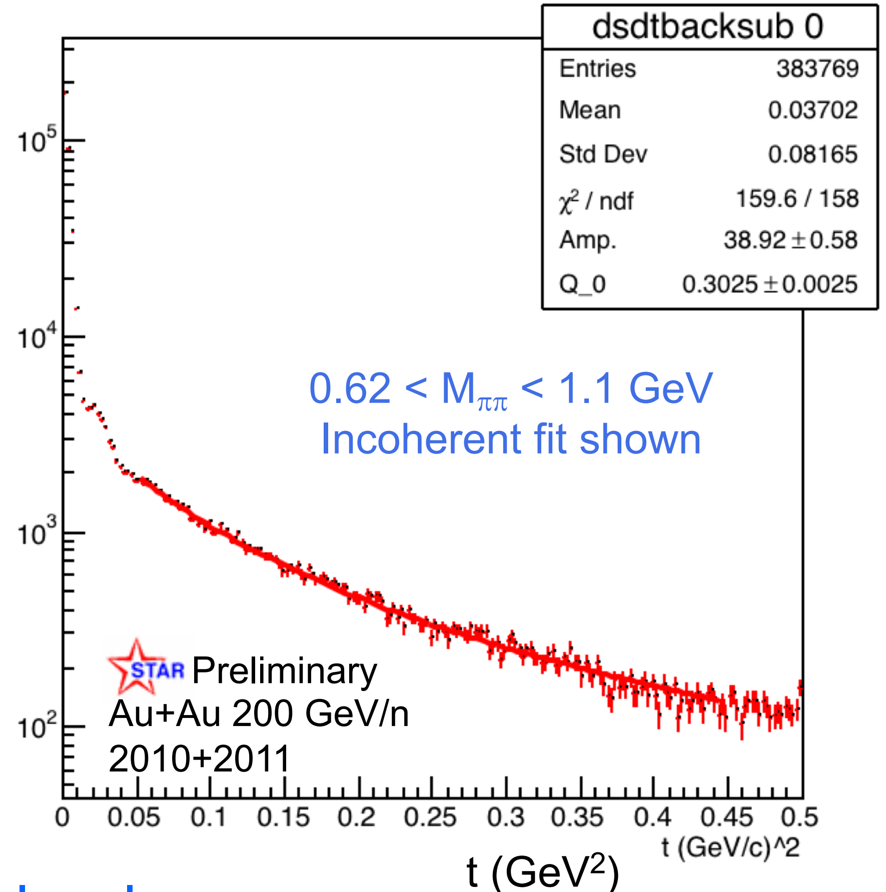
- Tight cuts (in backup); require> 10:1 signal:noise ratio
  - Like-sign pairs quantify background
  - Mass spectrum well fit by ρ + direct ππ + ω (with interference)



Incoherent fitting

- $d\sigma_{incoherent}/dt$ fit to a dipole form factor
  - Q_0^2=0.099 GeV^2 in STAR paper
- Fit in range 0.05< t < 0.45 GeV^2
  - Wider range than STAR paper
  - Minimize statistical uncertainty & distance for extrapolation
- Q_0 similar to STAR paper
- χ^2/DOF = 160/158 -> good
- Exponential gives a poor χ^2/DOF
- The dipole must fail as t->0
  - $E_{threshold}$ = 8 MeV for n emission
    - p_T ~ 122 MeV/c
  - $E_{threshold}$ = 77 keV for γ emission
  - Need to account for nuclear shell levels

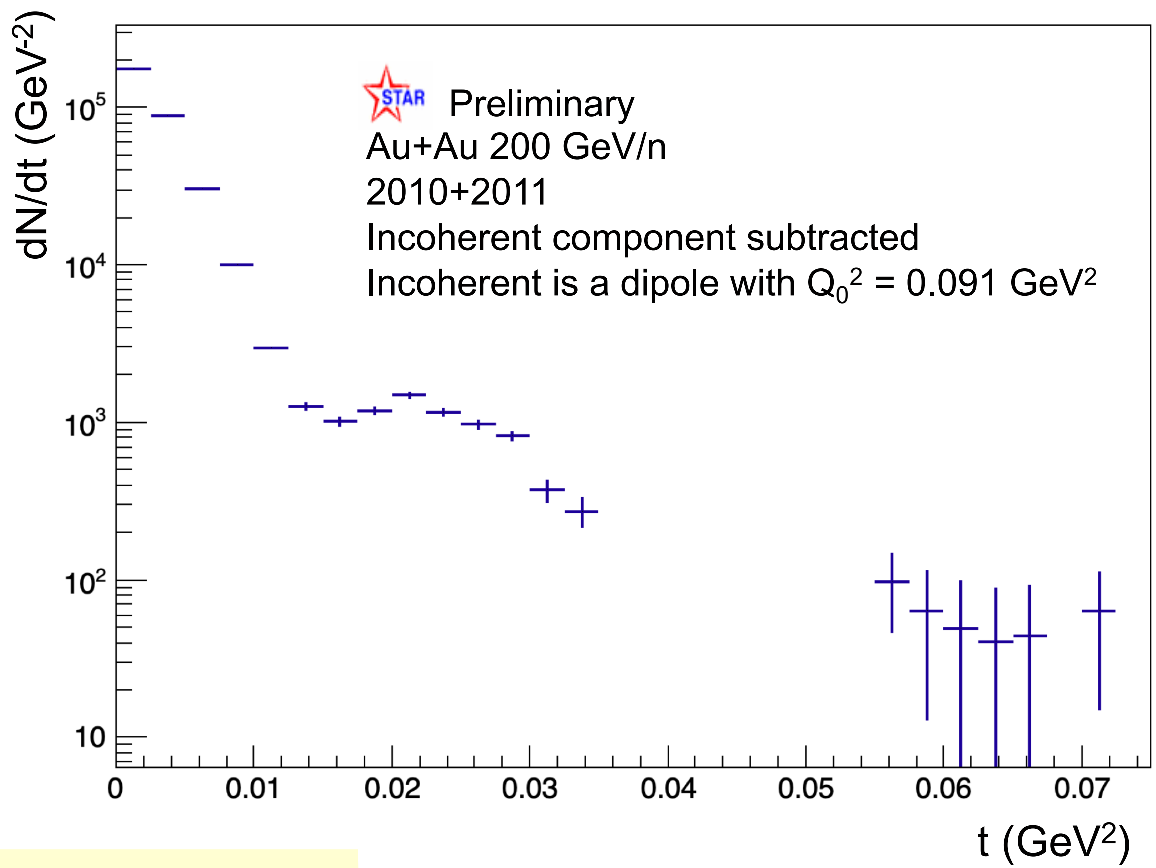
$$\frac{d\sigma}{dt} = \frac{A/Q_0^2}{(1+|t|/Q_0^2)^2}$$



STAR, Phys. Rev. **C96**, 054904 (2017)

Coherent dσ/dt

- Subtract fitted incoherent contribution (from previous slide)
- Possible over-subtraction in region of diffractive minima
  - Sensitive to range used for incoherent fit
    - Possible failure of dipole approximation



Fitting to dσ/dt….

- Fit to a linear combination of dσ/dt(WS) + dσ/dt(BD)
  - dσ/dt (Data) = Λ dσ/dt(WS) + (1-Λ) dσ/dt(BD)
- Templates include 3 contributions:
  - Pomeron p_T
  - Photon p_T
  - Detector Resolution in pion pair p_T
    - Modelled as a 2-d Gaussian in p_x,p_y, with $\sigma(p_T)$=6 MeV/c*
    - Shown to be independent of pion pair p_T
- Transverse directions of all 3 components are uncorrelated
  - Convolute with random relative directions

*STAR, Phys. Rev. C **77**, 034910 (2008)

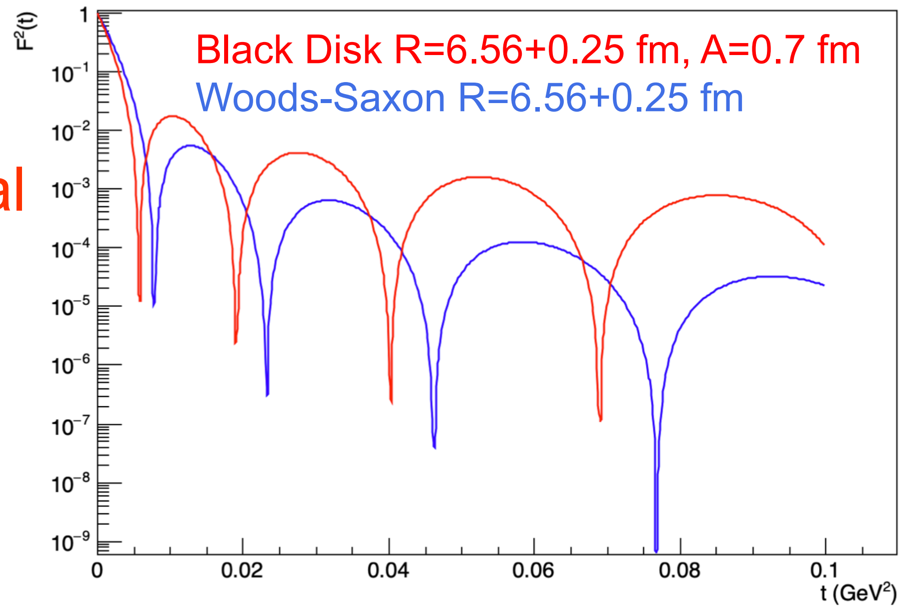
Pomeron t spectra

- ~(Nuclear form factor)^2
- For Woods-Saxon: convolution of uniform sphere + Yukawa potential

$$F(q) = \frac{4\pi\rho_0}{Aq^3}\left[\sin(qR_A) - qR_A\cos(qR_A)\right]\left[\frac{1}{1+a^2q^2}\right]$$

- For black disk:

$$F_2(q) = \frac{2J_1(qR_A)}{qR_A}$$



  - Even with same R_A, a black disk has different zeroes from a Woods-Saxon distribution
    - Zeroes are not evenly spaced; cannot match w/ different radii
  - For subsequent work, take R_A= 8 fm

Klein & Nystrand, PRL 84, 2330 (2000)

Photon p_T

- Depends on EM form factor
  - Woods-Saxons, no neutron skin
- Standard formula averages over all b
- Field strength varies with position in target – not a plane wave
- We require $b>2R_A$
  - The mutual Coulomb dissociation (XnXn) trigger biases the b-distribution by $1/b^4$ with respect to standard Weizsacker-Williams
  - p_T and b are conjugate variables
    - If we restrict b, we cannot cleanly calculate p_T
      - $\langle p_T \rangle$ should increase

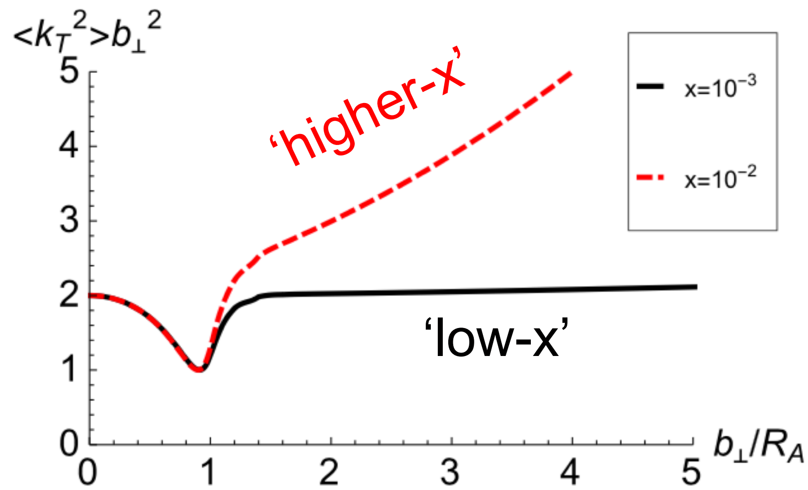
$$\frac{d^3N_\gamma(k,k_\perp)}{d^2k_\perp dk} = \frac{\alpha^2 Z^2 F^2(k_\perp^2 + k^2/\gamma^2)k_\perp^2}{\pi^2(k_\perp^2 + k^2/\gamma^2)^2}$$

Klein & Nystrand, PRL 84, 2330 (2000)

Relationship between photon <p_T> and <b>

- No model-independent answer
- GPD inspired approach

$$\langle k_T^2 \rangle = \frac{4Z^2\alpha}{xf^\gamma(x;b_\perp)} \int \frac{d^2k_T}{(2\pi)^2} \frac{d^2k'_T}{(2\pi)^2} e^{i(k_T - k'_T)\cdot b_\perp} \times \frac{(k_T \cdot k'_T)^2}{k^2 k'^2} F_A(k^2) F_A(k'^2) \ ,$$

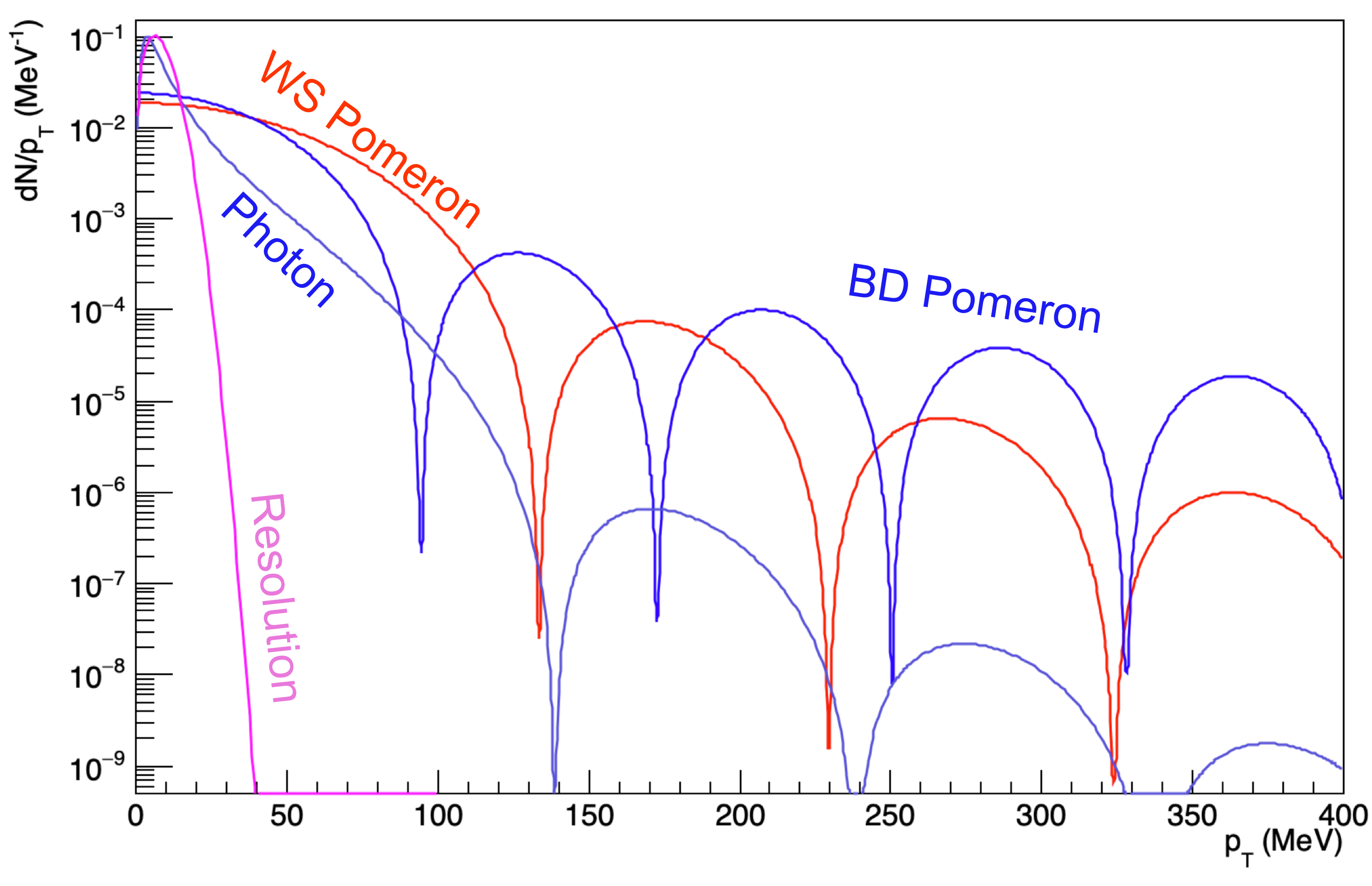


- Then <p_T^2> ~~ $1/b^2$
  - At low x
- Can integrate over impact parameter to get a scaling factor for the all-b spectrum
  - Assumes that the spectrum scales smoothly, with unchanged shape.
    - Only true at low x=photon energy/nucleon energy
    - Diffractive dips should not move.

SK, Al Muller, Feng Yuan and Bo-Wen Xiao, Phys. Rev. **D102**, 094013 (2020)

Template components

- Pomeron p_T is dominant
  - Uncertainties in photon p_T and resolution are less important
- Dip positions depend on choice of R_A ($R_{hadronic} > R_{EM}$)



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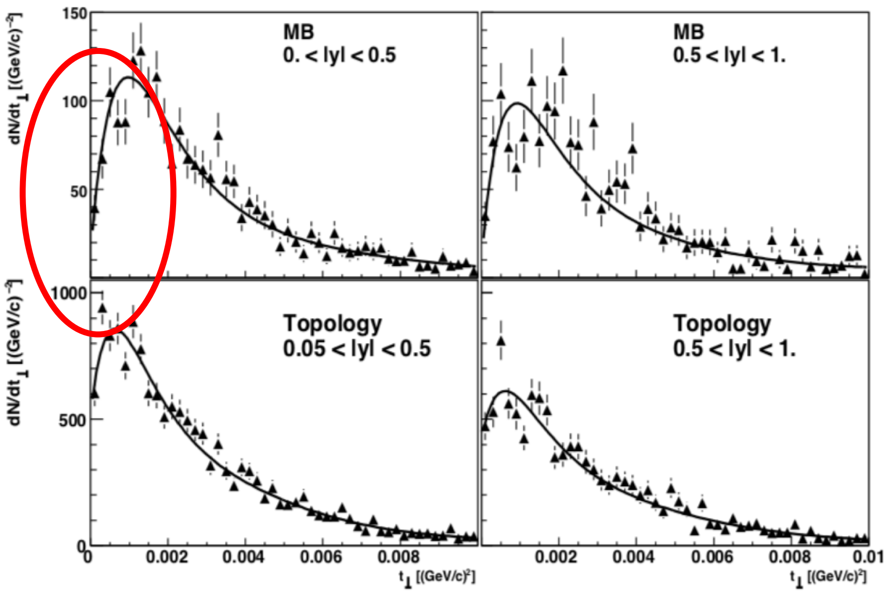
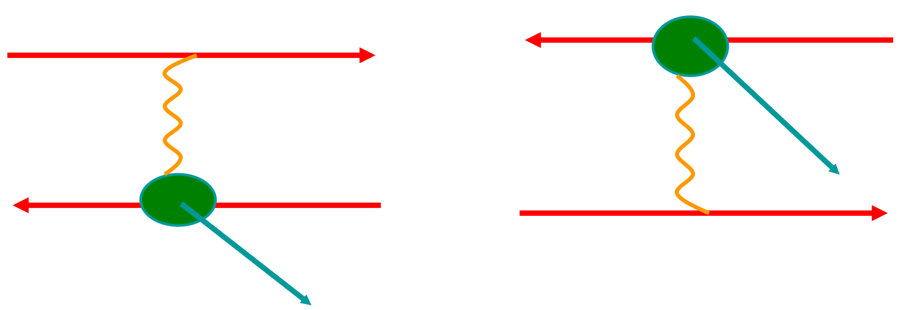
A missing component

- Interference between 2 diagrams
  - $\sigma \sim |A_1 - A_2 e^{ip \cdot b}|^2$
- Not easily amenable to template approach
- Solution: cut events with t>0.001 GeV^2

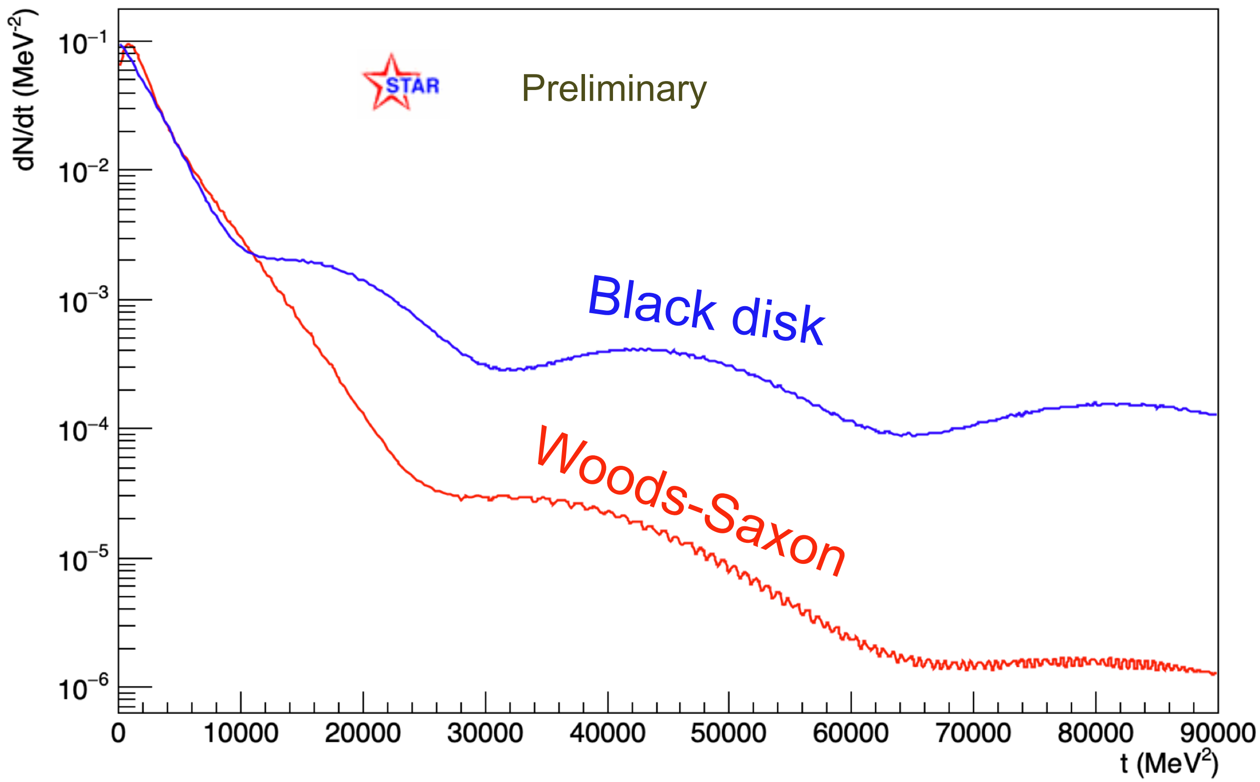




STAR, PRL **102**, 112301 (2009)

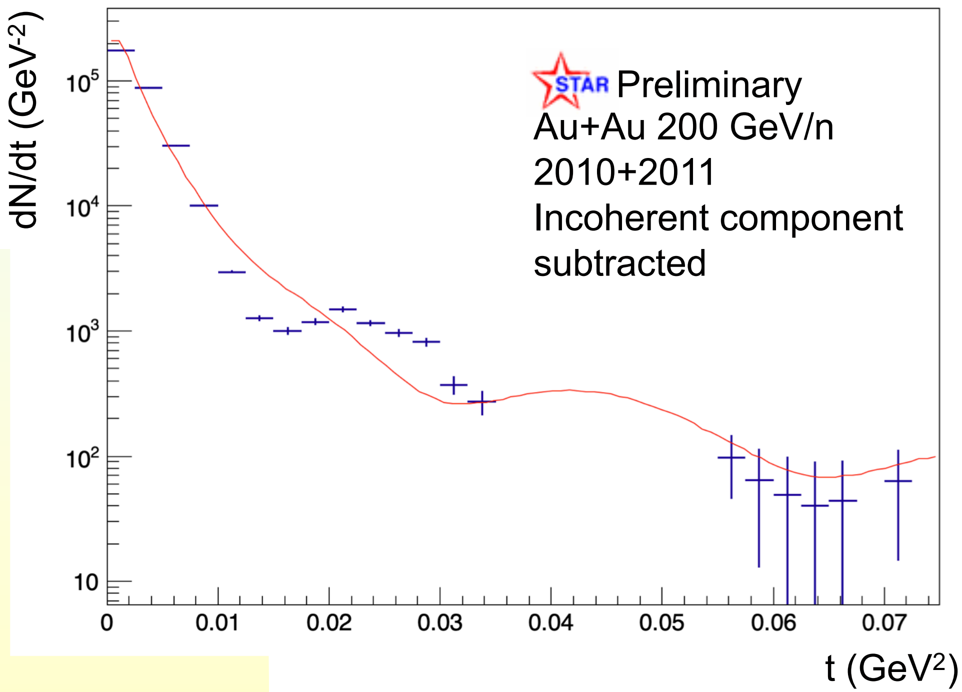
Full templates

- Combine all three components, with random relative azimuthal orientations
- Black disk and Woods-Saxon have minima at different *t* values, due to different functional form and chosen radii



Fit results – full mass range

- χ^2/DF=24770/28 terrible.
- Λ=0.71 $\pm$ 0.006 – 70% Woods-Saxon
- Fit would prefer a much larger nuclear radius (~ 9.5-10 fm)
  - No clear fix to 'radius problem'
  - Radius mismatch dominates the fit – cannot trust the Λ
- 1st diffraction dip is deeper in data than template
- Larger photon <p_T> would make problems worse



Lessons & problems for future UPC studies

- Incoherent subtraction
  - Dipole form factor problematic at small t*
- Limited t range
  - An accurate Fourier transform requires >= 2-3 diffractive minima**
  - For $t > 0.05$ GeV^2, it is hard to accurately remove incoherent production and other backgrounds*-?
- Photon p_T spectrum
  - The limited b range causes uncertainty in the photon p_T spectrum
  - The photon field is aplanar – stronger on the 'near' side of the nucleus than on the far side
- The black-disk and Woods-Saxon distributions do not mesh well.
- This analysis requires an over-large nucleus (9.5-10 fm)
  - A dipole-model calculation might be able to match this

Lessons for the EIC

- The photon flux should be simpler at the EIC.
- Fortunately, at the EIC, one can separate coherent/incoherent production by observing the products of nuclear breakup.
  - $d\sigma_{Incoherent}$ /dt is probably not smooth as t-> 0
  - Good separation (500:1, per the Yellow Report) is required. This requires the ability to observe ~ MeV (target frame) photons from nuclear deexcitations
- One probably needs to rely on a direct Fourier transform – it is not easy to fit to $d\sigma$/dt to a linear combination
- Good resolution for both the vector meson and the scattered electron are required to find the diffractive minima.

**Fourier Transform requirements studied for EIC by Thomas Ullrich

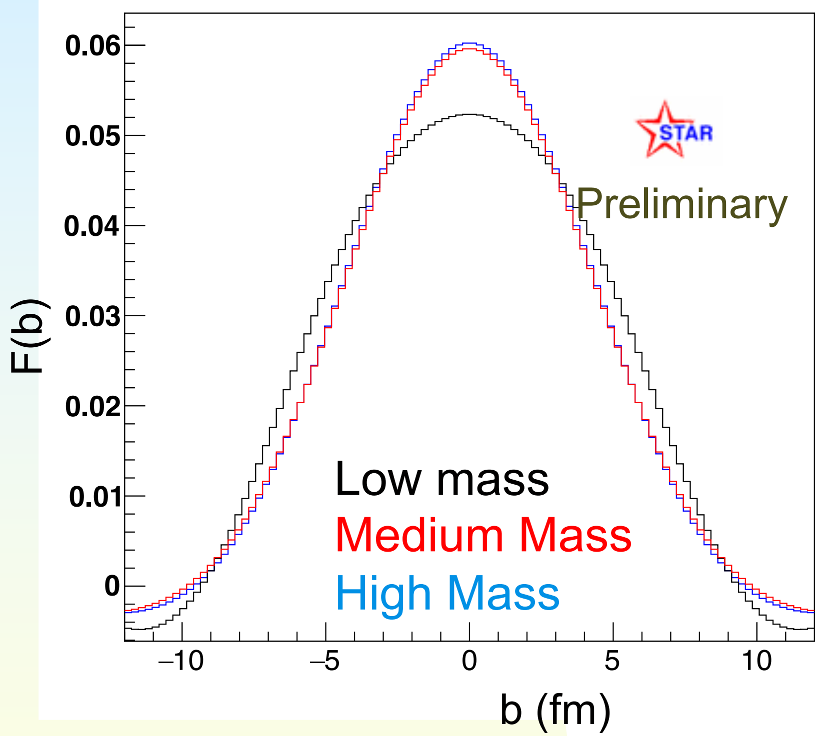
Backup…

Data set and cuts

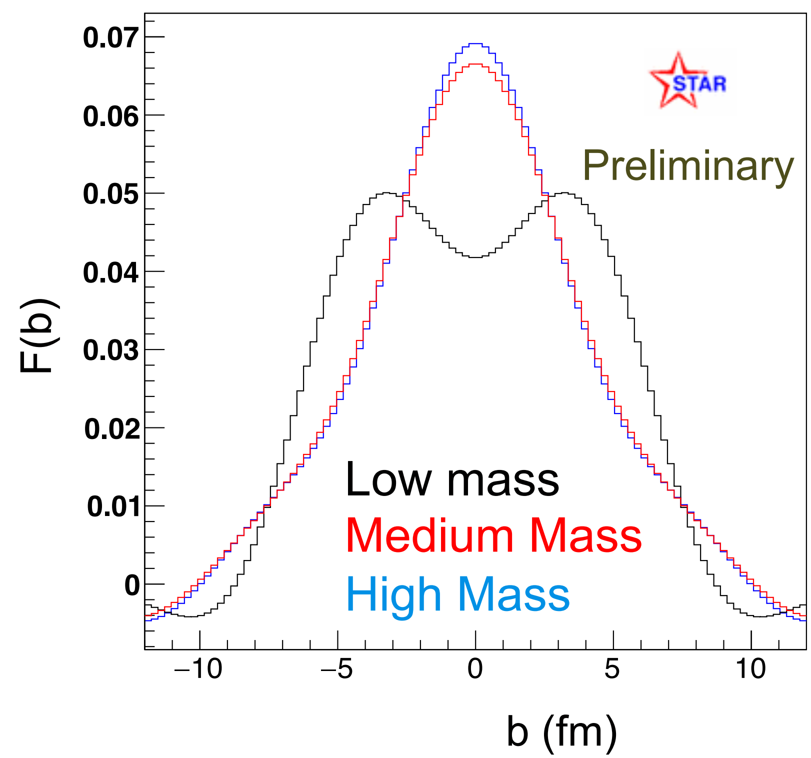
- Trigger: 2-6 tracks with $|y|<1$ and 1-4 neutrons in each ZDC
- Select $\pi\pi$ pairs coming from a single vertex with tight cuts
  - $|Z_{vtx}| < 50$ cm
  - $|Y_{\pi\pi}| > 0.04$ (removes cosmic-ray muons)
  - Each track must have at least 25 space points
  - $N_{primary\ tracks} = 2$
- Mass Cut: 0.62 GeV $< M_{\pi\pi} <$ 0.95 GeV
- Backgrounds:
  - $M_{\pi\pi} > 0.62$ GeV removes most $\gamma A \rightarrow \omega \rightarrow \pi^+ \pi^- \pi^0$ and $\gamma\gamma \rightarrow ee$
    - N($\pi\pi$ from $\omega \rightarrow \pi^+ \pi^- \pi^0$)/N($\pi\pi$ from ρ) ~ 0.05%
    - For $M_{\pi\pi} > 0.62$ GeV, $\pi^+\pi^-$ from ω are at low p_T,
      - Similar p_T as most ρ + direct $\pi\pi$ –> not a problem
  - Like sign pairs represent the hadronic background
    - Signal: like-sign background ratio > 10:1 in the coherent region

Effect of changing t_{max}

t_{max}=0.005 GeV²



t_{max}=0.009 GeV²



Variation with t_{max}, due to windowing

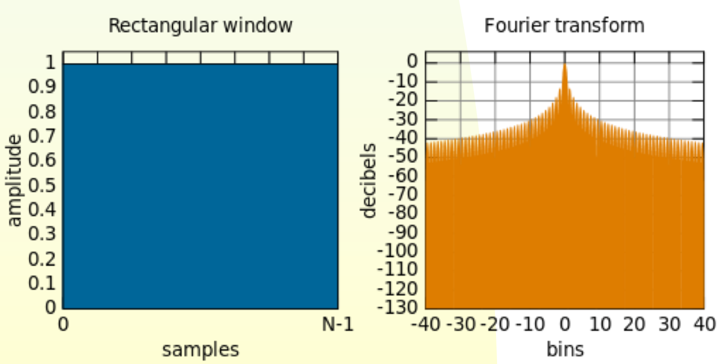
Especially for the low-mass curve

However, the trend does not vary with t_{max}

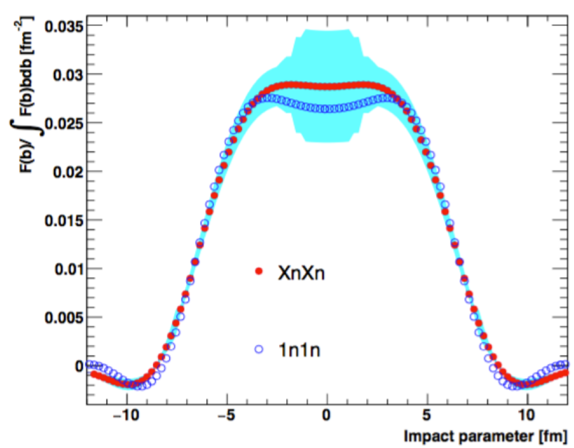
The low-mass distribution is always wider than the others, etc.

t_{max} sensitivity and windowing

- Fourier transforms assume integration over the full t range
  - The data have a finite range, so we need to choose t_{max} below the noise-dominated region.
- Input is $d\sigma/dt$ times a square window from 0 to t_{max}
  - -> Output is the convolution of the two transforms
- The biggest impact is in the region around $1/t_{max}$ -> small b
  - Change t_{max} -> change result at small b
  - This might be alleviated with a different windowing function, but the phase space is large.



From wikipedia



Systematic Uncertainties

- The uncertainties in the determination of the nuclear shape are dominated by the choice of t_{max} and windowing function.
  - A hard cut on t_{max} *is* a windowing function
- Other systematic uncertainties
  - Incoherent $d\sigma/dt$ subtraction
    - Variation of the fit range leads to small changes in $d\sigma/dt_{coherent}$ & F(b)
    - Small; slow variation with t -> is only important at small |b|
  - Backgrounds
    - Variation in cuts leads to variation in signal to noise ratio, but only small changes in $d\sigma/dt_{coherent}$ & F(b)
- The data are a mixture of interfering ρ^0, direct $\pi\pi$ and $\omega\rightarrow\pi\pi$. We assume that these have the same relationship between $M_{\pi\pi}$ and dipole size.
- We do not account for the photon p_T here.

Conclusions

- $d\sigma_{Coherent}/dt$ is sensitive to the transverse spatial distribution of gluons in a nucleus
  - F(b) is the 2-dimensional Fourier transform of $d\sigma/dt_{Coherent}$
- STAR UPC data provides large samples of photoproduced $\pi\pi$ which can be used for these studies
- There are a number of theory/phenomenology challenges
  - Subtracting $d\sigma_{Incoherent}/dt$ over a wide enough t range
  - Determining the correct, limited-b photon p_T spectrum
- These challenges will disappear at the EIC, as long as EIC detectors can very efficiently separate coherent and incoherent photoproduction.