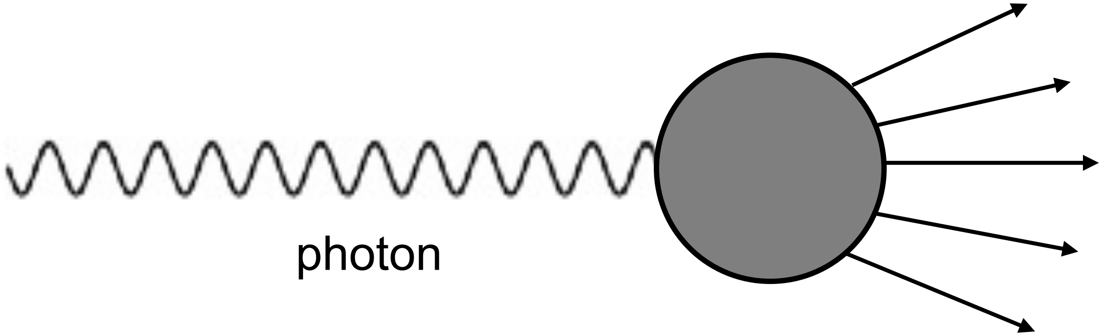
UPC *photoproduction* at high-energy hadron colliders



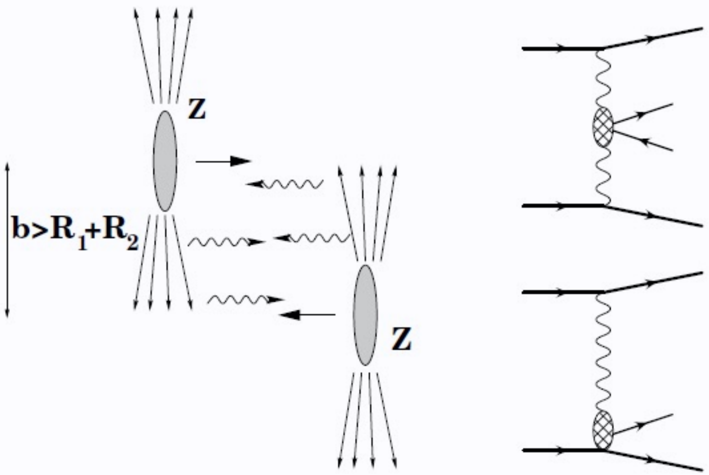
Kong Tu
BNL
04.25.2022

—— one step closer to the Electron-Ion Collider

Motivated by the STAR BUR 2022 and many great discussions with BNL colleagues

UPC – a general approach to photoproductions

Exclusive processes

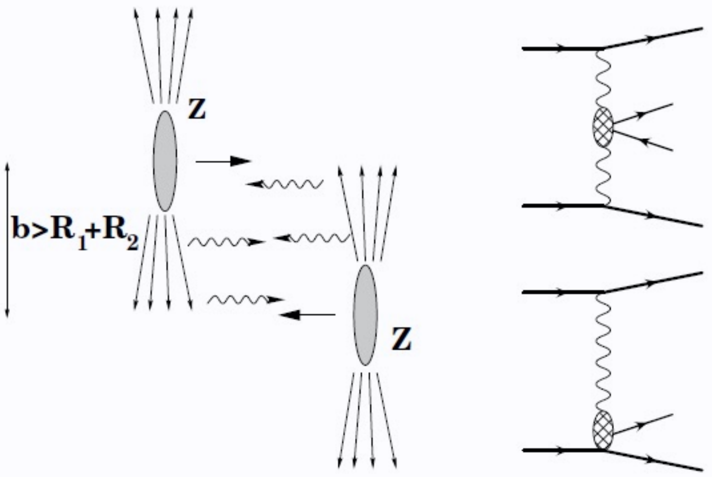


What we mostly focused on in the UPC physics – VM and dilepton

- Nuclear gluon density ~ *xG, low-x physics, saturation, shadowing, etc.*
- QED process

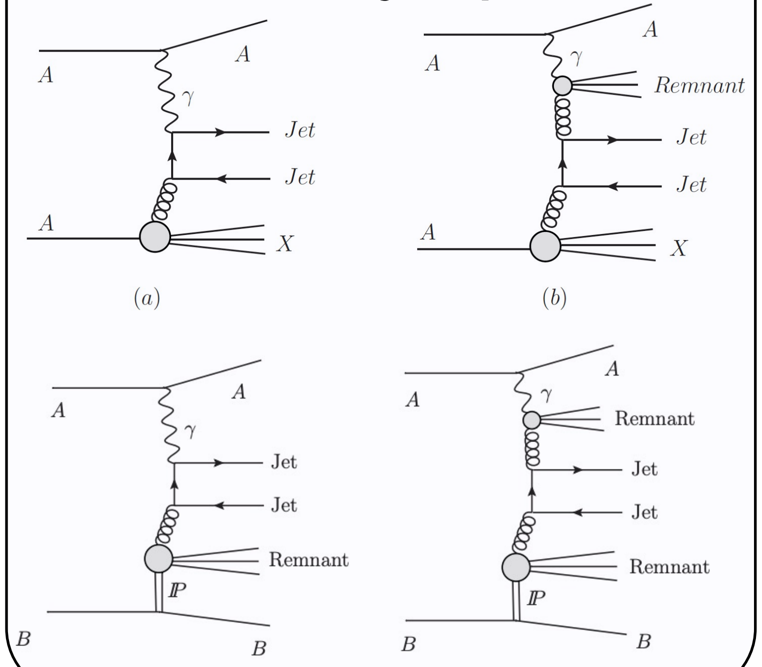
UPC – a general approach to photoproductions

Exclusive processes



What we mostly focused on in the UPC physics – VM and dilepton

Semi-inclusive/jets processes



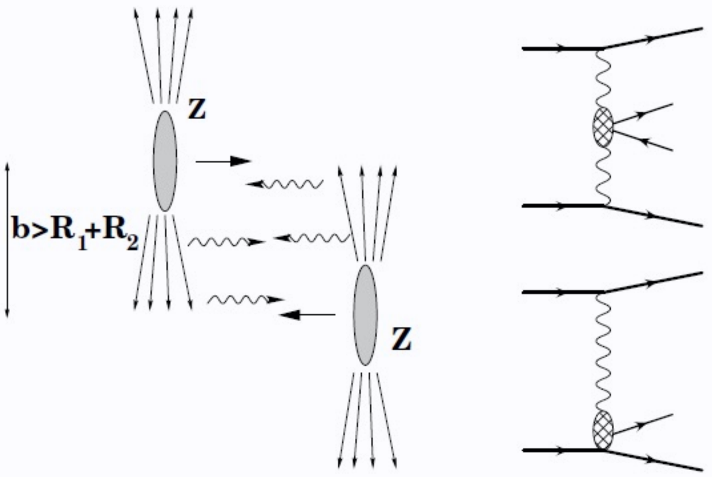
- Nuclear gluon density ~ *xG, low-x physics, saturation, shadowing, etc.*
- QED process

- nPDFs, *moderate-x at RHIC, anti-shadowing region!*
- QCD factorization breaking and diffractive nPDFs
- Photon structure.

UPC – a general approach to photoproductions

Submitted to PRD (April 15,2022)

Exclusive processes



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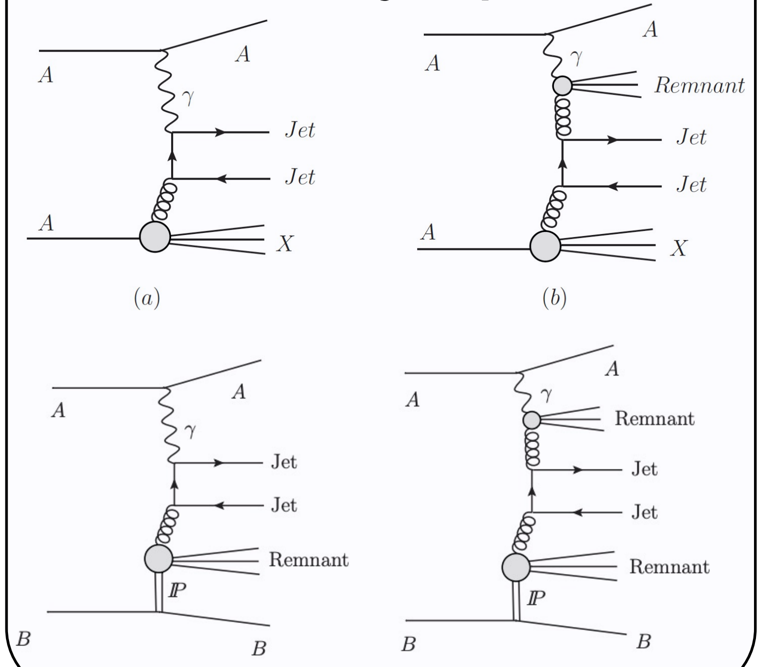
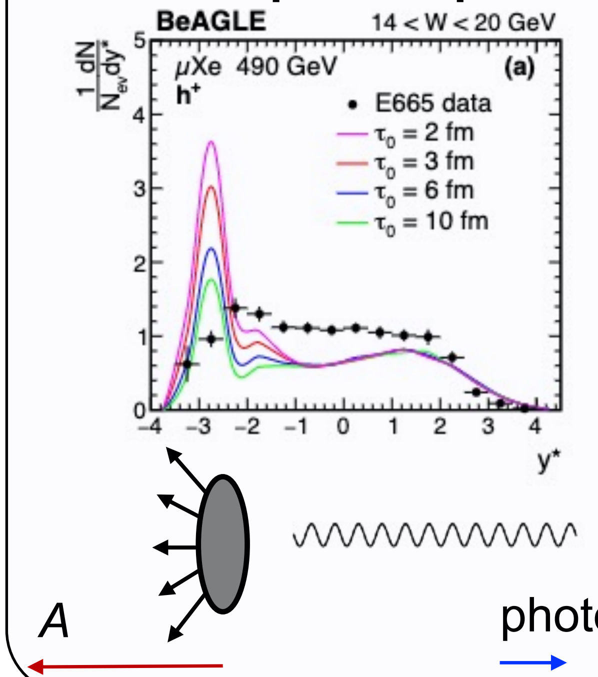


Inclusive particle production



- ➢ Nuclear gluon density ~ *xG, low-x physics, saturation, shadowing, etc.*
- ➢ QED process

- ➢ nPDFs, *moderate-x at RHIC, anti-shadowing region!*
- ➢ QCD factorization breaking and diffractive nPDFs
- ➢ Photon structure.

- ➢ Inclusive – sensitive to target fragmentation in nucleus, Intra-Nuclear Cascade, etc.
- ➢ Baseline for saturation studies

H1 publications on photoproduction over the entire HERA 1&2 (42 papers)

- Measurement of Exclusive pi+pi- and rho0 Meson Photoproduction at HERA
- Exclusive rho0 Meson Photoproduction with a Leading Neutron at HERA
- Elastic and Proton-Dissociative Photoproduction of J/psi Mesons at HERA
- Measurement of Beauty Photoproduction near Threshold using Di-electron Events with the H1 Detector at HERA
- Measurement of Beauty and Charm Photoproduction using Semi-muonic Decays in Dijet Events at HERA
- Measurement of Inclusive and Dijet D*-Meson Cross Sections in Photoproduction at HERA
- Diffractive Dijet Photoproduction in ep Collisions at HERA
- Inelastic Production of J/psi Mesons in Photoproduction and Deep Inelastic Scattering at HERA
- Prompt Photons in Photoproduction at HERA
- Inclusive Photoproduction of rho^0,K^{*0} and \phi Mesons at HERA
- Tests of QCD Factorisation in the Diffractive Production of Dijets in Deep-Inelastic Scattering and Photoproduction at HERA
- Diffractive Open Charm Production in Deep-Inelastic Scattering and Photoproduction at HERA
- Inclusive D*-Meson Cross Sections and D*-Jet Correlations in Photoproduction at HERA
- Measurement of Charm and Beauty Dijet Cross Sections in Photoproduction at HERA using the H1 Vertex Detector
- Diffractive Photoproduction of Rho Mesons with Large Momentum Transfer at HERA
- Photoproduction of Dijets with High Transverse Momenta at HERA
- Measurement of Charm and Beauty Photoproduction at HERA using D* mu Correlations
- Measurement of Prompt Photon Cross Sections in Photoproduction at HERA
- Diffractive Photoproduction of J/psi Mesons with Large Momentum Transfer at HERA
- Measurement of inclusive jet cross sections in photoproduction at HERA
- Search for Odderon-Induced Contributions to Exclusive pi^0 Photoproduction at HERA
- Diffractive Photoproduction of Psi(2S) Mesons at HERA
- Inelastic Photoproduction of J/Psi Mesons at HERA
- Energy Flow and Rapidity Gaps Between Jets in Photoproduction at HERA
- Measurement of Dijet Cross Sections in Photoproduction at HERA
- Photoproduction with a Leading Proton at HERA
- Inclusive Photoproduction of Neutral Pions in the Photon Hemisphere at HERA
- Elastic Photoproduction of J/psi and Upsilon Mesons at HERA
- Measurement of Di-jet Cross-Sections in Photoproduction and Photon Structure
- Charged Particle Cross Sections in Photoproduction and Extraction of the Gluon Density in the Photon
- Measurement of the Inclusive Di-Jet Cross Section in Photoproduction and Determination of an Effective Parton Distribution in the Photon
- Photoproduction of K^0 and Lambda at HERA and a Comparison with Deep Inelastic Scattering
- Diffractive Dissociation in Photoproduction at HERA
- Photoproduction of D^* Mesons in Electron-Proton Collisions at HERA
- Elastic and Inelastic Photoproduction of J/psi Mesons at HERA
- Elastic Photoproduction of Rho0 Mesons at HERA
- Comparison of Deep Inelastic Scattering with Photoproduction Interactions at HERA
- Single Inclusive Parton Cross Sections in photoproduction and the Photon structure
- Photoproduction of J/Psi Mesons at HERA
- Inclusive Charged Particle Cross Sections in Photoproduction at HERA
- Measurement of Inclusive Jet Cross Sections in Photoproduction at HERA
- Total Photoproduction Cross Section Measurement at HERA Energies

Similar for ZEUS, not listed.

H1 publications on photoproduction over the entire HERA 1&2 (42 papers)

Analyses without VMs, jets, or HFs.

1) Prompt Photons in Photoproduction at HERA
2) Inclusive Photoproduction of rho^0,K^{*0} and \phi Mesons at HERA
3) Measurement of Prompt Photon Cross Sections in Photoproduction at HERA
4) Inclusive Photoproduction of Neutral Pions in the Photon Hemisphere at HERA
5) Charged Particle Cross Sections in Photoproduction and Extraction of the Gluon Density in the Photon
6) Photoproduction of K^0 and Lambda at HERA and a Comparison with Deep Inelastic Scattering
7) Single Inclusive Parton Cross Sections in photoproduction and the Photon structure
8) Inclusive Charged Particle Cross Sections in Photoproduction at HERA
9) Total Photoproduction Cross Section Measurement at HERA Energies

An important part of photoproduction has not been studied in **high-energy photo-nucleus collisions**.

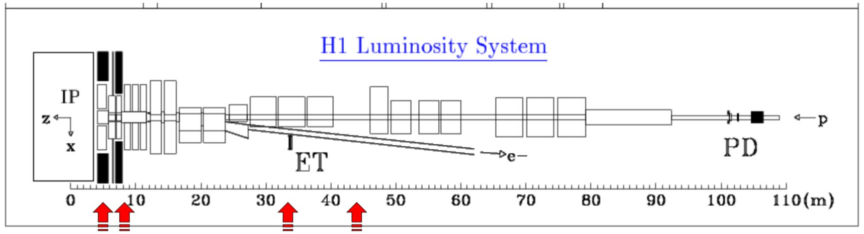
(of course, there were low-energy data from E665, HERMES, Jlab 6 & 12, etc)

Similar for ZEUS, not listed.

Challenge of event kinematics

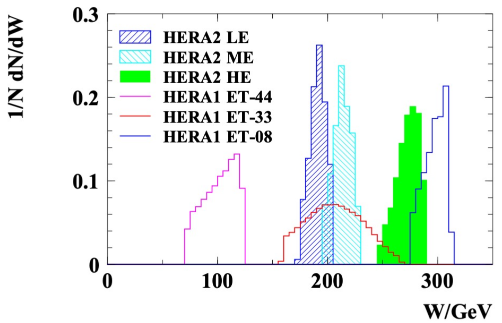
Very small scattering angle → very low Q^2

With electron tagger



☺ $Q^2 < 0.01$ GeV^2; precise kinematics; trigger

😐 Limited acceptance

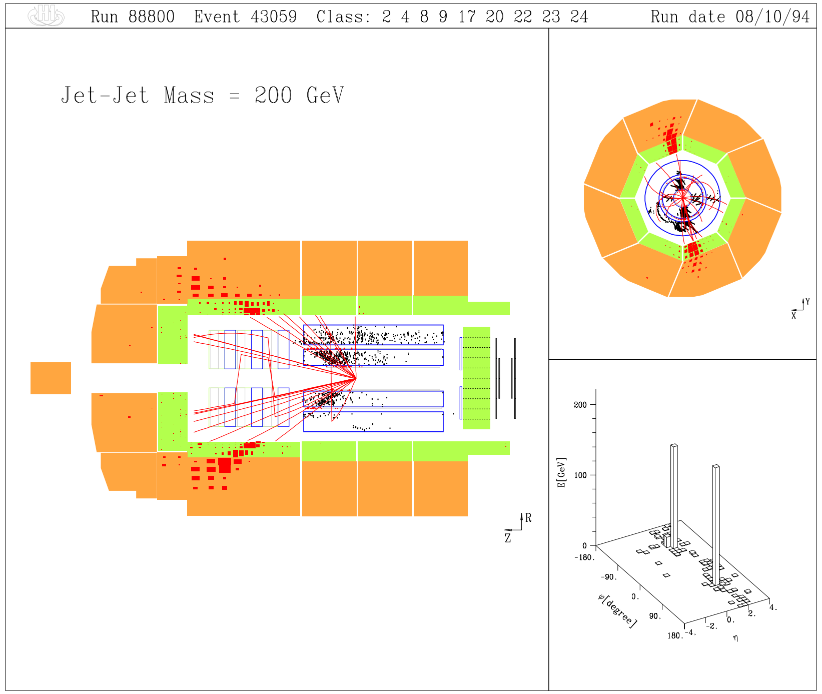


- 3 taggers at HERA1, 1 - at HERA2
- large coverage in W, complementarity
- look at best available data:

  HERA1 – $99/00e^+$ (nominal)

  HERA2 – $06/07e^+$ (HE,LE,ME)

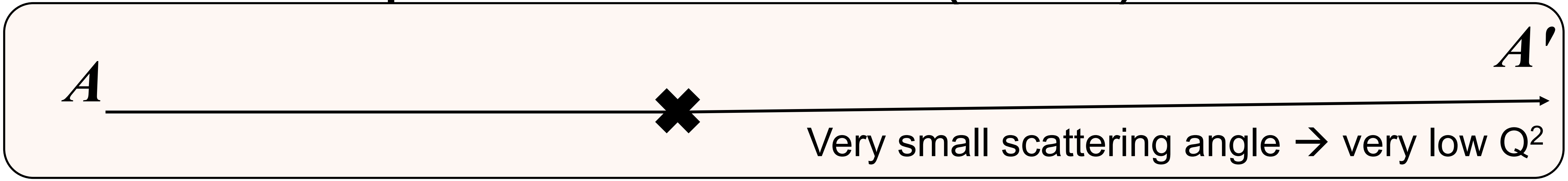
Without electron tagger

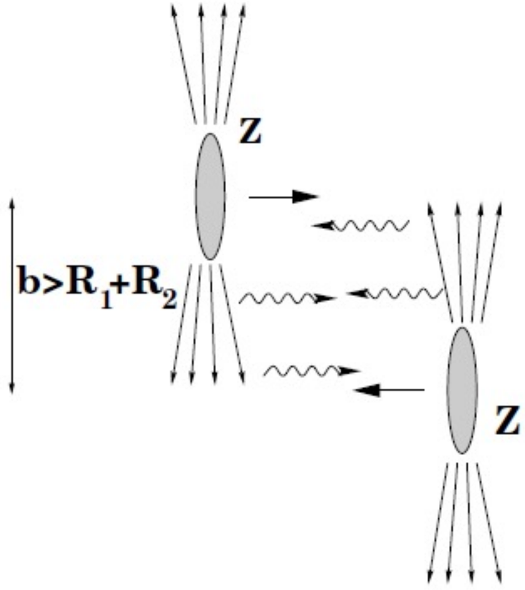


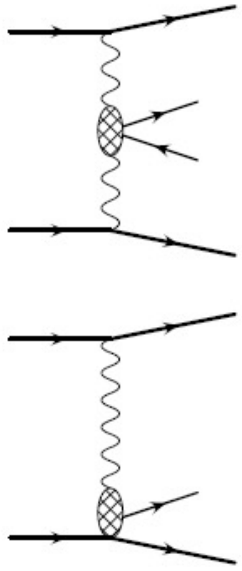
Fully reply on the hadronic final states, e.g., jets

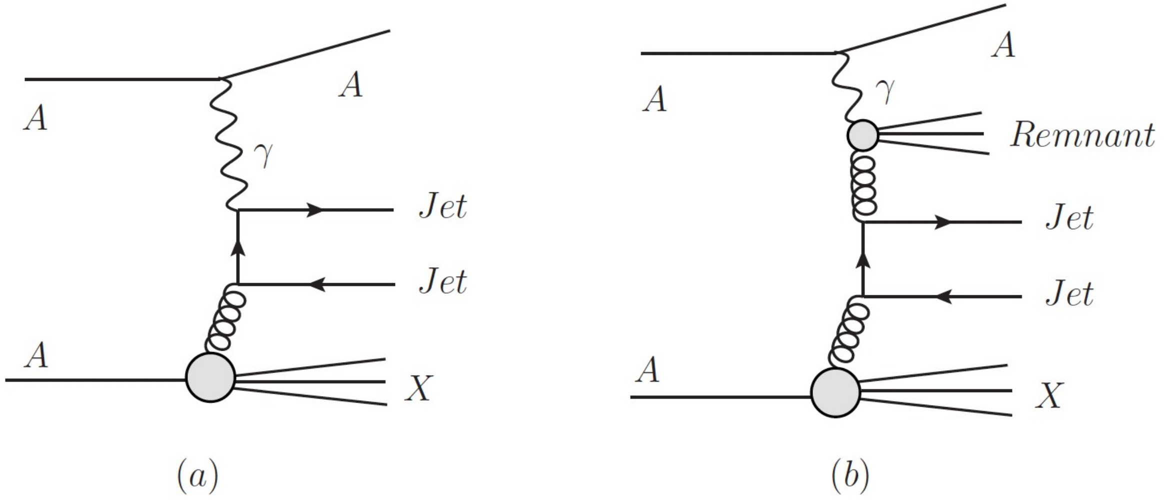
One example, https://www-h1.desy.de/psfiles/papers/desy09-135.pdf

Ultra-Peripheral Collisions (UPC)









Exclusive:
- ➢ Vector Meson (J/psi, Upsilon)
- ➢ dileptons

Less exclusive:
- ➢ Jets, dijets, etc

Ultra-Peripheral Collisions (UPC)

Very small scattering angle → very low Q^2

Exclusivity tells us the kinematics:

Photon energy $k \sim M/2 \exp(-y)$
Photon-N energy $W^2 \sim 2E_pM \exp(-y)$
Momentum fraction (LO) $x \sim M^2/W^2$

* Issue: incoherent VM production, this kinematics is not accurate.

Exclusive:

- Vector Meson (J/psi, Upsilon)
- dileptons

Kinematics/scales imposed by Jets:

Z_γ, x_γ, x_A are given by jet mass and jet rapidity.

$$z_\gamma \equiv \frac{m_{\rm jets}}{\sqrt{s}} e^{+y_{\rm jets}} \, , \quad x_{\rm A} \equiv \frac{m_{\rm jets}}{\sqrt{s}} e^{-y_{\rm jets}}$$

Less exclusive:

- Jets, dijets, etc

Ultra-Peripheral Collisions (UPC)

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* Issue: incoherent VM production, this kinematics is not accurate.

How can we access the inclusive part of photoproduction?

Kinematics/s… ts:

Z_γ, x_γ, x_p…
rapidity…

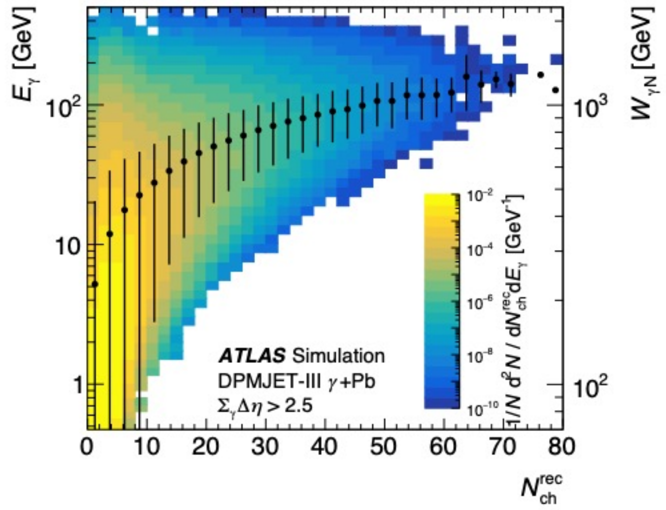
$z_\gamma \equiv$ …

Exclusive:
- ➢ Vector Meson (J/psi, Upsilon)
- ➢ dileptons

Le…
- ➢ Jets, …, etc
- ➢ Inclusive or diffractive

UPC inclusive particle photoproduction?

D. Perepelitsa (QM 2022)

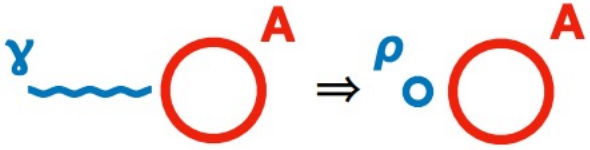


According to DPMJET,

@ N_{ch} = 15:
$<E_\gamma>$ ~ 30 GeV, $\sqrt{s_{\gamma N}}$ ~ 600 GeV

@ N_{ch} = 30:
$<E_\gamma>$ ~ 60 GeV, $\sqrt{s_{\gamma N}}$ ~ 800 GeV

Vector Meson Dominance (VMD) paradigm - most of these proceed as, e.g., ρ+A interactions



- The closest it gets is done by ATLAS and recent STAR preliminary results on baryon stopping (N. Lewis)
- Basically, only average photon energy and average W can be inferred with particle multiplicity

Lessons learned from HERA

- Kinematic reconstruction without electron tagging, definitely not as good as with the electron tagging. But better than an *average* like ATLAS did?

Electron Method:

$$\begin{aligned} Q^2 &= 2E_eE'_e(1+\cos\theta_e) \\ y &= 1-\frac{E'_e}{2E_e}(1-\cos\theta_e) \\ x &= \frac{Q^2}{sy} \end{aligned}$$

Hadron Method:

$$\begin{aligned} \delta_{had} &= \sum_{i=1}^{\#hadrons} E_i(1-\cos\theta_i) \\ &= E_{had} - p_{z\,had} \\ y &= \frac{\delta_{had}}{2E_e} \\ Q^2 &= \frac{p^2_{t\,had}}{1-y} \\ x &= \frac{Q^2}{sy} \end{aligned}$$

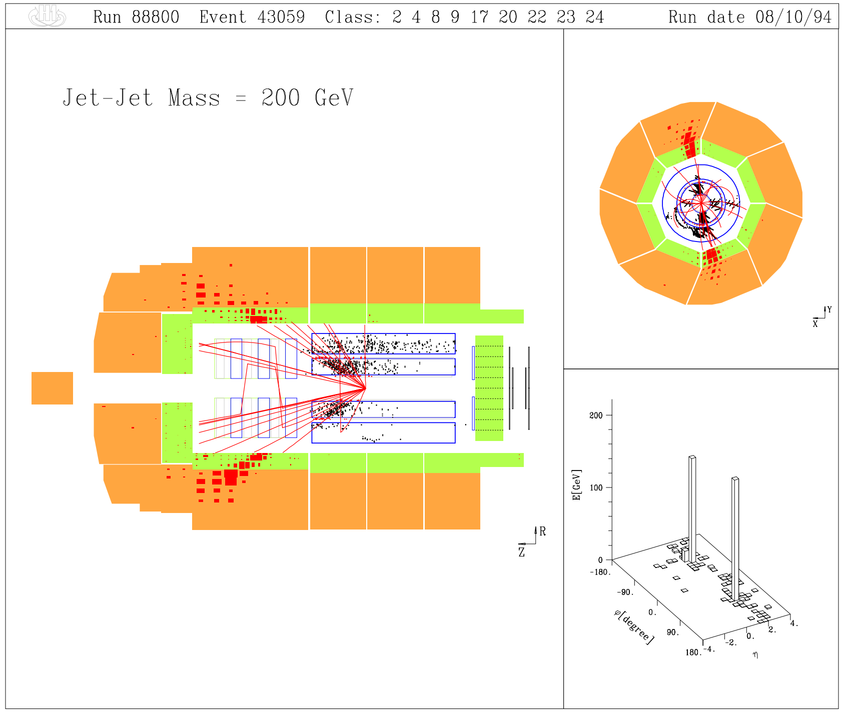
DIS or photoproduction kinematics reconstruction was always important at HERA

How to do it in UPC?

- Use the hadron method and see if it works

Hadron Method:

$$
\begin{aligned}
\delta_{had} &= \sum_{i=1}^{\#hadrons} E_i(1-\cos\theta_i) \\
&= E_{had} - p_{z\ had} \\
y &= \frac{\delta_{had}}{2E_e} \\
Q^2 &= \frac{p_{t\ had}^2}{1-y} \\
x &= \frac{Q^2}{sy}
\end{aligned}
$$



UPC nucleus replaces the incoming electron

Analysis procedure

- Step. 1 – Monte Carlo generator of UPC inclusive production

(well, we don't have such thing; but, we have eA MC – BeAGLE, https://eic.github.io/software/beagle.html)

- Step. 2 – UPC photon flux and photon energy (k) distribution (only k is needed, $Q^2 \sim 0$, no p_T)
- Step. 3 – Reweigh the eA events with UPC photon flux and reconstruct event kinematics with hadronic final-states.

A wide range of applications and guide us to do this in the data!

UPC photon flux and k

- Photon number density (k, b)

$$N(k,b) = \frac{Z^2\alpha}{\pi^2}\frac{k}{(\hbar c)^2}\frac{1}{\gamma^2}\left[K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right]$$

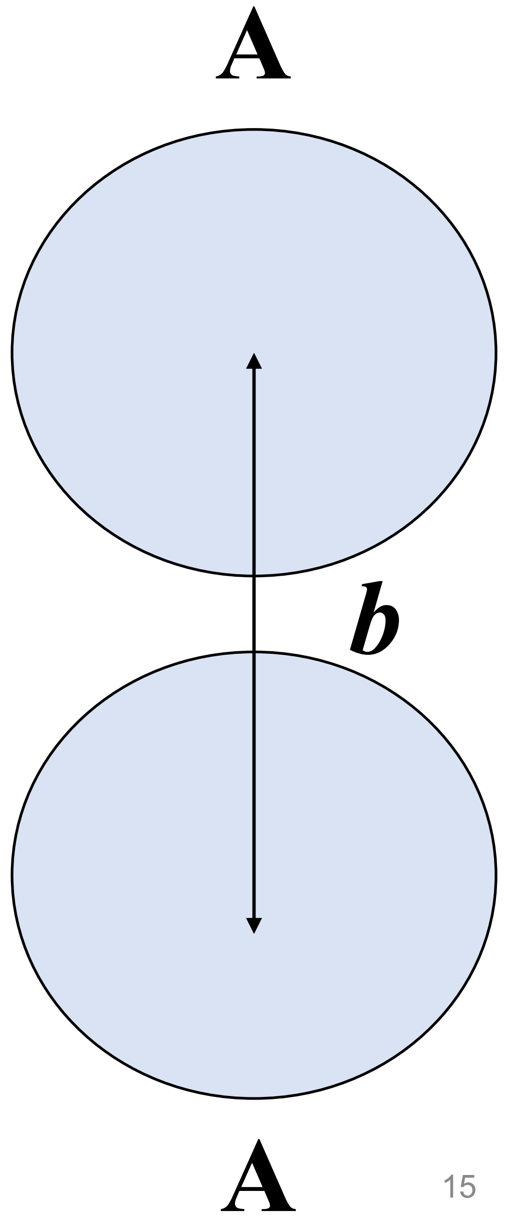
- Probability of no hadronic interaction:

$$P_{\mathrm{NOHAD}}(\vec{b}) = e^{-\sigma_{\mathrm{NN}}T_{\mathrm{AA}}(\vec{b})}$$

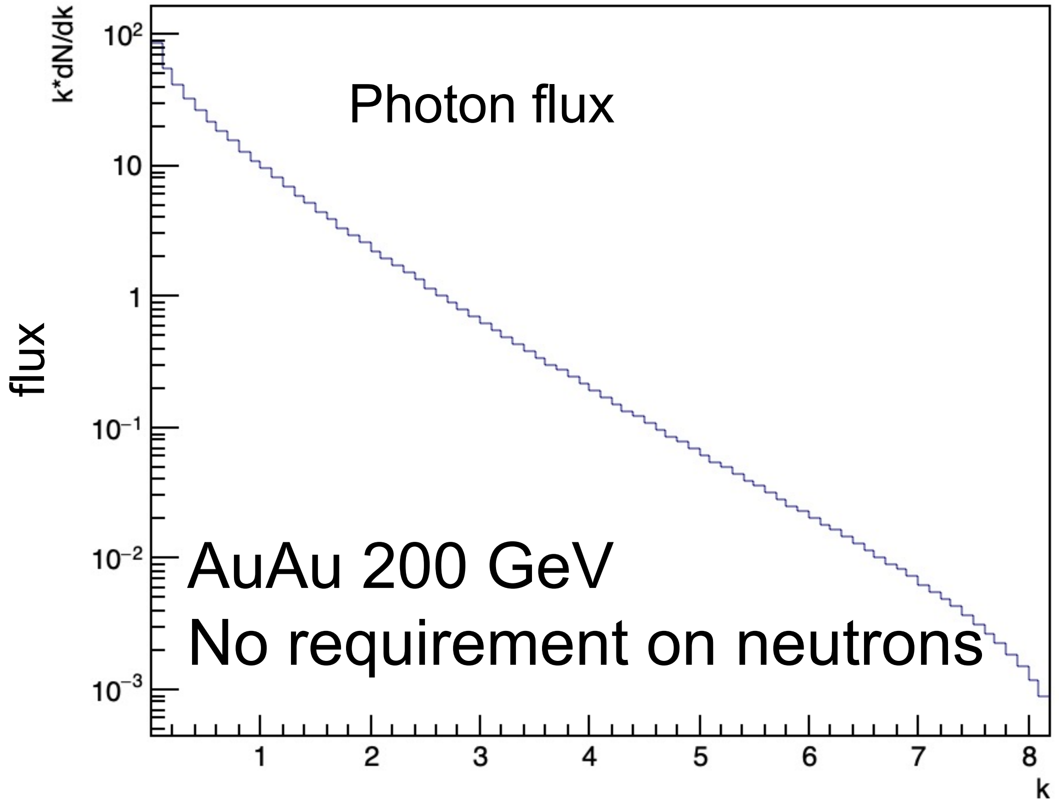
- Photon spectrum:

$$\frac{dN_\gamma(k)}{dk} = \int d^2b P_{\mathrm{NOHAD}}(\vec{b})N(k,\vec{b})$$

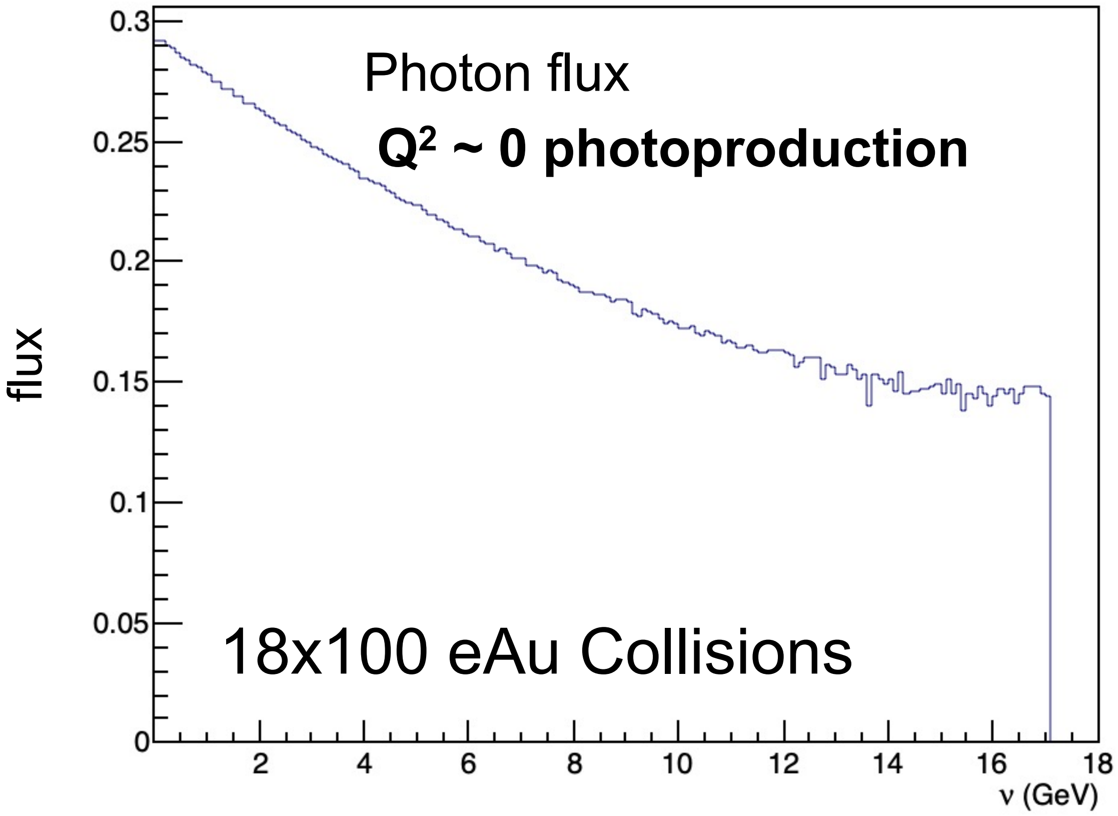
(STARLight)



STARLight
UPC



BeGLAE
eA

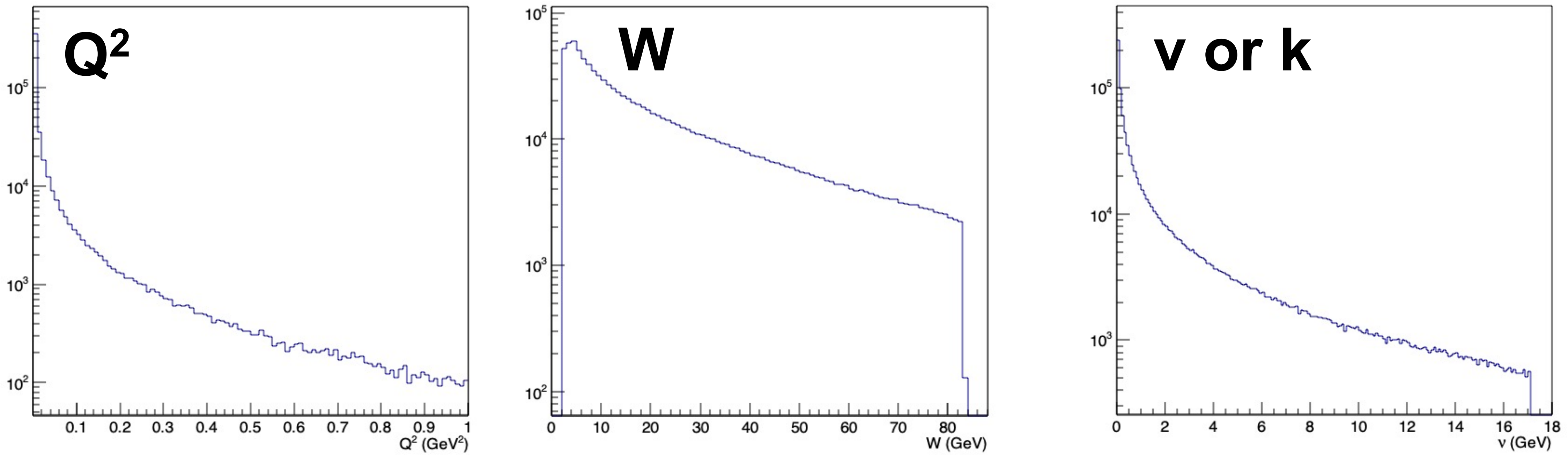


Very different photon energy distributions

BeAGLE events

- Basic setup -
  - Initial PYTHIA-6 photoproduction eN event, $Q^2 < 1$.
  - 18x100 eAu collisions – 100 GeV/nucleon beam momentum for gold
  - Multiple nucleon interactions (genShd=3) and nPDF (EPS09) are implemented. The intranuclear cascade is turned on.
  - Nuclear remnants are break up by FLUKA.
  - 1M events with inelasticity $1e-3 < y < 0.95$. The low y phase space is because UPC photon energy is low.
  - These events do NOT have coherent diffraction!
- In photoproduction, what matters is:
  - Q^2 is ~ 0
  - W^2 is the energy^2 between photon and nucleus.

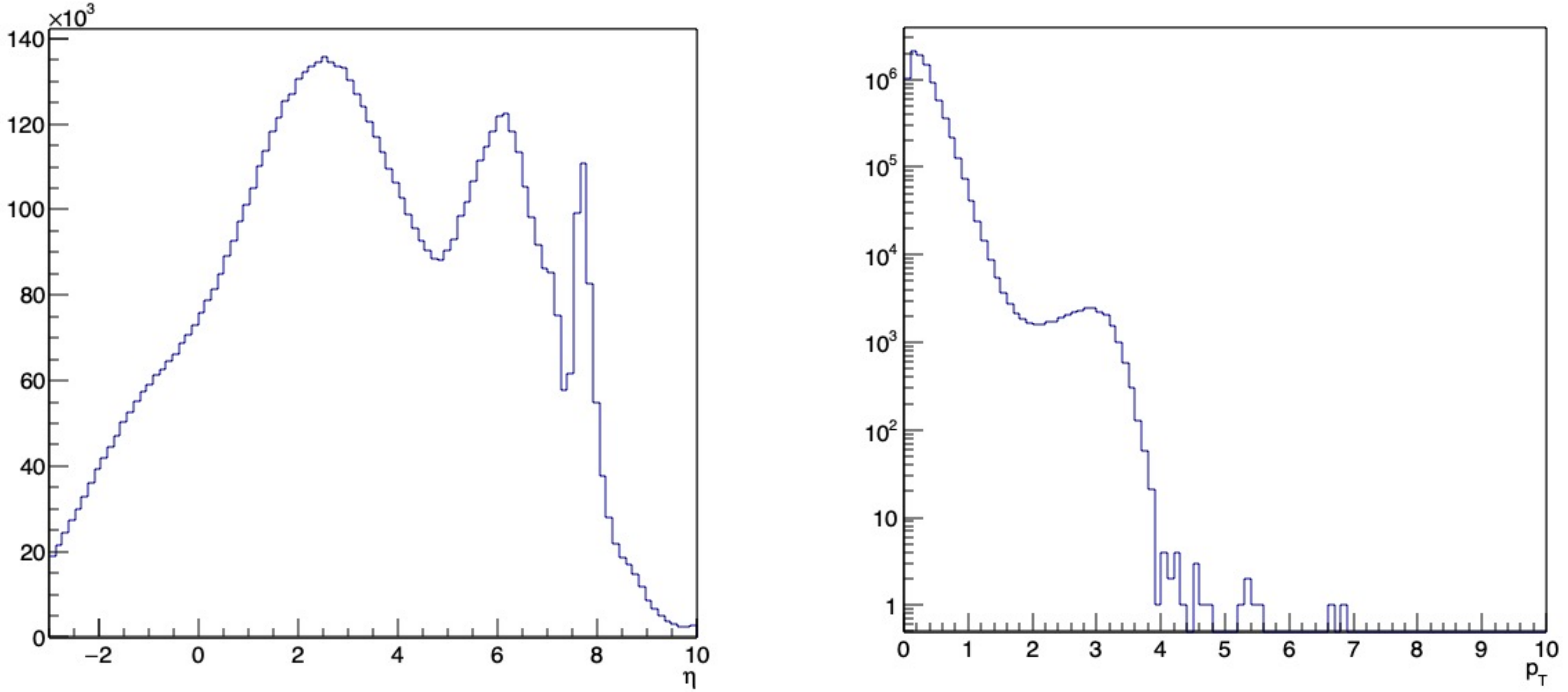
Event distribution - eAu 18x100 GeV



Highest photon-nucleus c.m.s energy is ~ 80 GeV, ~ the upper limit of what EIC can achieve

Charged stable particles

Stable particles include nuclei 2<A<197, dominated at far forward rapidity



STAR acceptance is much improved with forward upgrades, 2.5 < eta < 4.0

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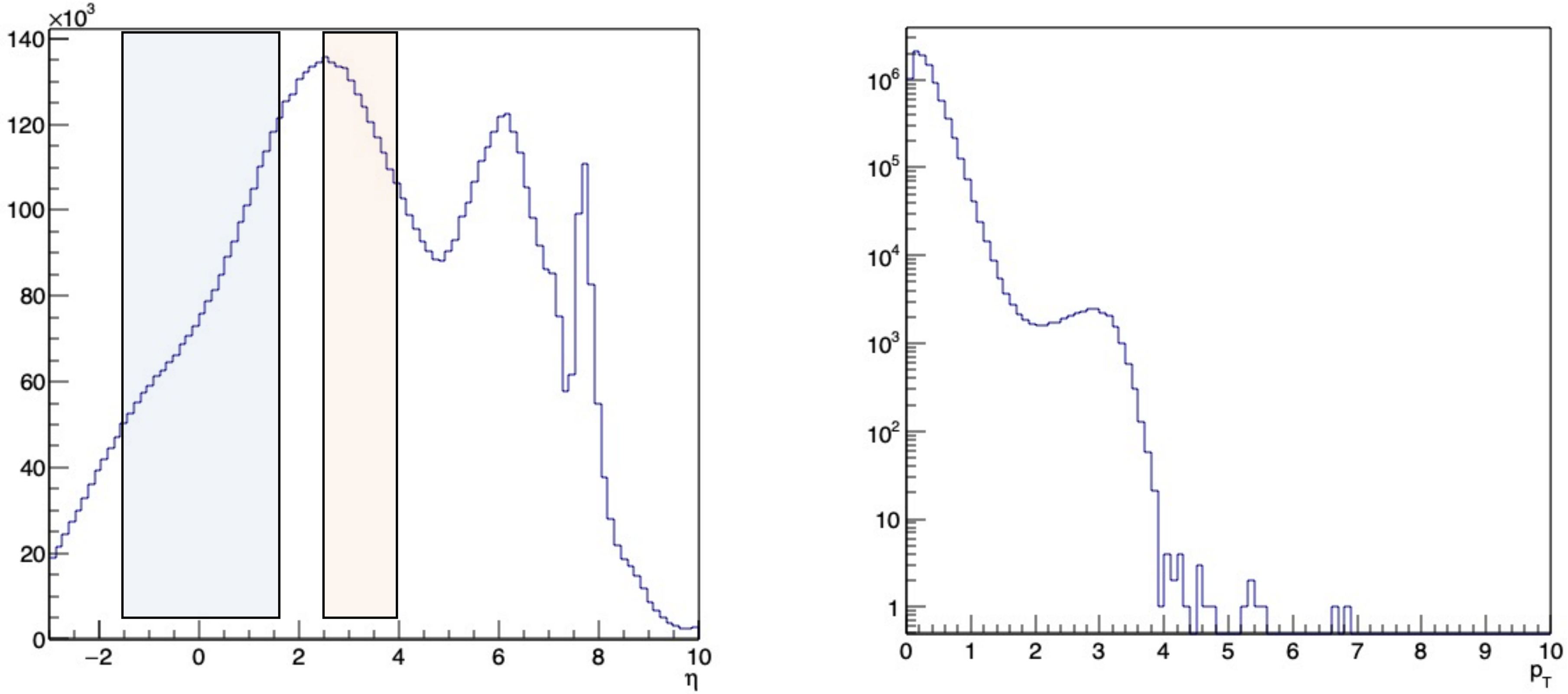
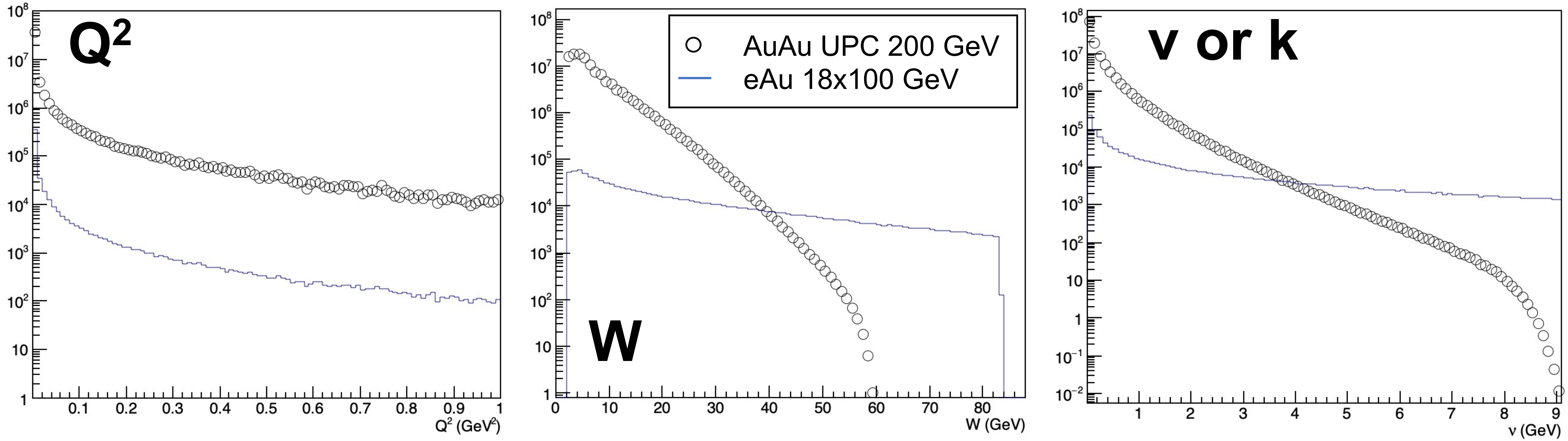


STAR acceptance is much improved with forward upgrades, 2.5 < eta < 4.0

BeAGLE reweighed – UPC events



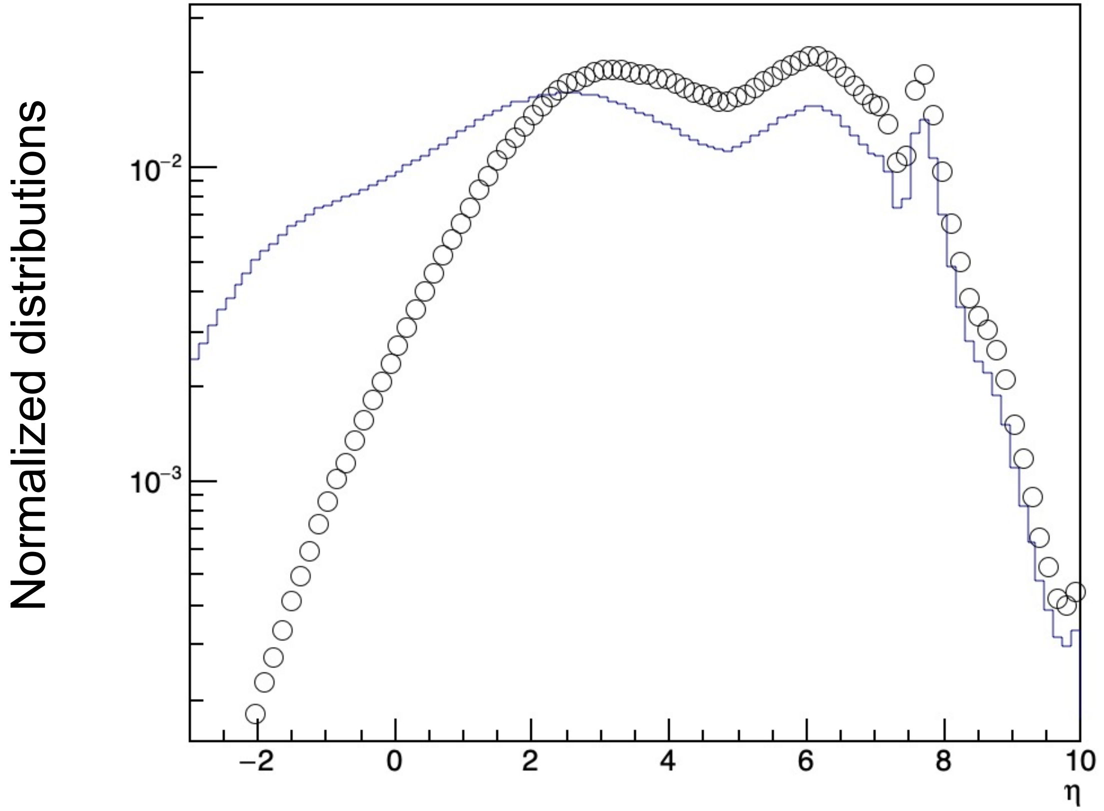
Here, the magnitude difference reflects the difference in photon flux! With the same luminosity, the number of events are much higher.

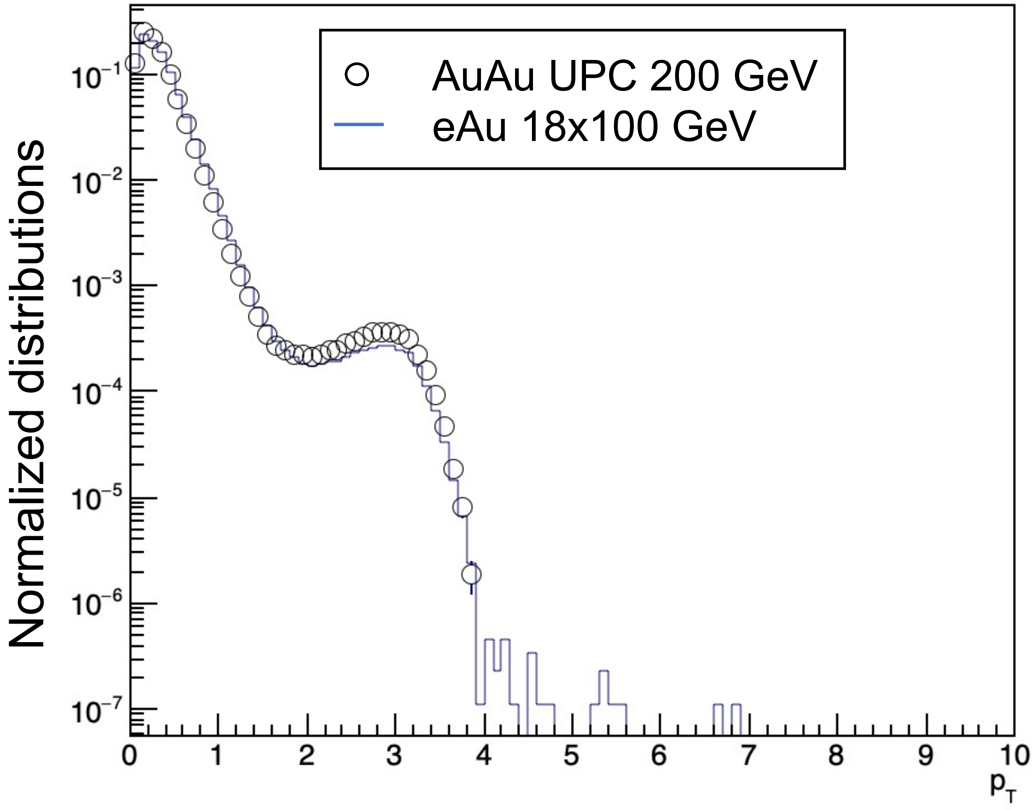
200 GeV AuAu UPC

RHIC UPC energy can only go up to 40~50 GeV realistically, since the photon energy falls very quickly

Charged stable particles - UPC

Stable particles include nuclei 2<A<197, dominated at far forward rapidity

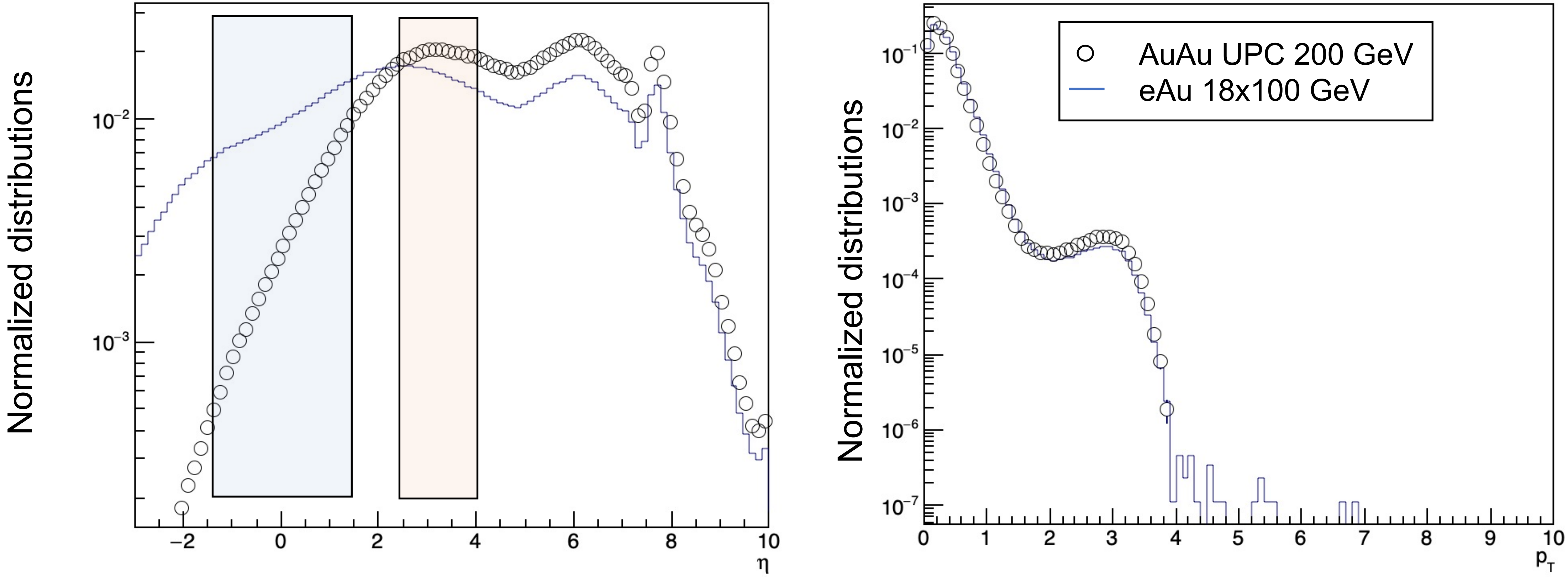




Central pseudorapidity distribution is very different in UPC!

Charged stable particles - UPC

Stable particles include nuclei 2<A<197, dominated at far forward rapidity



Central pseudorapidity distribution is very different in UPC!

Event reconstructions – Hadron only

$$\Sigma_{had} = \Sigma(E_i - p_{z,i}),$$

$$Q^2 = \frac{p_{T,had}^2}{1-y}$$

$$y = \frac{\Sigma_{had}}{2E_{\mathrm{Au}}}$$

$$W = \sqrt{sy - Q^2 - m_{\mathrm{nucleon}}^2}$$

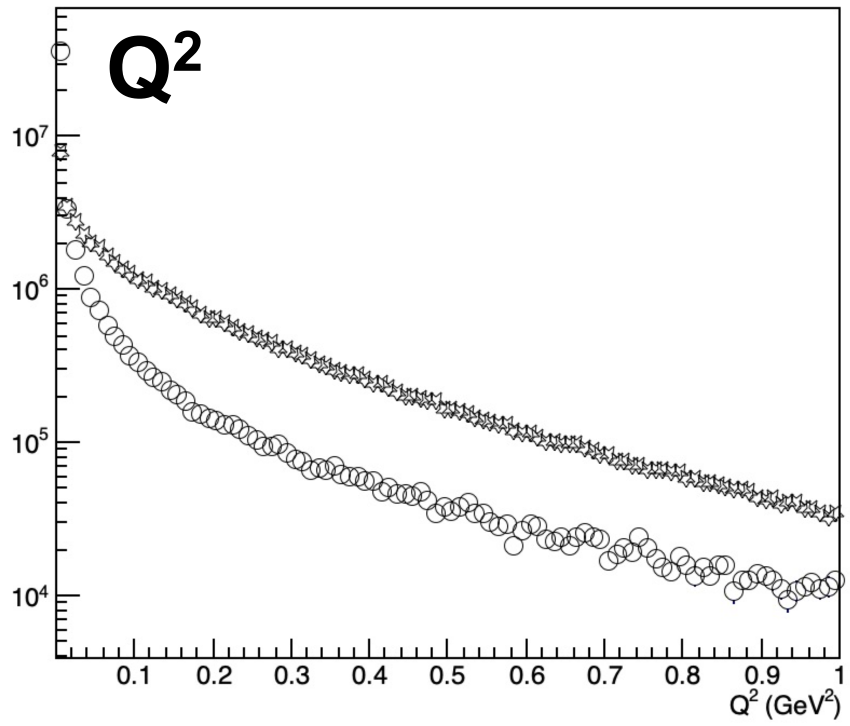
$$x = \frac{Q^2}{sy}$$

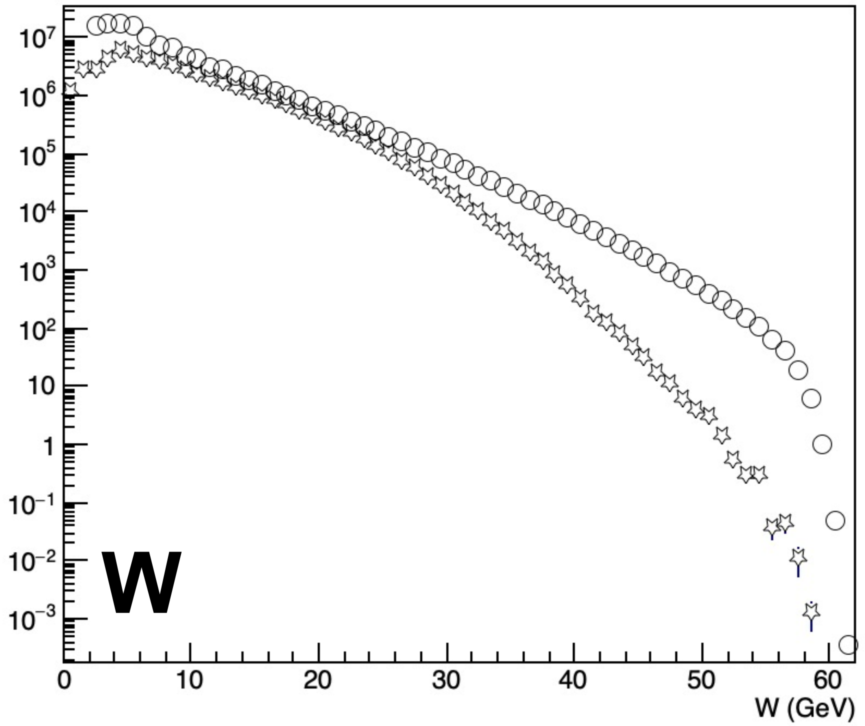
Conversion:

- Au beam (photon emitter) ~ electron beam, E_{Au} instead of E_e
- Target is the nucleon (average proton and neutron mass). Like in UPC Jpsi measurement, all W is calculated based on γN.
- Almost equivalent to an untagged ep photoproduction event!

Performance – STAR (|η|<1.5)

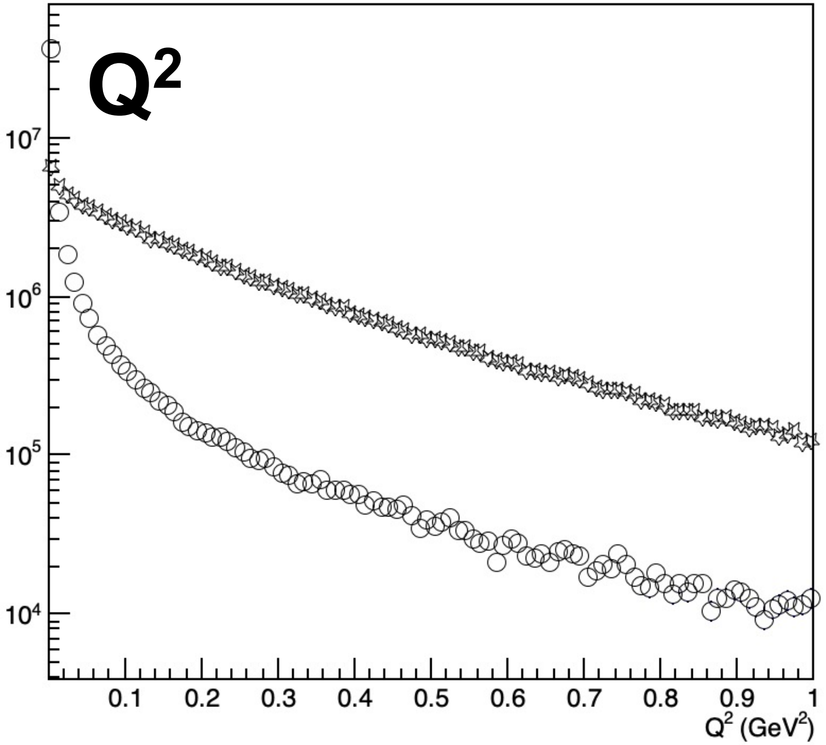
- Hadronic Final-States (HFS) is only based on (-1.5<η<1.5).
- No detector effect.

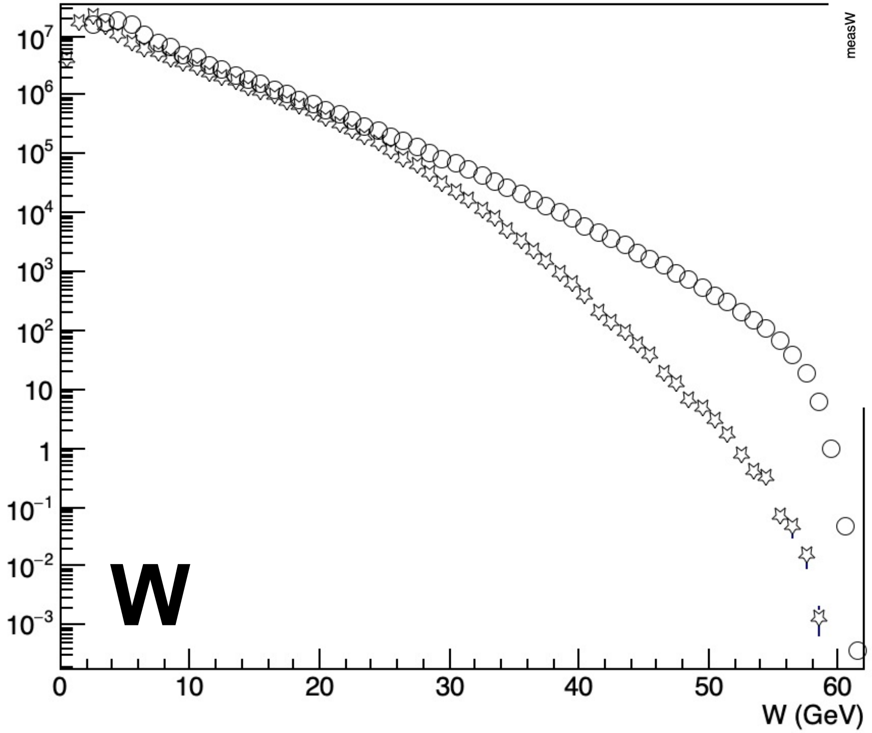




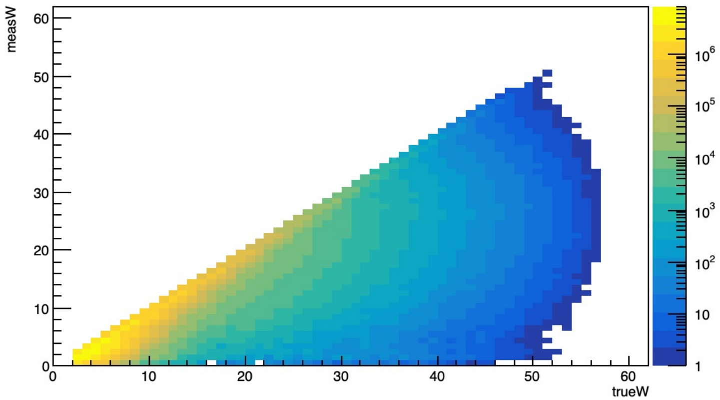
Performance – STAR (|η|<1.5+2.5 <η<4.0)

- Hadronic Final-States (HFS) is only based on (|η|< 1.5+2.5 <η<4.0).
- No detector effect.





Smearing from this HFS method



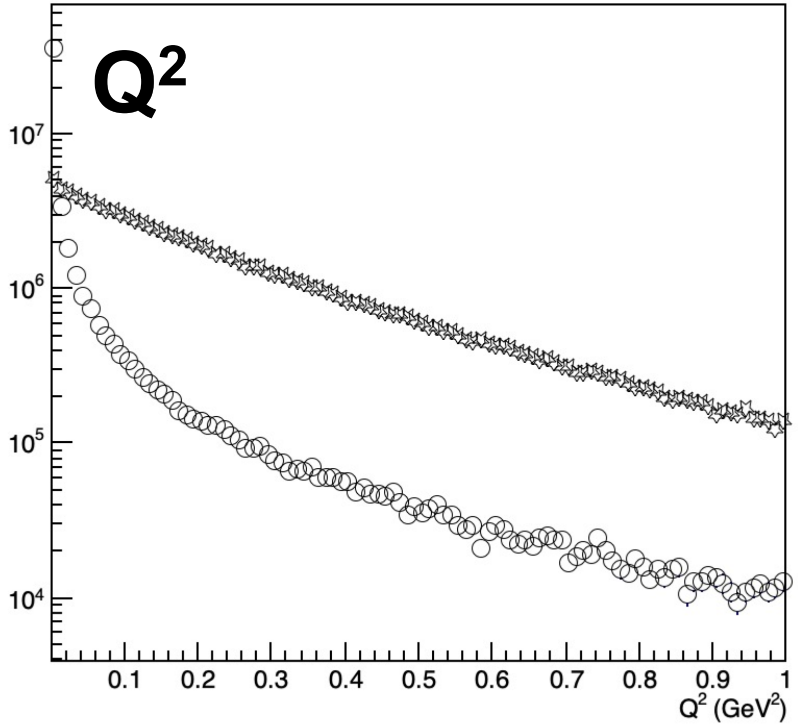
Cutting measW > something can be useful or unfolding?

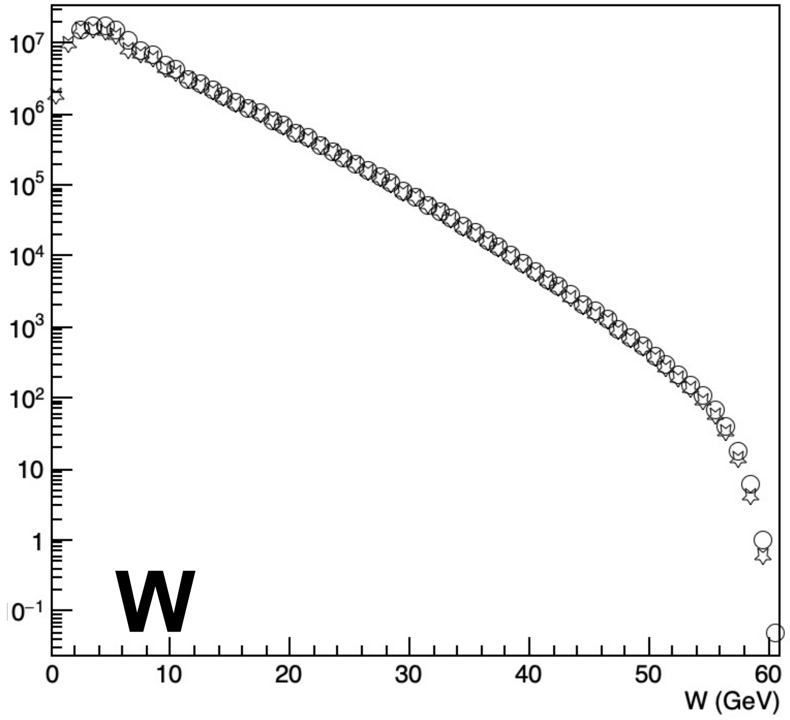
fSTAR can do a reasonable job!

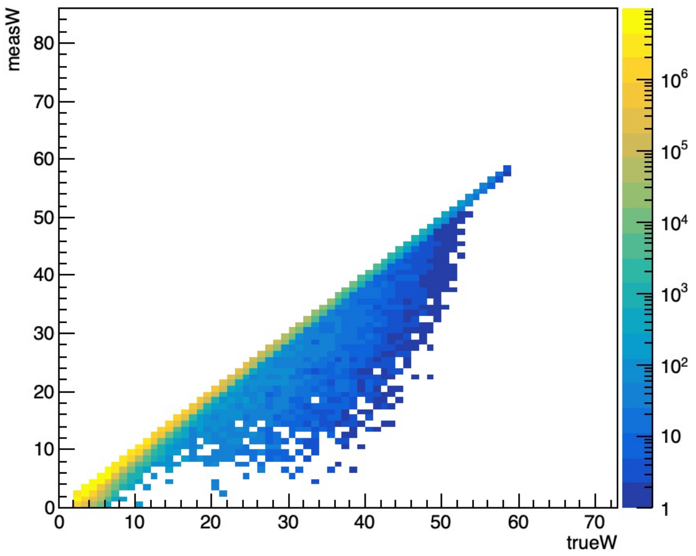
Performance – what if *STAR* (|η|<4.0)

- Hadronic Final-States (HFS) is only based on (|η|<4.0).
- No detector effect.

Smearing from this HFS method





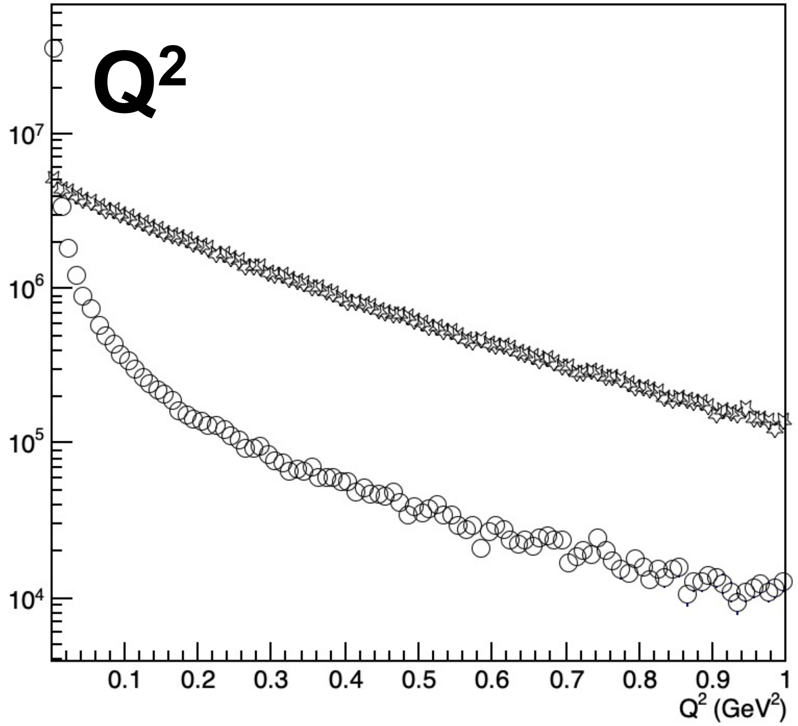


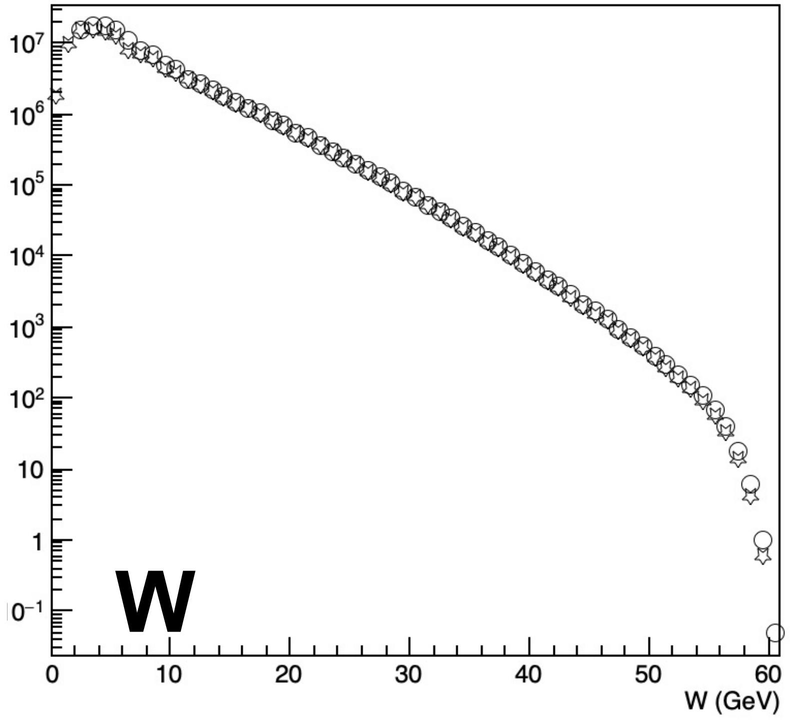
This gets better!

It is much easier to get W than Q^2 ! In UPC, we know Q^2 is small, a limit might be good enough

Performance – what if *STAR* (|η|<4.0)

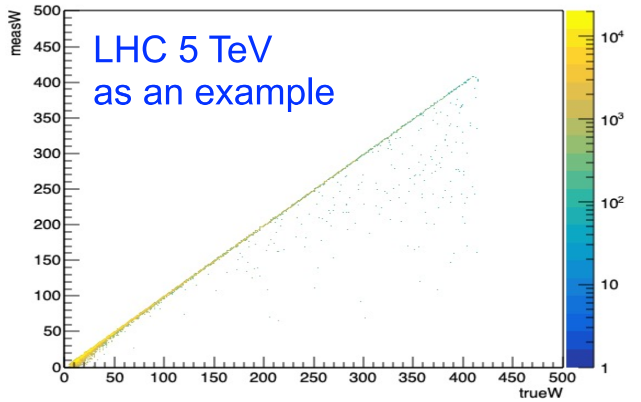
- Hadronic Final-States (HFS) is only based on (|η|<4.0).
- No detector effect.





This can be achieved at the LHC at Run-4?

Photon energy goes higher W~400 GeV or higher!



It is much easier to get W than Q^2 ! In UPC, we know Q^2 is small, a limit might be good enough

Examples, ideas…

Initial-state heavy-ion physics ~ EIC physics

	Particle correlations (photo—nucleus)	**Baryon Stopping**	**Inclusive charged particles**	**Inclusive photoproductio n cross section**
Now	NA?	No <W> is reported	NA	NA
with STAR Forward Upgrade.	Quantitative handle on W. Comparison to pp/pA.	Quantitative handle on W, comparison to hadronic collisions	Cross section, spectrum as a function of W.	Baseline for UPC Jpsi to see non-linear gluon effect (e.g., saturation)

Our recent preprint, arXiv:2204.xxxx

and many more.. such as in pA, with target polarization, etc.

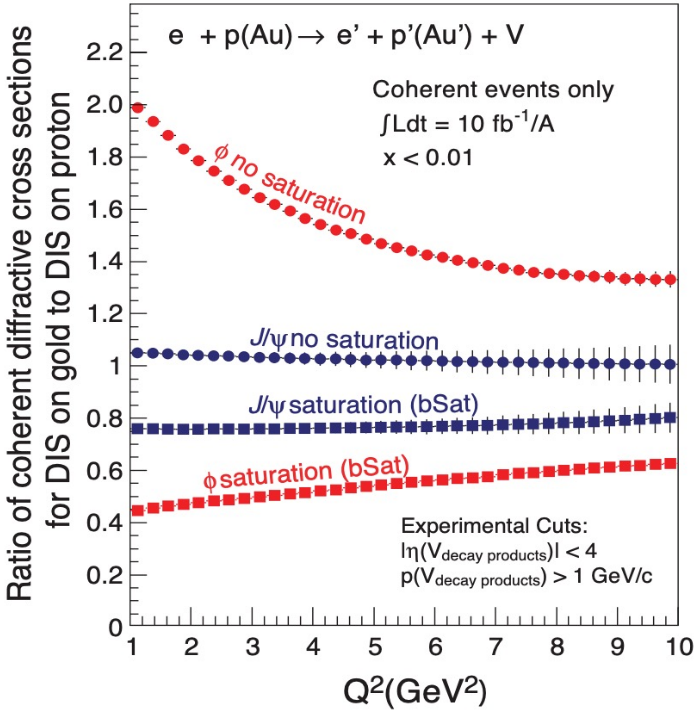
RHIC and LHC photoproduction program, together complements what the EIC will bring us. Early study better prepares what's coming in +10 years

Inclusive process for STAR 2023+

Physics opportunity.

- φ meson photoproduction, first time opportunity and a now-or-never type of measurement!
- **(if with) Half-field running of STAR.**
- **Extensive studies have shown** φ meson is the best to see saturation in UPC (Ullrich, Tobias)

- Ultimate measurement of non-linear gluon dynamics at RHIC?



Double ratio

$$\frac{\left[\dfrac{\sigma_{J/\psi}(M_x^2 = 10)}{\sigma_{\text{inc}}}\right]_{\text{Au}}}{\left[\dfrac{\sigma_{J/\psi}(M_x^2 = 10)}{\sigma_{\text{inc}}}\right]_{\text{p}}}$$

- Photoproduction is at the regime with the **largest difference btw bsat and nonbsat?**
- Qualitatively different to the LTA nuclear shadowing model!

Summary

- Photoproduction has a large cross section and is accessible in heavy-ion UPCs. The challenge is event reconstruction for inclusive photoproduction.
- In this work, based on the hadron-only method, event kinematics can be significantly constrained. In UPC, Q^2 is very small and a limit is mostly sufficient. C.M.S energy W is important and can be accessed by final-state particles (large acceptance helps, e.g., STAR forward upgrade, LHC Run-4, etc)

- **BeAGLE model can be used as UPC inclusive generator.**

- Jets (e.g., photoproduction of dijets) and inclusive observables are very powerful but not very well studied in nuclei – great opportunities ahead of us.

(Stay tuned, we are working on simulations…)

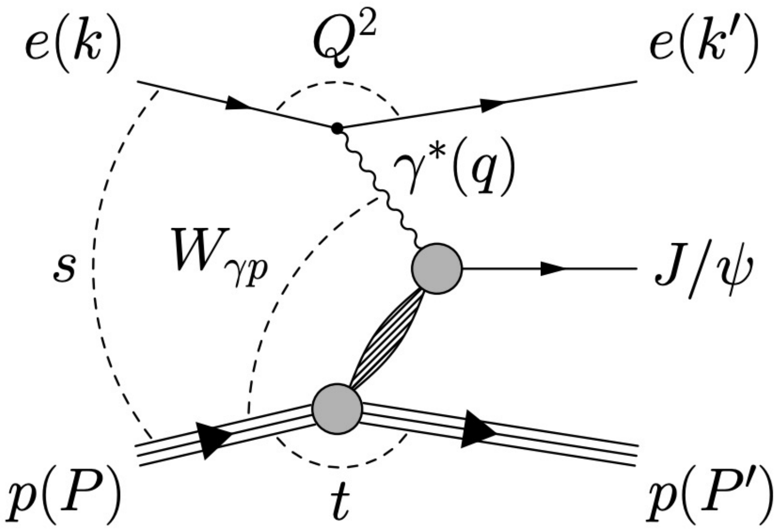
*Many thanks to B. Schmidke, J. Adams, Z. Zhang, X. Chu, Z. Xu, D. Brandenburg for fruitful discussions.

Back up

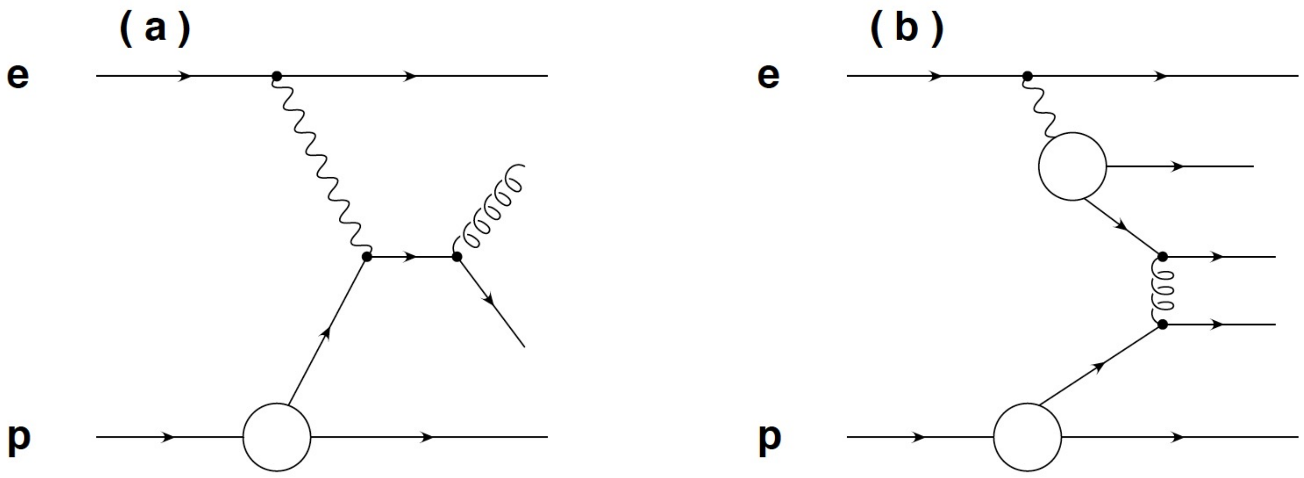
Collisions with quasi-real photons

- Inclusive, semi-inclusive/jets/HFs, and exclusive photoproduction are important processes to probe nucleon and **nuclear** structure;

- Examples that are well known – VM and dijets photoproduction.



Vector Meson exclusive production

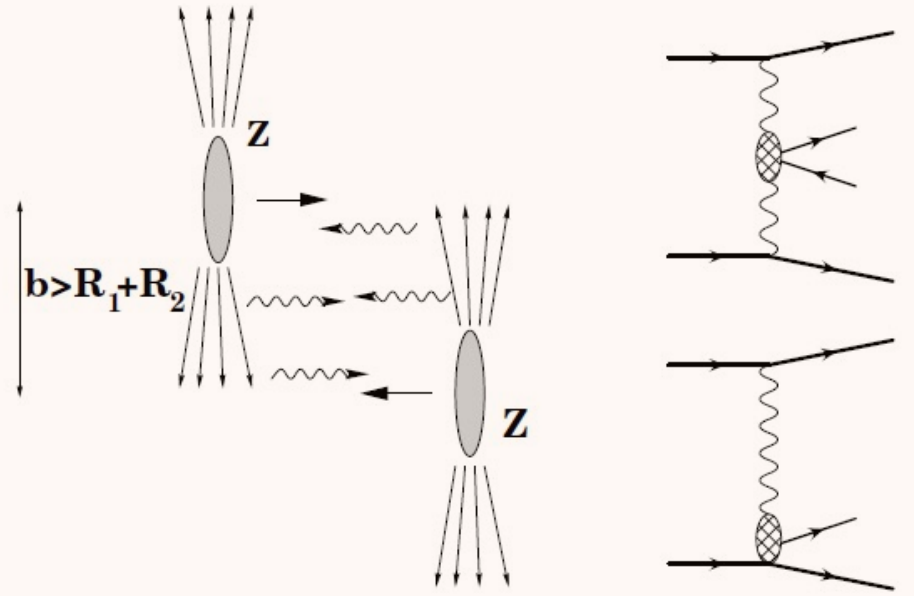


Dijets with direct/resolved photons

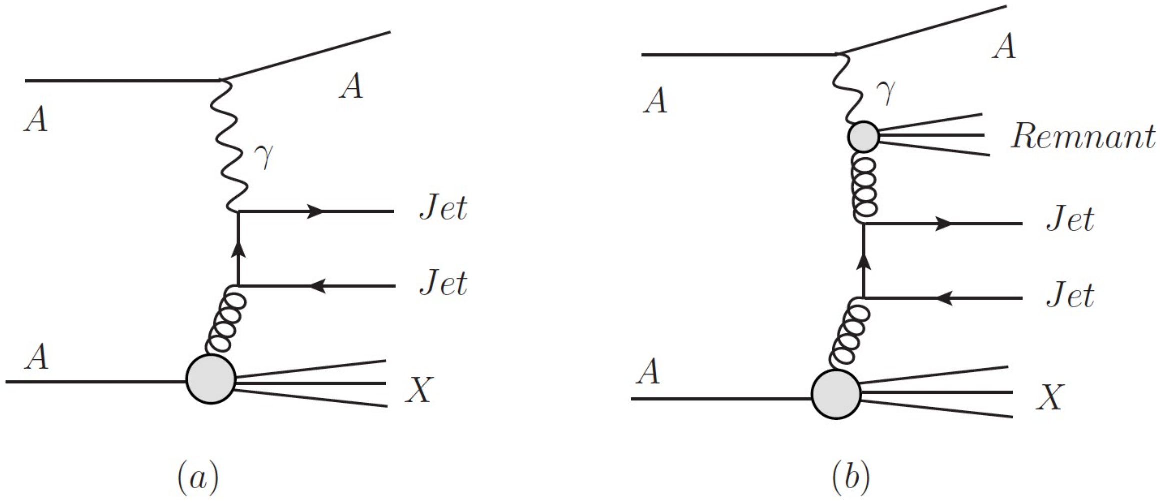
Collisions with quasi-real photons from UPCs

- Ultra-Peripheral Collisions (UPCs) has been a great tool for studies in heavy/light nuclei…

- Examples that are well known – VM and dijets photoproduction.



Vector Meson exclusive production



Dijets with direct/resolved photons