Report from the Theory Working Group

Alessandro Bacchetta, Wim Cosyn, Felix Ringer, ***Anna Staśto***

Who are we ?

Theory Working Group

We solicit overarching questions/topics from the EIC community for discussions involving both **theorists** and **experimentalists**.

Please submit questions for the EIC User Group's Theoretical Physics Working Group using **google form** from the **wiki page**

Alessandro Bacchetta (Pavia)

Wim Cosyn (FIU)

Felix Ringer (ODU/JLab)

Anna Staśto (Penn State)

https://wiki.bnl.gov/eicug/index.php/Theory

Any input is welcome, thank you for your help!

Activities: topics and speakers

MC event generators for EIC

Ilkka Helenius

Frank Krauss

Elke Aschenauer

Markus Diefenthaler (discussion)

Parton showers

Jian Zhou

Weiyao Ke

Exclusive Vector - Meson production

Jakub Wagner

Kong Tu

Odderon in DIS

Sanjin Benić

Spencer Klein

Monte Carlo event generators for EIC

Ilkka Helenius

Frank Krauss

Overview of status of MC for DIS

General-purpose event generators

Simulate full collision events

Exclusive hadronic final states

- Hard parton-level scattering
- Multiparton interactions
- Parton showers, NLO matching & multi-jet merging
- Hadronization, colour reconnection, rescattering

Electron-ion collisions

- DIS: $Q^2 \ll 1$ GeV
- Photoproduction: $Q^2 \approx 0$
- Heavy-ion target

HERWIG 7

- Current version 7.3.0
- DIS with NLO merging
- Photoproduction in progress

PYTHIA 8

- Current version 8.310
- Photoproduction with PS and MPI
- DIS: Dipole shower, Vincia, Dire

SHERPA 2

- Current version 2.2.15 (3.0.0beta1)
- DIS with matching & merging
- Photoproduction at NLO

Specific purpose

Matrix-element generators

- Madgraph5
  - Up to $\sim$ 4 jets for DIS
  - Direct processes in photoproduction
- Powheg
  - Some first studies but currently not applicable

Other relevant tools

- Cascade
  - TMDs
- Sartre
  - Exclusive vector mesons
- Beagle
  - Nuclear remnants
- EpIC
  - Exclusive processes
- eHijing
  - Cold nuclear matter hadronization

Monte Carlo event generators for EIC

Ilkka Helenius

Frank Krauss

Summary

- Plenty of recent developments on general purpose MC generators
- Validation and tuning required

⇒ Data as RIVET analysis

⇒ Input from experimental side

Outlook

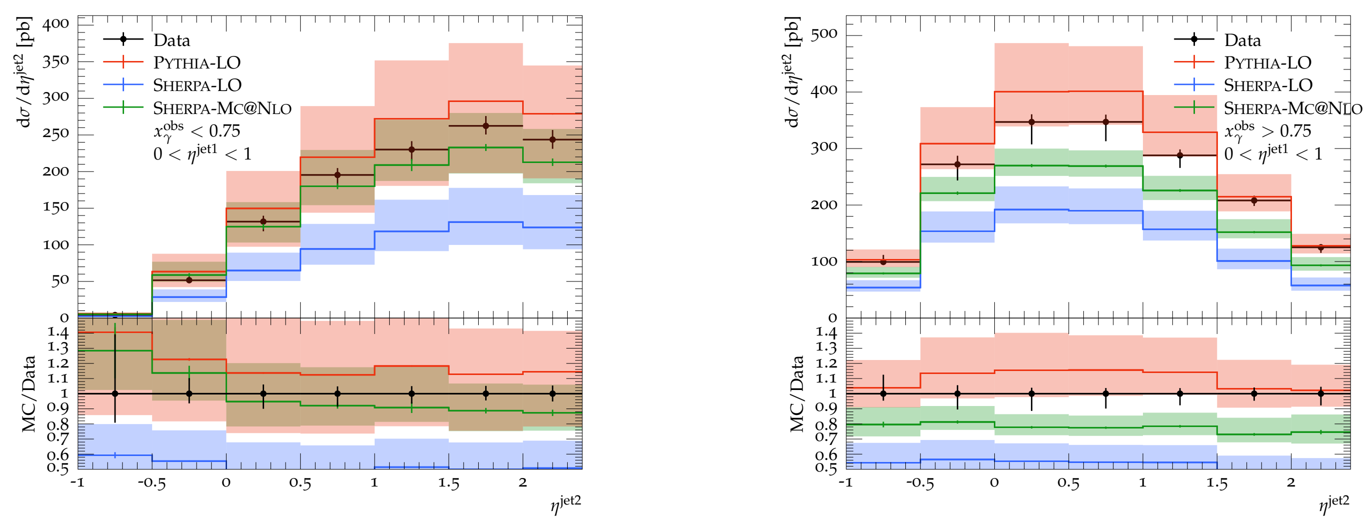
- Many things still to improve
  - Nuclear target
  - Phase-space between DIS and photoproduction

Example of validation/tuning of MC with HERA data

Recent/ongoing projects

Comparison of Pythia, Sherpa and Herwig for jet photoproduction

IH, P. Meinzinger, S. Plätzer, *in progress* [ZEUS_2001_S4815815]



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Dedicated workshop:

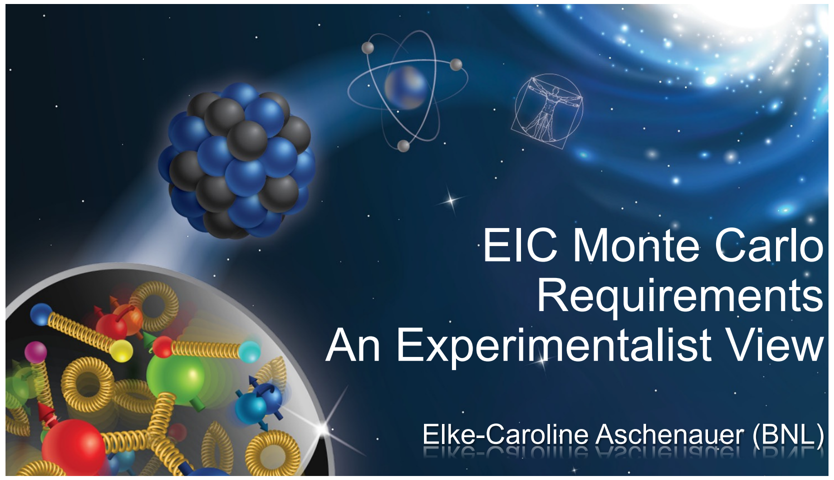
MC4EIC workshop `https://conference.ippp.dur.ac.uk/event/1292/`

see next talk by Frank Krauss

EIC Monte Carlo requirements

Elke Aschenauer

Markus Diefenthaler



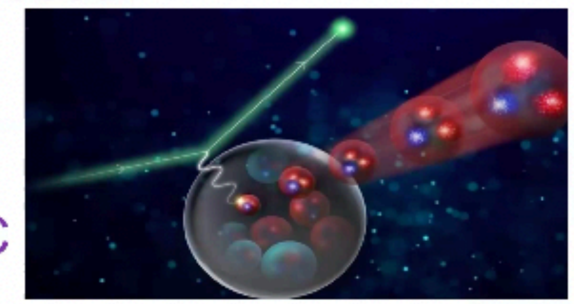
- MC Generators crucial to realize full potential of the diverse EIC program: high precision measurements require high precision simulations
- Need both ep and eA, for wide range of nuclei from light to heavy
- Include nuclear effects in initial state and hadronization. Modelling of breakup. Coherent vs incoherent.
- Possibility to test saturation/nonlinear effects.
- Radiative corrections
- Inclusion of spin dependent effects : hard scattering, PS, hadronization
- Inclusion of transverse momentum dependence: TMD physics
- Exclusive processes: specialized vs general purpose MC
- Transition from photoproduction to high Q^2 : 2 PDFs vs 1 PDF

Parton shower generator at small x with saturation

Jian Zhou

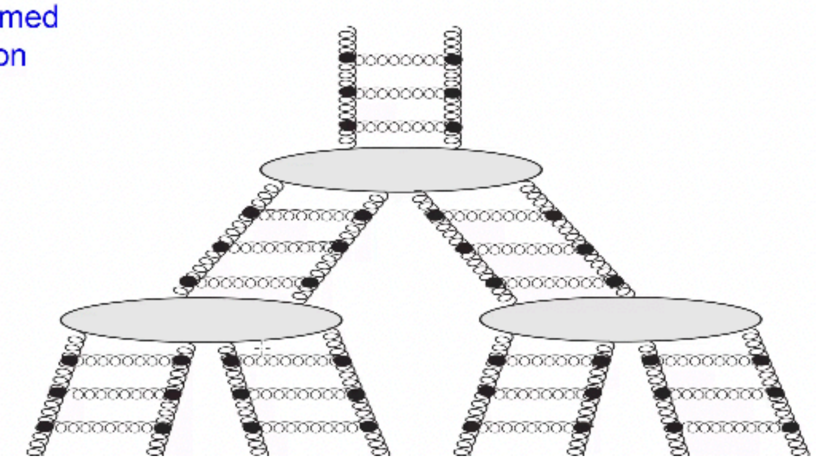
Why small x parton shower generator

- ➢ Saturation effect is absent in all existing generators
- ● Aim at developing a PS algorithm to be used:
  - ➢ Phenomology in eA collisions @EIC
  - ➢ Forward physics in pA collisions @LHC
  - ➢ Cosmic ray event generator



➢ **GLR equation** 2 →1 gluon fusion & $\ln\frac{1}{x}$ Gribov-Levin-Ryskin,1983

"Fan" diagram resumed by the GLR equation



Use a GLR equation as a basis for an algorithm

Parton shower generator at small x with saturation

Jian Zhou

The standard GLR equation(unfolded one)

$$\frac{\partial N(\eta,k_\perp)}{\partial\eta}=\frac{\bar\alpha_s}{\pi}\left[\int\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp+l_\perp)-\int\frac{\mathrm{d}^2l_\perp}{(k_\perp-l_\perp)^2}\frac{k_\perp^2}{2l_\perp^2}N(\eta,k_\perp)\right]-\bar\alpha_s N^2(\eta,k_\perp)$$

- Resolved and unresolved branching:

$$\int\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp+l_\perp)\approx\int_\mu\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp+l_\perp)+\int_0^\mu\frac{\mathrm{d}^2l_\perp}{l_\perp^2}N(\eta,k_\perp)$$

- Folded GLR equation: virtual correction is manifestly resumed to all orders

$$\frac{\partial}{\partial\eta}\frac{N(\eta,k_\perp)}{\Delta(\eta,k_\perp)}=\frac{\bar\alpha_s}{\pi}\int_\mu\frac{\mathrm{d}^2l_\perp}{l_\perp^2}\frac{N(\eta,l_\perp+k_\perp)}{\Delta(\eta,k_\perp)}$$

- Non-Sudakov form factor

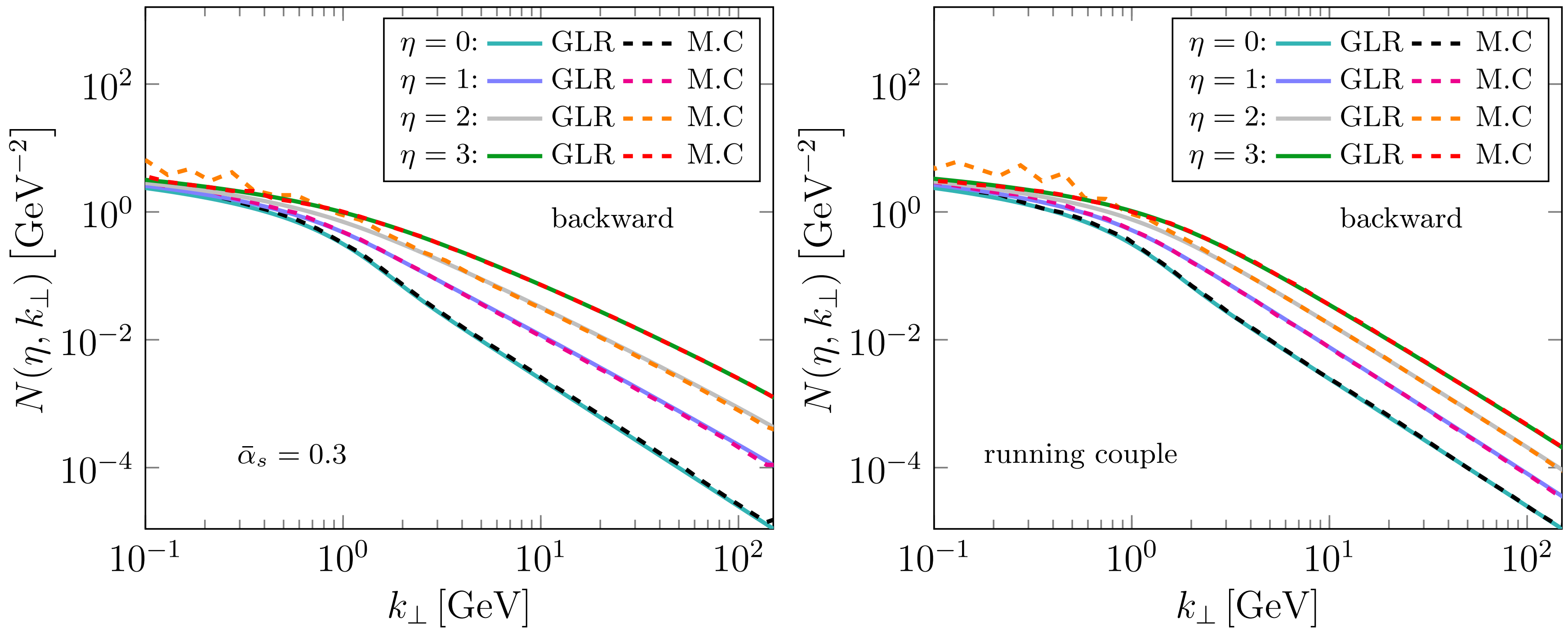
$$\Delta(\eta,k_\perp)\qquad\exp\left\{-\bar\alpha_s\int_{\eta_0}^{\eta}d\eta'\left[\ln\frac{k_\perp^2}{\mu^2}+N(\eta',k_\perp)\right]\right\}$$

Shi-Wei-ZJ, 2022

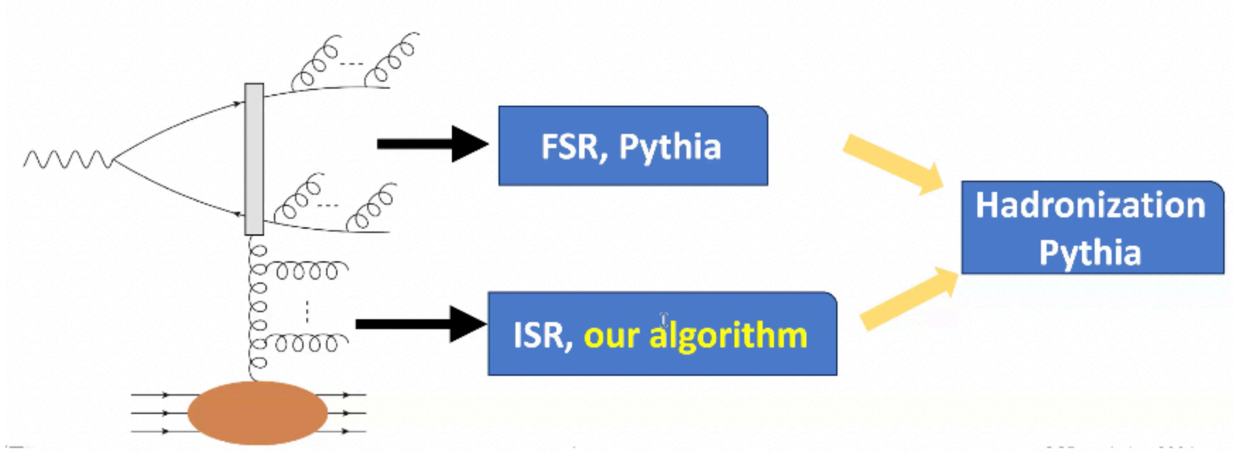
Parton shower generator at small x with saturation

Jian Zhou

- Both forward and backward evolution can be implemented
- Matched to the numerical solution
- Includes kinematical constraint



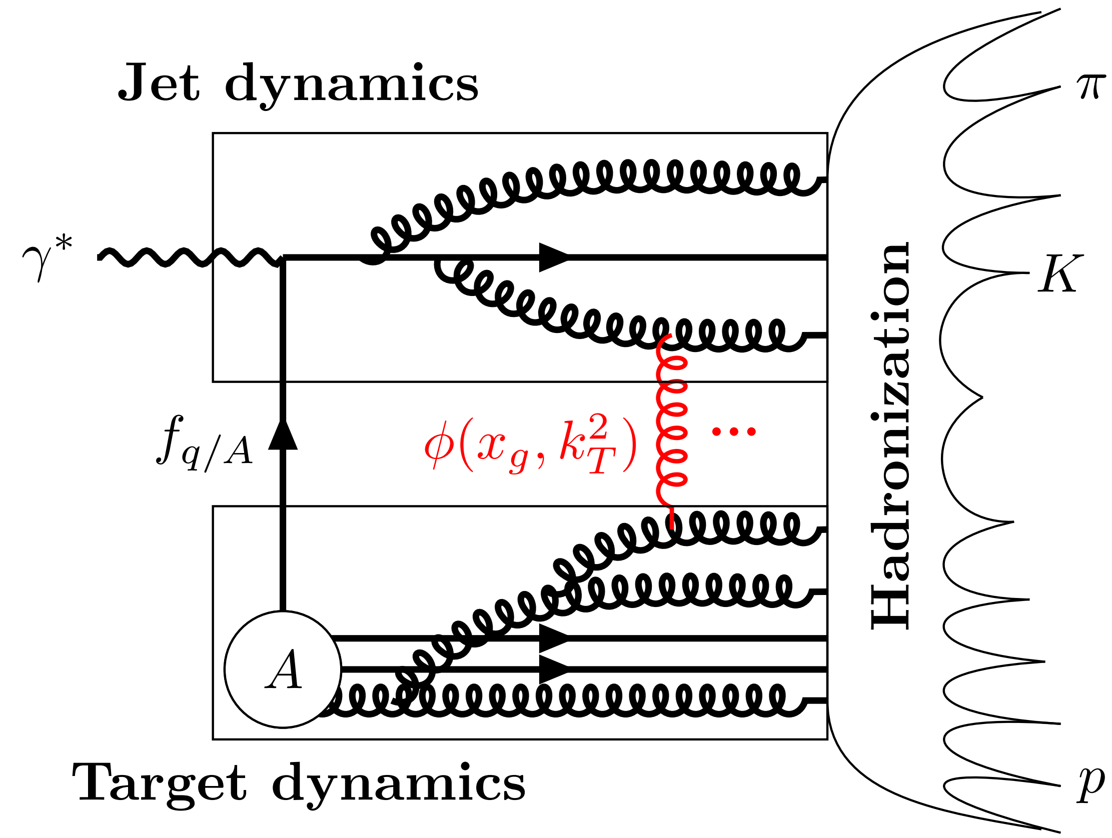
- Algorithm for joint small x and k_T resummation constructed
- Full final state generation: FSR and hadronization with PYTHIA (need to consider color flow)



eHIJING event generator for jet tomography in eA

Weiyao Ke

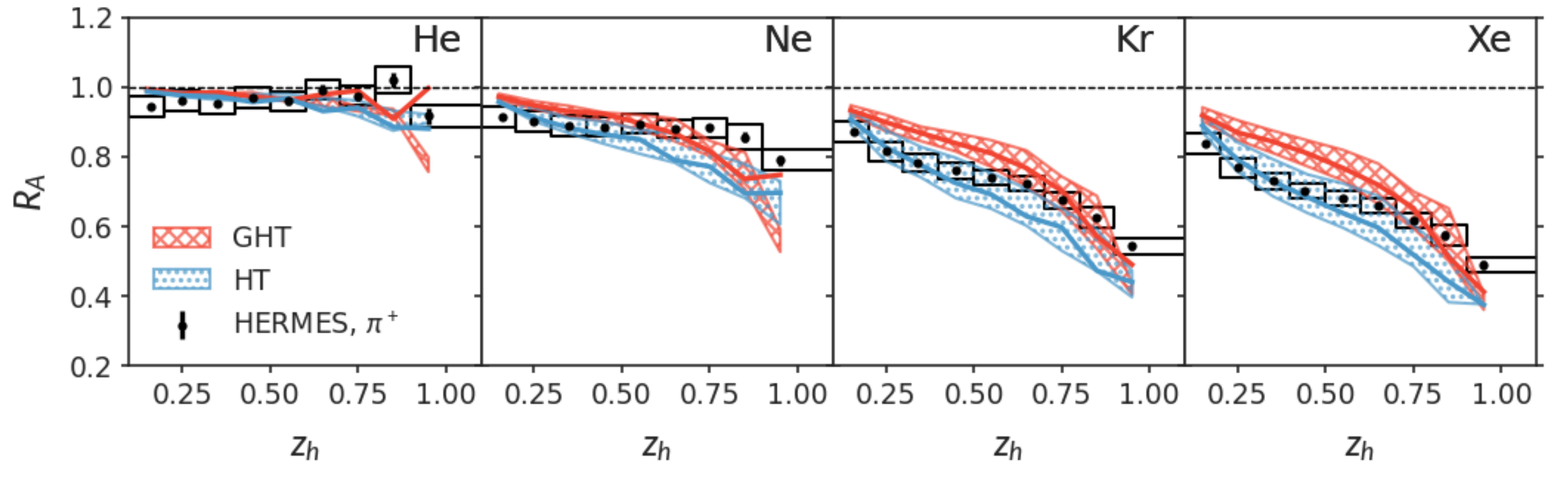
eHIJING focuses on details of jet dynamics



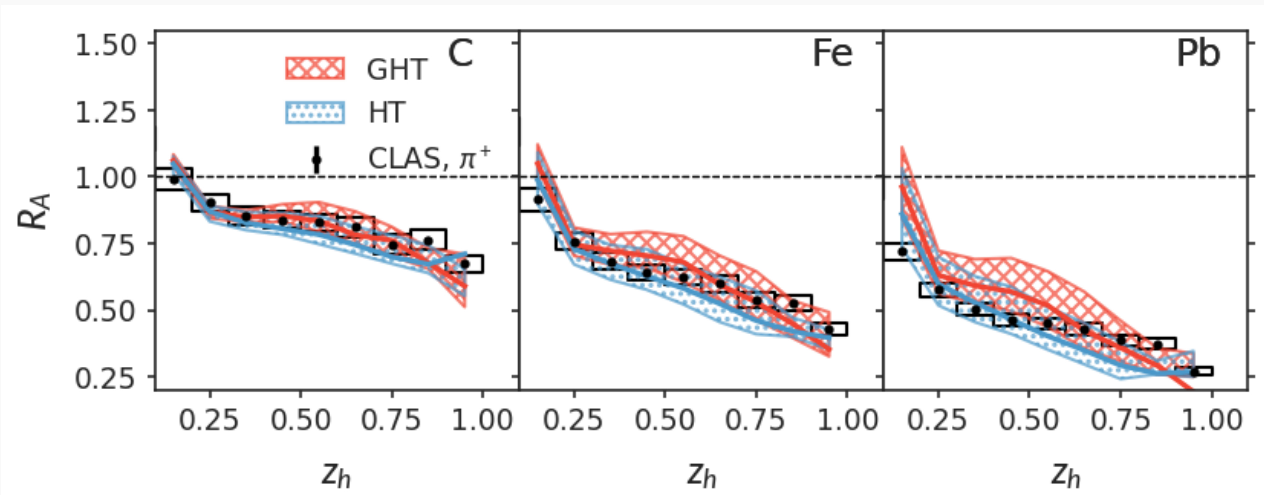
Ingredients in eHIJING:

- Nuclear PDFs given by EPPS
- Distribution of Glauber gluons between jet and target given by saturation inspired model
- Jet evolution simulated within higher twist framework for medium modified splitting functions

Results from eHIJING



HERMES, NPB 780(2007)1-27 $\langle Q^2 \rangle \approx$ 2-2.5 GeV^2.



CLAS PRC105(2022)015201

Weiyao Ke

- R_A is suppressed at large z_h as expected from the parton energy loss in matter.
- The systemic dependence on nuclear size is reproduced.

Exclusive VM production in collinear factorization

Gluon GPDs in the exclusive production of heavy mesons

Jakub Wagner

Heavy VM exclusive production: troubles in collinear factorization

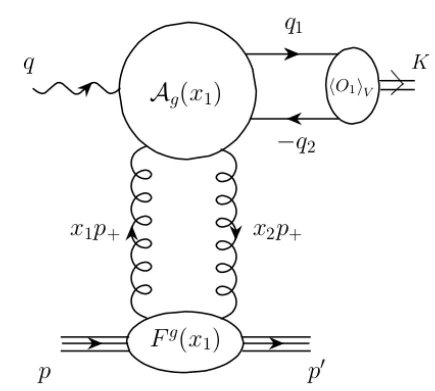


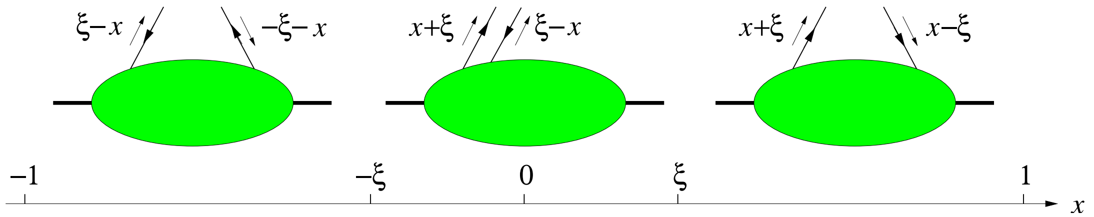
Figure 1: Kinematics of heavy vector meson photoproduction.

D. Yu. Ivanov , A. Schafer , L. Szymanowski and G. Krasnikov - **Eur.Phys.J. C34 (2004) 297-316**

The amplitude $\mathcal{M}$ is given by factorization formula:

$$\mathcal{M} \sim \left(\frac{\langle O_1\rangle_V}{m^3}\right)^{1/2} \int_{-1}^{1} dx \left[T_g(x,\xi)\, F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t) \right] ,$$

$$F^{q,S}(x,\xi,t) = \sum_{q=u,d,s} F^q(x,\xi,t) \,.$$



At LO only gluons contribute

- Factorization scale dependance,
- Three variables x, ξ, t .

Troubles of collinear factorization: need of resummation

Jakub Wagner

Photoproduction amplitude and cross section - LO and NLO.
NLO/LO for large W:

$$\sim \frac{\alpha_S(\mu_R) N_c}{\pi} \ln\left(\frac{1}{\xi}\right) \ln\left(\frac{\frac{1}{4}M_V^2}{\mu_F^2}\right)$$

- Large scale dependence
- Instability when going from LO to NLO
- Large logs of ξ

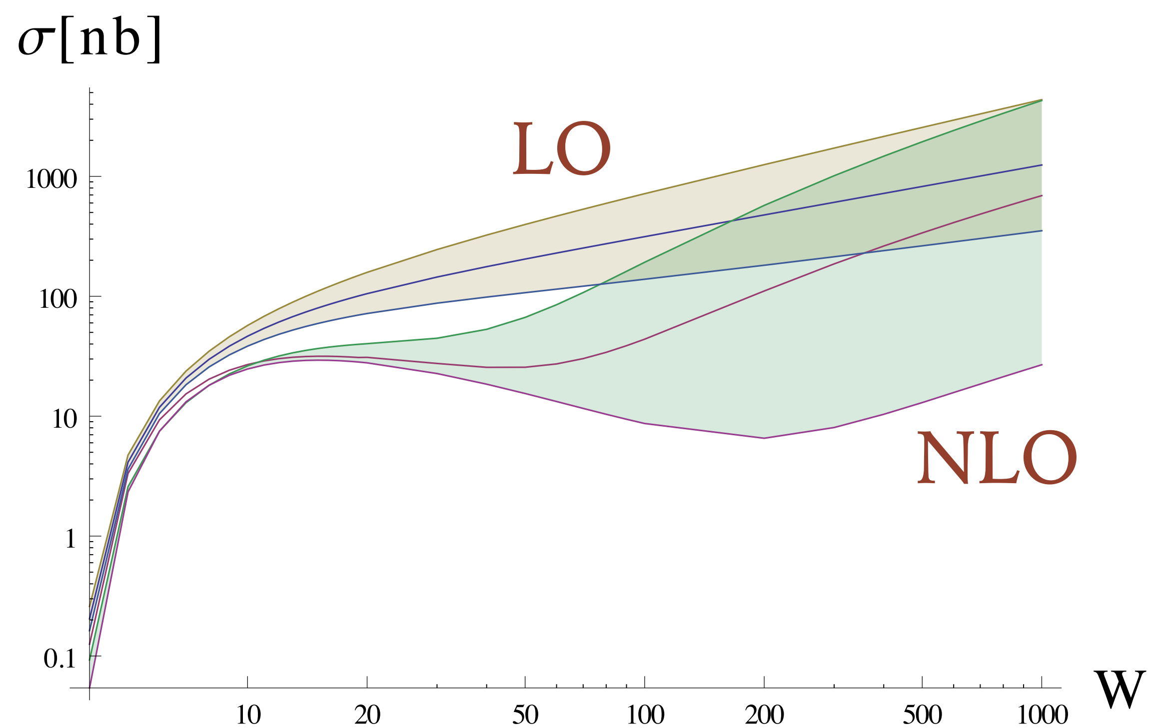


Figure: Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO

Resummation
D.Yu. Ivanov, Blois 2007 Conference arXiv:0712.3193

At higher orders powers of energy log are generated

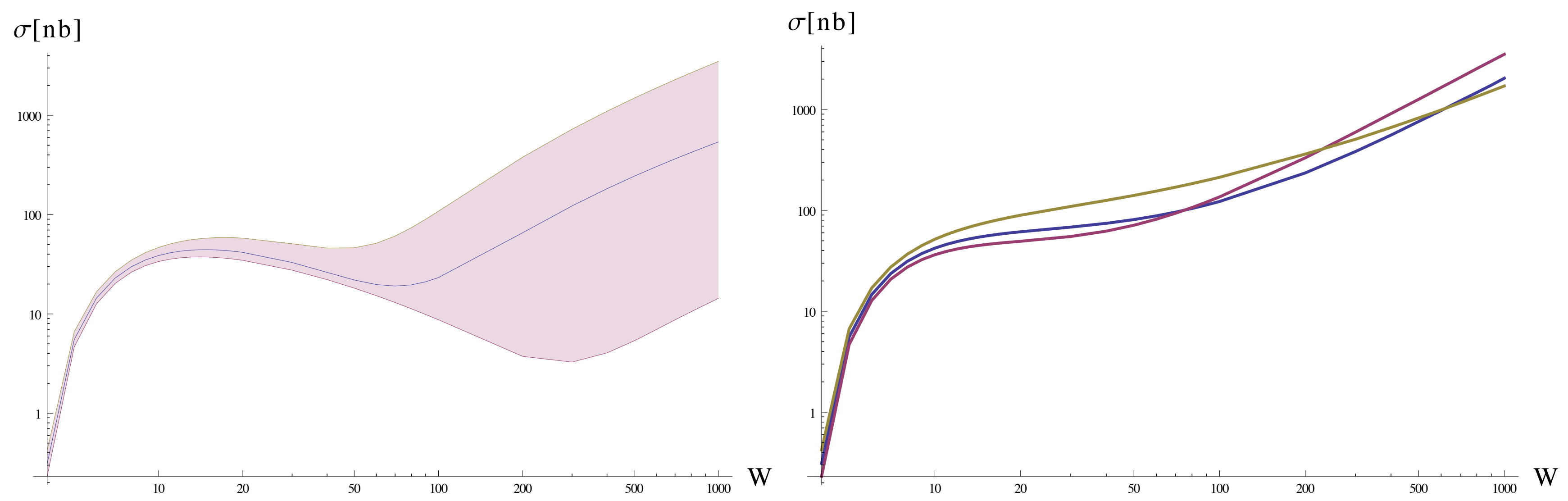
$$\mathcal{I}m A^g \sim H^g(\xi,\xi) + \int_\xi^1 \frac{dx}{x} H^g(x,\xi) \sum_{n=1} C_n(L) \frac{\bar{\alpha}_s^n}{(n-1)!} \log^{n-1} \frac{x}{\xi}$$

Resummation in collinear framework

Jakub Wagner

Resummed cross section for J/ψ

Ivanov, Pire, Szymanowski, Wagner, EPJ Web Conf. 112 (2016) 01020, arXiv:1601.07338



NLO Resumed

Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$

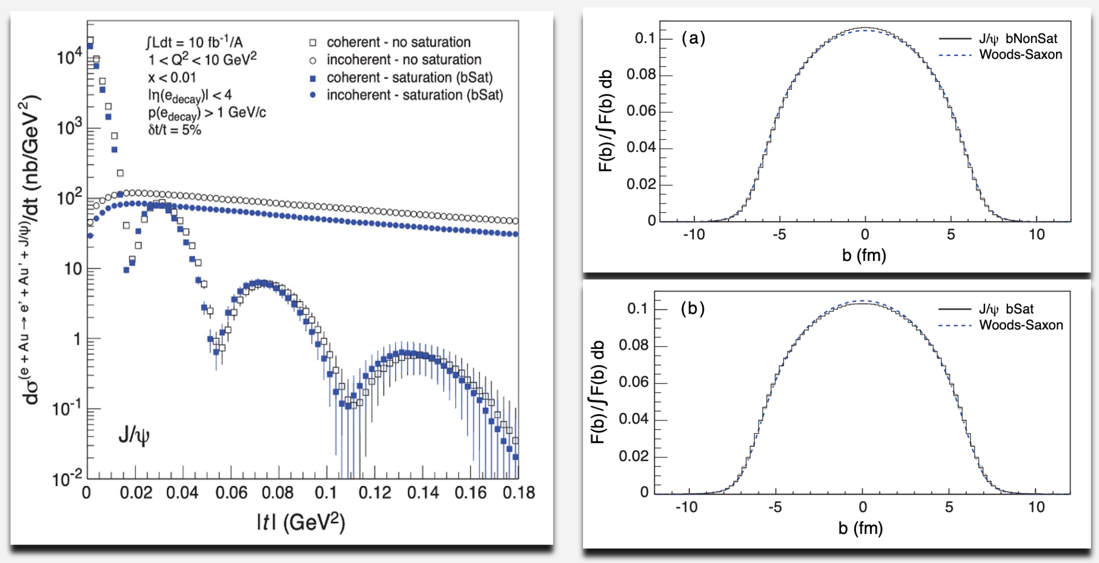
Remarks: only forward evolution, $\mu_R = Q$.

- Limit of collinear approach for low scales and high energy
- Small x logs resummation stabilizes the result

Exclusive VM on nuclei

Kong Tu

Reality check: can we really measure the exclusive VM in eA at the EIC?



EIC White paper

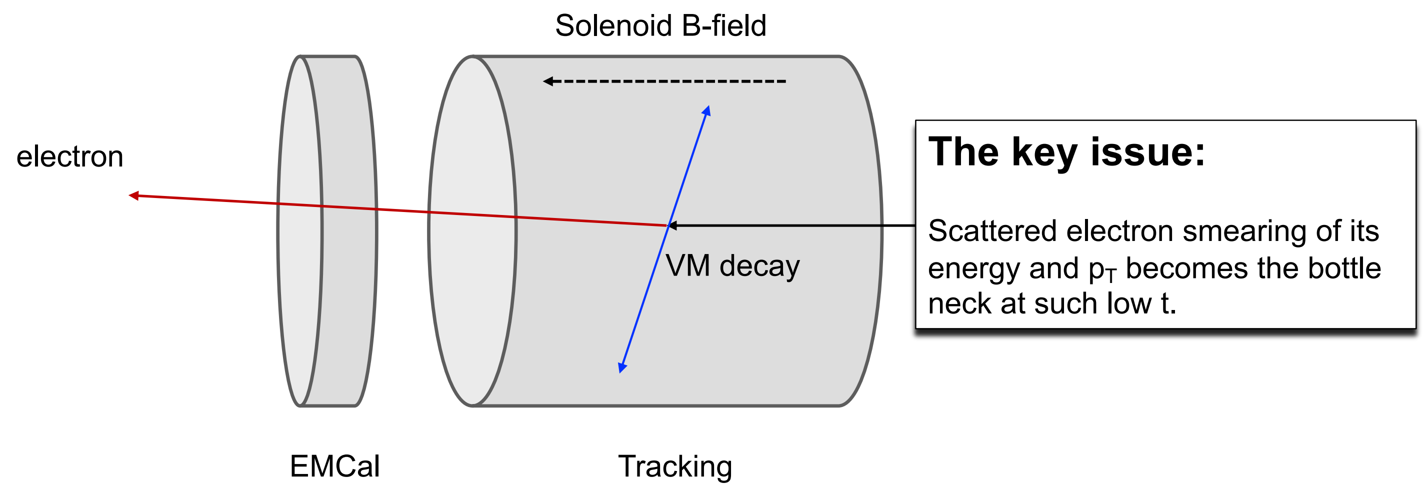
Kong Tu (BNL)

- Measuring coherent can provide insight into spatial distribution in nuclei
- Distinguish impact of saturation
- Two problems:
  - Resolution in t, bottleneck from scattered electron
  - Rejection of huge incoherent background

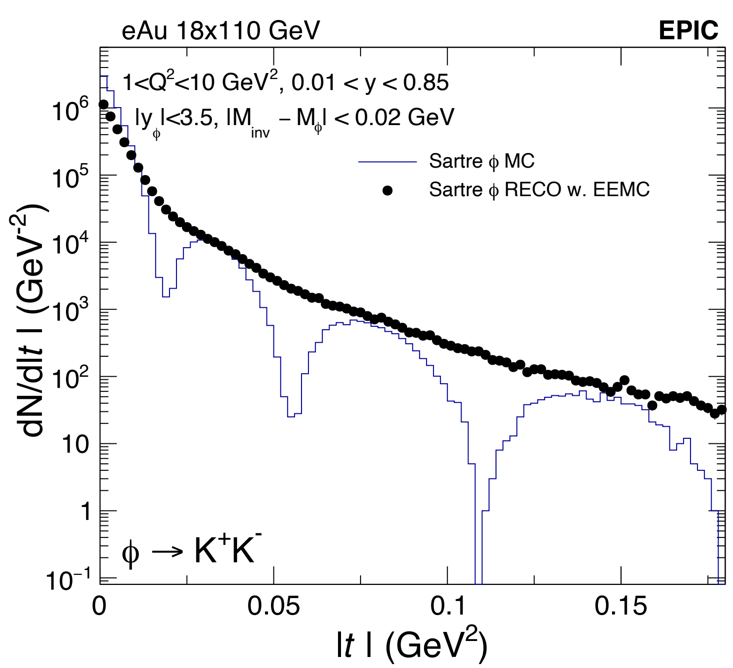
Scattered electron resolution problem

Kong Tu

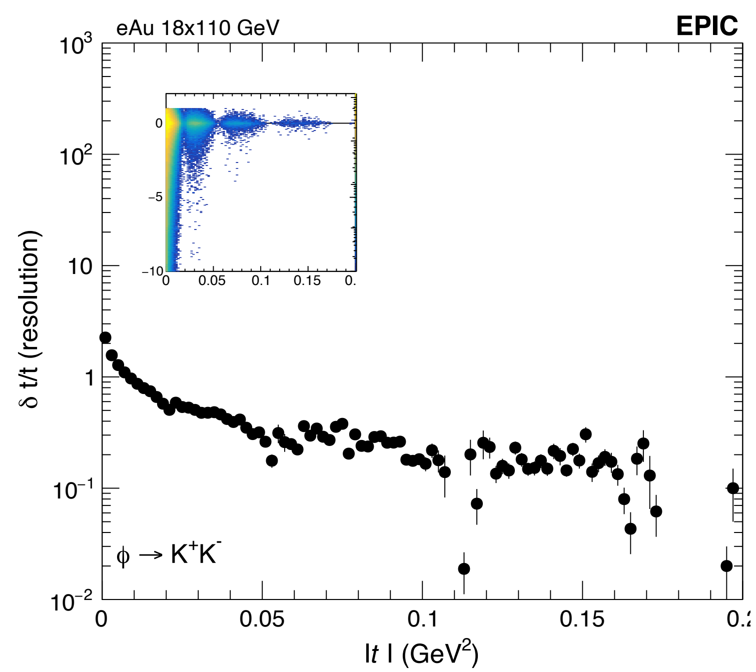
The bottleneck: scattered electron resolution which affects t distribution



Simulation Campaign Dec 2023



No background, neither machine nor physics



Resolution is 200% at low t and 20% at high t

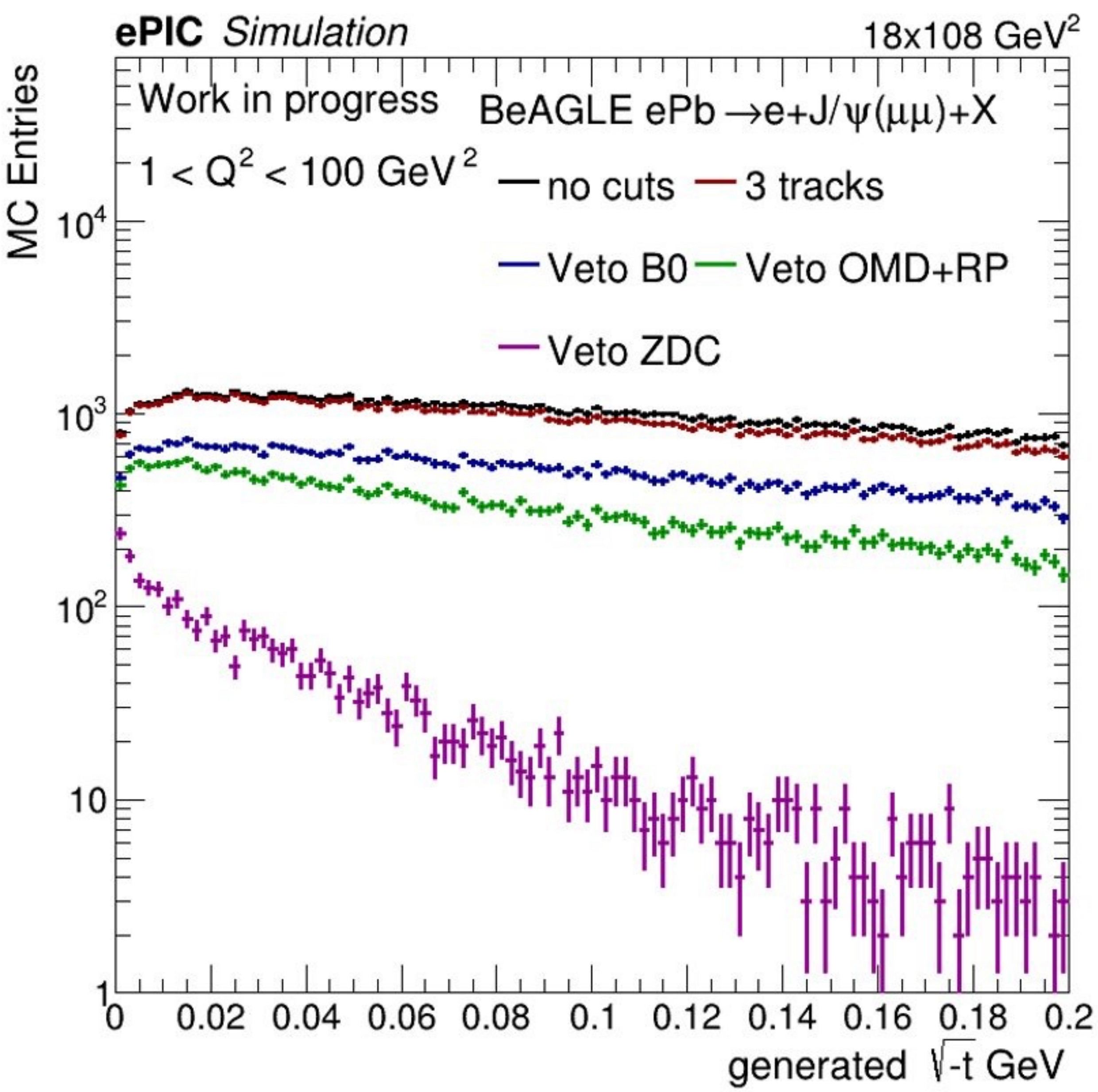
Incoherent background

Kong Tu

Study from Michael Pitt, Eden Mautner

Rejection of incoherent enough for 1st but not 2nd or 3rd minimum

IP8 seems to be more promising for the rejection of incoherent



Odderon

Sanjin Benić

Odderon in hadronic collisions

. suggested 50+ years ago – colorless **C-odd** exchange to govern the pp vs pp̄ cross section difference

Lukaszuk, Nicolescu (1973)
Ewerz (2003)

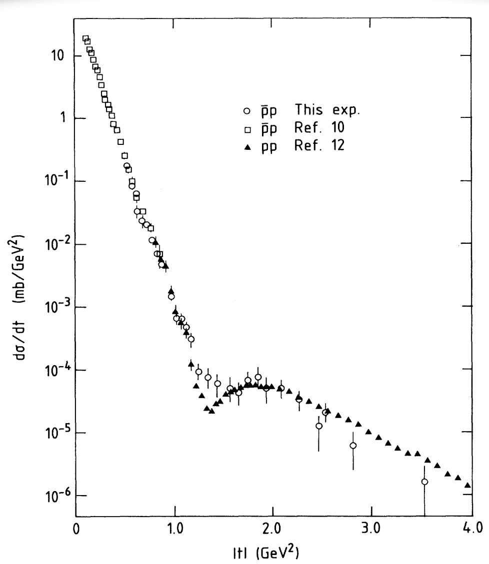
Potential signal at ISR

VOLUME 54, NUMBER 20 PHYSICAL REVIEW LETTERS 20 MAY 1985

Measurement of $\bar{p}p$ and pp Elastic Scattering in the Dip Region at $\sqrt{s} = 53$ GeV

A. Breakstone,[1],[a] H. B. Crawley,[1] G. M. Dallavalle,[5] K. Doroba,[6] D. Drijard,[3] F. Fabbri,[3] A. Firestone,[1] H. G. Fischer,[3] H. Frehse,[3],[b] W. Geist,[3],[c] G. Giacomelli,[2] R. Gokieli,[6] M. Gorbics,[1] P. Hanke,[5] M. Heiden,[3],[c] W. Herr,[5] E. E. Kluge,[5] J. W. Lamsa,[1] T. Lohse,[4] W. T. Meyer,[1] G. Mornacchi,[3] T. Nakada,[5],[d] M. Panter,[3] A. Putzer,[5] K. Rauschnabel,[4] F. Rimondi,[2] G. P. Siroli,[2] R. Sosnowski,[6] M. Szczekowski,[3] O. Ullaland,[3] and D. Wegener[4]
[1] *Ames Laboratory and Iowa State University, Ames, Iowa 50011*
[2] *Dipartimento di Fisica dell'Università and Istituto Nazionale di Fisica Nucleare, Bologna, Italy*
[3] *CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[4] *Institut für Physik der Universität, Dortmund, Germany*
[5] *Institut für Hochenergiephysik der Universität, Heidelberg, Germany*
[6] *University and Institute for Nuclear Studies, Warsaw, Poland*
(Received 1 February 1985)

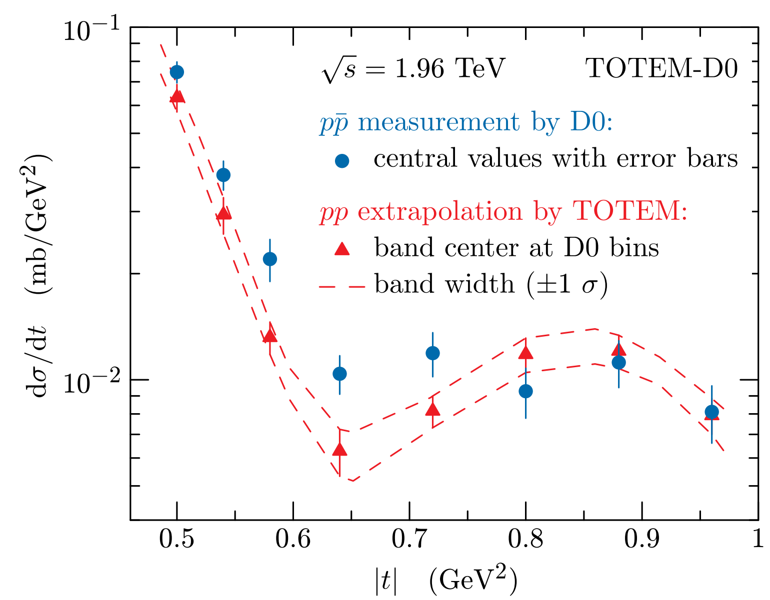
We have measured the differential cross section for $\bar{p}p$ and pp elastic scattering at $\sqrt{s} = 53$ GeV in the interval $0.5 < |t| < 4.0$ (GeV/c)^2 at the CERN intersecting storage rings using the split-field magnet detector. The shape of the differential cross section differs significantly between $\bar{p}p$ and pp scattering in the region $1.1 < |t| < 1.5$ (GeV/c)^2, with $\bar{p}p$ data showing a less pronounced dip structure than pp data.



PHYSICAL REVIEW LETTERS 127, 062003 (2021)

Odderon Exchange from Elastic Scattering Differences between pp and $p\bar{p}$ Data at 1.96 TeV and from pp Forward Scattering Measurements

TOTEM & D0 collaborations



Odderon in DIS

Sanjin Benić

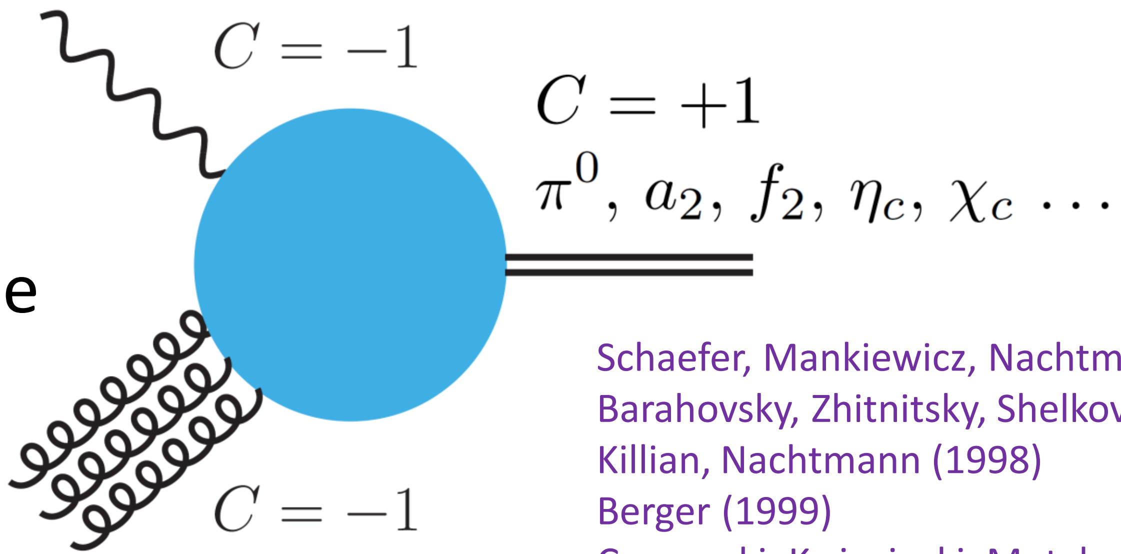
Need 3 gluons in QCD
to have color singlet
C - odd exchange

Odderon in the DIS?

. for pp it is difficult to make perturbative QCD computation

. DIS offers more theoretical control

➡ a **direct** discovery of the (hard) odderon in DIS?



. exclusive reactions that tag onto the negative C-parity in the target

. in DIS C=+1 light meson/quarkonia in the final state

Schaefer, Mankiewicz, Nachtmann (1991)
Barahovsky, Zhitnitsky, Shelkovenko (1991)
Killian, Nachtmann (1998)
Berger (1999)
Czyzewski, Kwiecinski, Motyka, Sadzikowski (1997)
Bartels, Braun, Colferai, Vacca (2001)

Sanjin Benić

Odderon searches in DIS: light mesons

. First searches conducted at HERA for light mesons:

Vol. 33 (2002) *ACTA PHYSICA POLONICA B* No 11

INVESTIGATION OF POMERON- AND ODDERON INDUCED PHOTOPRODUCTION OF MESONS DECAYING TO PURE MULTIPHOTON FINAL STATES AT HERA* **

THOMAS BERNDT

For the H1 Collaboration

In this contribution the first search at HERA for Odderon induced reactions is presented and contrasted with cross section measurements for Pomeron induced processes. The searches are performed in the channels $\gamma p \to \pi^0 N^*$, $\gamma p \to f_2(1270)X$ and $\gamma p \to a_2 X$, where N^* denotes an excited nucleon state. The rates found are compatible with the background alone, and the upper limits derived therefrom are confronted with the ex-

H1 collaboration (2001,2002)

$\sigma(\gamma^* p \to \pi^0 N^*) < 49$ nb

$\sigma(\gamma^* p \to f_2 X) < 16$ nb

$\sigma(\gamma^* p \to a_2 X) < 96$ nb

HERA kinematics:

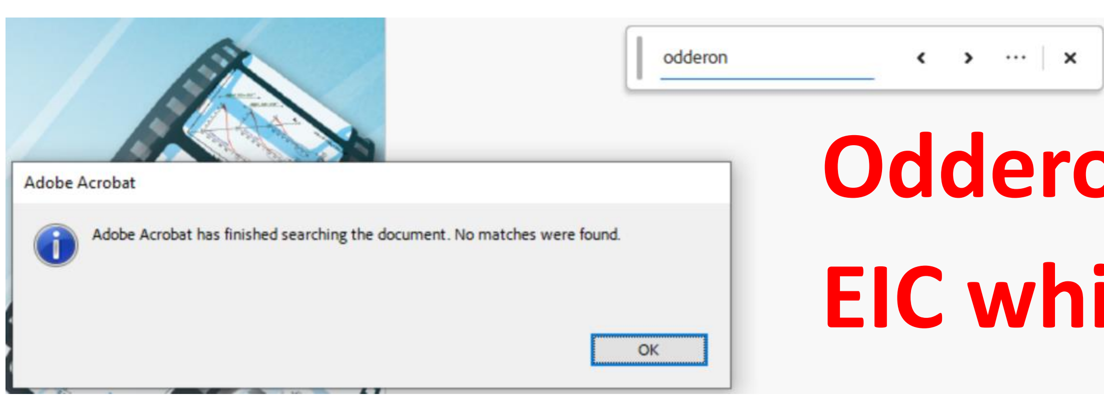
$0.02 < |t| < 0.3$ GeV^2

$Q^2 < 0.01$ GeV^2

$\langle W \rangle \sim 200$ GeV

about order of magnitude lower than the theory predictions at the time..

Berger (1999)



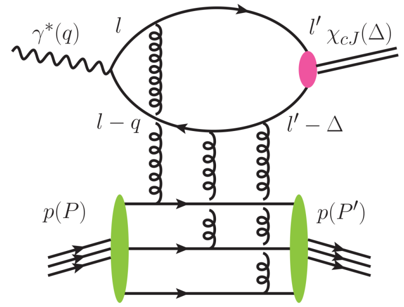
1212.1701 (EIC white paper)

Odderon not discussed in the EIC white paper

Predictions for exclusive χc

Sanjin Benić

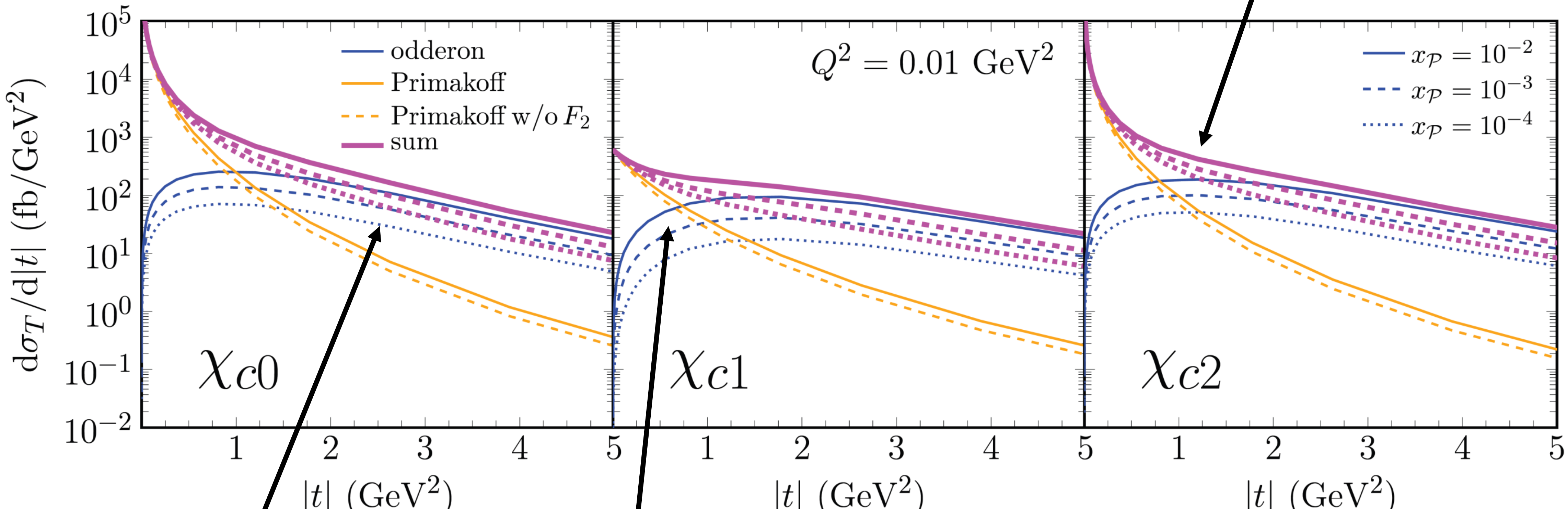
$$\gamma^*(q)p(P) \to \mathcal{H}(\Delta)p(P')$$



t-distributions

. Odderon important after |t|~ 1 GeV², low t-region dominated by Primakoff (photon exchange)

photon and Odderon interfere **constructively**



weak t-dependence

SB, Dumitru, Kaushik, Motyka, Stebel (2024)

Odderon drops with x->0 (saturation corrections)

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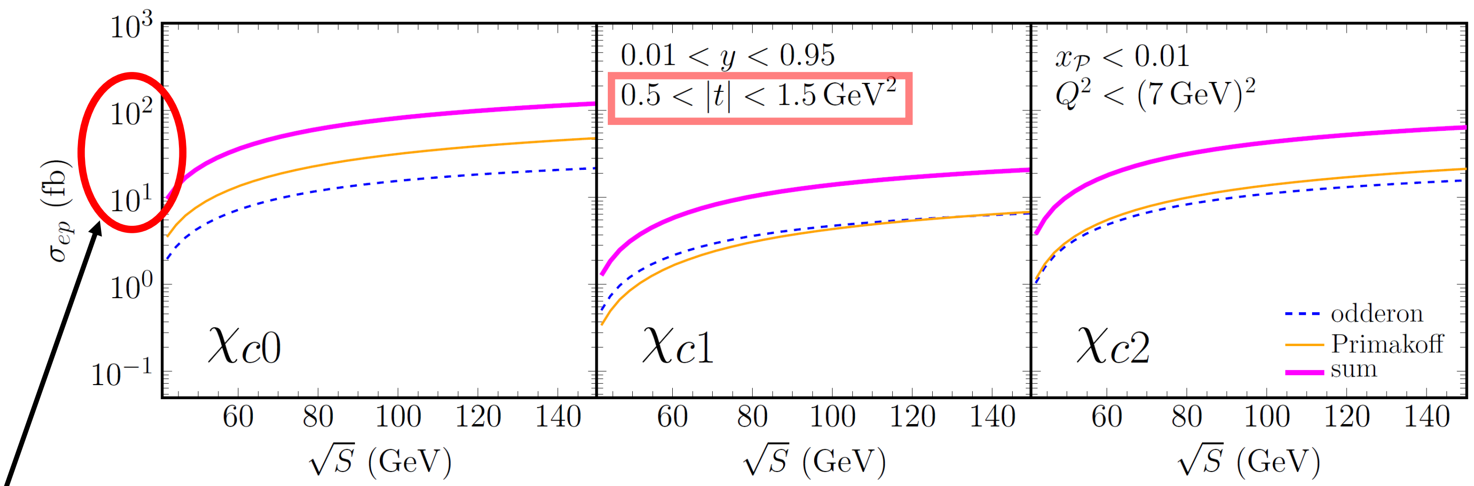
Cross section and rates at the EIC

Sanjin Benić



Is this enough for the EIC?

SB, Dumitru, Kaushik, Motyka, Stebel (2024)

Expected number of events at the EIC

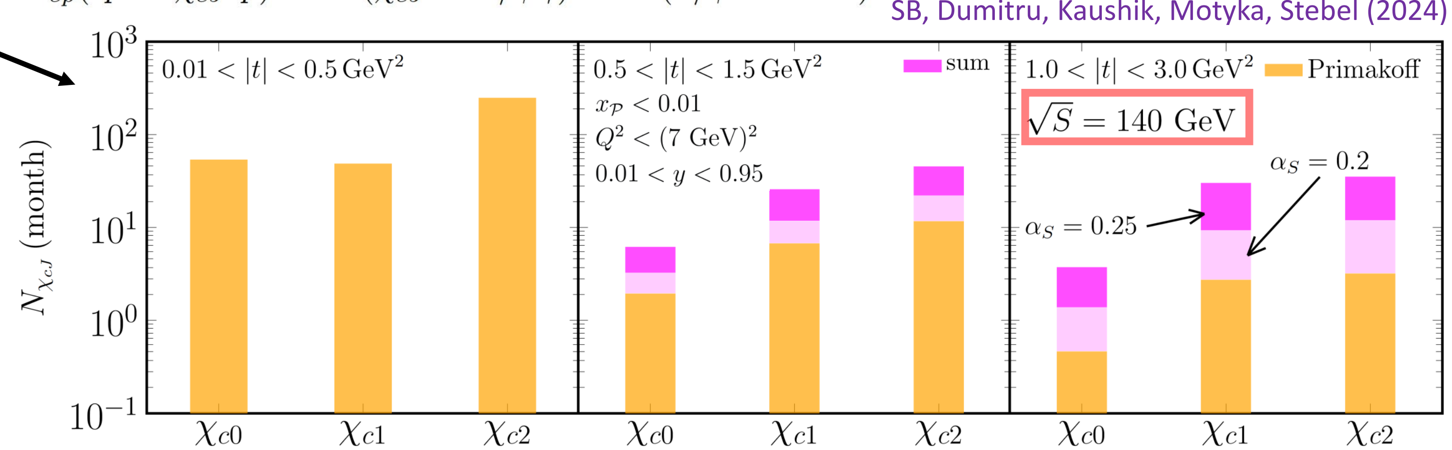
. detection channel: $\chi_{cJ} \to J/\psi\gamma$, $J/\psi \to l^+l^-$

. detector efficiency not taken into account!

$$N_{\chi_{cJ}} = L \times \sigma_{ep}(ep \to \chi_{cJ} ep) \times \mathrm{BR}(\chi_{cJ} \to J/\psi\gamma) \times \mathrm{BR}(J/\psi \to \ell^+\ell^-)$$

SB, Dumitru, Kaushik, Motyka, Stebel (2024)

number of events per month



. we predict **excess** in Odderon events over Primakoff background

. for χ_{c1} (34% BR to $J/\psi + \gamma$): with the EIC design luminosity 10^{34} cm^{-2} s^{-1} expect ~20 events/month (only Primakoff~5 events/month)

Lower energies also studied

Experimental perspective on exclusive χ_c

Spencer Klein

χ_c properties

State	Mass	Width
χ_{c0}	3415 MeV	10.7 MeV
χ_{c1}	3511 MeV	0.84 MeV
χ_{c2}	3556 MeV	1.98 MeV

- 3 χ_c states
- Two classes of useful decays: hadronic final states or $\gamma J/\psi$
  - Br (χ_{c1}-> $\gamma J/\psi$) = 34.3% (19.5% for χ_{c2} state,1.4% for χ_{c0})
  - Specific hadronic final states have Br of at most a few percent.
    - Tedious to add up enough different hadronic states to achieve a reasonable efficiency.
- Mass separation ~ 50-100 MeV
  - Tough, but ~ within ePIC capabilities for all-charged final states
    - χ_{c0} - χ_{c1} has similar $\Delta M/M$ as Υ(2S) - Υ(3S)
  - May be challenging for states containing neutrals

χ_{c0} largest cross section but smallest Br to $\gamma J/\Psi$

Mass separation not large, may worry abut beam energy spread

Background from decays of higher state

Spencer Klein

Process dominated by $\gamma\gamma$ except at large t, hence rates small, few events after cuts on t, ($\mathscr{L} = 100\ \mathrm{fb}^{-1}$, efficiency 70%, Br=2% for χ_{c0})

Another background

- Vector meson dominance → large Ψ(2S) production rate
  - σ(ep-> Ψ(2S)p) = 1.4 nb for 18 GeV e on 275 GeV p
  - 30,000 times larger than for χ_{c0}
- Br (Ψ(2S)-> $\gamma\chi_{c0}$) = 9.8 ± 0.2%
  - 3,000 times larger than direct χ_{c0} production
  - In Ψ(2S) rest frame photon energy = 260 MeV
    - Good energy for calorimetry, but solid angle < 100%
    - If ~95% coverage, then missed-photon background is 150 times larger than direct χ_{c0} production
    - Also, some photons may be Lorentz downshifted below threshold
- Missing energy/momentum cuts could eliminate some background
  - Missing photons with low p_T probably cannot be adequately rejected
- χ_c from Υ(2S) probably have similar p_T spectrum to χ_c from ~~$\pi\emptyset$~~ γO

Spencer Klein

Conclusions

- The χ_c states are interesting to study as possible channels to detect the Odderon.
- However, the rates are low, and there are many possible final states
  - The χ_{c0} is most copiously produced, so may be the most attractive experimental target
- Backgrounds are large
  - $\gamma\gamma$–> dominates over γ + Odderon, except at large |t|
  - γP -> Ψ(2S)->$\gamma\chi_c$ dominates over direct χ_c production mechanisms
    - Vector meson dominance strikes again!

Outlook

INT Workshop : *Bridging Theory and Experiment at the Electron-Ion Collider*

Organizers: Alessandro Bacchetta, Wim Cosyn, Felix Ringer, Anna Staśto

Tentative dates: June 2-6, 2025

Topics: diffraction, Monte Carlo generators, radiative corrections,…

Workshop embedded in an INT program:

Precision QCD with the Electron - Ion Collider

Organizers: Renee Fatemi, Huey-Wen Lin, Werner Vogelsang

If you think there is some topic worth of discussing in TH group please submit suggestions through:

https://wiki.bnl.gov/eicug/index.php/Theory

…or send us an email