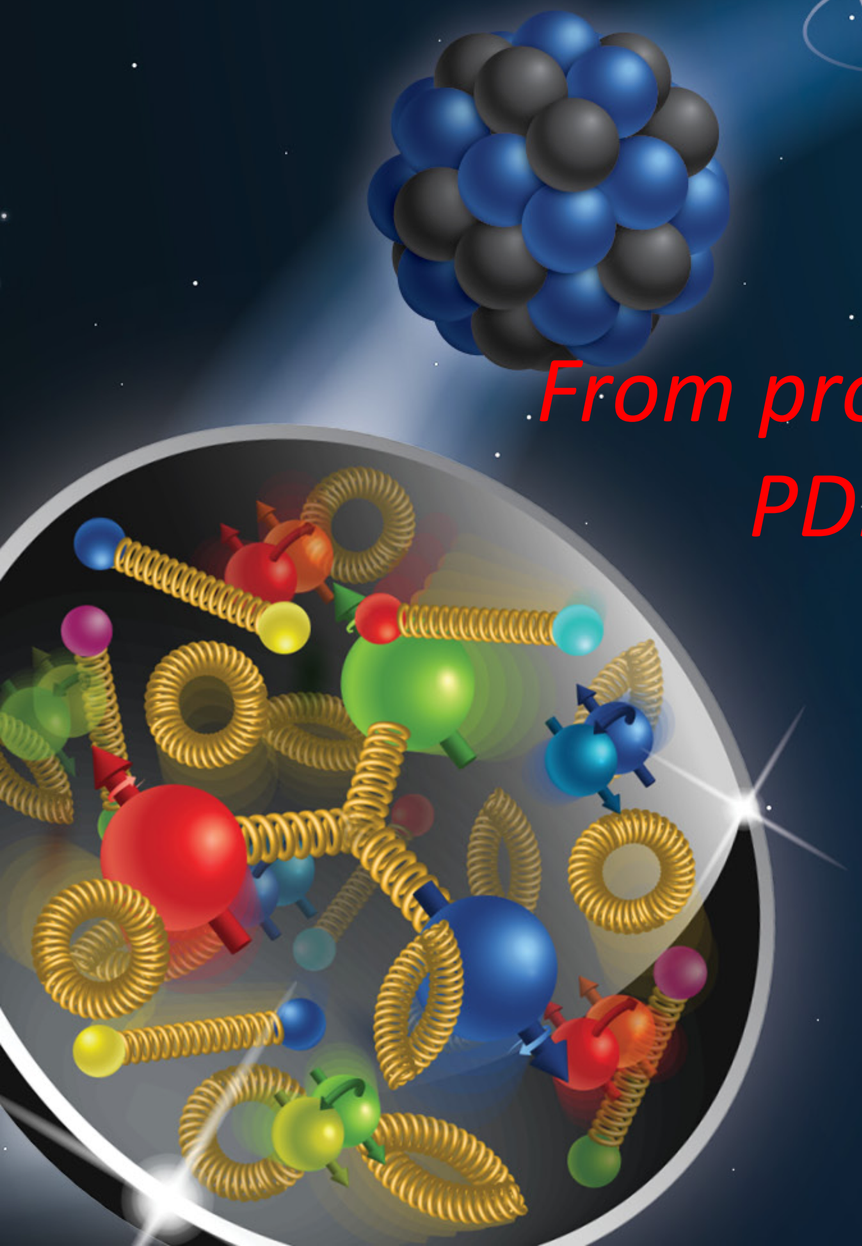


From proton to nuclear GPDs and PDFs at EIC (and RHIC)

Salvatore Fazio

Brookhaven National Lab

INT 18-3, weeks 5-6

Seattle WA

29 October -09 November 2018

BROOKHAVEN NATIONAL LABORATORY

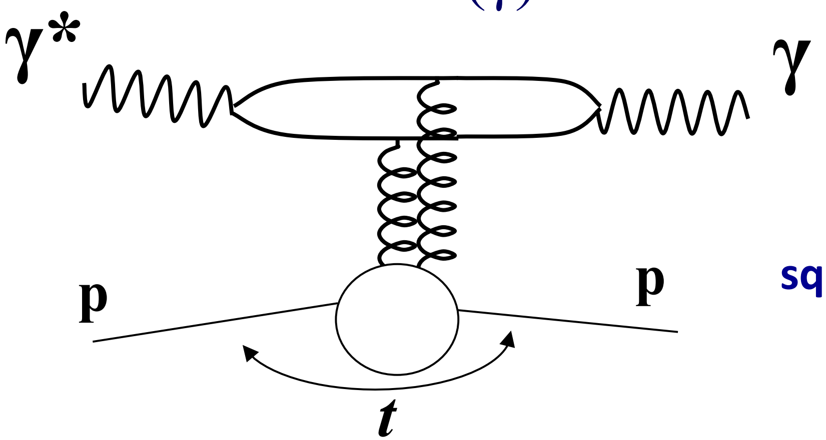
U.S. DEPARTMENT OF ENERGY | Office of Science

Plan of the talk

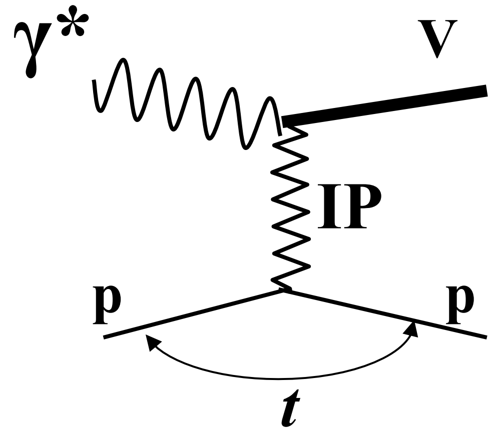
- **Imaging with an EIC**
- **e+p (*also talk on week 1 and 4*)**
  - **DVCS Impact studies**
  - **DVMP**
- **e+A**
  - **nPDFs, GPDs in nuclei, saturation (*also talk on week 4*)**
  - **Gluon GPD in UPC at RHIC**
- **Access to Wigner function (in e+p and e+A)**
- **Final discussion**

Exclusive Vector Meson and real photon production

DVCS (γ)



VM (ρ, ω, φ, J/ψ, Y)



square 4-momentum at the *p* vertex:

$$t = (p' - p)^2$$

Scale: Q^2 ⟷ $Q^2 + M^2$

DVCS:

- Very clean experimental signature
- No VM wave-function uncertainty
- Hard scale provided by Q^2
- Sensitive to both quarks and gluons [via Q^2 dependence of xsec (scaling violation)

VMP:

- Uncertainty of wave function
- J/Psi → direct access to gluons, c+bar-c pair produced via quark(gluon)-gluon fusion
- Light VMs → quark-flavor separation

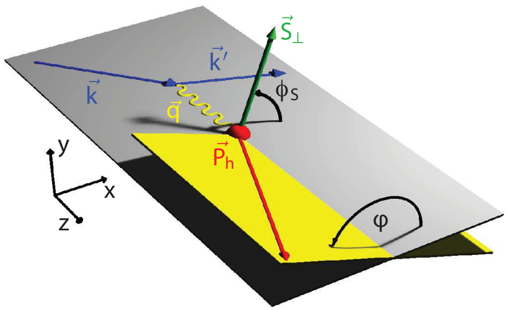
Alternative/complementary way to quark-flavor separation

DVCS on a real neutron target → polarized Deuterium or He^3

Accessing the GPDs in exclusive processes

$$\frac{d\sigma}{dt} \sim A_0 \left[|H|^2 (x,t,Q^2) - \frac{t}{4M_p^2} |E^2| (x,t,Q^2) \right]$$

Dominated by H
slightly dependent on E

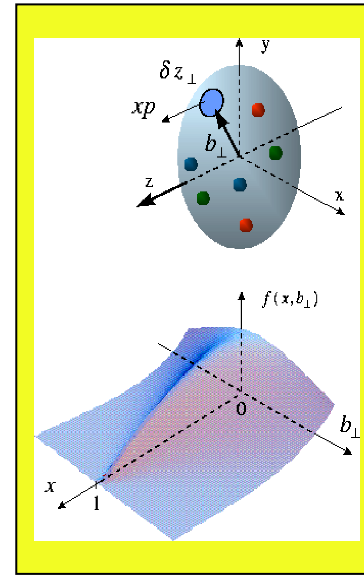


$$\varphi = \phi_h - \phi_l$$

Angle btw the production and scattering planes

$$\varphi_s = \Phi_T - \phi_h$$

Angle btw the scattering plane and the transverse pol. vector



$$A_C = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} \propto Re(A)$$

→ **Requires a positron beam**
done @ HERA

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}} \left[F_2(t) H(\xi,\xi,t,Q^2) - F_1(t) E(\xi,\xi,t,Q^2) + \ldots \right]$$

→ ***sin($\Phi_T - \phi_N$)***
governed by E and H
Requires a polarized proton-target

Spin-Sum-Rule in PRF: from g_1

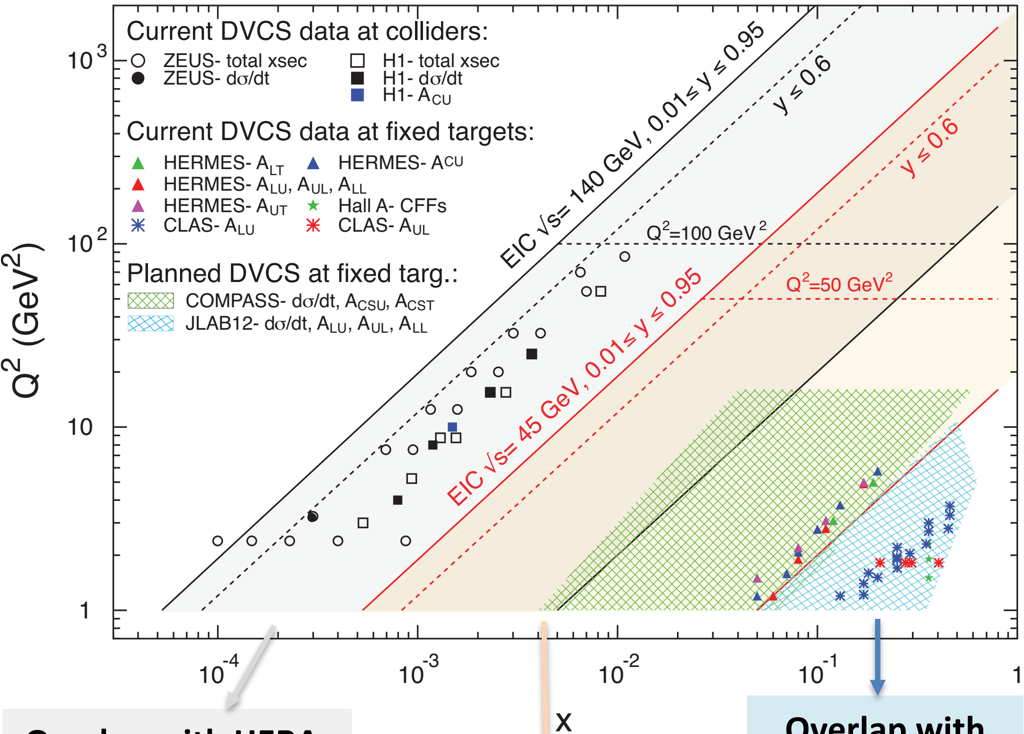
$$\frac{1}{2} = J_q^z + J_g^z = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}_q^z + J_g^z$$

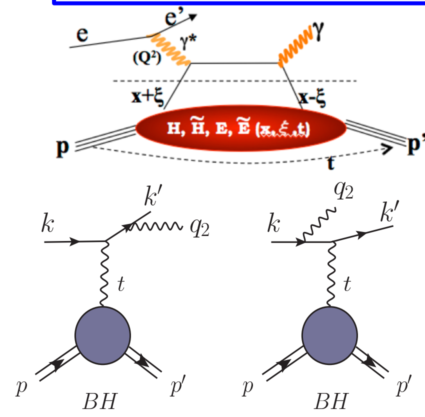
$$J_{q,g}^z = \frac{1}{2}\left(\int_{-1}^{1} x\,dx \left(H^{q,g} + E^{q,q} \right) \right)_{t \to 0}$$

responsible for orbital angular momentum
a window to the SPIN physics

DVCS at an EIC

E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093





DVCS signal

Bethe-Heitler QED bkgd.

Overlap with HERA:
Large impact on current fits at low x

Intermediate region:
Fine mapping of the GPDs evolution

Overlap with JLAB12:
Sanity check

HERA results limited by lack of statistics

EIC: the first machine to measure cross sections and asymmetries

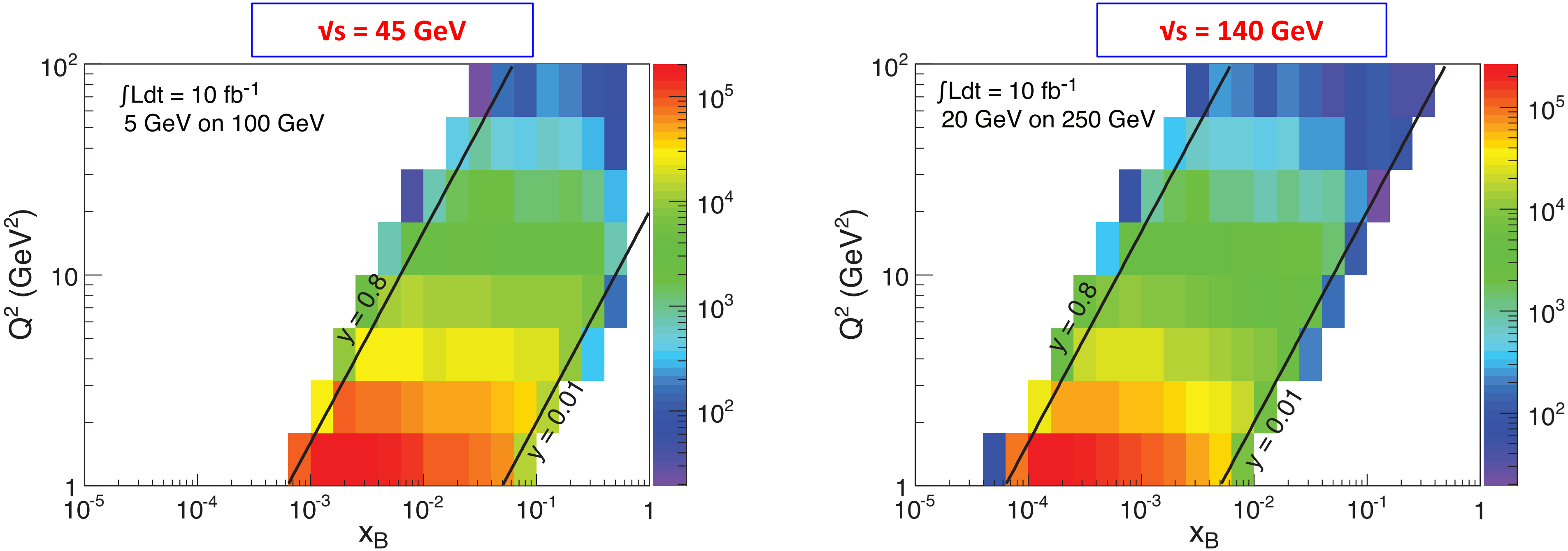
Comprehensive EIC studies

- Signal extraction "a la HERA"
- xSec meas.: Specific requirements to suppress BH
  → keep BH/sample below 60% at high energies
- Radiative Corrections evaluated
- detector acceptance & smearing
- t-slope: b=5.6 compatible with H1 data
- |t|-binning is (3*resolution)
- 5% systematic uncertainties

DVCS at a high luminosity collider

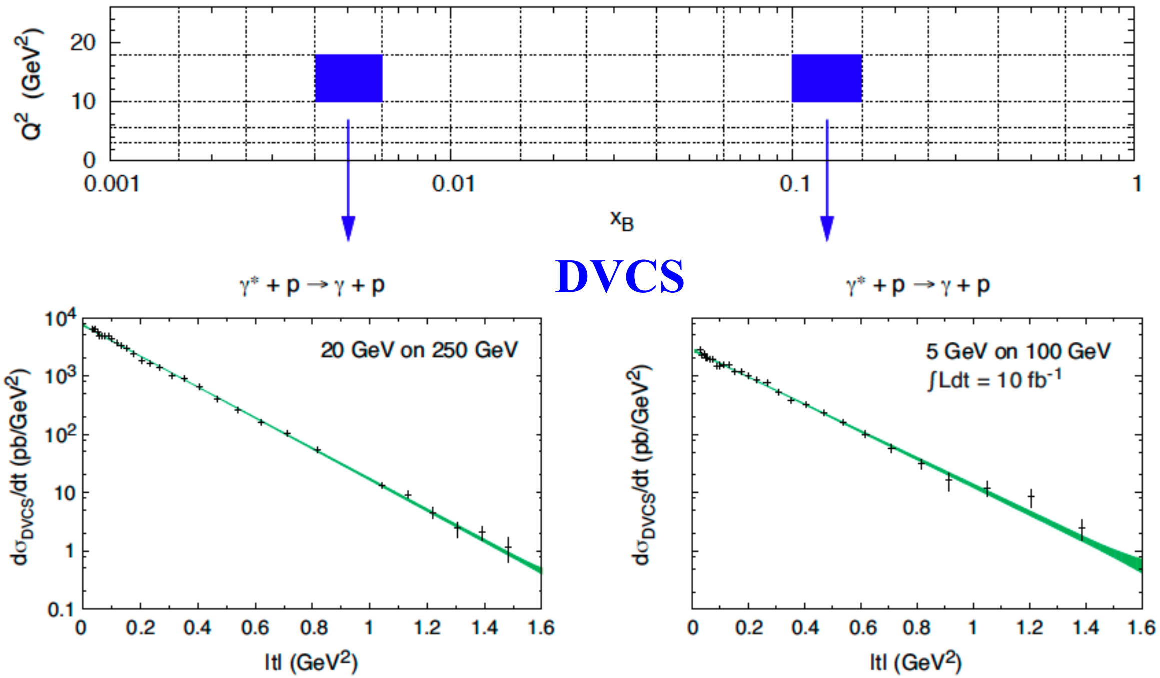
The code MILOU by E. Perez, L Schoeffel, L. Favart [arXiv:hep-ph/0411389v1]
is Based on a GPDs convolution by: A. Freund and M. McDermott [http://durpdg.dur.ac.uk/hepdata/dvcs.html]

- EIC will provide sufficient lumi to bin in multi-dimensions
- wide x and Q^2 range needed to extract GPDs



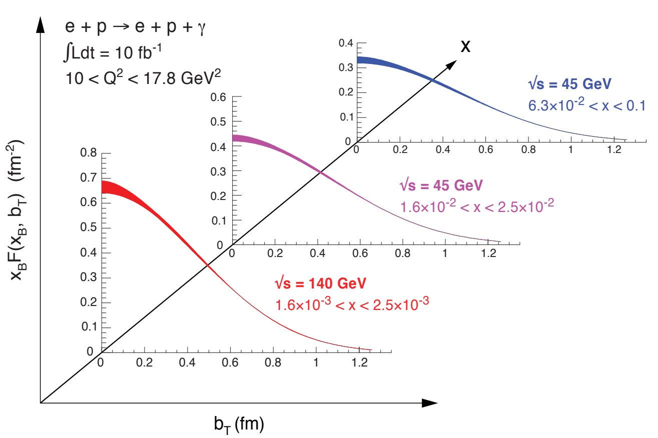
… we can do a fine binning in Q2 and W… and even in |t|

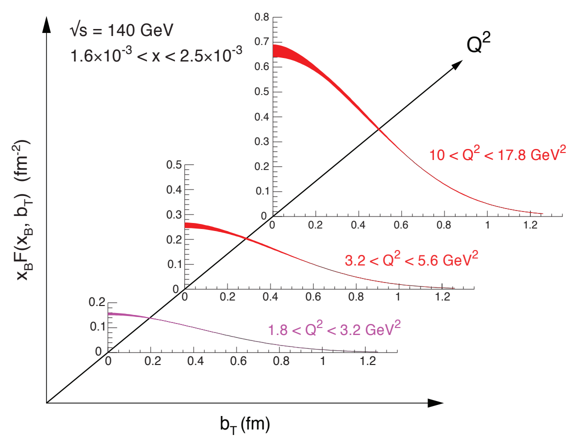
DVCS & J/ψ differential cross section



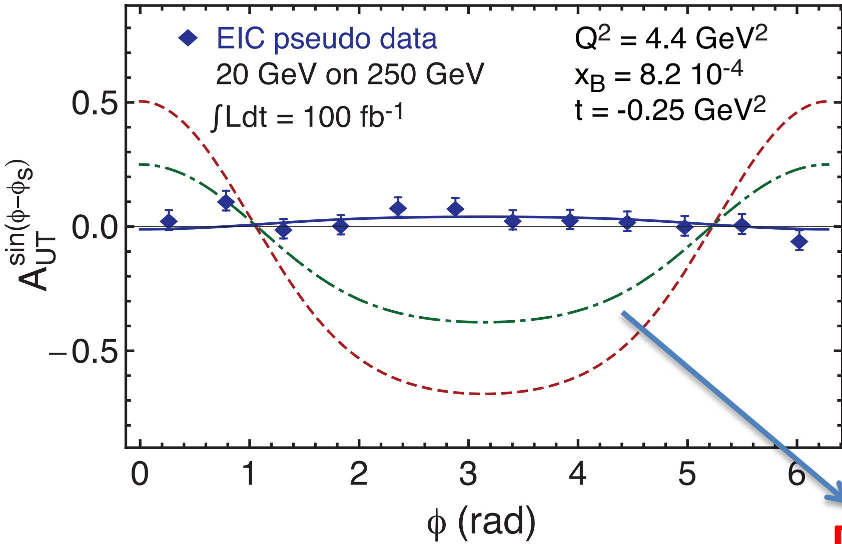
Luminosity: 10 fb^{-1}

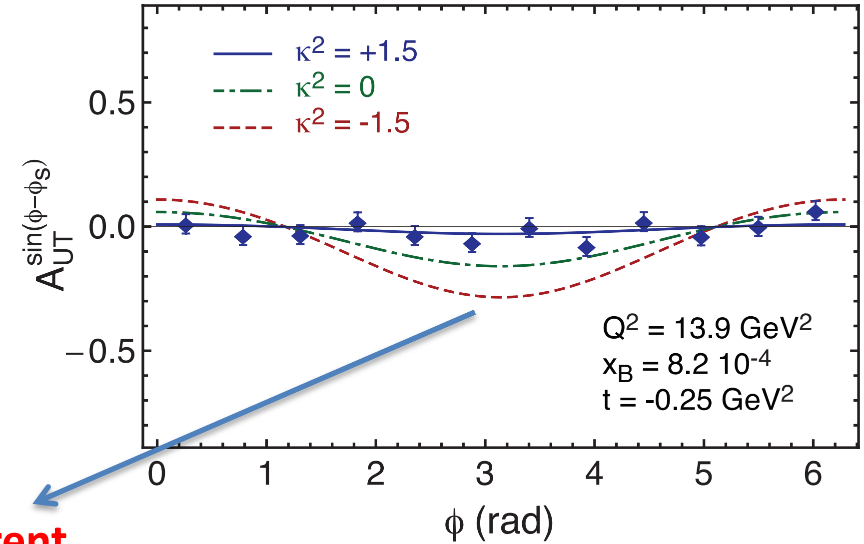
- **Measurement dominated by systematics**
- Fourier transf. of dσ/dt → partonic profiles





Transverse target-spin asymmetry





Different assumptions for E

$$A_{UT} \propto \sqrt{\frac{-t}{4M^2}}\left[F_2(t)H\left(\xi,\xi,t,Q^2\right)-F_1(t)E\left(\xi,\xi,t,Q^2\right)+\ldots\right]$$

sin(Φ$_T$−φ$_N$)
governed by E and H

Spin-Sum-Rule in PRF: from g_1

$$\frac{1}{2}=J_q^z+J_g^z=\frac{1}{2}\Delta\Sigma+\sum_q \mathcal{L}_q^z+J_g^z$$

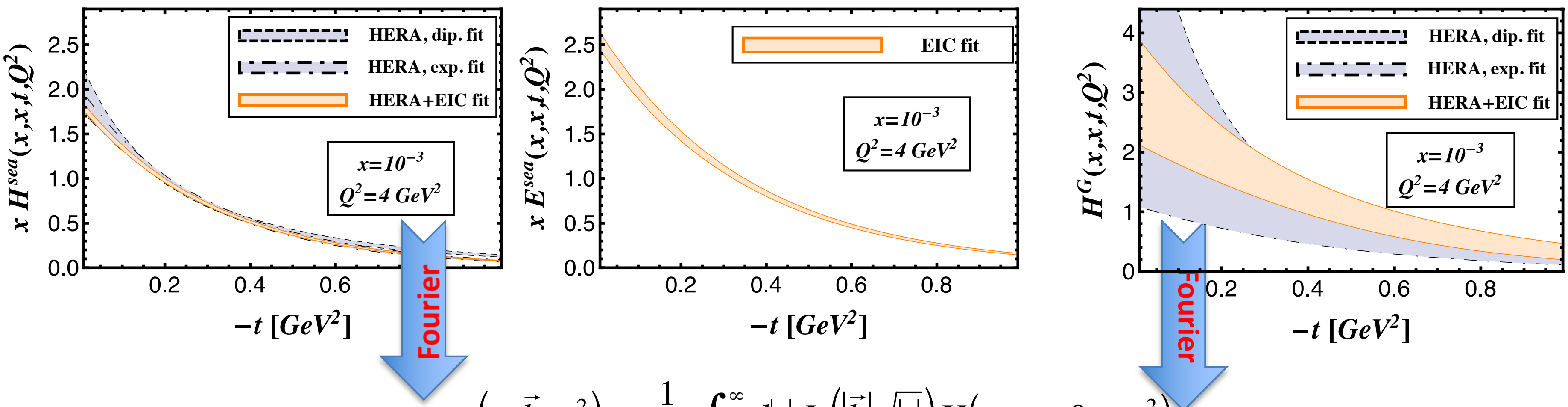
$$J_{q,g}^z=\frac{1}{2}\left(\int_{-1}^{1}x\,dx\left(H^{q,g}+E^{q,q}\right)\right)_{t\to 0}$$

Gives access to GPD E

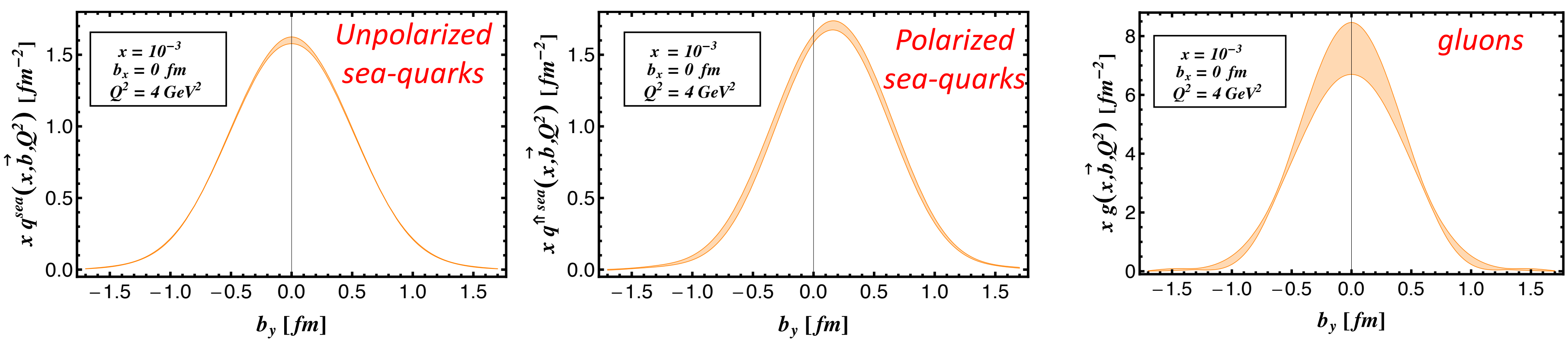
E.C. Aschenauer, S. F., K. Kumerički, D. Müller
JHEP09(2013)093

DVCS-based imaging

- A global fit over all mock data was done, based on: [Nuclear Physics B 794 (2008) 244–323]
- Known values *q(x)*, *g(x)* are assumed for H^q, H^g (at t=0 forward limits E^q, E^g are unknown)

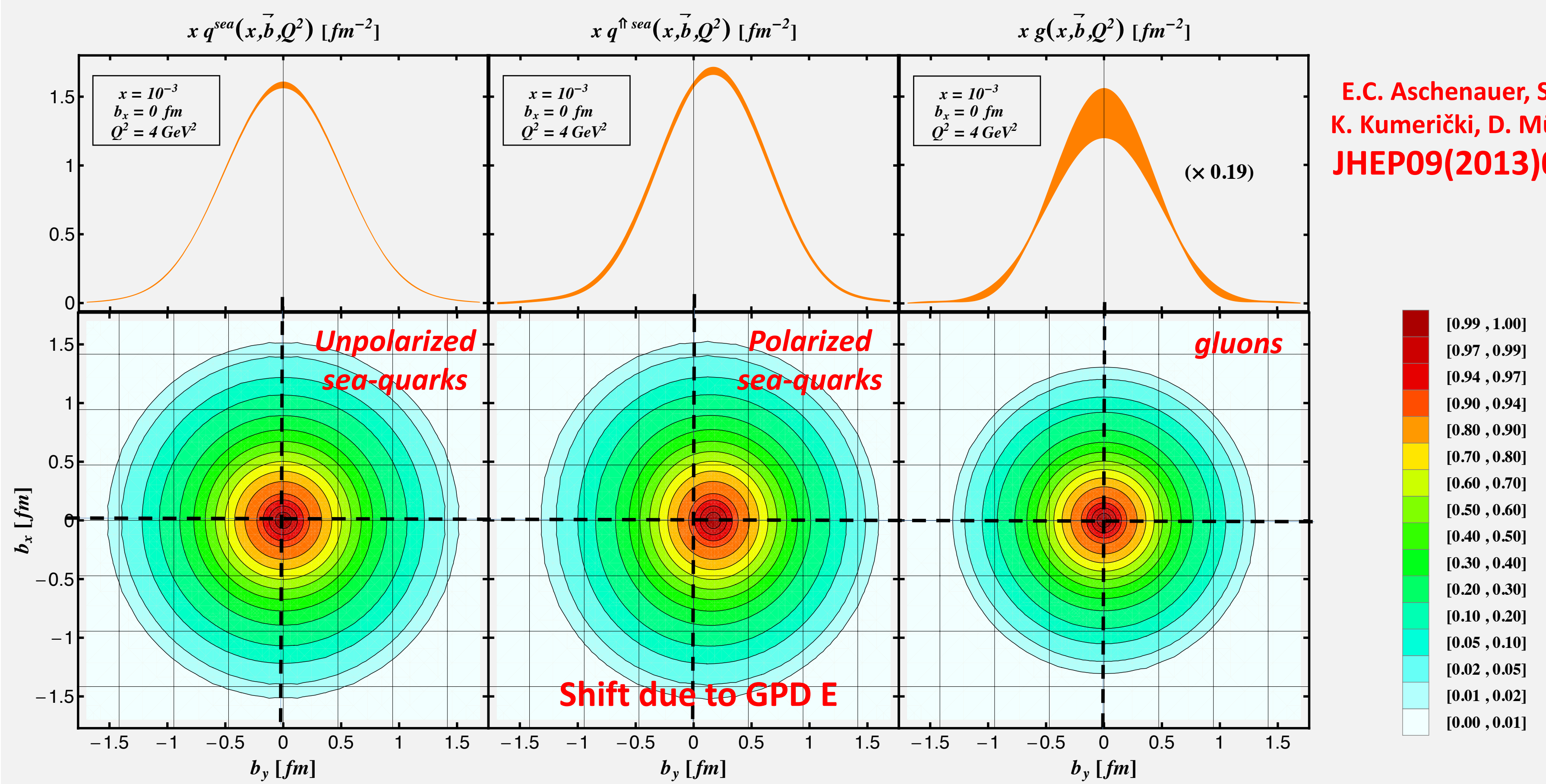


$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0\left(|\vec{b}|\sqrt{|t|}\right) H\left(x,\eta=0,t,\mu^2\right)$$



E.C. Aschenauer, S. F., K. Kumerički, D. Müller, JHEP09(2013)093

Spatial Imaging – as in the EIC White Paper



E.C. Aschenauer, S. F., K. Kumerički, D. Müller, JHEP09(2013)093

Impact of EIC (based on DVCS only):

- ✓ **Excellent reconstruction of H^{sea}, and H^{g} (from $d\sigma/dt$)**
- ✓ **Reconstruction of sea-quarks GPD E**

Other capabilities still to be evaluated?

- GPD H-Gluon is nice but can be much better by including J/ψ
- Access to GPD E-gluon → orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)

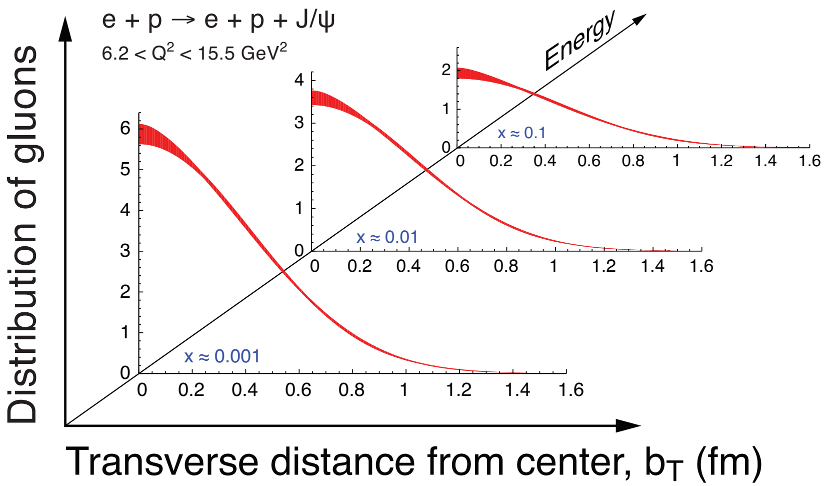
Time to move on…

How to separate flavors?

Method 1 – VMP

rho0: 2u+d 9/4g
omega: 2u-d /4g
phi: s,g
rho+: u-d
J/psi: g

We simulated the J/Psi cross section and the Fourier transform but never included it on GPDs fits



Challenges of VMP (if compared to DVCS)

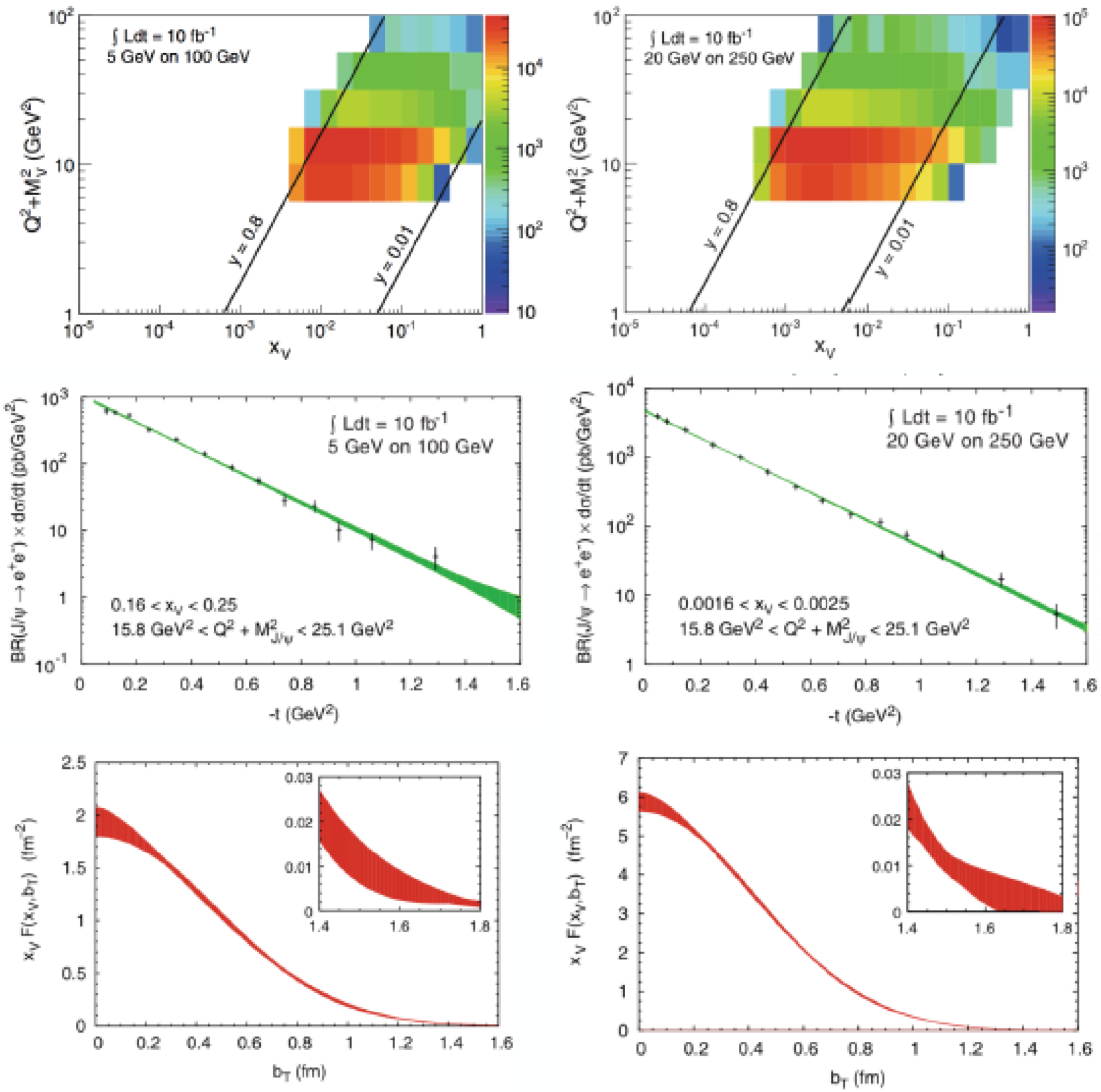
- Uncertainty on wave function
- measuring muons vs electron decay channel

Method 2 – DVCS on protons and neutrons

- **We do not a real neutron target → Use Deuterium (D)**
- **We incoherent DVCS on D (D can break up) but coherent on n (tagged by ZDC)**
- **One still needs J/psi to directely access the gluons and extract Eg**

Imaging gluons with J/ψ

EIC White Paper



Luminosity: 10 fb^{-1}

- Measurement dominated by systematics
- Fourier transf. of dσ/dt → partonic profiles

Only possible at EIC: from valence quark region, deep into the sea!

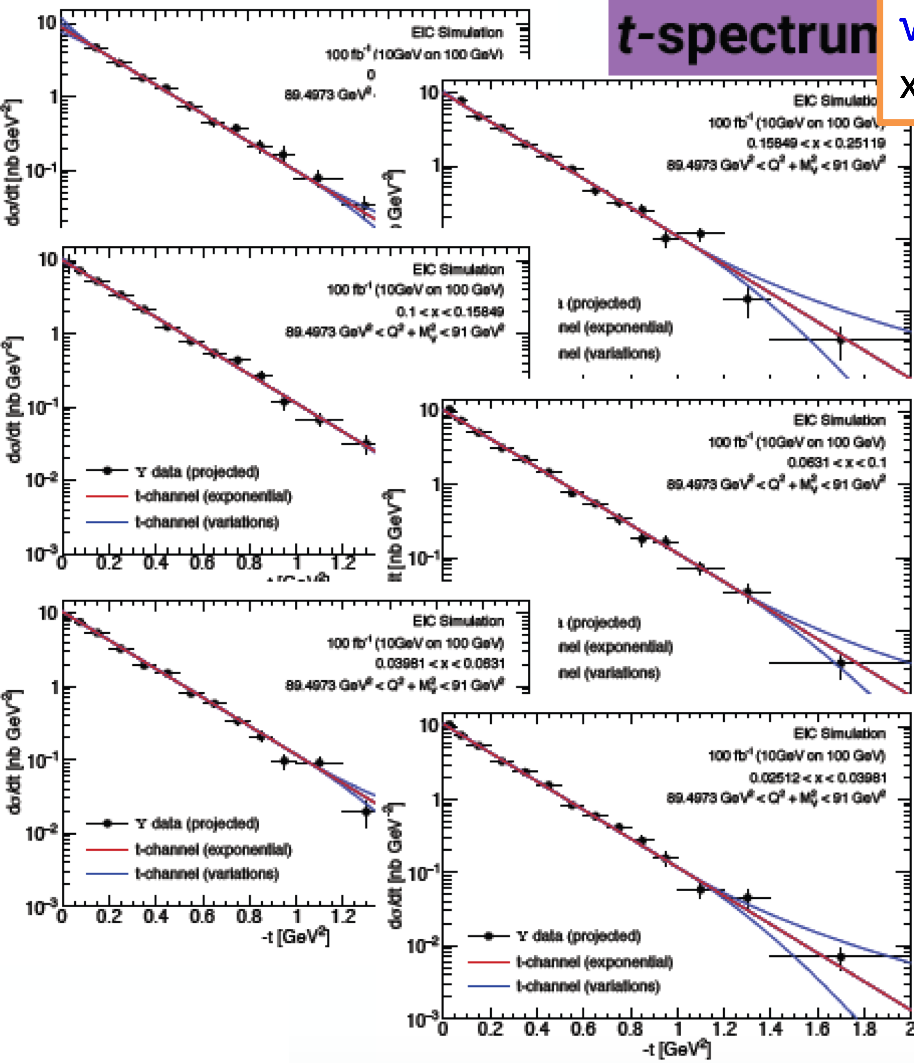
Average densities

Imaging gluons with Υ(1s)

S. Joosten, Z.-E. Meziani
2018 EICUG Meeting

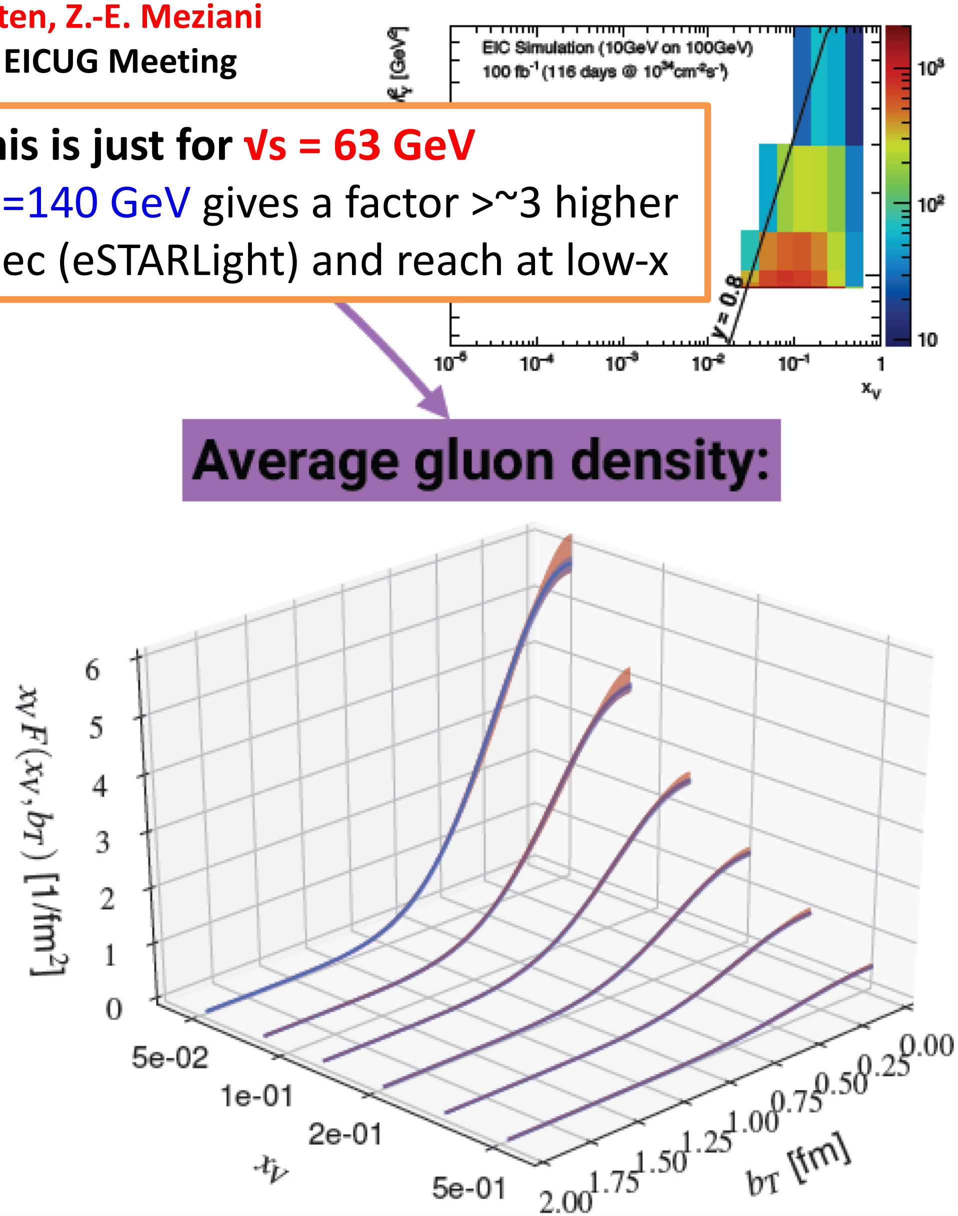
- Nominal EIC detector
- 10x more luminosity
- Electron and muon channels

t-spectrum



This is just for √s = 63 GeV
√s=140 GeV gives a factor >~3 higher xSec (eSTARLight) and reach at low-x

Average gluon density:



Next-generation GPD studies with exclusive meson production at EIC

Center for Frontiers in Nuclear Science

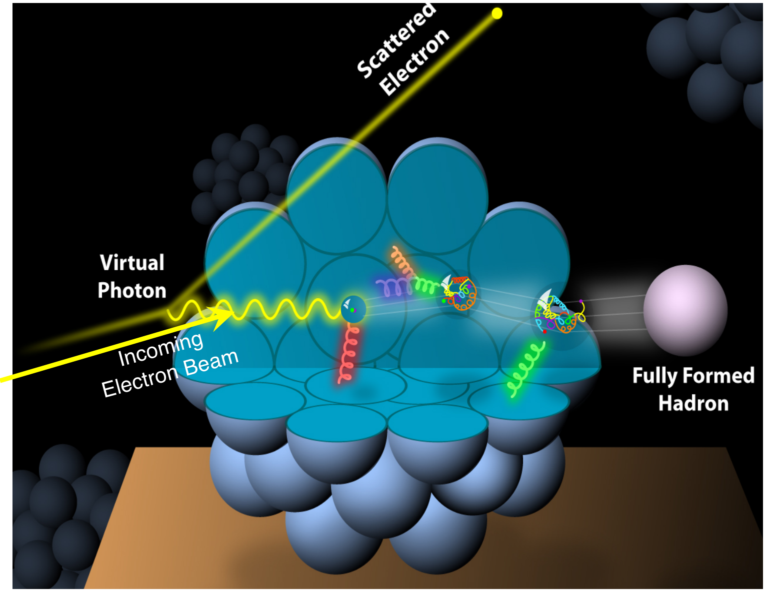
https://indico.bnl.gov/event/4346/

Outcomes of the Workshop

- **QCD factorization with finite-size effects provides realistic description of exclusive meson production**
  - Use in GPD & imaging studies
  - Need theoretical work: NLO corrections, relation between approaches
- **UPCs at LHC extend energy frontier in heavy quarkonium production**
  - LHCb, ALICE results for $\gamma + p \rightarrow J/\psi + p$ (up to $W \sim 1.5$ TeV)
  - Consistent with HERA data; no indications of nonlinear effects
- **Meson production could become essential tool for GPD studies at EIC**
  - Dedicated community, great interest
- **Next-level impact studies need GPD-based physics models**
  - Aim for GPD extraction with uncertainties
- **PARTONS project (H. Moutarde et al) can play important role in integrating GPD efforts at JLab12 and EIC**

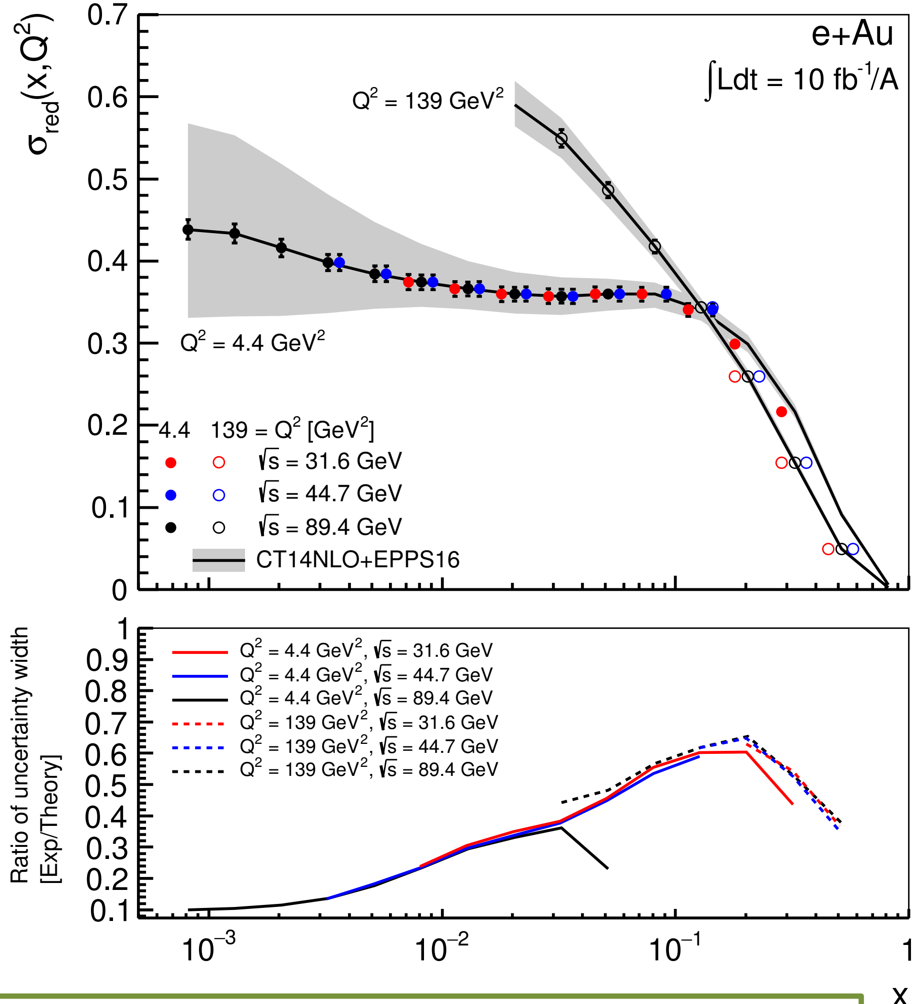
Next follow up: Warsaw January 22-25 2018

Nuclear PDFs and GPDs
an Electron-Ion Collider (EIC)



- How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?
- Where does the saturation of the gluon density set in?

Reduced Cross Section & F_2 (e+Au)



(See talk by Pia Zurita)

$$\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{1+\left(1-y\right)^2} F_L\left(x,Q^2\right)$$

- **Systematics = 3%**
- Stat. and Sys. error summed in quadrature **(Sys. dominate!)**
- Gluon extraction via scaling violation → $d\sigma(x,Q^2)/d\ln Q^2$ (requires ~> 1 decade in Q^2 at a fixed x)
- Comparison of linear with non-linear evolution in x will signal saturation

  ⇒ needs low-x reach

Large expected impact on current theory uncertainty, especially at low-x and low-Q^2

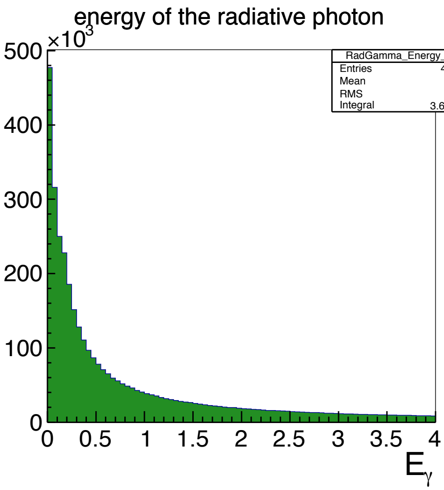
An EIC at its highest energy provides a factor 10 larger reach in Q^2 and low-x compared to available data

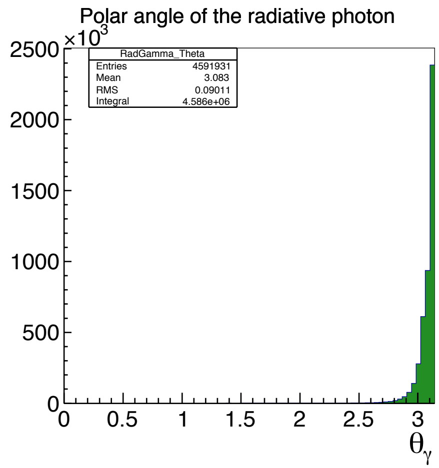
Radiated photons

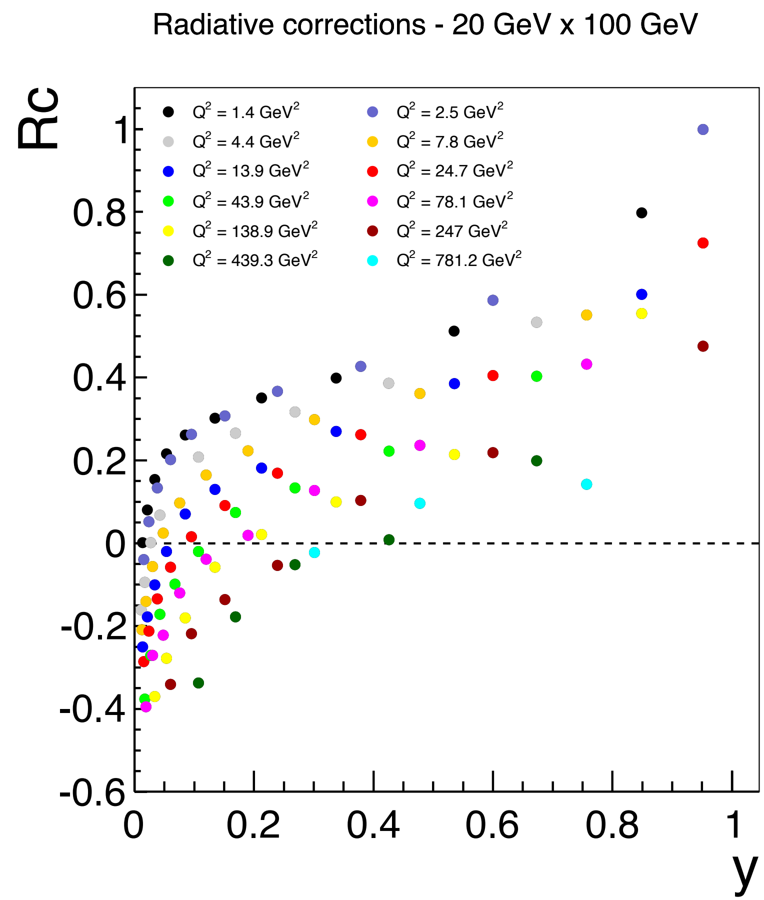
We use **Django simulator** including O(α) radiative effects

We look at photons radiated from the electron before or after the interaction

50% events radiate a photon







Radiated photons are

- Low energy (most of them < 1 GeV)
- uniformly distributed in the azimuthal angle
- collinear to the scattered electron ($\theta_\gamma > 3$ rad)

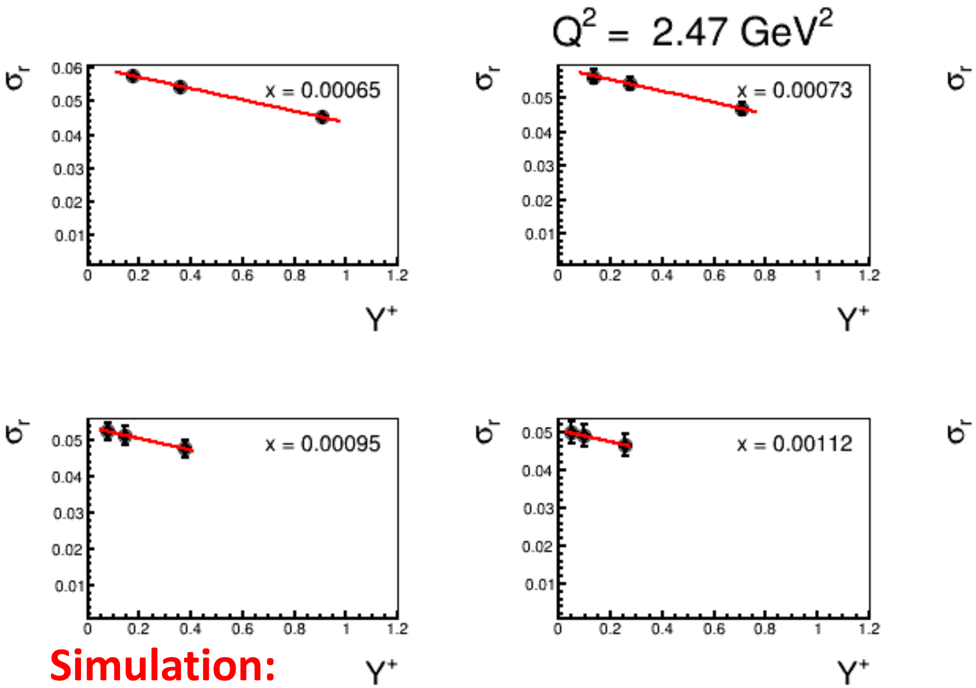
Correction factor:

$$Rc = \frac{\sigma_{red}\left(O(\alpha)\right)}{\sigma_{red}\left(Born\right)} - 1$$

Extracting F_L (e+Au)

Higher energy EIC: √s = 63, 78, 89 GeV

$$\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{1+\left(1-y\right)^2} F_L\left(x,Q^2\right) \qquad \frac{y^2}{1+\left(1-y\right)^2} = Y^+$$



Enough Lever Arm required (three points, $Y^+ > 0.2$)

Simulation:

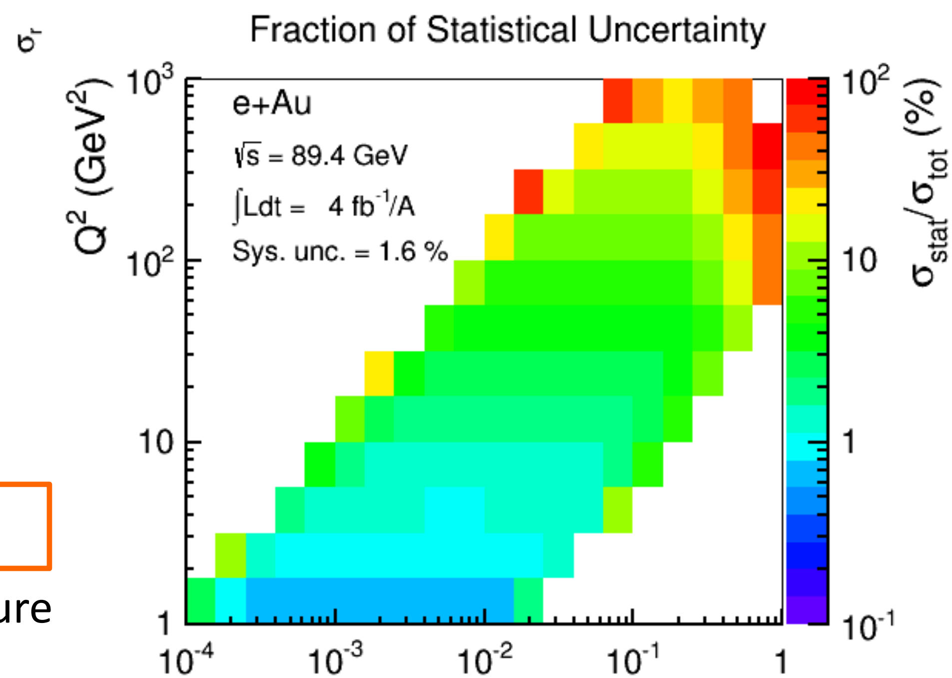
[√s = 32(63) GeV] –> L = 2 fb^{-1}/A

[√s = 39(78) GeV] –> L = 4 fb^{-1}/A

[√s = 45(89) GeV] –> L = 4 fb^{-1}/A

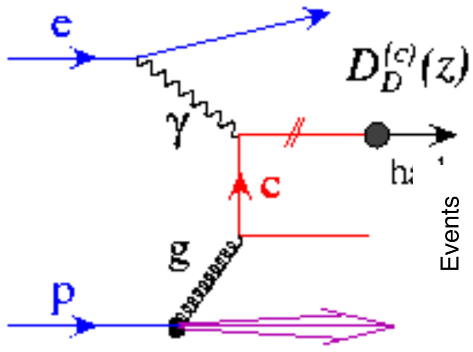
Total simulated event sample L = 10 fb^{-1}/A

- total error = stat. + sys. summed in quadrature
- assumed sys. = 3%



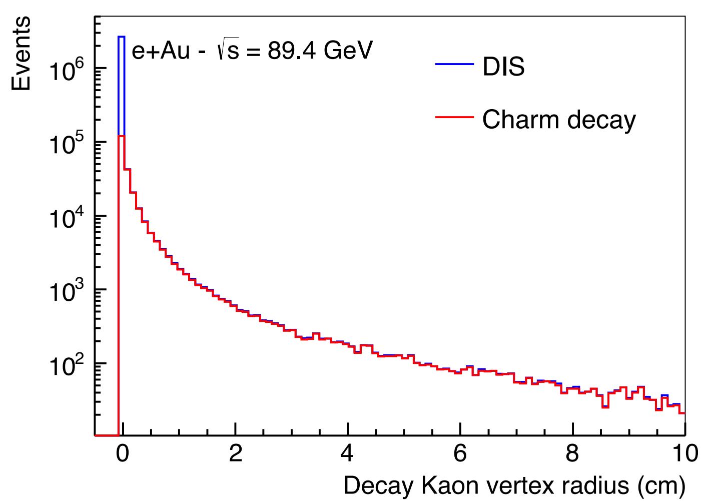
Errors still dominated by systematics

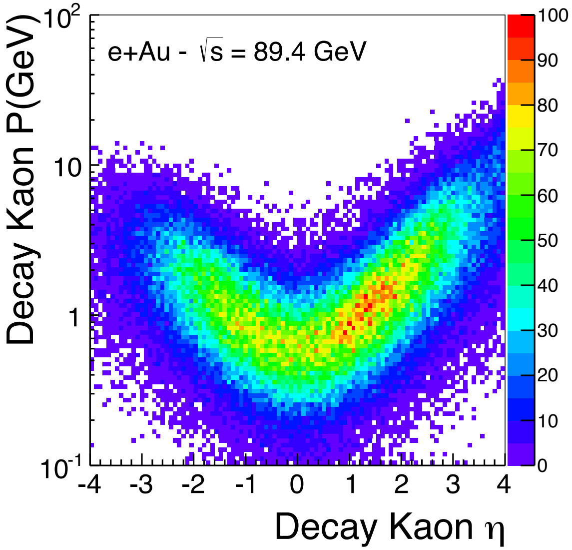
Charm production: a unique tool!



- Direct access to gluons at medium to high *x* by tagging photon-gluon
- Helps determining heavy quarks mass scheme

Novel probe!





Selection of charm-production events

We select **kaons** in the final state of the ***D*** meson decay, looking for:

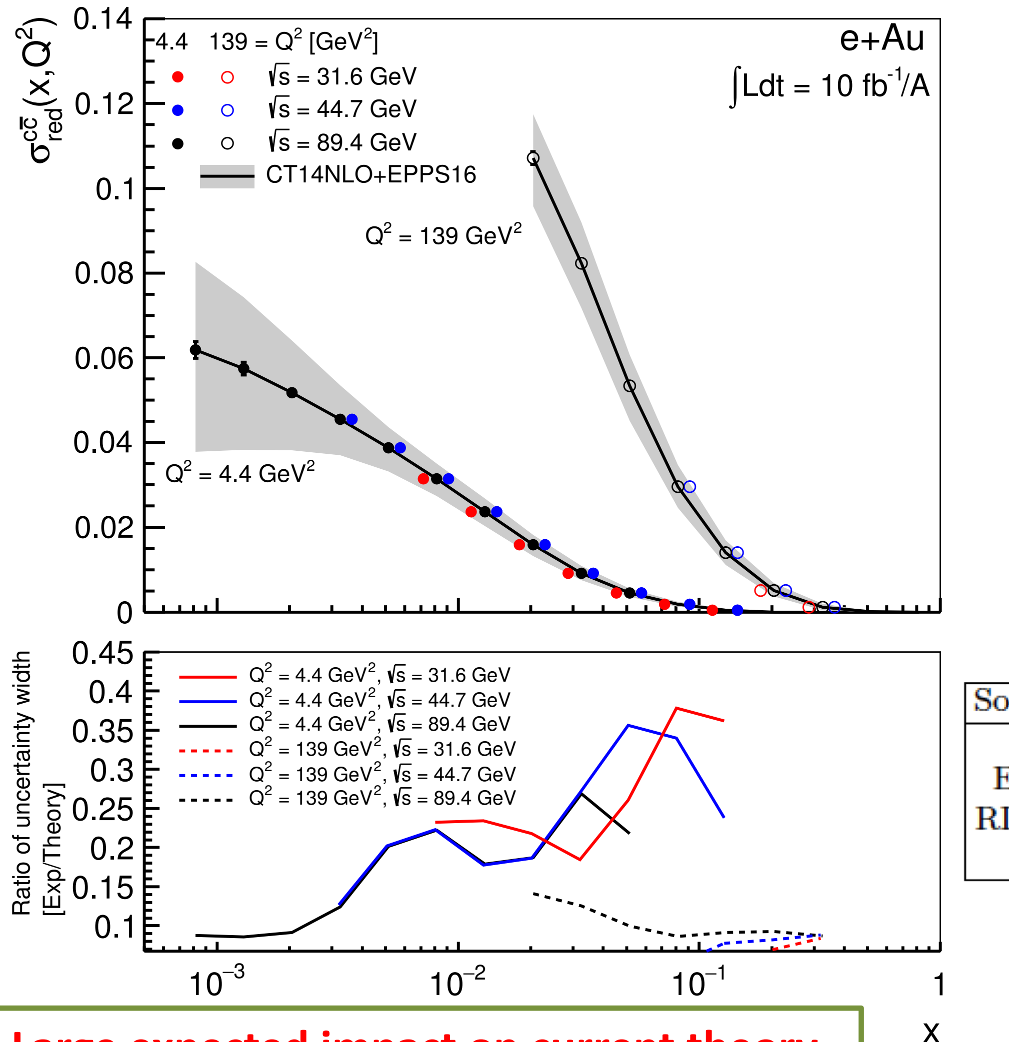
- a displaced vertex: 0.01 cm <|Vertex|< 3 cm
- Momentum within the acceptance of an EIC model detector (BeAST @ eRHIC)

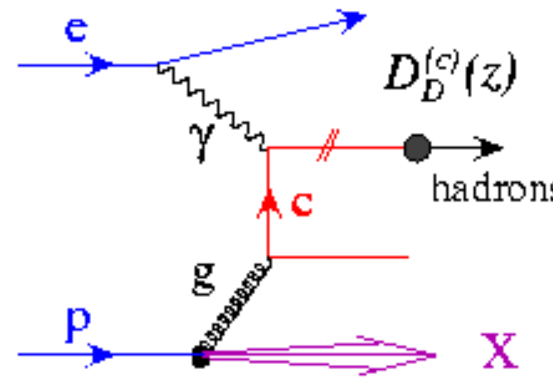
CENTRAL DETECTOR (-1 < η < 1)
dE/dx -> 0.2 GeV < P < 0.8 GeV
RICH -> 2 GeV < P < 5 GeV

FORWARD (1 < η < 3.5)
RICH -> 2 GeV < P < 40 GeV

REAR (-3.5 < η < -1)
RICH -> 2 GeV < P < 15 GeV

Charm - reduced Cross Section & F_2 (e+Au)





- Systematics = 7%
- Stat. and Sys. error summed in quadrature **(Sys. dominate!)**
- No world data exist!

Sources of Uncertainty	Value in σ_r (%)	Value in $\sigma_r^{c\bar{c}}$ (%)
Luminosity	1.4	1.4
Electron id. and eff.	1.6	1.6
RICH and dE/dx PID	0	3
Vertex finding	0	1

Large expected impact on current theory uncertainty, in the whole x range

Q^2(GeV^2)

Large expected impact on current theory uncertainty, especially at low-x and low-Q²

Charm selection: background & efficiency

Background study

We look at background from DIS events with kaons that pass the whole selection but are not coming from a charm decay.

The fraction of background over signal events is:

(selected bkg events) / (selected Charm Events)

Conclusion:

The B/S fraction is expected in the order of ~1% with a very light energy dependence

Efficiency study

We look at the efficiency of selection charm production events. The efficiency is defined as:

(selected Charm Events) / (charm Events in Acceptance)

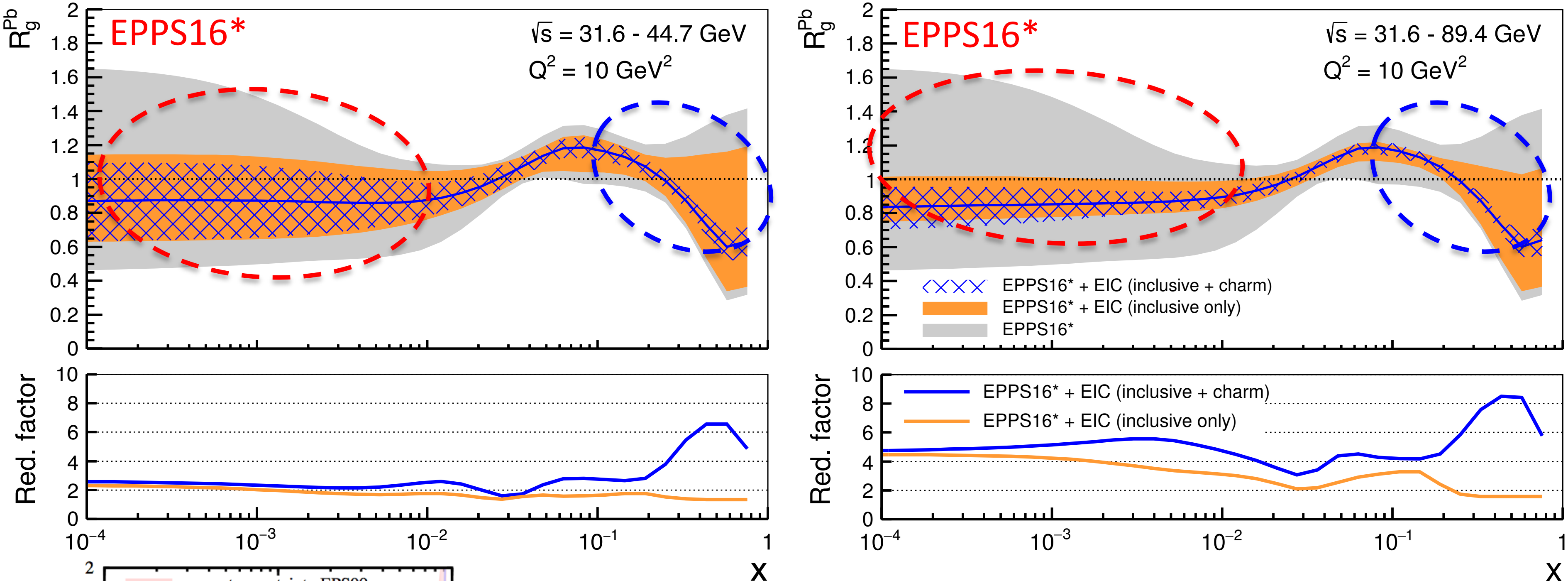
Conclusion:

The charm selection efficiency is expected in the order of ~28% with no significant energy dependence

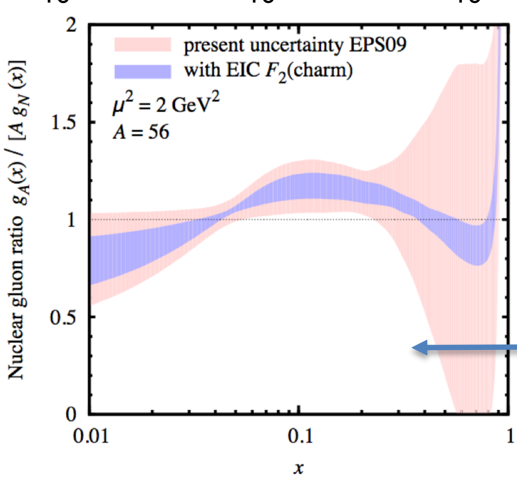
The EIC impact – gluons

EPPS16* → **functional form** with less constraints (for gluons) in extrapolating for $x < x_{data}$

low-energy scenario **(See talk by Pia Zurita)** high-energy scenario



E.C. Aschenauer, S. F., M.A.C. Lamont, H. Paukkunen, P. Zurita
Phys.Rev. D 96 114005 (2017)



Inclusive DIS alone has a huge effect at low-*x*

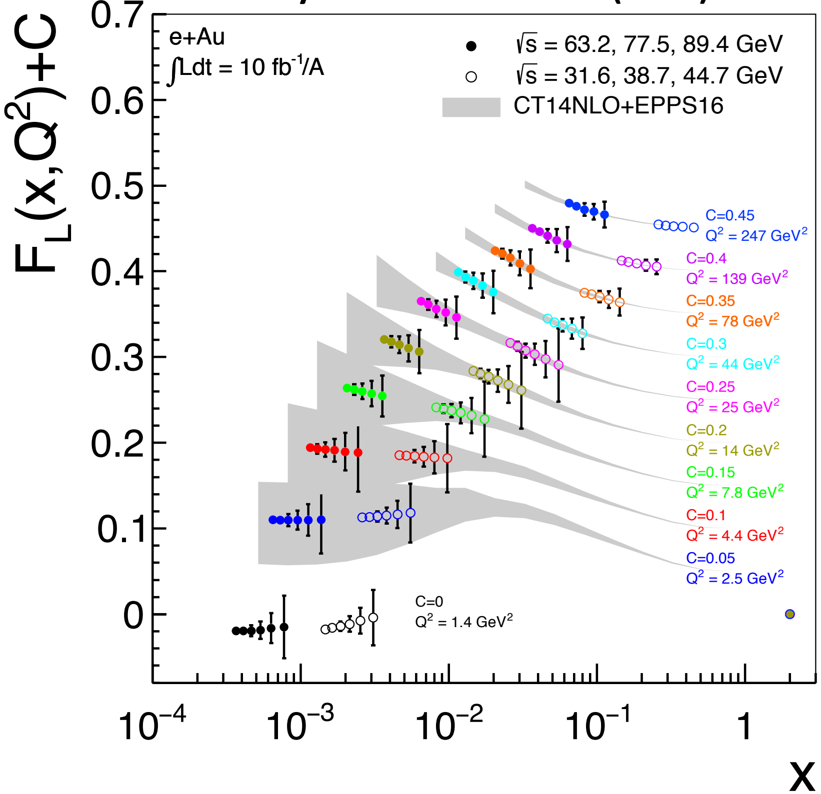
Charm has a dramatic effect at high-*x*

See also C. Weiss et al.
Santa Fe Jets and heavy flavor Workshop Jan 18

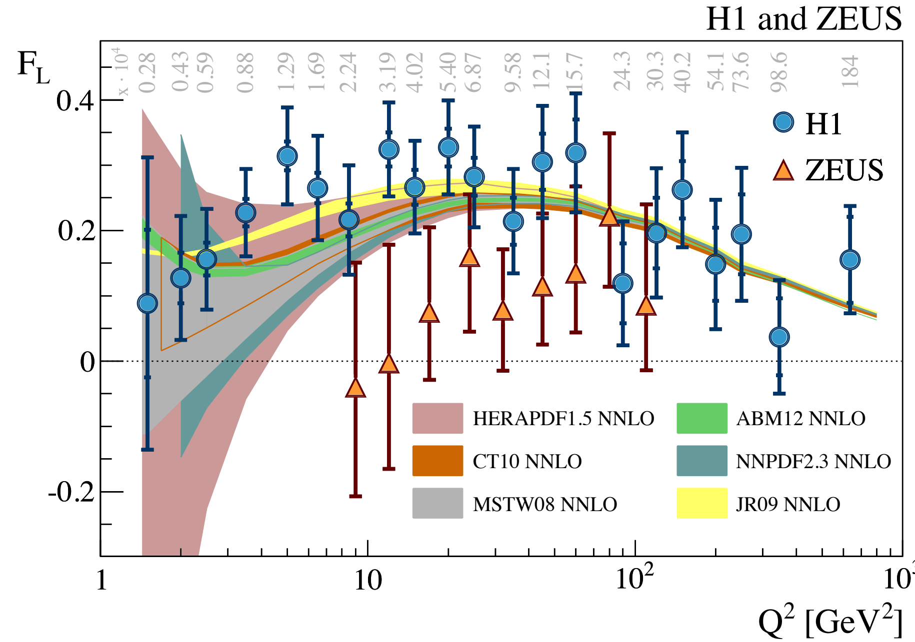
Proton SFs

e+Au F_L - EIC

Phys.Rev. D 96 114005 (2017)



Proton F_L - HERA



Not only for nuclei!

Comparable precision for proton Structure Functions in e+p scattering, to even higher Q^2 at high x

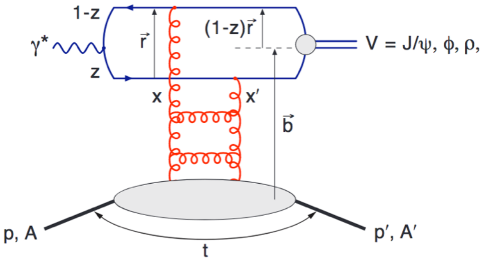
→ Beyond what HERA achieved: precise measurement of proton F_L

Proton PDFs

Therefore EIC can have large impact on proton PDFs too!

- ✓ **e+Deutrium data** are sensitive to u/d quark flavor separation (need to account for nuclear modifications)
- ✓ **Electroweak data** allow to constrain s quark PDFs as well as **SIDIS +FF**

Imaging the gluons in nuclei



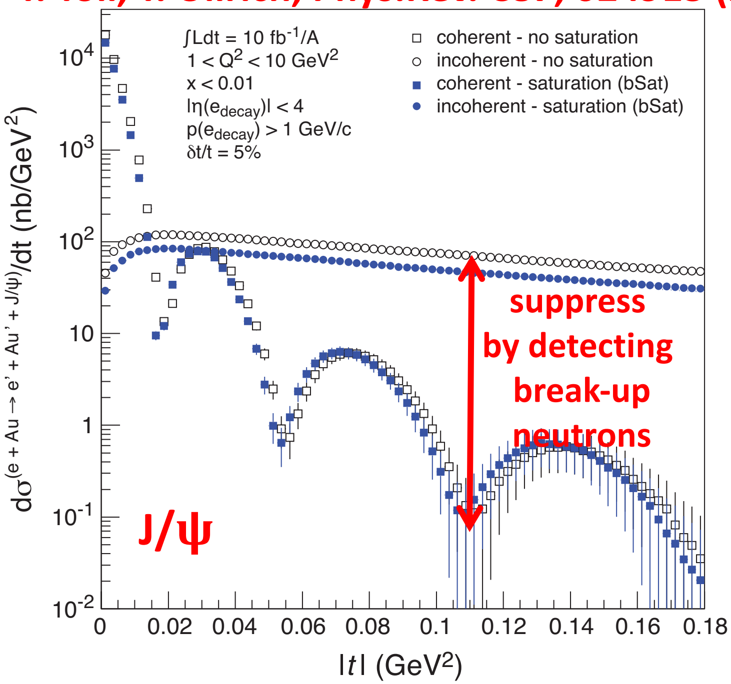
Diffractive physics in eA

→ Measure spatial gluon distribution in nuclei

→ Reaction: $e + Au \rightarrow e' + Au' + J/\psi, \varphi, \rho$

→ Momentum transfer $t = |p_{Au} - p_{Au'}|^2$

T. Toll, T. Ullrich, Phys.Rev. C87, 024913 (2013)



Coherent requires forward scattered nucleus needs to stay intact

→ Veto breakup through neutron detection

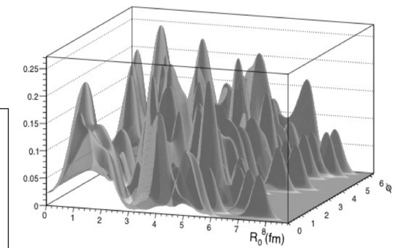
Hot topic:

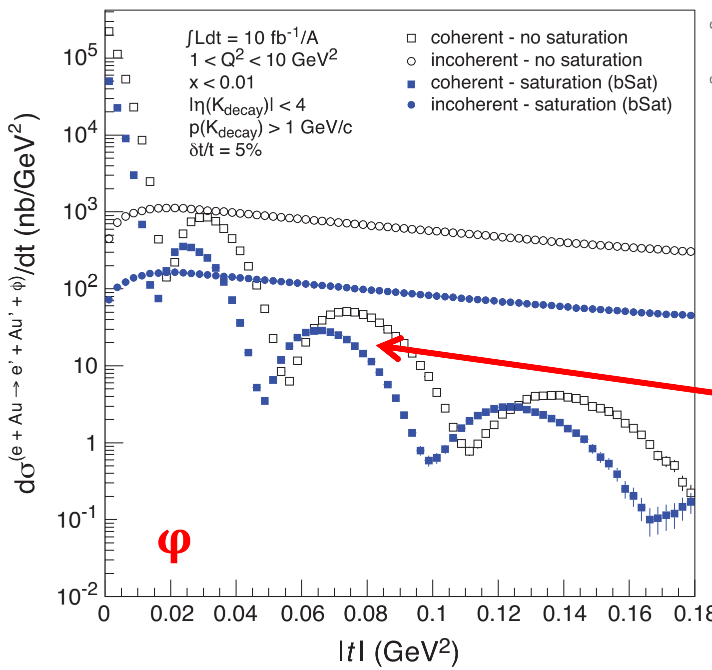
- ➢ Lumpiness of source?
- ➢ Just Wood-Saxon+nucleon $g(b_T)$

❑ coherent part probes "shape of black disc"

❑ incoherent part (large t) sensitive to "lumpiness" of the source [= proton] (fluctuations, hot spots, ...)

possible Source distribution with $b_T{}^g = 2$ GeV^{-2}

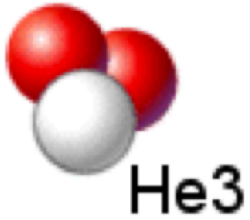




Imaging of light nuclei

- **Scattered light nuclei can be detected directedly.**
  - **The t momentum transfer can be directedly measured**

- **Full range of nuclear densities: from D → He4 (similar to heavy ions)**

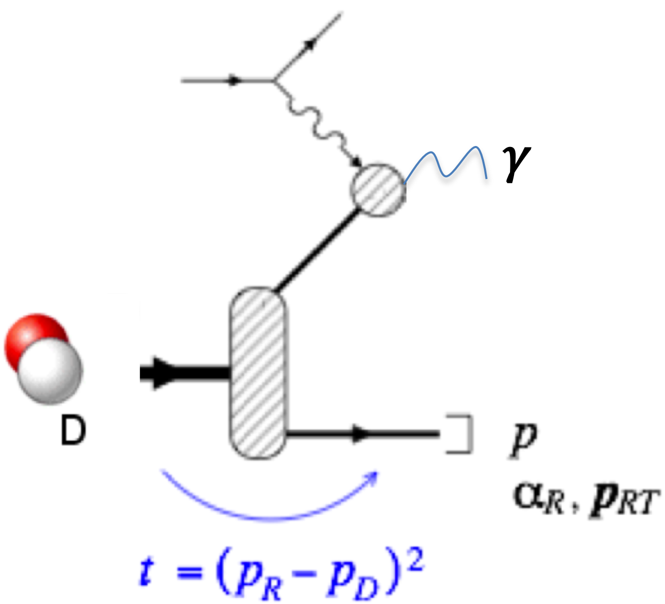


D is the least dense nucleus unbound

Polarized He3 beams will allow for simultaneous measurement of both tagged neutron structure and coherent diffraction on He3

- Interesting comparison since spin of He3 is dominated by the neutron

Measuring neutron via spectator tagging



- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor separation

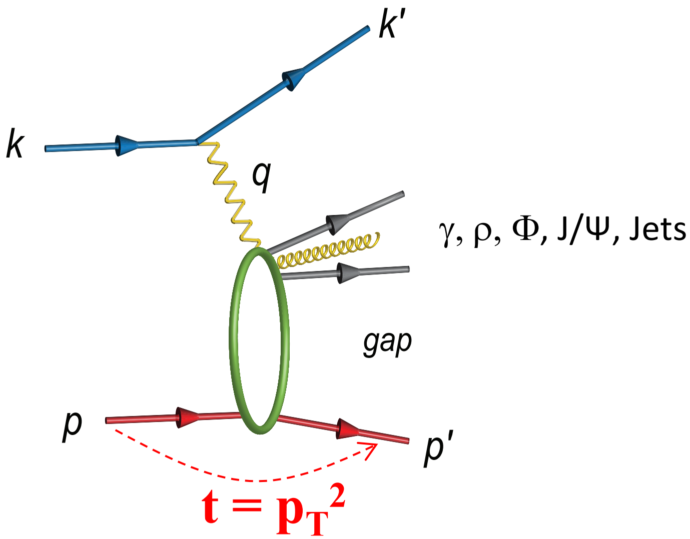
Using a Deuteron is the simplest case:

DVCS on incoherent D (D breaks up) but coherent on the neutron, the "double tagging" method

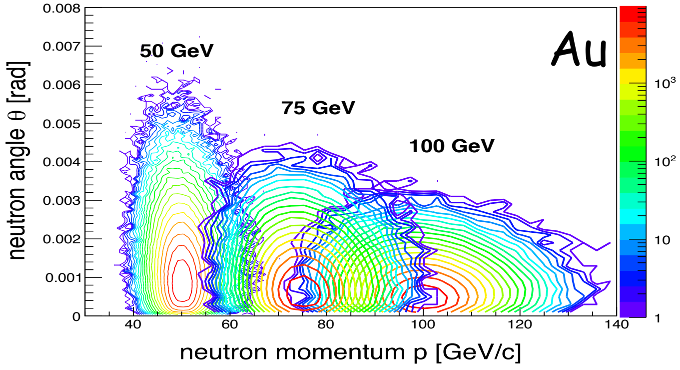
- **Tag DIS on a neutron (by the ZDC)**
- **Measure the recoil proton momentum**
- **The recoil proton momentum cone is**
  - $\alpha_R = (E_R + p_{R||})/(E_D + p_{D||})$ **and** p_{RT}
- Gives you a free neutron structure, not affected by final state interactions

Polarized He3 also experimentally easy but more complex theoretically

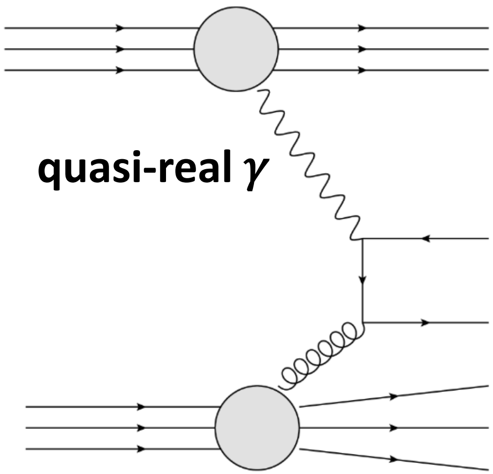
Detector Requirements for Exclusive Reactions in ep/eA



- Exclusivity criteria:
  - Large rapidity coverage or tracker and Calorimeter (ballpark $-4.5 < \eta < 4.5$)
  - Reconstruction of all particles in event
    - wide coverage in t (=p_T^2) → Roman pots
- eA: large acceptance for neutrons from nucleus break-up
  - Zero Degree Calorimeter
    - veto nucleus breakup
    - determine impact parameter of collision



Opportunities with Ultra-Peripheral Collisions



UPC at hard scale → production of a heavy meson

- Analog to photoproduction in e+p
- Can probe partonic structure of (nuclear) targets

UPCs @ LHC

J/ψ, ψ(2S) in:

Pb+Pb UPCs, [ALICE] Abelev et al. PLB 718 (2013) 1273; Abbas et al., EPJ C 73 (2013) 2617; Adam et al., PLB 751 (2015) 358;[CMS] PLB 772 (2017) 489,
P+Pb UPCs, [ALICE] Abelev et al., PRL 113 (2014) 232504,
p+p UPCs, [LHCb], Aaij et al., J. Phys. G 40 (2013) 045001; J. Phys. G 41 (2014) 055002

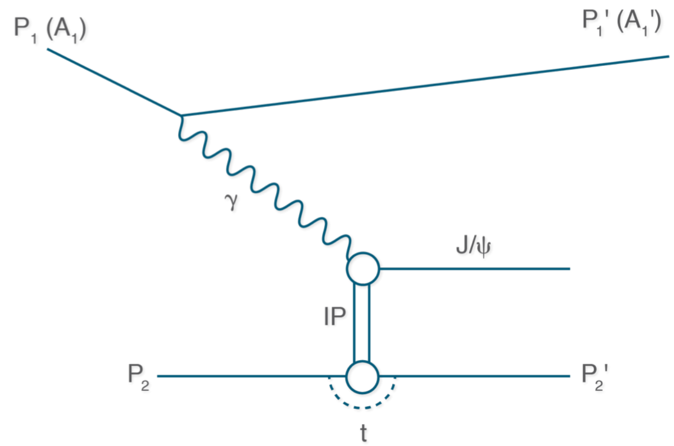
Y(1S,2S,3S) in p+p UPCs, [LHCb], Aaij et al., JHEP 1509 (2015) 084 and p+A UPCs, [CMS], Chudasama et al, PoS ICPAQGP 2015 (2017) 042 [arXiv:1607.00786 [hep-ex]]

(*and counting… LHC Run 2*)

UPCs @ RHIC

- In unpolarized cross section measurements, the sensitivity to GPD E is poor
- **Transversely polarized p+p UPC @ RHIC** → unique opportunity for extracting GPD E for the gluons before the EIC era!

The GPD Eg program at STAR



$$\epsilon = \frac{\sigma^{\uparrow}(\varphi) - \sigma^{\downarrow}(\varphi)}{\sigma^{\uparrow}(\varphi) + \sigma^{\downarrow}(\varphi)} = A_N \cdot \frac{1}{P}$$

Kinematic range: $10^{-4} < x < 10^{-1}$
STAR acceptance: $-1 < \eta < 2$

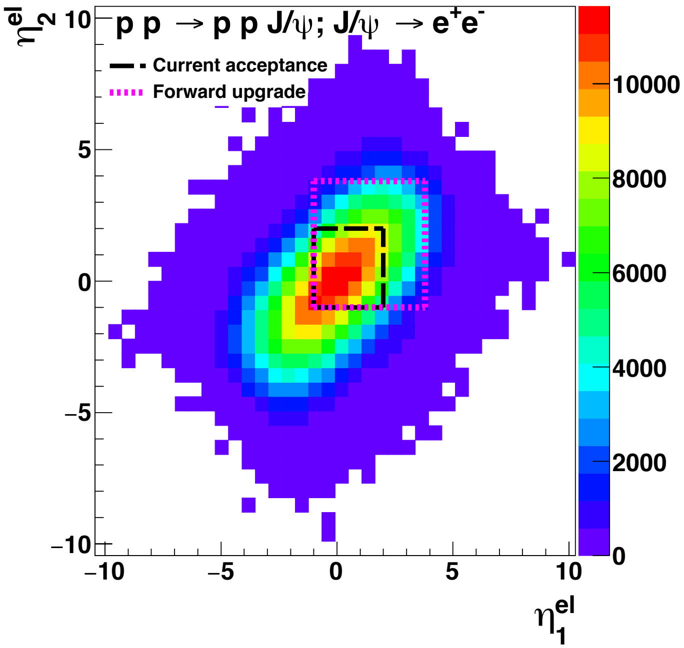
Run 17 (already on tape): 350 fb^{-1} of transversely polarized p+p collisions at √s=510 GeV
Run 21/22 (proposed): can collect an additional ~700 fb^{-1} at √s=510 GeV

eSTARLight simulation, accounting for known STAR detector efficiencies and acceptance, projects the collection of:

- **~28500 signal events** after analyzing our collected run 17 data
- **~57000 signal events** after adding data from the possible 21/22 runs

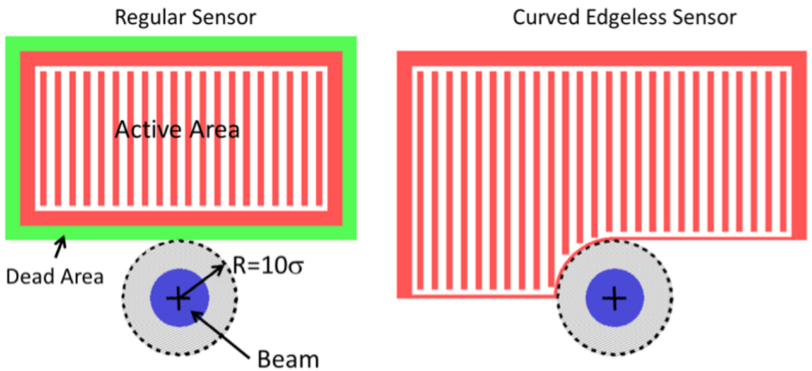
Enough for a pioneering extraction of GPD E for the gluons → crucial to tune EIC program

The GPD Eg program at STAR



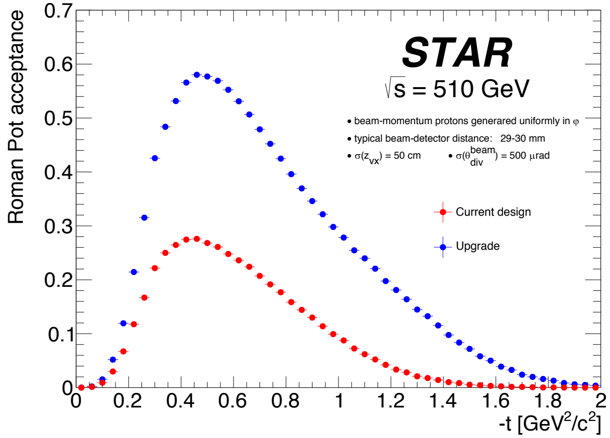
Electrons from J/ψ decay, already mostly within STAR acceptance (black dashed line)

→ Forward upgrade can further improve the acceptance (pink line), nice! Albeit not vital



Upgrade of STAR Roman Pots

- Currently only upper/lower square stations
- No space for full lateral stations
- Significant acceptance loss
- Plan is to upgrade the geometry to an L-shaped to cover the full azimuthal angle → Factor ~2 increase in statistics!



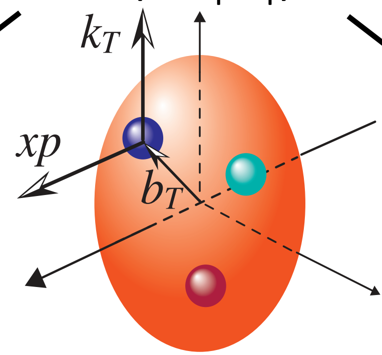
Direct access to Wigner function

Wigner function

$W(x,b_T,k_T)$ QCD genetic map

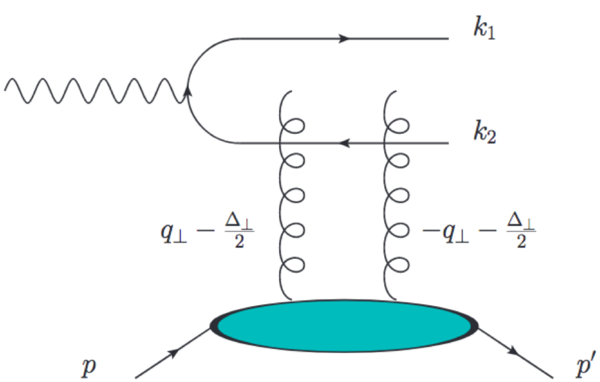
$\int d^2b_T$ $\int d^2k_T$

Momentum space *Coordinate space*



$f(x,k_T)$ $f(x,b_T)$

TMDs GPDs



Process: exclusive di-jet production

First proposed in e+p scattering by:

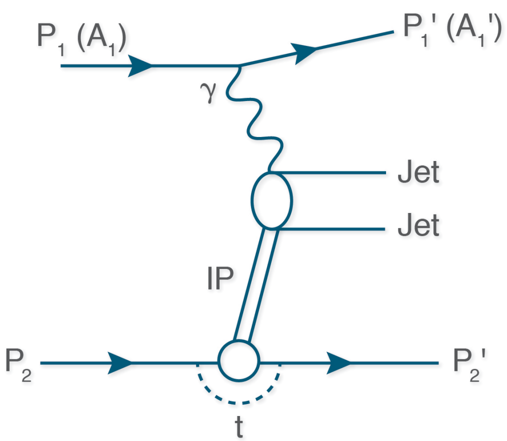
Yoshitaka Hatta, Bo-Wen Xiao, and Feng Yuan,
Phys. Rev. Lett. 116, 202301 (2016)

Later extended to UPC:

Y. Hagiwara, Y. Hatta, R. Pasechnik, M. Tasevsky, and O. Teryaev
Phys. Rev. D 96, 034009 (2017)

- **New important peace of EIC physics beyond the W.P.!**
- **EIC impact studies still be done**

Wigner function in UPC



Y. Hagiwara, Y. Hatta, R. Pasechnik, M. Tasevsky, and O. Teryaev
Phys. Rev. D 96, 034009 (2017)

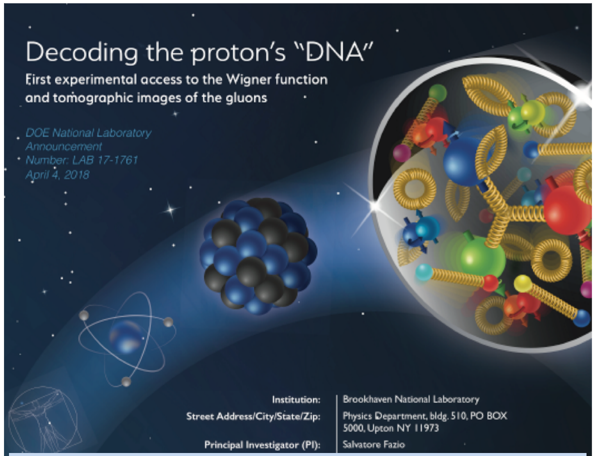
Type of collisions: p+p, A+p (where the first p,A is the photon source)
Exclusivity requirements:

- Veto proton(nucleus) break up with RPs (ZDC)
- Use RPs to measure the scattered diffractive protons

LHC: feasibility being exploited, challenging due to required low p_T of the jets

STAR @ RHIC:
→ ideal detector → large acceptance for low p_T di-jets (PRD**95**(2017)71103) + RPs
→ 2017 data: provides proof of principle
→ future **p↑+p RHIC runs** with upgrade of RP with curved edgeless sensors
→ factor of ~2 increase in acceptance

Estimated yield @ STAR: ~8000 events in p+p collisions at √s=510 GeV for a potential run 21/22 (Assumes RPs spectrometer upgrade)



Wigner & GPD Eg projections based on S.F.'s (*failed*) DOE Early Career Award proposal

Summary (& Discussion points)

e+p(A) physics program at EIC provides an unprecedented opportunity to study quarks and gluons in free protons and nuclei

Nice!
But we can't rest on our laurels!

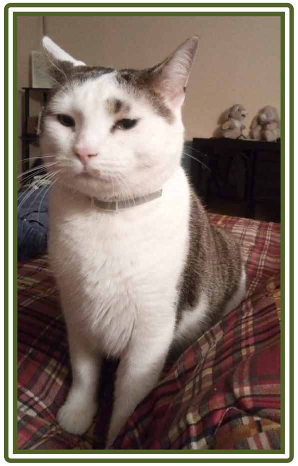
- **The "old" studies from the EIC WP era…**
  - DVCS and GPDs

E.C. Aschenauer, S. F., K. Kumerički, D. Müller, JHEP09(2013)093

- **Back to the board… new studies performed**
  - nPDFs (year 1 high impact physics!)

E.C. Aschenauer, S. F., M.A.C. Lamont, H. Paukkunen, P. Zurita, Phys.Rev. D 96 114005 (2017)
C. Weiss et al., Santa Fe Jets and heavy flavor Workshop Jan 18

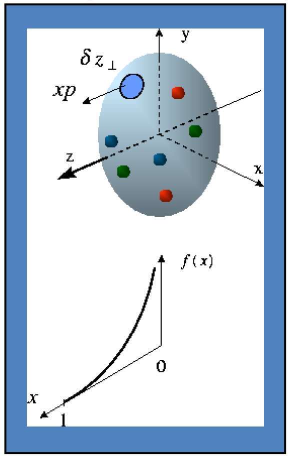
- **New excitement ahead**
  - Proton F_L, quark bottom
  - VMP and GPDs (global fits)
  - Nuclear GPDs
  - Wigner function!



Back up

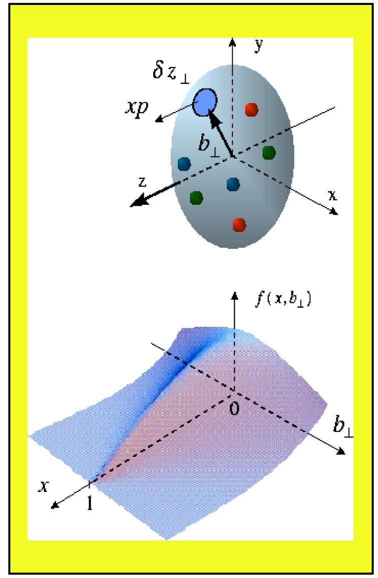
Generalized Parton Distributions

Longitudinal momentum & helicity distributions



$f(x)$

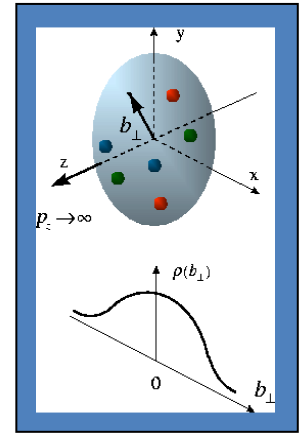
parton densities



$H(x,\xi,t)$

GPDs

transverse charge & current densities



$F_1(t)$

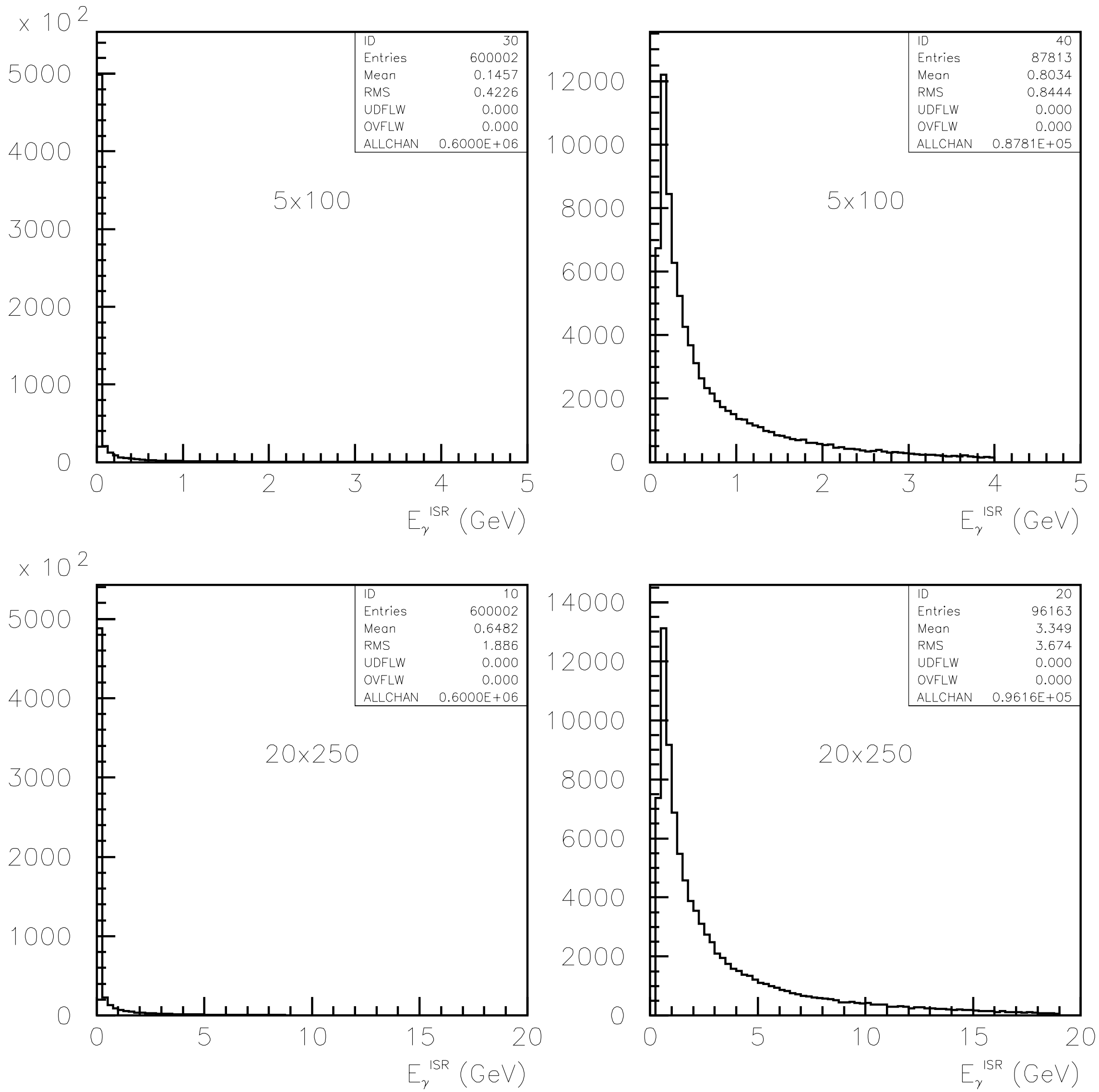
form factors

The nucleon (spin-1/2) has **four quark and gluon GPDs** (H, E and their polarized versions). Like usual PDFs, GPDs are non-perturbative functions **defined via the matrix elements of**

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\bar{P}^+z^-} \langle p'|\bar{q}(-\frac{1}{2}z)\gamma^+ q(\frac{1}{2}z)|p\rangle|_{z^+=0,\mathbf{z}=0}$$

$$= \frac{1}{2\bar{P}^+}\left[H^q(x,\xi,t,\mu^2)\bar{u}(p')\gamma^+u(p) + E^q(x,\xi,t,\mu^2)\bar{u}(p')\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m_N}u(p)\right]$$

Contribution from ISR

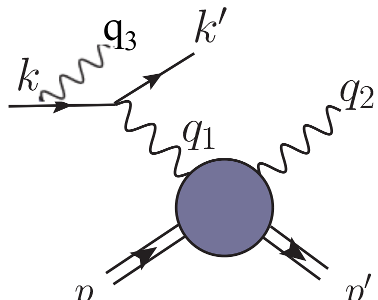


the energy spectrum of the emitted ISR photon for two different EIC beam energy combinations.

the right plots show the same photon spectra but requiring

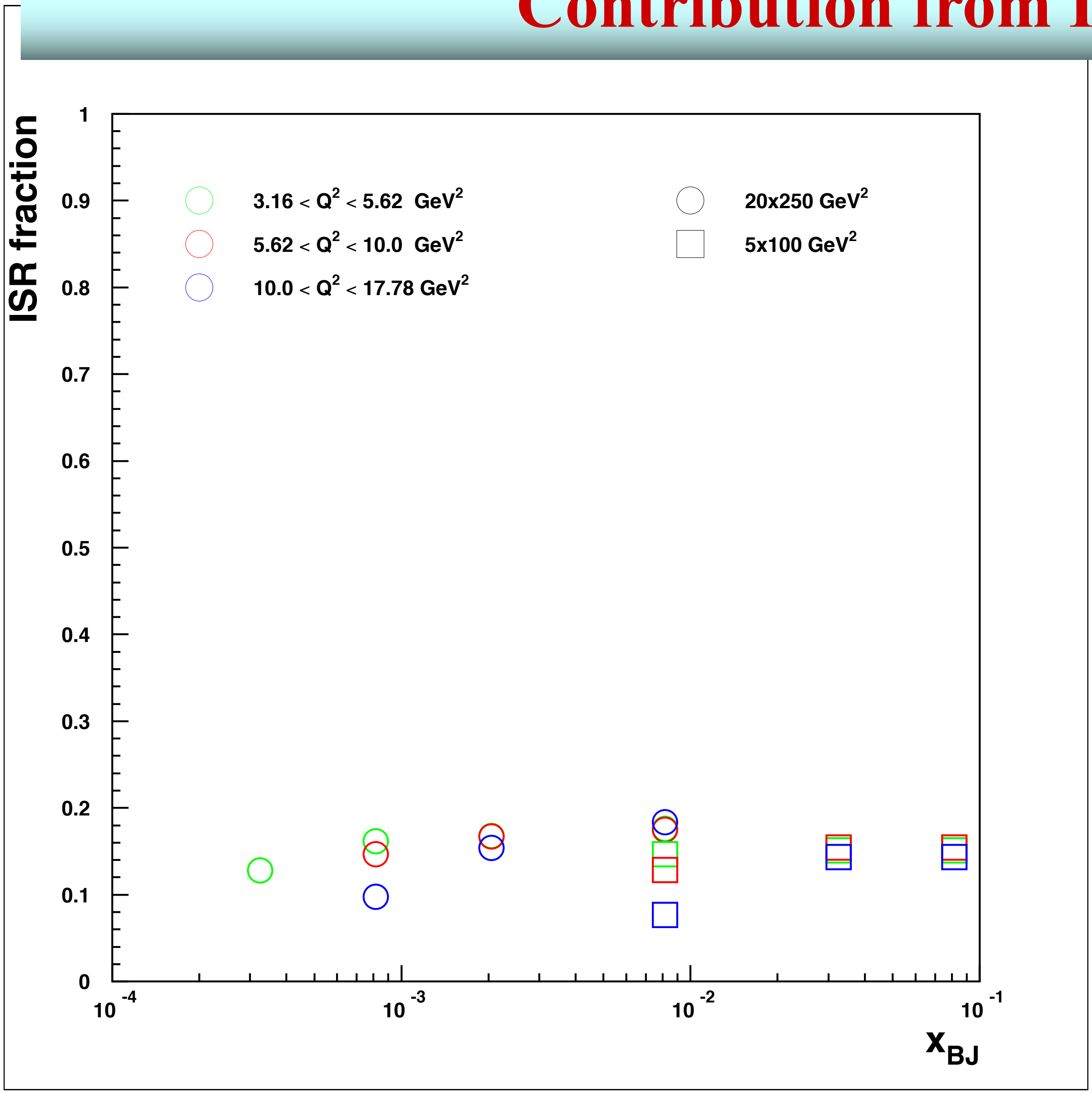
$E_\gamma = 0.02 * E_e$

Photons with $E_\gamma < 0.02\ E_e$ do not result in a significant correction for the event kinematics.



DVCS
&
BH -ISR

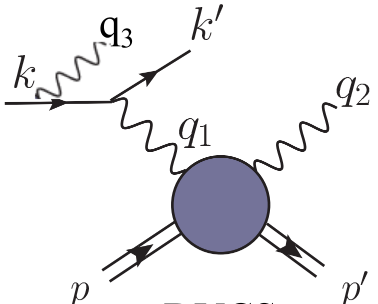
Contribution from ISR



Fraction of ISR events for three Q^2-bins as fct of x for two EIC beam energy combinations.

ONLY 15% of the events emit a photon with > 2% energy of the incoming electron

ISR photons with **E_γ < 0.02 E_e** do not result in a significant correction for the event kinematics.

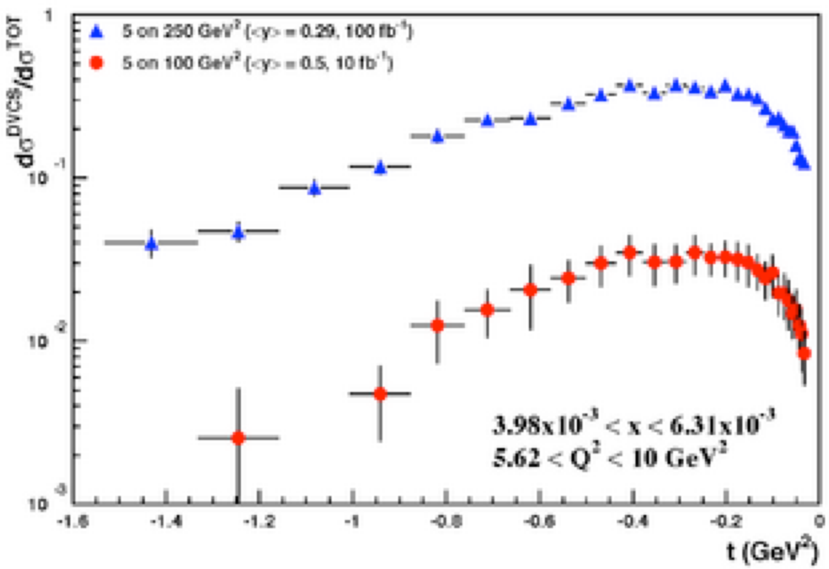


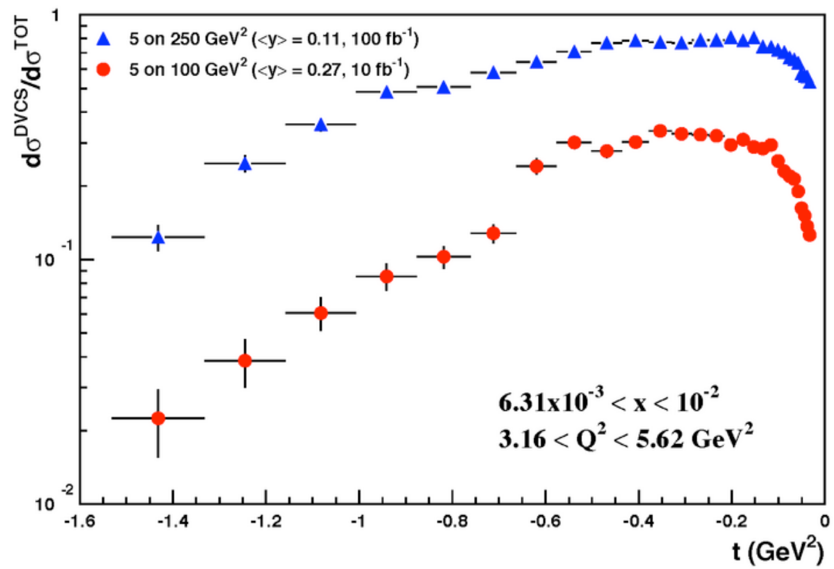
DVCS
&
BH -ISR

Rosenbluth separation

$$d\sigma = \mathrm{d}\sigma_{DVCS} + \mathrm{d}\sigma_{BH} + \mathrm{d}\sigma_{INT}$$

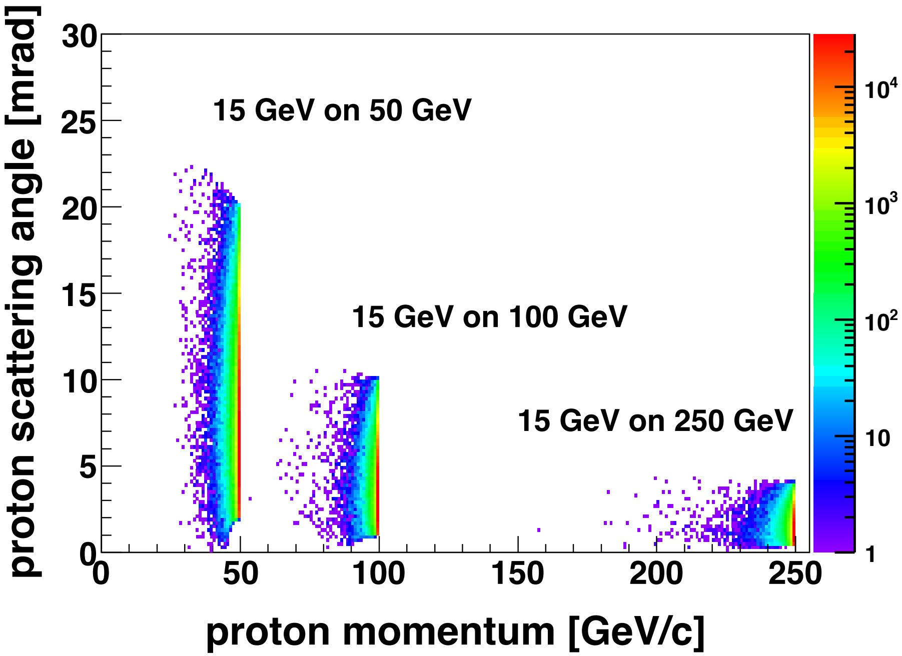
Rosenbluth separation of the electroproduction cross section into its parts





- The statistical uncertainties include all the selection criteria to suppress the BH
- exponential |t|-dependence assumed

Scattered Proton measurement



Remember:

p_T of proton critical for physics
$p_T = p' \sin(\Theta)$
$p'_L > 97\%$ of p_{Beam}

ZEUS Coll, JHEP 06 (2009) 074

Note:

high energy colliders (HERA, Tevatron, LHC, RHIC) use Roman Pots to detect these protons

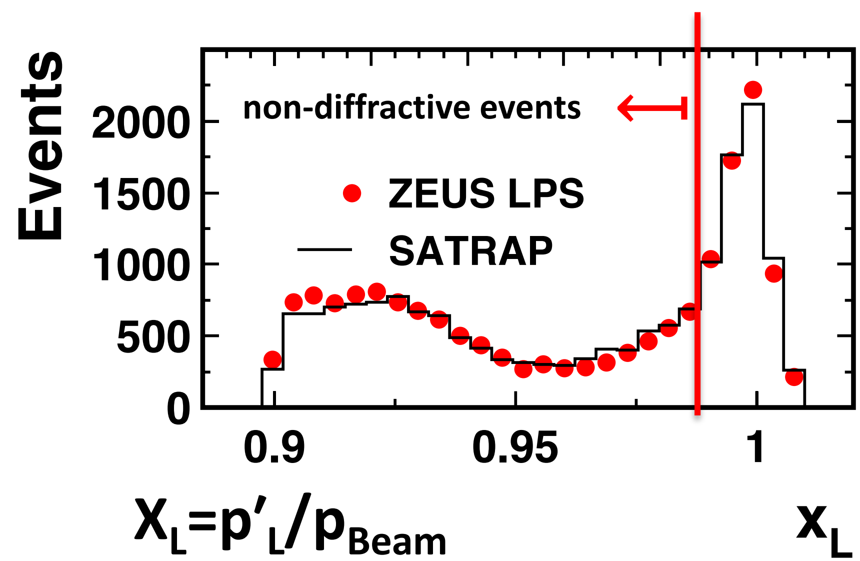
→ RPs are high resolution movable small tracking detectors (Si strips, Si pixels…), a crucial component

→ $\Theta < 10$ mrad

→ impact on large p_T-acceptance

→ small p_T-acceptance limited by beam divergence and immittance

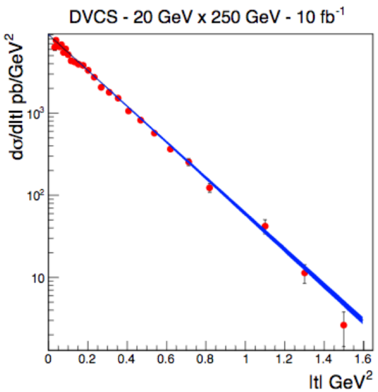
→ rule of thumb keep 10s between RP and beam



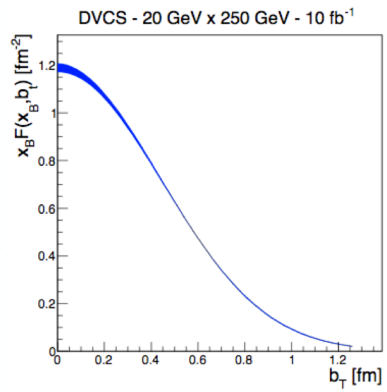
Impact of proton acceptance

Measurement

Physics observable (cross-section vs impact parameter)



Plots from EIC White Paper:

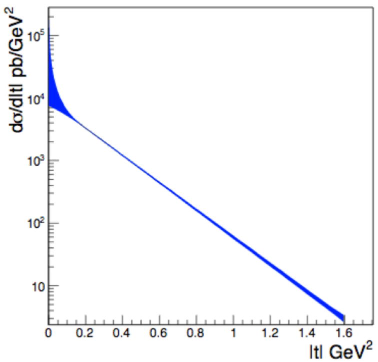


Requirement:

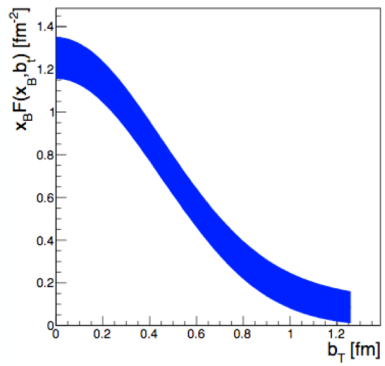
$\int L_{int}$=10fb^{-1}

$0.18 < p_t$ (GeV) < 1.3

$0.03 < |t|$ (GeV^2)< 1.6

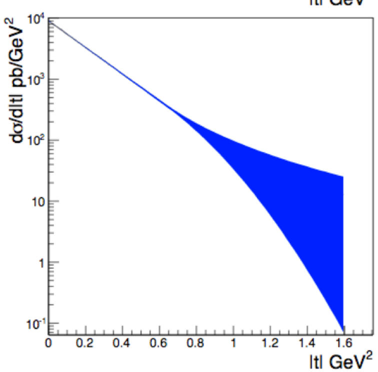


limited lower p_T-acceptance

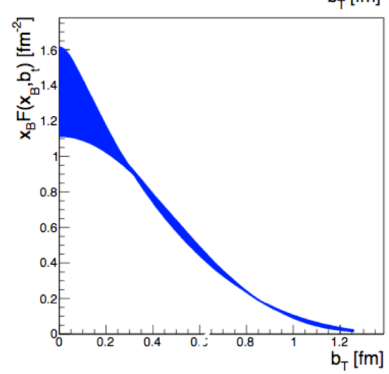


$\int L_{int}$=10fb^{-1}

$0.44 < p_T$(GeV) < 1.3



limited higher p_T-acceptance



$\int L_{int}$=10fb^{-1}

$0.18 < p_T$ (GeV) < 0.8

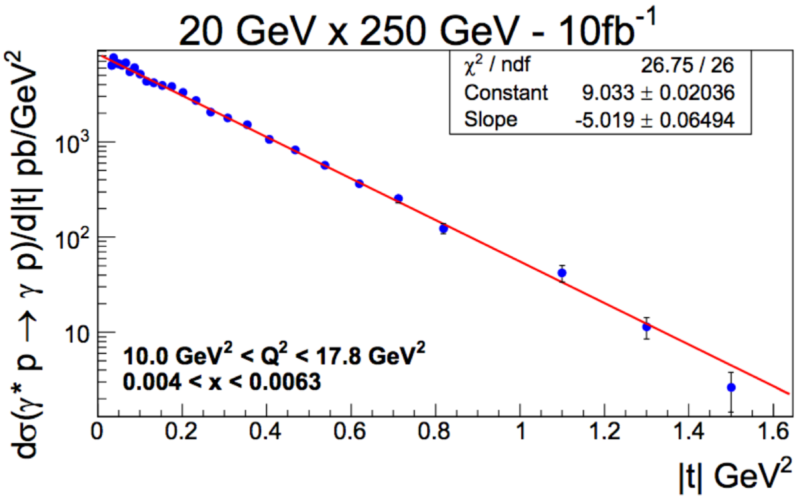
We need a proton spectrometer with large acceptance!

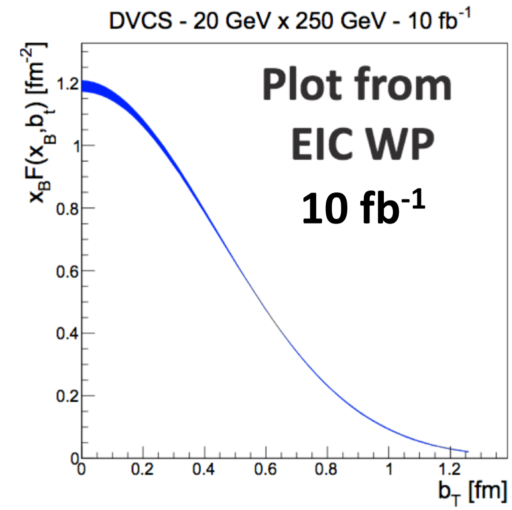
Impact of collected luminosity

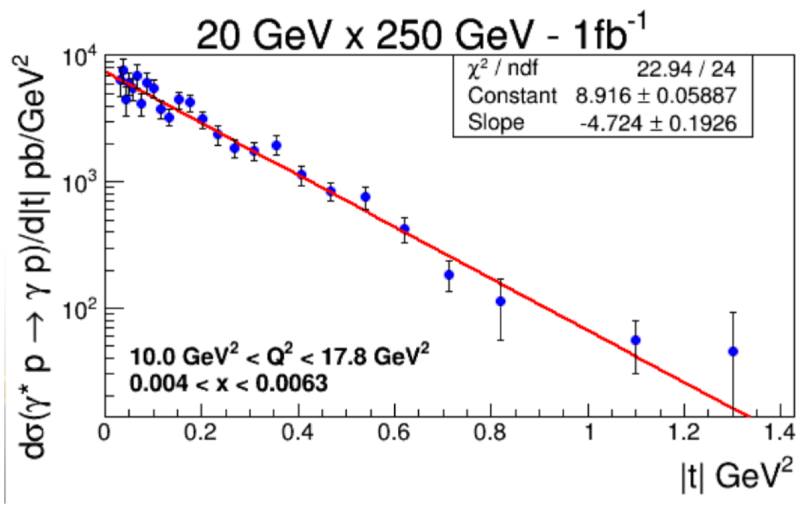
See also B. Mueller's talk

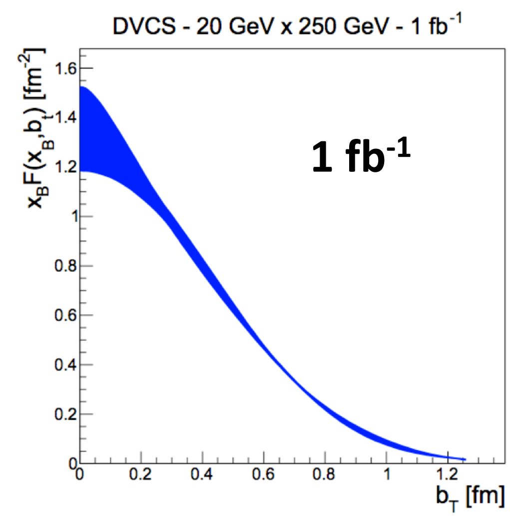
$0.18 < p_T < 1.3$ GeV

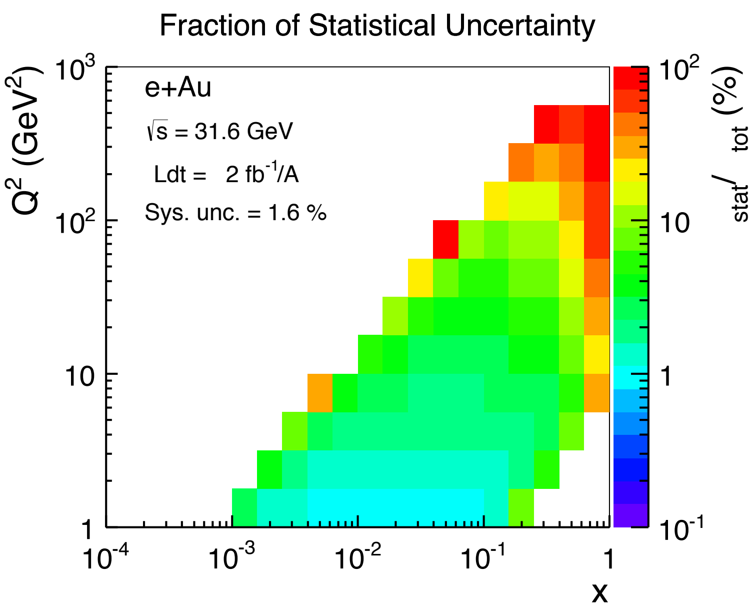
10 fb^{-1} → 1 fb^{-1}



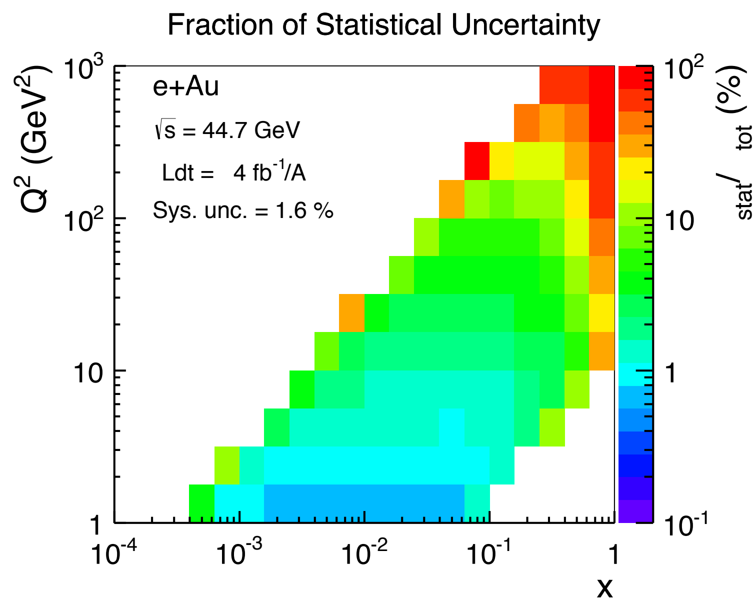




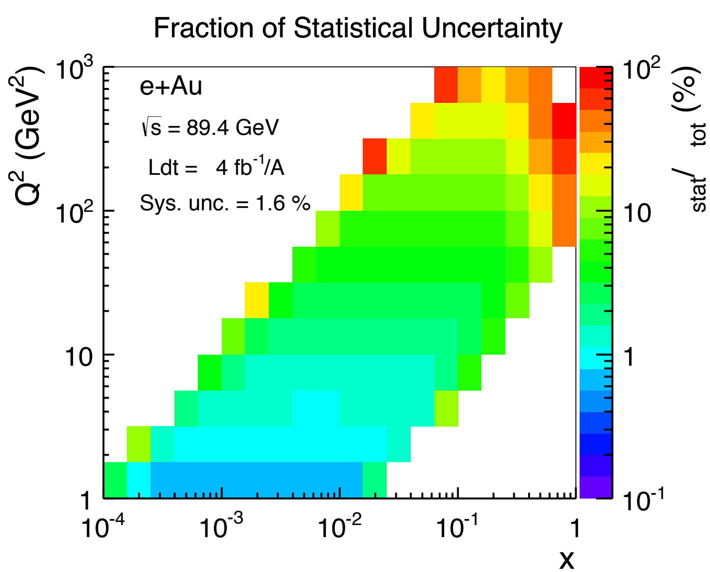




Fraction of Statistical Uncertainty
e+Au
√s = 31.6 GeV
Ldt = 2 fb⁻¹/A
Sys. unc. = 1.6 %
Q² (GeV²)
x
stat/ tot (%)



Fraction of Statistical Uncertainty
e+Au
√s = 44.7 GeV
Ldt = 4 fb⁻¹/A
Sys. unc. = 1.6 %
Q² (GeV²)
x
stat/ tot (%)

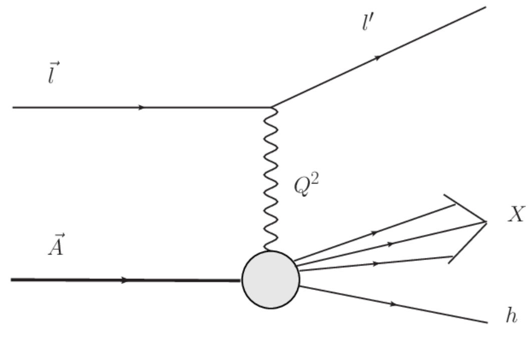


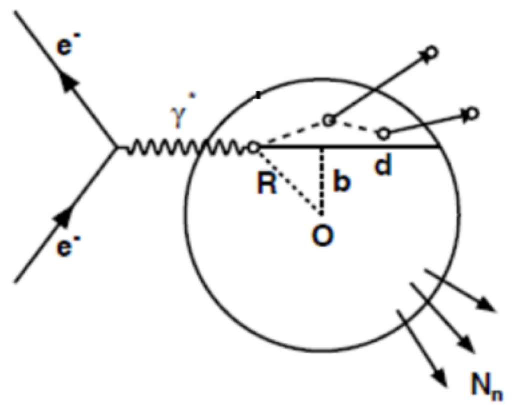
Fraction of Statistical Uncertainty
e+Au
√s = 89.4 GeV
Ldt = 4 fb⁻¹/A
Sys. unc. = 1.6 %
Q² (GeV²)
x
stat/ tot (%)

DIS on a nucleus

A more complex, multi-stage process:

1. Scattering on a parton
2. Debris from the collision interacts along the way out of the nucleus, causing an intranuclear cascade. Typically this leads to the knock out of several nucleons.
3. Resulting nucleus left in an excited state. This can lead to vaporization of nucleons and/or light nuclei (sometimes fission)
4. At lower excitation energies, emitting neutrons if preferred. No preference between charged/neutral particles at higher excitation energies. Below nucleon separation energy, the nucleus emits photons





Nuclear Modifications – Present Knowledge

Measure different structure functions in e+A → constrain nPDF

Latest state-of-the-art nPDF is EPPS16

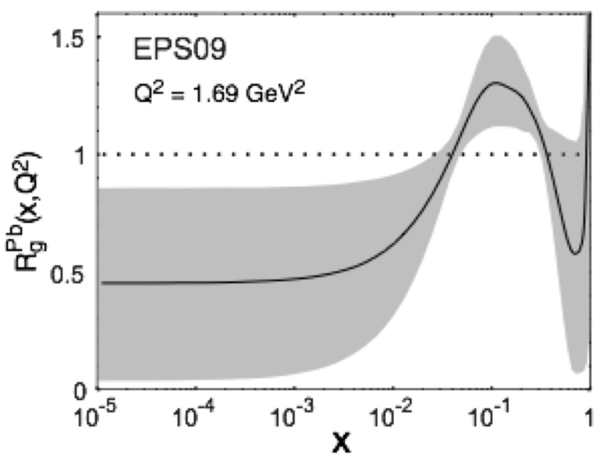
K. J. Eskola, P. Paakkinen, H. Paukkunen, C. A. Salgado [Eur.Phys.J. C77 (2017) no.3, 163]

- Replacing EPS09. Quark flavors are now separated
- includes latest LHC data
- **EPPS16*→ functional form** with less constraints (for gluons) in extrapolating for $x < x_{data}$

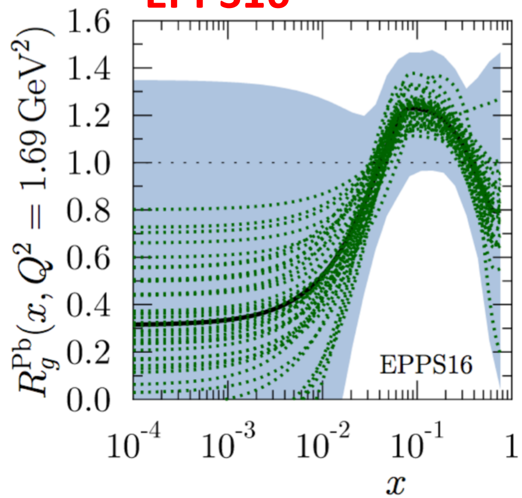
  ⇒ critical to study the impact of the high precision EIC data!
- **What is the possible impact of an Electron-Ion Collider?**

Ratio: $g(x,Q^2)_{Pb}/g(x,Q^2)_p$

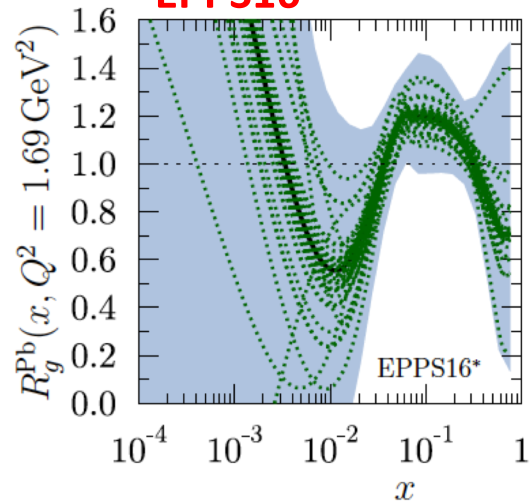
EPS09



EPPS16



EPPS16*



Reduced Cross Section & Structure Functions

$$\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{1+\left(1-y\right)^2} F_L\left(x,Q^2\right) \qquad \frac{y^2}{1+\left(1-y\right)^2} = Y^+$$

- Structure functions can be extracted from the reduced cross section
- Pseudo-data are generated using **PYTHIA** and according to **EPS09** central values
- In order to extract F_2 from the reduced cross section, we adopted the same method used at HERA [e.g. see HERMES paper on arXiv:1103.5704]
- F_L extracted from the reduced cross section by fitting the slopes in Y^+ for different √s at fixed x, Q^2 → requires running at (at least) three different c-o-m energies

Simulation:

e+Au sample simulated using PYTHIA

5(20) GeV electrons X 50 GeV Au [√s = 32(63) GeV] –> L = 2 fb^{-1}/A

5(20) GeV electrons X 75 GeV Au [√s = 39(78) GeV] –> L = 4 fb^{-1}/A

5(20) GeV electrons X 100 GeV Au[√s = 45(89) GeV] –>L = 4 fb^{-1}/A

Total simulated event sample (for each electron energy) **L = 10 fb^{-1}/A**