DVCS studies @ EIC
Whte Paper -> Yellow Report -> ATHENA -> ...ePIC

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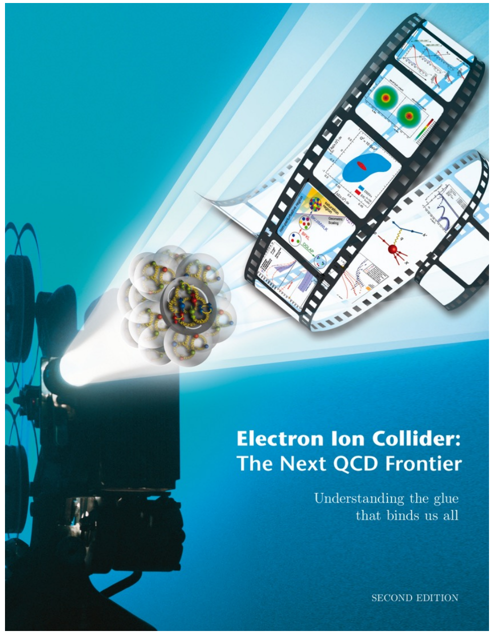
EPIC Workshop
Saclay - Oct 26-28, 2022

credits and outline

- DVCS studies
  - Pre-White Paper (INT report) and White Paper era
  - The Yellow Report era
  - ATHENA proposal
  - Current updates
- Presentation based on the work of many beyond myself:
  - Kemal Tezgin, Pawel Sznajder, Kong Tu...

The INT report and WP era!

arXiv:1108.1713

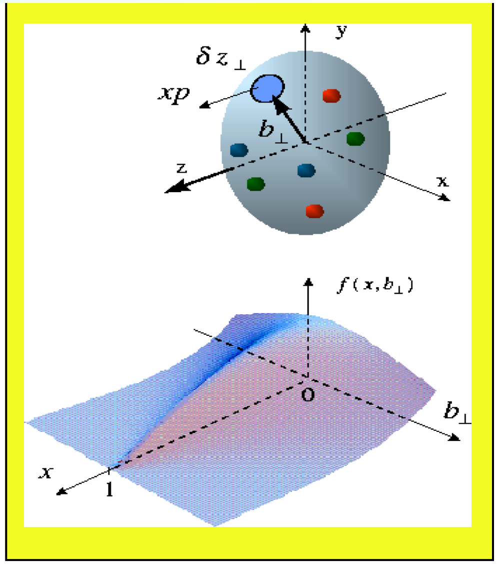


Eur. Phys. J. A (2016) 52: 268

Accessing GPDs

$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

The nucleon (spin-1/2) has **four quark and gluon GPDs**



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

→ **Dominated by H slightly dependent on E**

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

→ ***sin($\Phi_T - \phi_N$)*** **governed by E and H**

[Requires a polarized proton target]

Responsible for total orbital angular momentum through Ji sum rule:
a window to the SPIN physics

$$\sum_{q=u,d,s} J^q(Q^2) + J^G(Q^2) = \frac{1}{2}\hbar$$

[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

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

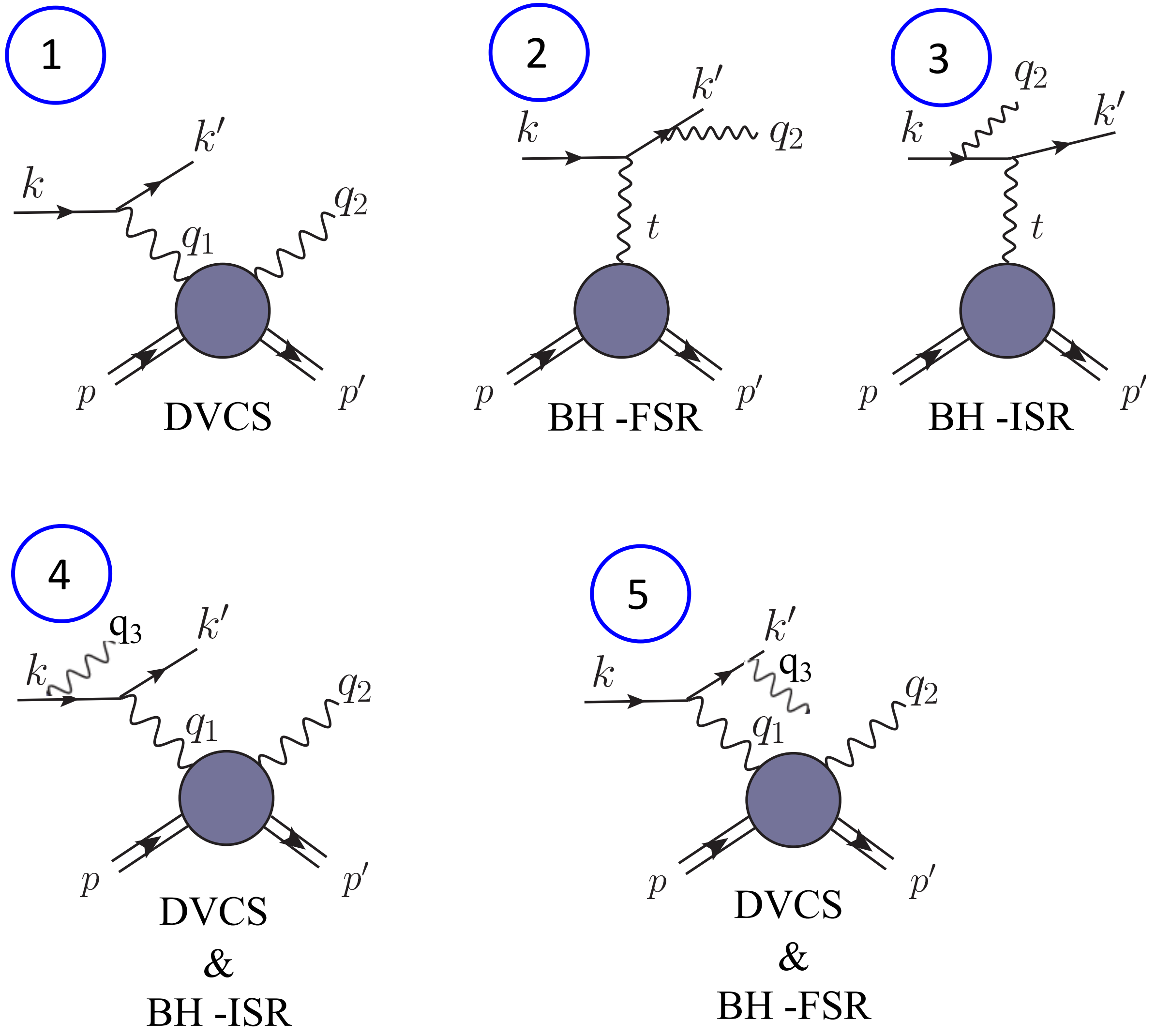
→ **Done @ HERA**

[Requires a positron beam]

Re(A) related to D-term, “last global unknown property” of a hadron, related to distribution of forces inside the nucleon

[M. V. Polyakov and P. Schweitzer, Int. J. Mod. Phys. A 33, no. 26, 1830025 (2018)]

Relevant processes

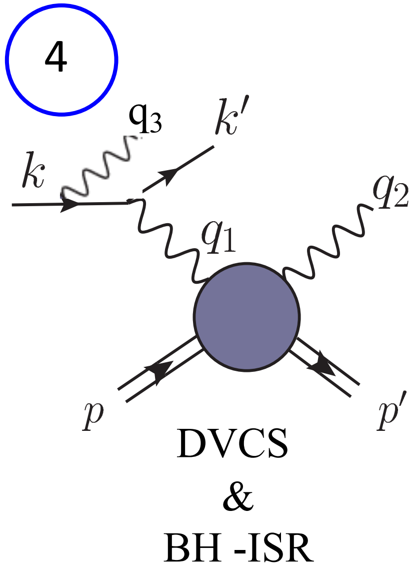


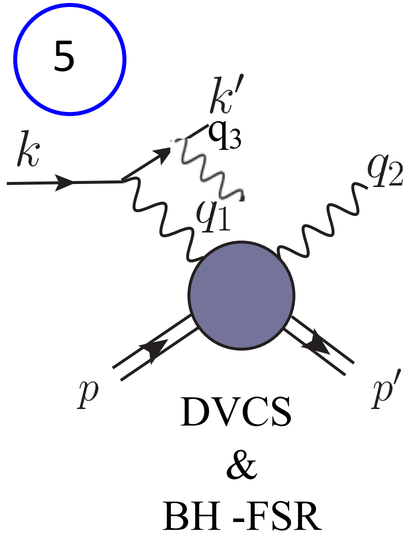
DVCS and Bethe-Heitler have the same final state topology

The relevant processes are:

- DVCS (1)
- BH initial (3) and final (2) state rad.
- ISR (4) and FSR (5) in DVCS

Radiative corrections





process 5 (FSR):

photon collinear to the outgoing scattered lepton

- If lepton is band only little in magnetic field, EM-cluster of photon and lepton collapse to one
  →no contribution (total electron energy measured correctly)
- If photon and lepton are separated enough in magnetic field, it leads to 3 EM-clusters in event
  →no contribution (event will not pass DVCS selection criteria)

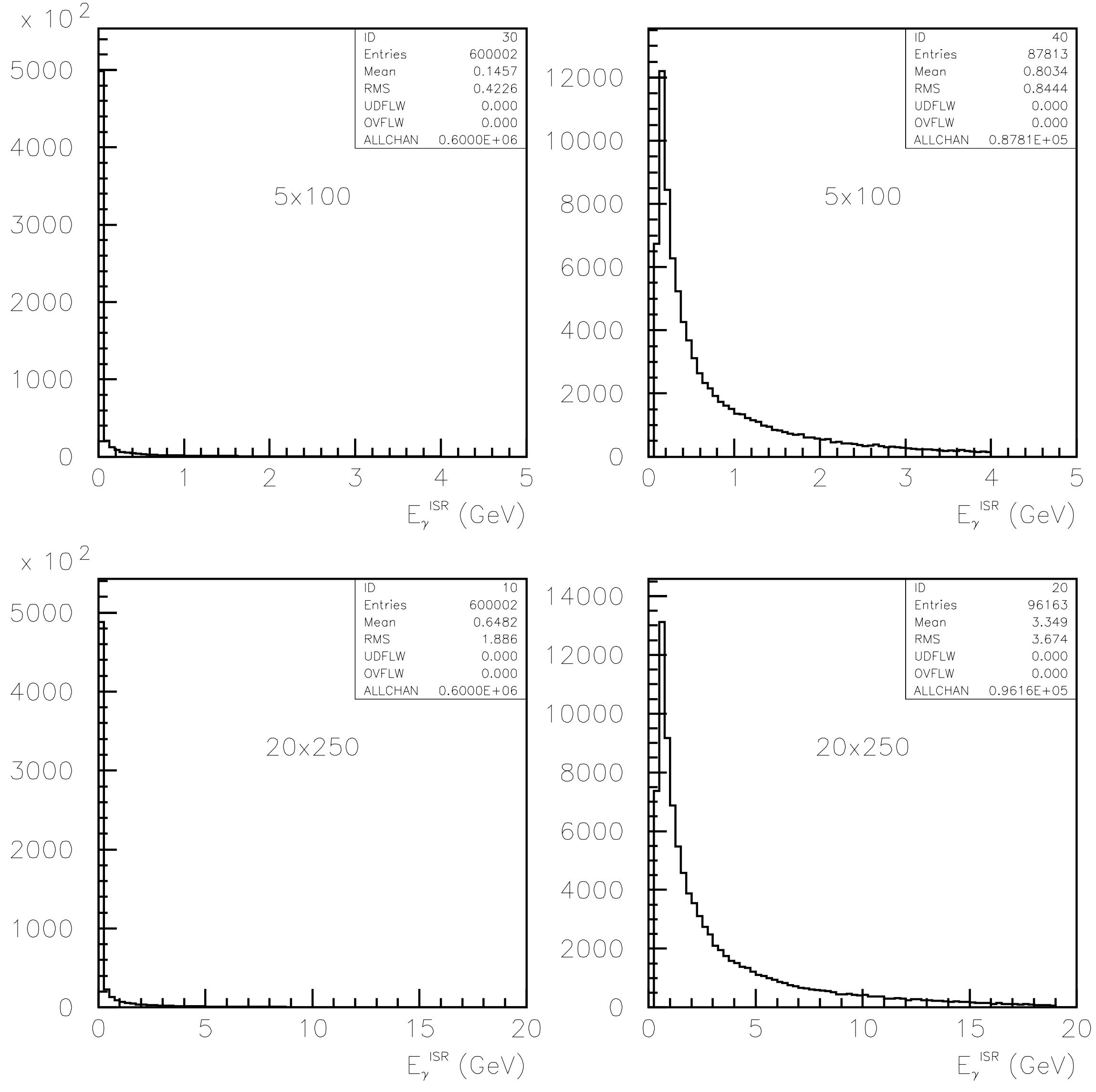
process 4 (ISR):

Photon collinear to the incoming beam and goes down the beam line

→this contribution can only be estimated via MC

→this causes a correction of the kinematics (x and Q^2) and some systematic uncertainty

Contribution from ISR

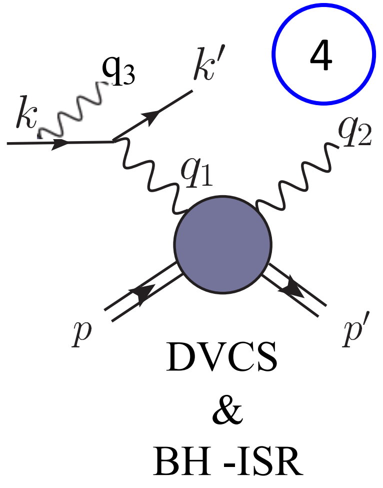


The energy spectrum of the emitted BH photon in process 4 for two different EIC beam energy combinations.

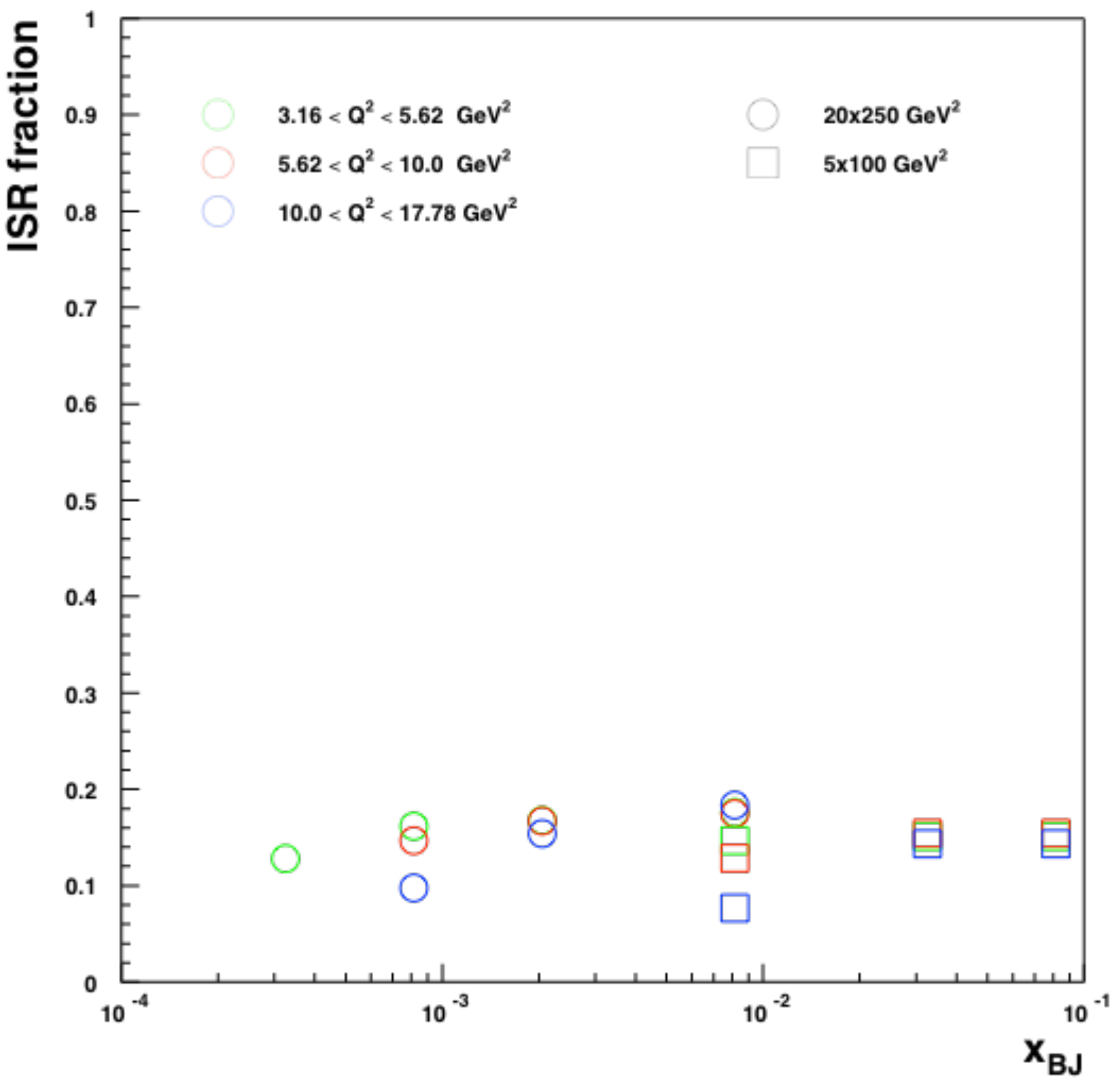
The right plots show the same photon spectra but requiring:

$E_\gamma = 0.02 * E_e$

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



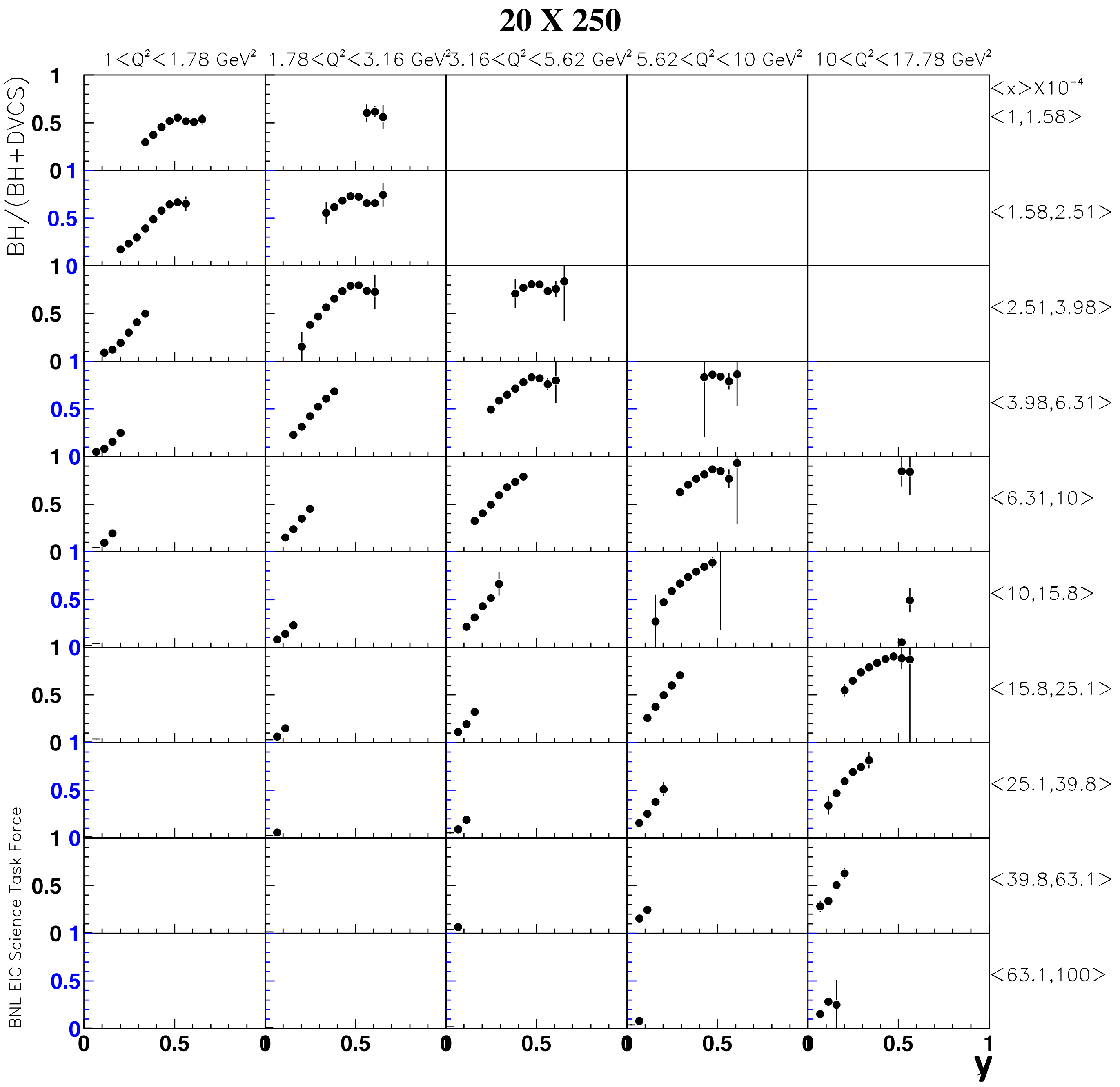
Contribution from ISR



Fraction of process 4 (ISR events) for 3 Q^2-bins as fct. of x for 2 EIC beam energy combinations

Only ISR with $E_\gamma = 0.02\ E_e$

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



BH contamination

Special selection criteria (see Kemal's talk) can be optimized to suppress BH below 60% at large y>0.5

20 x 250 GeV²

- **BH subtraction will be not an issue for y<0.6**
- **But... BH subtraction will be relevant at lower energies and large y, in many x-Q² bins**
- **Low energy consiguratinons require extra care**

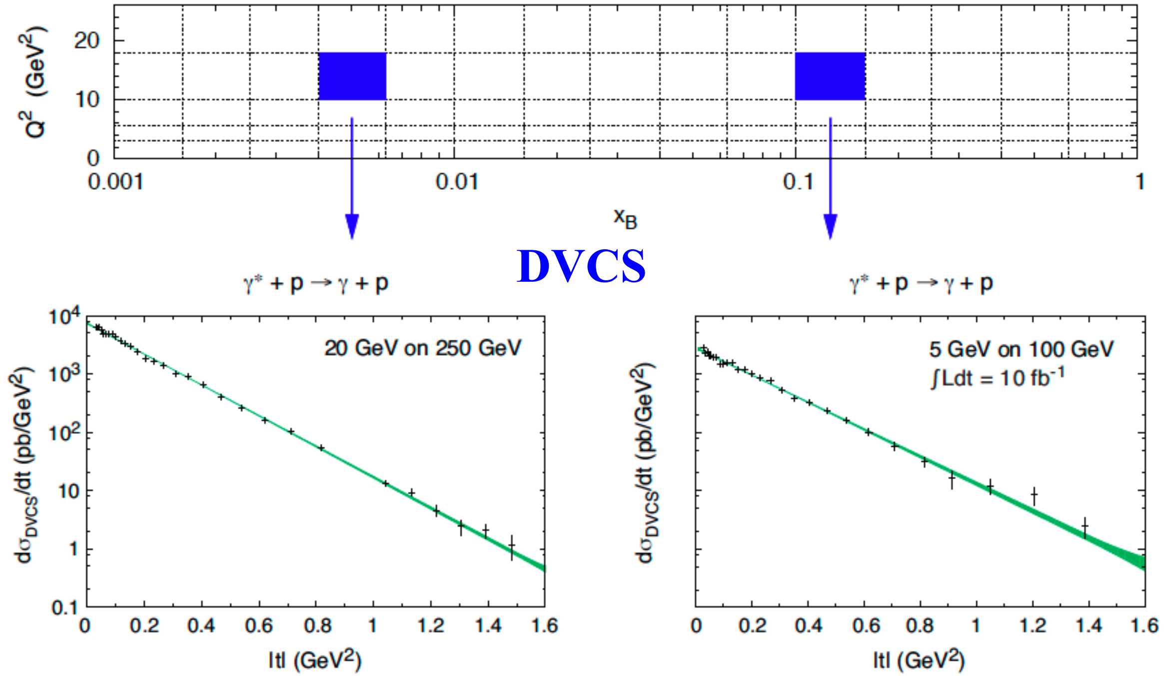
Generator: MILOU

Now confirmed by simulations with the novel EpIC generator

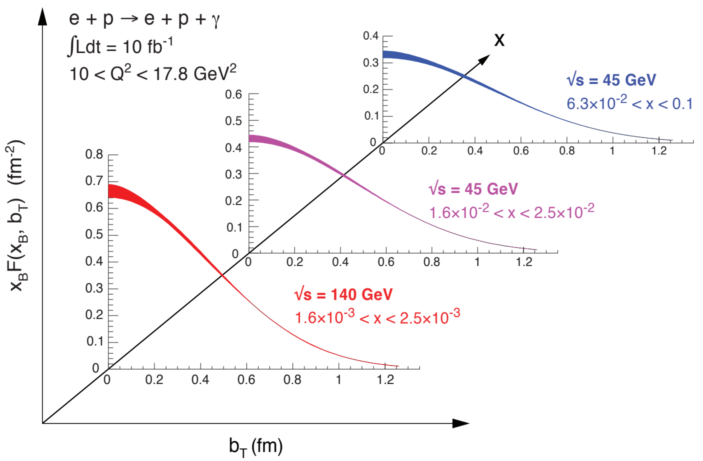
DVCS – differential cross section

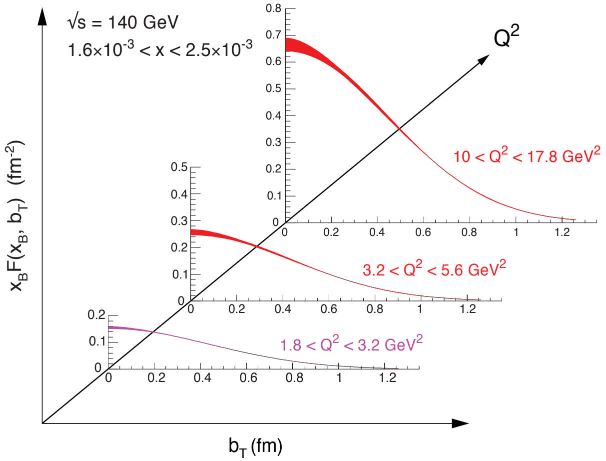
$\int L = 10fb^{-1}$

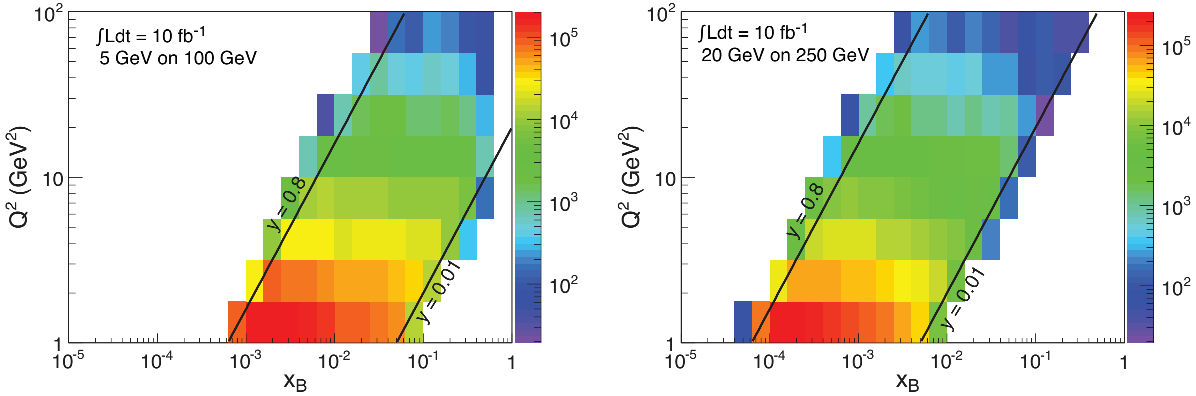
EIC White Paper



- **L = 10 fb^{-1} per energy configuration**
- **Measurement dominated by systematics**
- Fine binning in a wide range of x-Q^2 needed for GPDs
- **Assumed t-range:** 0.03 < |t| (GeV^2) < 1.6
- Fourier transform of dσ/dt → partonic profiles



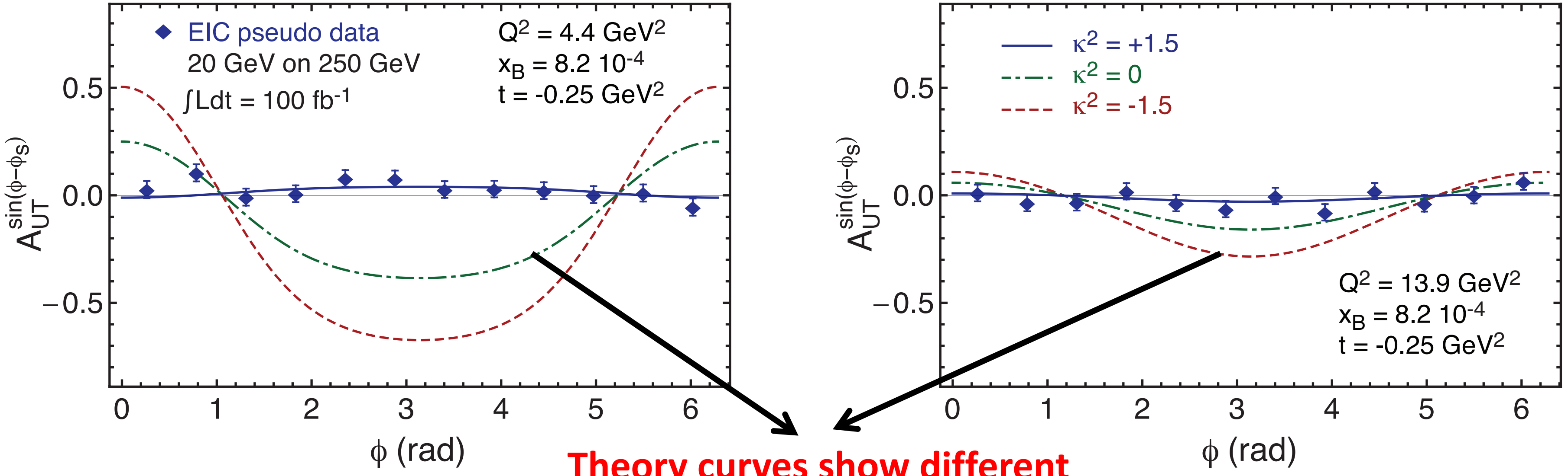




DVCS – Transverse T. Spin Asymmetry

$\int L = 100 fb^{-1}$

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



Theory curves show different assumptions for E

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

Transversely polarized protons: sin($\Phi_T - \phi_N$)

gives access to GPD E

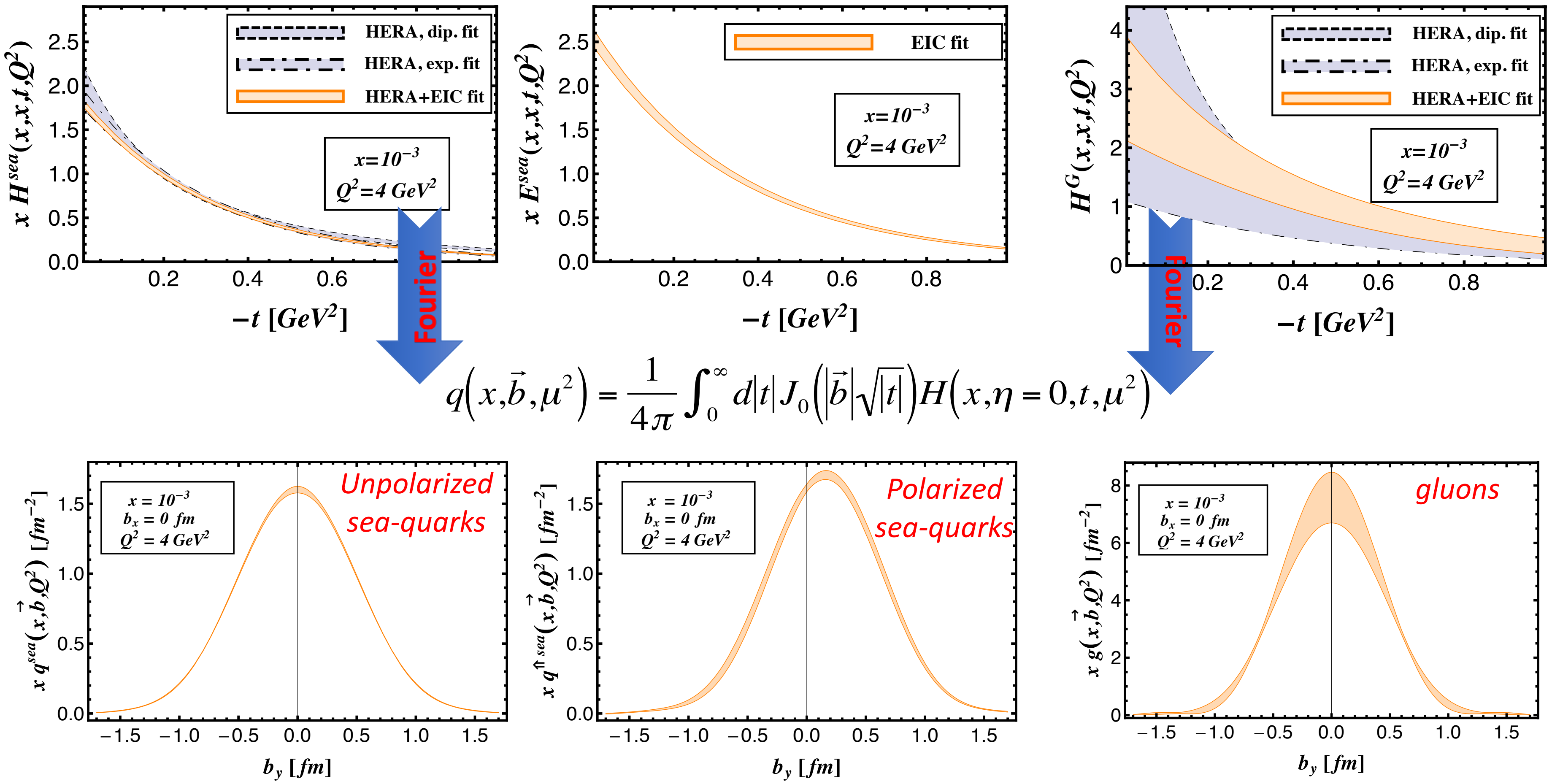
Access to orbital angular momentum through "Ji sum rule"

[X.D. Ji, Phys. Rev. Lett. 78, 610 (1997)]

$$\sum_{q=u,d,s} J^q\left(Q^2\right) + J^G\left(Q^2\right) = \frac{1}{2}\hbar$$

DVCS-based spatial imaging

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

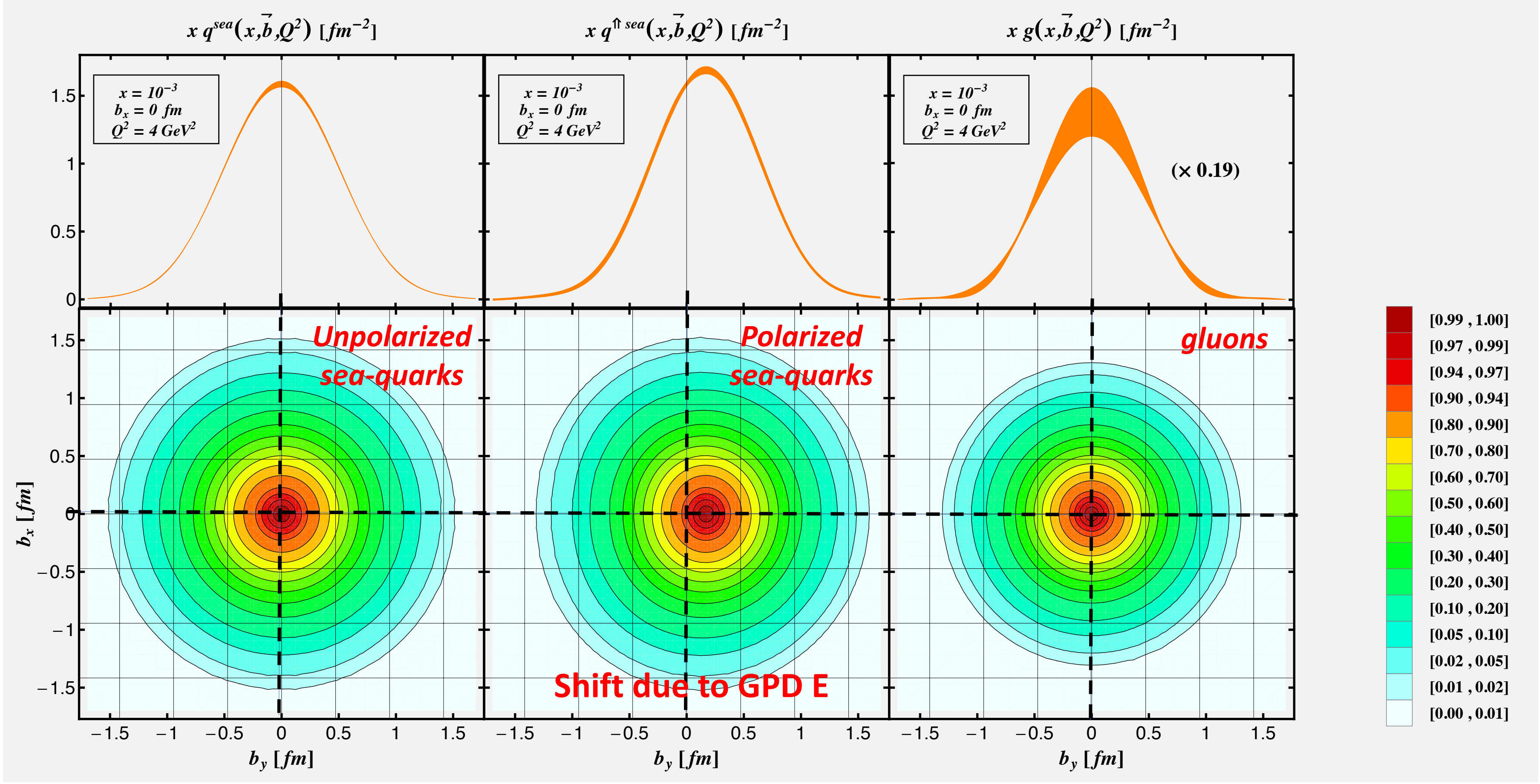


$$q\left(x,\vec{b},\mu^2\right) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0\left(|\vec{b}|\sqrt{|t|}\right) H\left(x,\eta=0,t,\mu^2\right)$$

- **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)**

DVCS-based spatial imaging

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



Much still to be investigated!

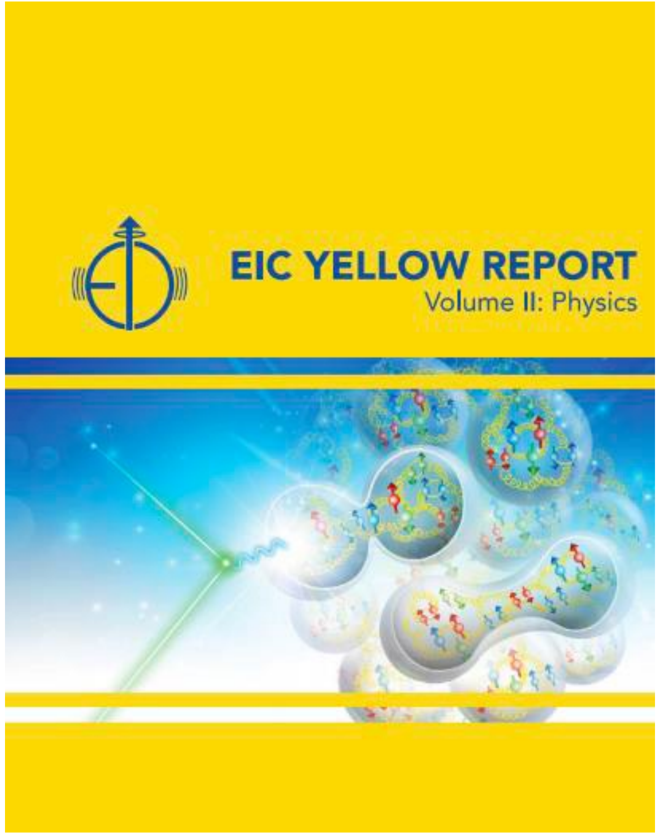
- Gluon GPD H can be much improved by including J/ψ
- Access to gluon GPD E → orbital momentum (Ji sum rule)
- Flavor Separation of GPDs (VMP and/or DVCS on deuteron)
- Nuclear imaging (modification of GPDs in p+A collisions)

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**

The Yellow Report studies



arXiv:2103.05419

Comparison of GK and KM20 in MILOU 3D

- We compare the generation of purely DVCS events in MILOU with GK (by PARTONS) and KM20 @ EIC beam energies
- Generation parameters as follows:

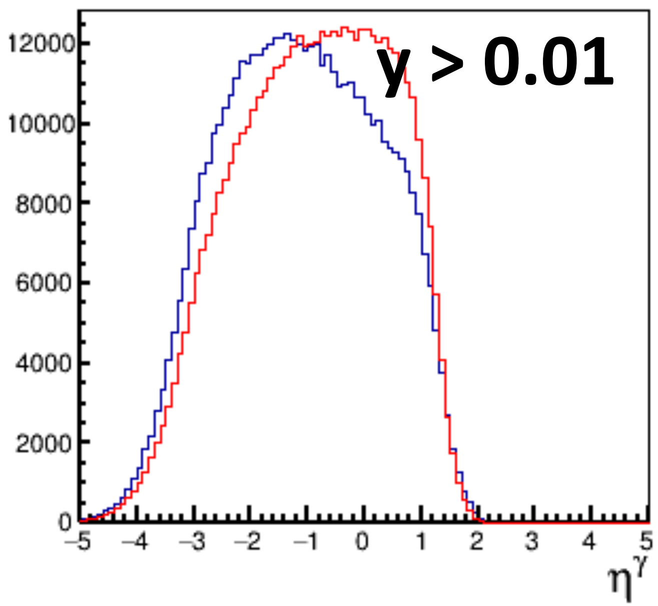
# of Generated Events: 500k /configuration

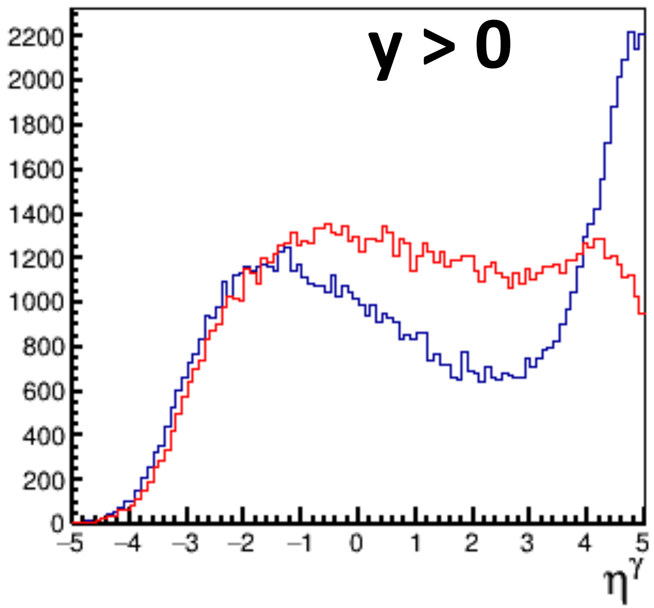
Kinematical cuts at generation level

- $10^{-4} < x < 0.9$
- $1.0 < Q2 < 100$ GeV^2
- $0.01 < |t| < 1.6$ GeV^2
- **$0.01 < y < 0.95$ [inelasticity]**
- $E^{el}_{min} = 0.5$ GeV

Photons at Forward Rapidity

MILOU (GK, KM20)

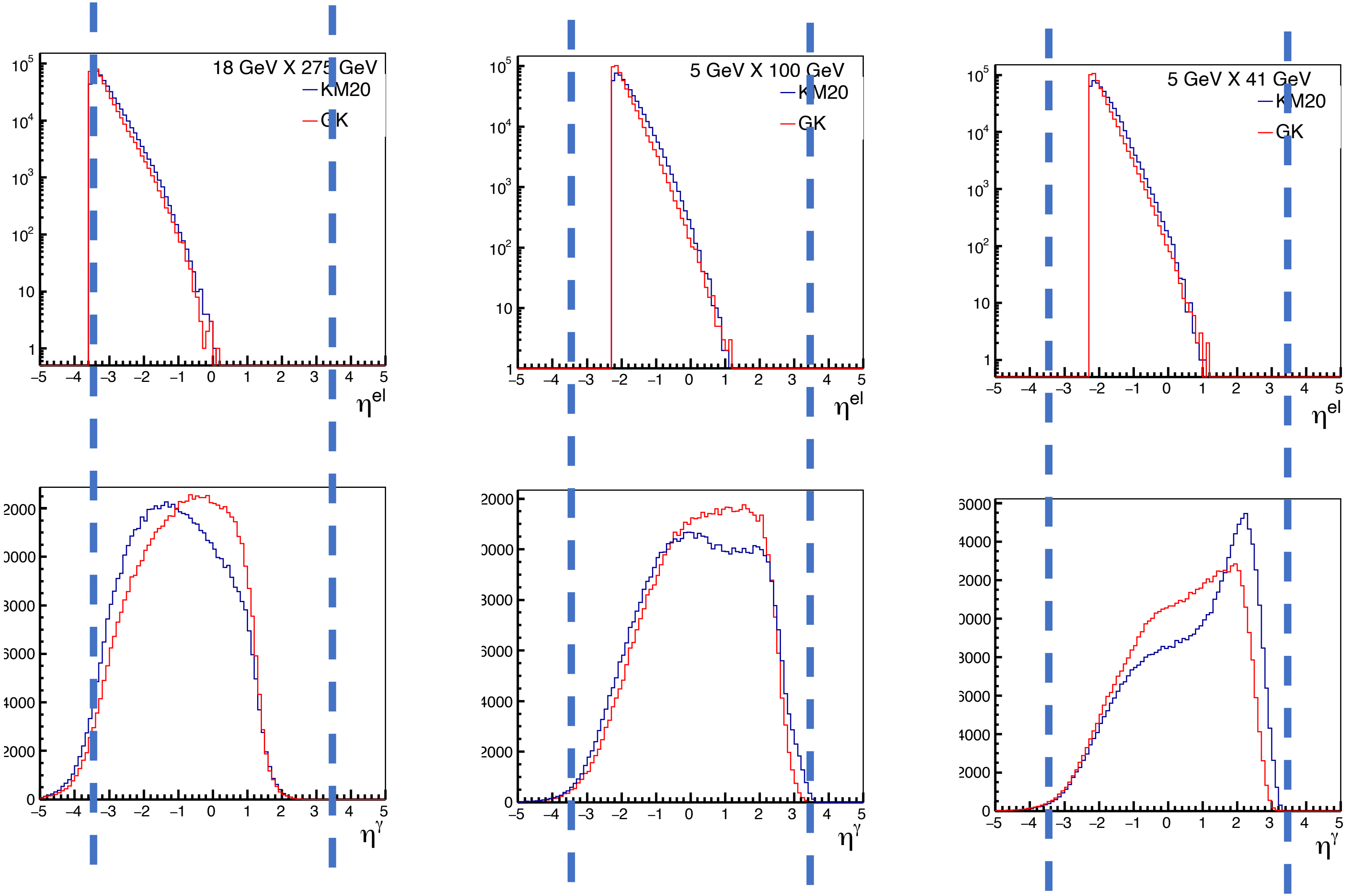




- Photons extended to forward rapidity!
- There was some discussion on this withing the Y.R., as it seemed to contrast with expectations from W.P. and plots with MILOU
- After investigation we found that this is driven by the lower inelasticity cuts (commonly assume y>0.01)

DVCS – model comparison

Blue dashed bars mark |η|<3.5 acceptance



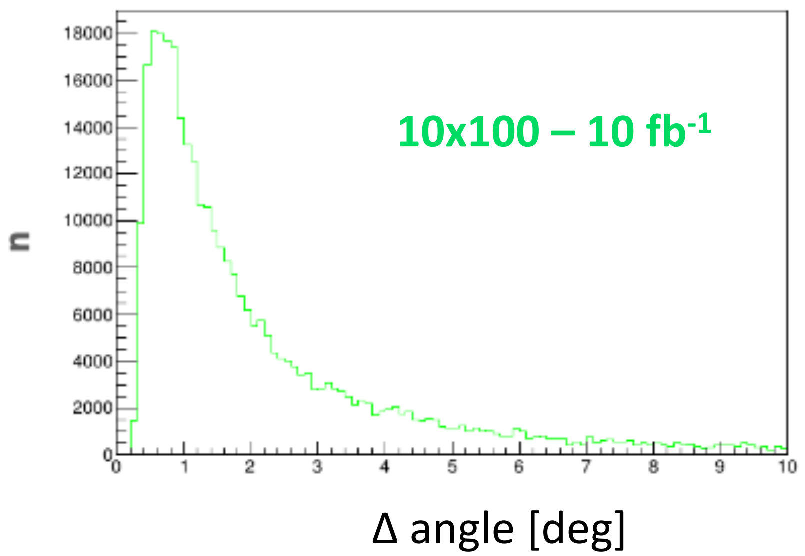
Simulated with MILOU 3D

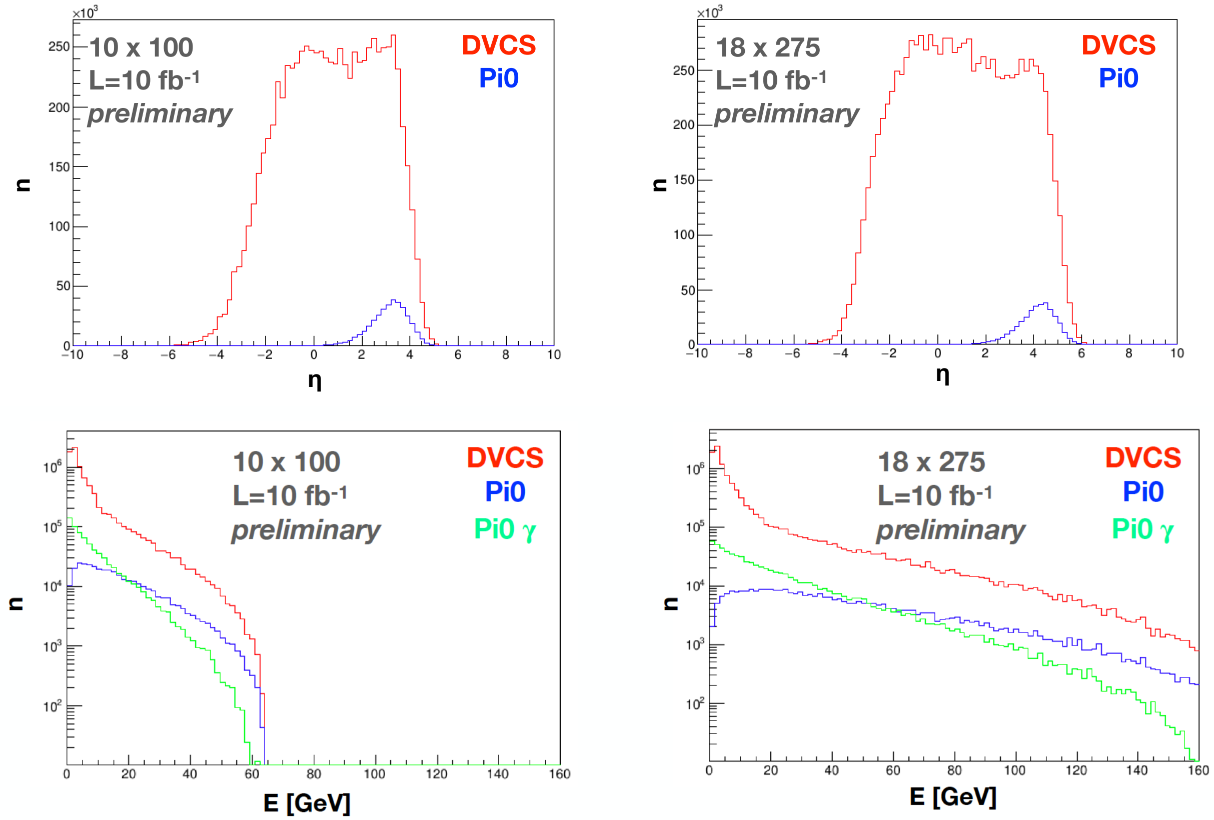
- Not a significant impact of |η|<3.5
- Al large energies, extending to η >~ -3.7 helps measuring the peak of the scattered electron

DVCS vs exclusive π^0

- Why we worry about a background from "$\pi^0 \to \gamma\gamma$" ?
  1) The two decay photons could merge into one
  2) One of the photons could go out of the acceptance
- Study based on Goloskokov-Kroll model
- Kinematic range:
  - $10^{-4} < x_B < 0.7$
  - $1\ \mathrm{GeV}^2 < Q^2 < 1000\ \mathrm{GeV}^2$
  - $0 < |t| < 1\ \mathrm{GeV}^2$

DVCS vs exclusive π^0





Take away message:

- π^0 x-sec lower than signal (DVCS)
- Min 2γ angle ~0.2 deg
- Exclusive π^0 can reach high momentum/energy (but xSec decreases with meson's energy)

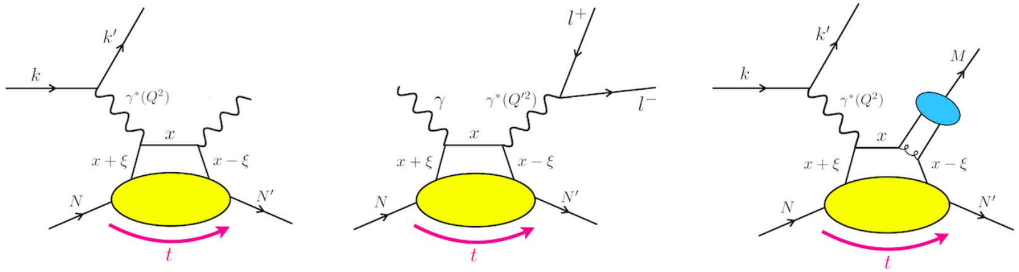
Studies at the times of the ATHENA proposal

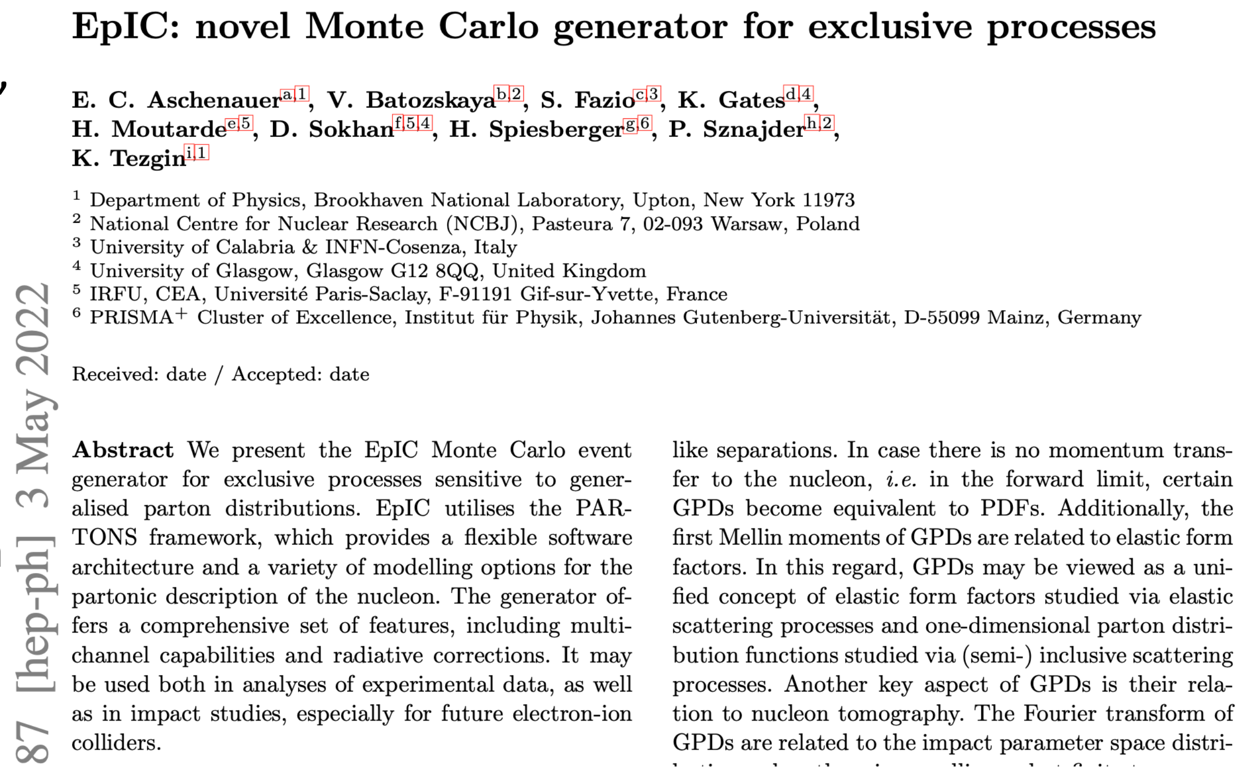
Accepted on: JINST_063P_0522

The EpIC generator: a new tool!

Kemal Tezgin's talk

- **EpIC:** an event generator for exclusive reactions
  - Named after EIC and the philosopher *Epicurus*
  - Note: we inspired the name for EIC detecor-1 ☺
- EpIC uses the PARTONS framework (http://partons.cea.fr), takes advantage of:
  - two state-of-art GPD models (GK, KM20)
  - flexibility for adding new models
- Multiple channels: DVCS, TCS, π^0
  - Initial and final state radiative corrections are implemented based on the collinear approximation
  - flexibility for adding all exclusive mesons





EpIC: novel Monte Carlo generator for exclusive processes

E. C. Aschenauer[a1], V. Batozskaya[b2], S. Fazio[c3], K. Gates[d4], H. Moutarde[e5], D. Sokhan[f5,4], H. Spiesberger[g6], P. Sznajder[h2], K. Tezgin[i1]

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Received: date / Accepted: date

87 [hep-ph] 3 May 2022

Abstract We present the EpIC Monte Carlo event generator for exclusive processes sensitive to generalised parton distributions. EpIC utilises the PARTONS framework, which provides a flexible software architecture and a variety of modelling options for the partonic description of the nucleon. The generator offers a comprehensive set of features, including multichannel capabilities and radiative corrections. It may be used both in analyses of experimental data, as well as in impact studies, especially for future electron-ion colliders.

like separations. In case there is no momentum transfer to the nucleon, *i.e.* in the forward limit, certain GPDs become equivalent to PDFs. Additionally, the first Mellin moments of GPDs are related to elastic form factors. In this regard, GPDs may be viewed as a unified concept of elastic form factors studied via elastic scattering processes and one-dimensional parton distribution functions studied via (semi-) inclusive scattering processes. Another key aspect of GPDs is their relation to nucleon tomography. The Fourier transform of GPDs are related to the impact parameter space distri-

arXiv:2205.01762

Accepted for publication on: EPJC

The EpIC generator

Kemal Tezgin's talk

- EpIC uses mini FOAM to generate random events
- GPDs framework:

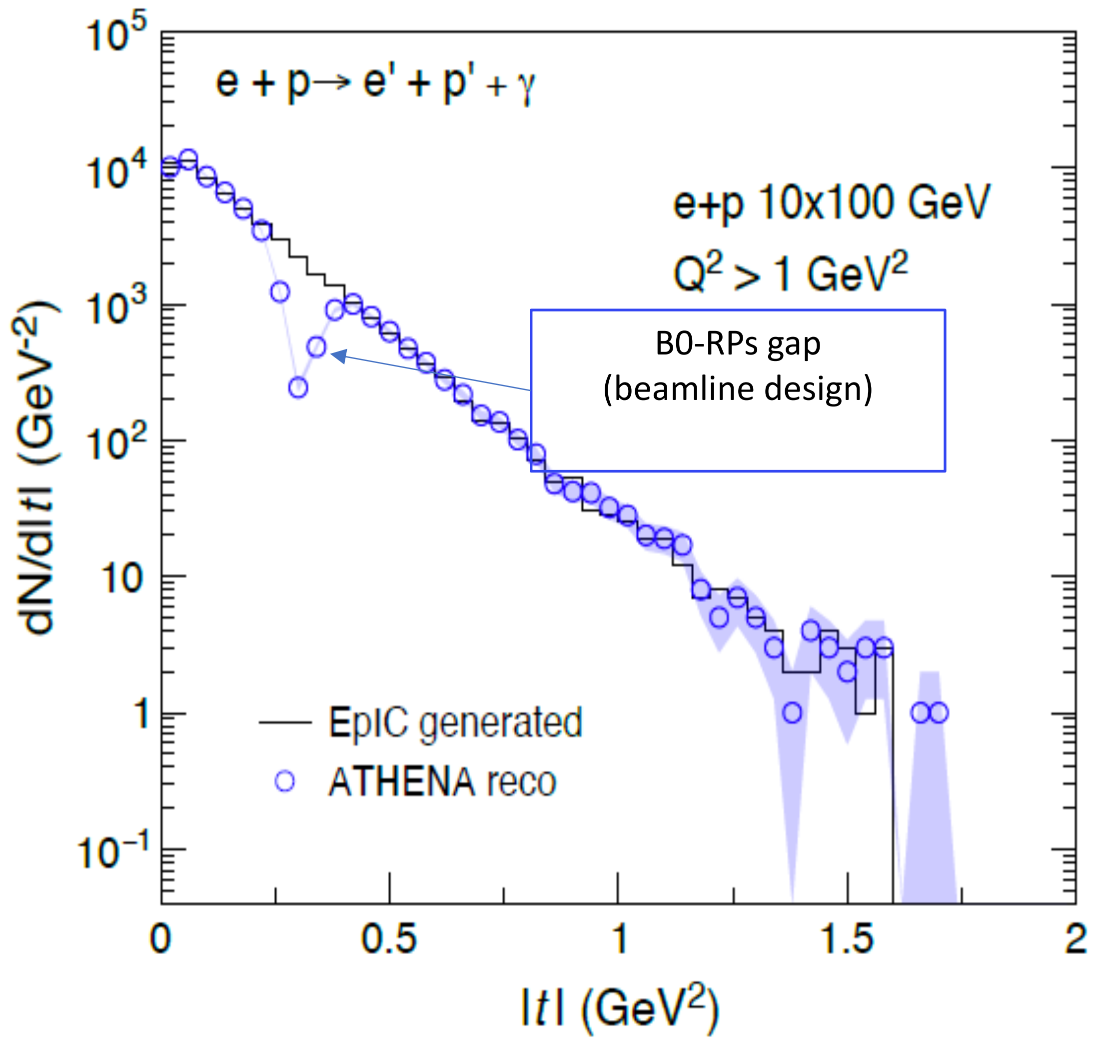
GPDs → CFFs → Observables

- Written in **C++**, XML interface for automated tasks, open source
- Flexible Architecture that utilises a modular programming paradigm
- Used for the ATHENA proposal: DVCS and TCS performance studies

- **Input file:** model, model parameters, number of events, kinematic limits, beam and target type, beam helicity, target polarization, beam and target energy, mFOAM parameters
- **Output file:** 4-vectors of all particles

ATHENA performance plots

- Plot made with full simulation
- DVCS events simulated using EpIC



Key:

- Acceptance (including FF)
- γ/π^0 separation in ECAL
- t- lever arm in FF spectrometers

Observables:

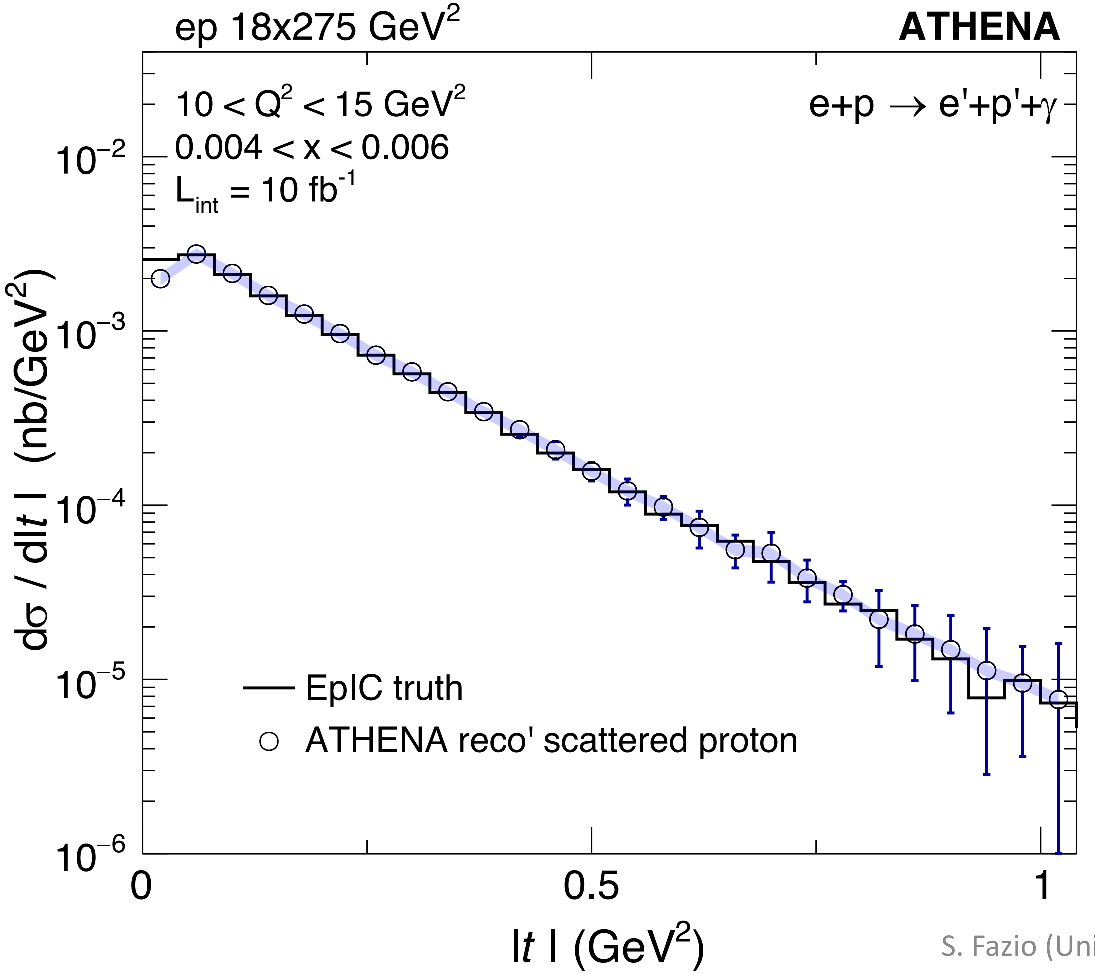
$d\sigma/dt$; A_{LU}; A_{UT}

Asymmetries (DVCS & TCS):

GPDs via amplitude-level interference with Bethe-Heitler

ATHENA performance plots

- Plot made with full simulation
- DVCS events simulated using EpIC



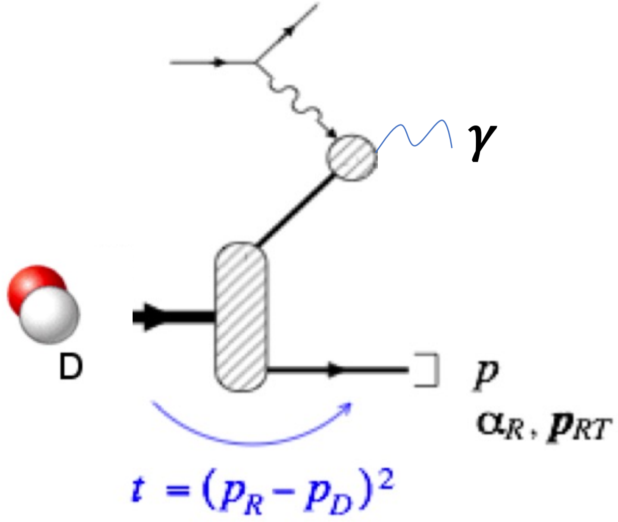
- **Process: DVCS**

$$e + p \to e' + p' + \gamma$$

- **Parameters**
  - $10 < Q^2 < 15$ GeV^2
  - $0.004 < x < 0.006$
  - Beam energy: 18 GeV x 275 GeV e+p
  - Luminosity = 10 fb^{-1}
- **Uncertainties**
  - 1M simulated events
  - **Error bars (statistical)** are rescaled to 10 fb^{-1} equivalent;
  - **Blue band (systematics):** *assumed 8%* constant systematics

  → Note that estimating systematics at the current stage is nearly impossible. Arbitrary 8% is a very conservative number)

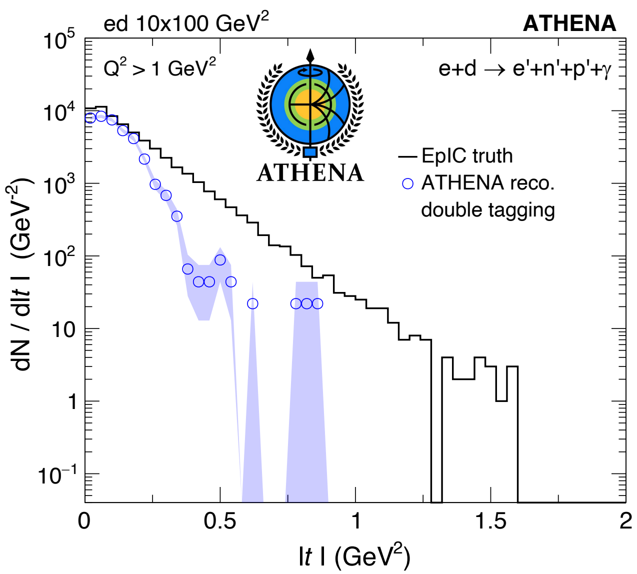
Study of neutrons with light nuclei

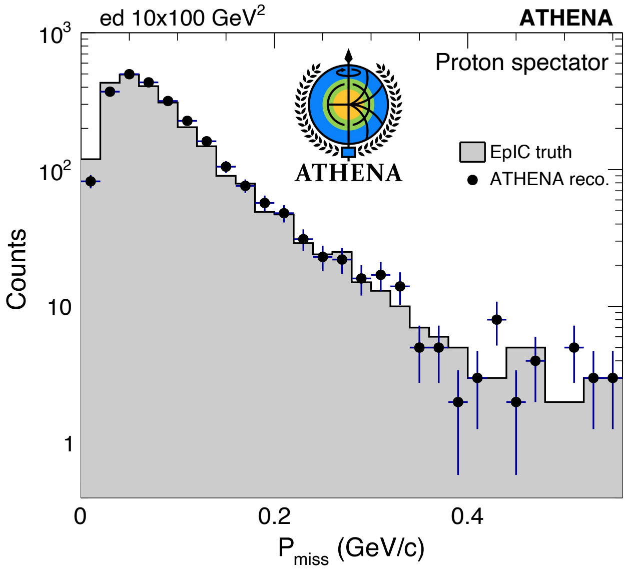


- Possibility to study neutron structure
- DVCS on neutron compared to proton is important for flavor u/d separation

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

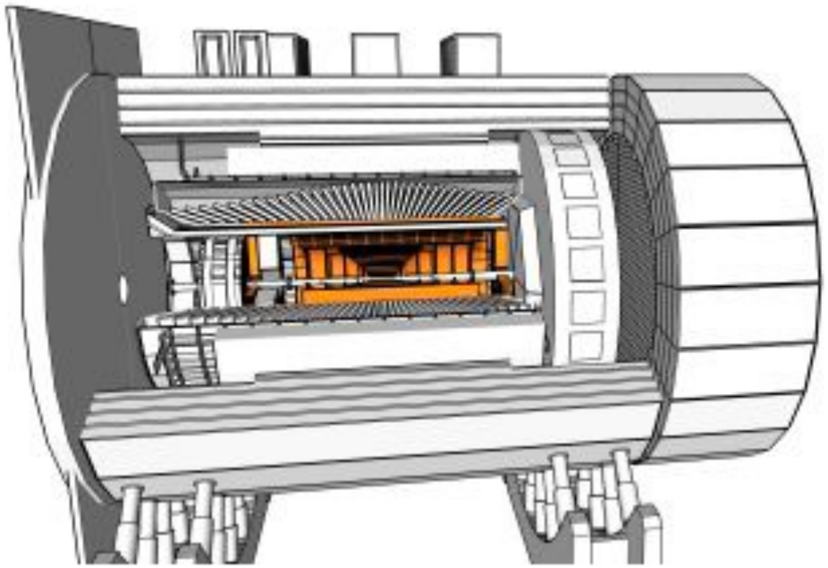




ATHENA – DVCS on e+D:

- 80-90% acceptance at low |t|,
- |t|-acceptance loss at higher value mostly due to the loss in tagging the active neutron in ZDC.
- Alternatively, |t| can be measured via scattered *e* and γ → higher acceptance at large |t|.
- Proton momentum is well reconstructed

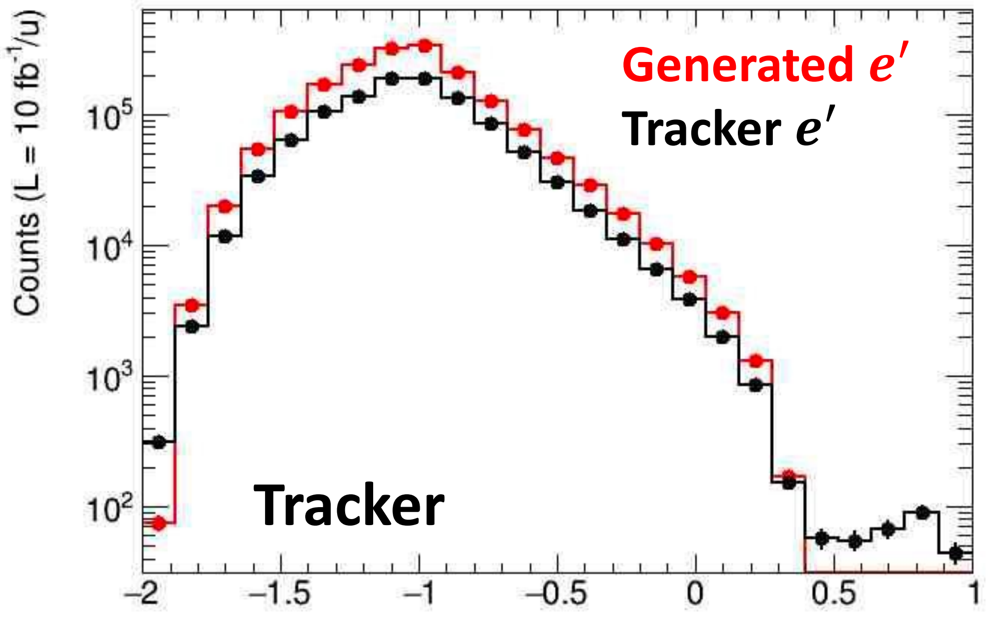
After Preproposal time
the dawn of the ePIC detector



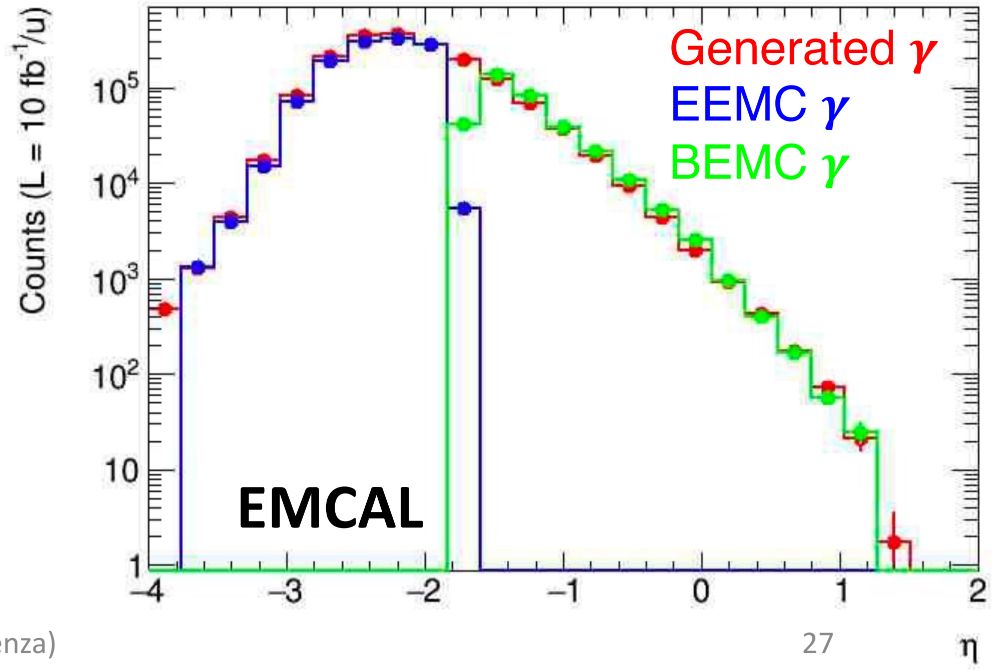
DVCS with ^{4}He

Process which can give understanding of EMC effect, and tomographic view of nucleons.

- Pure DVCS illustrated by “Handbag Mechanism”
- TOPEG MC generator: by Perugia+Orsay
- Detector simulation: EpIC with fun-4-all
- Electron detection:
  - electron: # of tracks in internal Si tracker = 1
  - electron acceptance ~= 88.3%
- Photon detection:
  - # ele tracks = 1 && # ECAL hits > 0 && max cluster energy: E_{max} > 250 MeV
  - photon acceptance ~= 86.1%



By Gary Penman



New Radiative corrections studies

- EpIC generator includes both ISR & FSR
- Pure DVCS with 10 GeV electron and 100 GeV proton

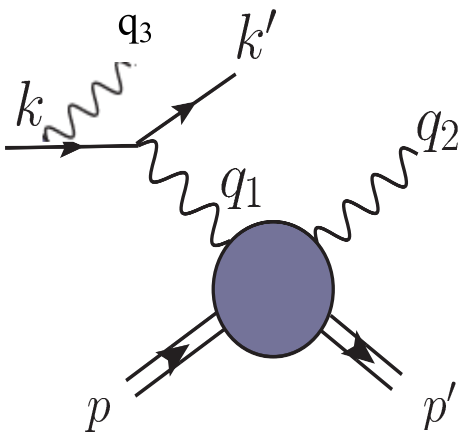
- Kinematic cuts:

$0.0001 < xB < 0.63$

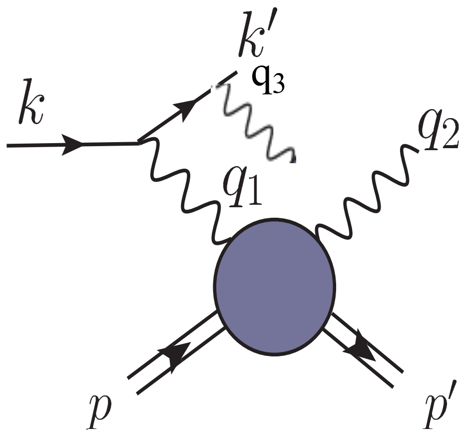
$1\ \mathrm{GeV}^2 < Q^2 < 100\ \mathrm{GeV}^2$

$0.04 < |t| < 1.3\ \mathrm{GeV}^2$

$0.01 < y < 0.6$



DVCS + ISR



DVCS + FSR

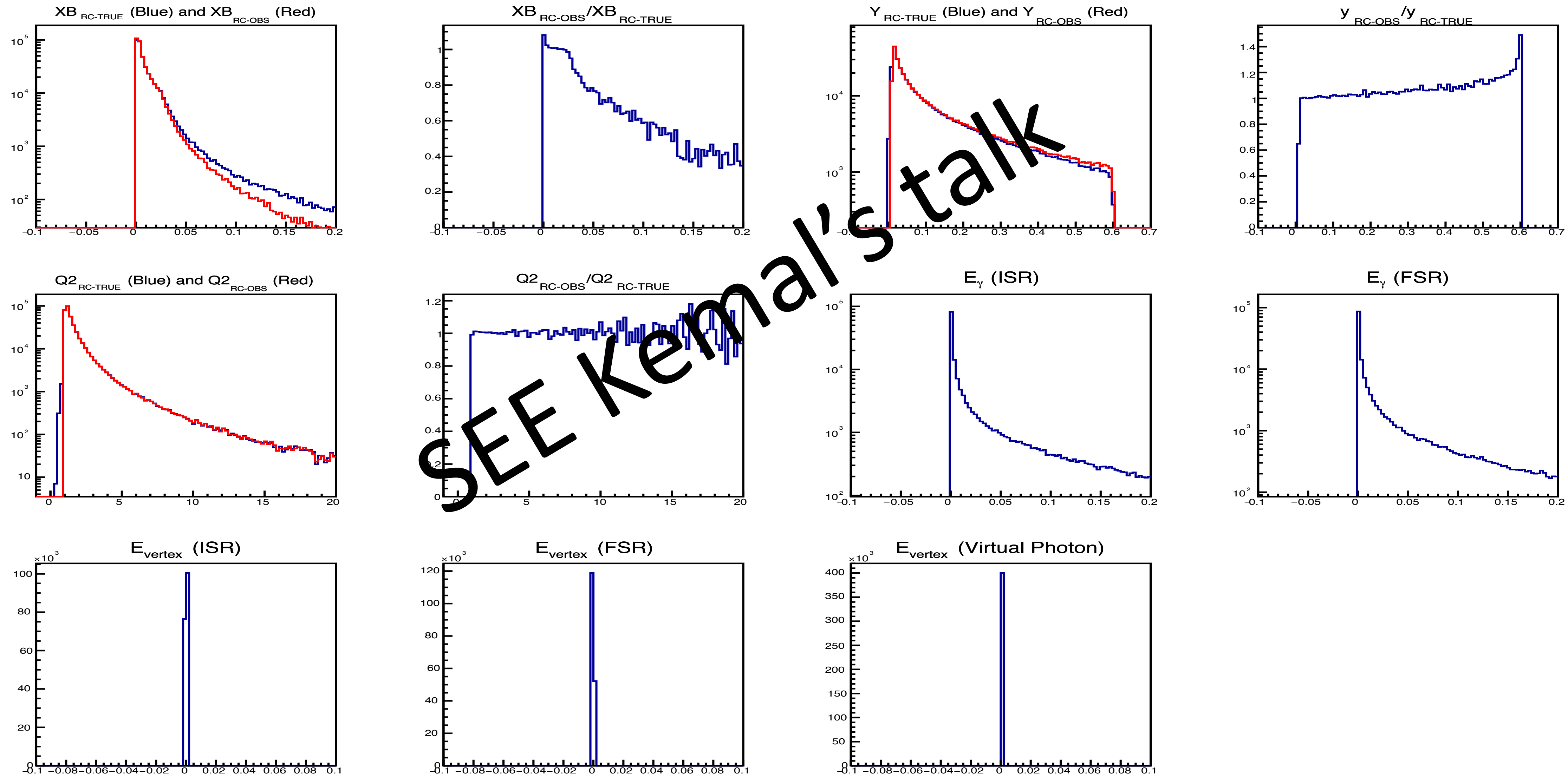
To reduce radiative corrections (established at HERA!) :

- FSR: e/gamma separation in EMCAL (granularity)
- $\sum E - Pz$ >~ $2E_e$ (cut little below this threshold)

10 x 100 GeV^2

No cut on $\sum \mathrm{E} - Pz$ & $\epsilon = 10^{-6}$

ϵ param. linked to minimum rad. photon energy



SEE Kemal's talk

The present: impact studies!

- We aim at performing new impact studies for extracting GPDs, similarly to what was done in JHEP09(2013)093, now with:
  - geant-4 simulation of the ePIC detector response and realistic event reconstruction
  - BH subtraction in xsec and π^0 background studies
  - state of art models: GK and KM20
  - we should reassess pi0 with a full simulation
- Status of ePIC detector simulation:
  - full GEANT4 bases simulation exists: DD4HEP, Jana2 (EICRecon) ...
  - first “serious” full-simulation campaign to start (hopefully) in November
- EpIC generator (see Kemal’s talk!):
  - fully replaces MILOU & MILUO 3D. Maintained, using state or art models
  - Anyone encouraged to use it: arXiv:2205.01762
  - Suggested future: add mesons, light ions (D, He) including incoherent D