Exclusive, Diffractive and Tagging WG

Spencer Klein, Rachel Montgomery, Axel Schmidt,
Daria Sokhan (CEA Saclay / U. of Glasgow)

EICUG Meeting – Stonybrook, New York, USA

27th July 2022

Charge to the Physics WGs

- *Work with the Detector Working Groups to perform constant validation of the performances for physics observables. Emphasis should be placed on studies of key physics processes in the NAS report, the EIC White Paper, Yellow Report, and detector proposals.*

- *When alternative technological solutions are examined, work with the detector groups to provide quantitative information on the physics performance of the proposed solutions.*

- *In collaboration with the Computing/Software and Simulations WGs, further develop simulation and data analysis tools. Organize workshops as needed to provide training in the use of these tools for collaborators.*

- *Over time, extend the existing scope of physics processes being studied, with an emphasis on those processes called out by the DPAP as being significant for the science program and yet not studied by the proto-collaborations.*

WG organisation

- Mailing list: eic-projdet-ExclDiff-l@lists.bnl.gov

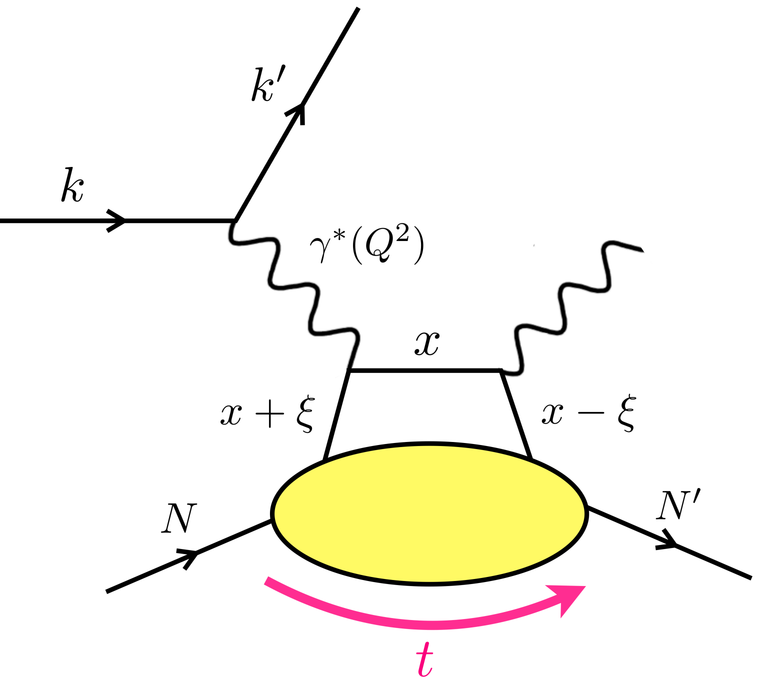
  Subscribe at: https://lists.bnl.gov/mailman/listinfo
- Wiki pages:
  https://wiki.bnl.gov/eic-project-detector/index.php/ExclusiveDiffractionTagging
- Roughly bi-weekly meetings on Mondays at noon NY time.
- Met 4 times: 20th May, 6th and 27th June, 11th July.
- Indico pages: https://indico.bnl.gov/category/419/
- Topics discussed and presentations:
  - Kick-off: charge to WG, path forward – start with comparison of ATHENA and ECCE studies to identify and understand major differences, areas that need further study.
  - Pion Form Factor at ECCE – Stephen Kay (U. of Regina)
  - Near-threshold Upsilon production in ep with ATHENA – Yuanjing Ji (LBNL)
  - VM reconstruction from ATHENA – Kong Tu (BNL)
  - VM reconstruction from ECCE – Peter Steinberg (BNL)
  - Backward production in ATHENA – Zachary Sweger (U. of California, Davis)
  - DVCS in ep from ECCE – Igor Korover (MIT)

Studies for proposals:

	ATHENA	ECCE
* **DVCS in ep**	EpIC	MILOU3D
* **DVCS (incoherent) in ed**	EpIC	
* **DVCS on He-4**		TOPEG
* **TCS in ep**	EpIC	EpIC
* **J/Psi in ep**		lAger, eSTARlight
* **J/Psi in eA**		lAger, eSTARlight
* **Φ in eAu/Pb**	SARTRE, BeAGLE	SARTRE, BeAGLE
* **Y(1S, 2S, 3S) in ep**	eSTARlight, lAger	
* **u-channel: ω, ρ in ep**	eSTARlight	
* **X,Y Ψ(2S) in ep -> J/Ψ $\pi^+\pi^-$ p**	elSpectro	elSpectro
* **Pion Form Factors**		*
* **Pion Structure Functions**		*
* **A^n_1 (He-3 double tagging)**		*

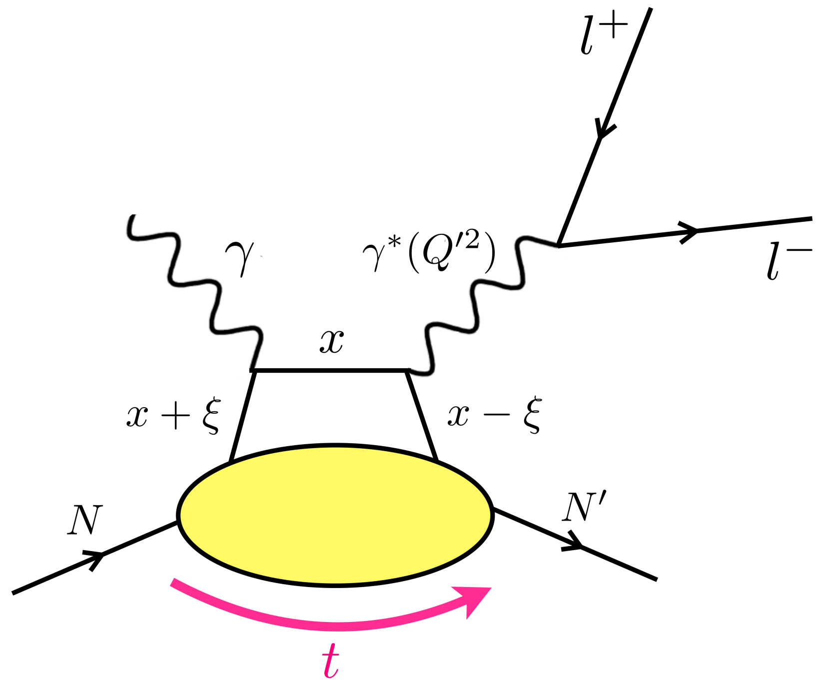
Exclusive processes

Deeply Virtual Compton scattering (DVCS):



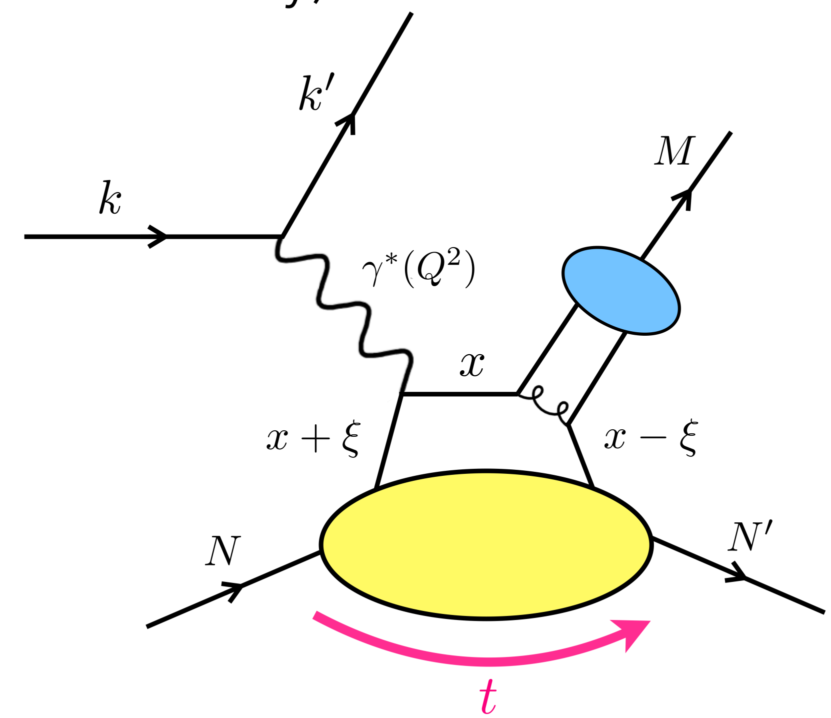
$$\gamma^* p \to p' \gamma$$

Timelike Compton Scattering (TCS):



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

Meson production (one of many):



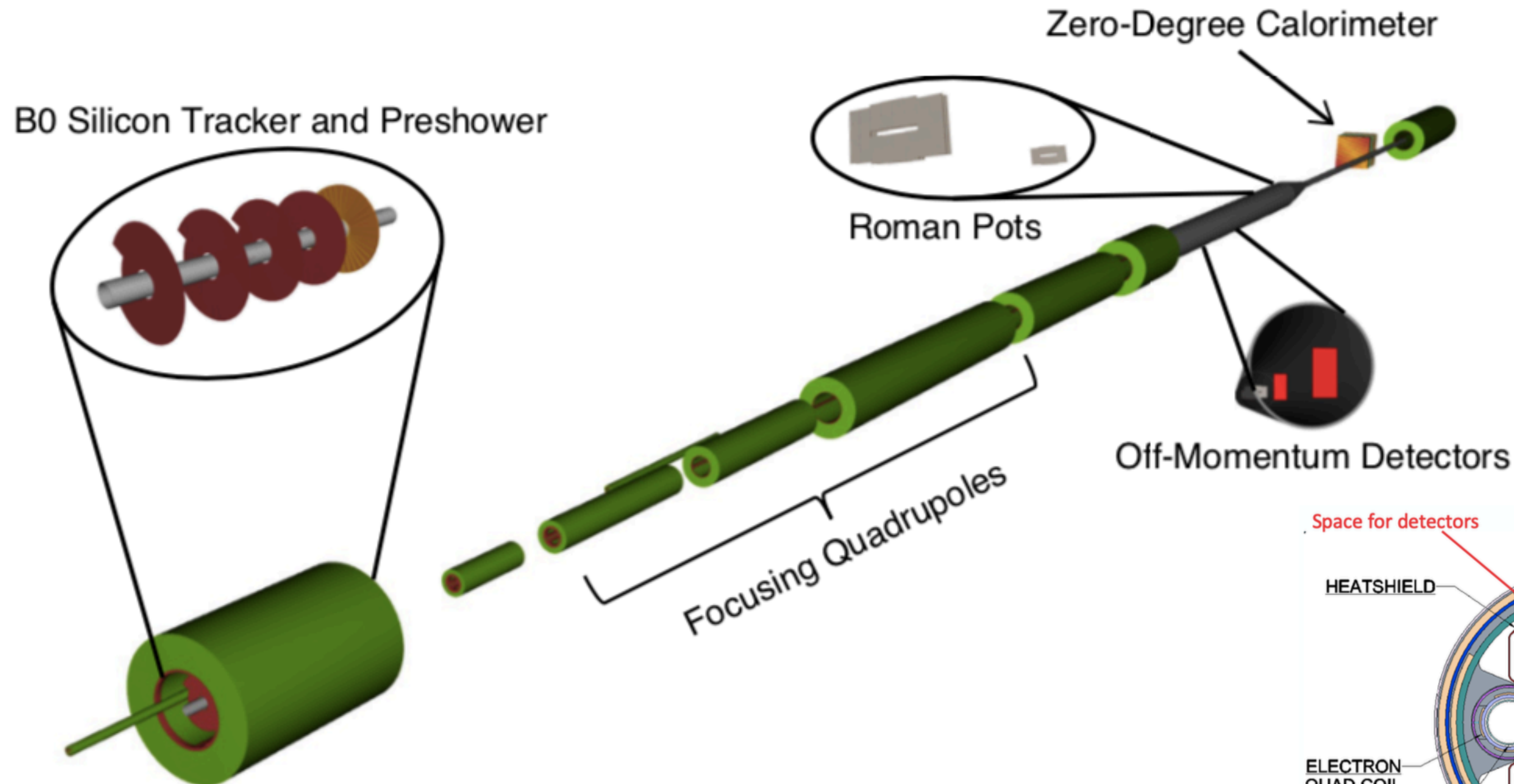
- Access to Generalised Parton Distributions (GPDs), tomography of the nucleon, composition of nucleon spin (contribution to orbital angular momentum), mechanical properties of the nucleon (pressure, shear forces)
- Diffractive meson production: saturation probe (in eA), gluon distributions, at-threshold production sensitive to mass generation.
- Scattering from the meson cloud: meson form factors, structure functions – structure of mesons.
- Spectroscopy: structure of nucleons, search for exotics.

Recoil protons in *ep*

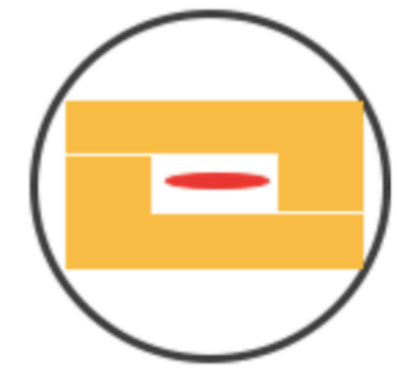
- The impact parameter information in DVCS/TCS or meson-production processes is encoded in t. Require accurate measurement of t across a wide range in *ep* collisions:

$$0.03 < |t| < 1.6\ \mathrm{GeV}^2 \qquad t = (p' - p)^2$$

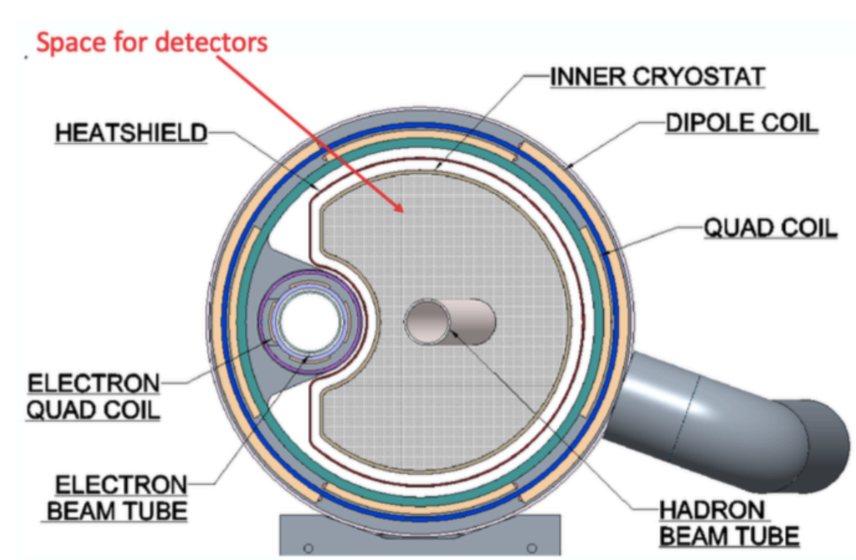
- Scattered protons detected in Roman Pots (for the lowest values of t) and in the B0 spectrometers (for higher values).



ATHENA proposal



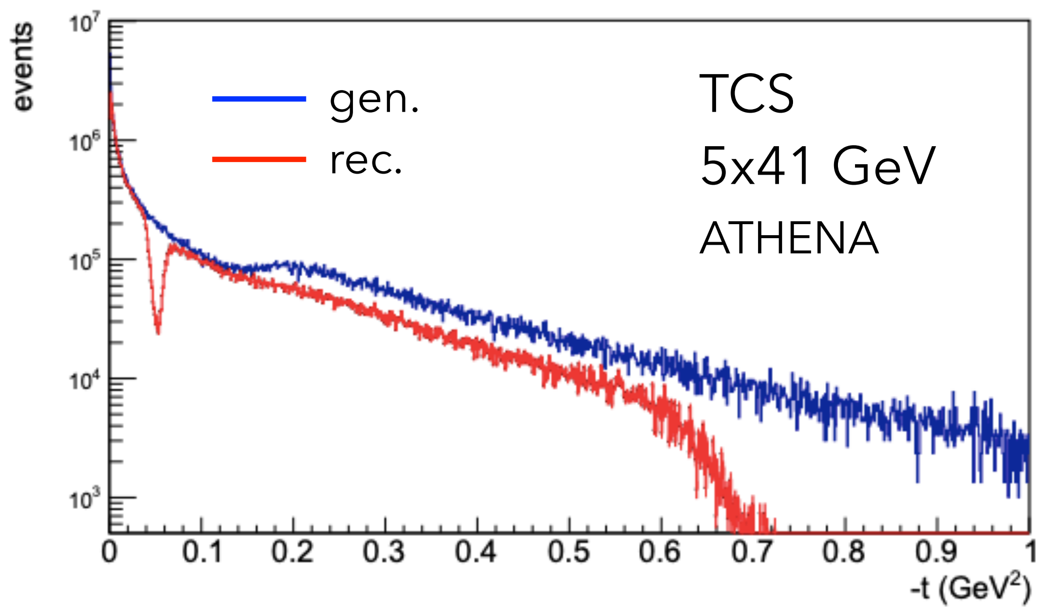
Hadron beam-pipe and Roman Pots in cross-section

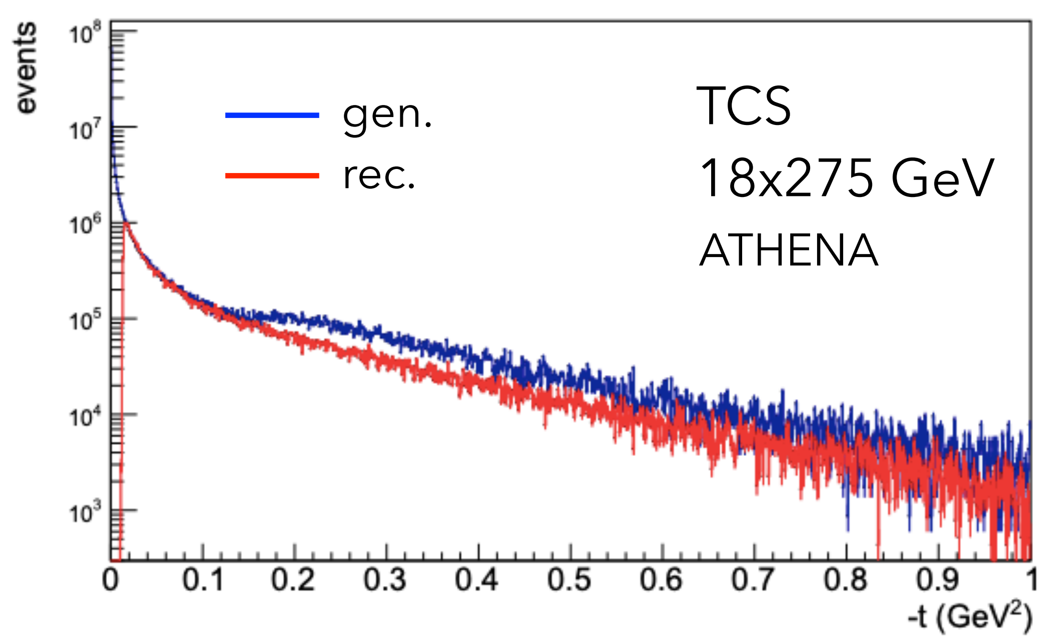


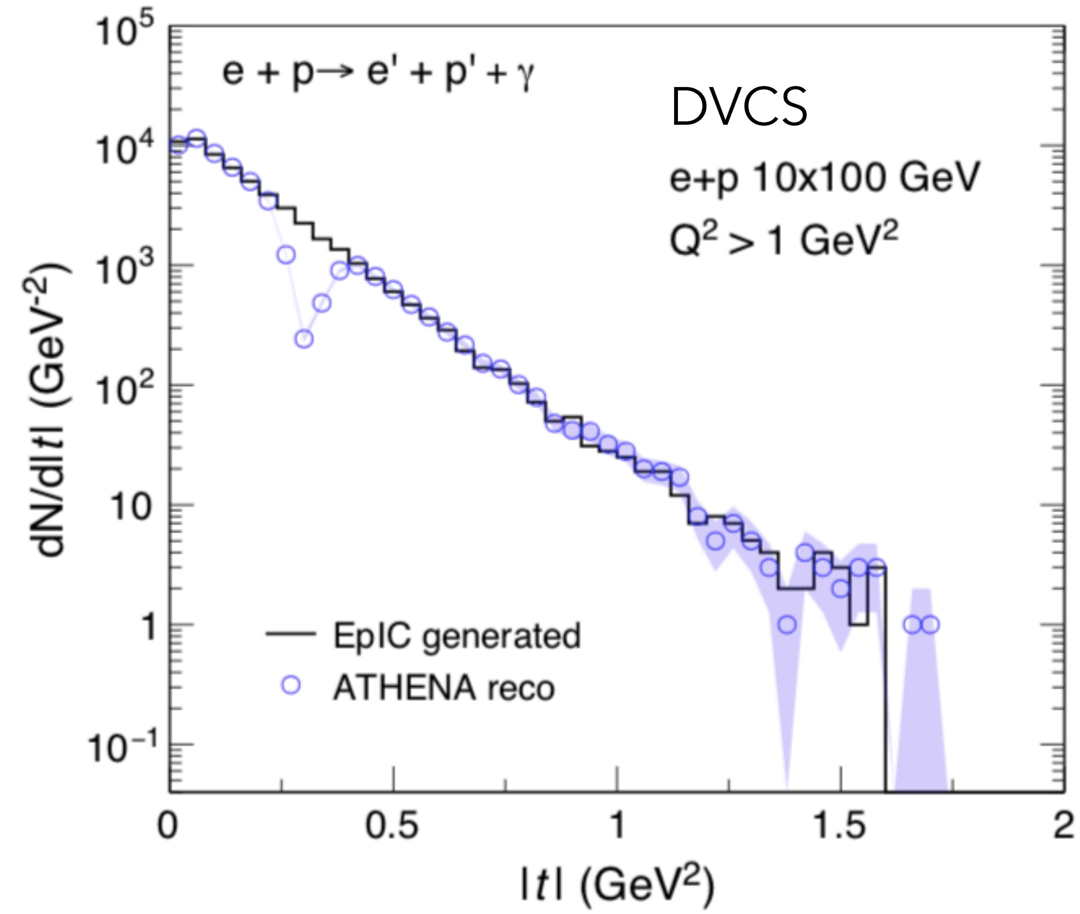
EIC Yellow Report B0 spectrometer configuration

Recoil protons in *ep*

- Scattered protons detected in Roman Pots (for the lowest values of *t*) and in the B0 spectrometers (for higher values).





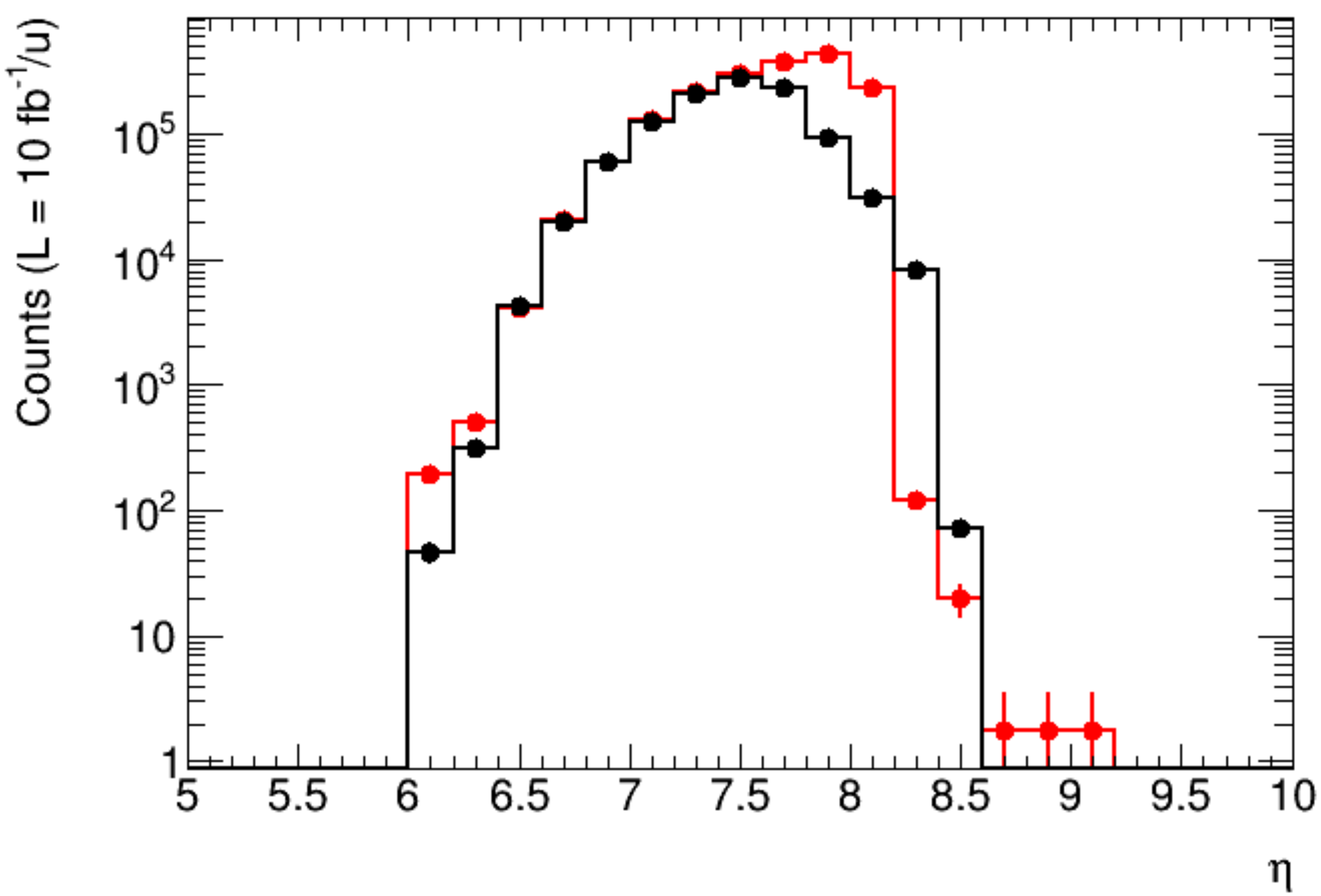


Dip in *t*-distribution is due to a gap between Roman Pots and B0 tracker: intrinsic to IR. Gap position depends on proton beam-energy.

Plots: Kong Tu (BNL), D. S.

Coherent DVCS on He-4

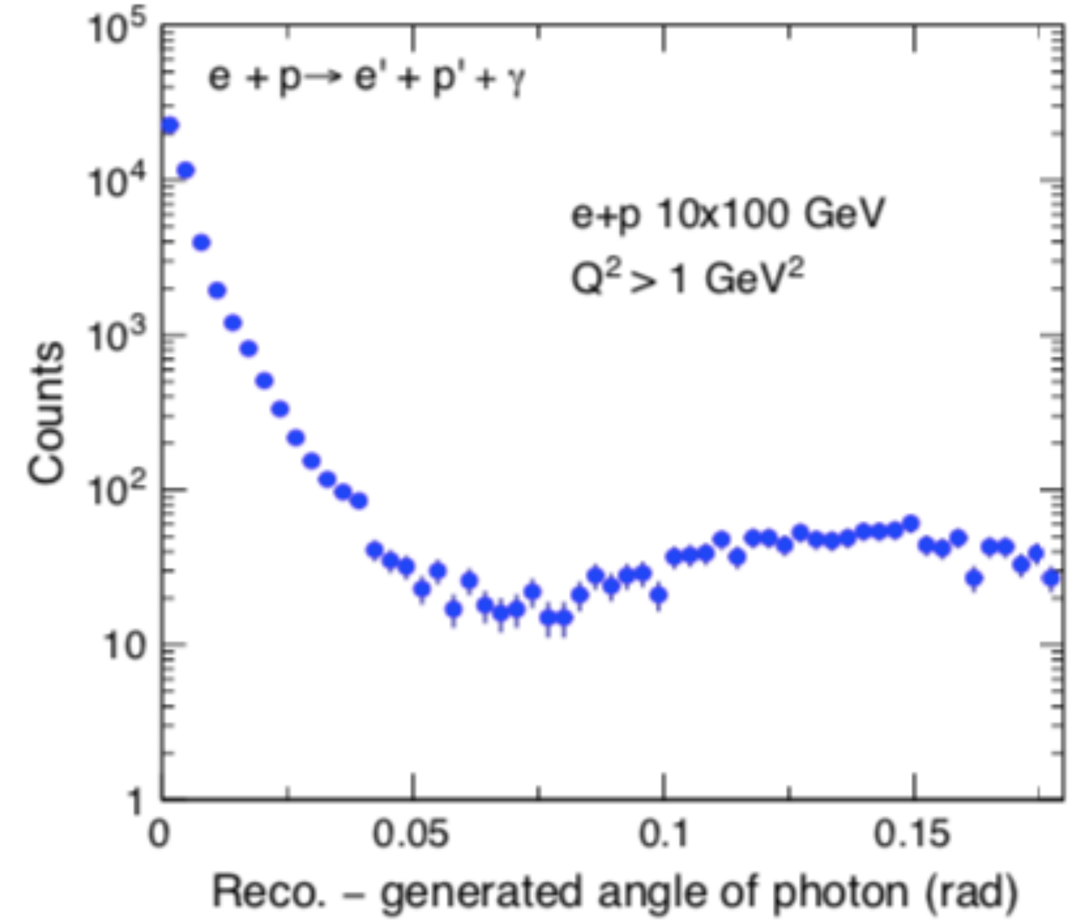
- GPDs, EMC effect, coherent vs incoherent DVCS studies
- Spin-0 nucleus: parametrisation of coherent amplitude in terms of only one GPD
- Study done using ECCE detectors, 5 x 164 GeV
- e′ and real photon detected in central detector ECALs
- Acceptance of He′ ions in forward direction crucial
- Optimisation of far forward beam line acceptance settings (high acceptance setting) yielded ~58% event acceptance

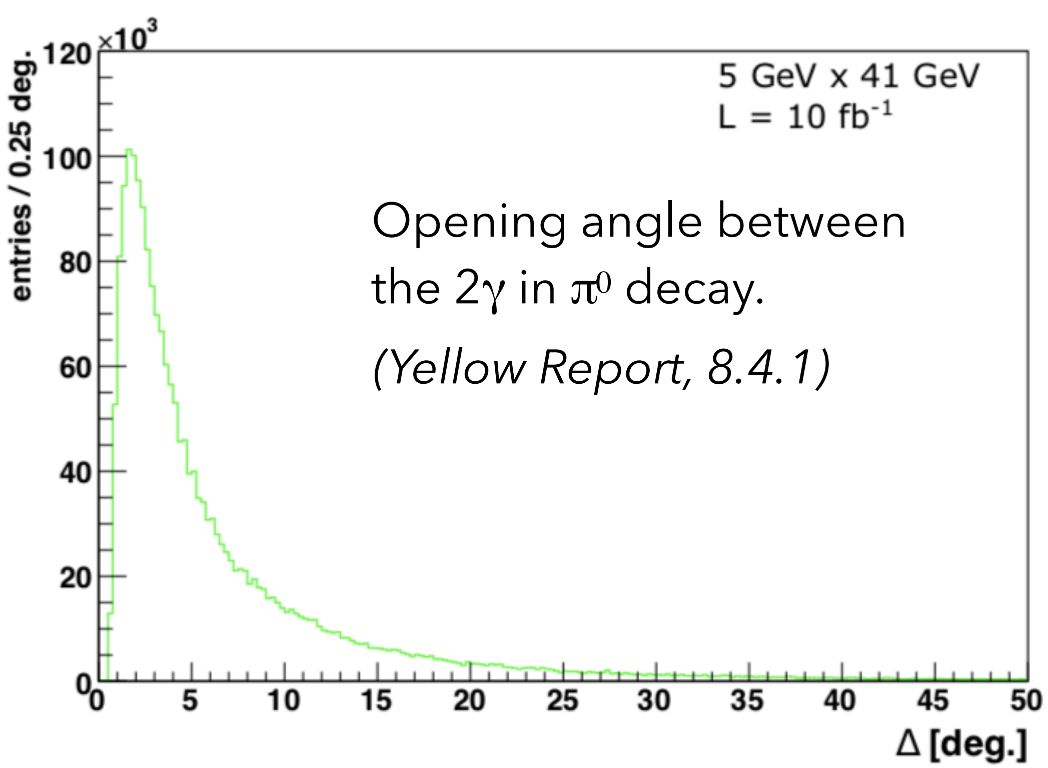


Plots: Gary Penman (Glasgow)

Detecting photons (DVCS/π^0)

* The DVCS channel requires detection of the produced photon in the ECAL. Biggest background comes from mesons that decay into 2γ pairs, mainly π^0. Two challenges to suppress it:
  - One photon may be missed and the π^0 event may mimic a DVCS one: address by providing maximum calorimeter acceptance in the kinematic range of interest (central rapidities, central detector: barrel + end-caps).
  - The two photons from the decay may merge into one cluster in the ECAL (if their opening angle is small) and be reconstructed as a single photon: address by having a high ECAL resolution.





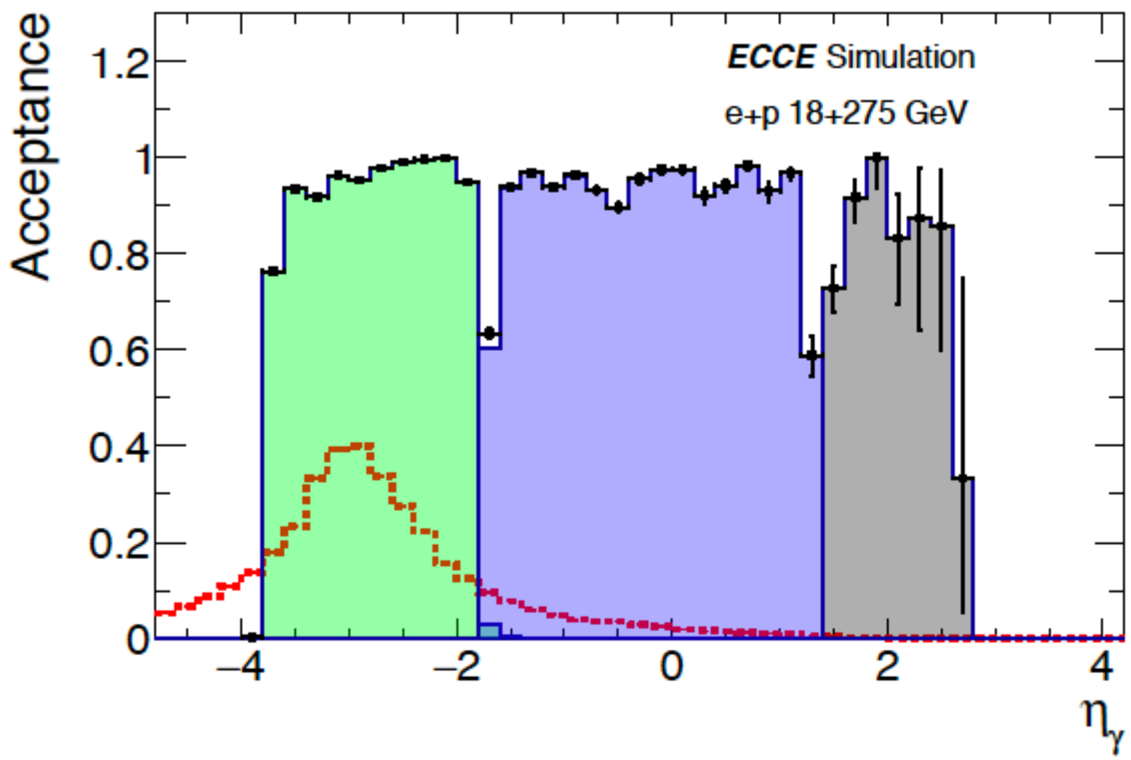
Opening angle between the 2γ in π^0 decay.

(Yellow Report, 8.4.1)

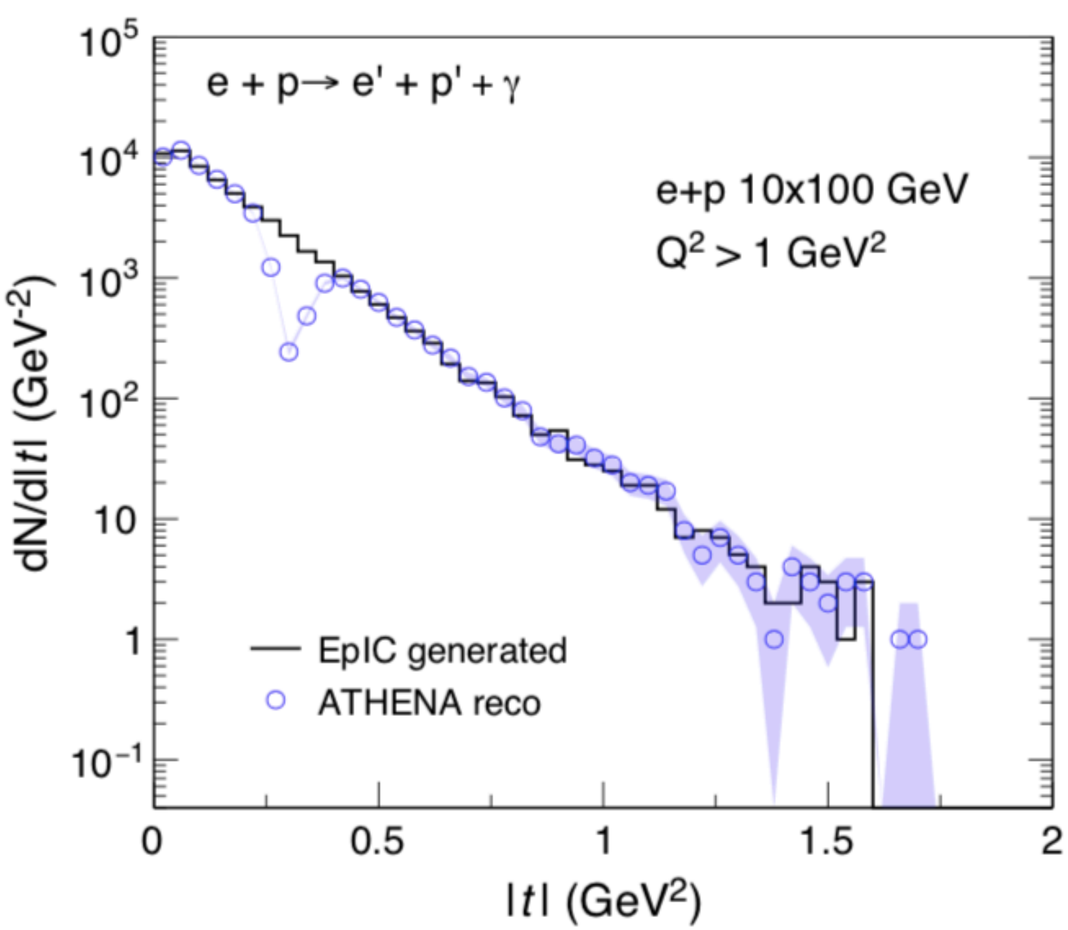
- Difference between generated and reconstructed DVCS photon mainly < 0.17mrad (1deg): smallest opening angle for π^0 decay.

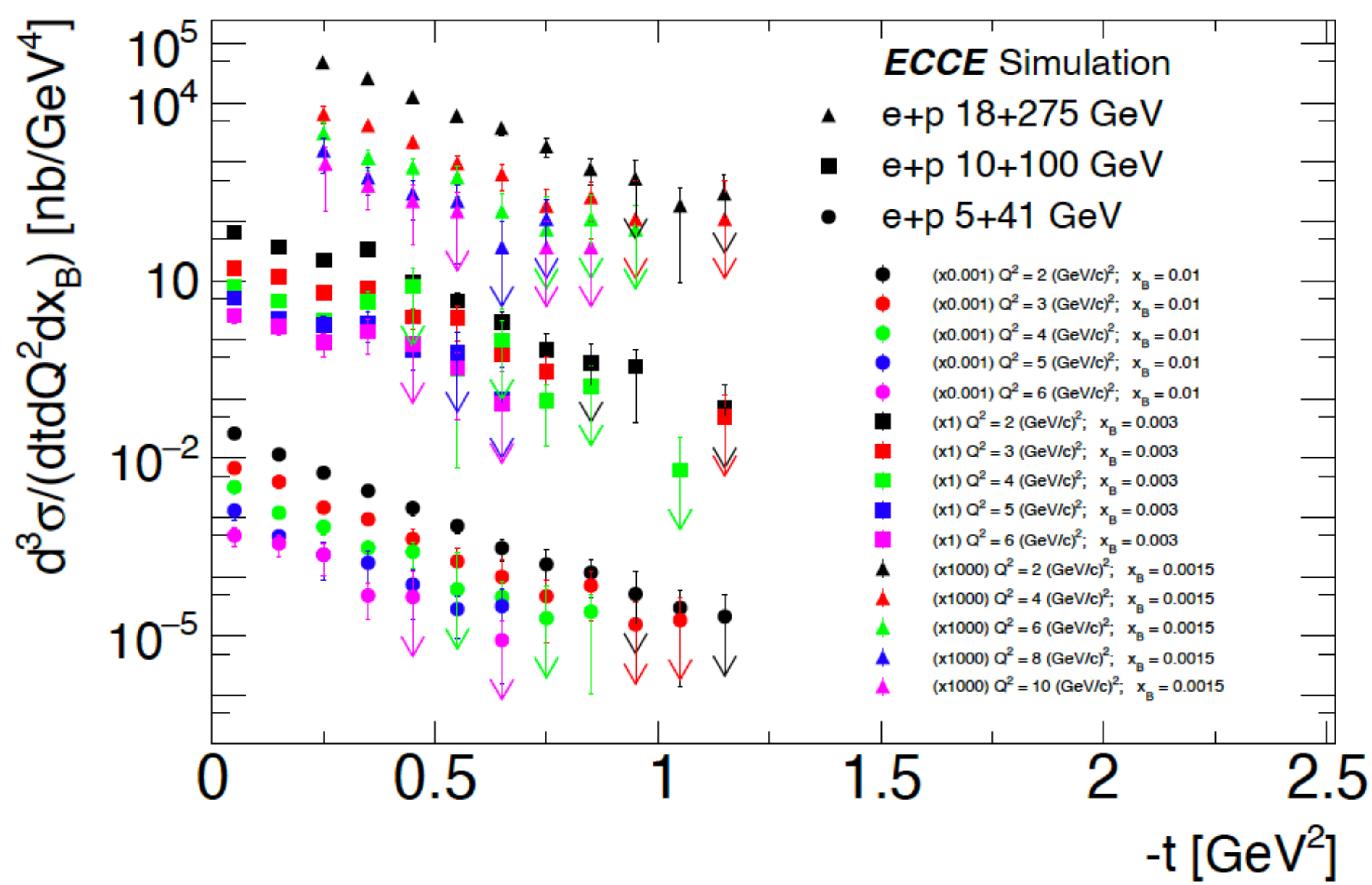
Plots: I. Korover (MIT),
Kong Tu. (BNL)

DVCS

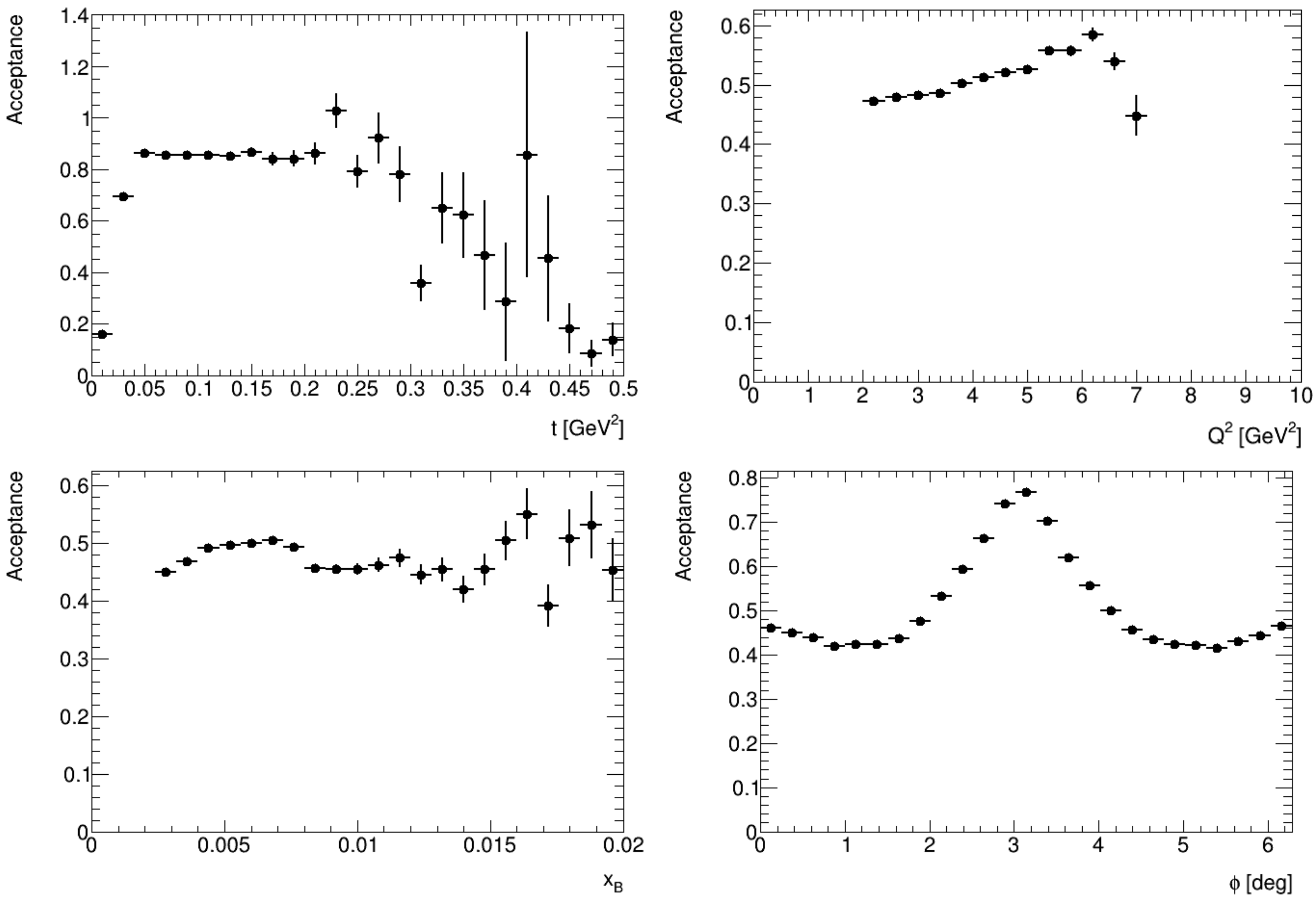


- Practically hermetic coverage for photons, wide range of *t*.
- Multi-dimensional binning possible





Coherent DVCS on He-4: acceptances



ECCE
$2.0 \leq Q^2 \leq 5.0$ GeV^2
$0.002 \leq x_B \leq 0.01$
$0.01 \leq -t \leq 0.1$ GeV^2
$0 \leq \phi \leq 2\pi$

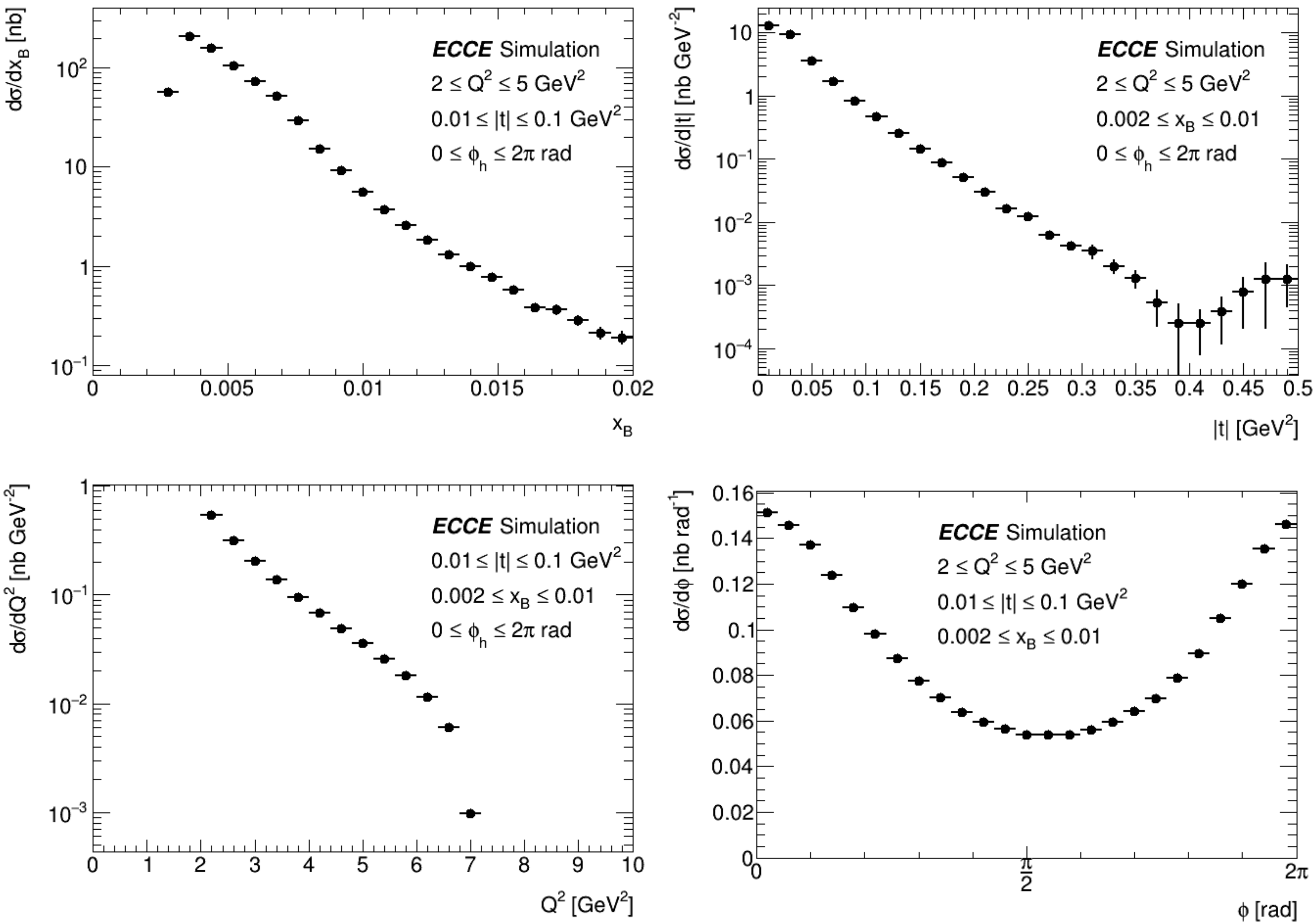
σ = 0.71 nb
(MC Integral)

5 x 164 GeV

ϕ : angle between leptonic and hadronic planes

Plots: Gary Penman (Glasgow)

Coherent DVCS on He-4: cross-sections



5 x 164 GeV

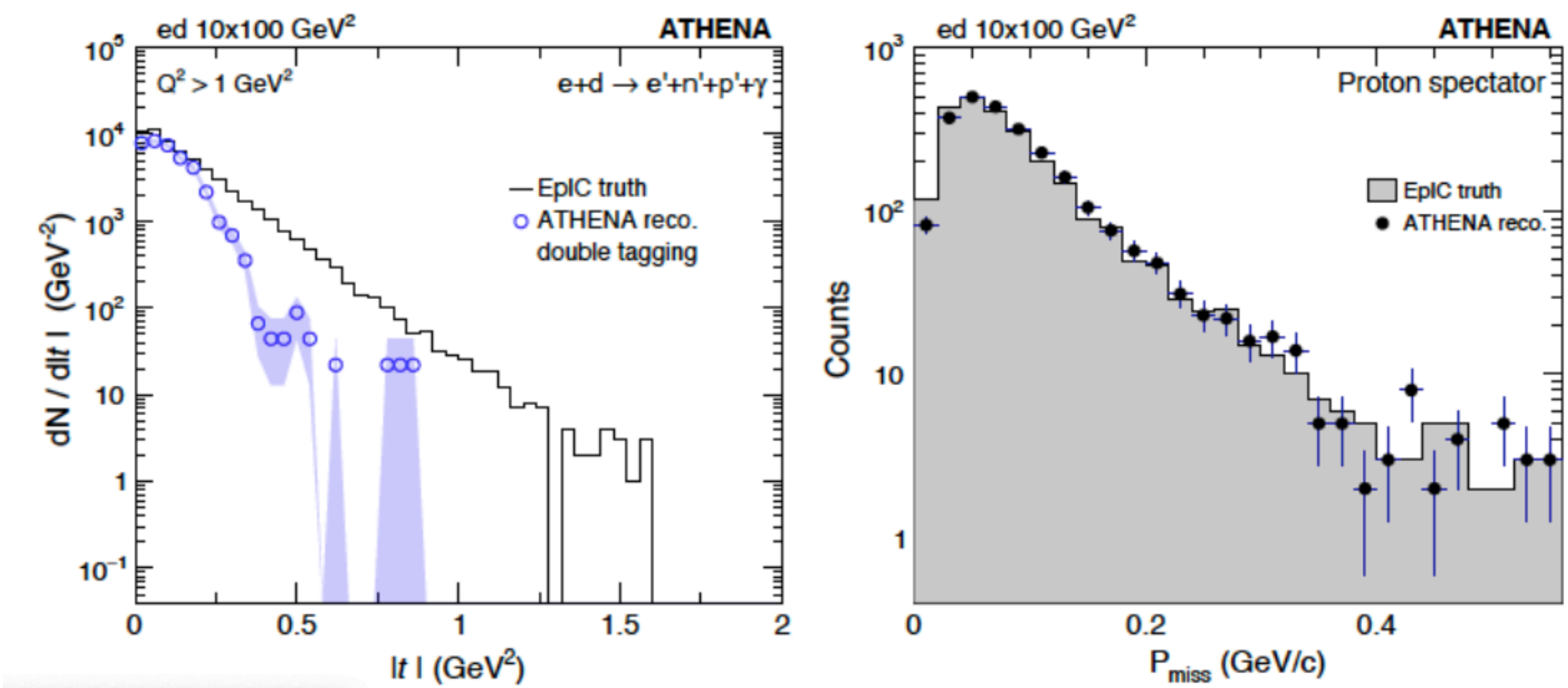
ϕ : angle between leptonic and hadronic planes

Plots: Gary Penman (Glasgow)

Plots: Kong Tu (BNL)

DVCS in ed

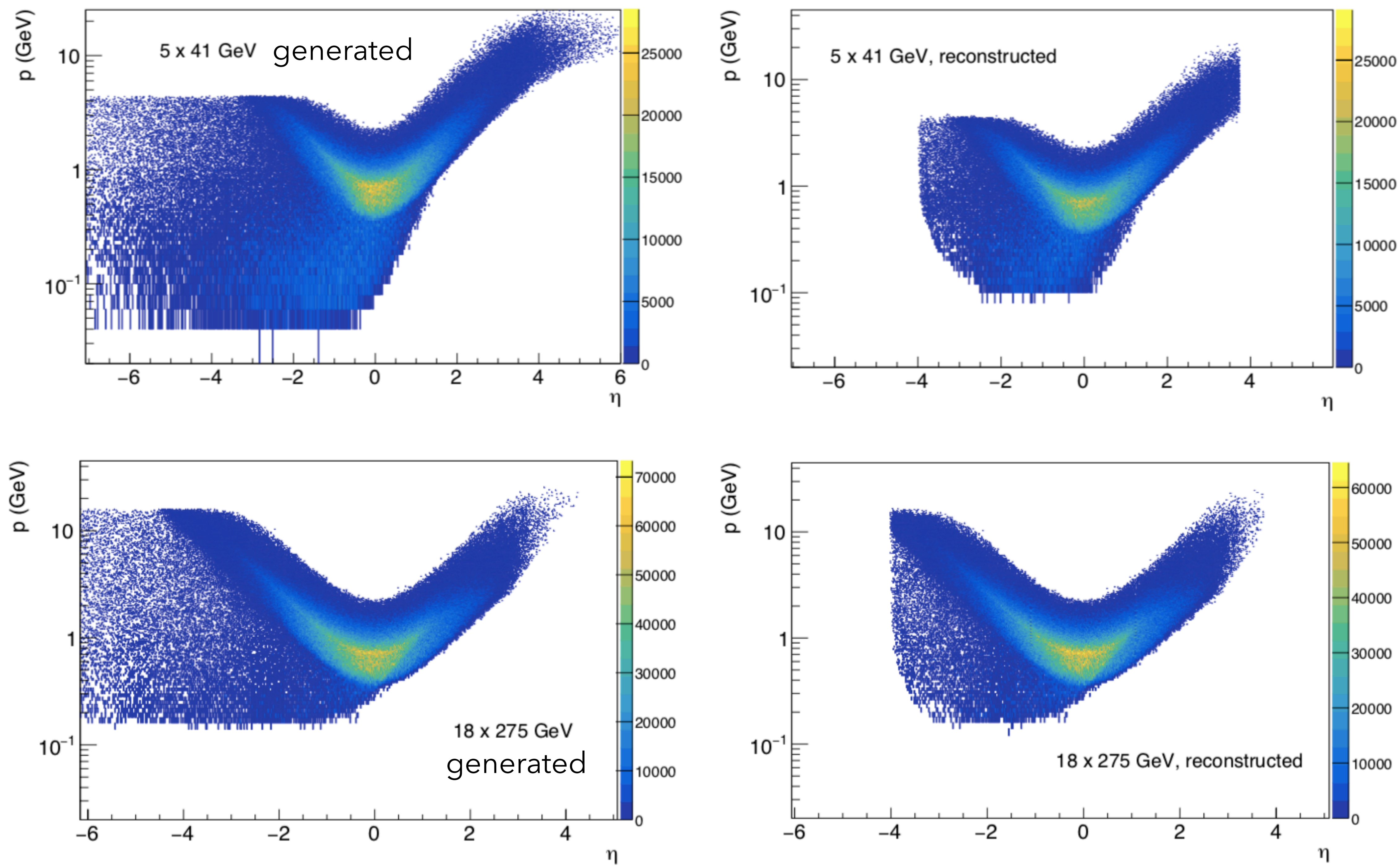
- Enables measurement on neutron in deuterium: quark-flavour separation of GPDs, sensitivity to other Compton Form Factors (eg: Im E in DVCS beam-spin asymmetry on neutron vs Im H in BSA on proton).
- Both the spectator proton and the scattered neutron tagged in the measurement.
- Spectator proton is used to determine initial neutron momentum, to enable reconstruction of *t*:



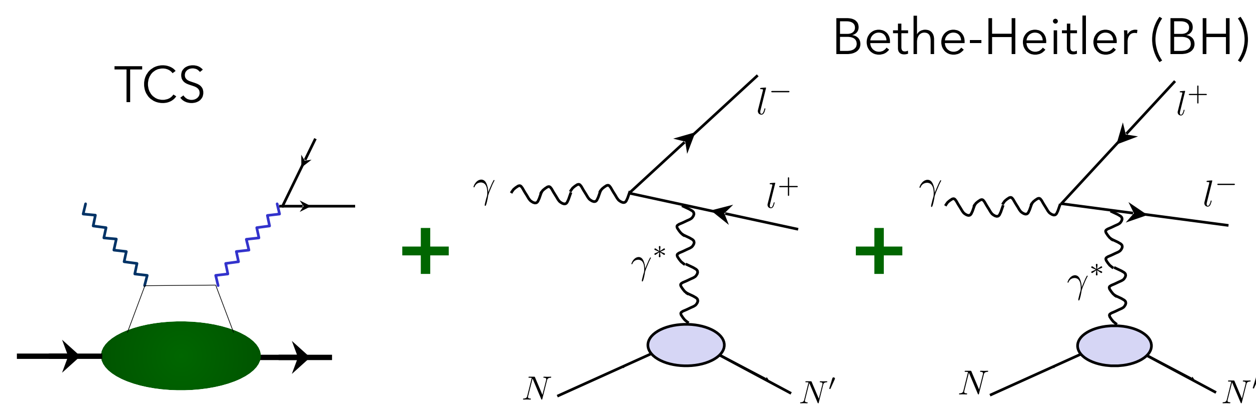
- Scattered neutron tagged in ZDC: loss of *t*-acceptance at high *t* is due to limitations of ZDC acceptance. Can obtain better *t* acceptance from electron - photon.

TCS e⁺e⁻

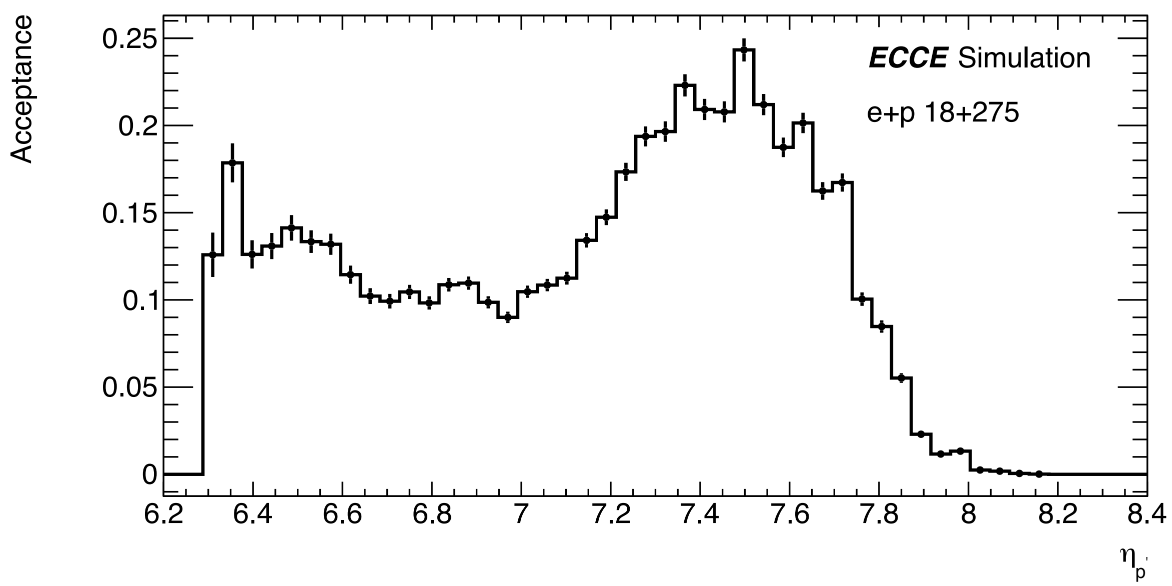
- TCS-produced virtual photon decays into e^+e^- pairs at mid-rapidity – need excellent acceptance in central region (barrel+ end-caps), as scattered electron will in general be reconstructed though missing mass and momentum (low-Q^2 tagger can provide direct detection only in a part of the phase space).

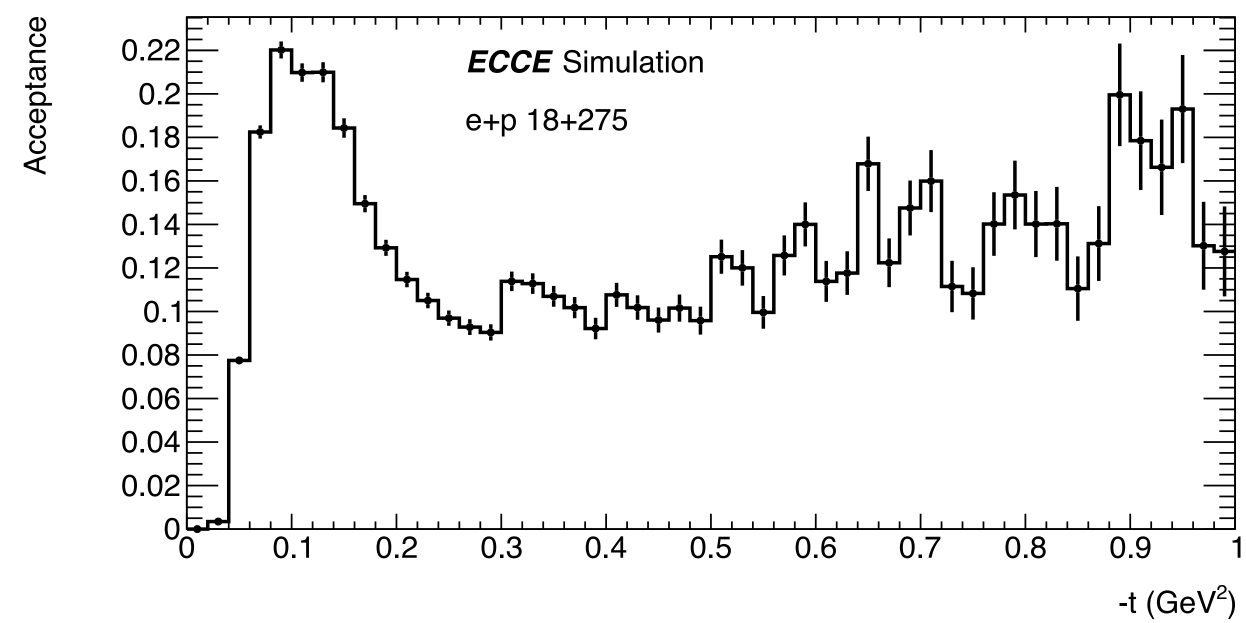


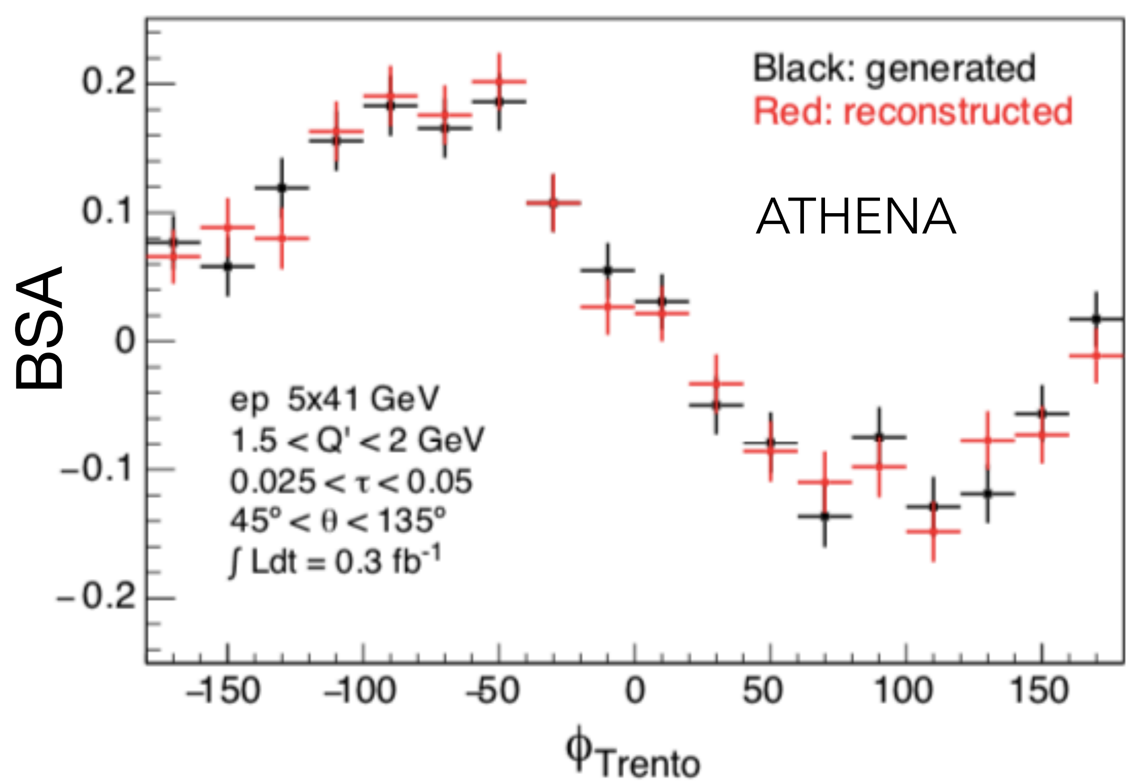
TCS (+ BH + Int) e^+e^-: observables

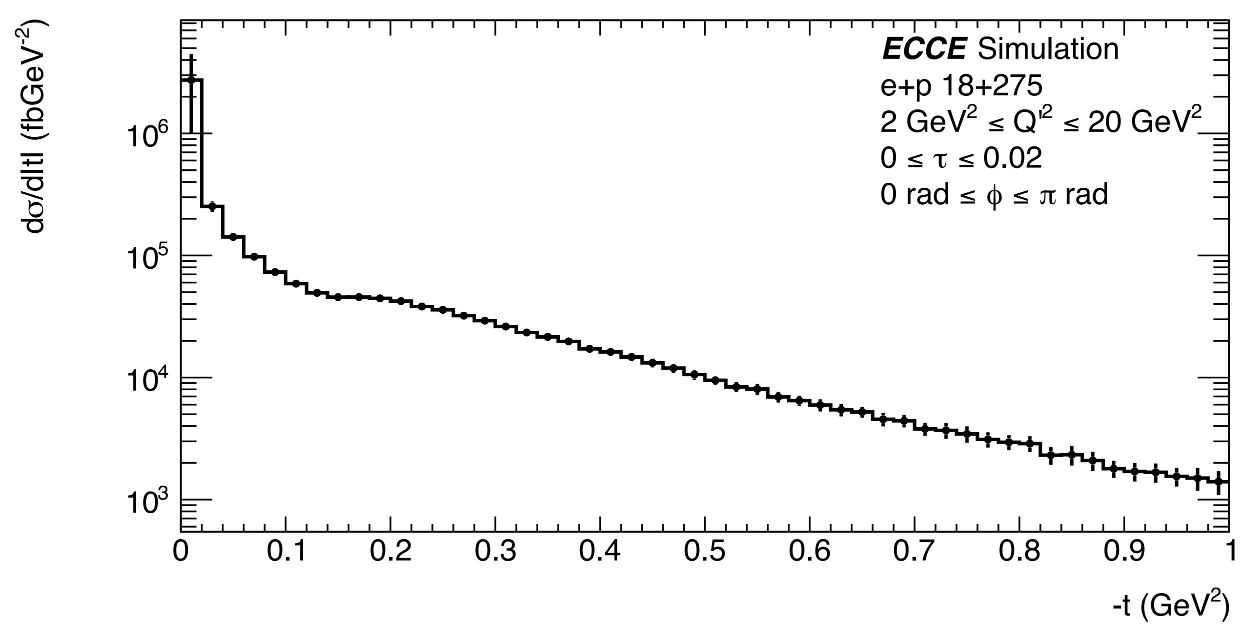


$$\sigma(\gamma p \rightarrow p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$



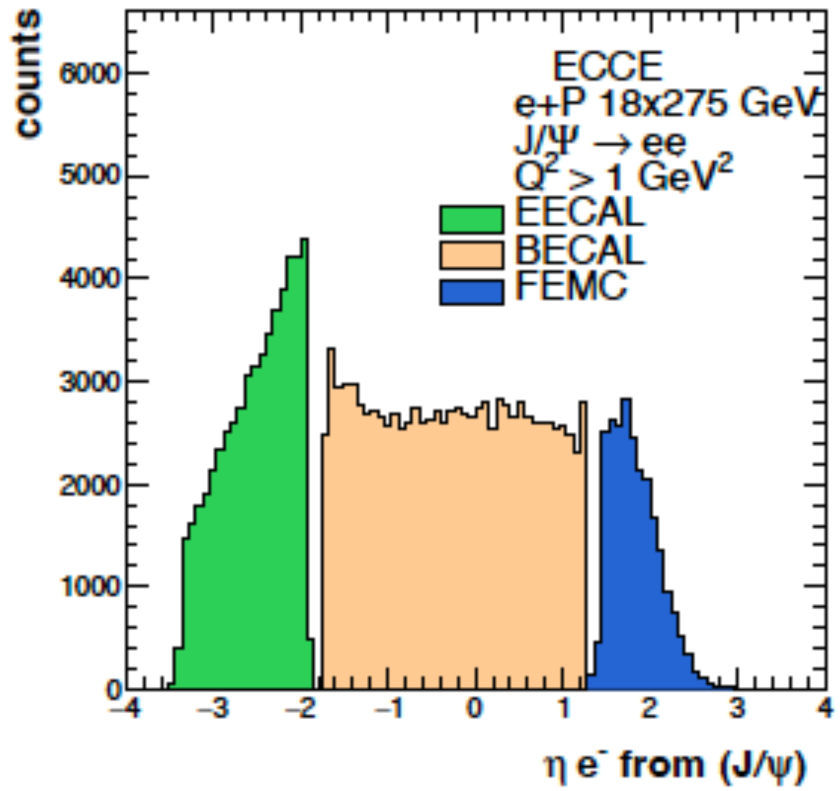


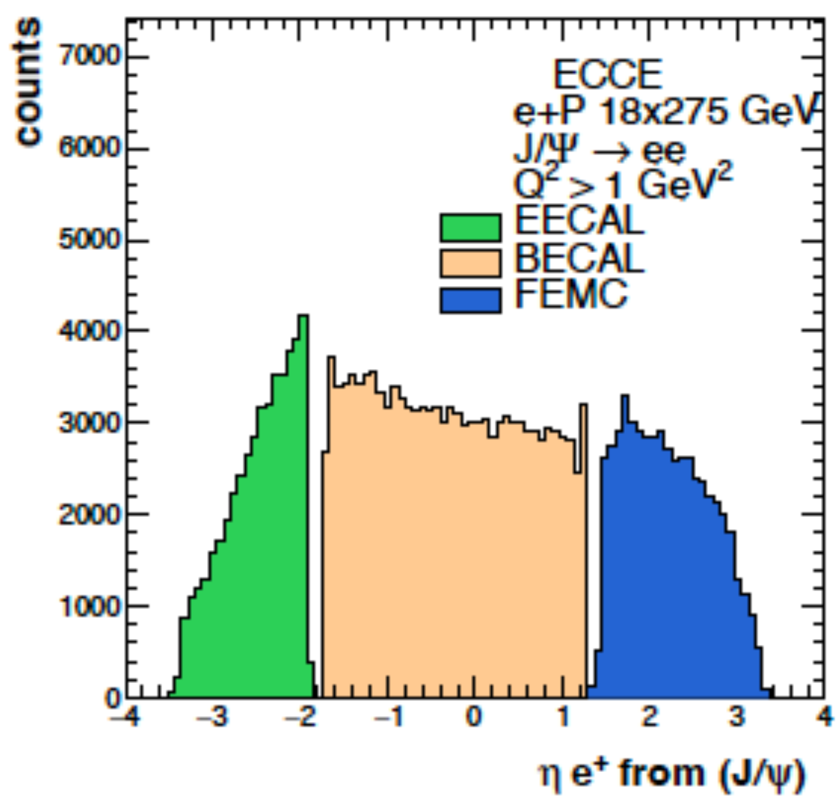


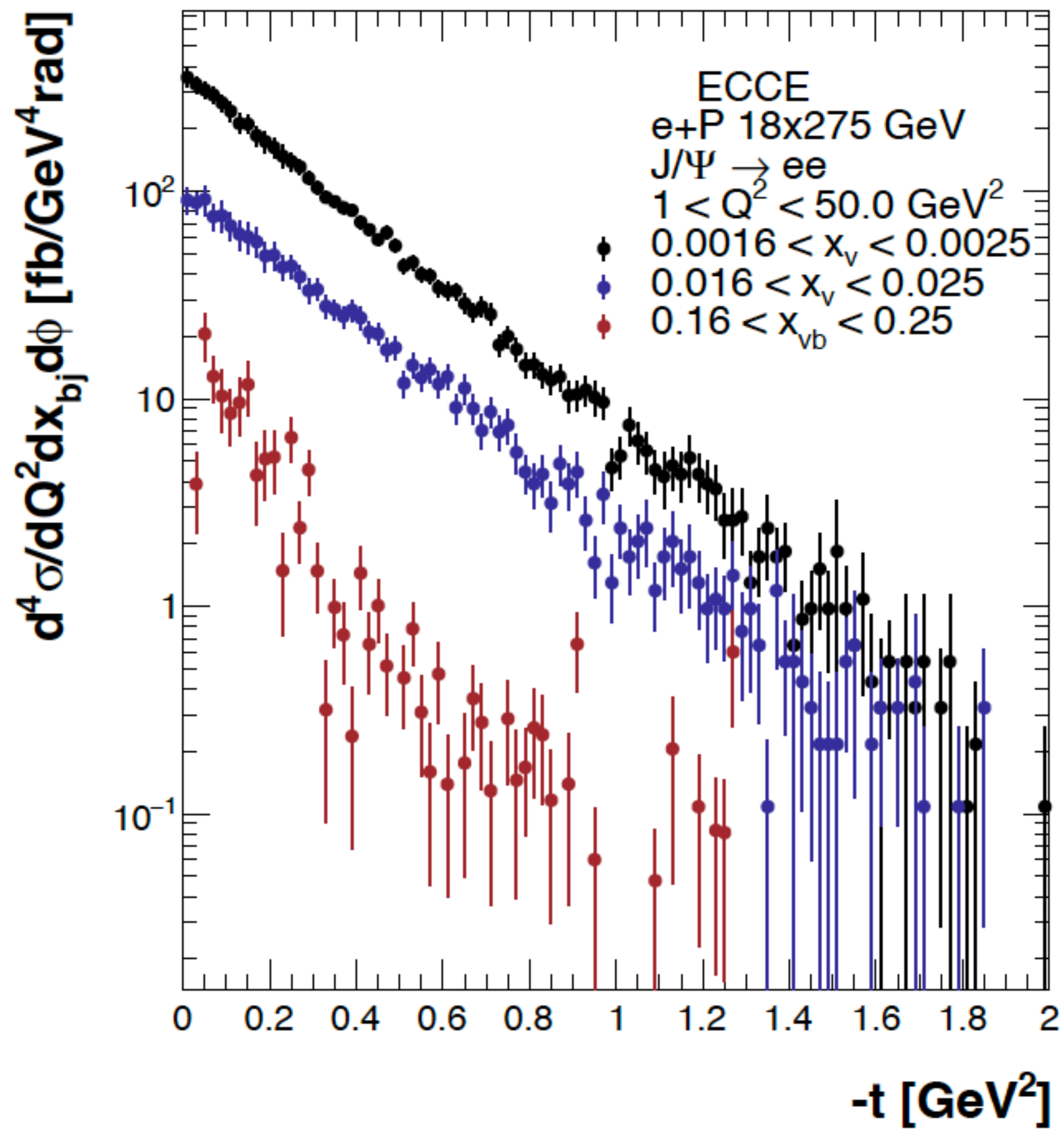


Plots: Kayleigh Gates (Glasgow), D.S.

J/Psi production







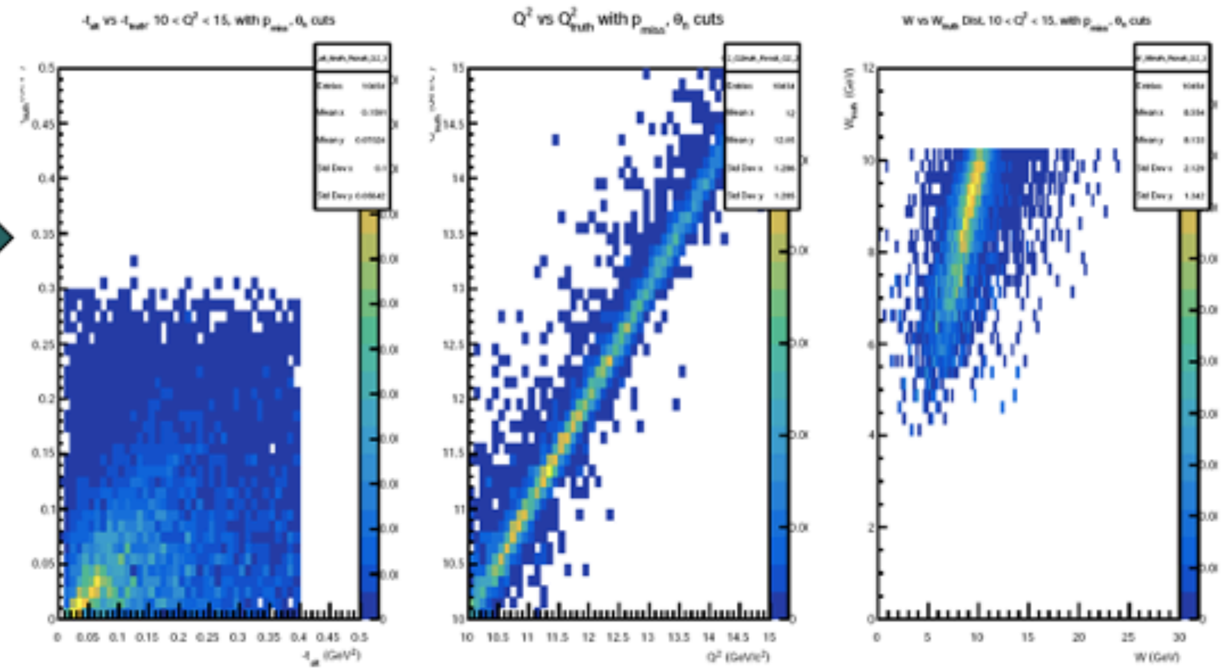
- Excellent acceptance coverage for J/Psi decay leptons
- Multi-dimensional binning

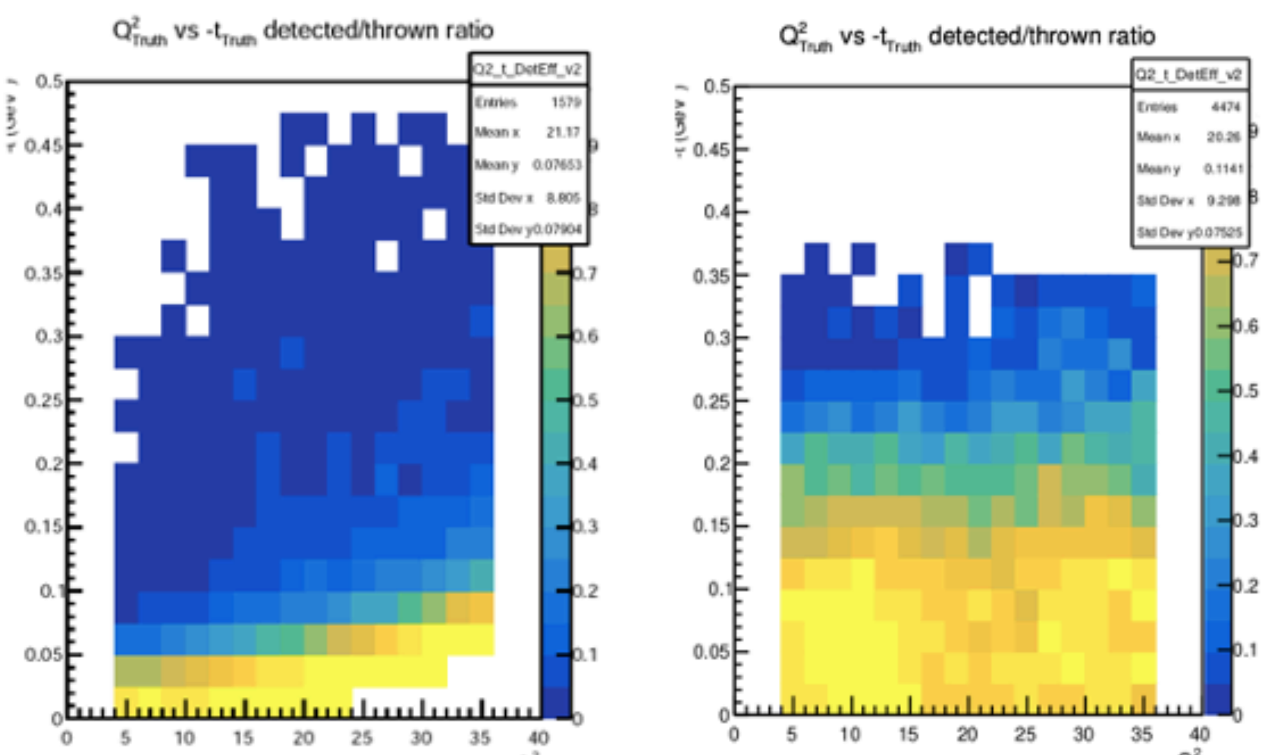
Plots: N. Santiesteban

Deep Exclusive Meson Production $p(e,e'\pi^+n)$

- **Continuing pion form factor studies with 5x100 beam profiled in Yellow Report and ECCE proposal**
- Investigating 5x41 and 10x100 and comparing IR6:IR8, to better understand detector requirements, and improve overlap w/JLab-12

$-t, Q^2, W$: reconstr (x) vs true (y)
→ excellent reconstruction resolution for $10<Q^2<15$ @ 5x100





5x41 10x100

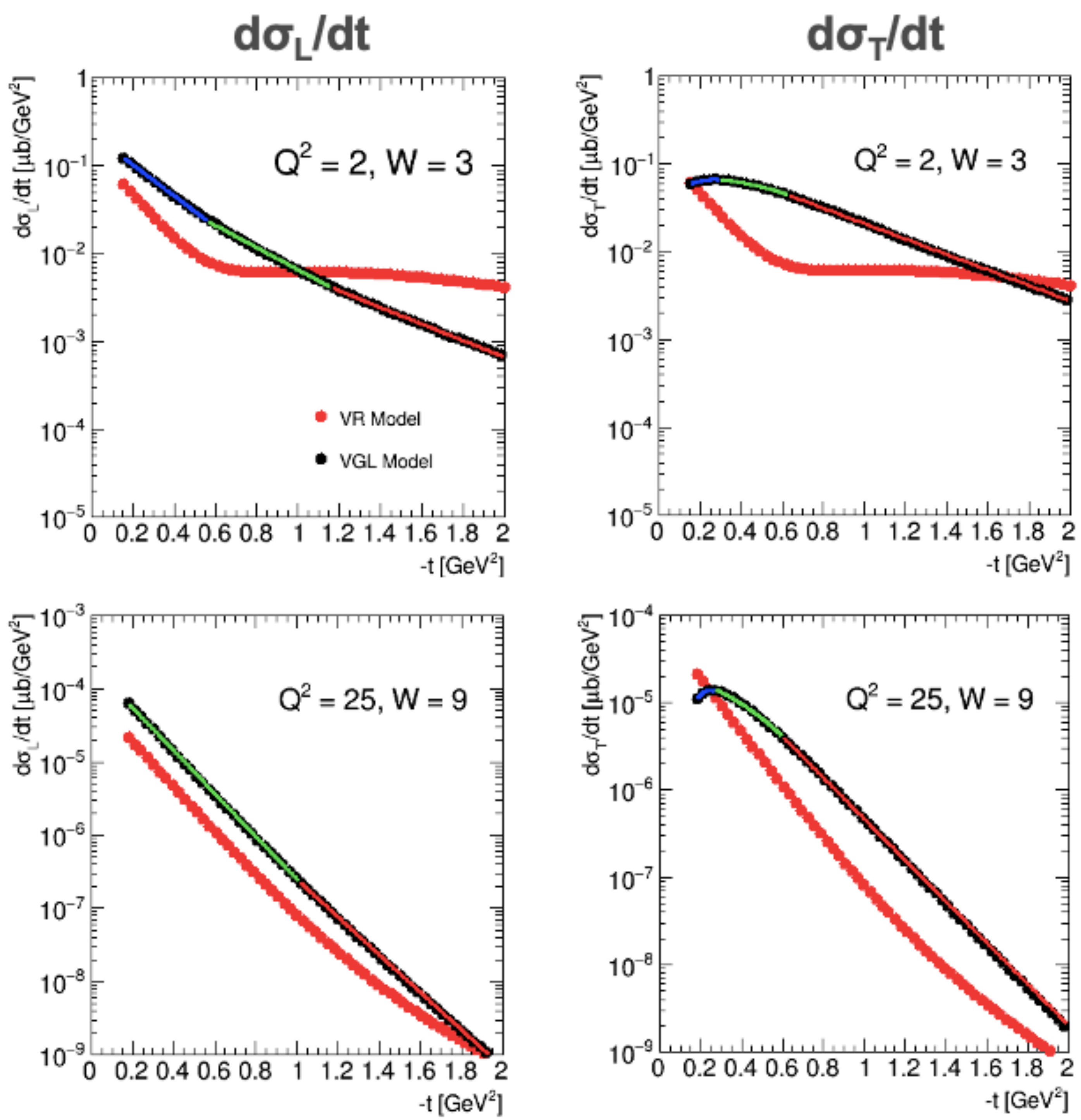
IR6 detect effic vs Q^2, $-t$:
Triple coin after cuts
Effic higher @ 10x100
Study still in progress

Plots by Stephen Kay (Regina) & Maggie Kerr (Mt Allison)

University of Regina

Deep Exclusive Meson Production *$p(e,e'K^+\Lambda)$*

- **Writing an improved exclusive K^+ physics generator, to enable feasibility studies of K^+ form factor measurements at EIC**



Plots by Love Preet (Regina)

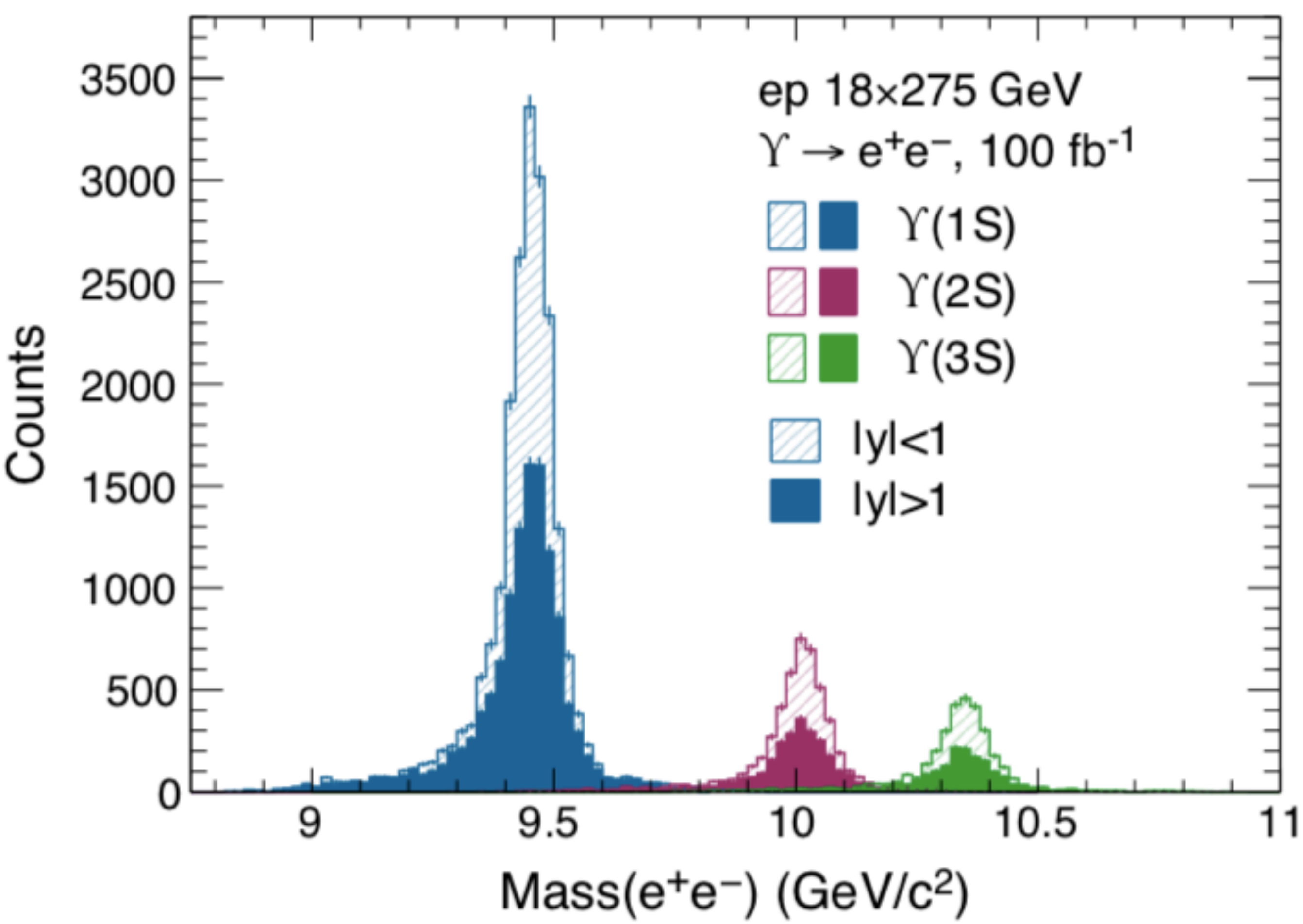
- We compared Vrancx-Ryckebush (VR) and Vanderhaeghen-Guidal-Laget (VGL) Regge models of exclusive K^+ electroproduction
- **DEMP event generator will use a parameterization of $d\sigma_L$, $d\sigma_T$ from VGL model for $2<W<10$, $1<Q^2<35$, $0<-t<2.0$,** as it behaves better at high $-t$
- Implementation and testing of the generator is in progress

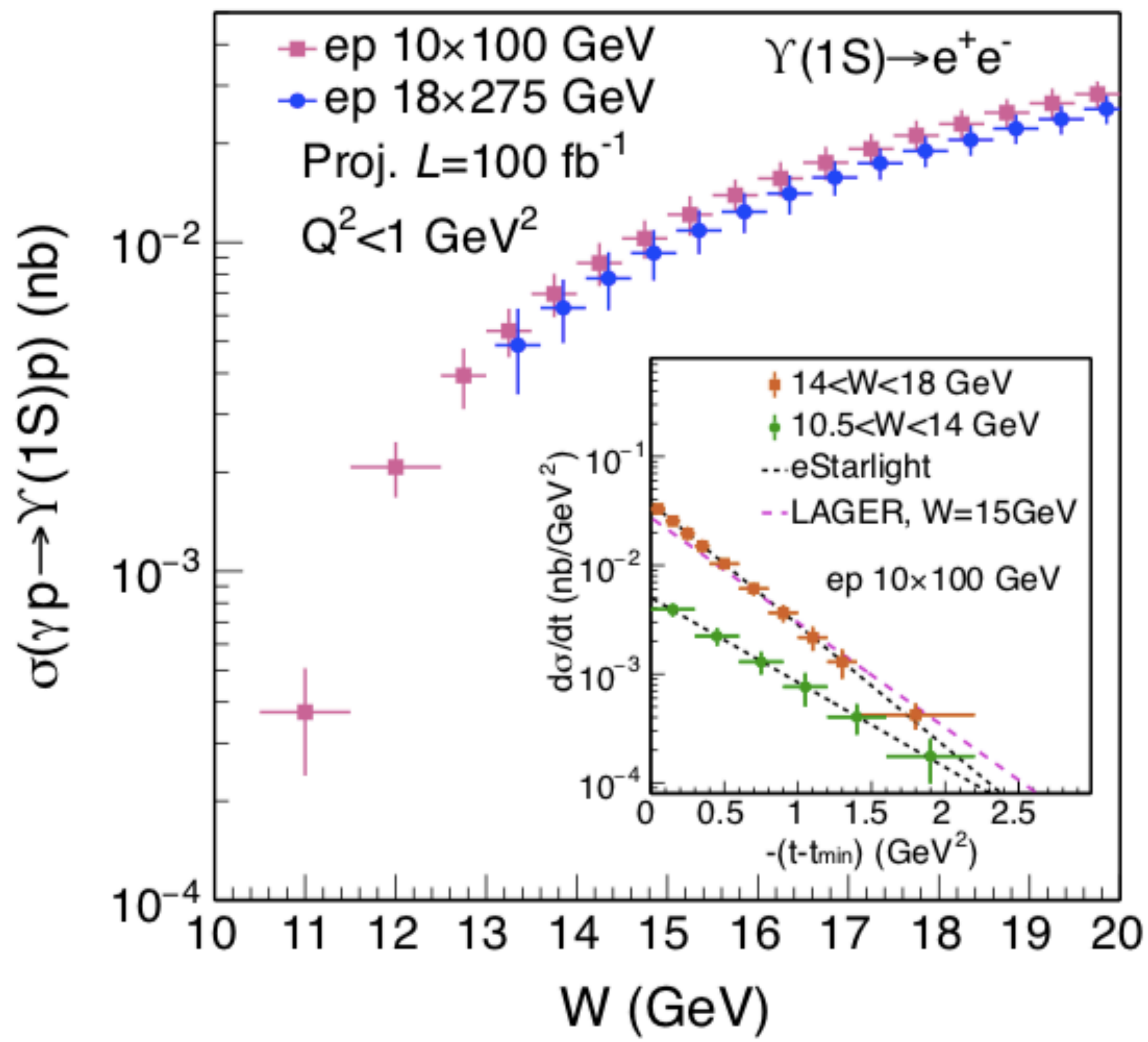
University of Regina

Upsilon-production

- Sensitivity to gluon distributions, information on colour correlations, upsilon-proton scattering lengths, possibly saturation. Near-threshold production: little-known, twist-4 effects contribute significantly.

Photoproduction ($Q^2 < 1$ GeV^2) and electroproduction ($Q^2 > 1$ GeV^2).

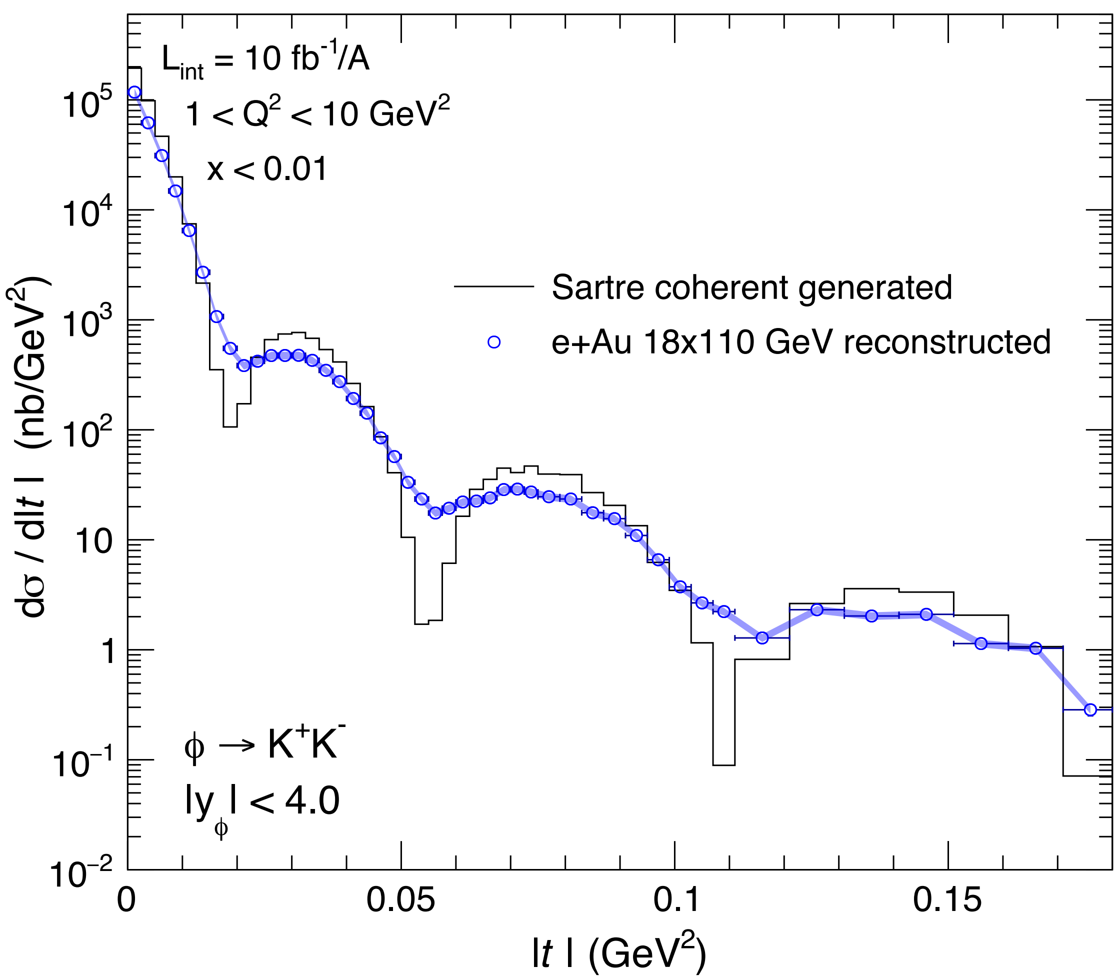




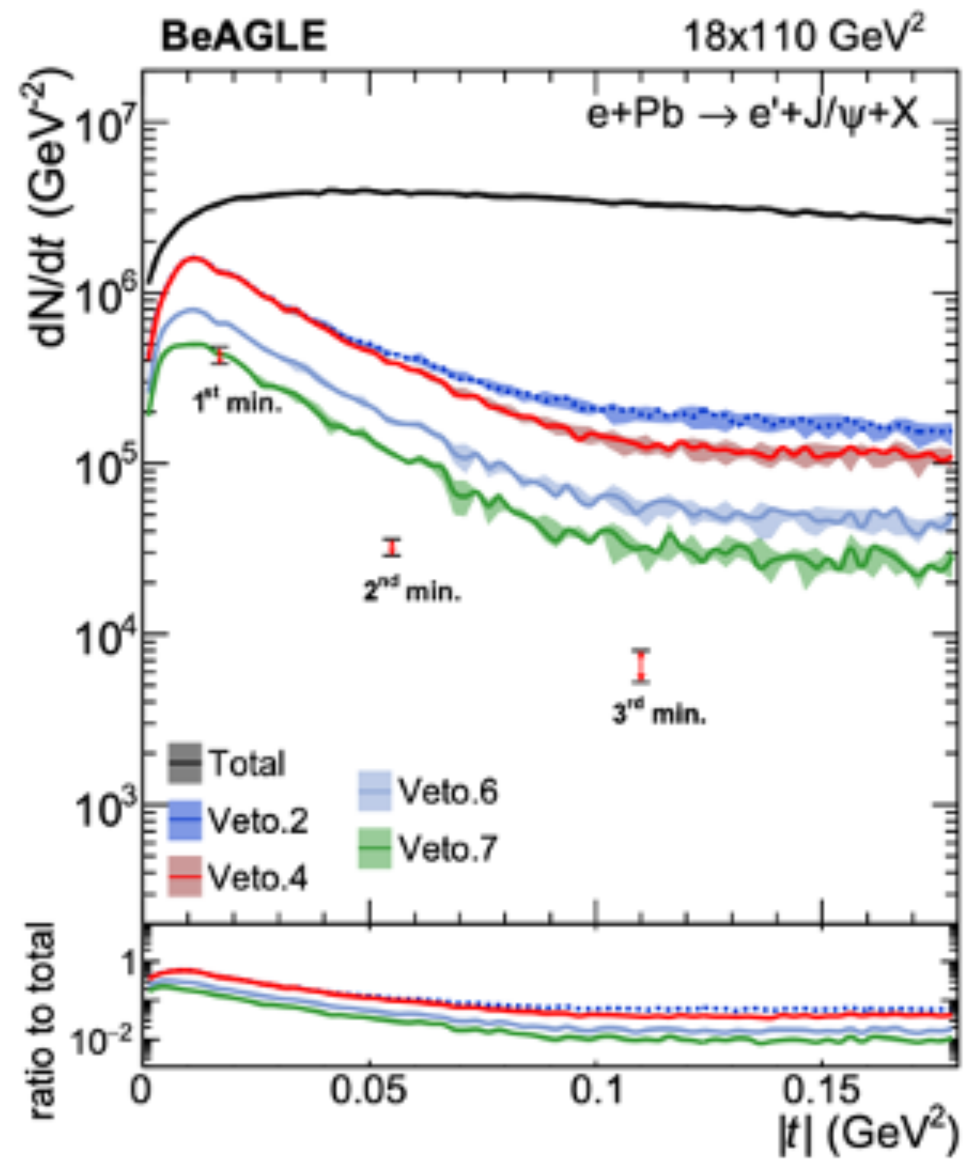
Plots: Yuangjing Ji (LBNL)

Coherent VM production in eA

- Gluon distributions in nuclei and a probe of saturation (in Q^2-depedence).
- Detector challenge: reconstruct t from leptons and mesons, not from nuclei (these escape undetected): resolution is crucial to identify t minima.
- Suppression of incoherent background by vetoing nuclear break-up in Far-Forward detectors.



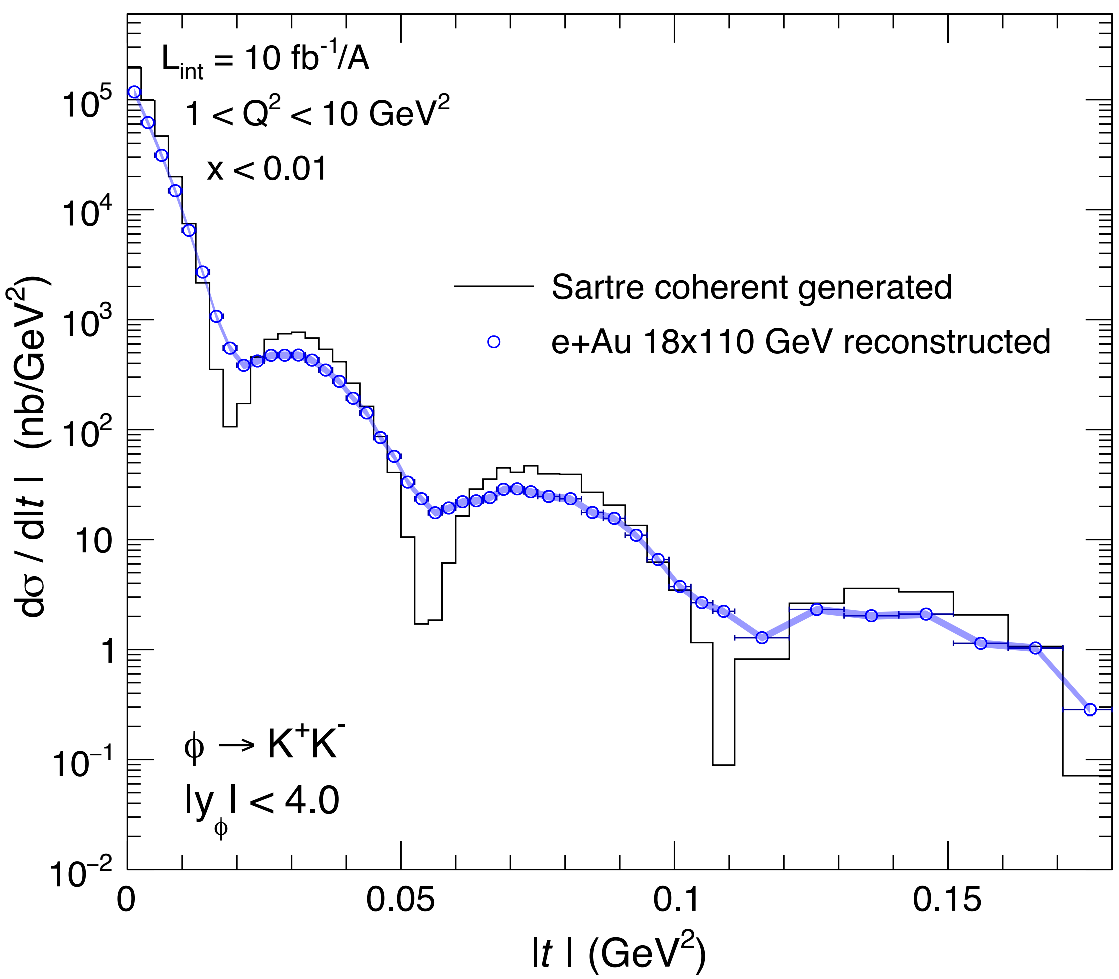
Plot: Kong Tu (BNL)



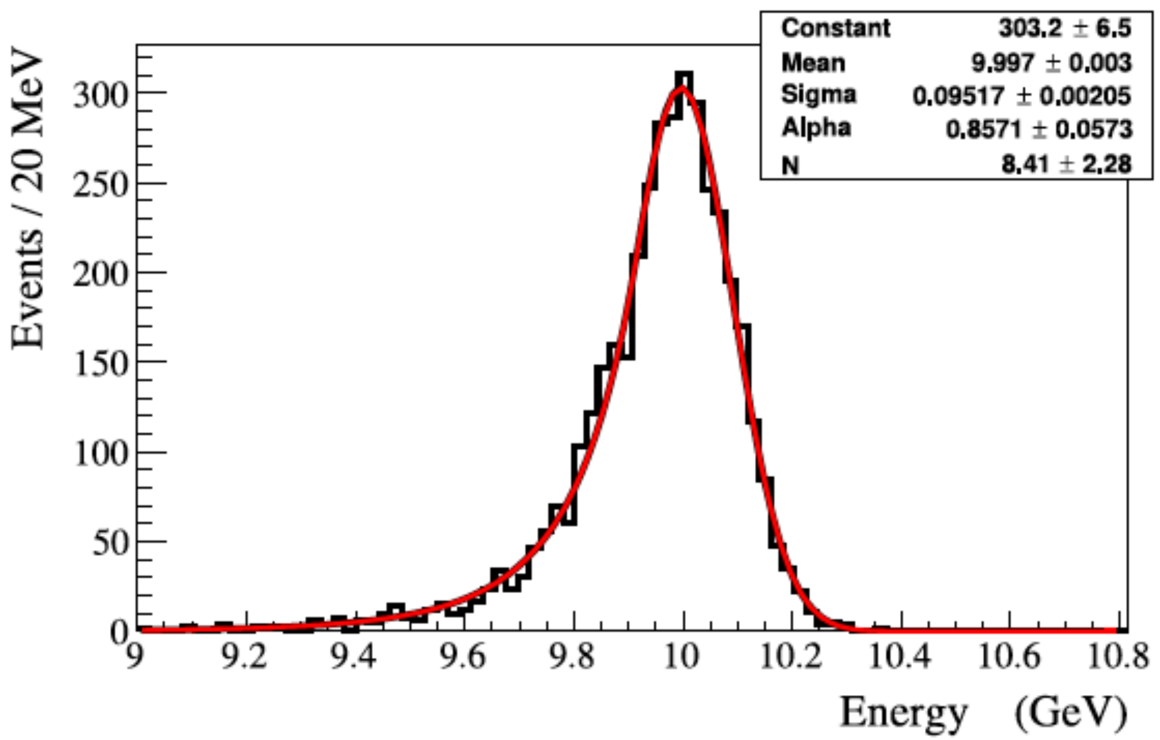
Phys. Rev. D **104**, 114030

Coherent VM production in eA

- Gluon distributions in nuclei and a probe of saturation (in Q^2-depedence).
- Detector challenge: reconstruct *t* from leptons and mesons, not from nuclei (these escape undetected): resolution is crucial to identify *t* minima.
- Suppression of incoherent background by vetoing nuclear break-up in Far-Forward detectors.



Plot: Kong Tu (BNL)

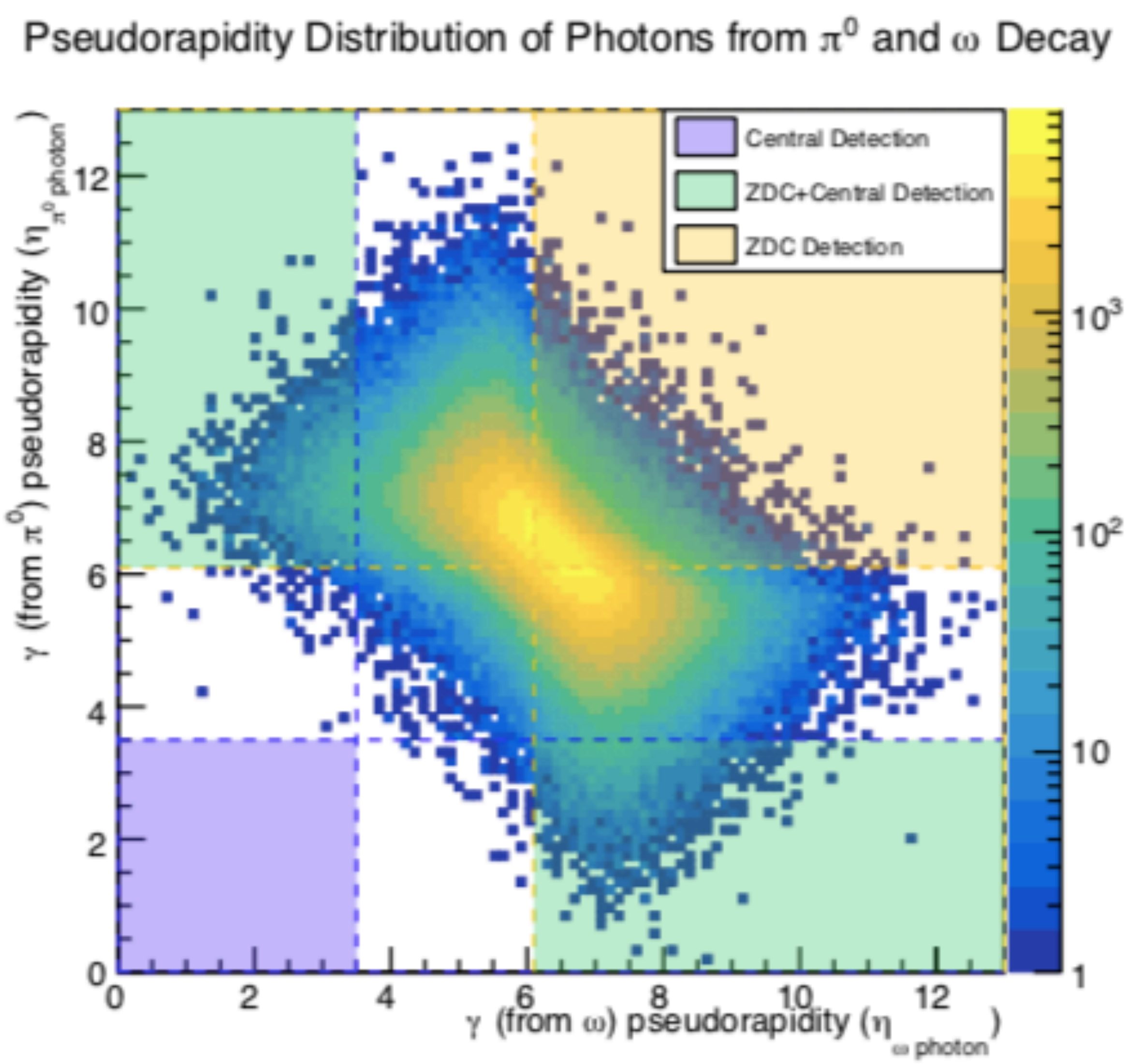


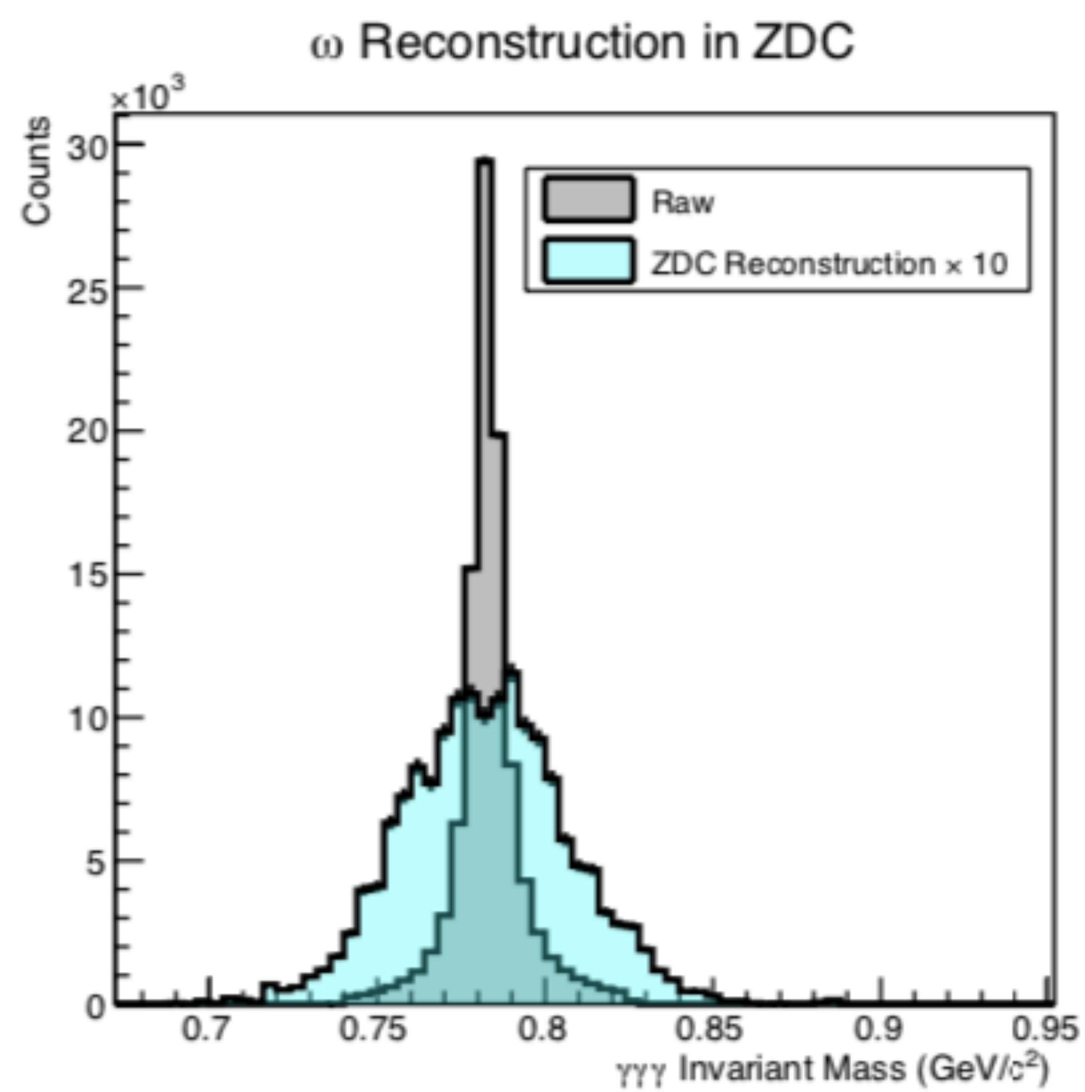
Nucl.Instrum.Meth.A 1013 (2021) 165683

Beam tests of $PbWO_4$ crystals at JLab: non-Gaussian tail in the electron energy reconstruction

Backward production of omega

- Similar to normal meson photo-production, but proton at mid-rapidity and meson goes forward with high momentum: u-channel.
- Sensitivity to Transition Distribution Amplitudes (TDA).
- Proton (a few hundred MeV) detected in central detector. Photons from meson decay detected in a combination of central and ZDC. $\omega \to \pi^0 \gamma$

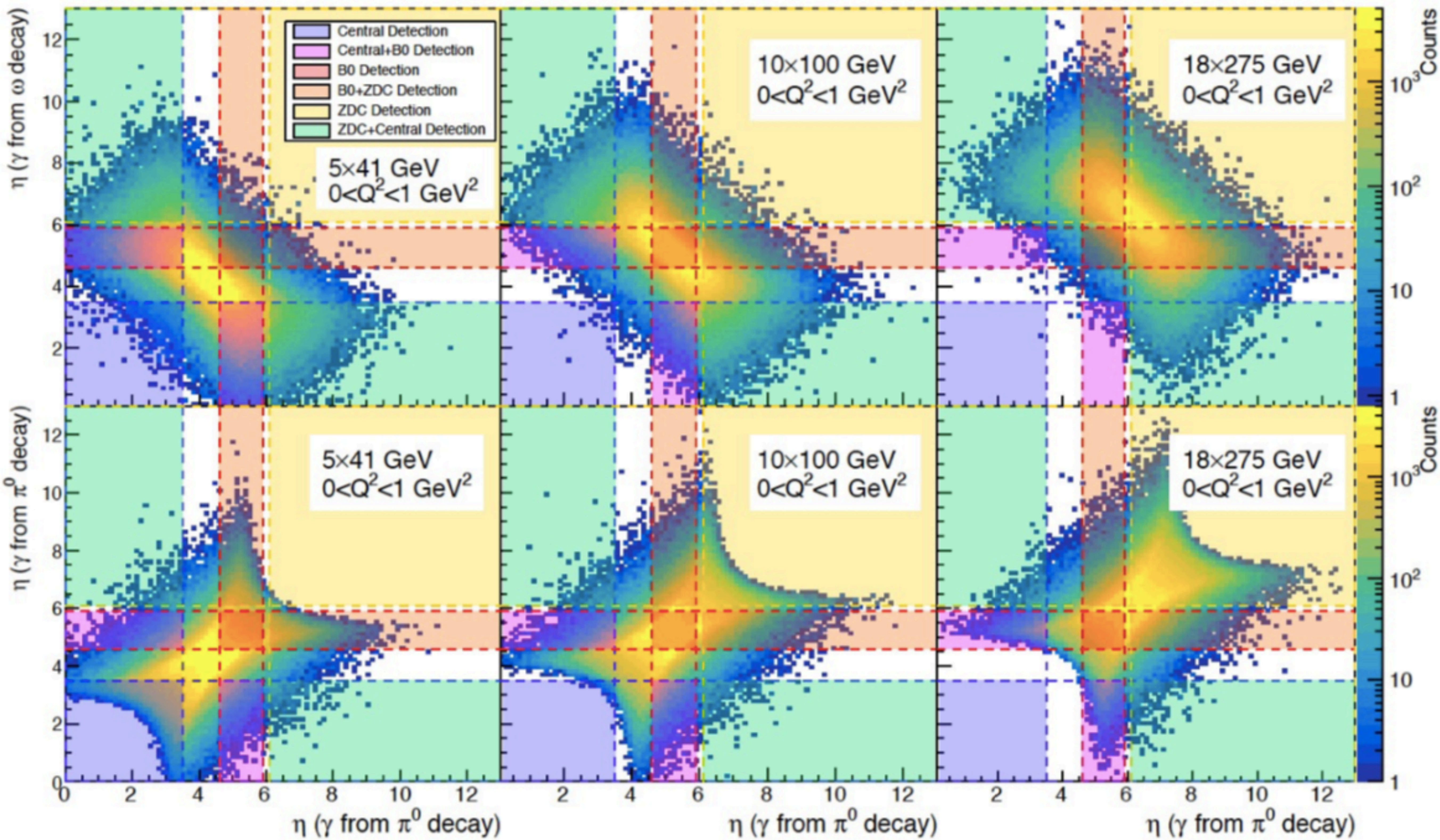




Plots: Zachary Sweger (UC Davis)

18 x 275 GeV, $Q^2 < 1$ GeV^2

Backward production of omega

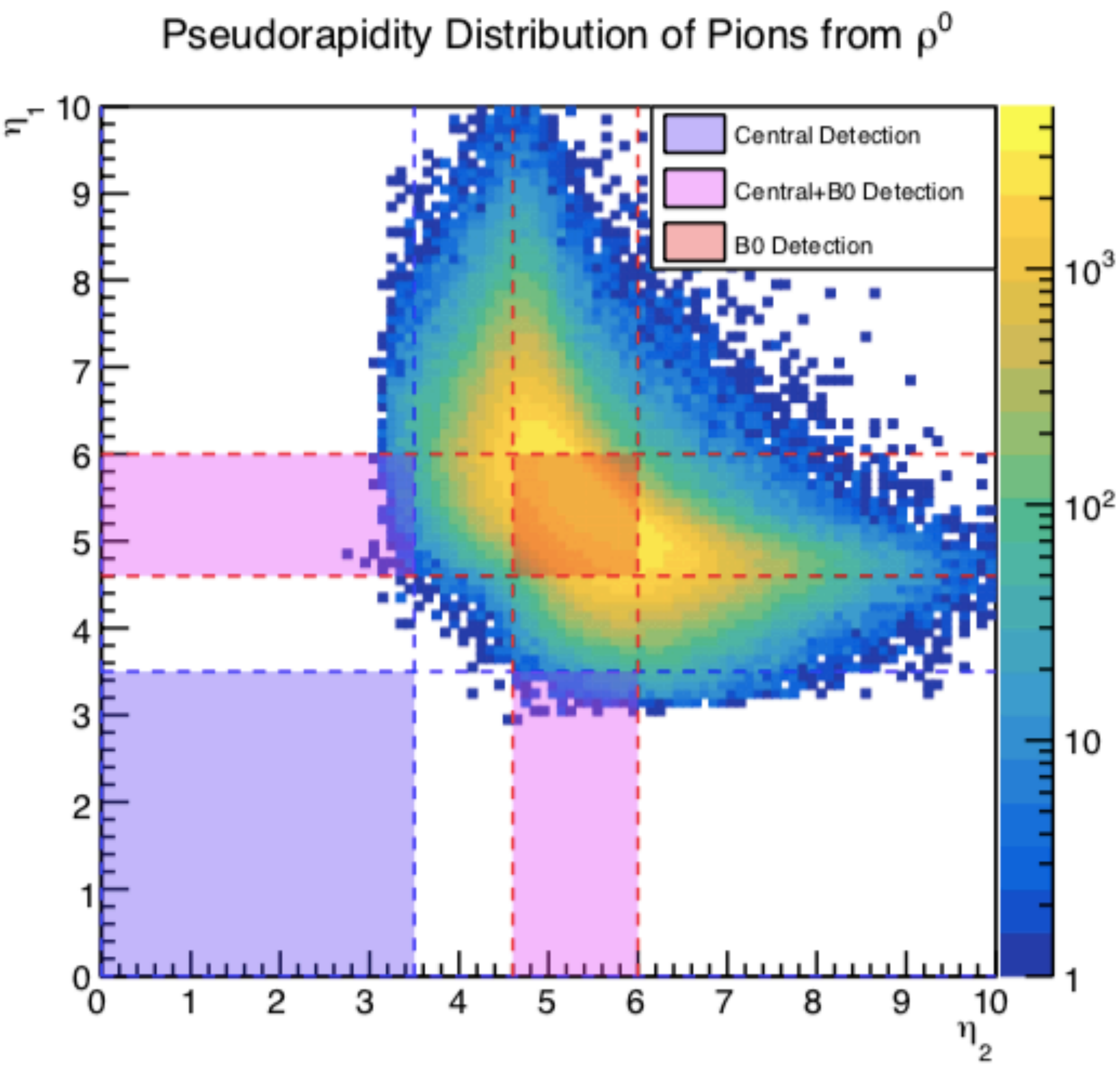


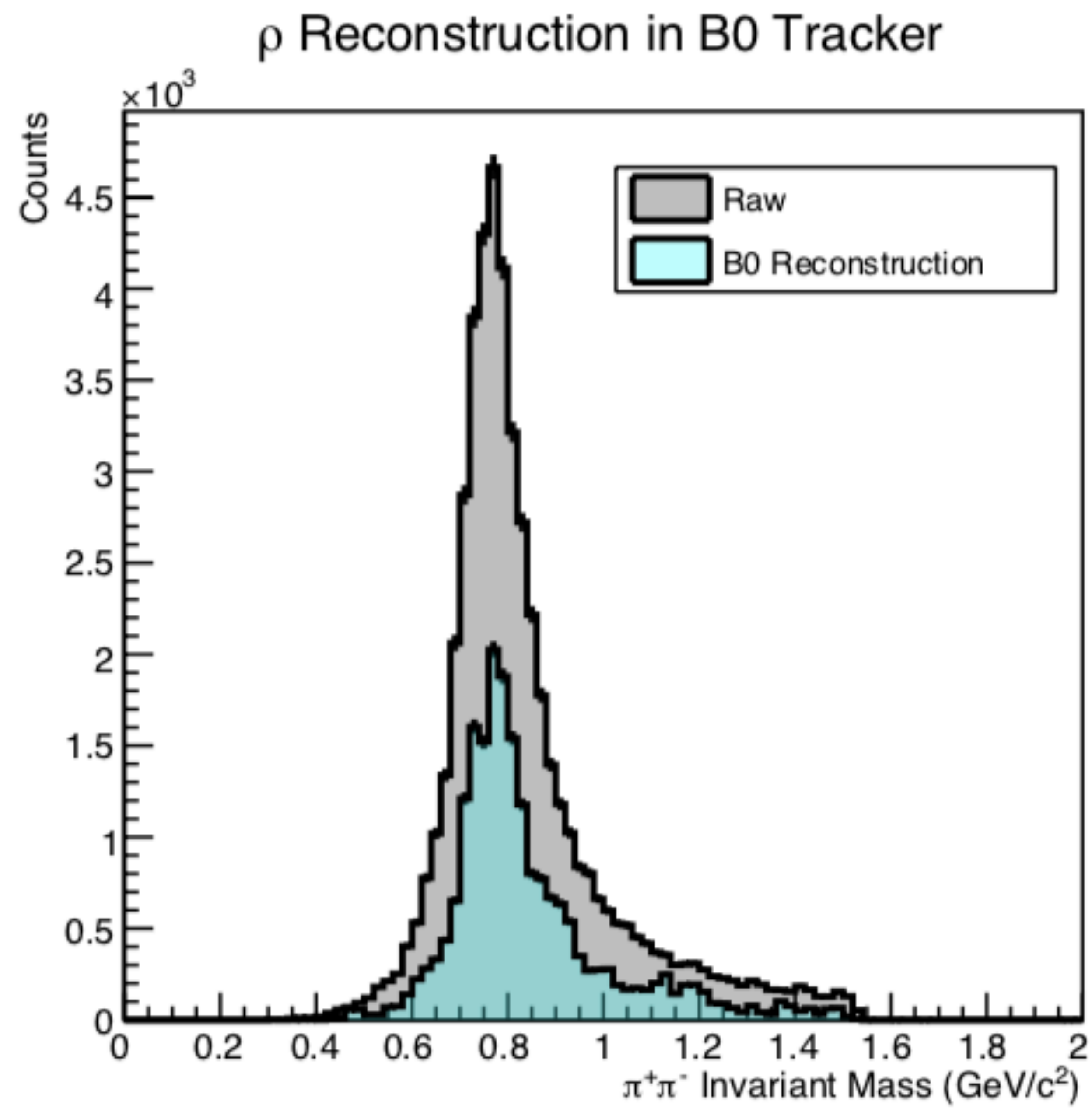
Proton beam energy	ω eff. cent.+ZDC	ω eff. cent.+B0+ZDC
41 GeV	1.4%	18%
100 GeV	1.3%	41%
275 GeV	6%	63%

Plots: Zachary Sweger (UC Davis)

Backward production of rho

- Charged mesons in the u-channel production can also be reconstructed using Central detector, ZDC and B0 tracker. $\rho \to \pi^+\pi^-$

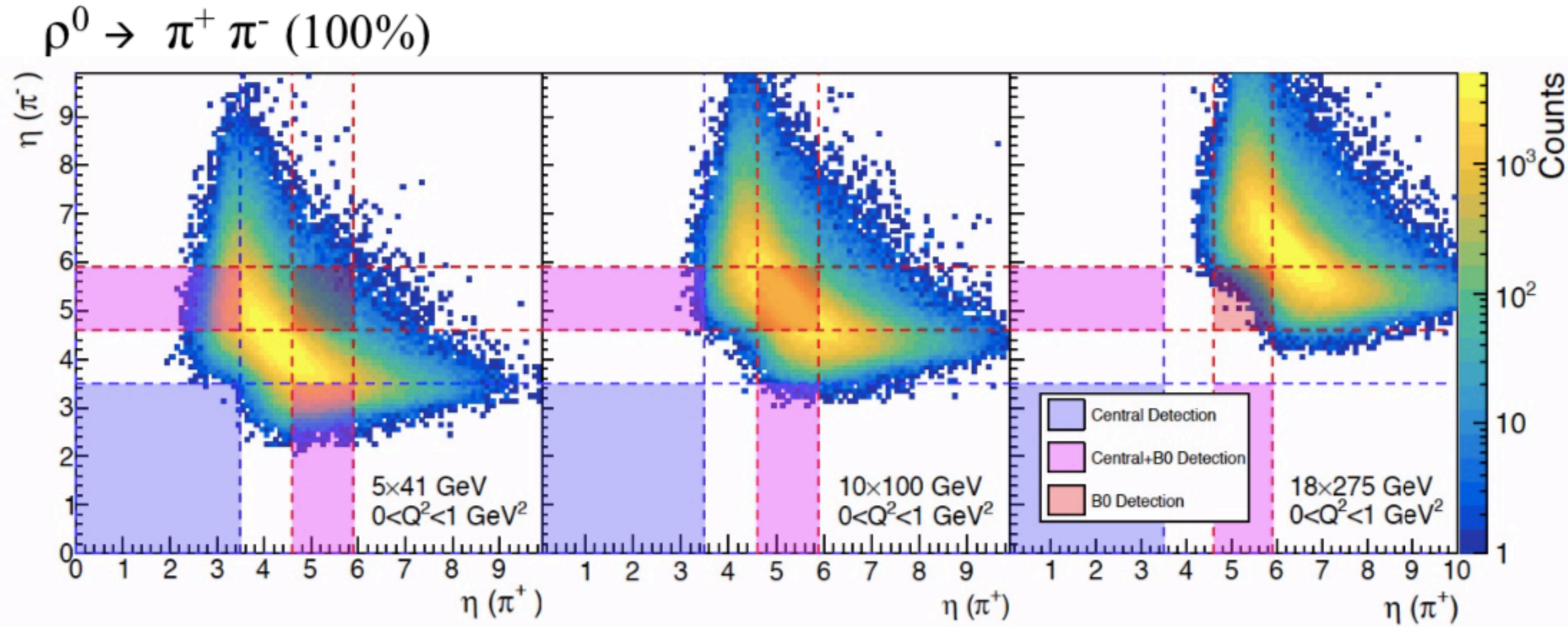




10 x 100 GeV, $Q^2 < 1$ GeV^2

Plots: Zachary Sweger (UC Davis)

Backward production of rho



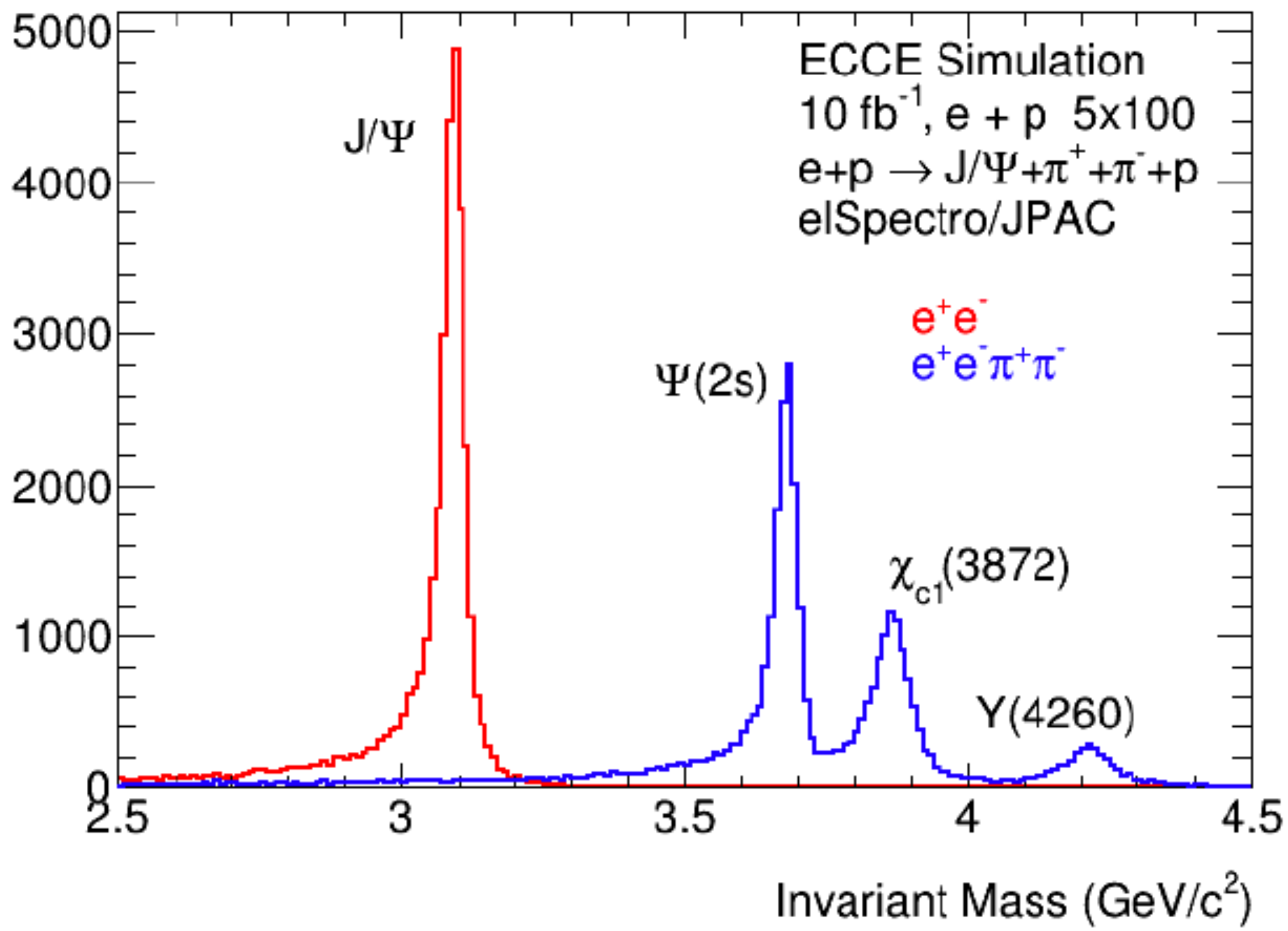
Proton beam energy	ρ eff. cent.+B0
41 GeV	13%
100 GeV	49%
275 GeV	0.7%

- Paper published:

https://link.aps.org/doi/10.1103/PhysRevC.106.015204

Plots: Zachary Sweger (UC Davis)

XYZ Spectroscopy



- XYZ Spectroscopy, spectroscopy of mesons with charm quarks
- New XYZ states have unexpectedly narrow widths inconsistent with quark model predictions
- Resolution sufficient to separate states
- Some kinematics and decays may benefit from low Q^2 tagger

Plots: Derek Glazier (Glasgow)

Survey of topics and person-power

* DVCS
* DVCS with He-4
* Incoherent DVCS on deuteron
* TCS
* Exclusive / diffractive vector mesons – needs hands as many channels of interest, study electron acceptance
* Upsilon production
* J/Psi in ep
* Background estimations of VM photo- and electroproduction, quarkonia at threshold and sub-threshold.
* Backwards (u-channal) production: vector mesons, photon.
* Pion / kaon form factors
* Pion / kaon structure functions
* XYZ Spectroscopy – needs background events at low Q2
* Lambda in the target fragmentation

Summary

* WG meeting roughly fortnightly
* All studies from the proposal stage are continuing: refinement of generators and analysis strategies, simulations with updated detector geometries
* Some studies from proposal stage are already published or submitted for publication:

  U-channel production: https://link.aps.org/doi/10.1103/PhysRevC.106.015204

  ECCE Exclusive, Diffractive & Tagging studies submitted to NIM A.

* Spectroscopy publication in preparation. Intention to publish ATHENA WG studies.
* Conducted survey of current studies / future interest from WG members: 16 responses, some additional channels mentioned.
* Will seek closer cooperation with the software group – development of benchmarks.


Thank you!
Any questions?

TCS observables

- Unpolarised cross-sections:
  sensitive to $\mathcal{R}e\ \mathcal{H}$.

$$\frac{d^4\sigma_{INT}}{dQ'^2 dt d\Omega} = A\frac{1+\cos^2\theta}{\sin\theta}[\cos\phi\ \mathrm{Re}\tilde{M}^{--} - \nu\cdot\sin\phi\ \mathrm{Im}\tilde{M}^{--}]$$

$$\tilde{M}^{--} = \left[F_1\mathcal{H} - \underbrace{\xi(F_1+F_2)\tilde{\mathcal{H}}}_{} - \underbrace{\frac{t}{4m_p^2}F_2\mathcal{E}}_{}\right]$$

suppressed

- Circularly-polarised photon cross-section: access to $\mathcal{I}m\ \mathcal{H}$.
- More promising observables: asymmetries and cross-section ratios.
- Photon-polarisation (beam-spin) asymmetry:

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

access to $\mathcal{I}m\ \mathcal{H}$

- Forward - backward asymmetry:

$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ-\theta, 180^\circ+\phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ-\theta, 180^\circ+\phi)}$$

access to $\mathcal{R}e\ \mathcal{H}$

P. Chatagnon et al. (CLAS): arXiv:2108.11746 [hep-ex], *accepted (PRL)*

DVCS and TCS

- **DVCS in ep** – EpIC generator – Salvatore Fazio (INFN Calabria)

18 x 275, 5 x 100, 5 x 41 GeV^2

10M events at each setting

Using Goloskokov-Kroll model

Kinematic acceptance cuts:

$10^{-4} < x < 0.6$

$1 < Q^2 < 100\ GeV^2$

$0.01 < y < 0.95$

$0.01 < |t| < 1.6\ GeV^2$

Golden channel summaries

* **TCS in ep** – EpIC generator
– Daria Sokhan (Saclay / Glasgow), Kayleigh Gates (Glasgow)

18 x 275, 5 x 100, 5 x 41 GeV^2

Positive and negative electron helicities

10M events at each setting

Kinematic acceptance cuts:

$0 < Q^2 < 0.15$ GeV^2

$0.01 < y < 0.95$

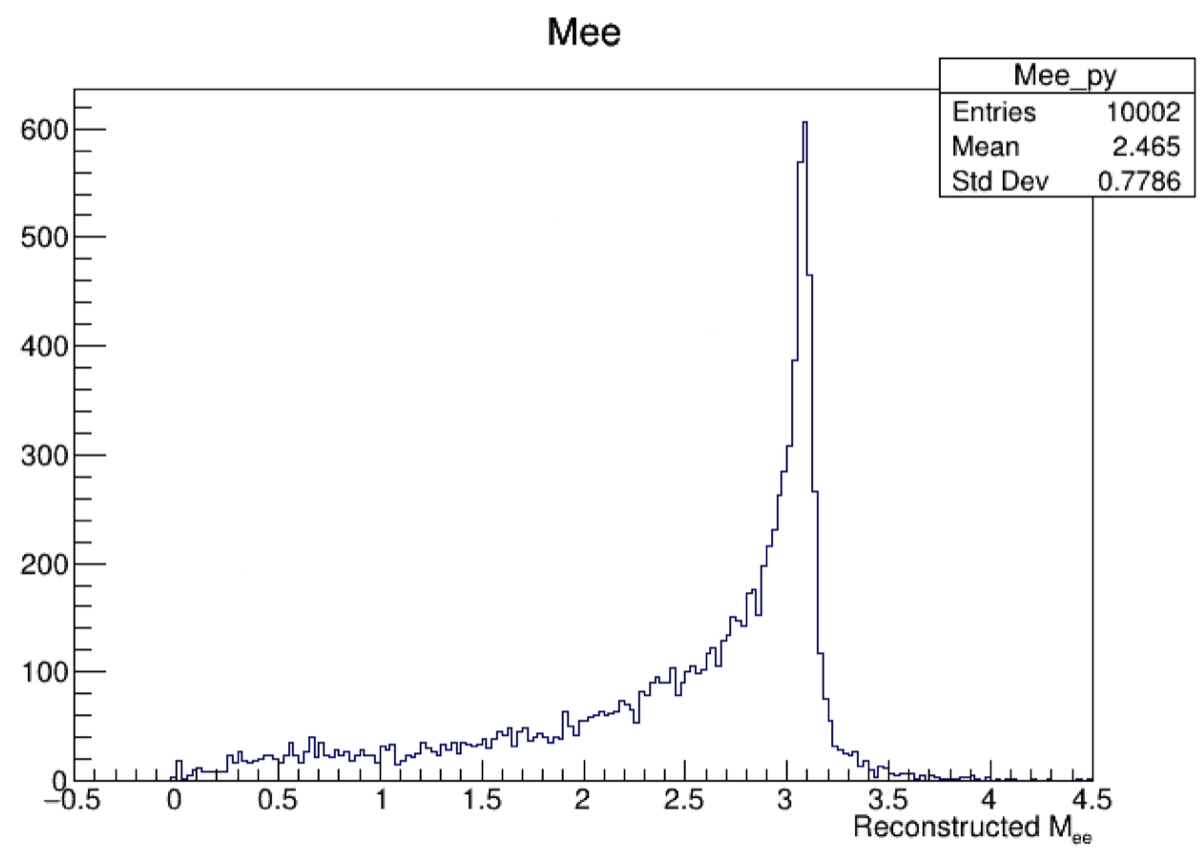
$0.01 < |t| < 1$ GeV^2

$2 < Q'^2 < 10$ GeV^2

Golden channel summaries

- **X,Y Ψ(2S) in ep -> J/Ψ $\pi^+\pi^-$ p** – elSpectro
  – Derek Glazier (Glasgow), Justin Stevens (W&M)

5 x 100 GeV^2, predominantly very low Q^2 (no cuts),
10k test-sample (processed),
300k submitted – awaiting output,
After analysis, will repeat for other beam energies.
Test sample: strong bremsstrahlung observed on the e^+e^- from the J/Ψ decay – this, however, used an old geometry and should be improved in the current frozen version.



Golden channel summaries

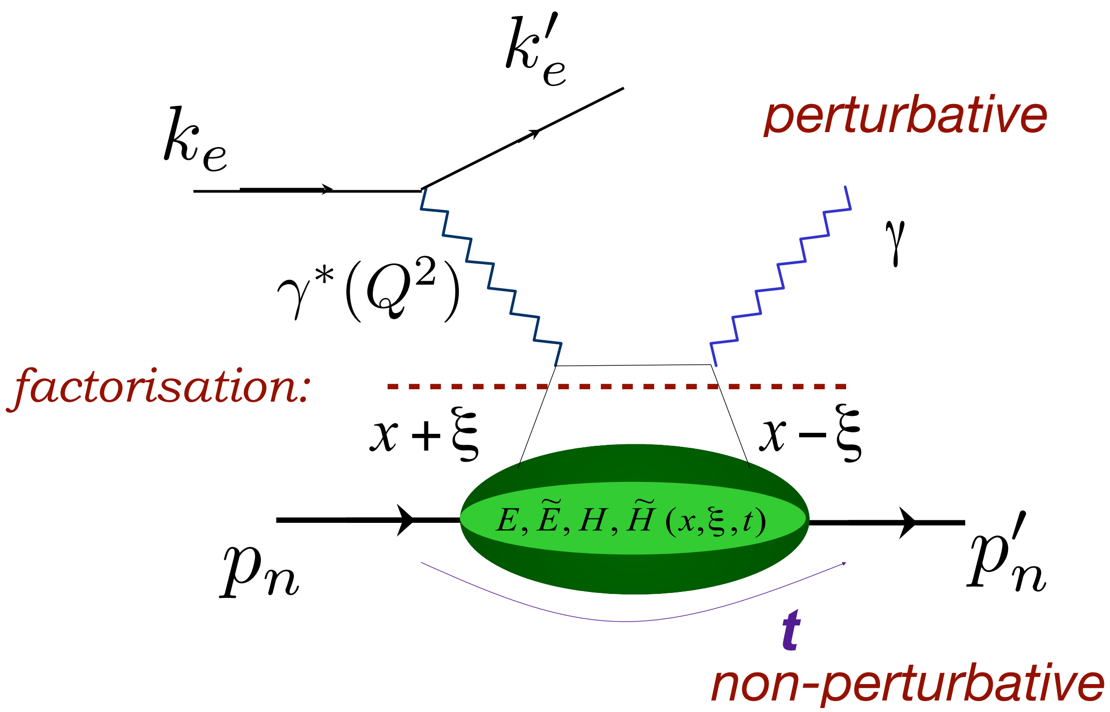
* **Φ in eAu** – SARTRE and BEAGLE – Kong Tu (BNL)

    $1 < Q^2 < 20$ GeV^2, 18 x 110 GeV^2
    10M events in SARTRE
    100k events in BEAGLE
    $Q^2 < 0.2$ GeV^2, 18 x 110 GeV^2 in BEAGLE
    Full stat. samples available: 100M

* **Υ(1S, 2S, 3S) in ep** – eSTARlight – Spencer Klein (LBNL)

    Photoproduction ($Q^2 < 1$ GeV^2) and electroproduction ($Q^2 > 1$ GeV^2)
    18 x 275 GeV^2
    Test-sample simulated so far: photoproduction, top energy, 5k events

Deeply Virtual Compton scattering



"Handbag" diagram

$$Q^2 = -(\mathbf{k}-\mathbf{k}')^2 \qquad t = (\mathbf{p}'_\mathbf{n} - \mathbf{p}_\mathbf{n})^2$$

$$\textit{Bjorken variable:}\; x_B = \frac{Q^2}{2\mathbf{p}_\mathbf{n} \cdot \mathbf{q}}$$

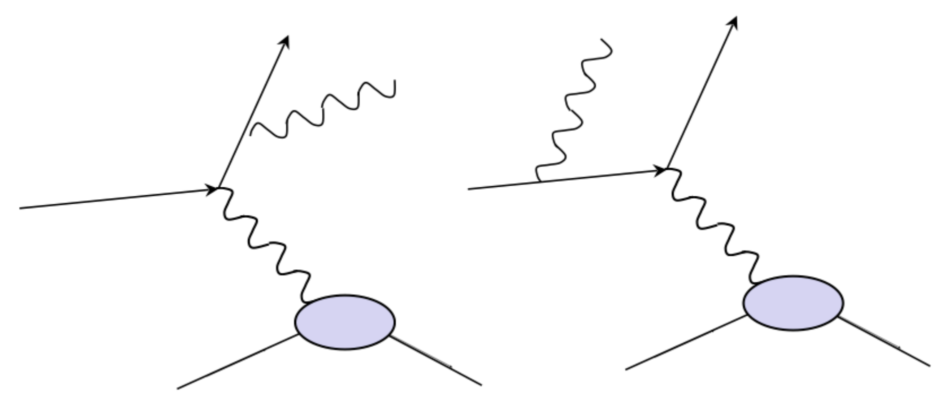
$x \pm \xi$ *longitudinal momentum fractions of the struck parton*

$$\textit{Skewness:}\; \xi \cong \frac{x_B}{2 - x_B}$$

* At high exchanged Q^2 and low t access to four parton helicity-conserving, chiral-even GPDs:

$$E^q, \tilde{E}^q, H^q, \tilde{H}^q(x, \xi, t)$$

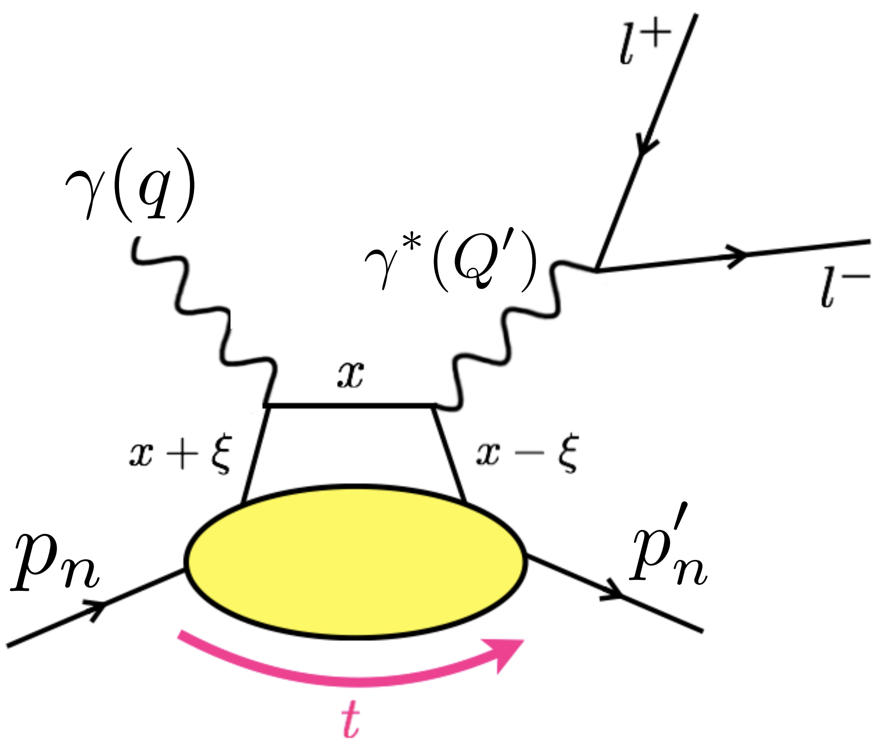
* Experimentally, measure DVCS, Bethe-Heitler and their interference:



$$d\sigma \propto |T_{DVCS}|^2 + |T_{BH}|^2 + \quad T_{BH}T^*{}_{DVCS} + T_{DVCS}T^*{}_{BH}$$

* Observables are parametrised in terms of Compton Form Factors (CFFs): complex functions where $\mathcal{Re}$ parts are integrals of GPDs over x and $\mathcal{Im}$ parts are GPDs at $x = \pm\xi$

Timelike Compton Scattering



- Time-reversal process of DVCS: parametrised in terms of same Compton Form Factors (their complex conjugates).
  - Verification of GPD universality.
  - Another route to access the D-term.

$$Q' = l^+ + l^- \qquad \xi = \frac{\tau}{2-\tau}$$

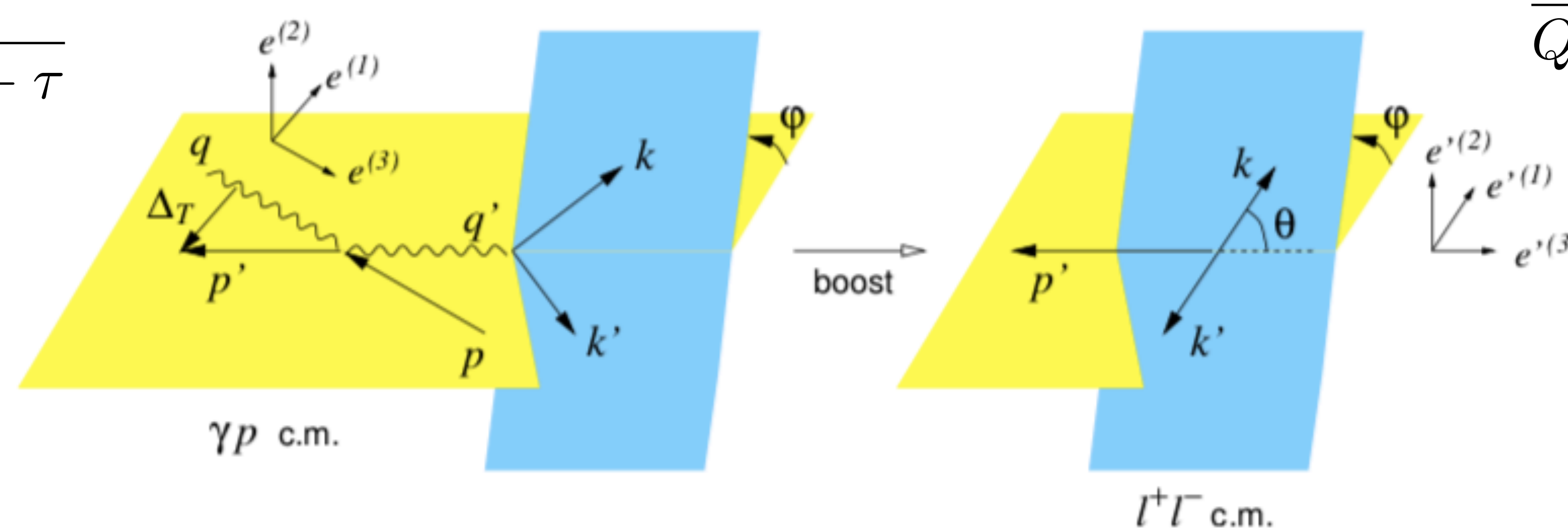
$$s = (q + p_n)^2$$

$$\tau = \frac{Q'^2}{s - m_p^2}$$

θ: angle between l^+ and scattered proton in lepton CMS

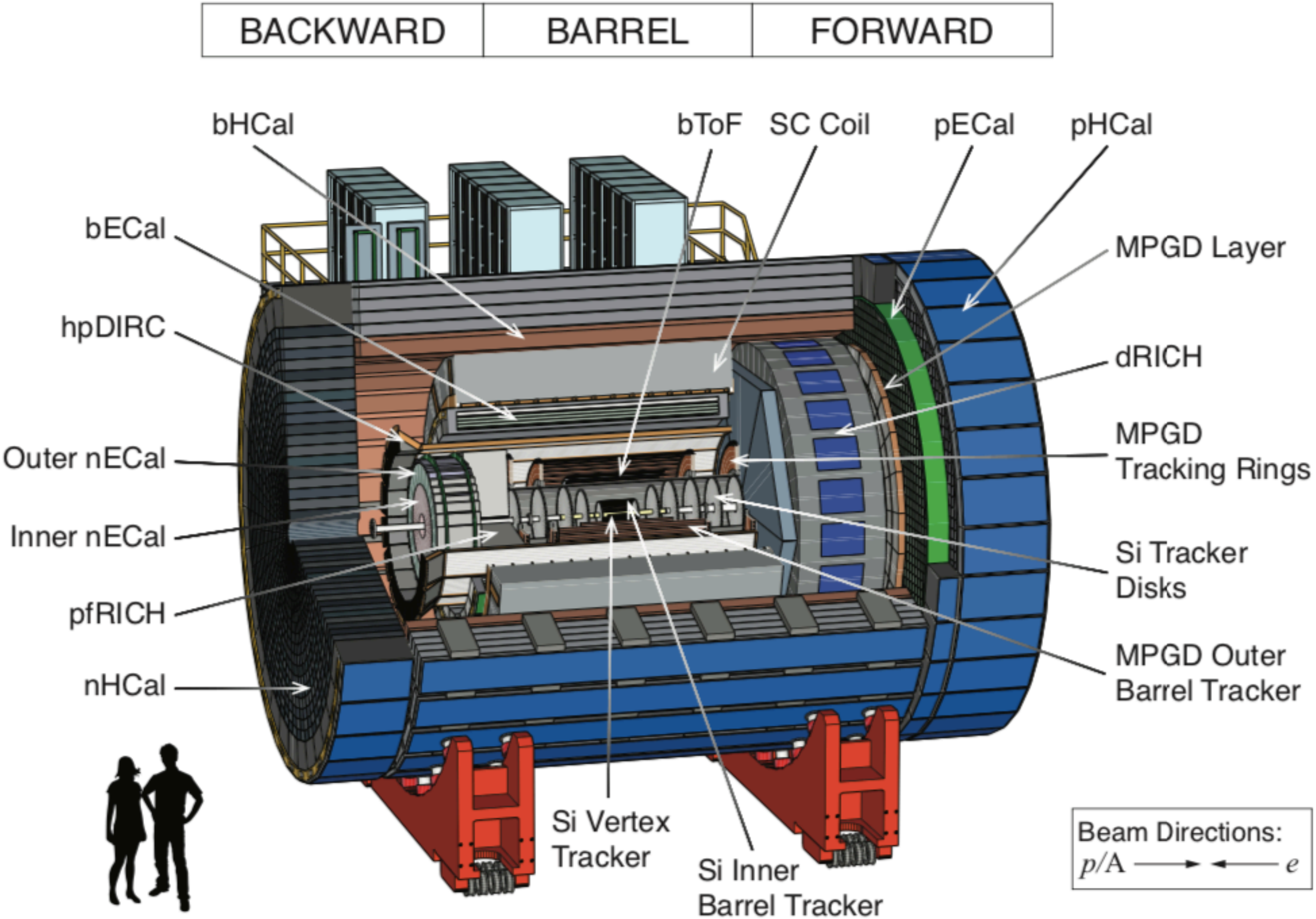
- Factorisation ensured by hard scale of γ* virtuality:

$$\frac{t}{Q'^2} << 1$$



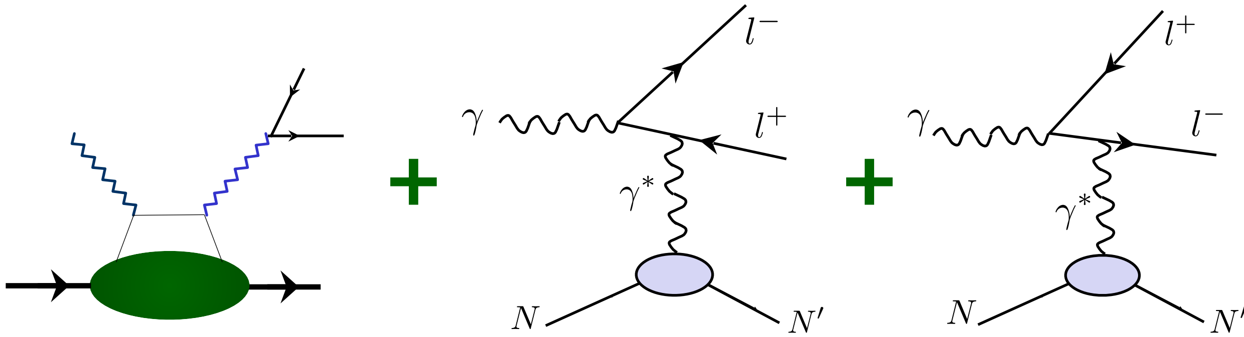
- Measurements establish dependence on Q^2, x, t and φ (angle between leptonic and hadronic planes).

Central ATHENA Detector

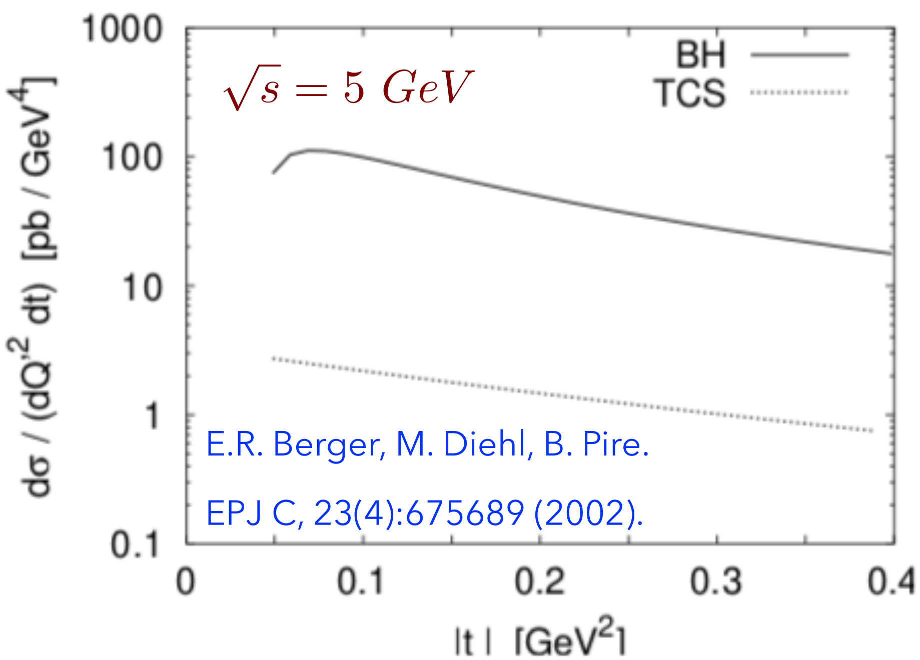


TCS observables

- Similarly to DVCS, TCS process interferes with Bethe-Heitler at the amplitude level.



$$\sigma(\gamma p \to p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT}$$

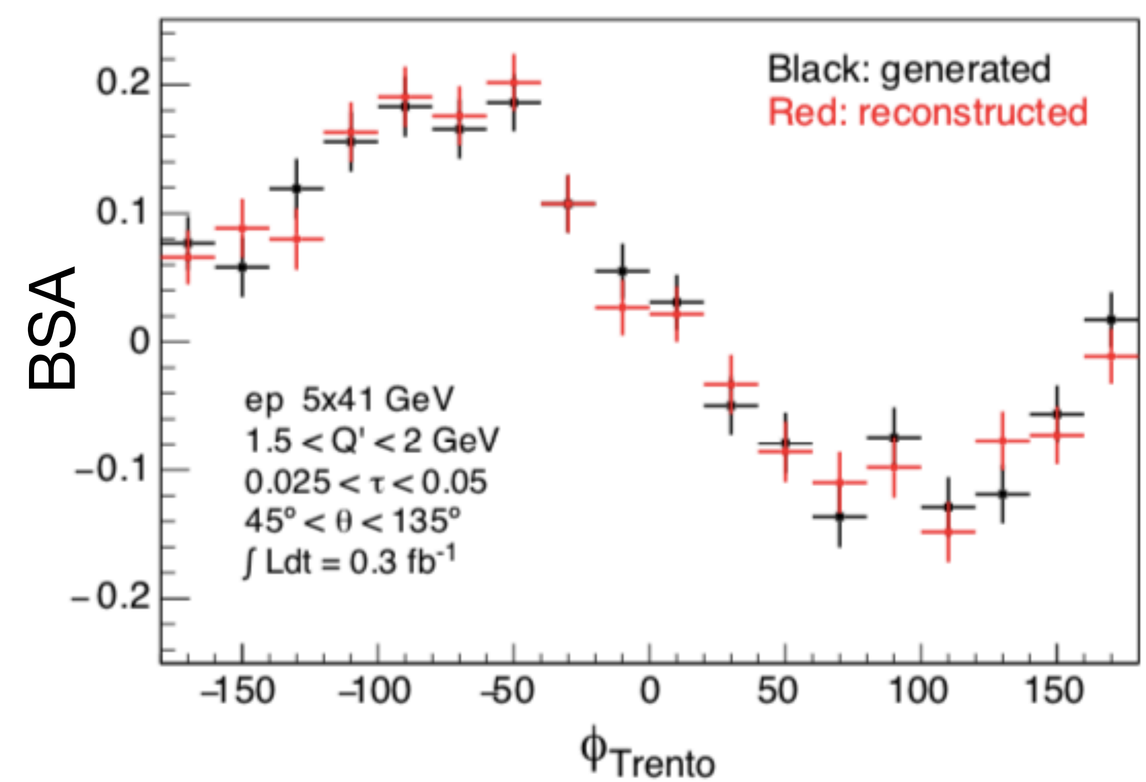


- TCS suppressed by factor of 100 wrt BH: hard to measure cross-sections. Asymmetries dominated by interference term.

- Photon-polarisation (beam-spin) asymmetry:

$$A_{\odot U} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-}$$

access to $\mathcal{Im}\ \mathcal{H}$

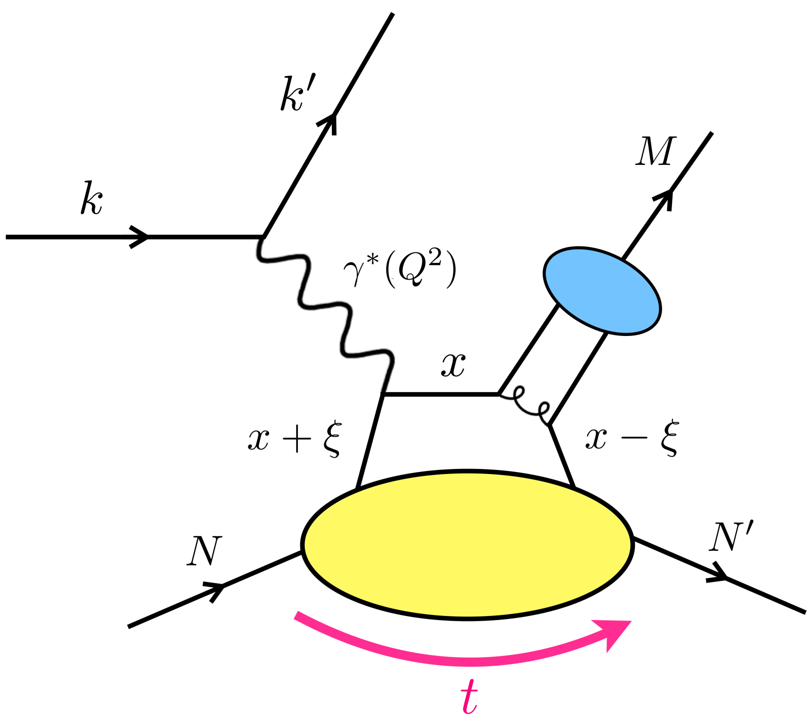


- Forward - backward asymmetry:

$$A_{FB}(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(180^\circ - \theta, 180^\circ + \phi)}{d\sigma(\theta,\phi) + d\sigma(180^\circ - \theta, 180^\circ + \phi)}$$

access to $\mathcal{Re}\ \mathcal{H}$

GPDs through meson-production



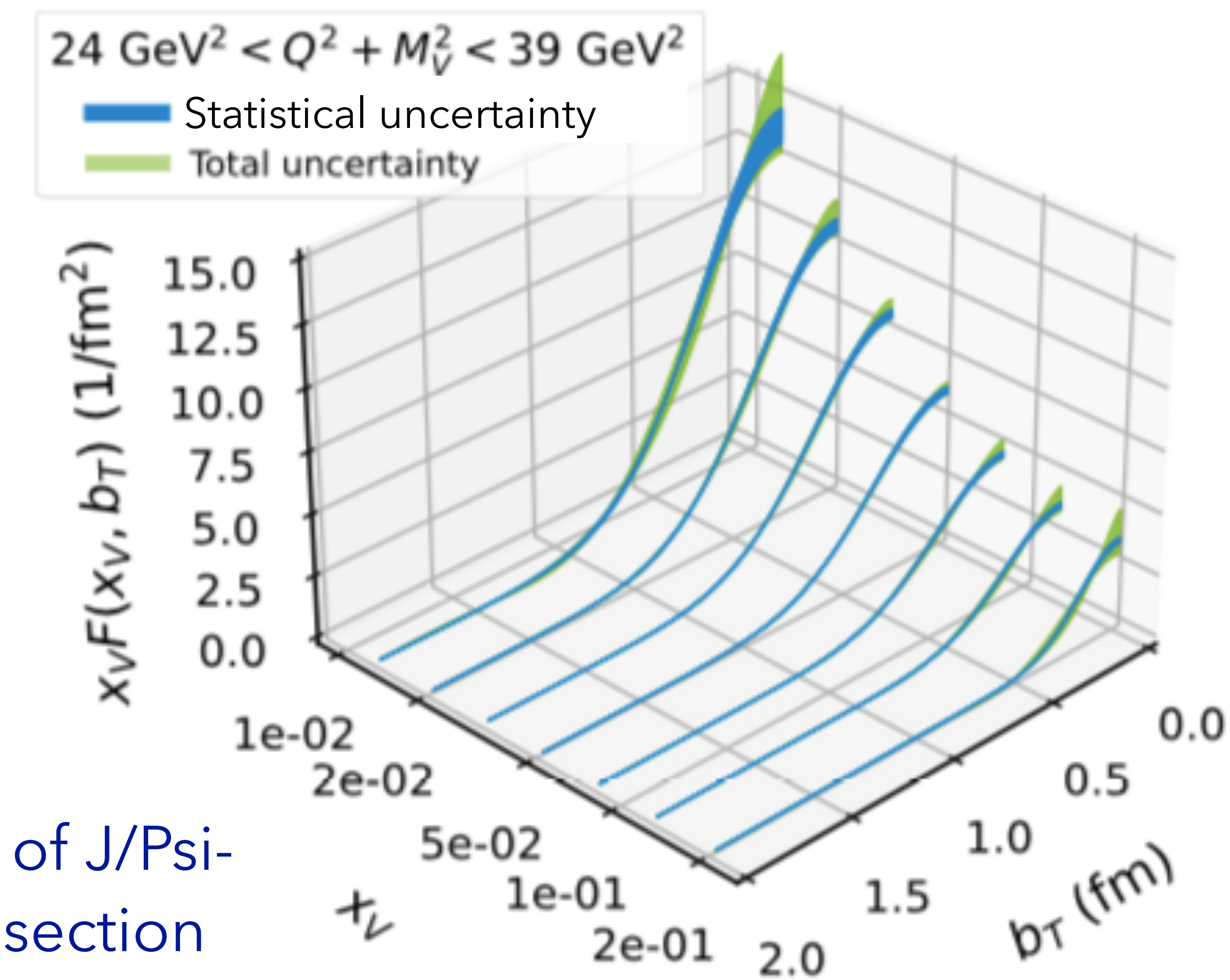
- Hard exclusive electro-production of vector mesons gives access to gluon GPDs, particularly clean in heavy mesons: J/Ψ and Υ

  Hard scale in the scattering given by: $Q^2 + M_v^2$

  Hence: $x_v = \frac{Q^2+M_v^2}{2\mathbf{p}\cdot\mathbf{q}}$

- Light vector-meson production additionally enables flavour-decomposition of GPDs.

- J/Ψ production additionally sensitive to the trace anomaly.



Fourier transform of J/Psi-production cross-section