Experimental Aspects of Deep Virtual Exclusive Scattering

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Outline of Lectures

I. Experimental Methods
II. Physics Analysis and Results
III. Deep Virtual Exclusive Scattering at the EIC
IV. Prospects for DVCS with Positron Beams & ~20 GeV CEBAF

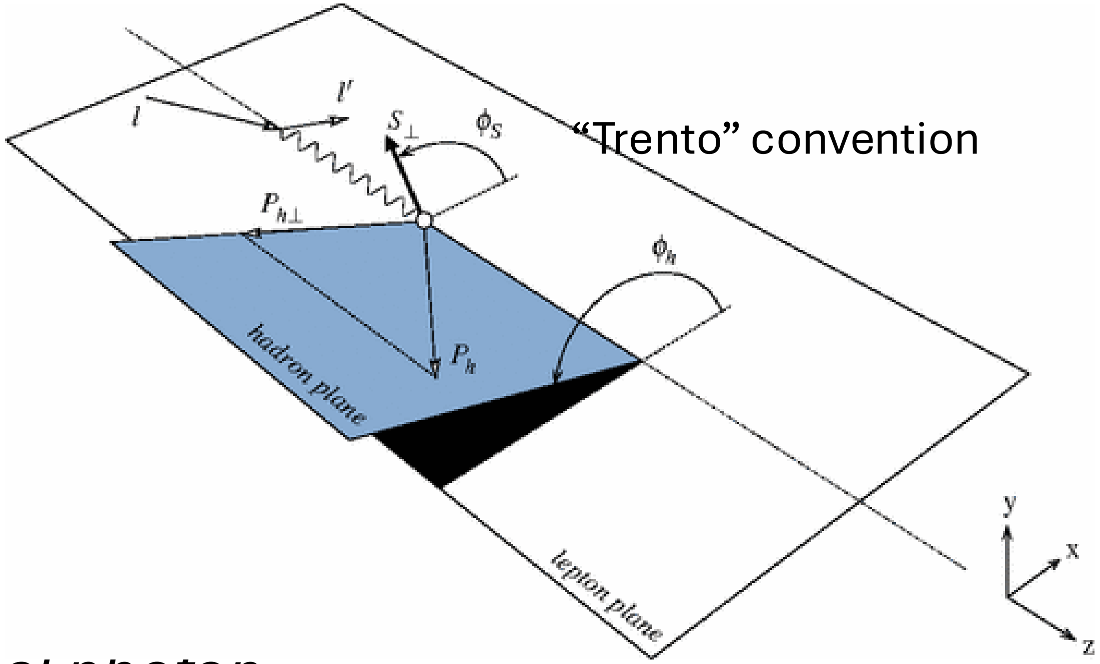
Exclusive reactions

- Example Reactions : $W^2 = (q + P)^2 = M^2 + 2q \cdot P - Q^2$
  - $ep \rightarrow ep\gamma$
  - $ep \rightarrow ep\pi^0 \rightarrow ep\gamma\gamma$
  - $ep \rightarrow ep\phi \rightarrow epKK$
- How to resolve exclusive channel from backgrounds?
  - Examples of background channels to exclusive $ep \rightarrow ep\gamma$
    - $ep \rightarrow eN\pi\gamma$
      - H(e,e'γ)X: Exclusive events at $M_X^2 = M^2 = 0.88$ GeV^2
        Threshold for *N** production: $M_X^2 = (M+m_\pi)^2 = 1.15$ GeV^2
    - $ep \rightarrow ep\pi^0$, with one photon from $\pi^0 \rightarrow \gamma\gamma$ undetected
    - $eA \rightarrow e(A-1)N\,\gamma$, nuclei in target e.g. NH3
    - Random Coincidences: (e,e') $\otimes$ (e,γ) $\otimes$ …
- Resolve the exclusive channel or suppress the excitation continuum

What do we measure?

- Cross sections (both spin-independent and spin-dependent)
- Single- and double-spin asymmetries
- Spin-dependent cross section (single-spin)
  - $d\sigma(+) - d\sigma(-) \propto Im$[Interference of 2 amplitudes]
- Asymmetries are less difficult to measure: $\frac{d\sigma(+)-d\sigma(-)}{d\sigma(+)+d\sigma(-)}$
  - In DVES, we don't *a priori* know the denominator.
- Experimental test of factorization: Q^2-dependence of $d\sigma$

Exclusive Kinematics



"Trento" convention

- Deep exclusive, Q^2, W^2 "large"
  - Q^2, W^2 → $x_B = \frac{Q^2}{2q\cdot P}$
- Electroproduction kinematics
  - $q^\mu = (l - l')^\mu$
  - $\Delta^\mu = (q - q')^\mu \qquad t = \Delta^2 < 0,$ *q' = final photon*
  - M. Cuic (lecture 1) $\xi = \frac{\Delta\cdot\bar{q}}{2\bar{P}\cdot\bar{q}} \approx \xi_B = \frac{\bar{q}^2}{2\bar{P}\cdot\bar{q}} \approx \frac{x_B}{2-x_B}$
  - C. Weis (lecture 2), definitions of ξ, η
  - Fixed target: azimuthal angle ϕ of final γ (or meson) around q-vector direction
    - Collider kinematics, define from invariant e.g. $\epsilon_{\mu\nu\rho\sigma}P^\mu k^\nu\, k'^\rho q'^\sigma$
- Polarized Beam, Targets

Choice of light-cone vectors:

- $n^\mu, \tilde{n}^\mu$, such that $n^2 = 0 = \tilde{n}^2$ and $n \cdot \tilde{n} = 1$
- DIS: Construct from linear combination of *q* and *P*
  - In target rest-frame, the spatial components of $n^\mu, \tilde{n}^\mu$ are along **q**
  - For Collider (HERA, EIC) spatial direction is more complicated
- DVCS, DVMP: Infinite families of choices, **all** agree in limit $\frac{\Delta^2}{Q^2} \to 0$
  - Some Examples
    - *(q,P):* "DIS"
    - *(q+q',P+P'):* "Symmetrized" (BKM?) PRD **82** 074010 (2010)
    - *(q,P+P'):* C. Weiss lecture 2
    - (q,q'): Braun, Manashov, Pirnay (BMP) PRL **109**, 242001 (2012)
  - Definitions of ξ, η differ by terms of order Δ^2/Q^2
  - Kinematic pre-factors in the cross section formulae change similarly
  - GPDs[BKM] = linear combination of GPDs[BMP]

Experimental techniques

- Full detection of all three final state particles $e' p' \gamma$
  - CLAS/CLAS12, some of the HERMES data, some of the HERA data
  - Very challenging for nuclei, but one ^{4}He($e,e'\gamma\alpha$) experiment (and more to come)
- Detect 2 of 3 particles, and infer the third by missing mass
  - Virtual Compton Scattering near threshold H$(e,e'p)\gamma$ ➔ Polarizabilities
  - DVCS: H$(e,e'\gamma)p$
    - For $-\Delta^2 \ll Q^2$ final state photons are close to the q-vector direction
  - High luminosity running with small acceptance, high resolution spectrometers
    - Limited kinematic range in $t = \Delta^2$
  - More precise control of systematics
    - Cross sections

CLAS/CLAS12 DVCS Pubs

Beam Spin Asymmetries

- G. Christiaens *et al.* [CLAS], Phys. Rev. Lett. **130** (2023) 211902
- P. Chatagnon *et al.* [CLAS], Phys. Rev. Lett. **127** (2021) no.26, 262501 (TVCS)
- A.Hobart *et al.* [CLAS], [arXiv:2406.15539] (nDVCS)
- G. Gavalian *et al.* [CLAS], Phys.Rev.C **80** (2009) 035206
- *F. X. Girod et al. (CLAS Collaboration), Phys. Rev. Lett.* **100**, *162002 (2008).*
- *S. Stepanyan, et al. (CLAS Collaboration), Phys. Rev. Lett.* ***87***, *182002 (2001).*

Cross Sections

- *H. S. Jo et al. (CLAS Collaboration), Phys. Rev. Lett.* **115**, *212003 (2015).*

Longitudinal Polarized Target

- *E. Seder et al. (CLAS Collaboration), Phys. Rev. Lett.* **114**, *032001 (2015).*
- *S. Chen et al. (CLAS Collaboration), Phys. Rev. Lett.* **97**, *072002 (2006).*
- ‘12 GeV’ data coming soon!

Hall A DVCS Pubs (Hall C coming soon-ish)

Proton DVCS

- C.Muñoz Camacho *et al*, Phys.Rev.Lett.**97**,262002(2006).
- M.Defurne *et al*., Phys.Rev.C **92**,055202(2015).
- M.Defurne *et al*., Nature Communications **8**,1408 (2017).

Neutron DVCS (deuteron target)

- M.Mazouz *et al*, Phys.Rev.Lett. **99** (2007) 242501
- M.Benali *et al*., Nature Physics**16**,191(2021).

Proton DVCS with 11 GeV electron beam

- F.Georges *et al*., Phys.Rev.Lett.**128**, 252002(2022).

(e,e'π^0)

- E. Fuchey *et al*., Phys.Rev.C **83** (2011) 025201,
- M.Defurne *et al*., Phys.Rev.Lett. **117** (2016) 26, 262001
- M.Mazouz *et al*, Phys Rev. Lett **118** (2017) 22, 222002
- M. Dlamini *et al*., Phys.Rev.Lett. **127** (2021) 15, 152301

HERA: Collider: 1997–2007
27 GeV $\vec{e}^{\pm} \otimes$ 820 GeV p

ZEUS DVCS Publications

- S. Chekanov *et al., JHEP* **05** (2009) 108
- S. Chekanov *et al., Phys. Lett. B* **573** (2003) 46-62

H1 DVCS Publications

- F.D. Aaron *et al., Phys.Lett.B* **681** (2009) 391-399
- F.D. Aaron *et al.,* Phys.Lett.B **659** (2008) 796-806
- A. Aktas *et al.,* Eur.Phys.J.C 44 (2005) 1-11
- A. Adlof *et al., Phys.Lett.B 517 (2001) 47-58*

COMPASS

100-200 GeV muons incident on fixed target

- R. Akhunzyanov et al. [COMPASS] *Phys.Lett.B* 793 (2019) 188-194, *Phys.Lett.B* 800 (2020) 135129 (erratum)
  - e-Print: 1802.02739 [hep-ex]

Inspirehep.net: search “collaboration compass and title exclusive”

- 14 journal publications
- 30 conference papers

HERMES: Fixed (gas-jet) target in HERA electron ring

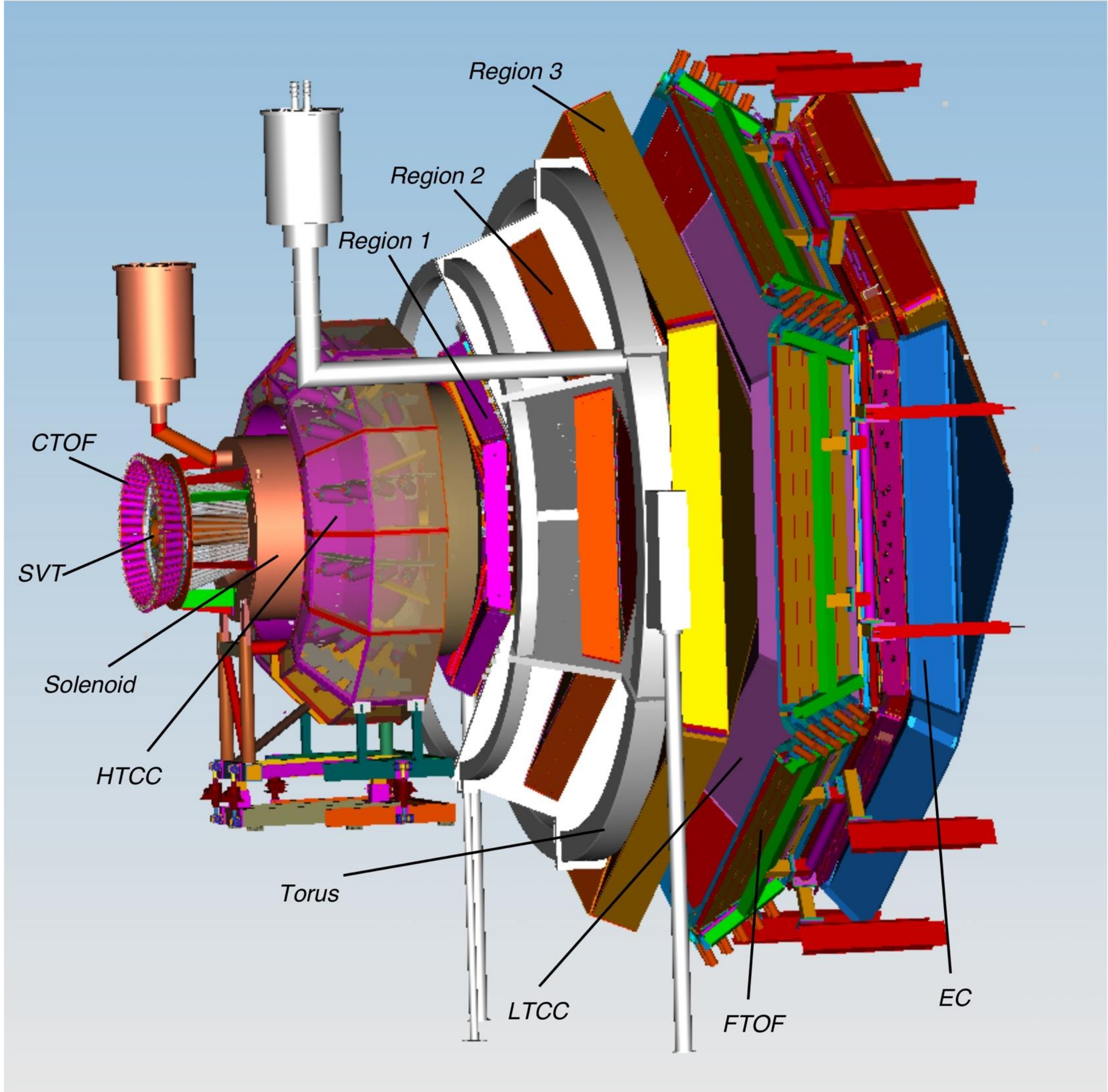
1) A. Airapetian *et al.,* JHEP **07** (2012) 032. “Beam-Charge Asym.”
2) A. Airapetian *et al.,* JHEP **10** (2012) 042. “Kinematically Complete”
3) A. Airapetian *et al.,* Nucl.Phys.B **842** (2011) 265-298. , “Longitudinally polarized D”
4) A. Airapetian *et al.,* Phys.Rev.C **81** (2010) 035202. “Nuclear Targets”
5) A. Airapetian *et al.,* Nucl.Phys.B **829** (2010) 1-27, “Deuterium”
6) A. Airapetian *et al.,* JHEP **11** (2009) 083.
7) A. Airapetian *et al.,* Phys. Lett. B **704** (2011) 15-23. “., “Transversely Polarized H”
8) A. Airapetian *et al.*, JHEP **06** (2010) 019.
9) A. Airapetian *et al.,* JHEP **06** (2008) 066.
10) A. Airapetian *et al.,* Eur. Phys. J. C **62** (2009) 659-694.
11) A. Airapetian *et al.,* Phys. Lett. B **679** (2009) 100-105.
12) A. Airapetian *et al.,* Phys.Rev.Lett. **87** (2001) 182001

CLAS12 Detector

- Central Detector
  - Tracking, TOF
- Forward Detector
  - Tracking, PID, EMCal
- Forward Tagger: $PbWO_4$

https://www.jlab.org/physics/hall-b/clas12

C.Hyde



CLAS12: H(e,e'γp) Single Event display

G.Christiaens *et al.*, Phys. Rev. Lett. **130** (2023) 211902

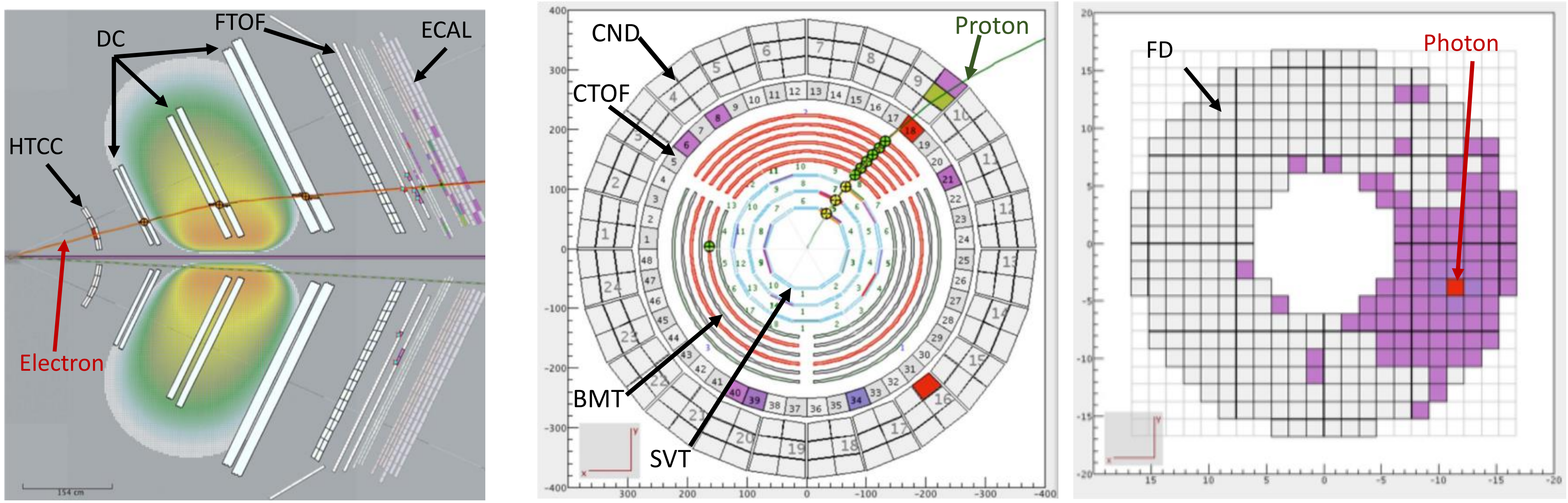


Figure 4.1: Schematic of a typical DVCS event, visualized using the CED tool (CLAS12 event display, see section 2.3.4). Lines (red squares for the FT) represent reconstructed particle tracks and colored shapes represent hits in the detector. The electron is reconstructed in the forward detector (left), the proton in the central detector (middle) and the photon in the forward tagger (right).

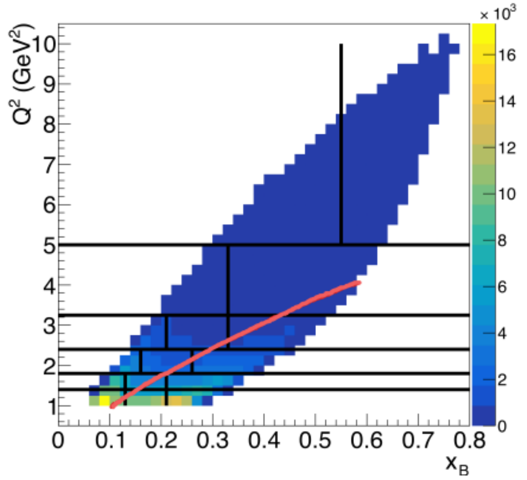


FIG. 3. CLAS12 phase space in Q^2 vs. x_B, showing the division into 16 bins. The red line indicates the approximate upper reach of CLAS data at 6 GeV.

- G.Christiaens, PhD Thesis, U.Glasgow Scotland, Feb. 2021: https://theses.gla.ac.uk/82288/

Example of CLAS/CLAS12 Exclusivity Analysis: H*(e,e'γp)*

Exclusivity Cuts:

- Cone Angle $\theta_{\gamma\gamma}$<0.6°: angle between detected γ and vector **q–P'**:
- $M_X^2(e,e'\gamma)$<1.25 GeV² "Missing mass squared of the proton"
- $E_{miss} = k + M - (k'+q' + E_p')$ < 0.5 GeV
- $P_{\perp,miss}$ < *0.125 GeV/c:* Missing transverse momentum (⊥ to (e,e') plane)
- Cuts optimized to minimize systematic errors on BSA

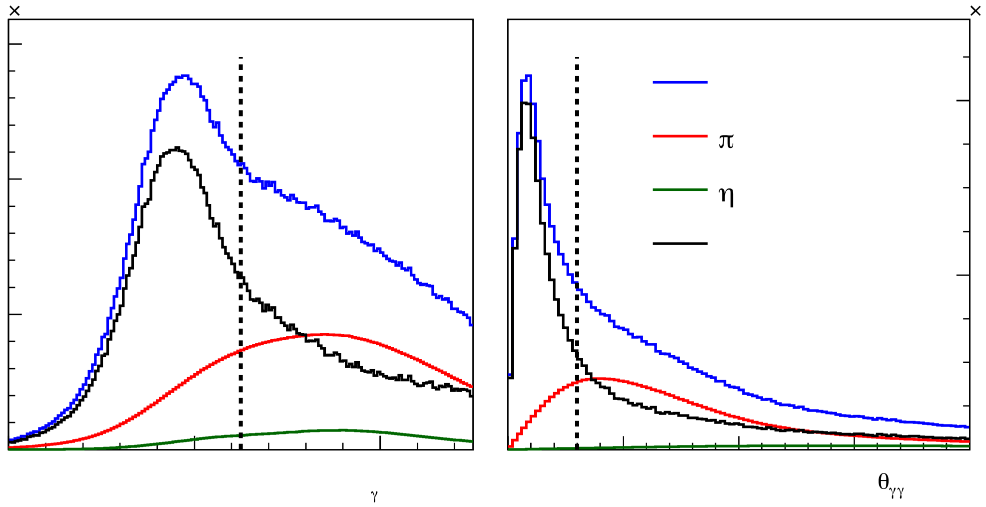
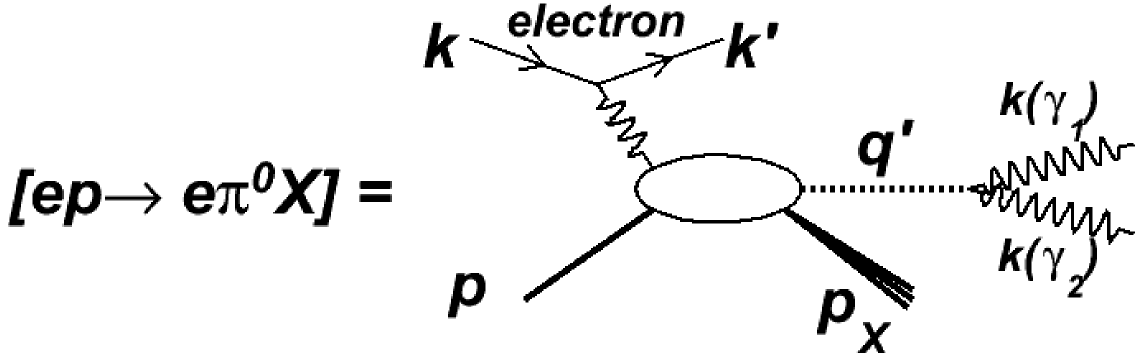


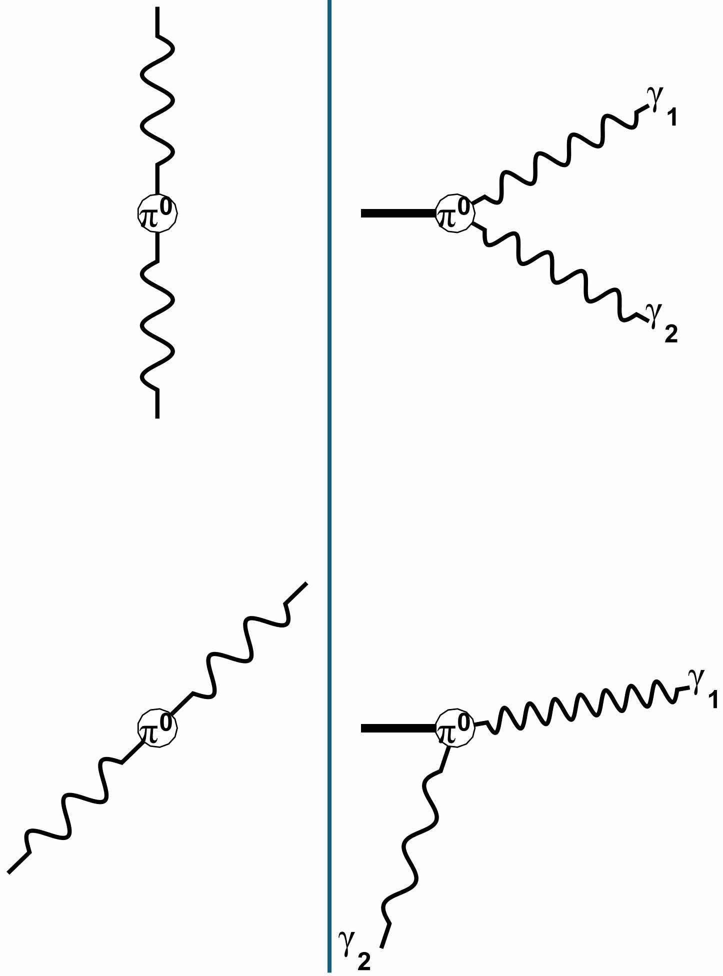
FIG. 2. Squared missing mass $M^2_{e'\gamma X}$ (left) and cone angle $\theta_{\gamma\gamma}$ (right) distributions prior to the application of any exclusivity cuts, for the full data-set showing the π^0 and η contamination and after subtraction. Dashed lines indicate the position of the cuts.

G.Christiaens *et al.* [CLAS], Phys. Rev. Lett. **130** (2023) 211902

π^0 background in DVCS



π^0 Rest Frame	Detector Frame



$M_X^2(e,e'\gamma_1) \approx W^2/2$

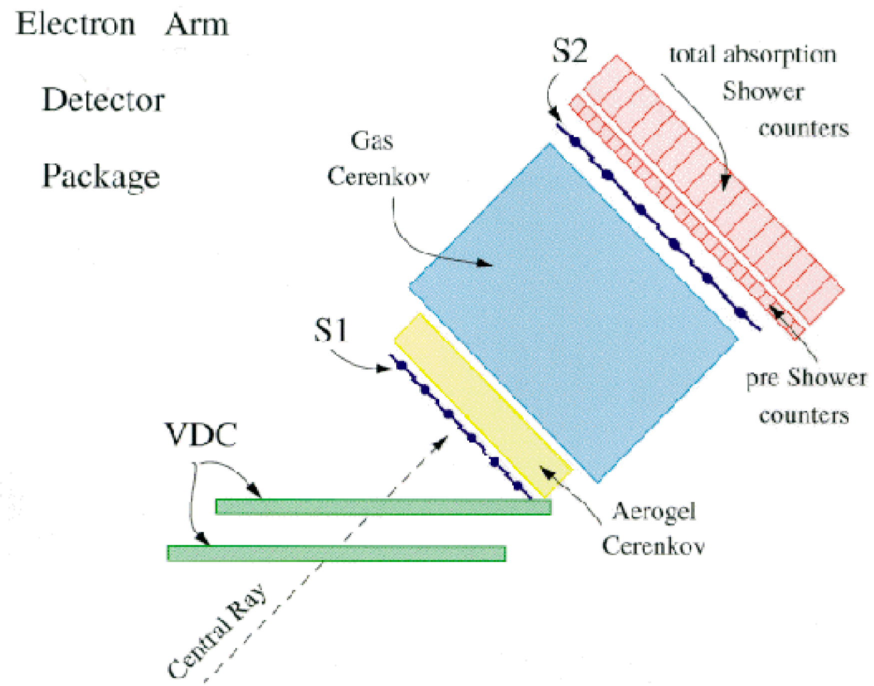
$M_X^2(e,e'\gamma_1) \approx M^2$

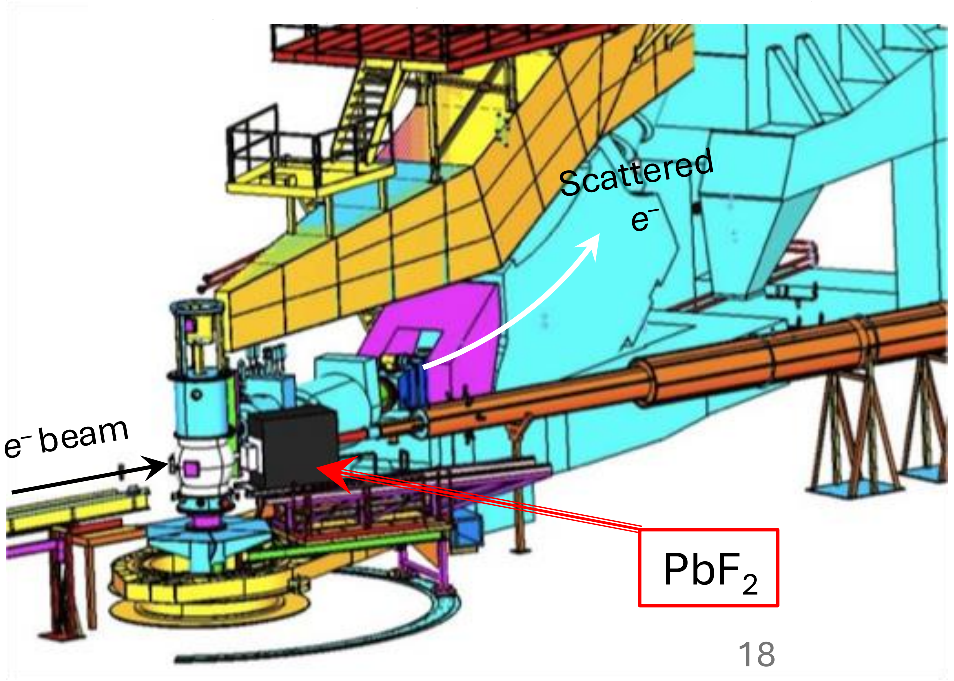
The (irreducible) π^0 background problem

- H(e,e'pγ) has an irreducible background of H(e,e'pγ)γ from $\pi^0 \to \gamma\gamma$ (and $\eta \to \gamma\gamma$) production
  - $\pi^0 \to \gamma\gamma$ is isotropic in pion rest-frame, boosted forward in lab frame
  - X=p+γ missing mass distribution in H(e,e'γ)pγ is uniform in M_X^2 from M_p^2 to W^2
  - Asymmetric decays (relative
- Statistical Solution
  - Measure (e,e'γ) and (e,e'$\gamma\gamma$) events
  - For each $\gamma\gamma$ =π^0 event, simulate [e.g. N_{sim} = 5000] isotropic $\pi^0 \to \gamma\gamma$ in the (e,e'π^0) event kinematics
    - Sort simulated events into sets of {0,1,2} - photons detected
    - Weight every simulation single-γ event by 1/N_2
    - This produces an H(e,e'γ)pγ event sample normalized to the experimental Luminosity$\otimes$Acceptance
  - Subtract the background simulation yield independently in every kinematic bin.

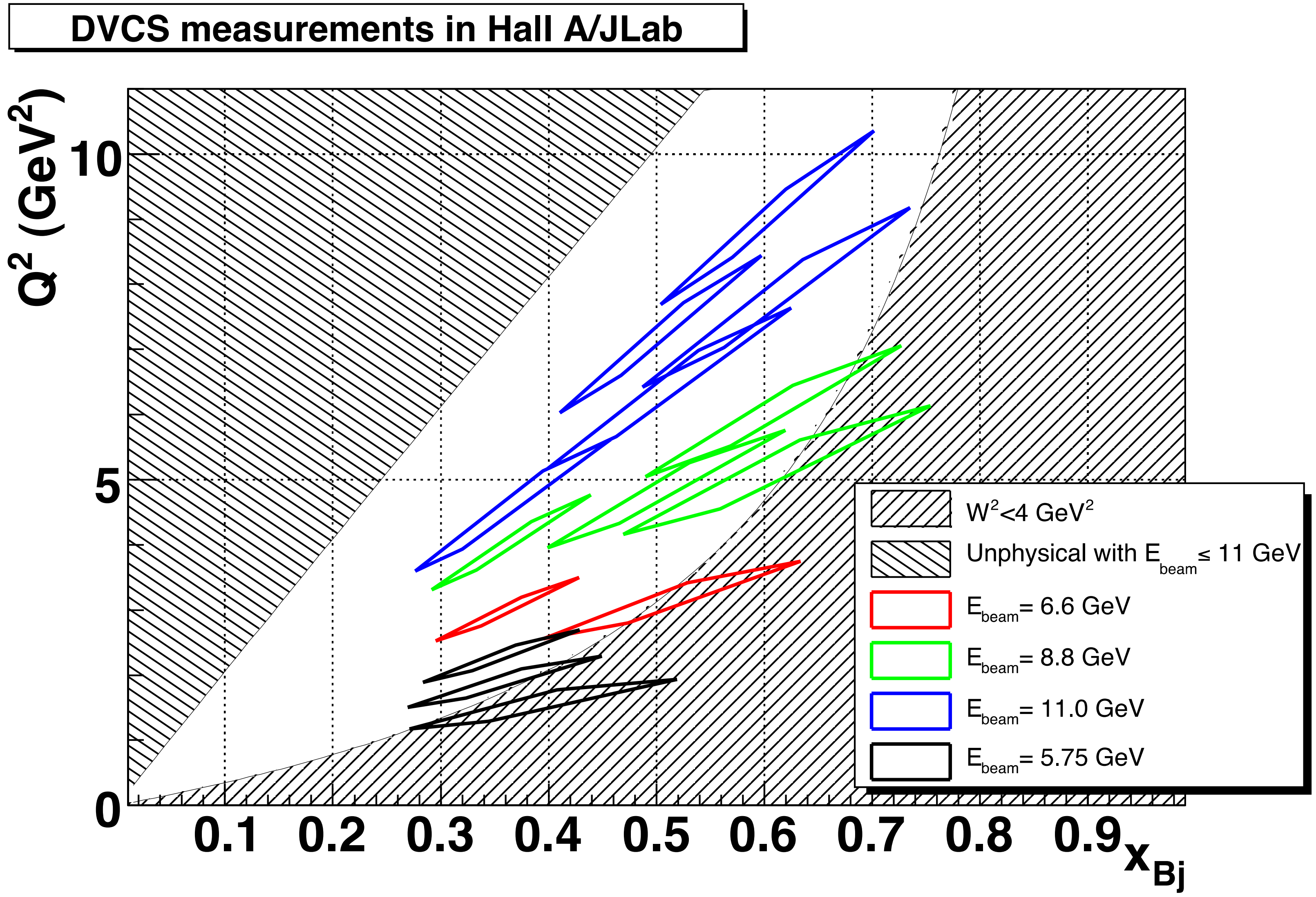
Hall A DVCS program

- Liquid H and D targets
- Detect scattered electron in "High Resolution Spectrometer"
- Detect gamma in PbF_2 Calorimeter
  - Radiation hard
  - Pure Cherenkov signal➔very fast light pulse (~1ns)
  - Tolerant to high rates from high luminosity (detector ~2m from target)





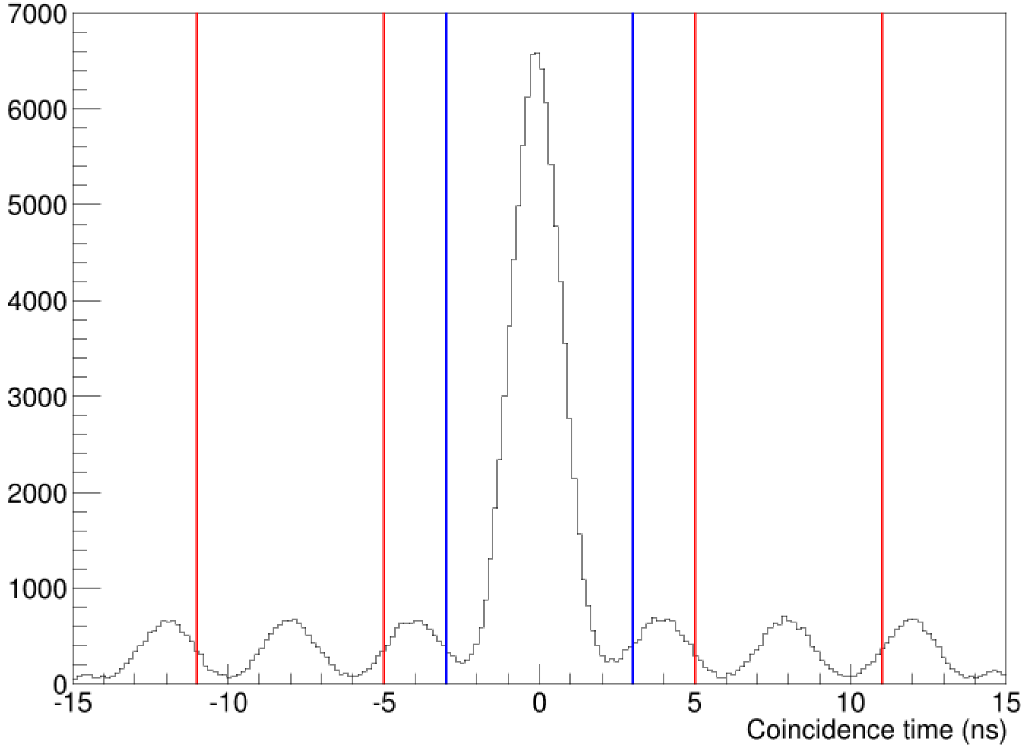
Hall-A DVCS Kinematic Coverage



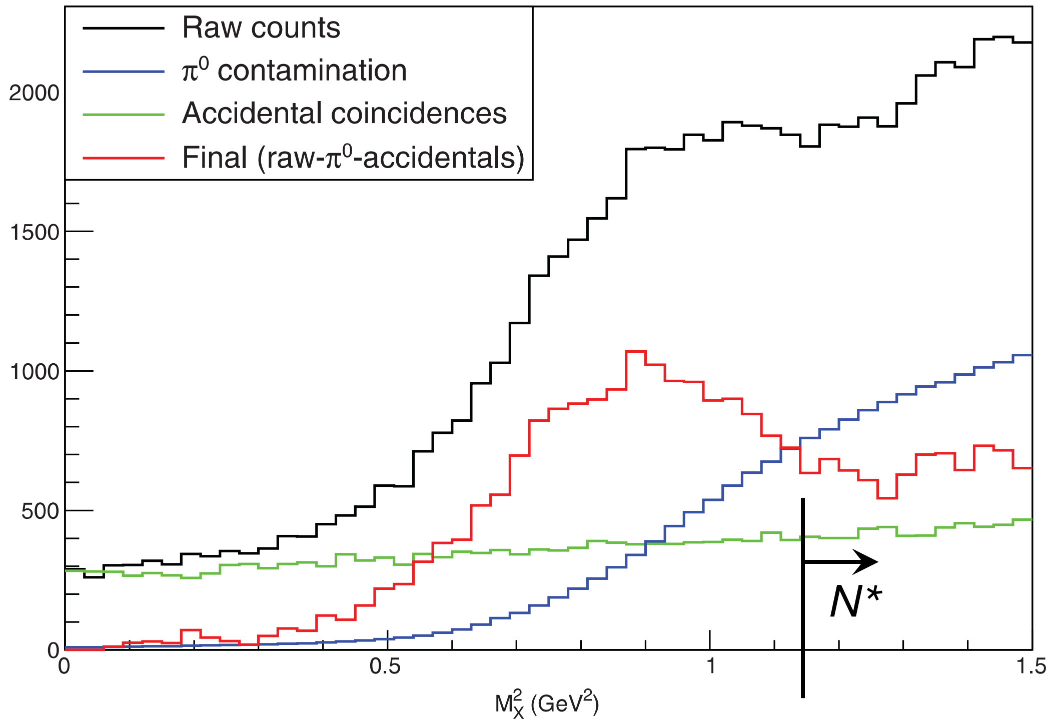
- Not shown: ‘6-GeV’ beam energy scan at $x_B = 0.36$
- Defurne *et al.*, NatComm **8**,1408 (2017).

Hall A DVCS: π^0 and accidental backgrounds and exclusivity result from '12GeV' H$(e,e'\gamma)X$

- 4 nsec time-structure of beam



Frédéric Georges, PhD U.Paris-Saclay, Oct 2018
https://theses.hal.science/tel-01925350/



F.Georges *et al., Phys.Rev.Lett.* **128** (2022) 25, 252002

See also NPS students for latest 2023-2024 Hall C results with higher resolution $PbWO_4$ calorimeter!

The N* problem: *ep* → *epγ* ⊕ *ep* → *eN*γ*…

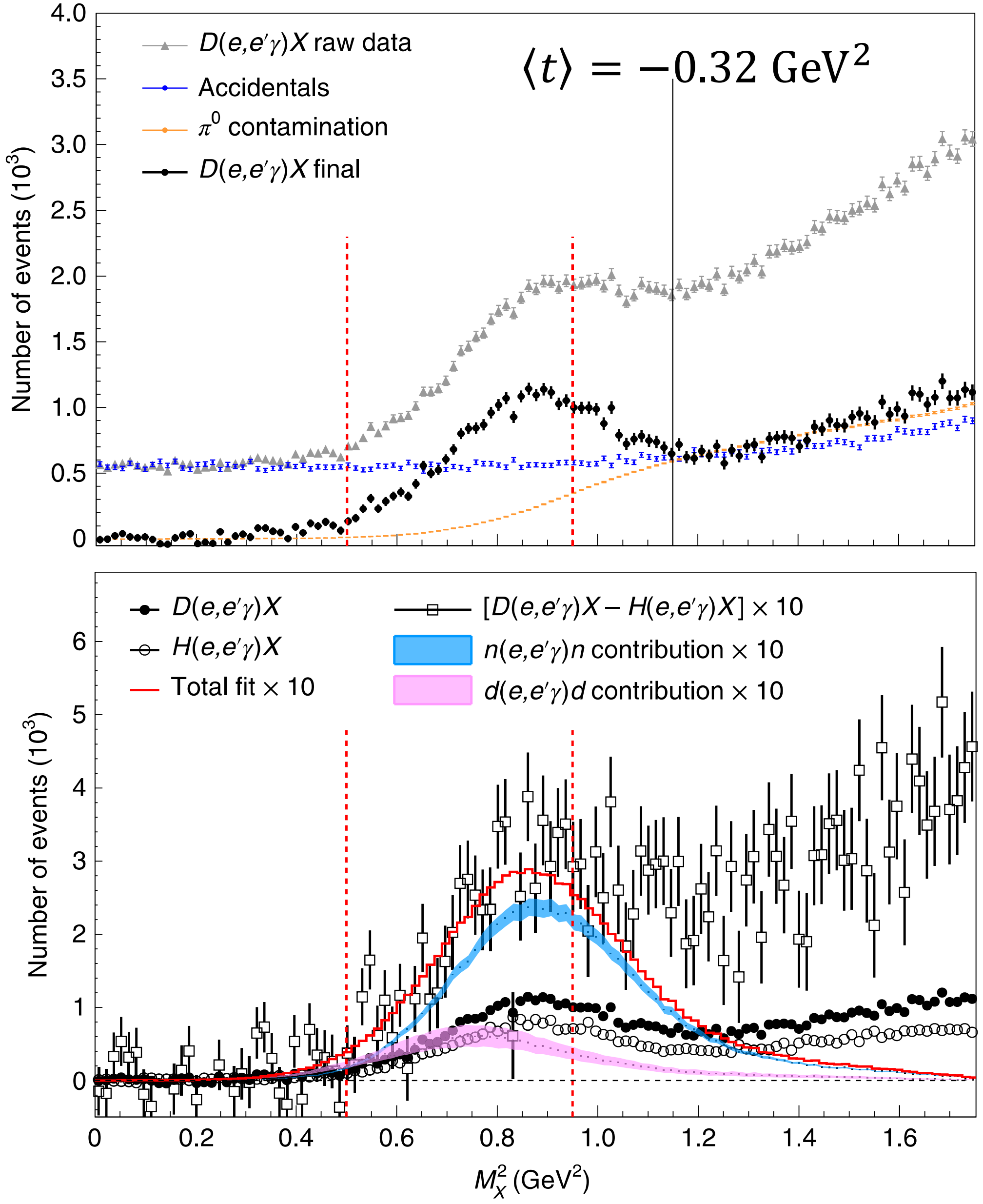
- Approximately excluded by experimental cuts,
  - Model estimates can be used to estimate systematic error from N*.
  - Frequently done with assumption of BH dominance
- Extract the N* channel explicitly
  - CLAS acceptance to reconstruct full event topologies
    - *ep* → *e(Nπ)γ* ⊕ *ep* → *e(Nππ)γ* ⊕ …
    - 'Soft-pion' theorems for S-wave at Nπ threshold give access to **nucleon** $\widetilde{\mathrm{H}}$**,** $\widetilde{\mathrm{E}}$
    - *N* → *Δ* transition GPDs have interesting quadrupole structure
      - C. Alexandrou et al., https://arxiv.org/abs/0910.3315
    - Preliminary CLAS (6GeV) results by B.Moreno *et al.*, p61 in **Exclusive reactions at high momentum transfer IV proceedings of the 4th workshop, Thomas Jefferson National Accelerator Facility, USA, 18-21 May 2010, A. Radyushkin, ed.**
    - Deep Virtual $H(e, e'\pi^-\Delta^{++})$: S. Diehl *et al. [CLAS], Phys.Rev.Lett.* **131** *(2023) 2, 021901*
  - A great opportunity with the Electron Ion Collider

Nuclear Targets and Nuclear Background

- Polarized targets
  - $\mathrm{N\overrightarrow{H}_3}$
    - Subtract N data (or C surrogate)
  - $^{3}\overrightarrow{\mathrm{He}}$, lots of glass (~2/3 of target thickness),
- The Quasi-Free process
  - D*(e,e'γ)X:*
    Approximately given by the incoherent sum
    ep→epγ $\oplus$ en→enγ $\oplus$ ed→edγ

Neutron DVCS in Hall A

- M.Benali *et al.*, Nature Physics **16**,191(2021).
  - Also M.Mazouz *et al*, Phys.Rev.Lett. **99** (2007) 242501
- Missing Mass is calculated for a target nucleon at rest:
  - QE peak at $M_X^2 \approx M_N^2 = 0.88\ \mathrm{GeV}^2$
  - Coherent deuteron peak at $M_X^2 \approx M_N^2 + t/2 \approx 0.72\ \mathrm{GeV}^2$



CLAS12 neutron DVCS analysis

- D*(e,e'nγ)*X: isolate events with *X*≈proton
  - Neutrons detected in ECAL, CTOF, or CND
- Cuts on
  - $M_X^2 = (k - k' + M_d - q' - p_n)^2$
  - Missing 3-Momentum (*np* relative mom. in *d*)
  - $t(q,\gamma) - t(d,n)$
  - $\phi(q,\gamma) - \phi(q,n)$
  - …

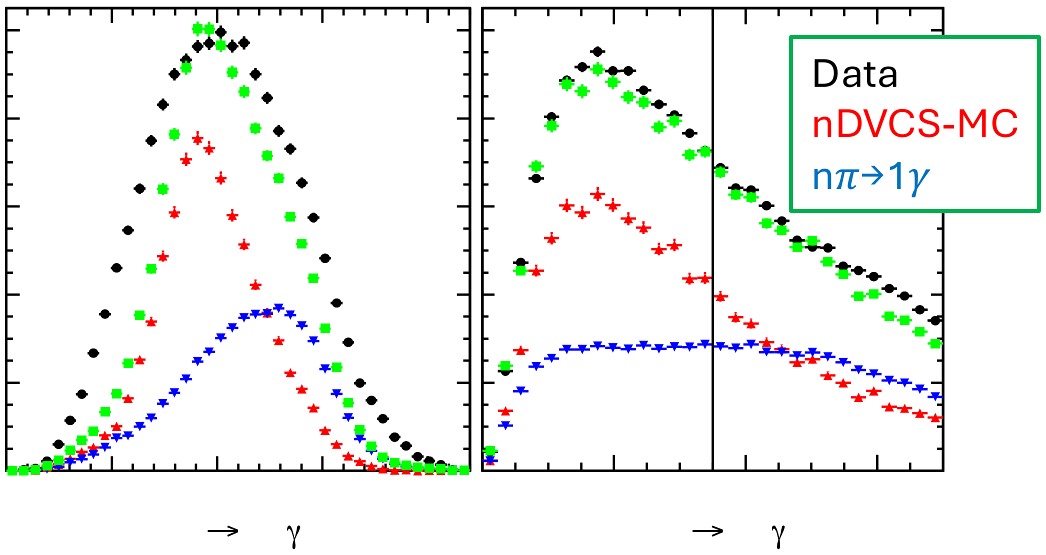


FIG. 2. Squared missing mass (left) and missing momentum (right) from $ed \to e'n\gamma X$. The line defines the applied cut on P_X. The data (black circles) are compared with simulations of neutron DVCS (red triangles) and of partially reconstructed π^0 background (blue upside-down triangles). The simulations are rescaled to match, approximately, the relative weights of each contribution to the data. The green squares are the sums of the two simulated contributions.

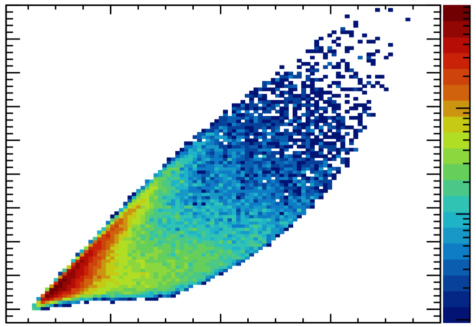


FIG. 3. Q^2 versus x_B for the nDVCS data sample with all selection cuts applied, showing the wide kinematic reach of CLAS12.

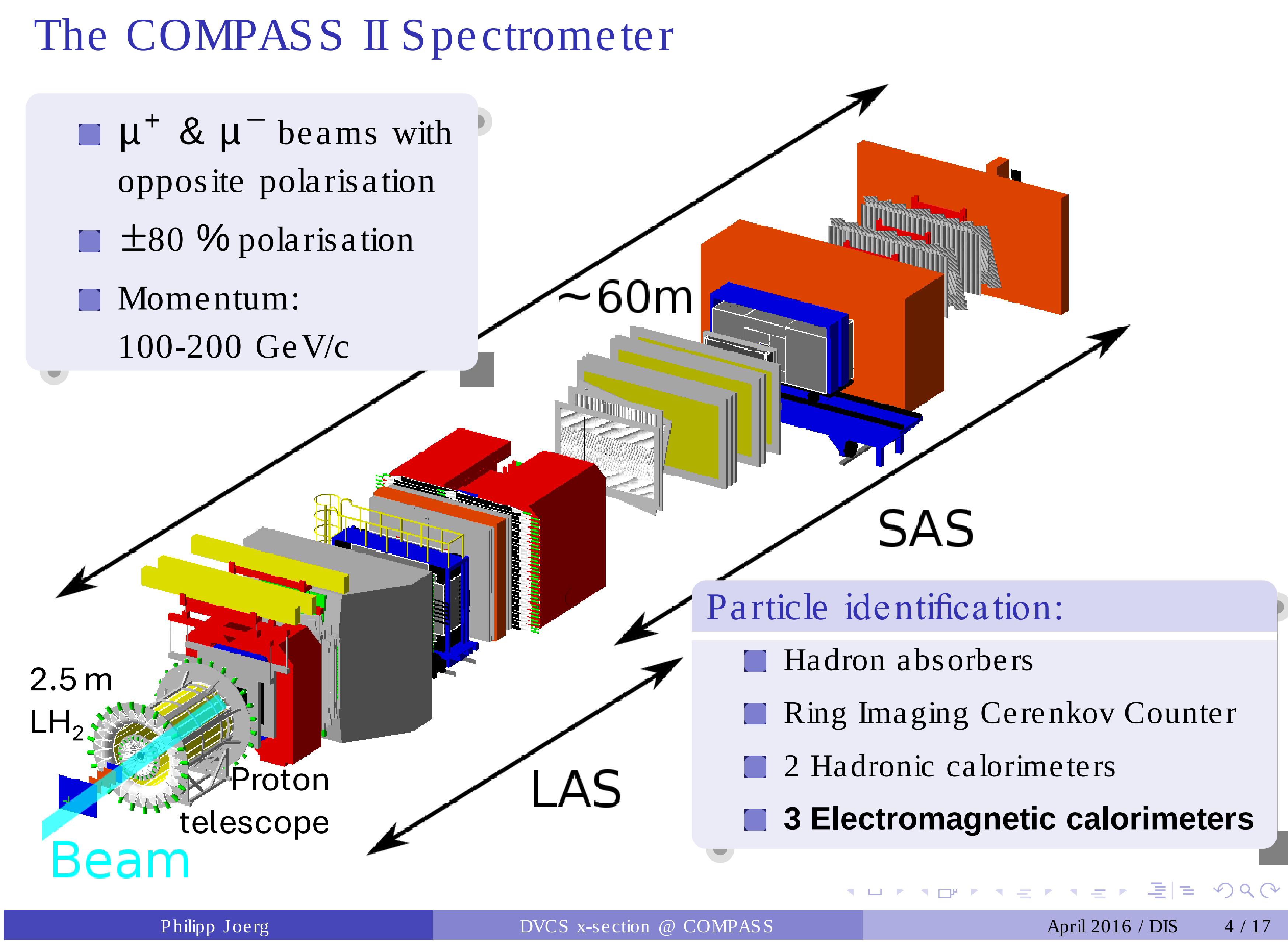
A.Hobart *et al.*, https://arxiv.org/abs/2406.15539

Other Fixed-Target exp’s: COMPASS, HERMES

- COMPASS:
  - 100-200 GeV muons incident on polarized and un-polarized targets
  - SPS protons impinge on a production target → High energy pions
    - Pions decay to muons (polarized by V–A weak decay)→ Momentum selection
- HERMES
  - 27 GeV stored e+ or e- beams on gas jet target (no walls).

DIS2016

- Slides from P.Jörg, https://indico.desy.de/event/12482/contributions/9002/
  - Proceedings: *PoS* DIS2016 (2016) 235 https://arxiv.org/abs/1702.06315
- R. Akhunzyanov *et al.*, *PhysLettB* **793** (2019) 188
  - $\langle x_B \rangle = 0.056$
  - $\langle Q^2 \rangle = 1.8\ \mathrm{GeV}^2$



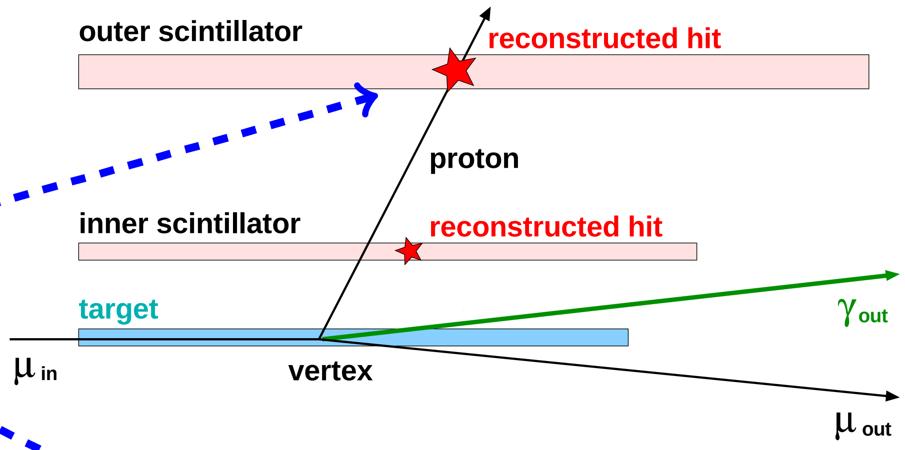
Exclusive Photon Events Selection

COMPASS

- Exclusivity by recoil proton detection

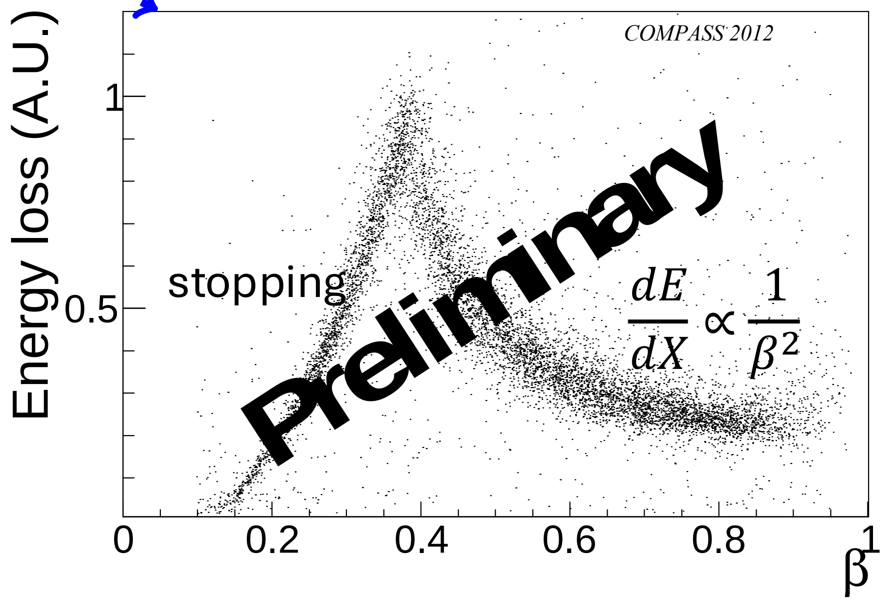
Signal amplitude in outer scintillators vs. β of recoiling particle

Proton signature clearly visible after all exclusivity conditions



Exclusivity conditions:

- $\Delta\phi = \phi^{proton}_{meas} - \phi^{proton}_{reco}$
- Vertex pointing (Δz)
- Transv. momentum balance: $\Delta p_{\perp} = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance: $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_{\gamma})^2$



COMPASS Exclusivity

- Absence of background outside cuts indicative of `diffraction’ → suppression of excitation of target in final state
- M_X^2 distributions not shown.

Exclusivity conditions:

- $\Delta\phi = \phi^{proton}_{meas} - \phi^{proton}_{reco}$
- Vertex pointing (Δz)
- Transv. momentum balance: $\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance: $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}} - p_\gamma)^2$

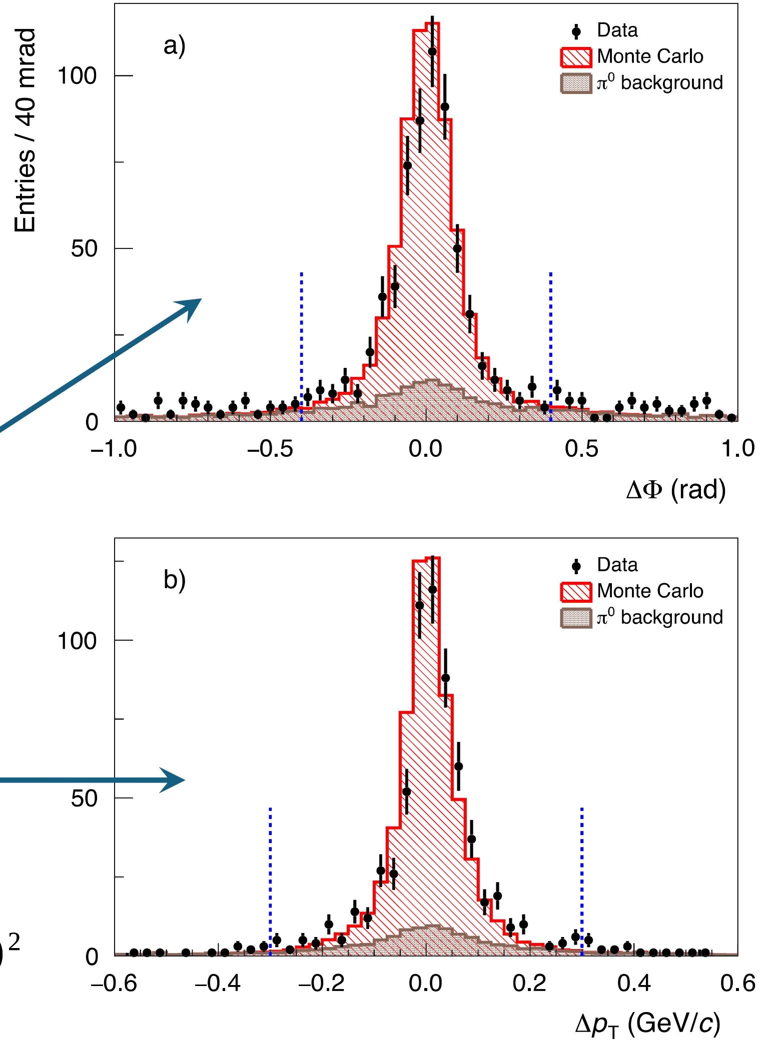
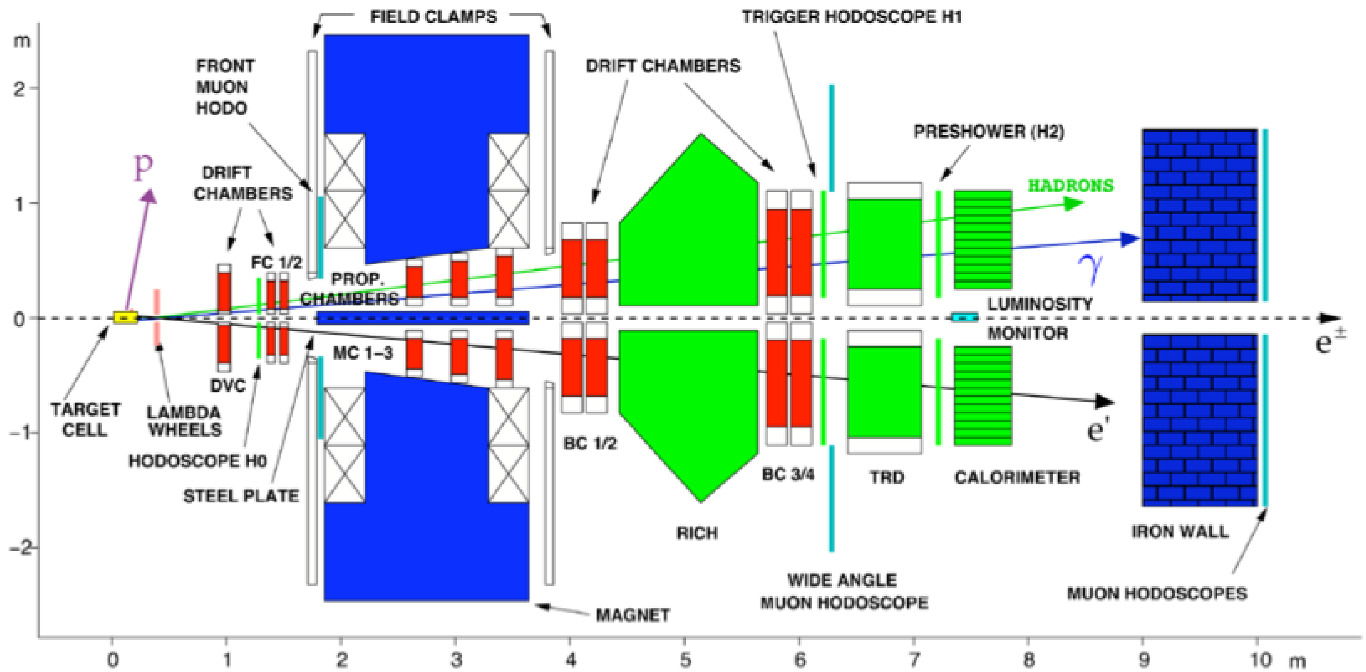


Fig. 2. Distribution of the difference between predicted and reconstructed values of (a) the azimuthal angle and (b) the transverse momentum of the recoiling proton candidates for $1\,(\mathrm{GeV}/c)^2 < Q^2 < 5\,(\mathrm{GeV}/c)^2$, $0.08\,(\mathrm{GeV}/c)^2 < |t| < 0.64\,(\mathrm{GeV}/c)^2$ and $10\,\mathrm{GeV} < \nu < 32\,\mathrm{GeV}$. The dashed blue vertical lines enclose the region accepted for analysis. Here, Monte Carlo also includes π^0 background.

HERMES

- 27.5 GeV $e^{\pm}$
- Gas-jet target into accelerator vacuum of HERA storage ring of 27.5 GeV
- DIS2012
  M. Murray et al,
  https://indico.cern.ch/event/153252/contributions/1396842/

DVCS @ HERMES



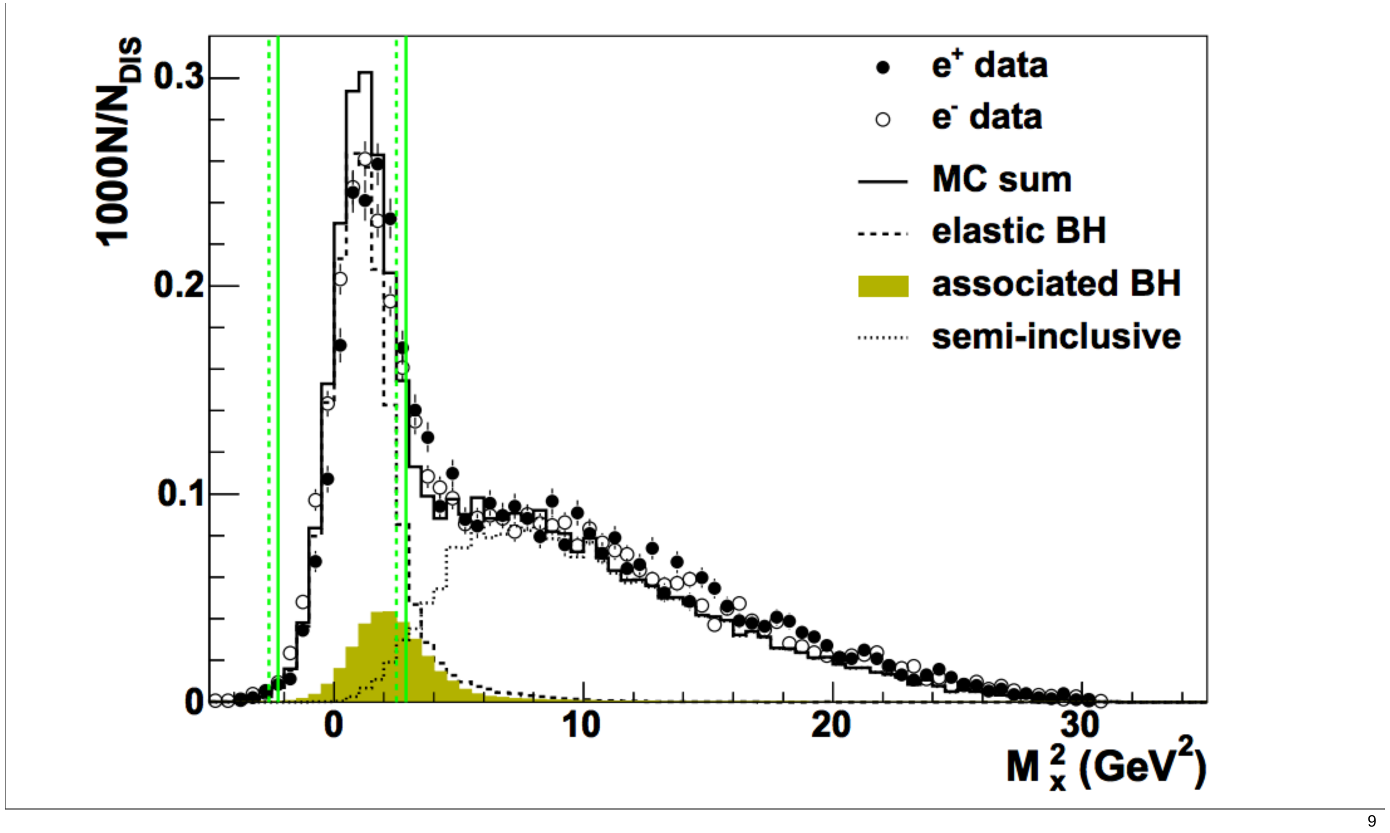
$\langle Q^2 \rangle \cong 2.4\ \mathrm{GeV}^2$ • $1\ \mathrm{GeV}^2 < Q^2 \equiv -q^2 < 10\ \mathrm{GeV}^2$

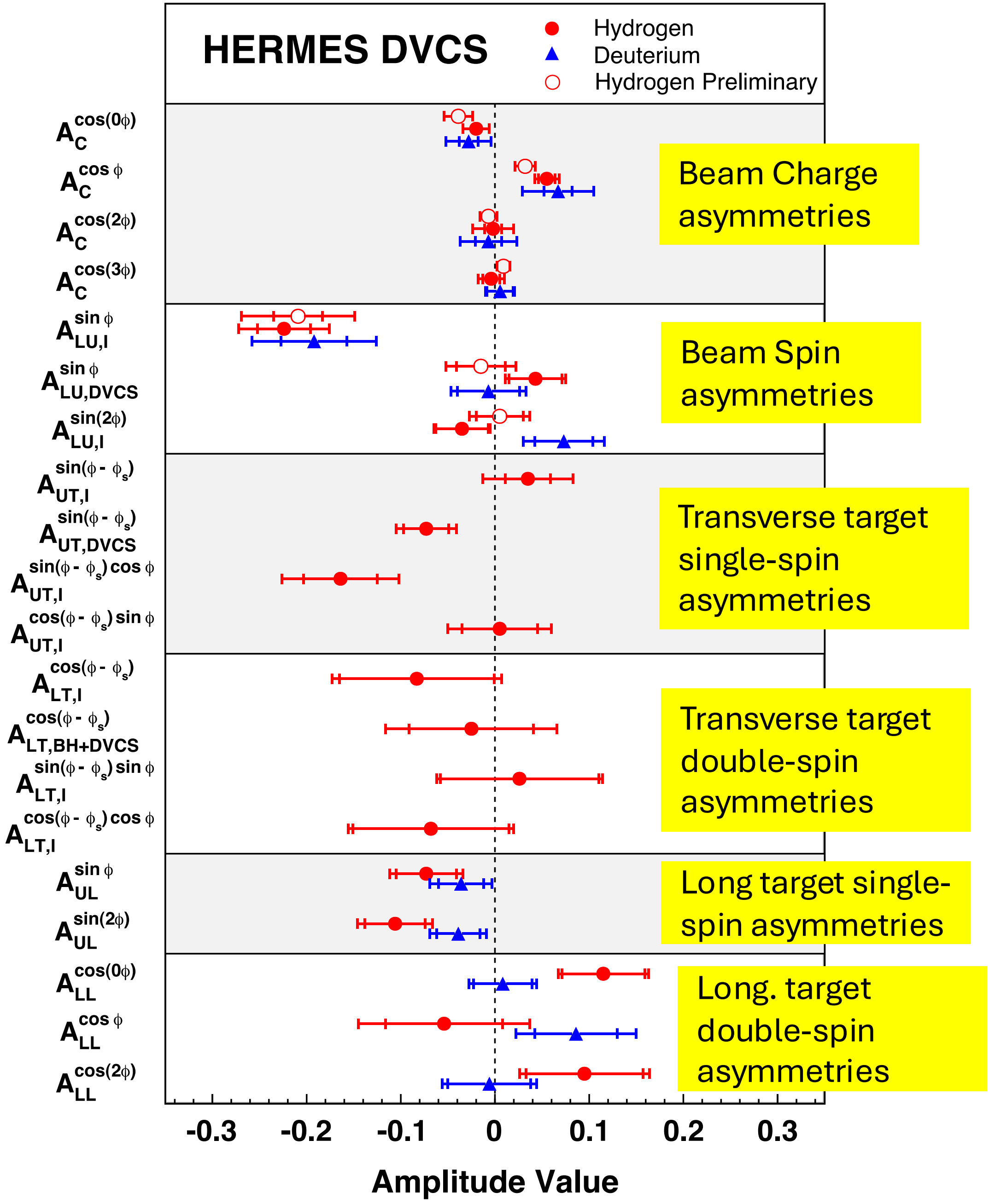
$\langle x_B \rangle \cong 0.1$ • $0.03 < x_B < 0.35$

$\langle -t \rangle \cong 0.1\ \mathrm{GeV}^2$ • $0\ \mathrm{GeV}^2 < -t \equiv -(p-p')^2 < 0.7\ \mathrm{GeV}^2$

8

HERMES, DIS2012:
H(e,e'γ)X

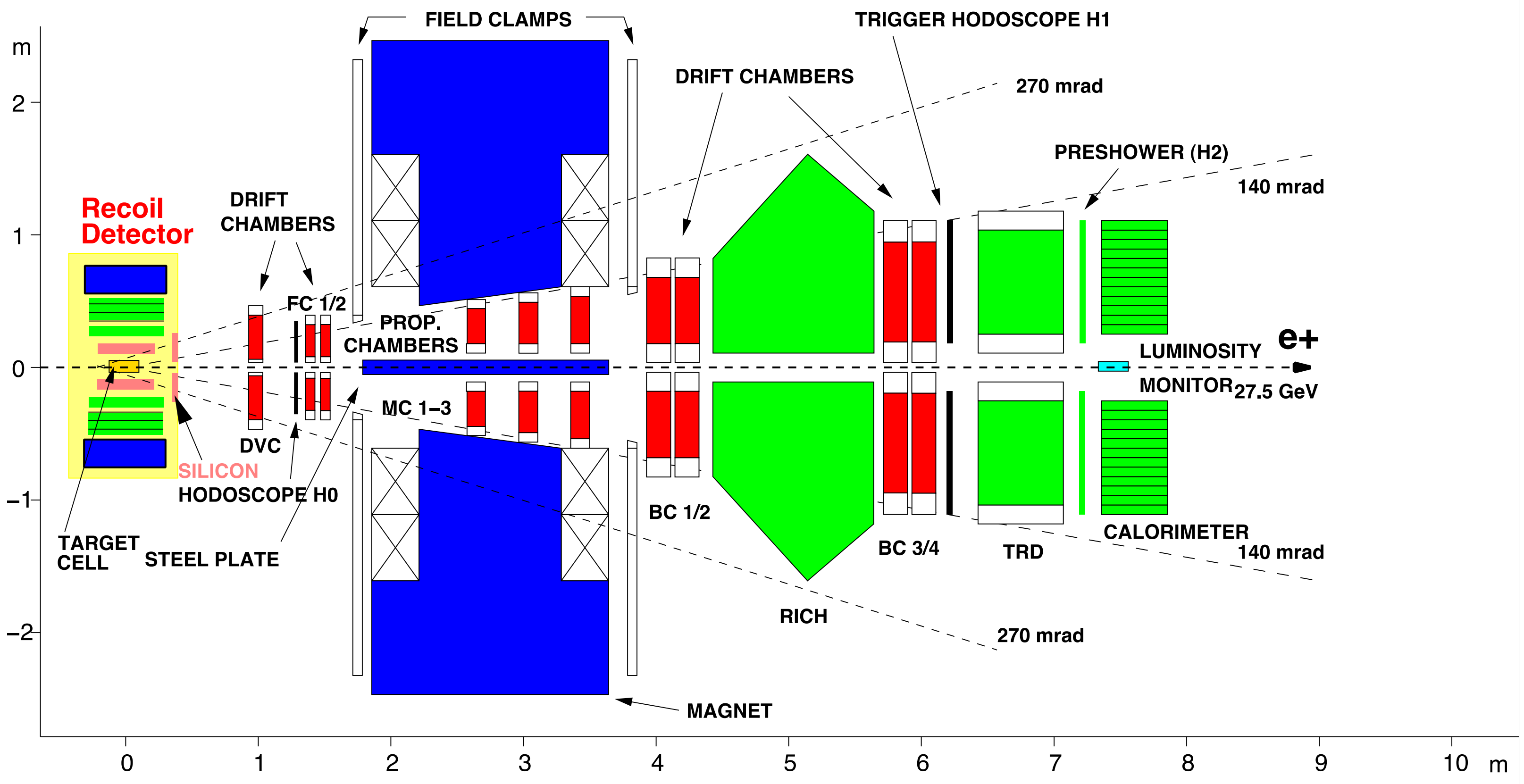




HERMES

- Recoil Tracker upgrade
- Kinematically complete (e,e'pγ) measurements
- Data on transversely polarized target

DVCS @ HERMES



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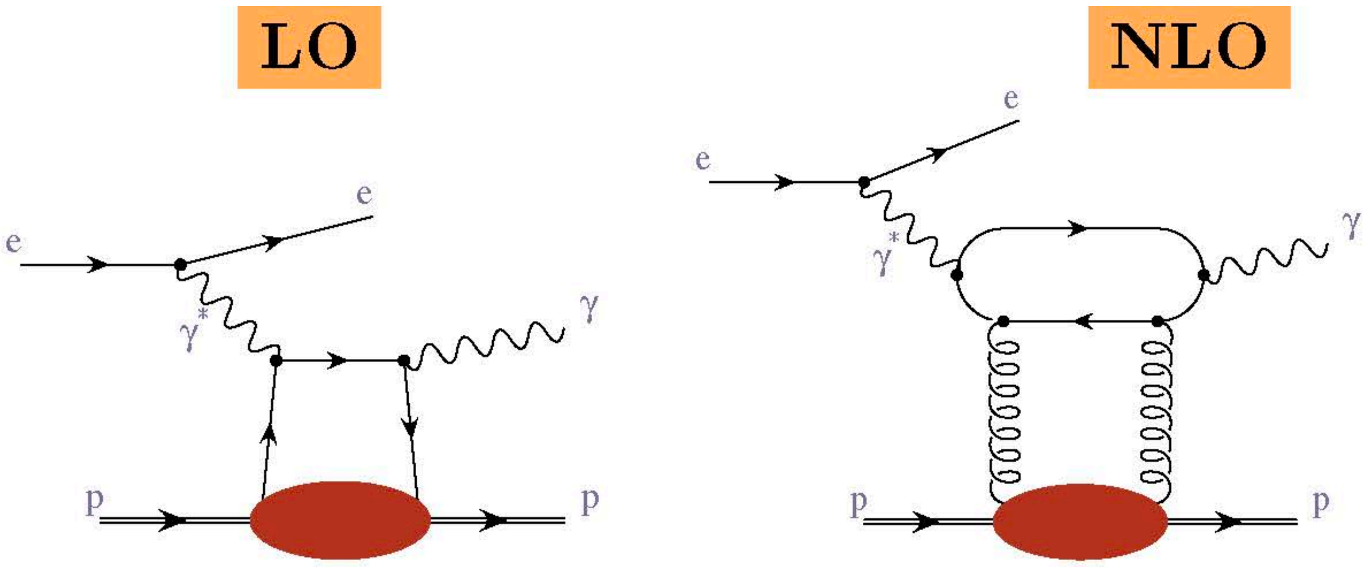
HERA DVCS: H1 & ZEUS

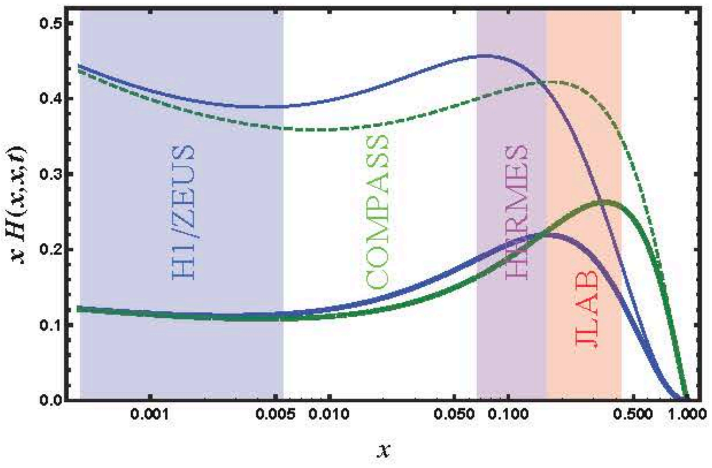
- DIS: QCD Evolution of parton distributions
  - ~20% of all events are diffractive: No evidence of beam proton breakup in final state
  - Both collaborations worked hard to add detectors in ~100m proton downstream space to better understand diffraction
  - Strong motivation for design of EIC with forward detectors fully integrated into accelerator lattice
- Most H1, ZEUS DVCS results are without forward detection of the proton
  - “Exclusivity by event topology”

Kinematic Reach: Fixed Targets & HERA

- Gluons expected to dominate in HERA kinematics



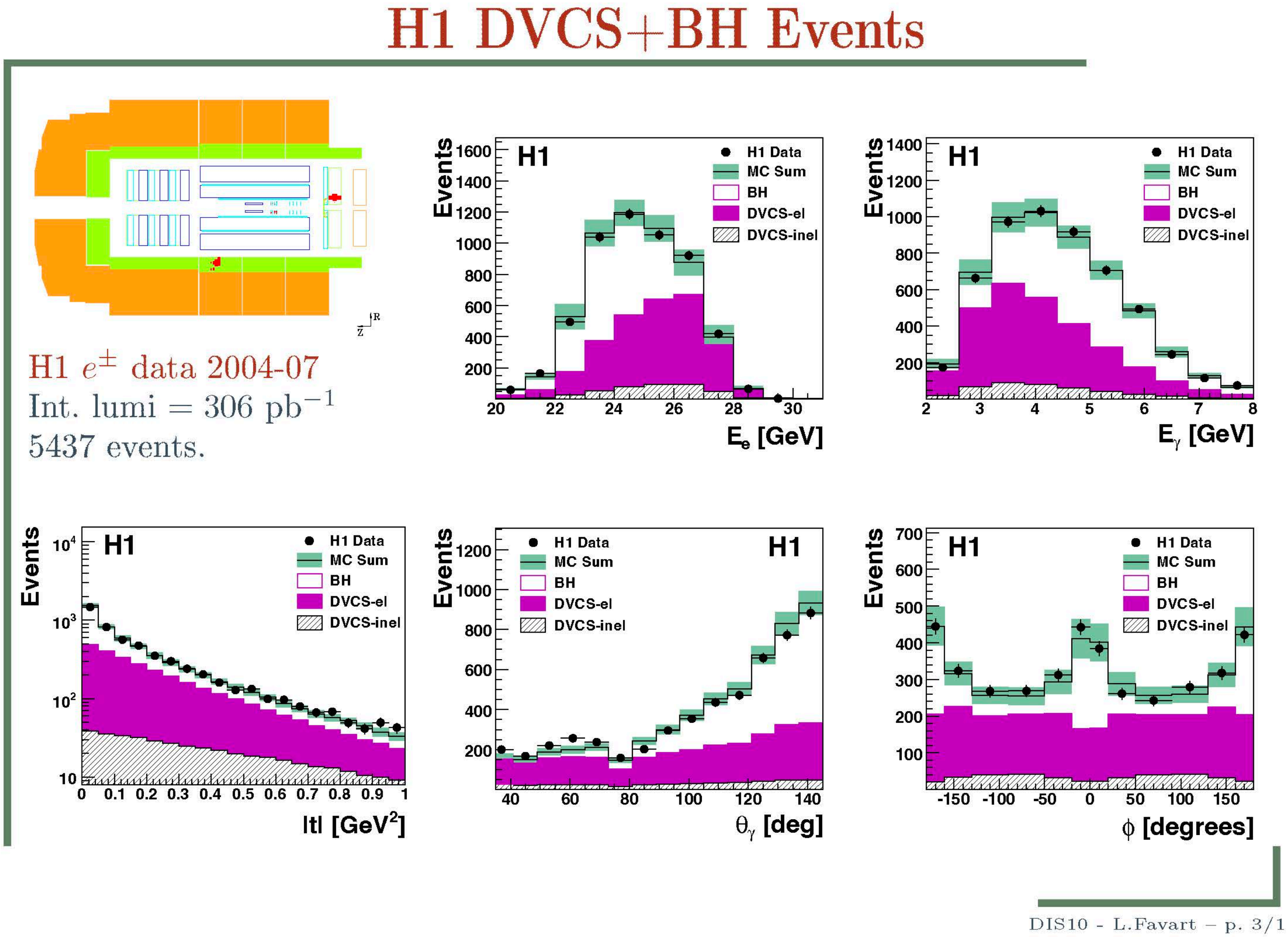
x H(x,x,t)



DIS2010

L.Favart, https://indico.cern.ch/event/86184/contributions/2108312/

- DVCS event is practically empty!
- Inelastic events modelled



Next Lecture

- How do we extract physics from cross sections and spin asymmetries?
- Summary of what we have learned.