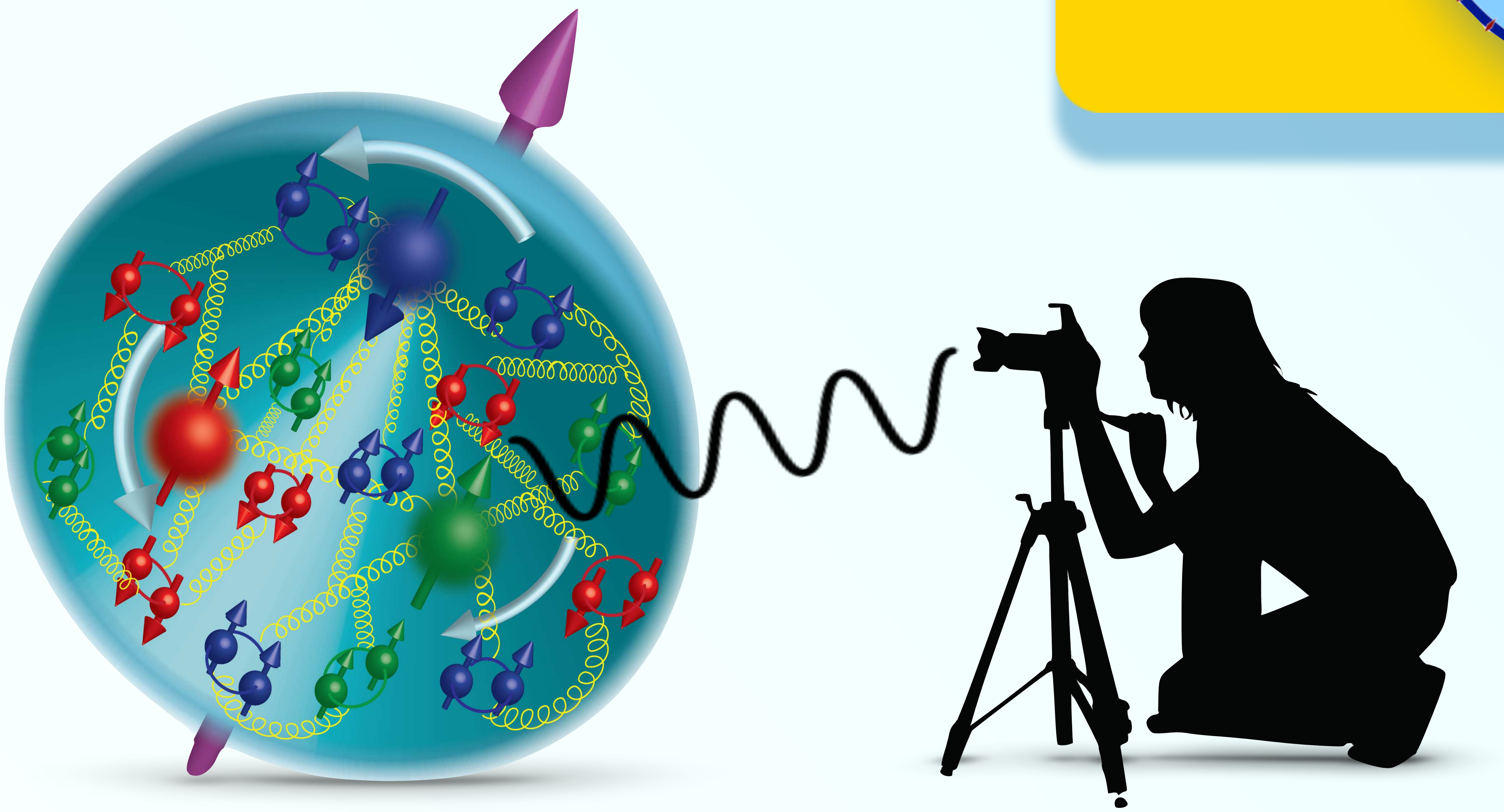
CPHI 2022

Correlations in partonic and hadronic interactions

Duke University (NC), March 7-12, 2022

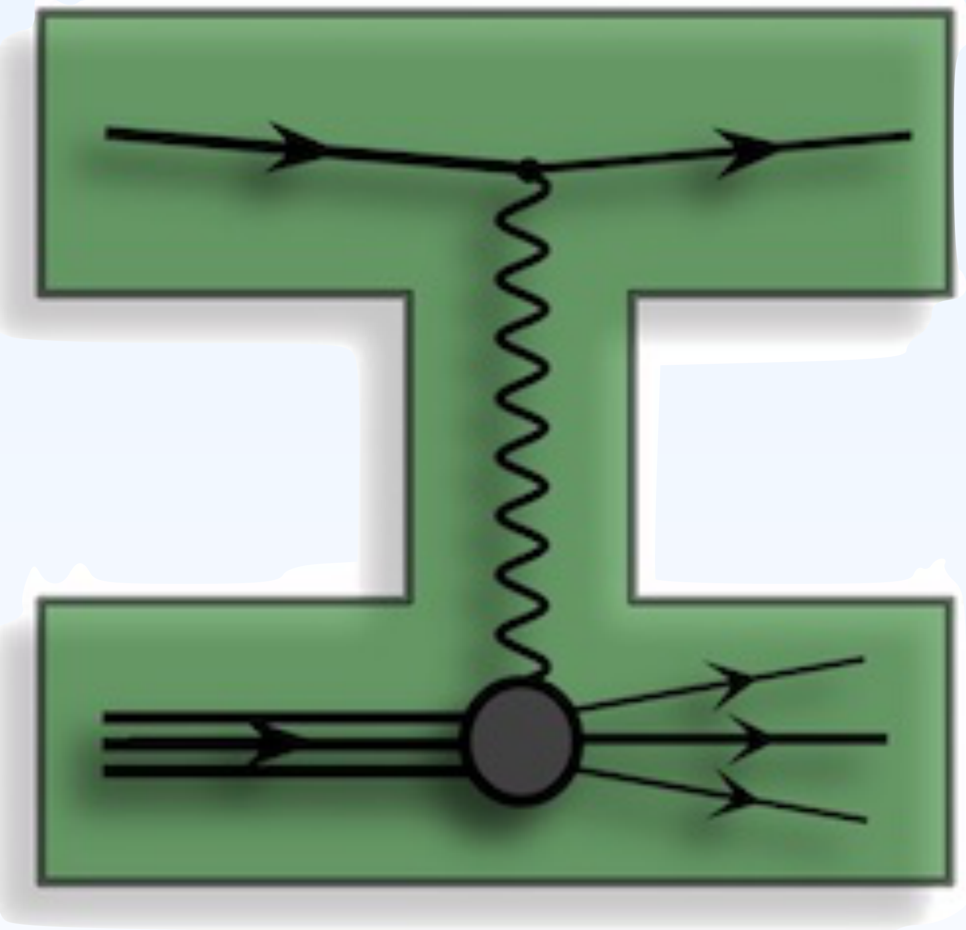
Generalized parton distributions at COMPASS



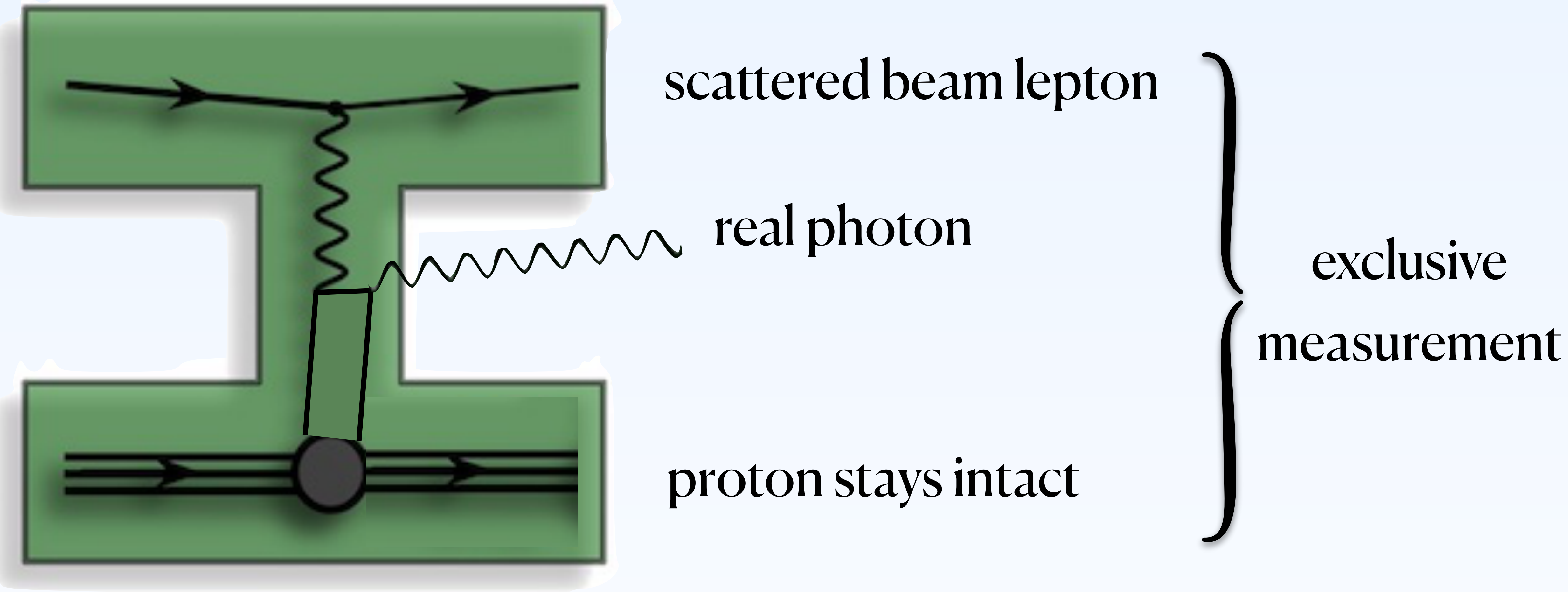
March 8, 2022

Caroline Riedl
for the COMPASS Collaboration

NSF ILLINOIS



inclusive or semi-inclusive
lepton-proton deep-inleastic
scattering



deeply virtual Compton
scattering (DVCS)

Physics questions

How do quarks & gluons, and their dynamics, make up proton spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_g$$

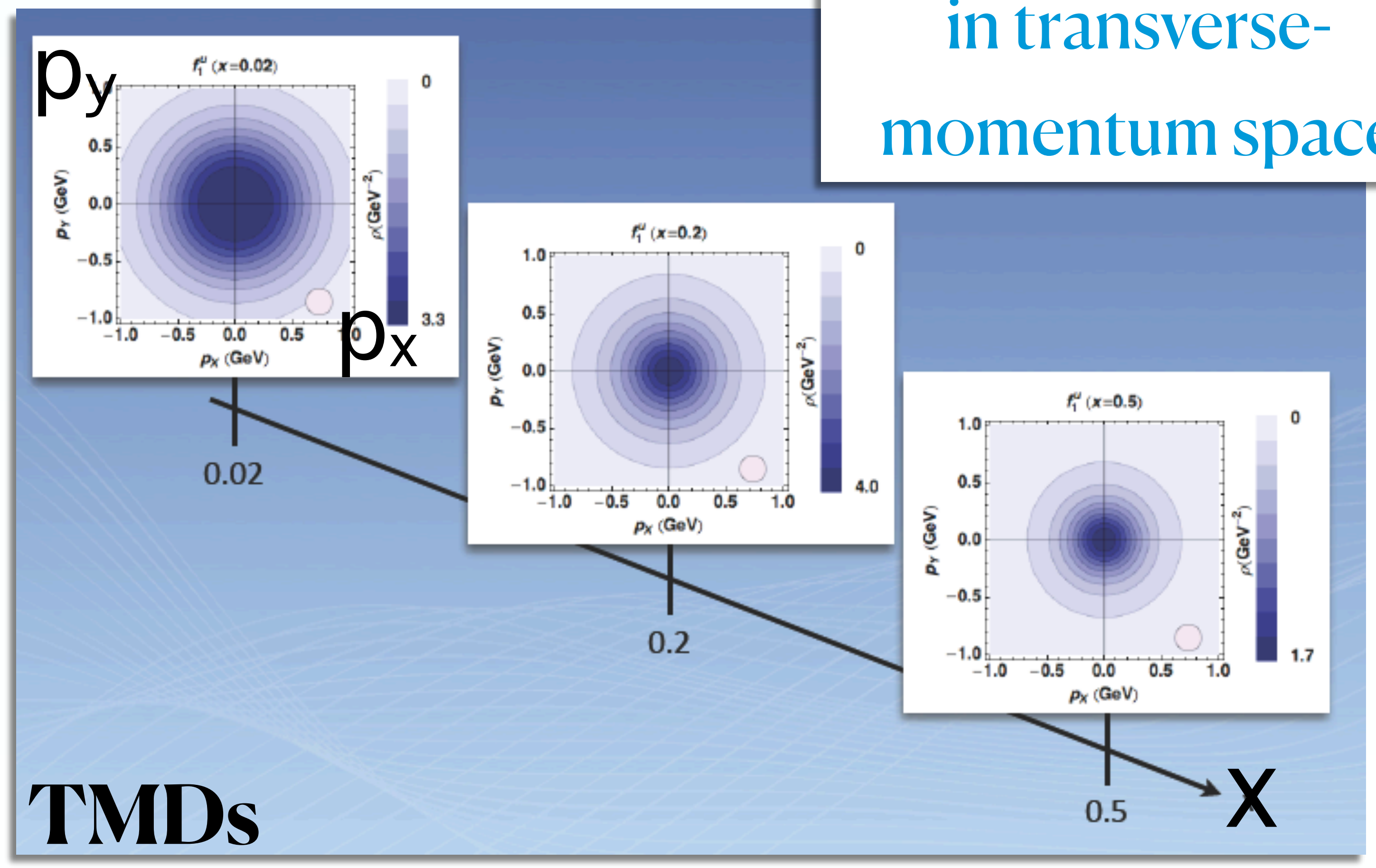
Spin puzzle

quark spin — gluon spin — orbital angular momenta of quarks and gluons

How is the proton spin correlated with the motion of quarks/gluons?

Nucleon tomography

How does the proton spin influence the spatial distribution of partons?



in transverse-momentum space

Transverse Momentum Dependent PDFs

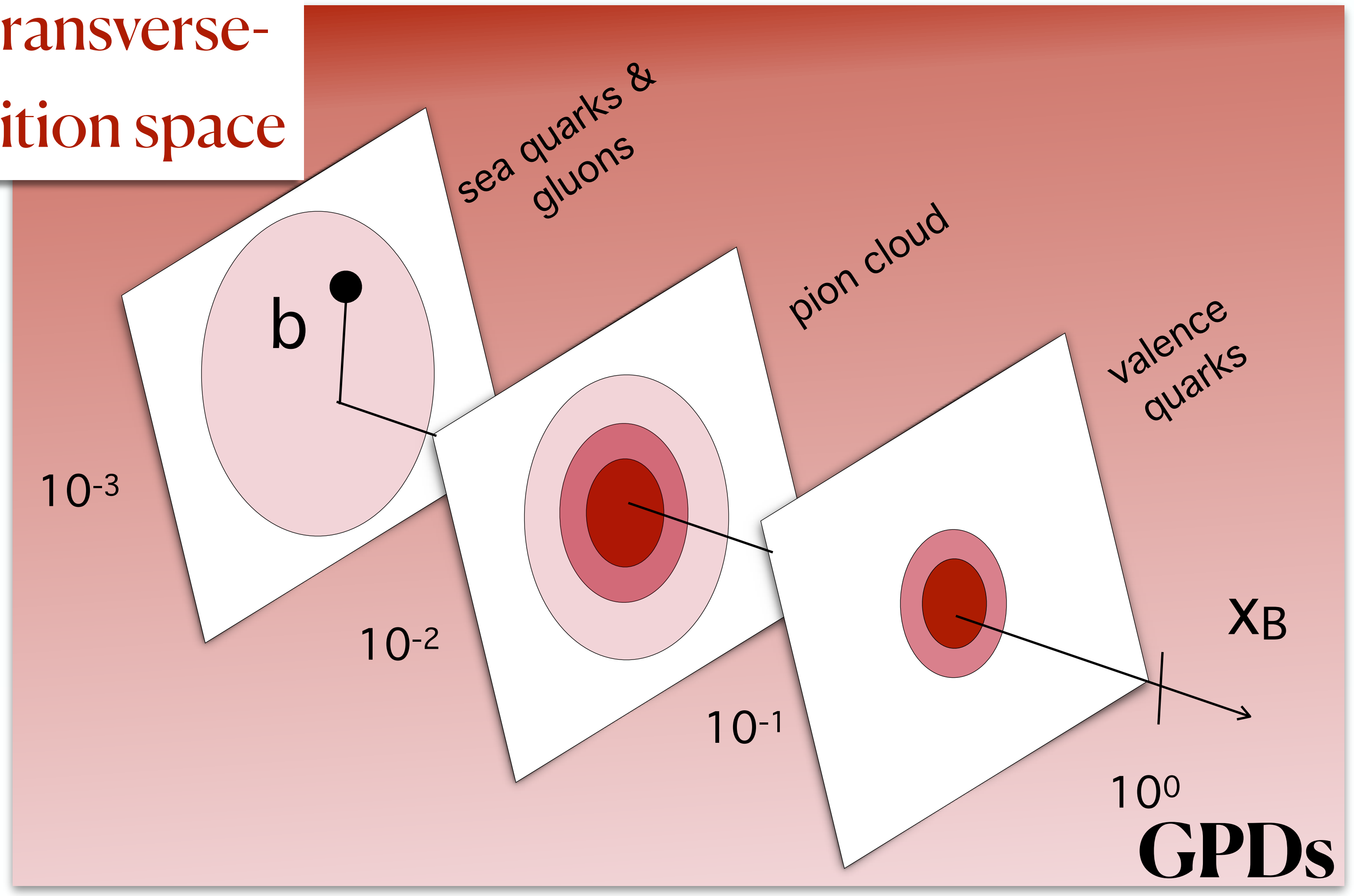
Generalized Parton Distributions

TMDs $f(x,k_T)$

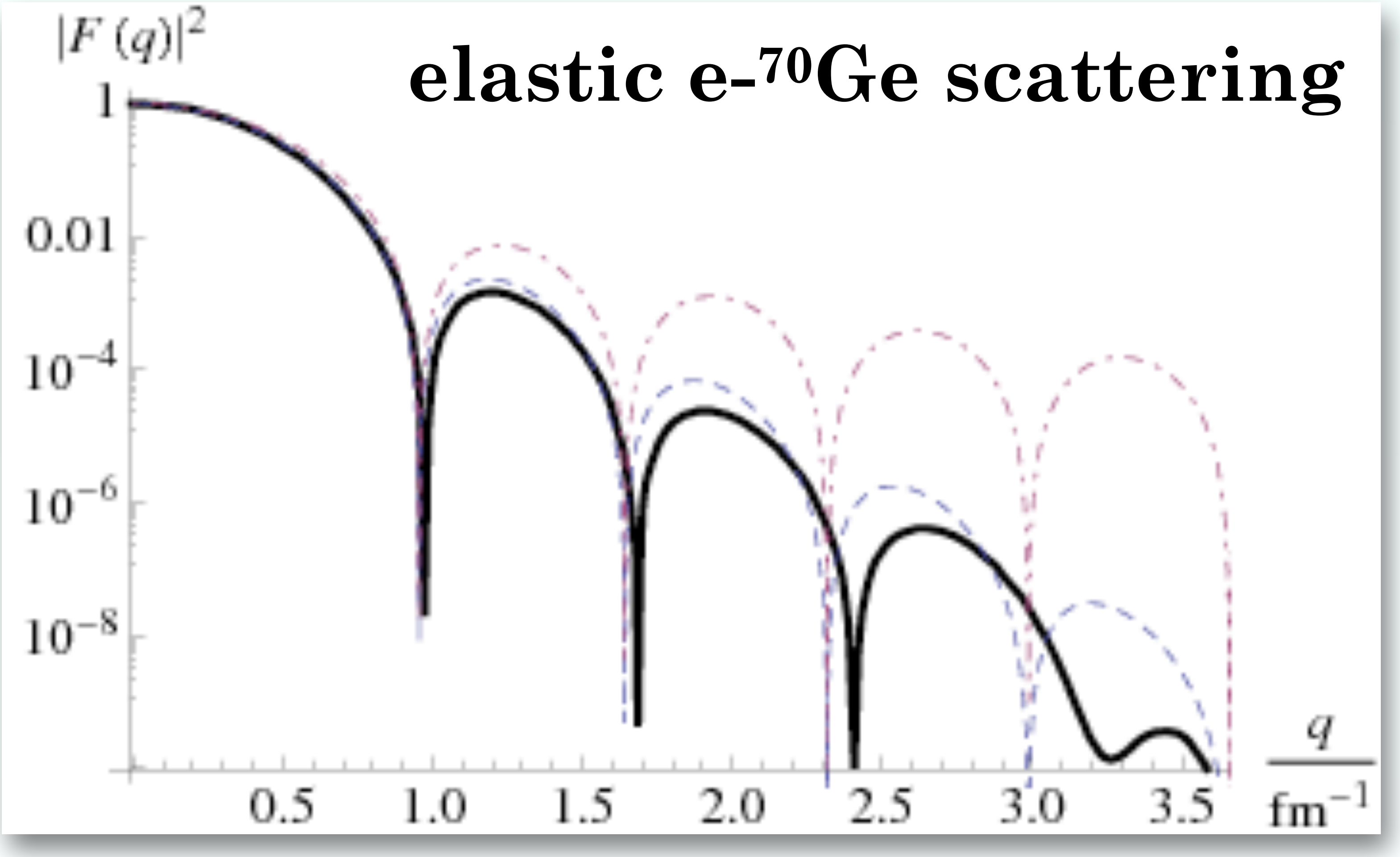
GPDs $H(x,\xi,t)$

k_T-integration → (collinear) PDFs $q(x)$, 1D ← $\xi=0, t=0$

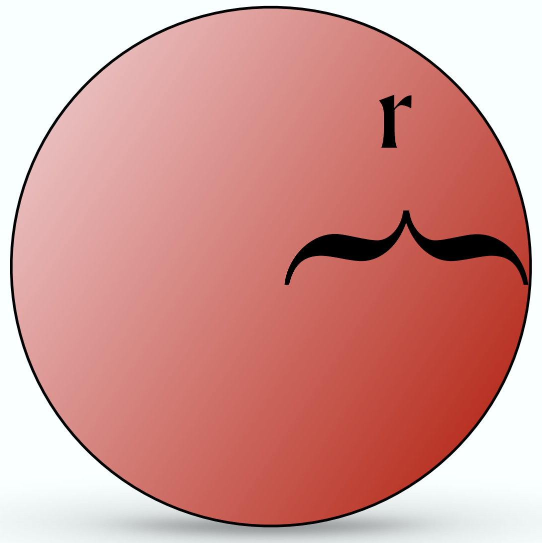
in transverse-position space



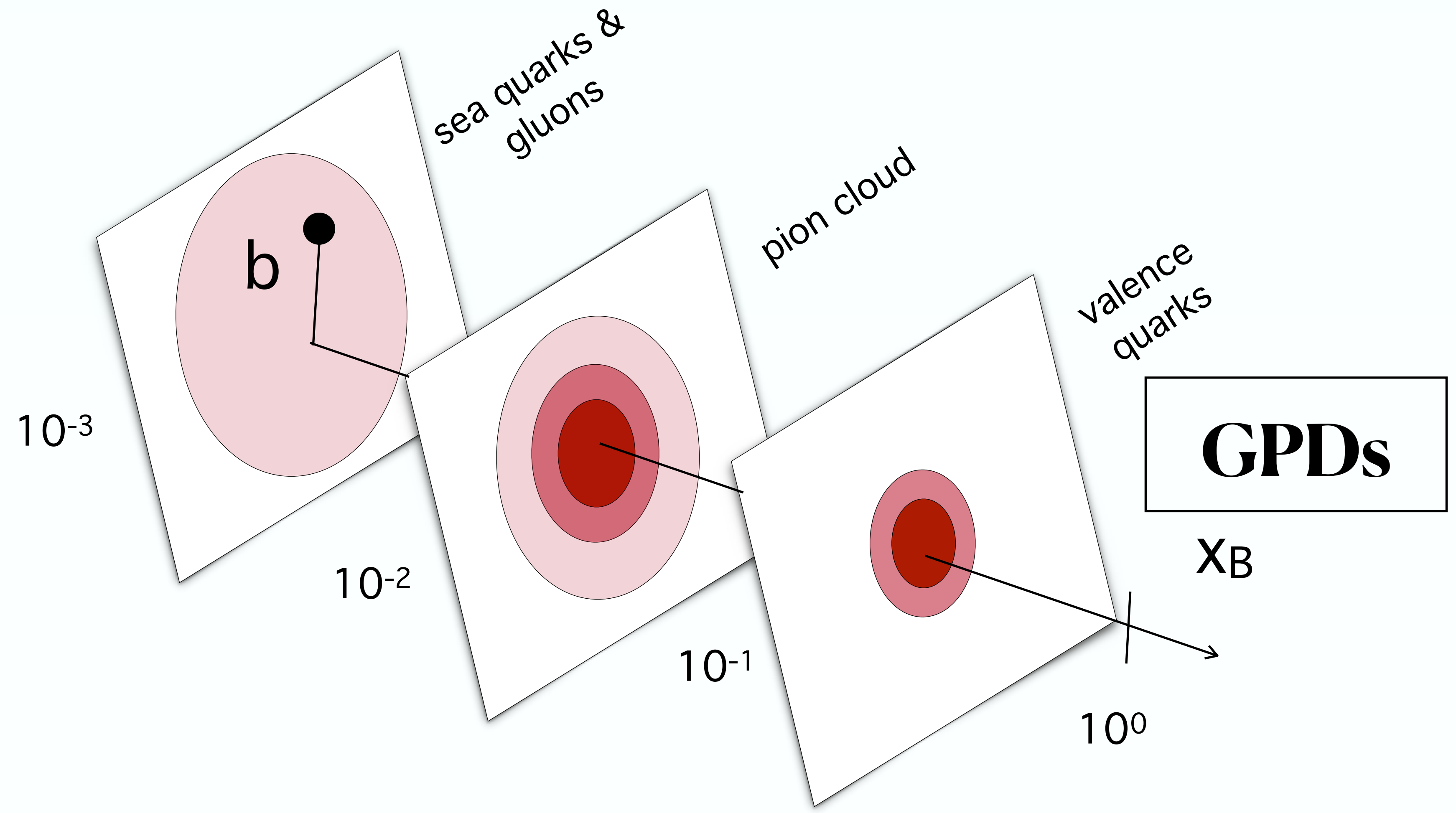
Generalized Parton Distributions



Form factors *from elastic scattering*

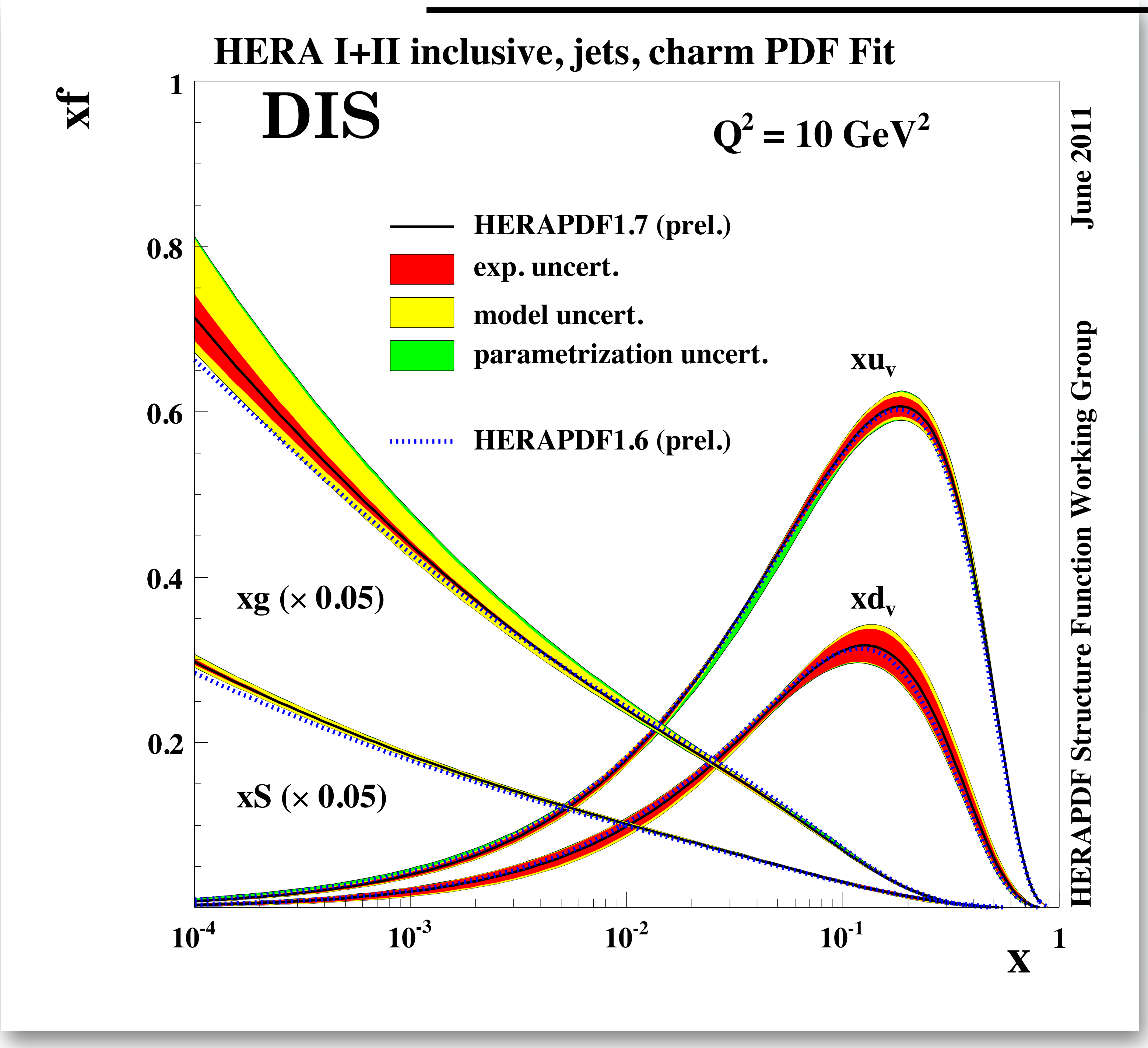


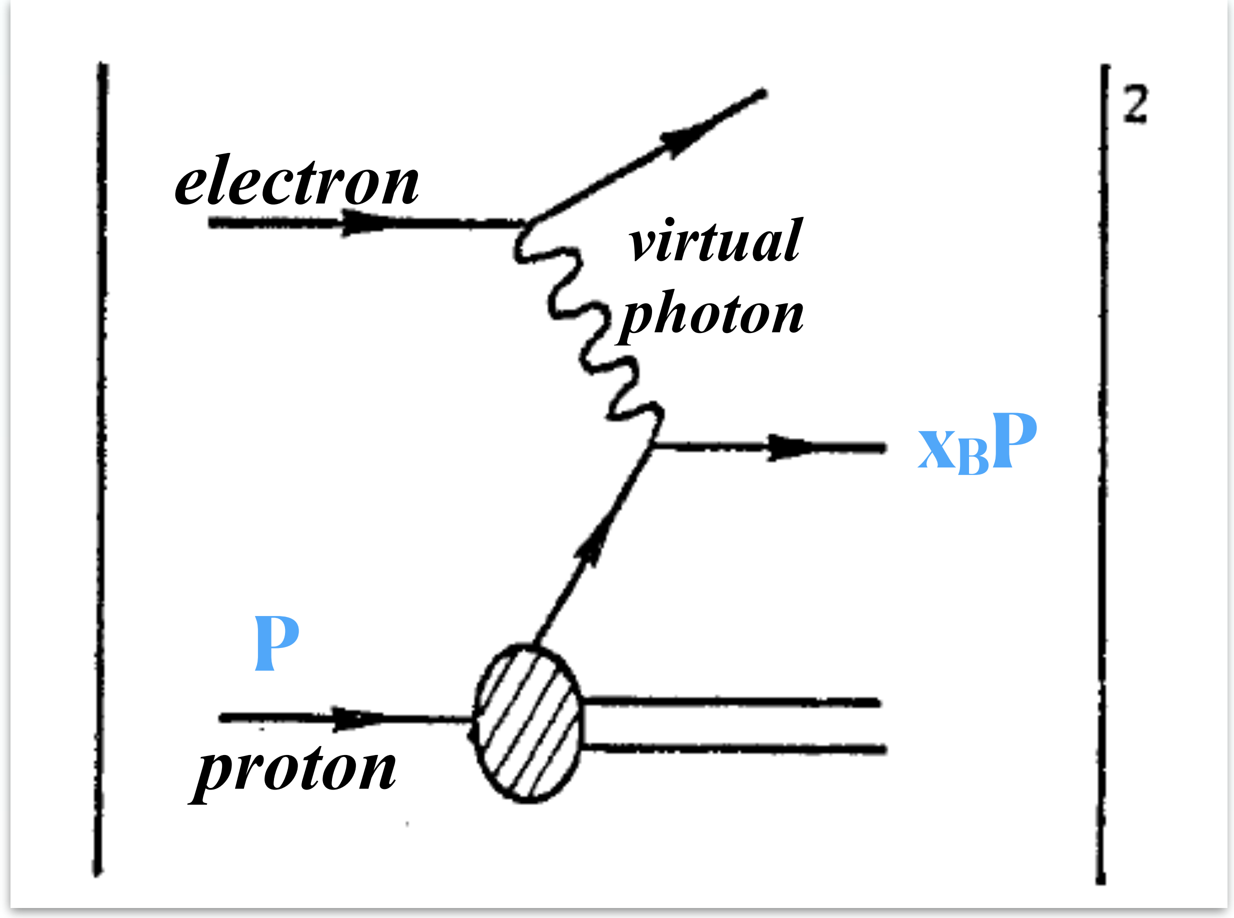
$$\int_{-1}^{1} H^q(x,\xi,t)\mathrm{d}x = F^q(t)$$



transverse parton positions

longitudinal parton momenta

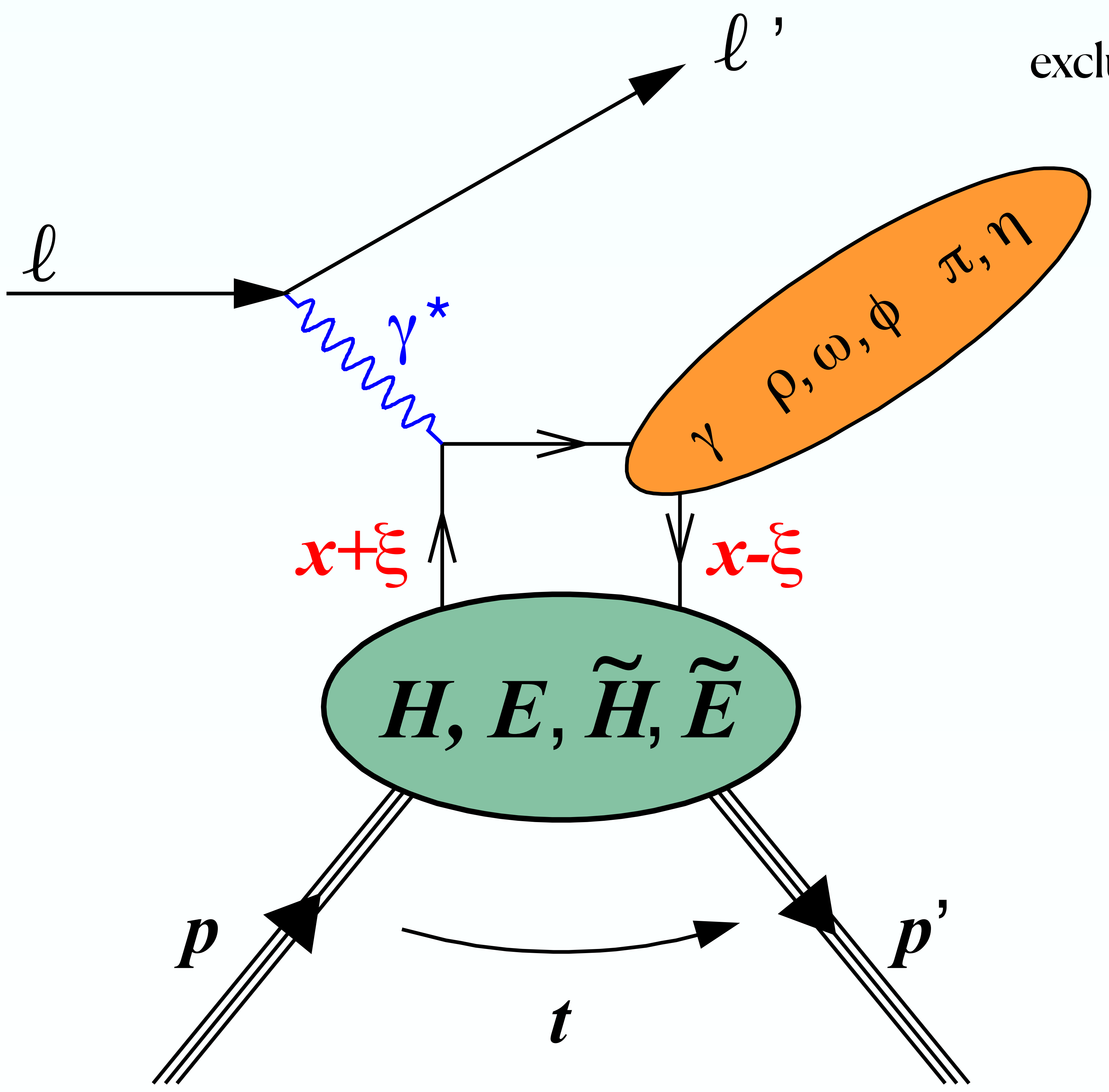




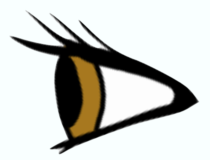
PDFs *from deep-inelastic scattering*

$$H^q(x,0,0) = q(x)$$

Hard exclusive reactions



exclusive measurement = detection of entire final state
(or assumed to be known)



Standard channels to access generalized parton distributions are DVCS & DVMP

$\ell p \rightarrow \ell p \gamma$ Deeply Virtual Compton Scattering (DVCS)

$\ell p \rightarrow \ell p M$ Deeply Virtual Meson Production (DVMP)

- *x, ξ*: longitudinal momentum fractions of probed quark
  - **skewness** $\xi \simeq x_B / (2\text{-}x_B)$ in Bjorken limit
  (Q^2 large & x_B, *t* fixed)
  - **average momentum *x*: mute variable**,
  not accessible in DVCS & DVMP. Is not *x*-Bjorken!

- ***t*: squared 4-momentum transfer to target**

Experimental access to GPDs

From HERMES & JLab-6 & HERA to COMPASS & JLab12 & RHIC to the EIC

- Different exclusive final-state particles allow to probe different GPDs
- 4 chiral-even GPDs (conserve quark helicity)
- 4 chiral-odd GPDs (flip quark helicity)

@leading twist for a spin-½ target

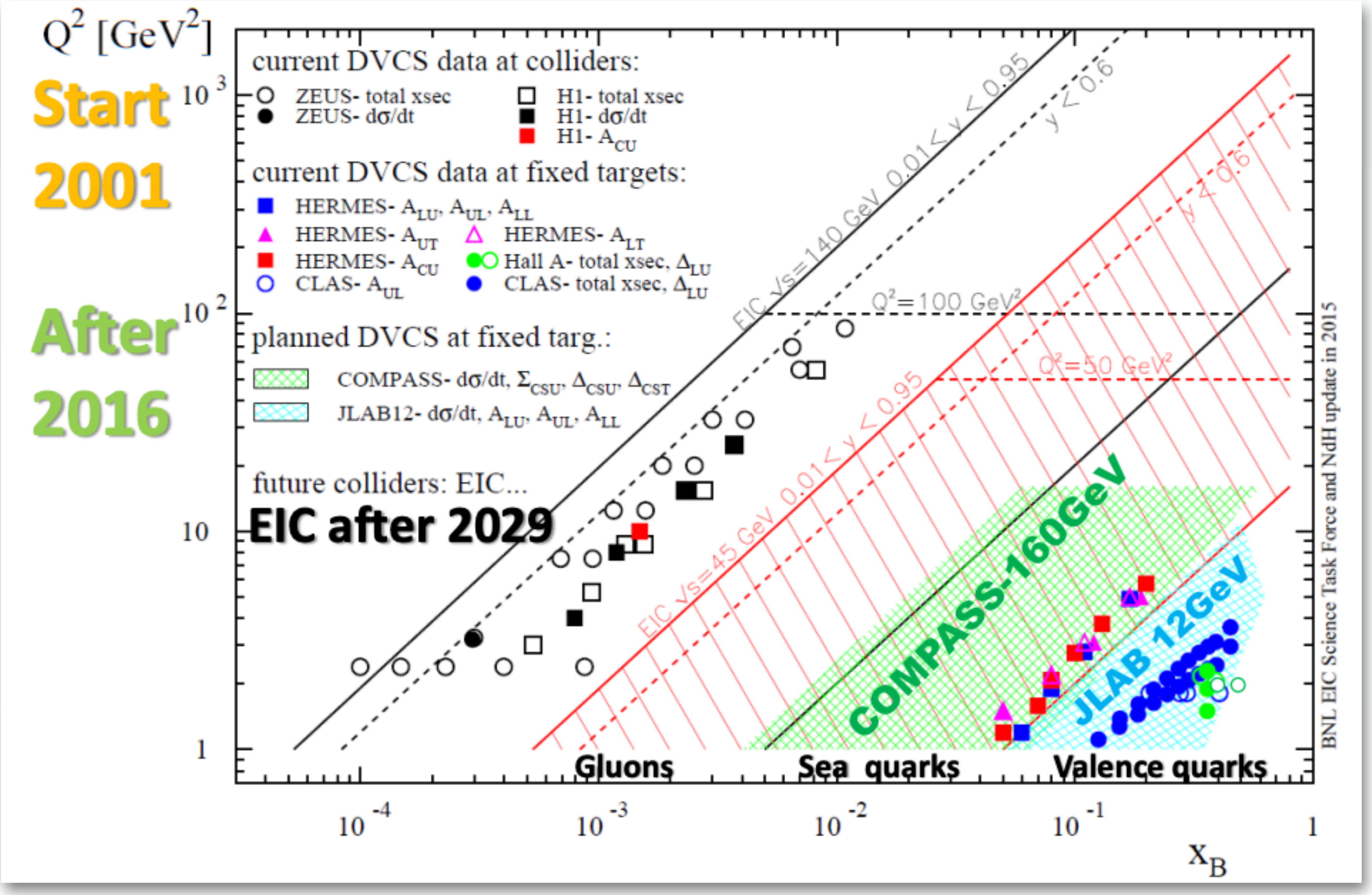
GPDs	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	**E**	**H**
depends on quark helicity	**Ẽ**	**H̃**

H → $F_1(x)$

H̃ → $g_1(x)$

forward limit $\xi \to 0, t \to 0$

$J^P=1^-$ vector mesons	$J^P=1^-$ photon (DVCS)
$J^P=0^-$ pseudoscalar mesons	



DVCS: Compton form factors (CFFs) ↔ GPDs

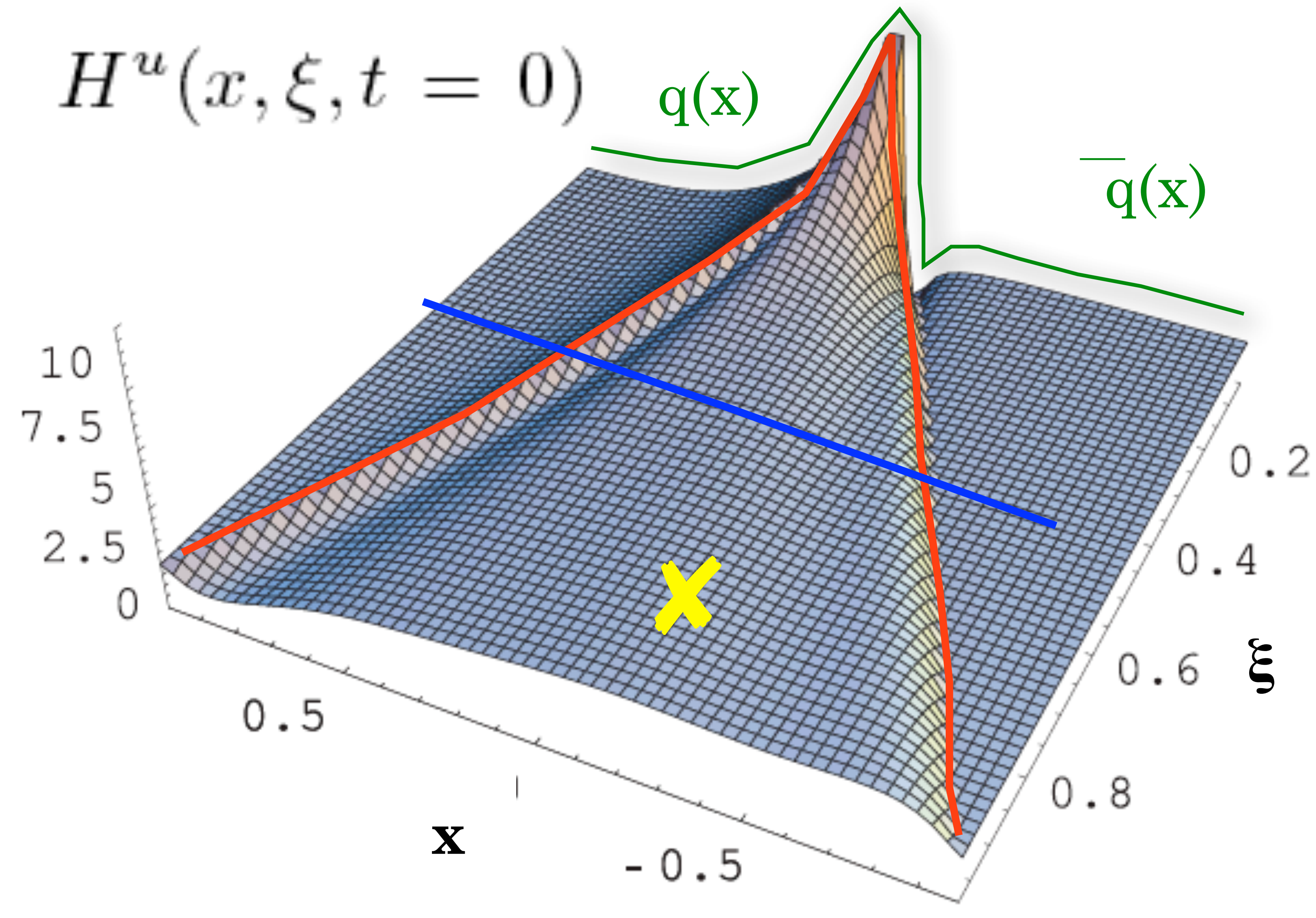
In DVCS, the experimentally accessed quantity is a (complex) **Compton Form Factor (CFF):**

$$\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} \mathrm{d}x \, \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\xi,\xi,t)$$

CFF **hard scattering kernel** ⊗ **GPD**

$$\mathcal{F}(\xi,t) = \sum_q \int_{-1}^{1} \mathrm{d}x \, C_q^{\mp}(\xi,x) F^q(x,\xi,t)$$

assuming factorization (Q^2 large & t small)



Im(τDVCS)
x=ξ

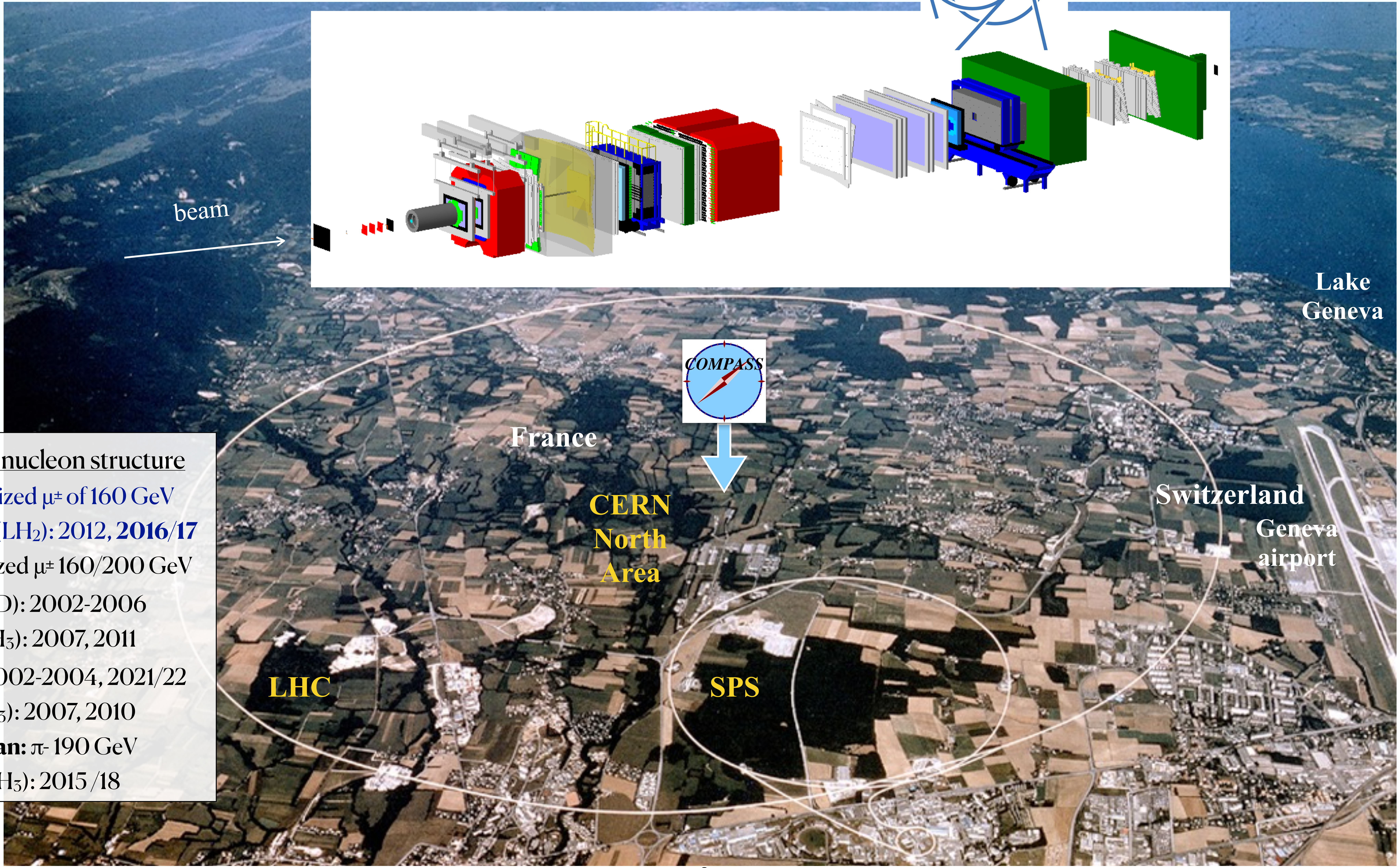
Re(τDVCS)
integral over *x*

Im(τDVCS)
|*x*|<*ξ*
DDVCS

Dispersion relation with D-term *D(t)*: related to shear forces and radial distribution of pressure inside the nucleon

$$\mathcal{R}e\mathcal{H}(\xi,t) = \mathcal{P}\int_{-1}^{+1} \mathrm{d}x \, \frac{\mathcal{I}m\mathcal{H}(x,t)}{x-\xi} + D(t)$$

COMPASS @ CERN



COMPASS nucleon structure

GPD: polarized $\mu^\pm$ of 160 GeV

unpol proton (LH_2): 2012, **2016/17**

SIDIS: polarized $\mu^\pm$ 160/200 GeV

d→ (^{6}LiD): 2002-2006

p→ (NH_3): 2007, 2011

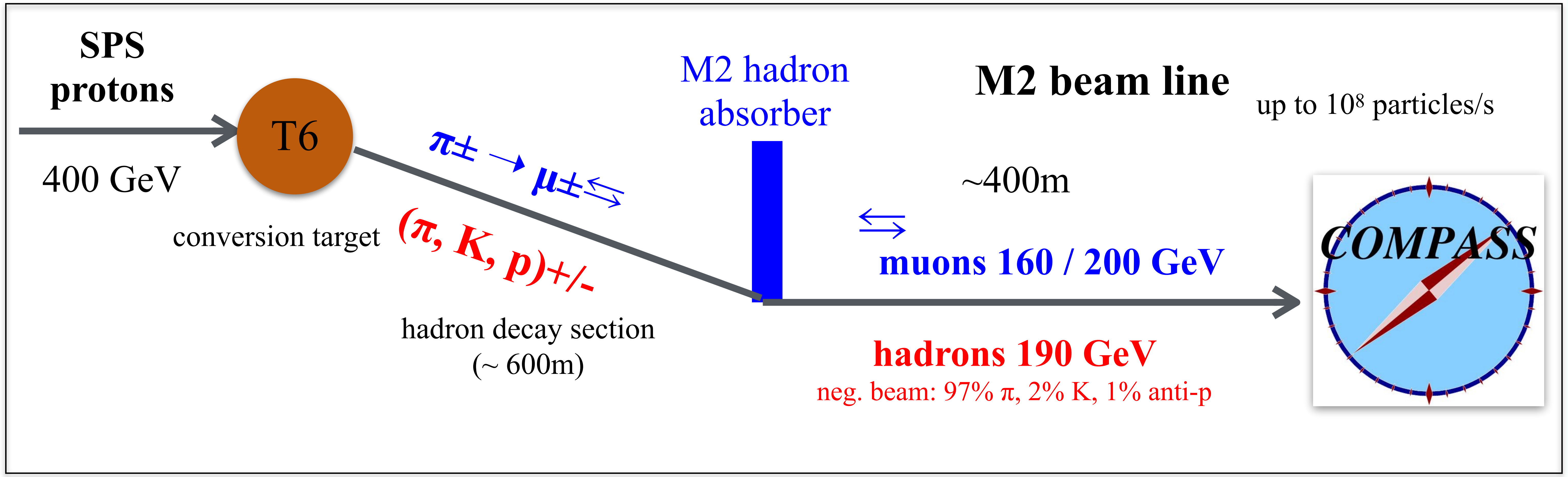
d↑ (^{6}LiD): 2002-2004, 2021/22

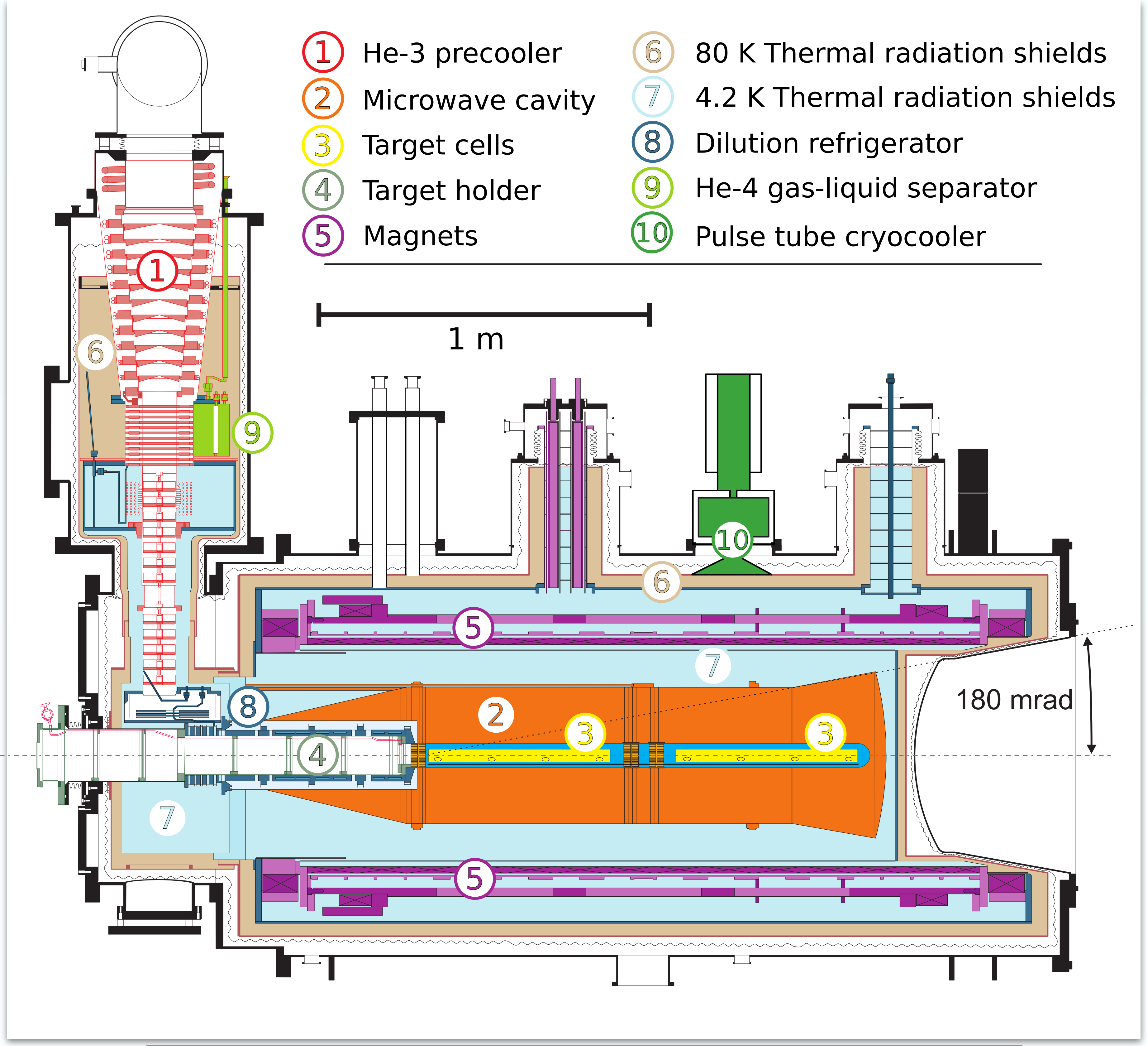
p↑ (NH_3): 2007, 2010

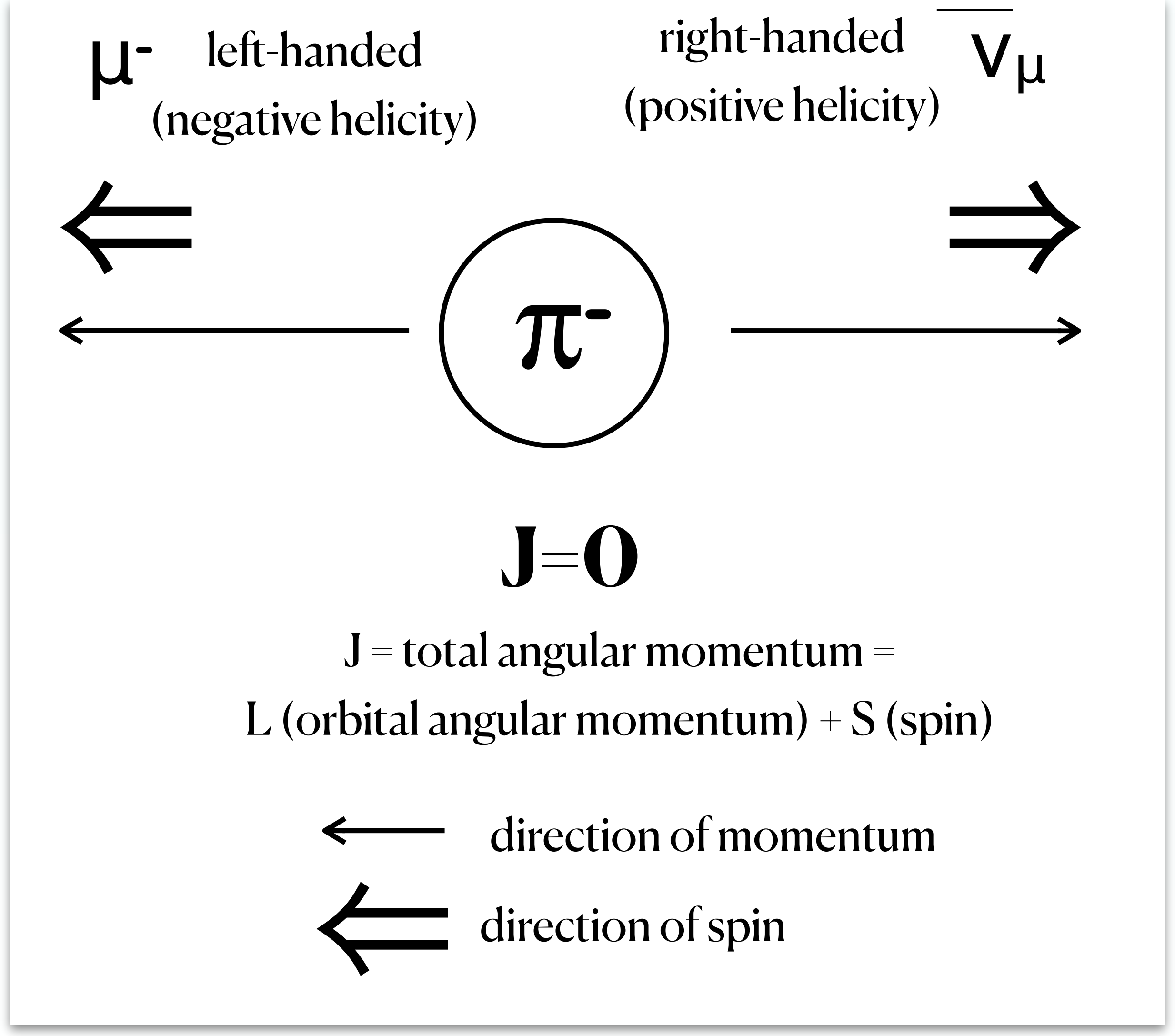
Drell-Yan: π^- 190 GeV

p↑ (NH_3): 2015 /18

CERN SPS polarized muon beams and COMPASS polarized target







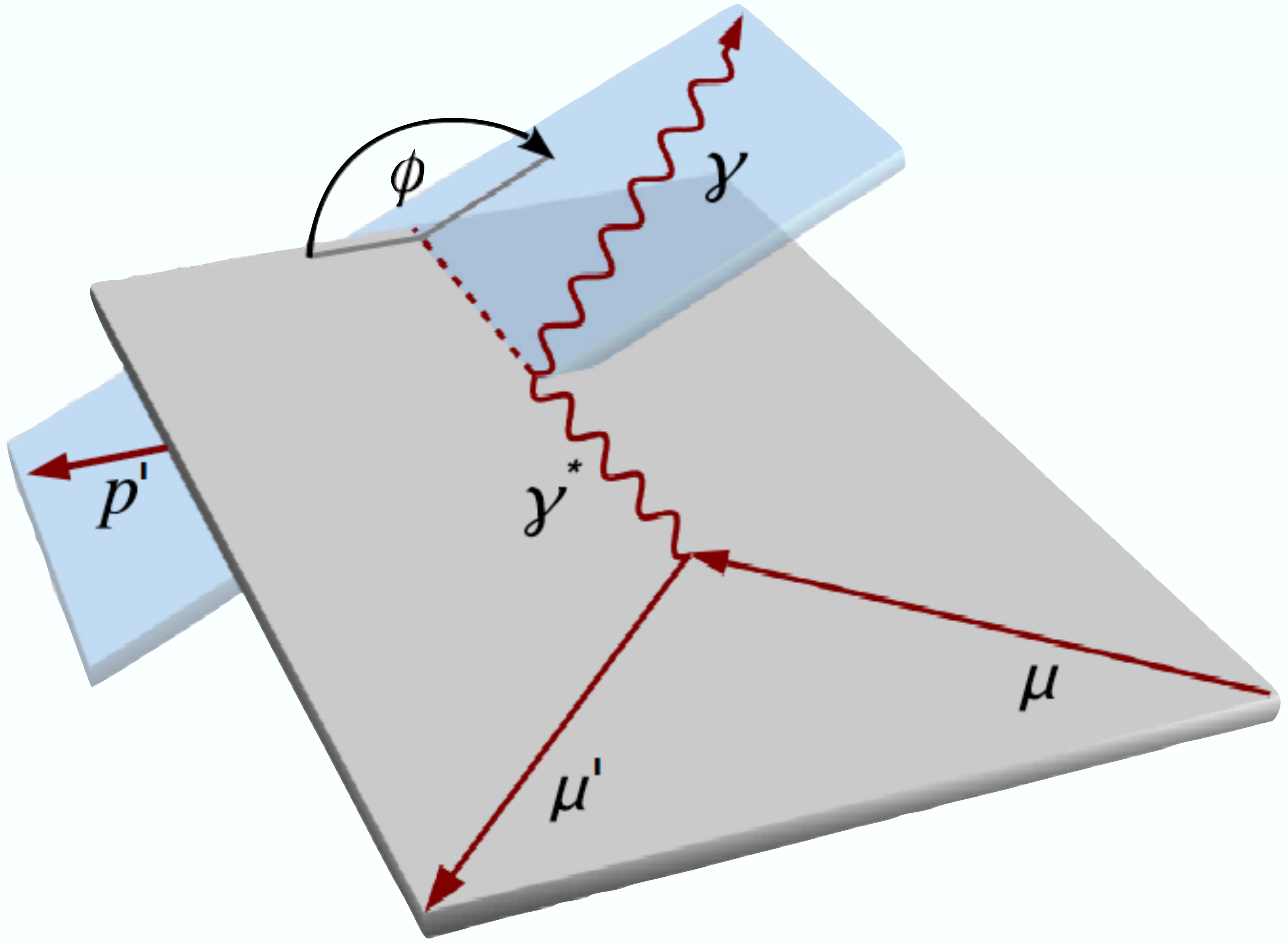
NH_3: ammonia beads, **^{6}LiD:** deuterated lithium
dilution factor ~ 0.22 (NH3), 0.5 (LiD)

- Polarization achieved by **Dynamic Nuclear Polarization (DNP)**
  - dilution refrigerator: ~60mK
  - dipole magnet (transverse): 0.5T
  - solenoid (longitudinal): 2.5T
  - microwave system

~ 80% for protons
~ 50% for deuterons

- Polarization determined with **Nuclear Magnetic Resonance (NMR)**

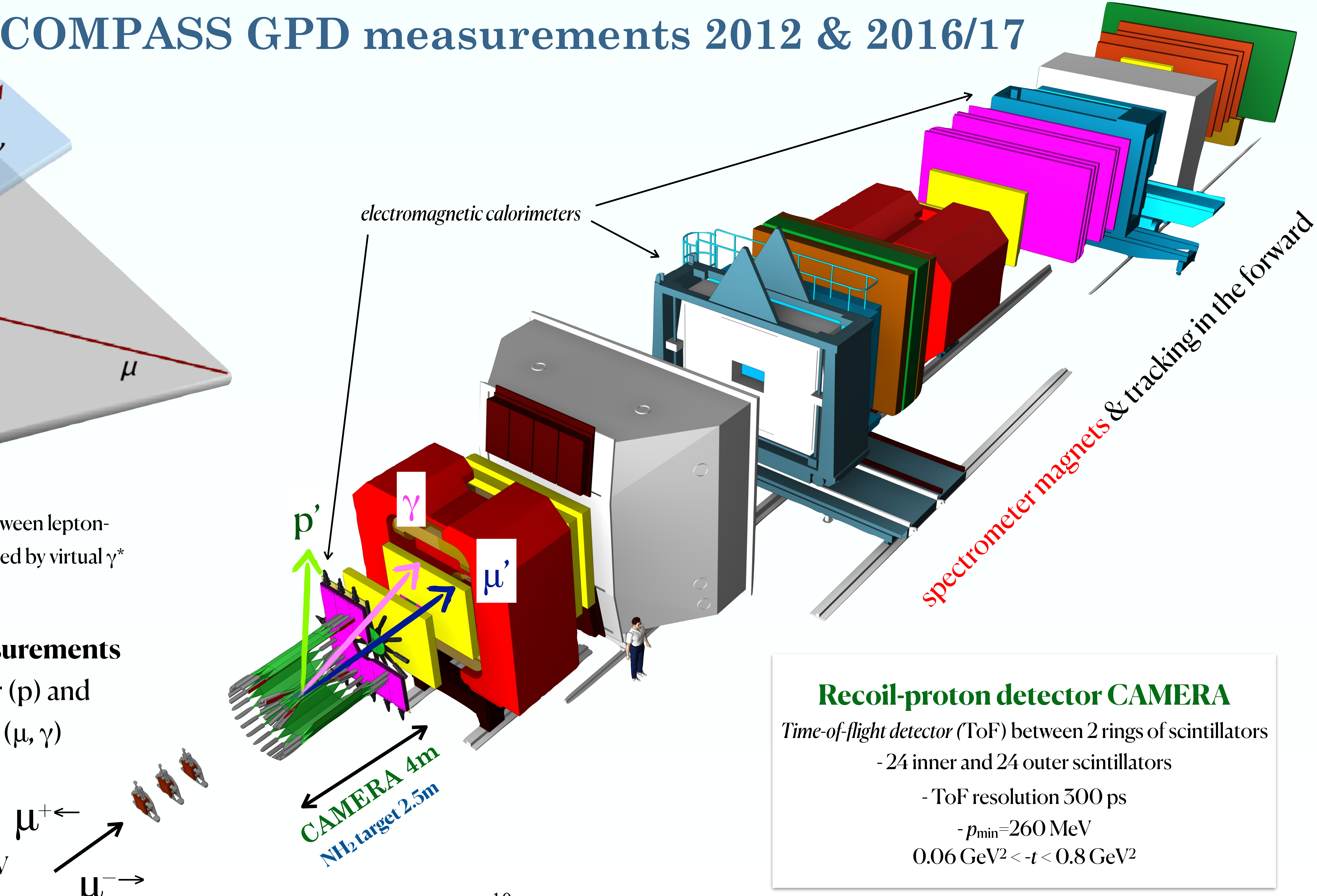
COMPASS GPD measurements 2012 & 2016/17



Azimuthal angle $\phi_{\gamma\gamma^*}$ between lepton-scattering μμ' plane and plane defined by virtual γ* and real γ photons

Separate kinematic measurements

in recoil-proton detector (p) and forward spectrometer (μ, γ)



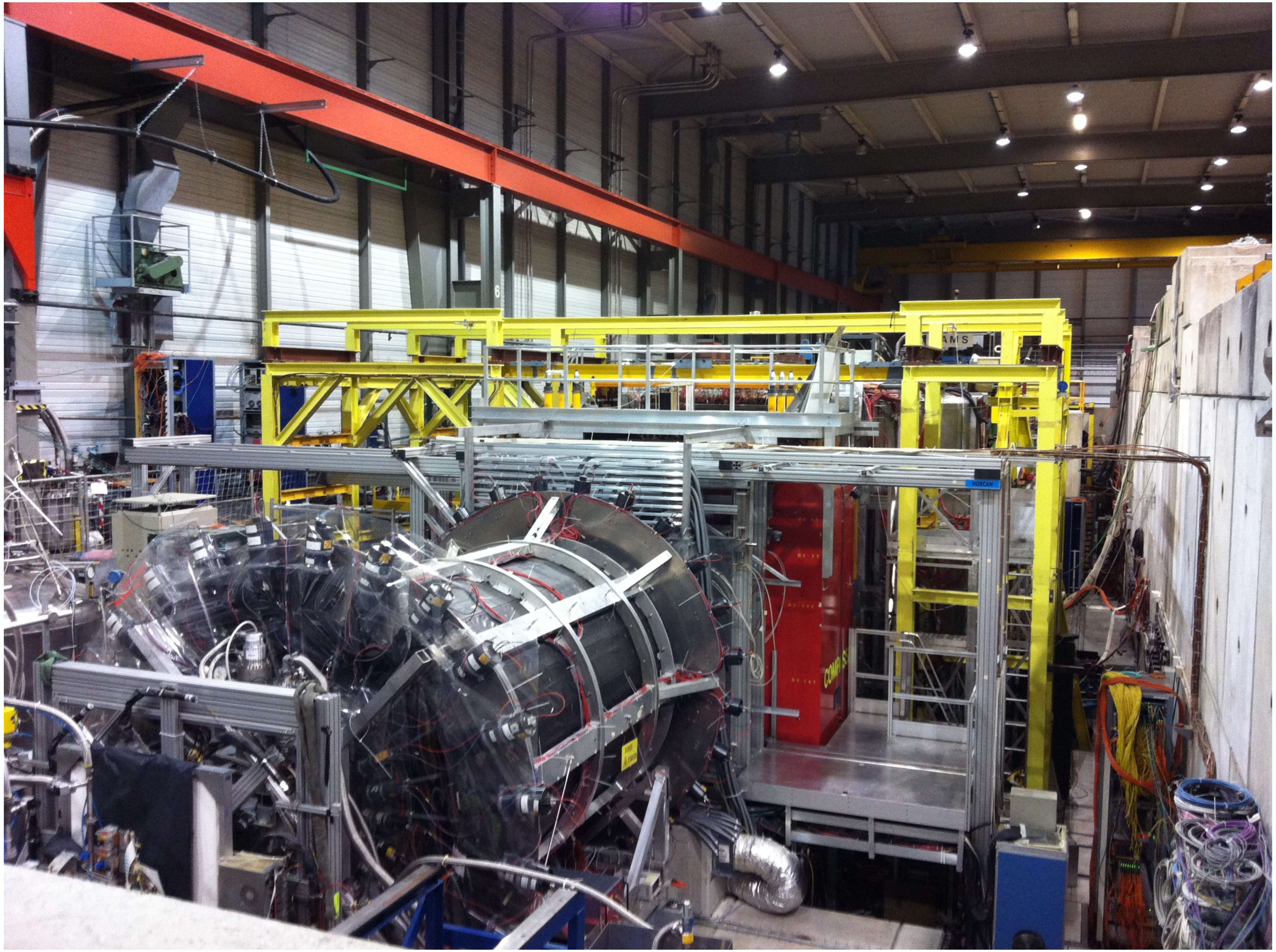
Recoil-proton detector CAMERA

Time-of-flight detector (ToF) between 2 rings of scintillators

- 24 inner and 24 outer scintillators
- ToF resolution 300 ps
- p_{min}=260 MeV

0.06 GeV² < -*t* < 0.8 GeV²

COMPASS GPD measurements 2012 & 2016/17



Selection of exclusive event sample

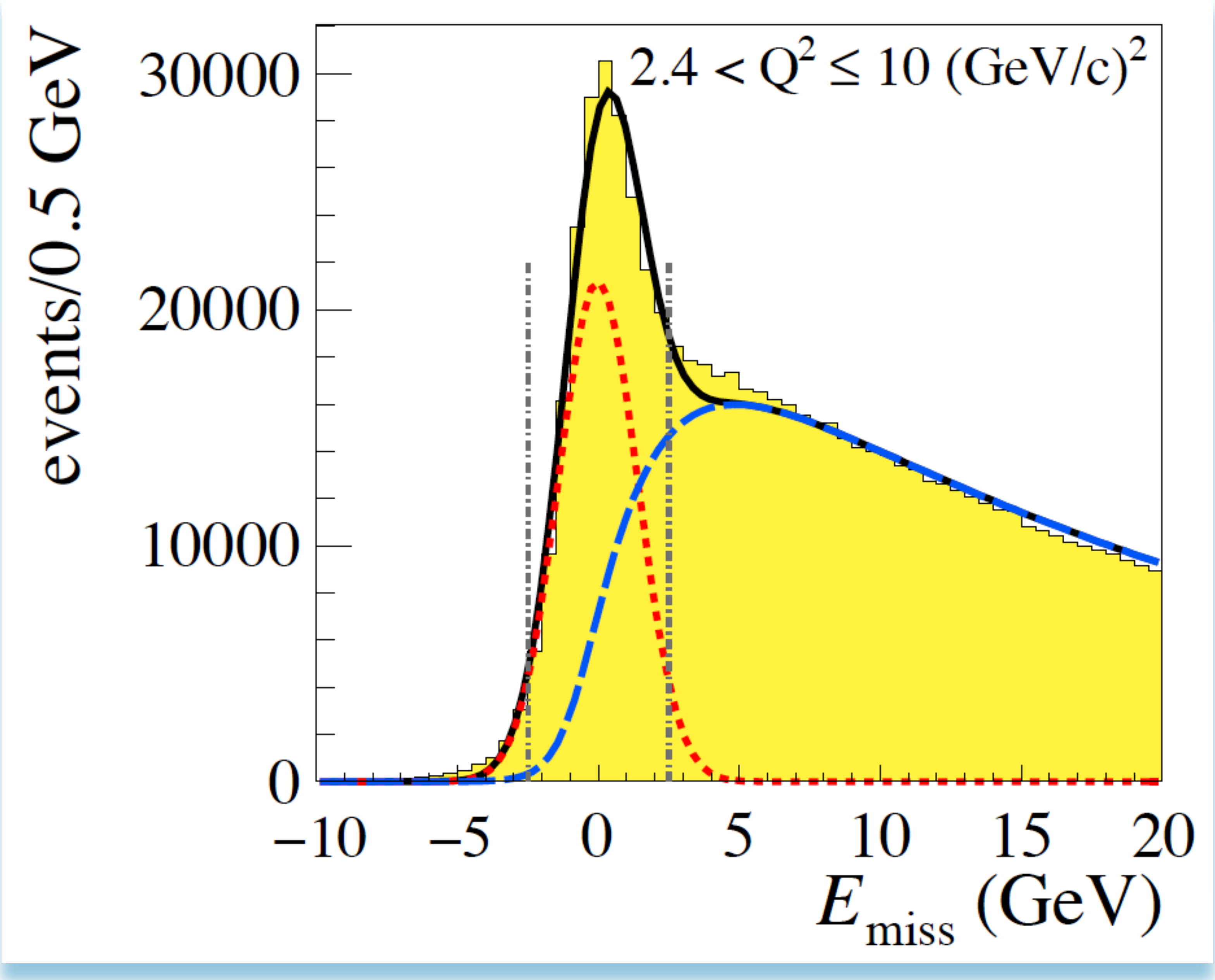
DVMP without recoil-proton detection:
missing energy technique assuming proton mass

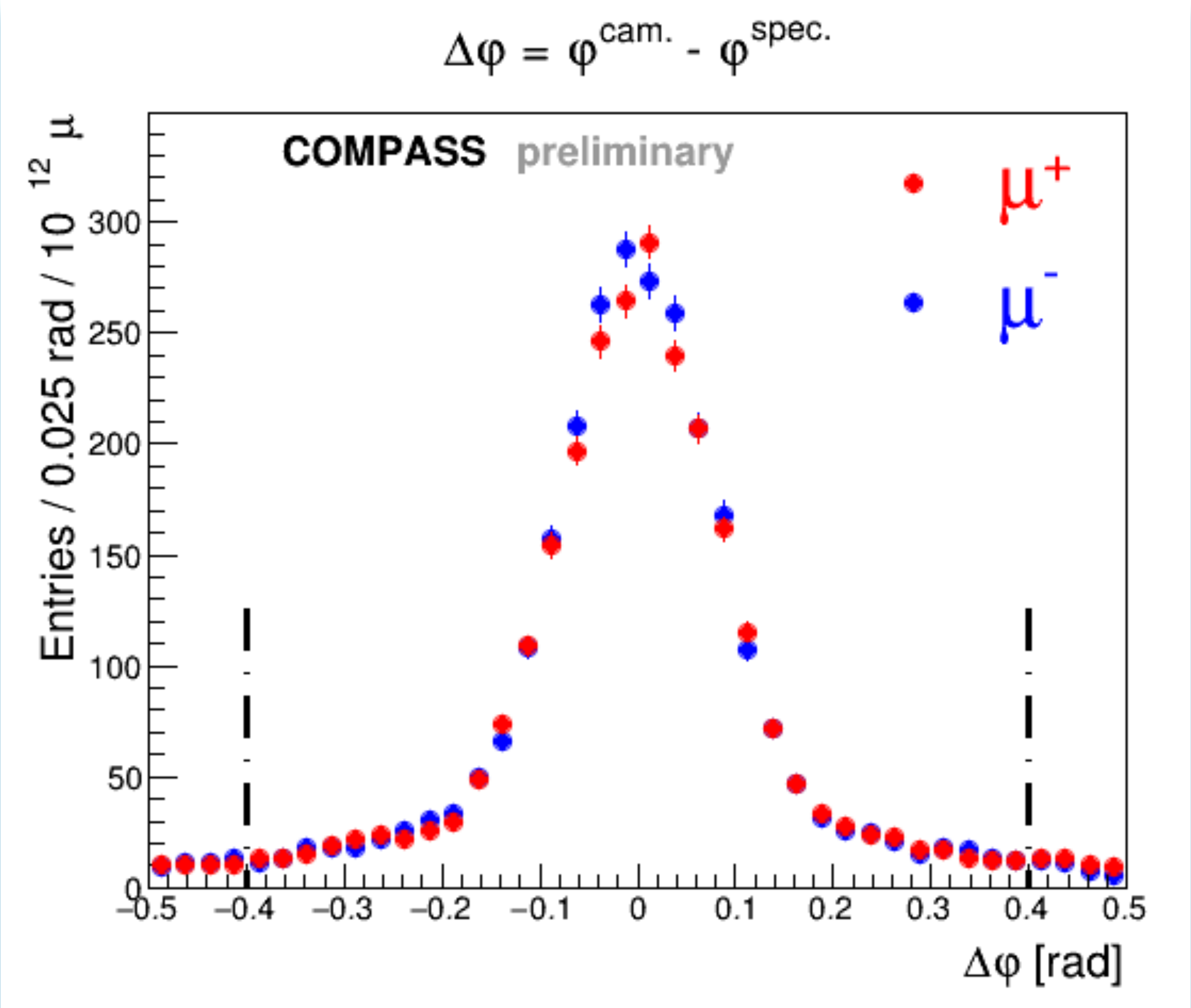
DVCS with recoil-proton detector (RPD):
comparison of proton kinematics measured in RPD vs. expected in spectrometer (from $\mu\gamma$)

Exclusive ρ^0 production

$\mu p^{(\uparrow)} \rightarrow \mu p \rho^0$

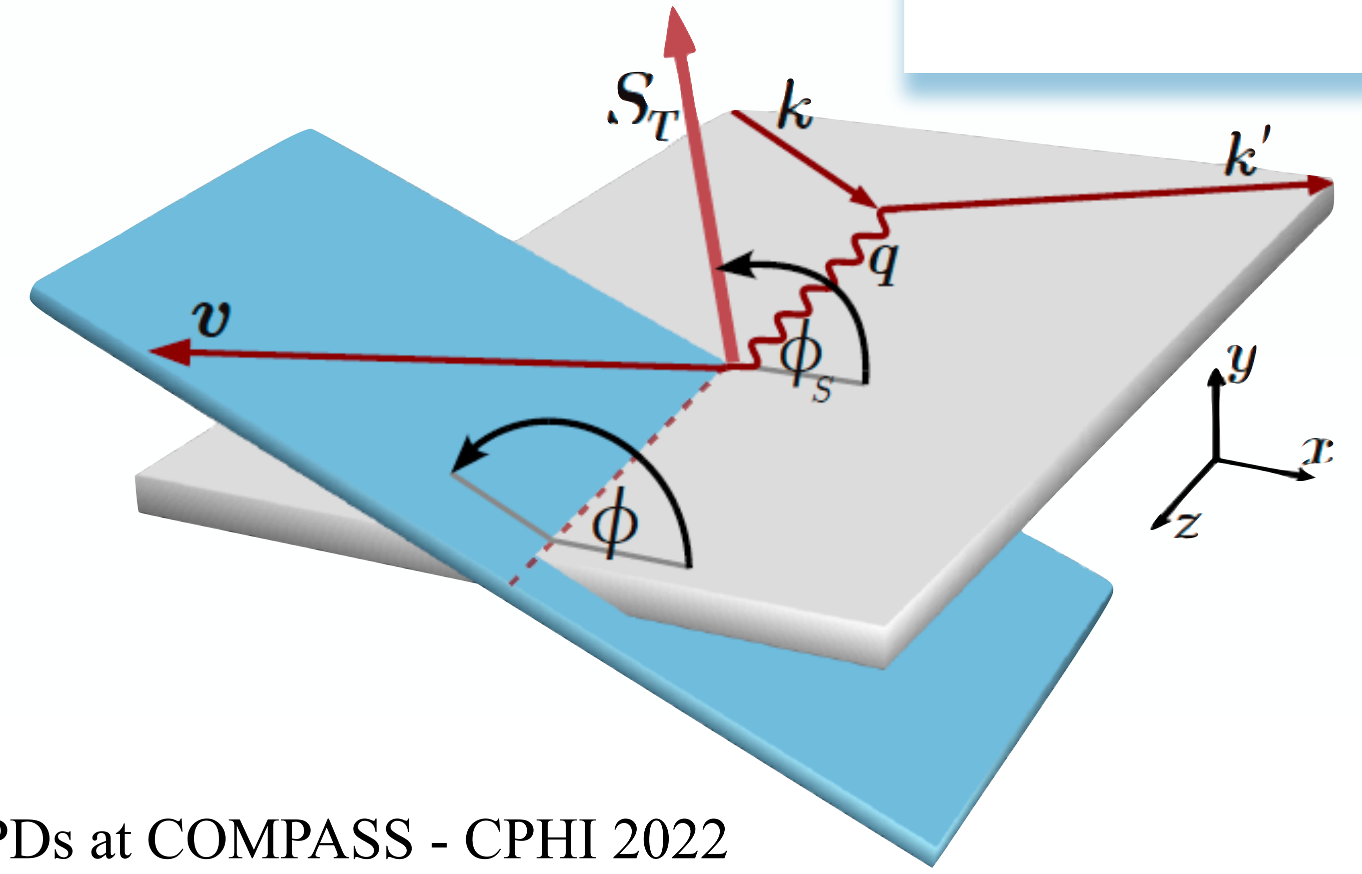
with simulated exclusive signal & SIDIS background





DVCS

$\mu^{\pm} p \rightarrow \mu^{\pm} p \gamma$



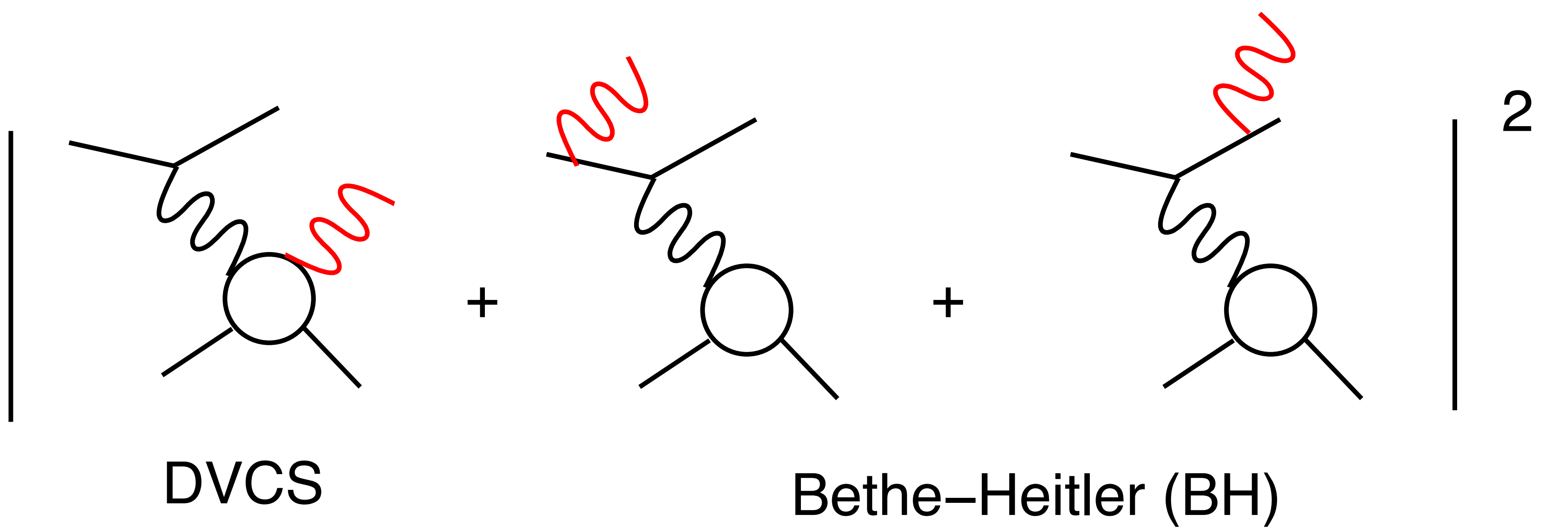
In case of transverse target polarization: additional **azimuthal angle** ϕ_S defined by direction of transverse target-polarization vector

+ kinematically complete event reconstruction via kinematic event fitting

Access to CFFs at COMPASS

ϕ-modulation in cross section (azimuthal asymmetry analysis)

DVCS $\sigma_{\gamma^*\gamma N} \sim \Big|$



$$= |\mathcal{T}_{\rm BH}|^2 + \boxed{(\mathcal{T}_{\rm DVCS}\mathcal{T}^*_{\rm BH} + \mathcal{T}^*_{\rm DVCS}\mathcal{T}_{\rm BH})} + |\mathcal{T}_{\rm DVCS}|^2$$

Analysis of azimuthal modulations (HERMES- and JLab-type) on DVCS on the unpolarized proton in progress

The DVCS / Bethe-Heitler interference term allows to disentangle **Re($\tau_{\rm DVCS}$)** and **Im($\tau_{\rm DVCS}$)** **magnitude** and **phase** of DVCS amplitude $\tau_{\rm DVCS}$

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}$$

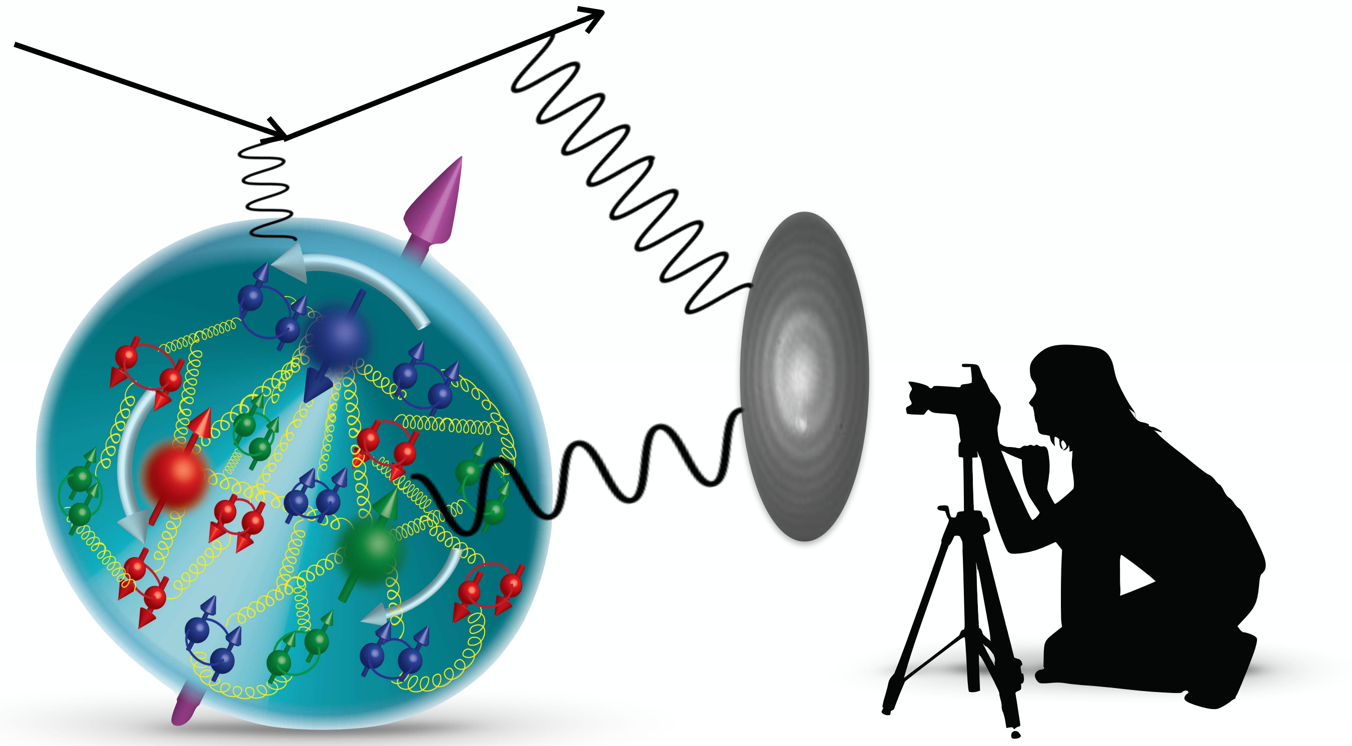
$$\mathcal{D}_{CS,U} \equiv d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}$$

dominant at small x_B
(remainder ~ 5% from KM / GK model)

$$\mathrm{Im}\left(F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

$$\mathrm{Re}\left(F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right)$$

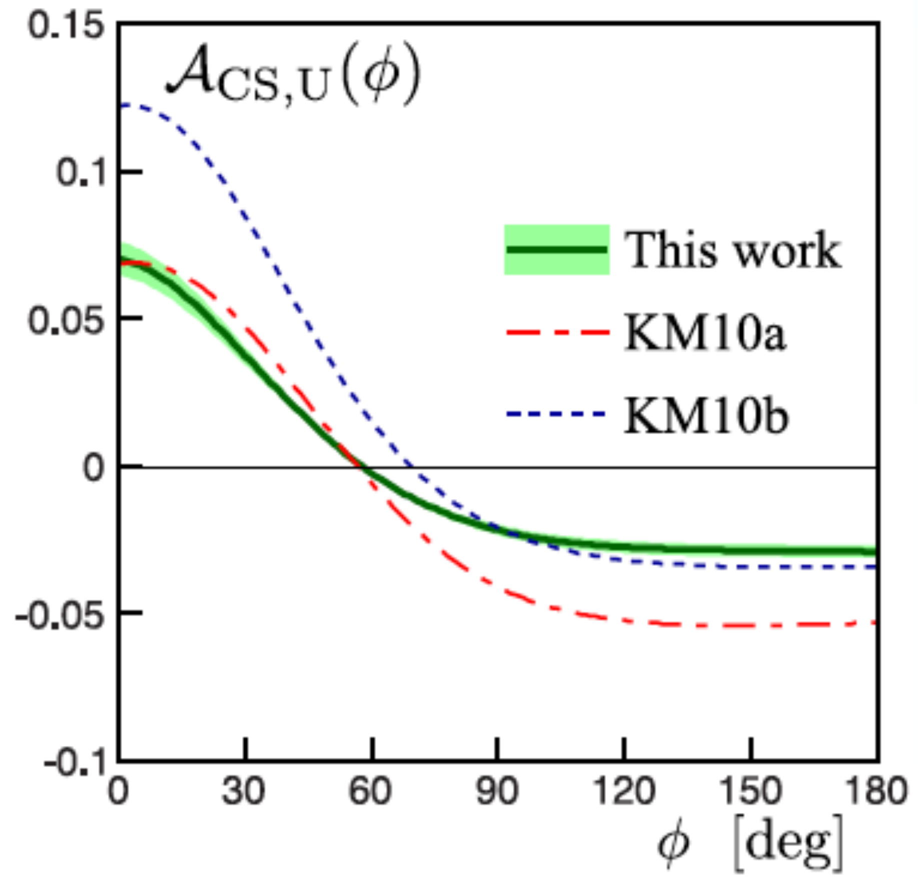
at leading twist (twist 2) on the proton



$$\mathcal{A}_{CS,U} \equiv \frac{d\sigma^{\overleftarrow{+}} - d\sigma^{\overrightarrow{-}}}{d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}}} = \frac{\mathcal{D}_{CS,U}}{\mathcal{S}_{CS,U}}$$

Spin-independent DVCS cross section ∝

$$4(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*) + \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$



Sign & magnitude of cosϕ amplitude for beam-charge asymmetry? (changes sign between HERMES and HERA)

Kroll, Moutarde, Sabatié, Eur. Phys. J. C (2013) 73:2278

Test of GPD universality: use DVMP data to constrain GPD parameters

Transverse imaging of the nucleon

DVCS cross section / transverse imaging

Impact-parameter representation of parton distribution function:

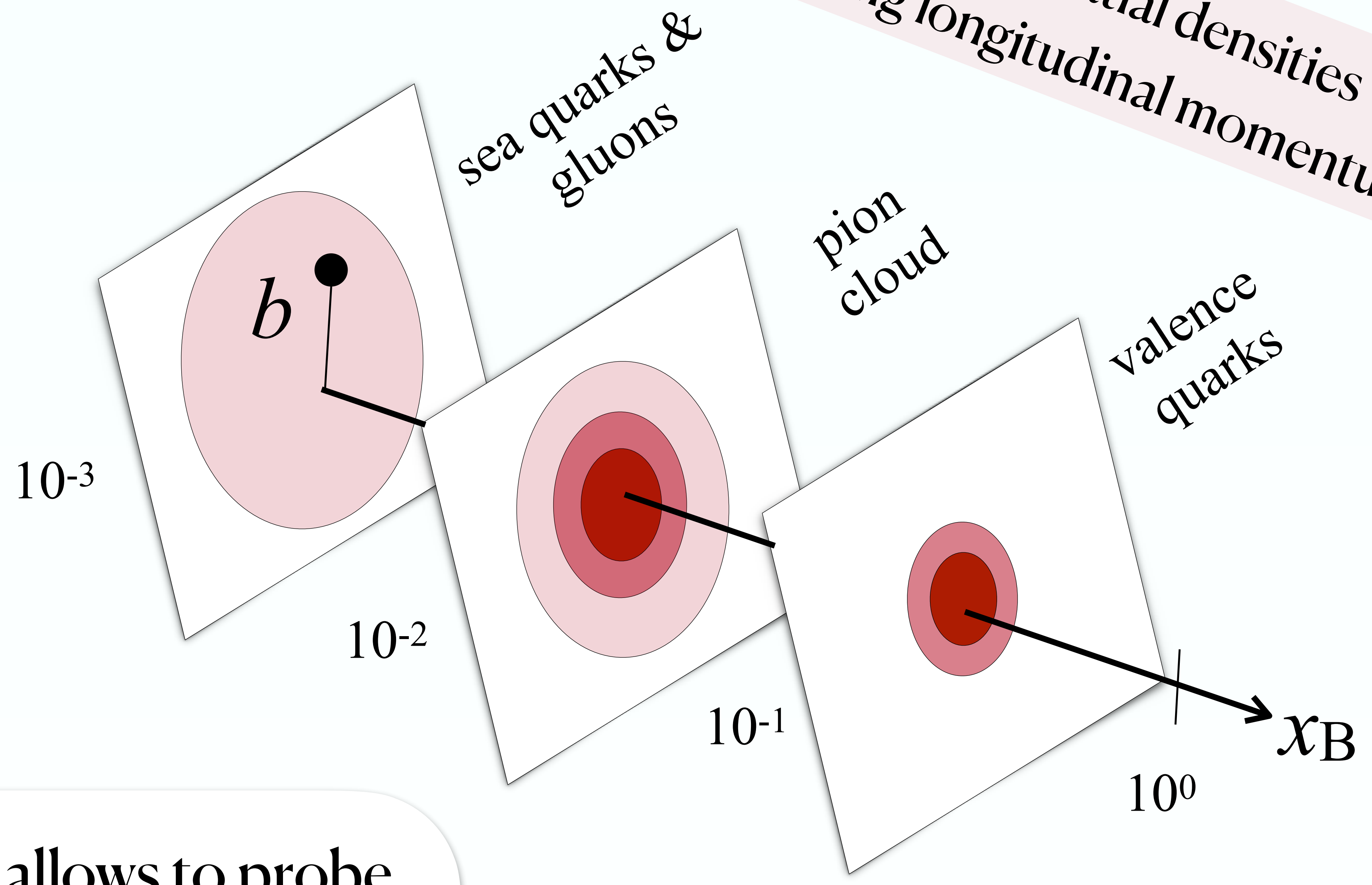
$$q^f(x, \boldsymbol{b}_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp} H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$$

[Burkardt, Int. J. Mod. Phys. A18 (2003) 173]

"spatial parton density = Fourier transform of GPD"

$\boldsymbol{b}_\perp$ is the impact parameter,
$\boldsymbol{\Delta}_\perp$ is the difference of initial and final transverse momenta,
$\boldsymbol{\Delta}_\perp^2$ is related to the Mandelstam-t

Mapping of spatial densities while scanning longitudinal momentum x_B



3-dim "tomographic images" of the nucleon in longitudinal momentum and transverse position

The differential DVCS cross section allows to probe the **transverse extension of partons** in the nucleon:

$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}}{\mathrm{d}t} \propto e^{-b|t|}$$

b = "*t*-slope" = average impact parameter

Extraction of pure DVCS yield at COMPASS

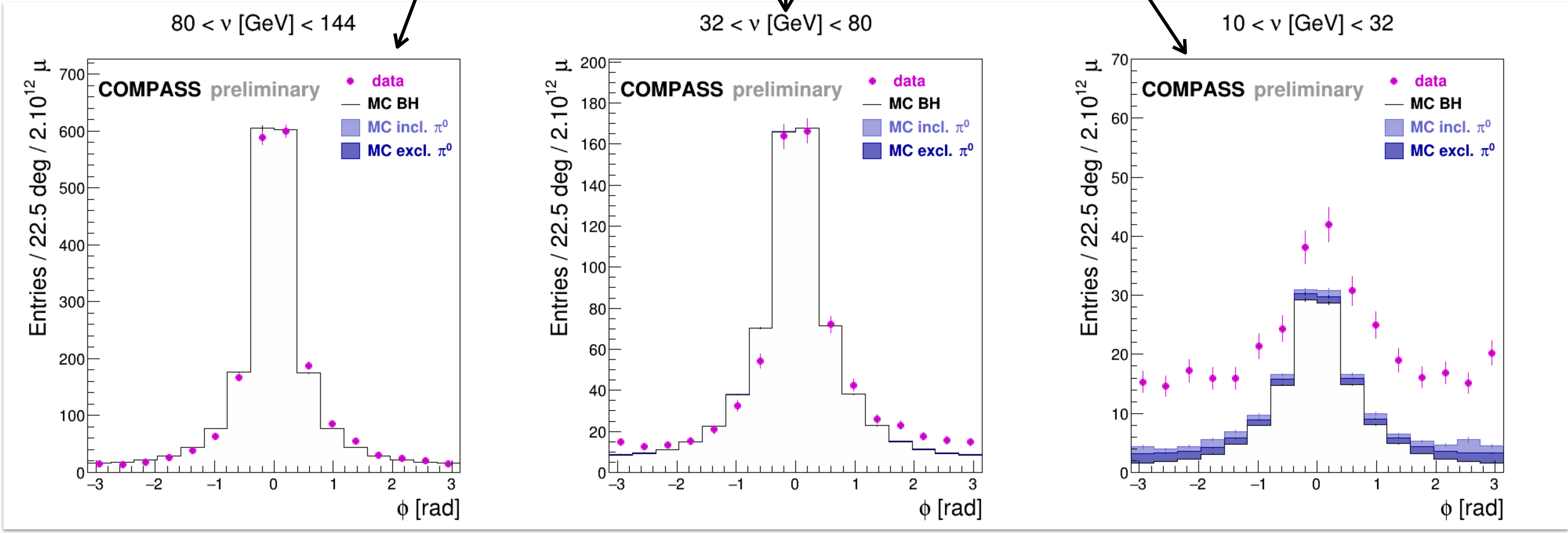
DVCS cross section / transverse imaging

$$|\mathcal{T}_{\mathrm{BH}}|^2 + (\mathcal{T}_{\mathrm{DVCS}}\mathcal{T}^*_{\mathrm{BH}} + \mathcal{T}^*_{\mathrm{DVCS}}\mathcal{T}_{\mathrm{BH}}) + |\mathcal{T}_{\mathrm{DVCS}}|^2$$

BH reference yield:
at small
$\langle x_B \rangle$=0.0085

DVCS amplitude:
ϕ-modulations in cross section
at medium $\langle x_B \rangle$=0.0200

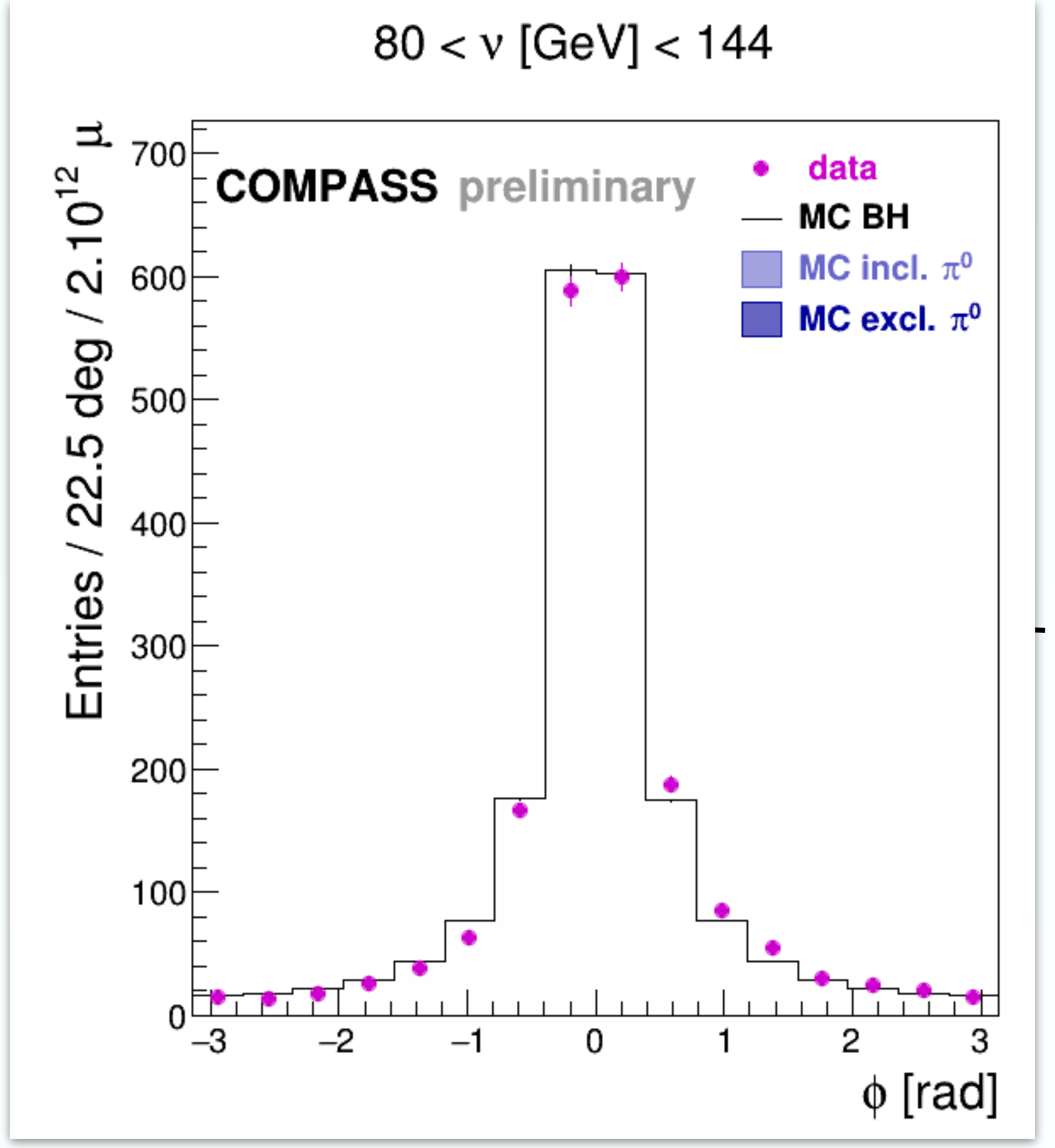
Transverse imaging:
ϕ-integrated cross section
at medium $\langle x_B \rangle$=0.0630

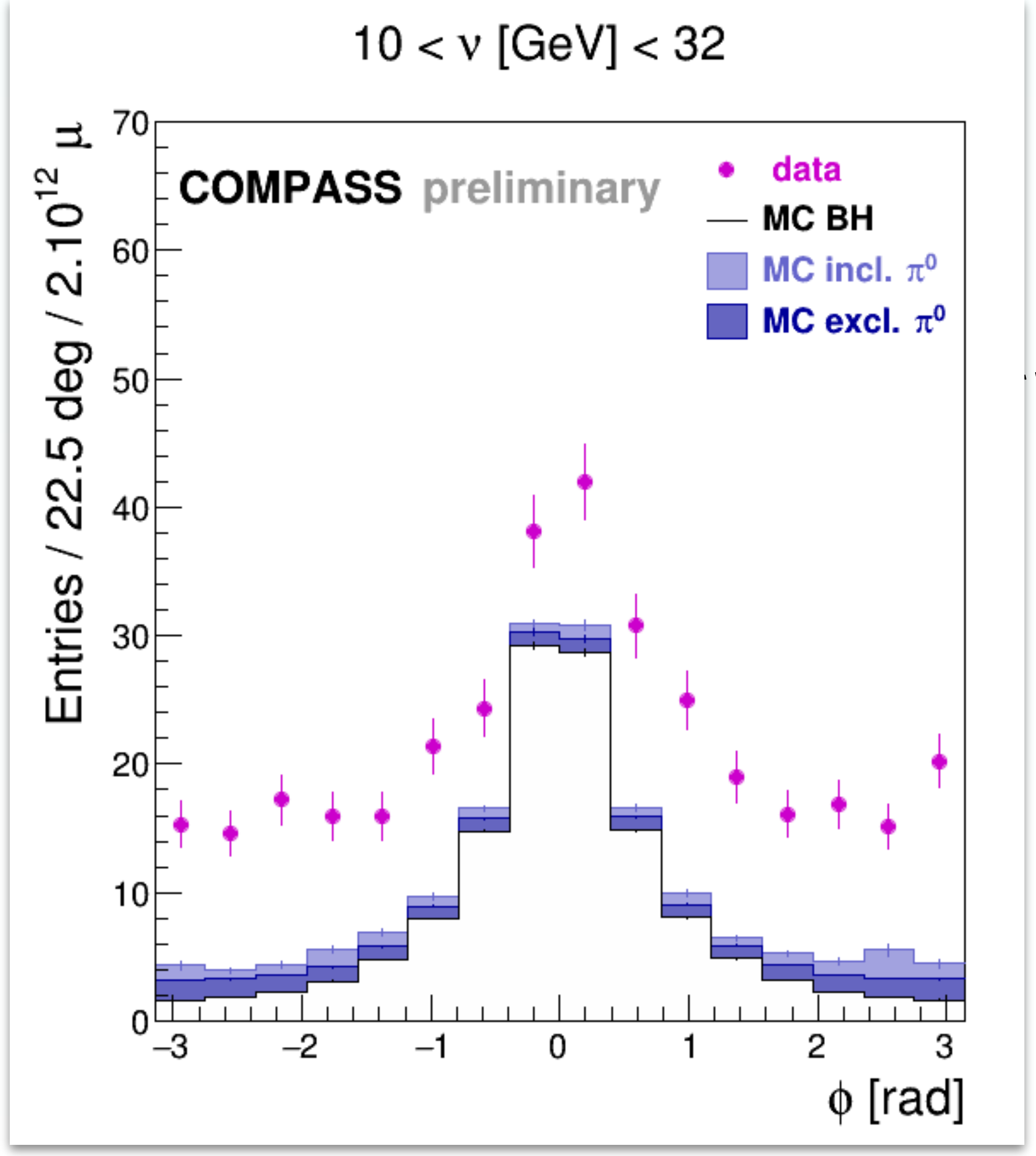


portion of the 2016 data = 2x 2012 data

Extraction of pure DVCS yield at COMPASS

DVCS cross section / transverse imaging





DVCS / BH: $\mu p \to \mu p \gamma$

π^0 production: $\mu p \to \mu p\, \pi^0 \to \mu p \gamma(\gamma)(X)$ exclusive or SIDIS

$\gamma\gamma$: "visible π^0", γ: invisible π^0 background

↓

Determine BH reference yield at low-x_B ⇔ high-ν: tune MC to data

↓

Subtract BH yield in high-x_B ⇔ low-ν bin

↓

Subtract measured visible π^0 yield in high-x_B ⇔ low-ν bin

↓

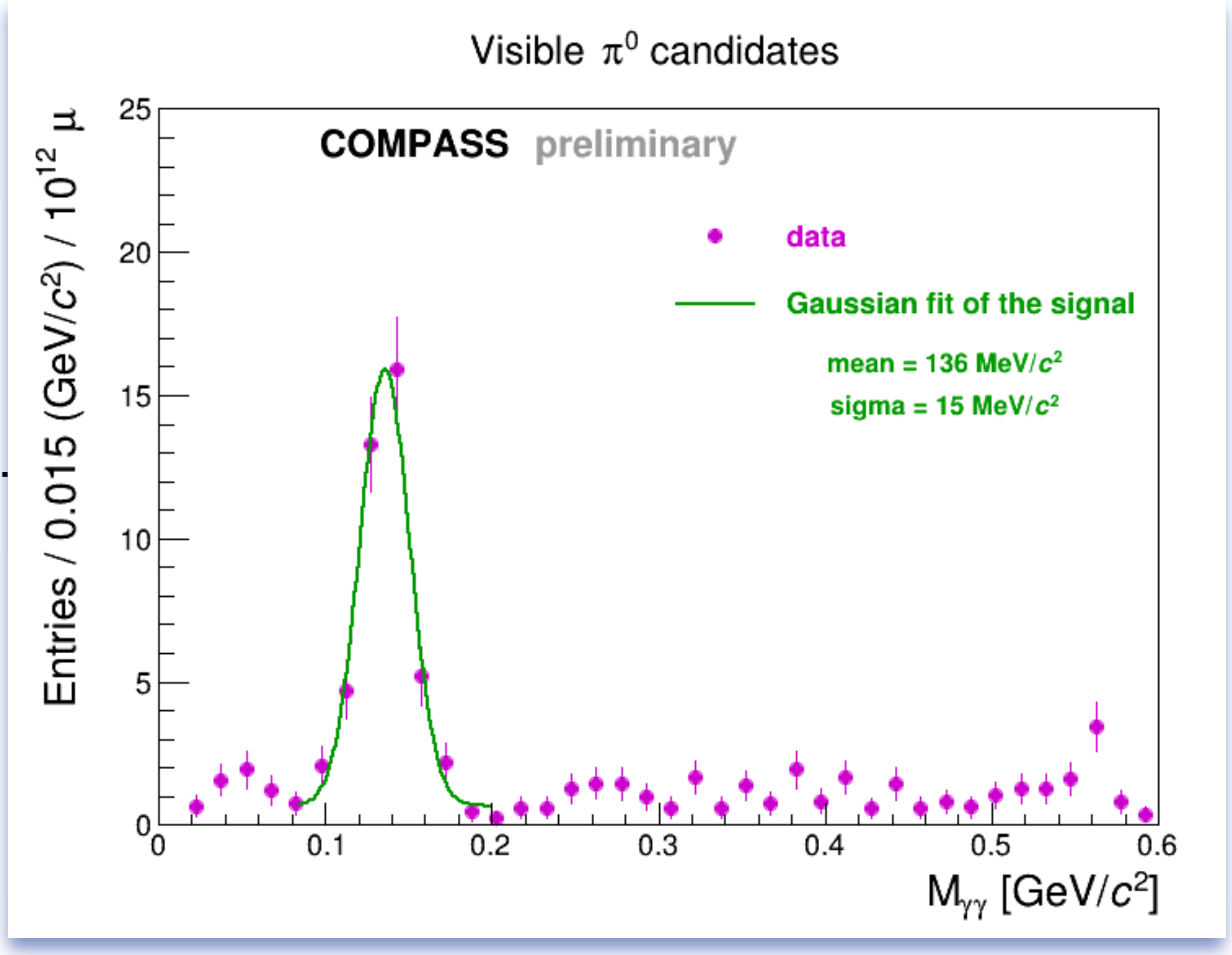
Estimate π^0 invisible background from MC:
SIDIS 40% (LEPTO) + exclusive 60% (HEPGEN with GK model)
with 10% uncertainty each

↓

Remove invisible π^0 yield
(invisible normalized to visible yield)

↓

Pure DVCS yield

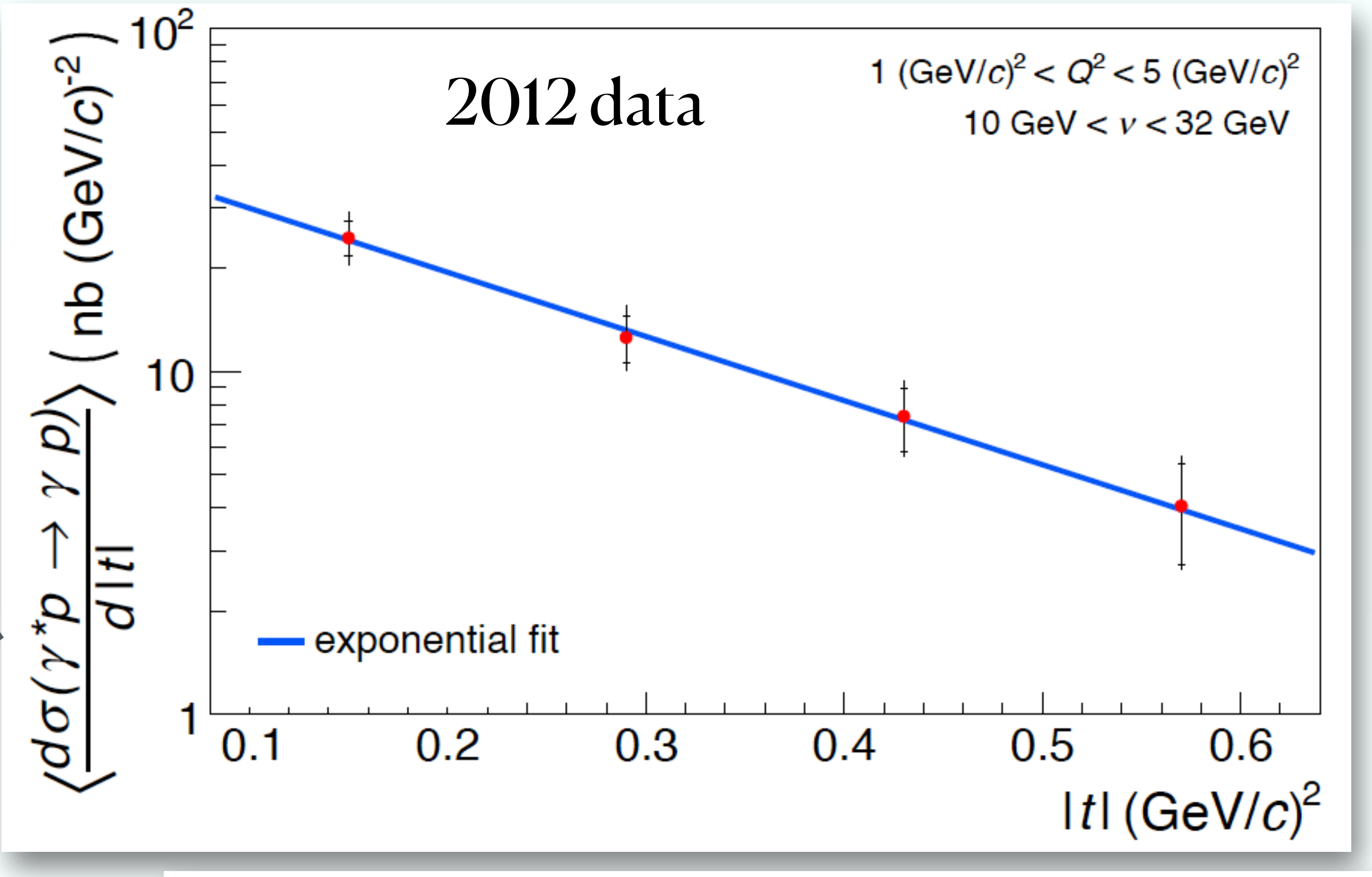


portion of the 2016 data = 2x 2012 data

COMPASS ϕ-integrated DVCS cross section

DVCS cross section / transverse imaging

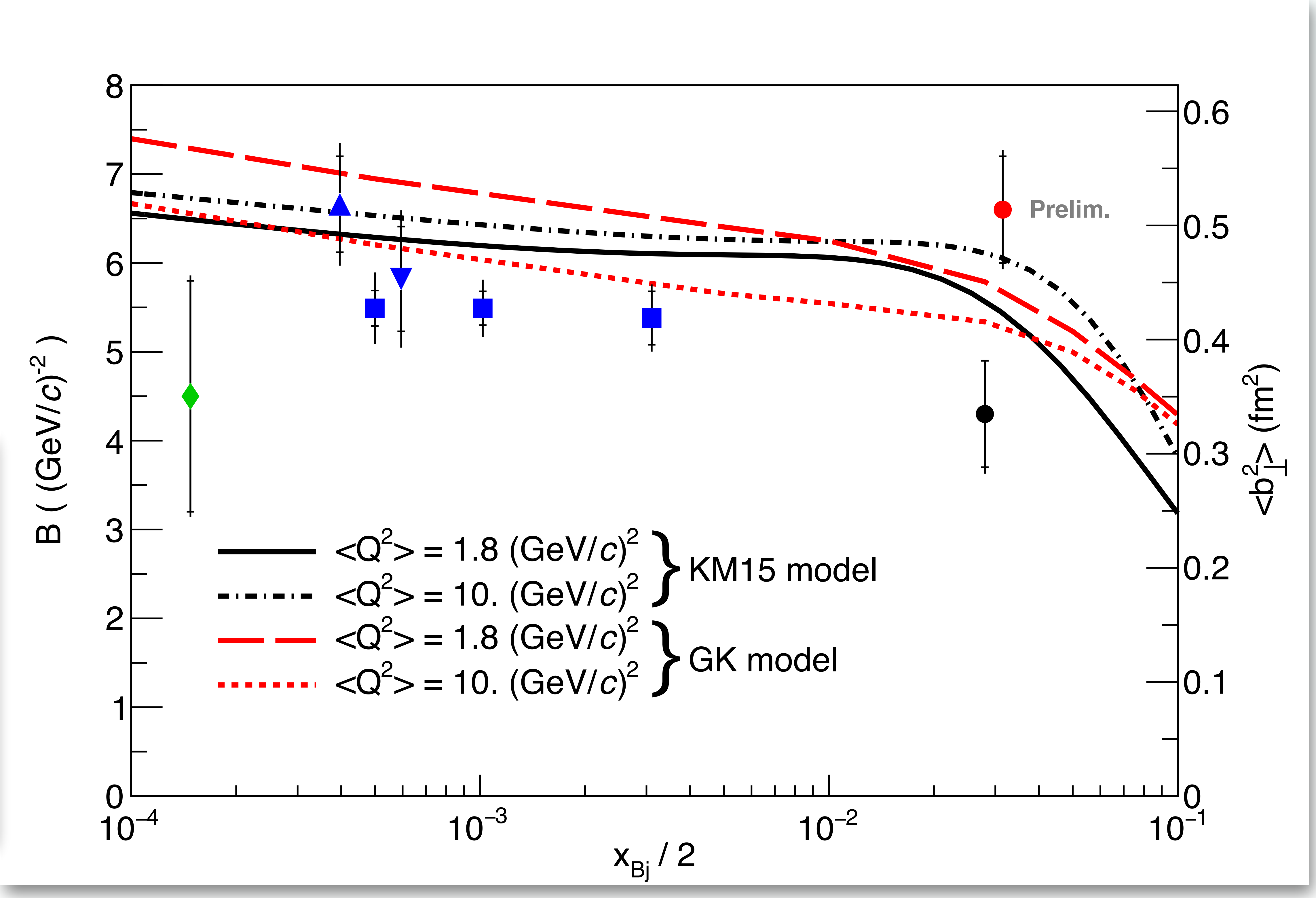
- Relation between parton average squared transverse extension and slope $\langle r_\perp^2(x_{Bj})\rangle \approx 2\langle B(x_{Bj})\rangle \hbar^2$
- Sea-quark domain between gluons and valence-quarks
- **Pilot run:** $\langle Q^2\rangle$=1.8 GeV^2 & $\langle x_{Bj}\rangle$=0.056
  2016/17 run: $\langle Q^2\rangle$=1.8 GeV^2 & $\langle x_{Bj}\rangle$=0.063 (ECal0 extension)
- So far, ≳ 30% of COMPASS cross-section data analyzed.



$$\frac{d\sigma^{DVCS}}{dt} \propto e^{-b|t|}$$

Differential DVCS cross section with b (or B) = "*t*-slope" = average impact parameter

2016/17 (≈23%)	● (red)	COMPASS:	$\langle Q^2\rangle$ = 1.8 (GeV/c)^2	This Analysis
2012	● (black)	COMPASS:	$\langle Q^2\rangle$ = 1.8 (GeV/c)^2	Phys. Lett. B793 (2019) 188
	◆ (green)	ZEUS:	$\langle Q^2\rangle$ = 3.2 (GeV/c)^2	JHEP 0905 (2009) 108
	▲ (blue)	H1:	$\langle Q^2\rangle$ = 4.0 (GeV/c)^2	Eur. Phys. C44 (2005) 1
	▼ (blue)	H1:	$\langle Q^2\rangle$ = 8.0 (GeV/c)^2	Eur. Phys. C44 (2005) 1
	■ (blue)	H1:	$\langle Q^2\rangle$ = 10. (GeV/c)^2	Phys. Lett. B681 (2009) 391



[COMPASS PLB 793 (2019) 188] (2012 data)

Exclusive meson production

DVMP

chiral-even GPDs at leading twist		chiral-odd GPDs at higher twist
H, E	$J^P=1^-$ vector mesons	H_T, E_T, $\bar{E}_T=2\tilde{H}_T+E_T$
$\tilde{H}$	$J^P=0^-$ pseudoscalar mesons	
longitudinally polarized virtual photon & vector meson)		

- Different mesons filter different quark flavors and have different sensitivity to gluon GPDs.

$$E^{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g\right)$$
$$E^{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{3}{4}E^g\right)$$
$$E^{\phi} = -\frac{1}{3}E^s + \frac{1}{8}E^g$$

Diehl, Vinnikov, Phys. Lett. B 609 (2005) 286

- Deeply virtual meson production allows also access to higher-twist chiral-odd GPDs.
- Some GPDs are related to transverse-momentum dependent PDFs (TMDs):
  - **GPD *E* ↔ Sivers TMD**: involve switch of nucleon helicity $\sim \vec{S}_T \cdot (\hat{P} \times \vec{k}_T)$
    ⇒ sensitive to spin-orbit correlations… orbital angular momentum
  - **GPD H_T ↔ transversity TMD**: both are chiral-odd
  - **GPD $\bar{E}_T$ ↔ Boer-Mulders TMD**: T-odd (as is Sivers TMD)
- Helicity conservation in interactions of light quarks with gluons or photons
  ⇒ initial parton helicity flip needs compensation by **higher-twist meson wave functions**

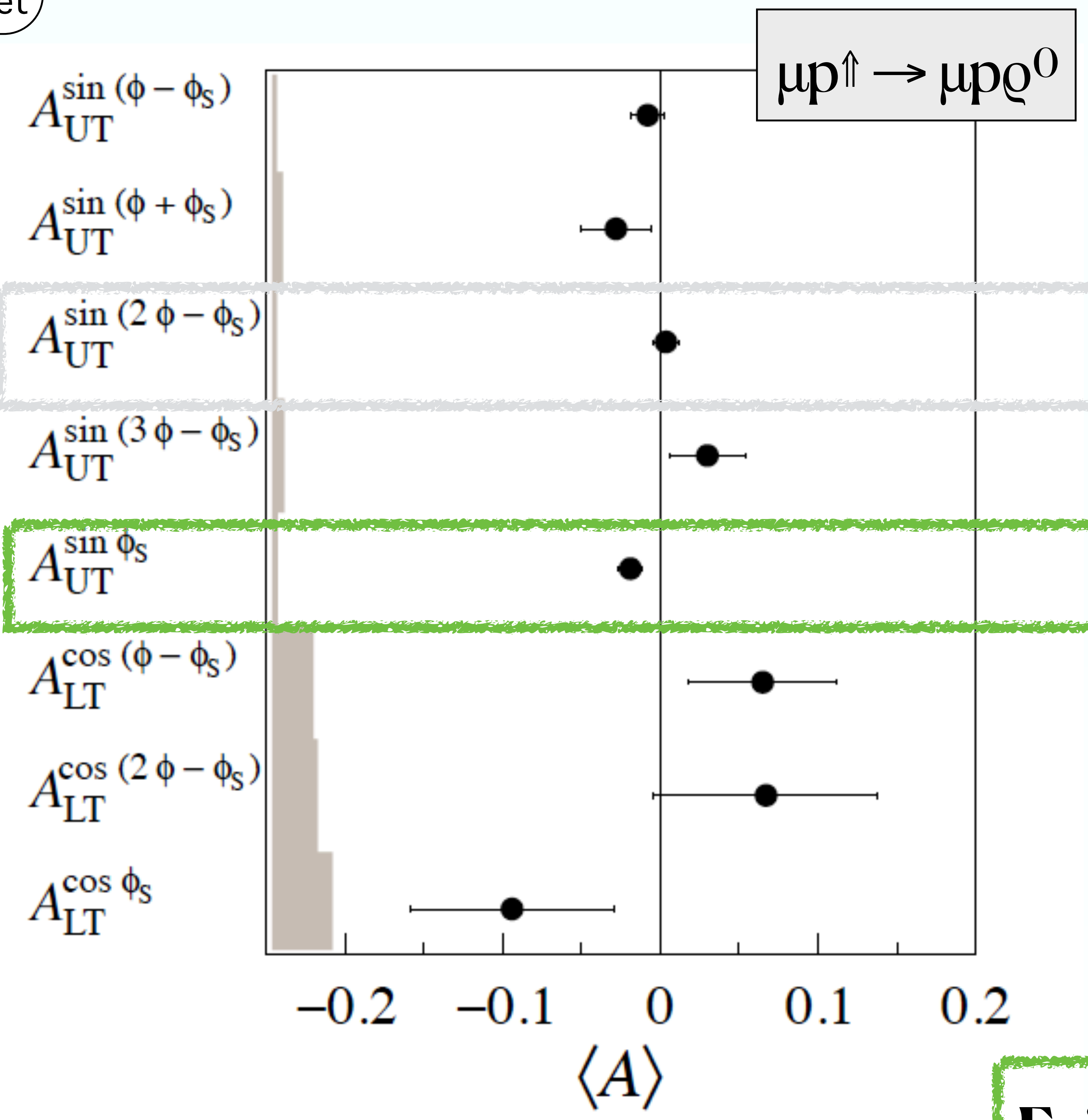
Goloskokov, Kroll, Eur. Phys. J. C 74, 2725 (2014)

We will now look at **transverse-spin asymmetries**, spin-density matrix elements (**SDMEs**), and the **cross section for exclusive π^0** production.

A_{UT}
Beam Target
polarization

Transverse-target spin asymmetries in DVMP

A_{UT}/chiral-odd GPDs

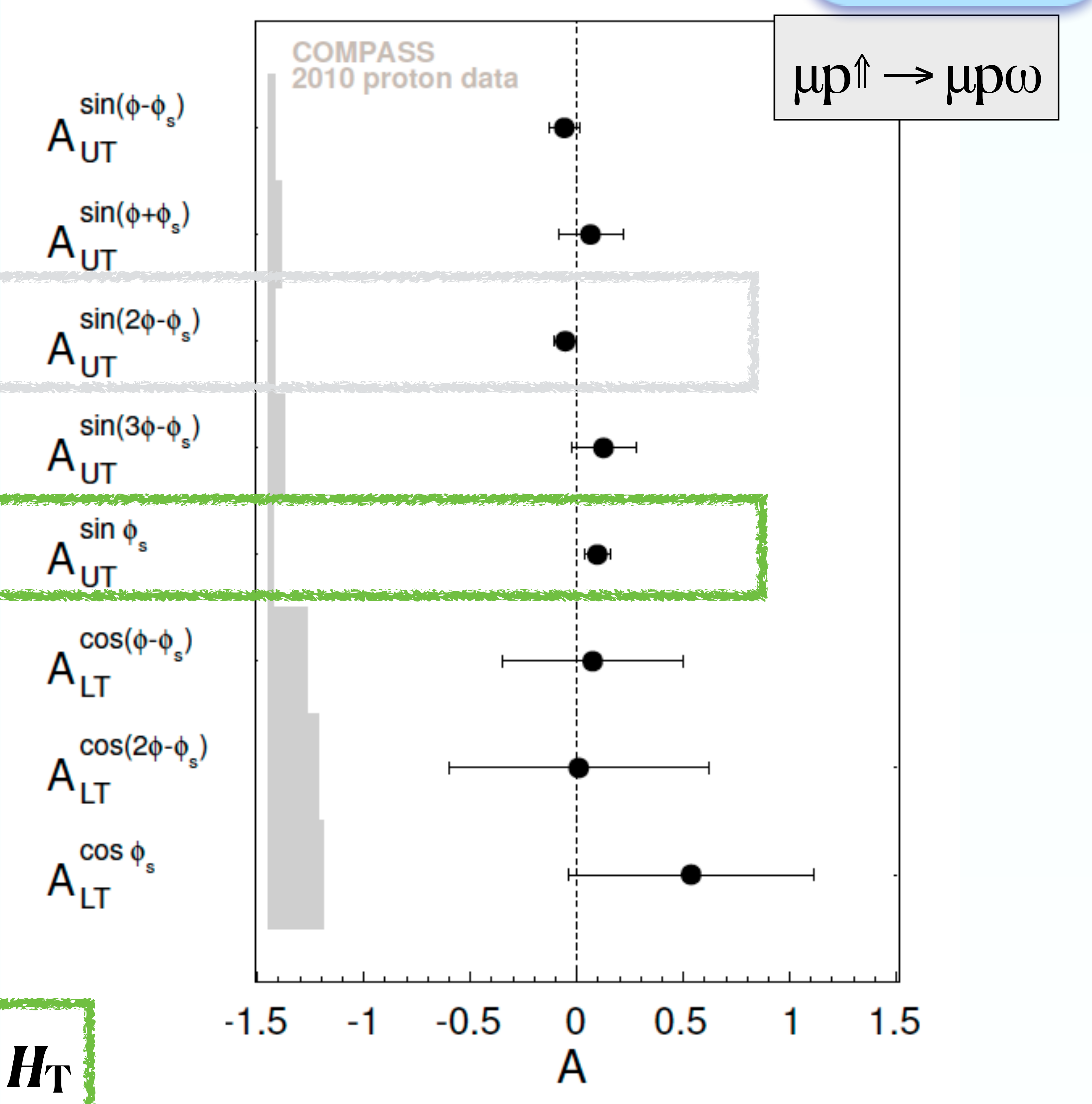


"**(E,H)** + $(\bar{E}_T,H_T)$"

"$(\bar{E}_T,E)$"

"(H_T,H) - $(\bar{E}_T,E)$"

"(H_T,H) - $(\bar{E}_T,E)$"



Evidence of existence of chiral-odd GPD H_T

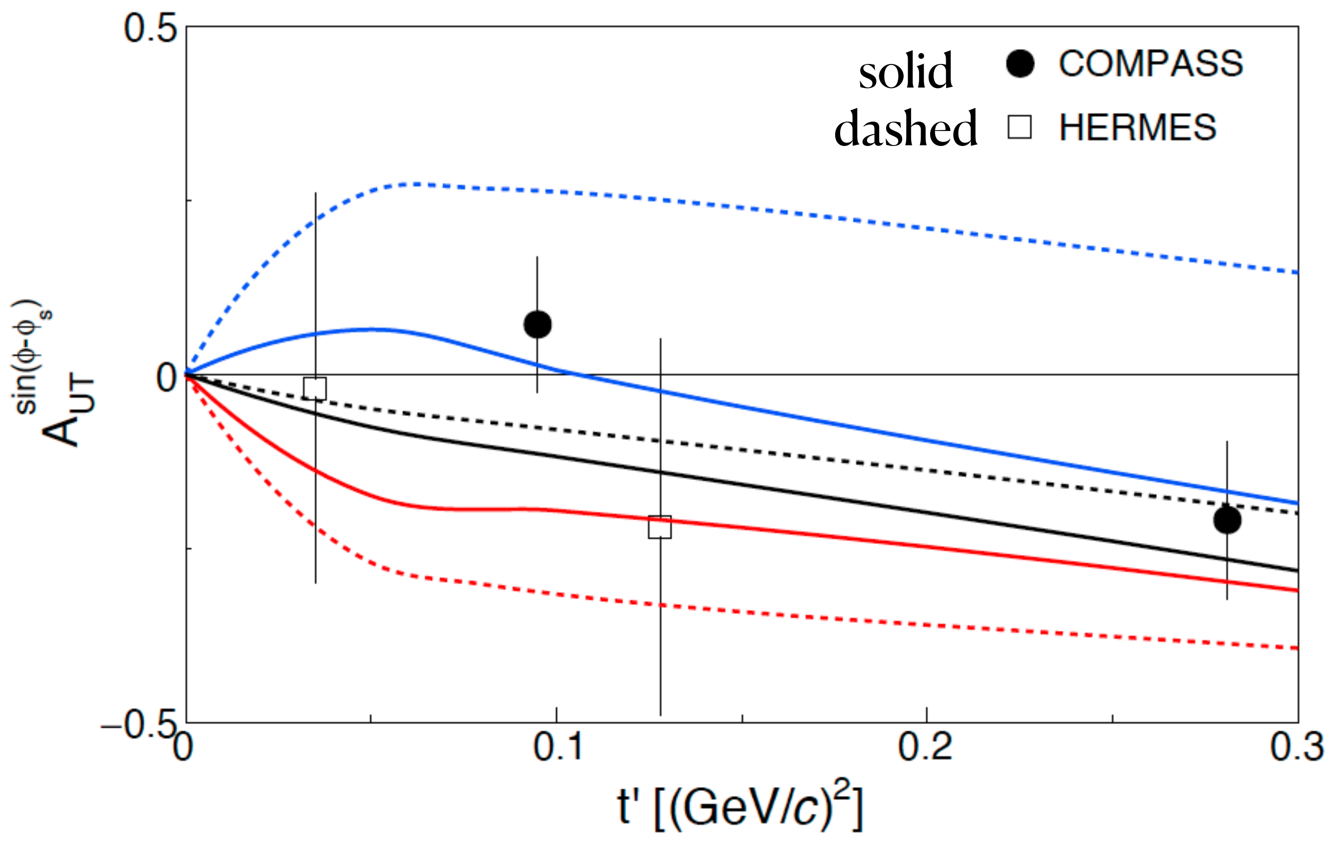
[COMPASS PLB B731 (2014) 19]

$$E^{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}E^g\right)$$
$$E^{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{3}{4}E^g\right)$$
$$E^{\phi} = -\frac{1}{3}E^s + \frac{1}{8}E^g$$

[COMPASS NPB 865 (2012) 1 (not shown, includes ϱ on deuteron)]

GPD *E*

- Cancellation effects for ϱ^0...
- GPD flavor separation by measuring both meson channels...



[COMPASS NPB 915 (2017) 454]

Contribution of **pion pole** expected to be sizeable for ω and small for ϱ^0

GK 2014

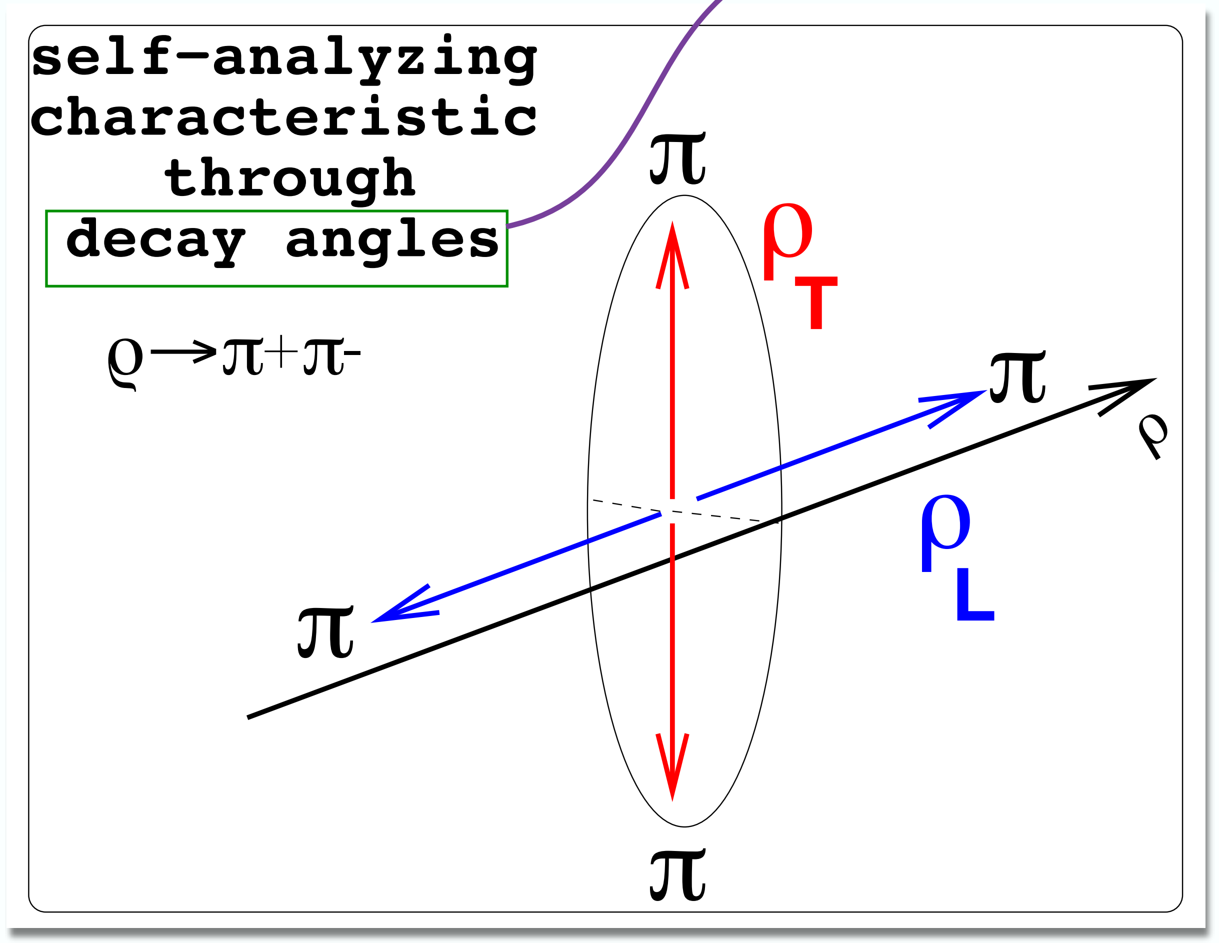
positive $\pi\omega$ form factor
no pion pole
negative $\pi\omega$ form factor

Spin density matrix elements in μp→μpVM

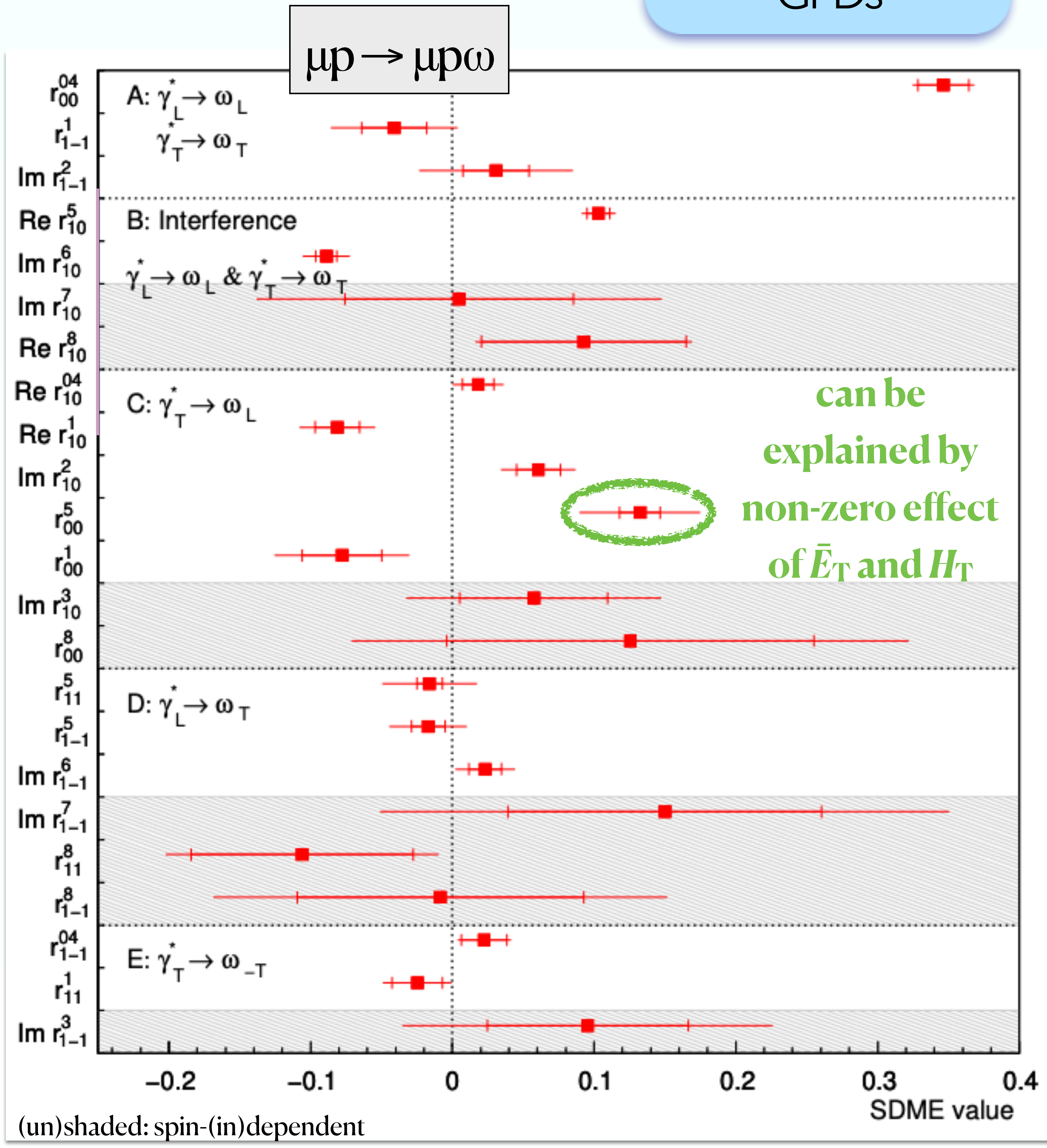
SDMEs / chiral-odd GPDs

$$\frac{d\sigma}{dx_B\, dQ^2\, dt} W(x_B, Q^2, t, \phi, \phi_S, \varphi, \vartheta)$$

$W(...)$ parametrized by SDMEs



- **Spin density matrix elements** describe how the spin components of the virtual photon are transferred to the created vector meson
- Test of s-channel helicity conservation (SCHC), $\lambda_{\gamma^*}=\lambda_{VM}$, : only SDMEs of classes A&B are not restricted to =0 if SCHC. Observed: considerable ~~SCHC~~ in $\gamma^*_T \rightarrow \omega_L$ (class C)
- SDMEs measurements provide further constraints on GPD parameterizations beyond cross-section and spin-asymmetry measurements.
- Sensitivity to chiral-odd GPDs $\boldsymbol{H_T}$ and $\boldsymbol{\bar{E}_T}$.



[COMPASS EPJC (2021) 81 126]

- Tests of hierarchy of helicity amplitudes
- Cross-section ratio R of longitudinal to transverse vector mesons, ...

$$R' = \frac{1}{\varepsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$

SDMEs $\mu p \rightarrow \mu p \varrho^0$ to be published

Exclusive π^0 cross section at COMPASS

$\mu p \rightarrow \mu p \pi^0$

π^0 cross section / chiral-odd GPDs

$$\frac{d^2\sigma_{\gamma^* p}}{dt d\phi} = \frac{1}{2\pi}\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos(\phi)\frac{d\sigma_{LT}}{dt}\right]$$

L, T indices indicate polarization of virtual photon. Double index = interference

$$\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8M^2}|\langle \bar{E}_T\rangle|^2\right]$$

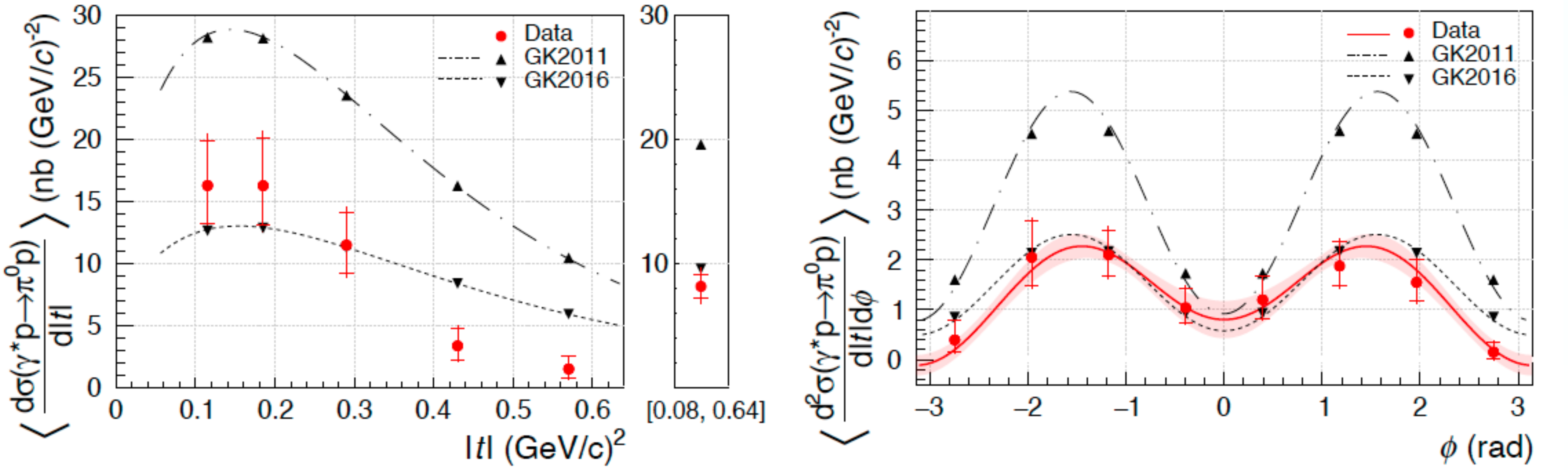
sensitivity to chiral-odd GPDs

$$t'|\langle \bar{E}_T\rangle|^2$$

$$\xi\sqrt{1-\xi^2}\sqrt{-t'}Re\left[\langle H_T\rangle^*\langle \tilde{E}\rangle\right]$$

Dip at small $|t|$ indicative of large effect by chiral-odd GPD $\bar{E}_T$

$$\left[(1-\xi^2)|\langle \tilde{H}\rangle|^2 - 2\xi^2 Re\left[\langle \tilde{H}\rangle^*\langle \tilde{E}\rangle\right] - \frac{t'}{4M^2}\xi^2|\langle \tilde{E}\rangle|^2\right]$$



COMPASS, PLB 805 (2020) 135454

Summary and outlook: GPDs at COMPASS

- 2012 GPD pilot run & 2016/17 GPD runs with recoil-proton detector
  Transverse runs without recoil-proton detector

- **DVCS**: *transverse extension of partons in the proton*
  - *t*-slope of DVCS cross section in the kinematic domain between the other fixed-target experiments and HERA ep collider
  - Azimuthal asymmetry analysis ongoing

- **DVMP**: *input for GPD constraints, in particular chiral-odd GPDs*
  - Transverse target spin asymmetries for ρ^0 and ω vector mesons
  - SDMEs for ρ^0 and ω vector mesons
  - π^0 cross section

- More data are being analyzed.

References

HEPGEN:

M.Gorzellik, PhD thesis, University of Freiburg (2018)

A. Sandacz and P. Sznajder, arXiv:1207.0333[hep-ph]

GK model:

S. V. Goloskokov and P. Kroll, Eur. Phys. J. C 42 (2005) 281

S. V. Goloskokov and P. Kroll, Eur. Phys. J. C 53 (2008) 367

S. V. Goloskokov and P. Kroll, Eur. Phys. J. C 65 (2010) 137

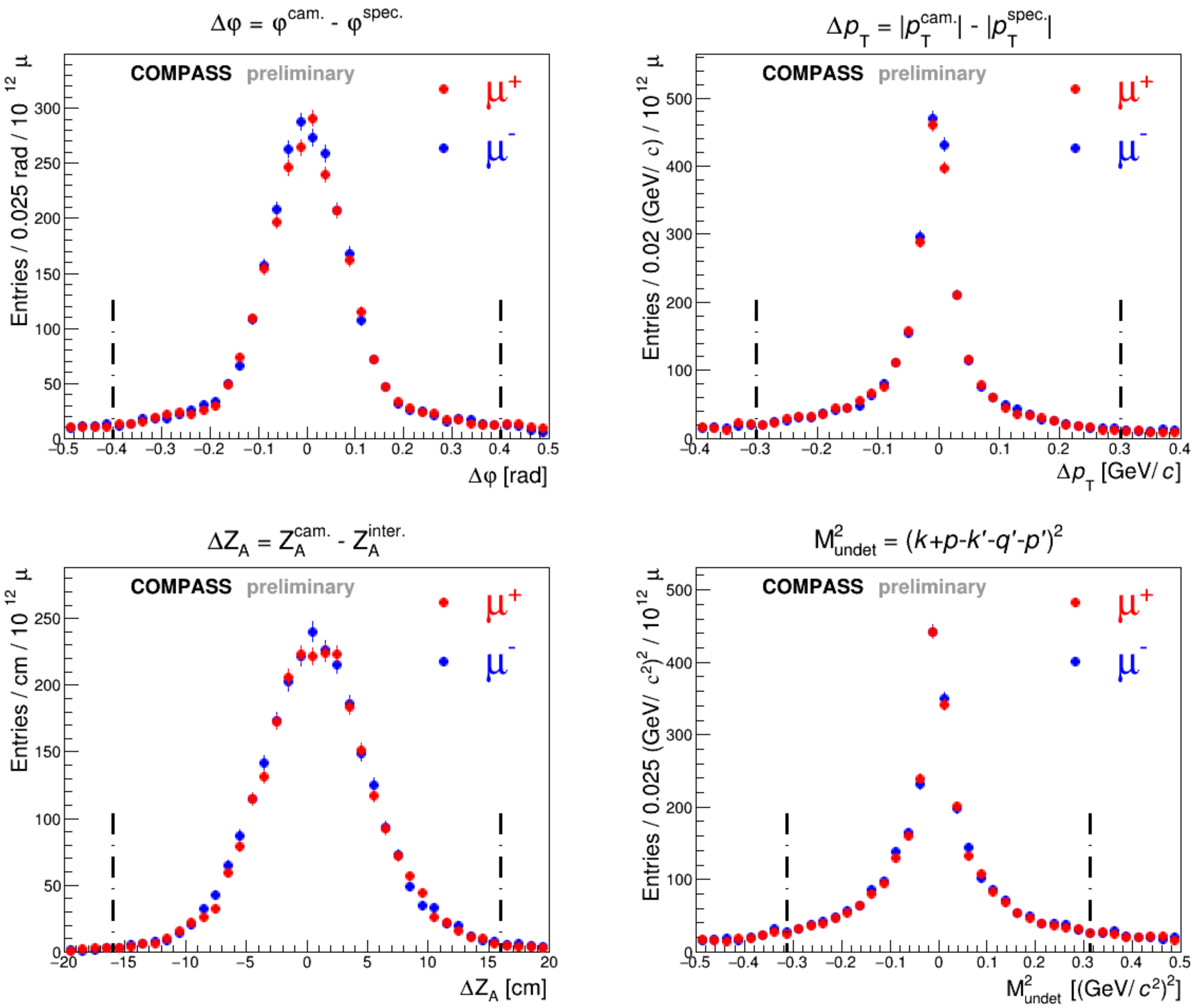
KM15 model:

K. Kumericki and D. Müller, Nucl. Phys. B 841 (2010) 1

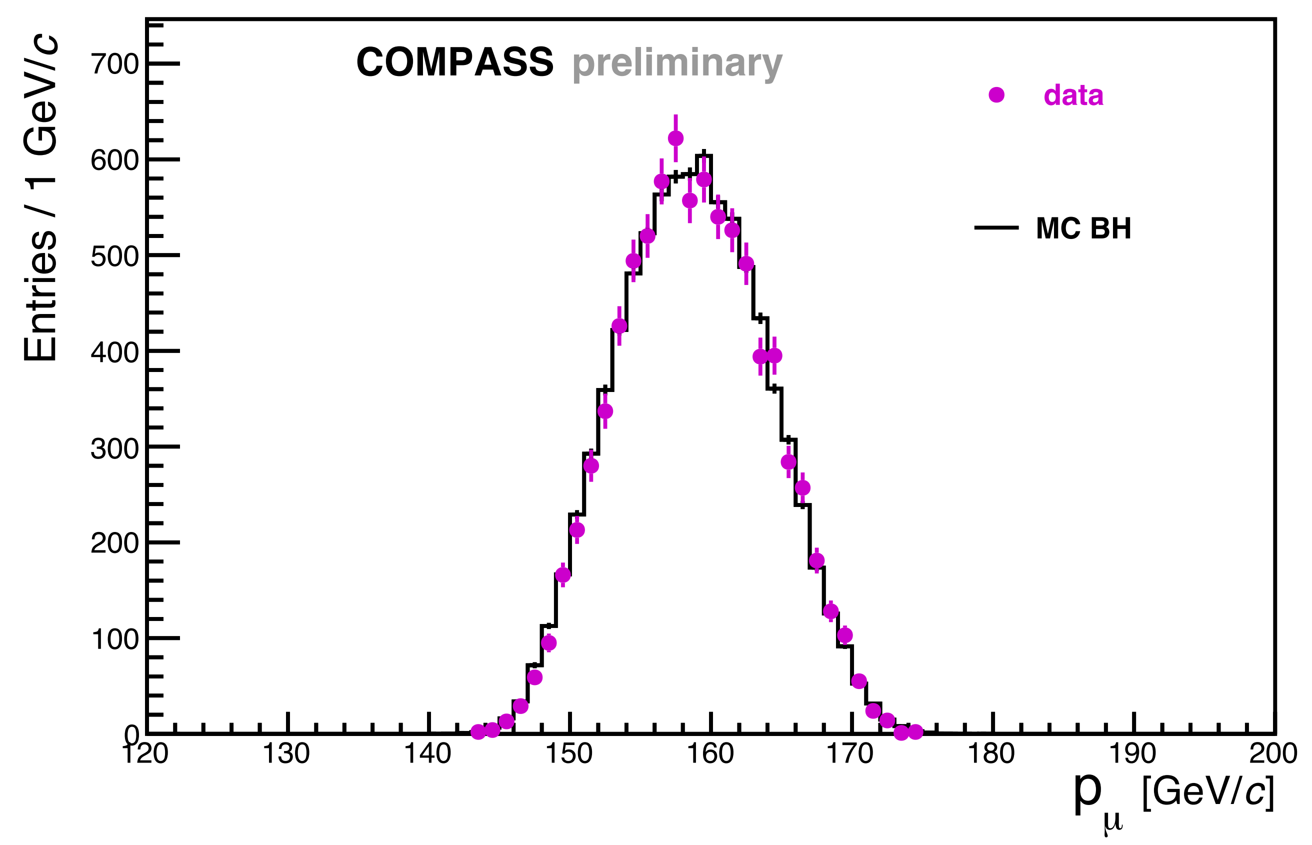
K. Kumericki and D. Müller, EPJ Web Conf. 112 (2016) 01012

Backup

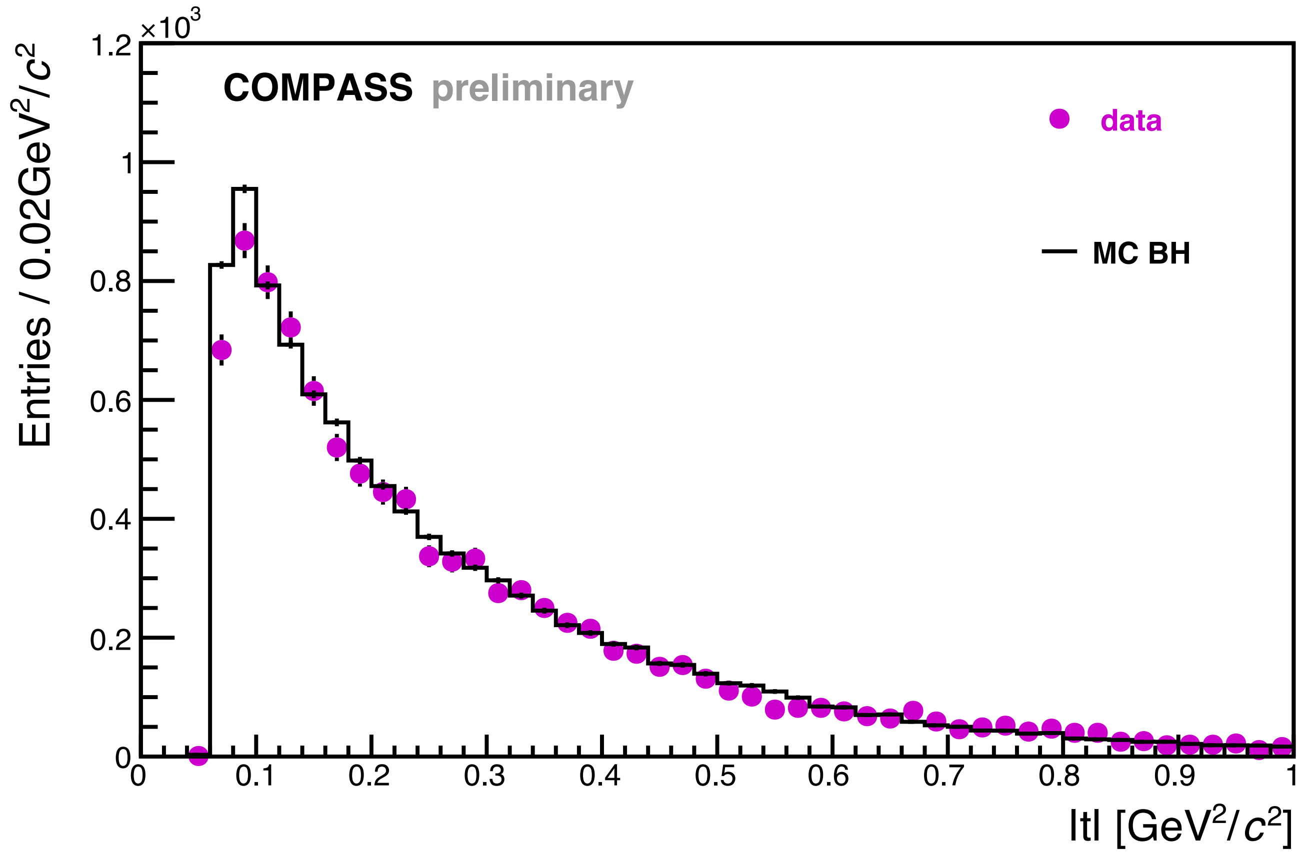
COMPASS DVCS 2016 data - 1D exclusivity cuts



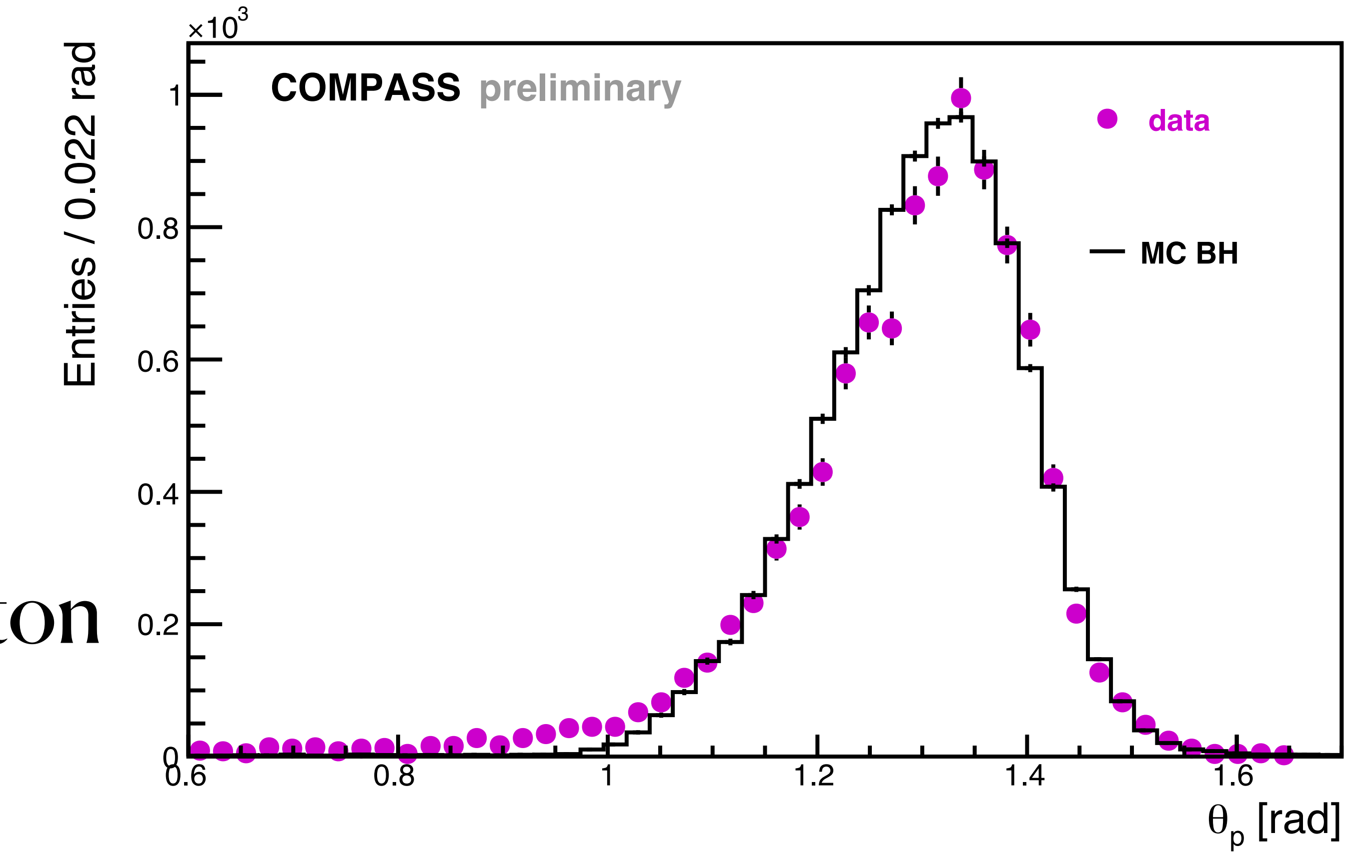
COMPASS DVCS 2016 data - BH data vs. MC, 80 < nu < 144 GeV

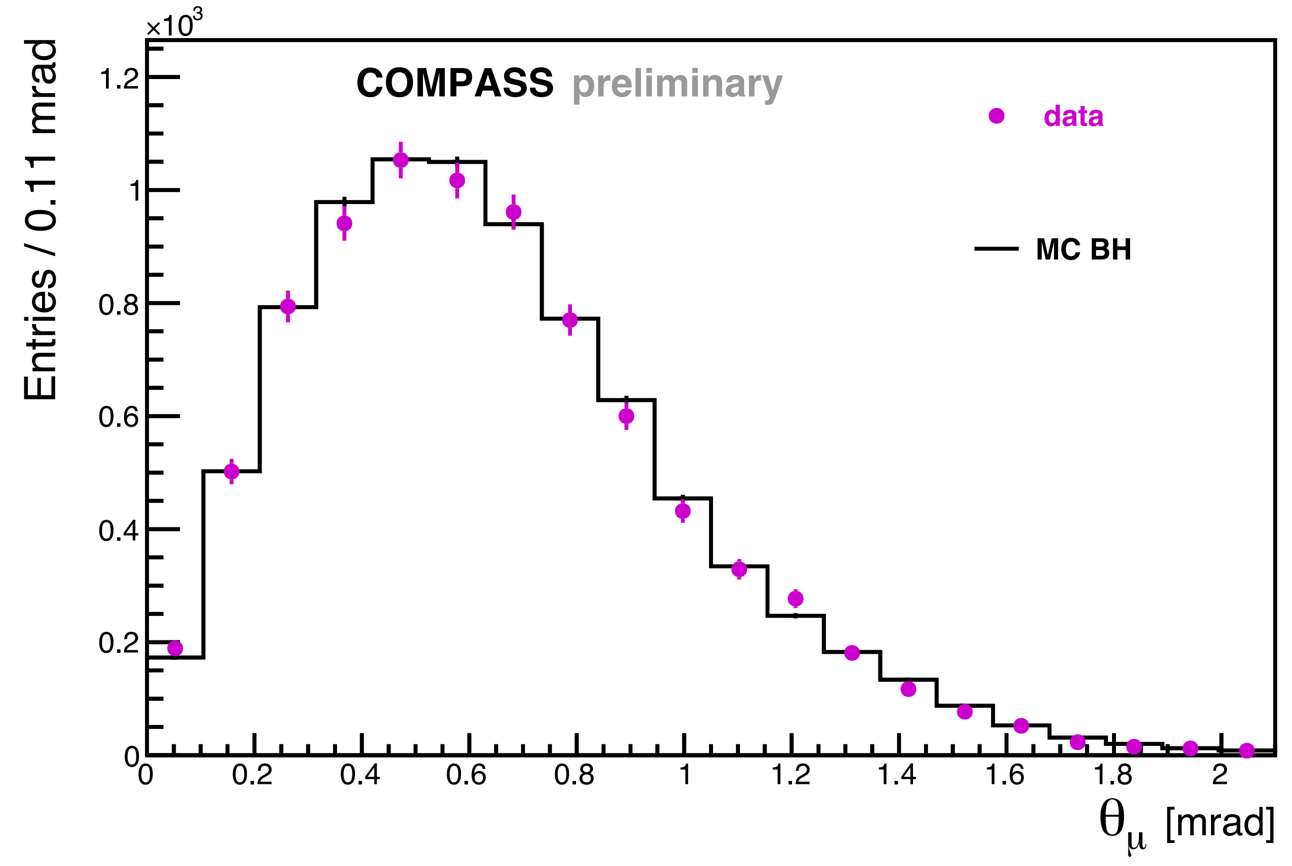


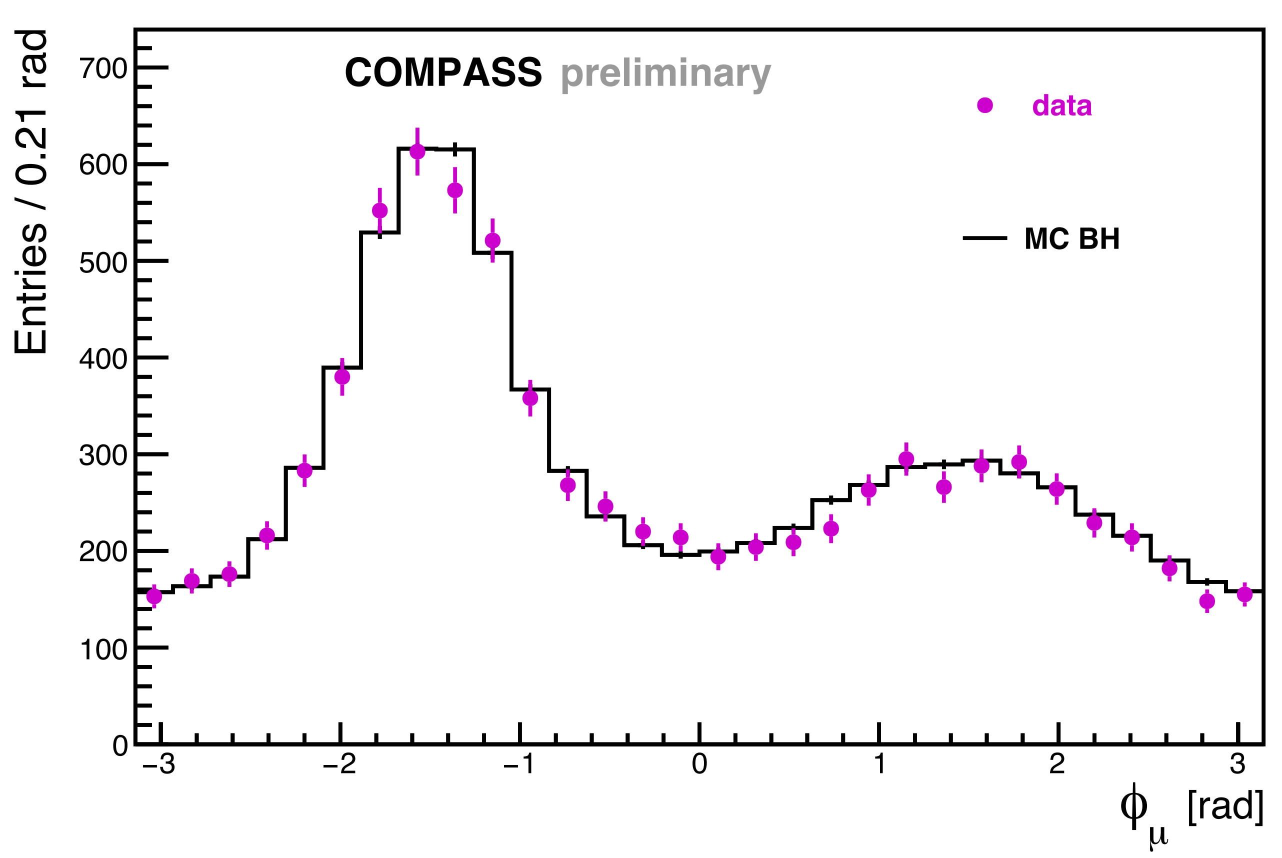
muon



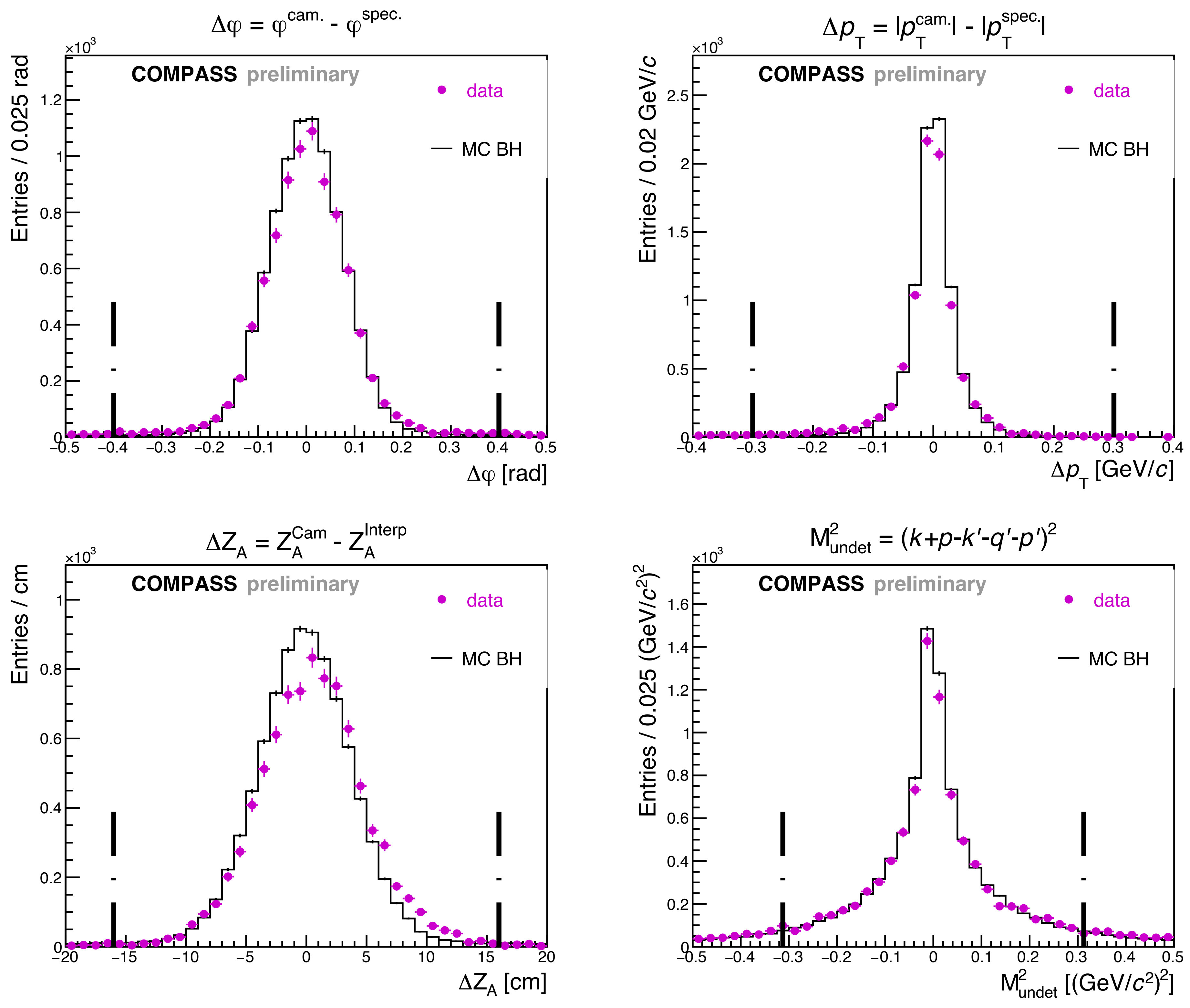
proton





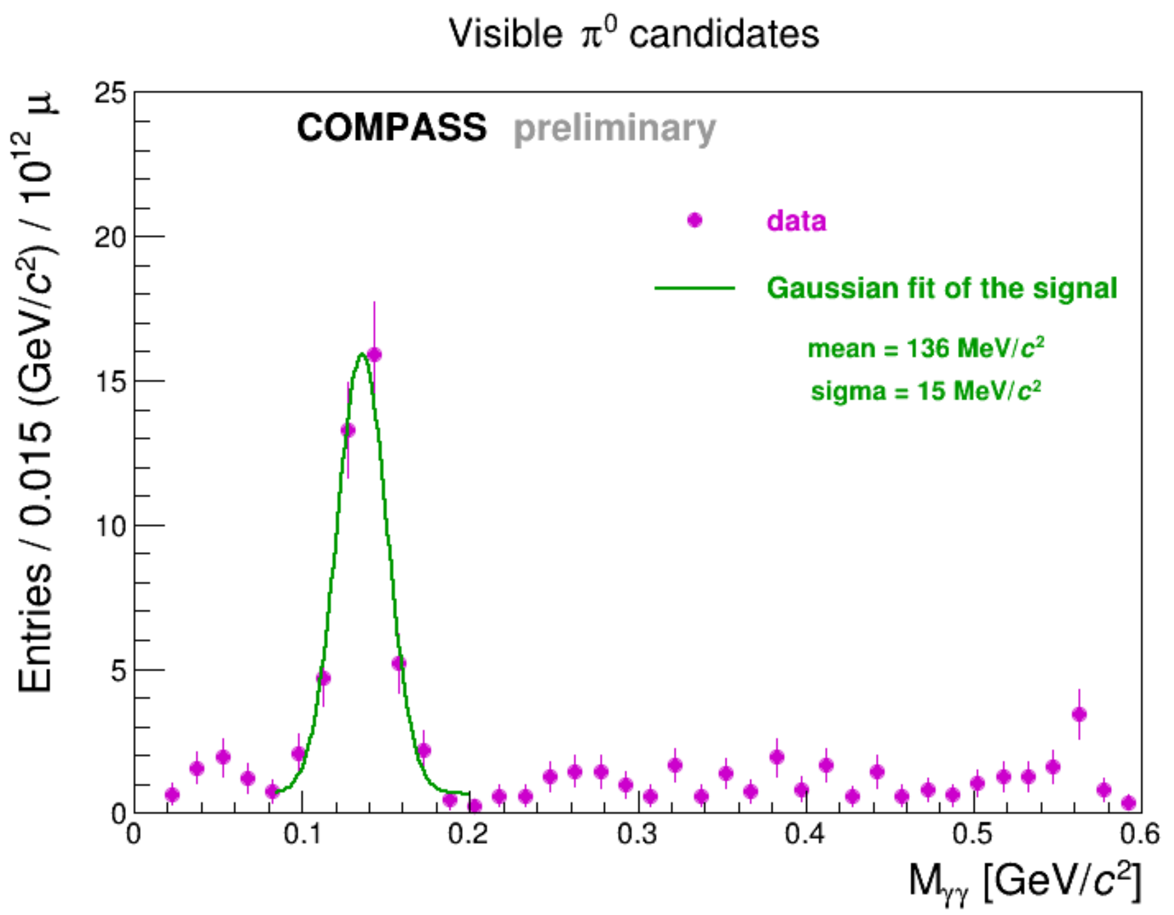


(incoming muon)

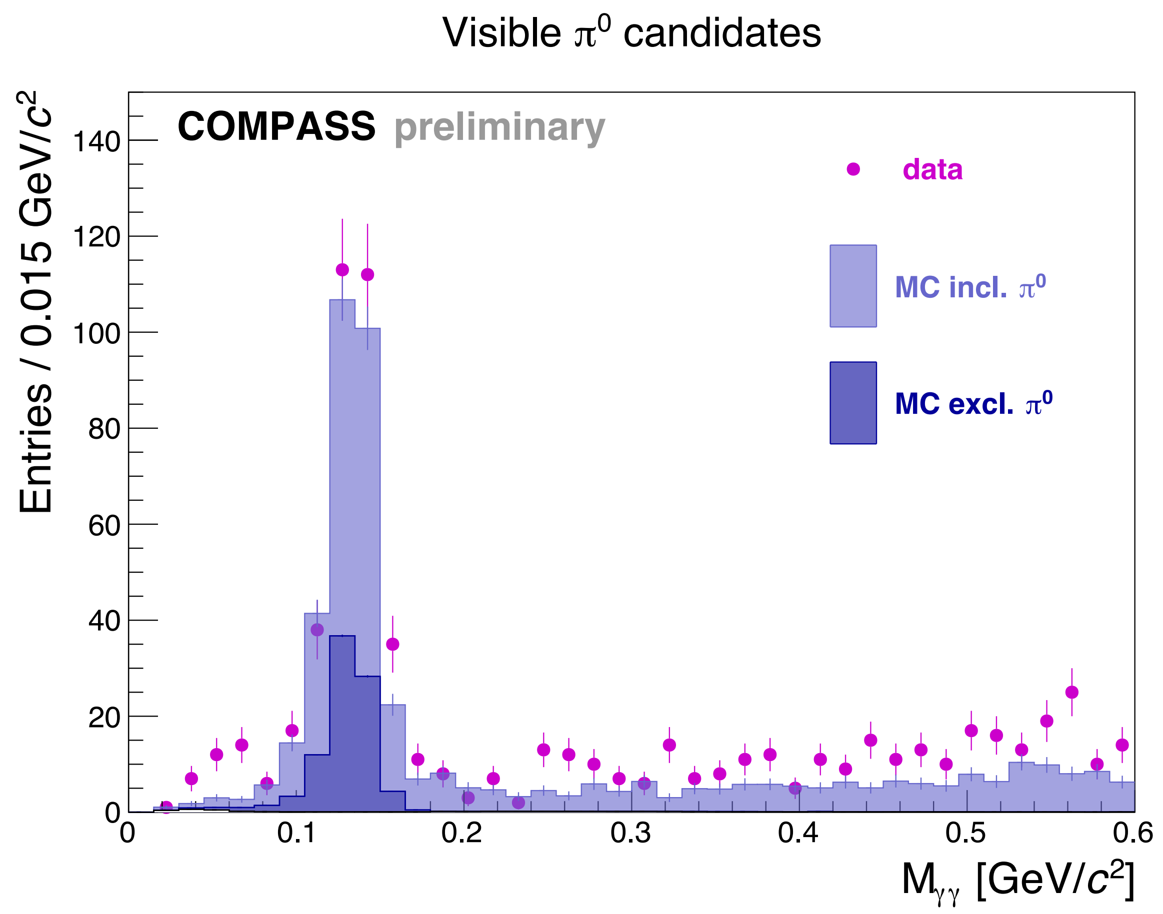


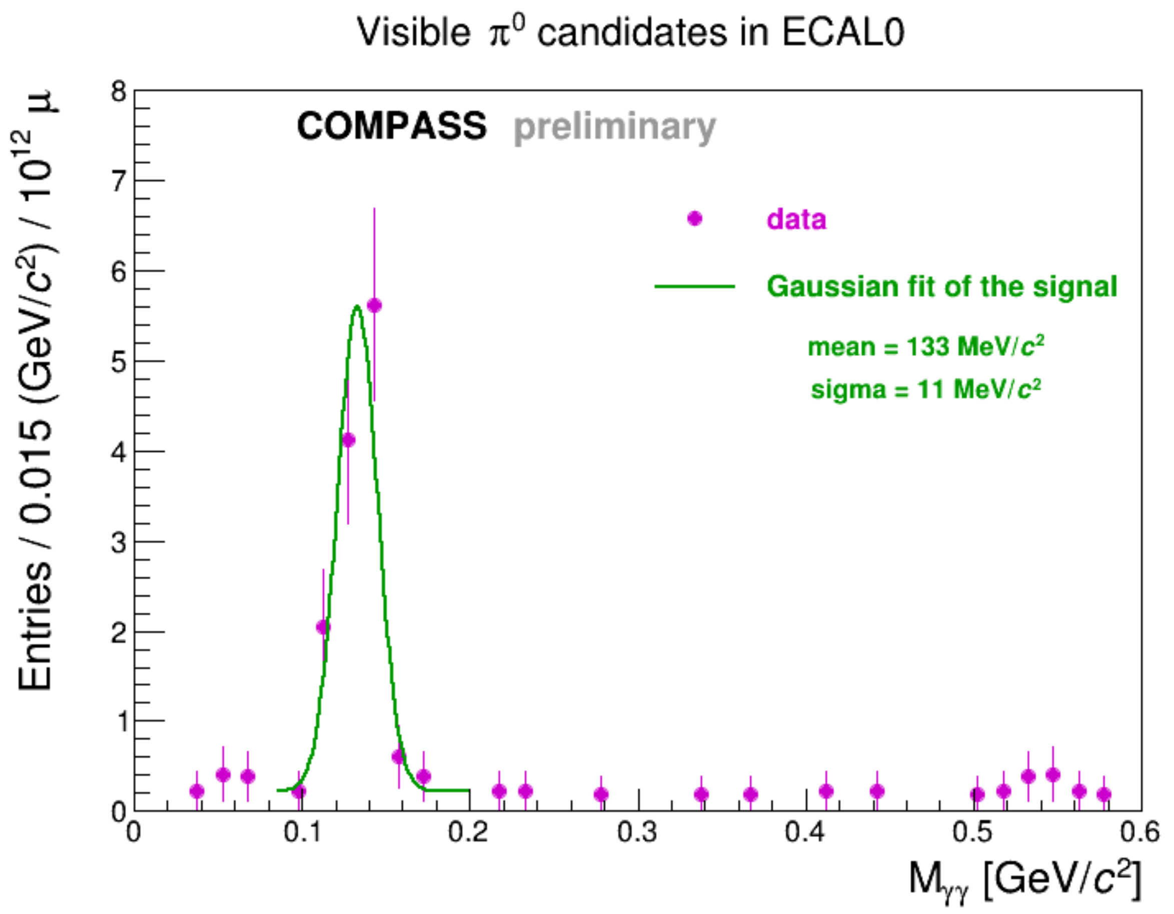
exclusive variables

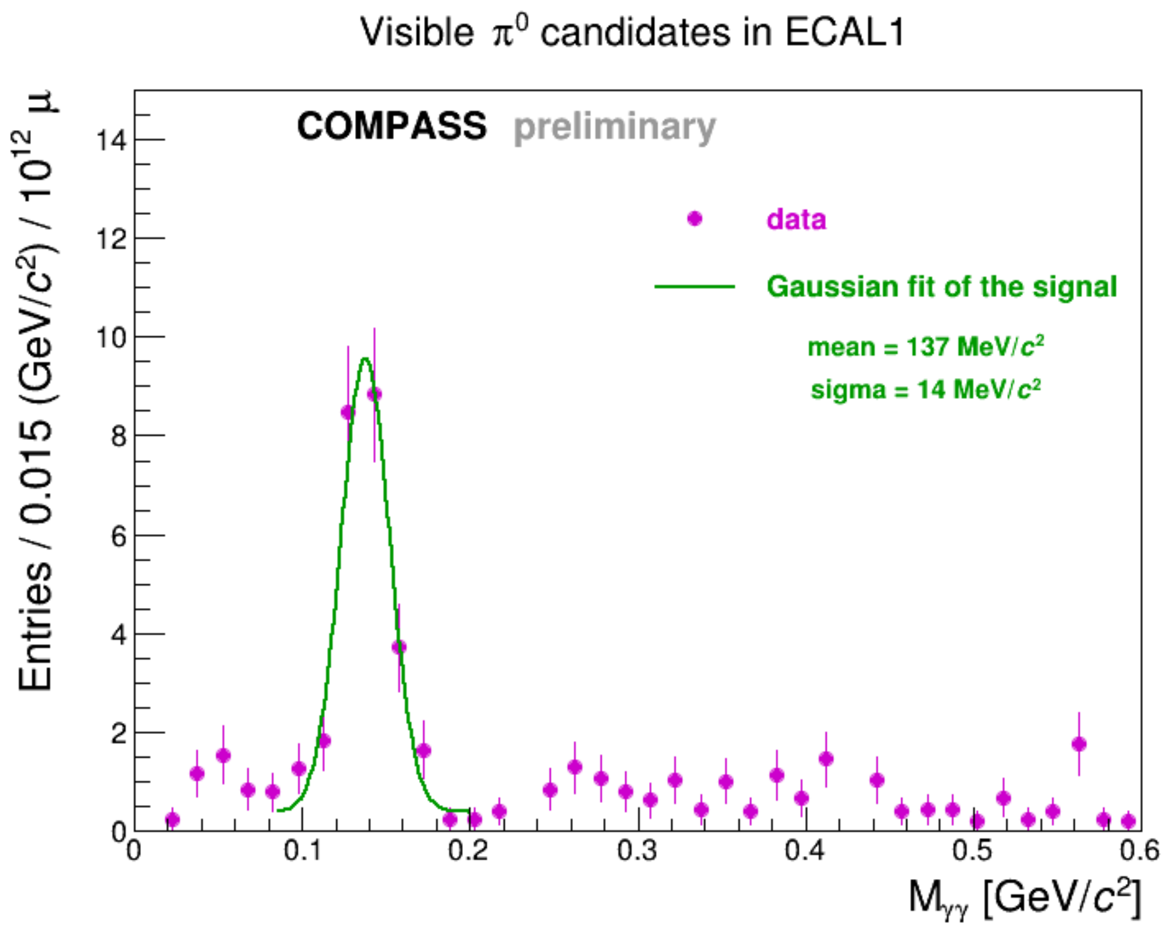
COMPASS DVCS 2016 data - invariant mass of visible π^0

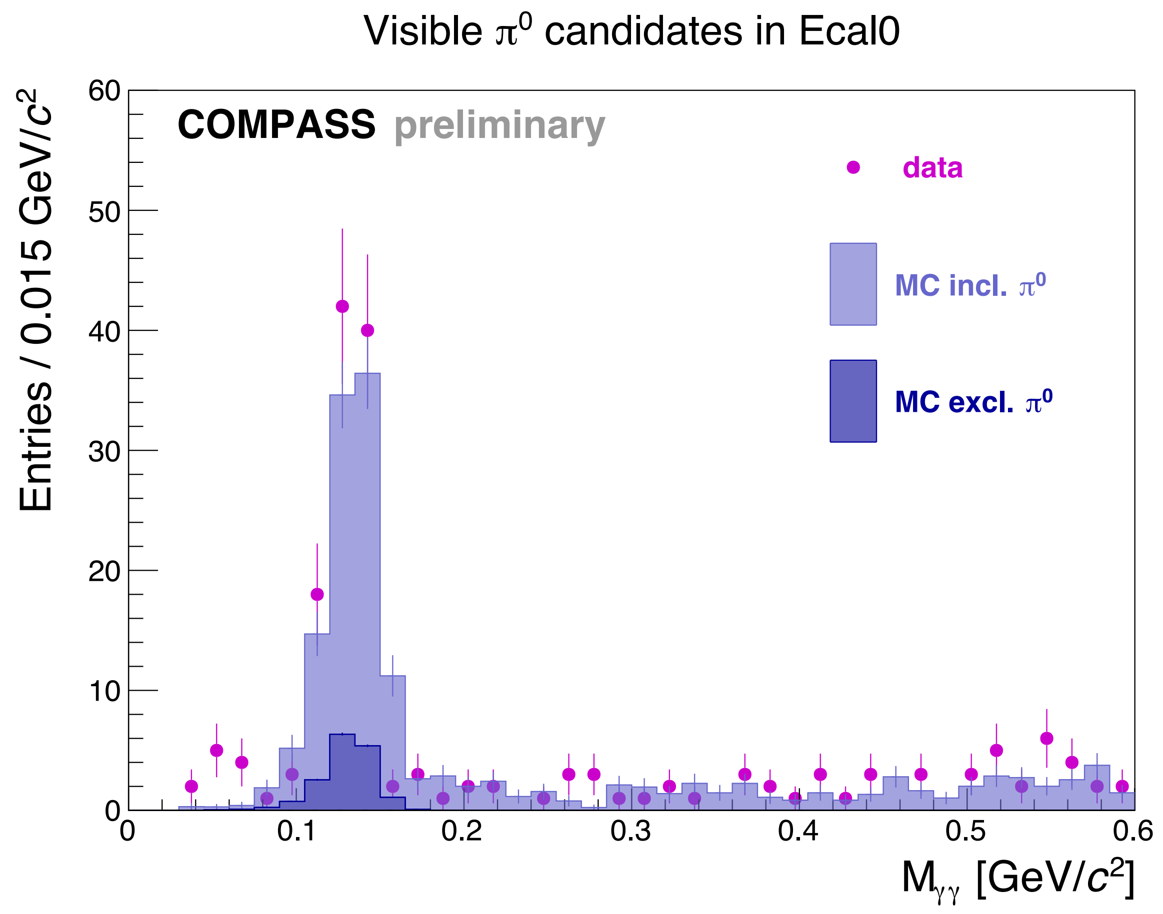


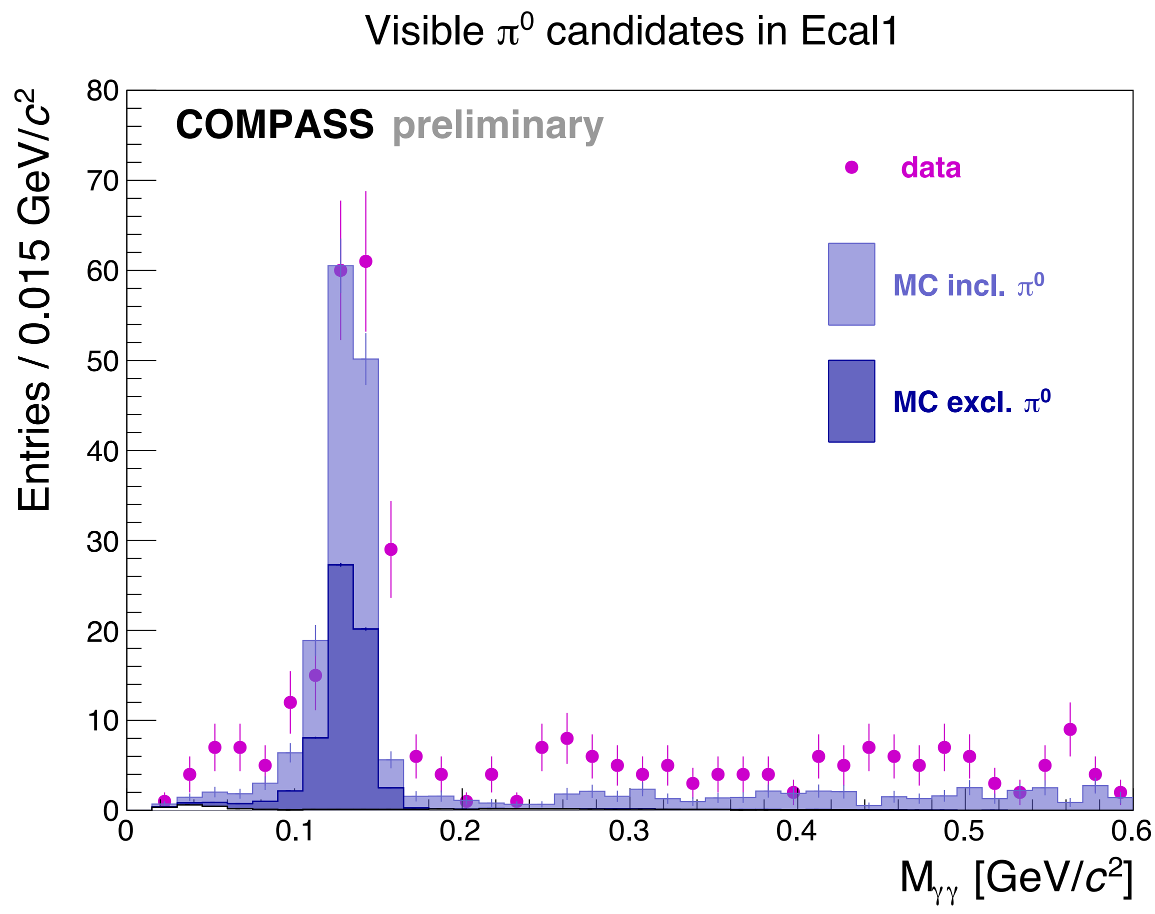
The visible π^0 contamination is removed in the ϕ-distribution



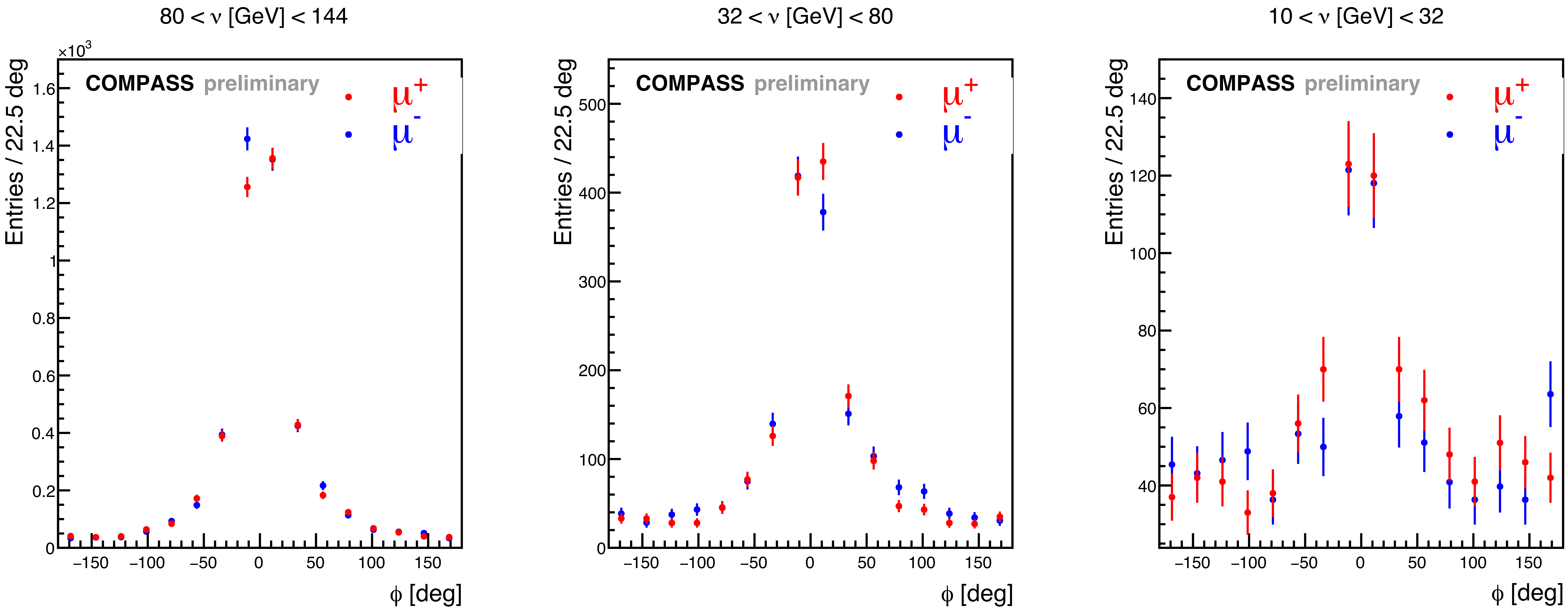








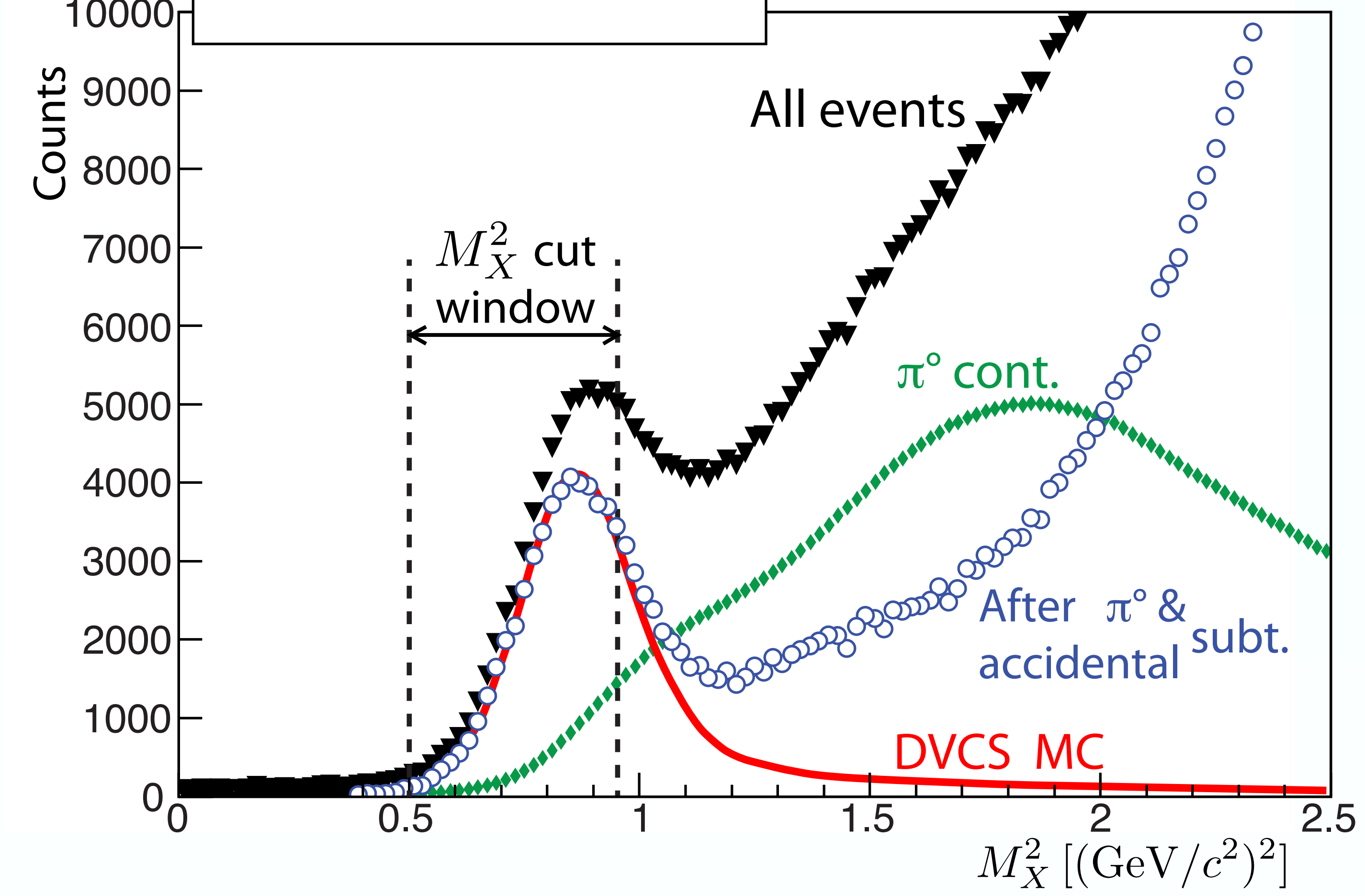
COMPASS DVCS 2016 data - $\phi^{\gamma\gamma^*}$ distributions



Selection of exclusive data sample

Hall-A DVCS: eγ detection

6 GeV

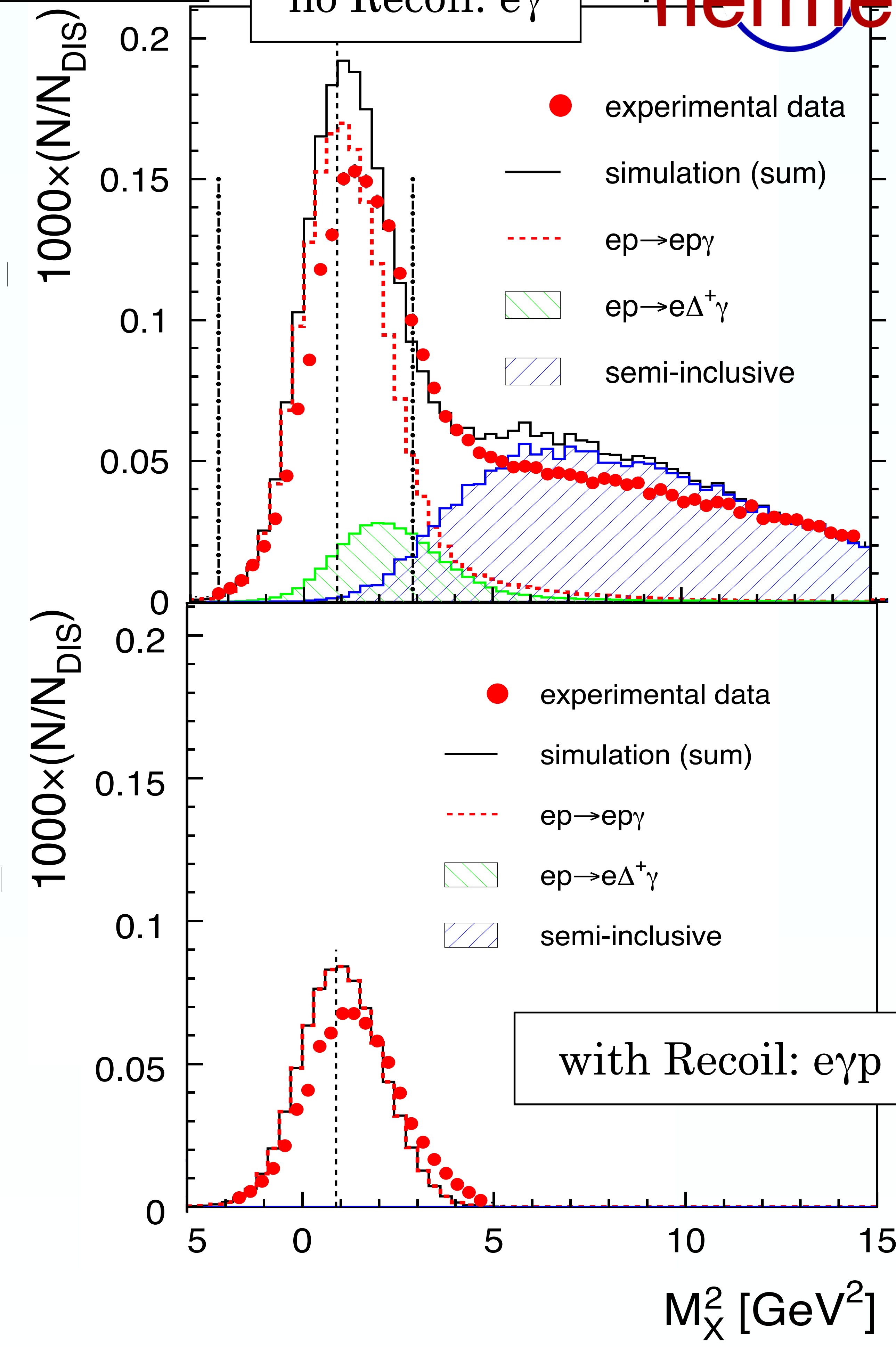


HERMES DVCS:

27.6 GeV

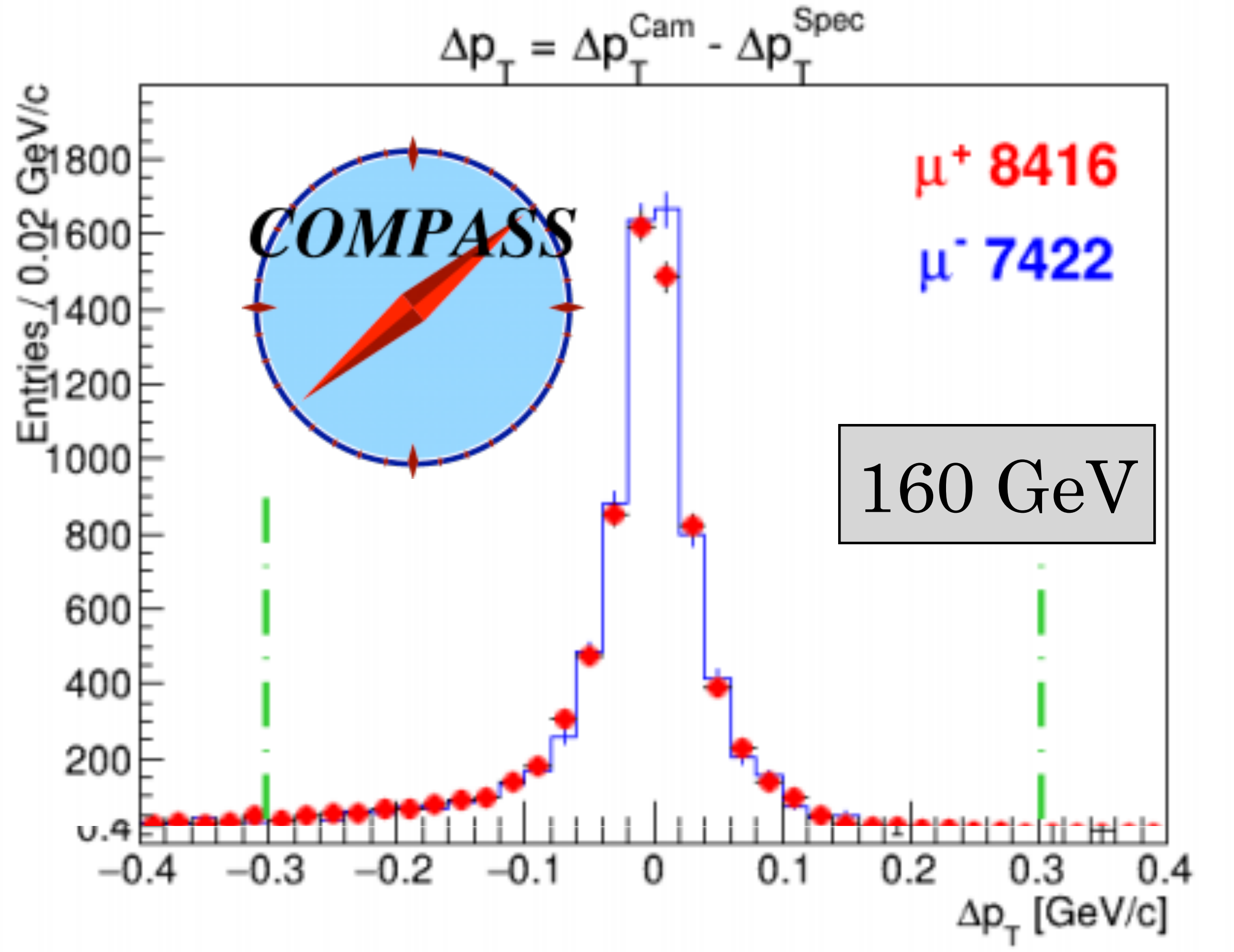
no Recoil: eγ

with Recoil: eγp

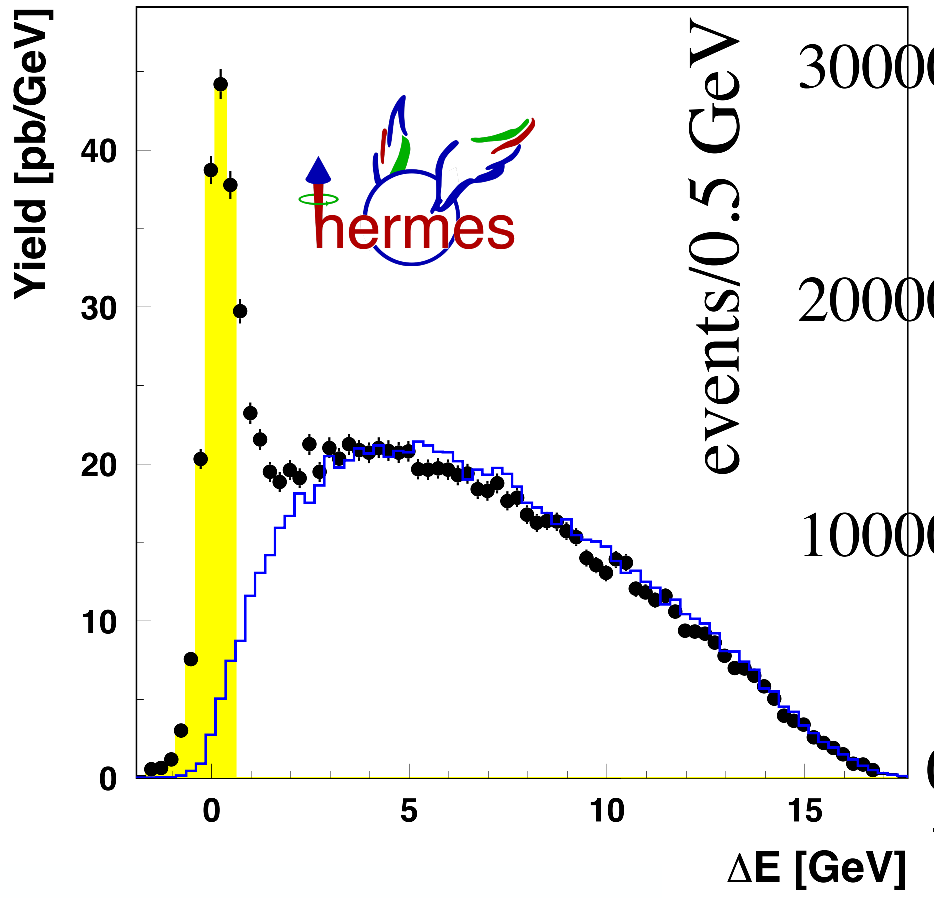


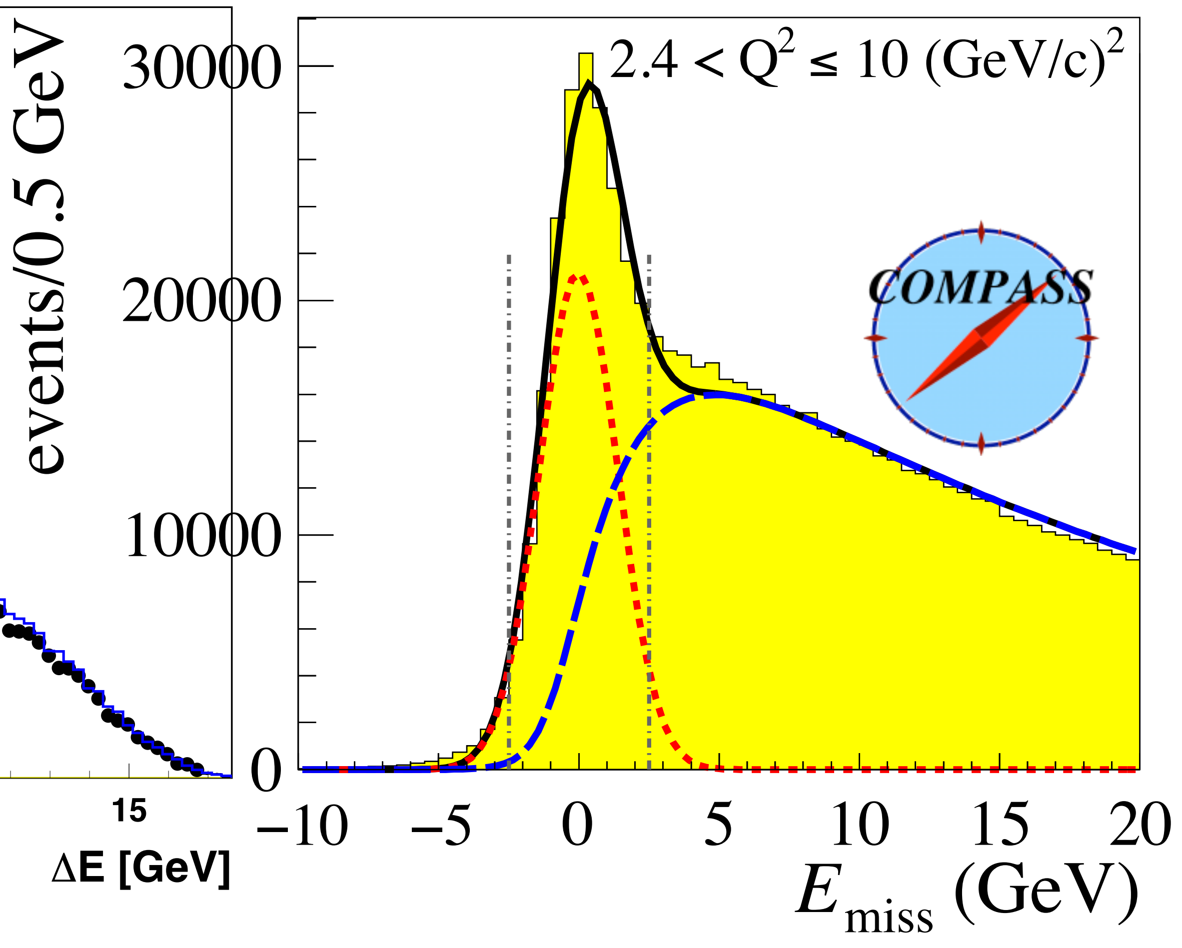
COMPASS DVCS: μγp detection

160 GeV



HERMES & COMPASS excl. ρ: ℓπ-π+ detection



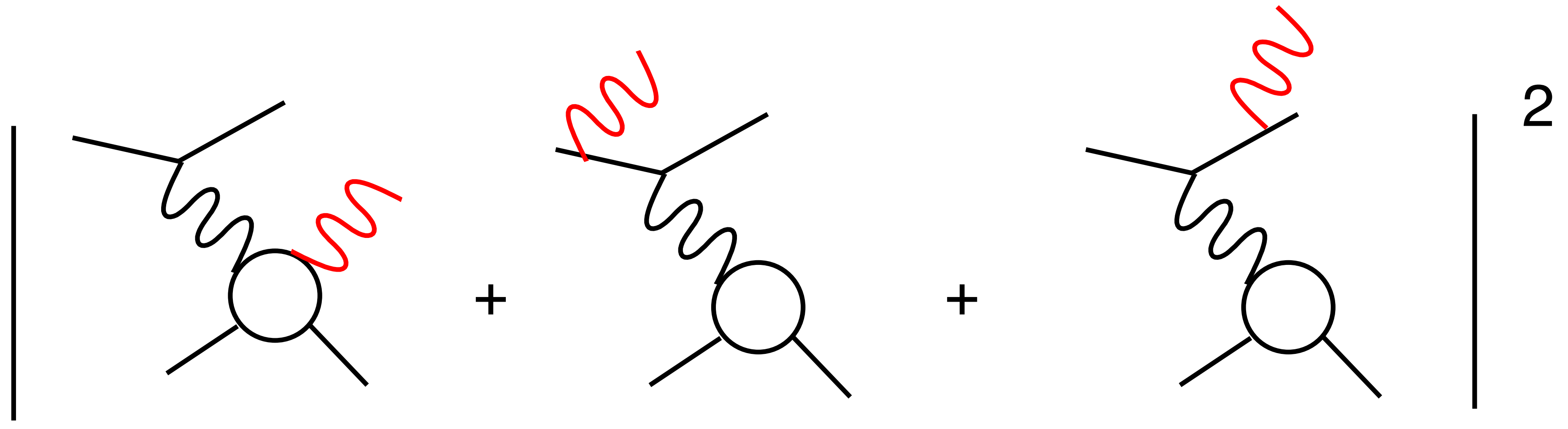


CLAS DVCS:
no Inner Calo: ep or epγ
with Inner Calo: epγ

H1/ZEUS DVCS:
eγ + forward veto
ZEUS subsample: epγ

Experimental access to CFFs at HERMES & JLab

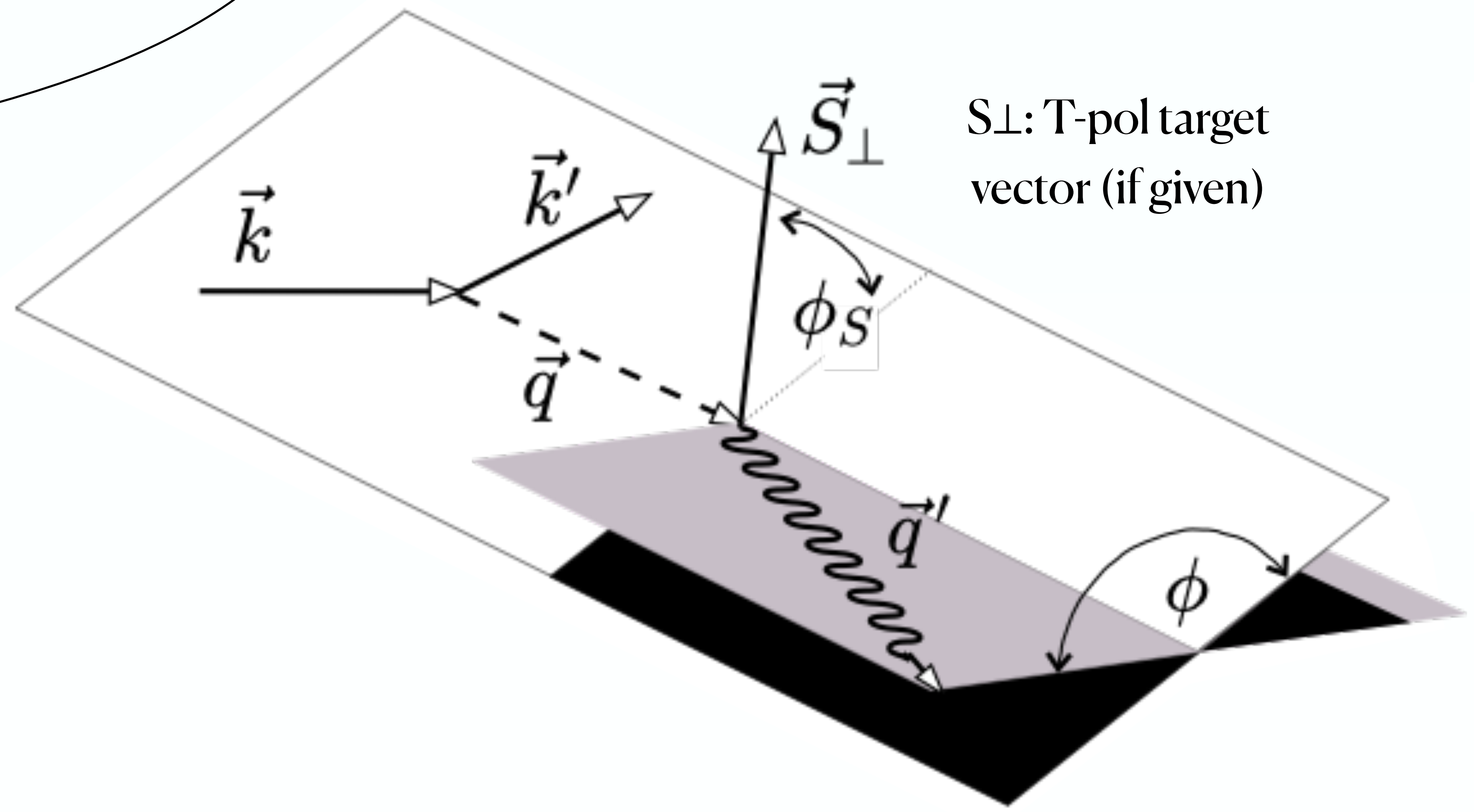
DVCS $\sigma_{\gamma^*\gamma N} \sim \left| \quad + \quad + \quad \right|^2$



DVCS — Bethe–Heitler (BH)

$$= |\mathcal{T}_{\rm BH}|^2 + \boxed{(\mathcal{T}_{\rm DVCS}\mathcal{T}^*_{\rm BH} + \mathcal{T}^*_{\rm DVCS}\mathcal{T}_{\rm BH})} + |\mathcal{T}_{\rm DVCS}|^2$$

The DVCS-Bethe_Heitler interference term helps to disentangle **Re(τ_{DVCS})** and **Im(τ_{DVCS})** **magnitude** and **phase** of DVCS amplitude τ_{DVCS}



$S_\perp$: T-pol target vector (if given)

Lepton k with charge C_B & polarization P_B off nucleon

Azimuthal angle ϕ between lepton scattering plane and plane spanned by virtual & real photons

Example: azimuthal beam-spin asymmetry

$\mathcal{A}_{\rm LU}(\phi)$ — L: Beam, U: Target polarization

$$\sigma(\phi; P_B, C_B) = \sigma_{\rm UU}(\phi)\cdot[1 + P_B\mathcal{A}^{\rm DVCS}_{\rm LU}(\phi) + P_B C_B \mathcal{A}^{\mathcal{I}}_{\rm LU}(\phi) + C_B\mathcal{A}_C(\phi)]$$

Different experimental configurations (beam polarization, beam charge, target polarization, and their combinations) provide access to different parts or aspects of CFFs.

Different experimental configurations to map out CFFs

$\mathcal{A}_{\mathrm{LU}}$ — Beam, Target polarization

$\Rightarrow$ target spin
$\rightarrow$ beam spin
$+$ beam charge

Best access

☞ unpolarized target:

$$F_1\mathcal{H} + \frac{x_B}{2-x_B}(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

$F_1\mathcal{H}$: dominant for the proton

$F_2\mathcal{E}$: dominant for the neutron

Compton Form Factors (CFFs)

$$\mathcal{A}_{\mathrm{LU}}(\phi) \equiv \frac{d\sigma^{\rightarrow} - d\sigma^{\leftarrow}}{d\sigma^{\rightarrow} + d\sigma^{\leftarrow}}$$

Beam-helicity asymmetry

More Fourier coefficients accessible with 2 beam charges

$\mathrm{Im}(\mathcal{H})$

$$\mathcal{A}_{\mathrm{C}}(\phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}}$$

Beam-charge asymmetry

$\mathrm{Re}(\mathcal{H})$

☞ longitudinally polarized target:

$$\frac{x_B}{2-x_B}(F_1+F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) + F_1\widetilde{\mathcal{H}} - \frac{x_B}{2-x_B}\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right)\widetilde{\mathcal{E}}$$

Longitudinal target-spin asymmetry

$$\mathcal{A}_{\mathrm{UL}}(\phi, e_\ell) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] - [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}{[\sigma^{\leftarrow\Rightarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Rightarrow}(\phi,e_\ell)] + [\sigma^{\leftarrow\Leftarrow}(\phi,e_\ell) + \sigma^{\rightarrow\Leftarrow}(\phi,e_\ell)]}$$

analog: **Double-spin (LL) asymmetry**

☞ transversely polarized target:

$$\frac{t}{4M^2}\left[(2-x_B)F_1\mathcal{E} - 4\frac{1-x_B}{2-x_B}F_2\mathcal{H}\right]$$

$\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S)$ $\mathcal{A}_{\mathrm{UT}}^{\mathrm{I}}(\phi,\phi_S)$ — **Transverse target-spin asymmetry**

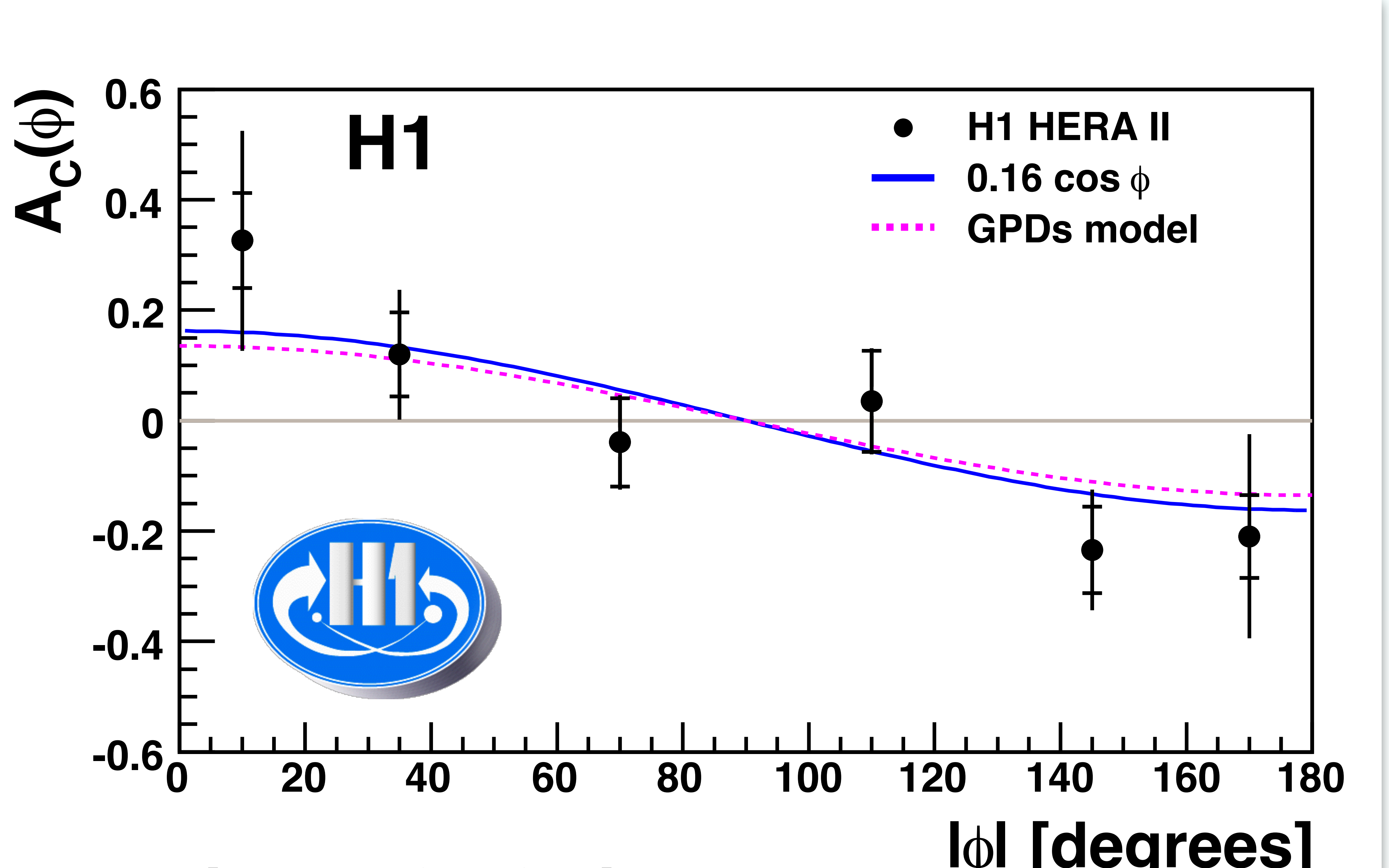
$\mathcal{A}_{\mathrm{LT}}^{\mathrm{I}}(\phi,\phi_S)$ $\mathcal{A}_{\mathrm{LT}}^{\mathrm{BH+DVCS}}(\phi,\phi_S)$ — **Double-spin (LT) asymmetry**

H1 & HERMES: DVCS beam-charge asymmetry

Re(τ_{DVCS}) > 0
for HERA (small x)

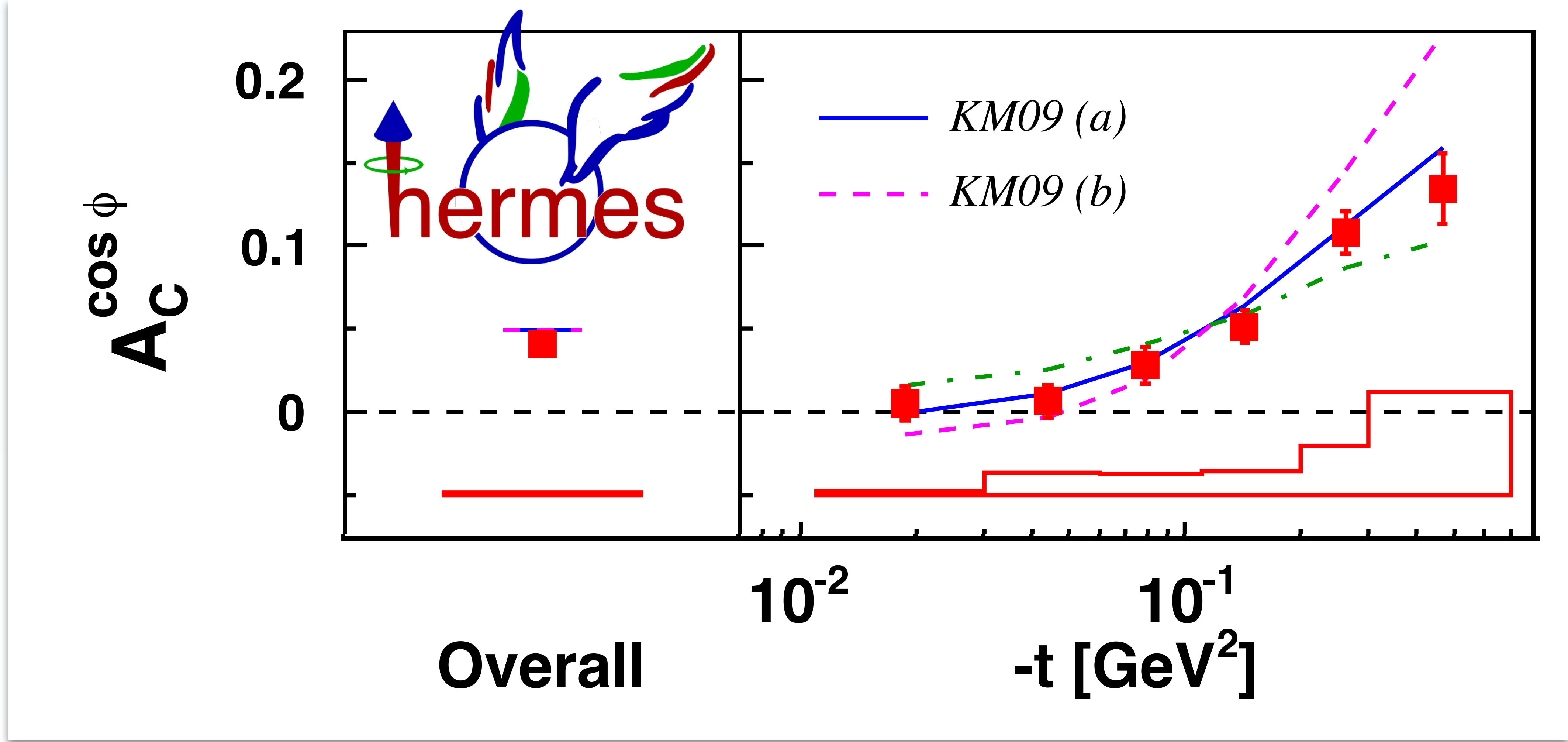
Re(τ_{DVCS}) < 0
for HERMES (larger x)

Where is the zero crossing? COMPASS measurement at intermediate energy



[H1 PLB 681 (2009) 391]

- ϱ = **Re(τ_{DVCS}) / Im(τ_{DVCS})**
  - ϱ=0.20 ± 0.05(stat) ± 0.08(sys)
  - In good agreement with theoretical calculation (dispersion relation)
- H1@HERA/DESY: first and only measurement at collider
  - low x_B=10^{-4}...10^{-2}
  - 6.5 < Q^2 < 80 GeV^2
  - 30 < W < 140 GeV
  - |t|<1 GeV^2



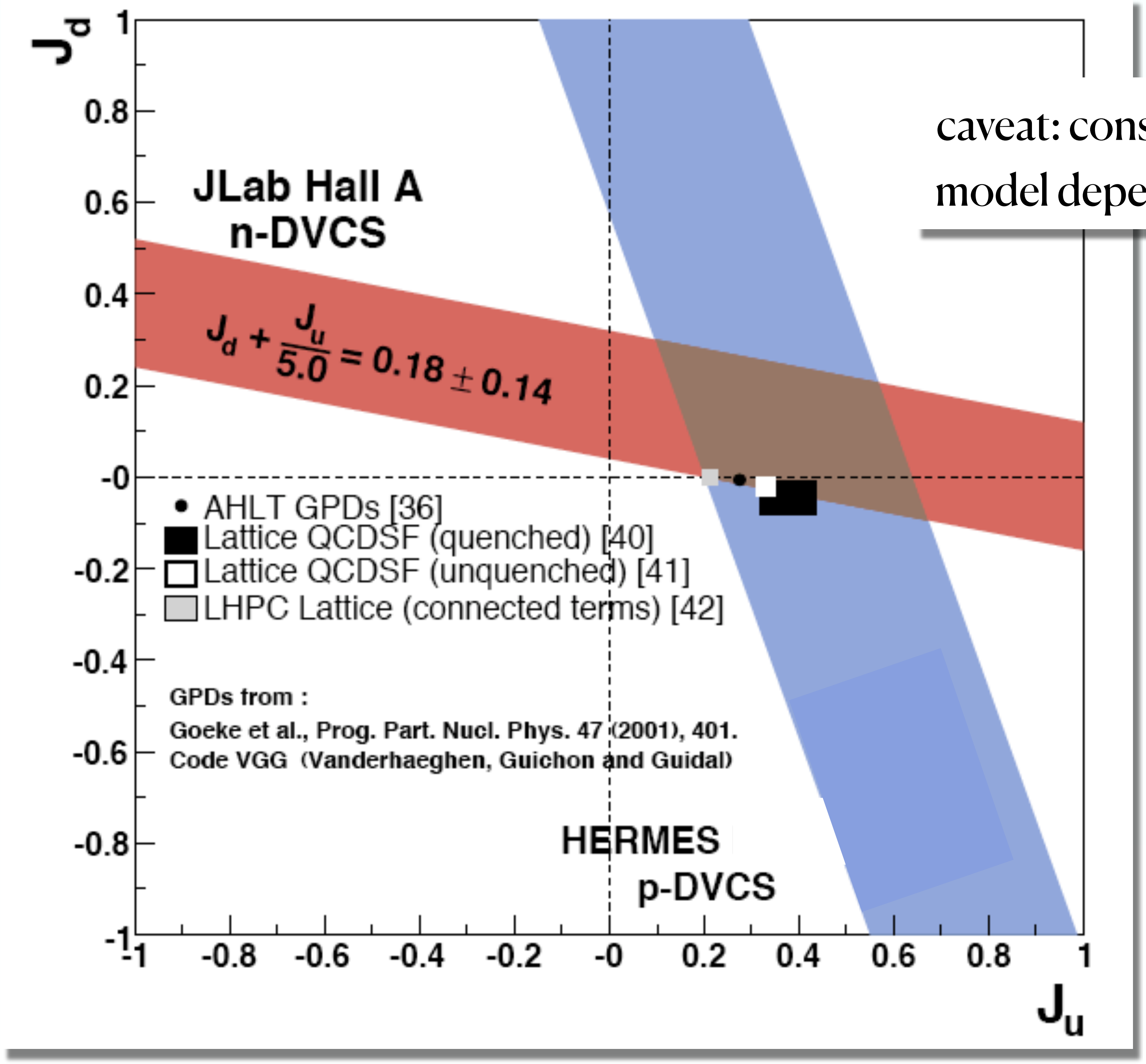
 [HERMES JHEP 07 (2012) 032]

GPD E linked to orbital angular momentum

Measurements sensitive to GPD ***E*** allow (in principle) to access the total angular momentum of partons, J_q.

Ji sum rule for the nucleon: [Ji, PRL 78 (1997) 610]

$$J_q = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} dx\, x \left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]$$



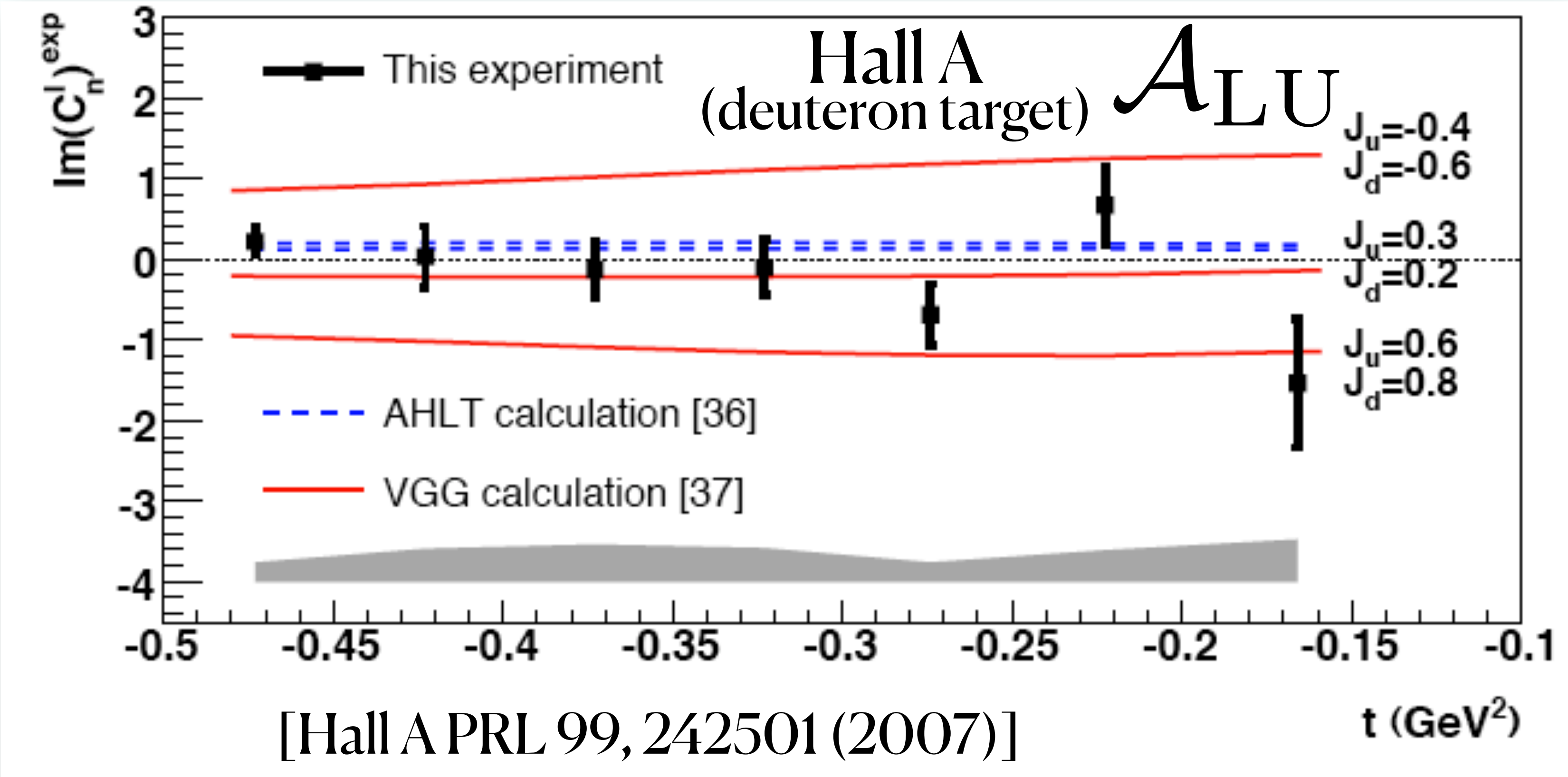
caveat: constraint model dependent

[Hall A PRL 99, 242501 (2007)]

HERMES and Hall-A DVCS asymmetries

(A) HERMES: **ep**↑ → **epγ** :
H-E (transversely polarized proton target) $\mathcal{A}_{UT}$

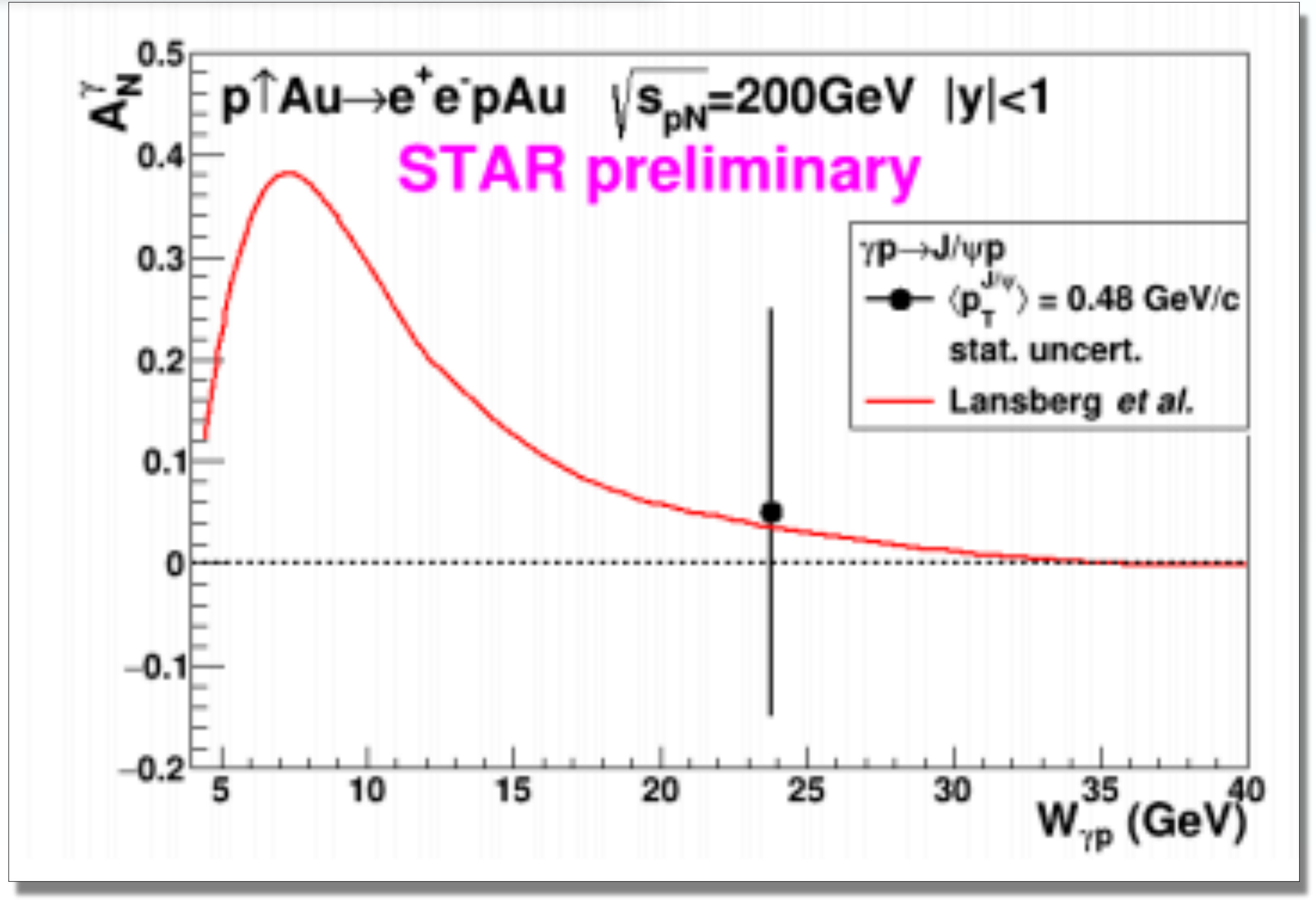
(B) Hall A: $\vec{e}$**n** → e n γ :
E dominant for the neutron $\mathcal{A}_{LU}$



[Hall A PRL 99, 242501 (2007)]

- More data from JLab12 and RHIC (STAR) to come.
- STAR: exclusive J/Psi production in ultra-peripheral p↑p collisions (UPC) → **gluon** GPD *E*

STAR exclusive J/Psi asymmetry



Vector meson production and decay