Extraction of the t-dependence of the pure DVCS x-section

P. Jörg (ALU Freiburg)

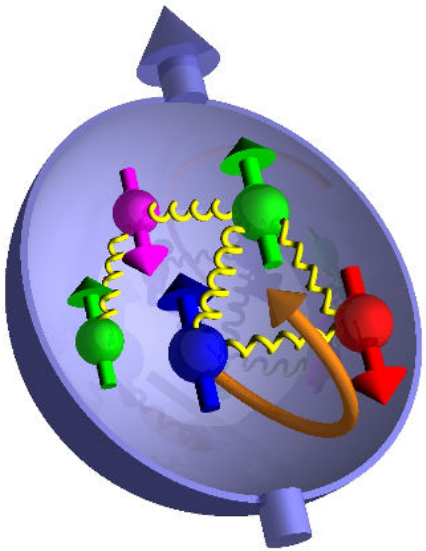
on behalf of the COMPASS Collaboration

DIS2016 - Hamburg, 13/04/2016

SEVENTH FRAMEWORK PROGRAMME

bmb+f - Förderschwerpunkt COMPASS Großgeräte der physikalischen Grundlagenforschung

The Spin Puzzle



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

(Jaffe&Manohar Nucl.Phys.B337 (1990))

- $\frac{1}{2}\Delta\Sigma \sim 0.15$ well known from DIS/SIDIS
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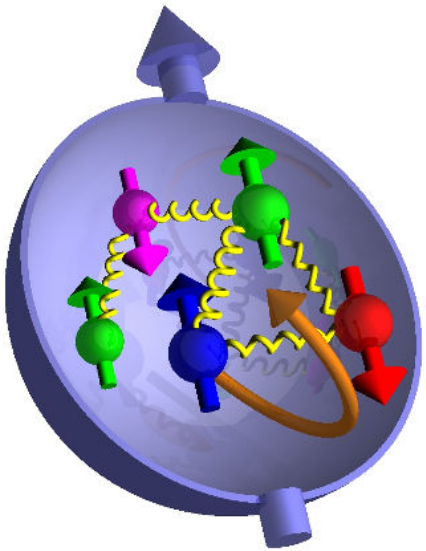

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The **Ji sum rule** connects the Generalized Parton Distributions (GPDs) H and E, measured in exclusive reactions, with the total angular momentum $J^{q,g}$, e.g.

$$J^q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{+1} x[H^q + E^q]dx$$

(Phys.Rev.Lett.78 (1997))

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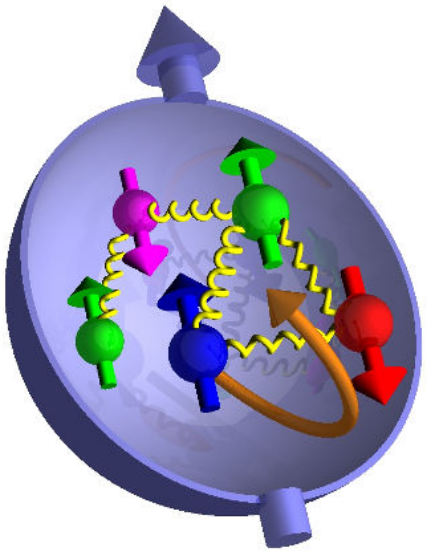

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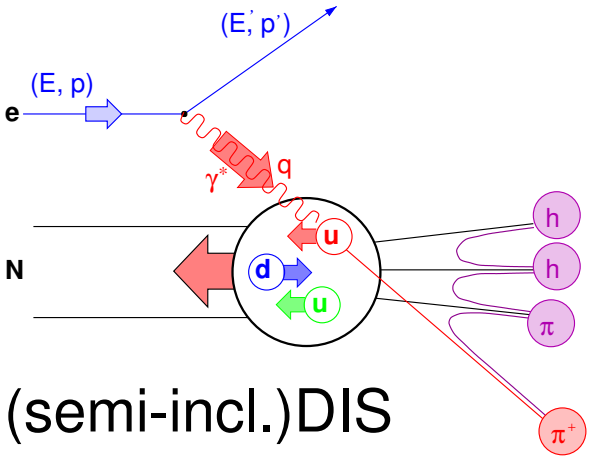
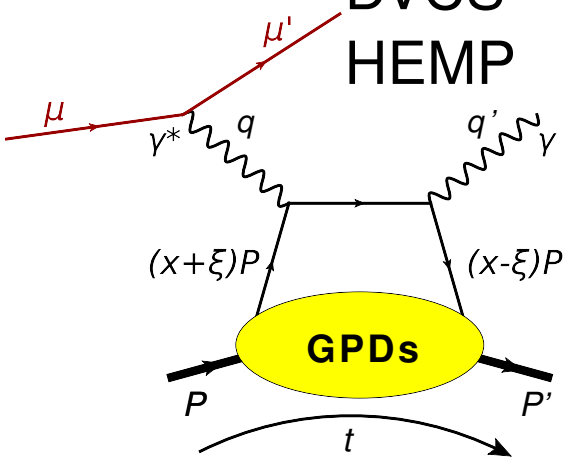
COMPASS experimental tools:

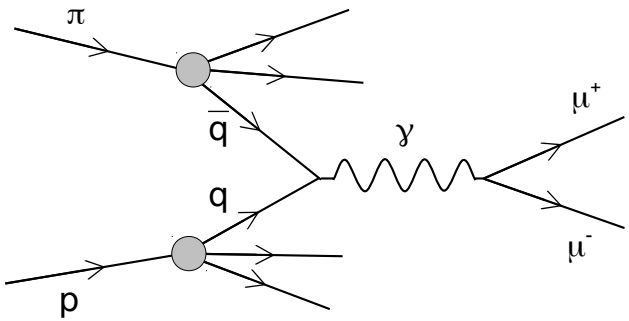


(semi-incl.)DIS

DVCS
HEMP



Pol. Drell-Yan



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This talk:

COMPASS experimental tools:

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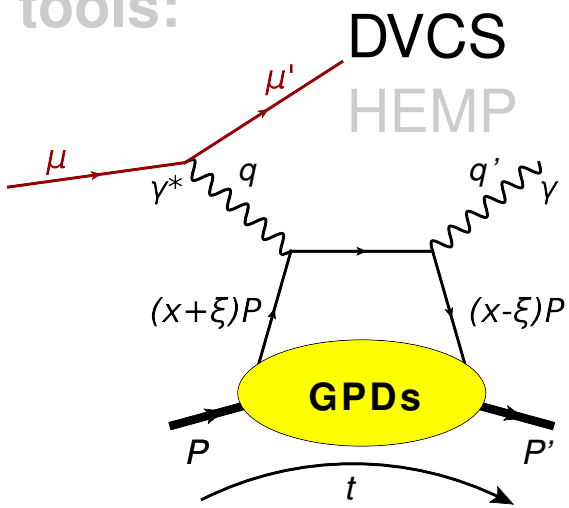
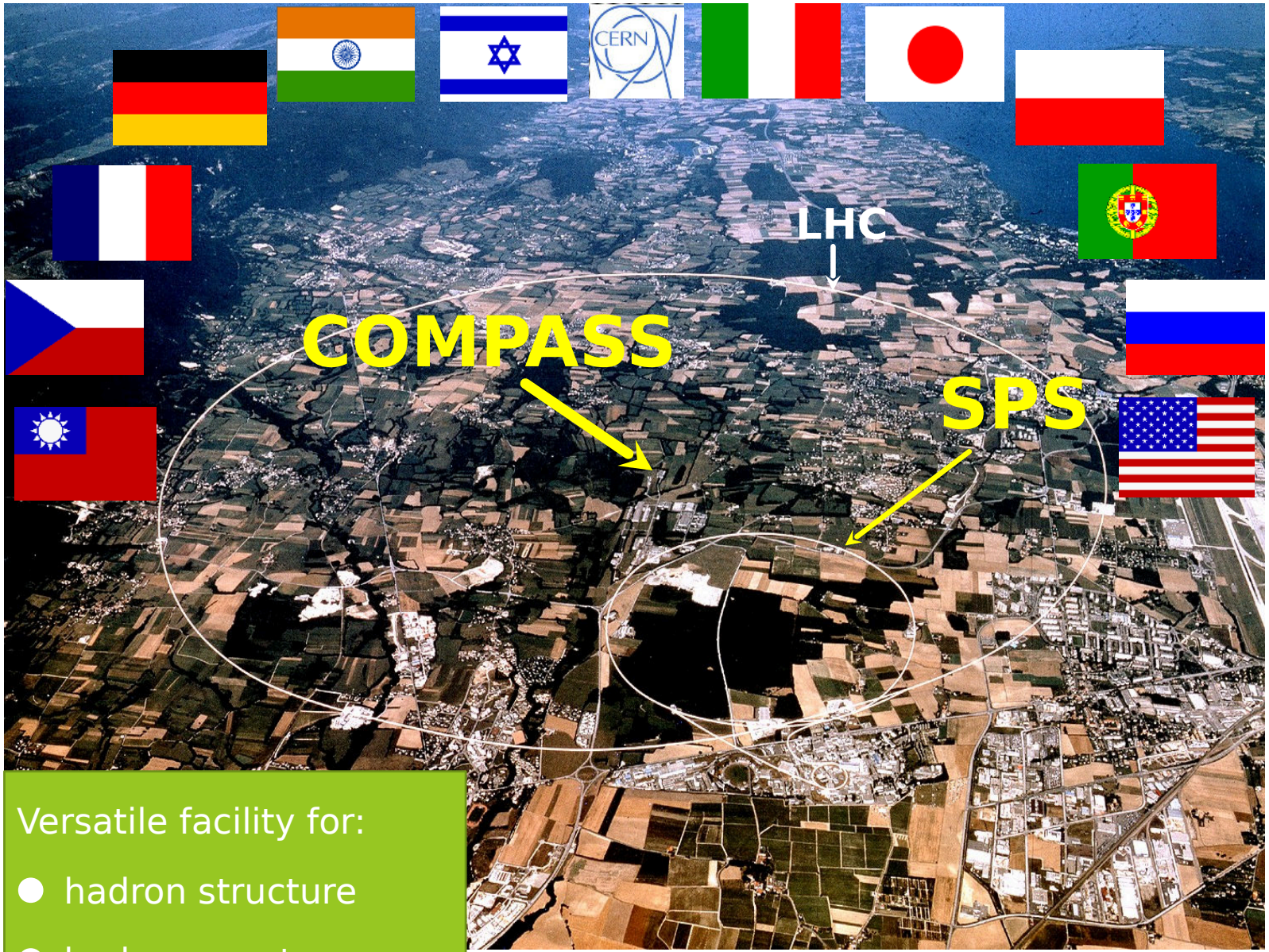


Pol. Drell-Yan

The COMPASS Experiment

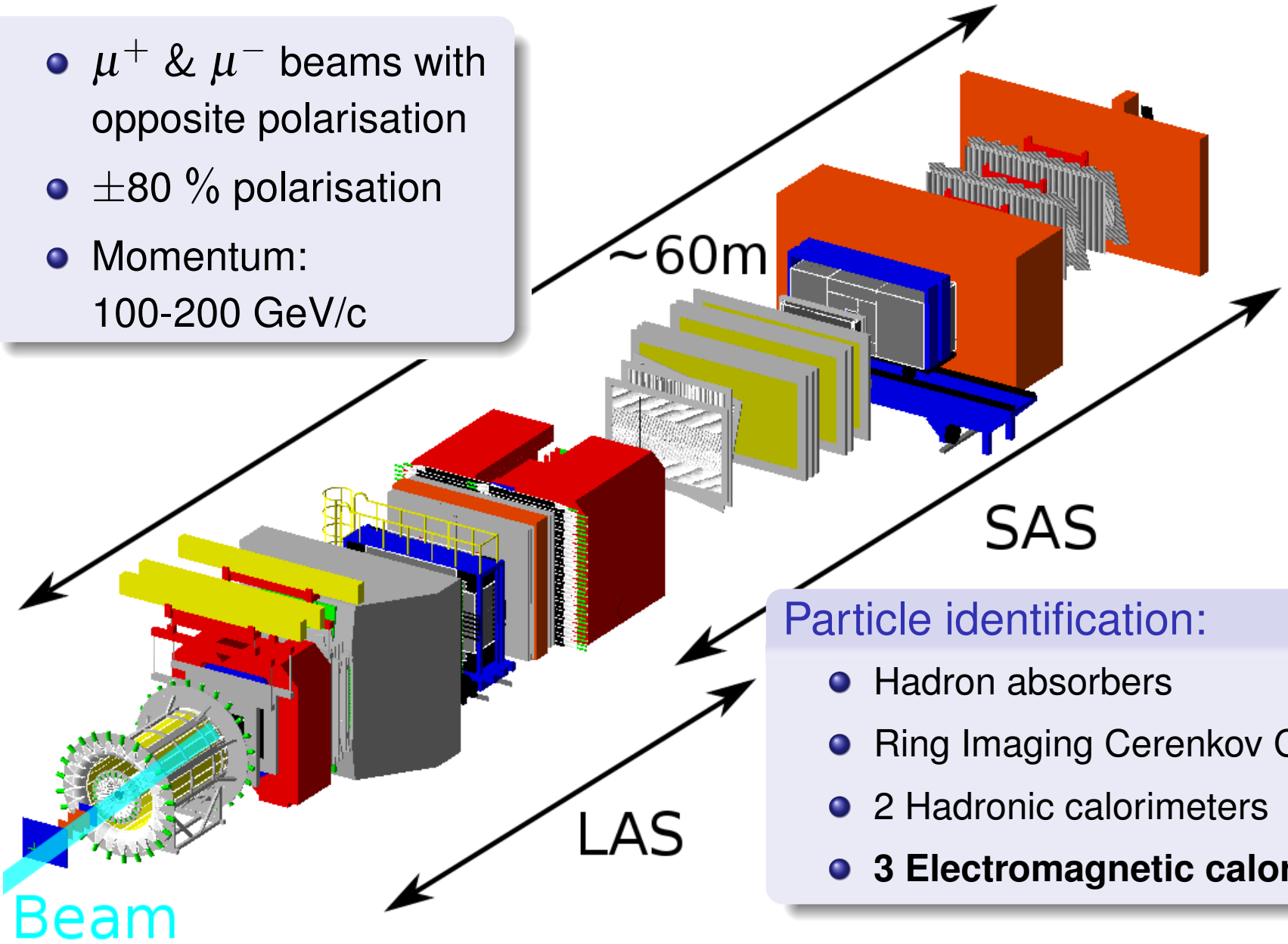


Versatile facility for:

- hadron structure
- hadron spectroscopy

The COMPASS II Spectrometer

- μ^+ & μ^- beams with opposite polarisation
- ± 80 % polarisation
- Momentum: 100-200 GeV/c



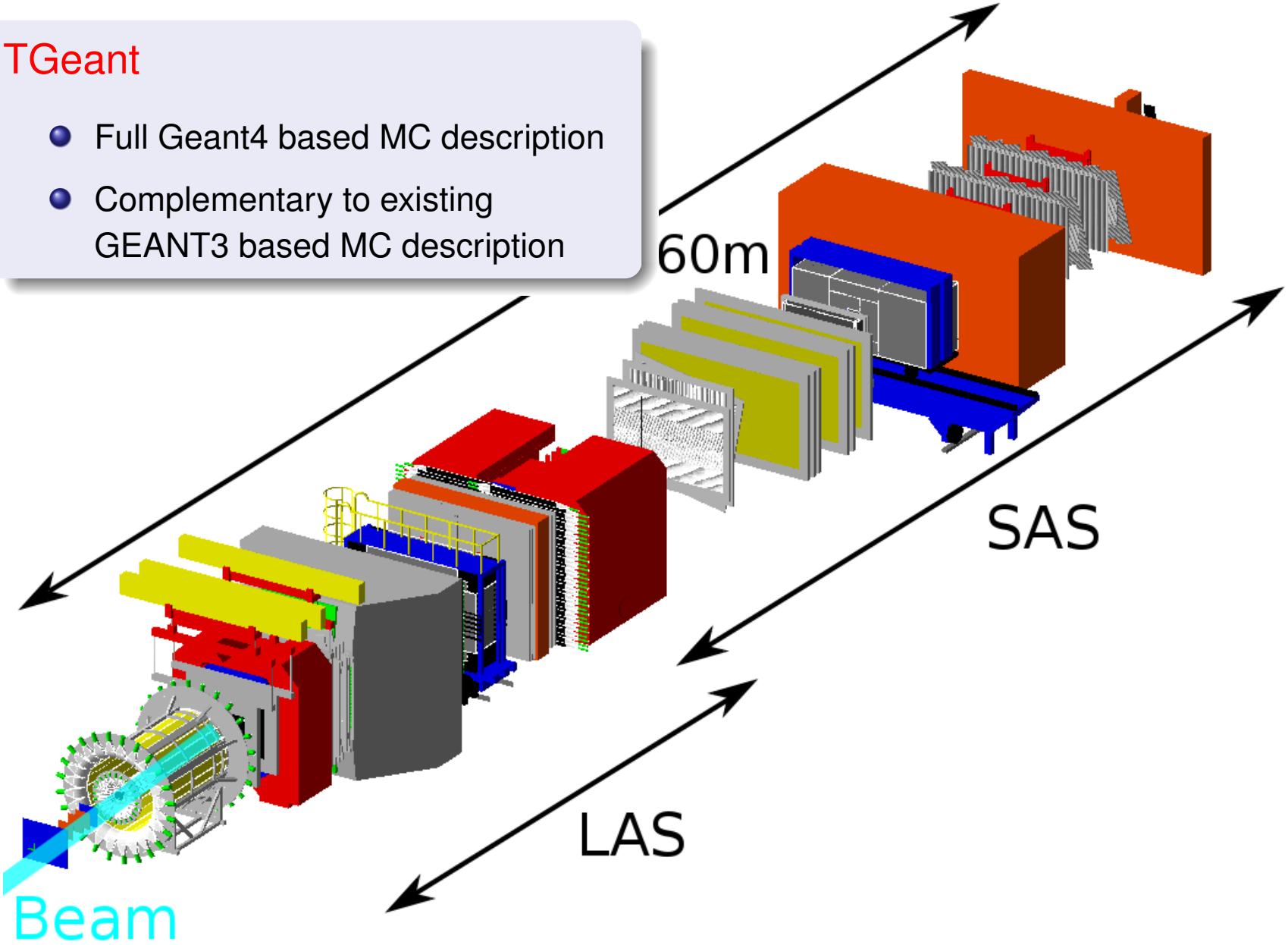
Particle identification:

- Hadron absorbers
- Ring Imaging Cerenkov Counter
- 2 Hadronic calorimeters
- **3 Electromagnetic calorimeters**

Upgrades for the DVCS Program

TGeant

- Full Geant4 based MC description
- Complementary to existing GEANT3 based MC description



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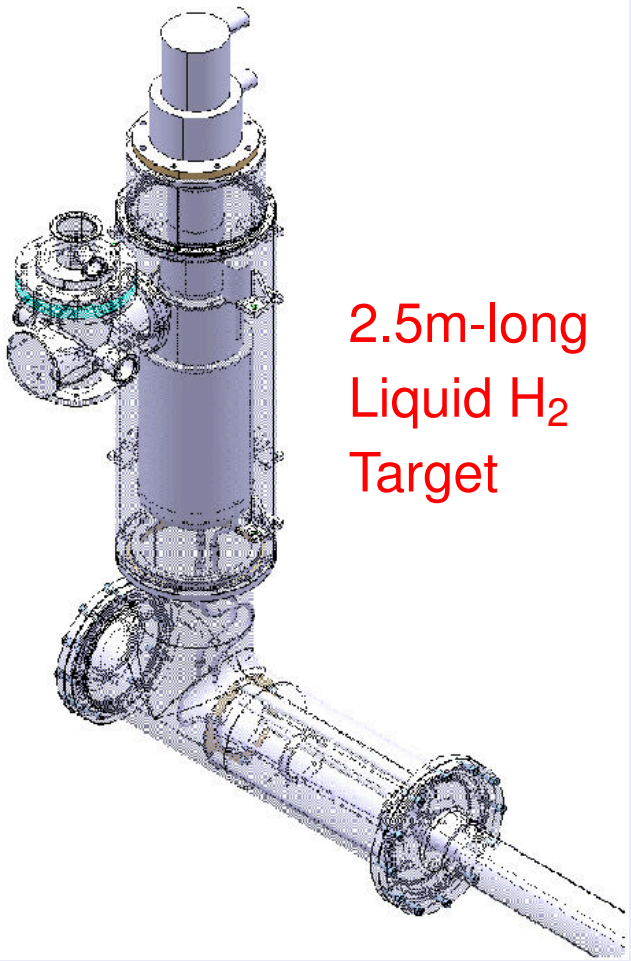
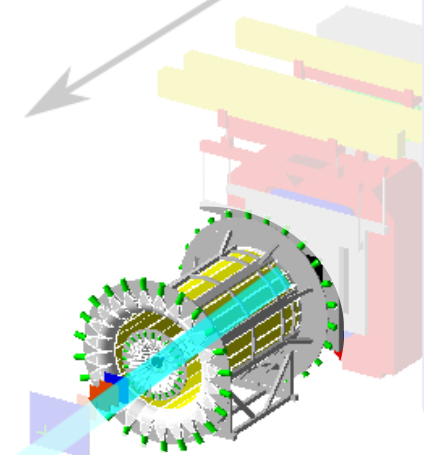
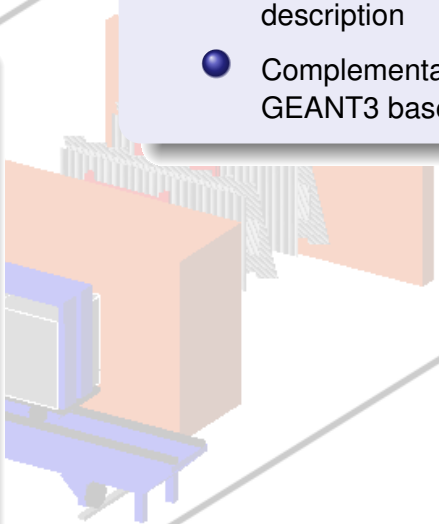


2.5m-long Liquid H_2 Target





SAS

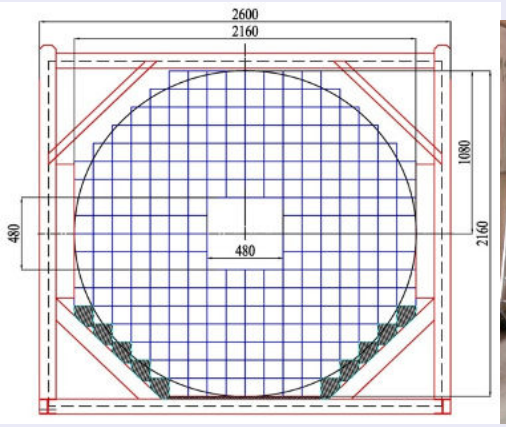
Beam

Upgrades for the DVCS Program

ECAL0 Calorimeter

Shashlyk modules + MAPD readout

$\sim 2 \times 2\ m^2$, $\sim$2200 ch.



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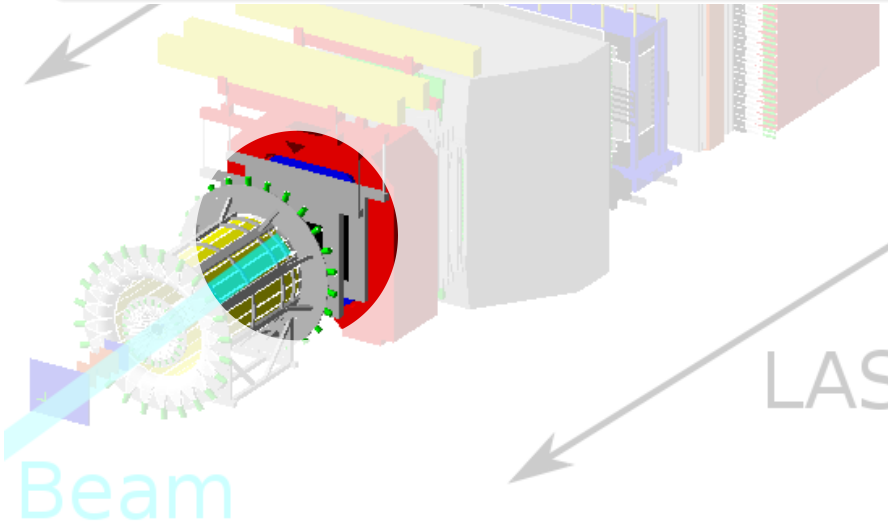

Upgrades for the DVCS Program

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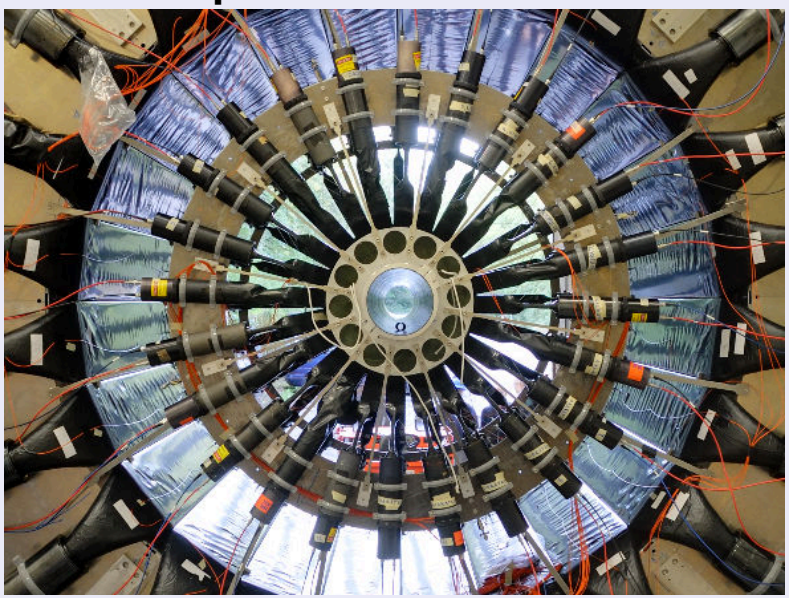
Target ToF System

24 inner & outer scintillators

1 GHz SADC readout

Goal: **310 ps** ToF resolution



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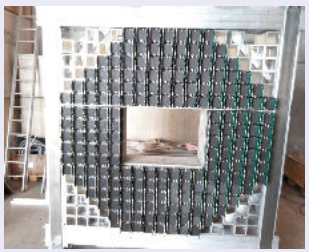
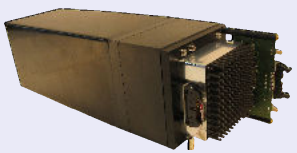
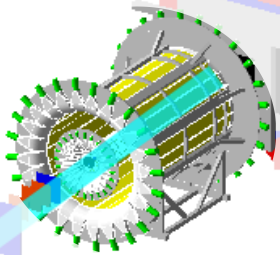
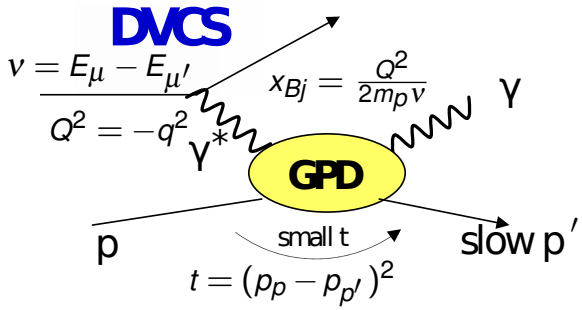
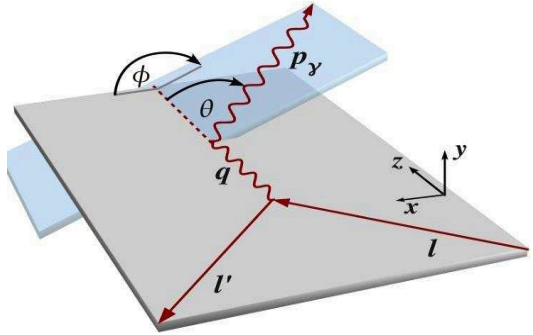
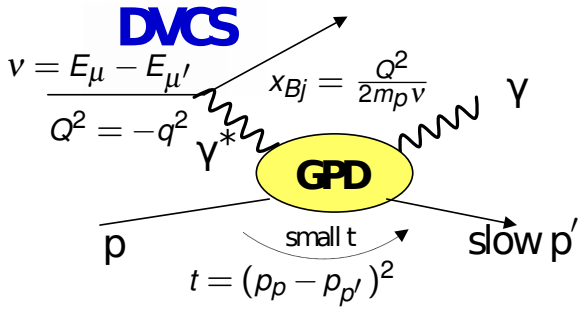


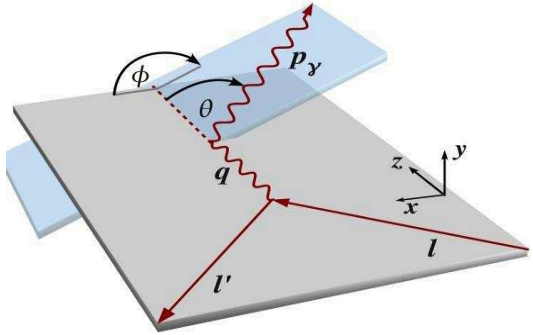





DVCS
$\nu = E_\mu - E_{\mu'}$
$x_{Bj} = \frac{Q^2}{2m_p\nu}$
$Q^2 = -q^2$
γ^*
GPD
γ
p
small t
slow p′
$t = (p_p - p_{p'})^2$

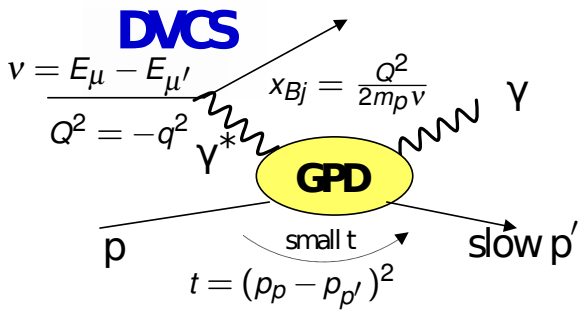

ϕ
θ
p_γ
q
z
y
x
l
l'

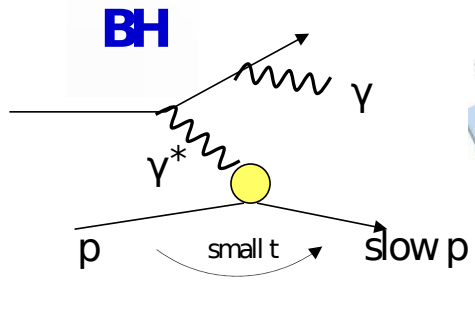


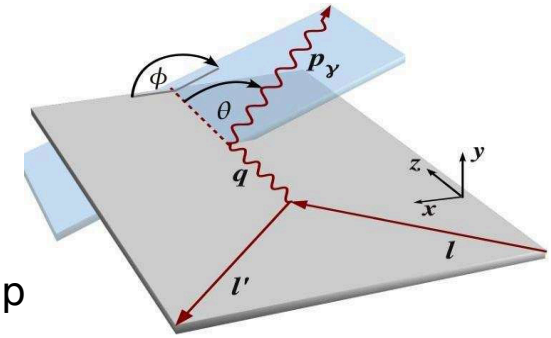


$$d\sigma \propto \underbrace{|T_{DVCS}|^2}$$

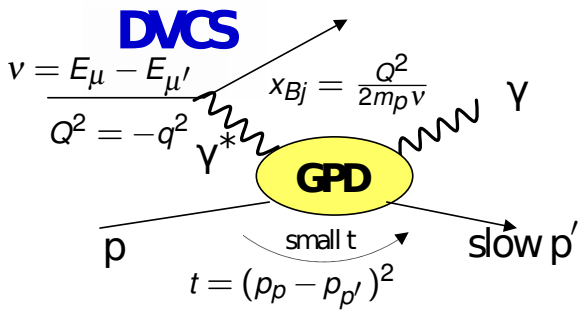
bilinear combination of GPDs

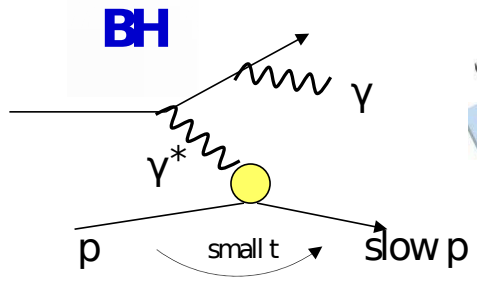


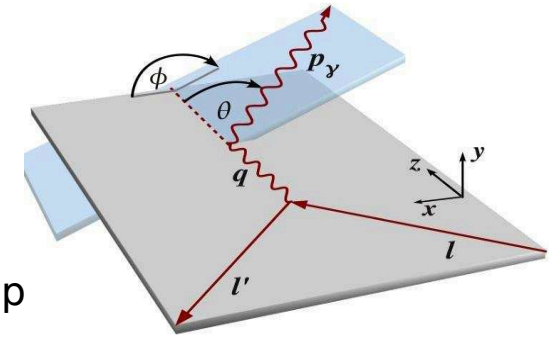




$$d\sigma \propto \underbrace{|T_{DVCS}|^2}_{\text{bilinear combination of GPDs}} + \underbrace{|T_{BH}|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$$







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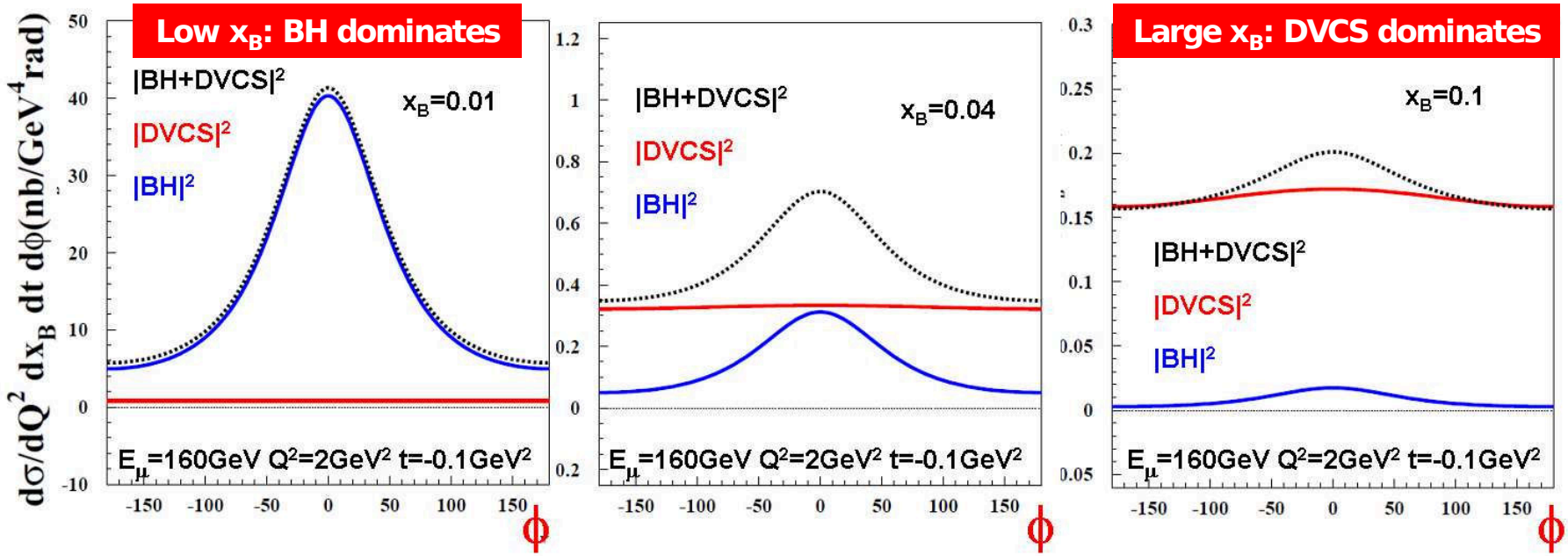

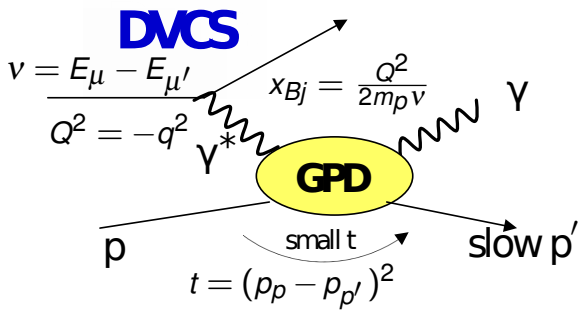

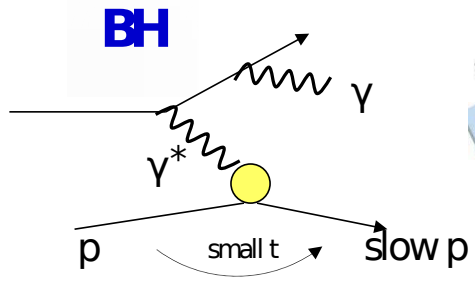

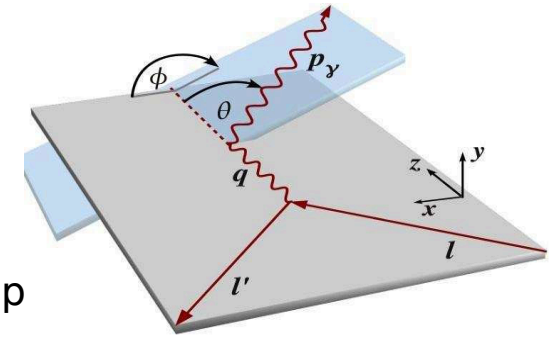

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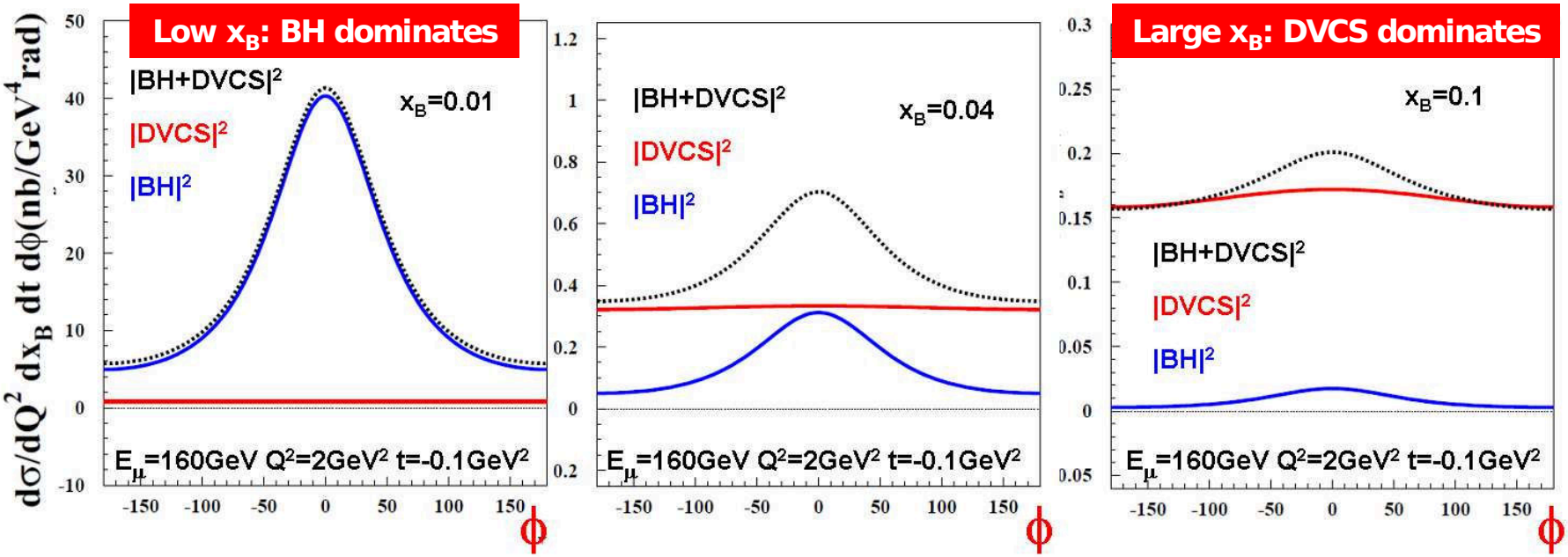
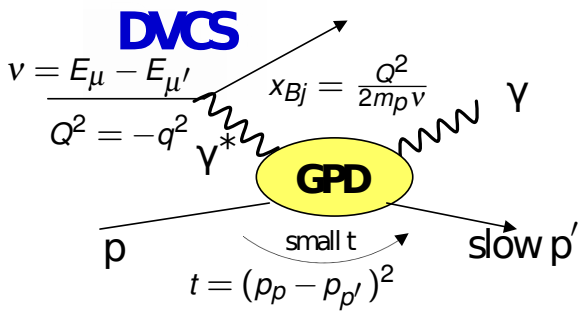
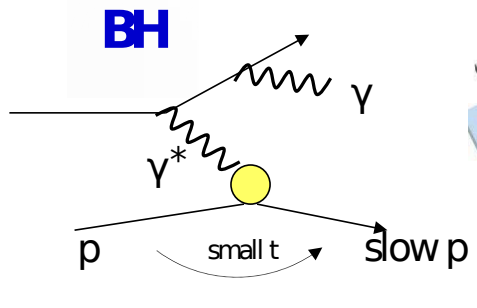
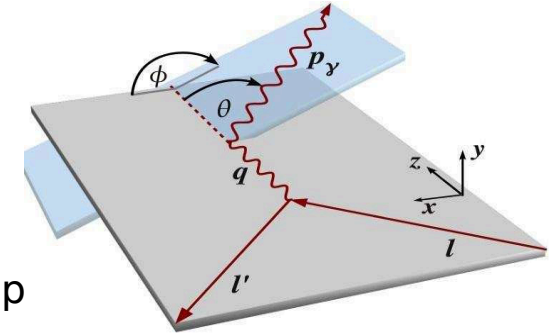


reference yield of almost pure Bethe-Heitler







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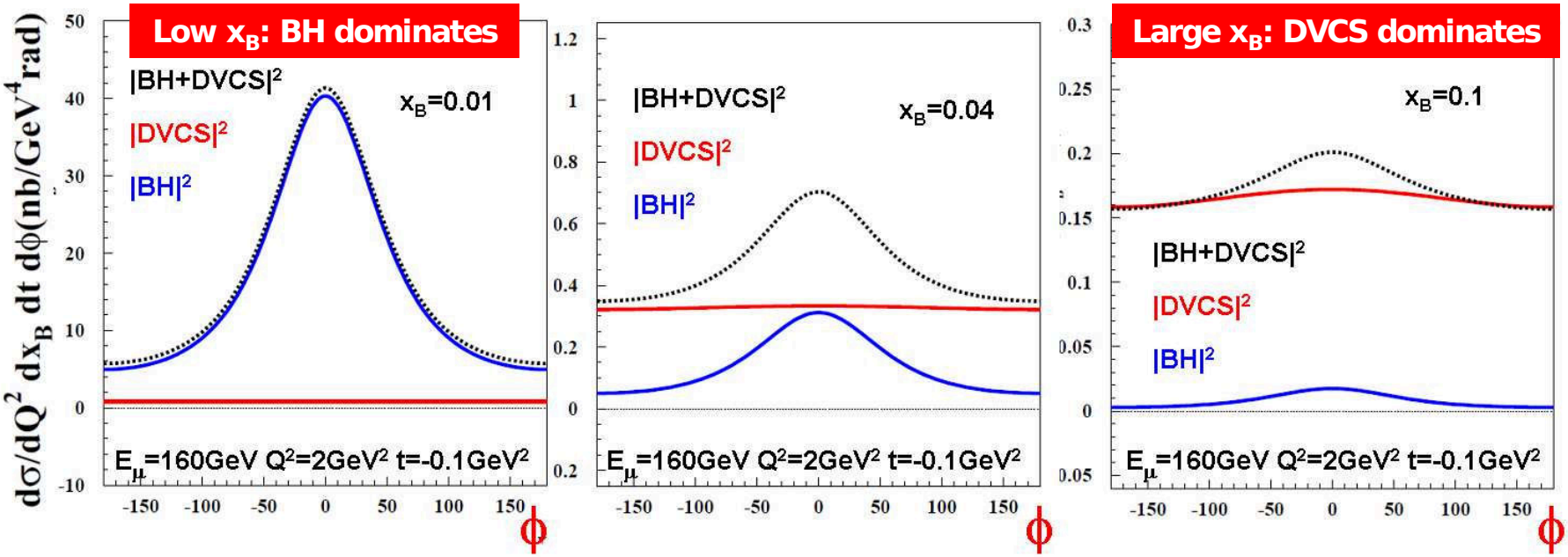
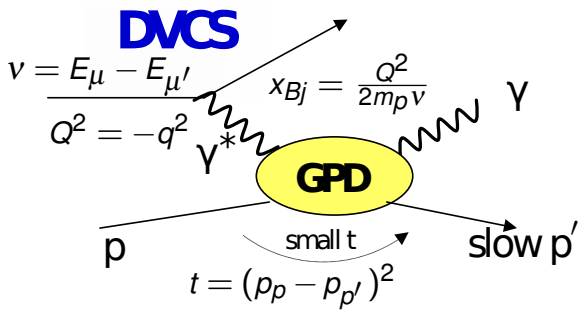
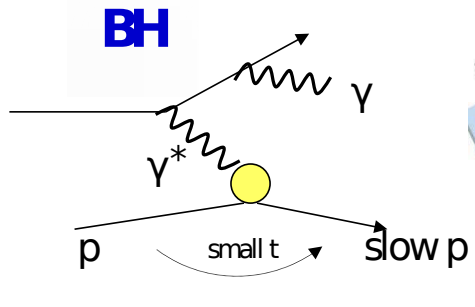
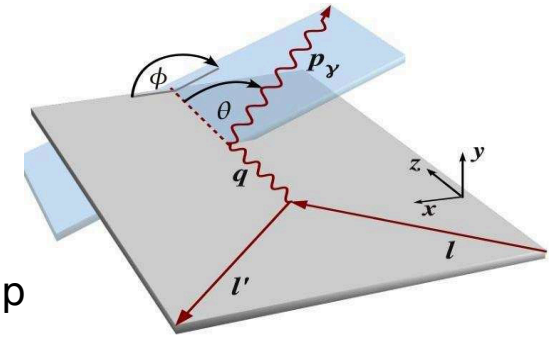


reference yield of almost pure Bethe-Heitler

Study DVCS with:
Re(T^{DVCS}) & Im(T^{DVCS})
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$







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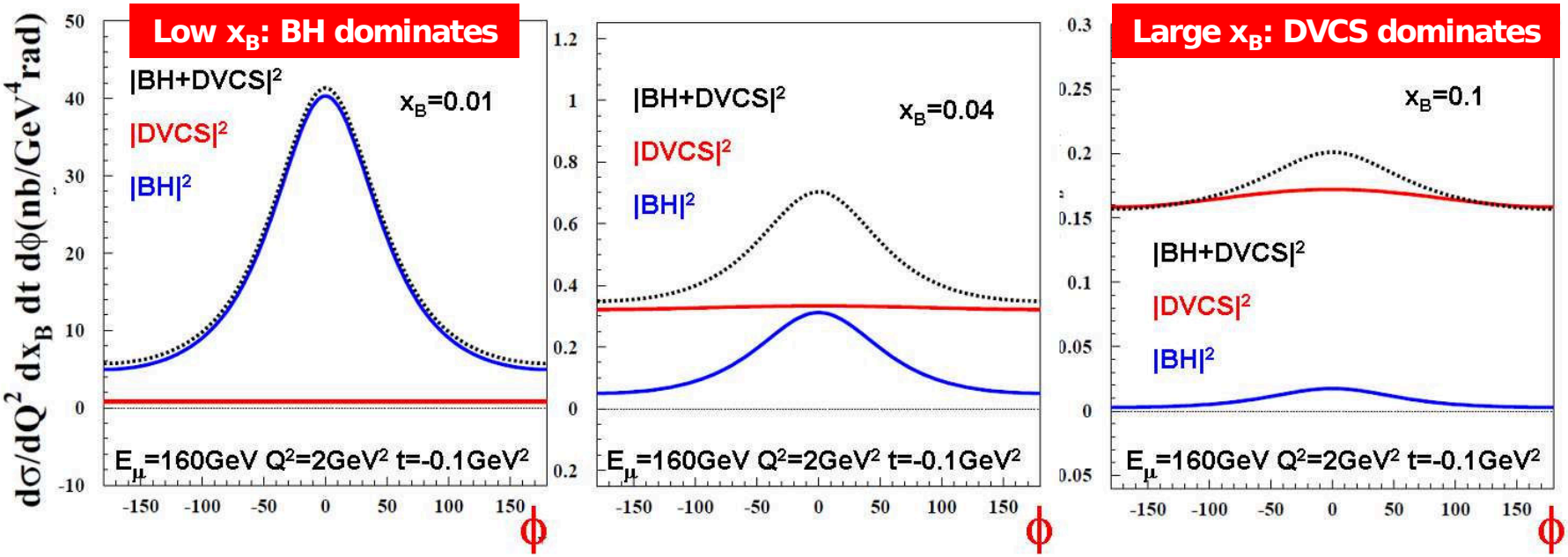


reference yield of almost pure Bethe-Heitler

Study DVCS with:
Re(T^{DVCS}) & Im(T^{DVCS})
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$

Transverse Imaging:
$d\sigma^{DVCS}/dt$
via $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$

Transverse Nucleon Imaging at $x_{Bj} > 0.03$

- Measure $S_{CS,U} = (d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$

$$S_{CS,U} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \,\mathrm{Im}\, I$$

note:

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS} \cos\phi_{\gamma^*\gamma} + c_2^{DVCS} \cos 2\phi_{\gamma^*\gamma}$$

$$\mathrm{Im}\, I \propto s_1^I \sin\phi_{\gamma^*\gamma} + s_2^I \sin 2\phi_{\gamma^*\gamma}$$

Transverse Nucleon Imaging at $x_{Bj} > 0.03$

- Measure $S_{CS,U} = (d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Subtract Bethe-Heitler (BH)

$$S_{CS,U} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I$$

$$S_{CS,U} \propto d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I$$

note:

$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + c_1^{DVCS} \cos\phi_{\gamma^*\gamma} + c_2^{DVCS} \cos 2\phi_{\gamma^*\gamma}$$

$$\mathrm{Im}\, I \propto s_1^I \sin\phi_{\gamma^*\gamma} + s_2^I \sin 2\phi_{\gamma^*\gamma}$$

Transverse Nucleon Imaging at $x_{Bj} > 0.03$

- Measure $S_{CS,U} = (d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Subtract Bethe-Heitler (BH)
- Integrate over $\phi_{\gamma^*\gamma}$

$$S_{CS,U} \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I$$

$$S_{CS,U} \propto d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I$$

$$S_{CS,U} \propto c_0^{DVCS}$$

$\Rightarrow$ PURE DVCS CONTRIBUTION

note:

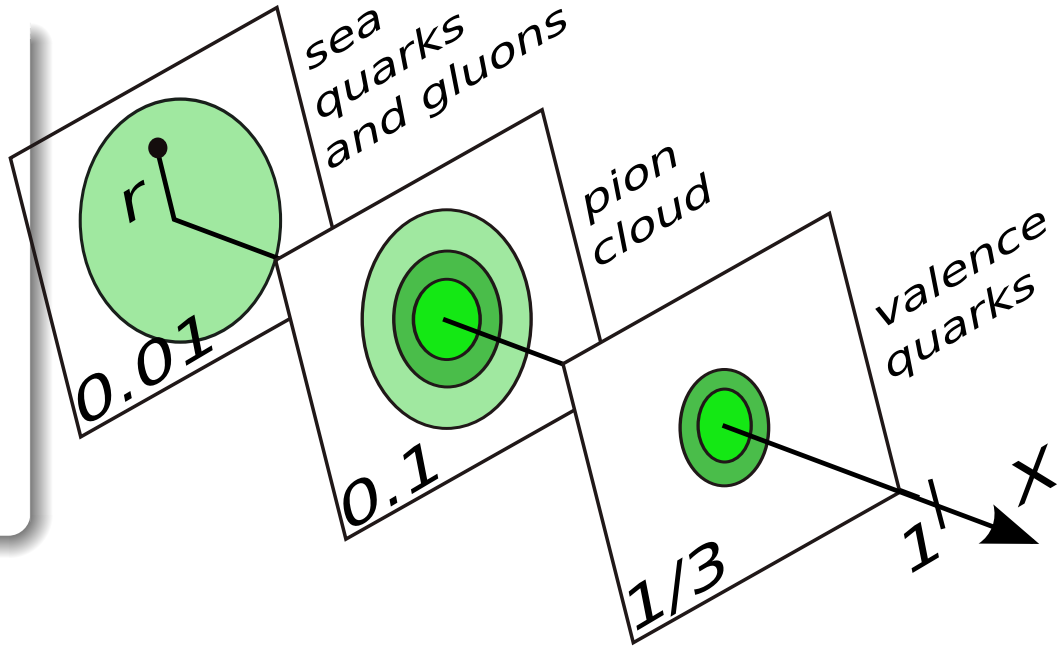
$$d\sigma^{DVCS}_{unpol} \propto c_0^{DVCS} + \cancel{c_1^{DVCS} \cos\phi_{\gamma^*\gamma} + c_2^{DVCS} \cos 2\phi_{\gamma^*\gamma}}$$

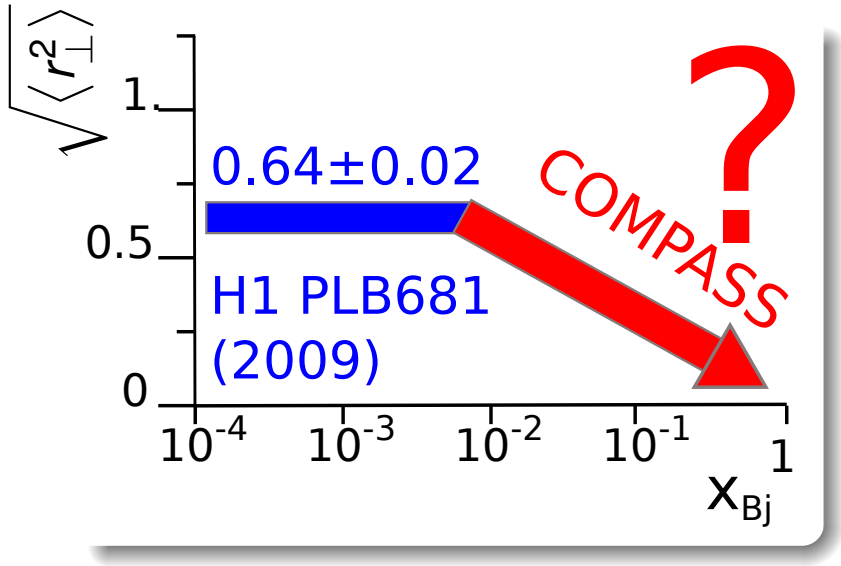
$$\cancel{\mathrm{Im}\, I \propto s_1^I \sin\phi_{\gamma^*\gamma} + s_2^I \sin 2\phi_{\gamma^*\gamma}}$$

Transverse Nucleon Imaging at $x_{Bj} > 0.03$

- Measure $S_{CS,U} = (d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Subtract Bethe-Heitler (BH)
- Integrate over $\phi_{\gamma^*\gamma}$

$$\frac{d\sigma^{DVCS}}{d|t|} \propto e^{-B|t|}; \; < r_\perp^2 > \underset{\text{at small } x_{Bj}}{\sim} 2B(x_{Bj})$$





Transverse Nucleon Imaging at $x_{Bj} > 0.03$

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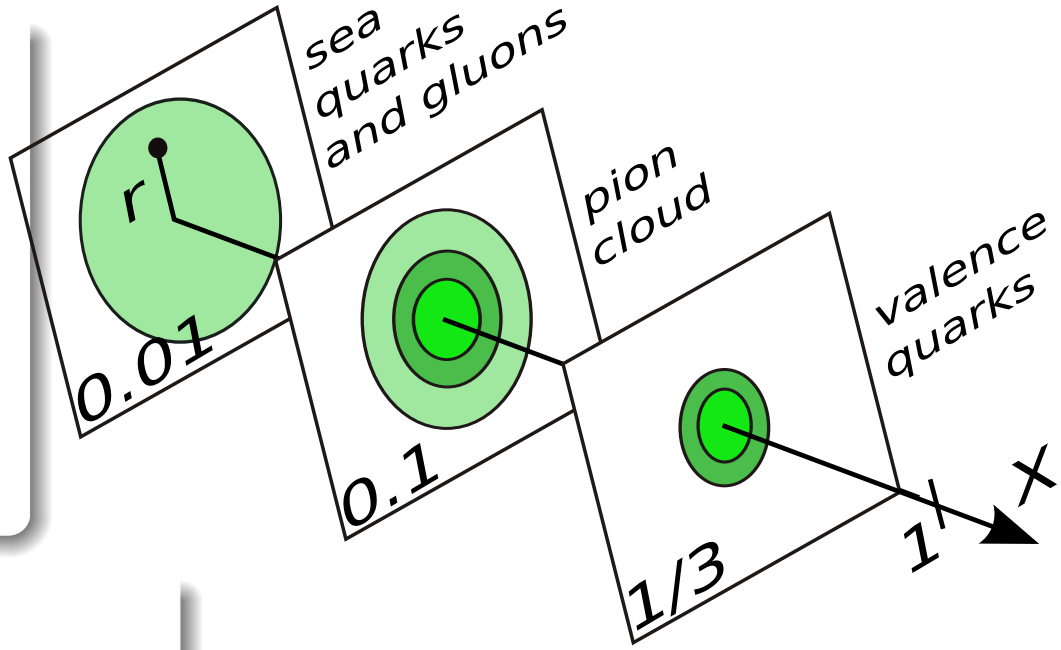
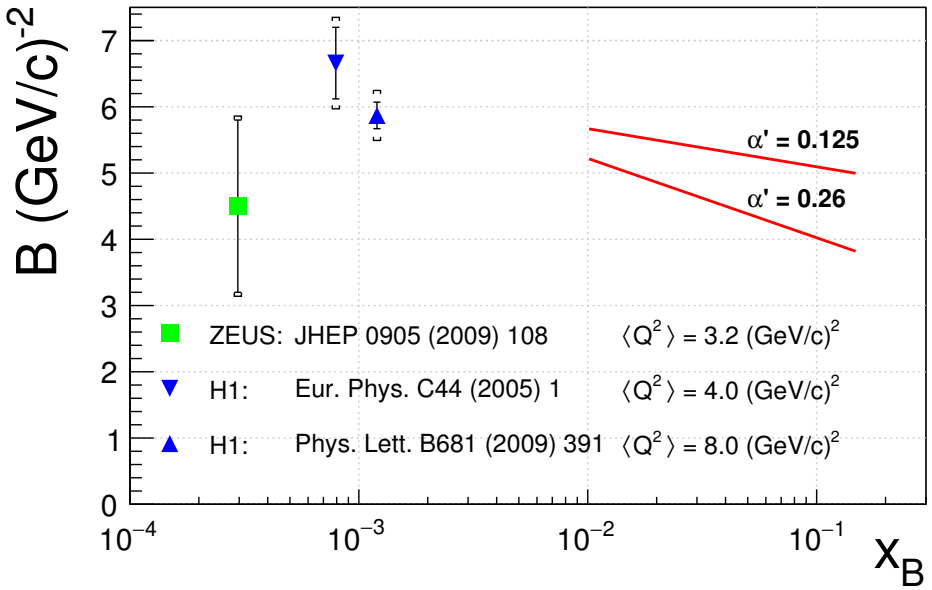
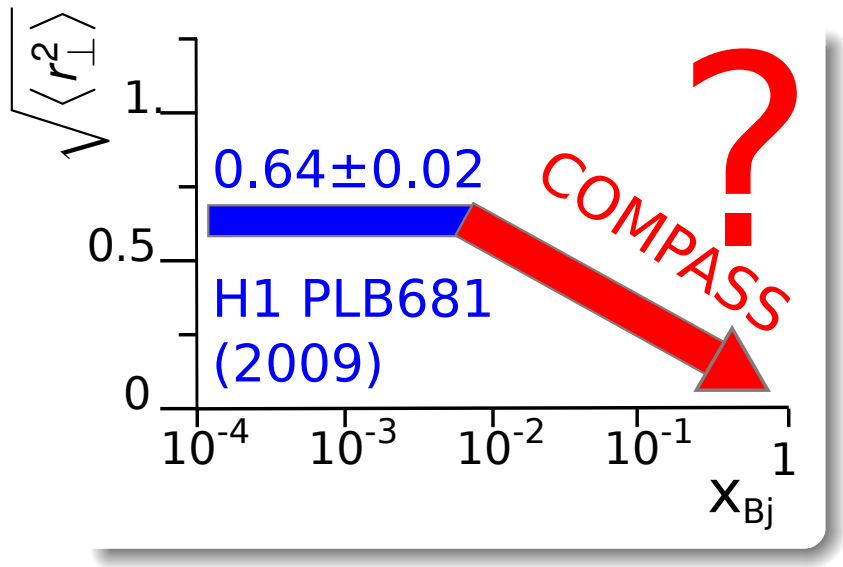
$$\frac{d\sigma^{DVCS}}{d|t|} \propto e^{-B|t|}; \; < r_\perp^2 > \sim 2B(x_{Bj})$$

at small x_{Bj}





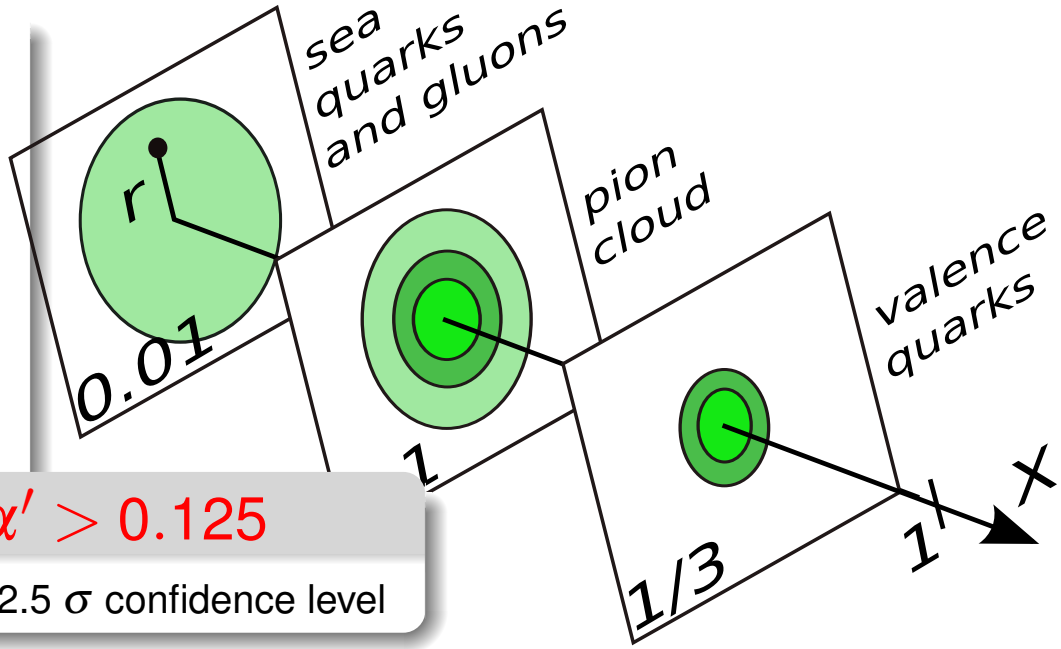


Transverse Nucleon Imaging at $x_{Bj} > 0.03$

- Measure $S_{CS,U} = (d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Subtract Bethe-Heitler (BH)
- Integrate over $\phi_{\gamma^*\gamma}$

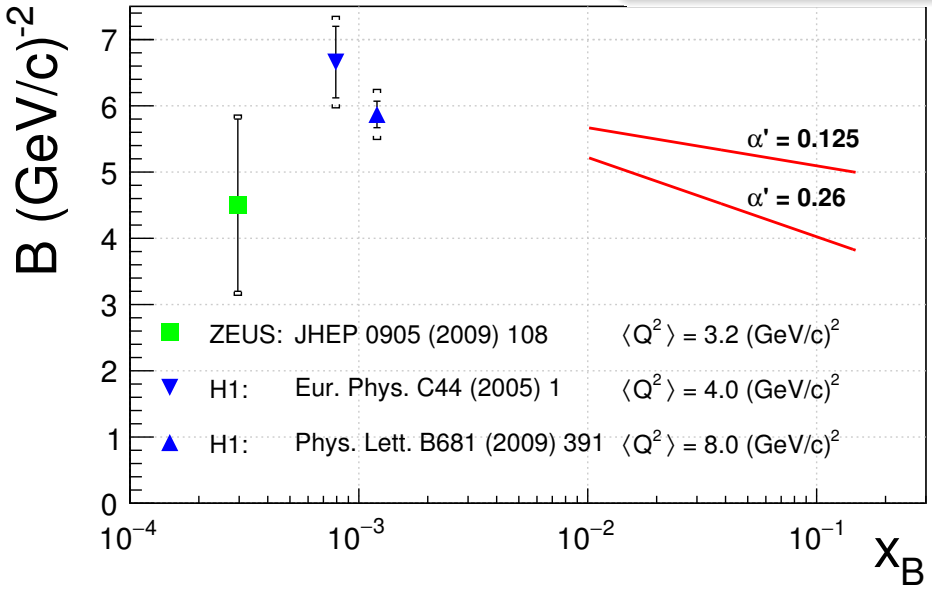
$$\frac{d\sigma^{DVCS}}{d|t|} \propto e^{-B|t|}; \; < r_\perp^2 > \sim 2B(x_{Bj})$$

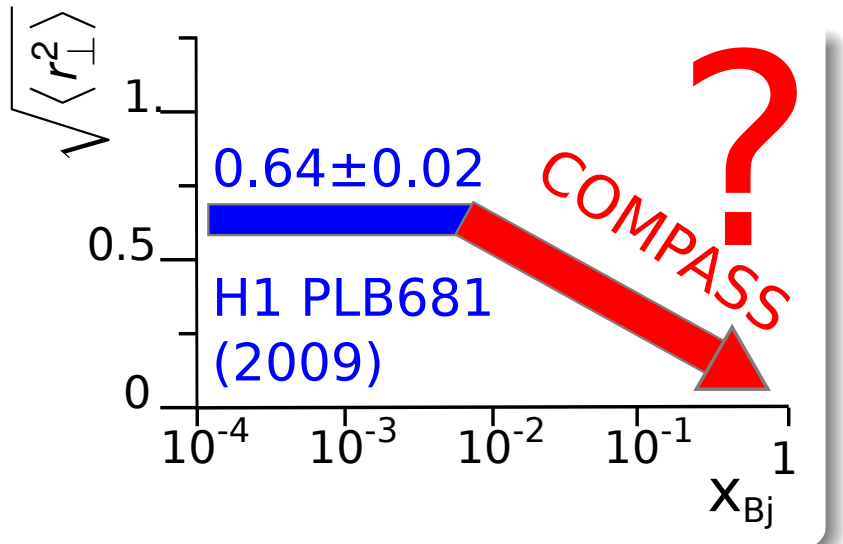
at small x_{Bj}

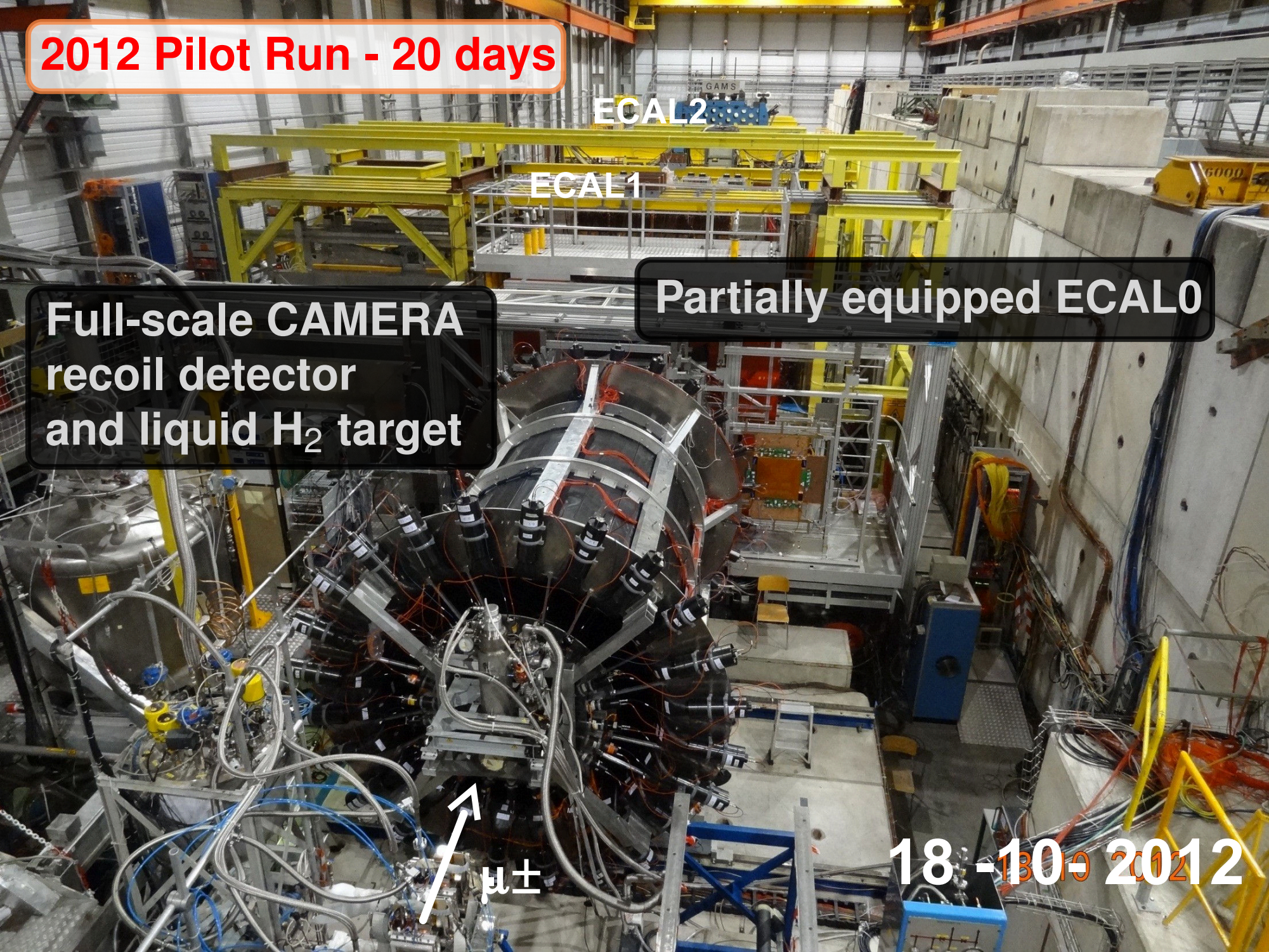


Measure $\alpha' > 0.125$

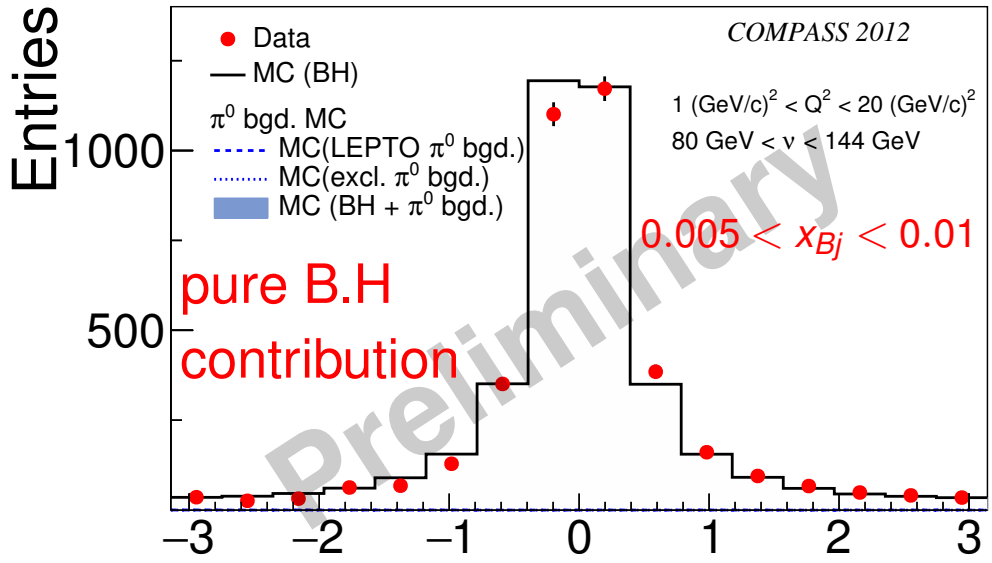
with more than 2.5 σ confidence level

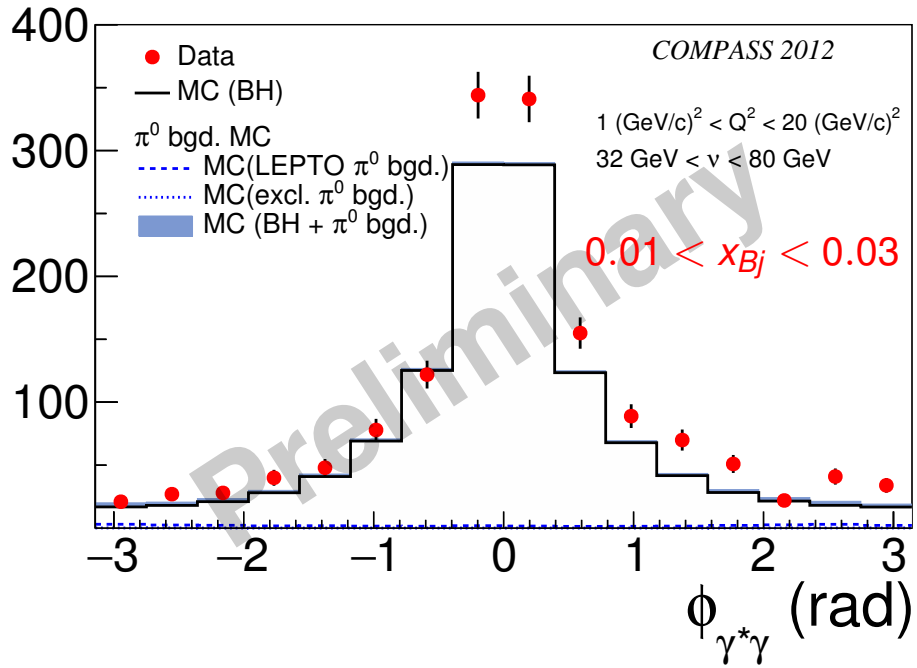


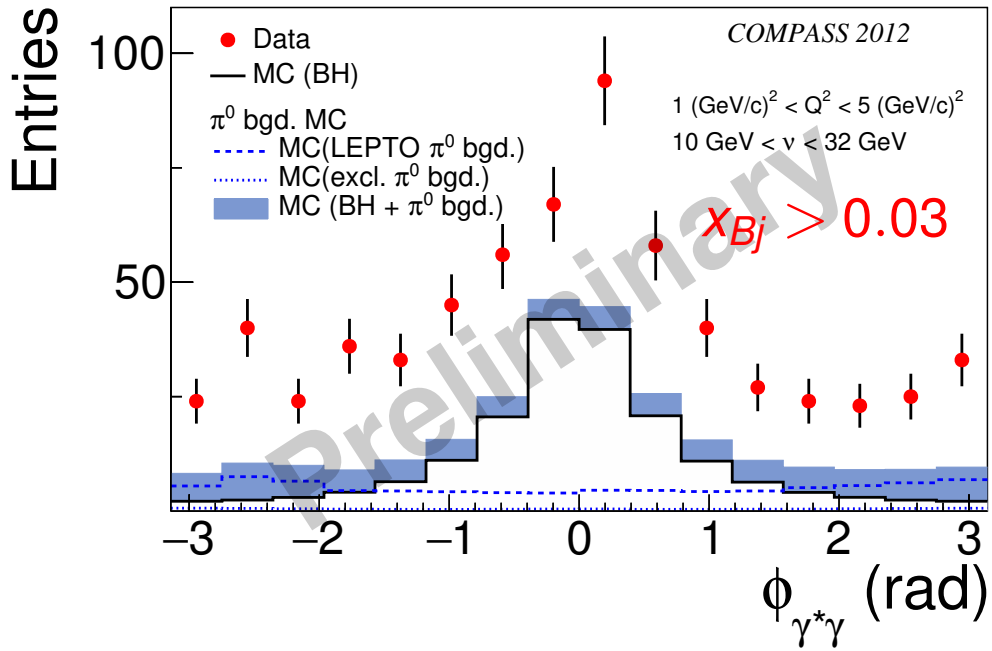


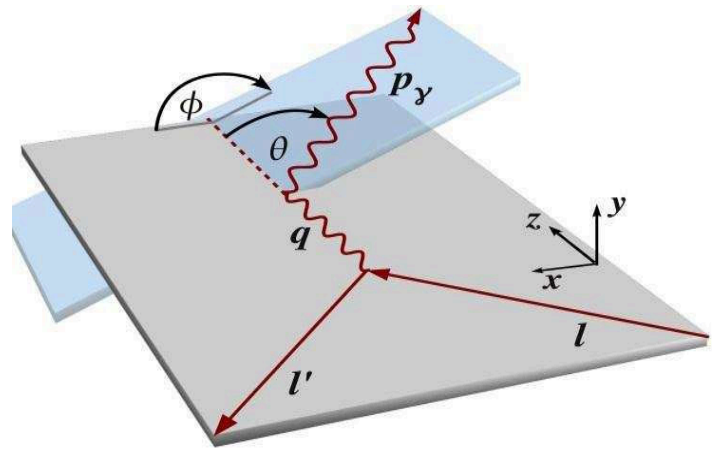

2012 Pilot Run - 20 days
ECAL2
ECAL1
Partially equipped ECAL0
Full-scale CAMERA
recoil detector
and liquid H_2 target
μ±
18 -10- 2012

Exclusive γ Azimuthal Distributions

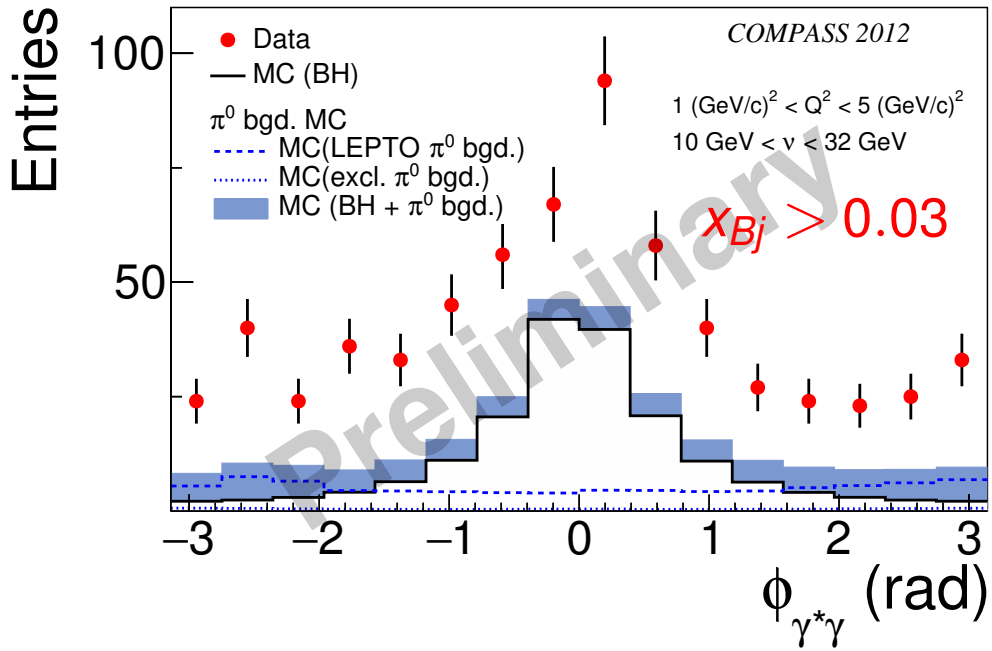






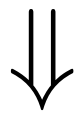


Exclusive γ Azimuthal Distributions



t-dependence of DVCS x-section

- Exclusive γ event selection
- π^0 bgd. estimation
- Kinematic fit
- Acceptance corrections
- Cross-section ($\gamma^* p \to \gamma p$)



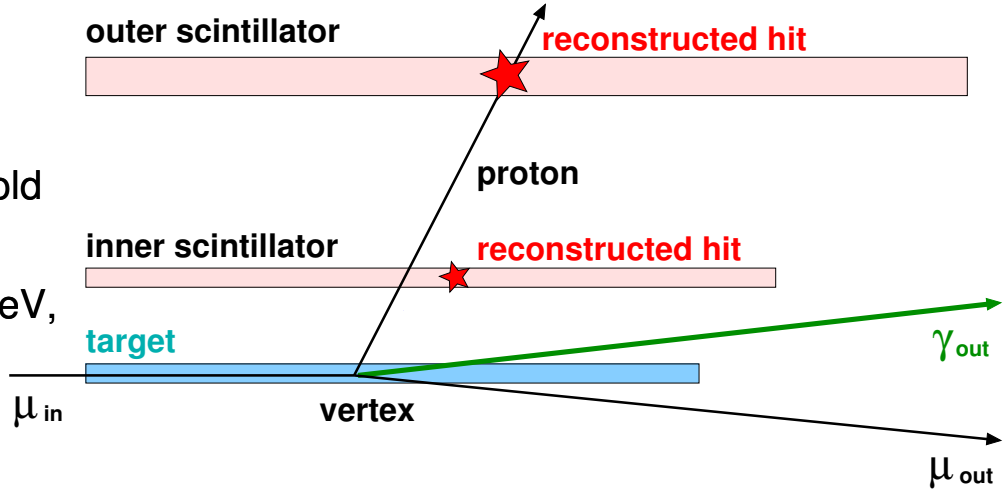
Exclusive Photon Events Selection

Reconstructed interaction vertex in **target volume**

One single photon above DVCS production threshold

$1\ (\mathrm{GeV/c})^2 < Q^2 < 5\ (\mathrm{GeV/c})^2$, $10\ \mathrm{GeV} < \nu < 32\ \mathrm{GeV}$,

$0.08\ (\mathrm{GeV/c})^2 < t < 0.64\ (\mathrm{GeV/c})^2$



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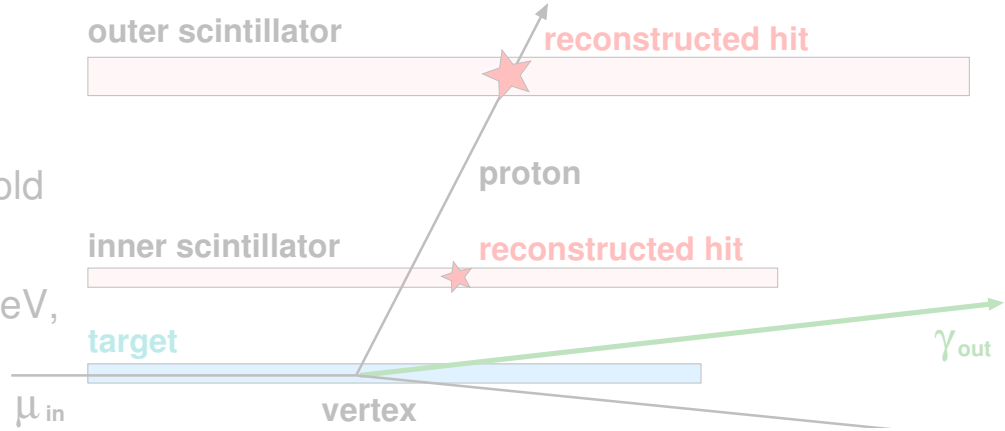
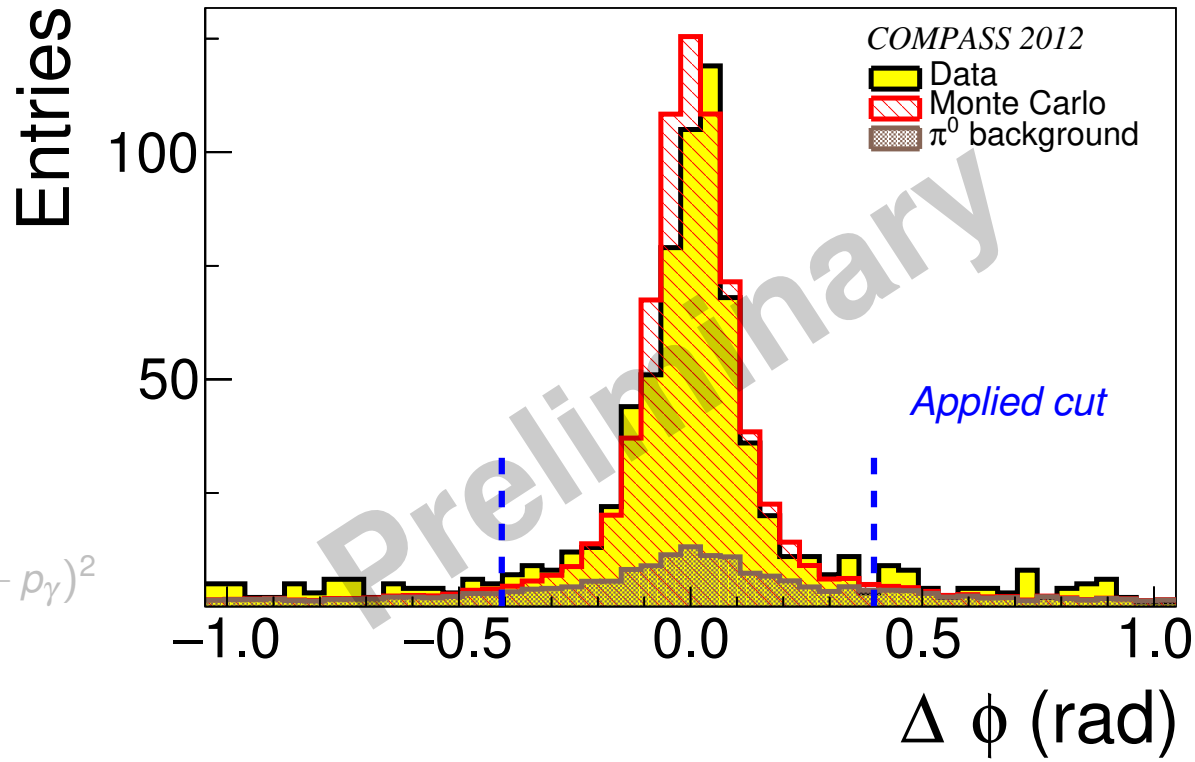


Exclusivity conditions:

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



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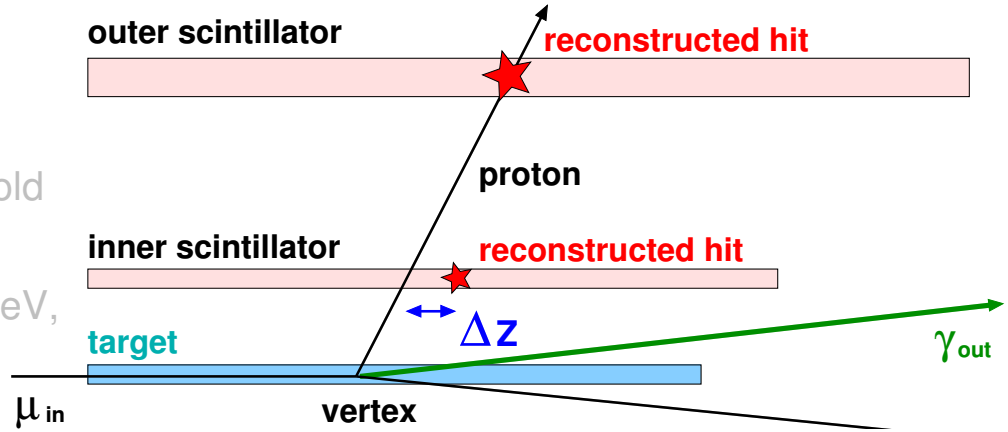

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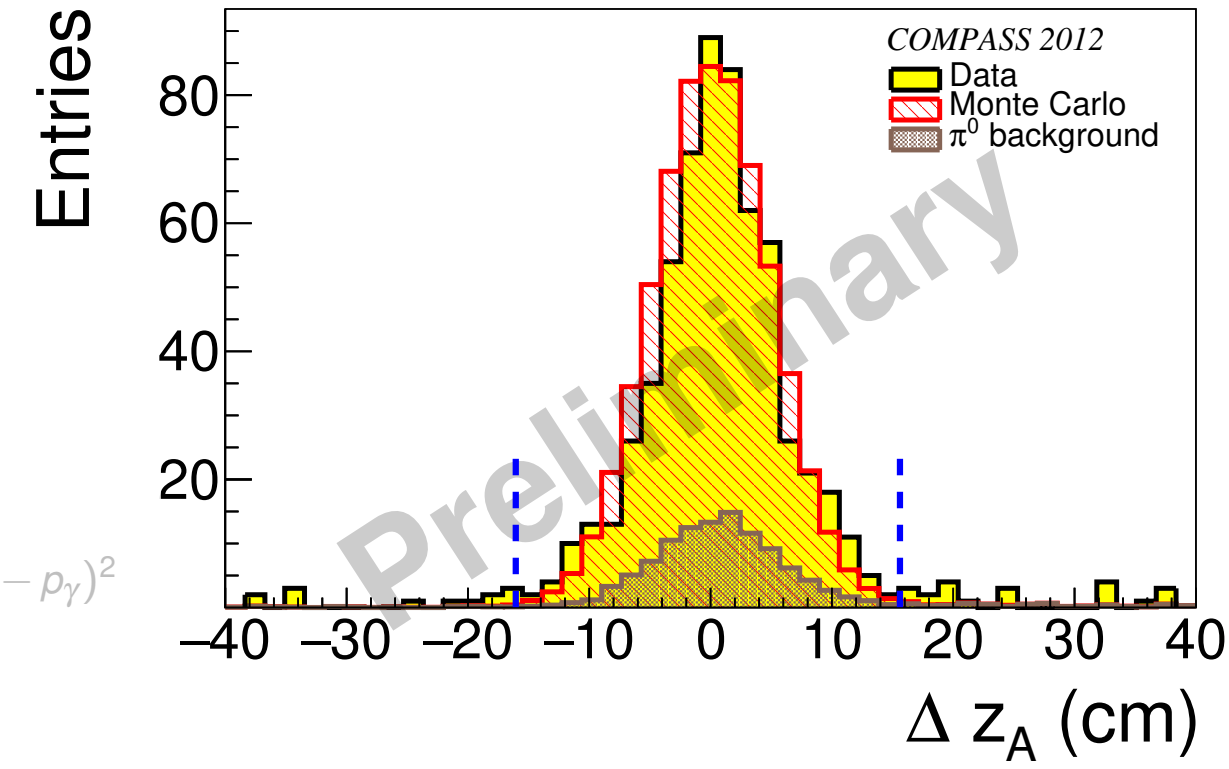

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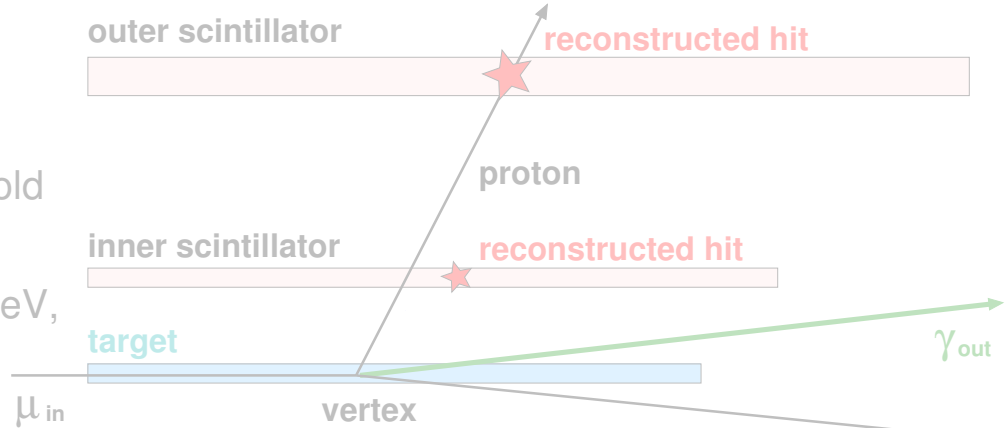

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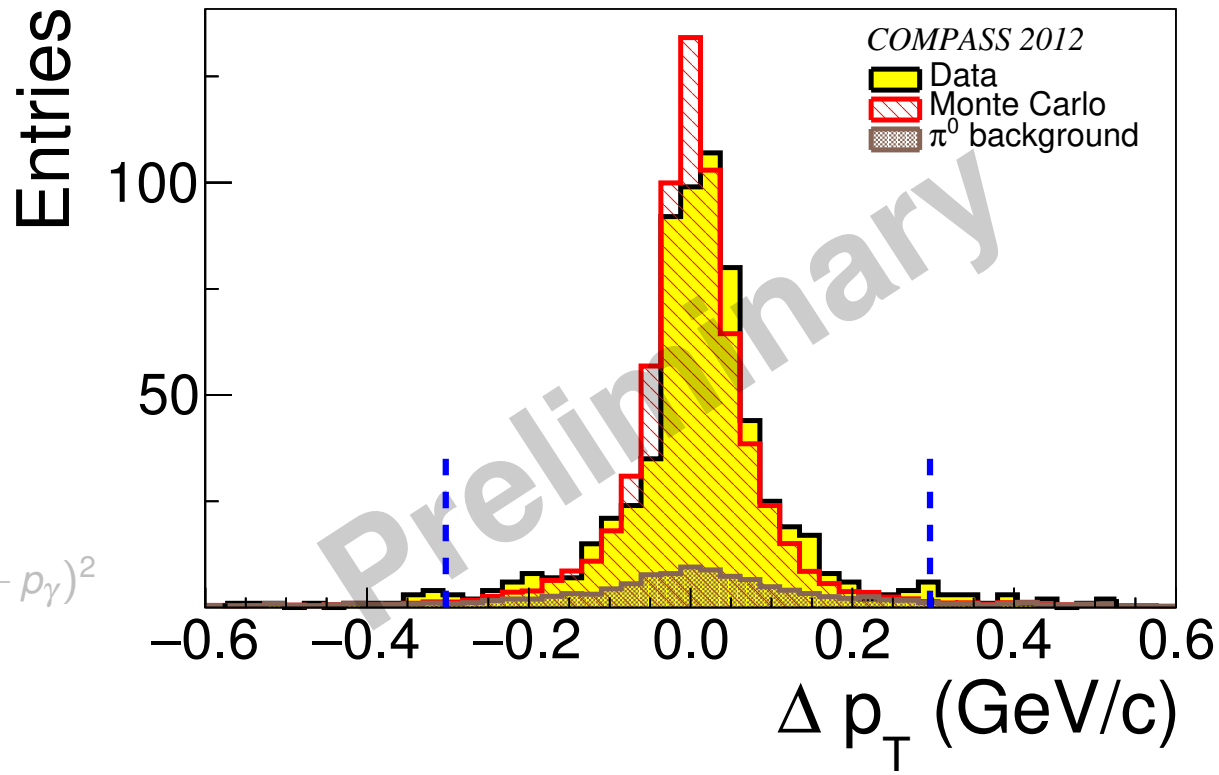

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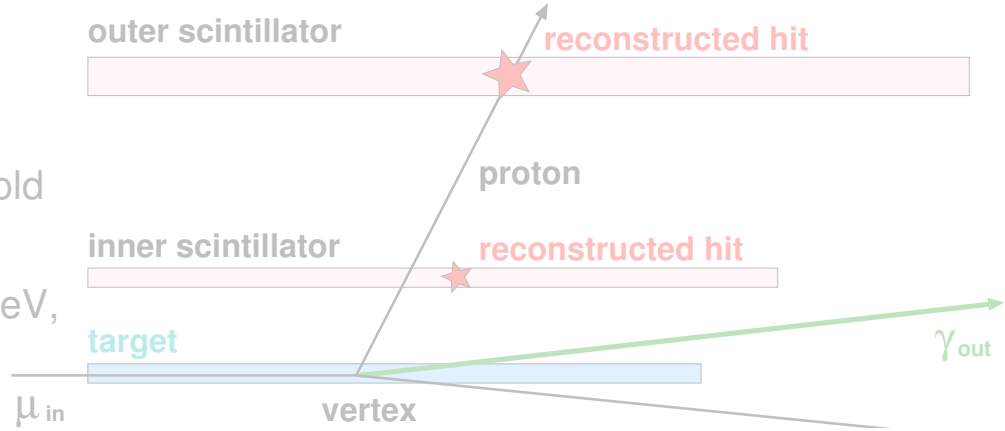

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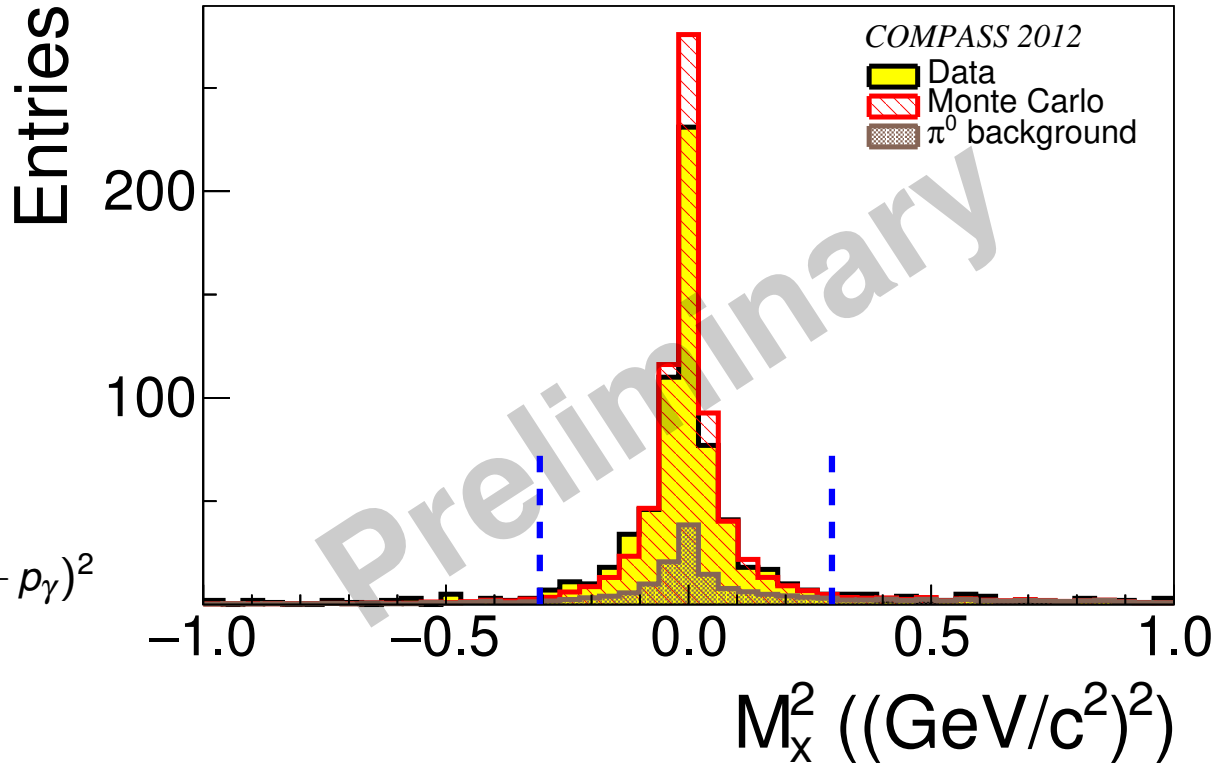
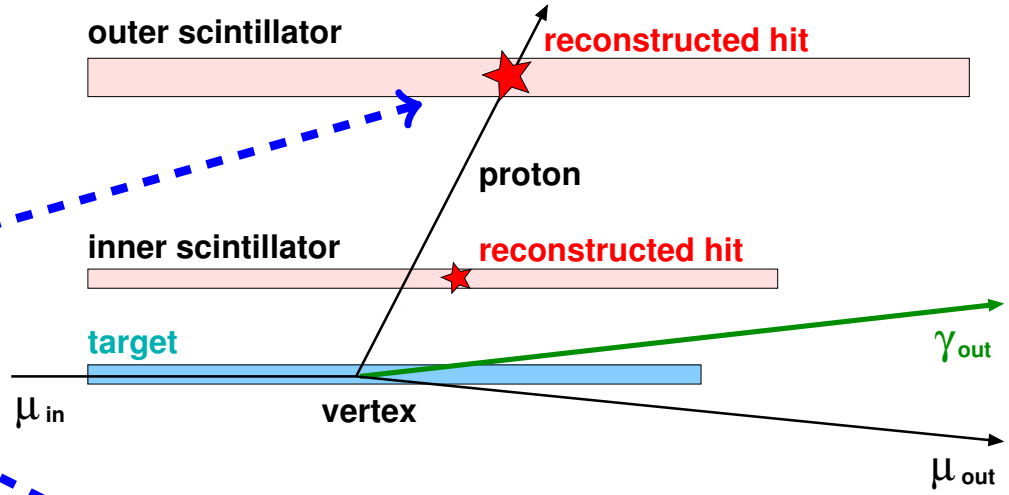


Exclusive Photon Events Selection

Signal amplitude in outer scintillators vs. β of recoiling particle

Proton signature clearly visible after all exclusivity conditions



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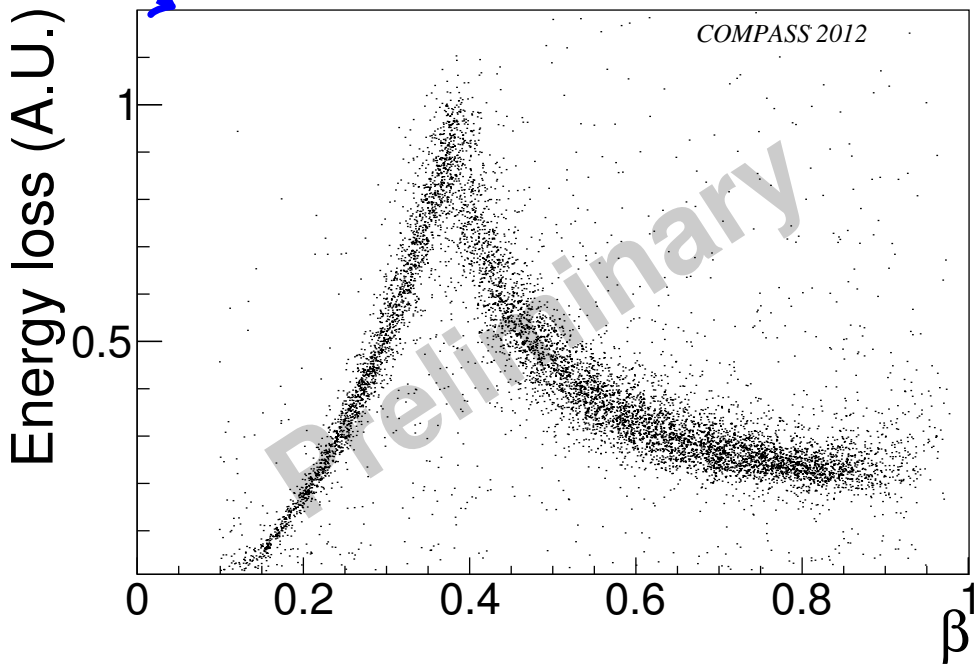
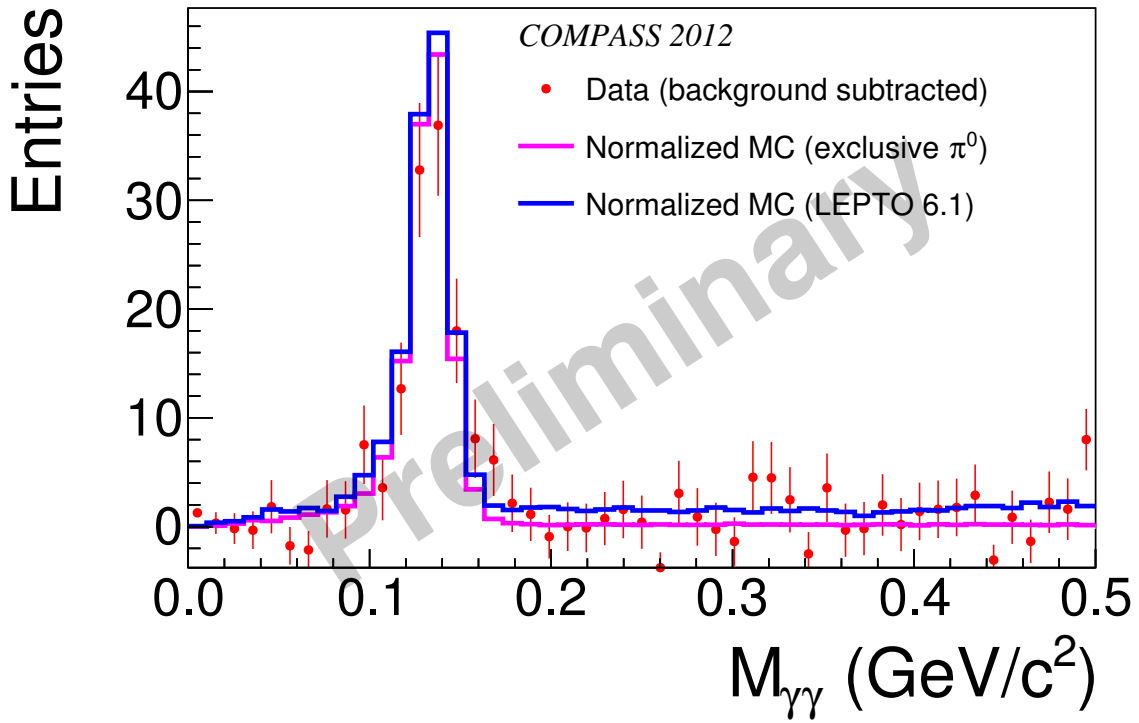


π^0 Background Estimation

Major background source for exclusive photon events

Two cases:

- **Visible** (both γ detected, easy to reject)
- **Invisible** (one γ "lost", estimated with MC)



$M_{\gamma\gamma}$ distribution ("Visible" π^0)

„Exclusive" γ (E_γ>4,5,10 GeV /Ecal0,1,2)
+ one γ below energy threshold

Semi inclusive LEPTO MC

or

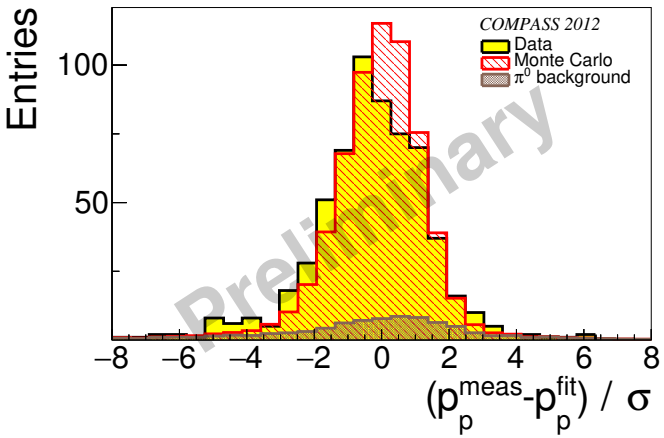
exclusive HEPGen++ MC (Golosgokov & Kroll model)

π^0 contribution normalized to $M_{\gamma\gamma}$ peak from real data

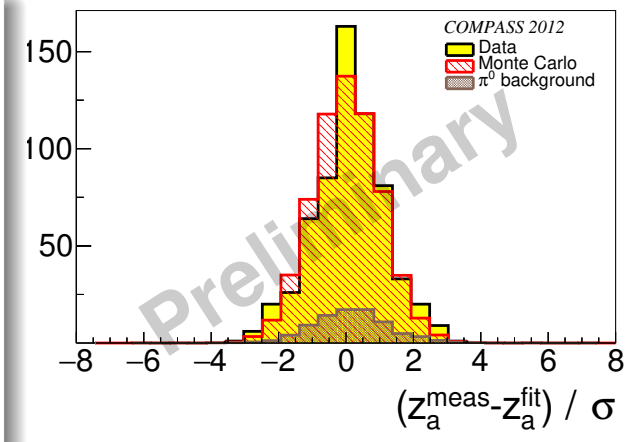
Kinematically constrained fit

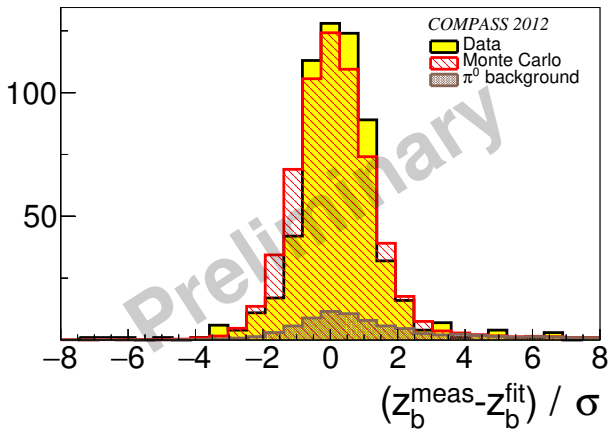
- constrained χ^2 minimisation with NDF=9
- full 4-momentum conservation of the reaction $\mu p \to \mu p \gamma$
- vertex constraints for μ,μ' and p' included in the fit

$\Rightarrow$ most accurate determination of t

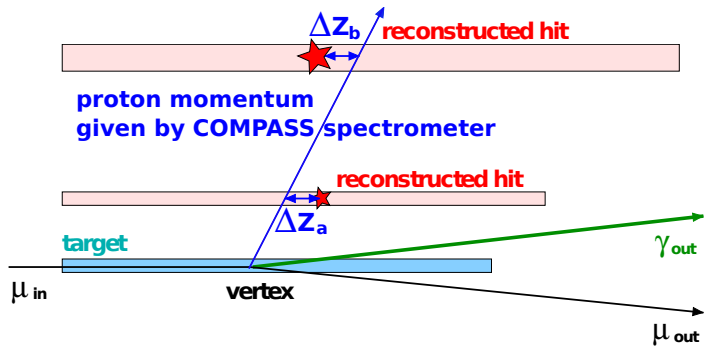


recoil proton momentum

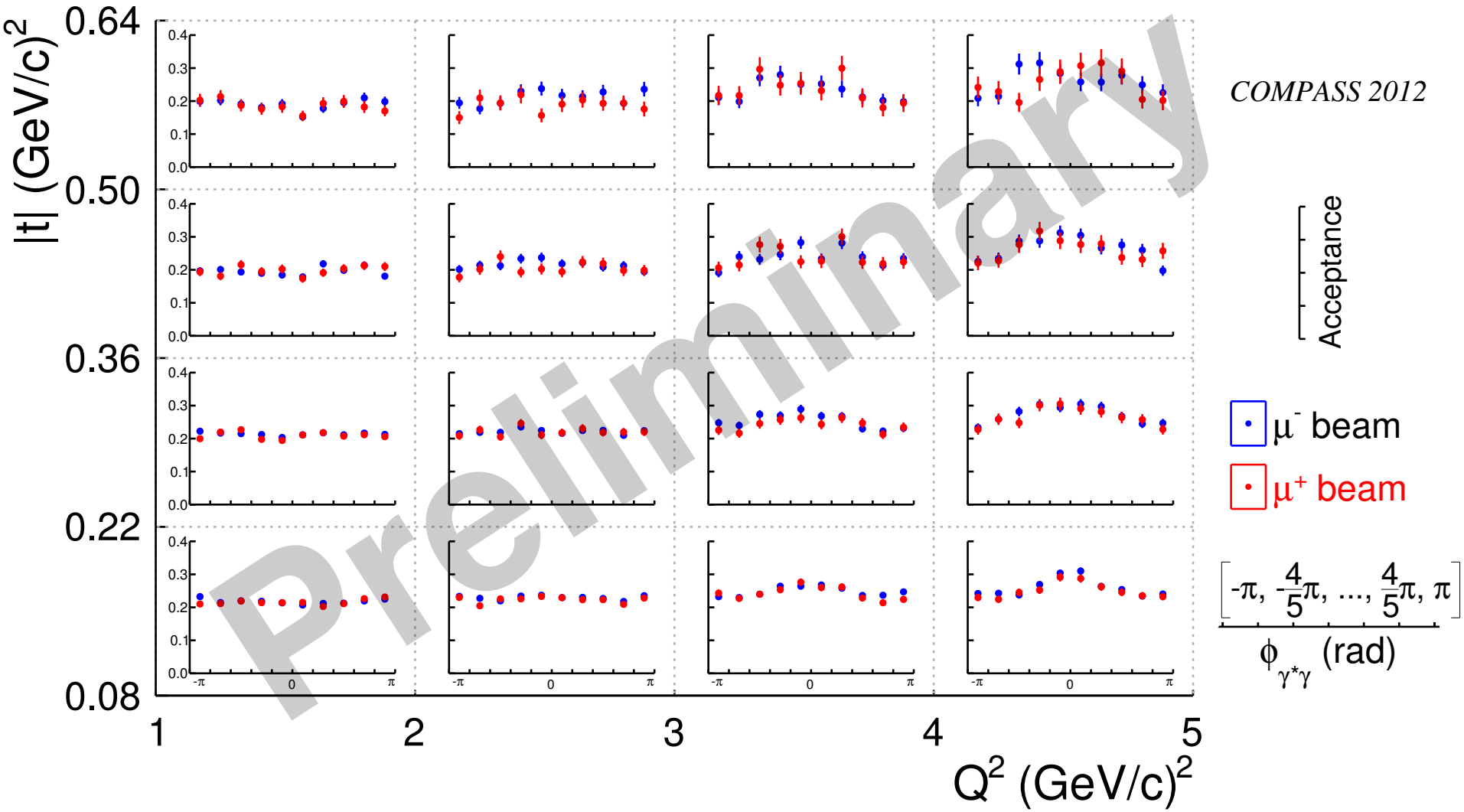




recoil proton direction



COMPASS acceptance for DVCS



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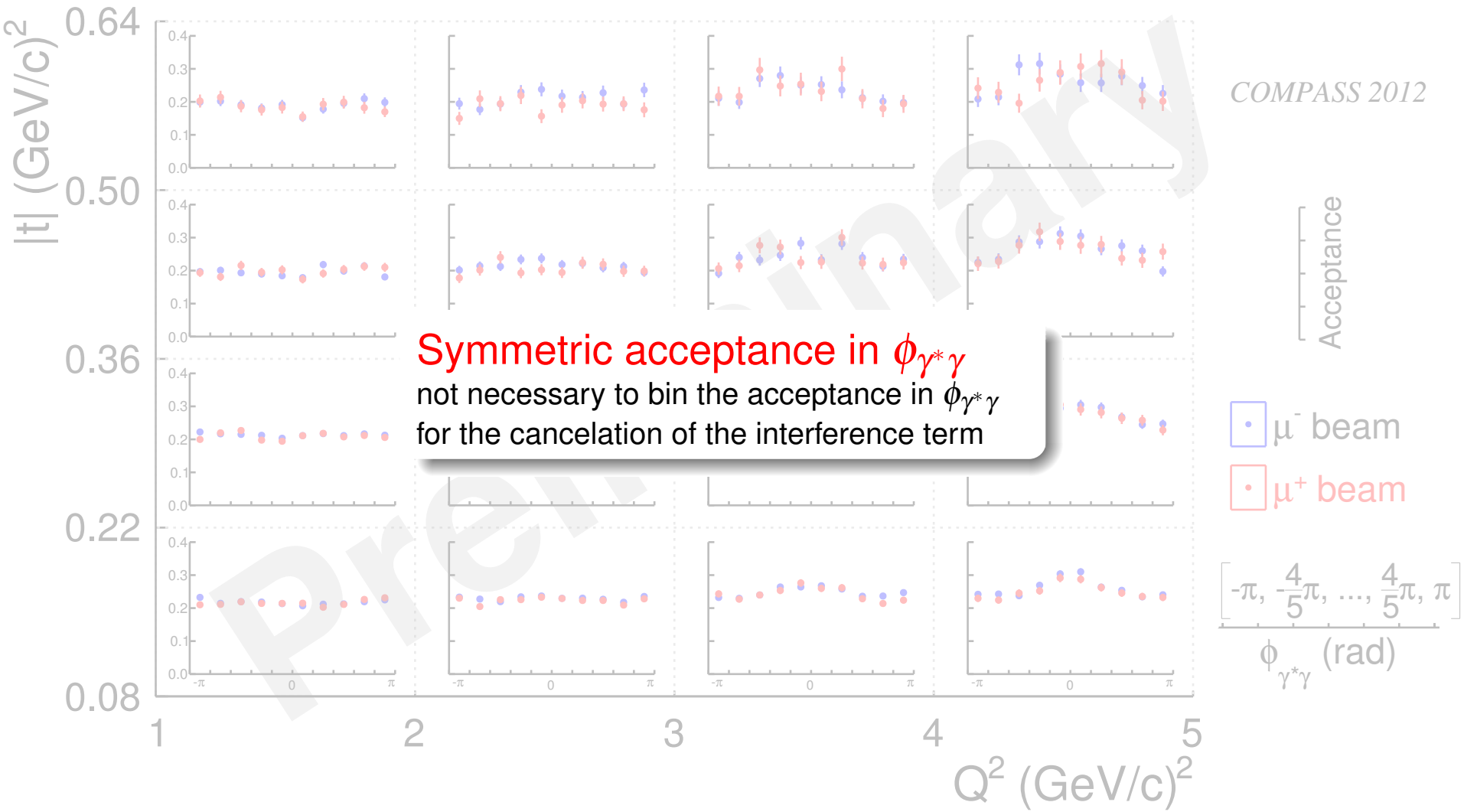

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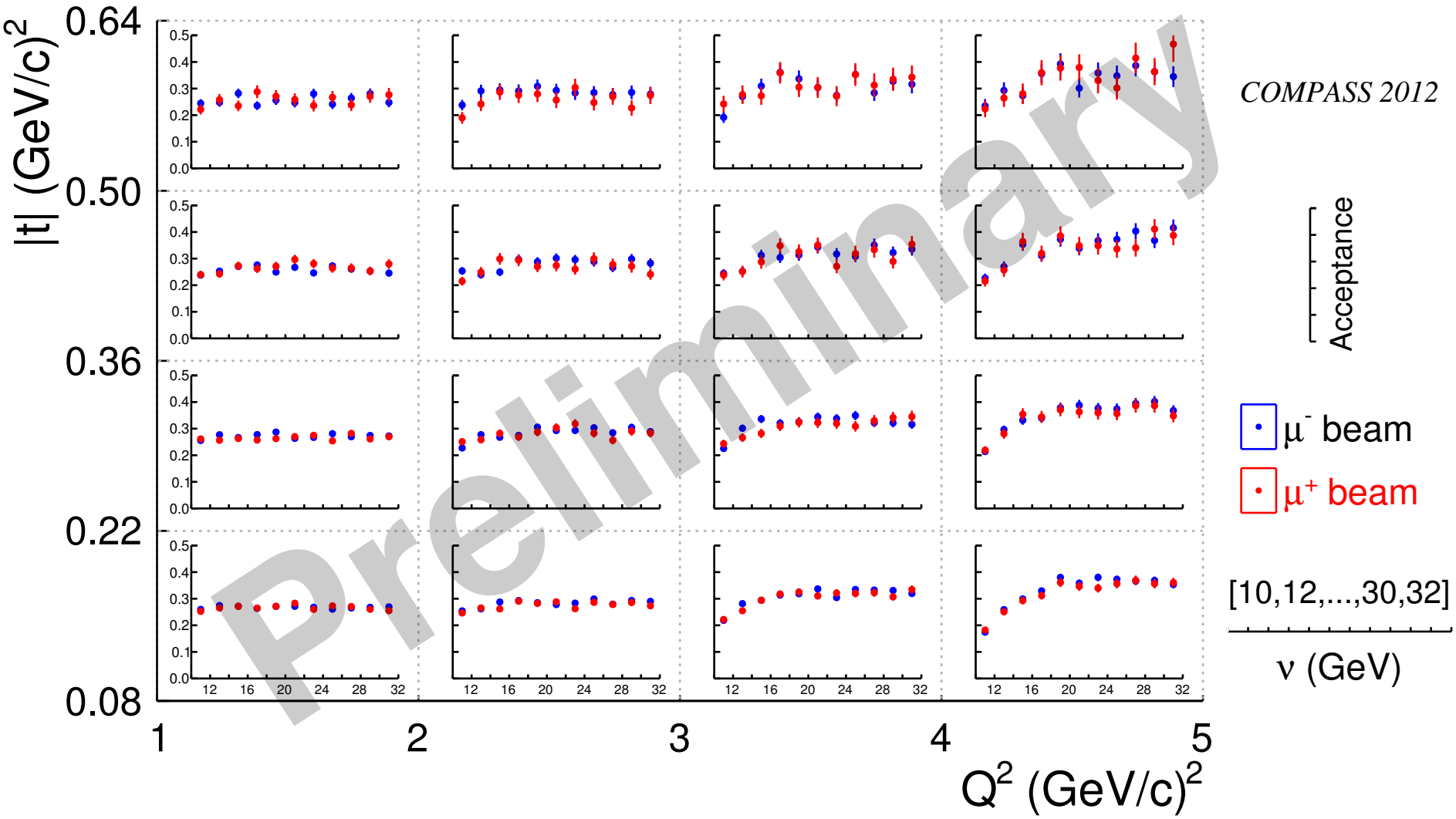

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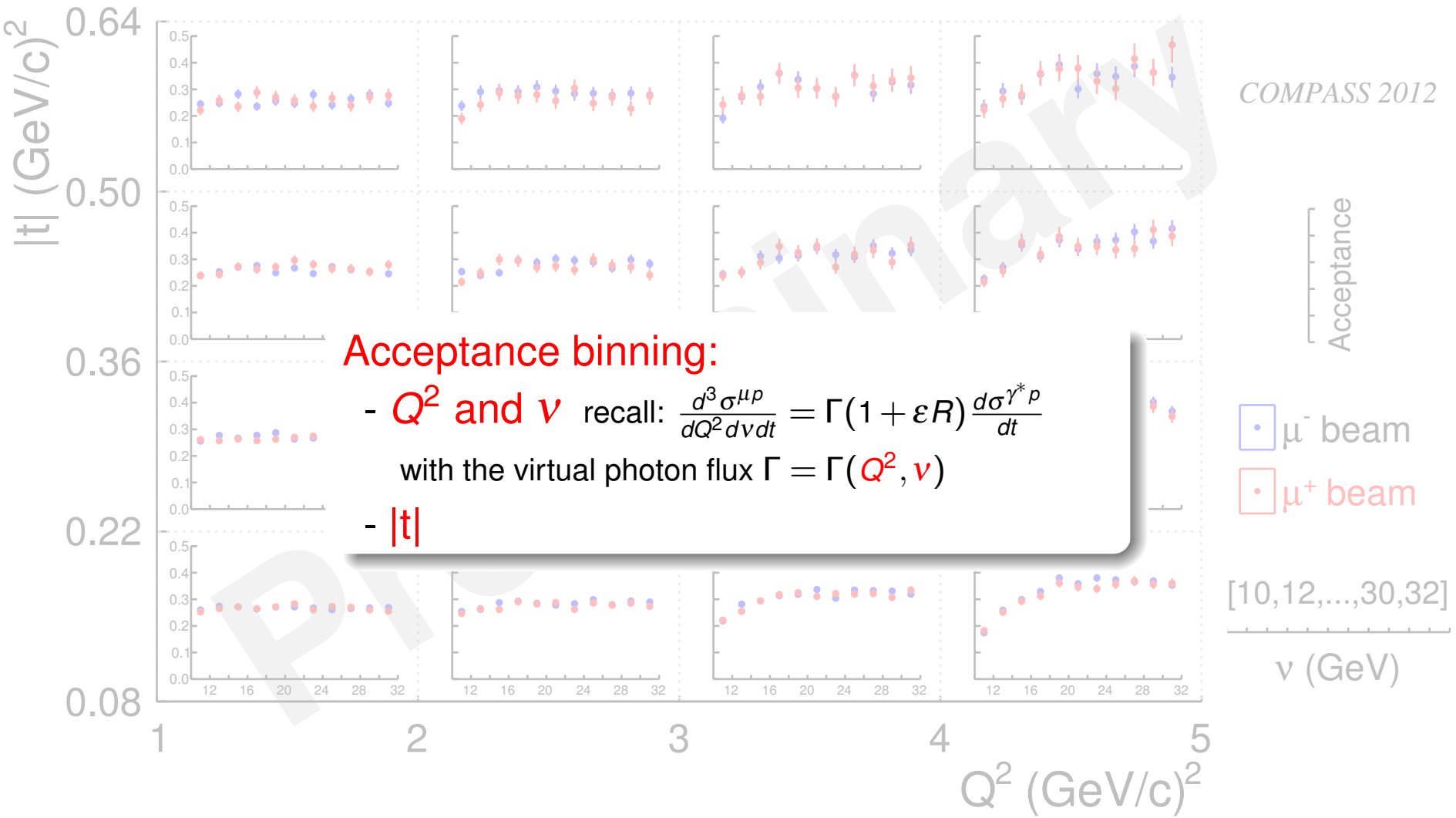
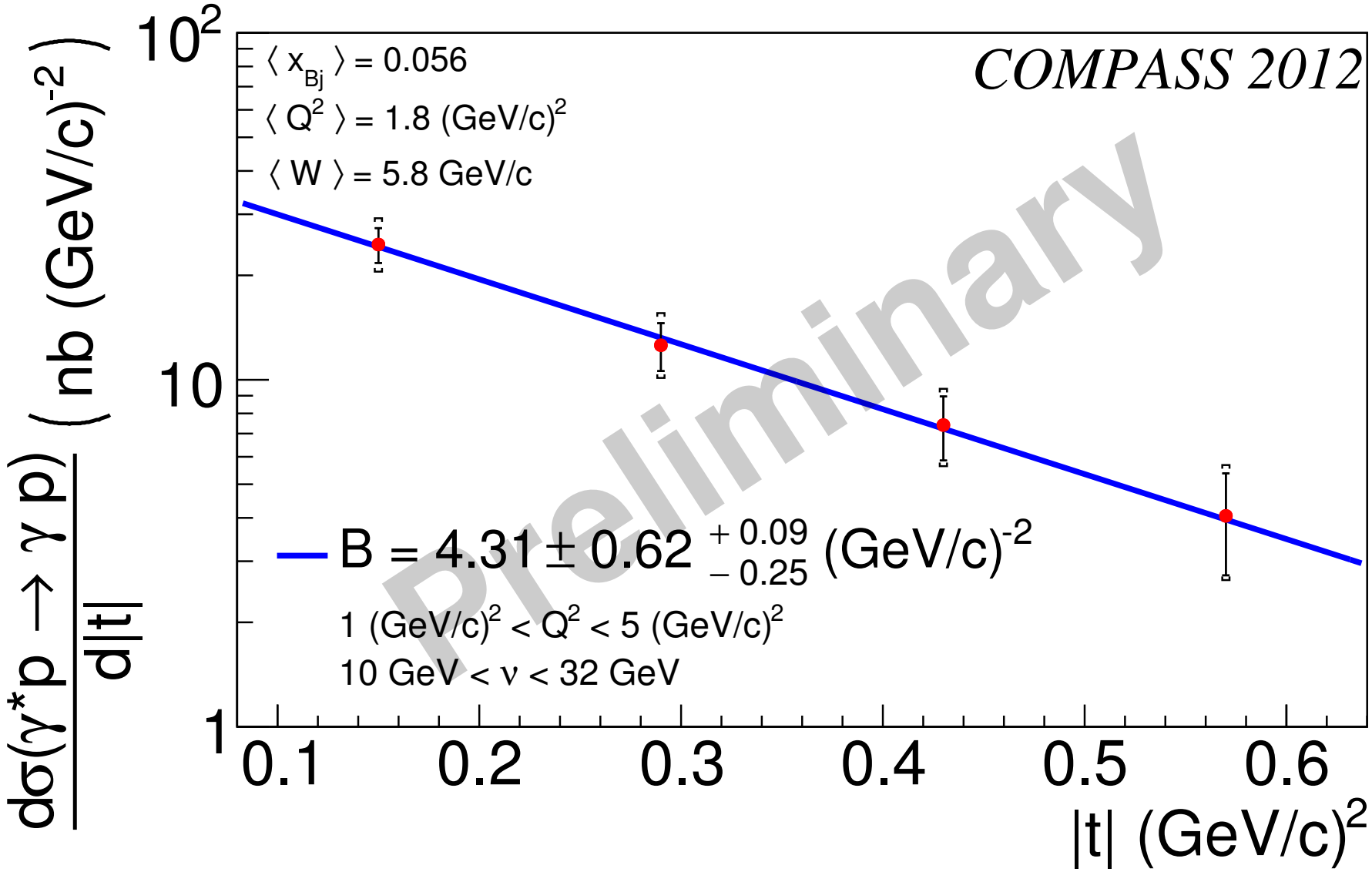
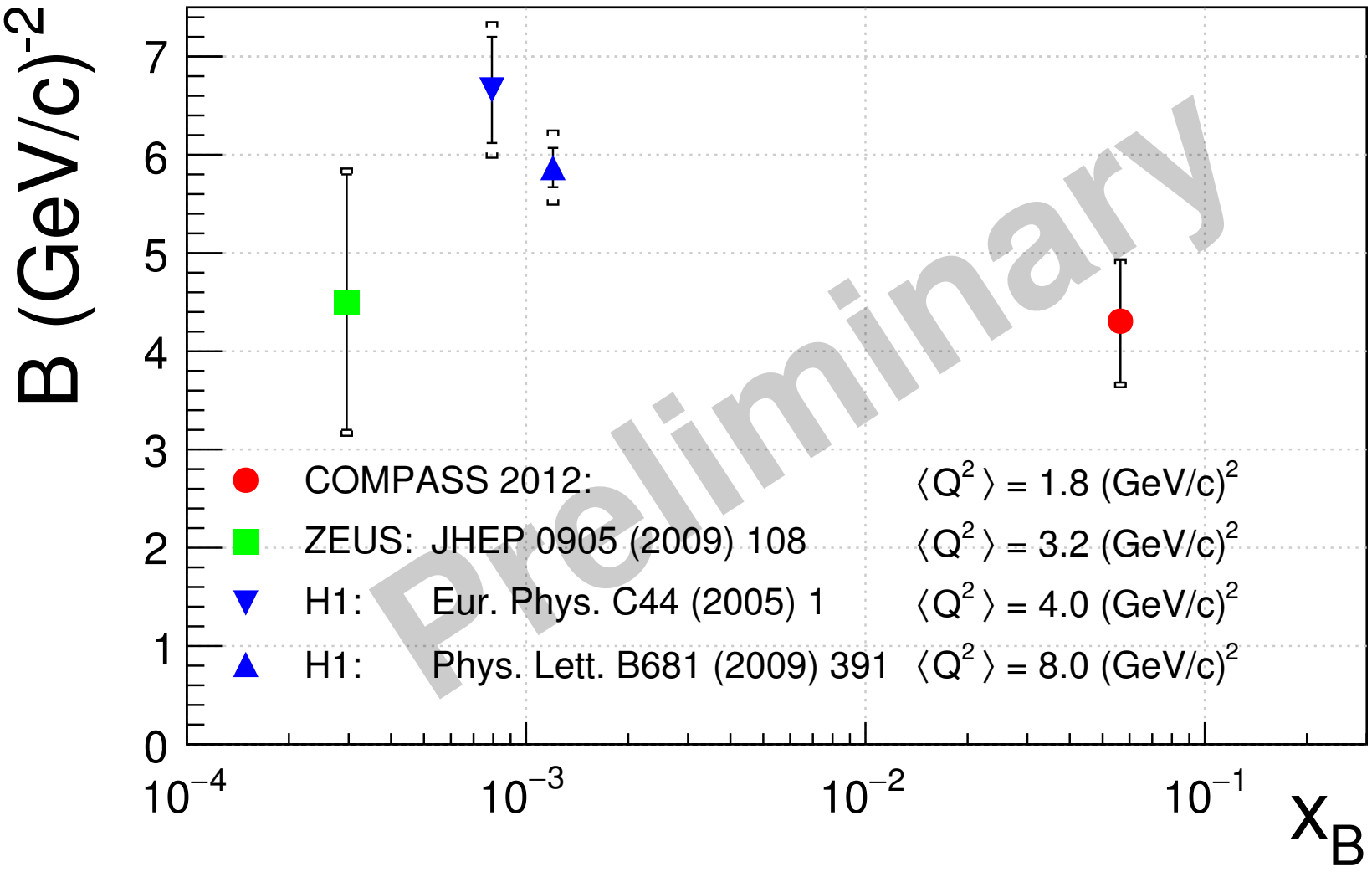


DVCS x-section and t-slope extraction

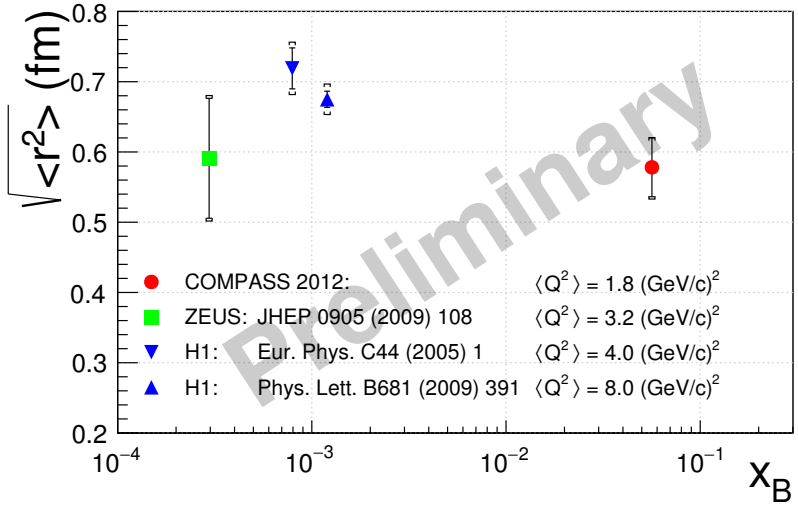


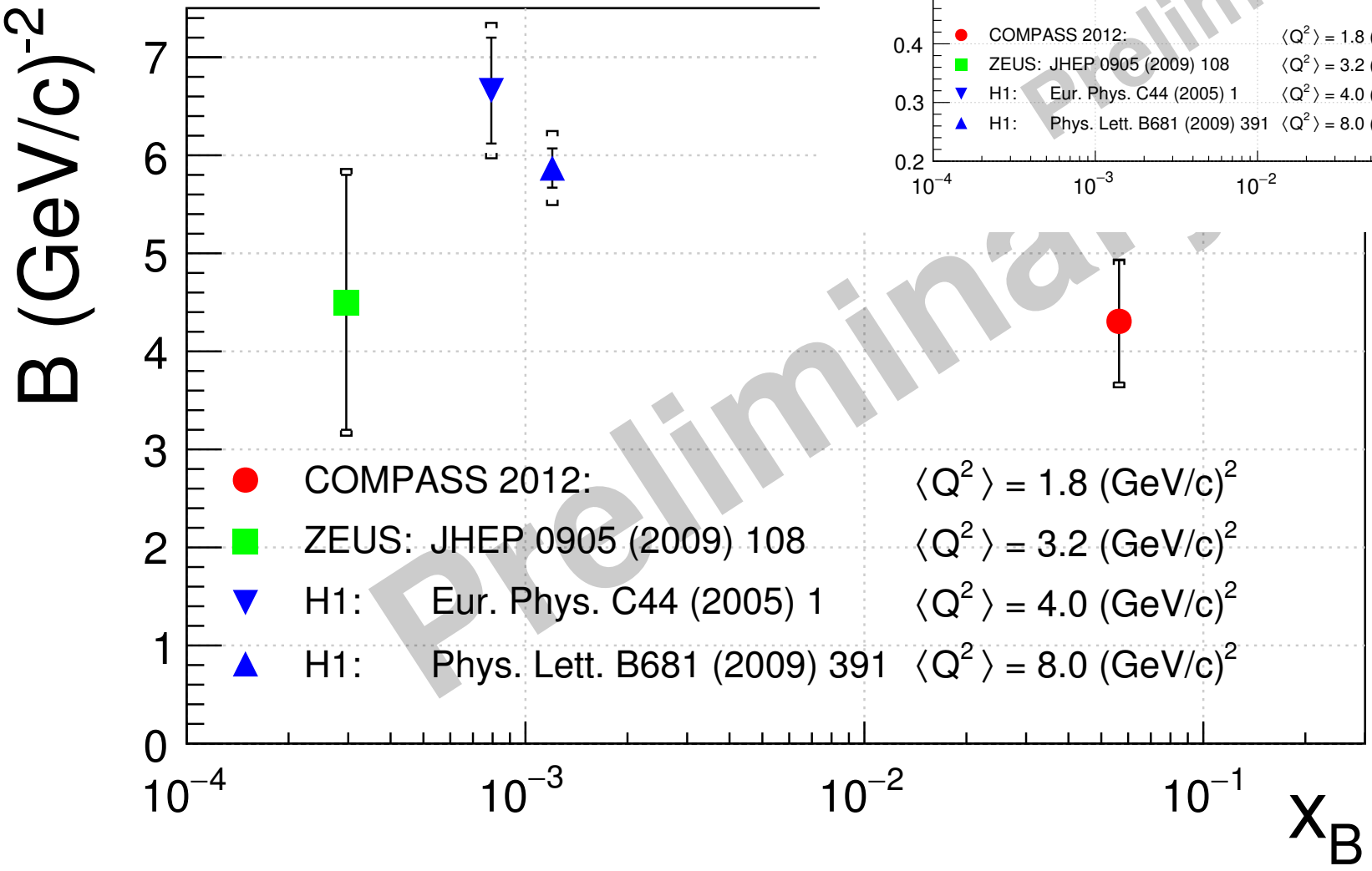
Comparison with HERA results

Model independent result

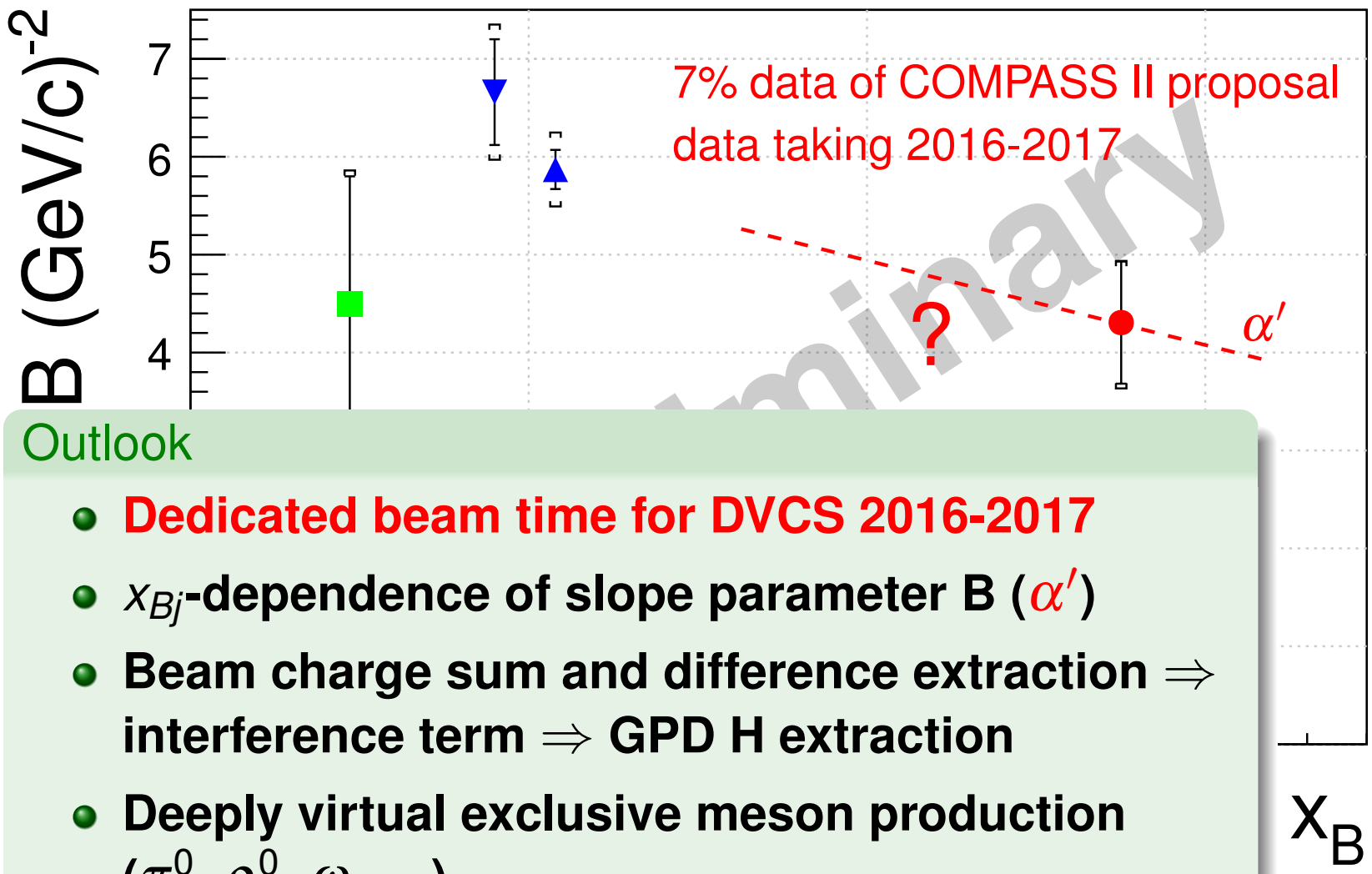


Comparison with HERA results





Comparison with HERA results



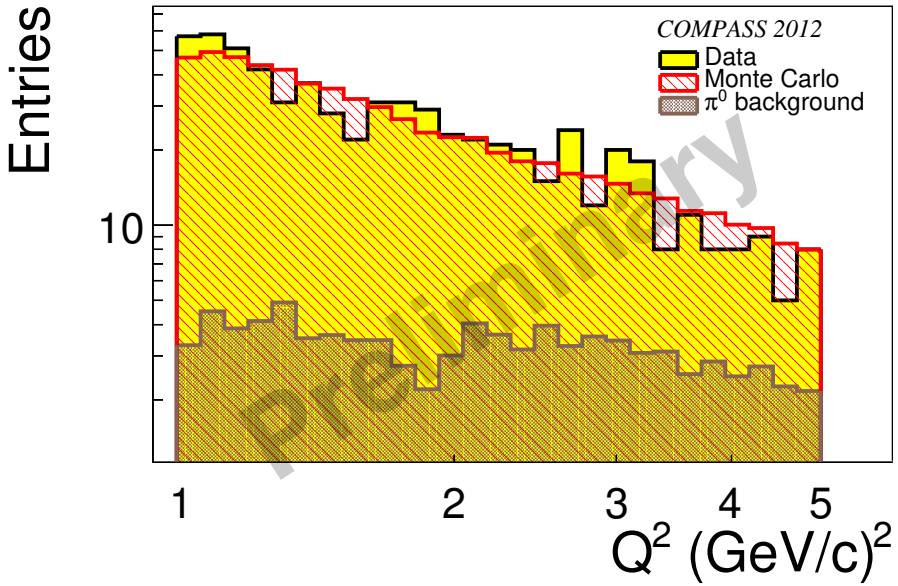
Outlook

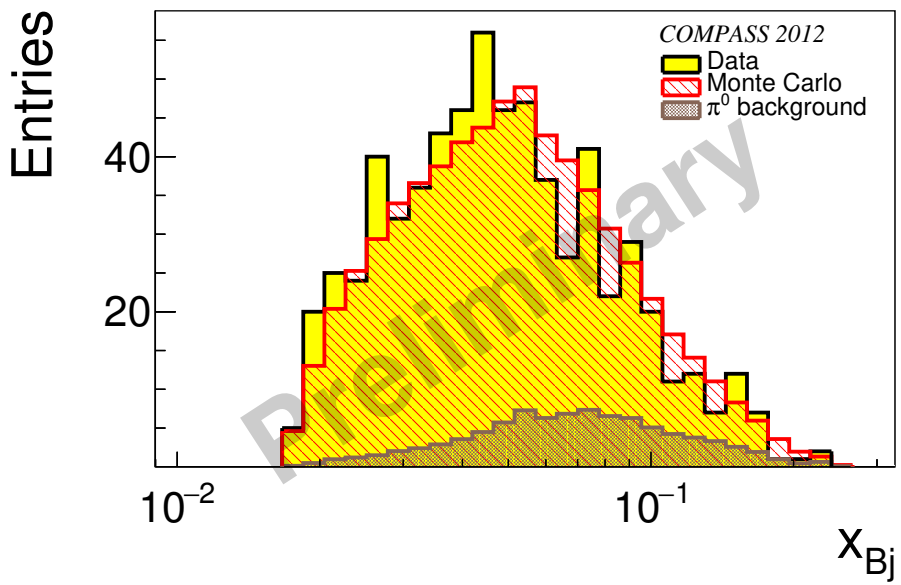
- **Dedicated beam time for DVCS 2016-2017**
- **x_{Bj}-dependence of slope parameter B (α')**
- **Beam charge sum and difference extraction $\Rightarrow$ interference term $\Rightarrow$ GPD H extraction**
- **Deeply virtual exclusive meson production (π^0, ρ^0, ω,...)**

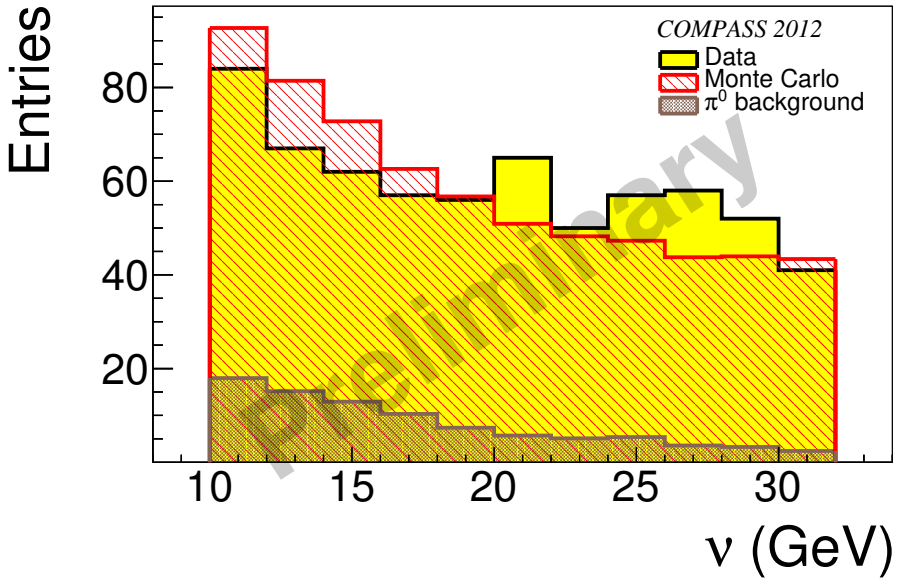
Thank you for your attention

Thank you for your attention

Kinematic distributions







Q^2 and ν (resp. x_{Bj}) after kinematic fit!

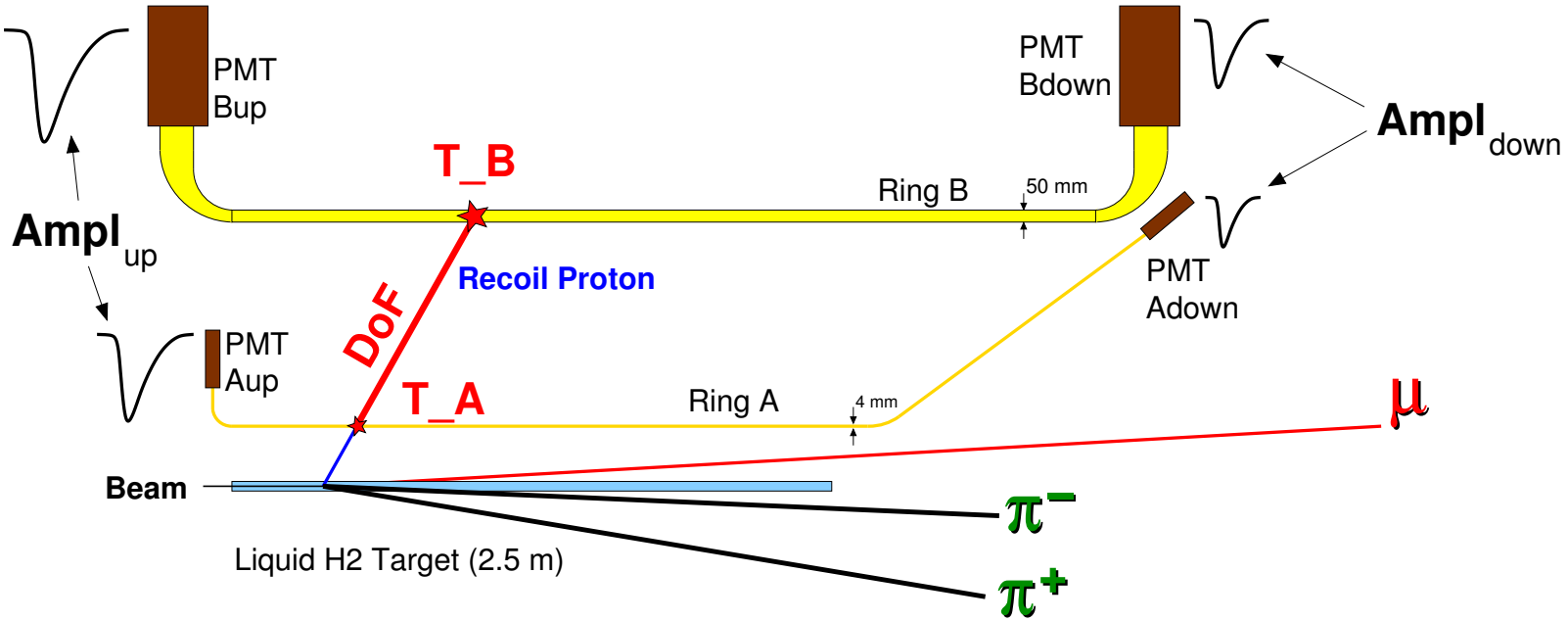
Monte Carlo prediction (the sum is shown)

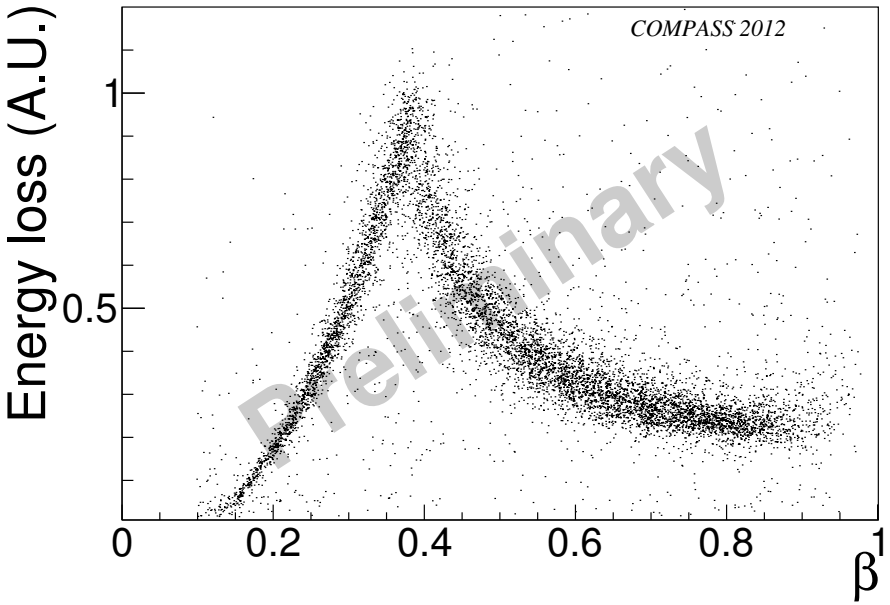
-(DVCS/BH): based on phenomenological model of DVCS x-section*

-π^0: parametrisation* linked to Golosgokov & Kroll + LEPTO (shown seperately)

*HEPGen++: Andrzej Sandacz, Christopher Regali

Recoil particle Measurement in CAMERA





$$E_{loss} \sim \sqrt{Ampl_{up} * Ampl_{down}}$$

$$\textbf{TOF} \rightarrow \left(t_{up} + t_{down}\right)_{A,B}$$

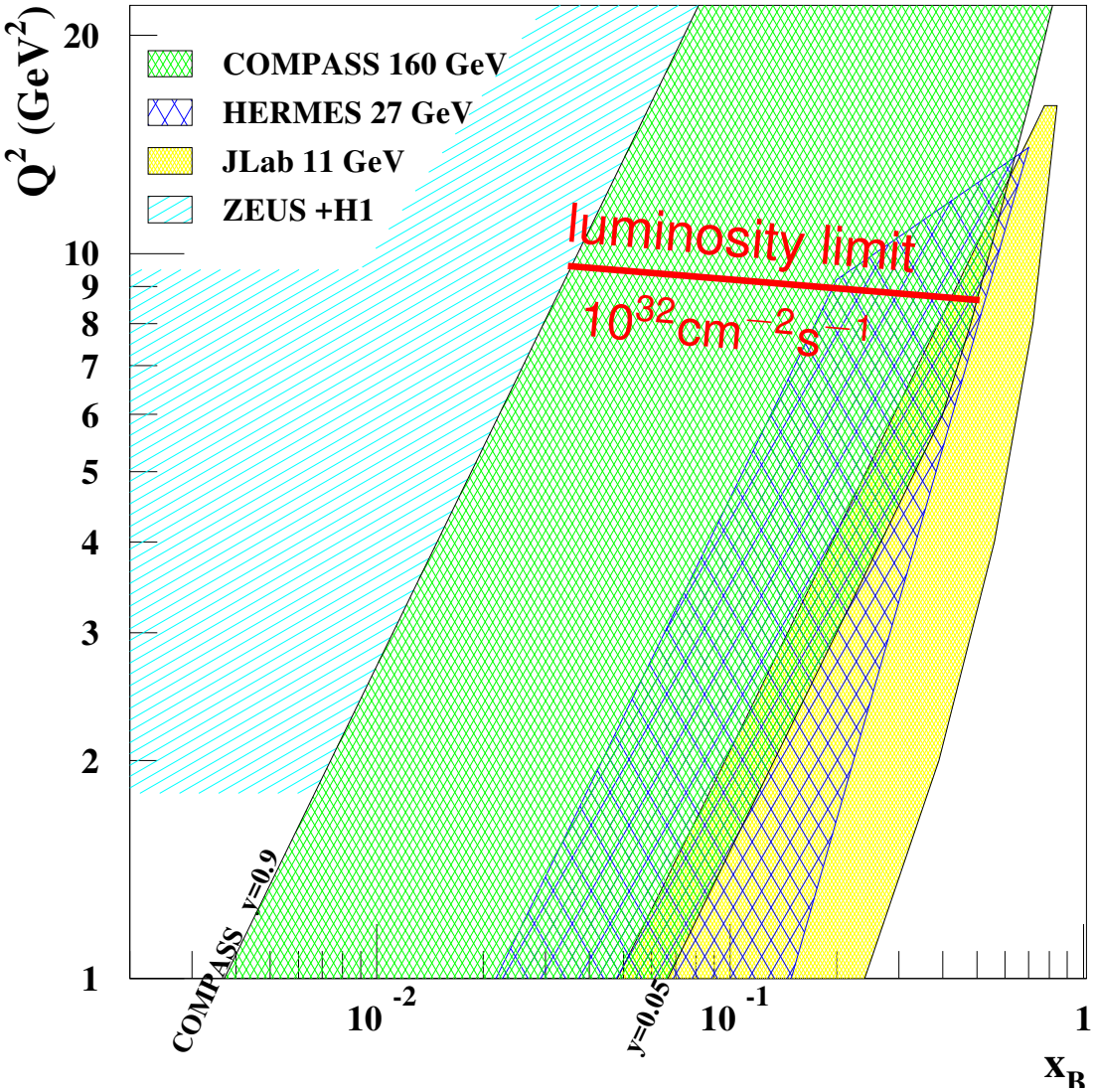
$$\textbf{z} \rightarrow t_{up} - t_{down}$$

Count rates: > 5 MHz in ring A

$\sim$1 MHz in ring B

What Makes COMPASS Unique?

COMPASS covers the unexplored region between collider (H1+Zeus) and low-energy fixed target (Hermes+JLab) experiments

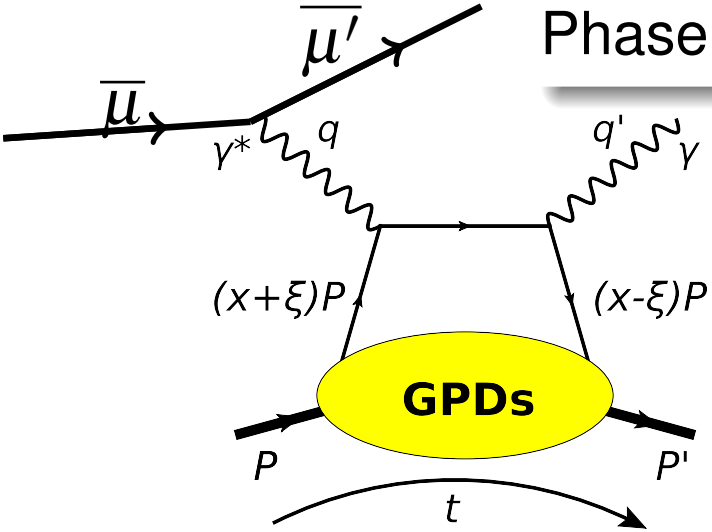


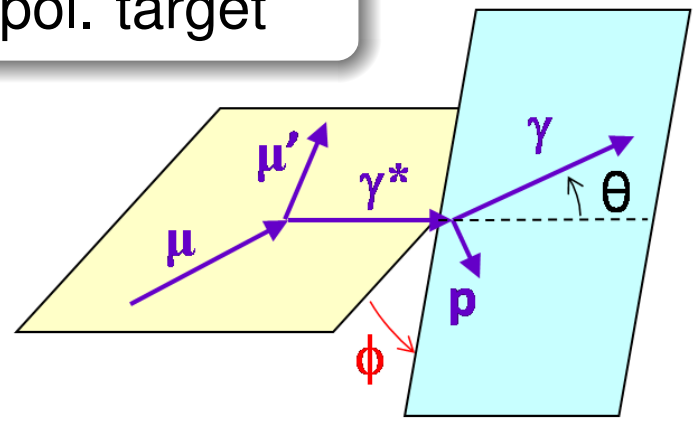
- μ^+ and μ^- beams
- momentum: $100 - 190\,\mathrm{GeV}/c$
- beam polarization: 80 %
  opposite for μ^+ and μ^-
- coverage of intermediate x_B
  - $\rightarrow$ low x_B: **pure BH**
    useful for normalization
  - $\rightarrow$ high x_B: **DVCS predominar**

$\rightsquigarrow$ **unexplored region between ZEUS+H1 and HERMES+JLab**

DVCS: What Can We Learn?

Phase 1: Polarized beam, unpol. target

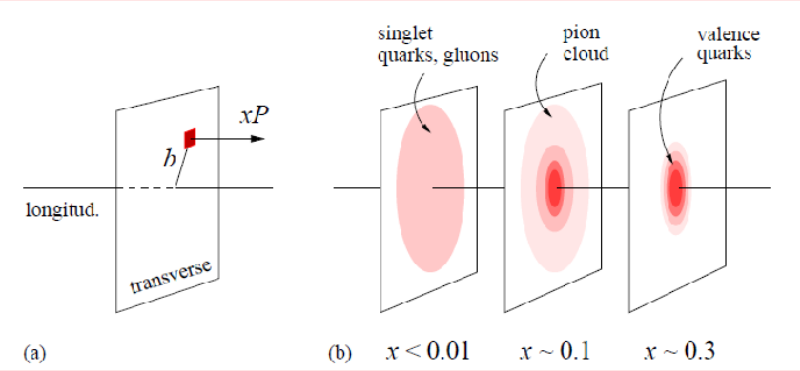




DVCS dominance at large x_B

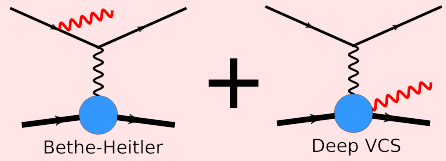
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



$\mathbf{r}_\perp$ parameter from slope of $d\sigma^{DVCS}/dt$

Interference between BH and DVCS



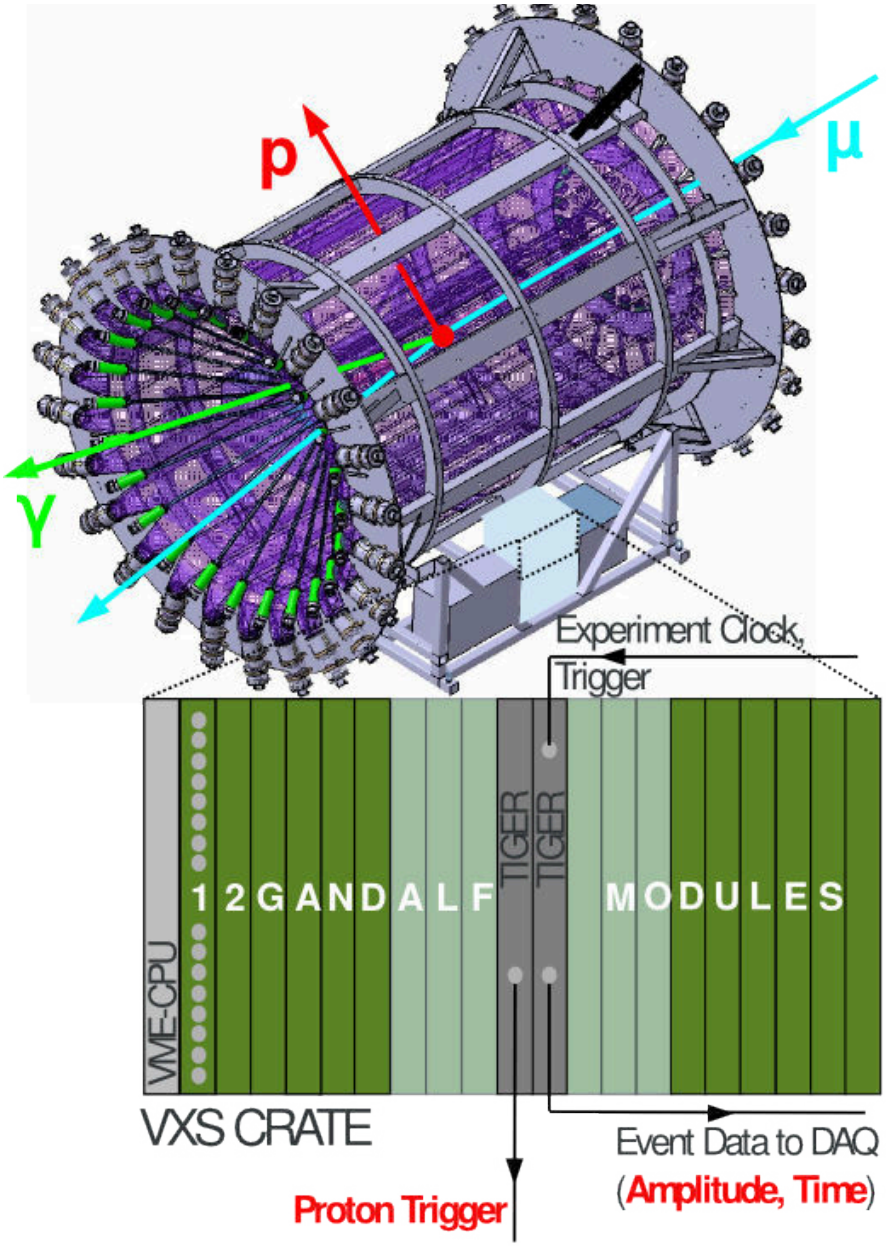
"Boost" of DVCS through int. term

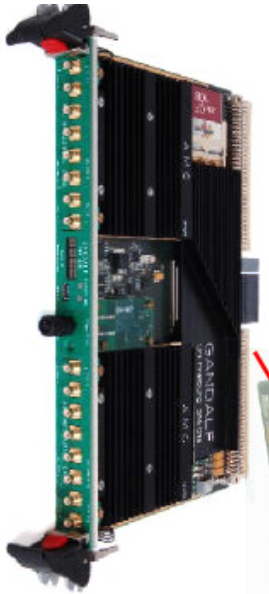
Measurement of $Re\mathcal{H}(\xi,t)$ and $Im\mathcal{H}(\xi,t)$ via ϕ-modulation of cross section

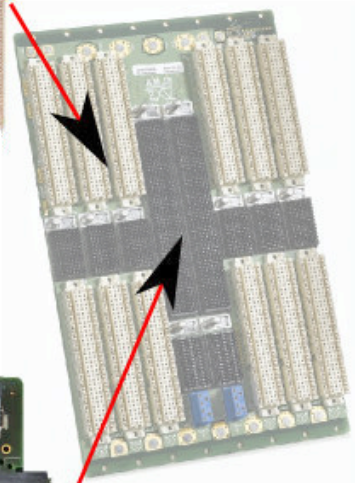
- $\mathbf{Re}\mathcal{H}(\xi,\mathbf{t}) = \mathbf{P}\int \mathbf{dx}\ \mathbf{H}(\mathbf{x},\xi,\mathbf{t})/(\mathbf{x}-\xi)$
- $\mathbf{Im}\mathcal{H}(\xi,\mathbf{t}) = \mathbf{H}(\mathbf{x}=\xi,\xi,\mathbf{t})$

Exp. constrain to GPD H

CAMERA Readout







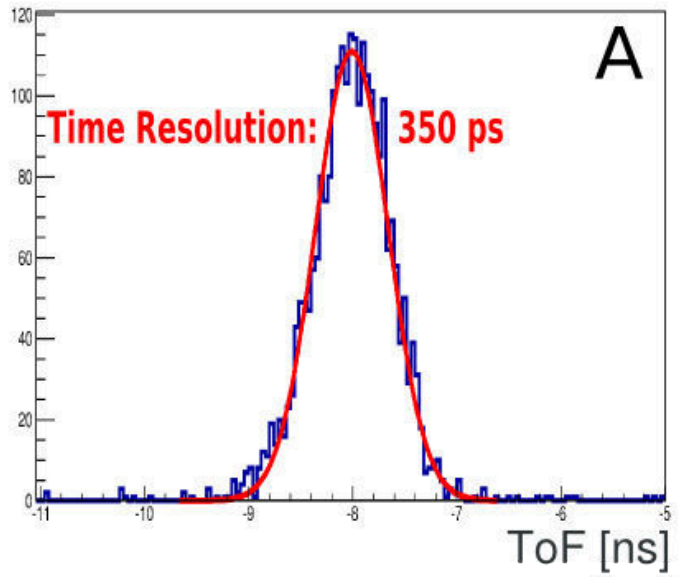
GANDALF

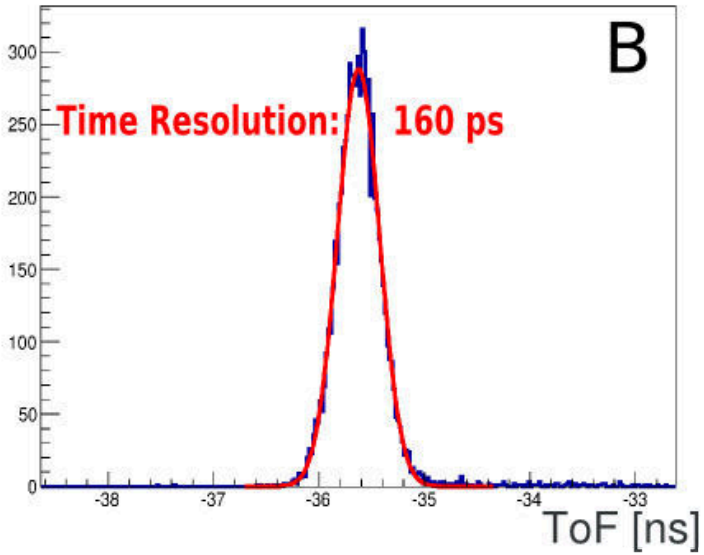
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

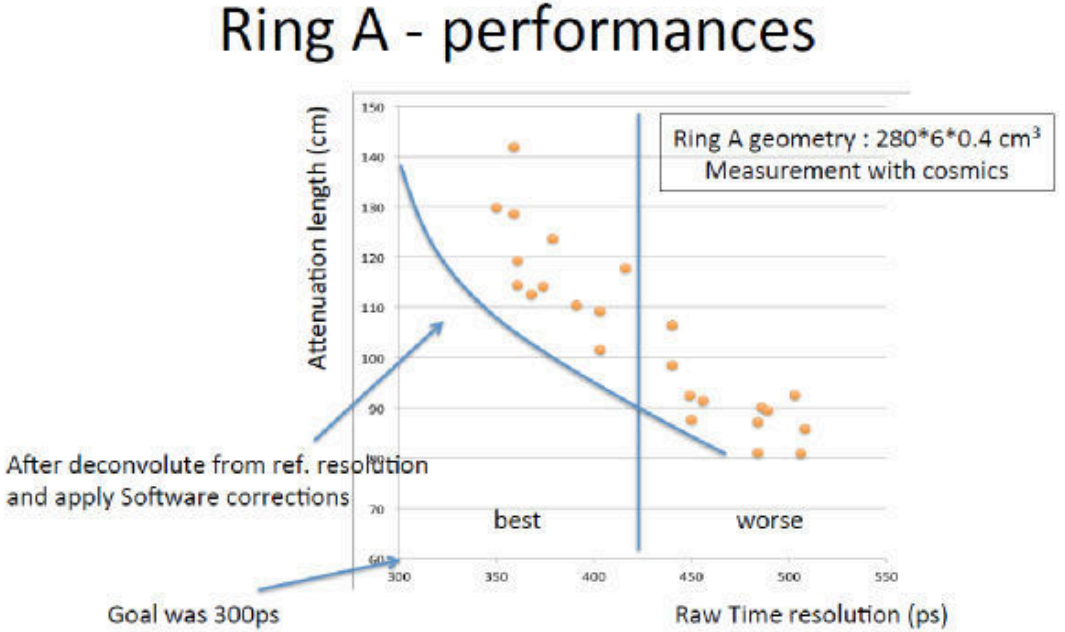
TIGER

Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express

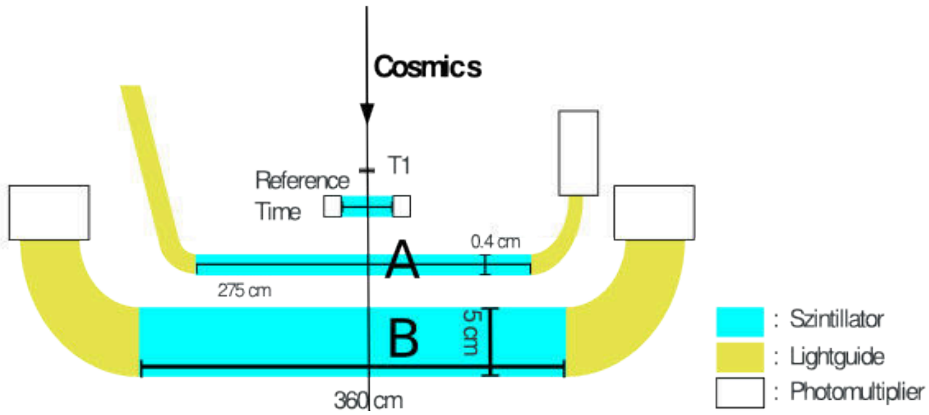
Time Resolutions Measured with Cosmics





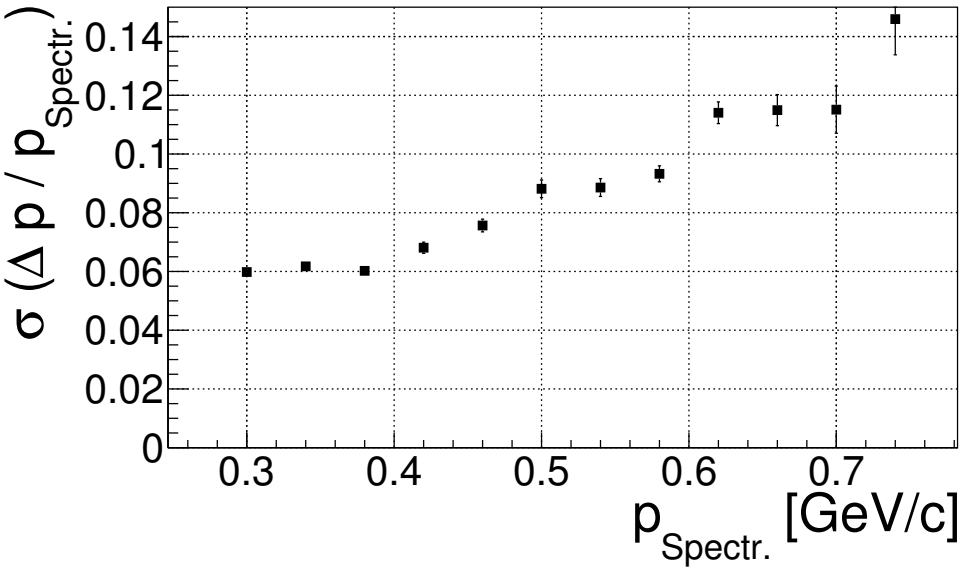


Att length better than 200 cm was expected

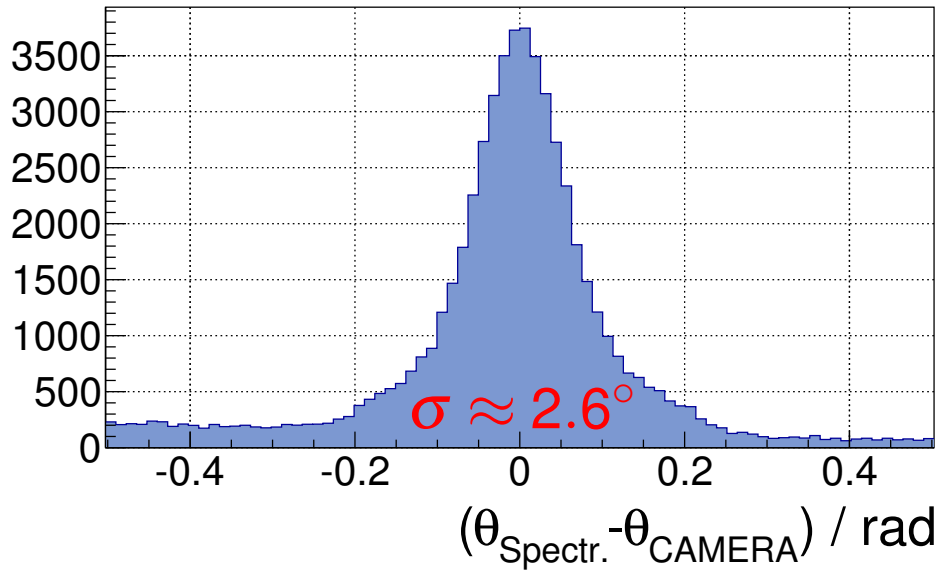


Summary of Present CAMERA Performances

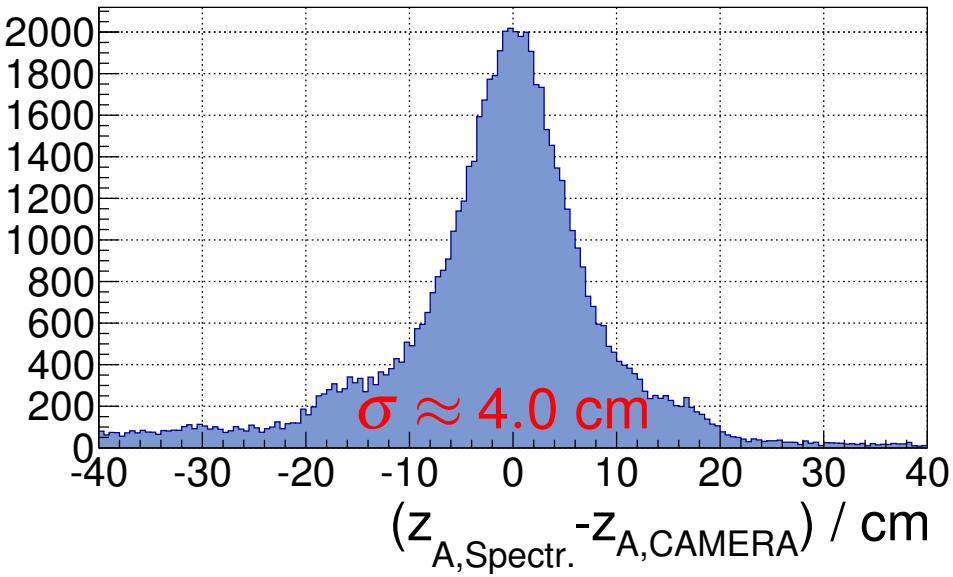
momentum resolution



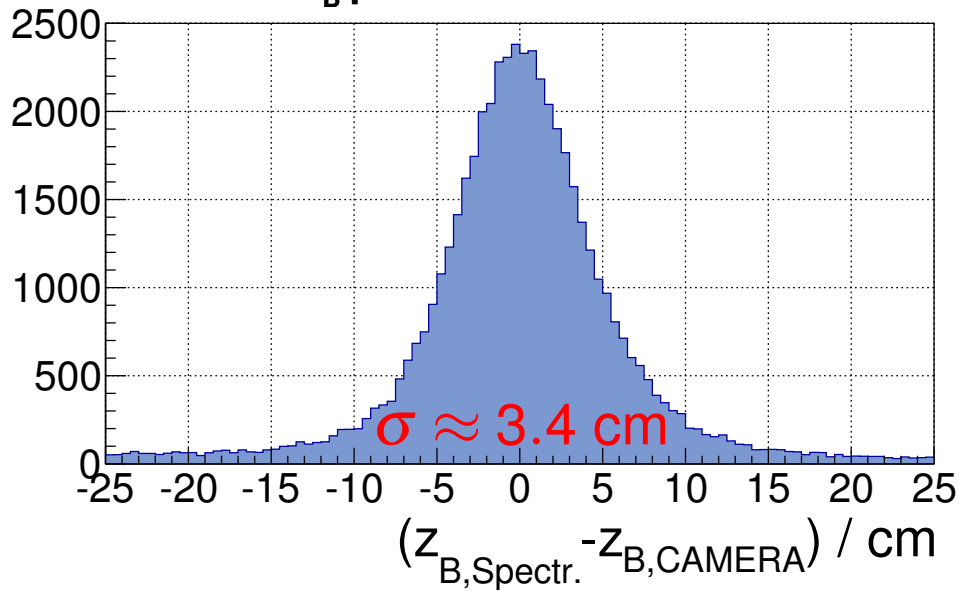
polar angle resolution



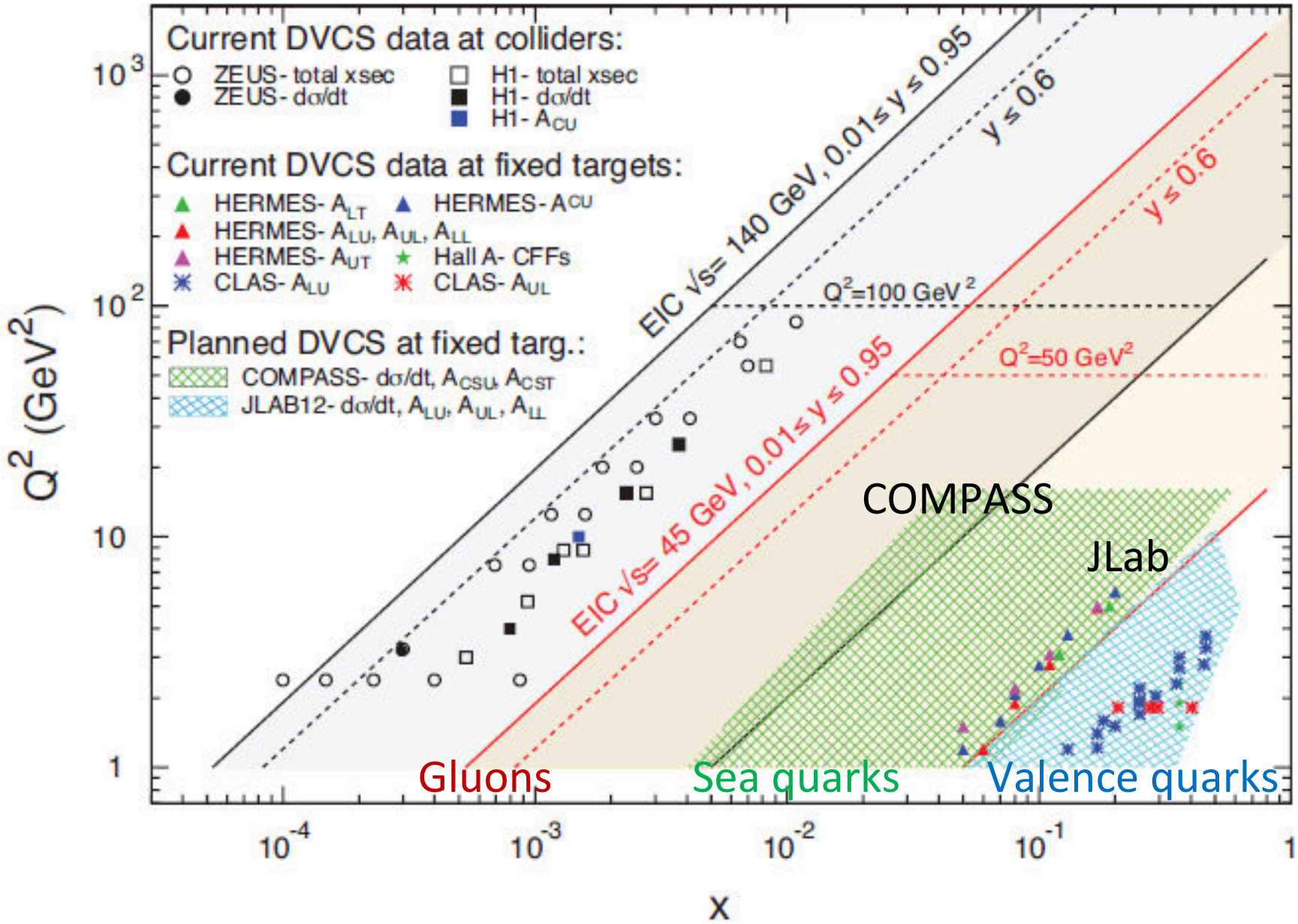
z_A position resolution



z_B position resolution



Past, Present and Future GPD Experiments



Measurements of DVCS and BH Cross-sections

cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

$$d\sigma_{(\mu p \to \mu p \gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol} + e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + e_\mu P_\mu\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

Charge & Spin Difference and Sum:

$$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto c_0^{Int} + c_1^{Int}\cos\phi \quad \text{and} \quad c_{0,1}^{Int} \sim F_1\, \mathcal{R}e\, \mathcal{H}$$

$$\mathcal{S}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + c_0^{DVCS} + K.s_1^{Int}\sin\phi \quad \text{and} \quad s_1^{Int} \sim F_1\, \mathcal{I}m\, \mathcal{H}$$

$$c_1^{Int} \propto \mathcal{R}e\left(F_1\,\mathcal{H} + \xi(F_1+F_2)\,\tilde{\mathcal{H}} - t/4m^2\, F_2\mathcal{E}\right)$$

NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics

✓ only leading twist and LO