Study of DVCS and HEMP processes at COMPASS

CIPANP 2012

St. Petersburg (FL), June 2012

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* on behalf of the COMPASS collaboration

Outline

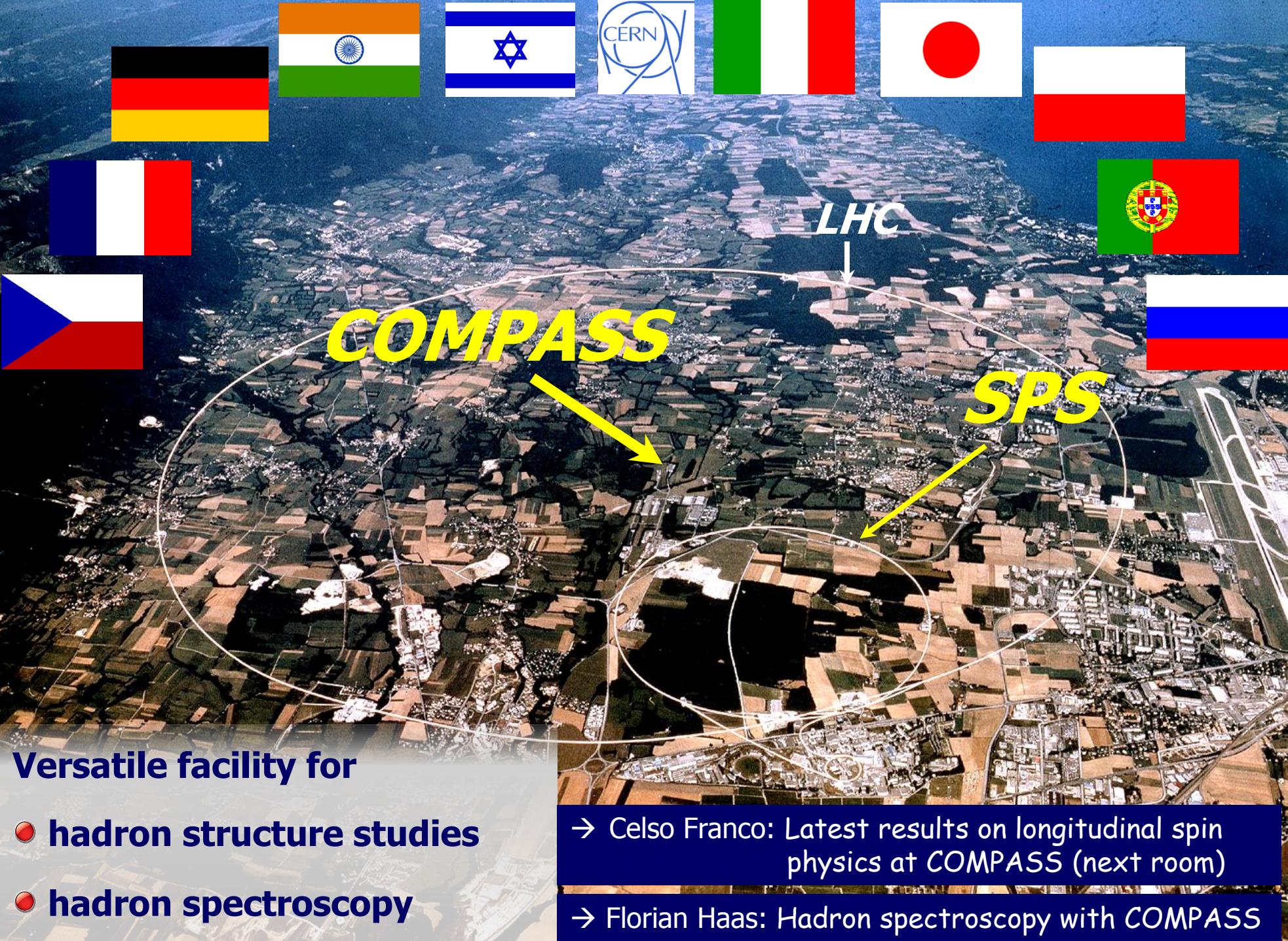
New results – pol. target:

HE ρ0 production

Outlook:

DVCS & HEMP – LH_2 target

(DVCS & HEMP– pol. Target)



Versatile facility for

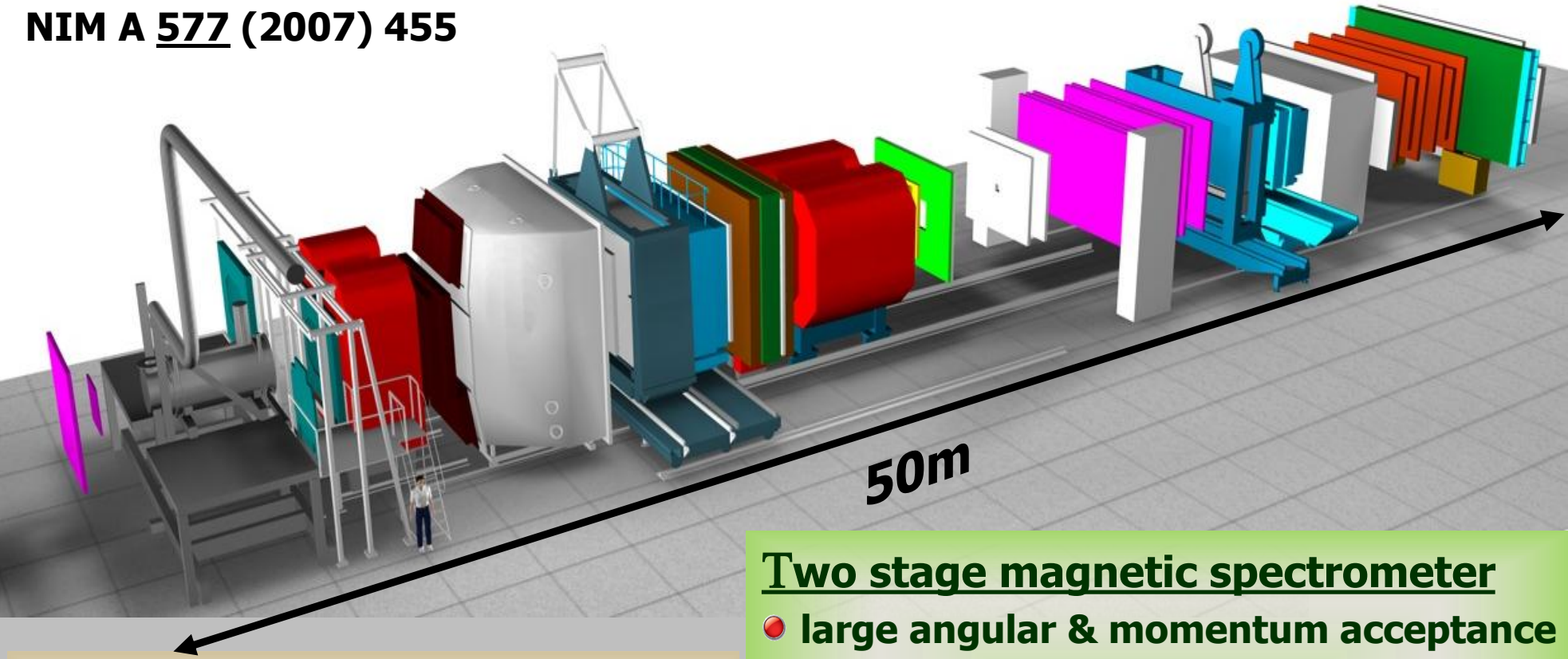
- **hadron structure studies**
- **hadron spectroscopy**

→ Celso Franco: Latest results on longitudinal spin physics at COMPASS (next room)

→ Florian Haas: Hadron spectroscopy with COMPASS

The COMPASS Experiment @ CERN

NIM A 577 (2007) 455



- μ^+, μ^- or hadron (π, K, p) beam
  - changeover within < 1h
- momentum: 100 - 200 GeV/c
- 80% polarization
- μ^+ & μ^- with opposite polarization

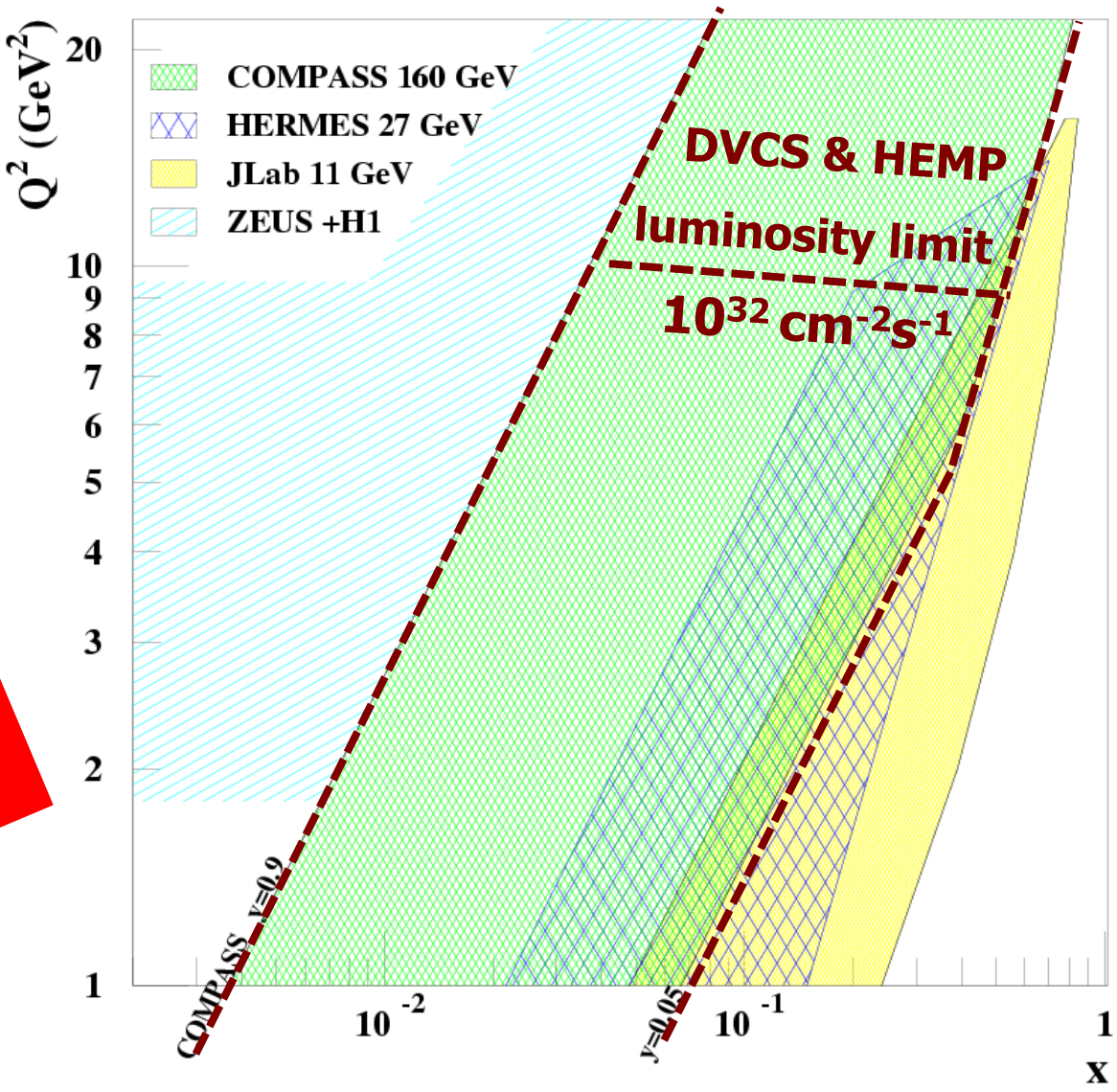
Two stage magnetic spectrometer

- large angular & momentum acceptance
- Particle identification
  - Ring Imaging Cerenkov Counter
  - Electromagnetic calorimeters
  - Hadronic calorimeters
  - Hadron absorbers

What makes COMPASS special for DVCS & HEMP

- μ^+ and μ^- beam
  100 - 200 GeV/c
- 80% polarization
- μ^+ and μ^- with
  opposite polarization

Unique feature of COMPASS @ CERN/SPS

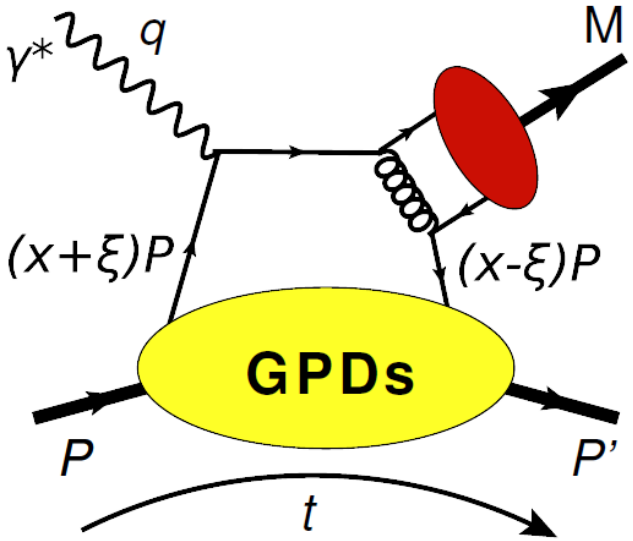


- Explore uncovered region between ZEUS/H1 and HERMES & Jlab

Hard Exclusive ρ^0 Production off Polarized Targets

(without recoil detector!)

Hard Exclusive Meson Production



Allows for flavor separation:

$E\rho^0 = 1/\sqrt{2}\,(2/3\,E^u + 1/3\,E^d + 3/8\,E^g)$

$E\omega = 1/\sqrt{2}\,(2/3\,E^u - 1/3\,E^d + 1/8\,E^g)$

$E\phi = -1/3\,E^s - 1/8\,E^g$

Cross section measurements:

- Pseudo-scalar: π, η, ... $\Rightarrow \tilde{H}$ & $\tilde{E}$
- Vector meson: ρ, ω, ϕ... $\Rightarrow$ **H** & **E**

$\rho : \omega : \phi \sim 9 : 1 : 2$

(at large Q^2)

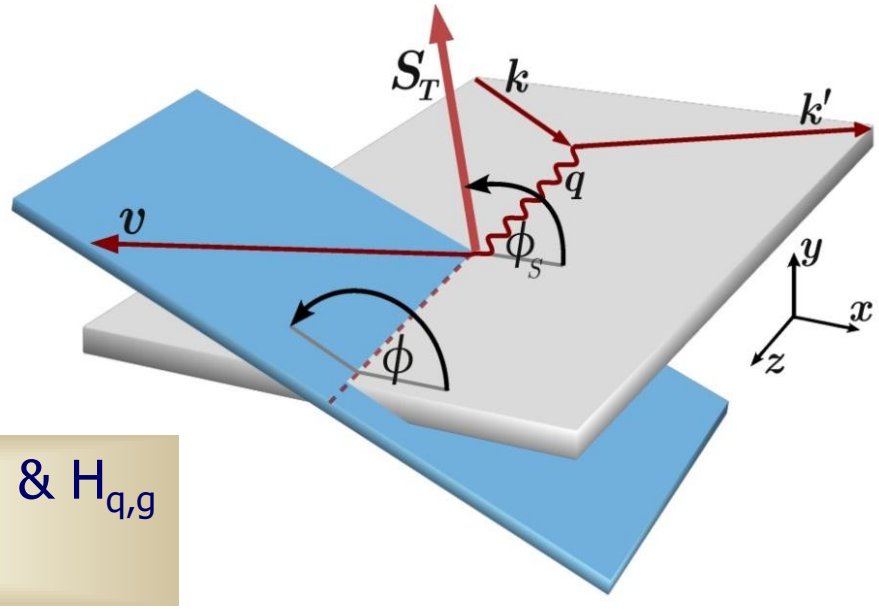
- Vector meson production from transversely polarized target asymmetry

$\Rightarrow$ **E/H**

Presently studied at COMPASS without RPD

HEMP with polarized Target

$$A_{UT}^{\sin(\phi-\phi_S)} \propto \sqrt{|-t'|}\,\frac{\mathrm{Im}\,(\mathcal{E}^{*}\mathcal{H})}{|\mathcal{H}|^{2}}$$



- $\mathcal{E}$ and $\mathcal{H}$ are weighted sums of GPD $E_{q,g}$ & $H_{q,g}$
- Provide access to GPD **E**

Constrain total angular momentum using Ji's relation:

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

Experimental Set-Up: Beam & Targets

Beam:

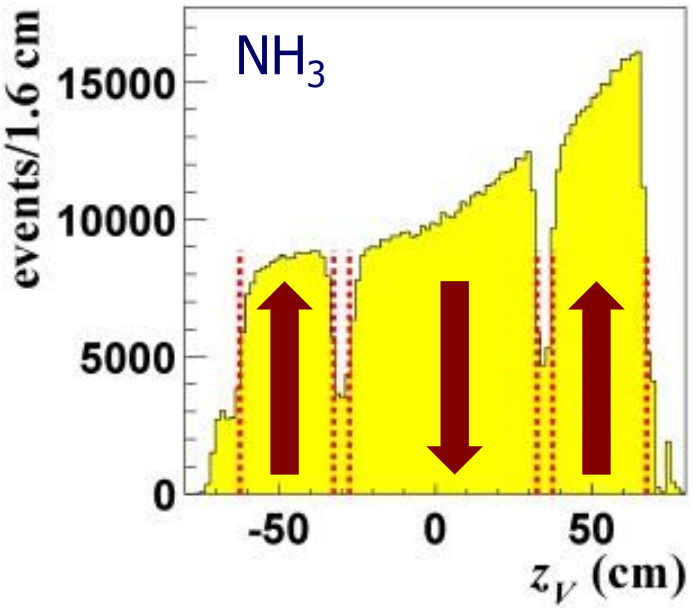
- 160 GeV μ^+

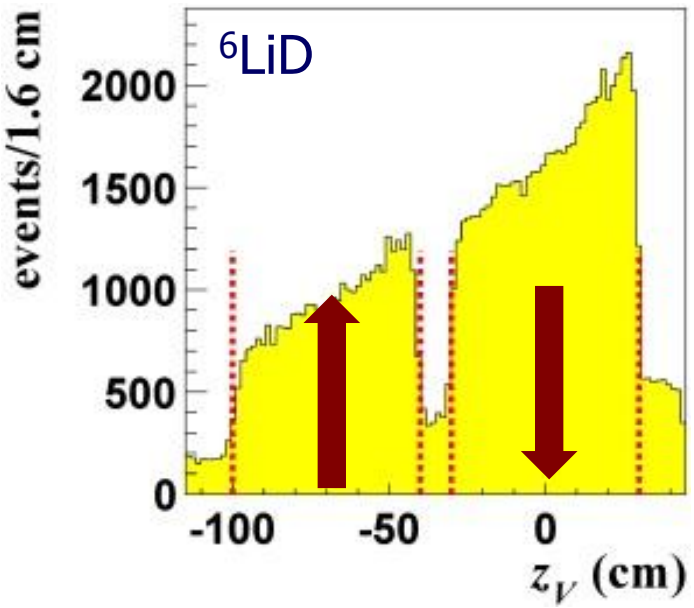
Targets:

- NH_3 - 2007 & 2010 (γ-proton asymmetries)
  <P>= 0.8 <f>= 0.25
  acceptance 70mrad → 180 mrad
- ^6LiD - 2003 & 2004 (γ-deuteron asymmetries)
  <P>= 0.5 <f>= 0.45

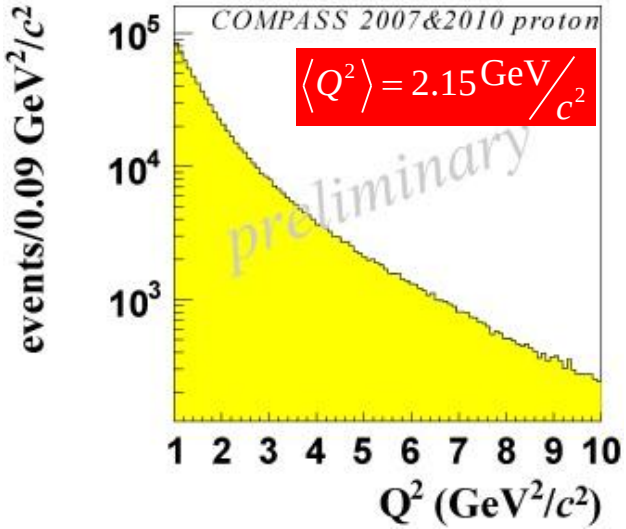
Event Signature:

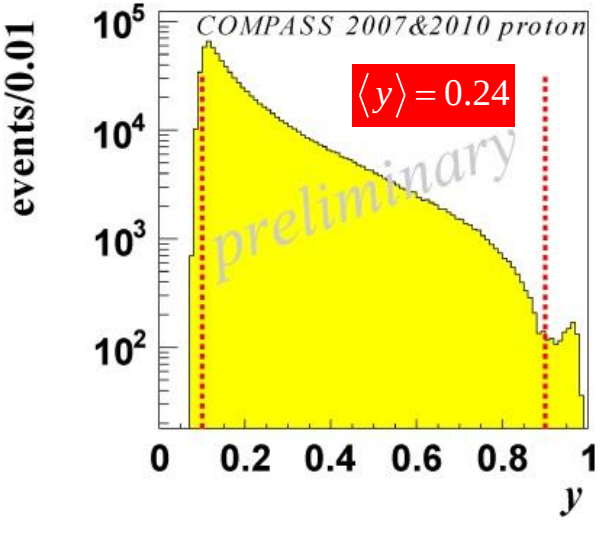
- $\mu^+ N \rightarrow \mu^+ N' \rho^0$
- $\rho^0 \rightarrow \pi^+ \pi^-$ (*BR* ~ 100%)

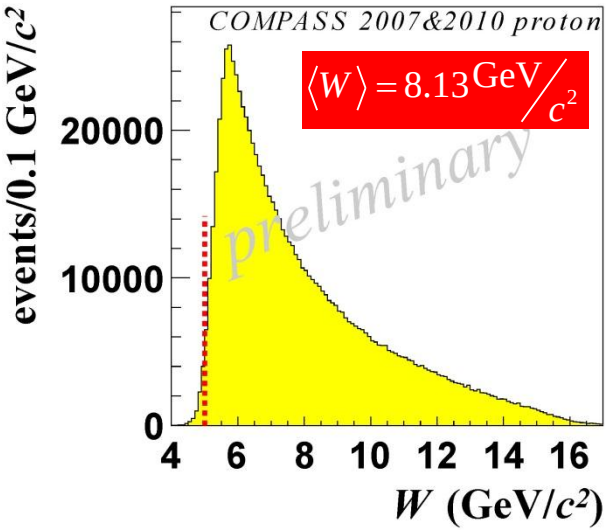


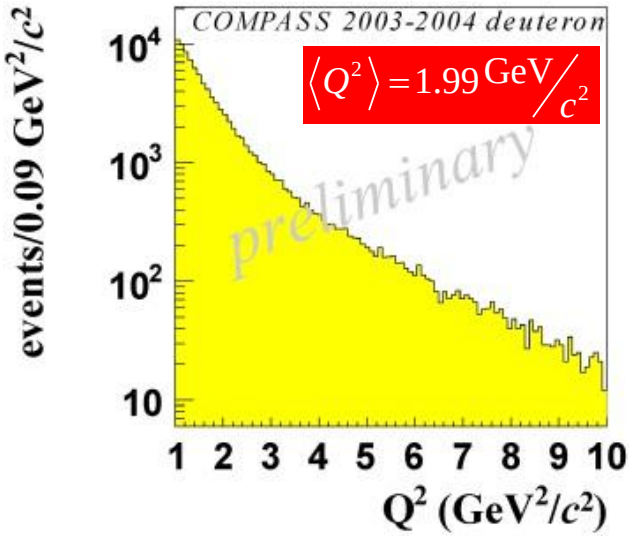


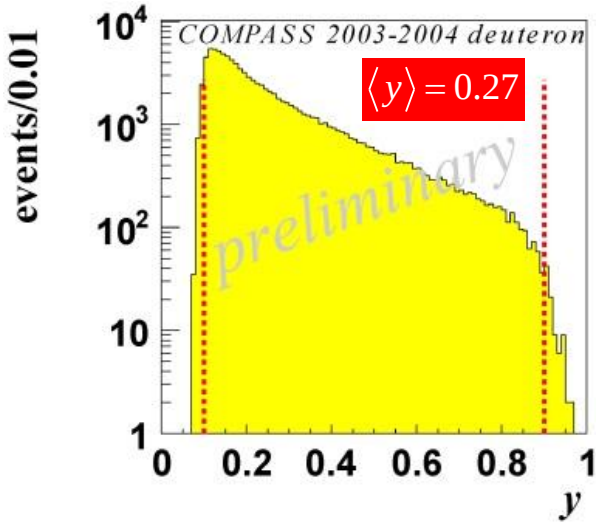
Selections to set Hard Scale

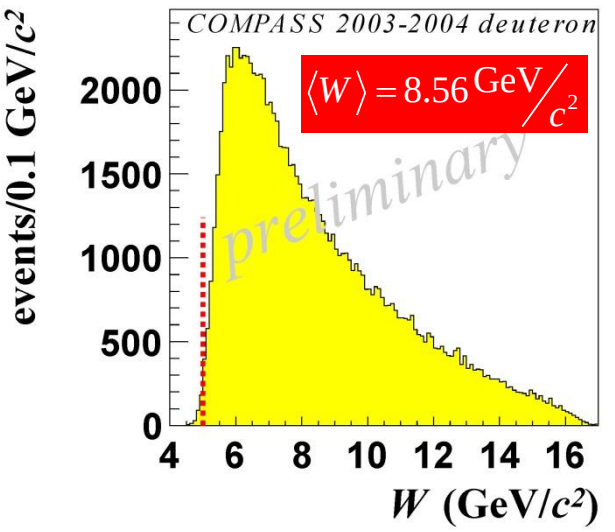






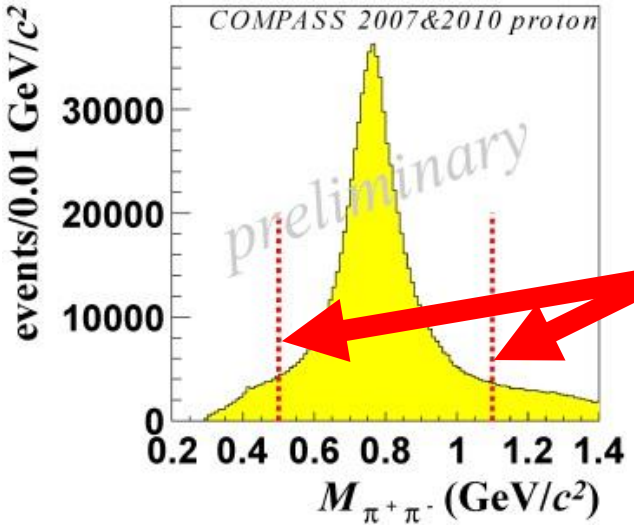






Selections for ρ^0 Production

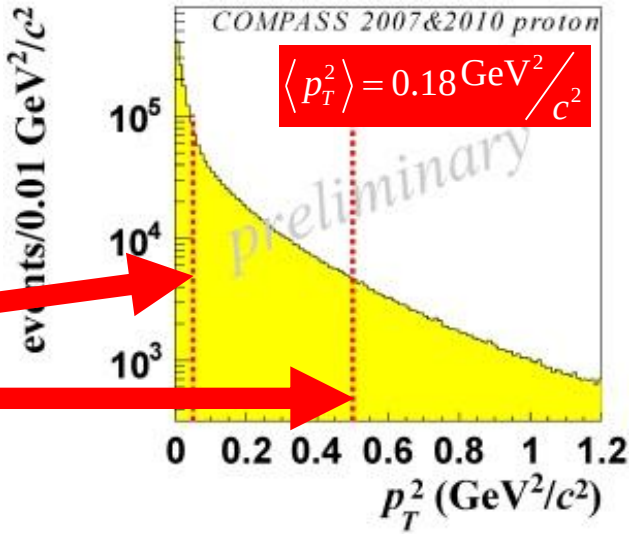
Assuming π mass

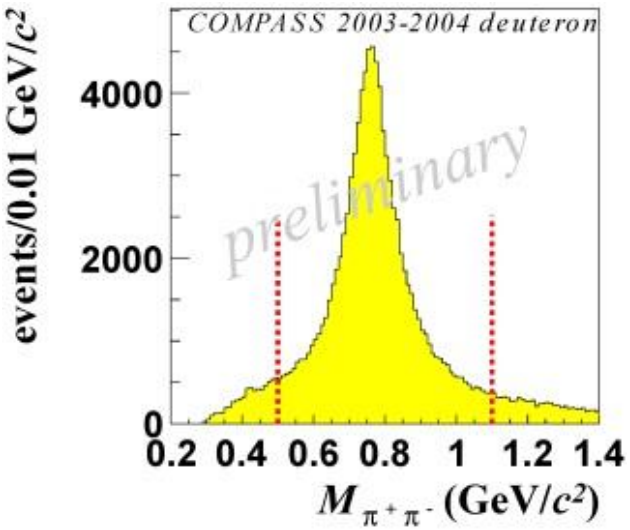


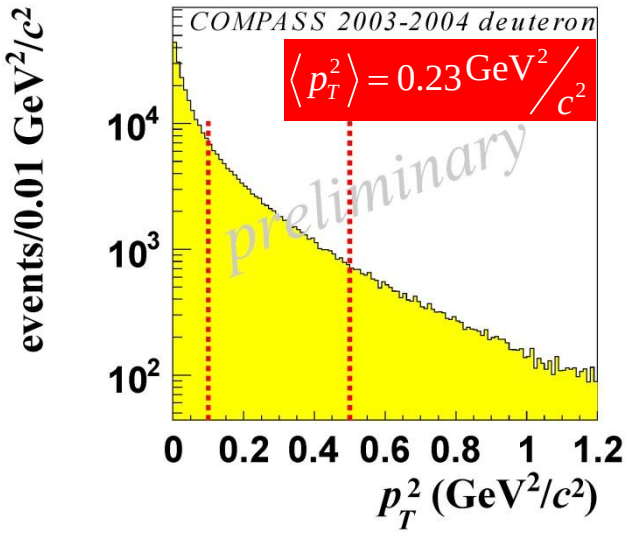
Cuts optimized to supress

- **non-resonant**
- **coherent nuclear**
- **SIDIS**

background

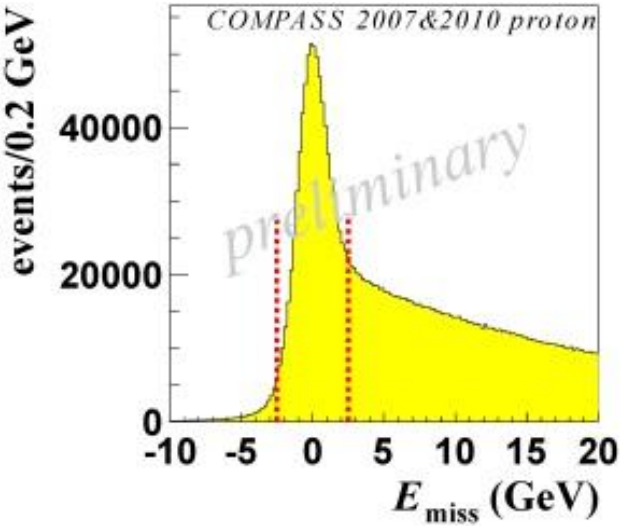


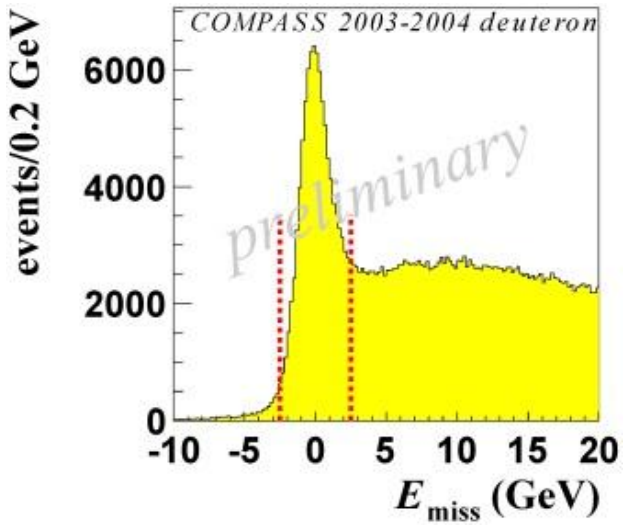




Exclusivity Cuts

No recoil detector → assuming π and p masses





Missing Energy Technique:

$$E_{miss} = \frac{M_X^2 - M_p^2}{2M_p} = E_{\gamma^*} - E_{\rho^0} + \frac{t}{2M_p}$$

- **14% contamination of diffractive dissociation (no attempt to remove it)**

Final sample:

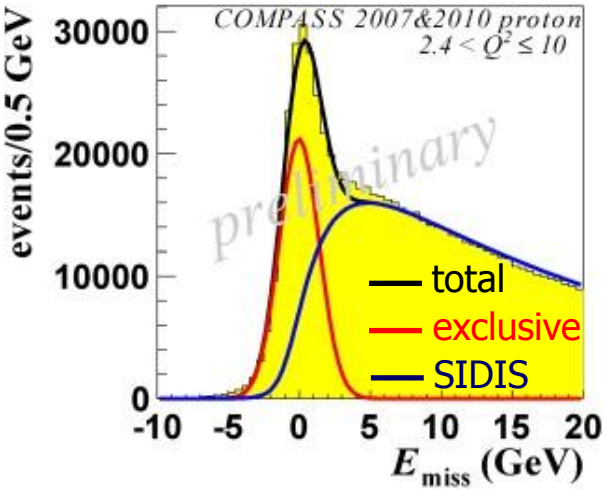
- **NH_3: 797000 events**
- **^{6}LiD: 97000 events**

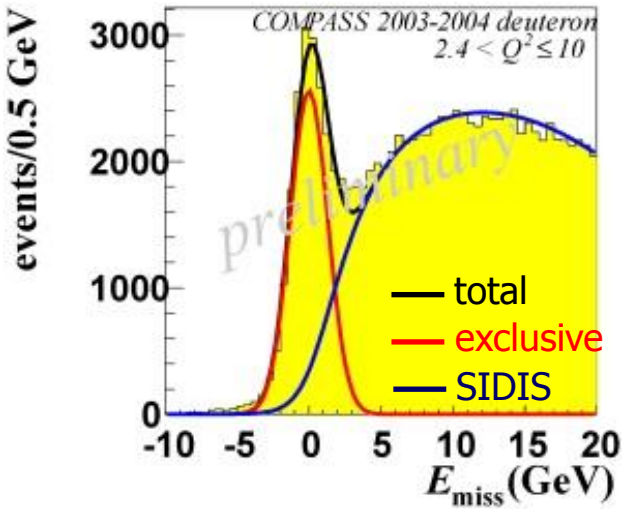
… but still strong SIDIS background

SIDIS Background Subtraction

Two examples:

Estimate & subtract background bin-by-bin

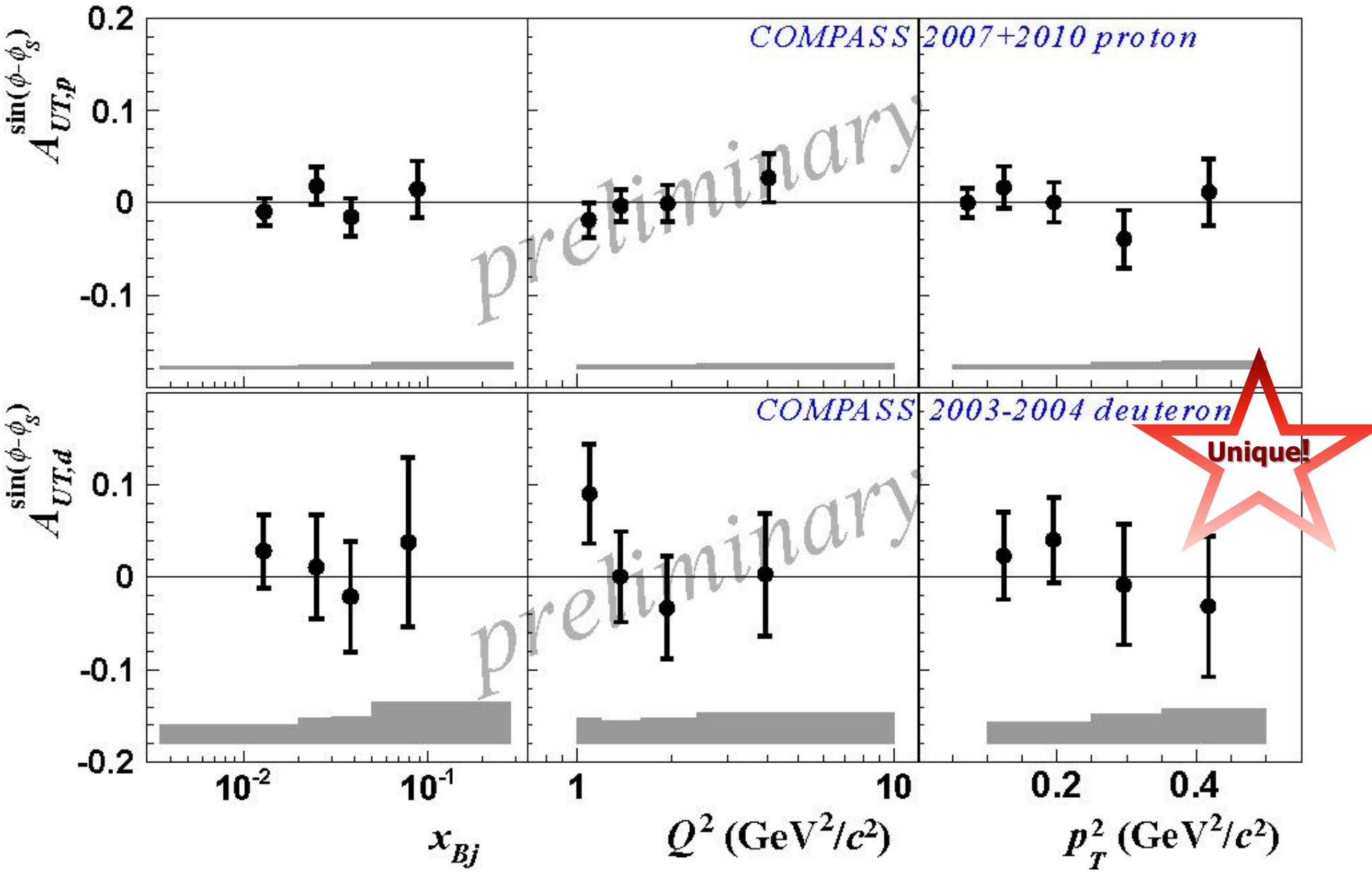




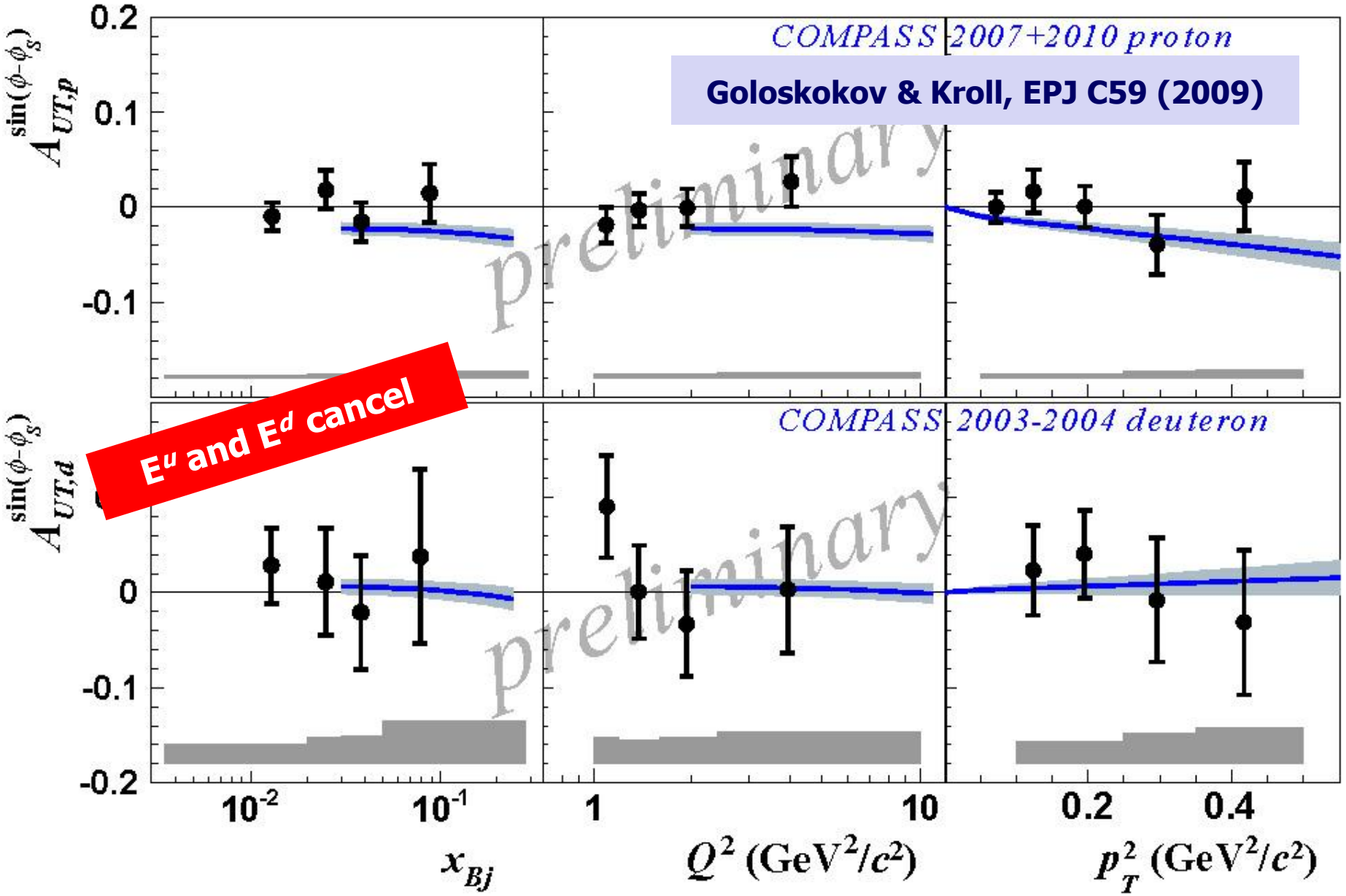
- **still 5…40% background from SIDIS**
  (depending on target cell, x_{Bj}, Q^2, p_T^2, $\phi - \phi_S$)
- **Fix shape of background using Data/MC like-sign events**
- **Estimate SIDIS background from fit to data**
- **Assume Gaussian shape for signal**

$A_{UT}^{\sin(\phi-\phi_S)}$ **by a binned max. likelihood**

Exclusive ρ^0 production on transverse pol. Targets

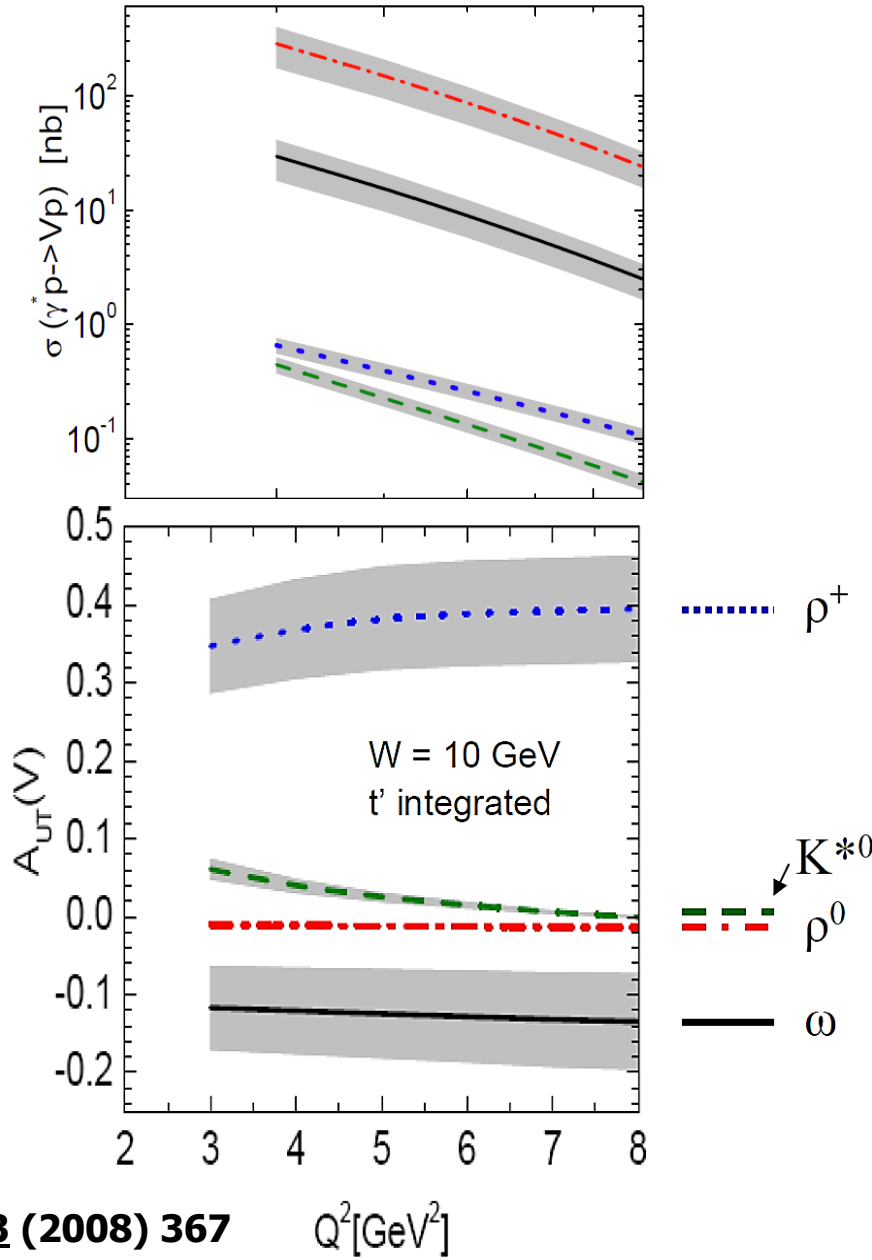


Exclusive ρ^0 production on transverse pol. Targets



What's next?

- Paper draft presently circulating inside collaboration
- Analysis of exclusive ρ^+, ω, ϕ and γ final states ongoing
- More modulations (higher twist)
- Extraction of spin density matrix elements



Goloskokov, Kroll EPJ C53 (2008) 367

Outlook

COMPASS II

Content of Proposal for COMPASS-II

DVCS & HEMP Measurements
Transverse Imaging
Beam charge & spin sum, difference and asymmetry
GPD H, later GPD E
Data taking (2012), 2015&16

Drell-Yan Measurements
Sivers PDF
Boer Mulders PDF
Test of factorization approach
Data taking 2014

Upgrade existing

COMPASS Spectrometer

@ CERN/SPS

PDFs and Fragmentation
s(x), Kaon FF
Data taking parasitically

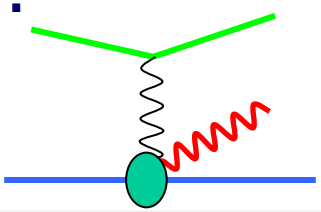
Pion and Kaon Polarizability
Chiral Perturbation Theory
Data taking 2012

Proposal submitted to CERN: 05/2010
Approval 12/2010

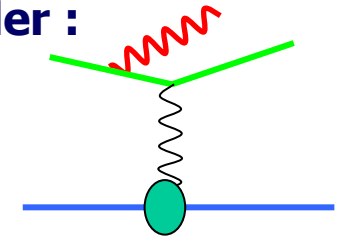
CERN-SPSC-2010-014/SPSC-P-340

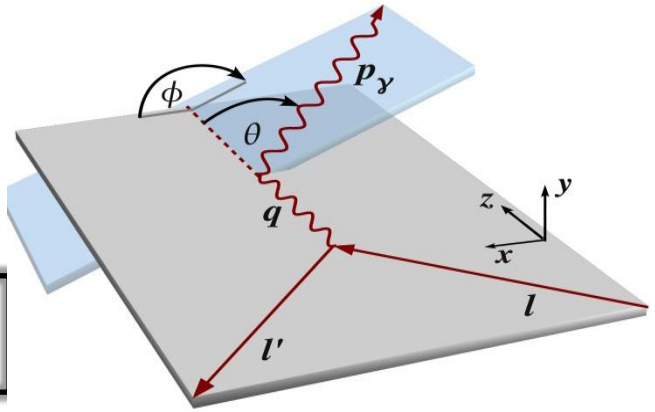
Bethe-Heitler & DVCS Cross Sections at 160GeV

DVCS :

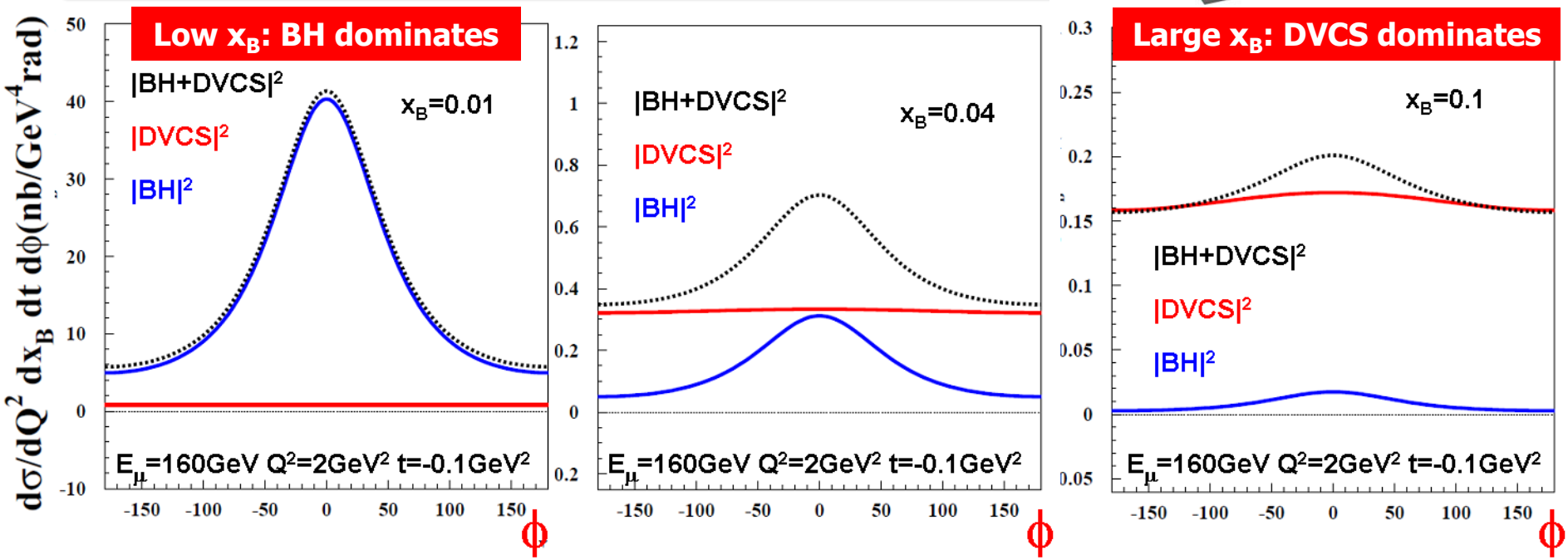


Bethe-Heitler :



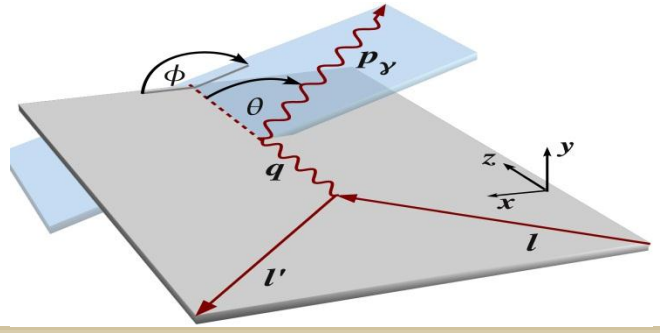


$$d\sigma \;\alpha\; |T_{DVCS}|^2 + |T_{BH}|^2 + \text{Interference Term}$$



- **Reference yield from almost pure BH**
- **Study DVCS through interference term**
  - $\mathcal{R}e\, T^{DVCS}$ & $\mathcal{I}m\, T^{DVCS}$
- **Study $d\sigma^{DVCS}/dt$**
  - **Transverse Imaging**

Observables (Phase 1) – unpolarized Target



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

- Beam Charge & Spin Sum:

$$S_{CS,U} = d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH}\,Im\,T^{DVCS}\right)$$

$$c_0^{DVCS+BH} + c_1^{DVCS+BH}\cos\phi + c_2^{DVCS+BH}\cos 2\phi)$$

$\frac{d\sigma}{d|t|}$

$$s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi$$

$Im(F_1\ \mathcal{H}\ )$

- Beam Charge & Spin Difference:

$$\mathcal{D}_{CS,U} = d\sigma^{+\leftarrow} - d\sigma^{-\rightarrow} = 2\left(P_\mu d\sigma^{DVCS}_{pol} + e_\mu a^{BH}\,\mathcal{R}e\,T^{DVCS}\right)$$

$$s_1^{DVCS}\sin\phi$$

$$c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi$$

$\mathcal{R}e(F_1\ \mathcal{H}\ )$

Projections

(some few examples)

- Unpolarized Target (COMPASS-II, Phase 1)
- Beam Charge and Spin Sum, Difference and Asymmetry
- … for DVCS and HEMP

Beam Charge & Spin Difference $S_{CS,U}$ - Transverse imaging

$$S_{CS,U} = d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH}\, Im\, T^{DVCS}\right)$$

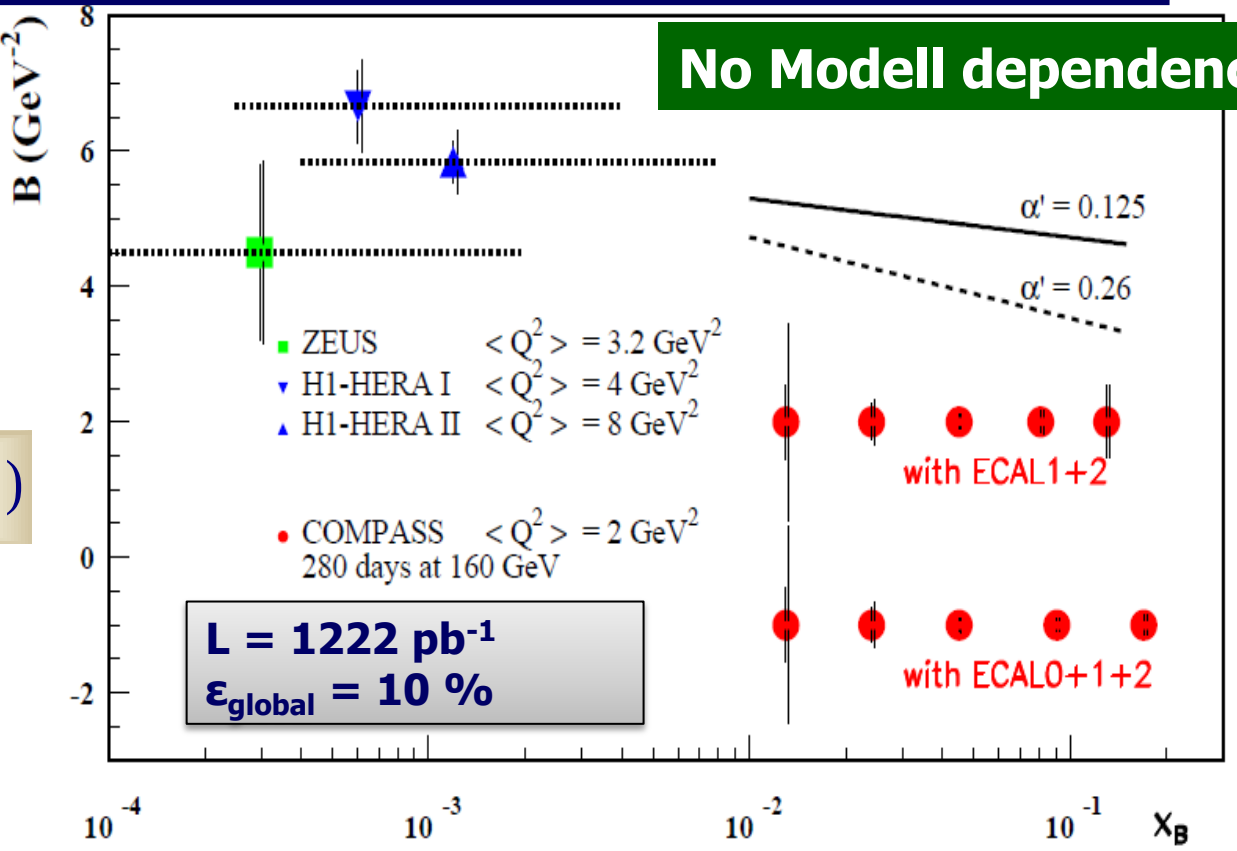
- Using $S_{CS,U}$
- Integrating over ϕ
- Subtracting BH

$$\frac{d\sigma}{d|t|} \propto e^{-B|t|}$$

$$\left\langle r_\perp^2(x_B)\right\rangle \sim 2B(x_B)$$

- Ansatz at small x_B: ($x \sim x_B$)

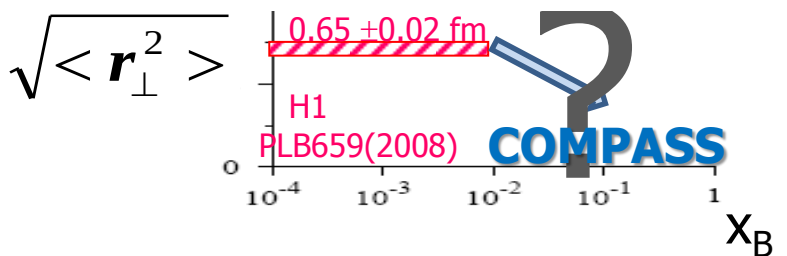
$$B(x_B) = b_0 + 2\alpha' \ln {x_0}/{x_B}$$



measure α′ with accuracy >2.5 σ

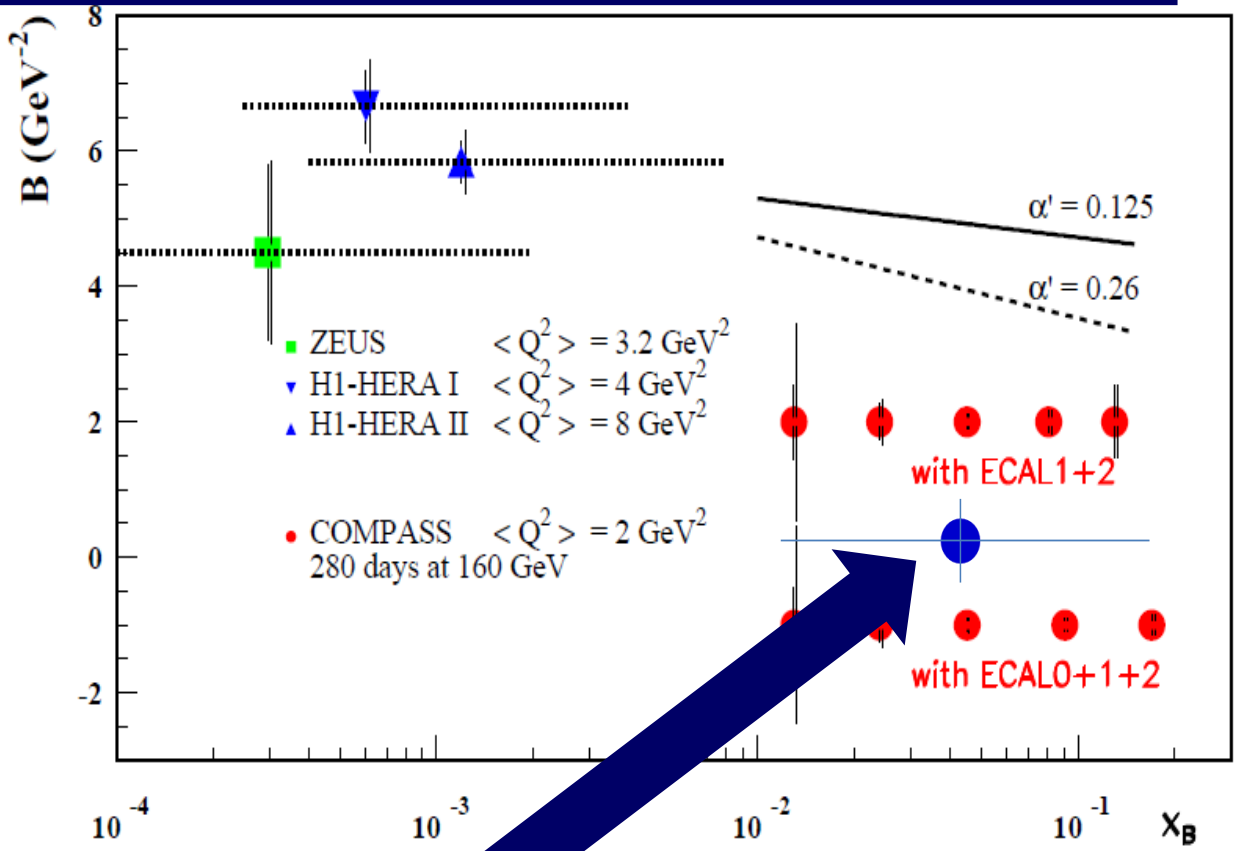
for: α′ > 0.26 (with ECAL 1+2)

α′ > 0.125 (with ECAL 0+1+2)



$S_{CS,U}$ - Transverse imaging - 2012

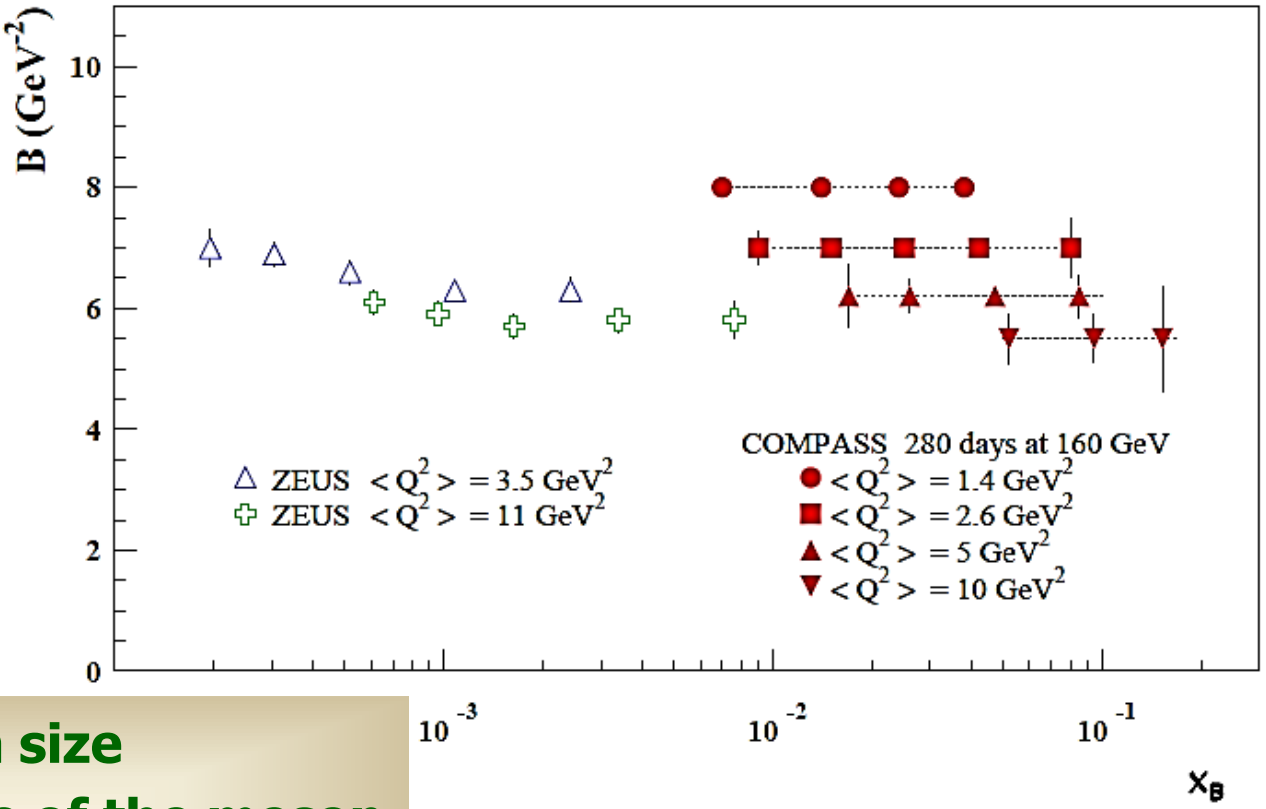
$$S_{CS,U} = d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} = 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu a^{BH}\, Im\, T^{DVCS}\right)$$



Projection for commissioning run 10/2012

Complementary: Hard Exclusive ρ^0 Production

$$\frac{d\sigma_{\rho VMP}}{d|t|} \propto e^{-B|t|}$$



Sensitive to the nucleon size
+ the transverse size of the meson

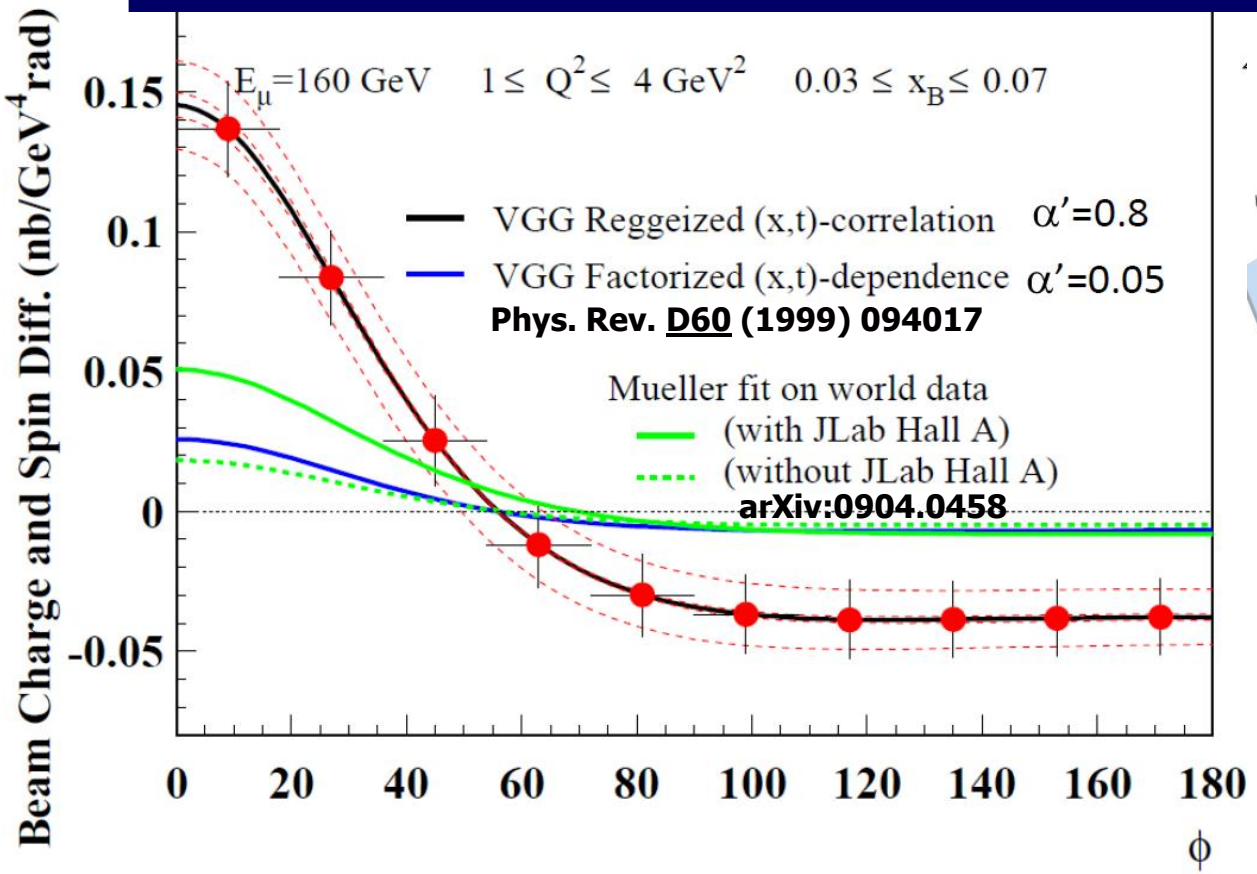
- **Q^2= 1 GeV^2 B ~ 8 GeV^{-2}**
- **Q^2= 10 GeV^2 B ~ 5.5 GeV^{-2}**

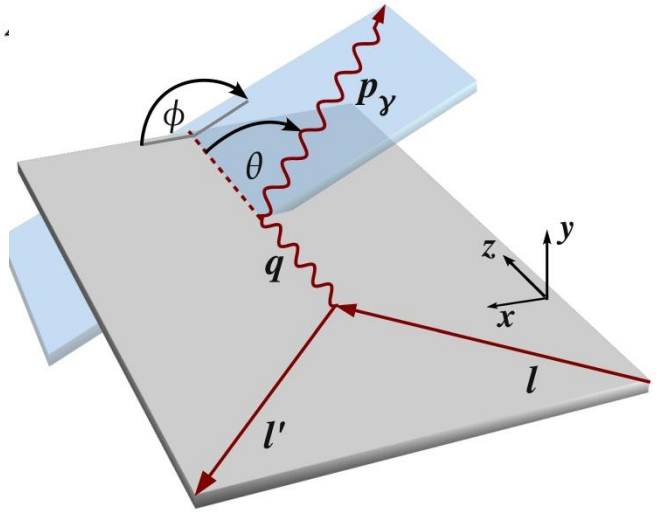
Will help to constrain
$H\rho^0 = 1/\sqrt{2}\,(2/3\,H^u + 1/3\,H^d + 3/8\,H^g)$

ρVMP model developed by A. Sandacz
- Normalized according Goloskokov and Kroll

Beam Charge & Spin Difference $\mathcal{D}_{CS,U}$

$$\mathcal{D}_{CS,U} = d\sigma^{+\leftarrow} - d\sigma^{-\rightarrow} = 2\left(P_\mu d\sigma_{pol}^{DVCS} + e_\mu a^{BH}\mathcal{R}e\,T^{DVCS}\right)$$





L = 1222 pb^{-1}
ε_{global} = 10 %

- **Control detector acceptance and beam flux with high precision**
- **Error band assumes a 3% systematic uncertainty between μ^+ and μ^-**
- **Use inclusive events and BH for check**

Beam Charge & Spin Asymmetry $\mathcal{D}_{CS,U} / \mathcal{S}_{CS,U}$

BCSA $= \mathcal{D}_{CS,U} / \mathcal{S}_{CS,U}$

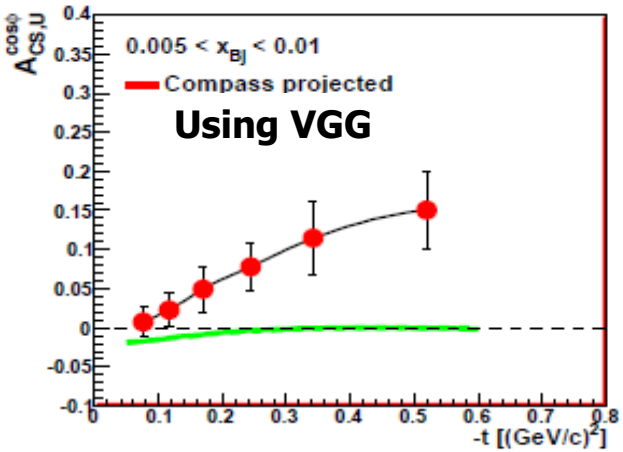
$= A_0 + A_{CS,U} \cos\phi + A_2 \cos 2\phi$

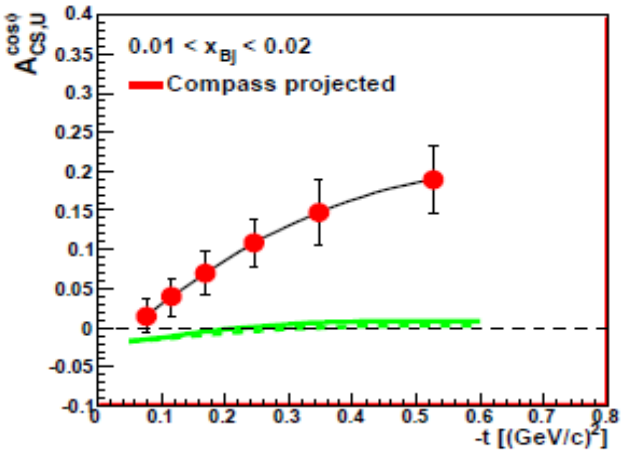
$\mathcal{Re}(F_1\mathcal{H}) > 0$ @ H1

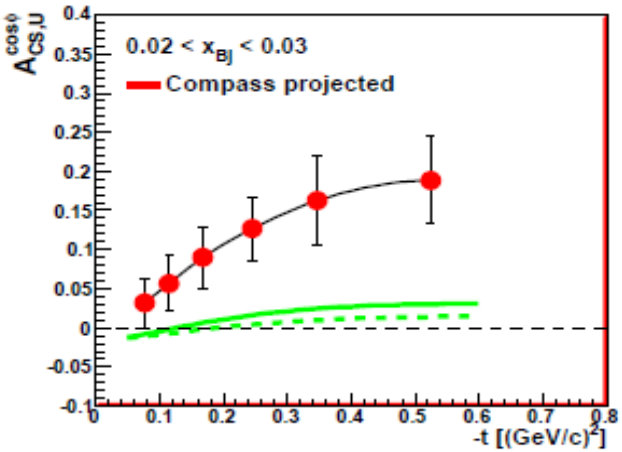
< 0 @ HERMES

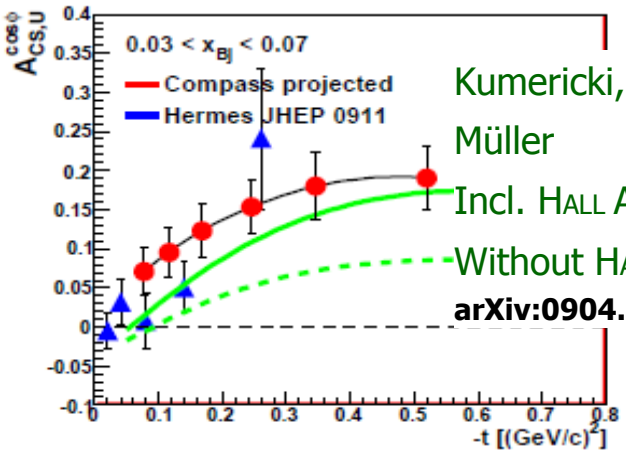
Node?

Measurement of c_1^{Int}







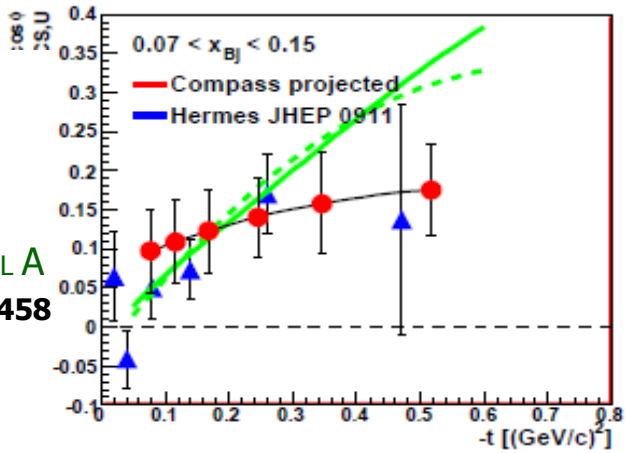


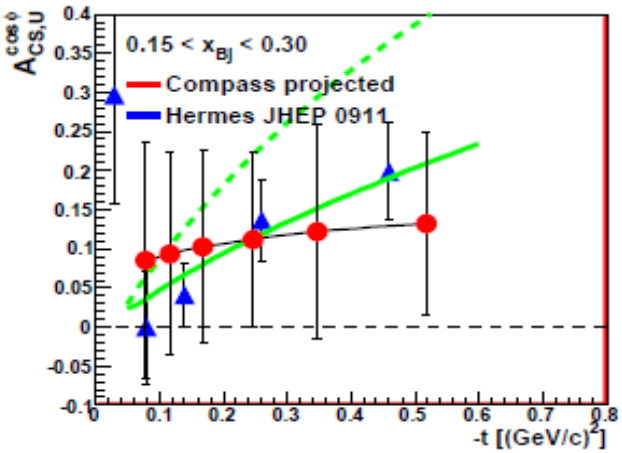
Kumericki, Müller

Incl. HALL A

Without HALL A

arXiv:0904.0458



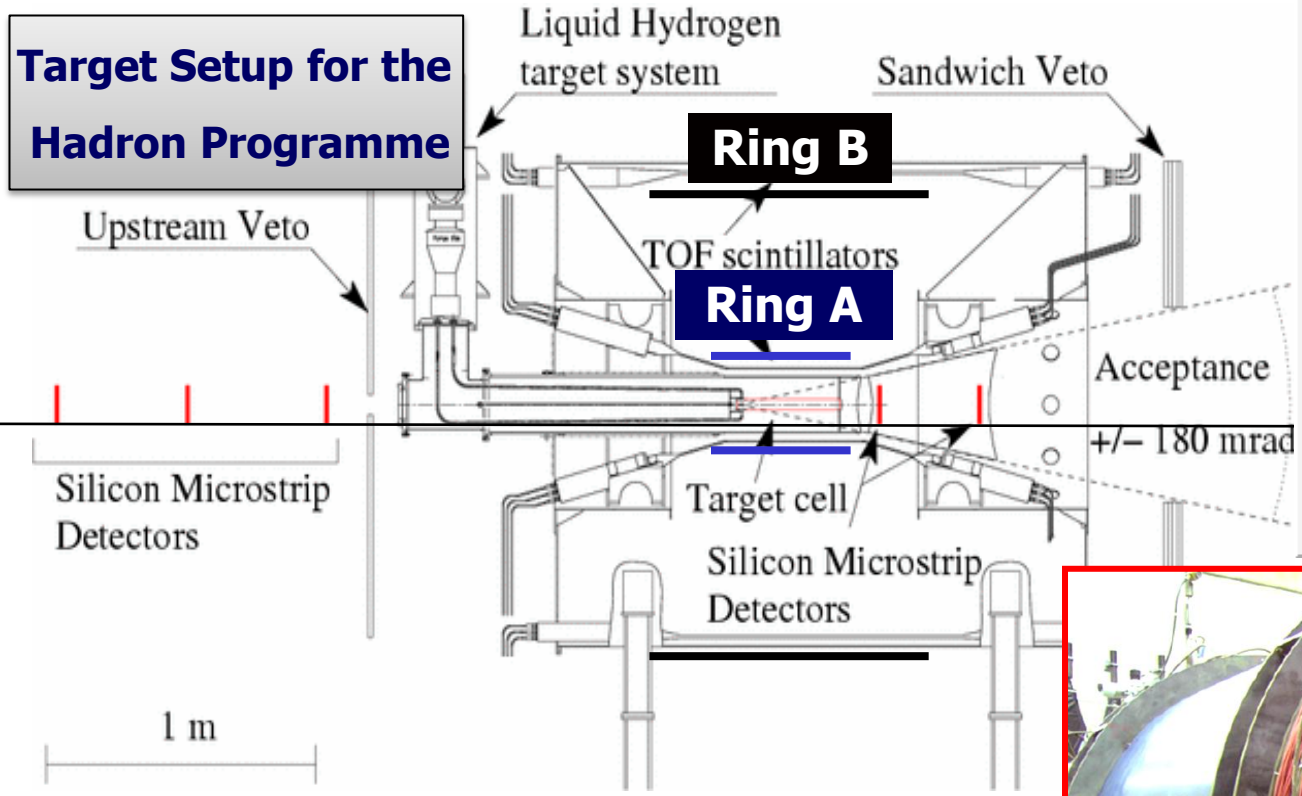


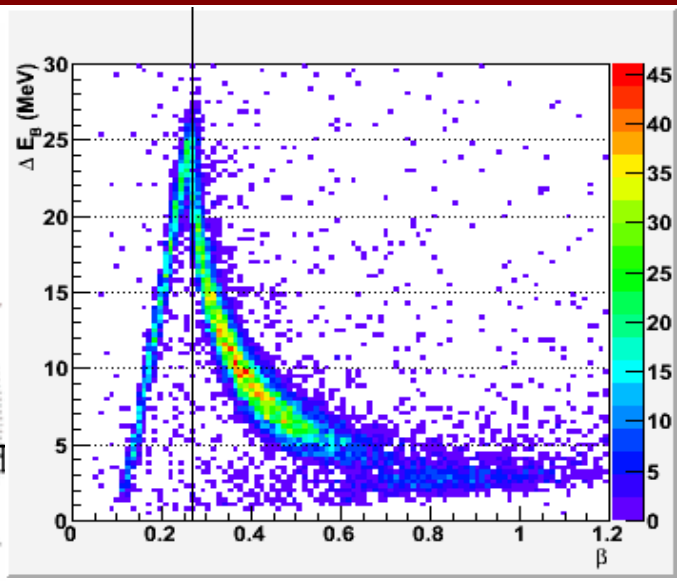
Beam Tests @ COMPASS

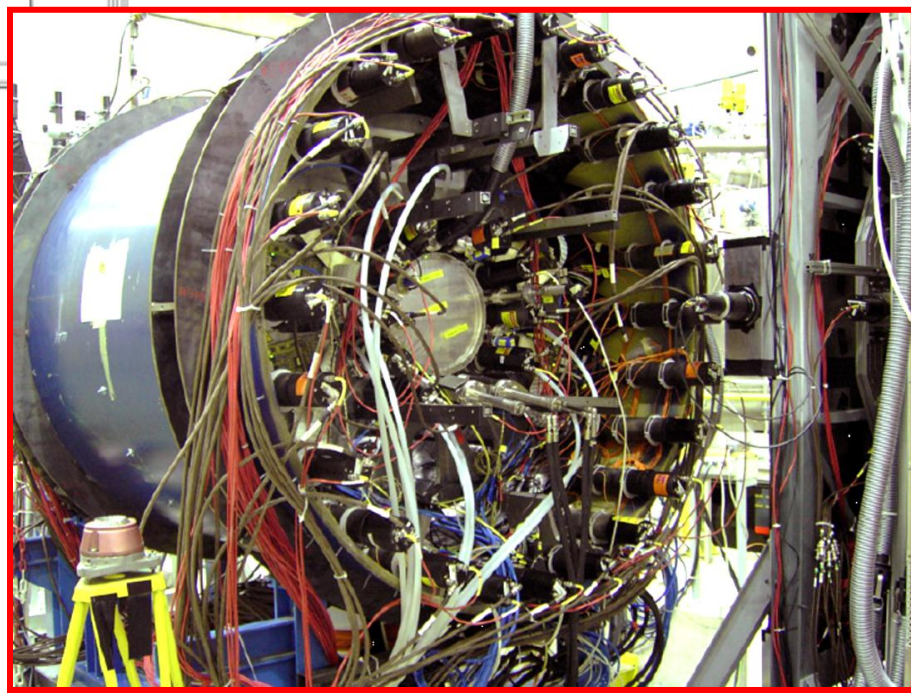
- 2008 (8 hours)
- 2009 (10 * statistics of 2008)

2008 & 2009 Beam Tests @ COMPASS

Target Setup for the Hadron Programme

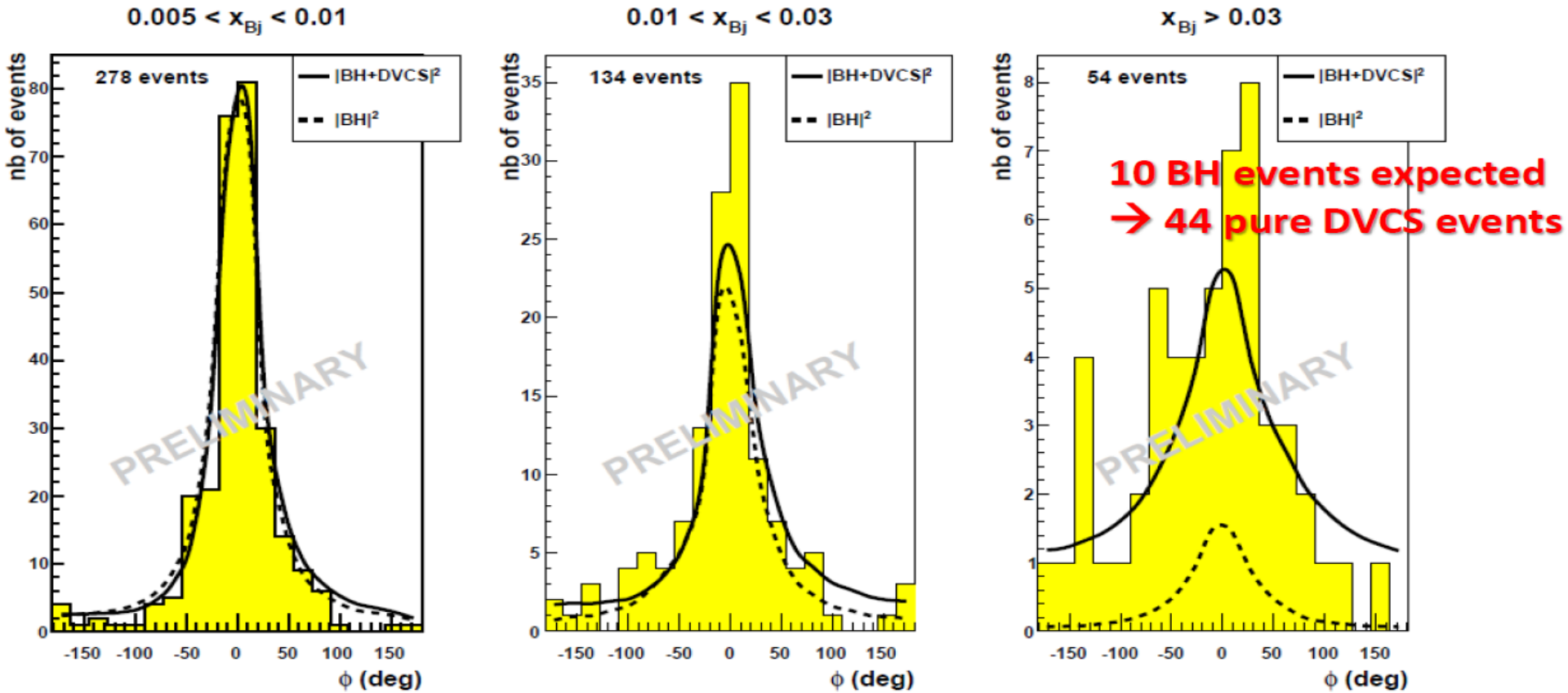






- Target : 40 cm LH2
- Recoil Detector (1m long)
- ECAL 1 & ECAL 2

First DVCS Signal observed @ COMPASS



- Detection efficiency :

  $\varepsilon_{\mu+p\to\mu+p+\gamma} = 0.32+/-0.13$

Global efficiency :

$\varepsilon_{global} = 0.13 +/- 0.05$

- $\mu+p \to \mu+p+\gamma$ efficiency
- SPS & COMPASS availability
- Dead time
- Trigger efficiency

Conclusion:

Projections of errors are realistic

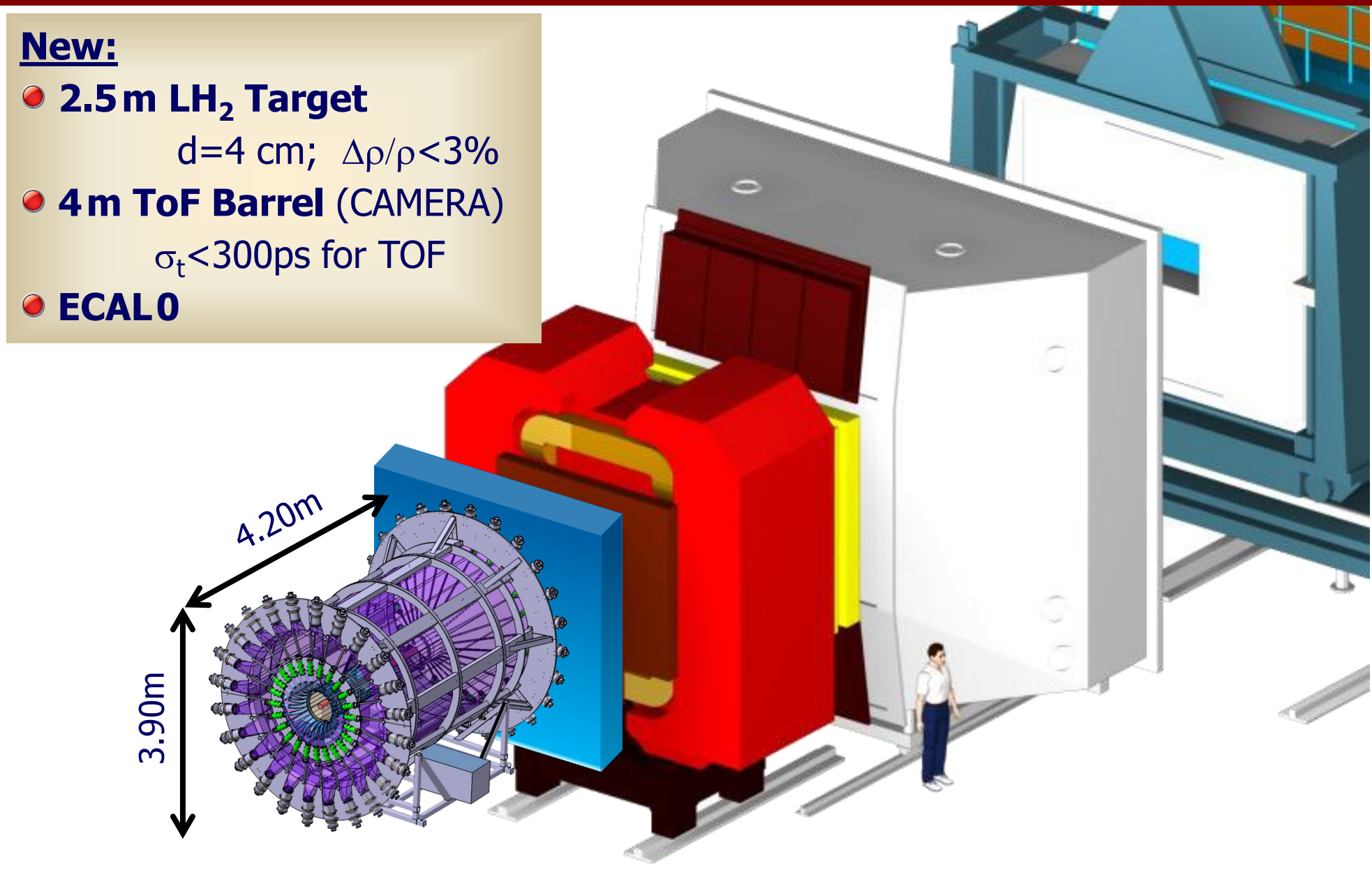
Main Detector Upgrades for COMPASS-II (DVCS/HEMP)

- Recoil-Proton Detector
- Electromagnetic Calorimeter (ECAL0)

New Target & Recoil-Proton Detector

New:

- **2.5 m LH_2 Target**
  d=4 cm; $\Delta\rho/\rho<3\%$
- **4 m ToF Barrel** (CAMERA)
  $\sigma_t<300$ps for TOF
- **ECAL0**



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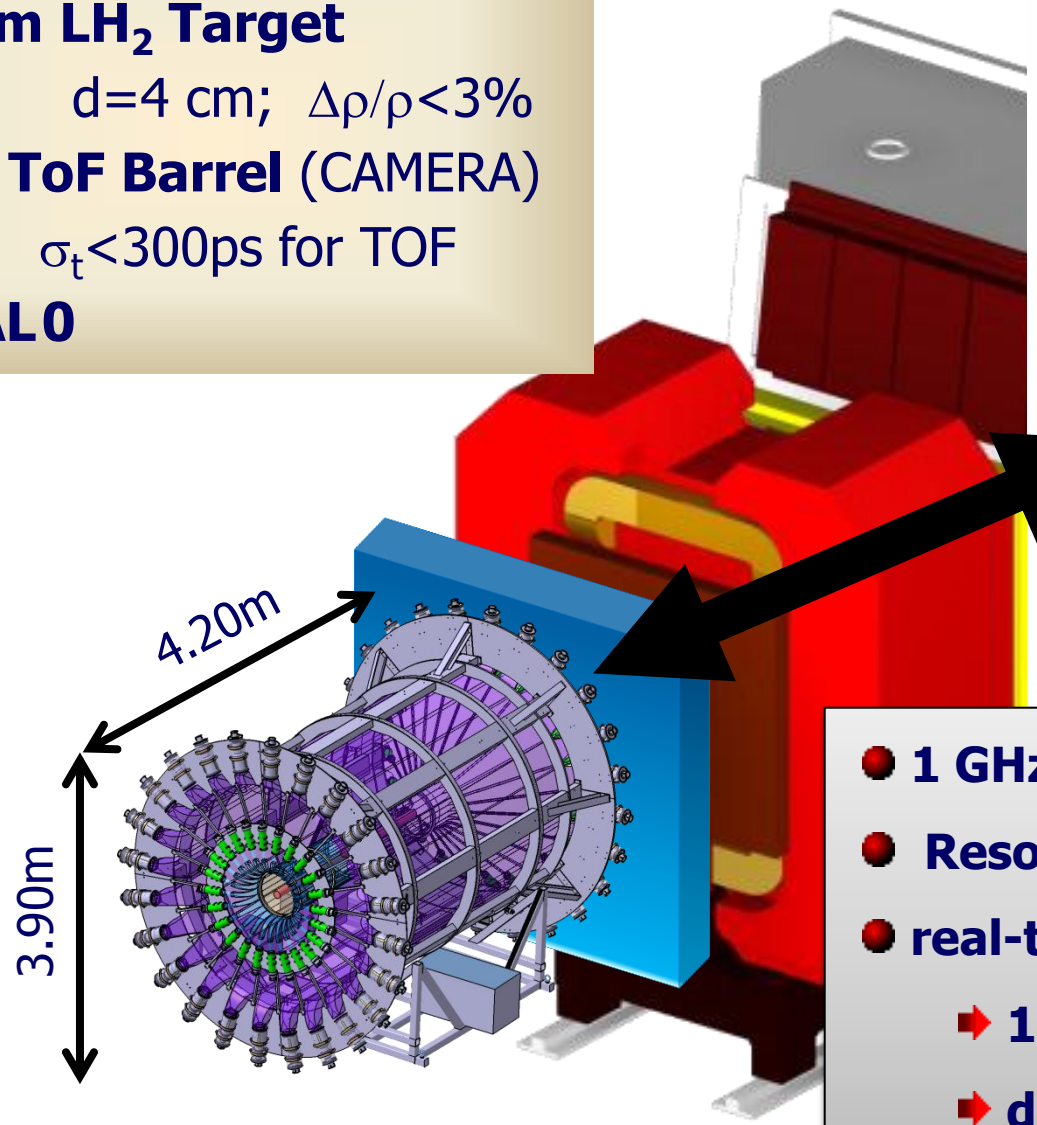
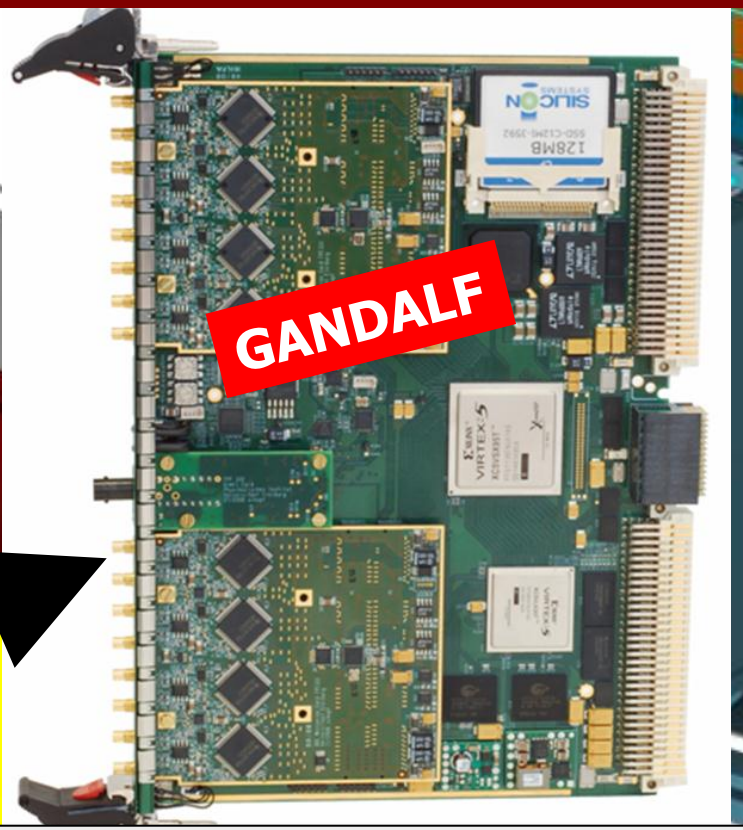




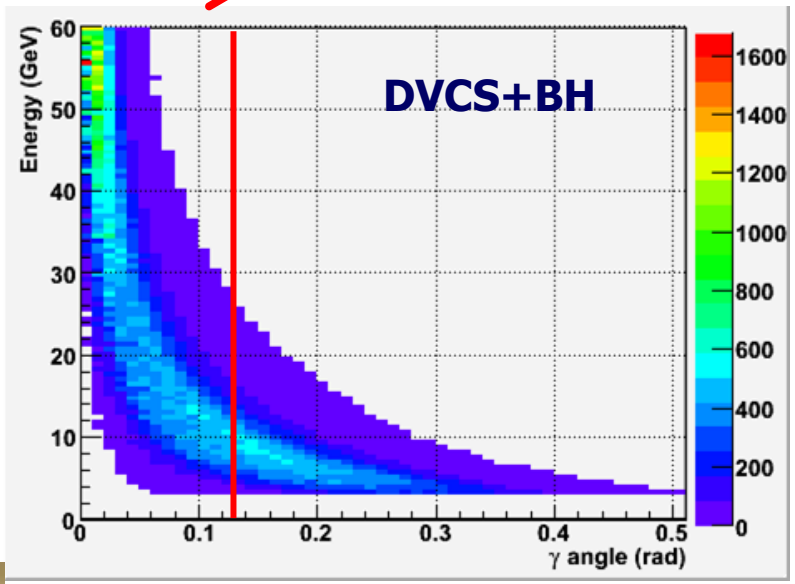
- **1 GHz digitization of PMT signal**
- **Resolution >10 ENOB**
- **real-time feature extraction**
  - **1st level trigger**
  - **detector signal digitization**

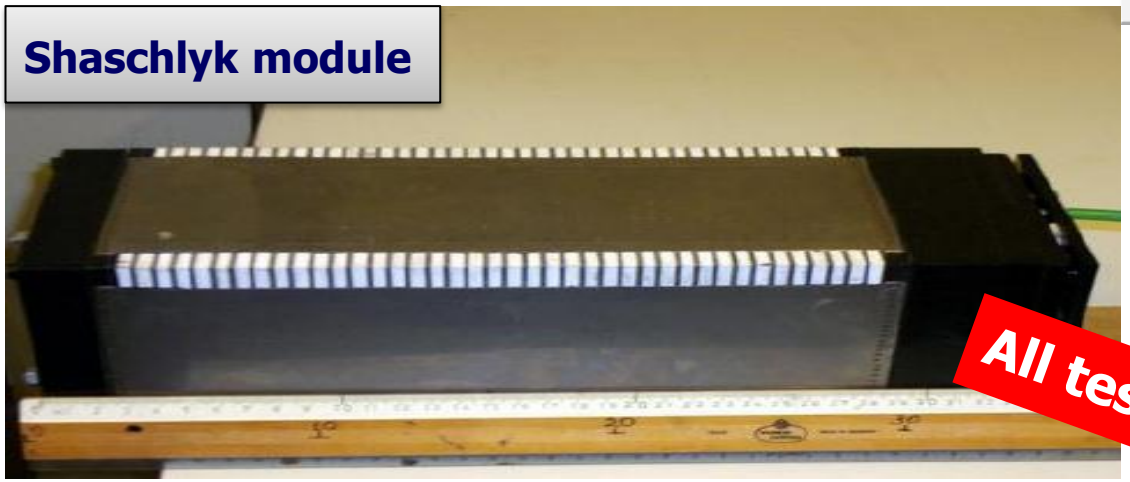
New Electromagnetic Calorimeter : ECAL0

Requirements

- Photon energy range 0.2- 30 GeV
- Size: 260 x 260 cm² ;
- Granularity 12 x 12 cm²
- Energy resolution < 10.0%/√E (GeV)
- Thickness < 50 cm,
- Insensitive to the magnetic field.

existing ECAL1&2





Conclusions

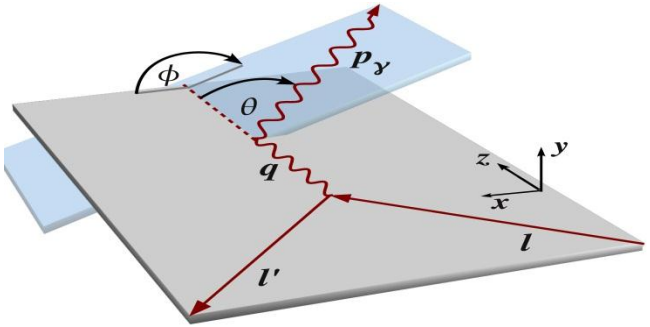
- **Azimuthal Asymmetries in polarized exclusive ρ^0 production**
  - small & compatible with zero
  - reasonable agreement with Goloskokov&Kroll prediction
  - may indicate E^u and E^d cancelation

- **COMPASS II: investigate quark GPDs using DVCS**
  - Covered x_B regime not accessible to any other experiment in near future
  - Frequent changes of beam charge and polarization – UNIQUE!
  - Study nucleon transversal dimension as function of x_B (Tomography)
  - Constrain GPD H through ϕ dependence of $\mathcal{D}_{CS,U}$

- **Phase 2: DVCS & HEMP with polarized NH_3 Target inside RPD**
  - Use knowledge of GPD H as input to constrain GPD E
  - Requires highly sophisticated recoil detection & polarized target systems

Backup

Cross Section & Angular Dependence



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

- $d\sigma^{BH} = \frac{\Gamma(x_B,Q^2,t)}{P_1(\phi)P_2(\phi)}(c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi)$ ← **Known (good for reference)**
- $d\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2Q^2}(c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi)$
- $d\sigma^{DVCS}_{pol} = \frac{e^6}{y^2Q^2}(s_1^{DVCS}\sin\phi)$
- $a^{BH}\,\mathcal{R}e\,T^{DVCS} = \frac{e^6}{xy^3tP_1(\phi)P_2(\phi)}(c_0^{Int} + c_1^{Int}\cos\phi + c_2^{Int}\cos 2\phi + c_3^{Int}\cos 3\phi)$
- $a^{BH}\,Im\,T^{DVCS} = \frac{e^6}{xy^3tP_1(\phi)P_2(\phi)}(s_1^{Int}\sin\phi + s_2^{Int}\sin 2\phi)$

Twist 2 **Twist 3** **Twist 2 gluon**

Input for Projections

- **Naturally polarized μ Beam with 160 GeV/c momentum → P_{Beam}=80%**
- **48 s SPS cycle with 9.6 s spill duration**
- **beam intensity 4.6 x 10^8 μ^+/spill = 9.6 x 10^6 μ^+/s (DC)**
- **3 times smaller intensity for μ^-**

- **data taking: 280 days → 70 days μ^+, 210 days μ^-**

- **Target:** **a) 2.5m liquid Hydrogen → $\mathcal{L}$ = 1 x 10^{32} $cm^{-2}s^{-1}$**
  b) 1.2m NH_3 (polarized) → $\mathcal{L}$ = 3.4 x 10^{32} $cm^{-2}s^{-1}$
  P_{target}=90%, dilution factor f=0.17

- **New recoil-proton detector**
- **ECAL1** (40…150mrad)**, ECAL2** (0…40mrad) **+ new ECAL0** (150…300mrad)

- **Global efficiency ε=0.1** (SPS, COMPASS, tracking, photon)

Parameterization of GPDs

Predictions based on different models

- **Factorisation:** $H(x,\xi,t) \propto q(x)\, F(t)$

- **Regge motivated t dependence:** **x-t correlation**

  Core of fast partons, meson cloud at larger distance

  $H(x,\xi,t) \propto q(x) \exp(-B|t|)$

  Ansatz: $B = \frac{1}{2}\left\langle b_\perp^2 \right\rangle = B_0 + 2\alpha' \ln \frac{x_0}{x}$ (α' slope of Regge trajectory)

  Valence quarks: $\alpha' \sim 1$ GeV^{-2} from form factors

  Gluons: α' small

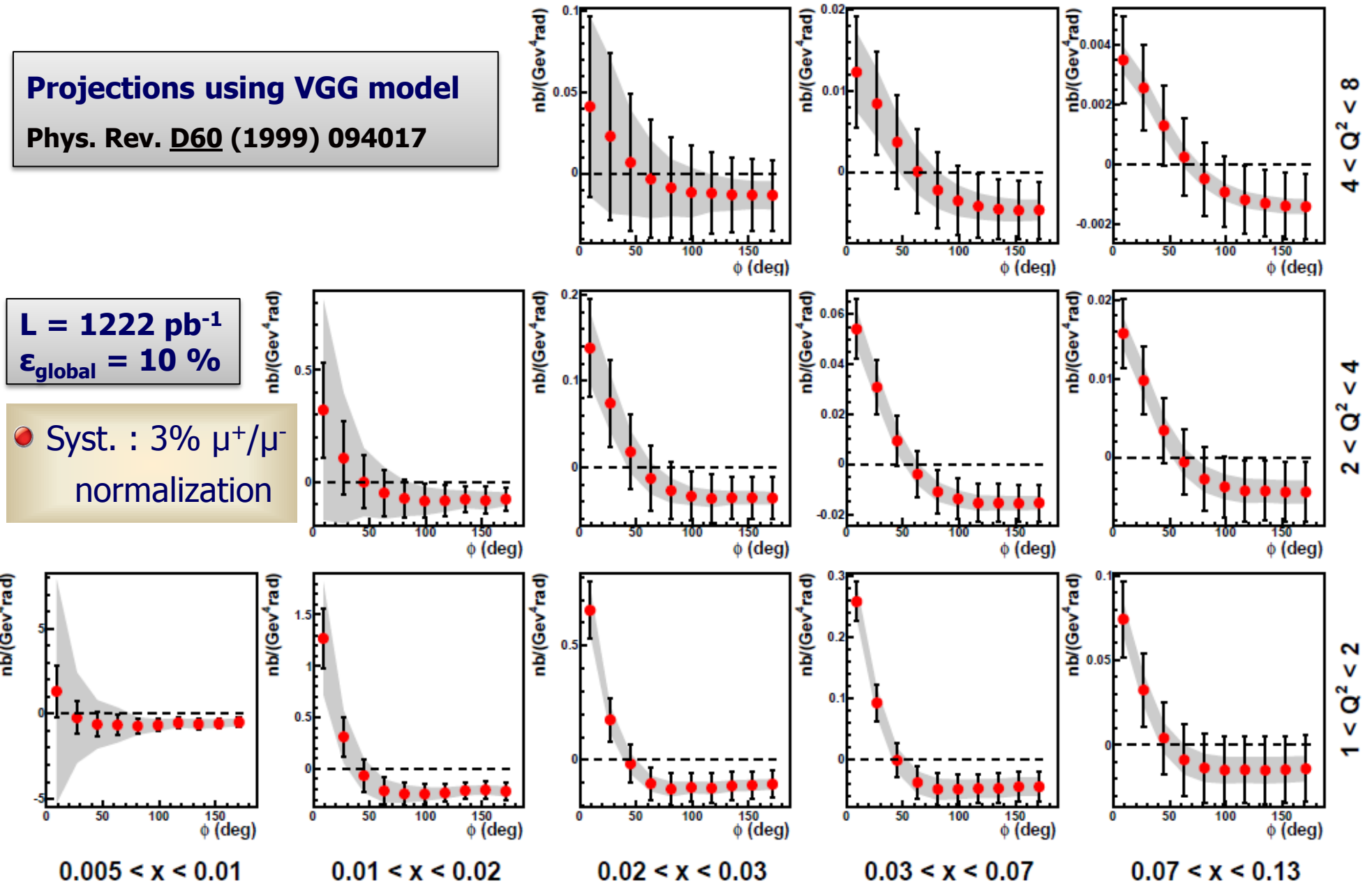
Beam Charge & Spin Difference $\mathcal{D}_{CS,U}$

Projections using VGG model

Phys. Rev. D60 (1999) 094017

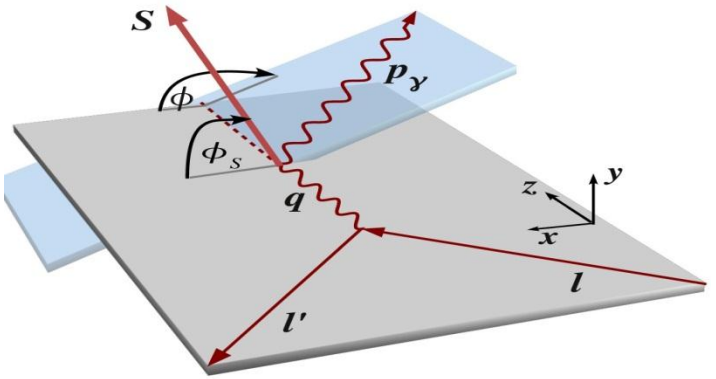
L = 1222 pb^{-1}
ε_{global} = 10 %

- Syst. : 3% μ^+/μ^- normalization



Observables (Phase 2) – polarized Target

$$d\sigma_{(\mu p\to\mu p\gamma)}(\phi,\phi_S) = d\sigma_U(\phi) + S_T\, d\sigma_T(\phi,\phi_S)$$



- Beam Charge & Spin Sum:

$$S_{CS,T} = \left\{d\sigma^{+\leftarrow}(\phi,\phi_S) - d\sigma^{+\leftarrow}(\phi,\phi_S+\pi)\right\} + \left\{d\sigma^{-\rightarrow}(\phi,\phi_S) - d\sigma^{-\rightarrow}(\phi,\phi_S+\pi)\right\}$$

- Beam Charge & Spin Difference:

$$\mathcal{D}_{CS,T} = \left\{d\sigma^{+\leftarrow}(\phi,\phi_S) - d\sigma^{+\leftarrow}(\phi,\phi_S+\pi)\right\} - \left\{d\sigma^{-\rightarrow}(\phi,\phi_S) - d\sigma^{-\rightarrow}(\phi,\phi_S+\pi)\right\}$$

- Lepton-Charge-Averaged Unpolarized Cross-Section:

$$\Sigma_{unpol} = \tfrac{1}{2}\left[\left\{d\sigma^{+\leftarrow}(\phi,\phi_S) + d\sigma^{+\leftarrow}(\phi,\phi_S+\pi)\right\} + \left\{d\sigma^{-\rightarrow}(\phi,\phi_S) - d\sigma^{-\rightarrow}(\phi,\phi_S+\pi)\right\}\right]$$
$$+ \tfrac{1}{2}\left[\left\{d\sigma^{+\leftarrow}(-\phi,\phi_S) + d\sigma^{+\leftarrow}(-\phi,\phi_S+\pi)\right\} + \left\{d\sigma^{-\rightarrow}(-\phi,\phi_S) - d\sigma^{-\rightarrow}(-\phi,\phi_S+\pi)\right\}\right]$$

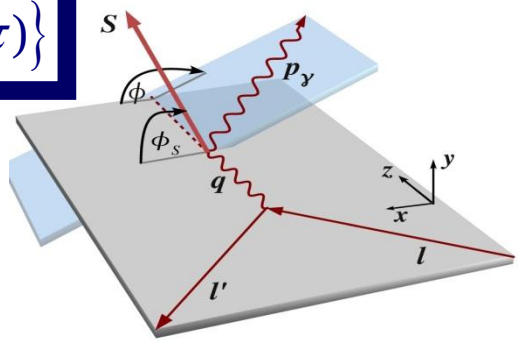
$$\mathcal{A}^{S}_{CS,T} = \frac{S_{CS,T}}{\Sigma_{unpol}}$$

$$\mathcal{A}^{\mathcal{D}}_{CS,T} = \frac{\mathcal{D}_{CS,T}}{\Sigma_{unpol}}$$

$\mathcal{D}_{CS,T}$ and Transverse Target Asymmetry

$$\mathcal{D}_{CS,T} = \left\{ d\sigma^{+\leftarrow}(\phi,\phi_S) - d\sigma^{+\leftarrow}(\phi,\phi_S+\pi) \right\} - \left\{ d\sigma^{-\rightarrow}(\phi,\phi_S) - d\sigma^{-\rightarrow}(\phi,\phi_S+\pi) \right\}$$

$$\mathcal{D}_{CS,T} \propto Im(\, F_2\mathcal{H} - F_1\mathcal{E}\,)\sin(\phi-\phi_S)\cos\phi$$



Beam: 160 GeV muon
Target: 1.2 m polarized NH_3
(P=90%, f=0.17)
2 years data taking
ε_{global} = 10 %

Constrain GPD E