Prospects for GPD study @ COMPASS

with Deeply Virtual Compton Scattering and Meson Production

Nicole d'Hose, CEA-Saclay, France, on behalf of the COMPASS Collaboration

NAPP2010 , Dubrovnik, 5 October 2010

COMPASS: A Facility to study QCD

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

Studies until 2011:

- **Nucleon Spin** with high energy polarized μ beams + polarized targets:
  longitudinal spin: gluon and quark helicity distribution
  -> Yann Bedfer's talk
  transverse spin and transverse momentum dependent distribution
  -> Christian Schill's talk
- **Spectroscopy** with hadron beams + LH2 (or solid) targets:
  Search of hybrids and glueballs to better understand quark and gluon confinement
  -> Alexander Austregesilo's talk

COMPASS-II: A Facility to study QCD

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY

COMPASS-II has been recommended by SPSC (29 sept 2010) for an initial period of 3 years (likely 2013-15)

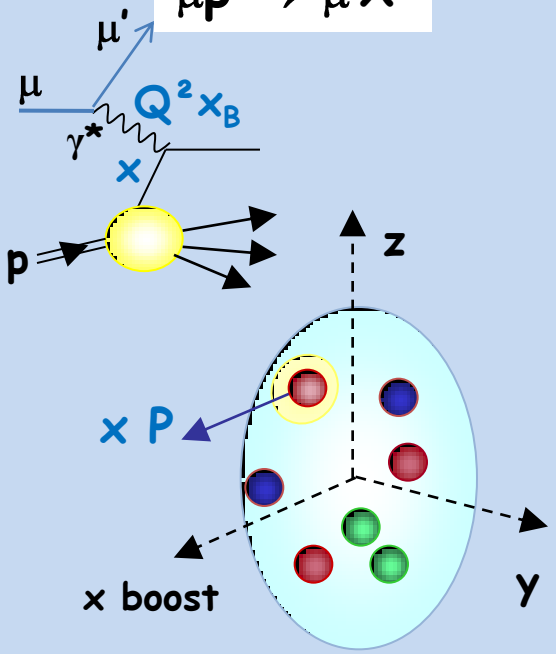
- ✓ Primakoff with π, K beam ➔ Test of Chiral Perturb. Theory
- ✓ DVCS & DVMP with μ beams + LH2 ➔ Transv. Spatial Distrib. with GPDs

  SIDIS ➔ Strange PDF and Transv. Mom. Dep. PDFs
- ✓ Drell-Yan with π beams ➔ Transverse Momentum Dependent PDFs

from inclusive reactions to exclusive reactions

Deep Inelastic Scattering

$\mu p \rightarrow \mu' X$

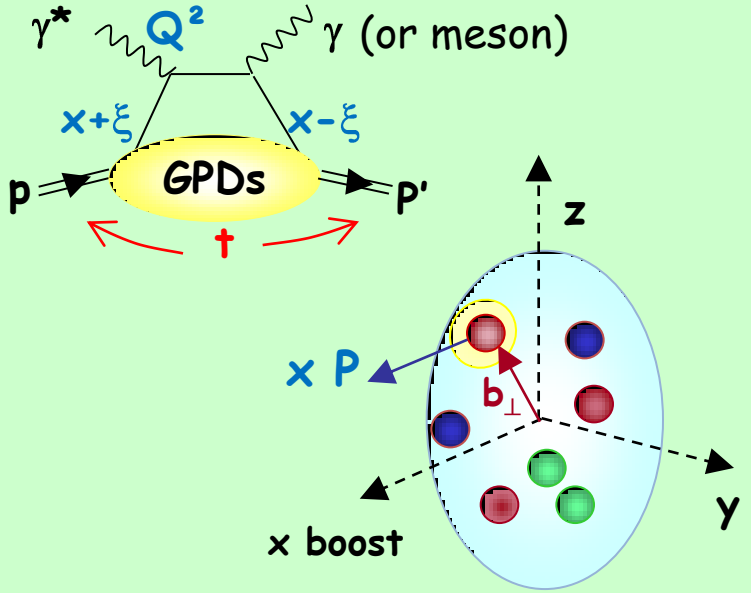


Parton Distribution $q(x)$

P_x

Deeply Virtual Compton Scattering

$\mu p \rightarrow \mu' p' \gamma$



Generalized Partons Distrib. $H(x,\xi,t)$

$(P_x, b_\perp)$

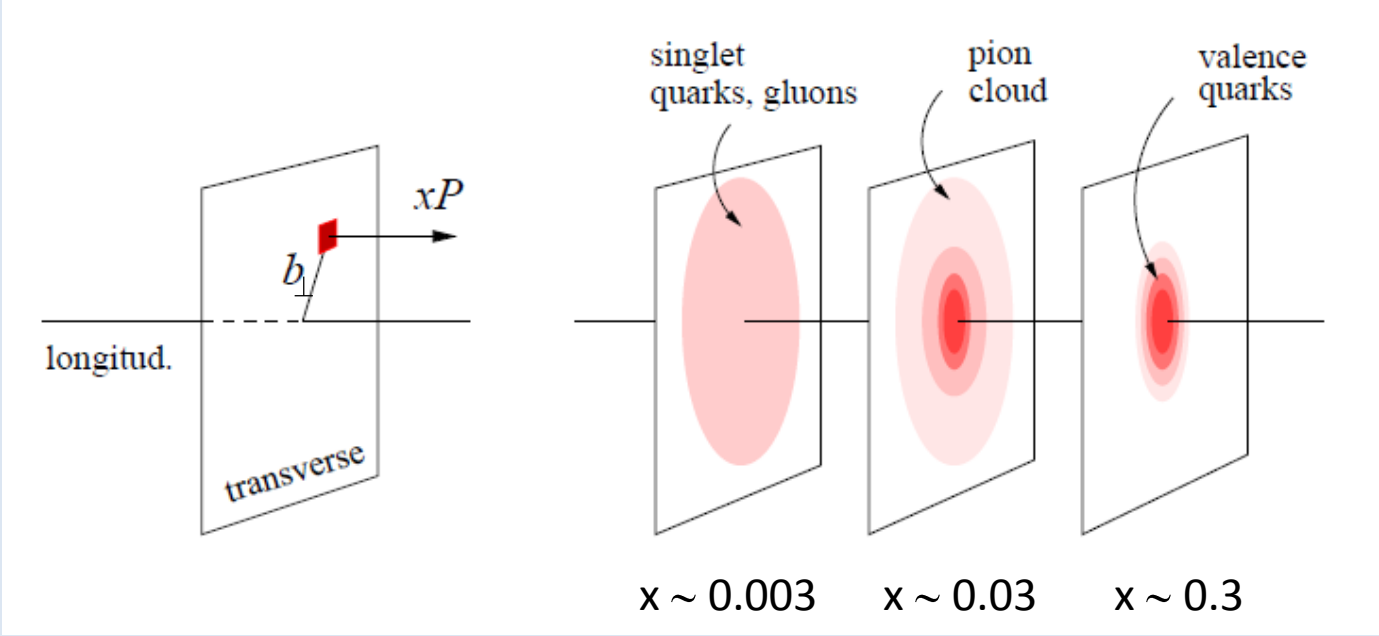
Observation of the Nucleon Structure

in 1 dimension

in 1+2 dimensions

Generalized Partons Distributions (H,E,…)

- Allow for a unified description of form factors and parton distributions
- Allow for transverse imaging (nucleon tomography) and give access to the quark angular momentum (through E)



Impact parameter $b_\perp$

Longitudinal momentum fraction x

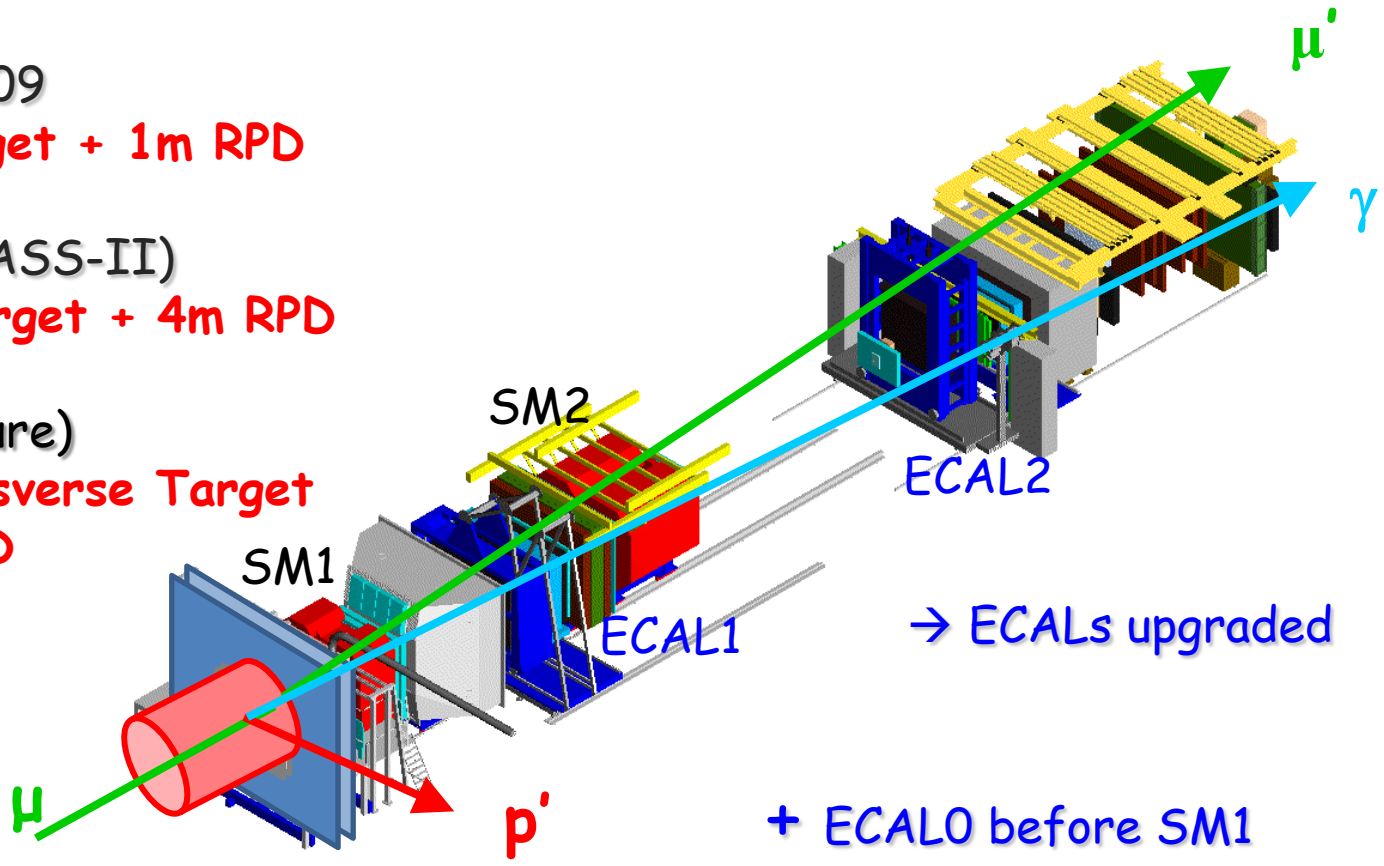
Tomographic parton images of the nucleon

Experimental requirement for exclusive measurement
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

Tests in 2008-09
40cm LH2 target + 1m RPD

Phase 1 (COMPASS-II)
2.5 m LH2 target + 4m RPD

Phase 2 (in future)
Polarised Transverse Target
integrating RPD



→ ECALs upgraded

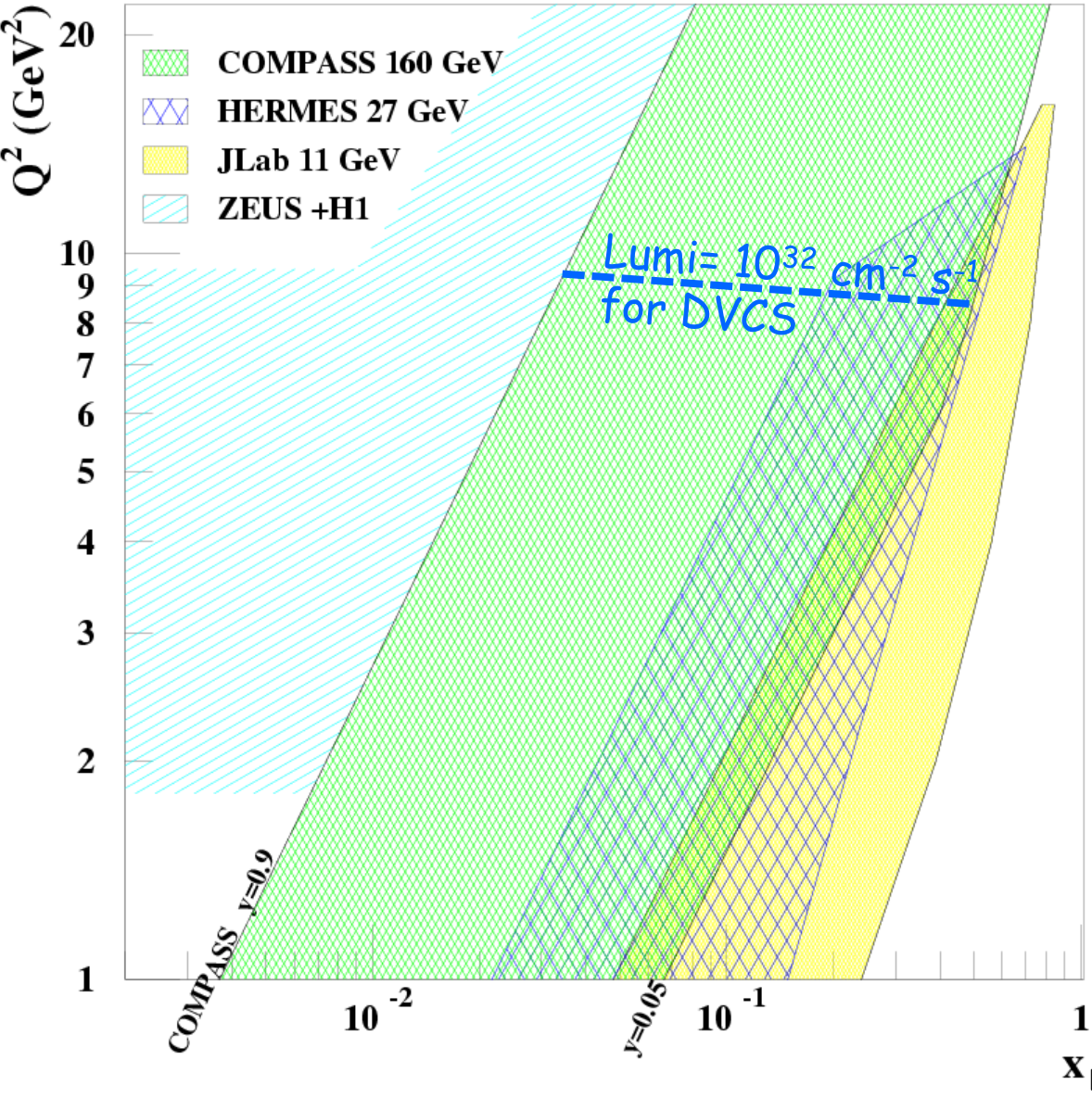
+ ECAL0 before SM1

$4.6\ 10^8\ \mu^+$

for $2.7\ 10^{13}$ protons per SPS spill
(9.6s each 48 s)

➔ Lumi= $10^{32}\ cm^{-2}\ s^{-1}$ with 2.5m LH2 target

What makes COMPASS unique for GPDs?

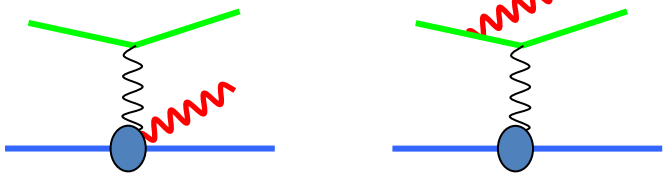


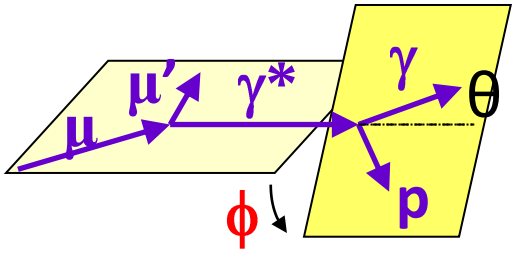
CERN High energy **muon** beam
- ✓ 100 - 190 GeV
- ✓ μ^+ and μ^- available
- ✓ 80% Polarisation

with opposite polarization

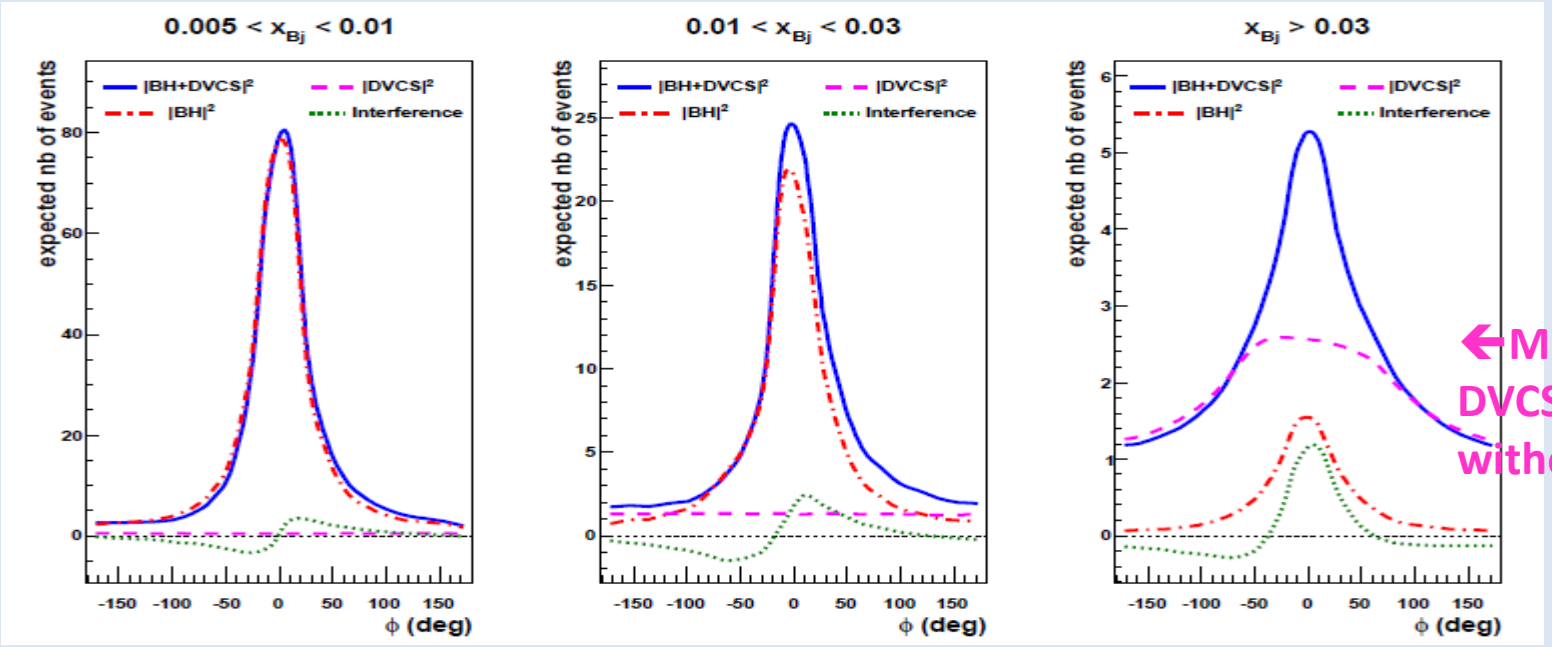
- Will explore the intermediate x_{Bj} region
- Uncovered region between ZEUS+H1 & HERMES + Jlab before new colliders may be available
- Transverse structure at $x \sim 10^{-2}$ essential input for phenemenology of high-energy pp collision (LHC)

Contributions of DVCS and BH at E_μ=160 GeV





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



Monte-Carlo Simulation for COMPASS set-up with only ECAL1+2

←Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

study of Interference

→ Re T^{DVCS} or Im T^{DVCS}

DVCS dominates

study of $d\sigma^{DVCS}/dt$

→ Transverse Imaging

Projections for Phase 1 in COMPASS-II (2013-15)

with recoil proton detection and hydrogen target

➔Transverse Imaging : $d\sigma/dt$

➔Constrains on the GPD H

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p\to\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol}$$

$$+ e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + e_\mu\, P_\mu\, a^{BH}\, Im\, A^{DVCS}$$

Phase 1: DVCS experiment to study the transverse imaging

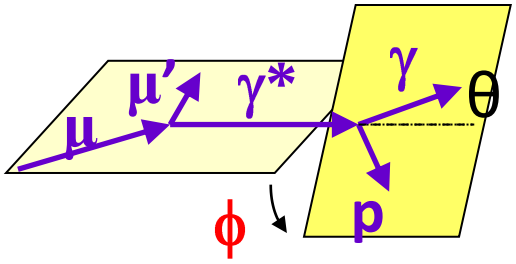
with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

$$S_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K.s_1^{Int}\sin\phi$$

$\downarrow$

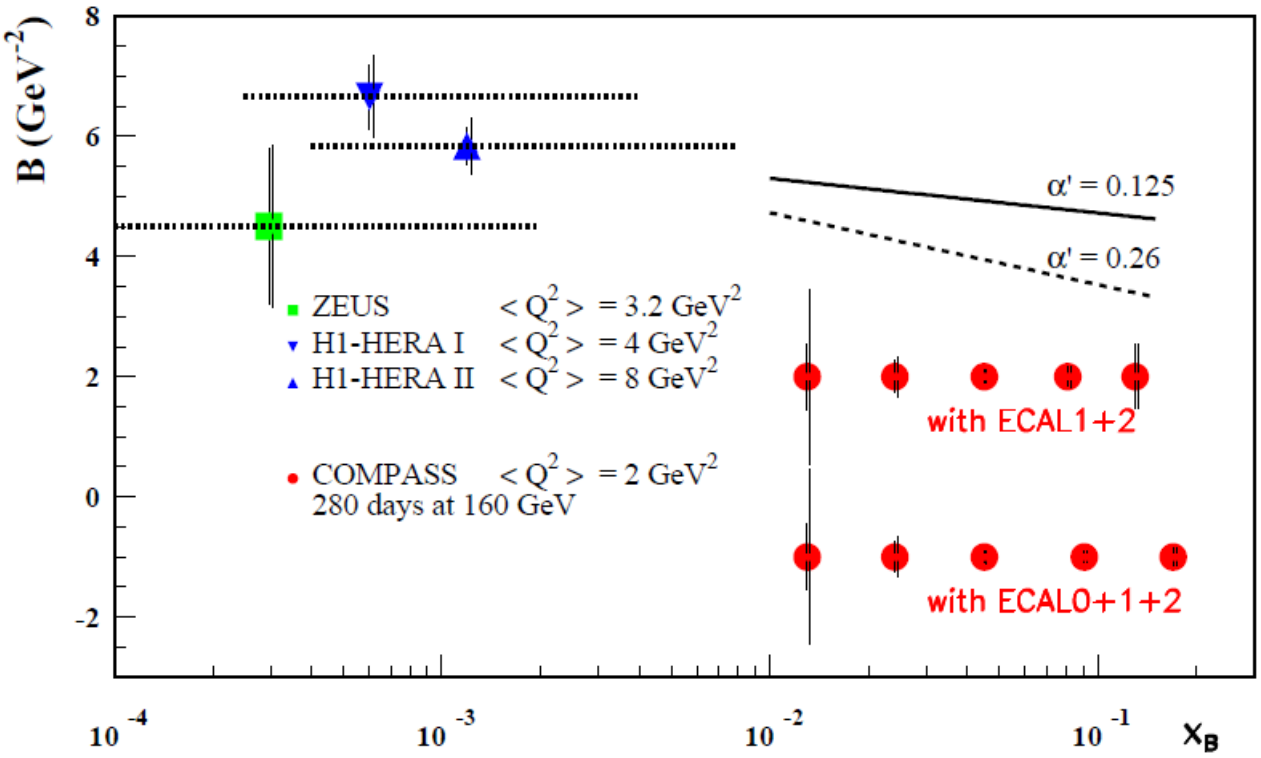
Using $S_{CS,U}$ and integration over ϕ and BH subtraction

$$d\sigma^{DVCS}/dt \sim \exp(-B|t|)$$



DVCS: Transverse imaging at COMPASS

$d\sigma_{DVCS}/dt \sim \exp(-B|t|)$



2 years of data
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$

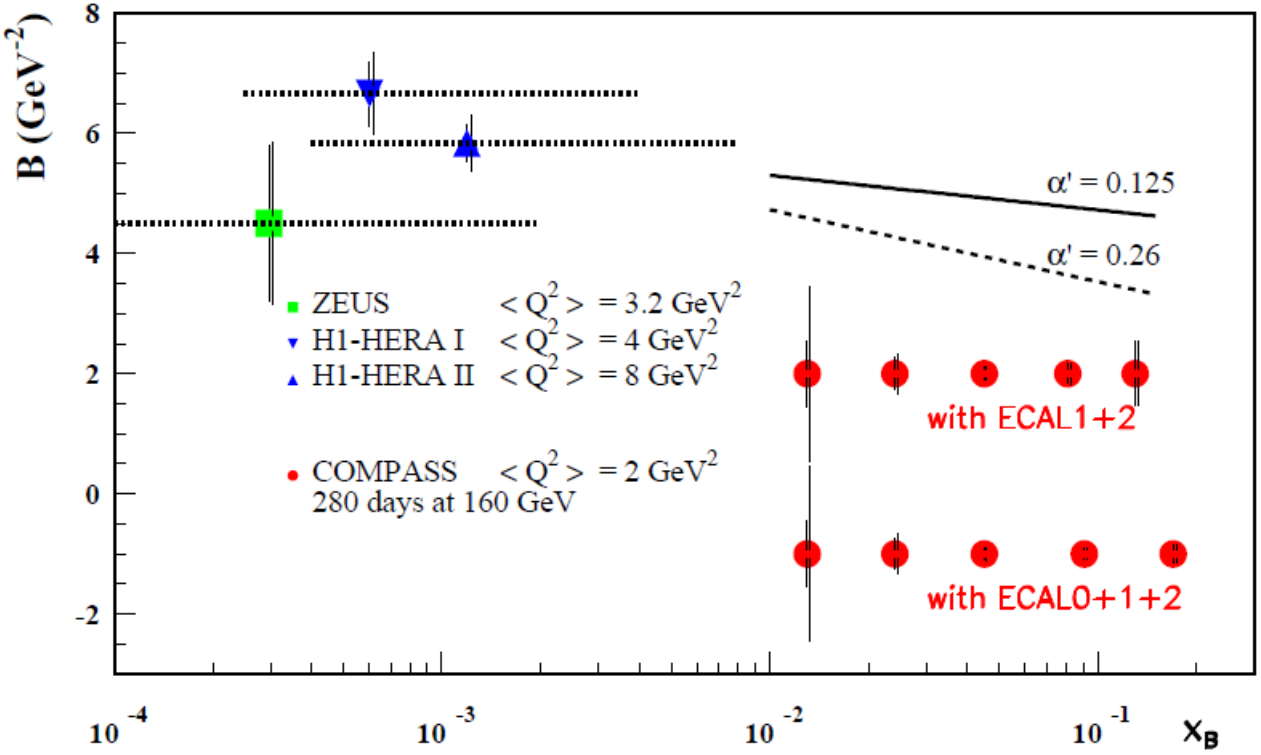
without any model we can extract $B(x_B)$

$$B(x_B) = \tfrac{1}{2} < r_\perp^2(x_B) >$$

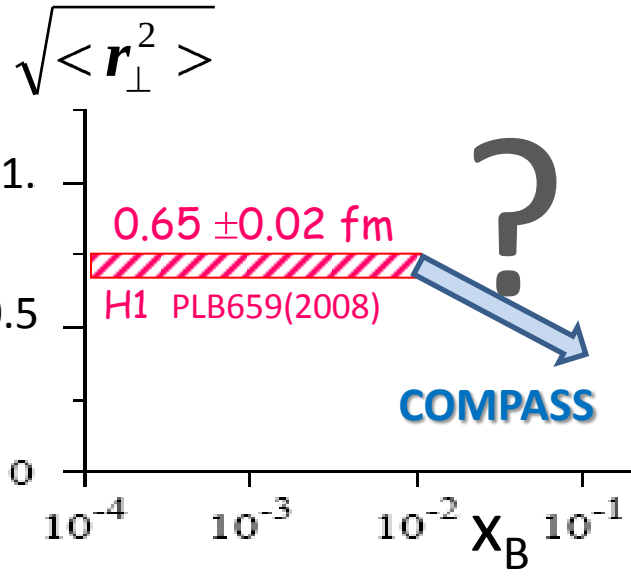
$r_\perp$ is the transverse size of the nucleon

DVCS: Transverse imaging at COMPASS

$d\sigma_{DVCS}/dt \sim \exp(-B|t|)$



Transverse size of the nucleon



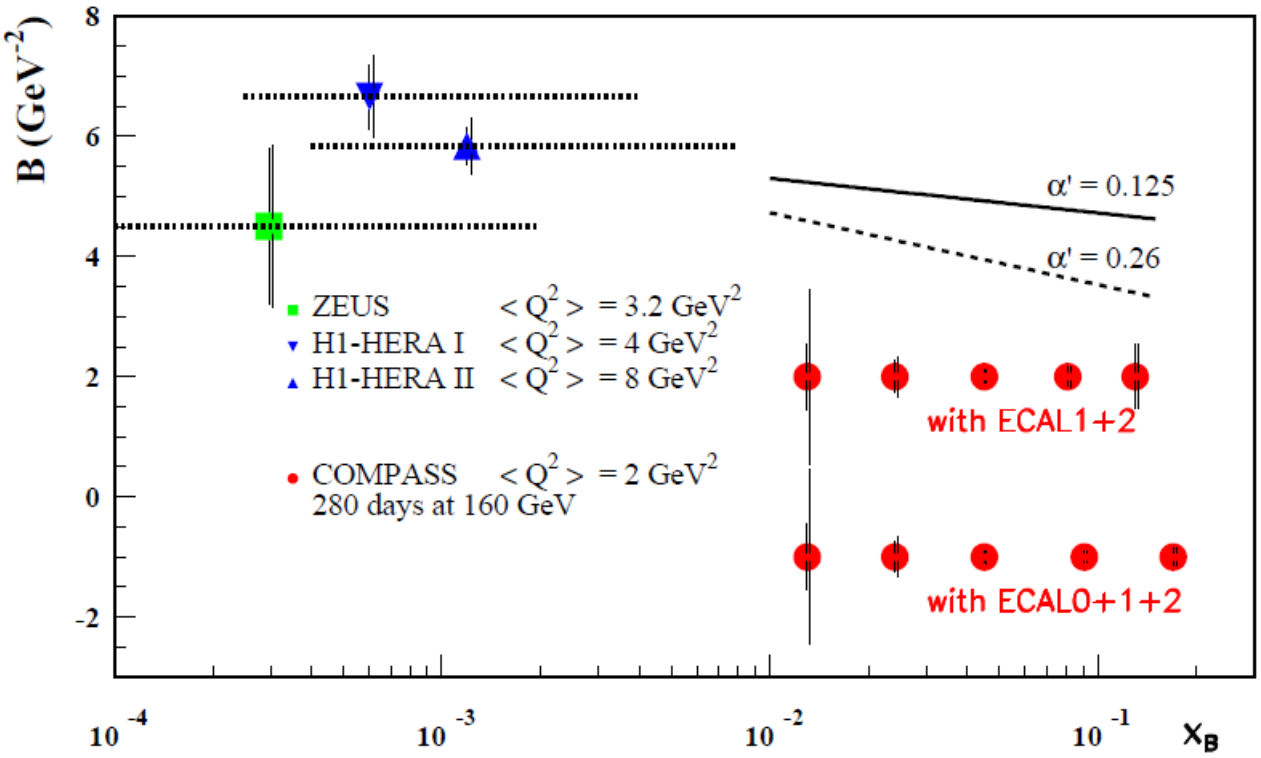
without any model we can extract $B(x_B)$

$$B(x_B) = \tfrac{1}{2} < r_\perp^2(x_B) >$$

$r_\perp$ is the transverse size of the nucleon

DVCS: Transverse imaging at COMPASS

$d\sigma_{DVCS}/dt \sim \exp(-B|t|)$



ansatz at small x_B inspired by Regge Phenomenology:

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

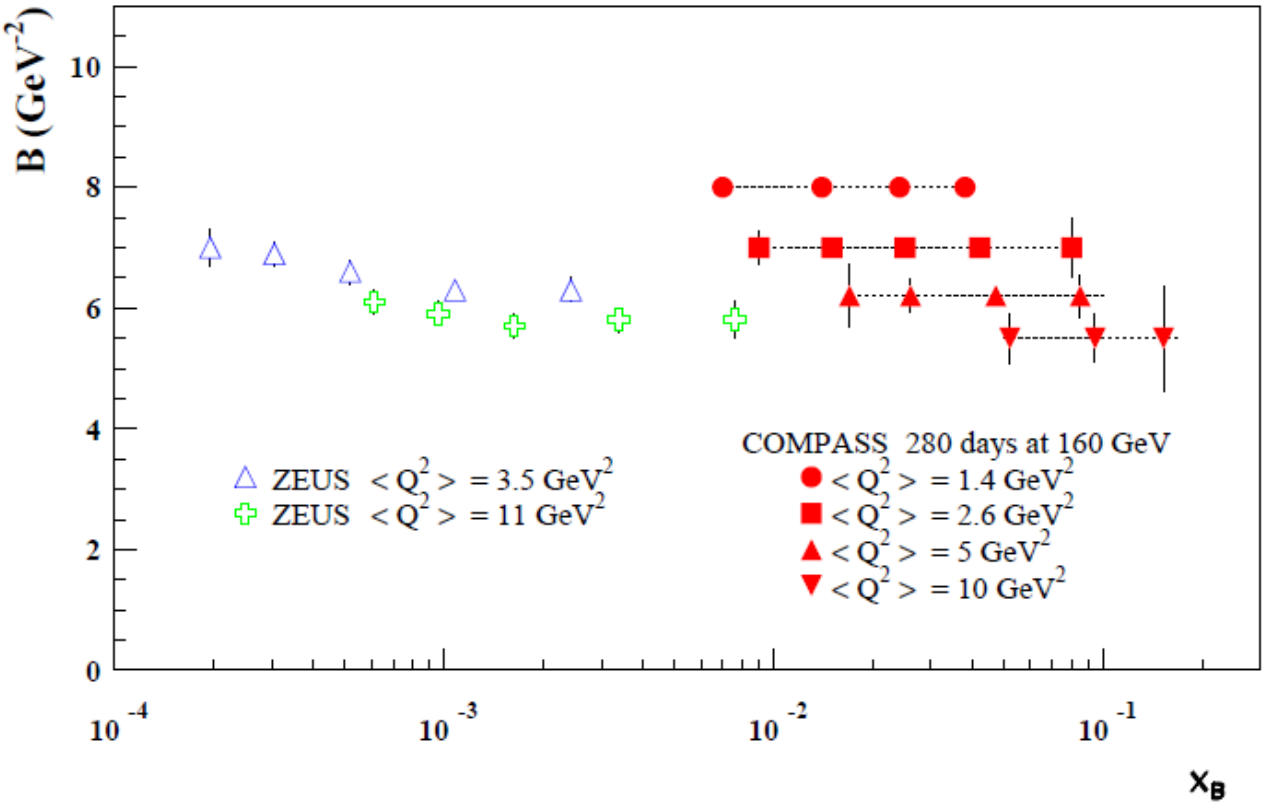
α' slope of Regge traject

with the projected uncertainties we can determine :

- B with an accuracy of 0.1 GeV^{-2}
- α' with an accuracy $\geq 2.5\,\sigma$
  if $\alpha' \geq$ **0.26** with ECAL1+2
  if $\alpha' \geq$ **0.125** with ECAL0+1+2

DVMP: Transverse imaging at COMPASS

$d\sigma_{DVMP}/dt \sim \exp(-B|t|)$



2 years of data
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$

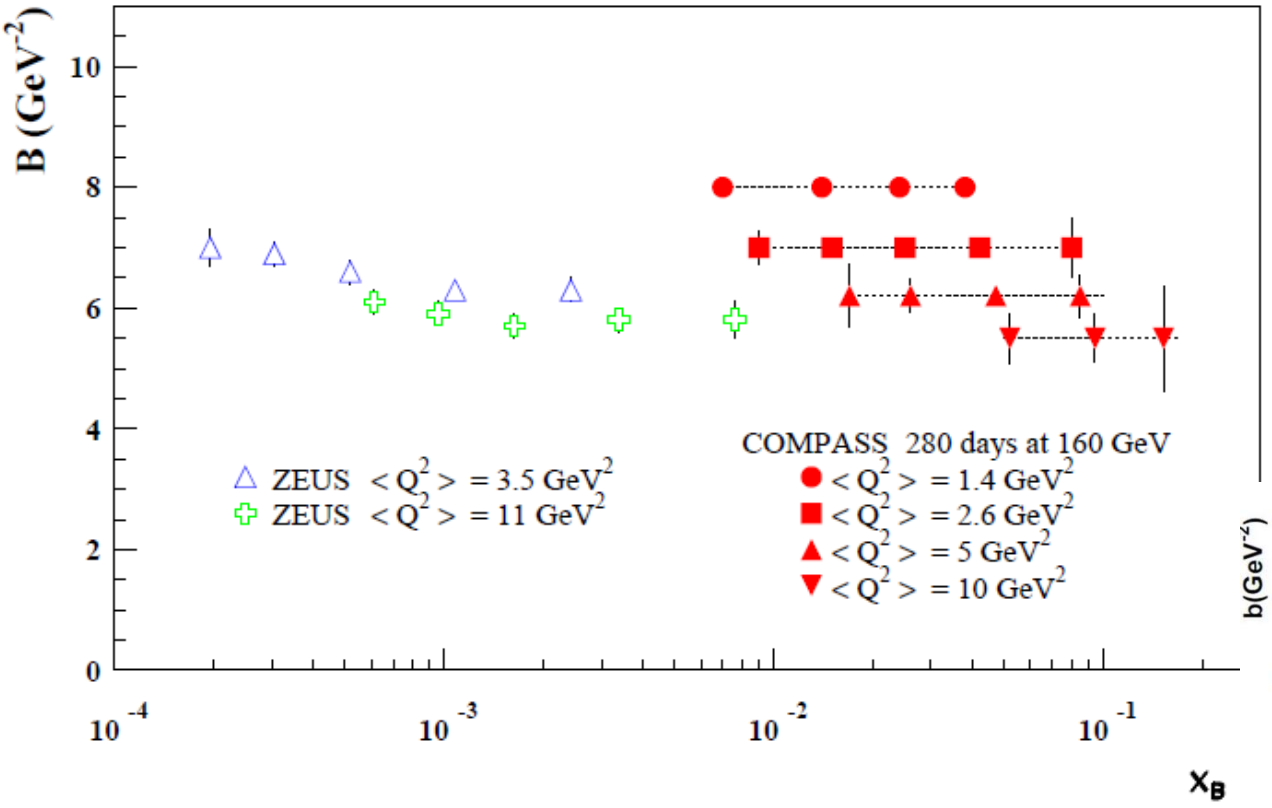
ρVMP model developed by Sandacz renormalised according Goloskokov and Kroll prediction

We are sensitive to the nucleon nucleon size
+ the transverse size of the meson

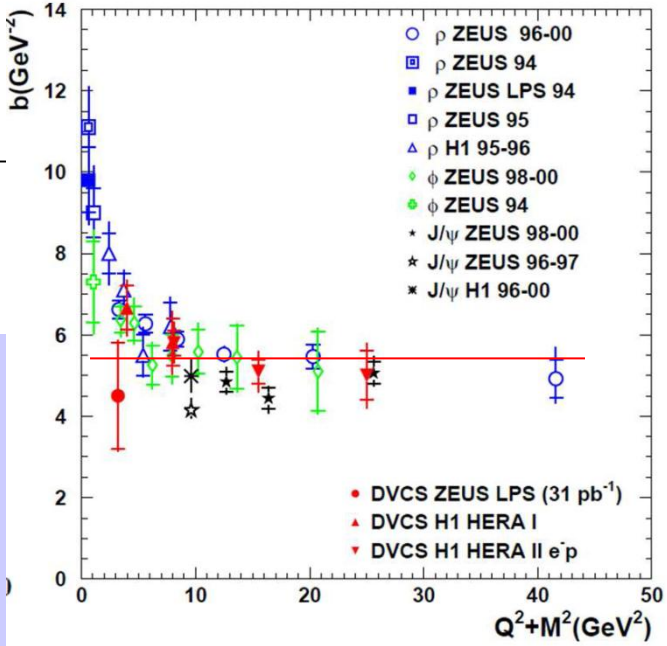
Q^2=1 GeV^2 B ~ 8 GeV^{-2}
Q^2=10 GeV^2 B ~ 5.5 GeV^{-2}

Transverse imaging at COMPASS

$d\sigma_{\rho VMP}/dt \sim \exp(-B|t|)$



2 years of data
160 GeV muon beam
2.5m LH_2 target
$\varepsilon_{global} = 10\%$



We are sensitive to the nucleon 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}

Deeply Virtual Compton Scattering

$$d\sigma_{(\mu p\to\mu p\gamma)} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVCS}_{pol}$$

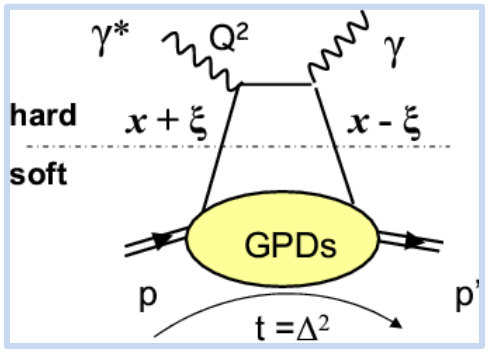
$$+ e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} + e_\mu\, P_\mu\, a^{BH}\, Im\, A^{DVCS}$$

Phase 1: DVCS experiment to constrain GPD H

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam + unpolarized 2.5m long LH2 (proton) target

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

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



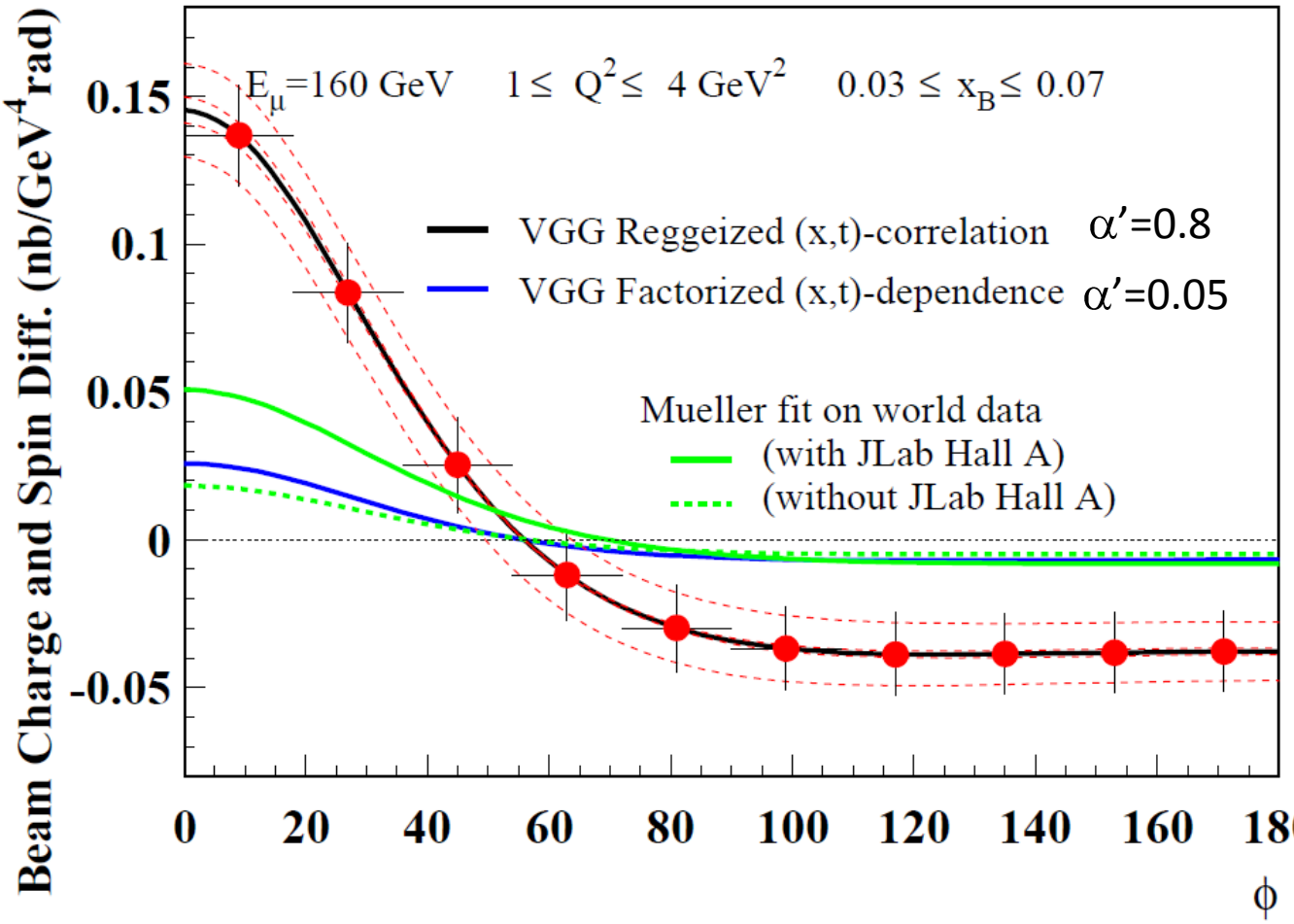
$\xi \sim x_B / (2-x_B)$

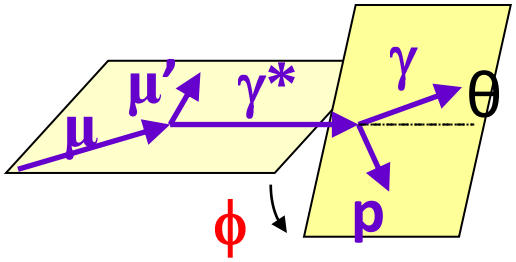
- $Im\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$
- $Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, H(x,\xi,t)/(x-\xi)$

dominance of H at COMPASS kinematics

Beam Charge and Spin Difference (using $\mathcal{D}_{cs,u}$)

Comparison to different models





2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

High precision beam flux and acceptance determination
Systematic error bands assuming a 3% charge-dependent effect between μ+ and μ- (control with inclusive evts, BH…)

Beam Charge and Spin Difference over the kinematic domain

Statistics and Systematics

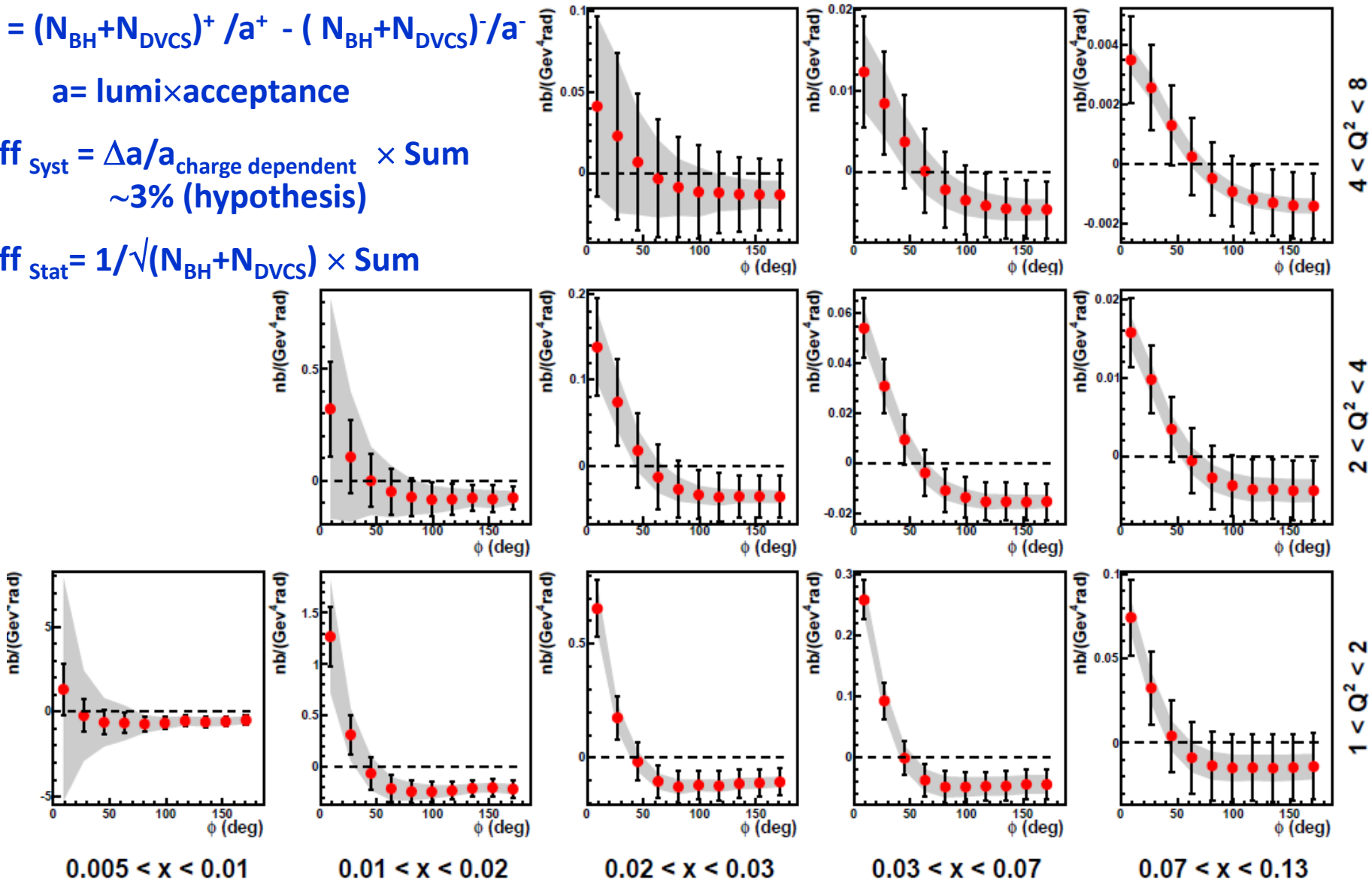
$\mathrm{Diff} = (N_{BH}+N_{DVCS})^{+}/a^{+} - (N_{BH}+N_{DVCS})^{-}/a^{-}$

a= lumi×acceptance

$\Delta\mathrm{Diff}_{Syst} = \Delta a/a_{\text{charge dependent}} \times \mathrm{Sum}$

~3% (hypothesis)

$\Delta\mathrm{Diff}_{Stat} = 1/\sqrt{(N_{BH}+N_{DVCS})} \times \mathrm{Sum}$



$\mathcal{D}_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) - d\sigma(\mu^{-\uparrow}) \propto C_0^{Int} + C_1^{Int}\cos\phi$ and $C_{0,1}^{Int} \sim \mathcal{R}e(F_1\mathcal{H})$

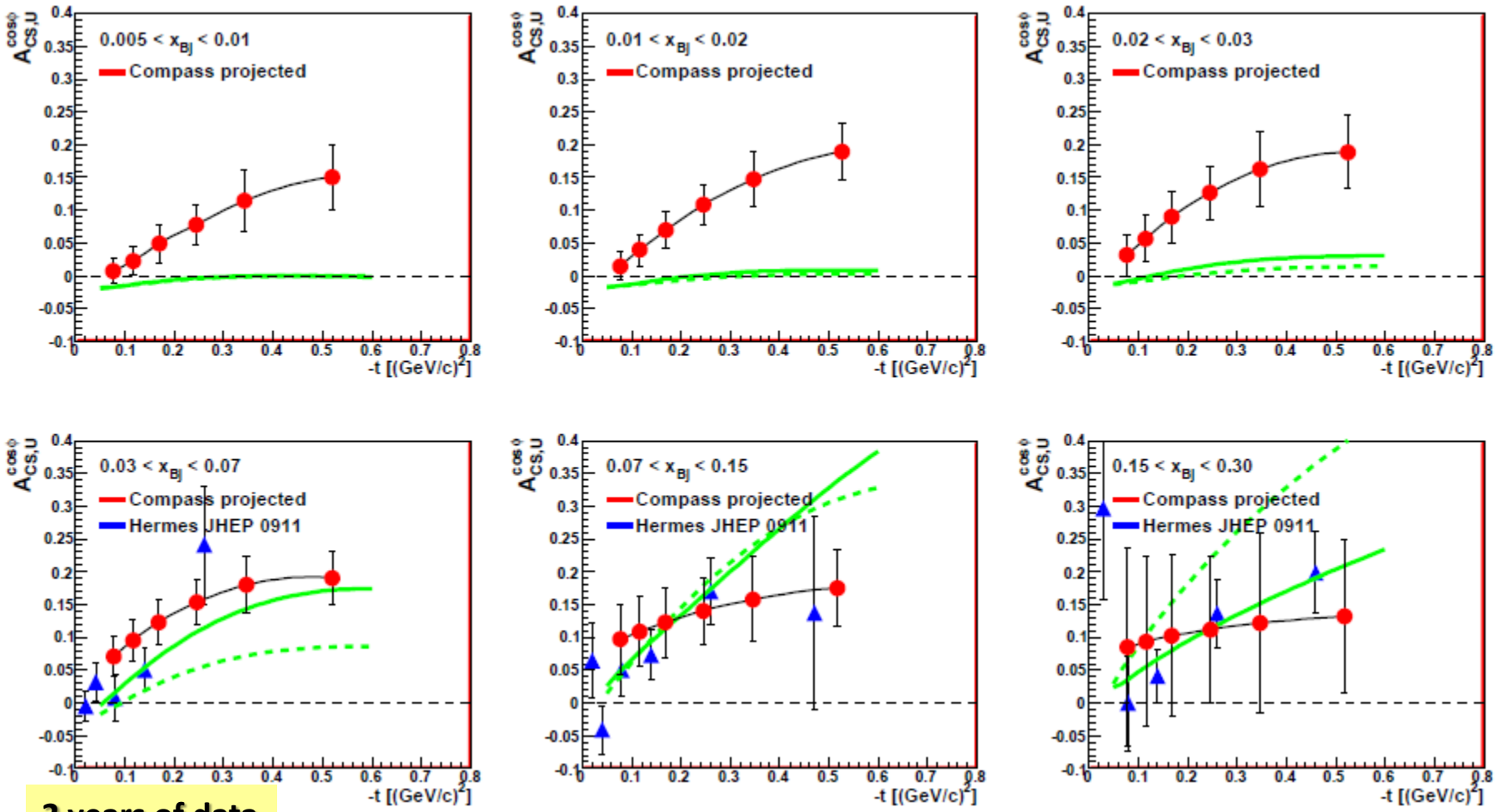
$A_{CS,U}^{\cos\phi}$ related to c_1^{Int}

Predictions with **VGG** and **D.Mueller**

$\mathcal{R}e(F_1\mathcal{H})$ **> 0 at H1**

< 0 at HERMES/JLab

Value of x_B for the node?



2 years of data

With ECAL2 + ECAL1 + ECAL0

Constrains on the GPD E

on transversely polarized protons (NH3 target)

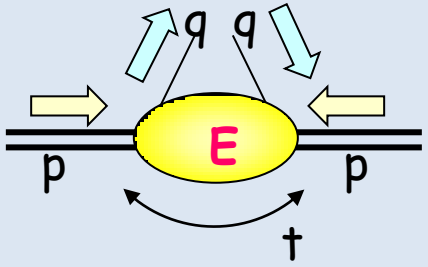
1) without recoil detection (2007 & 2010)

2) with recoil detection **Phase 2 (in future)**

the GPD **E** allows nucleon helicity flip

so it is related to the angular momentum

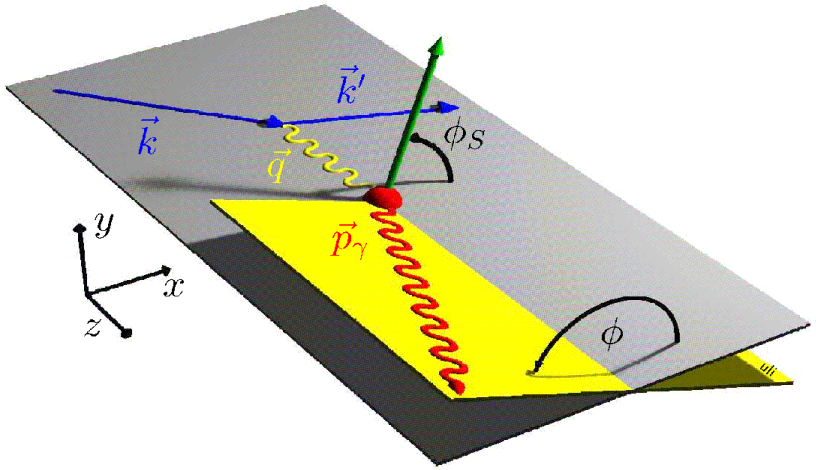
Ji sum rule: $2J_q = \int x \, (H^q(x,\xi,0) + E^q(x,\xi,0)) \, dx$



The GPD E is the 'Holy-Grail' of the GPD quest

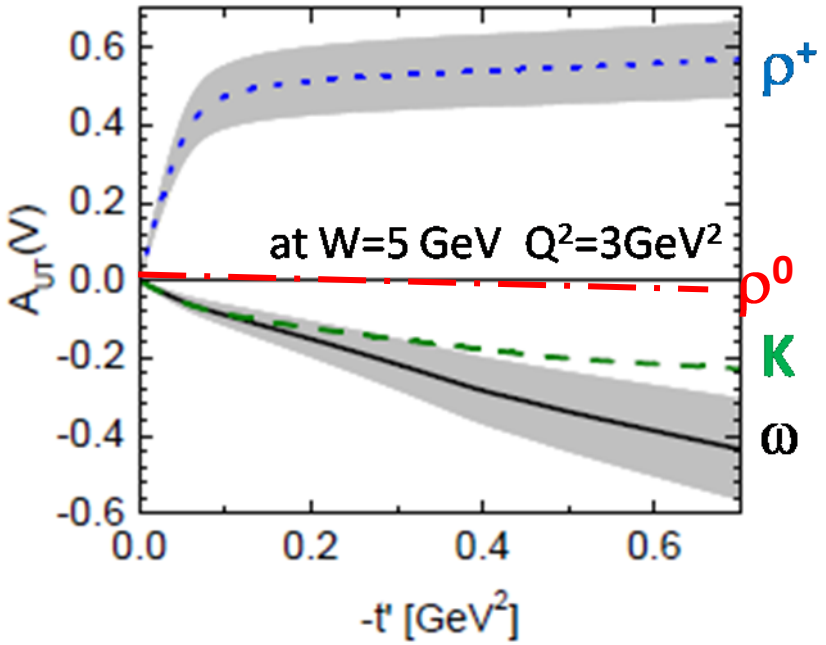
Deeply Virtual Meson Production

$$A_{UT}(\rho^0) \propto \sqrt{|-t'|}\, Im(\mathcal{E}^{*}\mathcal{H}) / |\mathcal{H}|^2 \times \sin(\phi - \phi_S)$$



Deeply Virtual Meson Production

$$A_{UT}(\rho^0) \propto \sqrt{|-t'|}\, Im(\mathcal{E}^* \mathcal{H}) / |\mathcal{H}|^2$$



$E\rho^0 \propto 2/3\ E^u + 1/3\ E^d + 3/8\ E^g$

$E\omega \propto 2/3\ E^u - 1/3\ E^d + 1/8\ E^g$

$E\rho^+ \propto \quad E^u - E^d - 3/8\ H^g$

$\kappa^q = \int e^q(x)\, dx$

$\rightarrow \quad E^u \sim -E^d$

Goloskokov-Kroll: the most complete model ($Q^2>3GeV^2$ $x<0.2$)

with H and E for quarks and gluons

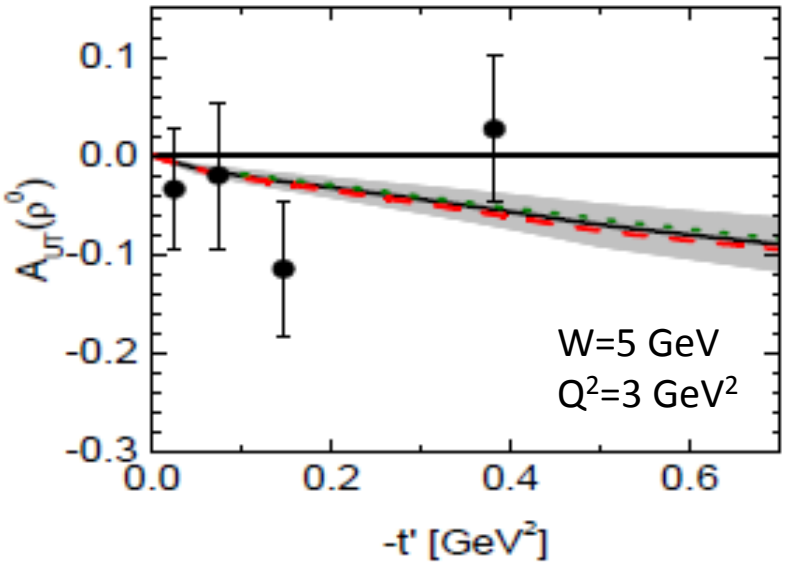
quark transverse degrees of freedom taken into account

the asymptotically dominant (longitudinal) amplitude for $\gamma_L^*\ p \rightarrow \rho_L\ p$
but also the one for transversely polarized photons and vector mesons $\gamma_T^*\ p \rightarrow \rho_T p$

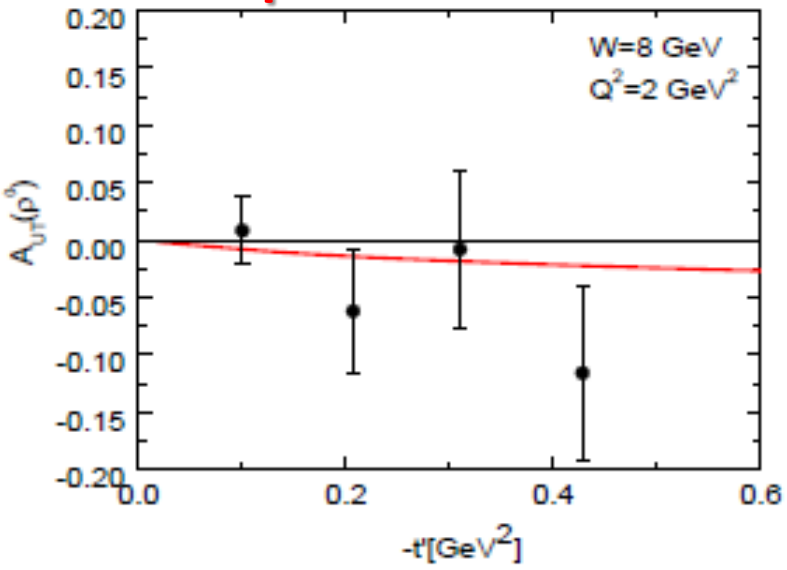
2007 results for the Transverse Target Asymmetry

$$A_{UT}(\rho^0) \propto \sqrt{|-t'|}\, Im(\mathcal{E}^{*}\mathcal{H}) / |\mathcal{H}|^2$$

Hermes



Compass 2007



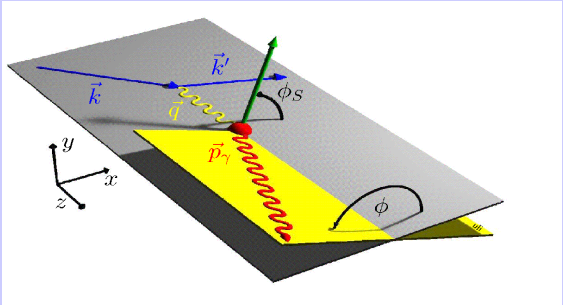
$A_{UT}(\omega)$ and $A_{UT}(\rho^+)$ should be more promising
To be completed with the analysis of 2010 data

Deeply Virtual Compton Scattering

Phase 2 (in future): DVCS experiment to constrain GPD E

with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam and **transversely** polarized NH3 (proton) target

$$\mathcal{D}_{CS,T} \equiv d\sigma_T(\mu^{+\downarrow}) - d\sigma_T(\mu^{-\uparrow}) \propto Im(F_2\mathcal{H} - F_1\mathcal{E})\sin(\phi - \phi_S)\cos\phi$$

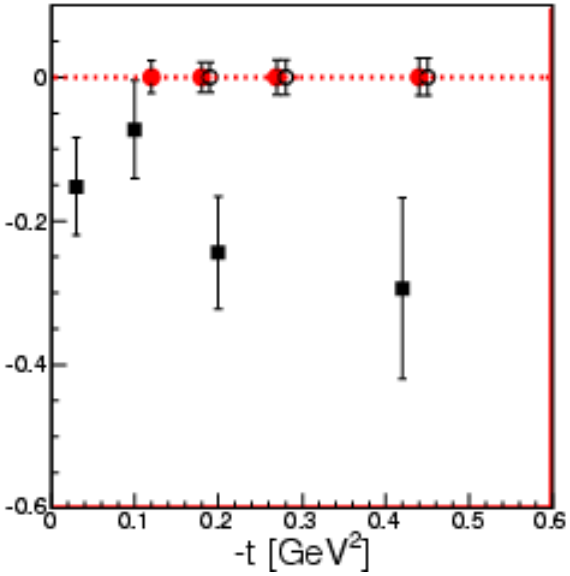


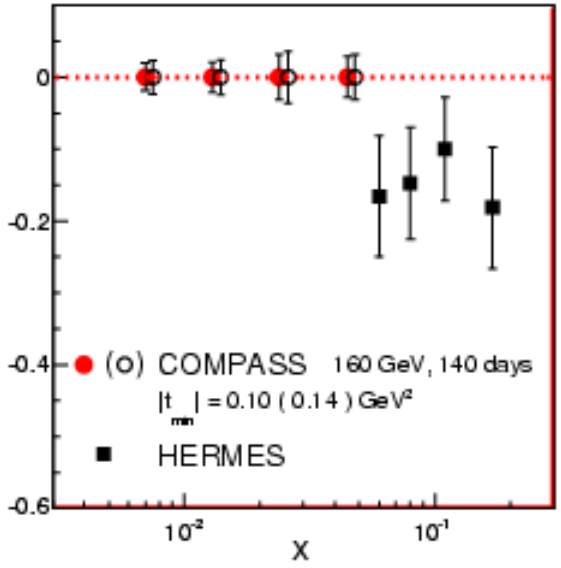
$D_{CS,T}$ and Transverse Target Asymmetry

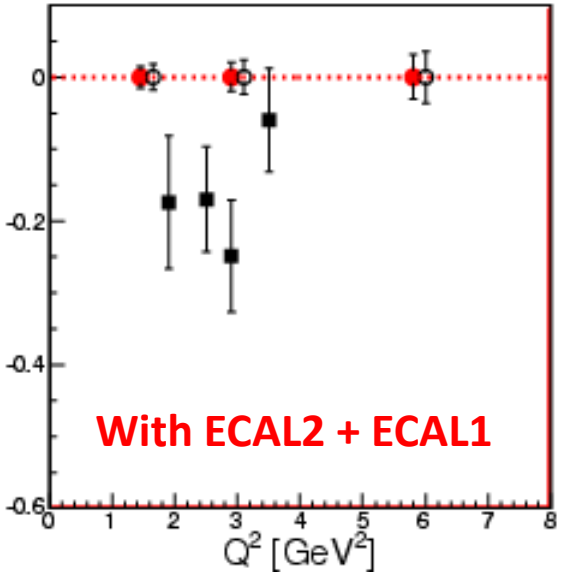
Prediction for phase 2 (in future)
With a transversely polarized NH3 (proton) target:

2 years of data
160 GeV muon beam
1.2 m polarised NH_3 target
ε_{global} = 10%

$A_{CS,T}^{\sin(\phi-\phi_s)\cos\phi}$ **related to H and E**

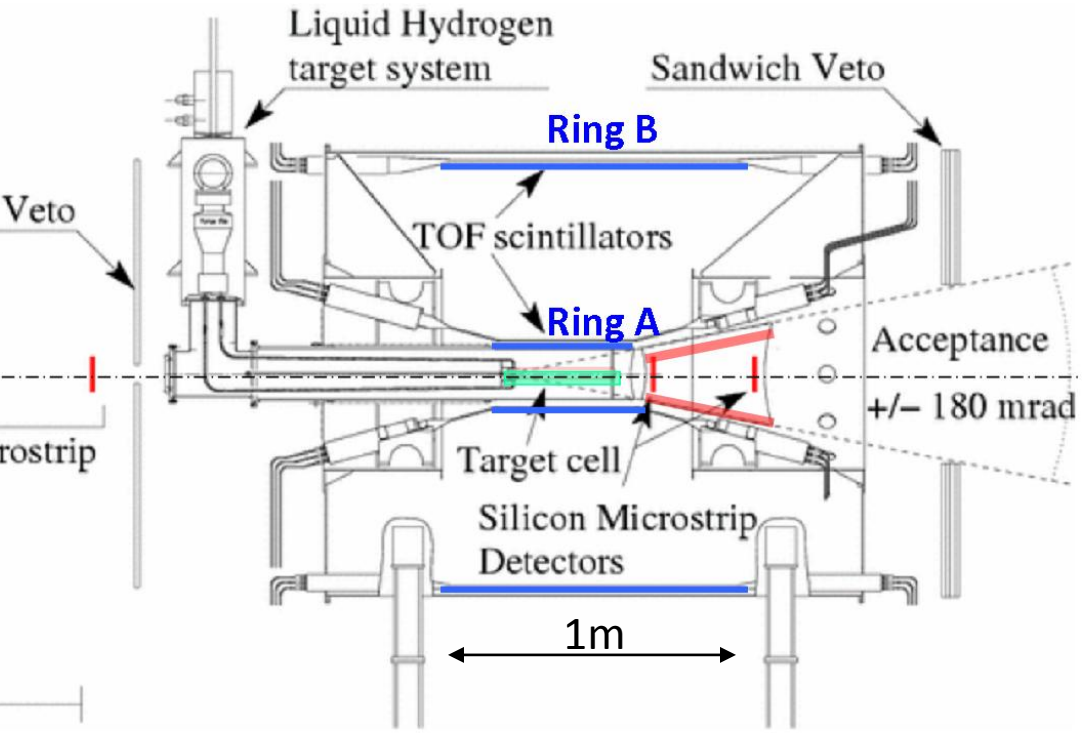


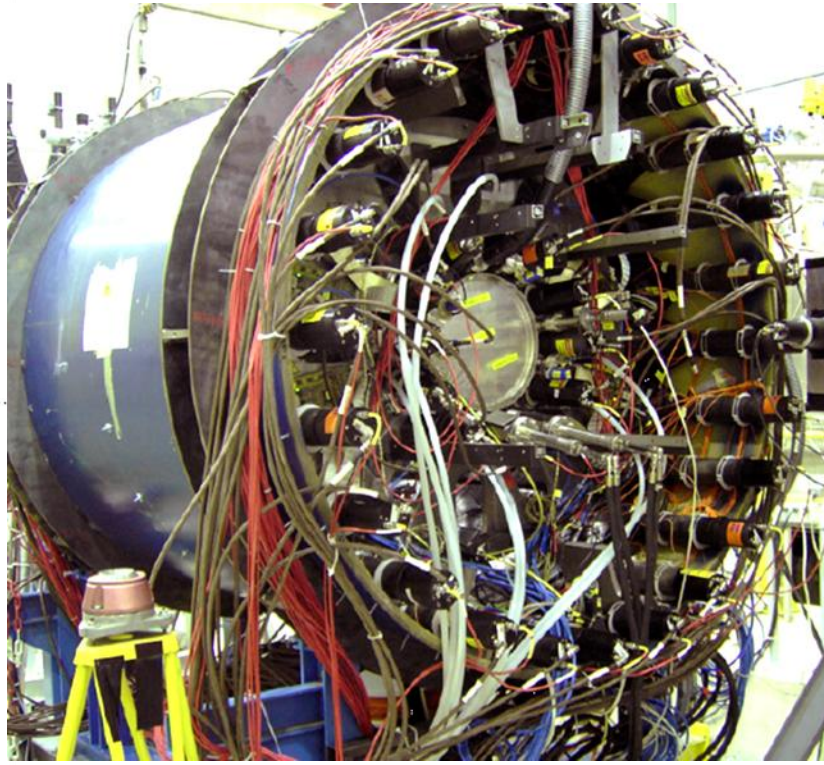




DVCS tests in 2008-9

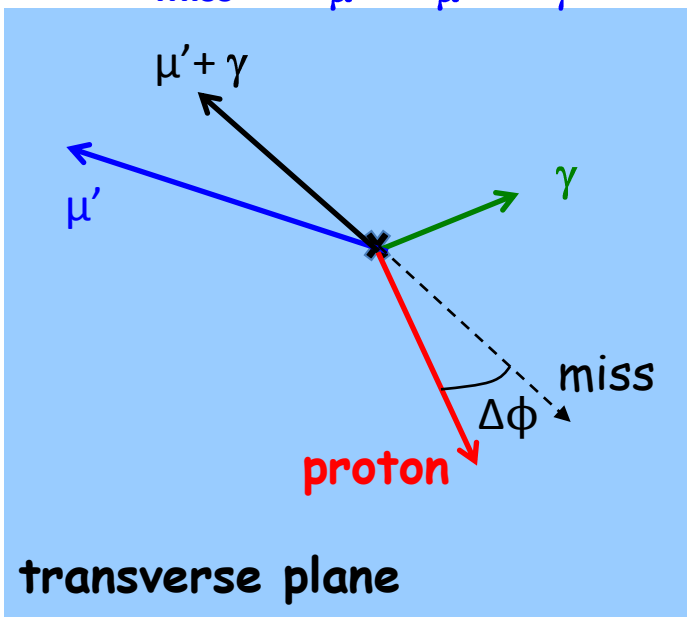
During the hadron program with 1m long recoil proton detector (RPD)
and 40cm long LH2 target
and the 2 existing ECAL1 and ECAL2

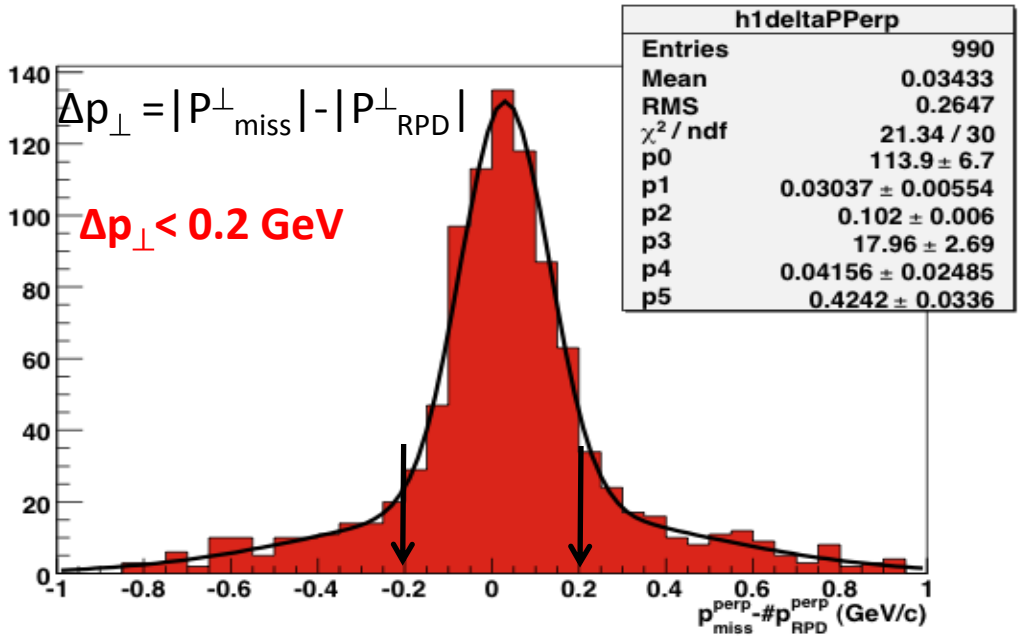


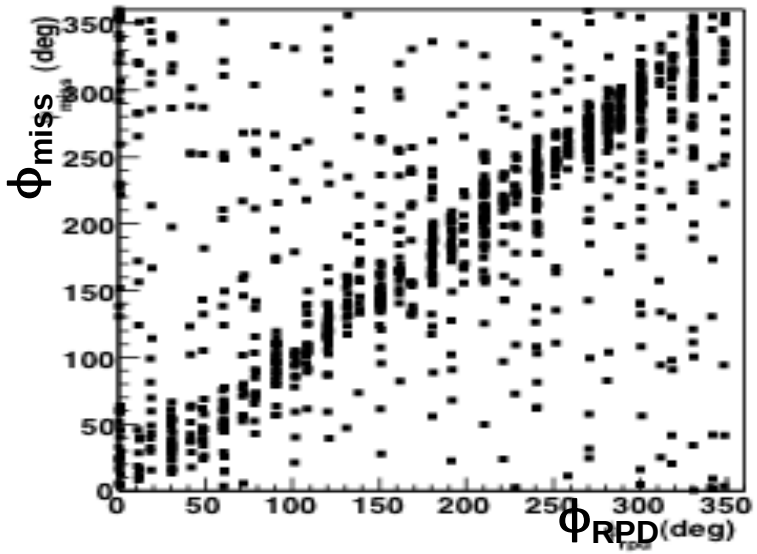


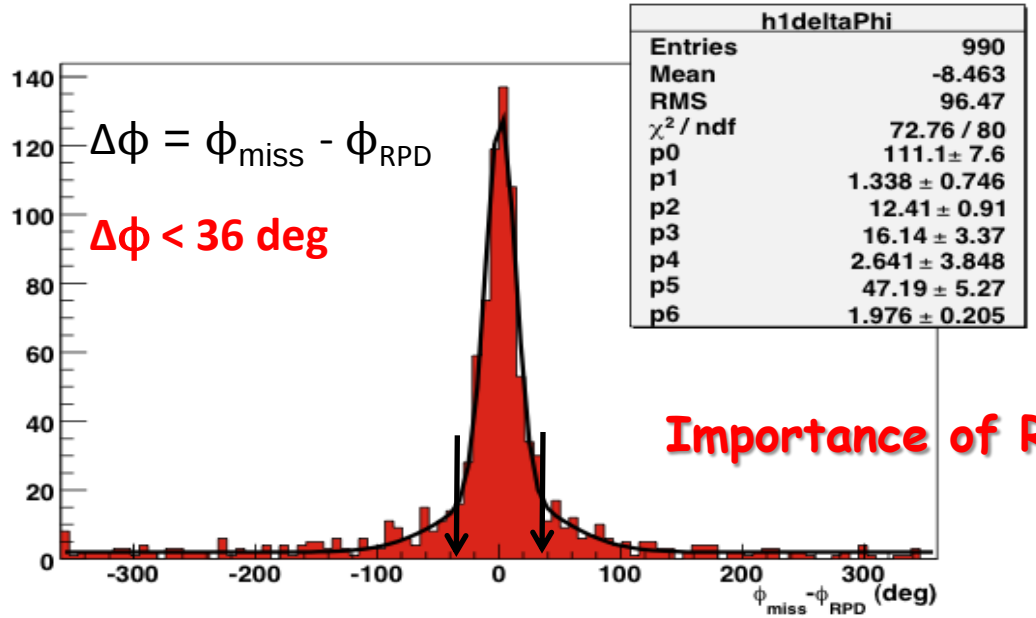
Kinematic constraints in the transverse plane

$\vec{P}_{miss} = \vec{P}_{\mu} - \vec{P}_{\mu'} - \vec{P}_{\gamma}$







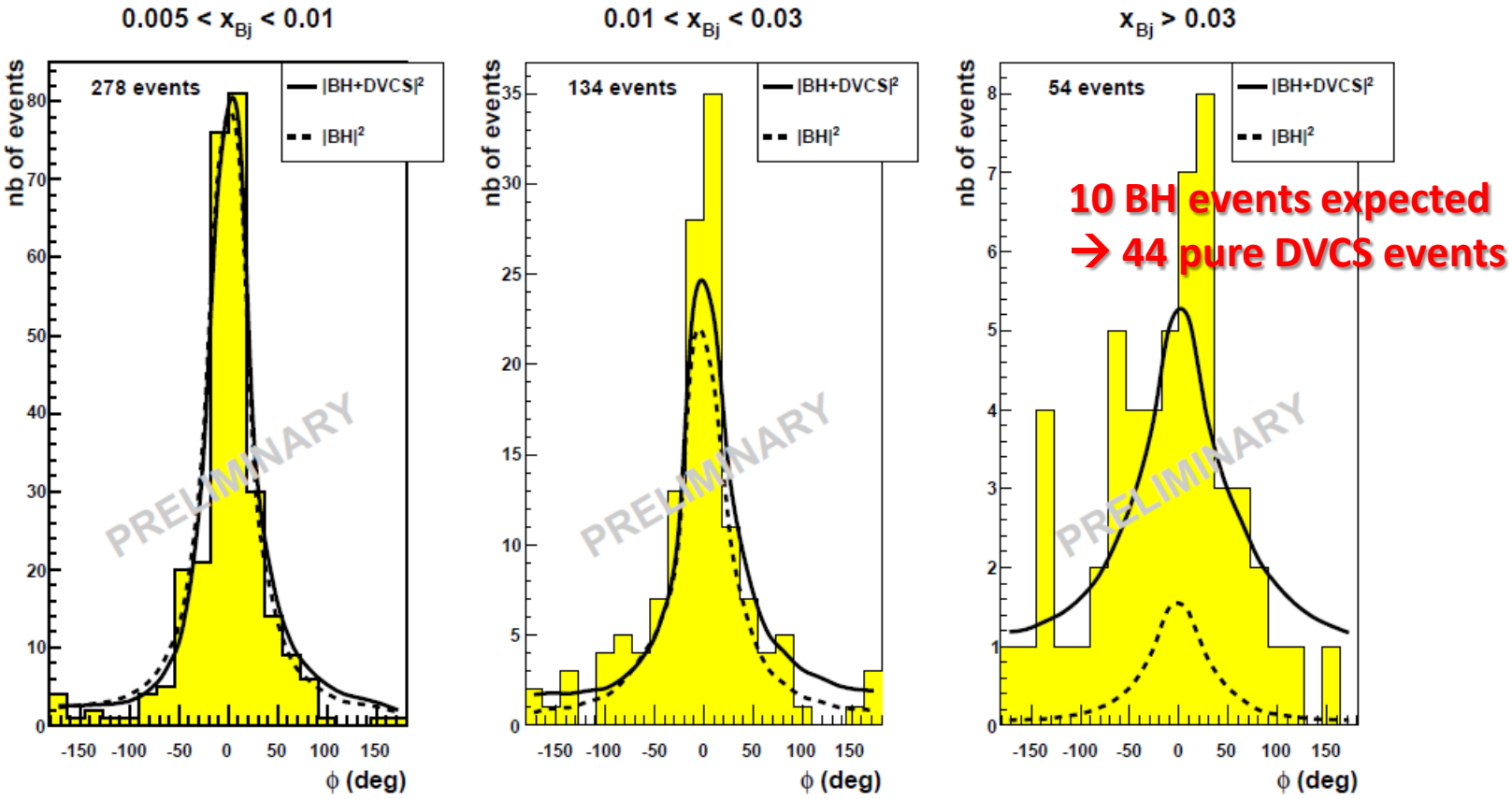


Importance of RPD

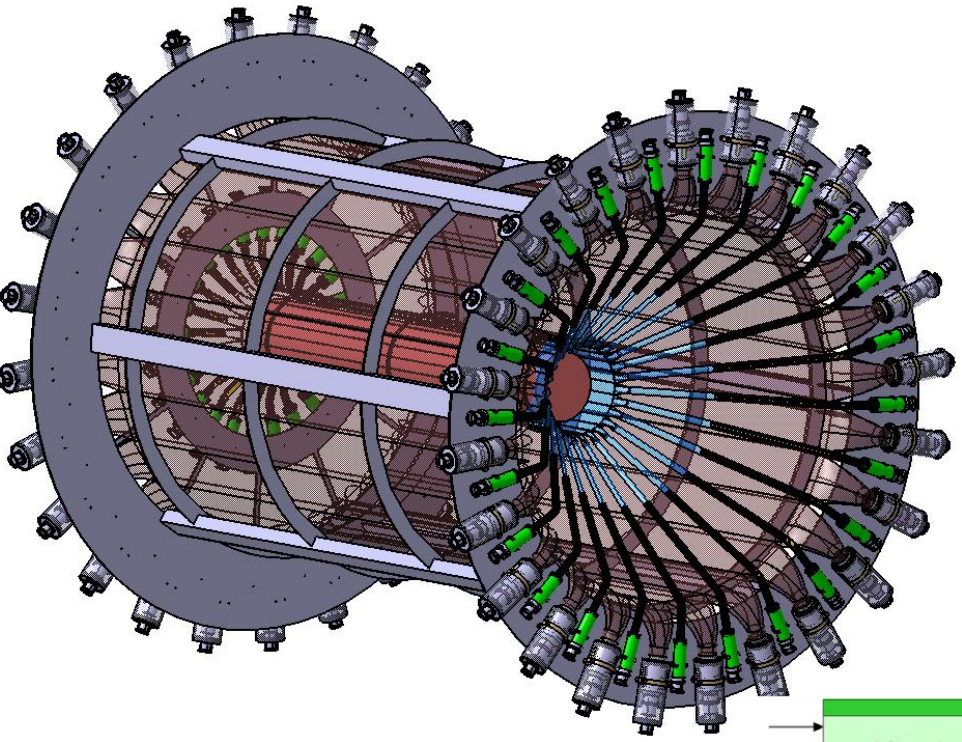
2008-9 tests: observation of BH and DVCS events

2008: observation of exclusive single photon production,
ε_{global} = 0.13 +/- 0.05 ➔ confirmed ε_{global} = 0.1 as assumed for simulations

2009: observation of BH and DVCS events



RPD design and its electronics

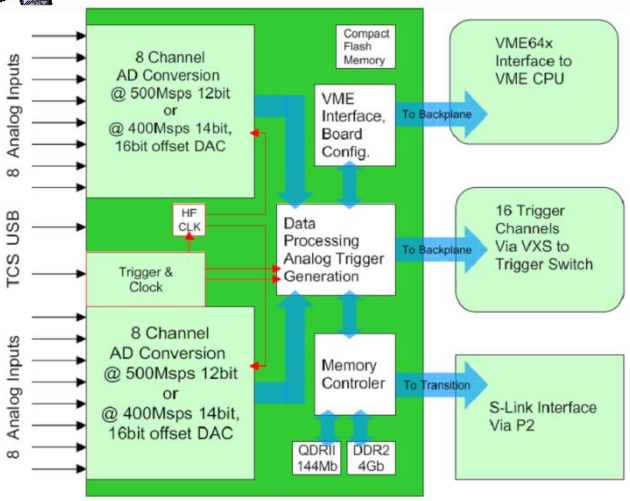


3.6 m long scintillator slabs
➔~ 300ps timing resolution

Tests made with
- 2006 MuRex (a 4m sector prototype)
- 2008-9: the present RPD (1m long)

Gandalf Project:

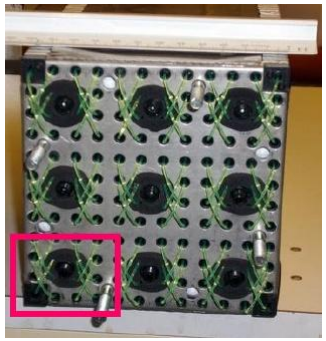
1 GHz digitalisation of the PMT signal to cope for high rate

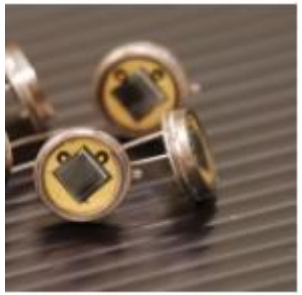


ECAL0

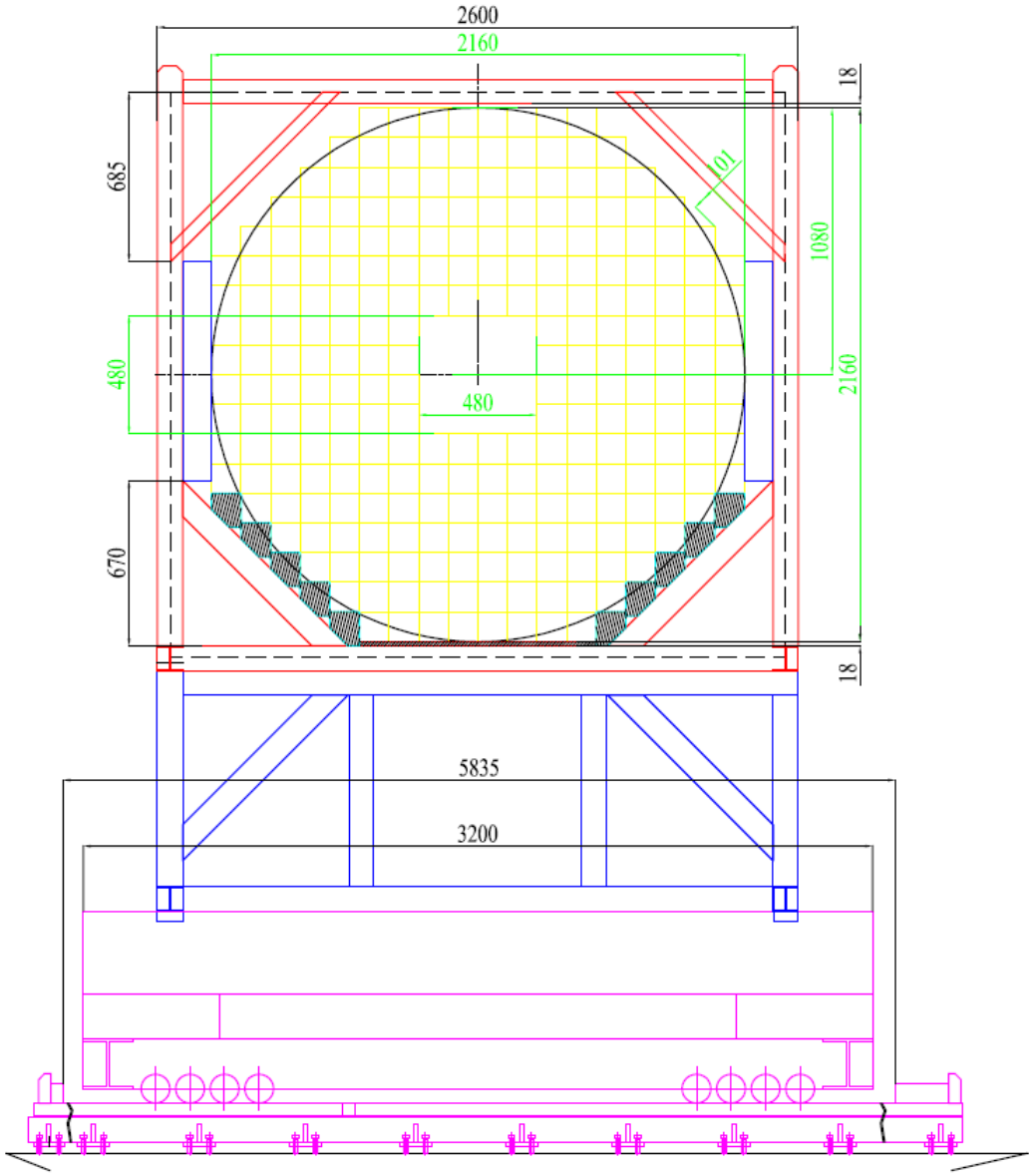
ECAL0 made of

248 modules (12 × 12 cm²)
of 9 cells read by 9 MAPDs





- Unsensitive to magnetic field
- High number of pixels
  (15 →40 kPix/mm² MAPD)
- Temperature dependence 3,4%/deg.
- High radiation hardness



Summary for GPD @ COMPASS

GPDs investigated with Hard Exclusive Photon and Meson Production

COMPASS-II

- the t-slope of the DVCS cross section …… LH_2 target + RPD……phase 1
  → transverse distribution of partons
- the Beam Charge and Spin Sum and Difference and Asymm…….phase 1
  → Re T^{DVCS} and Im T^{DVCS} for the GPD H determination

future addendum

- the Transverse Target Spin Asymm……polarised NH_3 target + RPD……phase 2
  → GPD E and angular momentum of partons

NEW HARDWARE:

phase 1

- Recoil Proton Detector and Liquid Hydrogen Target
- Complete angular hermiticity for ECAL1-2 + a new ECAL0

phase 2

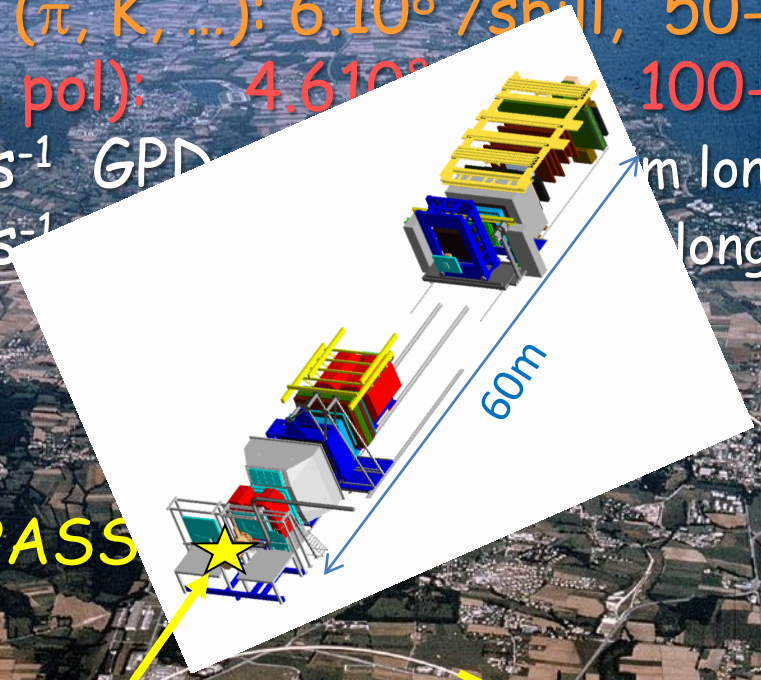
- Polarized target with integrated RPD

SPS proton beam: 2.6 10^{13}/spill of 9.6s each 48s, 400 GeV/c

- Secondary hadron beams (π, K, ...): 6.10^{8} /spill, 50-200 GeV/c
- Tertiary muon beam (80% pol): 4.6$10^{8}$ 100-200 GeV/c

-> Luminosity ~ 10^{32} cm^{-2} s^{-1} GPD m long LH target

~1.2 10^{32} cm^{-2} s^{-1} long NH_3 target



LHC

COMPASS

SPS

CNGS
Gran Sasso
732 kms

high energy beams, broad kinematic range, large angular acceptance

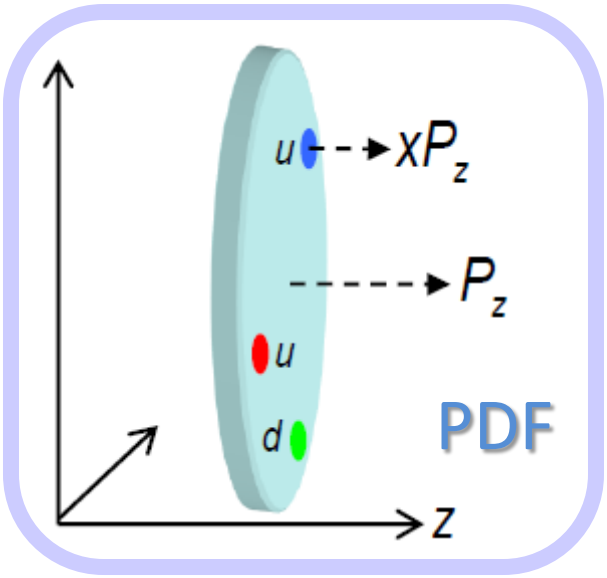
Exploring the 3-dimensional phase-space structure of the nucleon

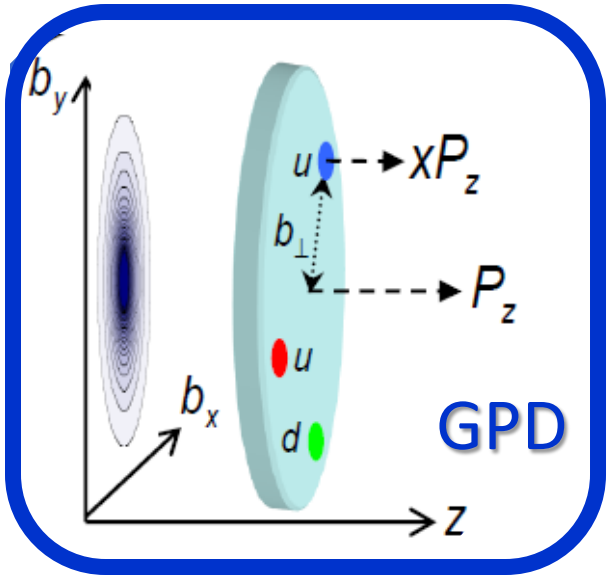
From Wigner phase-space-distributions (Ji, PRL 2003, Belitsky, Ji, Yuan PRD 2004)
We can build « mother-distributions » (Meissner, Metz, Schlegel, JHEP 0908:056 2009)

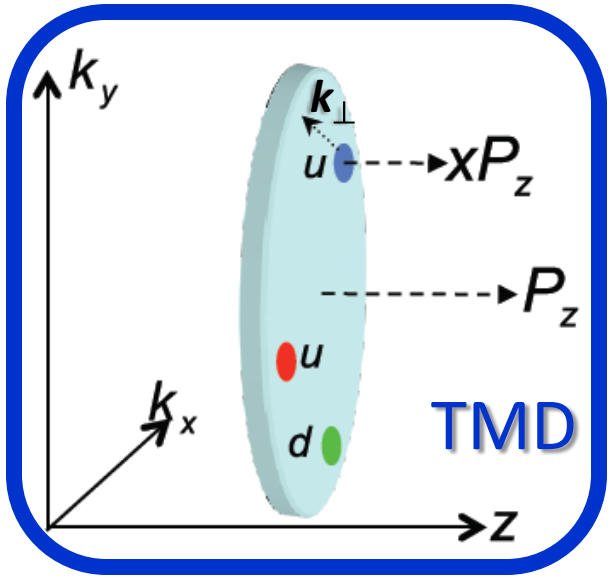
$$\mathcal{W}(x, b_\perp, k_\perp)$$

and derive

- ✓ GPD: Generalised Parton Distribution (position in the transverse plane)
- ✓ TMD:Transverse Momentum Distribution (momentum in the transv. plane)

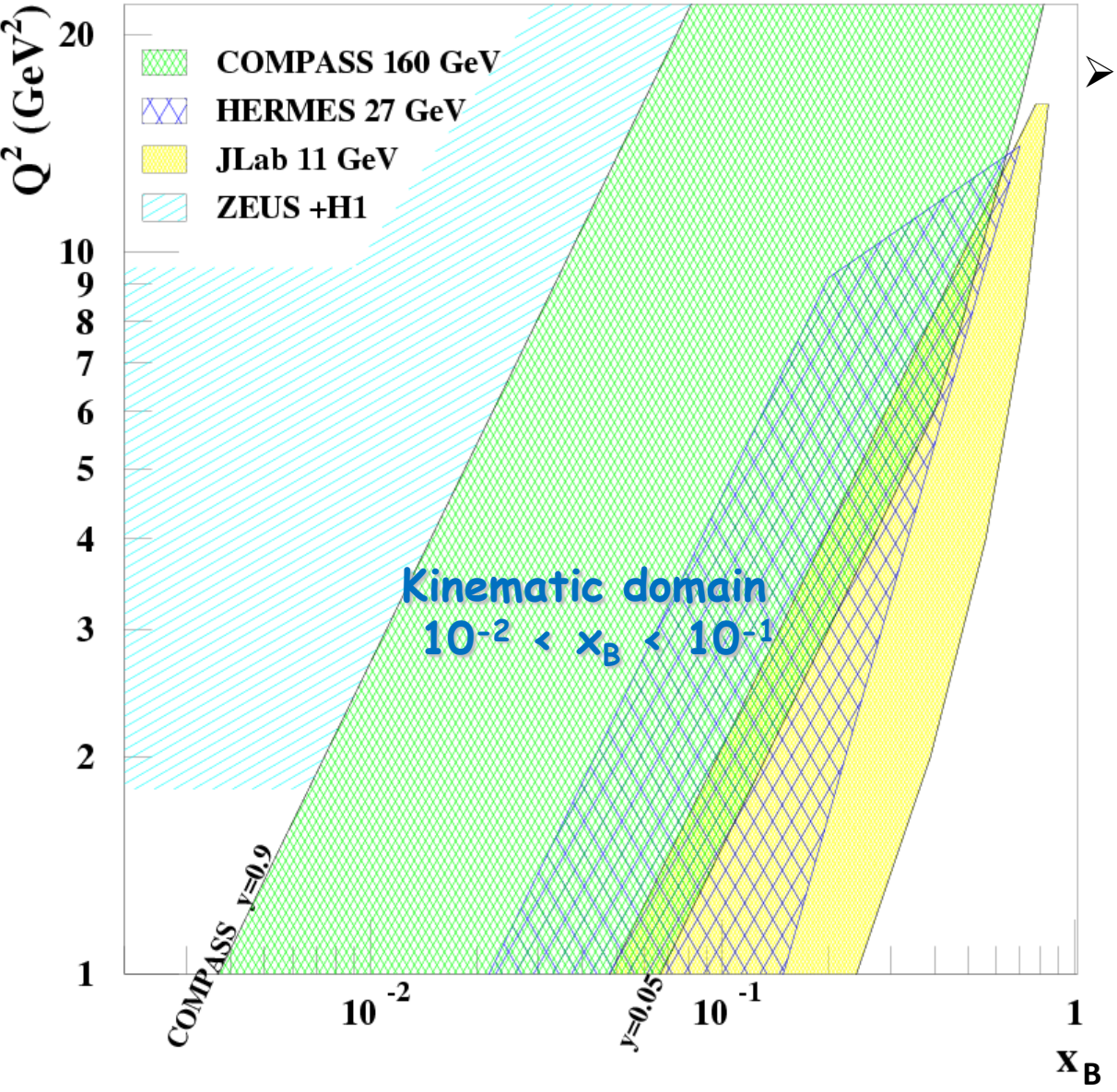




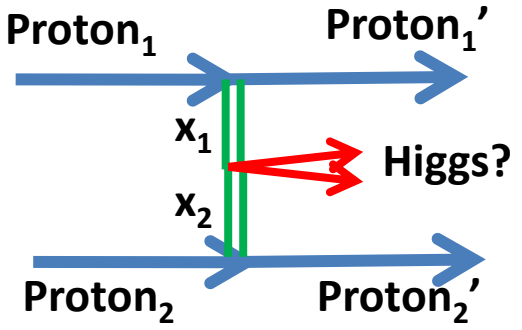


New research fields

What makes COMPASS unique for GPDs?



- Transverse structure at $x \sim 10^{-2}$ essential input for phenemenology of high-energy pp collision



$x_{1,2} = M_{Higgs} / \sqrt{s} \sim 10^{-2}$

M_{Higgs} = 140 GeV and $\sqrt{s}$ =14 TeV

Totem, FP420 Programs at LHC

Transverse imaging at COMPASS

$B(x_B) = \frac{1}{2} \langle r_\perp^2(x_B) \rangle$

distance between the active quark
and the center of momentum of spectators

Transverse size of the nucleon

mainly dominated by $H(x, \xi=x, t)$

Quark-Dipole Model
Regge Phenomenology

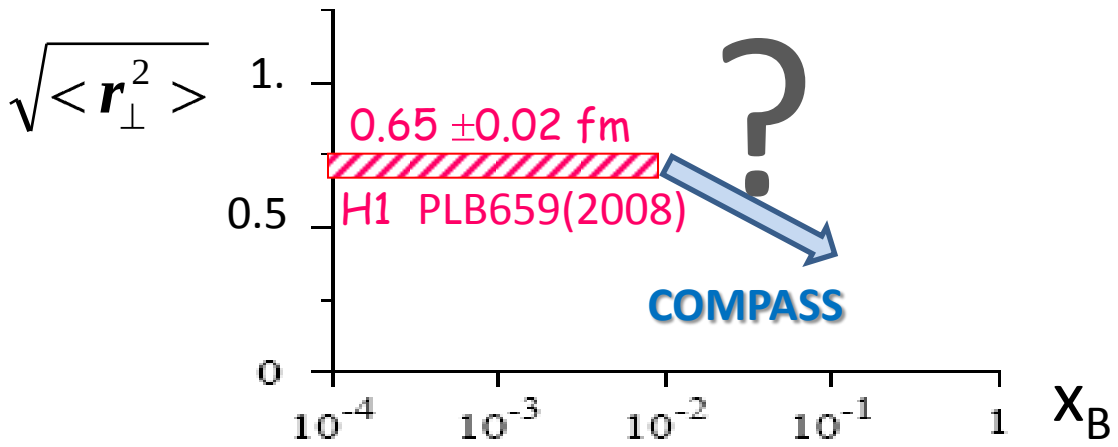
related to $\frac{1}{2} \langle b_\perp^2(x_B) \rangle$

distance between the active quark
and the center of momentum of the nucleon

Impact Parameter Representation

$q(x, b_\perp) \leftrightarrow H(x, \xi=0, t)$

Parametrisation with
Reggeized (x,t) correlation

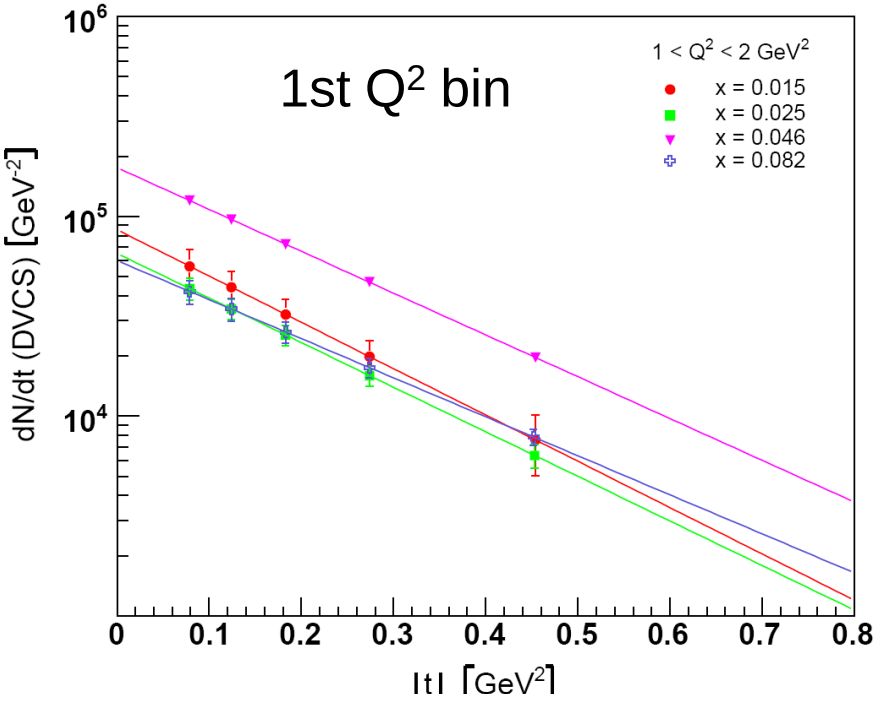


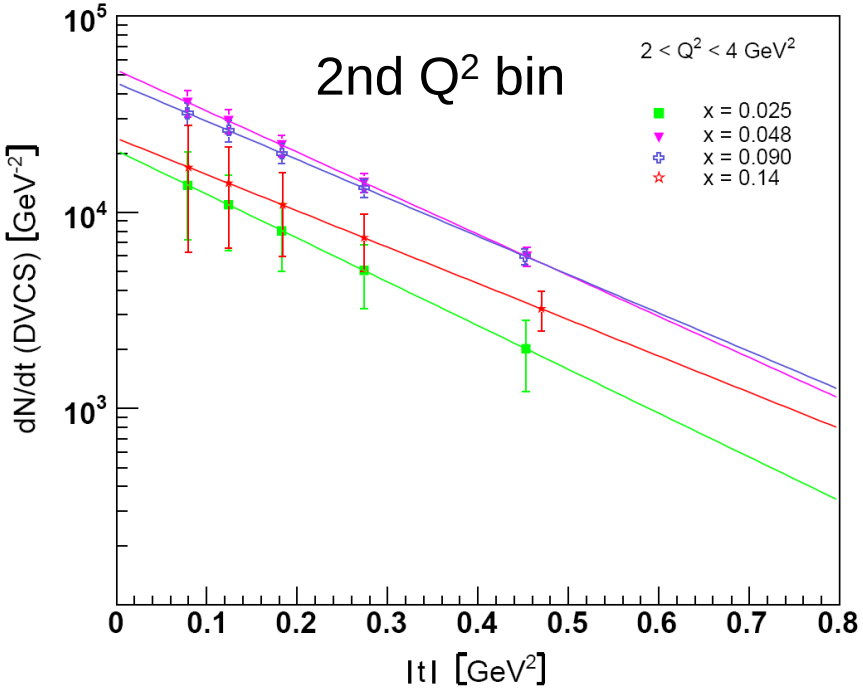
dN / dt for extracted DVCS

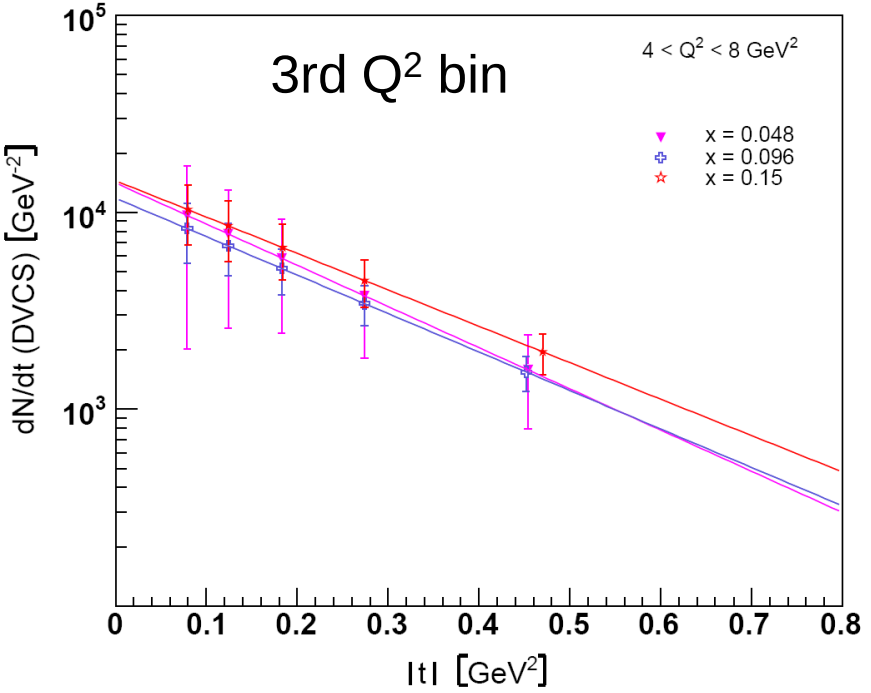
shown are statistical errors

dN / dt ~ exp(Bt)

B - fitted param.







Fraction of the angular momentum sum rule 'seen' in a kinematic domain

$$J^u = \frac{1}{2}\int_{-1}^{1} dx\, x\,[H(x,\xi,t=0)+E(x,\xi,t=0)]$$

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

$$\longrightarrow \frac{1}{2}\int_{0}^{1} dx\, x\,[q(x) + \bar{q}(x)]+[e(x)+\bar{e}(x)]$$

singlet contribution

exp	Kin domain	Ju fraction	Jd fraction	J gluon fraction
H1-ZEUS	5.10^{-4} - 5.10^{-3}	0.006	0.006	huge
COMPASS	5.10^{-3} - 0.2	0.14	0.08	0.4
HERMES	5.10^{-2} - 0.2	0.11	0.06	0.2
JLab	0.15 – 0.45	0.15	0.09	0.06

Calculation W-D Nowak CTEQ6L at Q^2=5GeV^2

H, $\tilde{H}$, E contribution for a Proton Target

$$A = F_1(t)\cdot \mathrm{H} + \frac{x_B}{2-x_B}\cdot \left(F_1(t)+F_2(t)\right)\cdot \tilde{\mathrm{H}} - \frac{t}{4M^2}F_2(t)\cdot \mathrm{E}$$

x=0.3

$-t$	$F_2^p(t)$	$F_1^p(t)$	$F_1^p(t)+F_2^p(t)\ \cdot x_B/(2-x_B)$	$(-t/4M^2)\cdot F_2^p(t)$
0.1	1.34	**0.81**	**0.38**	0.04
0.3	0.82	**0.56**	**0.24**	0.06

x=0.1

$-t$	$F_2^p(t)$	$F_1^p(t)$	$F_1^p(t)+F_2^p(t)\ \cdot x_B/(2-x_B)$	$(-t/4M^2)\cdot F_2^p(t)$
0.1	1.34	**0.81**	**0.11**	0.04
0.3	0.82	**0.56**	**0.07**	0.06

x=0.01

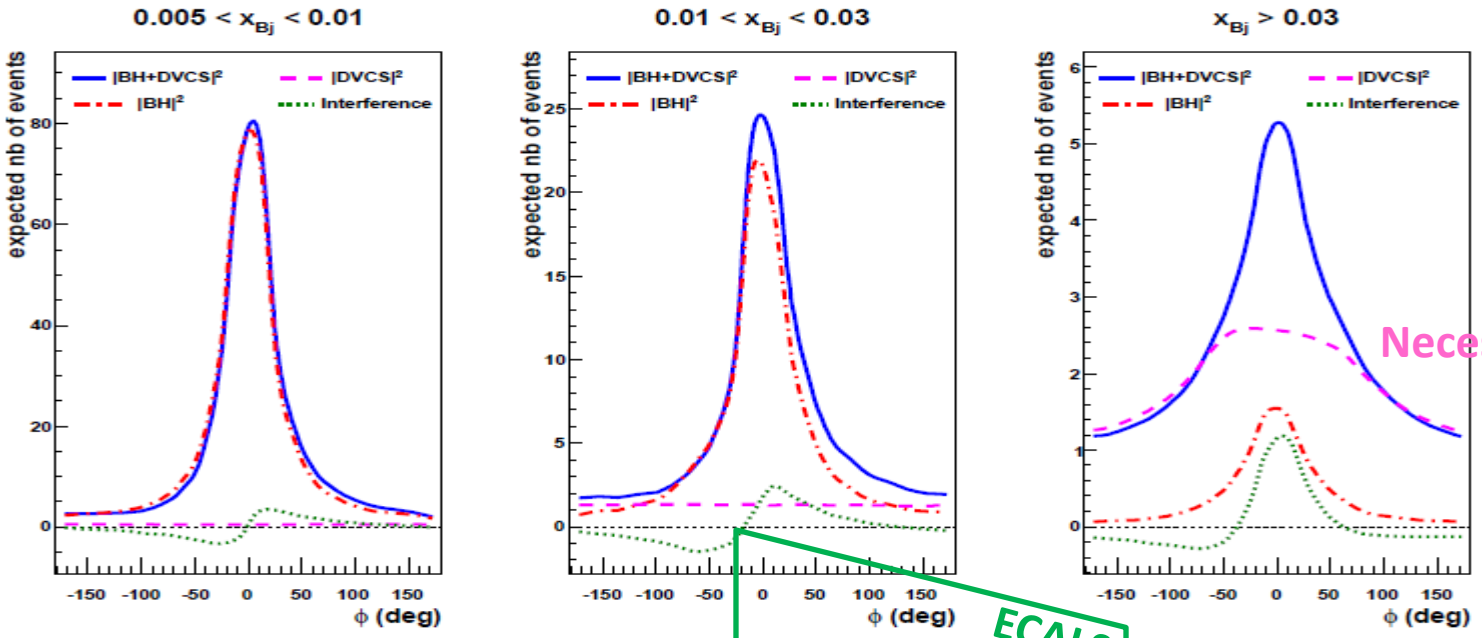
$-t$	$F_2^p(t)$	$F_1^p(t)$	$F_1^p(t)+F_2^p(t)\ \cdot x_B/(2-x_B)$	$(-t/4M^2)\cdot F_2^p(t)$
0.1	1.34	**0.81**	**0.01**	0.04
0.3	0.82	**0.56**	**0.005**	0.06

Model: Q^2=3, x=0.3, -t=0.3

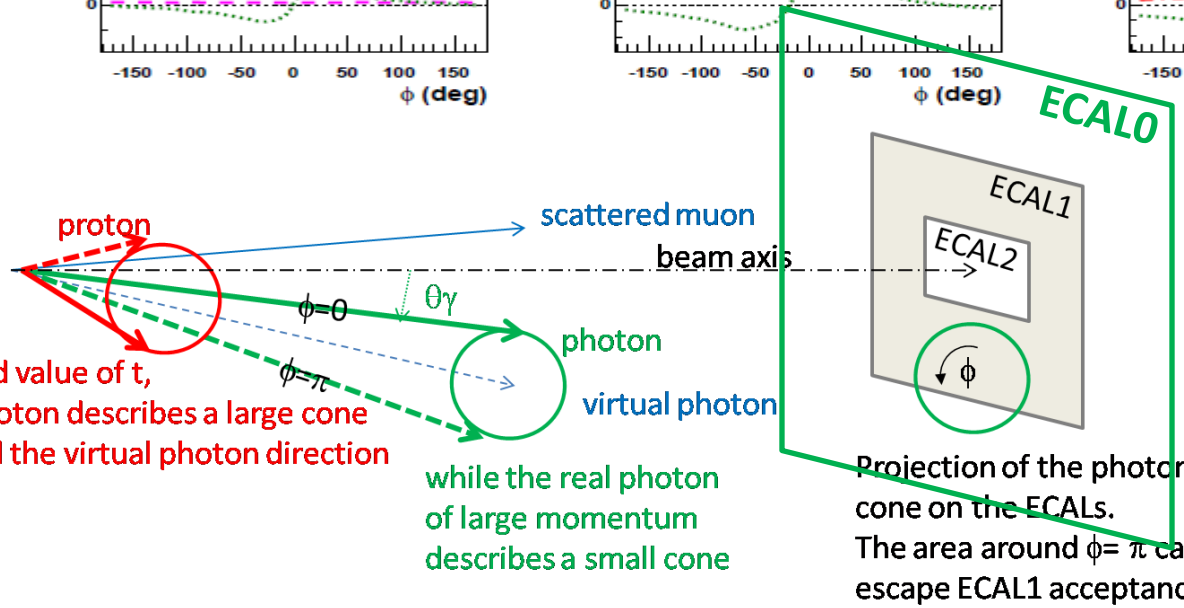
Goeke, Polyakov and Vanderhaeghen

Target	H	$\tilde{H}$	E
Proton	1.13	0.70	0.98

2009 test: BH and DVCS events



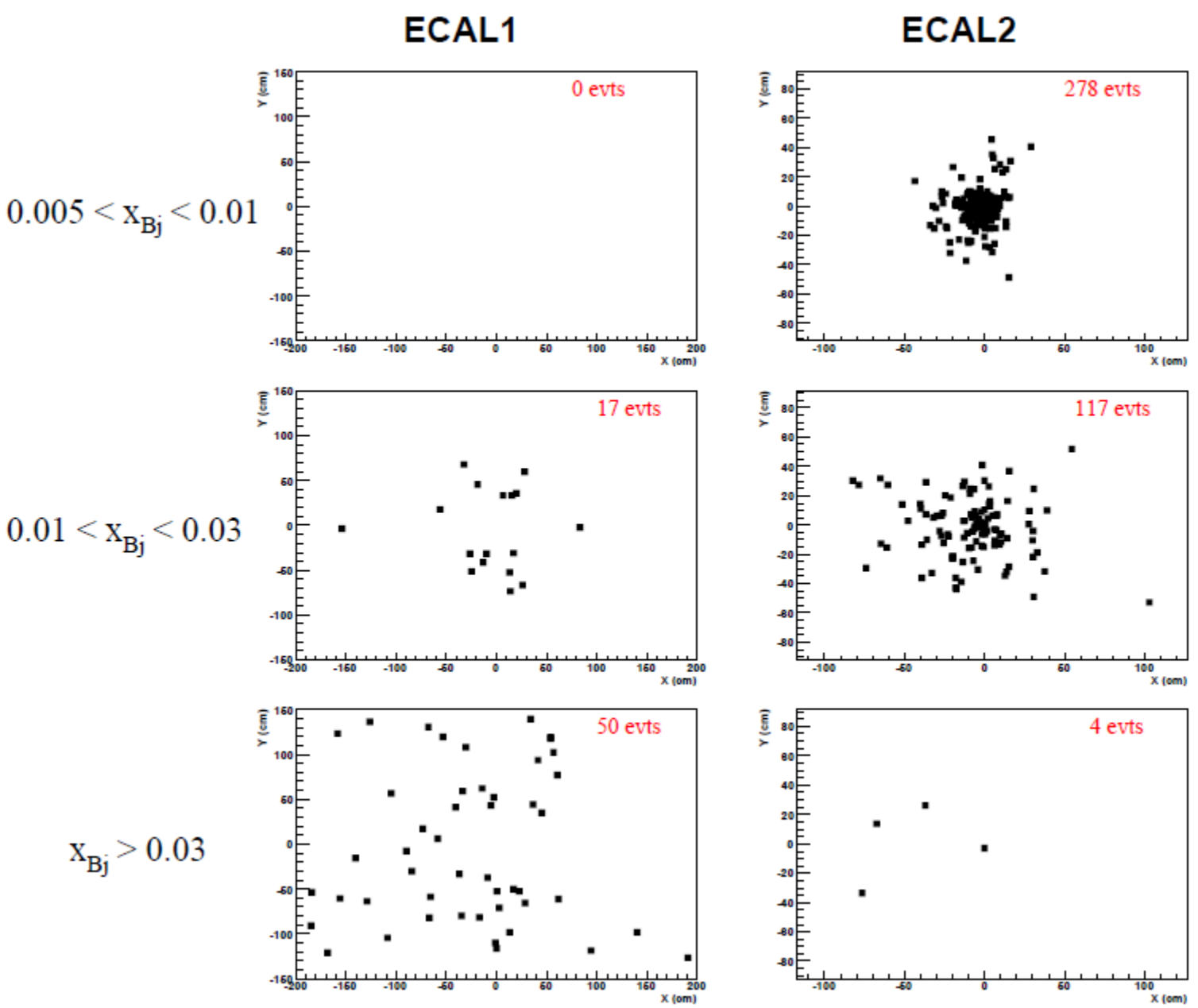
Necessity of ECAL0



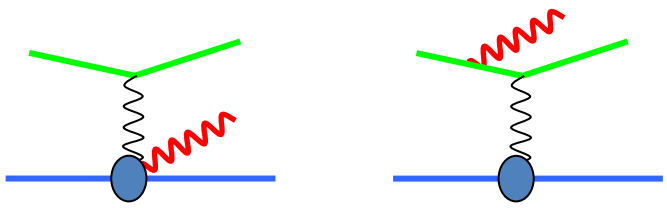
Necessity of a complete acceptance to match the outgoing photon

- ➔ **Necessity of ECAL0**
- ➔ **No gap of acceptance between ECAL1 and ECAL2**

2009 test: Distribution of the outgoing photon

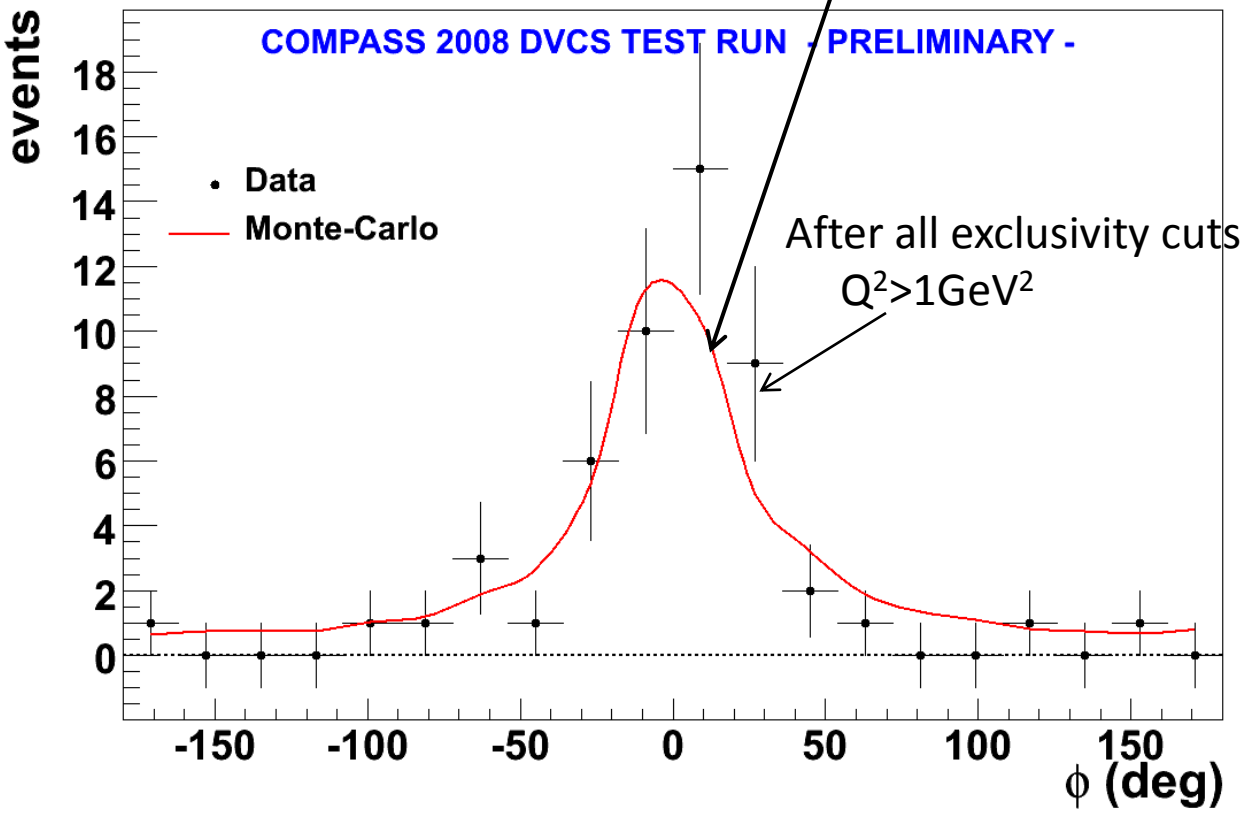


2008 test : Bethe-Heitler signal



Monte-Carlo simulation
of BH (dominant) and DVCS

➔ **Bethe-Heitler observed**



Detection efficiency :

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

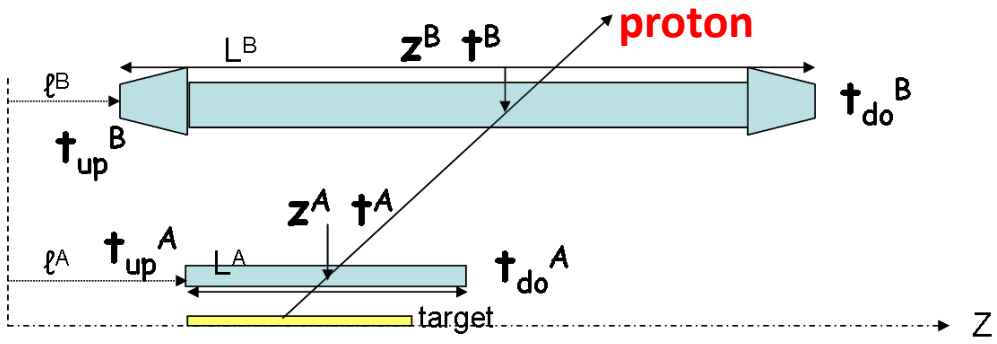
Global efficiency included also:
- SPS availability
- COMPASS Spectro availability
- Dead time
- Trigger efficiency

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

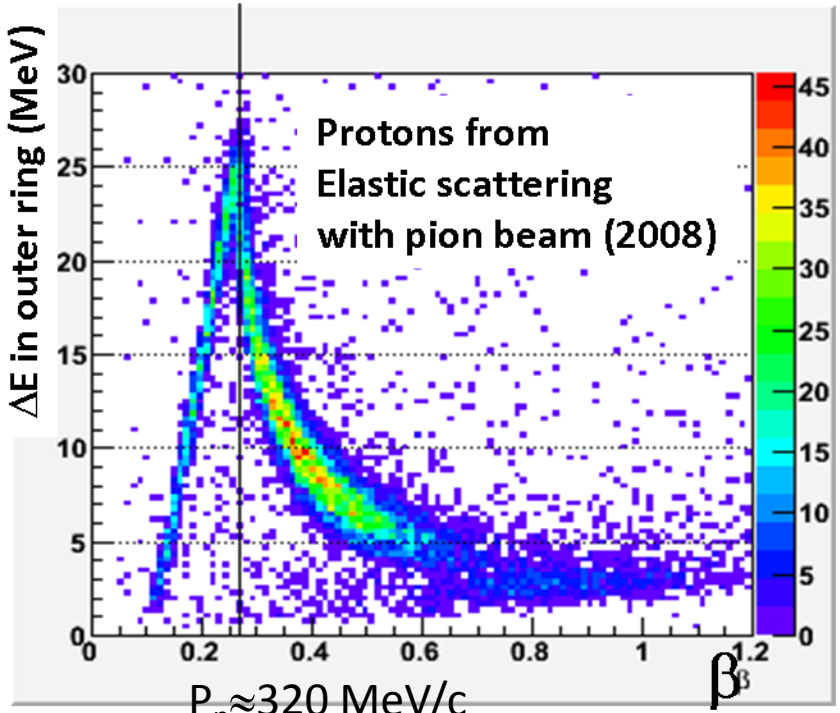
➔ **Projections of errors are realistic**

~ 8 times more data taken in 2009 to be shared in three x_B domains

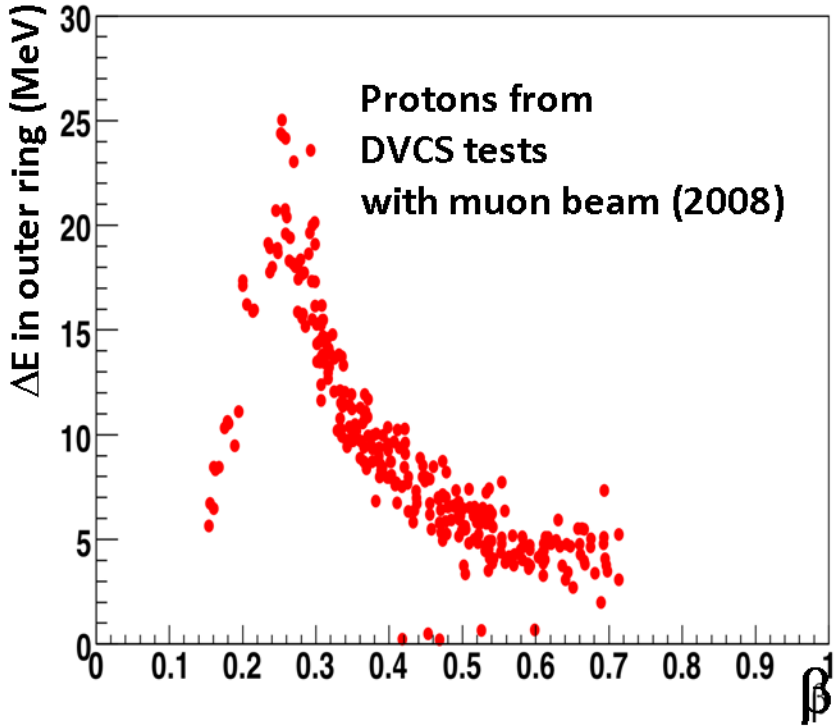
Clear Proton Identification using ToF



$\beta = d_{AB}/ToF$



$P_p \approx 320$ MeV/c



Protons stopped in B

Protons Escaping B

Measurements and Estimations for resolution

$$\frac{\Delta P}{P} \approx \frac{1}{1-\beta^2}\frac{\sin^2\vartheta}{R_B - R_A}\sqrt{\cos^2\vartheta(v_A^2\sigma_A^2 + v_B^2\sigma_B^2) + \beta^2 c^2 \sigma_{ToF}^2}$$

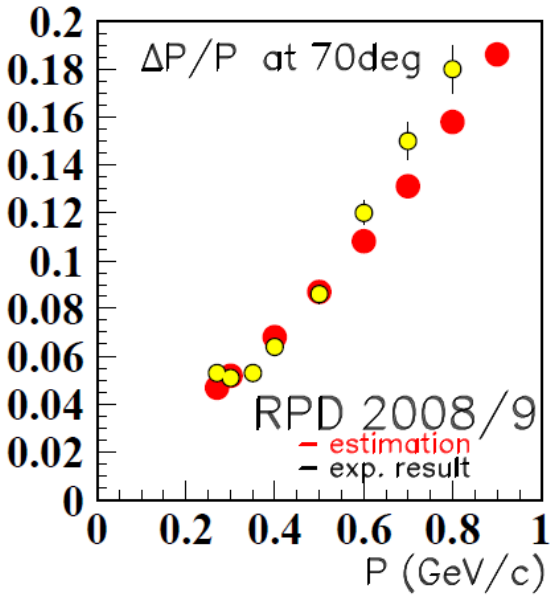
$$\frac{\Delta t}{t} \approx 2\frac{\Delta P}{P}$$

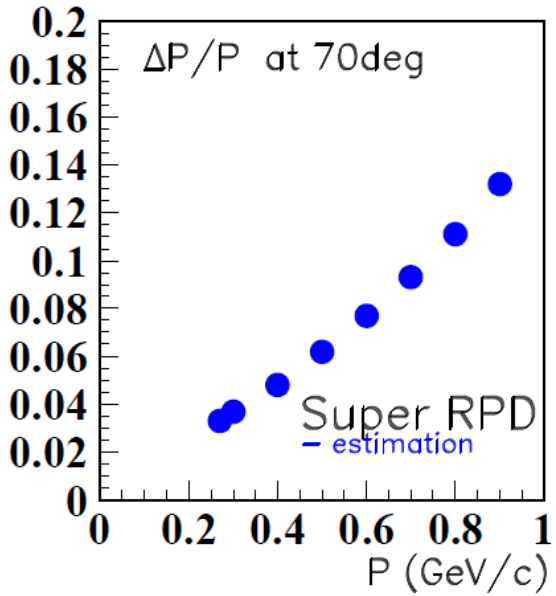
	RPD(2008)	MuRex (2006)
B	L=1m; th=1cm Atten length = 0.7m σ_B = 300 ps	L=4m; th=5cm Atten length = 4m σ_B = 200 ps
A	L=50cm; th=5mm σ_A = 180 ps	L=2.83m; th=4mm σ_A = 270 ps
ToF	σ_{ToF} = 350 ps R_B-R_A= 85-12 = 63 cm	σ_{ToF} = 310 ps R_B-R_A= 110-25 = 85cm

t_{min}=-0.06 GeV^2

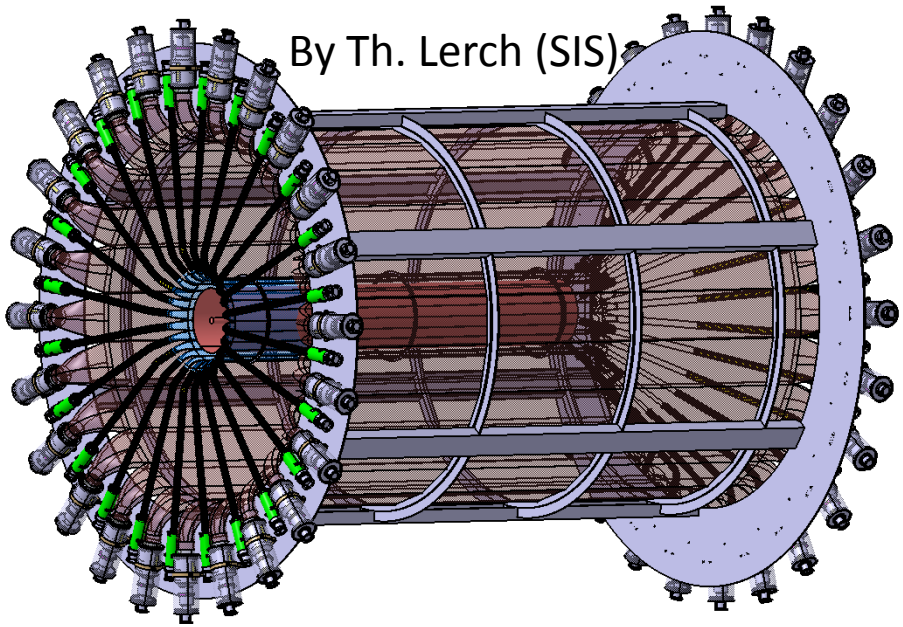
Good resolution in t

Importance for the the transverse imaging





Recoil Proton Detector and LH2 target



3.6 m long scintillator slabs
➔ 300ps timing resolution

Extrapolations rely on 2 studies:
- **MuRex (a 4m sector prototype)**
- **The present RPD (1m long)**

➔Integration with the LH2 target in the dense region before SM1 (with ECAL0 and MMs and DCs)

➔Definition of the best optical coupling between scintillators and PMTs