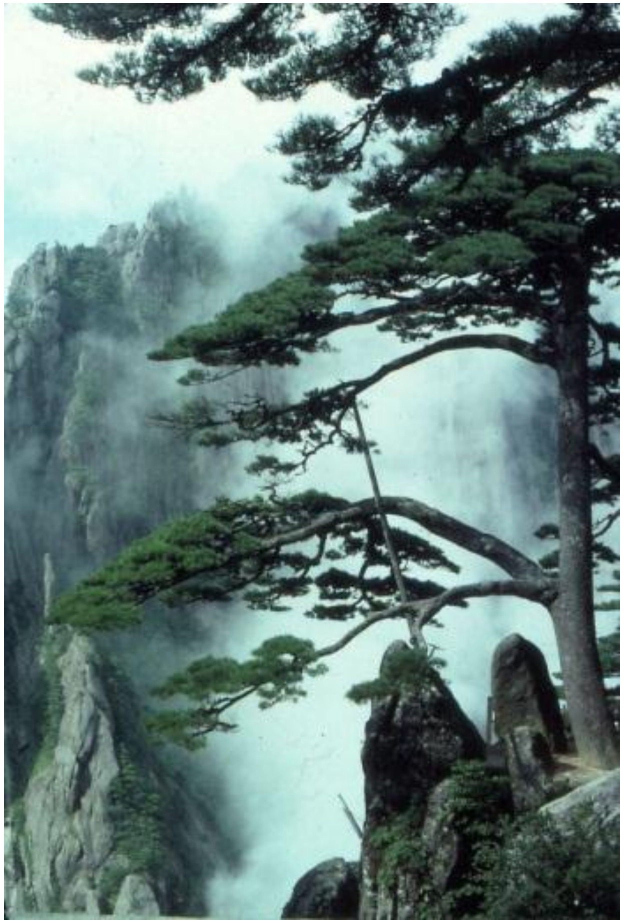
COMPASS-II: a Facility to study QCD

a fixe target experiment
at the CERN SPS

~ 250 physicists
from 24 Institutions
of 13 Countries

COMMON
MUON and
PROTON
APPARATUS for
STRUCTURE and
SPECTROSCOPY



Nicole d'Hose, CEA-Saclay, for the COMPASS Collaboration
At The fifth workshop on hadron physics in China and Opportunities in US
Huangshan, China, July 2, 2013

COMPASS-II: a Facility to study QCD

COMMON
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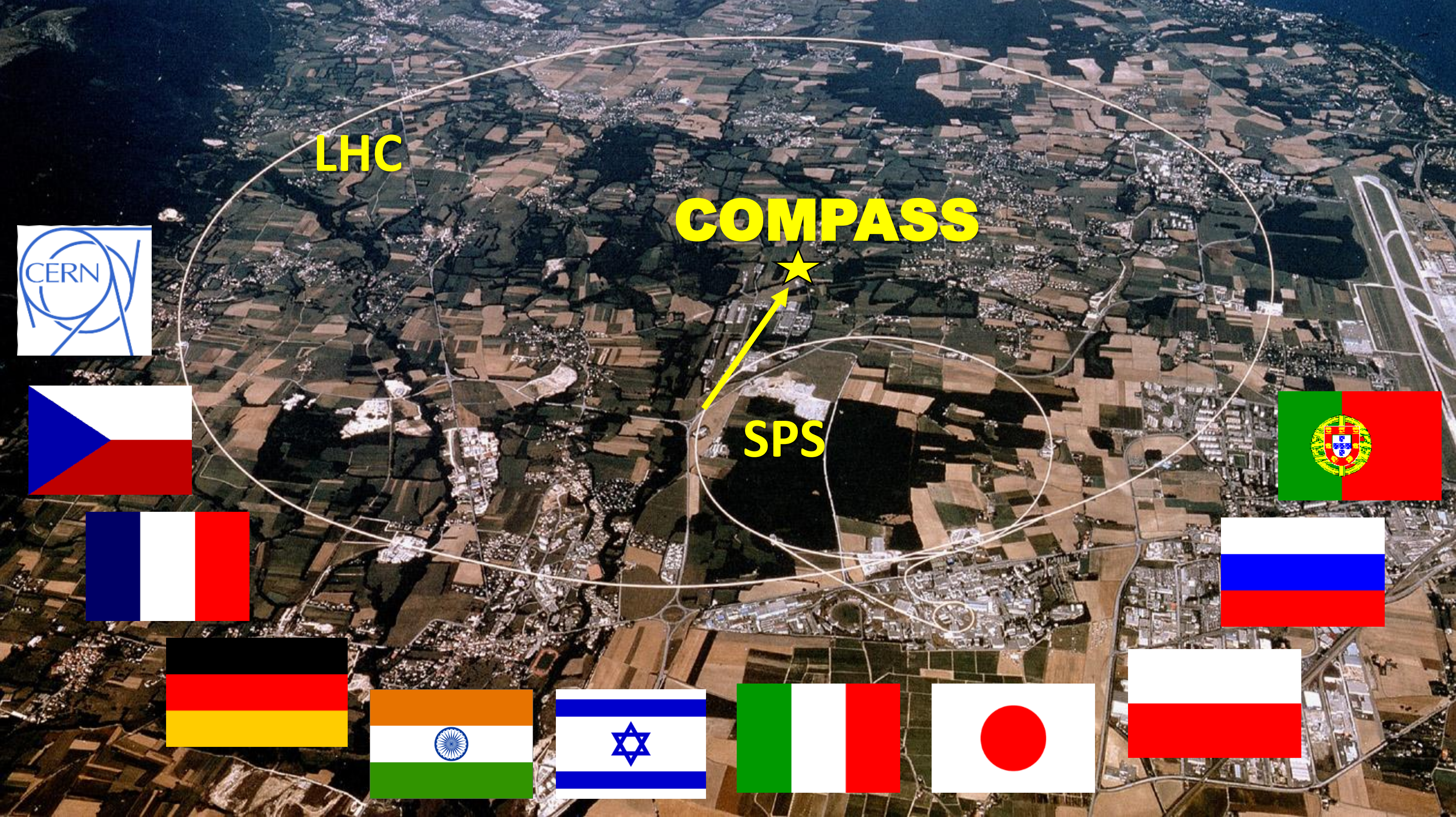
Long Term Plans for at least 5 years (starting in 2012)

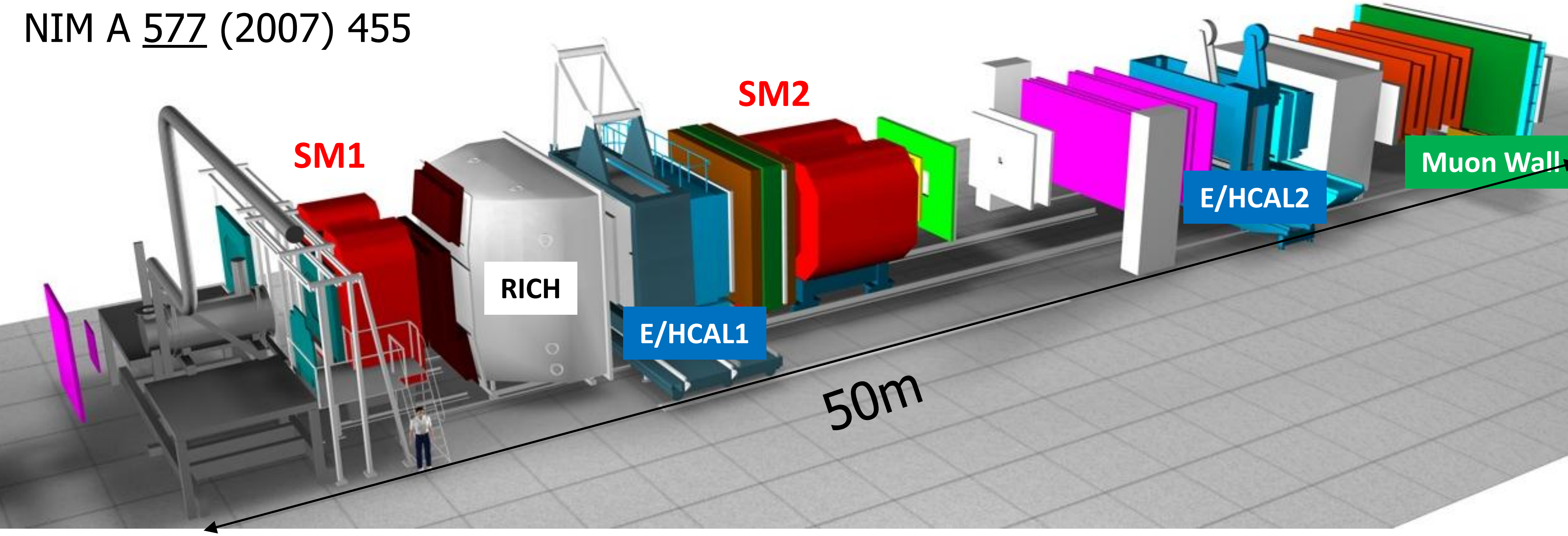
✓ Primakoff with π, K beam ➔ Test of Chiral Perturb. Theory	2012
	LHC shutdown
✓ Drell-Yan with π beams ➔Transverse Momentum Dependent PDFs	2015
✓ DVCS & HEMP with μ beams ➔ Transv. Position Dependent GPDs	2016-17
✓ SIDIS (with GPD prog.) ➔ Strange PDF and Transv. Mom. Dep. PDFs	**(+1month in 2012)**

COMPASS: Versatile facility to study QCD with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) and lepton (polarized $\mu^{\pm}$) beams of ~200 GeV for hadron spectroscopy and hadron structure studies using SIDIS, DY, DVCS, DVMP…



The COMPASS experiment at CERN

NIM A 577 (2007) 455

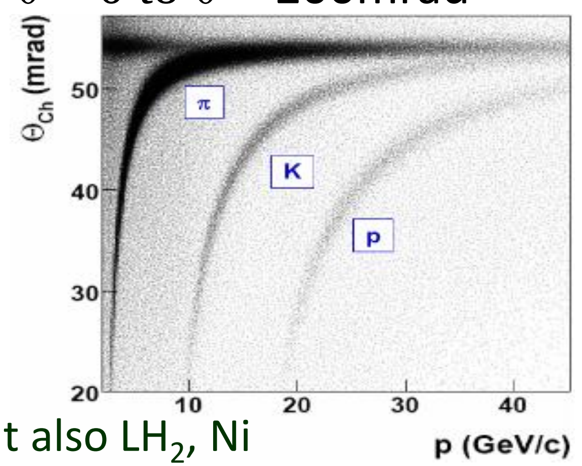


Two stage magnetic spectrometer for **large angular & momentum acceptance**

Variety of tracking detectors to cope with all particles from $\theta = 0$ to $\theta \approx 200$mrad

Particle identification with:

- Ring Imaging Cerenkov Counter
- Electromagnetic and Hadronic calorimeters
- Hadron absorbers

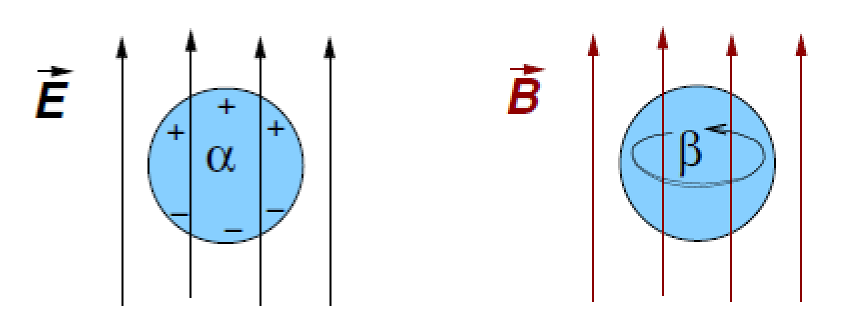


Targets: polarized ^{6}LiD, NH_3 (consecutive cells of ≠ polarisation) but also LH_2, Ni

QCD at low energy: Pion Polarisabilities and Chiral predictions

The pion: Goldstone boson (spontaneous breaking of chiral symmetry)
lightest quark-gluon bound state system
➔ understanding its internal structure is a fundamental challenge

The polarisabilities give the deformation of the pion shape by an EM field



$\alpha_\pi > 0$ S=0 diamagnetic contr. $\beta_\pi < 0$

2-loop ChPT prediction:

$\alpha_\pi + \beta_\pi = (0.2 \pm 0.1)\ 10^{-4}\ \mathrm{fm}^3$

$\alpha_\pi - \beta_\pi = (5.7 \pm 1.0)\ 10^{-4}\ \mathrm{fm}^3$

experiments: $\alpha_\pi - \beta_\pi$ from 4 to 14 $.10^{-4}\ \mathrm{fm}^3$

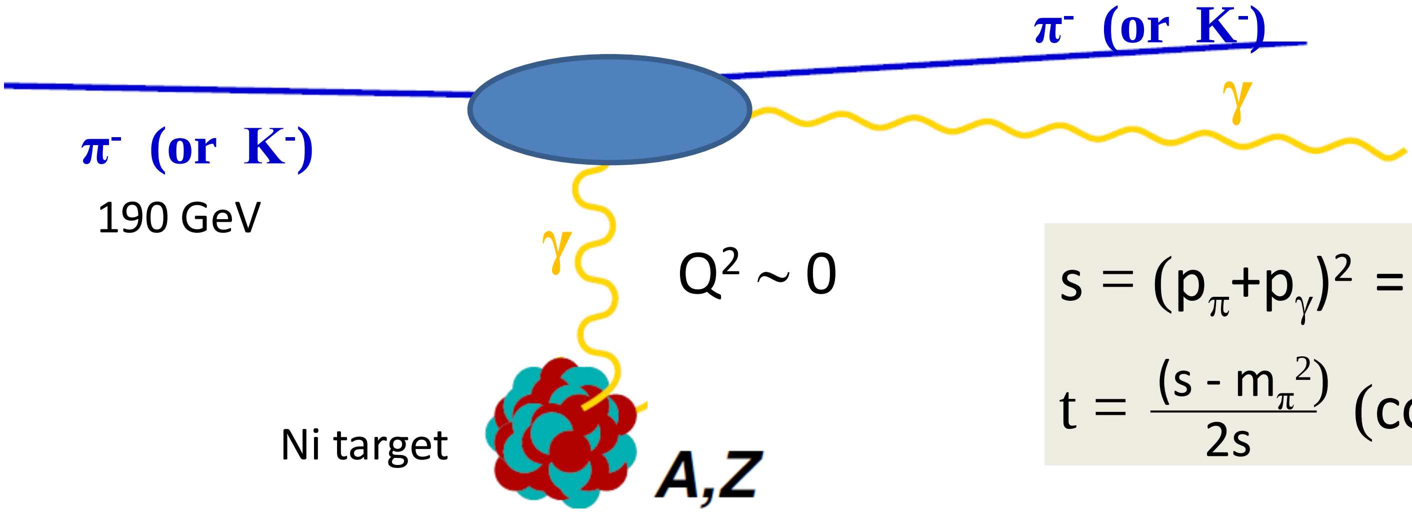
≠ methods:

$\gamma\, p \rightarrow \gamma\, \pi^+\, n$ MAINZ exper. EPJA23 (2005) (≠ ChPT pred.)

$\gamma\, \gamma \rightarrow \pi^+\, \pi^-$ (after Mark-II) future GLUEX experiment at JLab

$\pi^-\, \gamma \rightarrow \pi^-\, \gamma$ (after Serpukov) COMPASS experiment (the most direct measurement)

Primakoff experiments with π, K or inverse Compton Scattering on π, K



$$s = (p_\pi + p_\gamma)^2 = (\pi\gamma \text{ CM energy})^2$$

$$t = \frac{(s - m_\pi^2)}{2s} (\cos\vartheta_{cm} - 1)$$

The chiral perturbation theory (ChPT) predicts the low-energy behavior of the cross section with s varying from threshold (m_π^2) to a few m_π^2

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}}\right]_{\text{point-like}} + C.\frac{(s-m_\pi^2)}{s^2} \cdot \mathcal{P}(\alpha_\pi, \beta_\pi)$$

$\downarrow$

Deviation due to π polarisabilities

the point-like cross section is measured with the muon beam

Pion Polarisabilities measurement

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \left[\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}}\right]_{pt} + C.\frac{(s-m_\pi^2)}{s^2}\cdot\left((1-\cos\theta_{cm})^2(\alpha_\pi-\beta_\pi) + (1+\cos\theta_{cm})^2(\alpha_\pi+\beta_\pi)\frac{s^2}{m_\pi^4} + (1-\cos\theta_{cm})^3(\alpha_2-\beta_2)\frac{(s-m_\pi^2)^2}{24s}\right)$$

Polarisability effect with increasing s at backward or forward angle

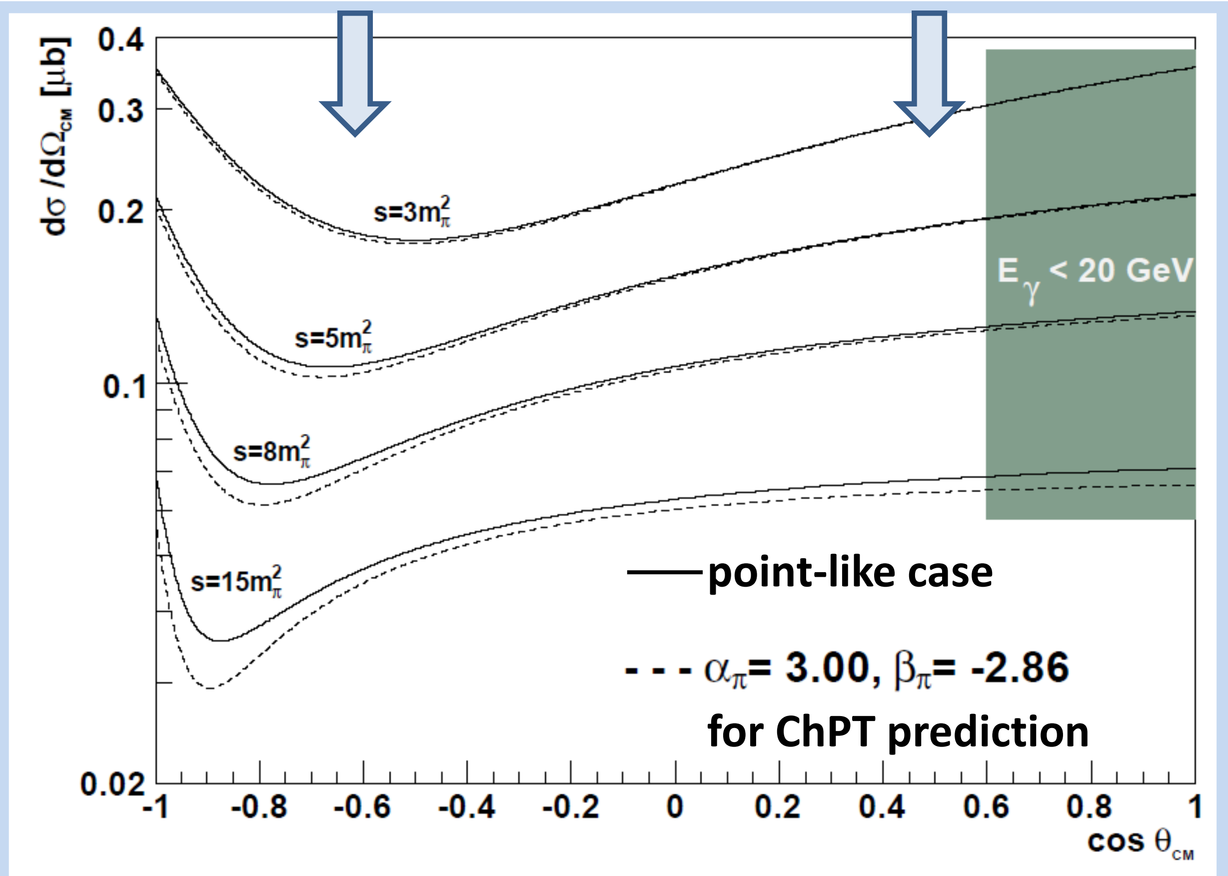
2009 data
$\alpha_\pi - \beta_\pi$ (in 10^{-4} fm^3)=
$3.7 \pm 1.4_{stat} \pm 1.6_{syst}$
AGREEMT WITH CHPT
STILL PRELIMINARY

2012 data, 3 components

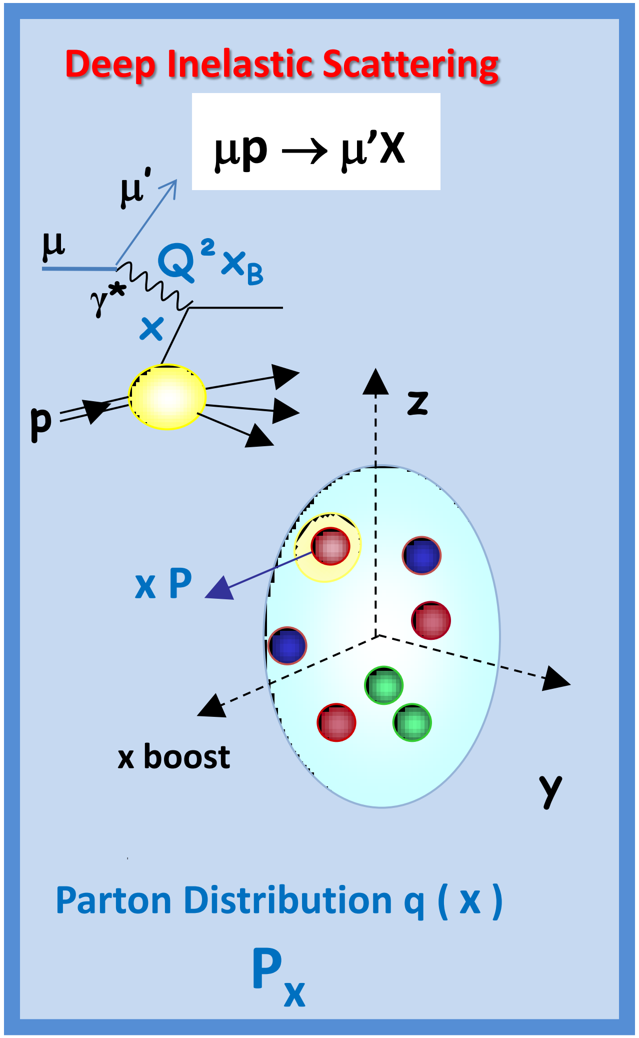
$(\alpha_\pi - \beta_\pi)$
$(\alpha_\pi + \beta_\pi)$
$(\alpha_2 - \beta_2)$

can be measured with an accuracy of 10%

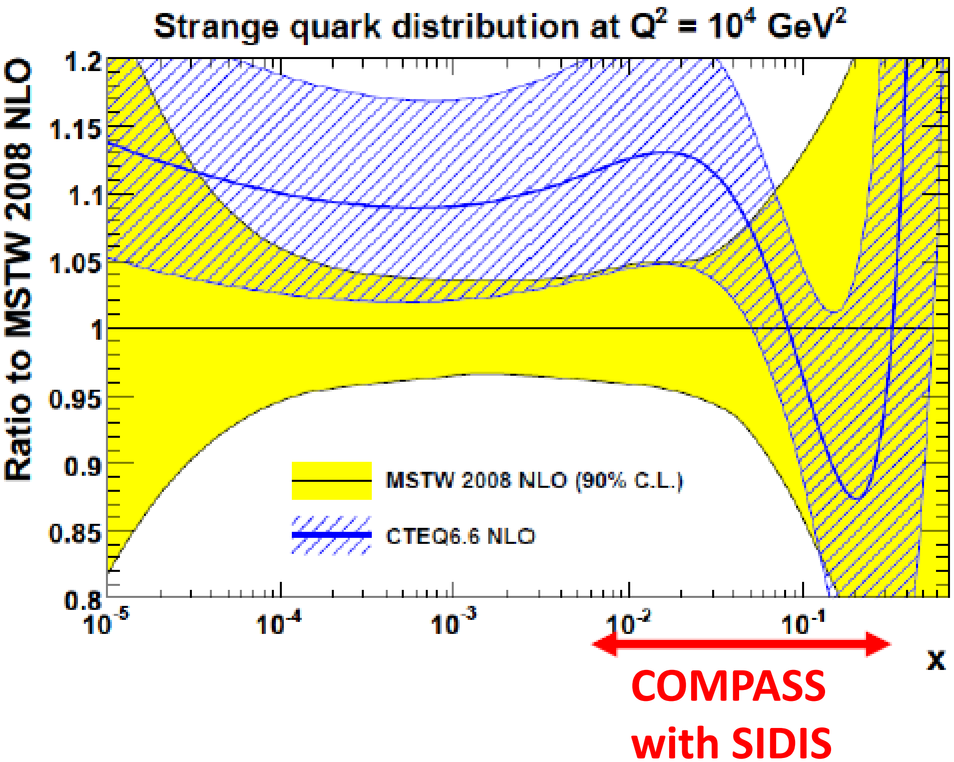
and kaon polarizabilities



QCD at high energy: Deep Inelastic Scattering



While unpolarised light quark PDF well constrained, strange quark distributions are not so well known



Semi-Inclusive Deep Inelastic Scattering

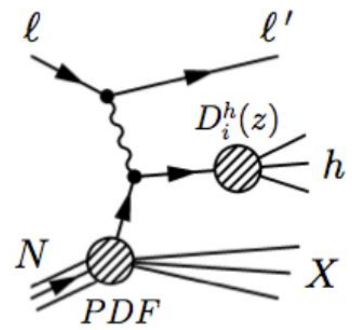
Semi-Inclusive DIS measurements
- with polarized targets (2002-2011)
- with a pure proton target (with GPD program)

Use of RICH detector and Calorimeters

Charge separation and identification K^+, K^-, K^0, π^+, π^-, π^0, Λ...

Major progress as compared to previous experiments

to strange PDFs: s(x) and Δs(x)



Hadron multiplicities at LO

$$\frac{\mathrm{d}N^h(x,z,Q^2)}{\mathrm{d}N^{DIS}} = \frac{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2)}$$

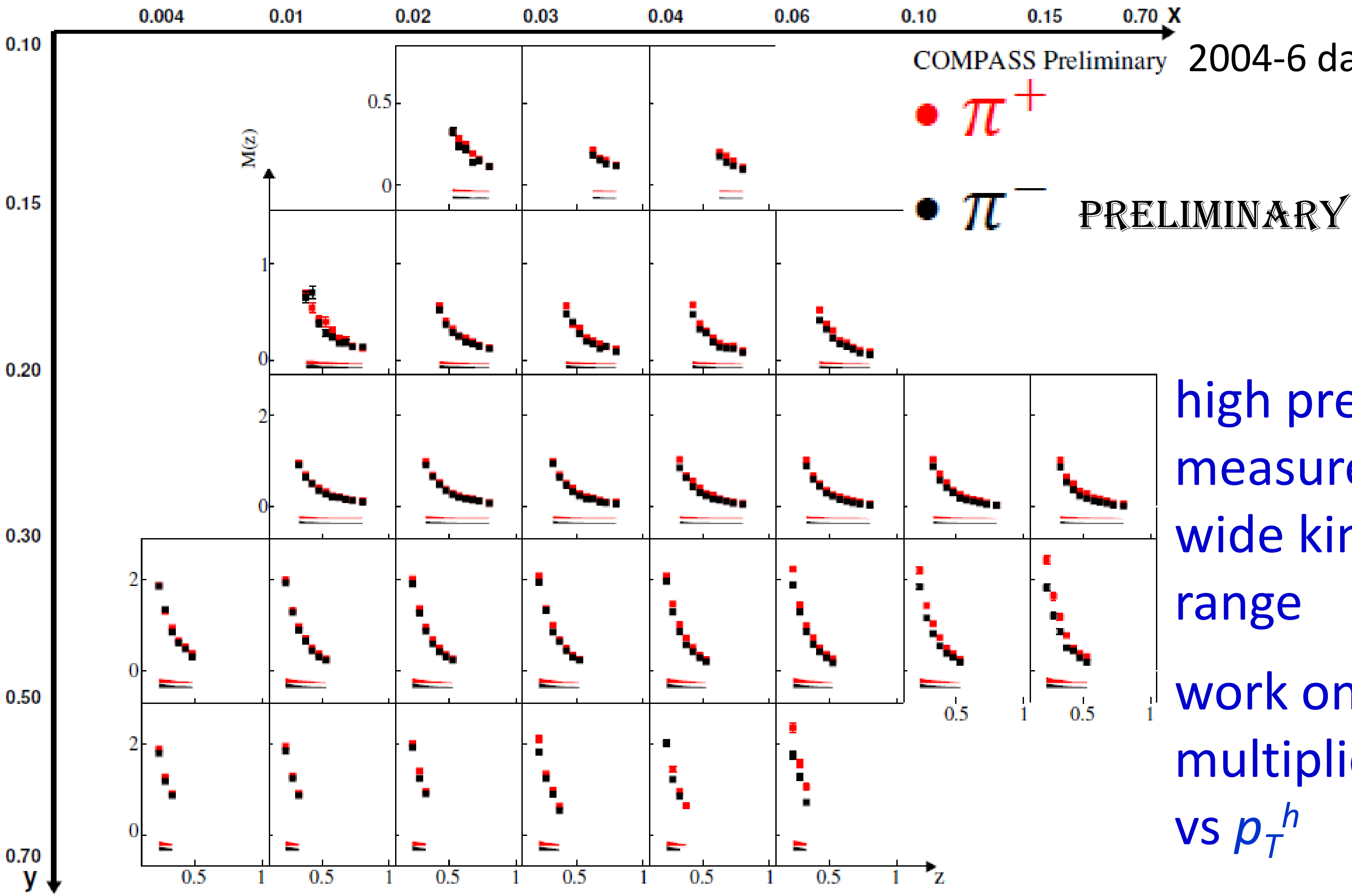
PDF
depend on x

quark Fragmentation Function
depend on z (fraction of energy of the outgoing hadron)

Final goal: extensive measurements *(x, z, Q^2, p_T^h)*
to provide inputs to NLO global analysis for both PDF and FF

SIDIS and multiplicities

Charged π^+ and π^- multiplicities vs z in (x,y) bins



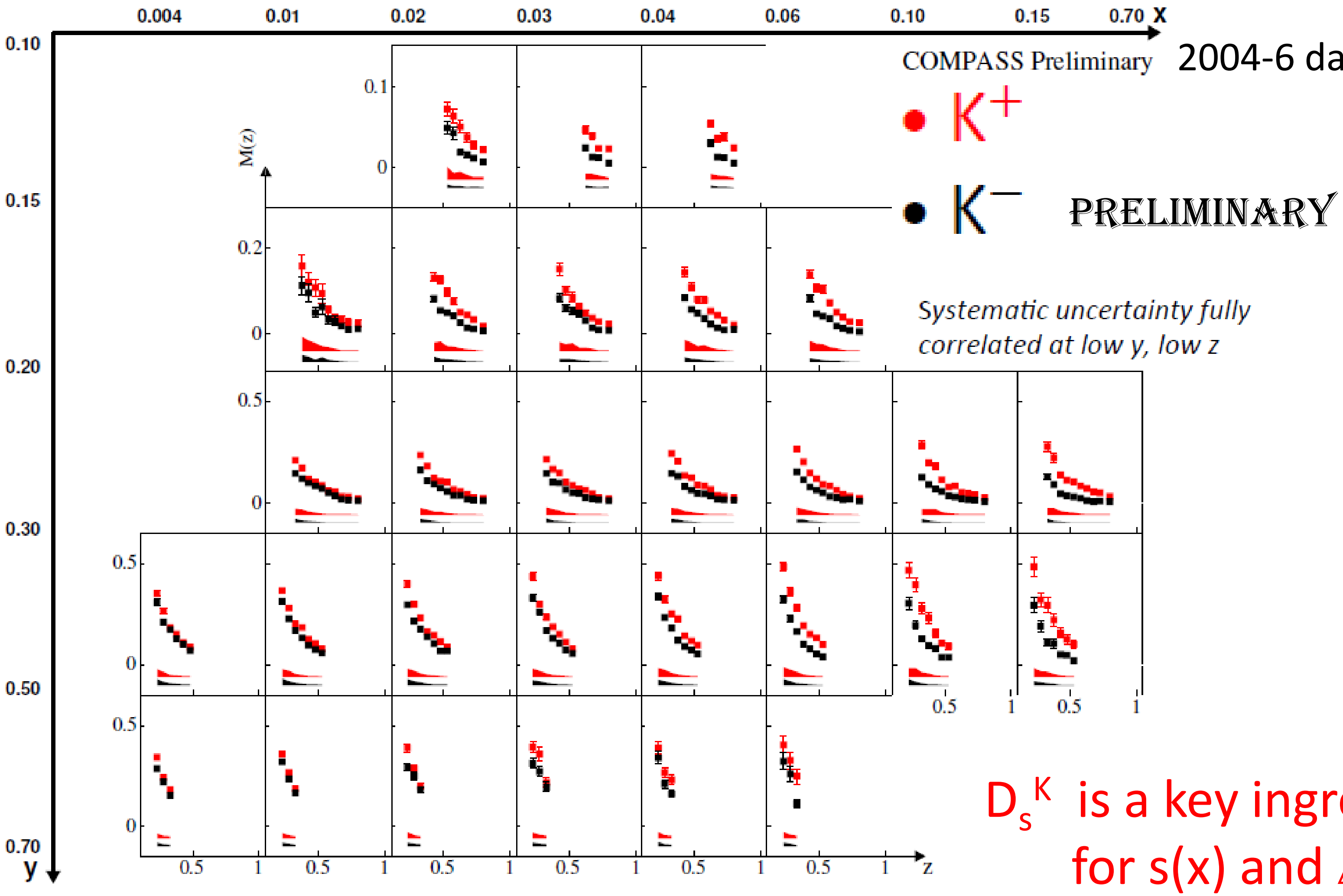
2004-6 data

high precision measurement in wide kinematic range

work ongoing for multiplicity studies vs p_T^h

SIDIS and multiplicities

Charged K^+ and K^- multiplicities vs z in (x,y) bins



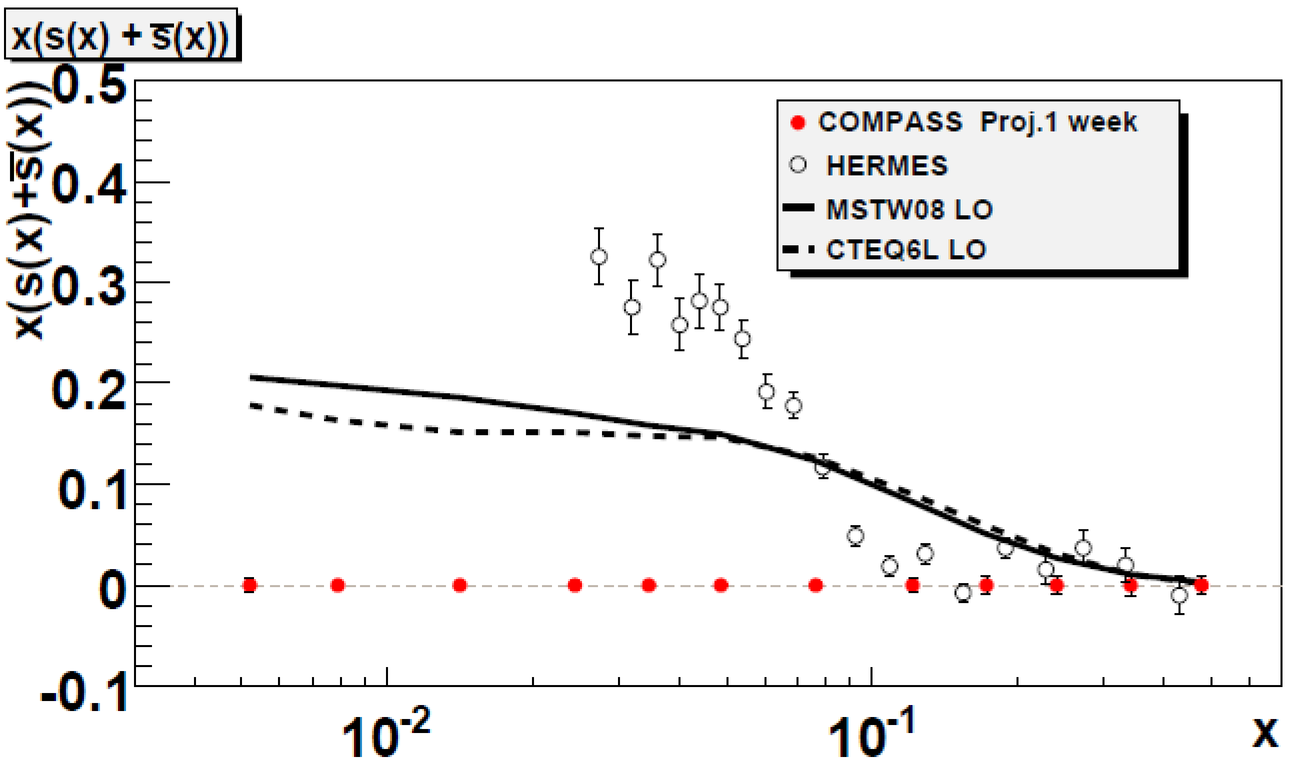
2004-6 data

Systematic uncertainty fully correlated at low y, low z

D_s^K is a key ingredient for for s(x) and $\Delta s(x)$

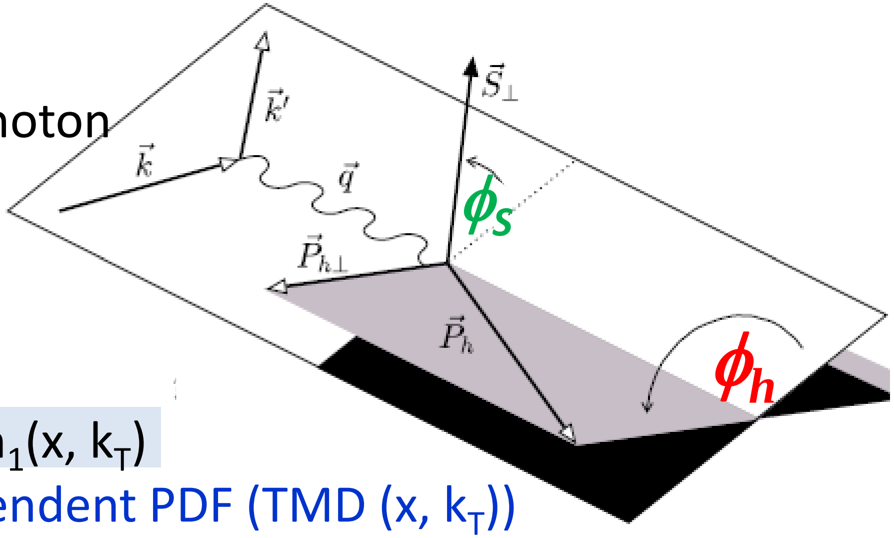
Projection for the strange PDF s(x)

LO analysis from COMPASS data alone integrated over z



Projection for 1 week with 2.5m LH_2 target ➔ high statistics

SIDIS and azimuthal asymmetries

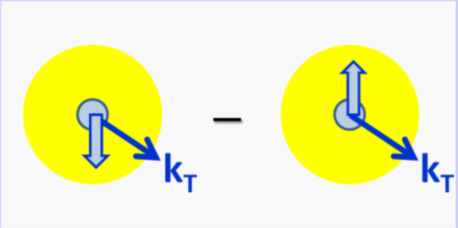


Asymmetries in the azimuthal angle ϕ_h of the outgoing hadron around the virtual photon can reveal quark transverse spin and quark transverse momentum (k_T) effects beyond the collinear approximation

At leading twist, not only $f_1(x, k_T)$, $g_{1L}(x, k_T)$, $h_1(x, k_T)$ but also 5 other Transverse Momentum Dependent PDF (TMD (x, k_T)) which do not survive after integration on k_T

2 examples of TMDs

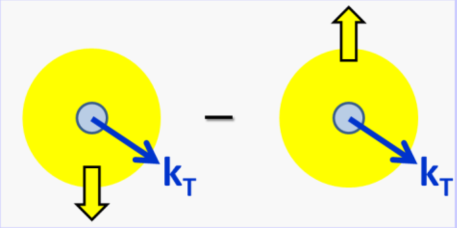
The **Boer-Mulders** function



correlates the quark k_T and the quark transverse spin (unpol N)

Chiral-odd and T-odd

The **Sivers** function



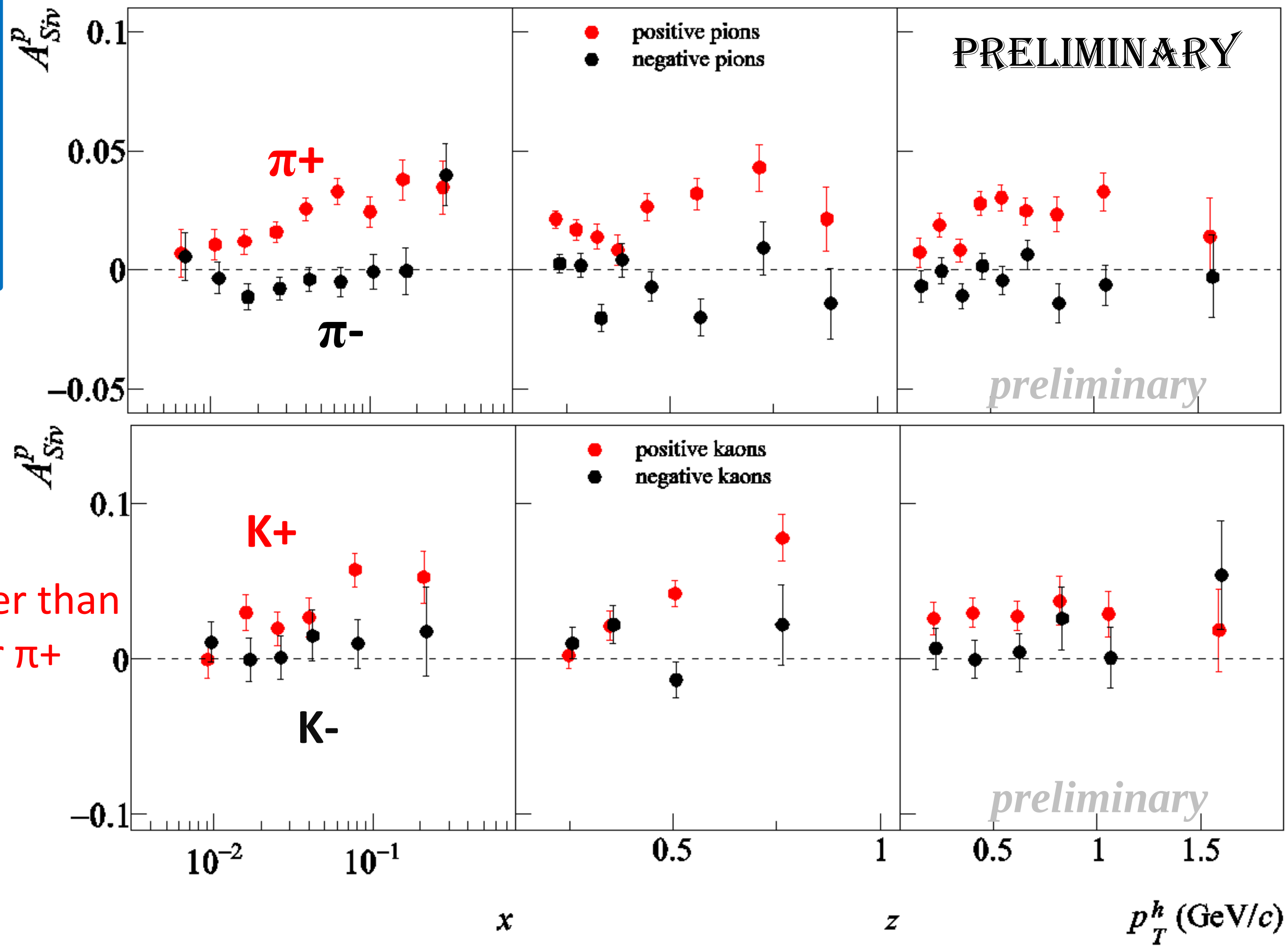
correlates the quark k_T and the nucleon spin (transv. Pol. N)

Chiral-even and T-odd

Sivers asymmetry on transv. pol. proton

$$A_{Siv}^{\sin(\phi_h-\phi_S)} \approx \frac{\sum_q e_q^2 \, f_{1T}^{\perp q} \otimes D_{1q}^h}{\sum_q e_q^2 \, f_1^q \otimes D_{1q}^h}$$

Combined 2007-2010 data



larger than for π+

In region of overlap, agreement with HERMES, but smaller strength

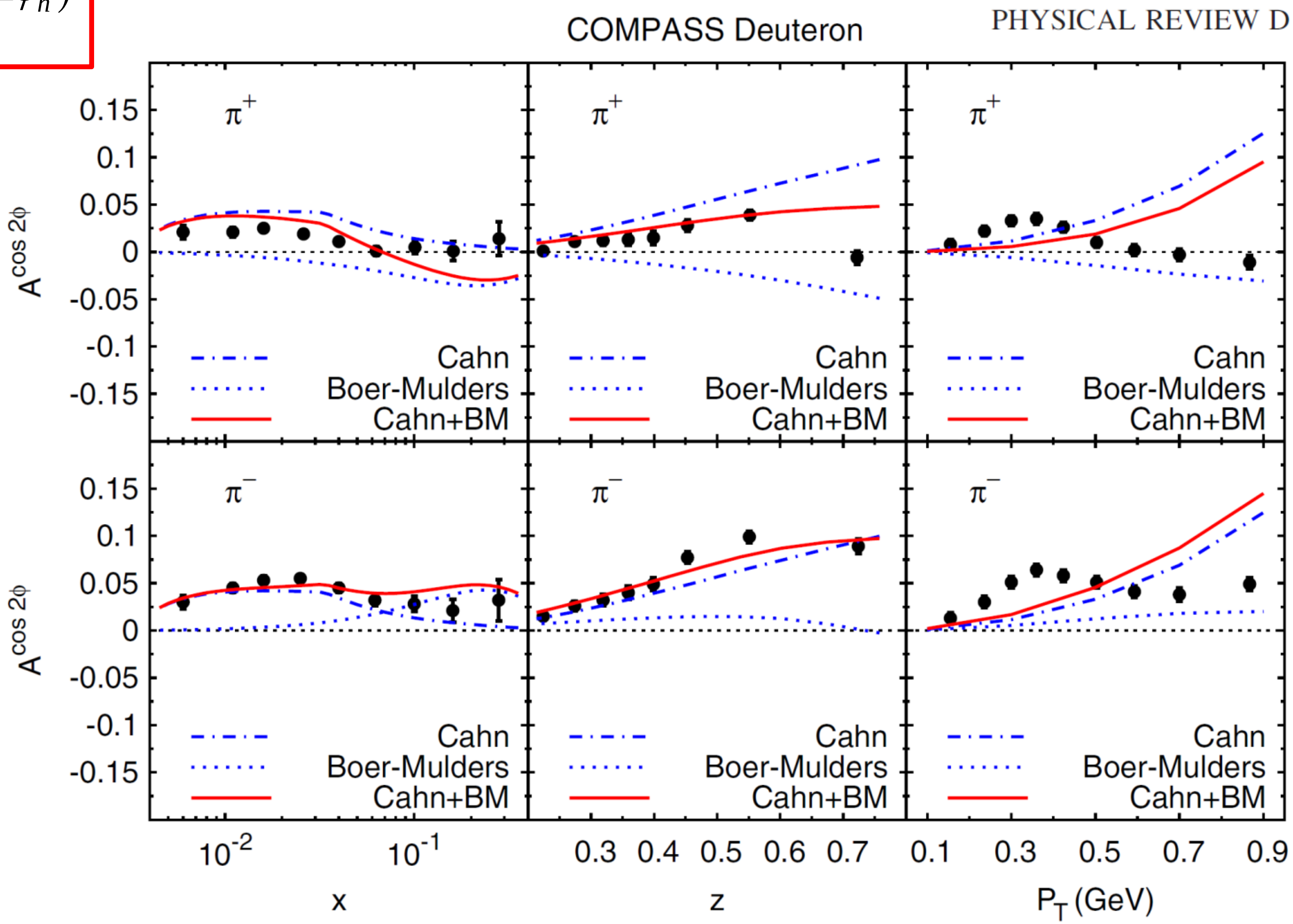
to be done soon: multidimensional analysis *(x, z, Q^2, $p_T{}^h$)*

Boer-Mulders and Cahn effects on unpol. deuteron

$$A^{\cos(2\phi_h)}$$

Vincenzo Barone,[1,2] Stefano Melis,[1,2] and Alexei Prokudin[3]

PHYSICAL REVIEW D **81,** 114026 (2010)

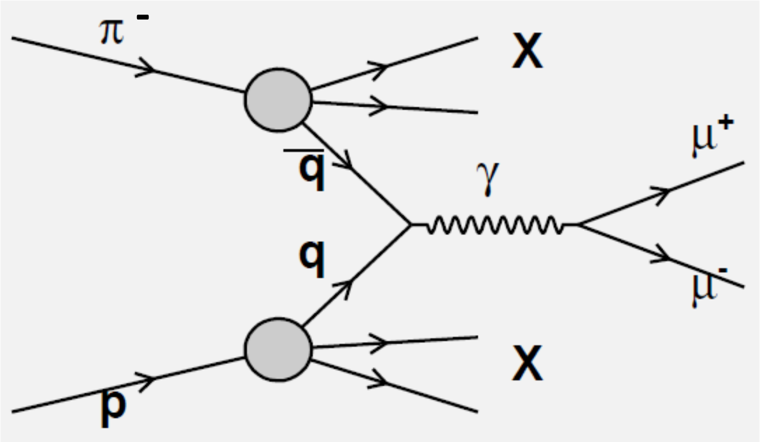


a multidimensional analysis seems to indicate a strong z dependence

➔many data collected and still to be collected in SIDIS with GPD program

After SIDIS, polarized Drell-Yan to study TMDs

Drell –Yan $\pi^- p^\uparrow \rightarrow \mu^+\mu^- X$



Cross sections:

In SIDIS: convolution of a TMD with a fragmentation function

In DY: convolution of 2 TMDs $\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f'_{u|p}$

→ complementary information and universality test

The polarized Drell-Yan process in π⁻ p

$$
\begin{aligned}
d\sigma^{DY} \propto \Big(1 &+ \int d^2k_{1T}\, d^2k_{2T}\, \mathcal{W}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2) \otimes h_1^{\perp}(x_2,k_{2T}^2)\cos 2\phi \\
&+ |S_T| \Big(\int d^2k_{1T}\, d^2k_{2T}\, \mathcal{X}(k_{1T},k_{2T})\, \bar{f}_1(x_1,k_{1T}^2) \otimes f_{1T}^{\perp}(x_2,k_{2T}^2)\sin\phi_S \\
&+ \int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Y}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2) \otimes h_{1T}^{\perp}(x_2,k_{2T}^2)\sin(2\phi+\phi_S) \\
&+ \int d^2k_{1T}\, d^2k_{2T}\, \mathcal{Z}(k_{1T},k_{2T})\, \bar{h}_1^{\perp}(x_1,k_{1T}^2) \otimes h_1(x_2,k_{2T}^2)\sin(2\phi-\phi_S)\Big)
\end{aligned}
$$

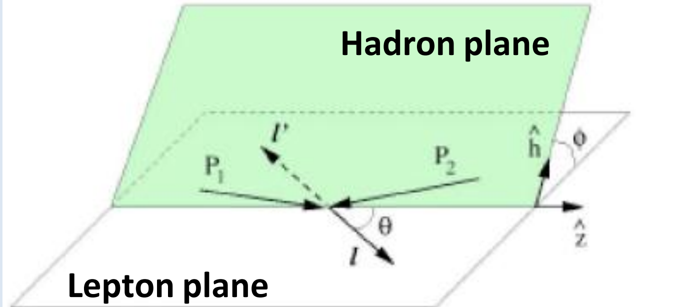
➔Access to TMDs for incoming pion ⊗ target nucleon
TMD as Transversity, Sivers, Boer-Mulders, pretzelosity

Collins-Soper frame (of virtual photon)

θ, ϕ lepton plane wrt hadron plane

target rest frame

ϕ_S target transverse spin vector /virtual photon

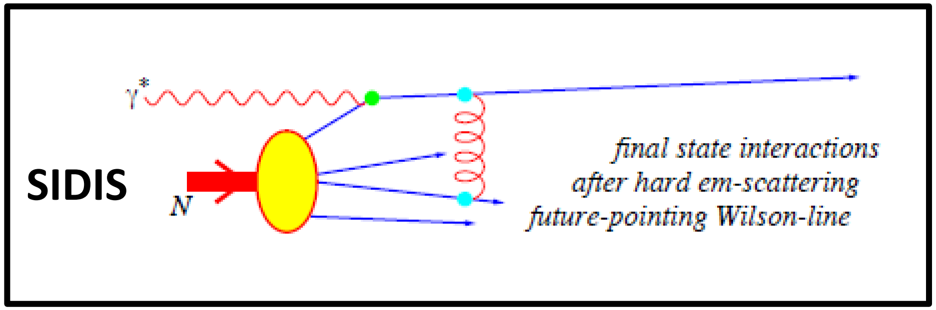


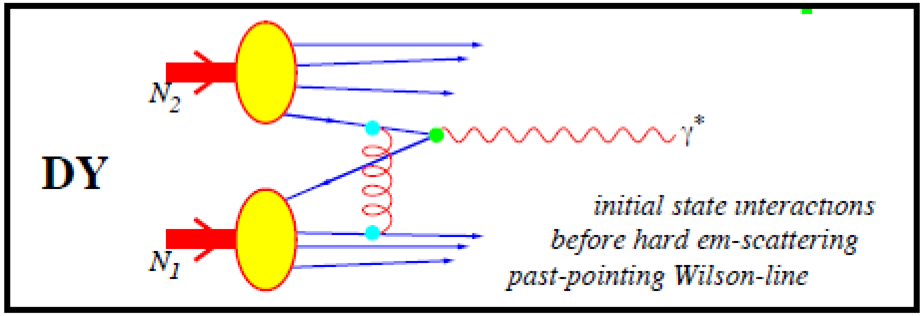
Experimental check of the change of sign of TMDs confronting Drell-Yan and SIDIS results

T-odd character of the Boer-Mulders and Sivers functions

In order not to be forced to vanish by time-reversal invariance
the SSA requires an interaction phase generated by
a rescattering of the struck parton in the field of the hadron remnant

Time reversal





these functions are process dependent, they change sign to provide the gauge invariance

Boer-Mulders

$$\boxed{h_1^{\perp}(SIDIS) = -h_1^{\perp}(DY)}$$

Sivers

$$\boxed{f_{1T}^{\perp}(SIDIS) = -f_{1T}^{\perp}(DY)}$$

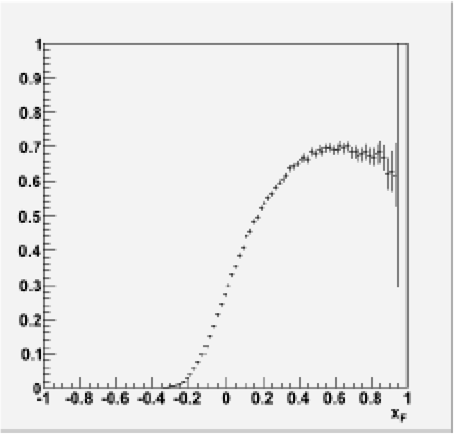
NEED EXPERIMENTAL VERIFICATION
SIGN + AMPLITUDE + SHAPE

TEST OF CONSISTENCY
OF THE APPROACH

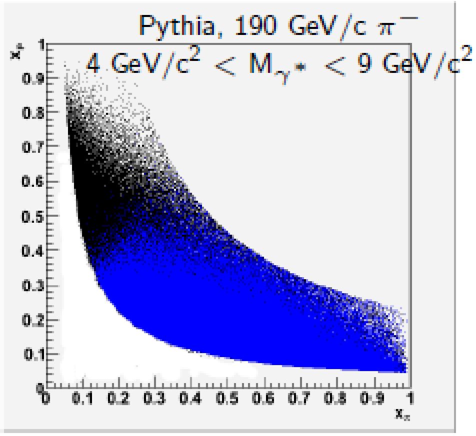
Why DY $\pi^{\pm} p^{\Uparrow}$ is very favourable at COMPASS?

σ^{DY} dominated by the annihilation of a valence anti-quark from the pion and a valence quark from the polarised proton

$$\boxed{\sigma^{DY} \propto f_{\bar{u}|\pi^-} \otimes f_{u|p}}$$



x_F acceptance plot



x_p vs x_π scatter plot: in black all generated events, in blue events in acceptance

Competitive experiments at

RHIC (STAR, PHENIX) collider $p^{\Uparrow} p$

Fermilab fixed target $p^{\Uparrow\Rightarrow} H,\ pH^{\Uparrow\Rightarrow}$

J-PARC fixed target $pp^{\Uparrow},\ \pi p^{\Uparrow}$

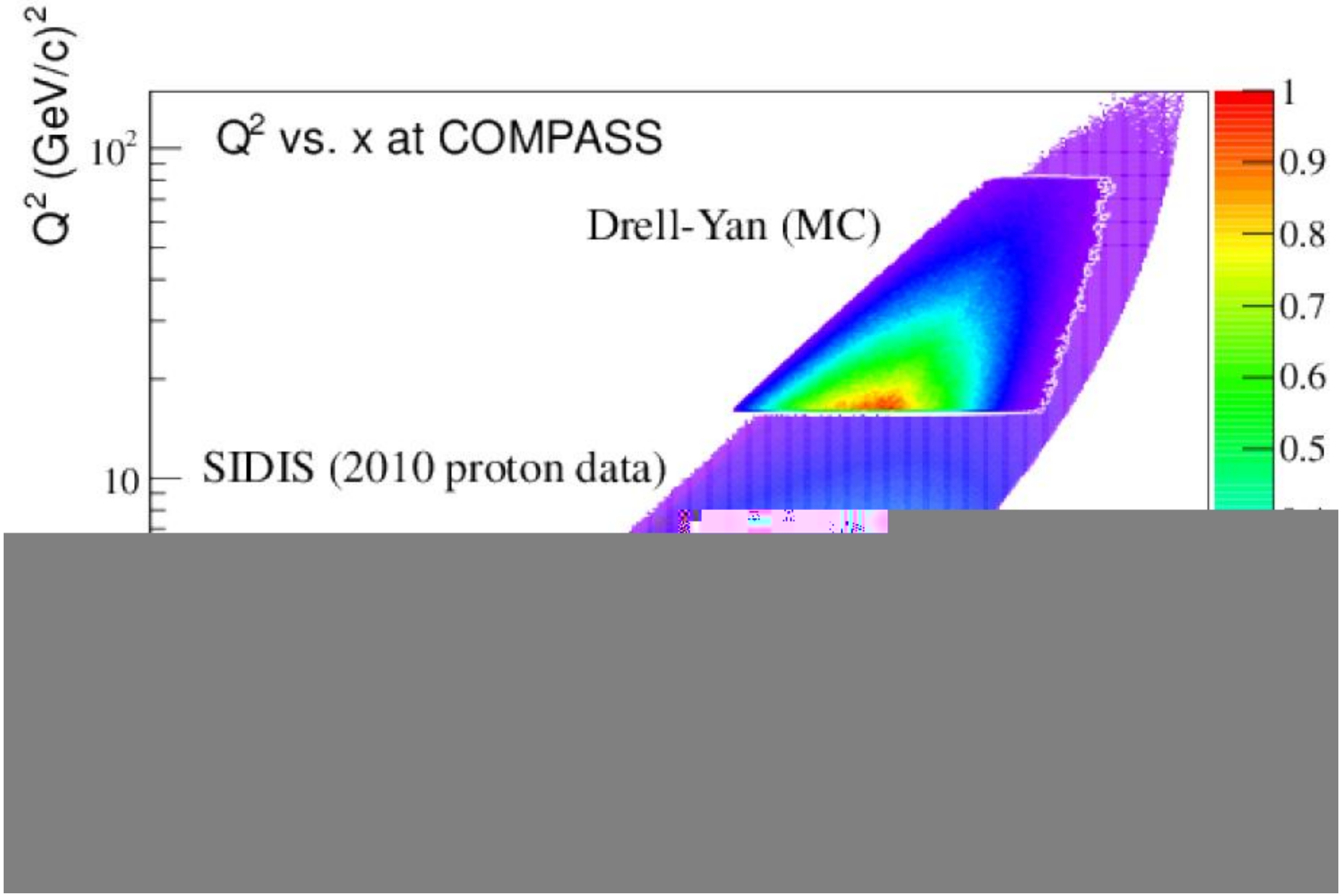
FAIR (PAX) collider $\bar{p}^{\Uparrow} p^{\Uparrow}$

NICA collider $p^{\Uparrow} p^{\Uparrow},\ d^{\Uparrow} d^{\Uparrow}$

large acceptance of COMPASS
in the valence quark region for p and π
where SSA are expected to be larger

COMPASS has the chance to be the first experiment to collect single polarized DY

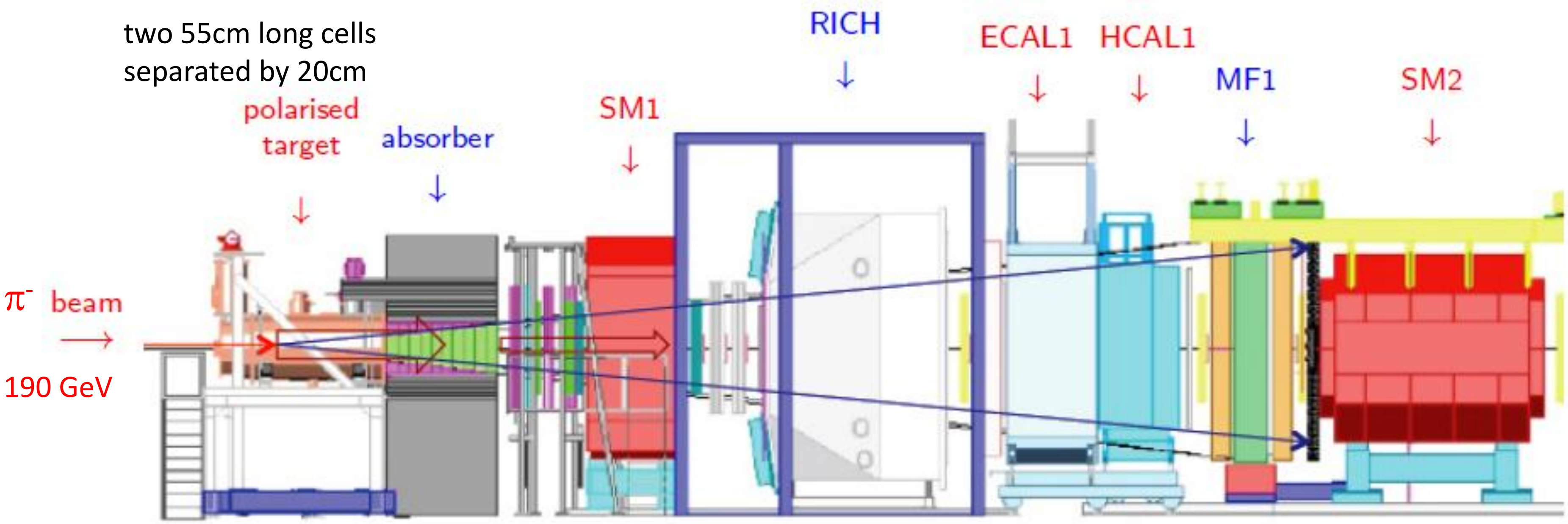
Q2 vs x phase space at COMPASS



The phase spaces of the two processes overlap at COMPASS

➔ Consistent extraction of TMD DPFs in the same region

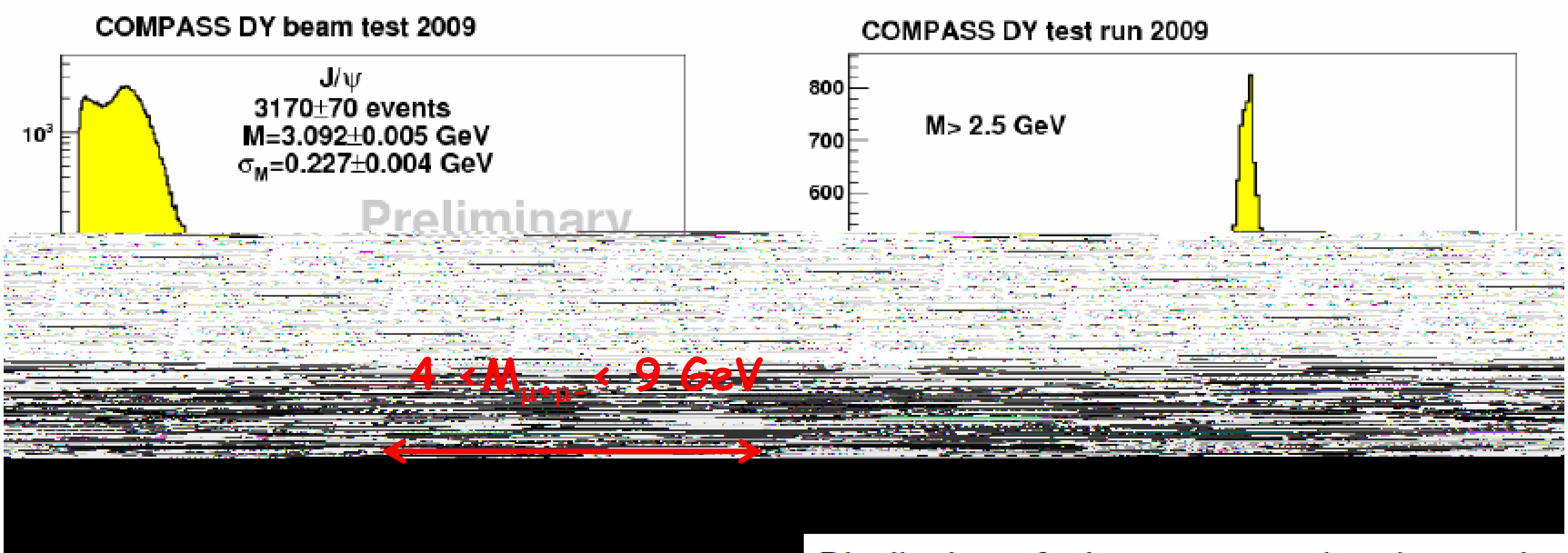
DY $\pi^- + p^\uparrow \rightarrow \mu^+\mu^- + X$ and COMPASS set-up



Key elements for a small cross section investigation at high luminosity

1. high intensity pion beam 10^8 π^- per second on a thick target (~1 interaction length)
2. a hadron absorber to stop secondary particles and
   a beam plug to stop the non-interacting beam
3. rearrangement of the target area to place the absorber
   - a new muon trigger in the first stage spectrometer (60% of the DY acceptance)
   - a vertex detector (SciFi) to improve the cell separation
4. RICH1, Calorimetry – also important to reduce the background

Results from DY tests in 2007-8-9 and 2012



Distributions of primary vertexes along beam axis

→ a vertex detector has been proposed

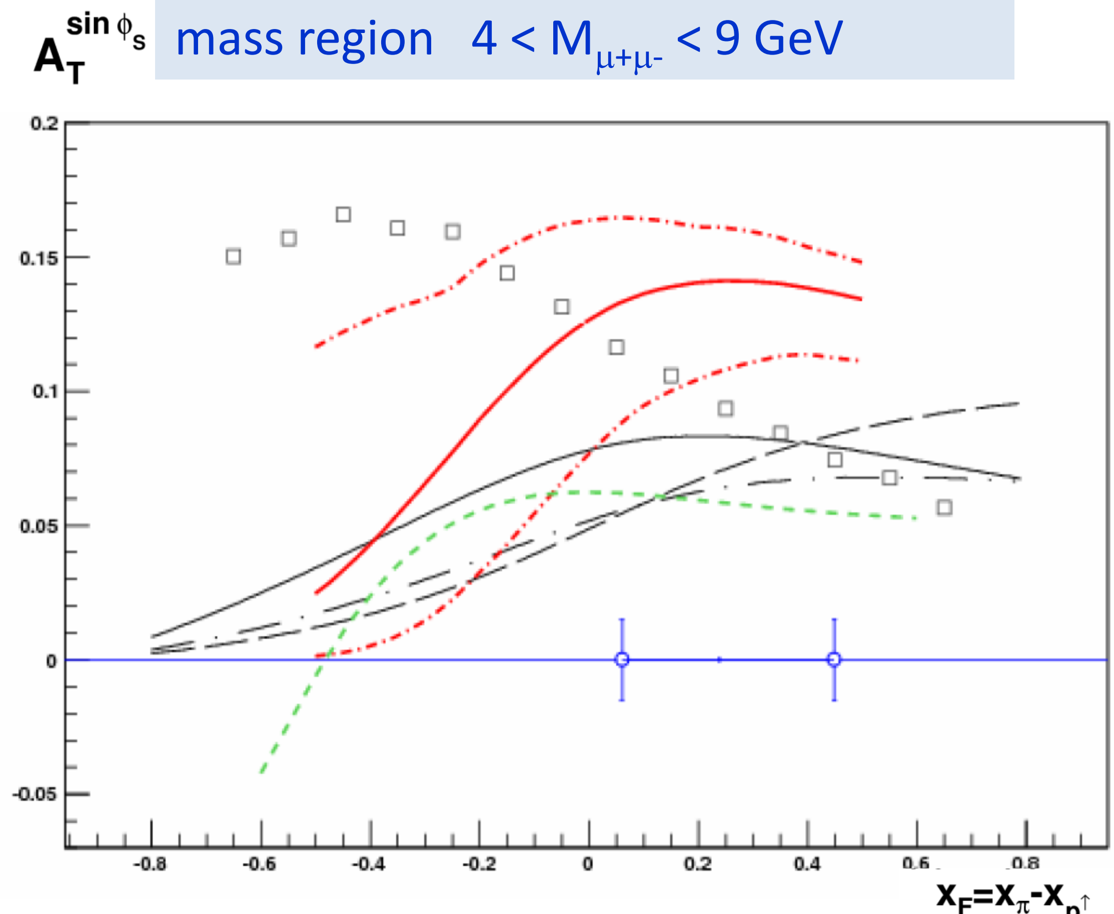
Recent test done in the condition of the future measurement with the hadron absorber.
During the short data taking, the J/ψ peak and DY events were observed as expected and the two cells were distinghished.

- Target temperature OK
- Detector occupancies OK
- Radioprotection limits respected
- Agreement with simulations

Predictions for Drell-Yan at COMPASS

$$A_T^{\sin\phi_S}(x_a, x_b) = \frac{2}{f\,|S_T|}\frac{\int d\phi_S d\phi \frac{dN(x_a,x_b,\phi,\phi_S)}{d\phi\, d\phi_S}\sin\phi_S}{N(x_a,x_b)}$$

Sivers asymmetry in the safe dimuon mass region $4 < M_{\mu+\mu-} < 9$ GeV



2 years of data
190 GeV pion beam
6 .10^8 π^-/spill (of 9.6s)
1.1 m transv. pol. NH_3 target
Lumi=1.2 10^{32} $cm^{-2}s^{-1}$

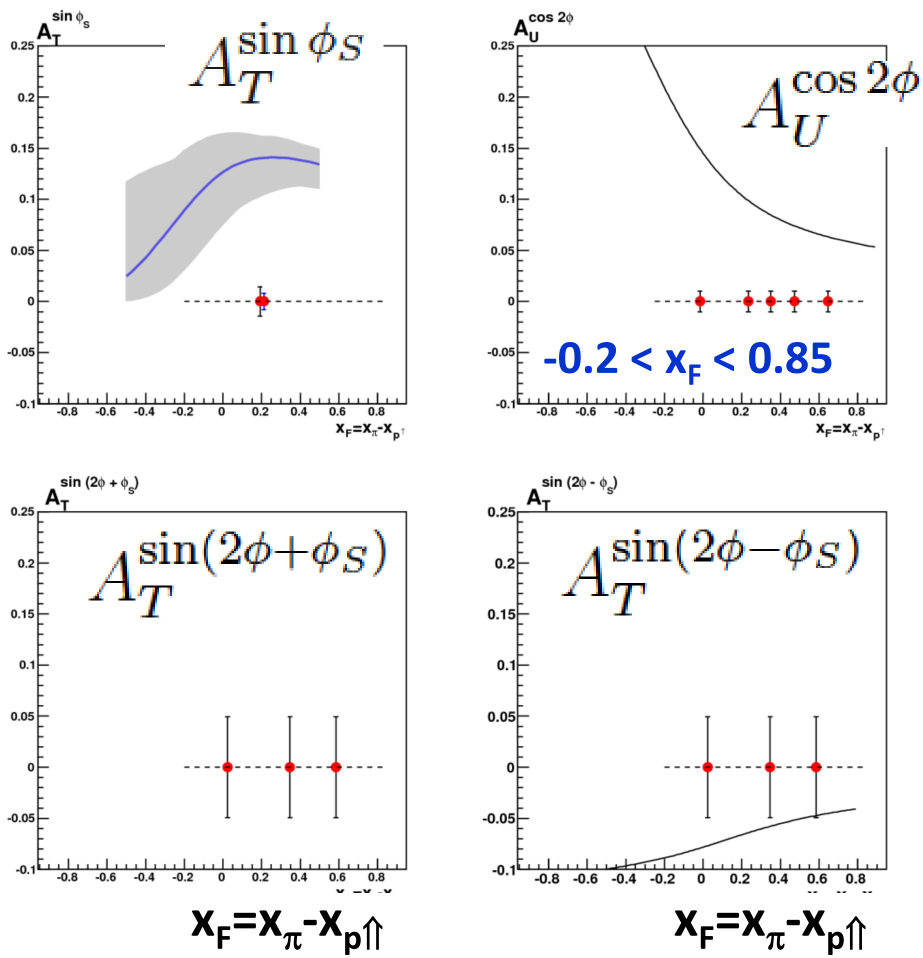
Red solid and dod-dashed line
Anselmino et al., PRD79 (2009)
Black solid and dashed:
Efremov et al., PLB612 (2005)
Black dot-dashed:
Collins et al., PRD73 (2006)
Squares:
Bianconi et al., PRD73 (2006)
Green short-dashed:
Bacchetta et al., PRD78 (2008)

Predictions for Drell-Yan at COMPASS

$$4. \leq M_{\mu\mu} \leq 9.\ \mathrm{GeV}/c^2$$

Sivers

M. Anselmino et al, Phys. Rev. D 79, 054010 (2009)



Boer-Mulders

B. Zhang et al, Phys. Rev. D

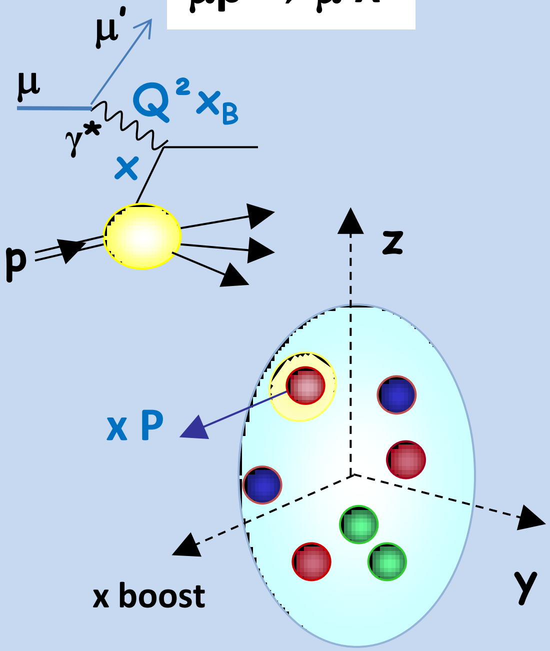
The first ever polarised Drell-Yan experiment sensitive to TMDs

from inclusive reactions

to exclusive reactions

Deep Inelastic Scattering

$\mu p \rightarrow \mu' X$

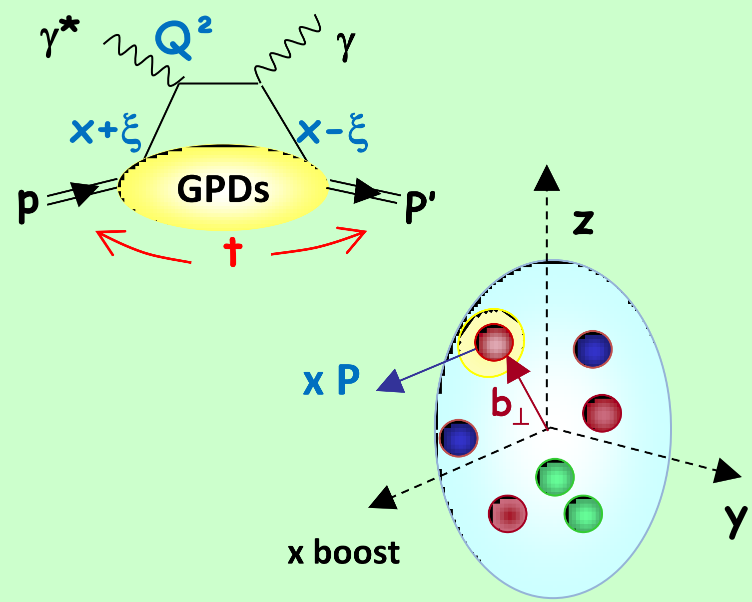


Distrib. de Partons q (x)

P_x

Deeply Virtual Compton Scattering

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



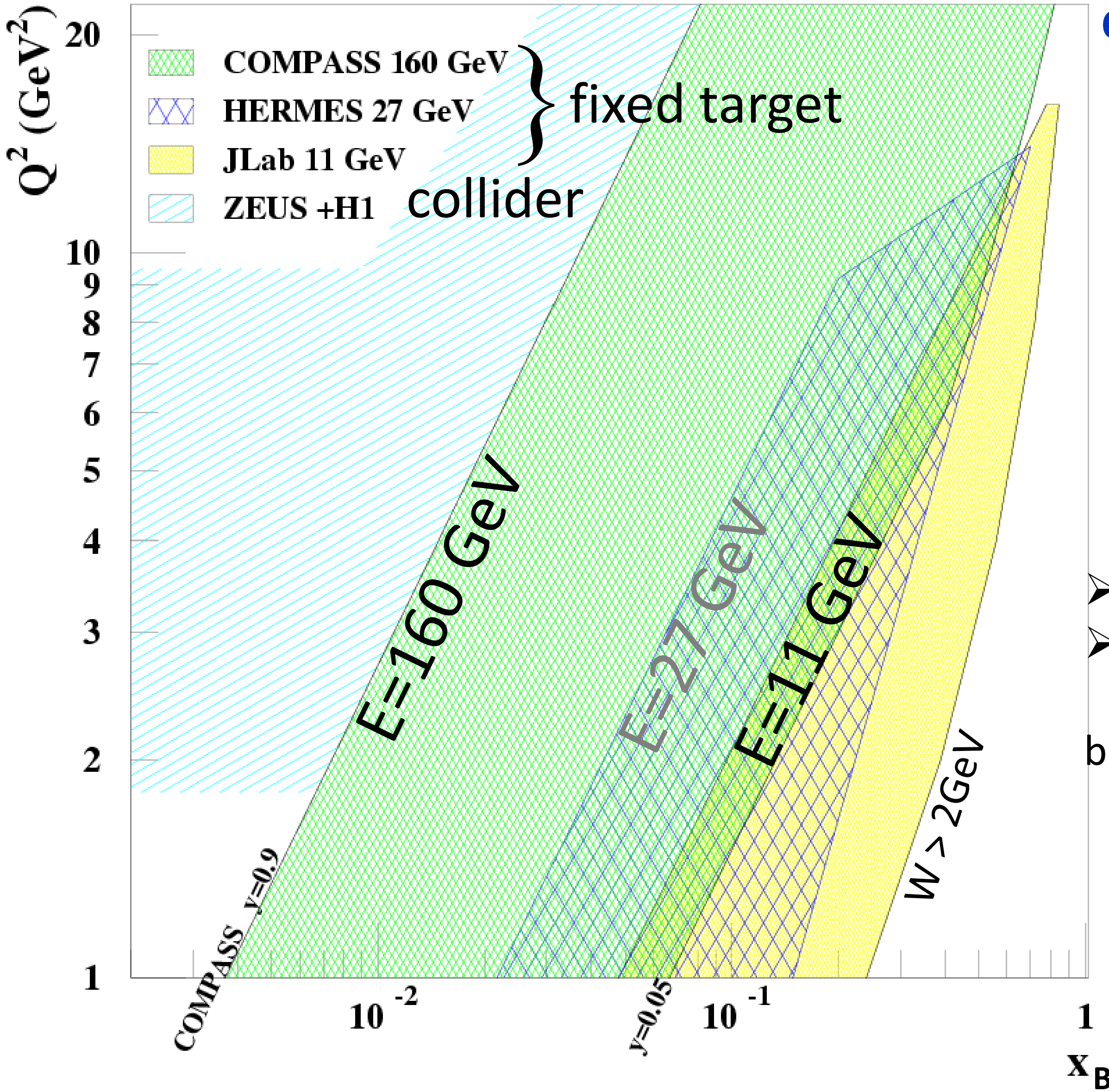
Generalized Partons Distrib. $H(x, \xi, t)$

$(P_x, b_\perp)$

Beyond collinear approximation -> Trans. Position ($b_\perp$) Dependent GPD in Excl. React.
-> as Trans. Momentum ($k_\perp$) Dep. PDF or TMD in SIDIS & DY

3D tomography

Kinematic domain (Q^2, x_B) for GPDs



COMPASS unique for GPDs

CERN High energy muon beam

- ✓ **100 - 190 GeV**
- ✓ **$\mu^{+\downarrow}$ and $\mu^{-\uparrow}$ available**
- ✓ **80% Polarisation with opposite polarization**
- ✓ **4.6 10^8 μ^+**

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

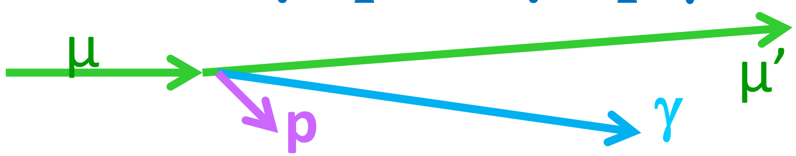
- Explore the intermediate x_{Bj} region
- Uncovered region between ZEUS+H1 & HERMES **+ Jlab** before new colliders may be available

It's time to show the impact of COMPASS

=> goal of the 2012 DVCS pilot run

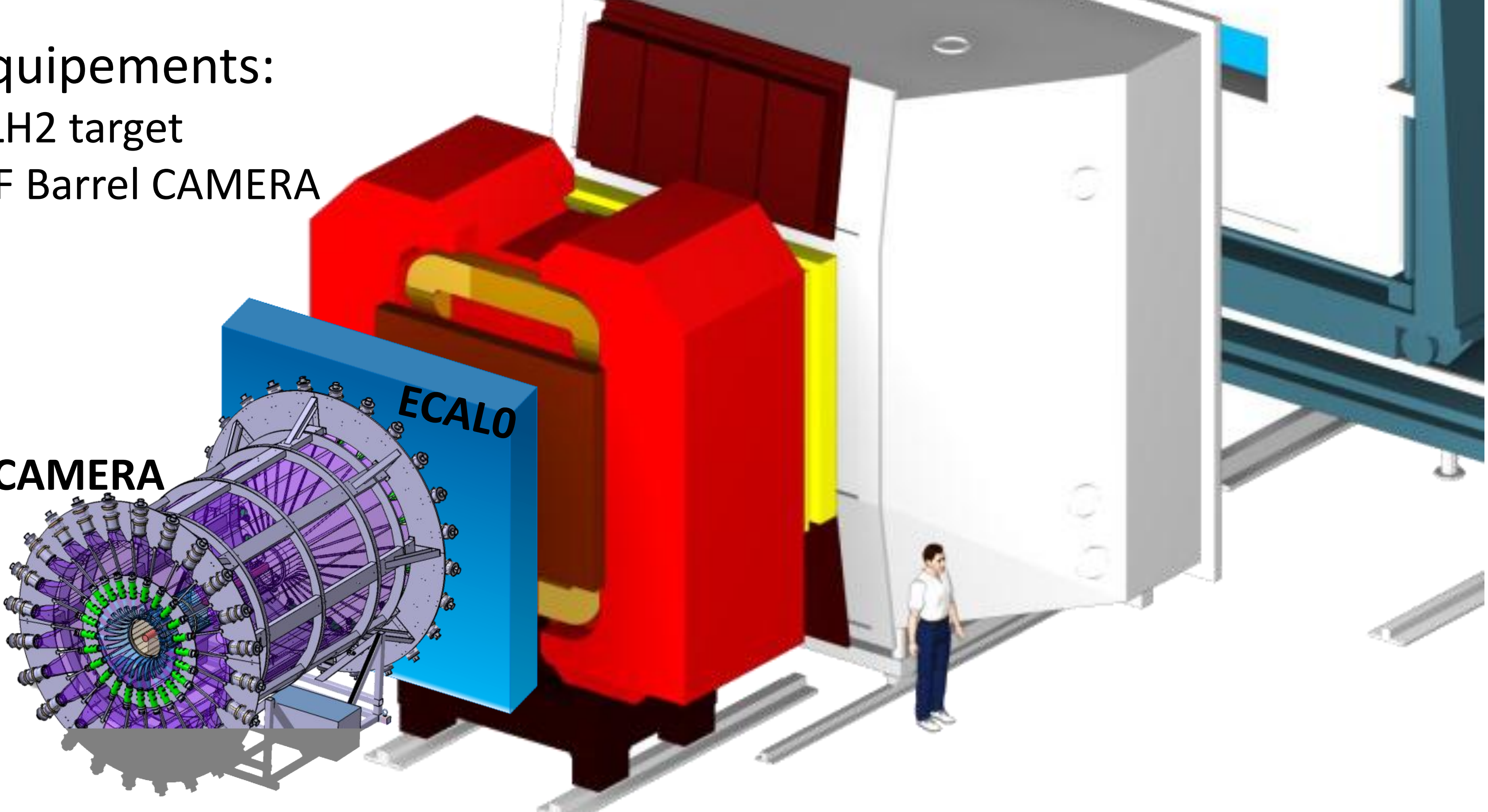
Upgrades of the COMPASS spectrometer

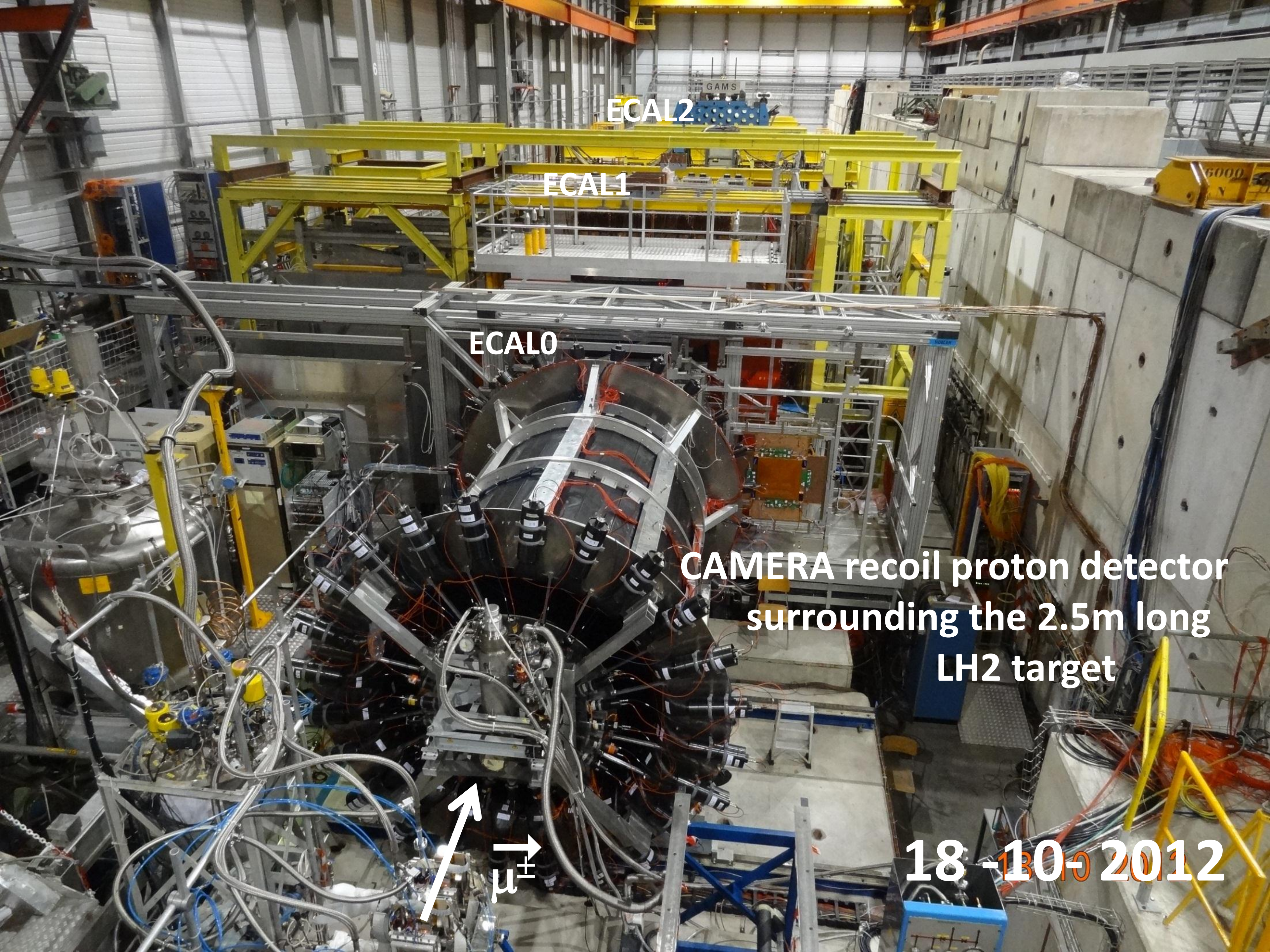
DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$



New equipements:

- ➢2.5m LH2 target
- ➢4m ToF Barrel CAMERA
- ➢ECAL0



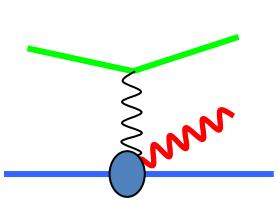

GAMS
ECAL2
ECAL1
ECAL0
CAMERA recoil proton detector
surrounding the 2.5m long
LH2 target
$\mu^{\pm}$
18 -10- 2012

Constraints on the GPD H

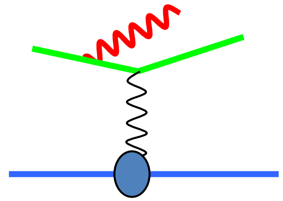
with recoil proton detection and hydrogen target

- Very first tests in 2008-9
- 1 month in november 2012
- 2 years 2016-17

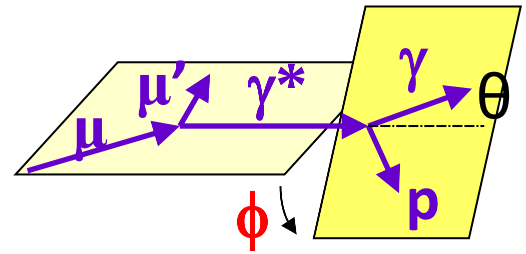
Contributions of DVCS and BH at E_μ=160 GeV



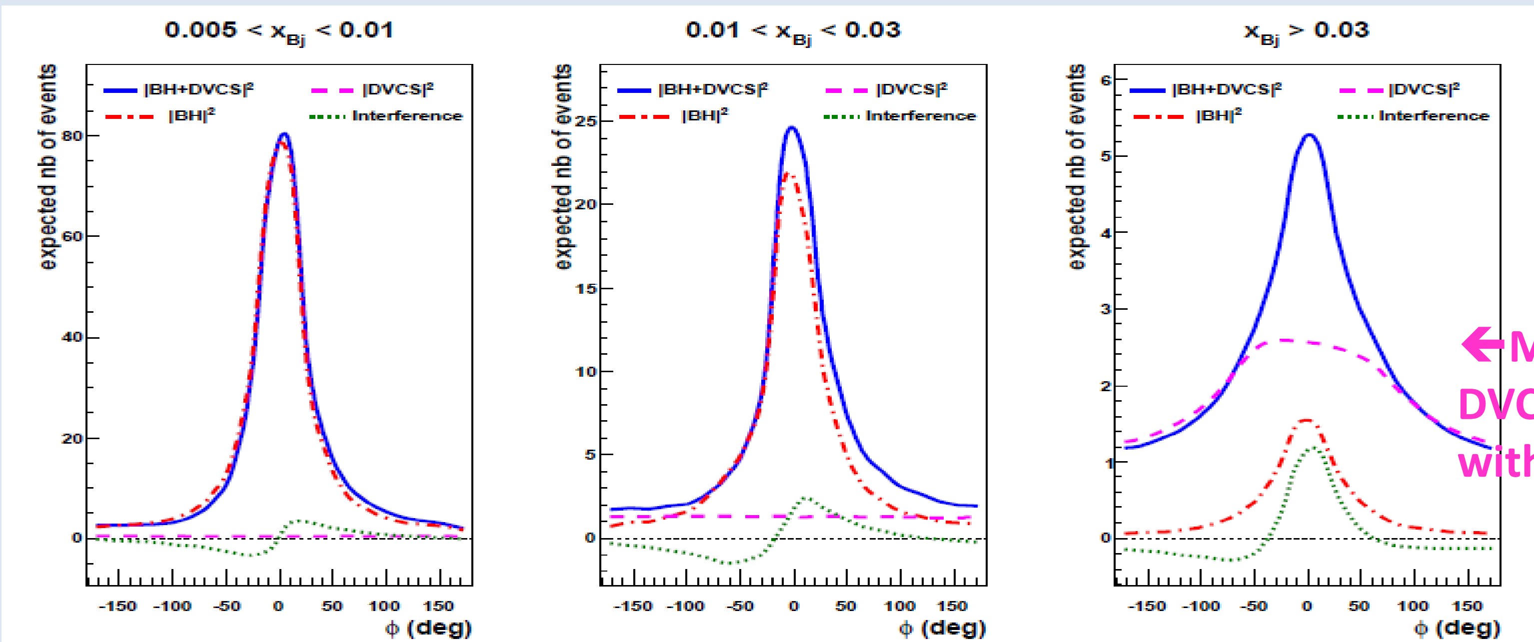
Deep VCS



Bethe-Heitler



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



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

← Missing DVCS acceptance without ECAL0

BH dominates

excellent reference yield

study of Interference

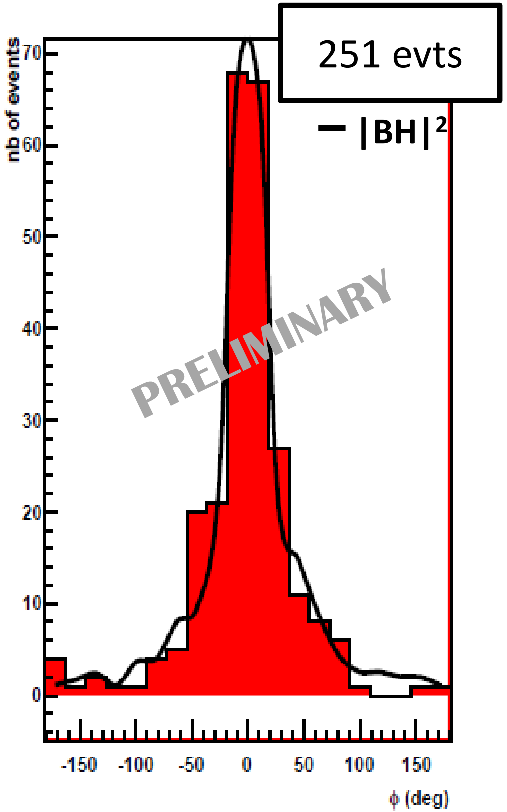
→ Re T^{DVCS} or Im T^{DVCS}

DVCS dominates

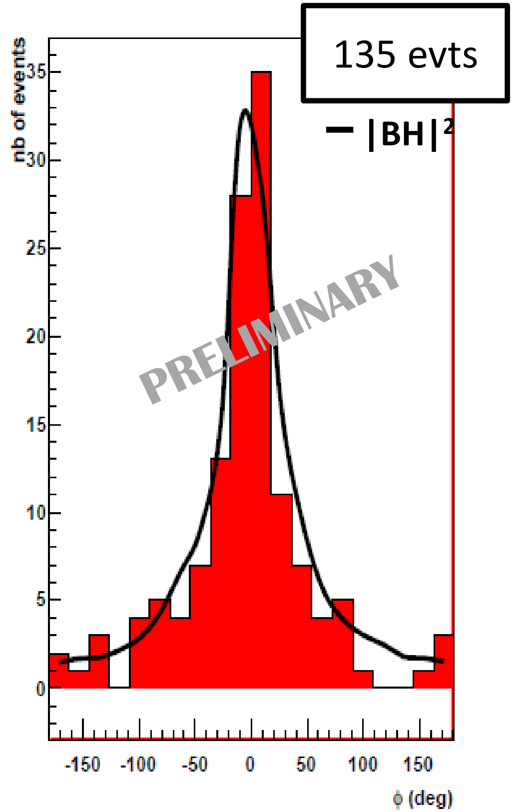
study of $d\sigma^{DVCS}/dt$

→ Transverse Imaging

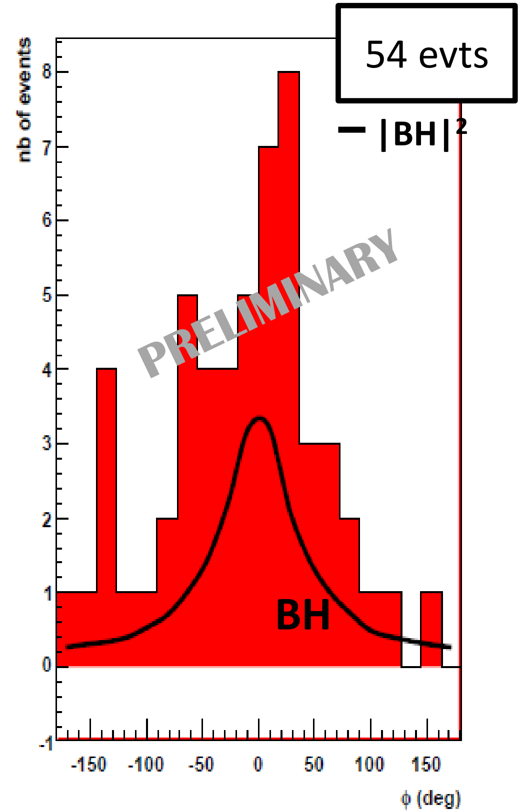
2009 DVCS test run (10 days, short RPD+target)



$0.005 < x_B < 0.01$



$0.01 < x_B < 0.03$



$0.03 < x_B$

$\epsilon_{\mu p \rightarrow \mu' \gamma p} \approx 35\%$

$\times\ (0.8)^4$ for SPS + COMPASS avail. + trigger eff + dead time

$\varepsilon_{global} \approx 0.14$ confirmed $\varepsilon_{global} = 0.1$
as assumed for COMPASS II predictions

54 evts ≈ 20 BH
+ 22 DVCS
+ about 12 γ from π^0

Deeply Virtual Compton Scattering

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

$$+ e_\mu\, \cancel{a^{BH}\, \mathcal{R}e\, A^{DVCS}} \qquad + e_\mu\, P_\mu\, a^{BH}\, \mathcal{I}m\, A^{DVCS}$$

Phase 1: DVCS experiment to study the transverse imaging

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

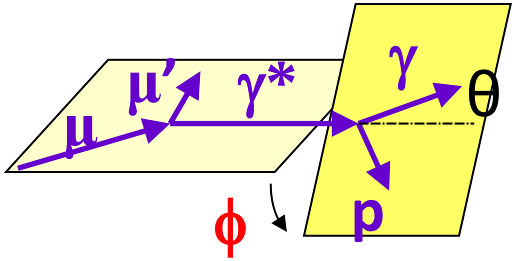
$$S_{CS,U} \equiv d\sigma(\mu^{+\downarrow}) + d\sigma(\mu^{-\uparrow}) \propto \boxed{d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + K.s_1^{Int} \sin\phi}$$

$$\downarrow$$

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

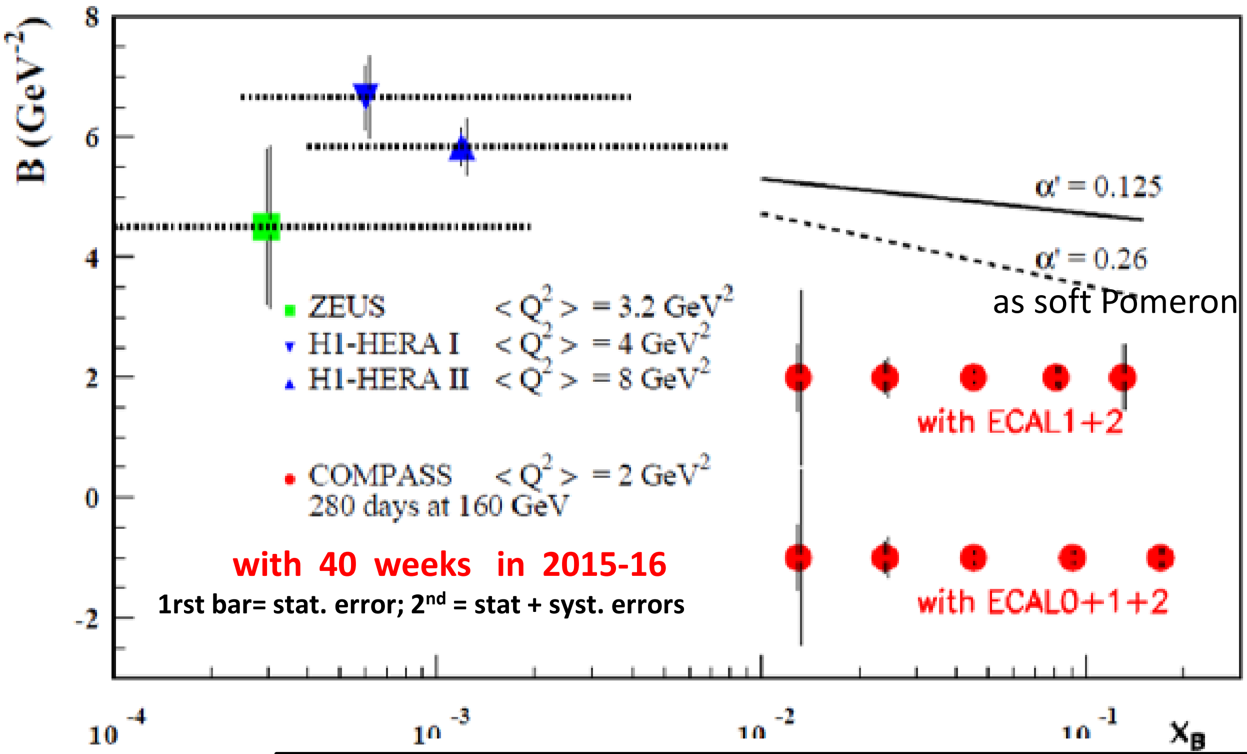
Using $S_{CS,U}$ and BH subtraction

and integration over ϕ



Transverse imaging at COMPASS

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

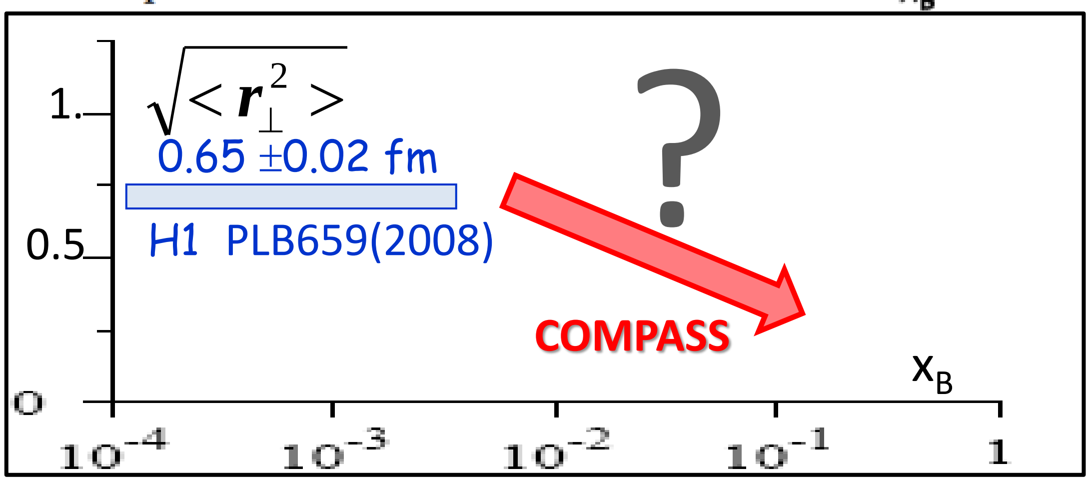


2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

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



Transverse imaging at COMPASS

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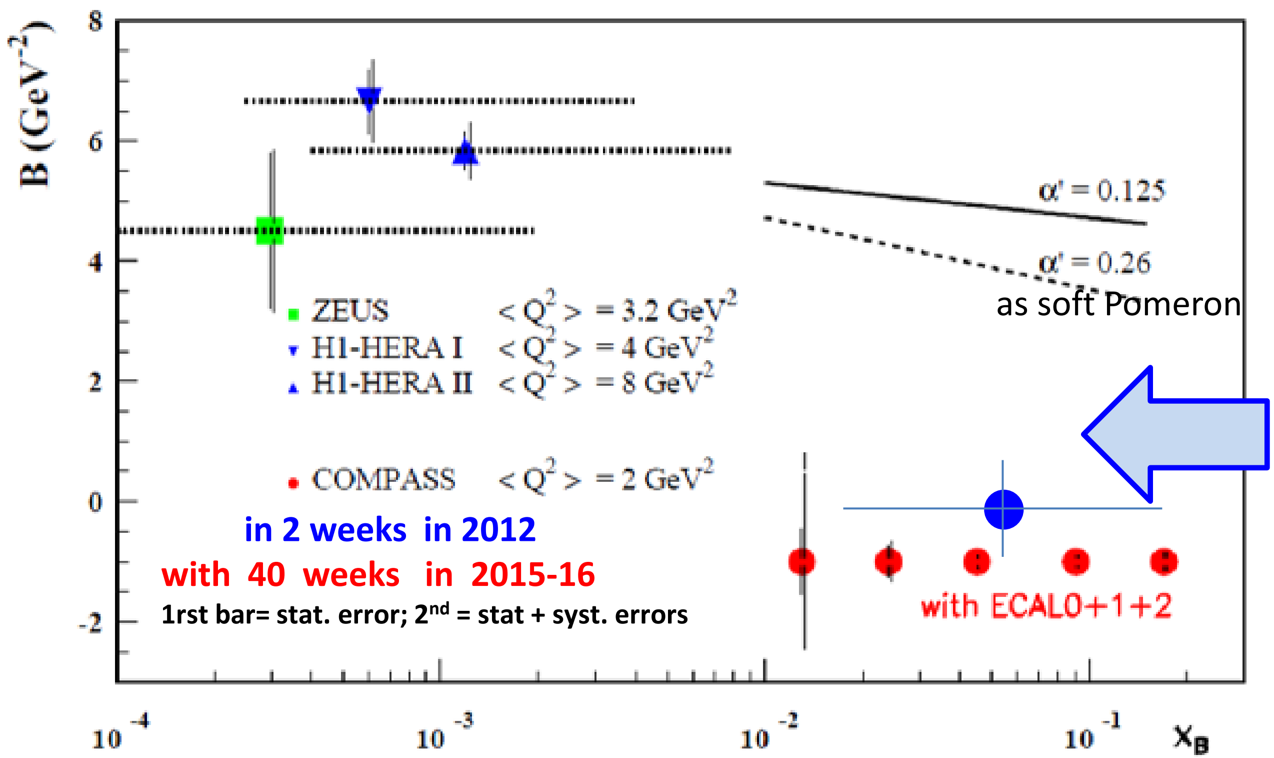


DVCS test in 2012

With 2 weeks
Using the 4m long RPD
+ the 2.5m long LH2 target

1/20 of the complete statistics

2012: we can determine one mean value of B in the COMPASS kinematic range

Deeply Virtual Compton Scattering

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

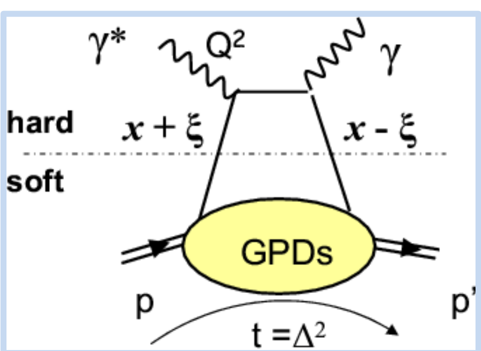
$$+ e_\mu\, a^{BH}\, \mathcal{R}e\, A^{DVCS} \qquad + e_\mu\, P_\mu\, \cancel{a^{BH}\, \mathcal{I}m}\, A^{DVCS}$$

Phase 1: DVCS experiment to constrain GPD H

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

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

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



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

Note: dominance of H at COMPASS kinematics

- $\mathcal{I}m\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$
- $\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, H(x,\xi,t)\,/(x-\xi)$

Related with a dispersion relation + Dterm

Deeply Virtual Compton Scattering

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

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

Phase 1: DVCS experiment to constrain GPD H

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

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

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

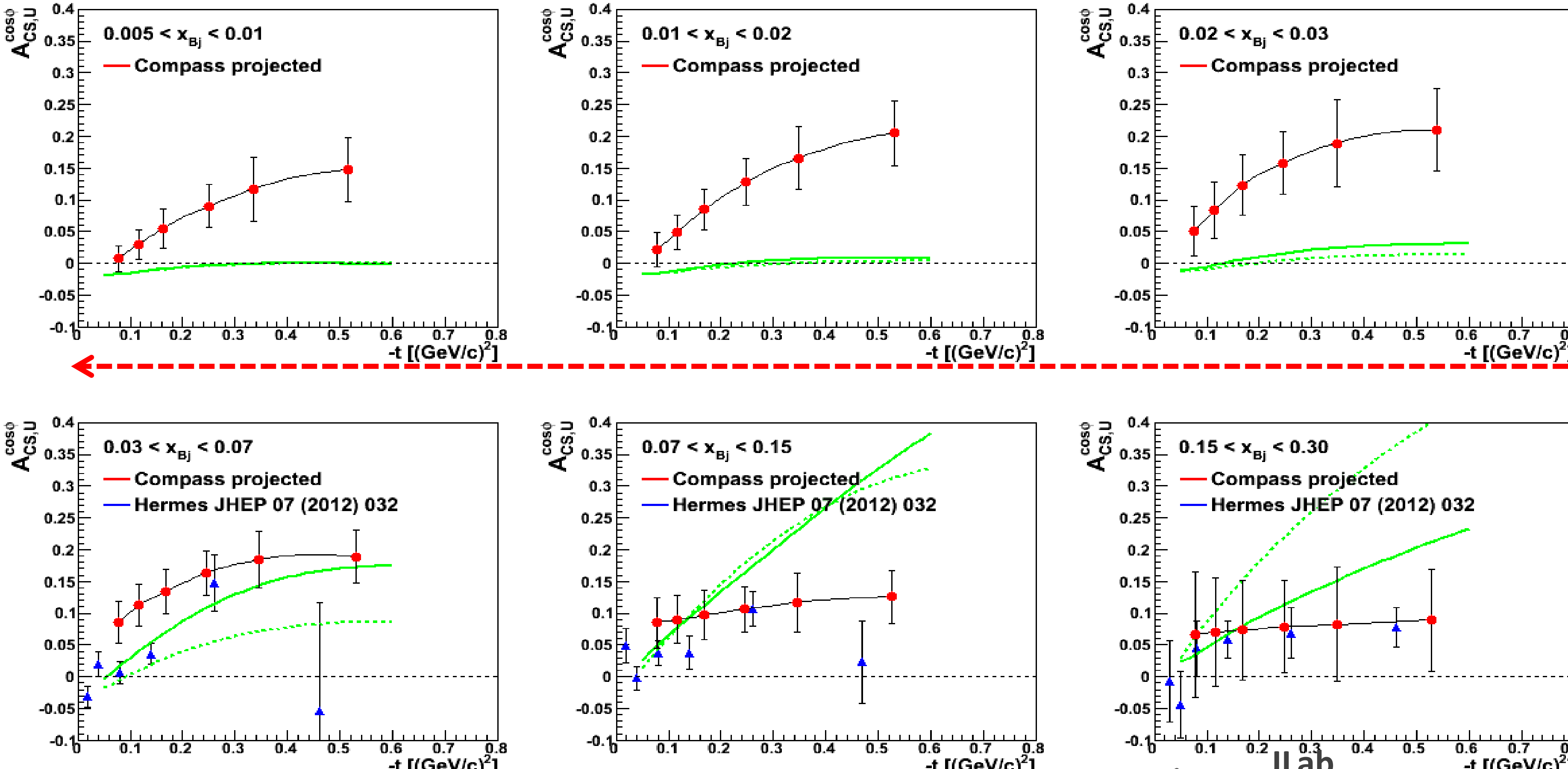
Angular decomposition of **sum** and **diff** of the **DVCS cross section** will provide umambiguous way to separate the *Re* and *Im* of the *Compton Form Factors* from higher twist contributions

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

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

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?



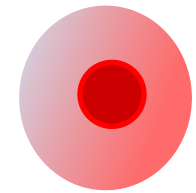
HERMES 10 years of data

COMPASS **2 years of data** **Eμ= 160 GeV** **1 < Q^2 < 8 GeV^2** **With ECAL2 + ECAL1 + ECAL0**

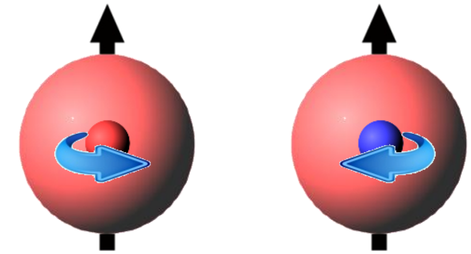
With transv. polarized target Constraints on other GPDs

Chiral-even GPDs

σ $\qquad H \rightarrow q$



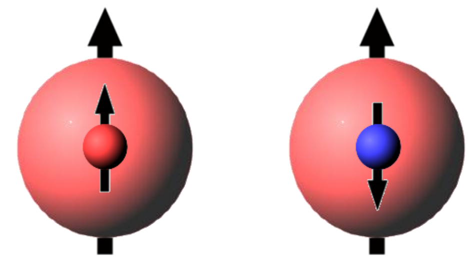
$A_{UT}^{\sin(\phi - \phi_S)}$ $\qquad E \longleftrightarrow f_{1T}^{\perp}$



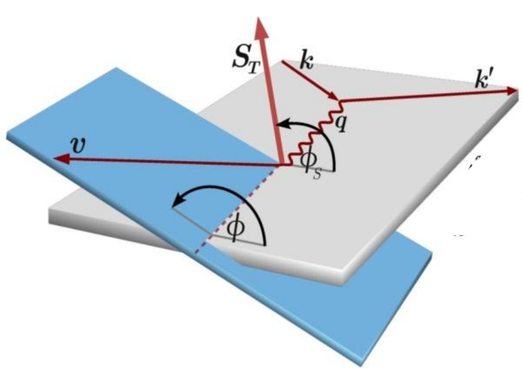
Sivers correlates
quark k_T and nucleon spin (transv. pol. N)

Chiral-odd GPDs

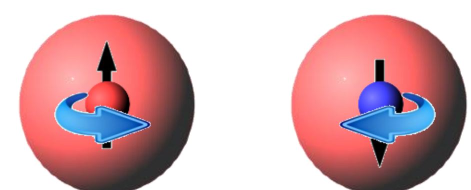
$A_{UT}^{\sin(\phi_S)}$ $\qquad H_T \longleftrightarrow h_1$



Transversity correlates
quark spin and nucleon spin (transv. pol. N)



$$\bar{E}_T = 2\tilde{H}_T + E_T \longleftrightarrow h_1^{\perp}$$

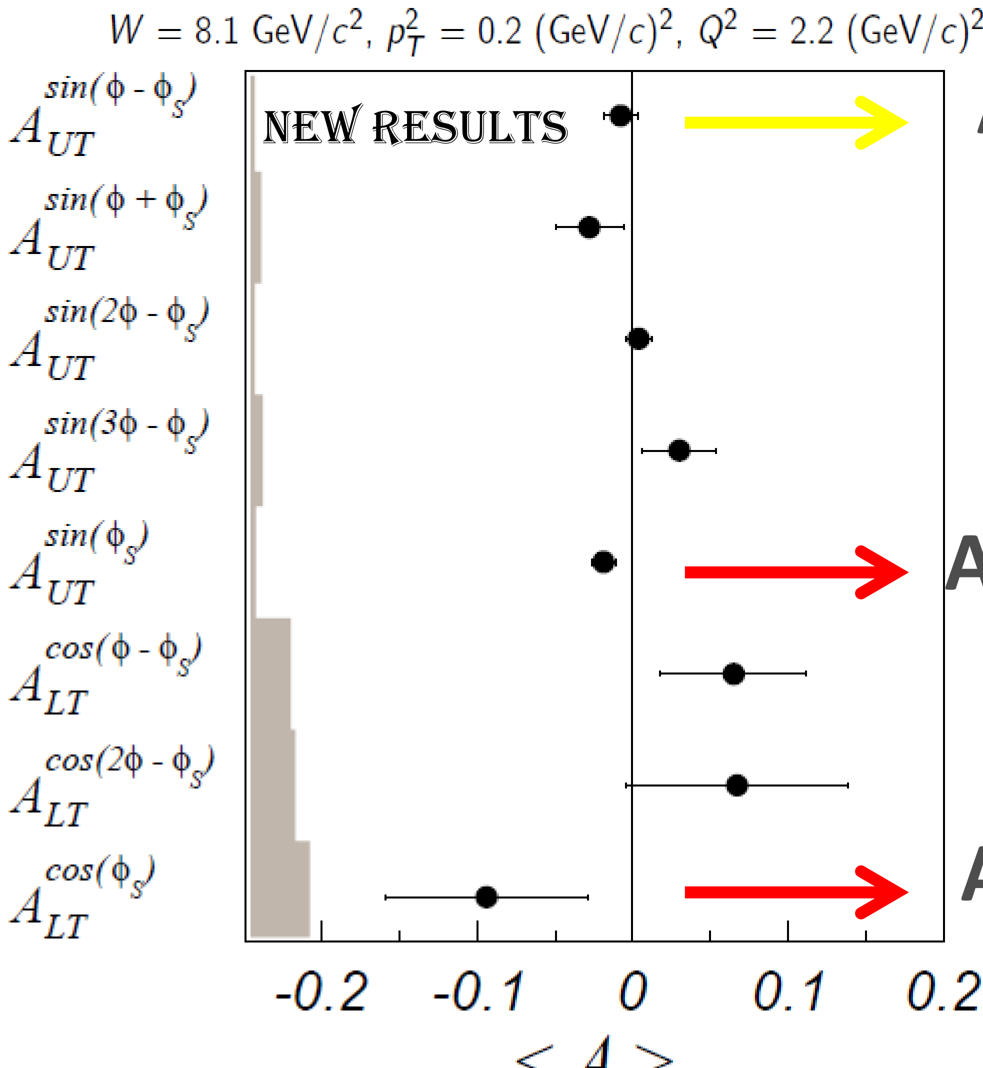


Boer-Mulders correlates
quark k_T and quark transverse spin (unpol N)

exclusive ρ^0 production –Transv. Polar. Target

$\mu\ p \rightarrow \mu' + \rho^0 + p_{\text{non détecté}}$, $\rho^0 \hookrightarrow \pi^+\pi^-$

COMPASS 2007-2010,without recoil detector



$A_{UT}^{\sin(\phi-\phi_S)} \propto Im(\mathcal{E}^* \mathcal{H})$

$E\rho^0 \propto 2/3\ E^u + 1/3\ E^d + 3/8\ E^g$
Cancellation between gluon and sea contributions and $E^{u\ val} \sim -E^{d\ val}$

$A_{UT}^{\sin(\phi_S)} \propto Im(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$

$A_{LT}^{\cos(\phi_S)} \propto Re(\mathcal{E}^* \bar{\mathcal{E}}_T - \mathcal{H}^* \mathcal{H}_T)$

H_T could be not small

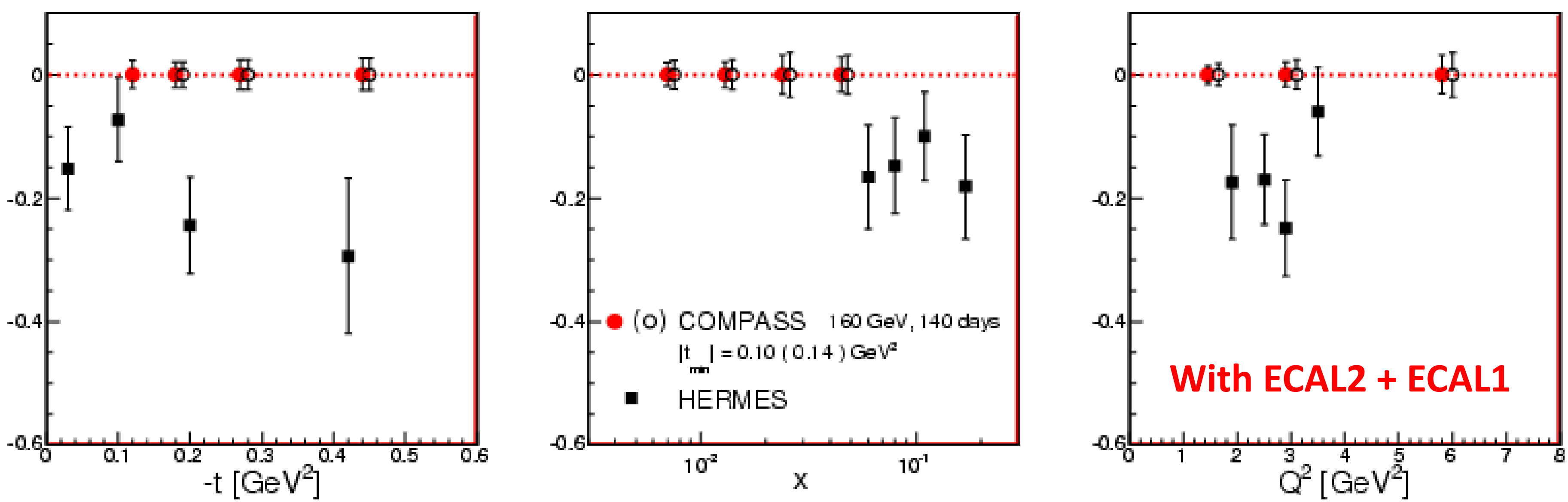
DVCS –Transv. Polar. Target

COMPASS-II (future addendum) **: with $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam** and **transversely** polarized NH3 (proton)

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

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

$A^{\sin(\phi-\phi_s)\cos\phi}_{\mathrm{CS,T}}$



Summary for GPD @ COMPASS

GPDs investigated with Hard Exclusive Photon and Meson Production

COMPASS-II 2016-17: **with LH_2 target + RPD (phase 1)** $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ **160 GeV**

- ✓ the t-slope of the DVCS and HEMP cross section
  → transverse distribution of partons
- ✓ the Beam Charge and Spin Sum and Difference
  → $\mathcal{R}e\, T^{DVCS}$ and $\mathcal{I}m\, T^{DVCS}$ for the GPD H determination
- ✓ Vector Meson ρ^0, ρ^+, ω, Φ
- ✓ Pseudo-saclar π^0

Using the 2007-10 data: **transv. polarized NH_3 target without RPD**

In a future addendum > 2017: **transv. polarised NH_3 target with RPD (phase 2)**

- ✓ the Transverse Target Spin Asymm
  → GPD E and chiral-odd (transverse) GPDs

For the next 10 years, before any collider is available, and complementary to Jlab 12 GeV, COMPASS@CERN can be a major player in QCD physics using its unique high energy (~200 GeV) hadron and polarised positive and negative muon beams

Boer-Mulders and Cahn effects on unpol. proton

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}\phi_h} = \frac{\alpha^2}{xyQ^2}\frac{1+(1-y)^2}{2}\Big[F_{UU} + \varepsilon_1 \cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon_2 \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + \lambda_\mu \varepsilon_3 \sin\phi_h F_{LU}^{\sin\phi_h}\Big]$$

Cahn effect → info on <k_T>

Boer-Mulders TMD ⊗ Collins FF + Cahn effect

Transverse imaging at COMPASS

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

$B(x_B) = ½ < r_\perp^2(x_B) >$

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

Transverse size of the nucleon

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

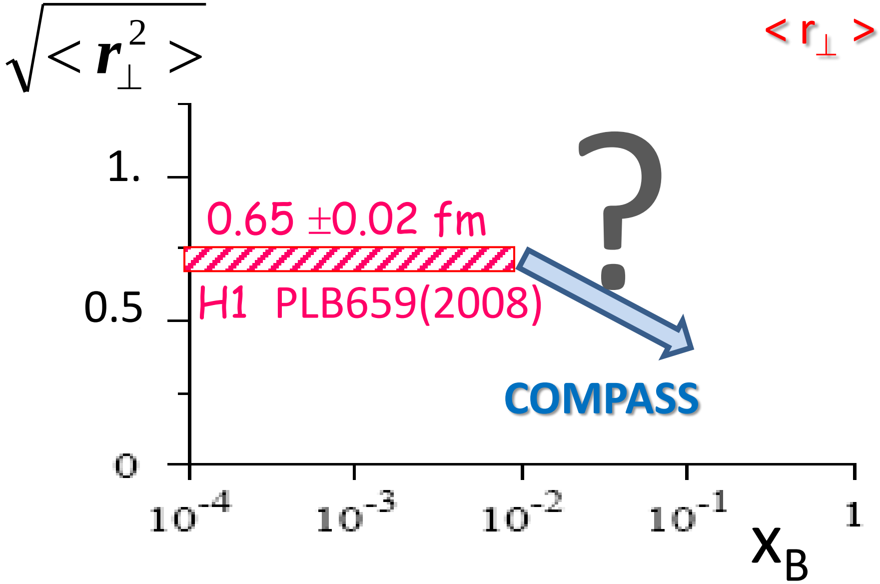
related to $½ < b_\perp^2(x_B) >$

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

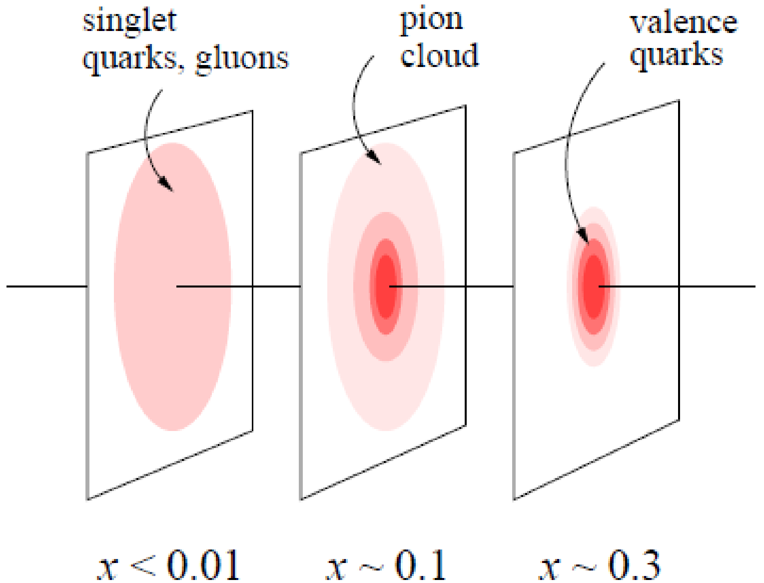
Impact Parameter Representation

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

$< r_\perp > \sim < b_\perp > / (1-x)$



Note 0.65 fm $= \sqrt{2/3} \times 0.8$ fm



Deeply Virtual Compton Scattering

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$$+ e_\mu\, a^{BH}\, \mathcal{Re}\, A^{DVCS} \qquad + e_\mu\, P_\mu\, \cancel{a^{BH}\, \mathcal{Im}}\, A^{DVCS}$$

Phase 1: DVCS experiment to constrain GPD H

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

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

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

Angular decomposition of **sum** and **diff** of the **DVCS cross section** will provide umambiguous way to separate the $\mathcal{Re}$ and $\mathcal{Im}$ of the *Compton Form Factors* from higher twist contributions

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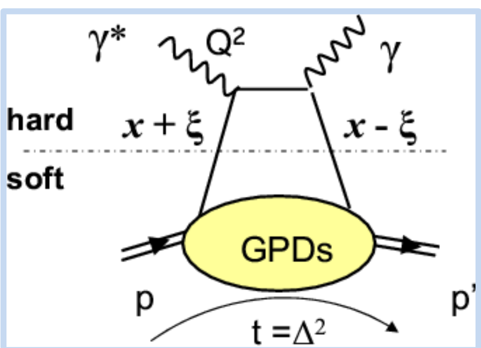


$\xi \sim x_B / (2-x_B)$

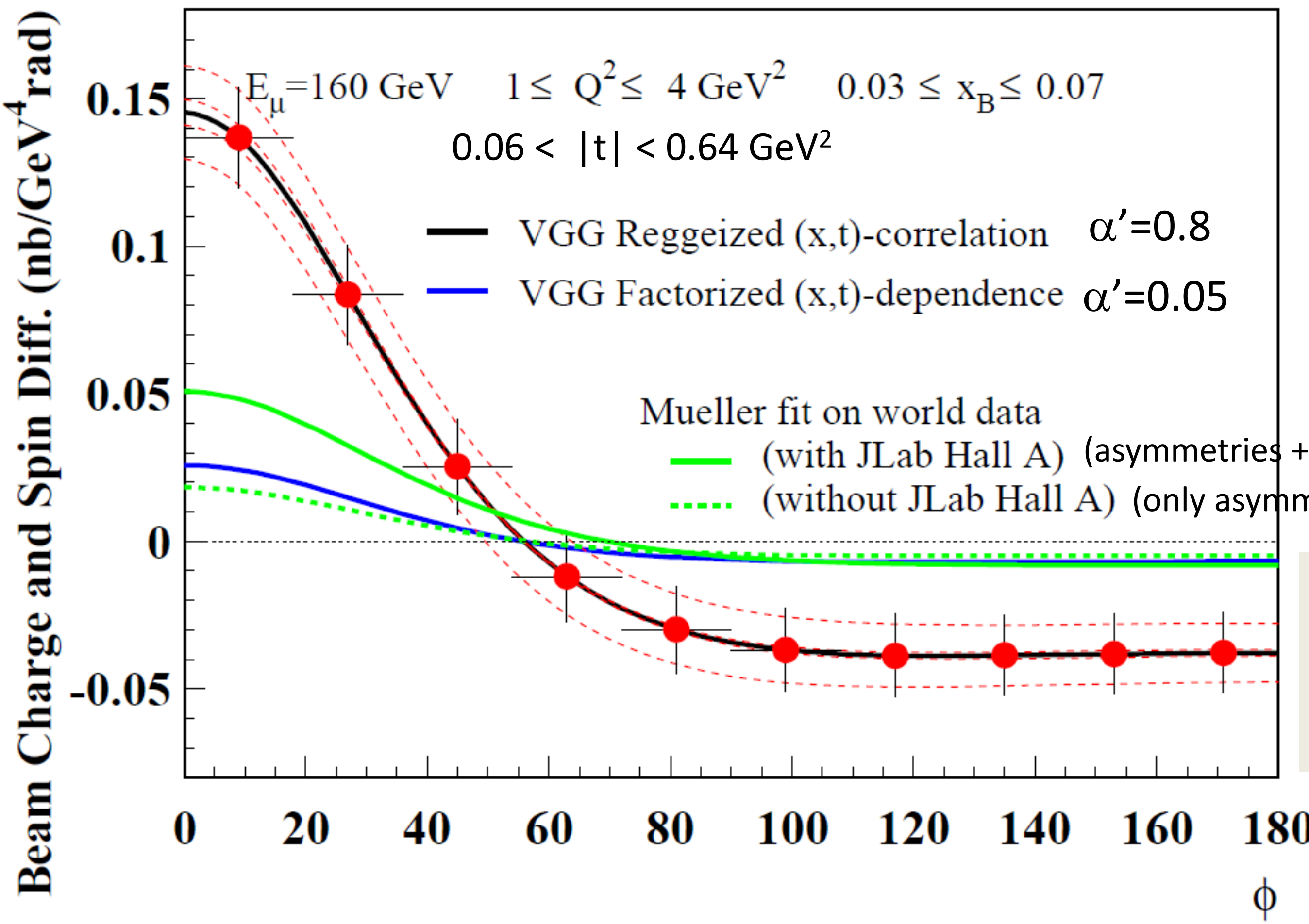
Note: dominance of H at COMPASS kinematics

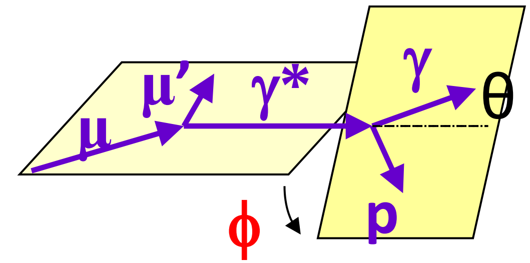
- $\mathcal{Im}\,\mathcal{H}(\xi,t) = H(x=\xi,\xi,t)$
- $\mathcal{Re}\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, H(x,\xi,t) / (x-\xi)$

Related with a dispersion relation + Dterm

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

Comparison to different models





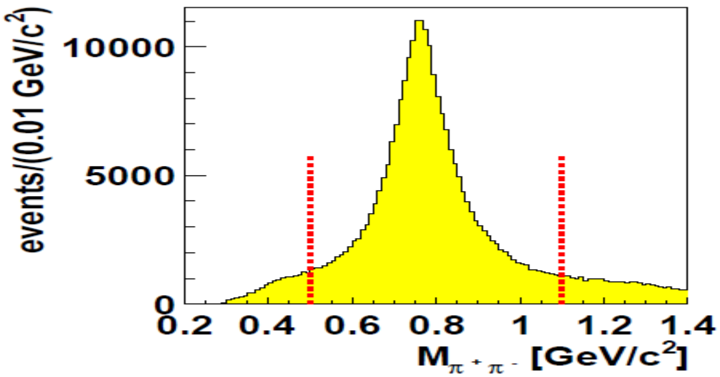
2 years of data
160 GeV muon beam
2.5m LH_2 target
ε_{global} = 10%

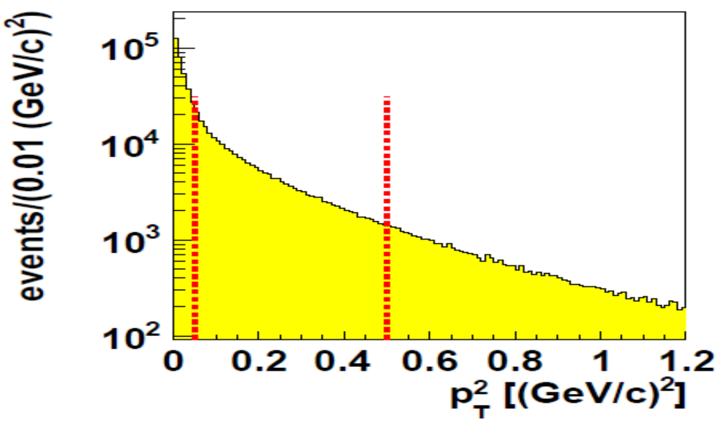
Note: Kroll, Moutarde, Sabatié predictions are of the same order of magnitude than Mueller predictions

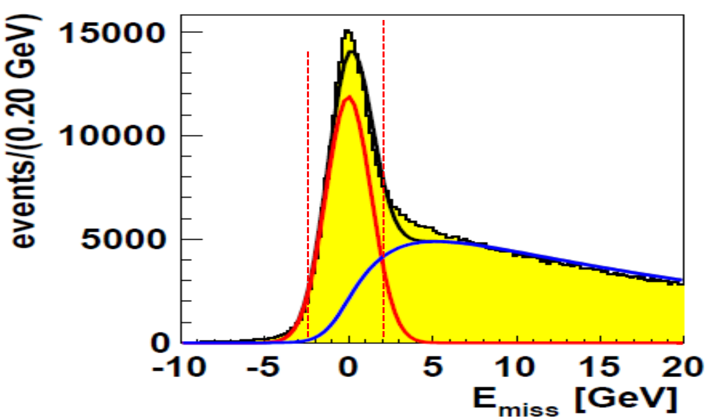
High precision beam flux and acceptance determination
Systematic error bands assuming a 3% charge-dependent effect between μ+ and μ- (control with inclusive evts, BH…)

Selection of Exclusive ρ° Production: $\mu\ p \rightarrow \mu'\ \rho^\circ\ p$

without RPD







$1 < Q^2 < 10$ GeV^2 $0.1 < y < 0.9$ $W > 4$ GeV $E_\rho > 15$ GeV

1- Assuming both hadrons are π

$0.5 < M_{\pi\pi} < 1.1$ GeV

To maximize the purity of the sample of ρ° / non resonant $\pi^+\pi^-$

2- Suppression of incoherent production on quasi-free protons in NH_3 polarized target

+ Suppression of SIDIS background

$0.05 < p_t^2 < 0.5$ GeV^2

Contamination of about a 5% coherent production

3- Exclusivity of the reaction

$$E_{\text{miss}} = \frac{M_X^2 - M_P^2}{2 \cdot M_P} = E_{\gamma^*} - E_{\rho^0} + t/(2 \cdot M_P)$$

$-2.5 < E_{miss} < 2.5$ GeV

Diffractive dissociation contamination ~14%

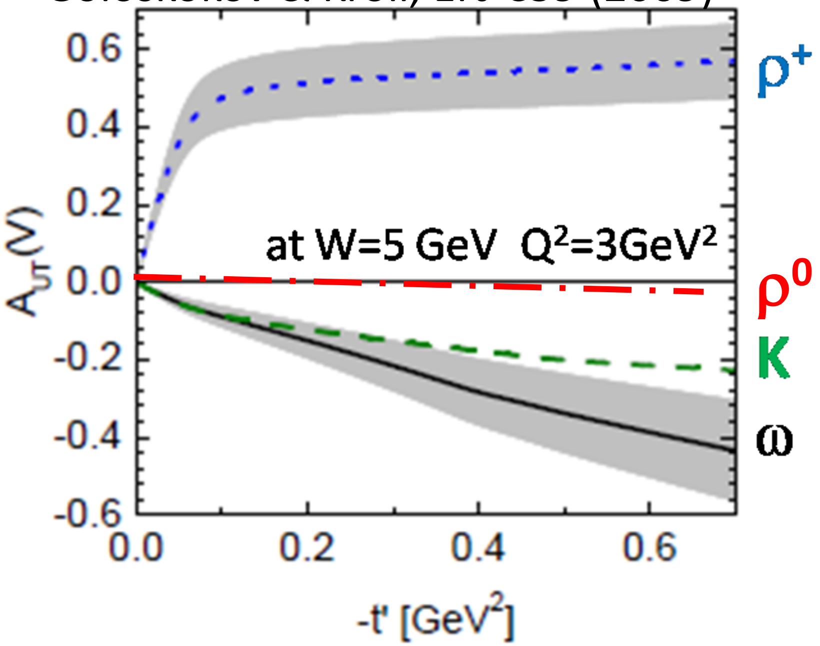
No attempt to remove it(motivated by HERA)

➔correction for SIDIS background (5 to 40%) in each bin (x_{Bj}, Q^2, p_T^2, cell and polar. State)

Hard Exclusive Vector Meson Production

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

Goloskokov & Kroll, EPJ C59 (2009)



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

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

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

Cancellation between gluon and sea contributions

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

$\rightarrow\ E^{uval} \sim -E^{dval}$

$A_{UT}(\rho^0)$ very small

$A_{UT}(\omega)$ and $A_{UT}(\rho^+)$ should be more promising

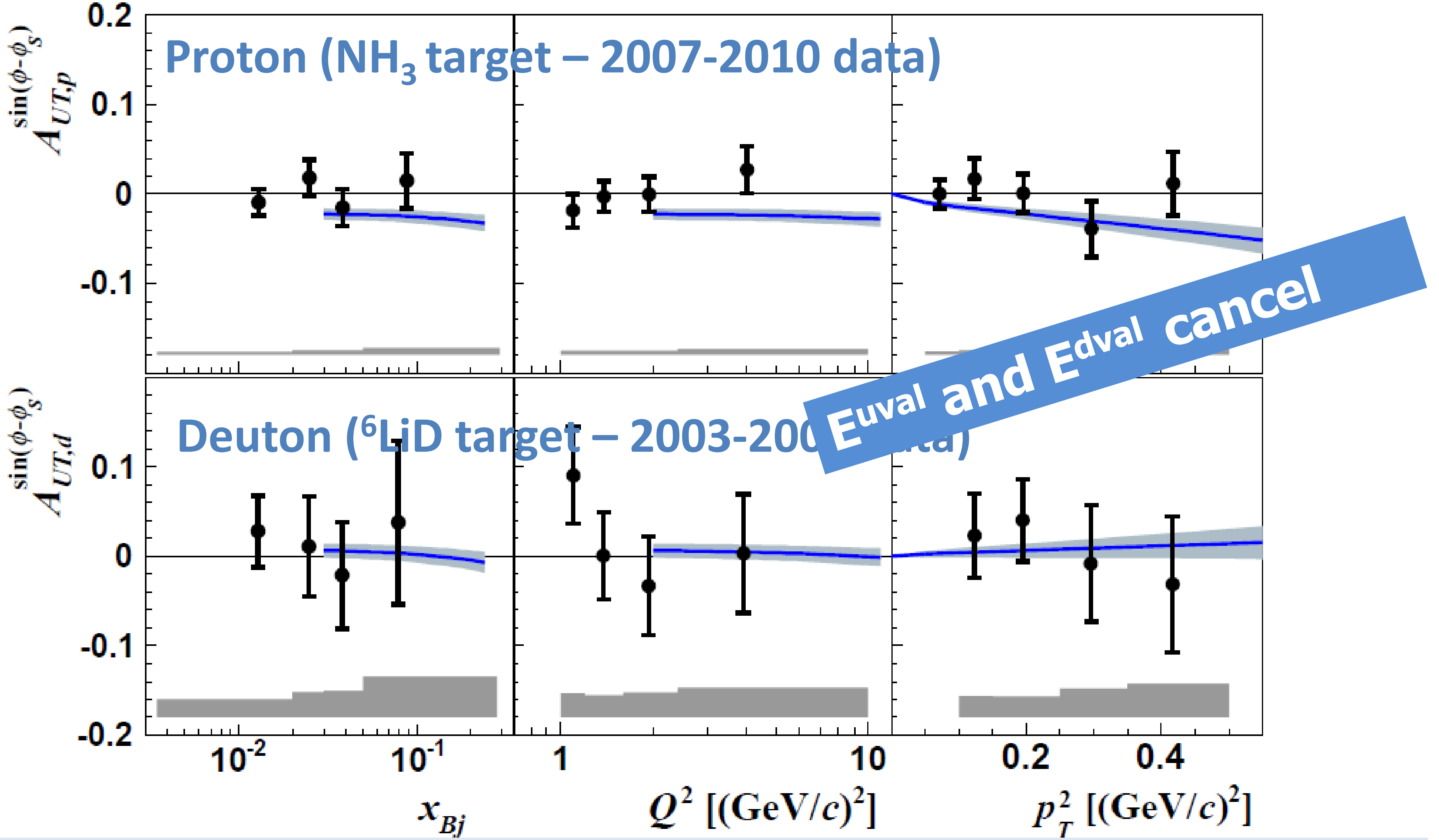
analysis on going for ω, ρ^+, ϕ and γ

Bins in **Φ - Φ_S**

asymmetry extraction
using a **1D** binned maximum likelihood fit
after subtracting the SIDIS background

Exclusive ρ° production on transerve polar. target

without Recoil Detection



COMPASS (NPB 865 1- July 2012) and predictions by Goloskokov & Kroll, EPJ C59 (2009)

New Analysis

Bins in Φ and Φ_S

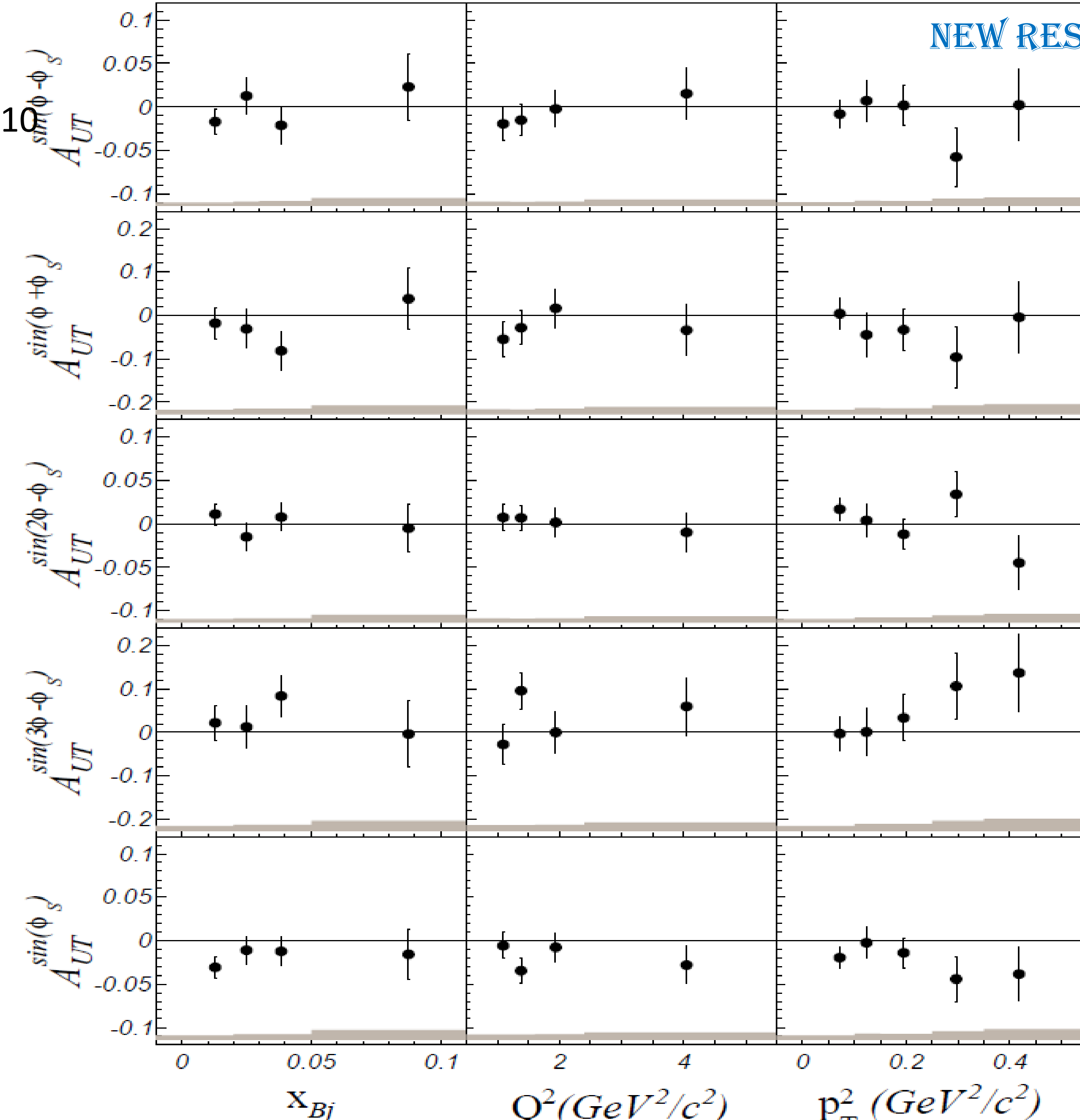
asymmetry extraction
using a **2D** binned maximum likelihood fit
After subtracting the SIDIS background

transv. pol. Protons

NH3 target 2007-2010

A_{UT}

NEW RESULTS

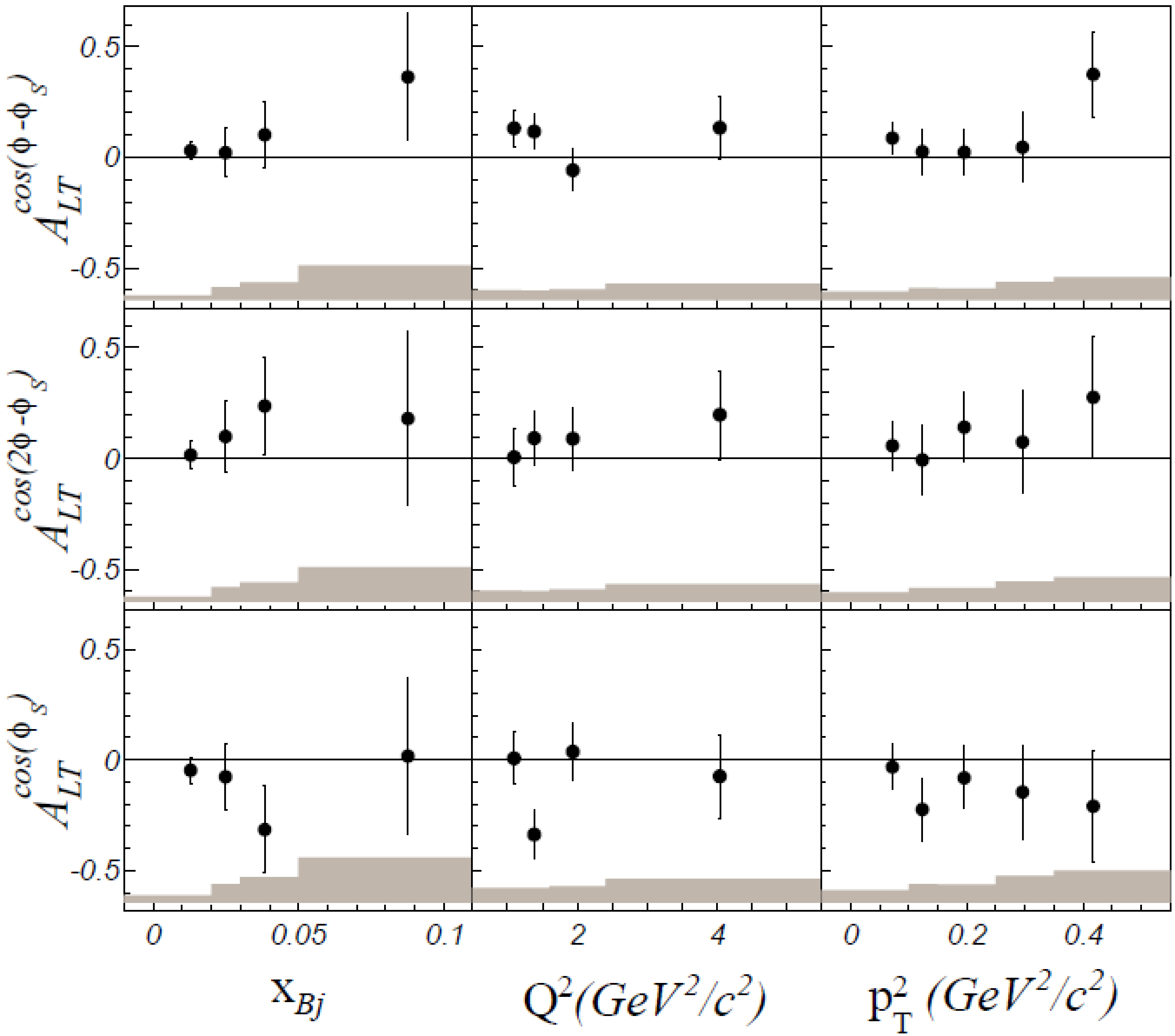


NEW RESULTS

transv. pol. Protons

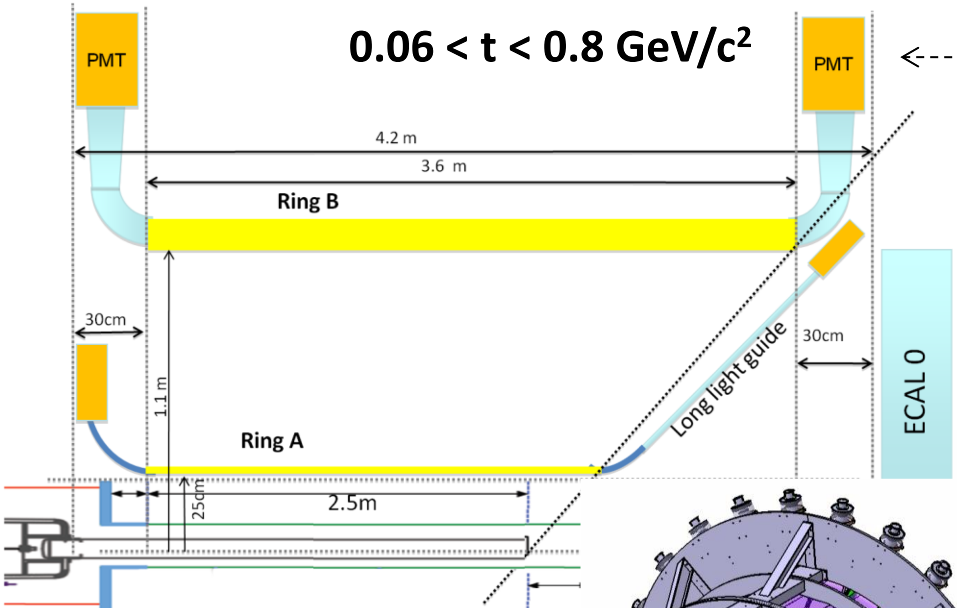
NH3 target 2007-2010

A_{LT}



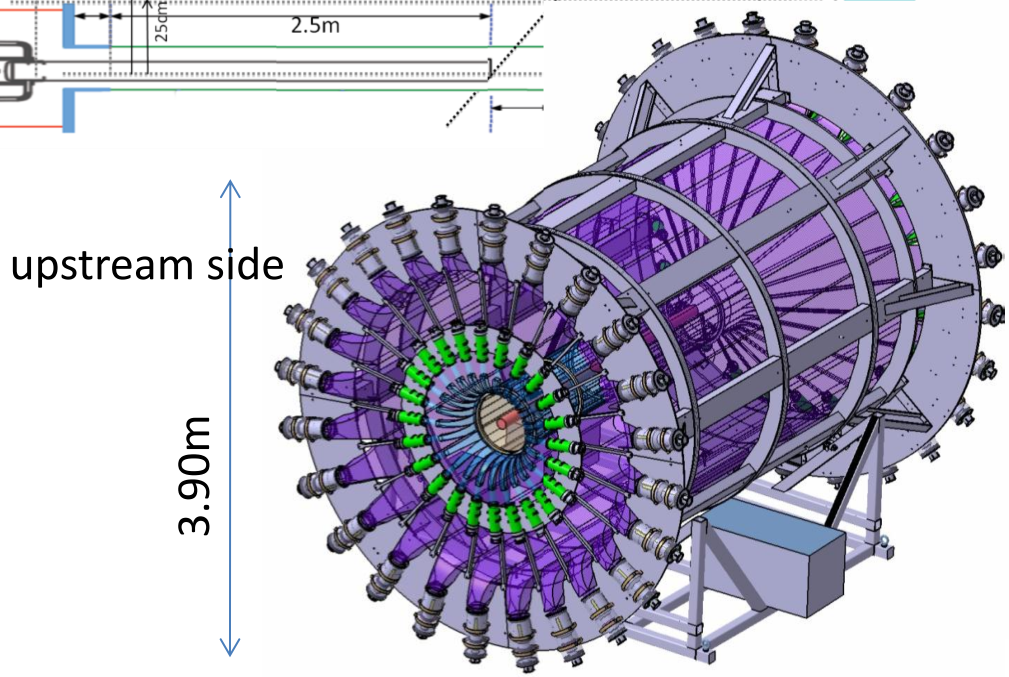
Recoil Proton Detector CAMERA

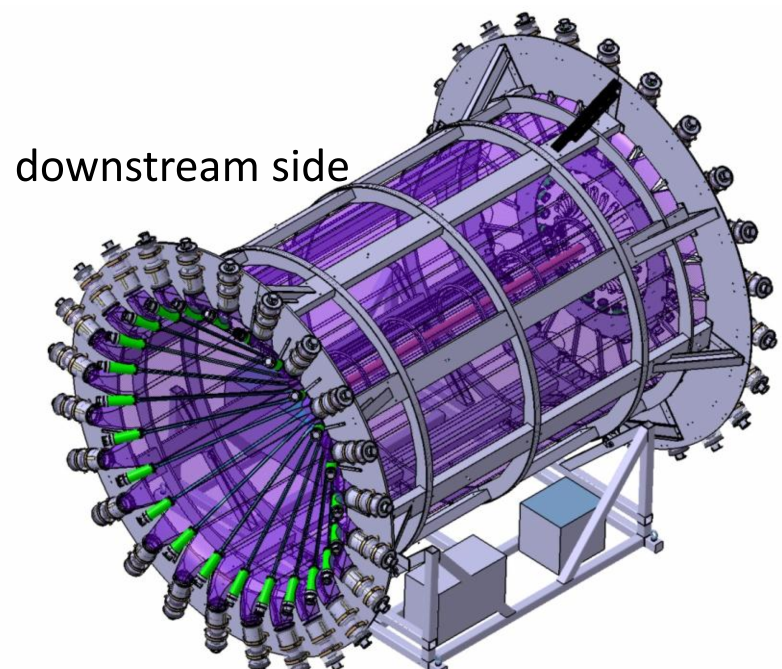
ToF between 2 rings of scintillators σ(ToF) < 300ps



1 GHz digitization of the PMT signal to cope with high rate

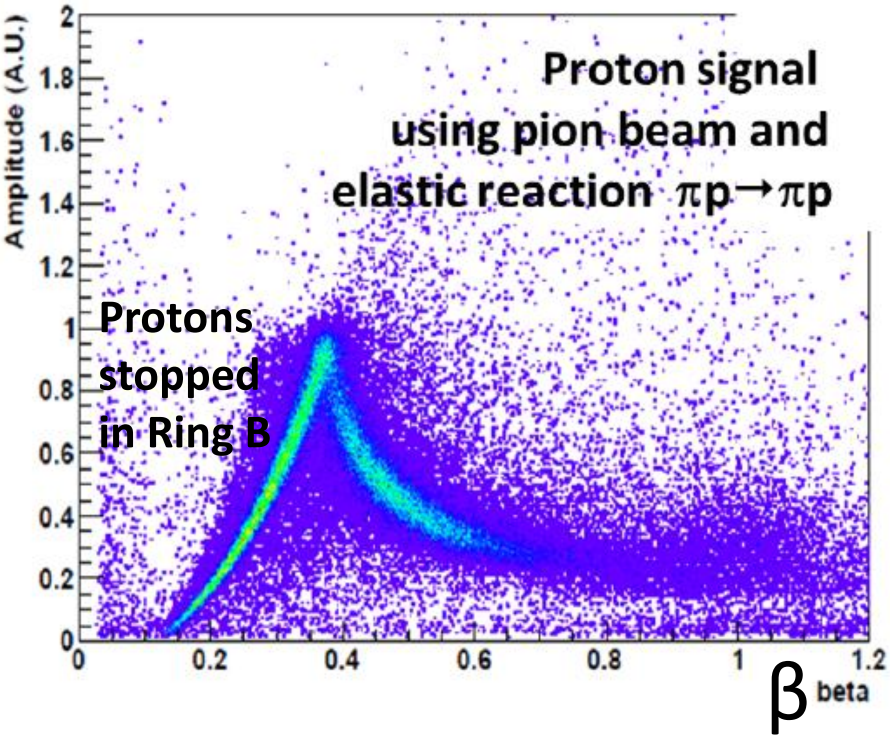
GANDALF boards ➔ First level trigger



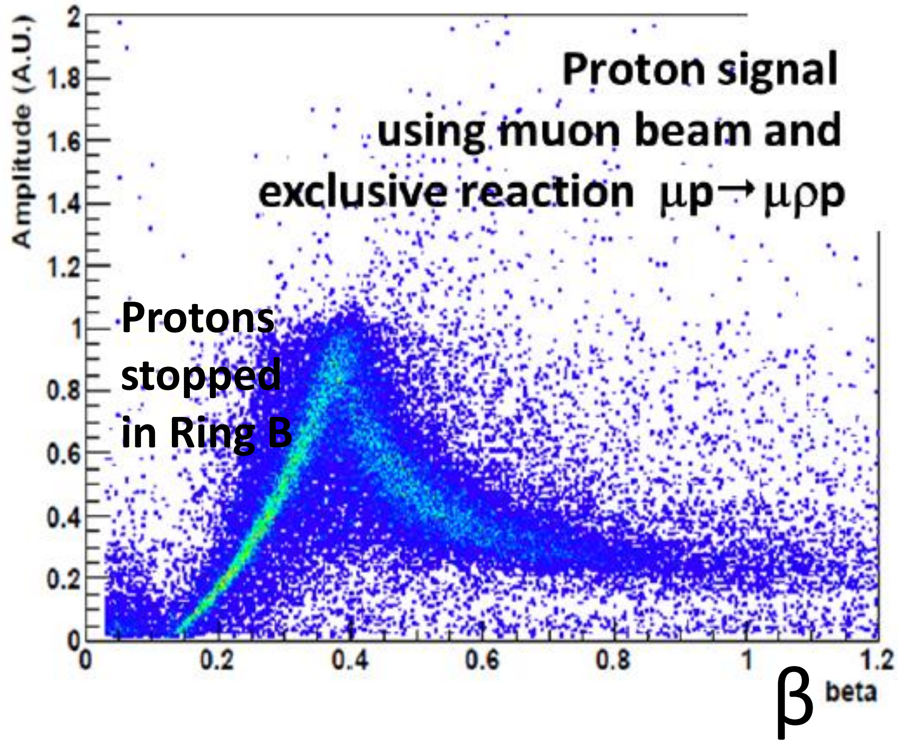


calibration of CAMERA

Energy lost in Ring B



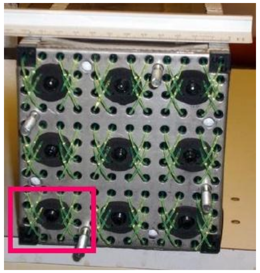
Energy lost in Ring B

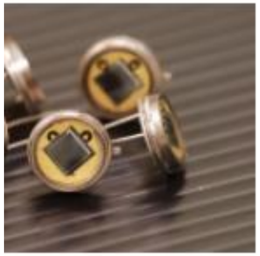


ECAL0 to enlarge the angular coverage

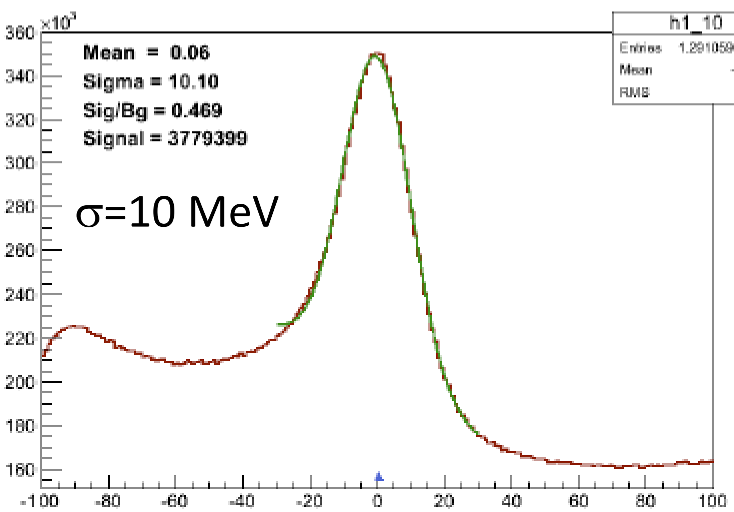
ECAL0 made of 200 modules (12×12 cm^2) of 9 cells read by 9 MAPDs

56 Modules are available for the 2012 setup
They are already calibrated (24 Oct 2012)

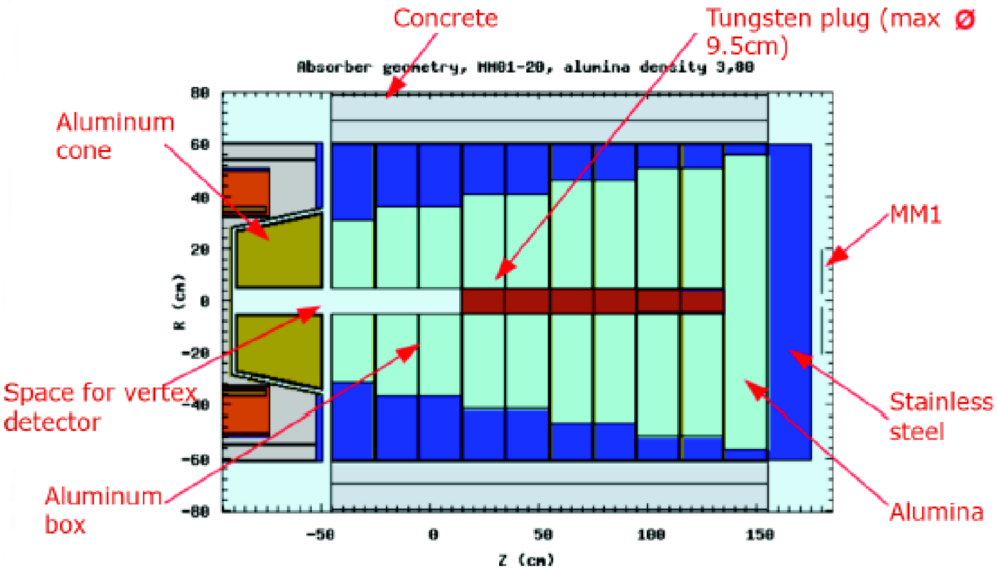


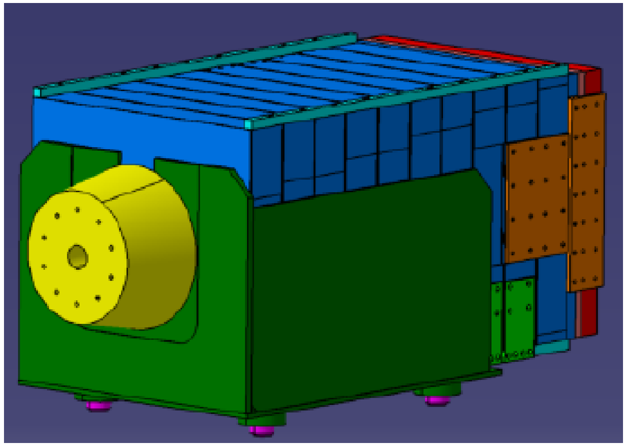


Invariant $\gamma\gamma$ mass spectra
for π^0 production using pion beam



The hadron absorber





Structure of the hadron absorber:

- 120cm tungsten beam plug
- aluminium conical part
- 200cm alumina (Al_2O_3)
- Stainless steel shielding sandwiches

+ absorber surrounded by
2m of iron-free concrete on each side