Generalized Parton Distributions @ COMPASS

« Expression of Interest » SPSC-EOI-005 and presentation to SPSC

→ writing of the proposal, preparation of the future GPD program ~2010

Physics Motivations

Now with ^6LiD or NH_3 polarized target
and without recoil detector

After 2010 with H_2 or D_2 target and a recoil detector
and a supplemented calorimetry

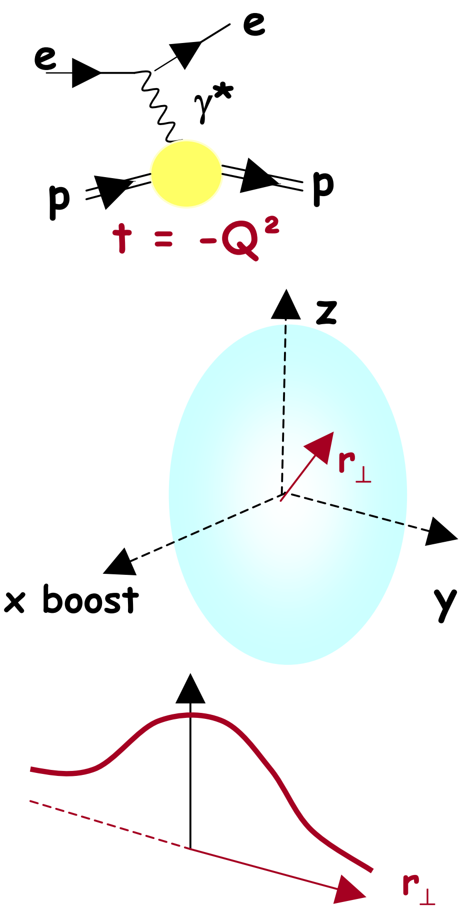
DSPIN-07
Dubna, September 3-7, 2007

Nicole d'Hose, Saclay, CEA/DAPNIA
On behalf of the COMPASS collaboration

GPDs ≡ a 3-dimensional picture of the nucleon partonic structure

Elastic Scattering

ep → ep

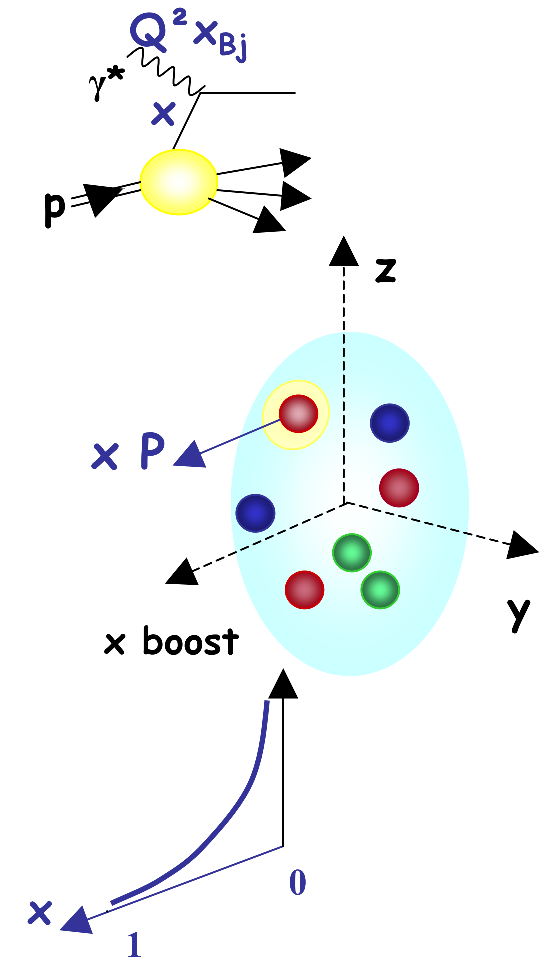


Form Factor F(t)

$r_{y,z}$

Deep Inelastic Scattering

ep → eX

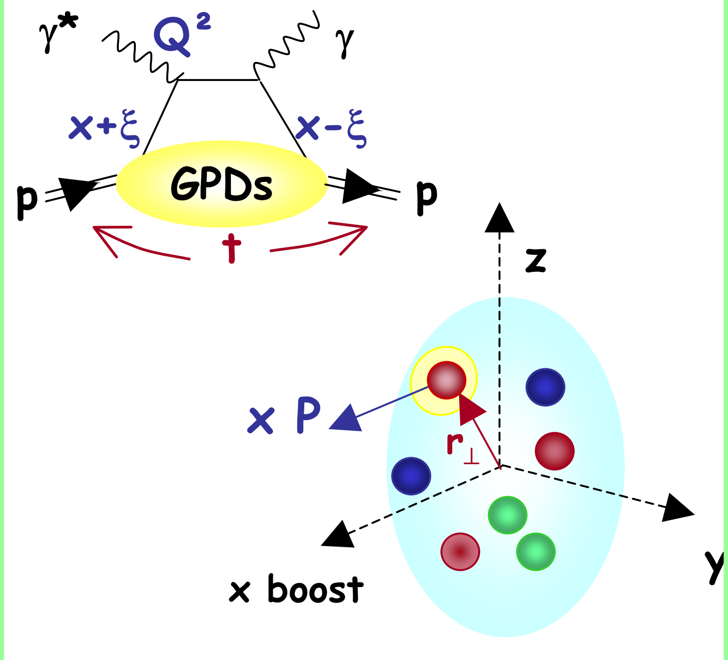


Parton Density q (x)

P_x

Hard Exclusive Scattering
Deeply Virtual Compton Scattering

ep → epγ



Generalized

Parton Distribution H(x, ξ, t)

(P_x, $r_{y,z}$)

Burkard, Belitsky, Müller, Ralston, Pire

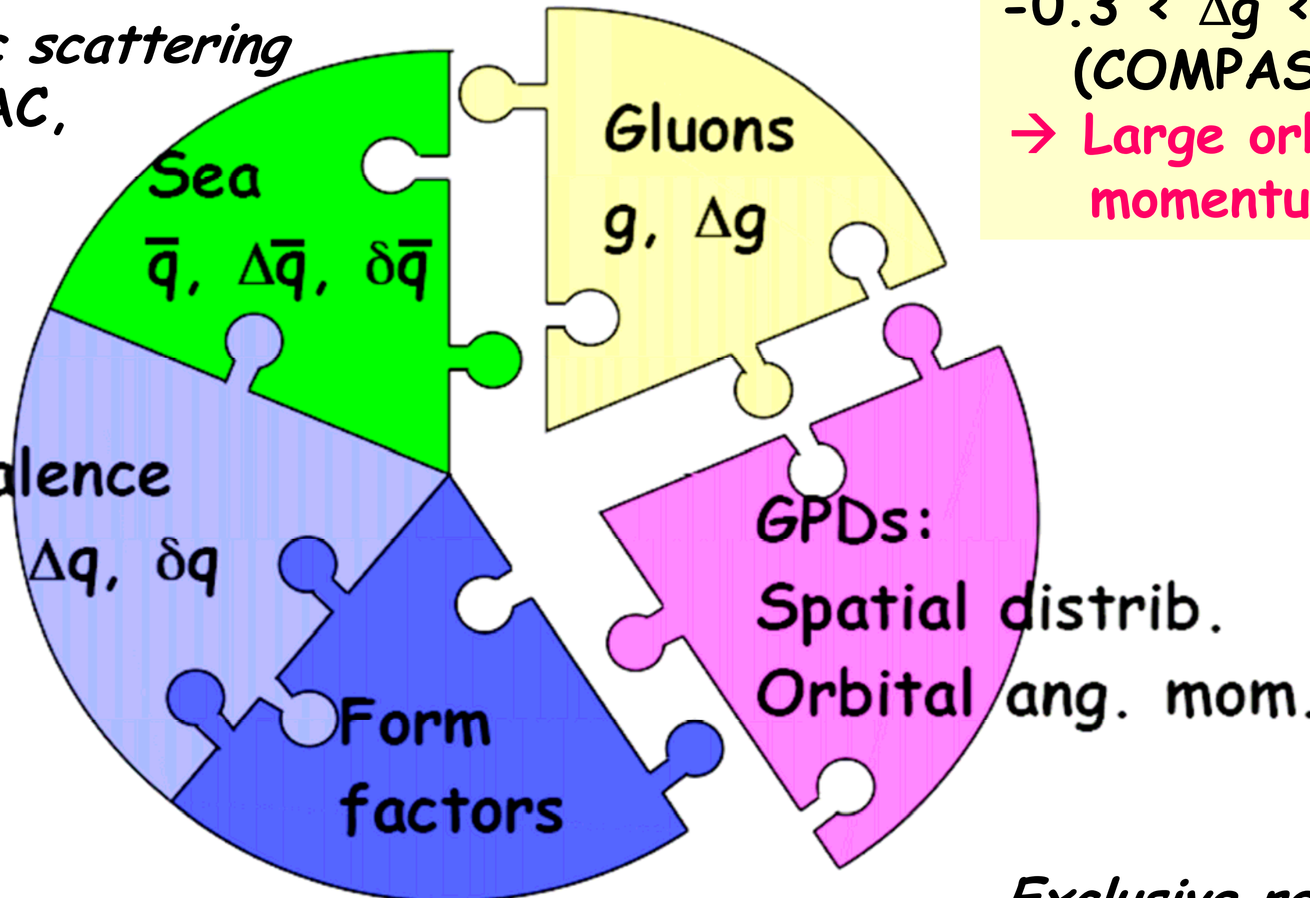
The complete nucleon map

Robust and exhaustive studies

Semi-inclusive reactions

-0.3 < Δg < 0.3
(COMPASS)
→ Large orbital momentum ?

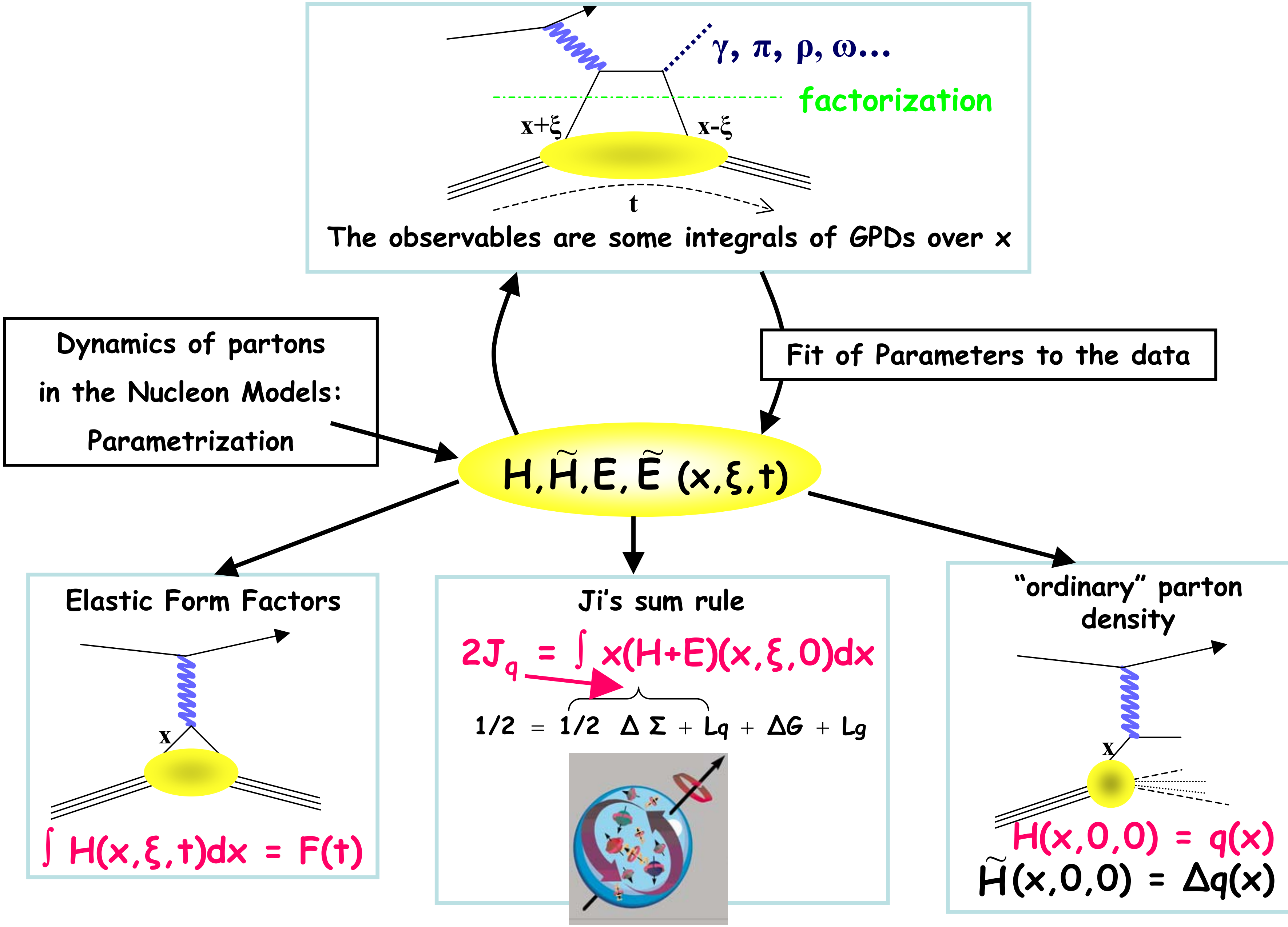
Deep inelastic scattering
at DESY, SLAC, CERN, JLab



Elastic scattering
still at JLab

Exclusive reactions
Nucleon tomography

GPDs and relations to the physical observables

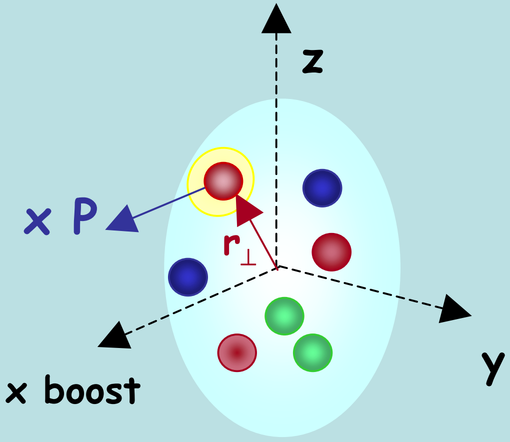


1rst goal of the « Holy-Grail »

Reveal a 3-dim picture of the nucleon partonic structure

or probability densities of quarks and gluons
in impact parameter space

$H(x, \xi, t)$ ou $H(P_x, r_{y,z})$

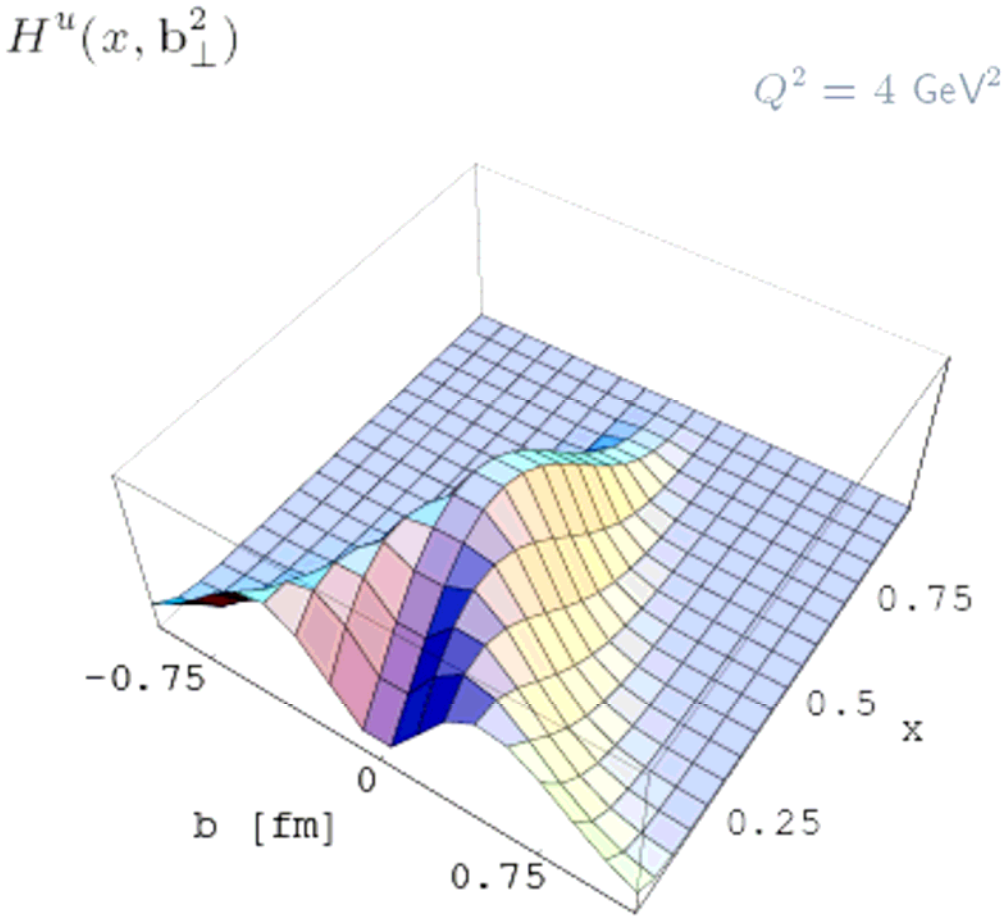


→ *measurement of Re(H) via VCS and BCA or Beam Charge Difference*

GPDs in Lattice

From Schierholz, JLab May 2007

probability densities of quarks and gluons in impact parameter space

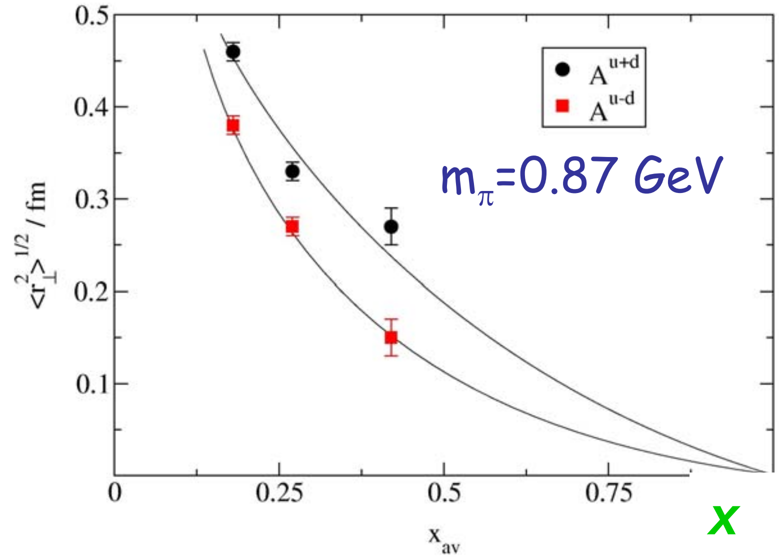


Sensitivity to the 3-D nucleon picture

Lattice calculation (unquenched QCD):

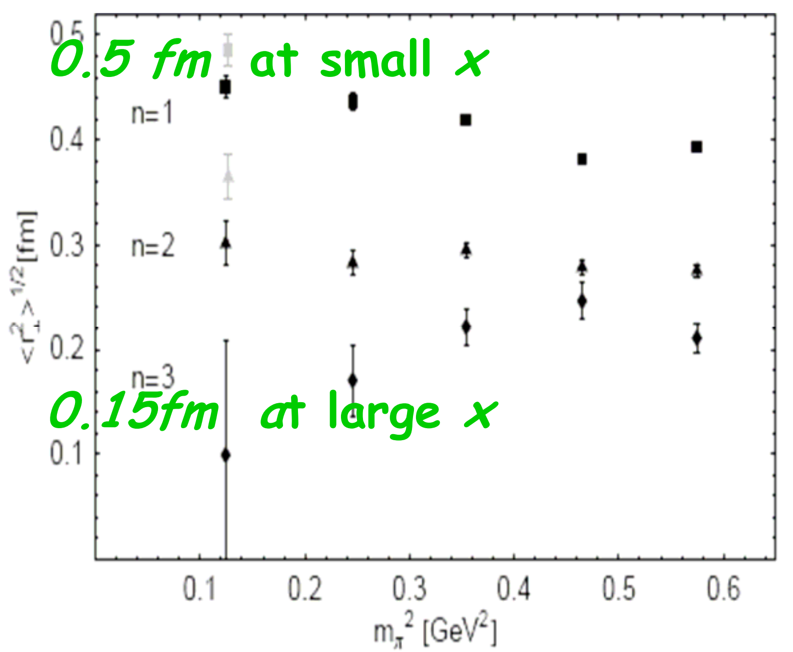
Negele et al., NP B128 (2004) 170
Göckeler et al., NP B140 (2005) 399

- fast parton close to the N center
  - ≡ small valence quark core
- slow parton far from the N center
  - ≡ widely spread sea q and gluons



Last result on 29 May 2007
First comprehensive full lattice QCD
In the chiral regime with m_π =0.35 GeV

Hägler et al., hep-lat 07054295
MIT, JLab-THY-07-651,
DESY-07-077, TUM-T39-07-09

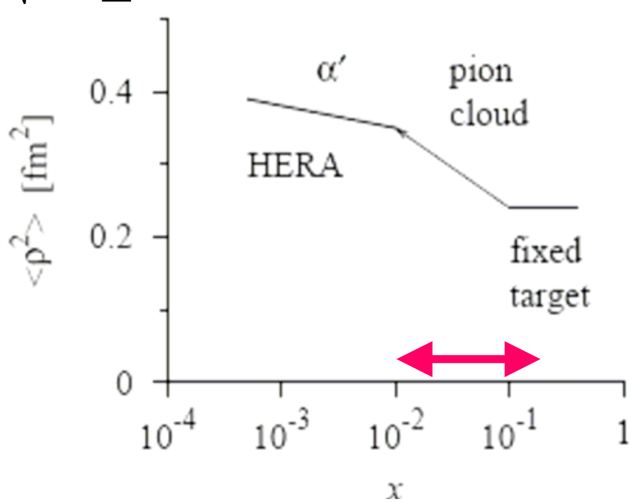


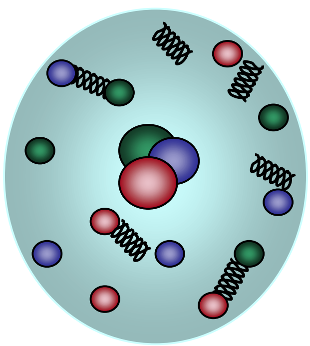
Sensitivity to the 3-D nucleon picture

Chiral dynamics: *Strikman et al., PRD69 (2004) 054012*
Frankfurt et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 403

at large distance : gluon density generated by the pion cloud
increase of the N transverse size for $x_{Bj} < m_\pi/m_p = 0.14$

$\sqrt{<r_\perp^2>}$ 0.6fm 0.4fm





Promising COMPASS domain

Figure 10: The average squared transverse radius of the gluon distribution in the nucleon, $\langle\rho^2\rangle = \int d^2\rho\, \rho^2 F_g(x,\rho;Q^2_{\text{eff}})$, as a function of x, as extracted from J/ψ photoproduction data ($Q^2_{\text{eff}} = 3\ \text{GeV}^2$) at various energies.

2 Parametrizations of GPDs

Factorization: $H(x,\xi,t) \sim q(x)\, F(t)$

or

Regge-motivated t-dependence: more realistic with x-t correlation

it considers that fast partons in the small valence core and slow partons at larger distance (wider meson cloud)

$\langle b^2_\perp \rangle = \alpha' \ln 1/x$ transverse extension of partons in hadronic collisions

$\Rightarrow$ $H(x,0,t) = q(x)\, e^{t \langle b_\perp^2 \rangle} = q(x) / x^{\alpha' t}$ (α'slope of Regge traject.)

This ansatz reproduces the

Chiral quark-soliton model: Goeke *et al.*, NP47 (2001)

More correct behavior at small and large x:

$\langle b^2_\perp \rangle = \alpha' (1-x) \ln 1/x + B(1-x)^2$

to reproduce perfectly the proton form factor

3 frameworks or models for GPD (x, ξ, t, Q^2)

Quark domain: *Vanderhaeghen, Guichon, Guidal (VGG)*
PRD60 (1999) 094017, Prog.Part.Nucl.Phys.47(2001)401-515

Double distribution x,ξ a la Radyushkin
x,t correlation
no Q^2 evolution

Gluon + quark domain ($x<0.2$): *Guzey*
PRD74 (2006) 054027 hep-ph/0607099v1

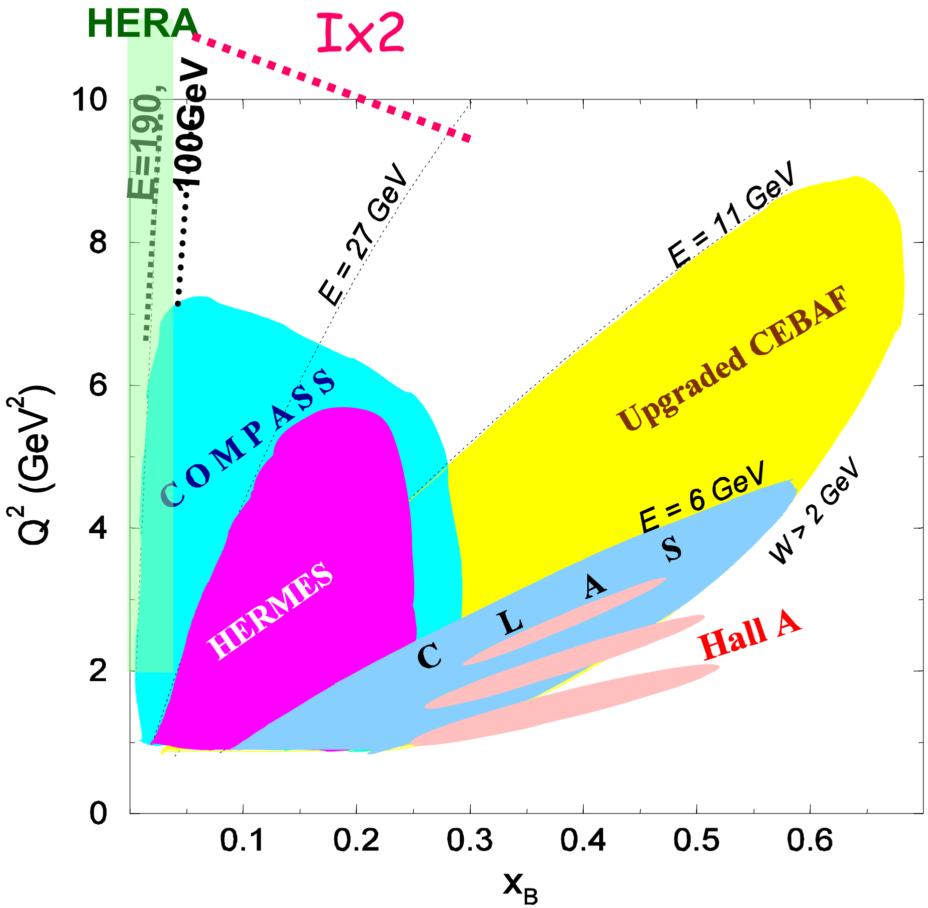
Dual parametrization with Mellin moments decomposition
QCD evolution + separation x, ξ and ξ, t

Gluon domain : *Freund, Frankfurt, Strikman (FFS) + Schoeffel*

$$\mathbf{GPD^{s,V,g}(x,\xi) \equiv Q^{s,V,g}(x)}$$

ξ Dependence generated via the QCD evolution

Competition in the world and COMPASS role



Gluons | valence quarks and sea quarks and gluons | valence quarks

COMPASS 2010 | JLab 12 GeV, FAIR,... 2014

COMPASS at CERN-SPS

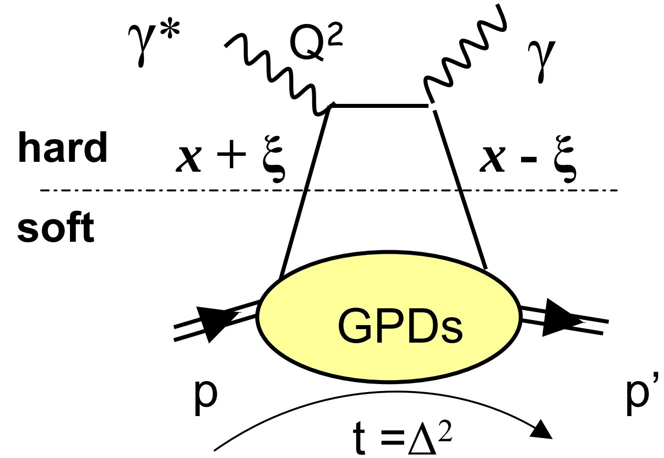
High energy muon beam
100/190 GeV

$\mu+$ or $\mu-$
change once per day
polar($\mu+$)=-0.80
polar($\mu+$)=+0.80

2.10^8 μ per SPS cycle

in 2010 ?
new Linac4
(high intensity H^- source)
as injector for the PSB
+ improvements
on the muon line

In DVCS and meson production
we measure integrals over the GPDs



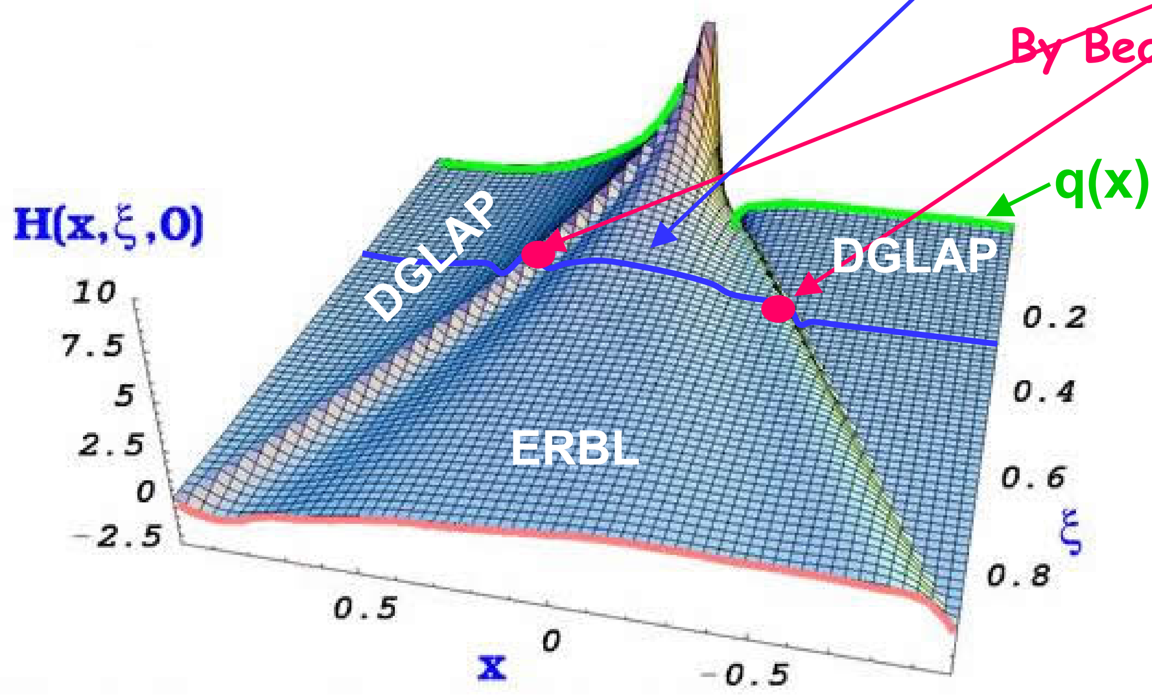
For example at LO in α_s:

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

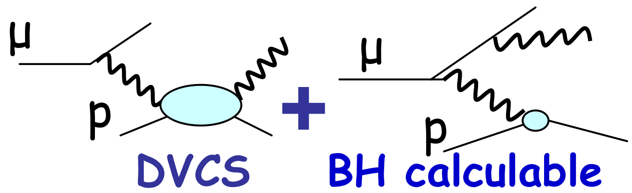
t, $\xi \sim x_{Bj/2}$ fixed

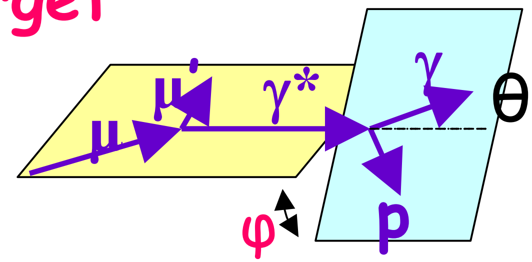
By Beam Charge difference

By Beam Spin difference



DVCS + BH with polarized and charged leptons and unpolarized target





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

$$d\sigma^{BH} = \frac{\Gamma(x_B, Q^2, t)}{P_1(\varphi)P_2(\varphi)}\left(c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right)$$ ← Known expression

$$d\sigma^{DVCS}_{unpol} = \frac{e^6}{y^2Q^2}\left(c_0^{DVCS} + c_1^{DVCS}\cos\varphi + c_2^{DVCS}\cos 2\varphi\right)$$

$$P_\mu \times d\sigma^{DVCS}_{pol} = \frac{e^6}{y^2Q^2}\left(s_1^{DVCS}\sin\varphi\right)$$

$$e_\mu \times a^{BH}\,\Re e A^{DVCS} = \frac{e^6}{xy^3tP_1(\varphi)P_2(\varphi)}\left(c_0^{Int} + c_1^{Int}\cos\varphi + c_2^{Int}\cos 2\varphi + c_3^{Int}\cos 3\varphi\right)$$

$$e_\mu P_\mu \times a^{BH}\,\Im m A^{DVCS} = \frac{e^6}{xy^3tP_1(\varphi)P_2(\varphi)}\left(s_1^{Int}\sin\varphi + s_2^{Int}\sin 2\varphi\right)$$

Twist-2 M^{11} >> Twist-3 M^{01} Twist-2 gluon M^{-11}

Belitsky, Müller, Kirchner

Both c_1^{Int} and s_1^{Int} accessible at COMPASS with $\overleftarrow{\mu}^+$ and $\overrightarrow{\mu}^-$

$$c_1^{Int} \propto \Re\mathrm{e} \qquad s_1^{Int} \propto \Im\mathrm{m} \left(F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} - \frac{t}{4m^2} F_2\mathcal{E} \right)$$

$$\Re\mathrm{e}\,\mathcal{H} = \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}$$

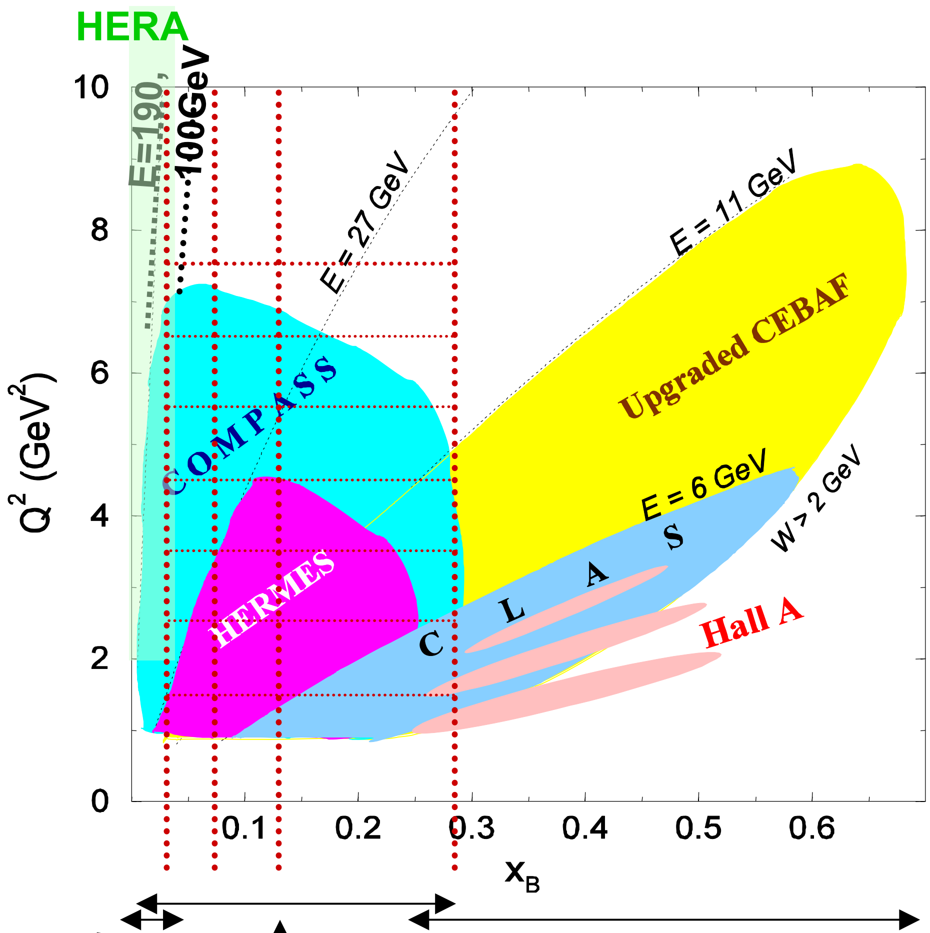
$$\Im\mathrm{m}\,\mathcal{H} = H(x=\xi,\xi,t)$$

with $\quad H = \sum_q e_q^2 H^q$

— F_1H dominance with a proton target

..... F_2E dominance with a neutron target (F1<<)
very attractive for Ji's sum rule study

Competition in the world and COMPASS role



Gluons

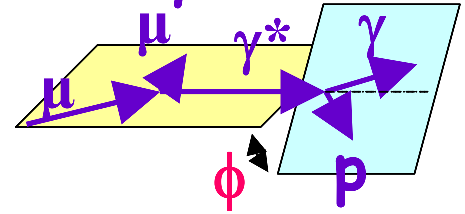
valence quarks and sea quarks and gluons

valence quarks

COMPASS 2010

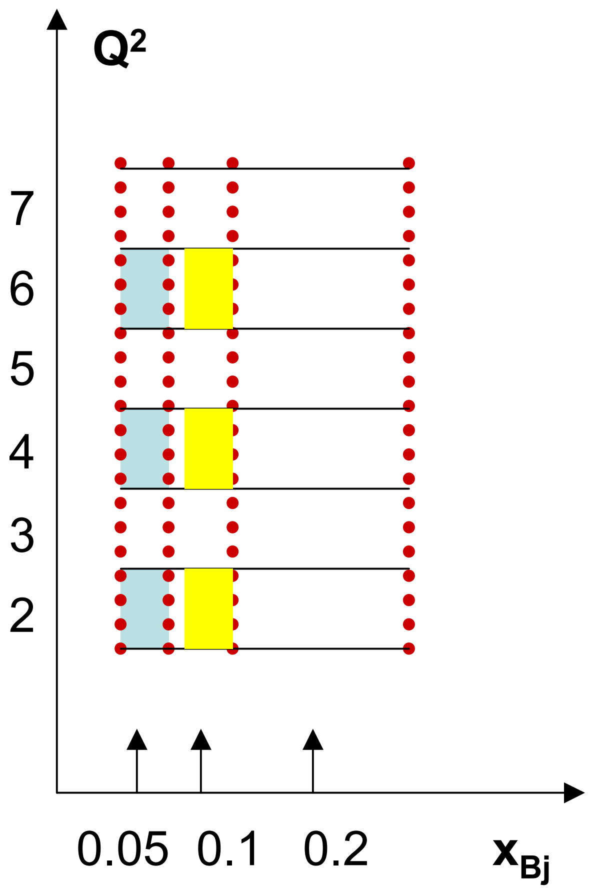
JLab 12 GeV 2014, FAIR, …

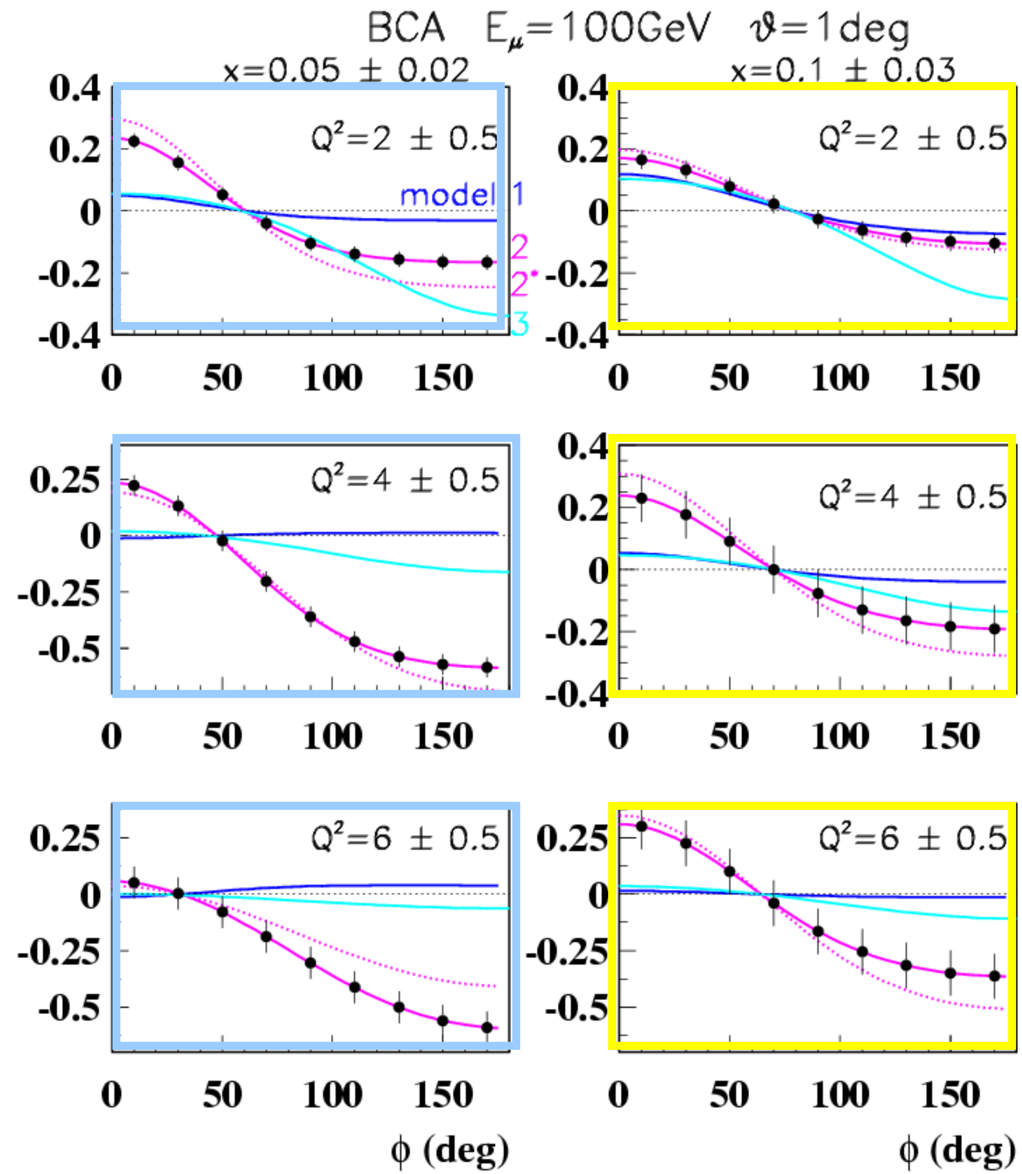
Beam Charge Asymmetry at Eμ = 100 GeV



COMPASS prediction
With a 2.5m H_2 target

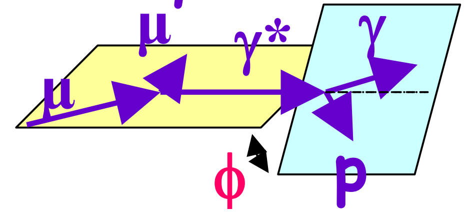
6 month data taking in 2010
25 % global efficiency





Beam Charge Asymmetry at Eμ = 100 GeV

COMPASS prediction



VGG: double-distribution in x, ξ

model 1: $H(x,\xi,t) \sim q(x)\, F(t)$

model 2 and 2*: correl x and t

$\langle b^2_\perp \rangle = \alpha' \ln 1/x$

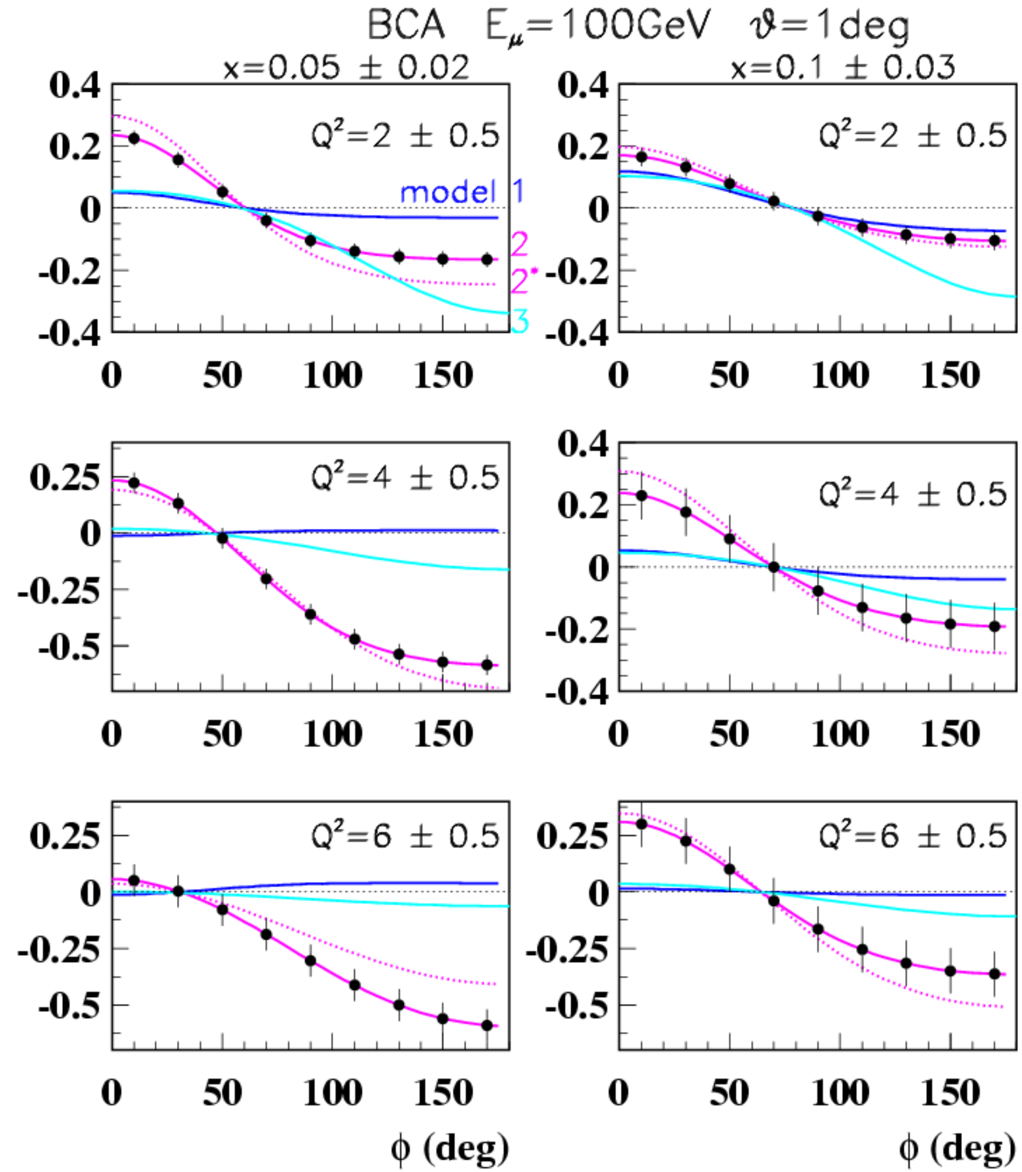
$H(x,0,t) = q(x)\, e^{\,t \langle b_\perp^2 \rangle}$
$= q(x) / x^{\alpha' t}$

α' slope of Regge traject.

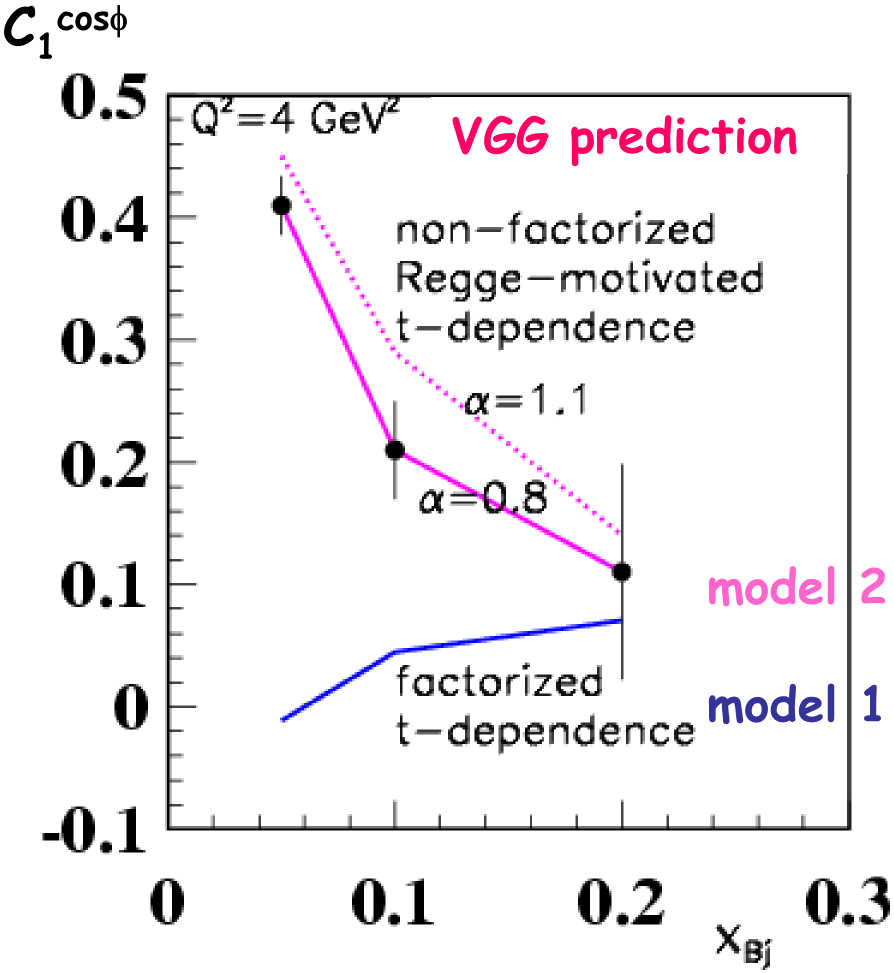
—— $\alpha' = 0.8$

.... $\alpha' = 1.1$

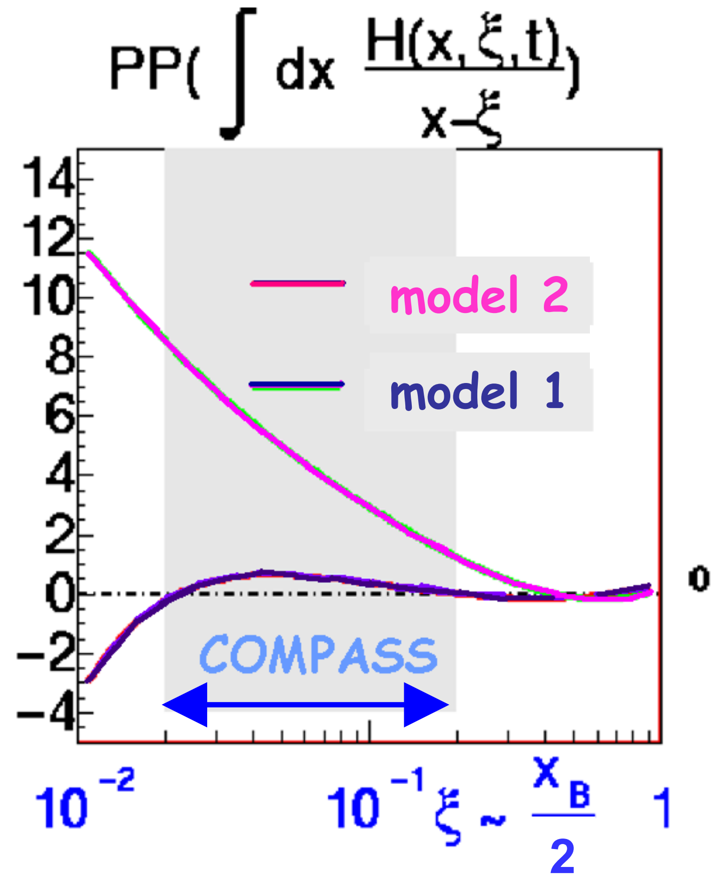
Guzey: Dual parametrization
model 3: also Regge-motivated
t-dependence with $\alpha' = 1.1$



$$BCA = \frac{c_0^{int} + c_1^{int}\cos\Phi + c_2^{int}\cos 2\Phi + c_3^{int}\cos 3\Phi}{\text{denominator(BH+DVCS)}}$$



$\supset$



α' determined within an accuracy of ~10% at xBj =0.05 and 0.1

2^{nd} goal of the « Holy-Grail »

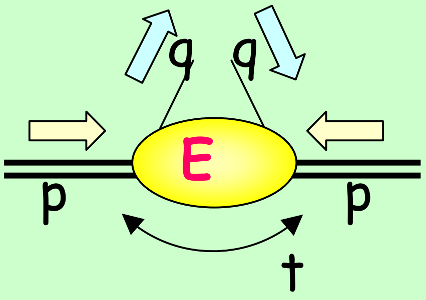
Contribution to the nucleon spin knowledge

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$

the GPDs correlation between the 2 pieces of information:
-distribution of longitudinal momentum carried by the partons $\vec{p}$
-distribution in the transverse plane $\vec{r}$

the GPD E allows nucleon helicity flip
so it is related to the angular momentum

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

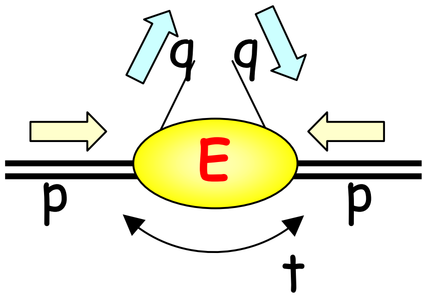


→ *with a transversely polarized target DVCS et MV*
→ *with a deuterium or neutron target DVCS*

modelisation of the GPD E (in a modified VGG code)

Factorization: $H(x,\xi,t) \sim q(x)\,F(t)$
(and Regge-motivated t-dependence)

the GPD E is related to angular momentum



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

unknown: $E^q(x,0,0) = e^q(x) = A_q q_{val}(x) + B_q \delta(x)$ (based on chiral soliton)

+ 2 sum rules:

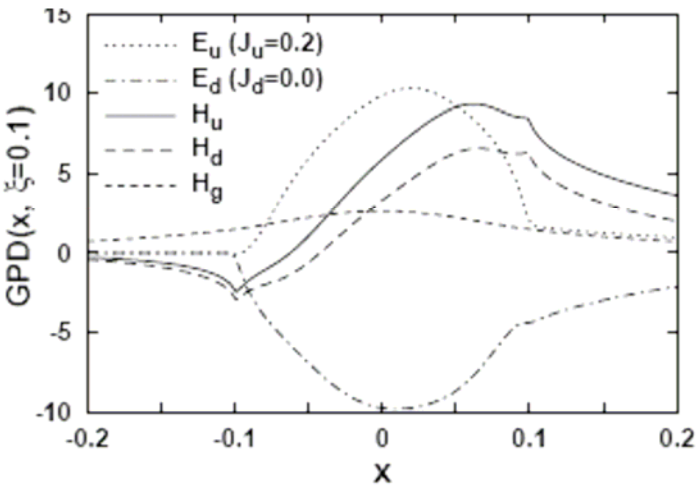
$$\kappa^q = \int e^q(x)\,dx$$

$$2J_q = \int x\,(q(x) + e^q(x))\,dx$$

→ A_q and B_q are functions of J_u and J_d

→ $E^u \sim - E^d$

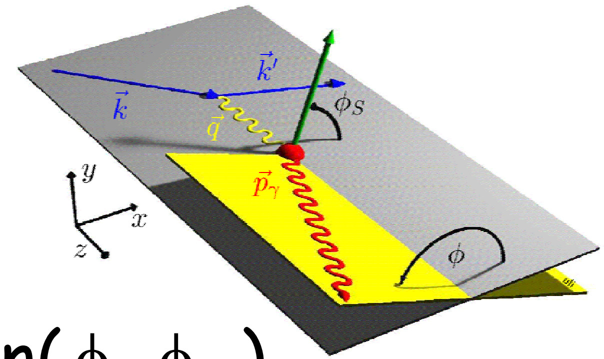
$E^g \sim 0$



-VGG code-

Model-Dependent Constraint on J_u and J_d

Through the modeling of GPD E



1-Transversaly polarised target

In Meson production :

$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \Im m(H\,E)\cdot\sin(\phi-\phi_S)$$

with COMPASS Li6D deuteron Data 2002-3-4 (J.Kiefer, G.Jegou)
NH3 proton Data 2007

In DVCS :

$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \Im m(F_2H - F_1E)\cdot\sin(\phi-\phi_S)\cos\phi$$
$$+\Im m(F_2\tilde{H} - F_1\xi\tilde{E})\cdot\cos(\phi-\phi_S)\sin\phi$$

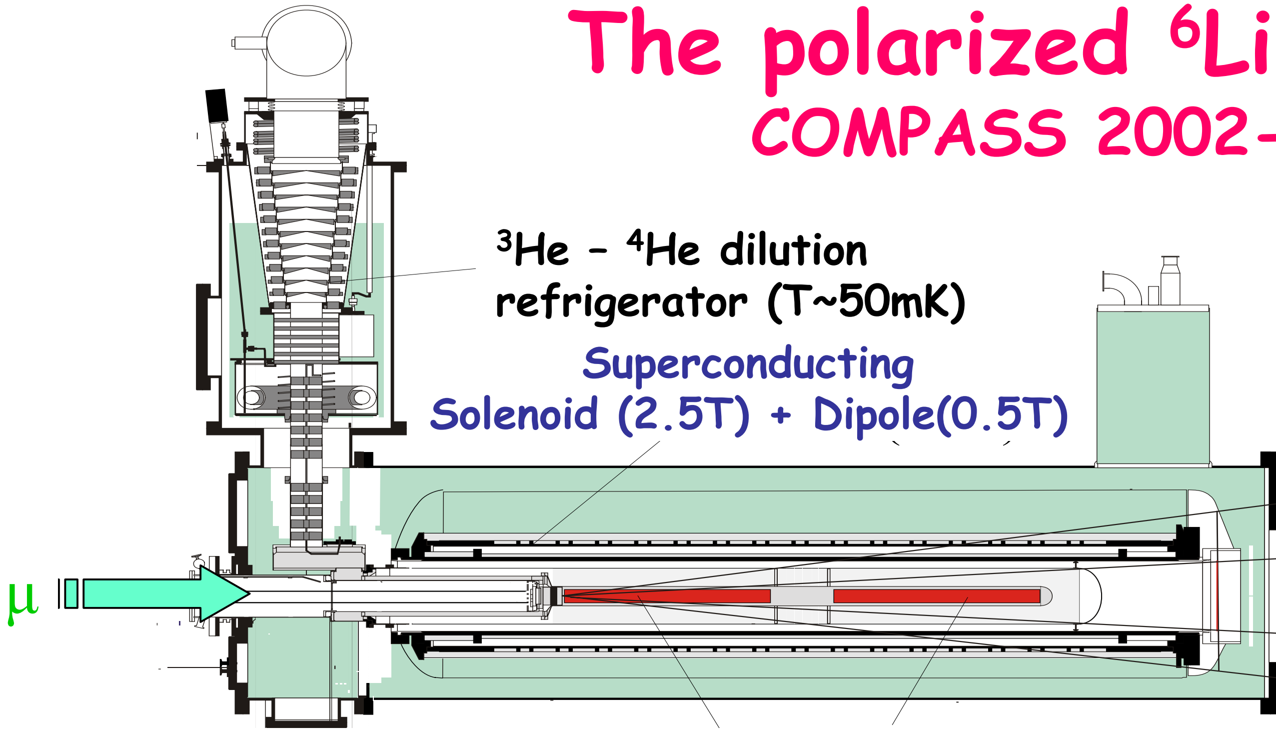
but… no recoil detection around the polarized target

2-Neutron (or deuterium) target + DVCS

$$d\sigma(\ell^+,\phi) - d\sigma(\ell^-,\phi) \propto \Re e(\cancel{F_1H} + i\,(F_1+F_2)\tilde{H} - \frac{t}{4m^2}F_2E)\cdot\cos\phi$$

for the complete program after 2010

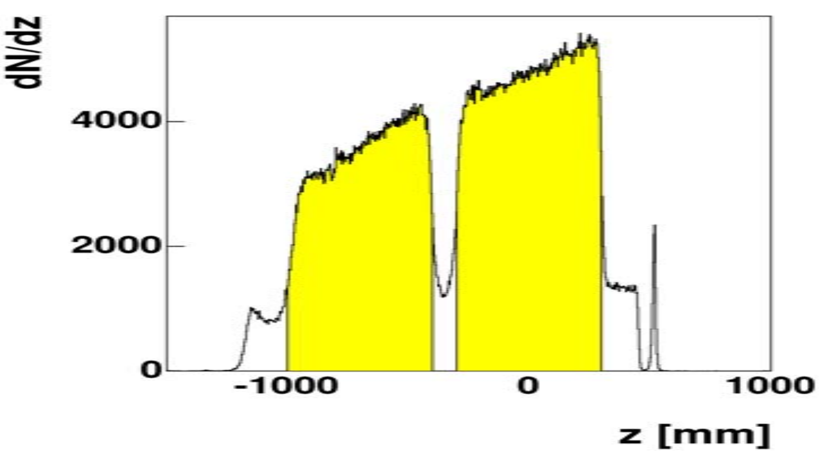
The polarized ^{6}LiD-Target
COMPASS 2002-3-4-6



Two 60cm long target cells with opposite polarization

Target Polarization ~ 50%

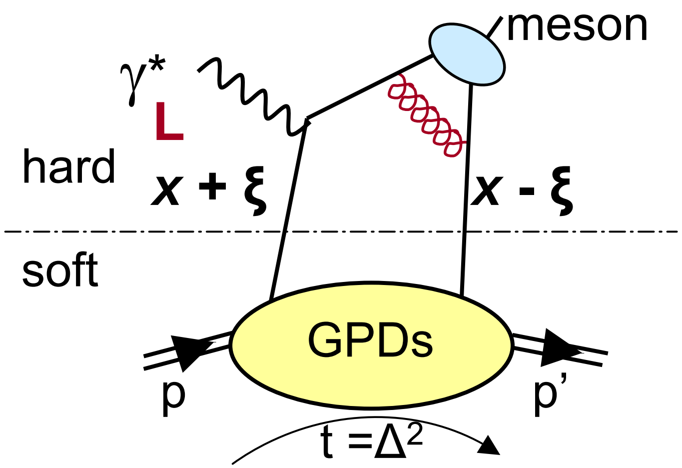
Dilution factor f ~ 0.36



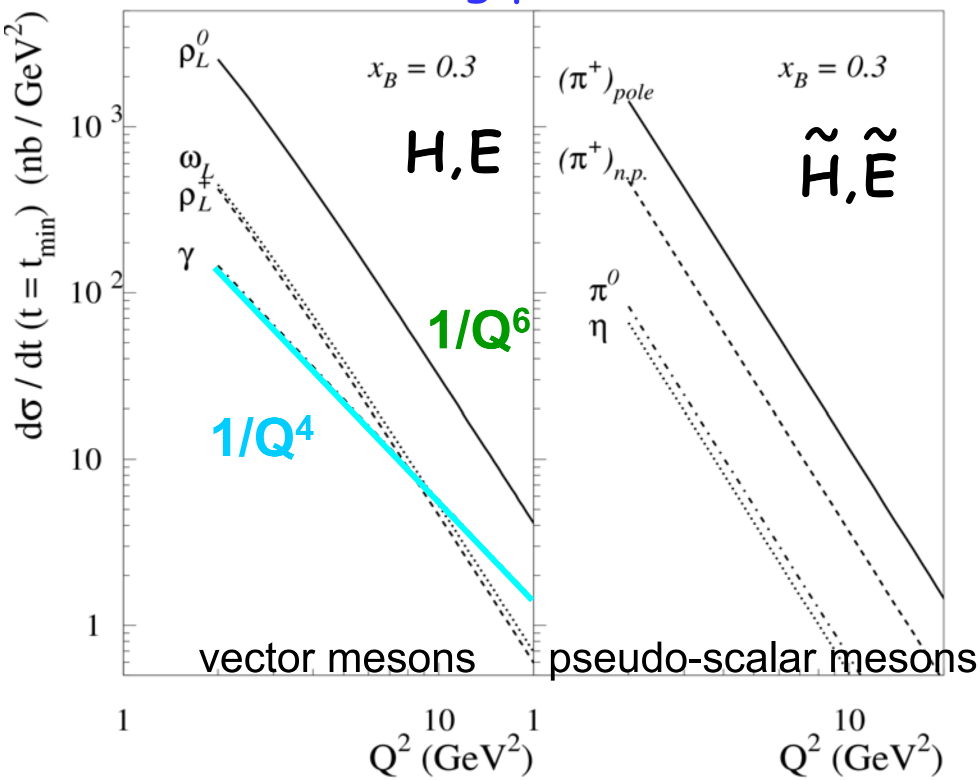
4 possible spin combinations:

longitudinal	transverse
❶ → ←	❸ ↑ ↓
❷ ← →	❹ ↓ ↑
Reversed every 8 hours	Reversed once a week

Hard exclusive meson production



Scaling predictions:



Collins et al. (PRD56 1997):

- factorization applies only for γ^*_L
- probably at high Q^2

Different flavor contents:

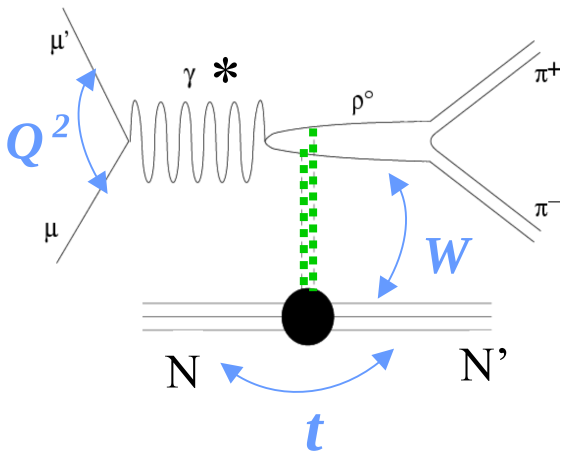
$H\rho^0 = 1/\sqrt{2}\,(2/3\ H^u + 1/3\ H^d + 3/8\ H^g)$

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

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

ρ production studied with present COMPASS data

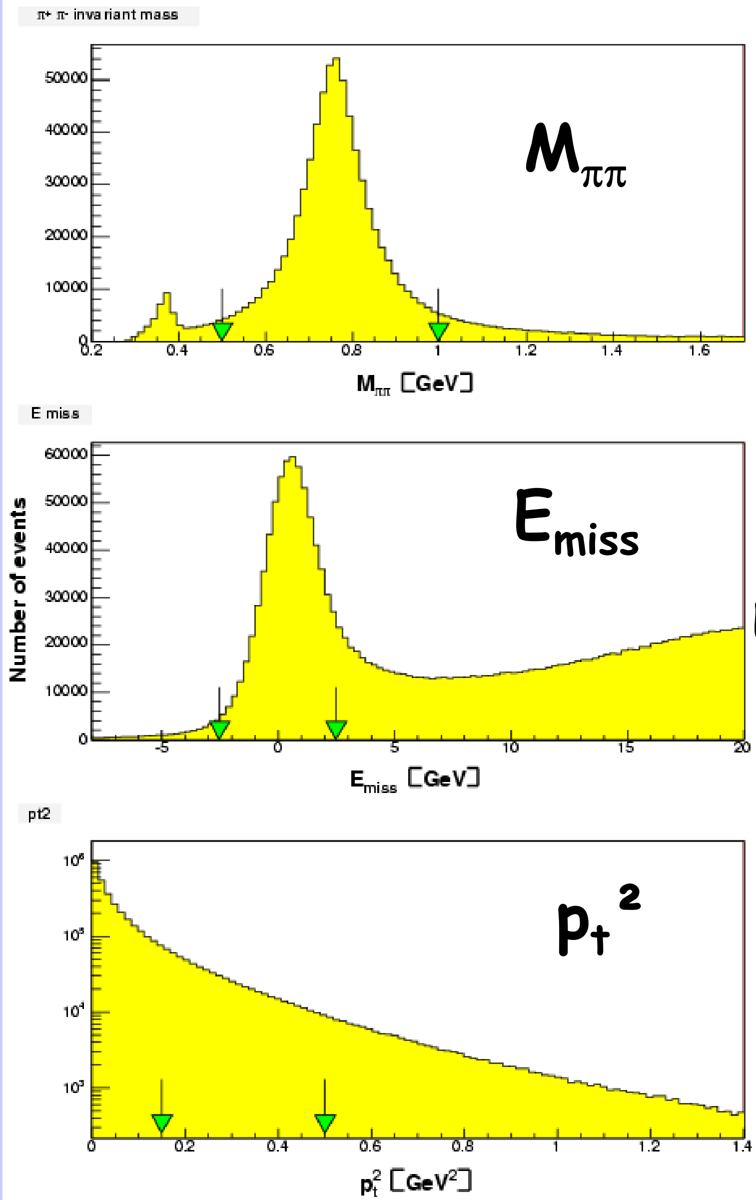
Selection of Incoherent exclusive ρ^0 production



quasi-free nucleons in
^{6}LiD polarized target

Kinematics:

ν > 30 GeV
$E\mu'$ > 20 GeV



Assuming
both hadrons are π
$0.5 < M_{\pi\pi} < 1$ GeV

Exclusivity of
the reaction
$E_{miss} = (M^2_X - M^2_N) / 2M_N$
$-2.5 < E_{miss} < 2.5$ GeV

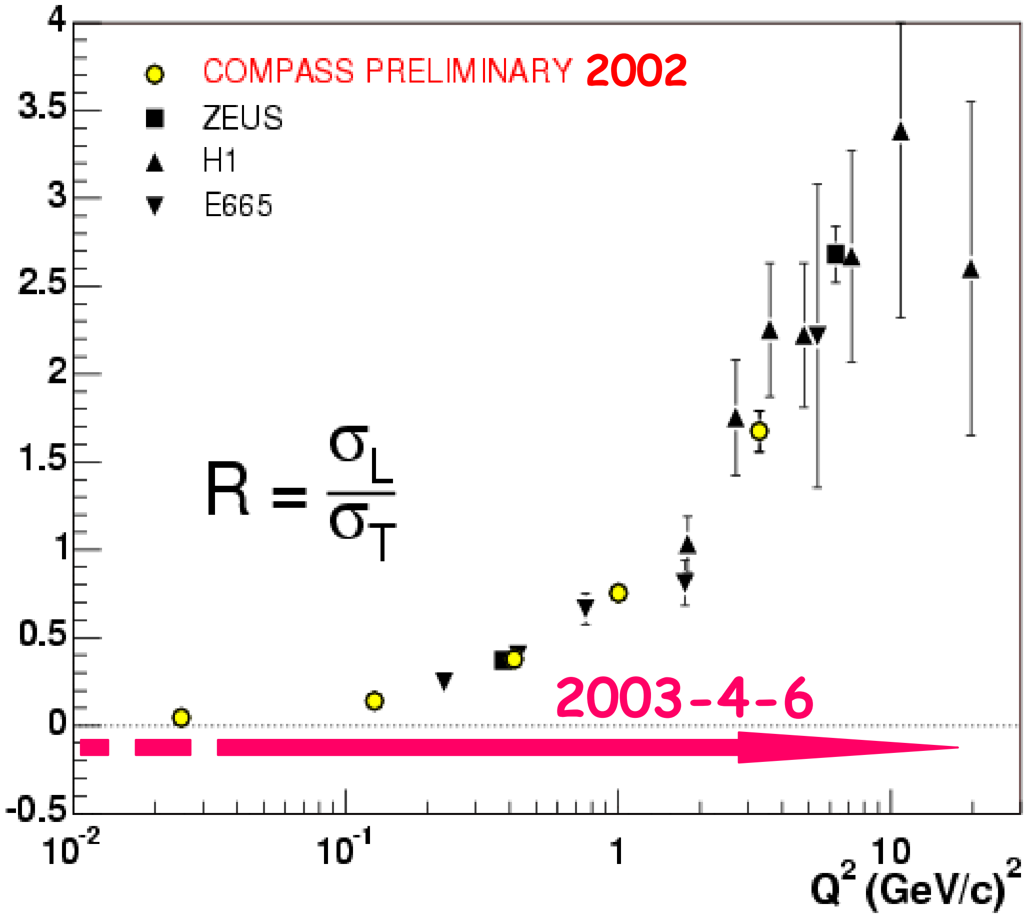
Incoherent production
$0.15 < p_t^2 < 0.5$ GeV^2
scattering off a
quasi-free nucleon

Background ~12%

Determination of $R_{\rho^\circ} = \sigma_L/\sigma_T$

With COMPASS + $\vec{\mu}$

Complete angular distribution $\Rightarrow$ Full control of SCHC



- High statitics from γ-production to hard regime
- Better coverage at high Q^2 with 2003-4-6 data

Impact on GPD study:

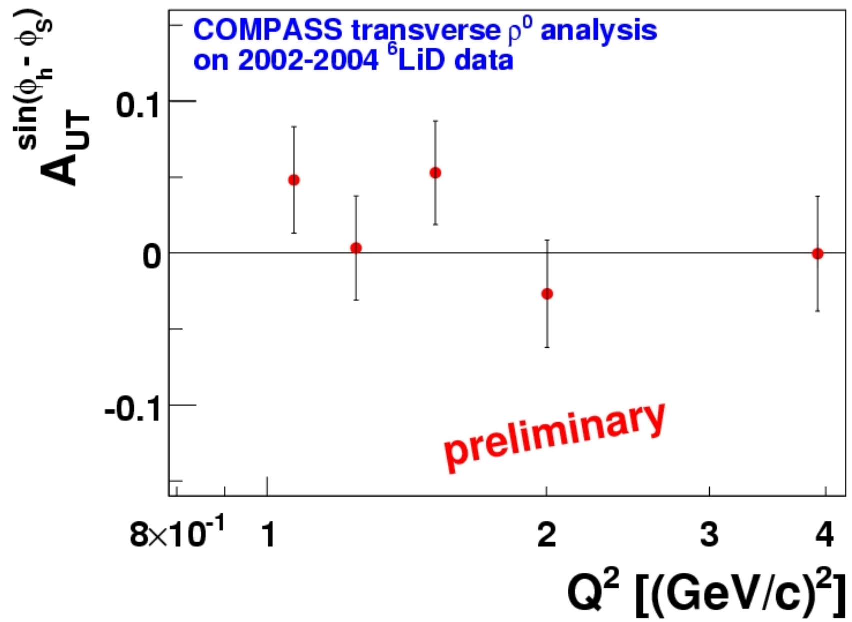
easy determination of σ_L

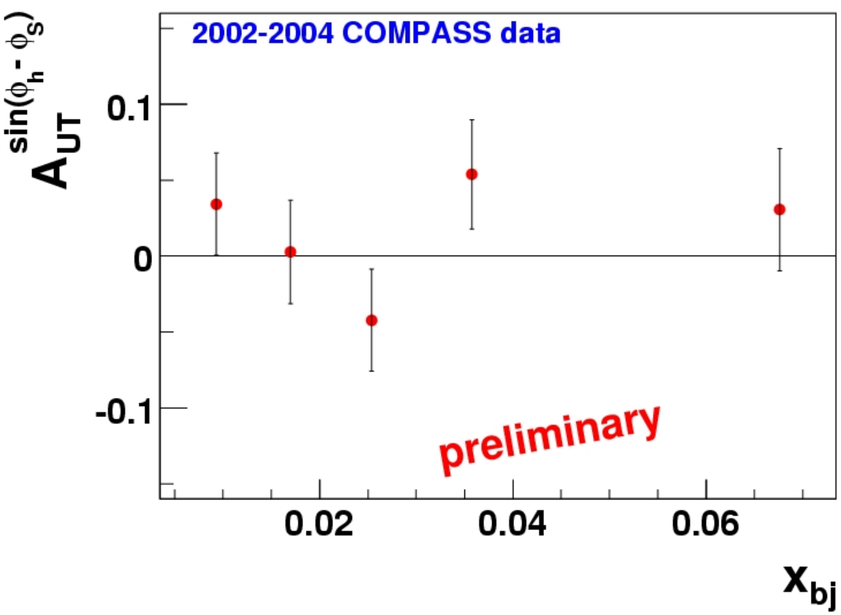
factorisation only valid for σ_L

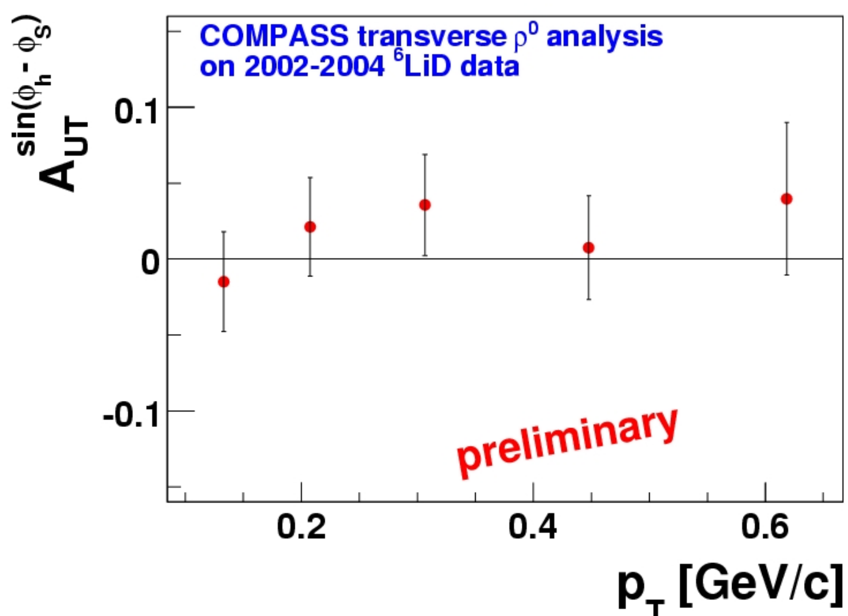
σ_L is dominant at $Q^2 > 2$ GeV^2

Preliminary Transverse Target Spin asymmetry A_{UT} in rho production off deuteron

COMPASS
$\langle Q^2 \rangle = 1.9\ GeV^2$
$\langle x \rangle = 0.03$







The way to get GPDs from the Transverse Target Spin asymmetry with ρ^0 production

1- Factorization for longitudinal photons only

Suppression of transverse component $\sigma_T/\sigma_L \sim 1/Q^2$

For COMPASS kinematics $\langle Q^2 \rangle = 2 GeV^2$ R= $\sigma_L/\sigma_T \sim 1$

→ *separation using the angular distribution of the ρ° decay + SCHC and the last works of Diehl and Sapeta*

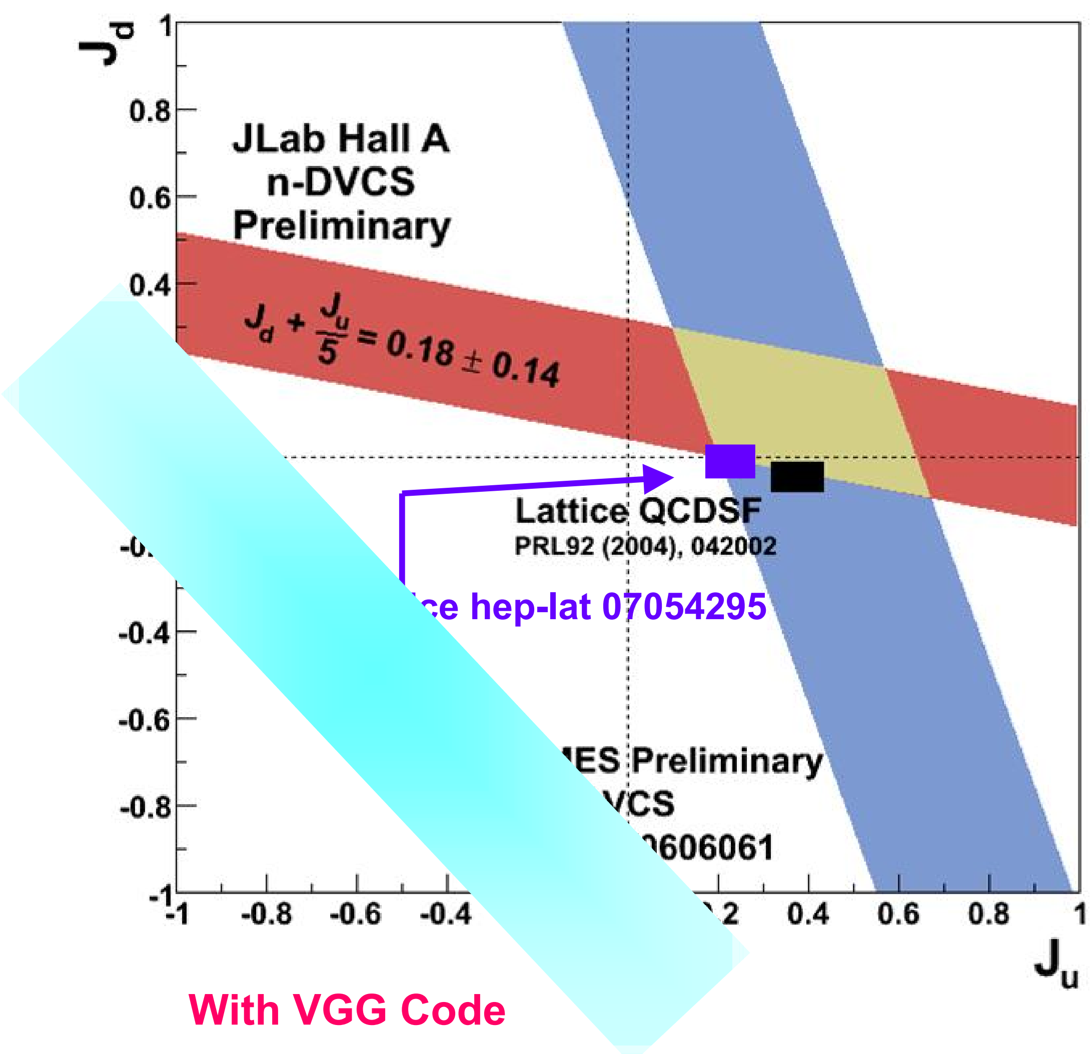
2- Coherent contribution → Pire, Cano, Strikmann?

Incoherent contribution → Kroll, Goloskokov (quark and gluon contribution)
Guzey (quark and gluon contribution)
VGG (mainly quark contribution)

→ *cut on P_T^2*

3- ^{6}LiD or Deuterium target in 2002-3-4 → proton + neutron contribution
NH_3 or Proton target in 2007 → proton contribution

Present status of
the MODEL-DEPENDENT Ju-Jd extraction



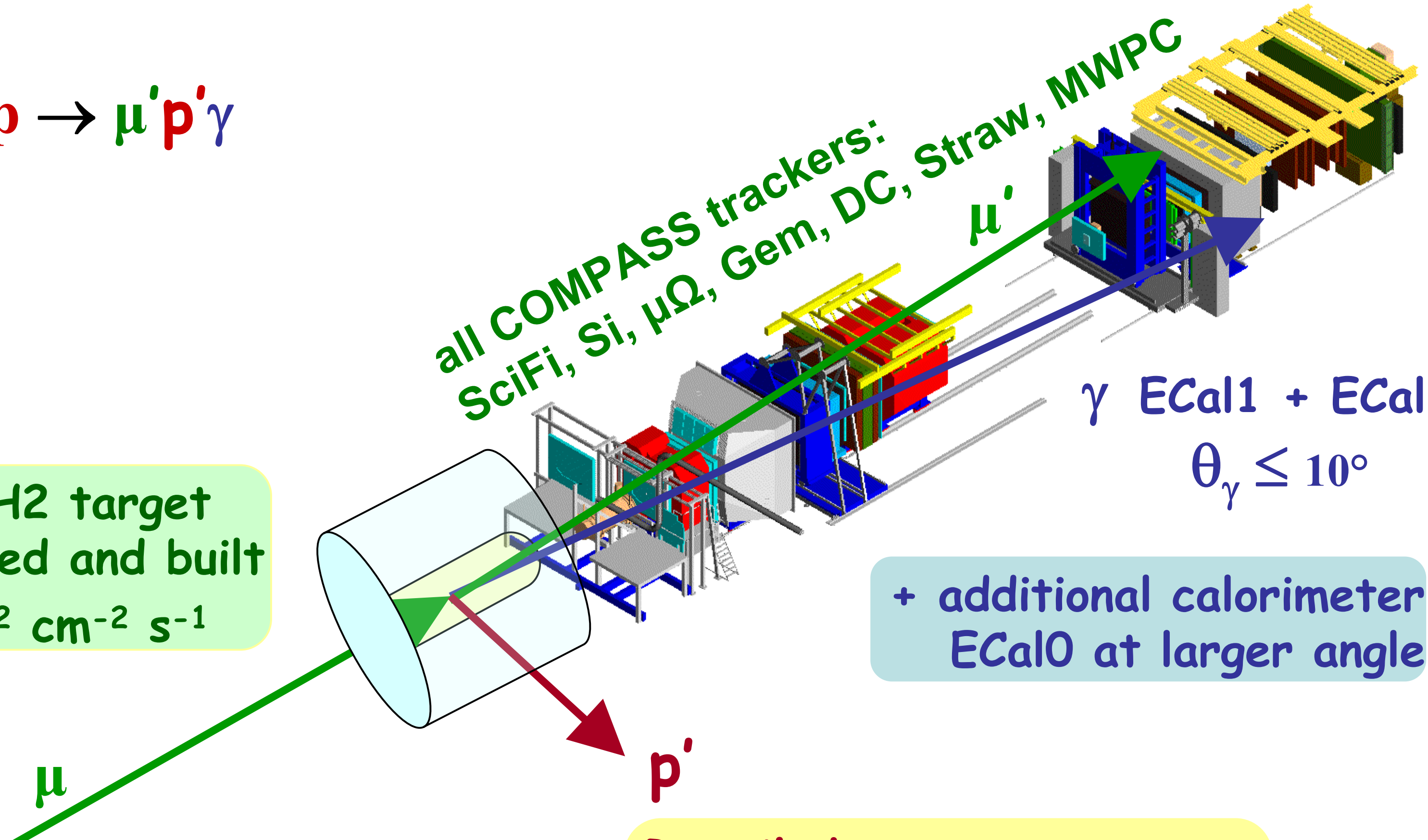
With VGG Code

expected results
with A_{UT} measured
in the rho production
at COMPASS

Additional equipment to the COMPASS setup

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

2.5m liquid H2 target
to be designed and built
$\mathcal{L}$ = 1.3 10^{32} cm^{-2} s^{-1}

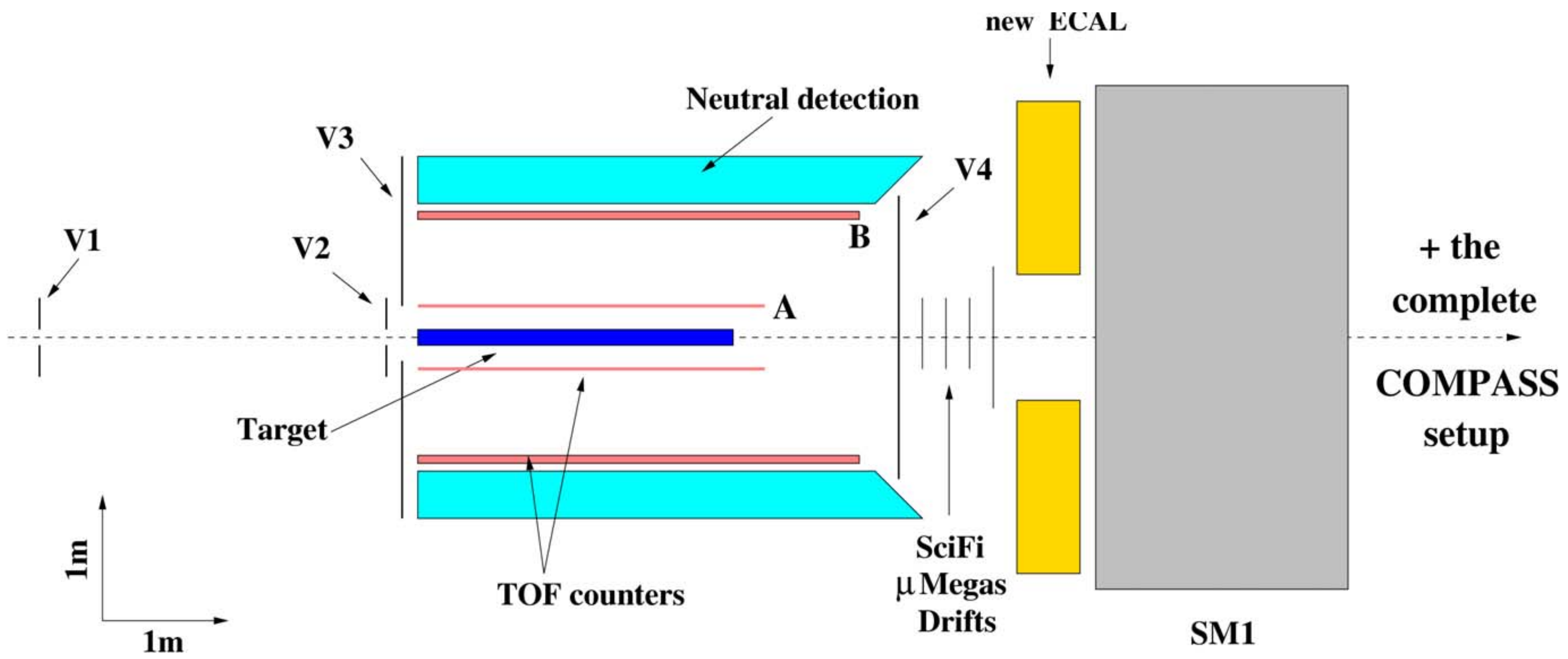


+ additional calorimeter
ECal0 at larger angle

Nμ=2.10^8/SPS cycle
(duration 5.2s, each 16.8s)

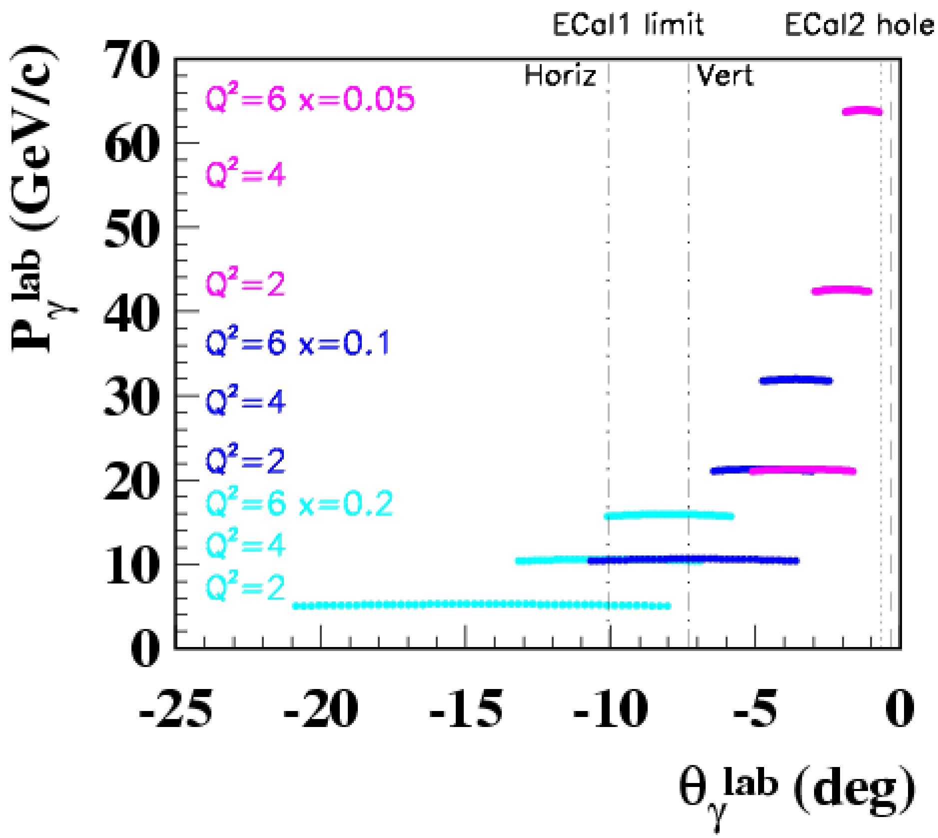
Recoil detector
to insure exclusivity
to be designed and built

Recoil detector + extra calorimetry



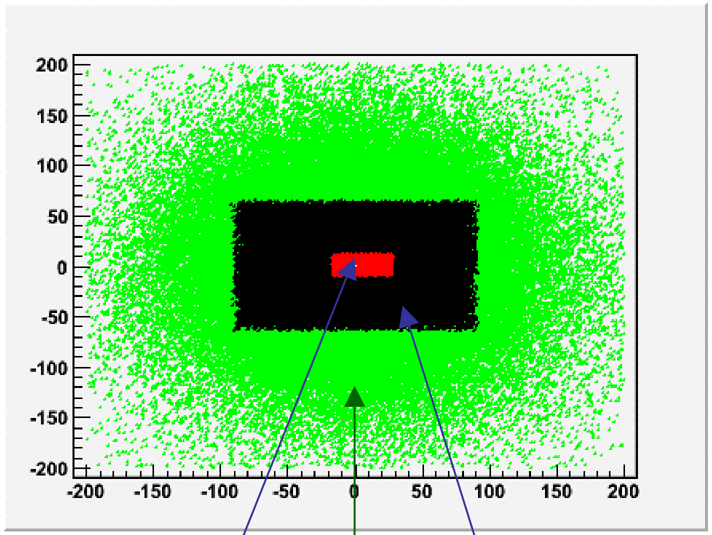
Calorimeter coverage foreseen for DVCS γ

DVCS γ kinematics



$\vartheta \nearrow$ $E\gamma \searrow$ threshold detection $\searrow$

DVCS γ impact point at ECAL 0 location

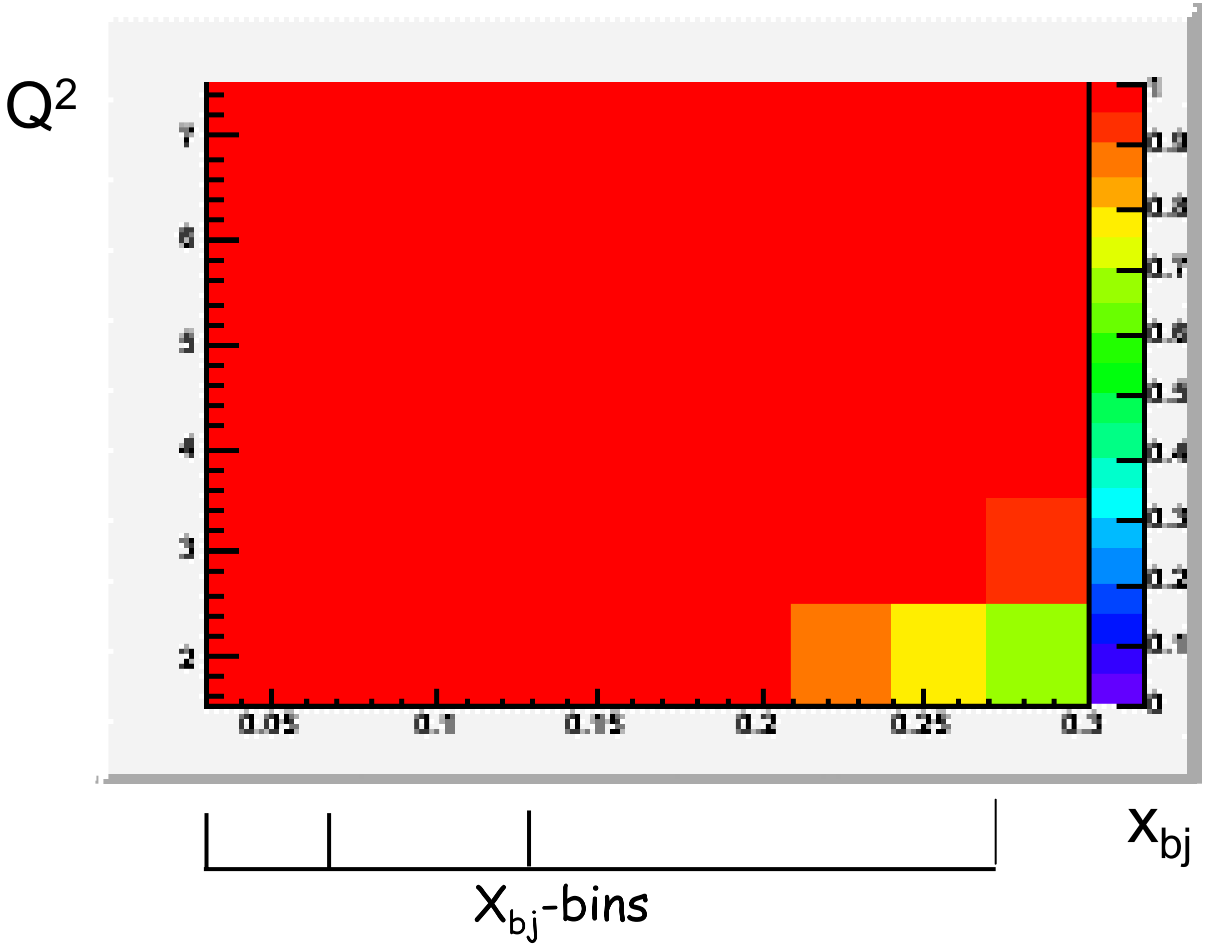


ECAL 2 (existing)

ECAL 1 (existing)

ECAL 0
To be built
Studied with the Dubna Group

Calorimeter acceptance

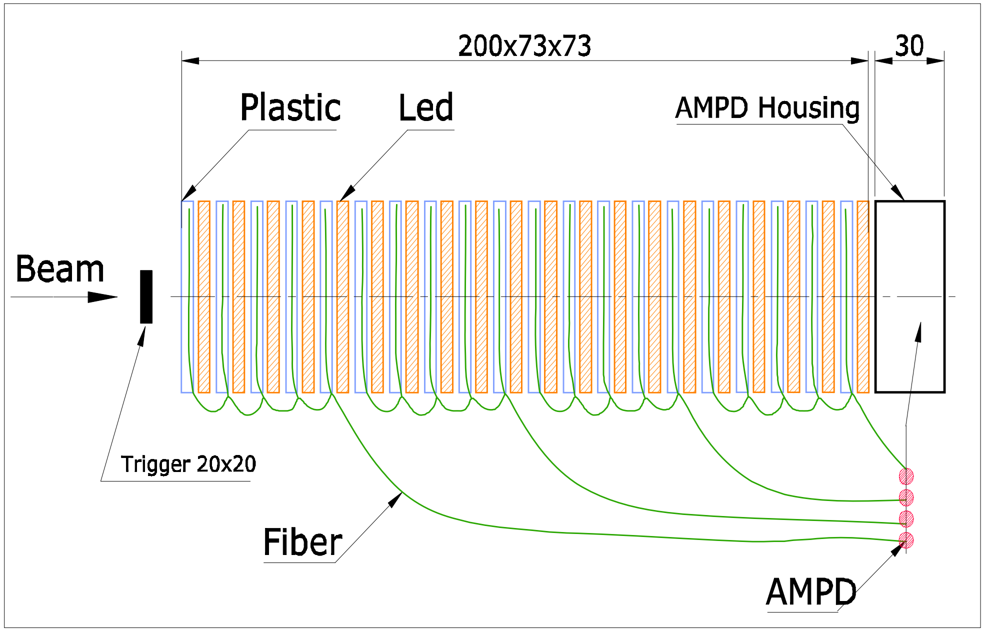


Existing Calorimeters

+ 3m x 3m ECAL0

+ 4m x 4m ECAL0

Studies for a new ECALO (Dubna,…)

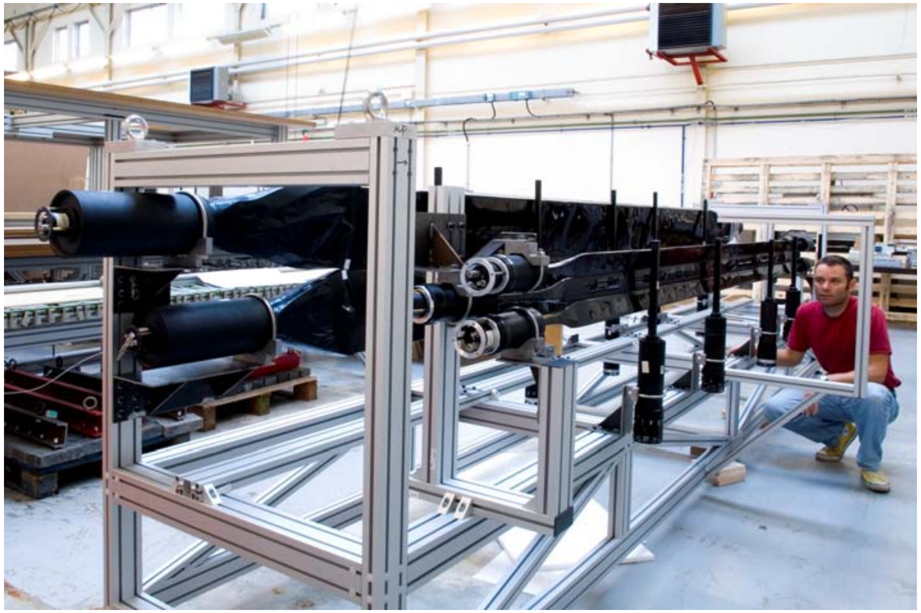


Light brought by light shifting fibers to Avalanche Micro-Pixel Photodiode
Very Challenging development for new and cheap AMPDs

- magnetic fielf
- low threshold detection
- high rate environment

New ASIC for preamplifier-shaper followed by a sampling ADC

Recoil Detector Prototype Tests (2006)



All scintillators are BC 408

A: 284cm x 6.5cm x 0.4cm

Equiped with XP20H0 (screening grid)

B: 400cm x 29cm x 5cm

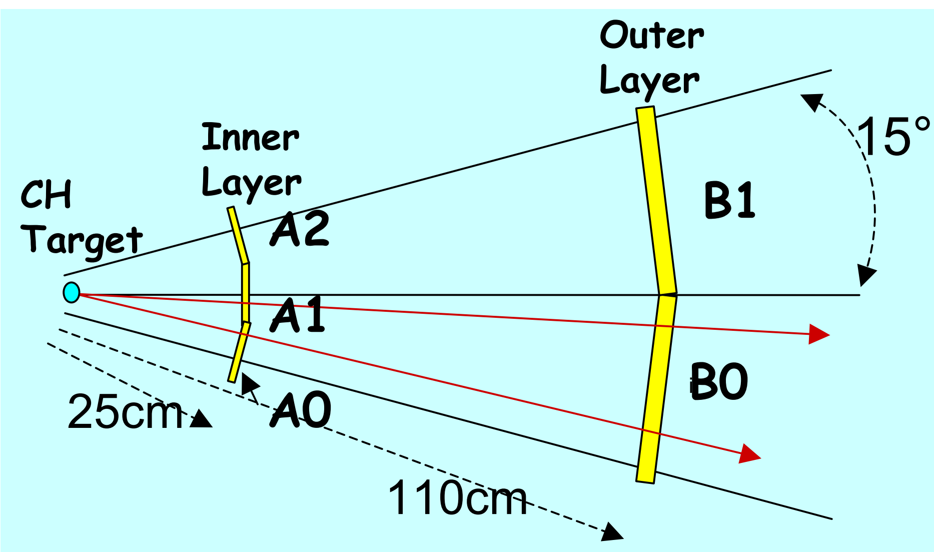
Equiped with XP4512

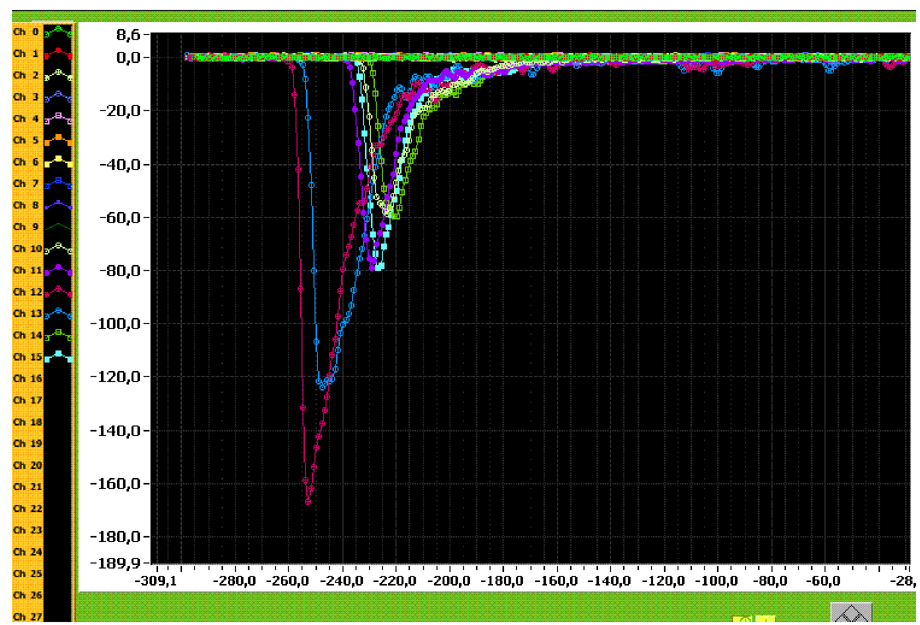
To reject the pile up

Use 1GHz sampler (300ns window)

MATACQ board

Designed by CEA-Saclay/LAL-Orsay





Requirements for the recoil detector

1) Time of Flight measurement

σ(ToF) < 300 ps → Δ P/P ~ 3 à 15 %

$t = (p-p')^2 = 2m(m-Ep')$

Δ t/t ~2 Δ P/P ⇒ 10 bins in t from t_{min} to 1 GeV^2

t is the Fourier conjugate of the impact parameter $r_\perp$
t is the key of the measurement

315 ± 12 ps have been achieved during the 2006 test
intrinsic limit due to the thin layer A

→ Further studies with the thick B layer + fast muon detector
Good solution for both proton and neutron measurement

2) Hermiticity + huge background + high counting rates

→ Detection of extra pi0 at a reasonable cost in a large volume

Conclusion & prospects

- Possible physics ouput
  - Sensitivity to total spin of partons : J_u & J_d
  - Sensitivity to spatial distribution of partons
  - Working on a variety of models (VGG, Müller, Guzey and FFS-Sch) to quantify the Physics potential of DVCS and HEMP at COMPASS

- Experimental realisation
  - Recoil Detection for proton and neutron (and extra π^0)
  - High performance and extension of the calorimetry

- Roadmap
  - Now with the transversely polarized targets: Li6D (→ 2006) and NH3 (2007)
  - 2008-9: A small RPD and a liquid H2 target will be available for the hadron program (ask for 2 shifts μ+ and μ-)
  - > 2010: A complete GPD program at COMPASS with a long RPD + liquid H2 target

  before the availability of JLab 12 GeV, FAIR, EIC…

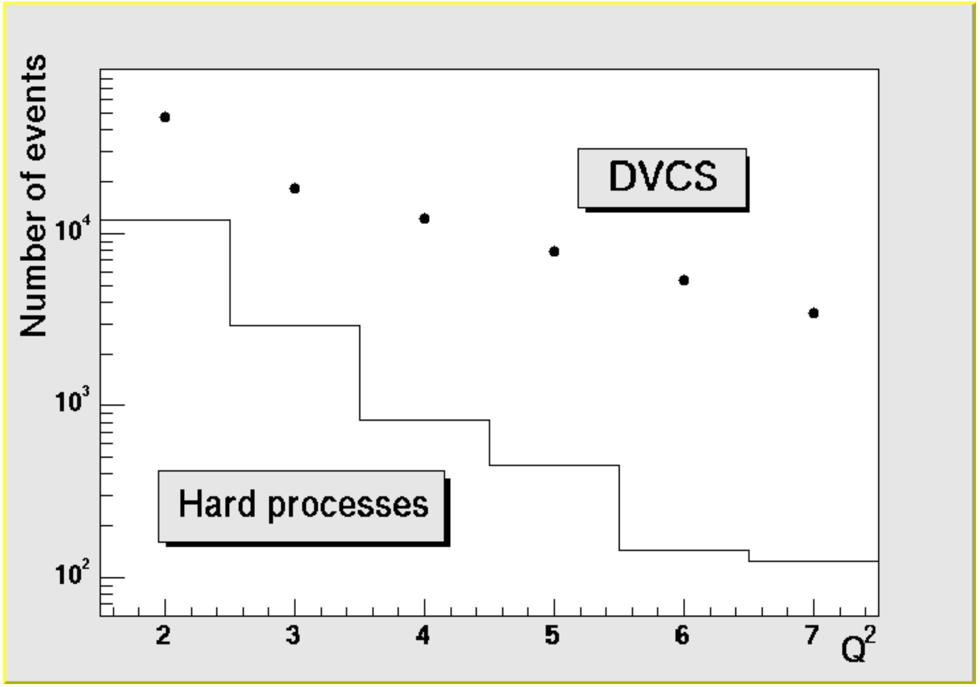
Physical Background to DVCS

Competing reactions: Deep pi0, Dissociative DVCS, DIS…

Study of DIS with Pythia 6.1 event generator

Apply DVCS-like cuts: one μ',γ,p in DVCS range

no other charged & neutral in active volumes



detector requirements:

24° coverage for neutral

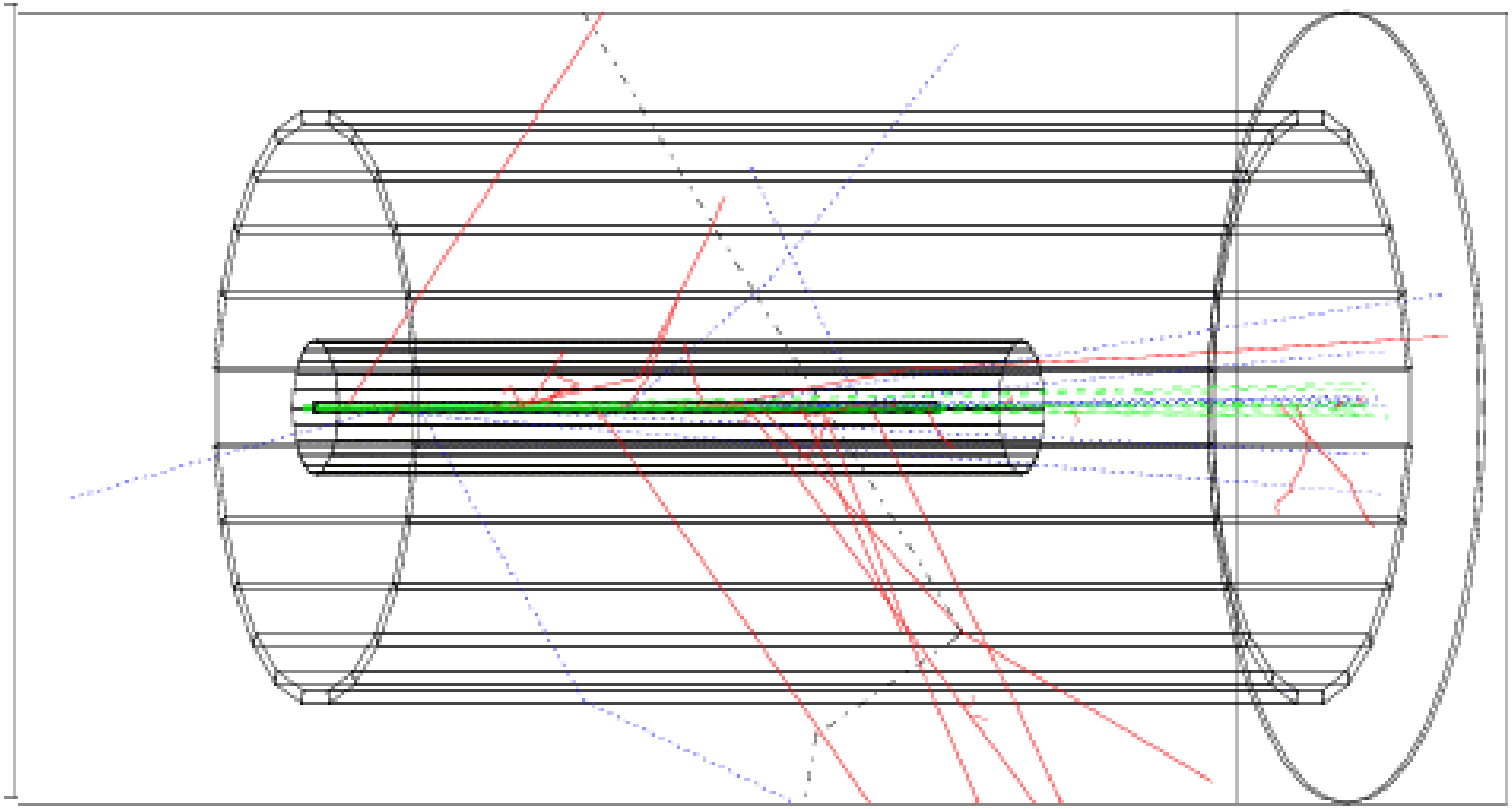
50 MeV calorimeter threshold

40° for charged particles

in this case DVCS is dominant

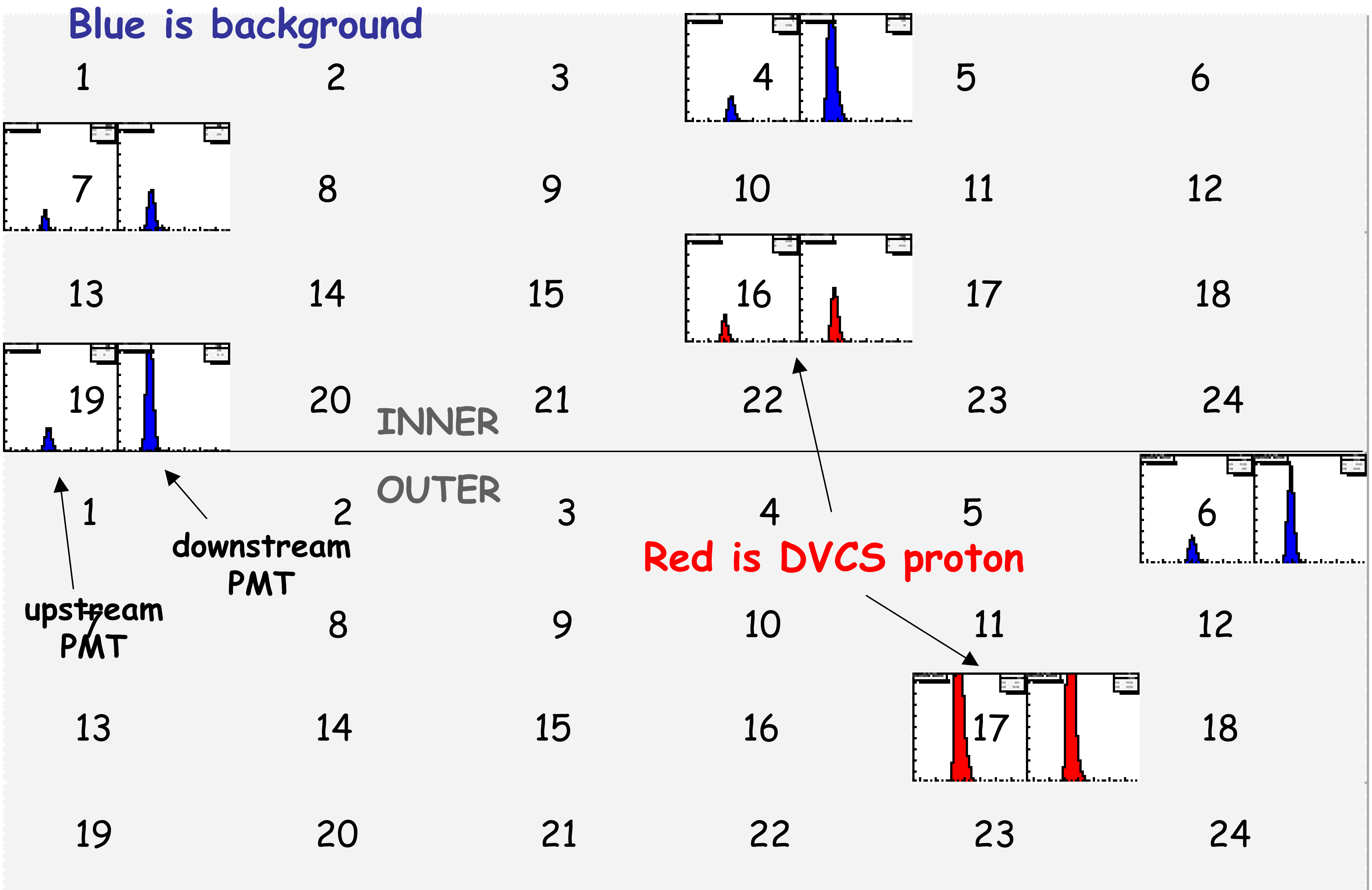
Geant Simulation of recoil detector

2 concentric barrels of 24 scintillators counters read at both sides around a 2.5m long H2 target

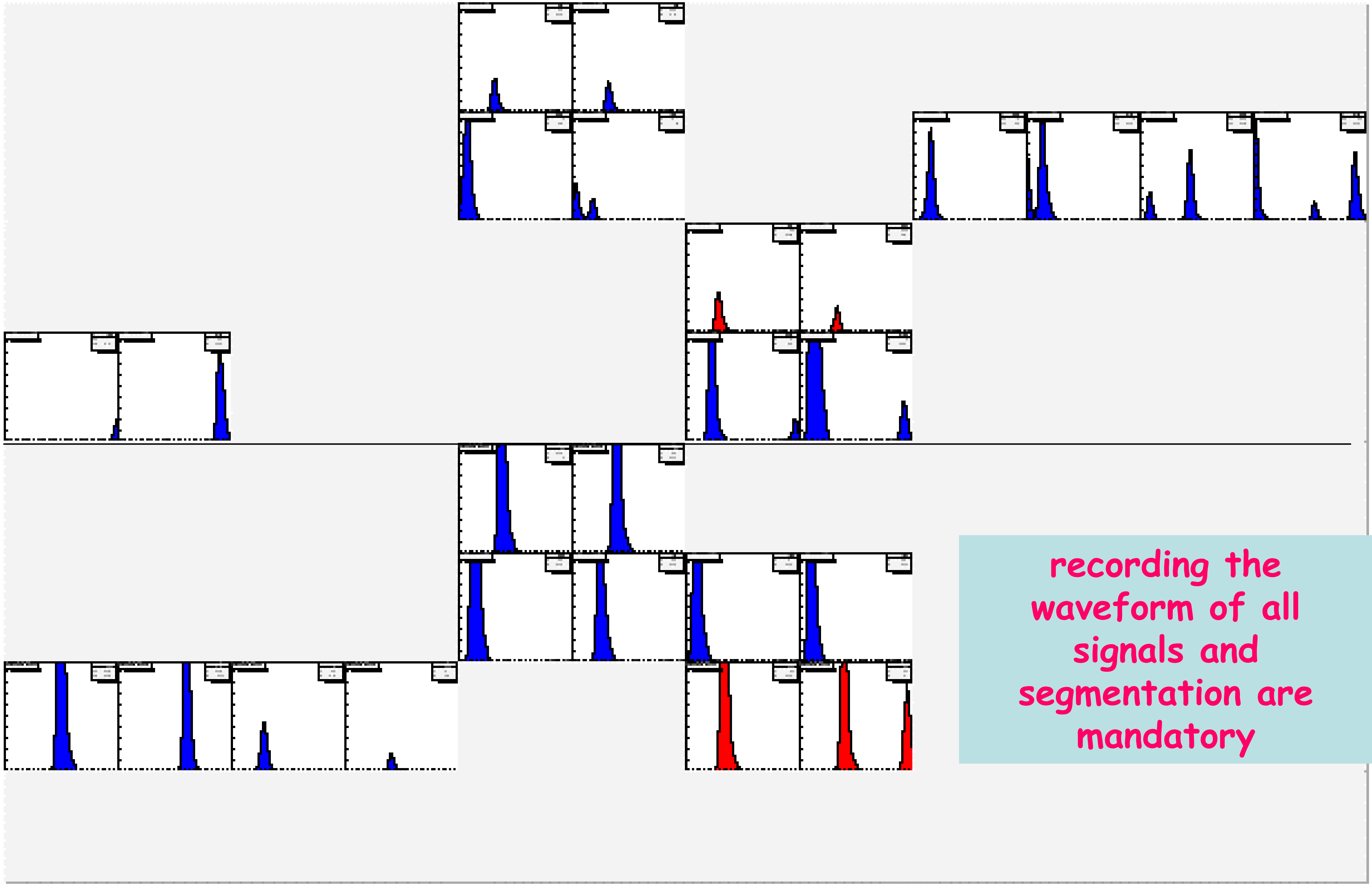


With simulation of δ-rays

PMT signals : only 1μ in the set-up



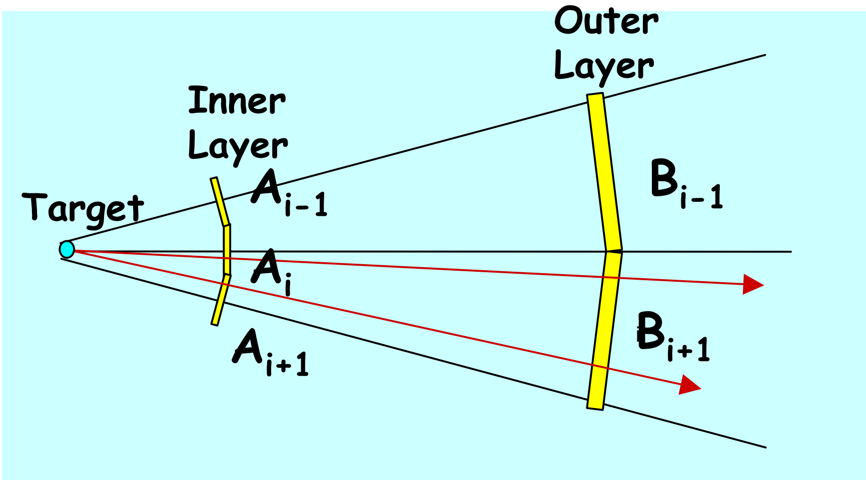
PMT signals : 2 10^8 μ/spill (5s)



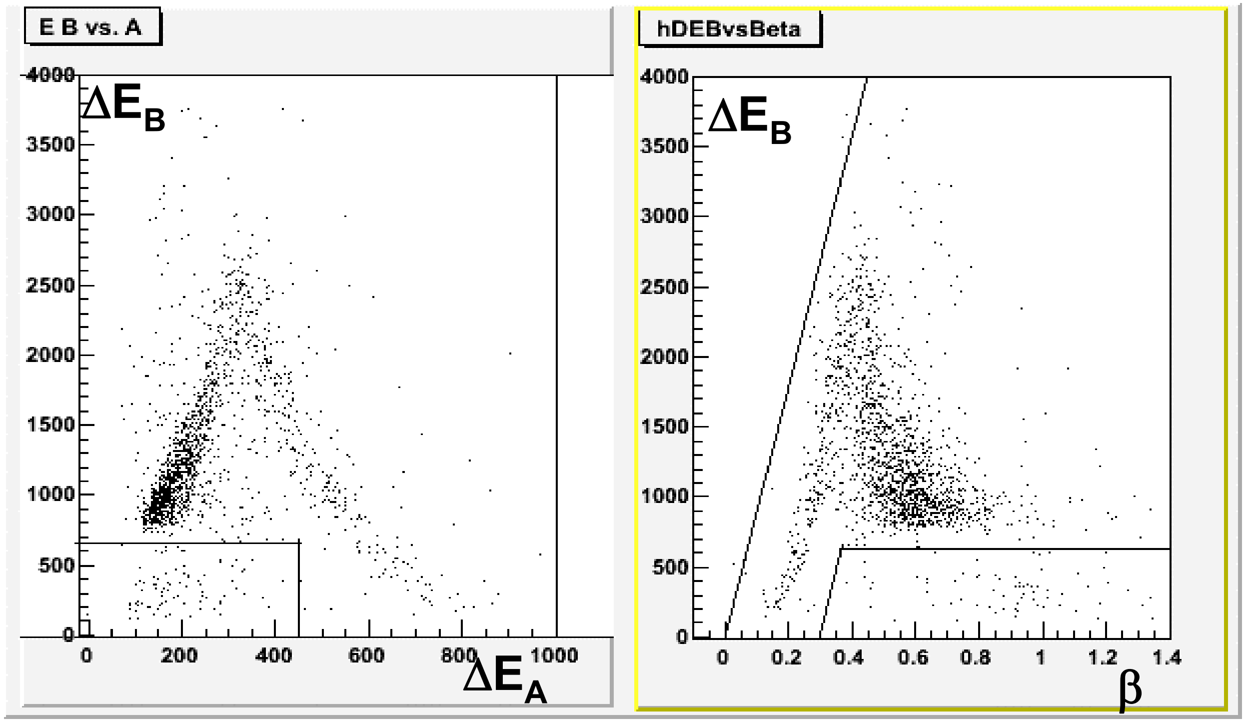
recording the waveform of all signals and segmentation are mandatory

Criteria for proton candidates

- Crude Waveform analysis
- Have points in corresponding A and B counters
- For each pair of "points"
  - Energy loss correlation
  - Energy loss vs β_{meas} correlation



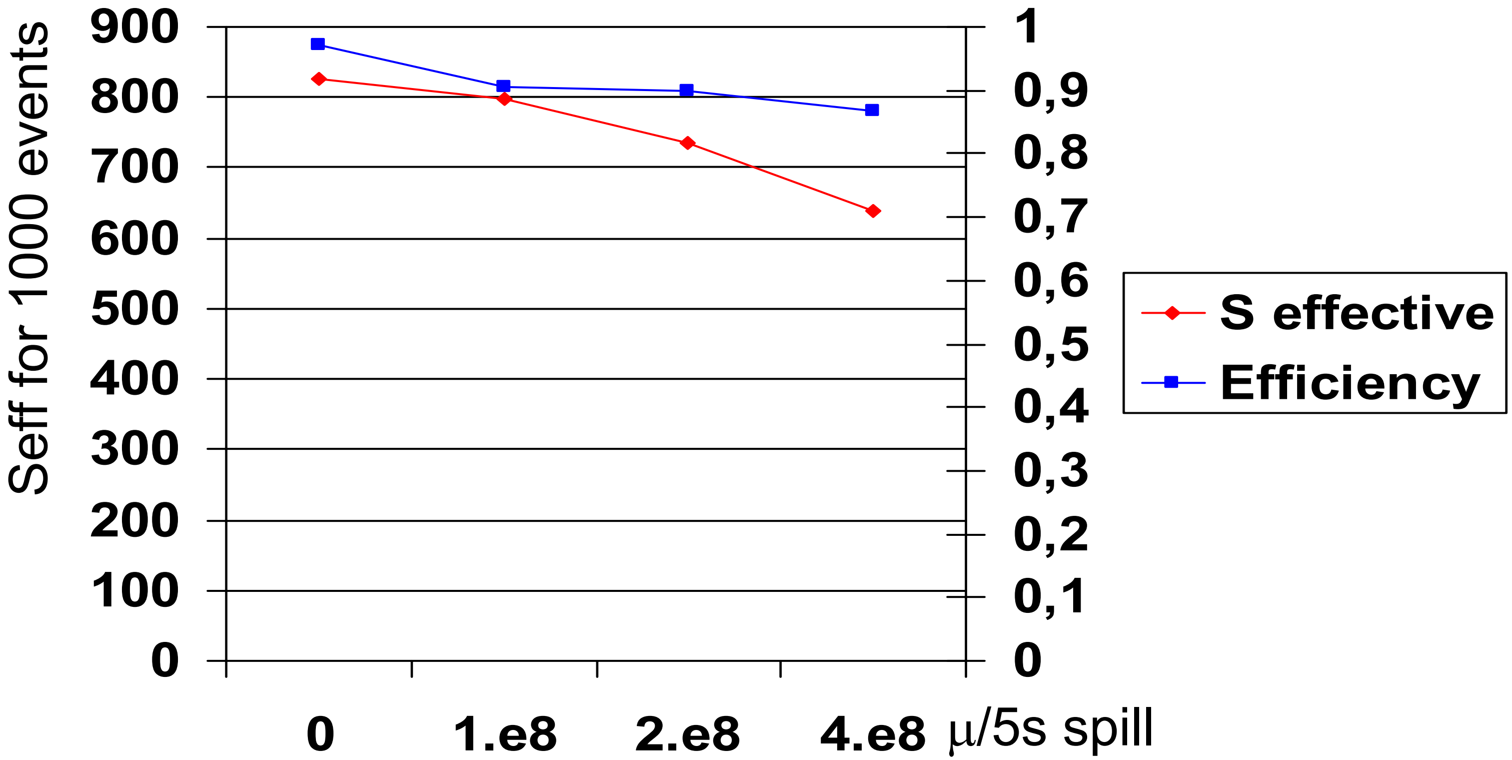
(no background in this plot – just for pedagogy)



Proton detection efficiency

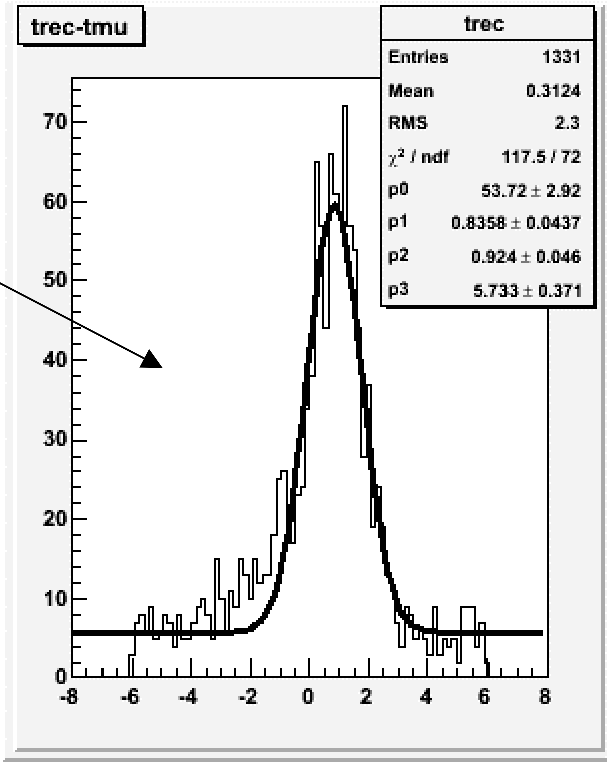
$$\text{Efficiency} = \frac{\text{number of events with proton identified}}{\text{number of “triggers”}}$$

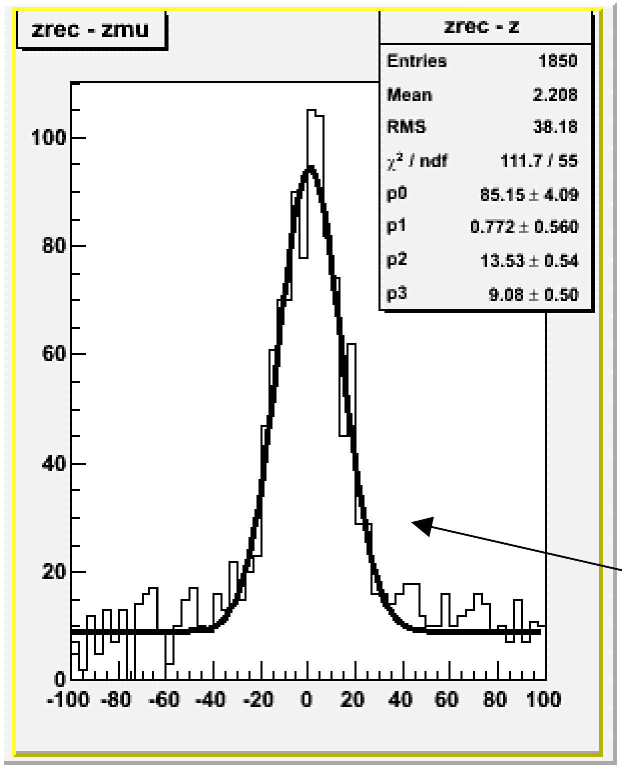
trigger = one event with at least one good combination of A and B with hits
identified proton = proton of good A and B combination, good energy correlation, and good timing with the muon



Coincidence with the scattered muon

Use reconstructed muon vertex time to constraint proton candidates

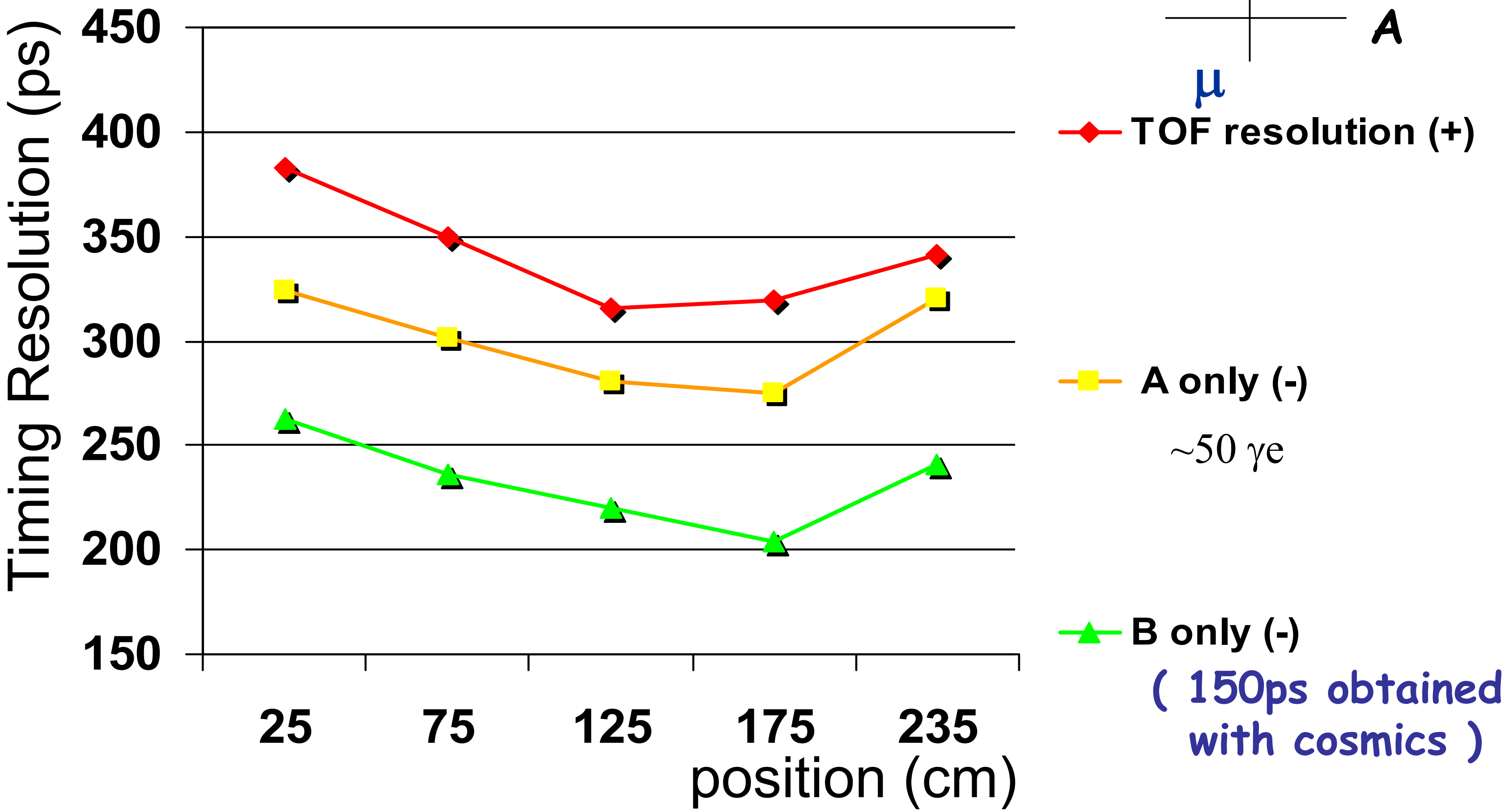


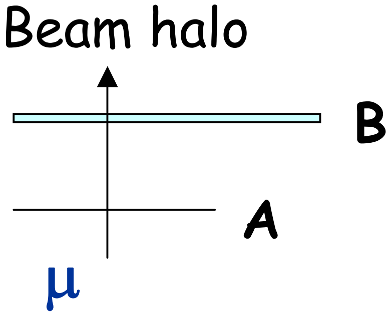


Use vertex position to evaluate the effective signal

$$S_{eff} = \frac{S}{1+B/S}$$

Timing resolution

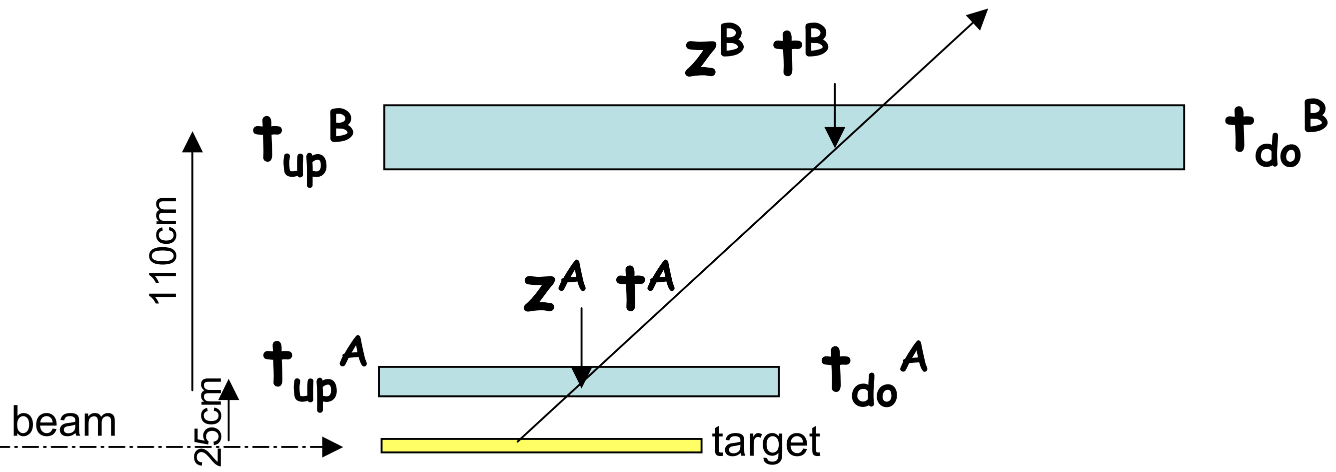




Reach 315 ps at the middle and 380 ps in the worst case at the edge

Performed with 160 GeV muon (0.8*MIP in A)
Expect better resolution for slow protons

Time of Flight measurement



$$z^B = (t_{up}^B - t_{down}^B)\, V^B/2 + L^B/2 + Cor_{up}^{tw} - Cor_{down}^{tw} + Off_{up} - Off_{down}$$

$$t^B = (t_{up}^B + t_{down}^B)/2 \quad + \underbrace{L^B/2V^B + Cor_{up}^{tw} + Cor_{down}^{tw} + Off_{up} + Off_{down}}$$

To be precisely determined (tw= time walk correction)

$$ToF = (t_{up}^B + t_{down}^B)/2 - (t_{up}^A + t_{down}^A)/2 + \ldots$$

Obtained results with the prototype in 2006 with the MATACQ

at CERN (muon halo)

$\sigma(t_{up}^{B} - t_{down}^{B}) = 200 \pm 6$ ps

$\sigma(t_{up}^{A} - t_{down}^{A}) = 270 \pm 6$ ps

at Saclay (cosmics) with external time references

$\sigma(t_{up}^{B} + t_{down}^{B}) = 145$ ps ± 10 ps

σToF= $\sigma\,[\,(t_{up}^{B} + t_{down}^{B}) - (t_{up}^{A} + t_{down}^{A})]$

$= 315 \pm 12$ ps

to be still improved but intrinsic limit due to the thin layer A