Deeply Virtual Compton Scattering and Generalized Parton Distributions

I. Motivations

II. Deeply Virtual Compton Scattering : COMPASS results

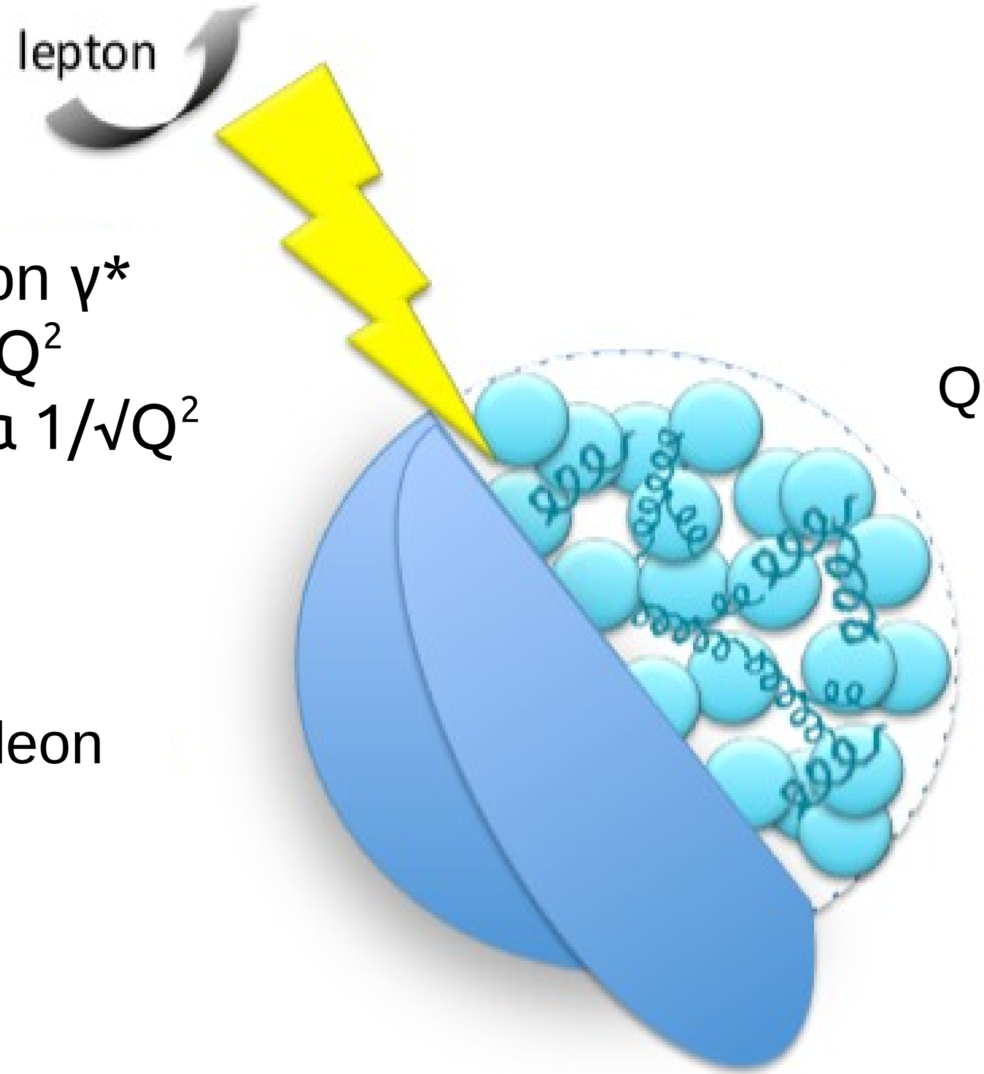
III. Timelike Compton Scattering : phenomenology and experimental perspectives at JLab at 12 GeV

IV. Extraction of the Generalized Parton Distributions

V. Future experiments: Timelike Compton Scattering and Double Deeply Virtual Compton Scattering

Marie Boër, IPN Orsay, France Seminar at LANL, August 18, 2015

I. Probe the nucleon with a virtual photon



virtual photon γ^*
virtuality = Q^2
resolution α $1/\sqrt{Q^2}$

$Q^2 \gg M^2$: partonic structure

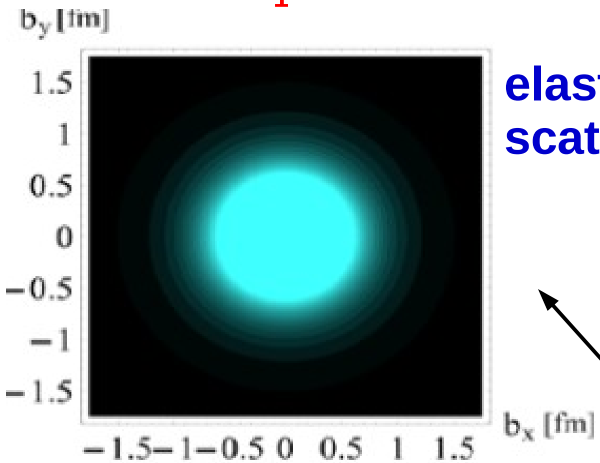
quarks, antiquarks, gluons

$Q^2 \ll M^2$: nucleon

pointlike probe
momentum and/or position distributions of partons in the nucleon

"3D" imaging : Generalized Parton Distributions (GPDs)

Form factors $F_1(t)$ → transverse charge densities



elastic scattering

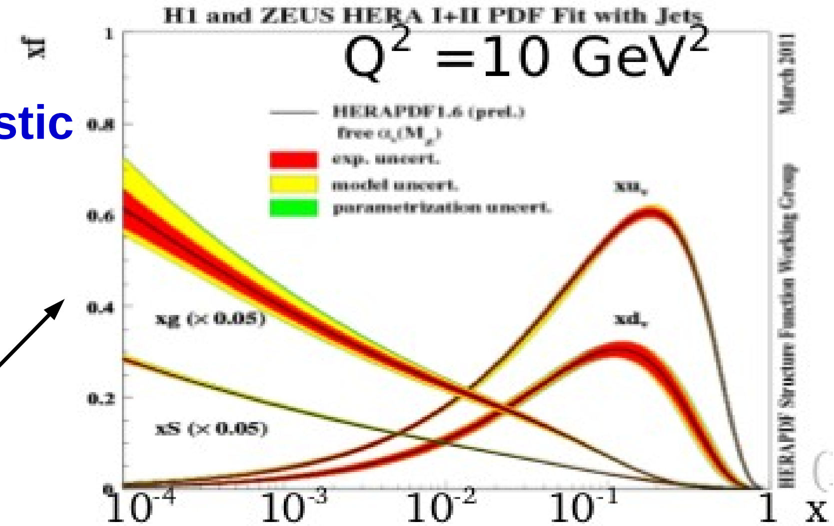
$\int dx$

inclusive deep inelastic scattering

$t = 0$

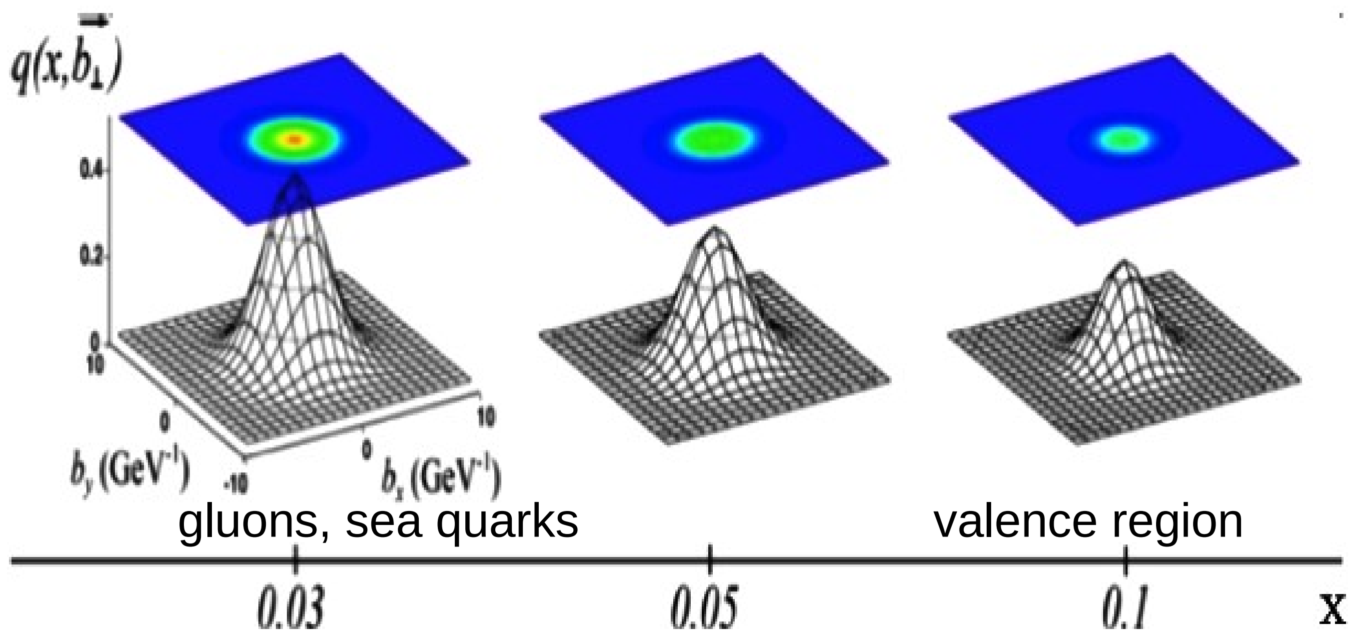
hard exclusive processes

Parton Distributions q(x)



Generalized Parton Distributions

Correlation between longitudinal momentum fraction x and transverse charge densities $b_{x,y}$

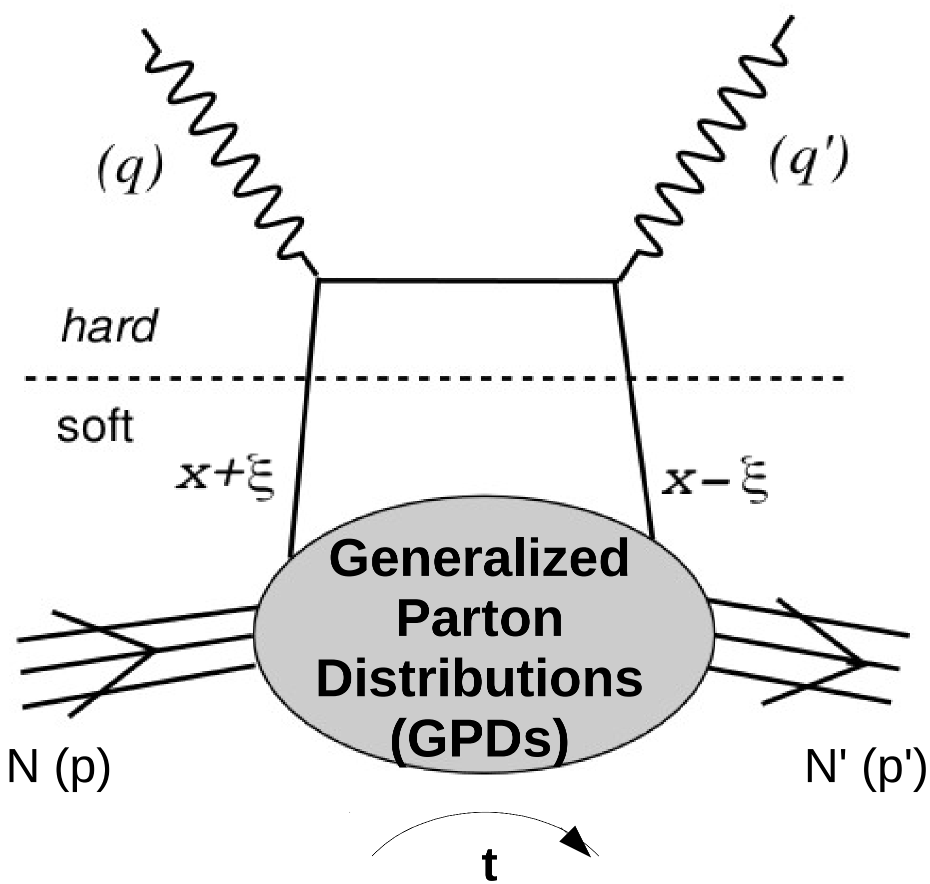


Nucleon tomography :
FT of GPD H (x, 0, $|t|=\Delta_\perp^2$)

x : longitudinal momentum fraction
t : momentum transfer squared

Deeply Virtual Compton Scattering processes

γ (*) N → γ (*) N'



Different exclusive processes involving photons, same GPDs :

- outgoing photon is real : spacelike Deeply Virtual Compton Scattering (DVCS) e N → e' γ N'

- incoming photon is real : Timelike Compton Scattering (TCS) TCS: γ N → e^+e^- N'

- both photons are virtual : Double Deeply Virtual Compton Scattering (DDVCS) e N → e' e^+e^- N'

(e stands for any lepton)

x : average longitudinal momentum fraction of the struck quark
ξ : longitudinal momentum transfer
t : momentum transfer squared
$Q^2 = -q^2$; $Q'^2 = +q^2$: hard scale

Generalized Parton Distributions (GPDs)

Ji decomposition of the soft part of the amplitudes

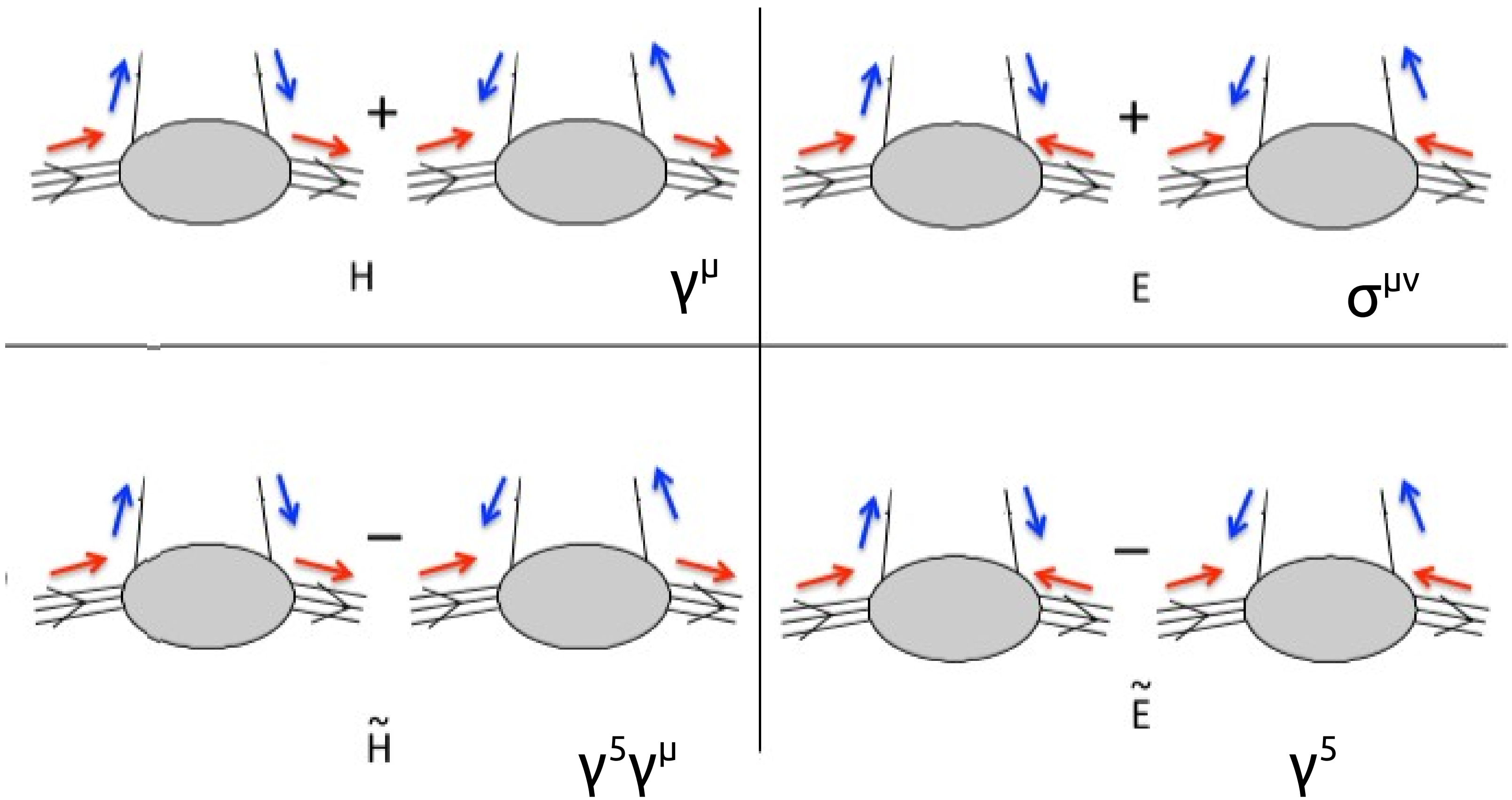
leading twist amplitudes, massless quarks, in DVCS, TCS and DDVCS off the nucleon : spin 1/2× spin 1/2

Chiral-even nucleon GPDs :

without nucleon spin flip | with nucleon spin flip

unpolarized GPDs

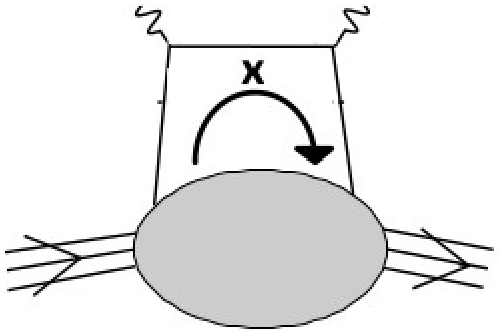
polarized GPDs



Similar decomposition for gluons GPDs

Accessing GPDs with Compton Form Factors

ξ, t = measurable
x = loop
x±ξ = propagator



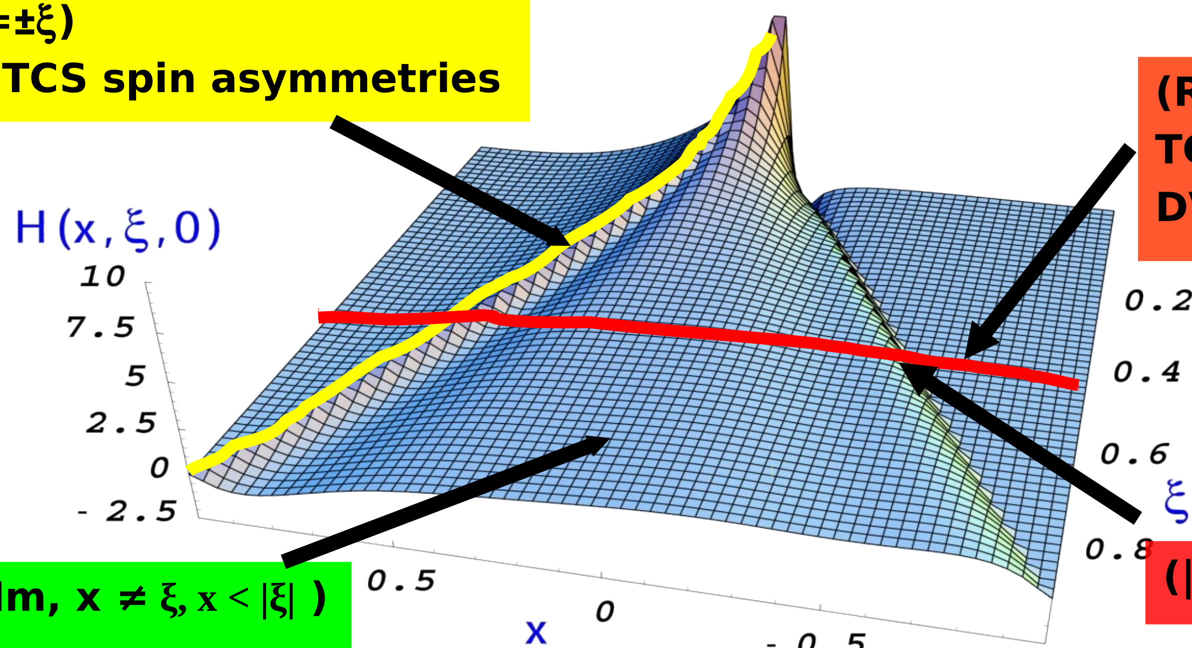
$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x\pm\xi+i\varepsilon}\,dx + \ldots \sim \underbrace{P\int_{-1}^{+1}\frac{H(x,\xi,t)}{x\pm\xi}\,dx}_{\mathrm{Re}\,(\mathcal{H})} \underbrace{-\, i\pi H(\pm\xi,\xi,t)}_{\mathrm{Im}\,(\mathcal{H})} + \ldots$$

Compton Form Factor (CFF)

CFF are extracted from different observables, at different kinematical points:

(Im, x=±ξ)
DVCS, TCS spin asymmetries

(Re) integrate GPD over x
TCS: spin assymetries
DVCS: charge asymmetry

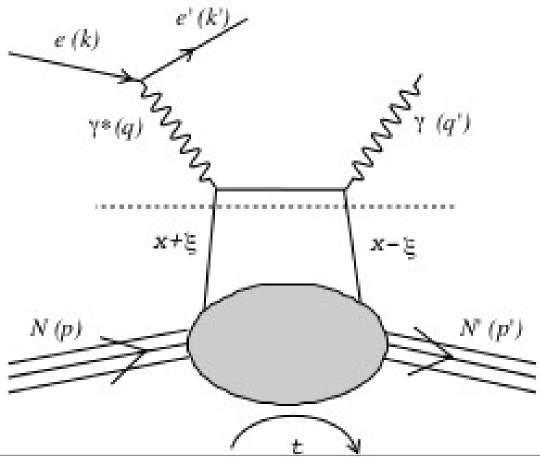


(|Im|^2+|Re|^2) : cross sections

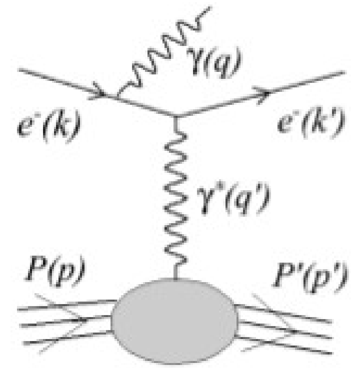
DDVCS : (Im, x ≠ ξ, x < |ξ|)
Deconvolution of x and ξ

Compton processes and interference with Bethe-Heitler

DVCS + BH
eN → e'γN'=

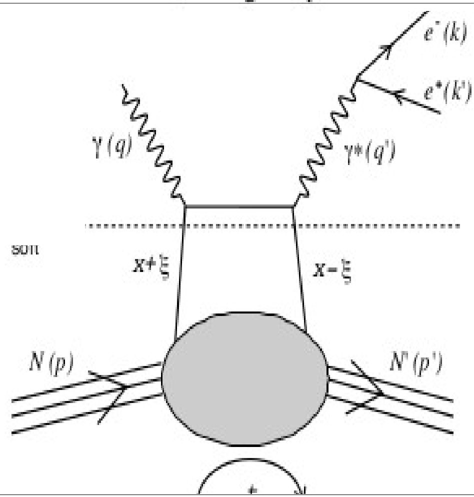


+

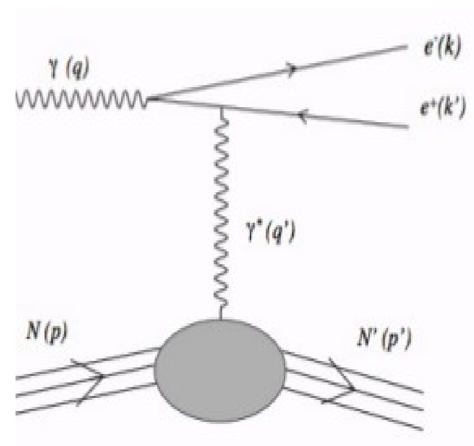


Bethe-Heitler (BH)
- same final state
- sensitive to FFs
- deconvolution: angular analysis of cross sections, spin / charge asymmetries...

TCS + BH
γN → e⁺e⁻N=



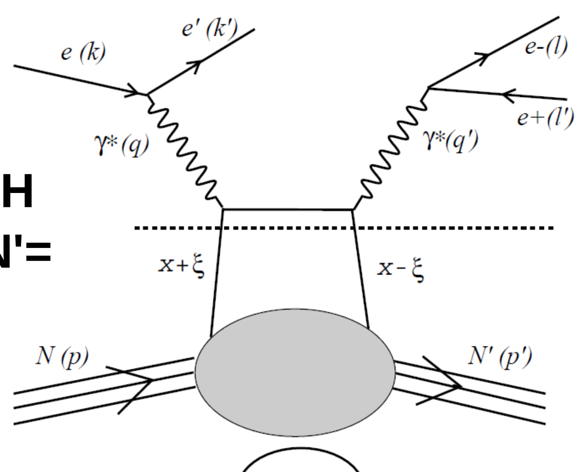
+

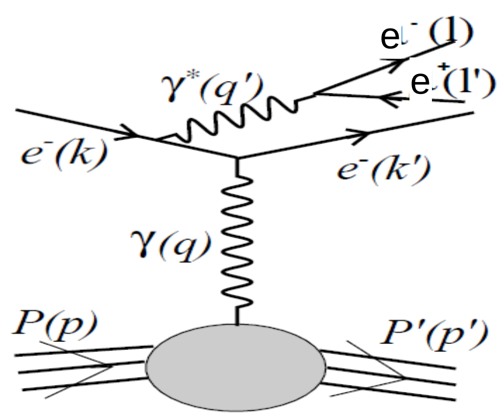


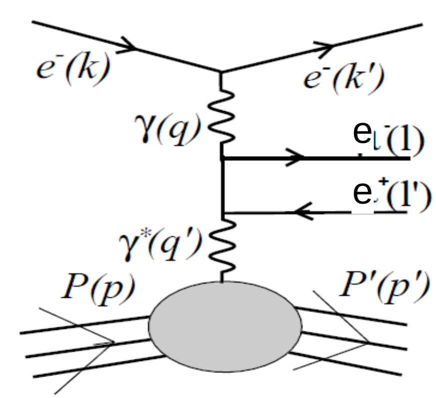
(leading order, leading twist)

(+ crossed diagrams)

DDVCS + BH
eN → e'e⁺e⁻N'=



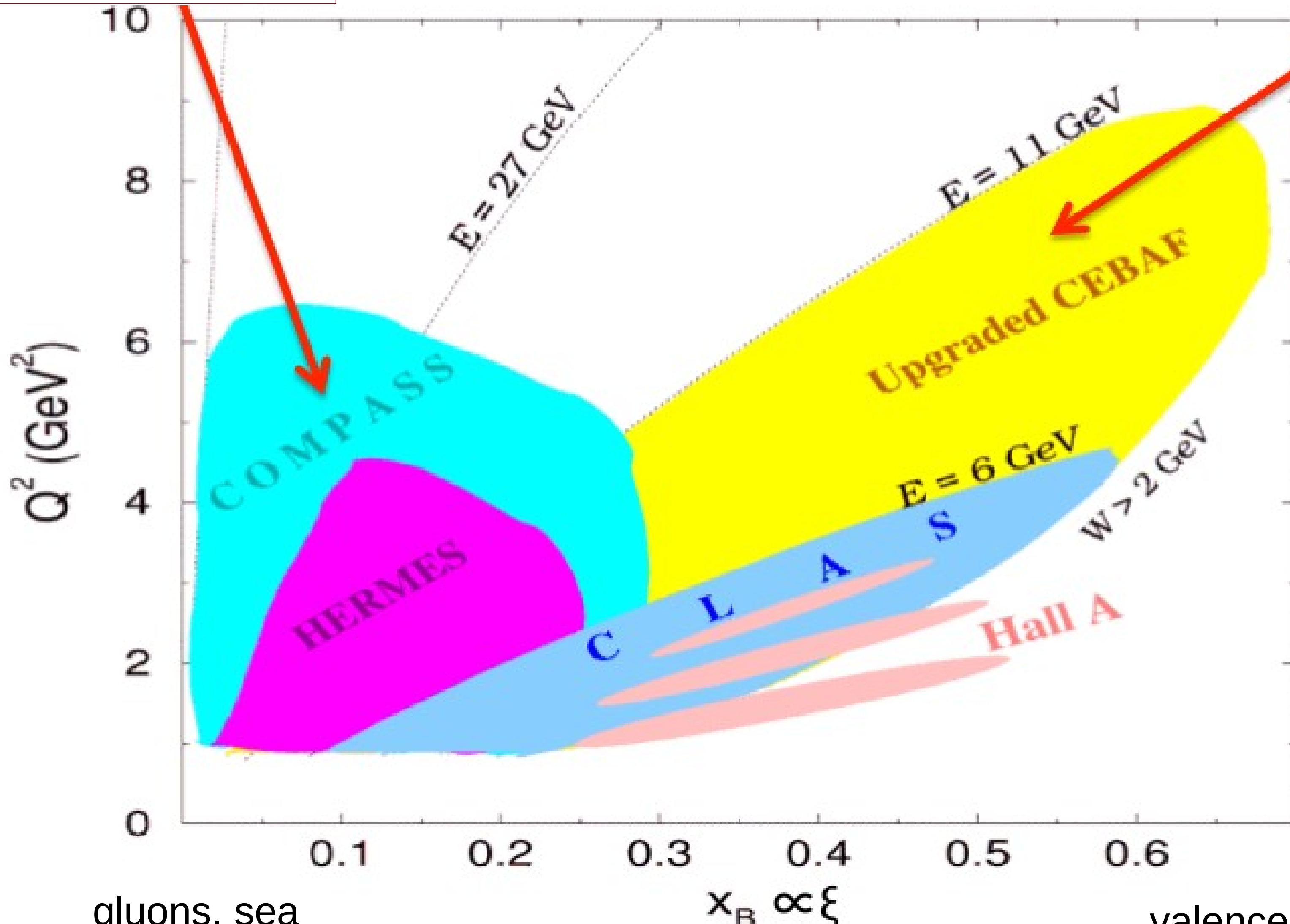




Fixed target experiments

II. DVCS at COMPASS
(test run data analysis)

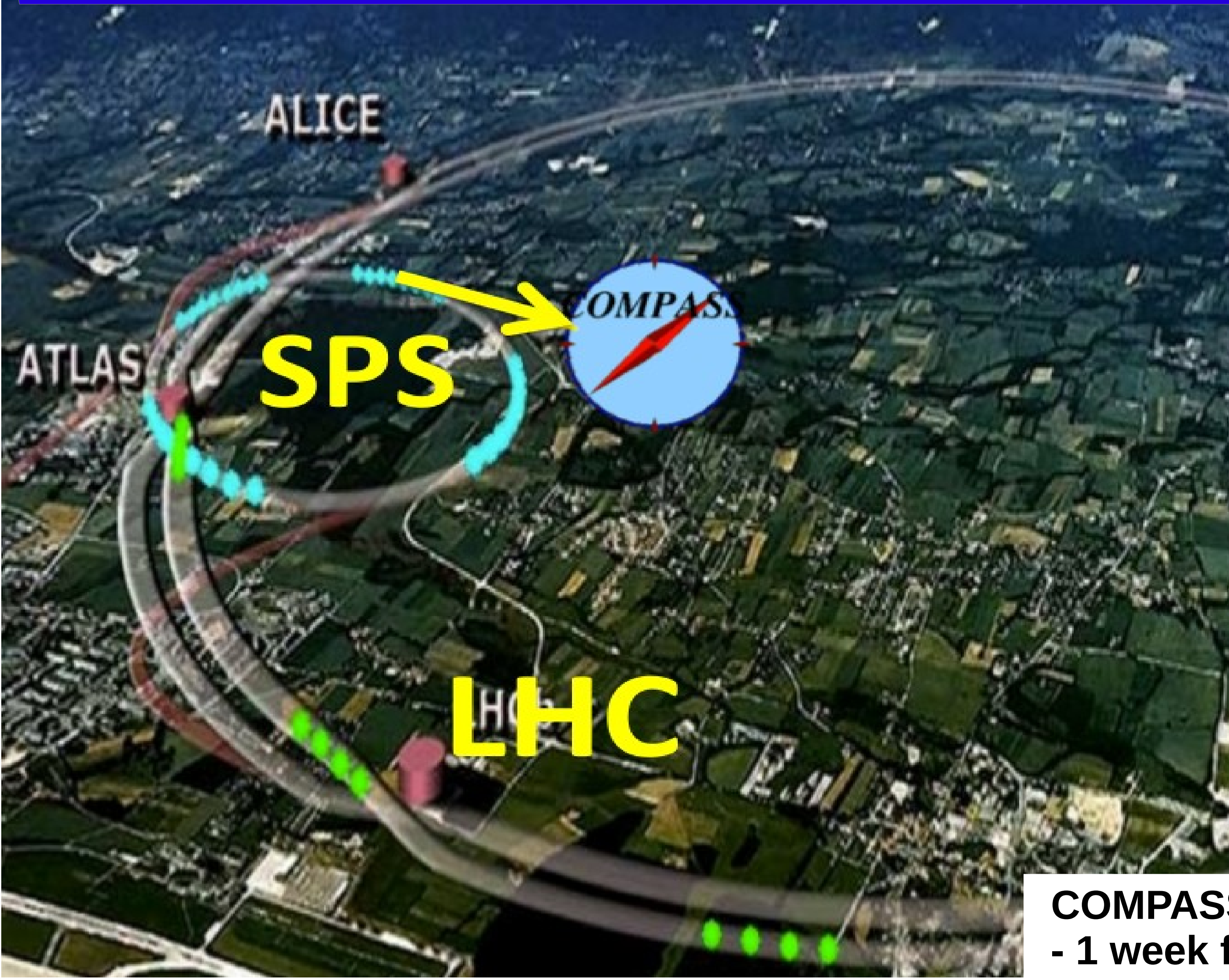
III - V. TCS and DDVCS
at JLab@12 GeV
(phenomenology and proposals)



gluons, sea

valence region

COMPASS at CERN, SPS



members: 220
institutes: 24
countries: 13
first run: 2002
muon beam:
160 – 190 GeV

(M2 beam line) proton extraction
→ secondary pion beam
→ polarized muon beam (80%)

COMPASS with muon beam in 2009 :
- 1 week for DVCS test run
- 160 GeV muons (μ^+ and μ^-)
- 10 second beam / 45 sec. (spills)

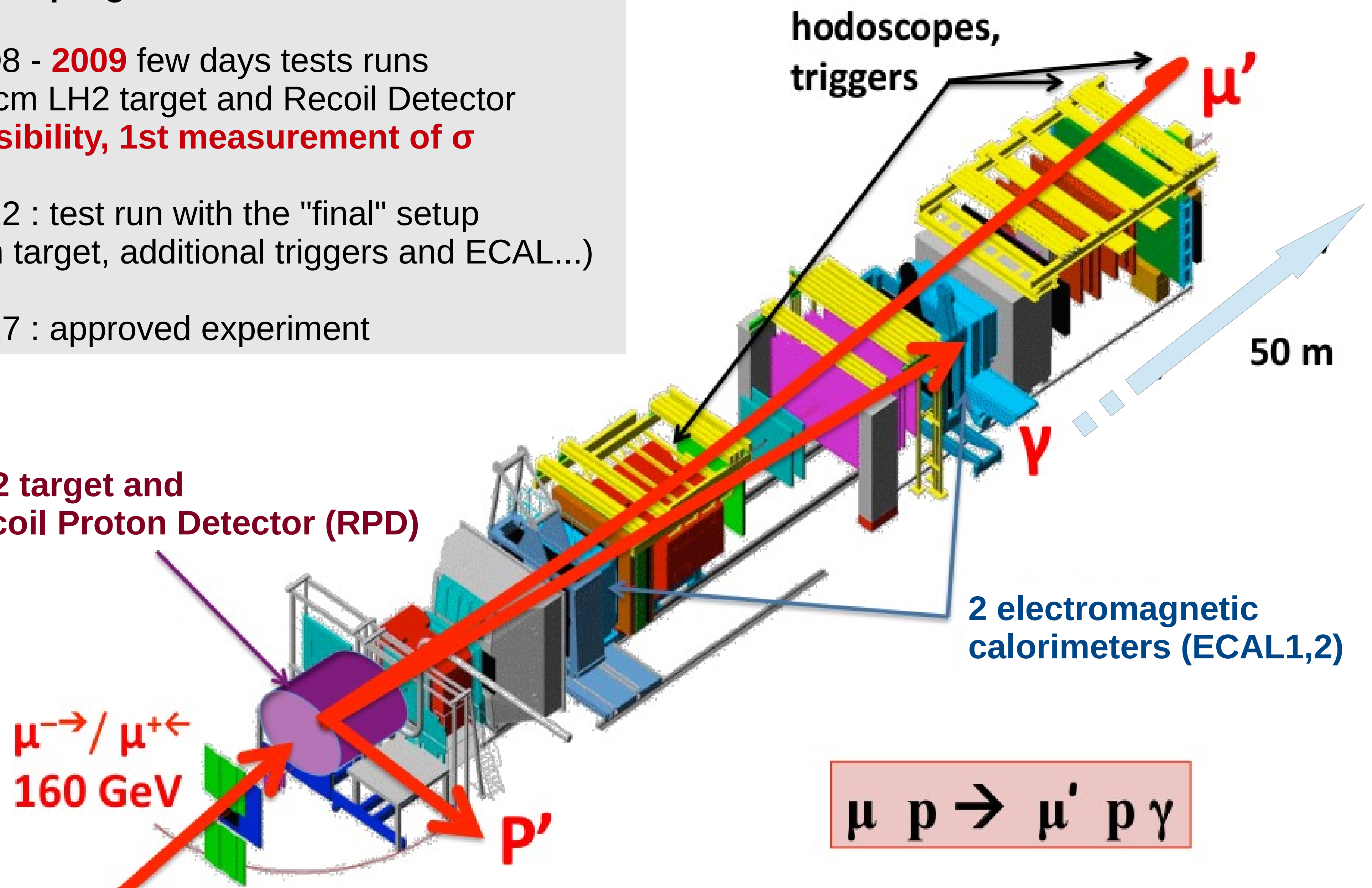
remark : flux μ+/μ- ~ 2.4

DVCS programs :

2008 - **2009** few days tests runs
40 cm LH2 target and Recoil Detector
feasibility, 1st measurement of σ

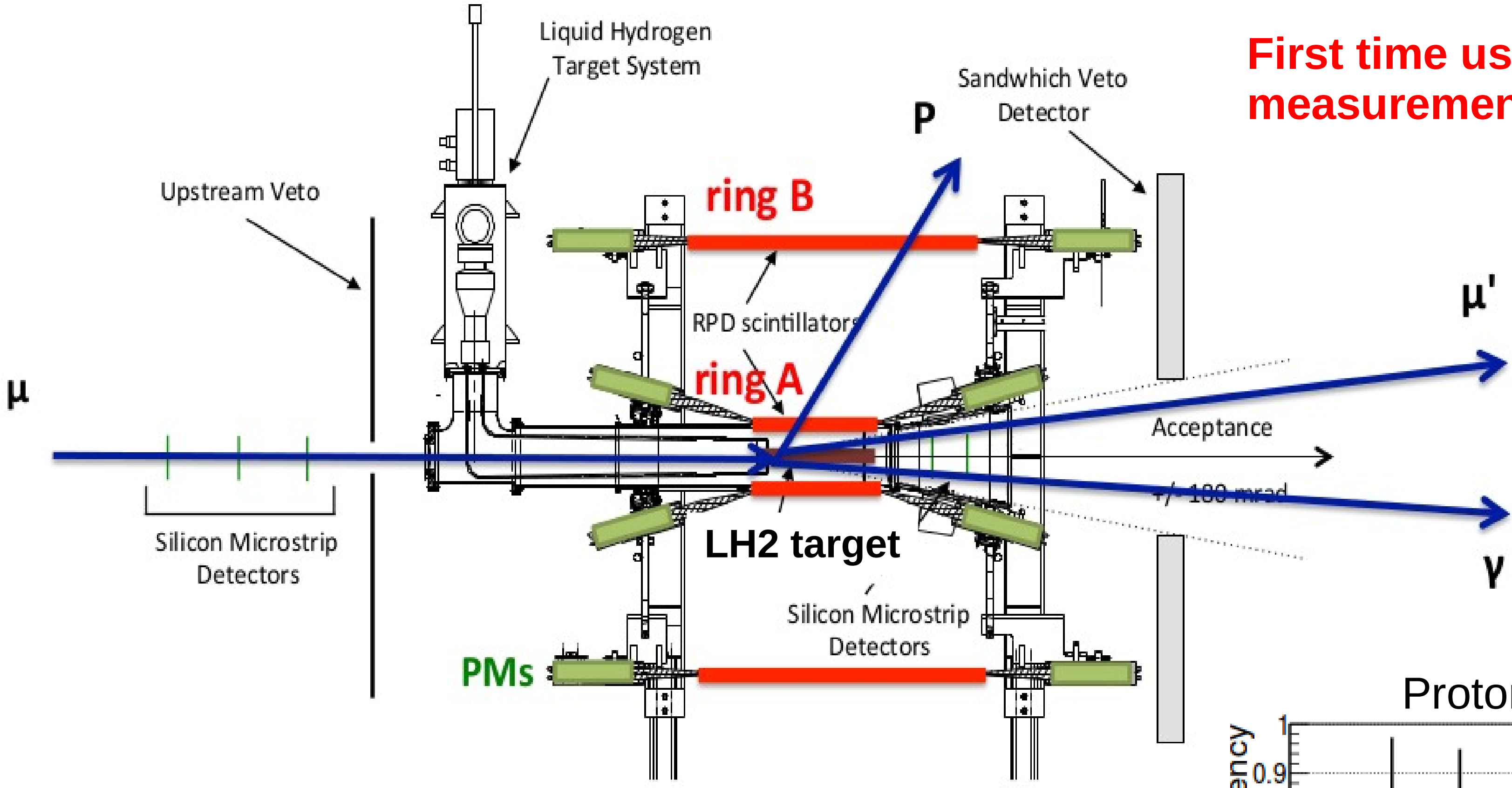
2012 : test run with the "final" setup
(2m target, additional triggers and ECAL...)

2017 : approved experiment

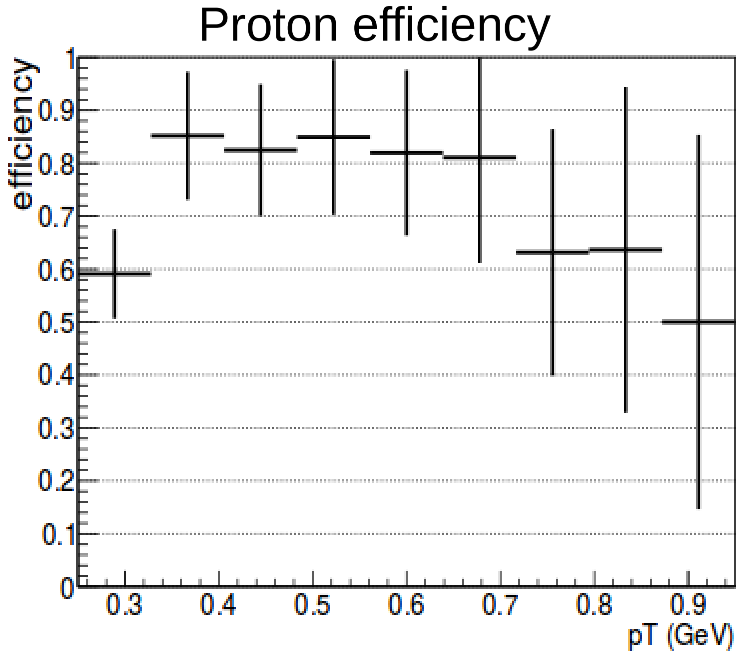


$\mu\ p \rightarrow \mu'\ p\ \gamma$

Recoil Proton Detector (RPD) and target area



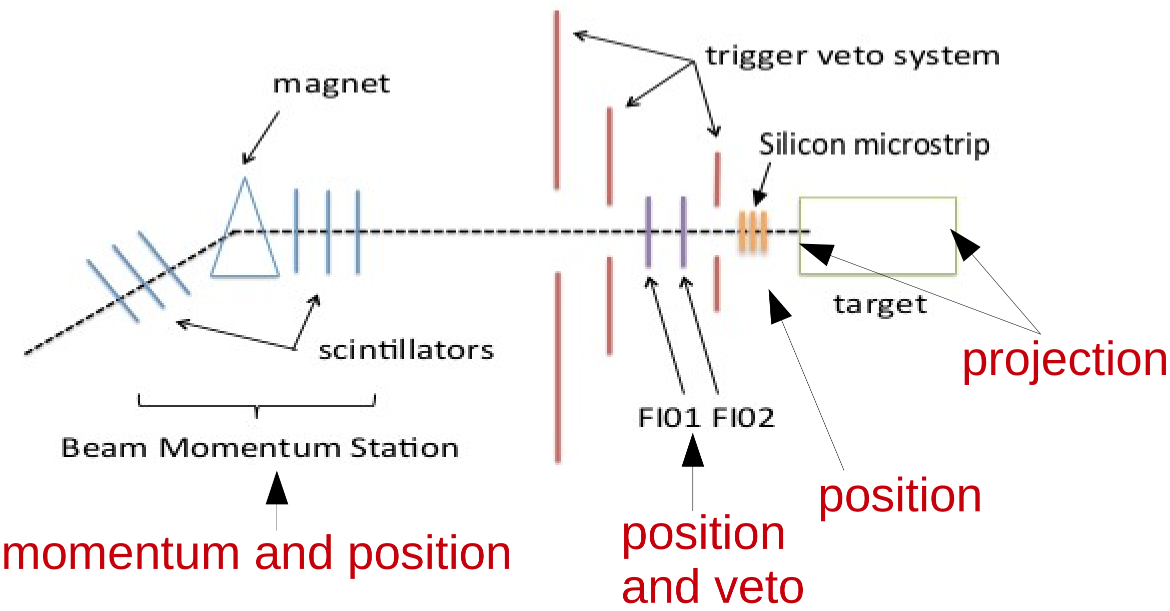
First time used for exclusive measurement at COMPASS

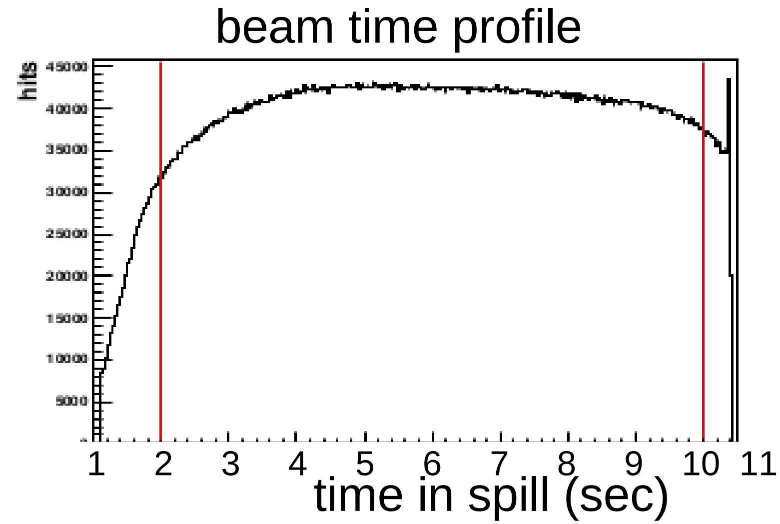


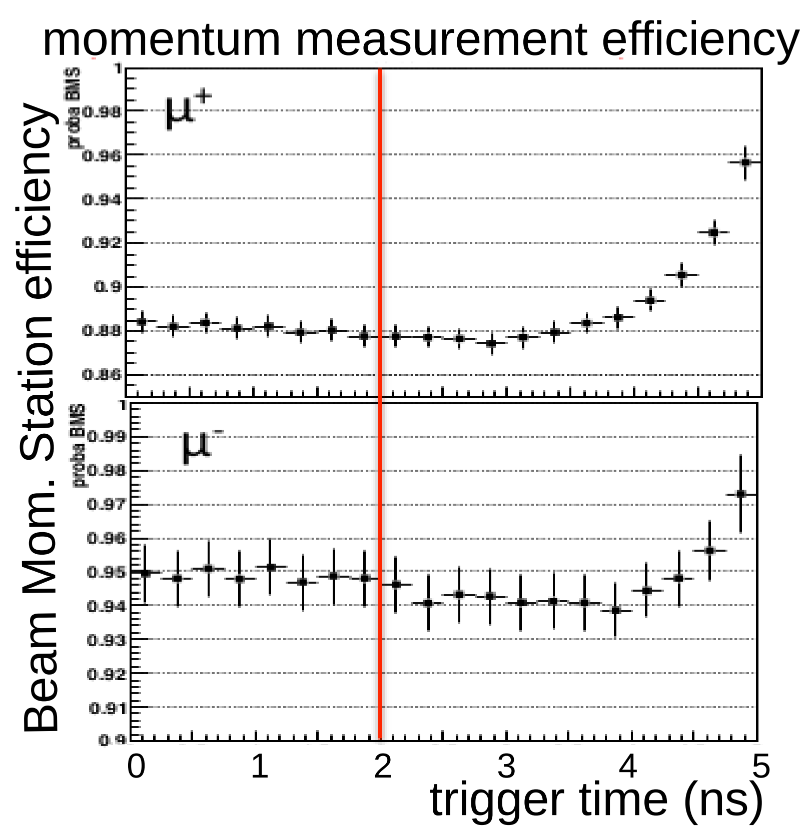
Two time of flight measurements :

- momentum: vertex, ring A, ring B in coincidence
- positions: PMs at both sides

- **muons are counted one by one**
- **requires a random trigger and a tracking system**
- **10 seconds beam / 45 seconds (spills)**







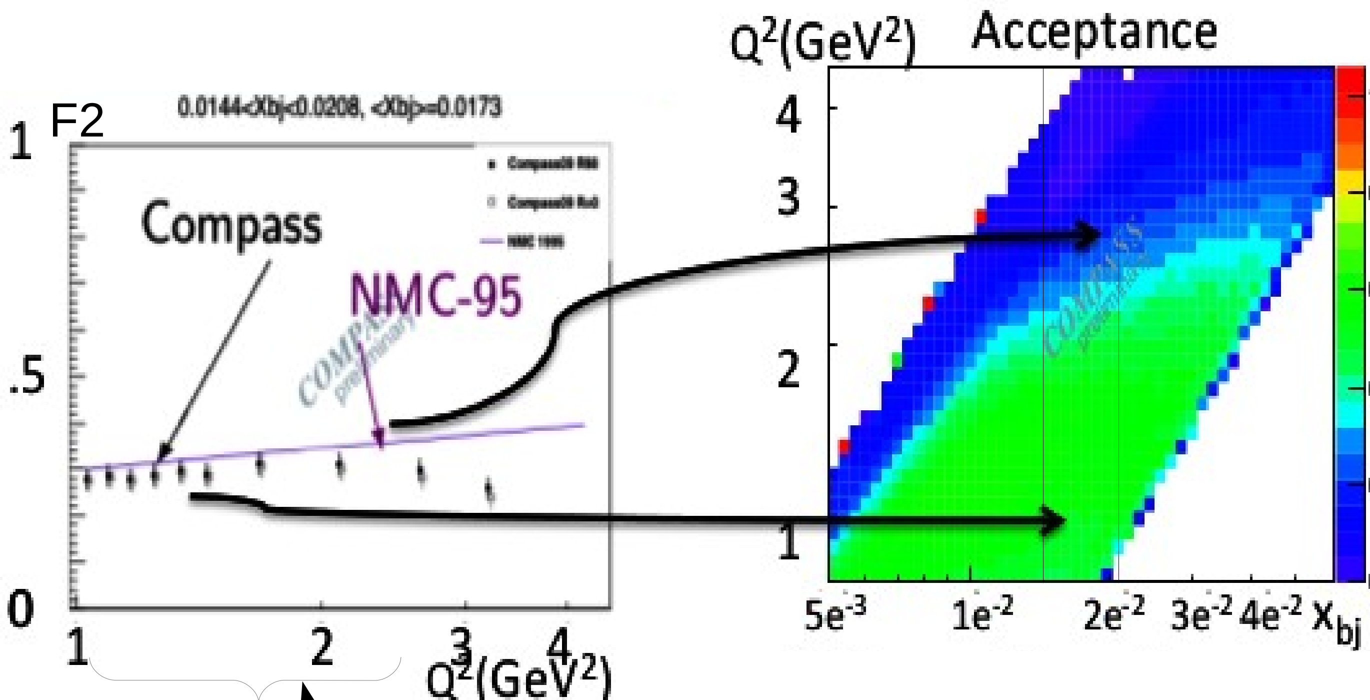
Integrated luminosity result :
$L(\mu^+)=3.60\ pb^{-1}$ (4%) ; $L(\mu^-)=0.114\ pb^{-1}$ (4%)

main systematics :
- target density (3%)
- pile-up (not included)
- efficiencies, timing cuts, projections
- trigger recovrement and coincidences
- dead time

$F_2\,(x_{bj}, Q^2)$ measurement

- validation of luminosity measurement
- include/check efficiencies and dead time in COMPASS Geant Monte-Carlo
- studies of systematics and corrections for scattered μ

→ 10 % agreement with NMC at low Q^2 : within statistical errors in 2009
→ discrepancies at high Q^2 : requires full spectrometer efficiencies measurement



DVCS measurement in 2009

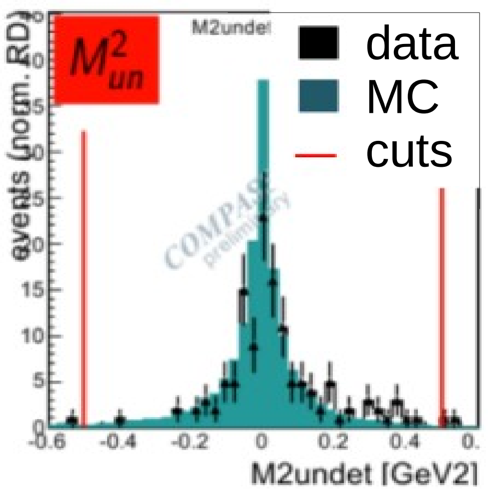
main systematics and corrections

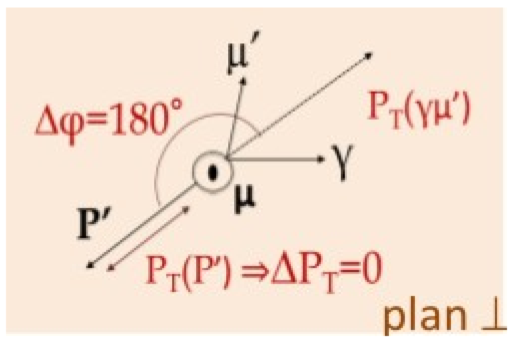
	correction (%)	syst %
pile-up	94 (μ+), 97 (μ-)	1
muon tracking	97	3
radiative corr.	$f(x_{bj}, Q^2)$	2
trigger efficiency	96	2
trigger (coincidences)	98	1

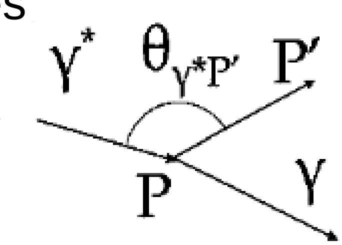
→ **first measurement of cross section in COMPASS normalized to luminosity**
→ **range of validity in (x_{bj}, Q^2) for DVCS studies**

DVCS analysis method

- **4 particles detected** : μ and μ' (hodoscopes), γ (2 ECAL), P' (recoil detector)
- **Kinematic**: $1<Q^2<4.5$ GeV^2, $.005<x_{bj}<.06$, $.006<-t<.8$ GeV^2, $.05<y<.9$
- **4 exclusivity cuts**: (μP)-(μ'γP') missing mass ; momentum balance ; angles



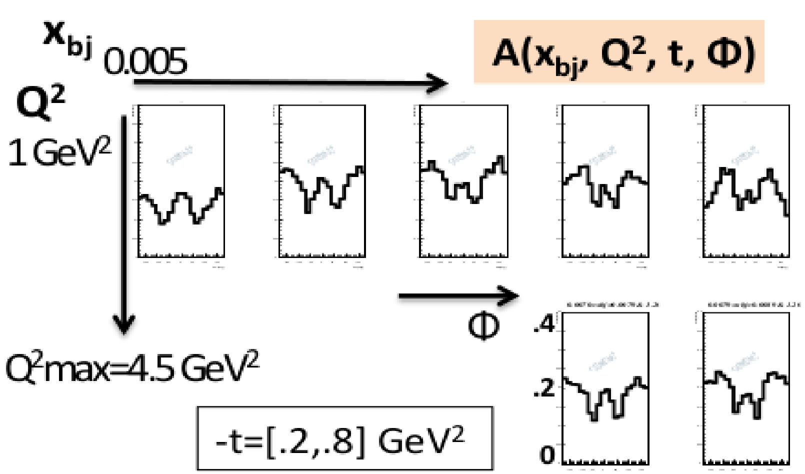




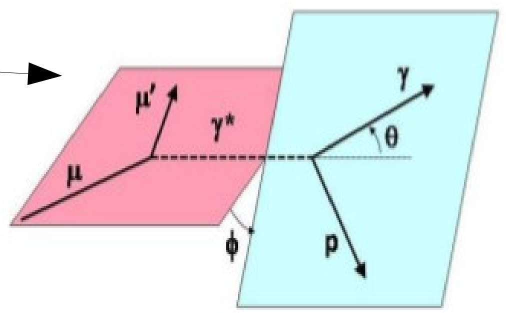
exclusivity cuts

$\lvert\Delta\Phi\rvert$	$0.3rad$
$\lvert\Delta P_T\rvert$	$0.2GeV$
$\lvert\Delta cos\theta\rvert$	0.15
$\lvert M^2_{undet}\rvert$	$0.5GeV^2$

- **acceptance** (Monte-Carlo, BH+modified FFS model for DVCS): by 4D event weighting



strong variations in Φ:
- non hermetic ECAL coverage
- beam pipe



ECAL positions corrected after this analysis

DVCS analysis : background subtraction

- **from Monte-Carlo studies**
LEPTO for DIS and HEPGen* for DVCS (FFS model) and exclusive π° (GK model)

- **parallel measurement of exclusive π° electroproduction cross section**
similar method as DVCS, limit of cross section set to **$\sigma(\pi^\circ)<20$ pb.GeV^{-4}[1σ]** in same kin. range

Background estimates :

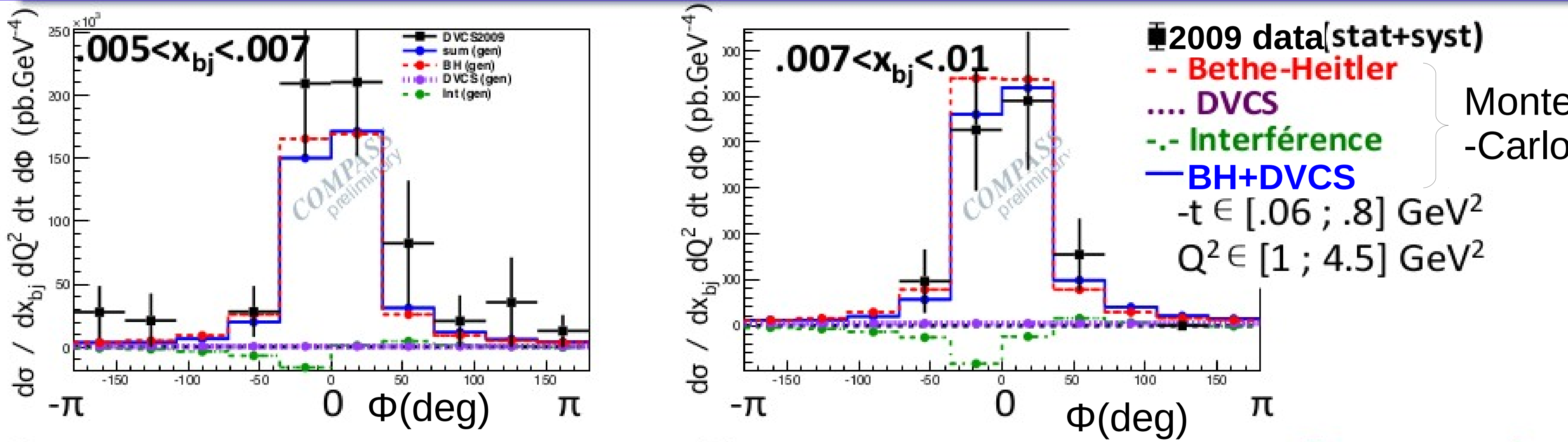
- "semi-inclusive" ($\mu P \rightarrow \mu P \pi^\circ/\eta ... \rightarrow \mu P \gamma X$) : negligible at small x_{bj}, 8%±8% large x_{bj}
- exclusive π° : $\mu P \rightarrow \mu P \pi^\circ \rightarrow \mu P \gamma \gamma$: negligible at small x_{bj}, <2 % at large x_{bj}
- diffractive dissociation : $\mu P \rightarrow \mu P^* \gamma \rightarrow \mu P \gamma X$: negligible

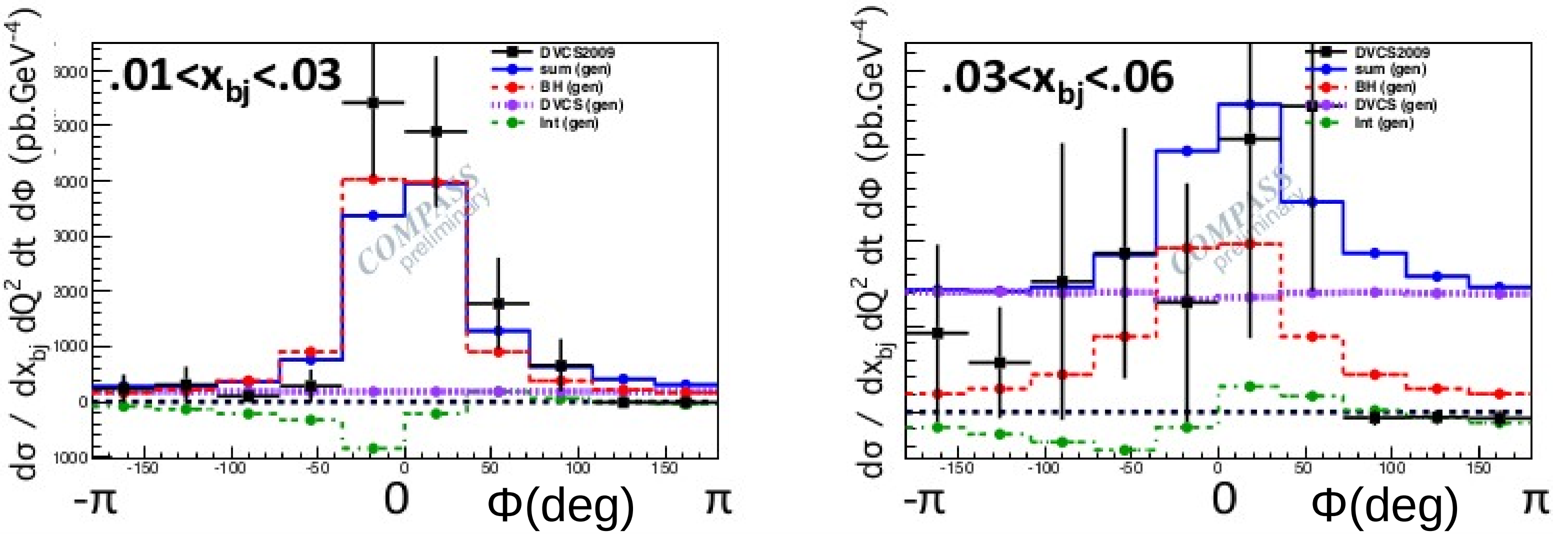
→ **only "semi-inclusive" background is corrected by event weighting**

→ **background << statistical uncertainties**

*Sandacz, Sznajder, arXiv:1207.0333

μP → μPγ = DVCS + Bethe-Heitler : cross sections





systematics

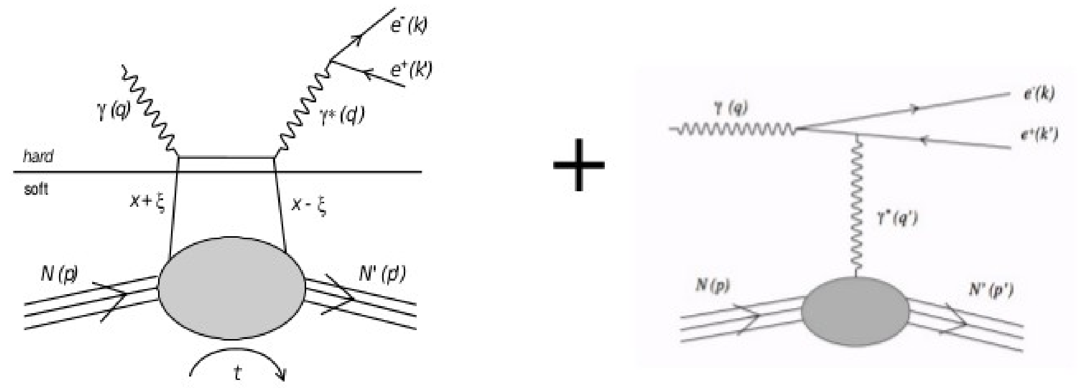
luminosity	0.04
$\delta\epsilon_{ECAL}$	0.10
$\delta\epsilon_{proton}$	0.15
$\delta\epsilon_{tracking}$	0.03
$\delta\epsilon_{hodo}$	0.02
$\delta\epsilon_{master}$	0.01
$\delta\tau_{pileup}$	0.01
sidis subtraction	$0 \rightarrow 0.08$
quadratic sum	~ 0.19

bins 1, 2, 3 : BH dominant → validation of σ(BH) measurement
bin 4 : DVCS signal expected (compatible) but too low statistic

→ large uncertainties but:
- test run data (some issues with triggers, limited setup...)
- first "absolute" cross section measurement in COMPASS
- same method used now for the 2012 run analysis
- hardware improvements after this work

III. TCS : observables and GPDs dependencies

$$\gamma N \rightarrow e^+ e^- N \quad =$$



Timelike Compton Scattering (TCS) sensitive to the nucleon GPDs

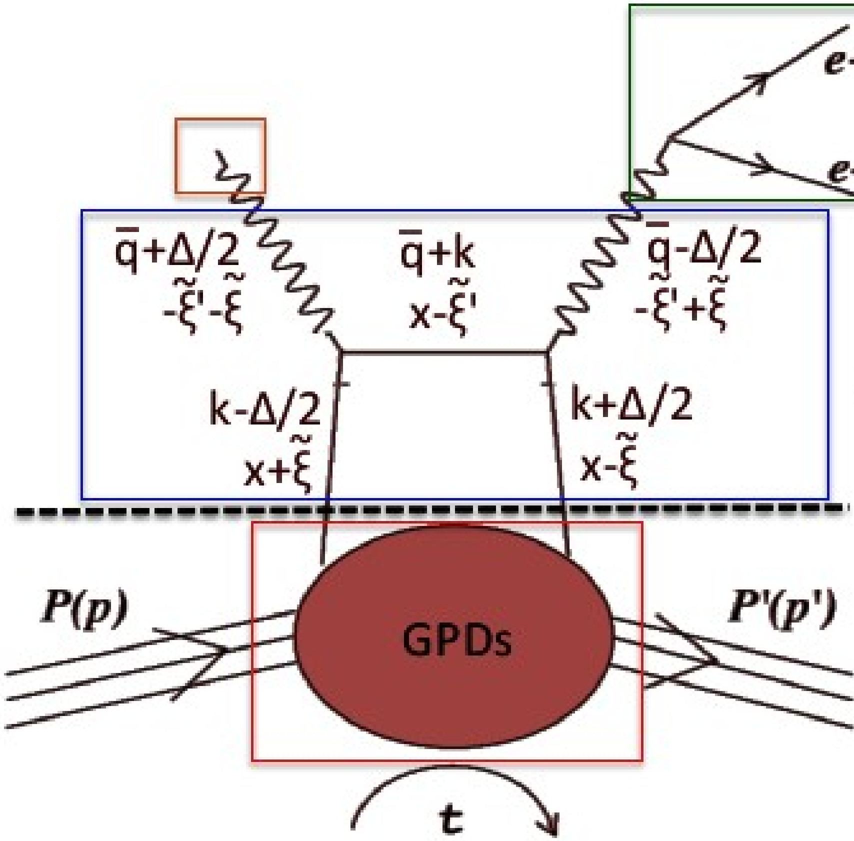
Bethe-Heitler (BH) sensitive to the nucleon Form Factors

Context :
- pioneering theoretical work in 2002*: unpolarized, beam polarized cross sections
- study of experimental feasibility in 2011** with JLab CLAS 6 GeV data
- first proposal for JLab @12 GeV CLAS12 accepted in 2012***

New here:
- unpolarized+polarized cross sections with higher twist corrections + gauge invariance rest.
- all single and double beam (circ., lin.) and / or target (Long. or ⊥) polarized spin asymmetries
- neutron target and sensitivity to quark angular momenta
- new LOI and proposal for JLab @12 GeV submitted in 2015

*Berger, Diehl, Pire, E.P.J. C23 (2002) 675. **R. Paremuzyan, PhD thesis (2011). ***E12-12-01 (2012)

TCS amplitude



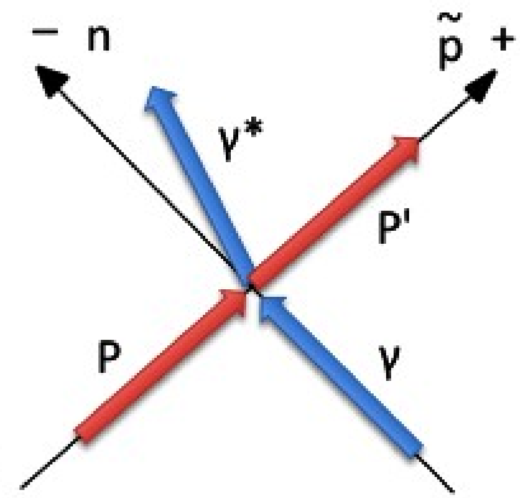
+ crossed diagram

in light cone frame :
- $\bar{q}$ and P colinear along z
  Δ momentum transfer
- Sudakov vectors $\tilde{p}^\mu$ and n^μ
- $\tilde{\xi}$ and $\tilde{\xi}'$ = "+" component of Δ and $\bar{q}$

$$\begin{cases} P = \frac{1}{2}(p+p') \\ \bar{q} = \frac{1}{2}(q+q') \\ \Delta = (p'-p) = (q'-q) \end{cases}$$

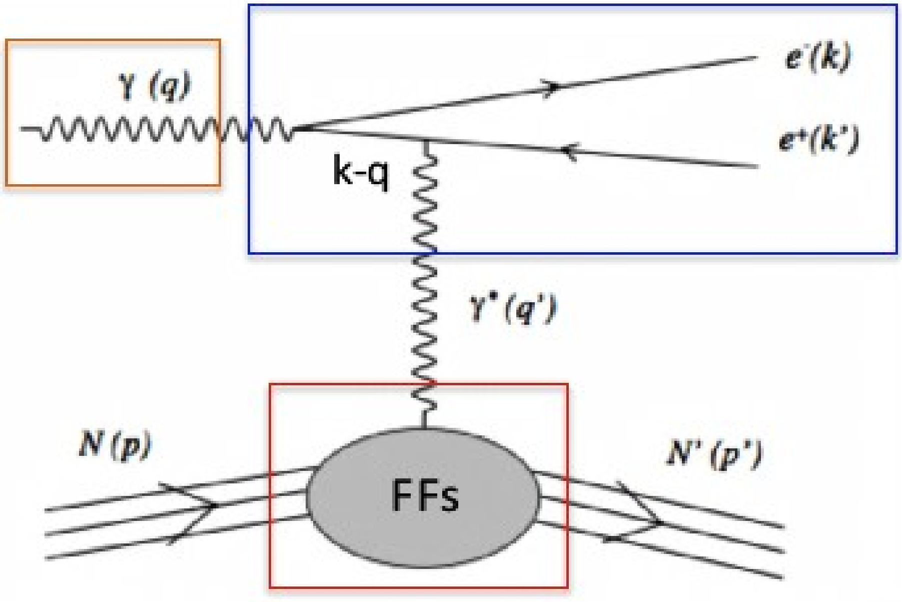
$$\Downarrow$$

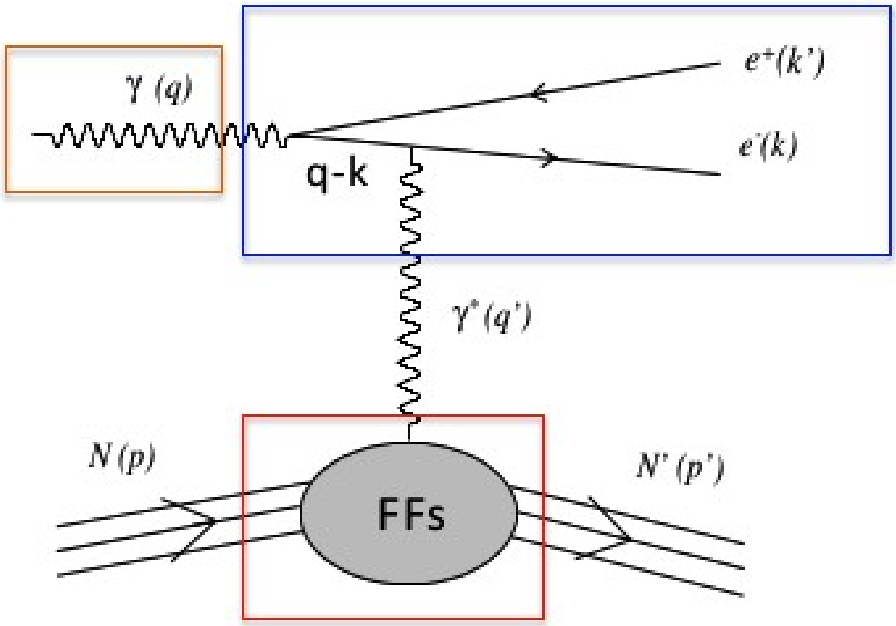
$$\begin{cases} P^\mu = \tilde{p}^\mu + \frac{\bar{m}^2}{2} n^\mu \\ \Delta^\mu = -2\tilde{\xi}\tilde{p}^\mu + \tilde{\xi}\bar{m}^2 n^\mu + \Delta_\perp^\mu \\ \bar{q}^\mu = -\tilde{\xi}'\,\tilde{p}^\mu - \frac{\bar{q}^2}{2\tilde{\xi}'} n^\mu \end{cases}$$



$$T^{TCS} = \boxed{-\frac{e^3}{q'^2}\bar{u}(k)\gamma^\nu v(k')}\boxed{\varepsilon^\mu(q)}\boxed{\begin{array}{l}\frac{1}{2}(-g_{\mu\nu})_\perp \int_{-1}^{1} dx\left(\frac{1}{x-\tilde{\xi}'+i\epsilon}+\frac{1}{x+\tilde{\xi}'-i\epsilon}\right) \\ -\frac{i}{2}(\varepsilon_{\nu\mu})_\perp \int_{-1}^{1} dx\left(\frac{1}{x-\tilde{\xi}'+i\epsilon}-\frac{1}{x+\tilde{\xi}'-i\epsilon}\right)\end{array}}\begin{array}{l}\cdot\left(H(x,\tilde{\xi},t)\bar{u}(p')\not{n}u(p)+E(x,\tilde{\xi},t)\bar{u}(p')i\sigma^{\alpha\beta}n_\alpha\frac{\Delta_\beta}{2M}u(p)\right) \\ \cdot\left(\tilde{H}(x,\tilde{\xi},t)\bar{u}(p')\not{n}\gamma_5 u(p)+\tilde{E}(x,\tilde{\xi},t)\bar{u}(p')\gamma_5\frac{\Delta.n}{2M}u(p)\right)\end{array}$$

BH amplitude and photoproduction cross section





$$T^{BH} = -\frac{e^3}{\Delta^2}\bar{u}(p')\left(\gamma^{\nu}F_1(t) + \frac{i\sigma^{\nu\rho}\Delta_\rho}{2M}F_2(t)\right)u(p)\,\boxed{\varepsilon^{\mu}(q)}\,\boxed{\bar{u}(k)\left(\gamma_\mu\frac{\not{k}-\not{q}}{(k-q)^2}\gamma_\nu + \gamma_\nu\frac{\not{q}-\not{k}'}{(q-k')^2}\gamma_\mu\right)v(k')}$$

$$\frac{d^4\sigma}{dQ'^2\,dt\,d\Omega}(\gamma p \to p'e^+e^-) = \frac{1}{(2\pi)^4}\frac{1}{64}\frac{1}{(2ME_\gamma)^2}\,|\,T^{BH} + T^{TCS}\,|^2$$

$\gamma\, N \rightarrow e^+ e^- N$

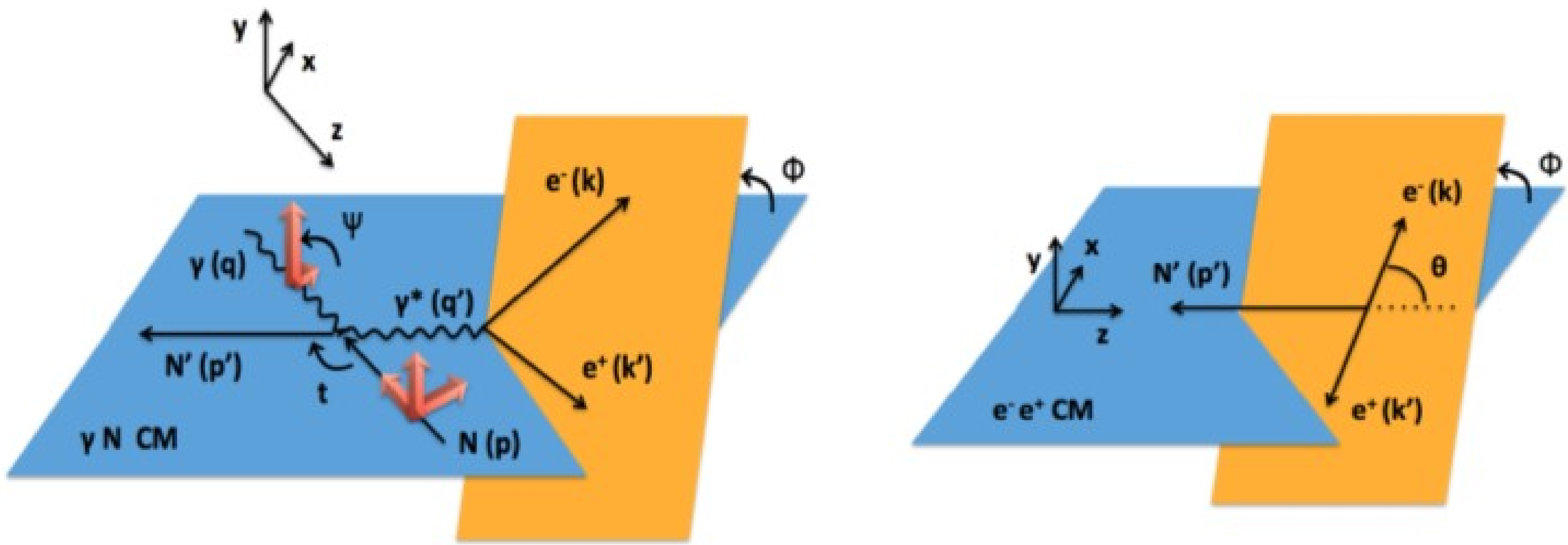
Fixed beam energy or ξ

$$\boxed{\frac{d\sigma}{dQ'^2\, dt\, d\phi\, d(cos\theta)}}$$

Ψ: (reaction plane, γ spin)

φ: (hadronic plane, e^+e^- pair)

θ: (γ^*, e^-)

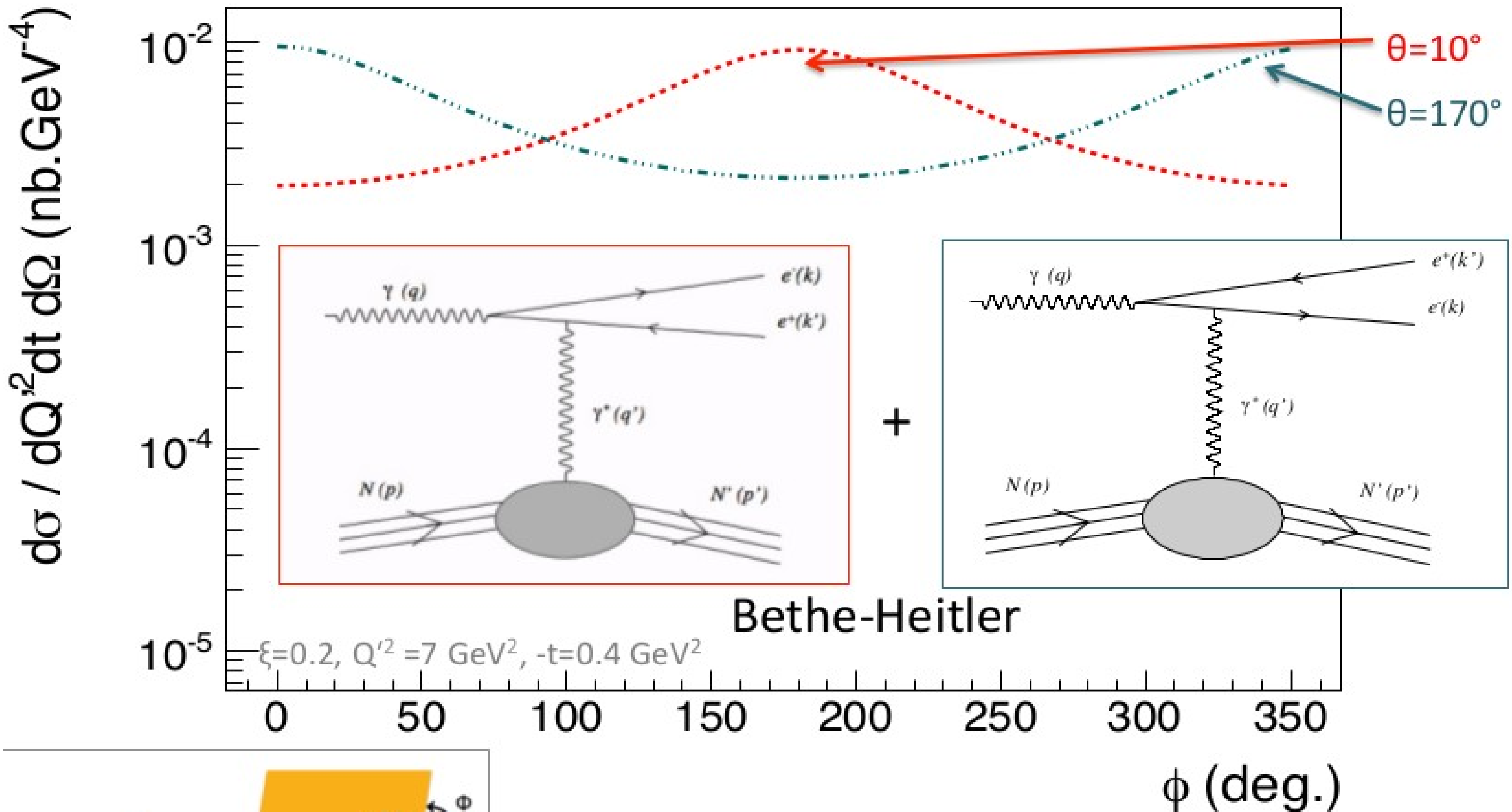


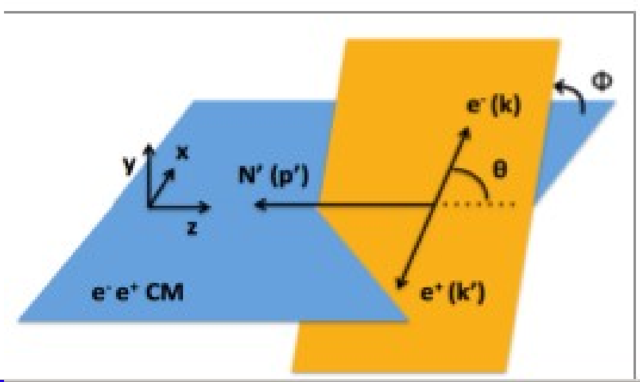
Notations

$\mathbf{A}_{i\,j}$: asymmetry

1st index: photon polarisation, $\odot$ = circular, **L** = linear, **U** = unpolarized

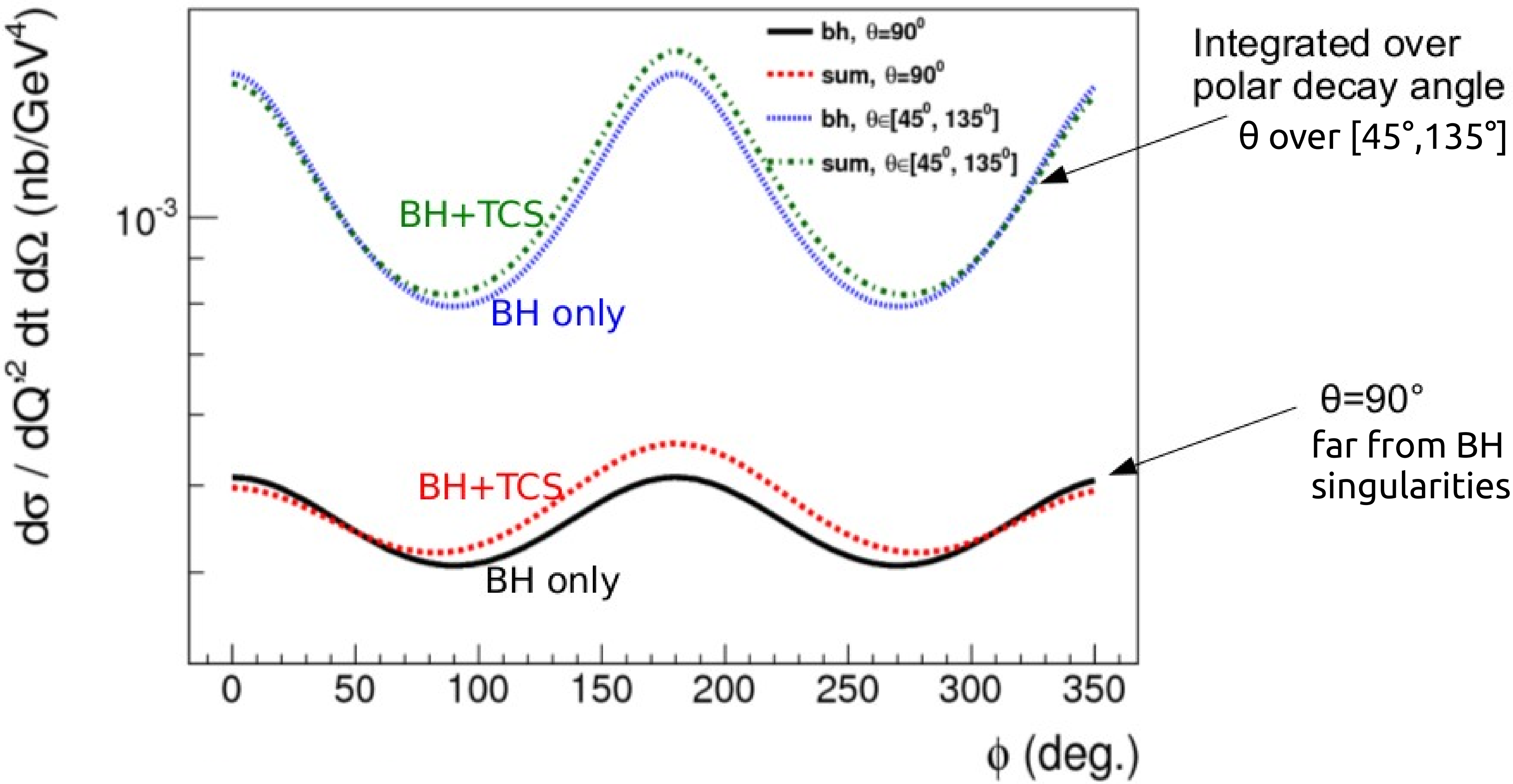
2d index: nucleon polarisation, **x** (transverse, in plane), **y** (transverse), **z** (longitudinal)





e⁻ in γ direction (θ → 0°) => singularity at φ=180°
e⁺ in γ direction (θ → 180°) => singularity at φ=0°

BH and TCS angular dependencies



BH is largely dominant

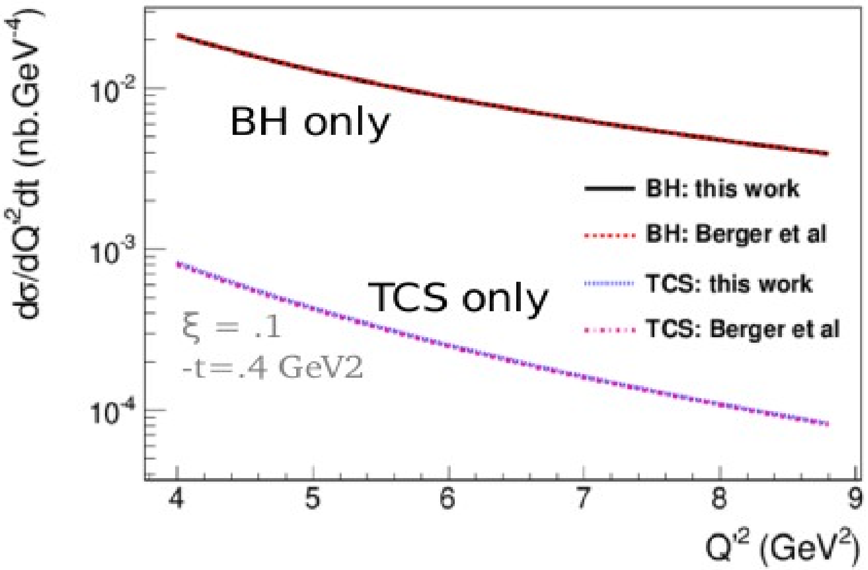
Integrated in all following figures

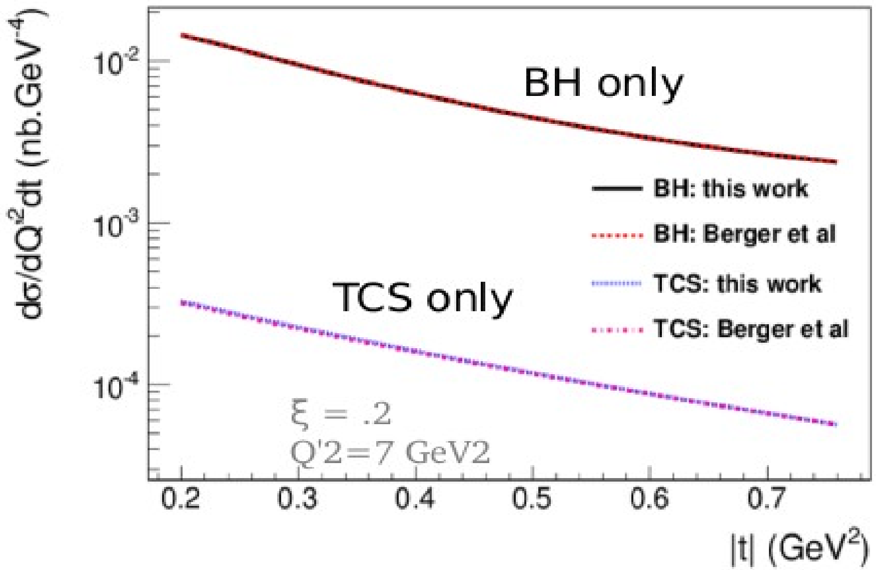
BH and TCS kinematical dependencies

cross sections vs Q'^2 and vs t

integrated over decay angles $\theta \in [45°, 135°]$, $\Phi \in [0°, 360°]$

- BH is always 1 or 2 order of magnitude larger than TCS
- order of pb





Comparison to the pioneering theoretical work

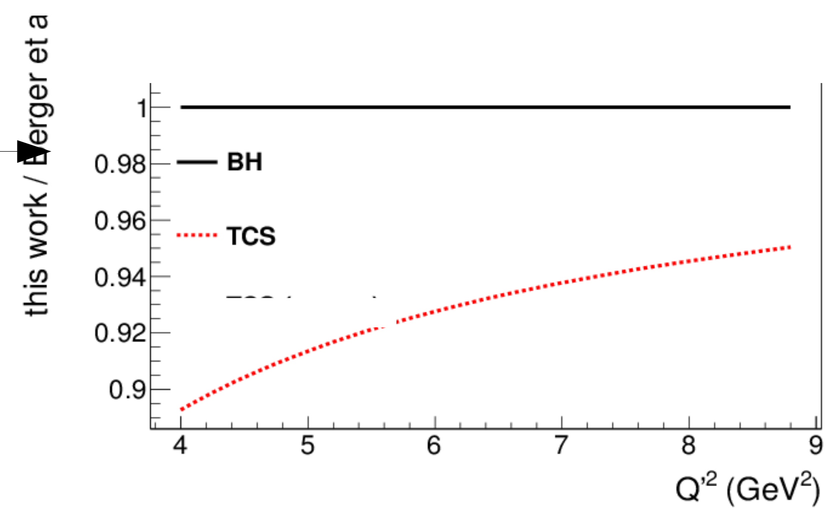
Berger, Diehl, Pire, E.P.J. C23 (2002) 675

Bethe-Heitler: ≈ equal

TCS: few % at low Q'^2

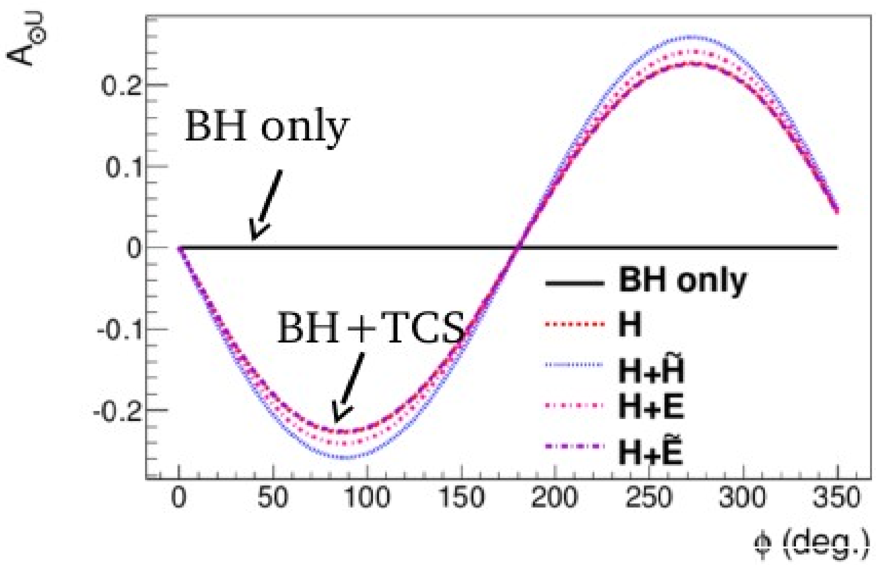
=> we waived some t/Q'^2 approximations

(higher twist corrections, gauge invariance)

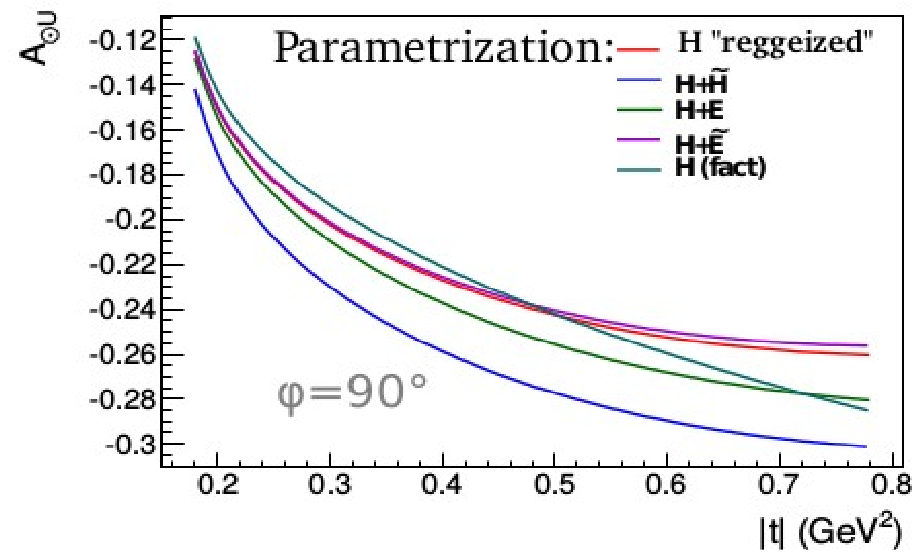


- Circularly Polarized

Angular dependence in Φ



Kinematical dependence in -t



$A_{\odot U}$ ∝ **imaginary part of amplitudes** ⇒ $A_{\odot U}$ = 0 for Bethe-Heitler

Asymmetry ≈20%

This observable : mostly sensitive to H and $\tilde{H}$

≈ 20% asymmetry coming from interference BH x TCS and sensitive to GPDs

Hall B CLAS12 proposal
E12-12-01 PAC39 (2012)

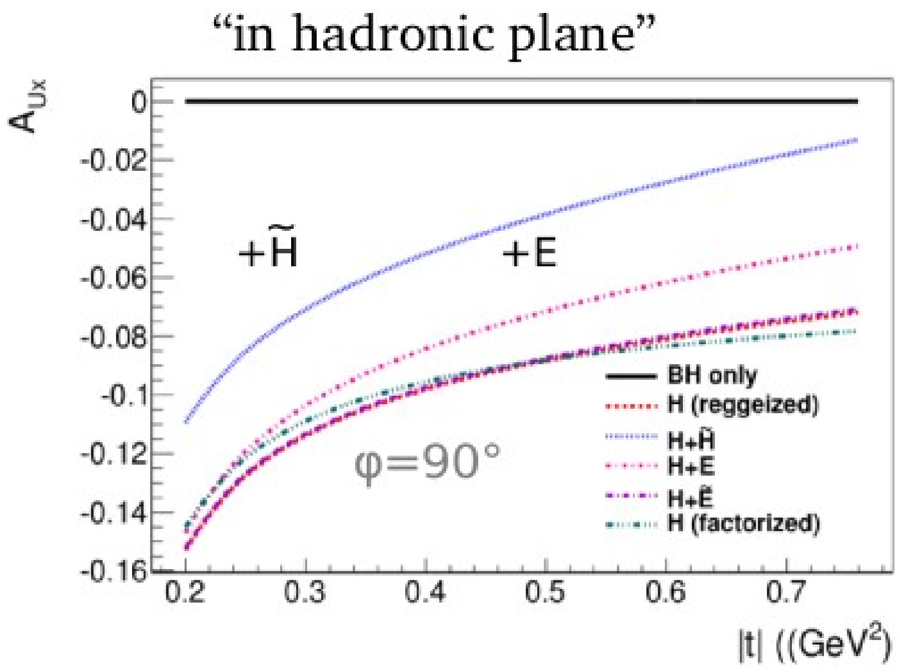
Hall A SoLID run group proposal
E12-12-006A PAC43 (2015)

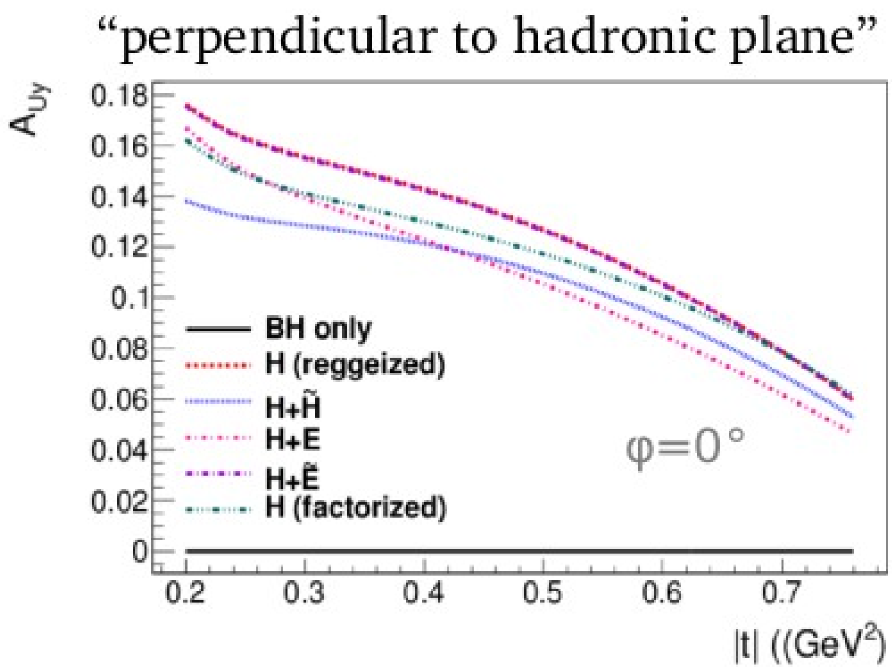
- Linearly Polarized

+ sensitive to real part of amplitudes
- more difficult experimentaly
= CLAS12 run group proposal ? Hall D ?

ξ=0.2, Q'2 =7 GeV2, -t=0.4 GeV2, θ ∈ [45°,135°]

Transversally polarized target asymmetries vs |t|





- **Im part of amplitudes ⇒ A_{Ui} [BH] = 0**
- **Sensitive to H, $\tilde{H}$, E 10% to 20% asymmetries**

Hall C LOI 12-15-007
PAC43 (2015)

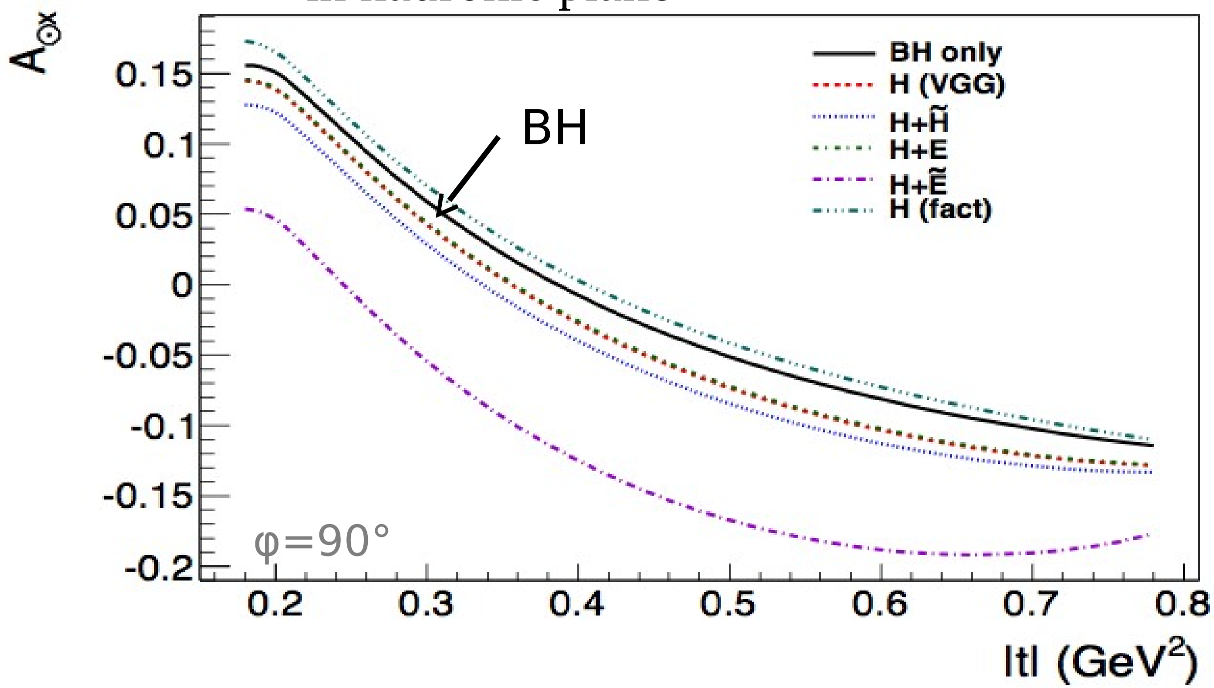
→ Spin physics with GPD E...

ξ=0.2, Q′2 =7 GeV2, -t=0.4 GeV2, θ ∊ [45°,135°]

Double Spin Asymmetries

Circularly polarized beam and transversally pol. target vs |t|

"in hadronic plane"



ξ=0.2, Q′2 =7 GeV2,
-t=0.4 GeV2,
$\theta \in$ [45°,135°]

- Very sensitive to the GPDs parameterization
- Sensitive to the real part of amplitudes
- But

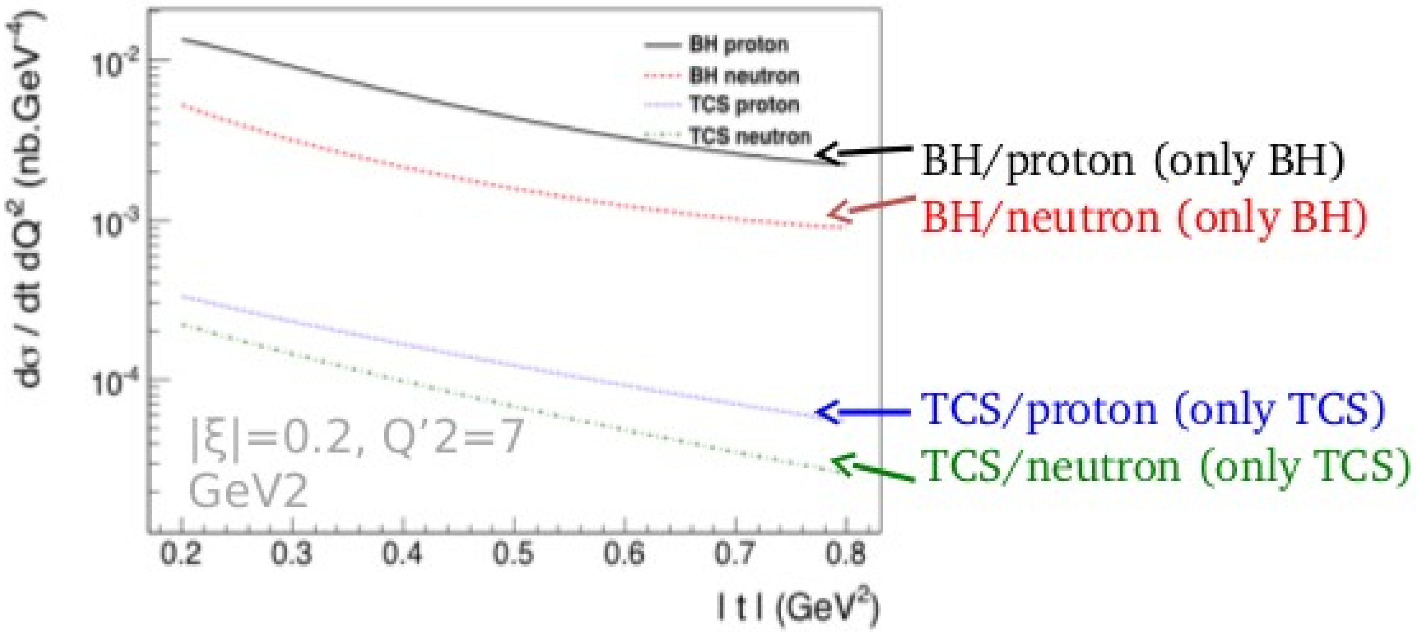
- A[BH]≠0 , few % deviation from TCS signal
- Bins in φ and θ preferable for signal
- Experimental difficulties (stat…)

Future
need high luminosity
+ resolution

BTSA with linearly polarized beam : sensitive to imaginary part of amplitudes

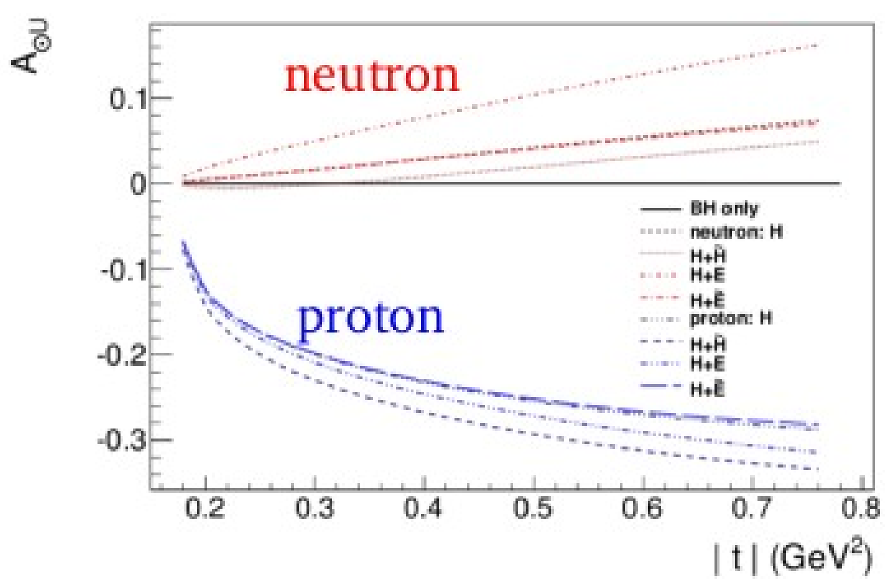
Comparisons : TCS off the proton and off the neutron

unpolarized cross sections TCS and BH



Future

JLab Hall A
SoLID ^{3}He target ?



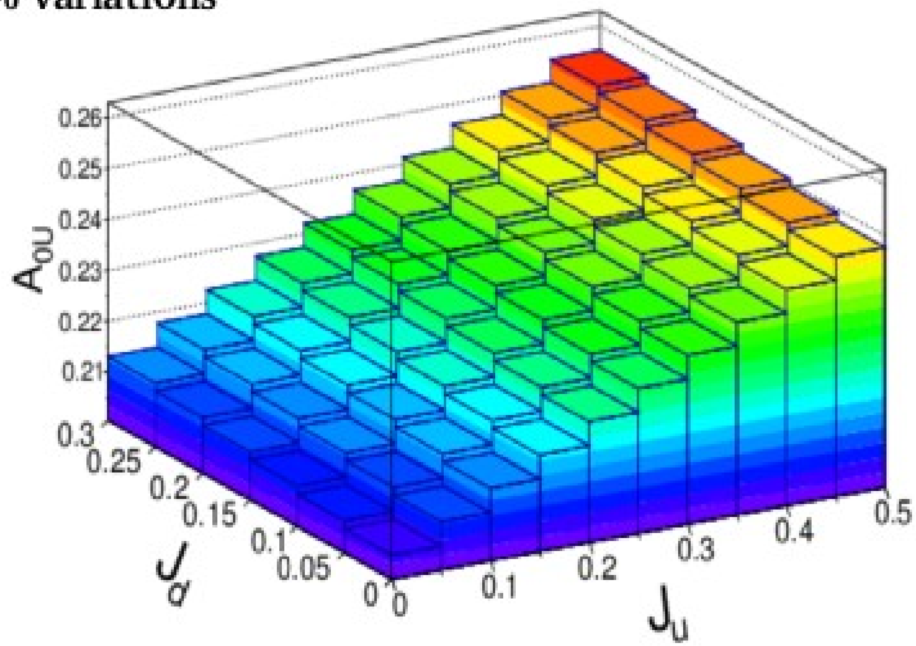
$\Longrightarrow$ TCS off neutron is measurable but is more difficult experimentaly
$\Longrightarrow$ Asymmetries $\approx$ same Φ and t dependancies and same magnitudes

- flavor separation : u and d quarks
- GPD E (next slide) => Ji sum rule

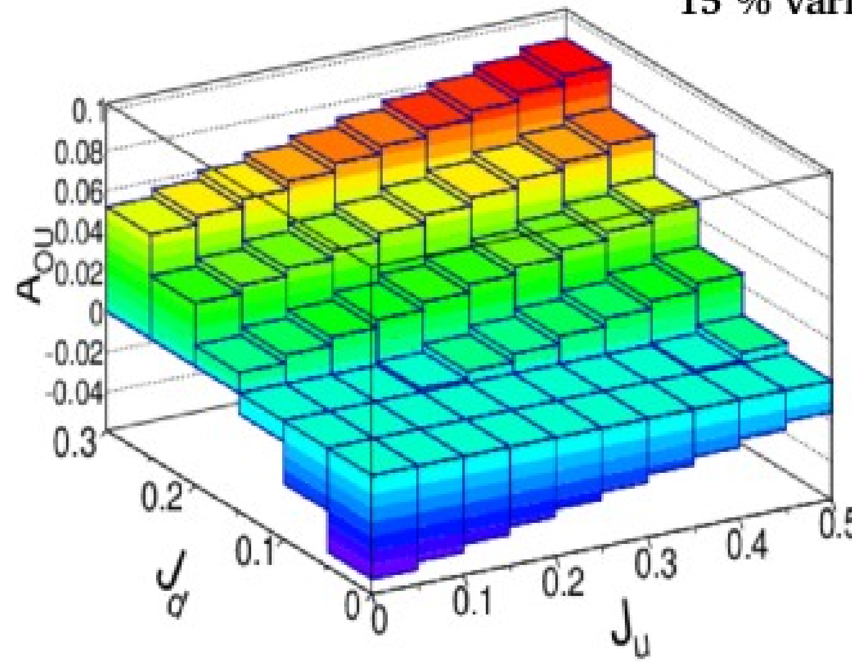
Spin physics with TCS off the proton and off the neutron

Sensitivity to GPD E in BSA:
BSA as a function of u and d quark angular momenta J_u and J_d (max amplitude)
BSA($-t$=.4 GeV^2) vs J_u and J_d for proton: **for neutron:**

5 % variations



15 % variations



Stronger sensitivity to J_u and J_d + change of sign for BSA off the neutron
→ Ji sum rule... studies of angular momenta of quarks

- **TCS is more sensitive than DVCS to the E parameterization and to the quark angular mom.**
- **TCS or DVCS on the neutron are more sensitive to J_q than on the proton**

Could we extract CFFs from TCS fits ?

Could we combine DVCS and TCS in fits ?

- **Pseudo-data based on these TCS calculation**
- **DVCS[1] method is expanded for TCS and TCS+DVCS**
- **Local fits: MINUIT + MINOS**

- several sets of observables, (ξ , t) points fitted independently
- 7 free parameters: CFFs ($\Im$m and Re [H, $\tilde{H}$, E], Re[$\tilde{E}$])
- the variation of parameters is limited in parameter space

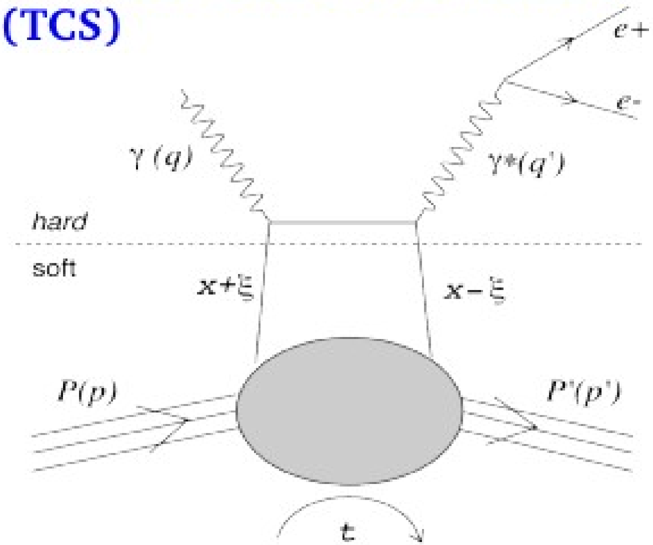
- **Systematic studies: error propagation and interpretations[2]**

[1] M. Guidal, EPJA 37 (2008) 319

[2] M.B.,M. Guidal J.Phys. G42 (2015) 3, 034023

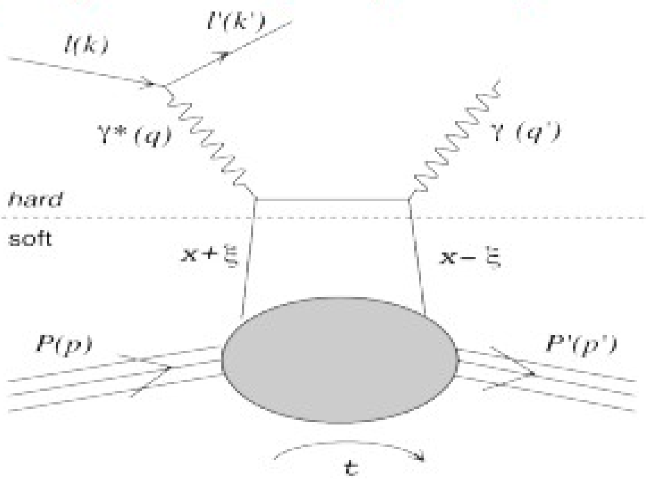
Fits of DVCS and of TCS : phase space for JLab at 12 GeV

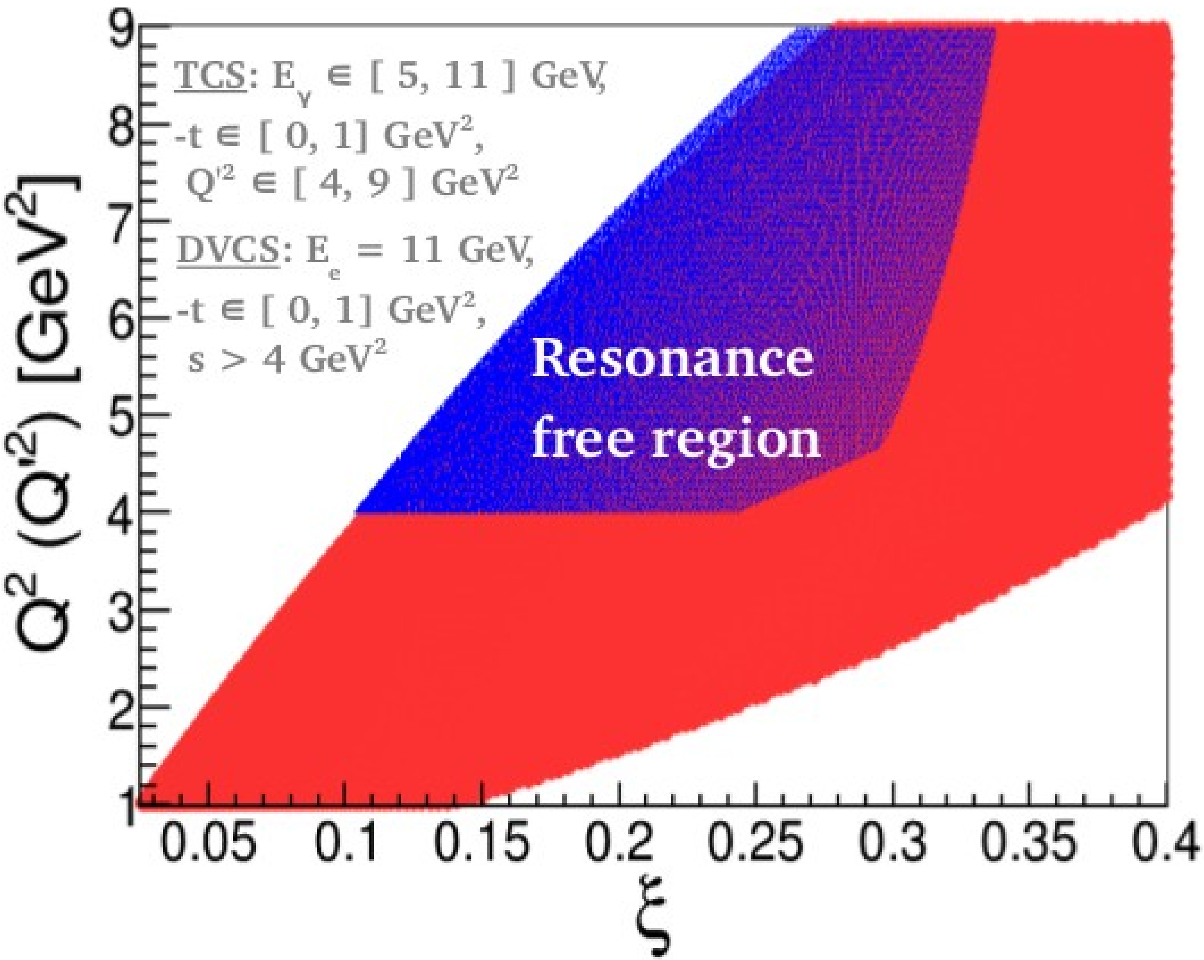
Timelike Compton Scattering (TCS)



Deeply Virtual Compton Scattering (DVCS)

Measurements already published (JLab, HERMES, H1, ZEUS)

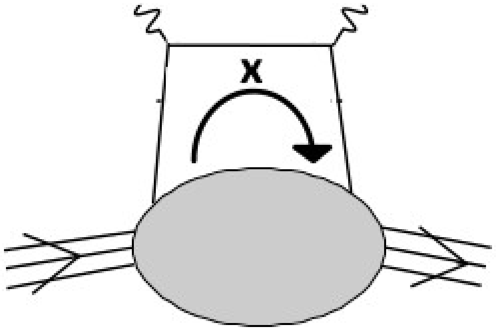




Interest of TCS and DVCS in parallel :

- Universality of GPDs
- Complementary observables
- Higher twist and higher order effects

ξ, t = measurable
x = loop



$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \underbrace{P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx}_{\mathrm{Re}\,(\mathcal{H})} \underbrace{- i\pi H(\pm\xi,\xi,t)}_{\mathrm{Im}\,(\mathcal{H})} + \ldots$$

Compton Form Factor (CFF)

7 free parameters (CFFs), limited amout of uncorrelated observable

1. DVCS fits : under-constrained but we can extract Im($\mathscr{H}$), Re($\mathscr{H}$) and Im($\tilde{\mathscr{H}}$) from data

2. TCS fits (simulations, 5-15 % uncertainties) : feasible, but less sensitive to the CFFs
→ comparisons to DVCS for $\mathscr{H}$, $\tilde{\mathscr{H}}$... *(next slide)*

3. Combined DVCS+TCS fits (simulations)
→ reduction of the error bars compared to the DVCS results
→ more independent observables : poorly constrained CFFs could be extracted ($\mathscr{E}$…)
→ possible study of higher twist and NLO effects

Fits of TCS only

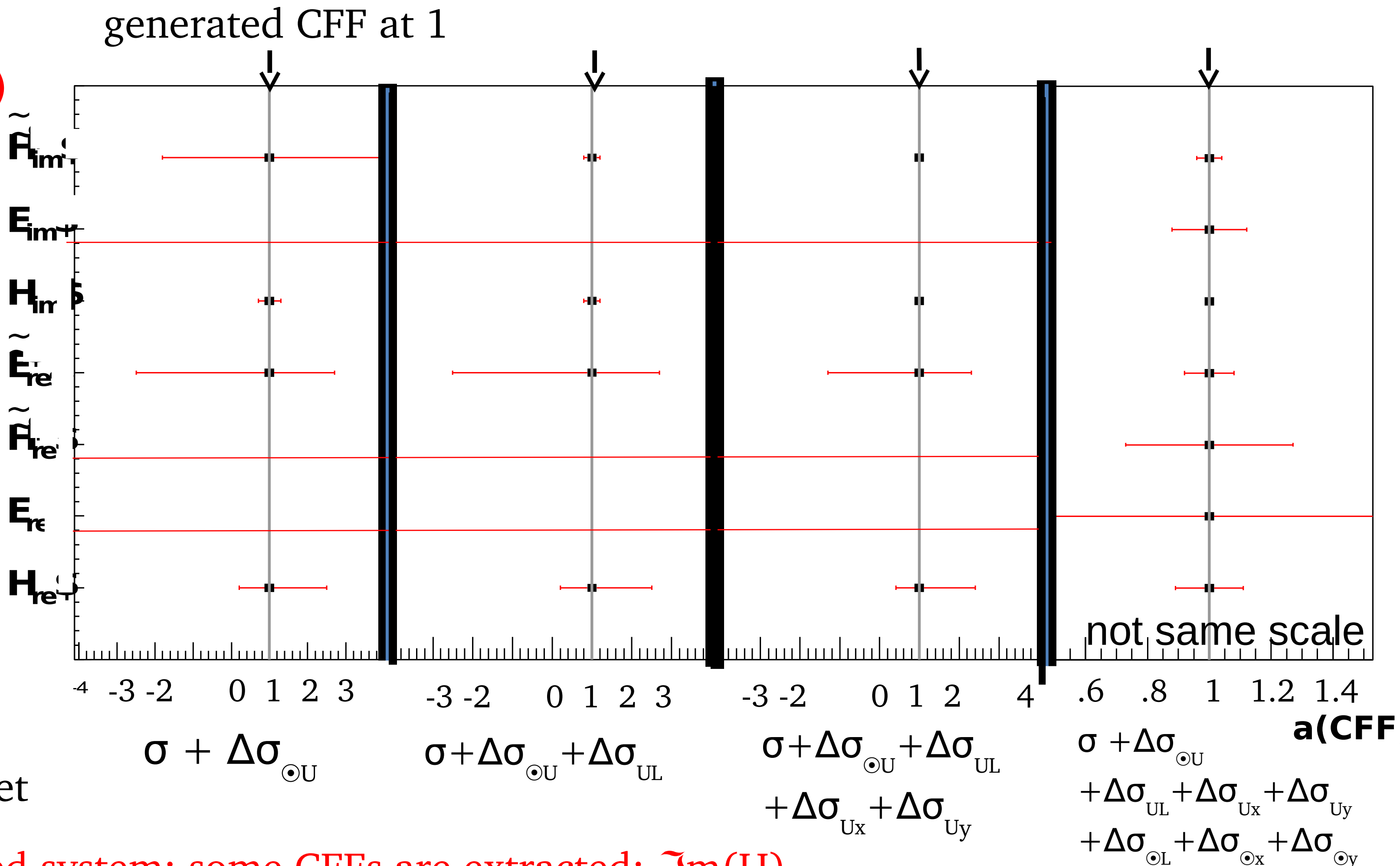
Set of results (uncertainties)

Compton Form Factors (CFFs)

simulations; without smearing $\delta\sigma = 5\%$, $\delta\Delta\sigma = 2\%$

generated "CFF" = 1

$\xi=0.2$, $Q'^2=7$ GeV2, $-t=0.4$ GeV2, $\theta = 90°$



Observables: With polarized beam and/or target

- underconstrained system: some CFFs are extracted: $\mathfrak{Im}(H)$
- 8 independant observables, 7 CFFs: all CFFs are extracted
- single spin asymmetries $\propto$ ImT $\Longrightarrow$ Im(CFFs) are extracted with smaller error bars
- compared to DVCS : more difficult with TCS, but complementary

CFFs can be extracted from TCS fits assuming 5% uncertainties on observables

Combined fits : DVCS + TCS (simulations)

Set of results (expected uncertainties)

DVCS + TCS in combination in fits.

	$(\sigma, \Delta\sigma_{LU})$ DVCS 5%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_ℓ 15%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_c 15%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_ℓ 5%	$(\sigma, \Delta\sigma_{LU})$ DVCS 5% + TCS_c 5%
$\sigma^+(Re\{\mathcal{H}\})$	+1.21	+0.92	+0.80	+0.54	+0.55
$\sigma^-(Re\{\mathcal{H}\})$	-0.84	-0.79	-0.83	-0.44	-0.45
$\sigma^+(Im\{\mathcal{H}\})$	+0.23	+0.20	+0.15	+0.11	+0.12
$\sigma^-(Im\{\mathcal{H}\})$	-0.50	-0.40	-0.21	-0.27	-0.19

+TCS $(\sigma+\Delta\sigma_{LU})$ +TCS $(\sigma+\Delta\sigma_{\odot U})$

Uncertainties are reduced by ~2

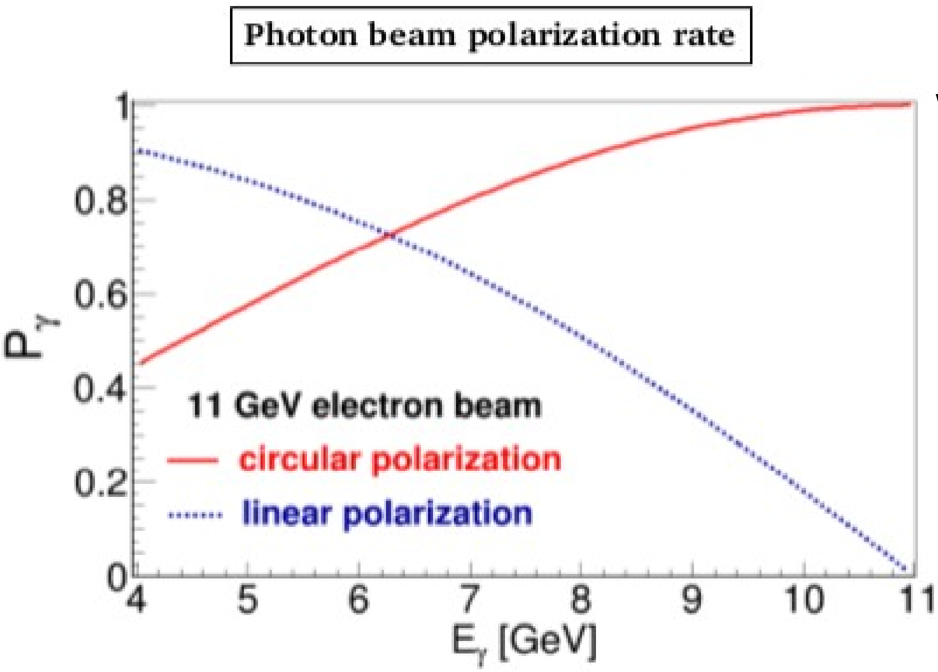
V. TCS : perspectives at JLab at 12 GeV

Unpolarized TCS+BH cross section
- Hall A SoLID run group proposal E12-12-006A (2015)
- Hall B CLAS12 proposal E12-12-001 (2012)

→ **GPD universality check**
Over-constraining GPD H
Access to Re(H)
Higher twist/ NLO effects

Beam Spin Asymmetries measurements at JLab at 12 GeV
- Hall A SoLID : circularly polarized BSA (approved)
- Hall B CLAS12 : circularly (approved) and linearly (future) BSA

→ (+ $\tilde{H}$)
Independant observable sensitive to Re(TCS)



with quasi-real photon beam (Q2<0.3 GeV2)
*85% electron polarization

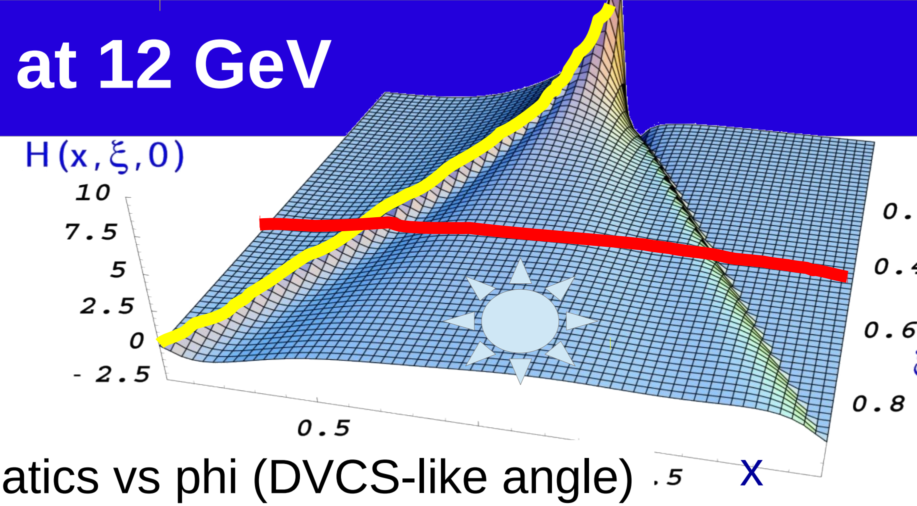
Target Spin Asymmetries measurements
- Hall C NPS : transversally polarized target , dedicated measurement. LOI 12-15-007 (2015).

→ **Good access to GPD E**
Complementarity of TCS and DVCS programs

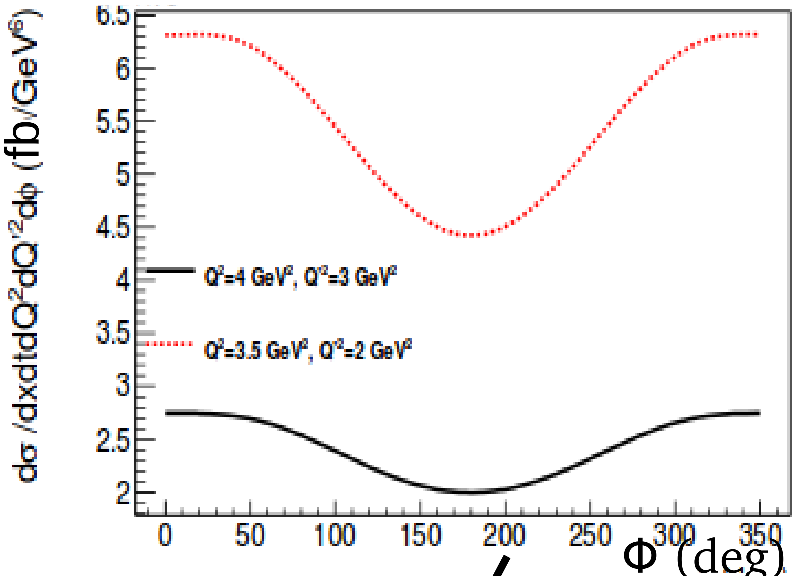
DDVCS : perspectives at JLab at 12 GeV

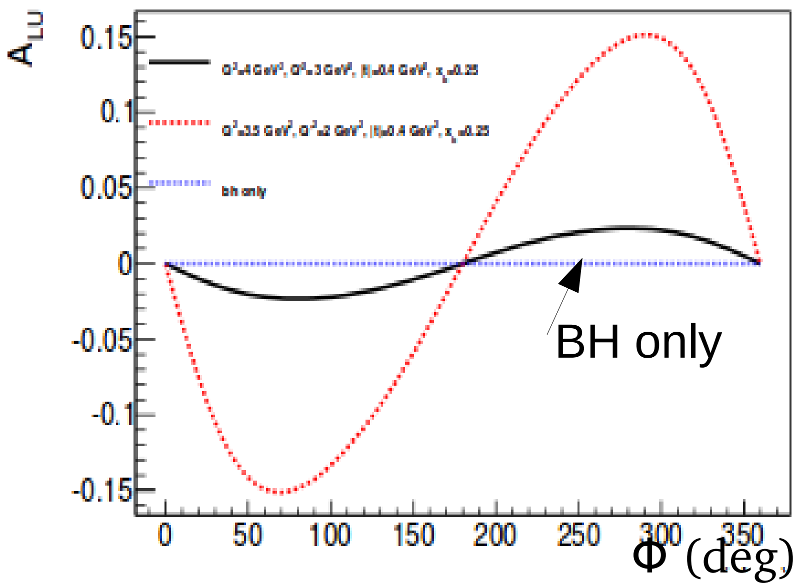
eP → e'P'μ$^+$μ$^-$

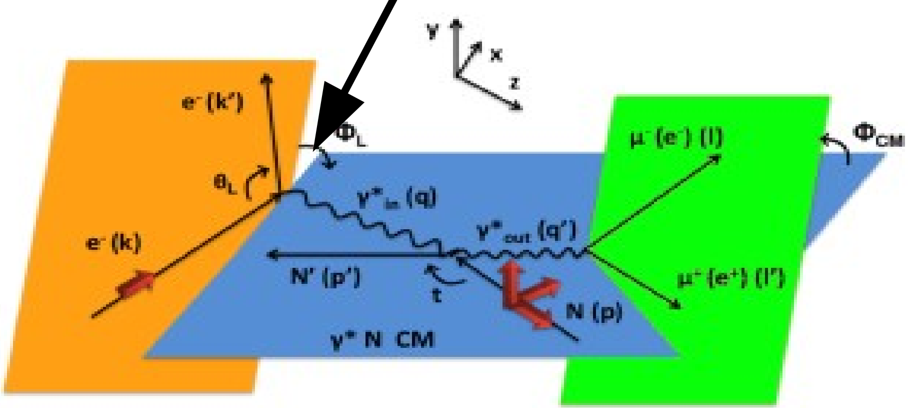
Interest : GPDs extracted at x ≠ ξ
→ needed for "3D" imaging
How : lever arm with Q^2/Q'^2 ratio



cross section and beam spin asymmetry for 2 kinematics vs phi (DVCS-like angle)

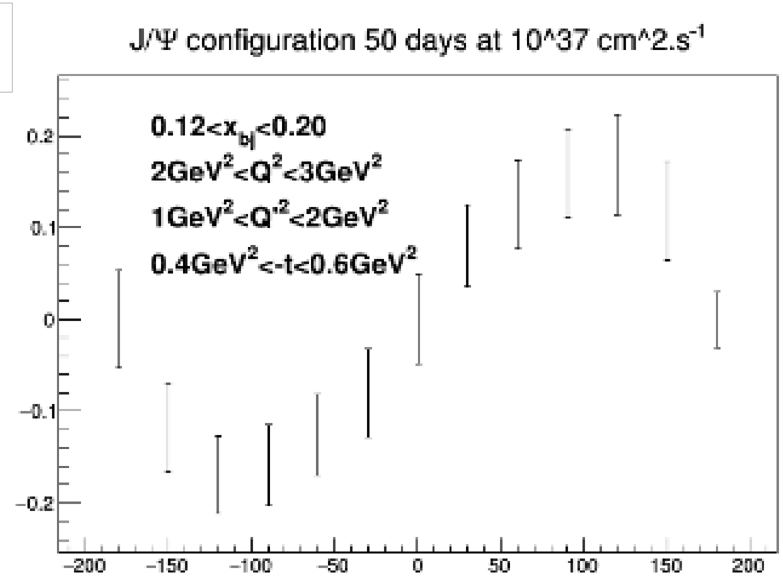






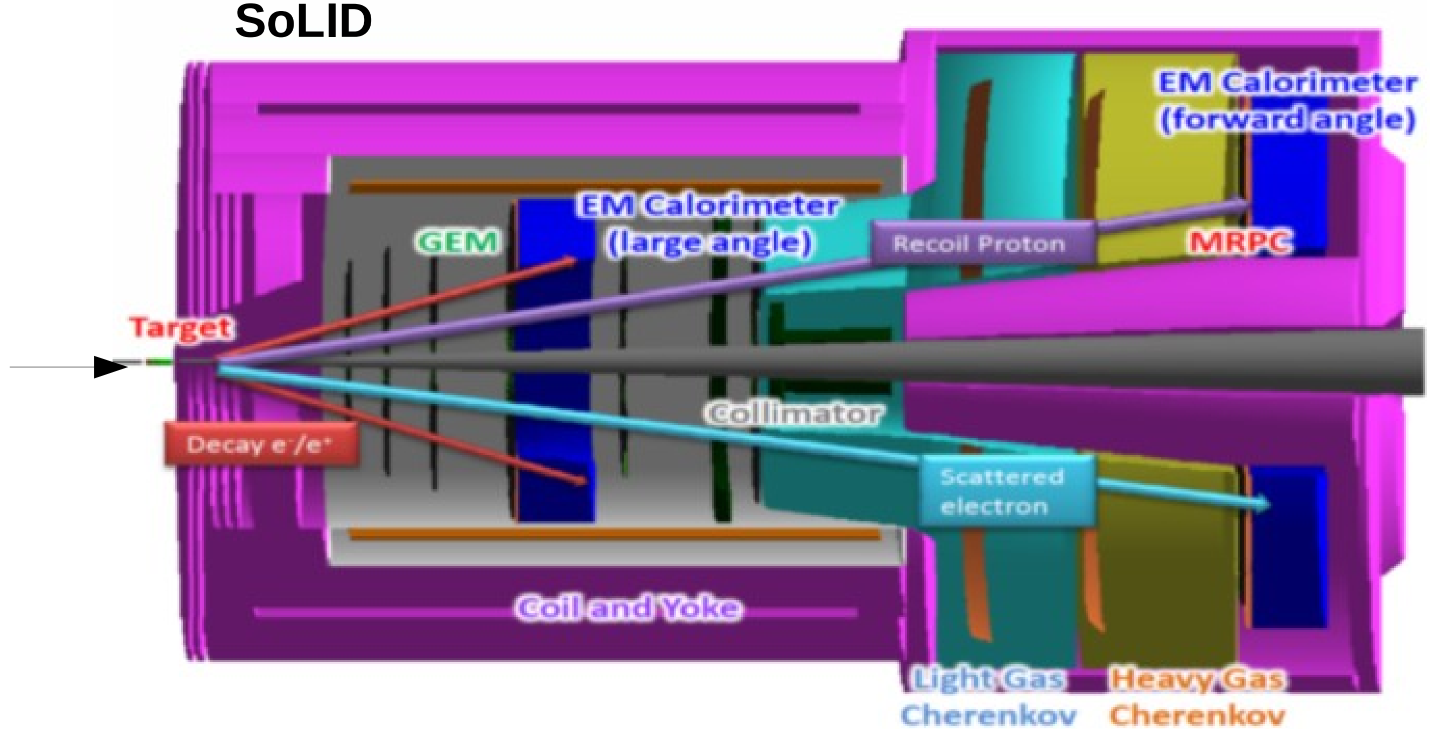
$eP \rightarrow e'P'\mu^+\mu^-$

Hall A SoLID : LOI 12-15-005 (2015),
Left figure= expected errors on A_{LU} with
J/Ψ approved configuration



Hall B CLAS12 : intern letter, LOI for dedicated run to be submitted in 2016

SoLID



+ CLEO
muons chamber

SUMMARY

I. Motivations : GPDs physics

- DVCS, TCS and DDVCS : different sensitivities to the same GPDs

II. DVCS at COMPASS

- **first cross section measurement** : **inclusive, exclusive photon and pi°**
- **luminosity at 4% level**

COMPASS note 2013-12
+ other internal notes

III. TCS phenomenology

- **all asymmetries** with polarized beam and/or target : GPD dependencies
- **proton and neutron** : flavor separation, spin physics...

E.Phys.J.A(2015) 51: 103
arXiv:1501.00270

(to be submitted)

IV. Fits of DVCS and of TCS

- DVCS : interpretation of uncertainties, error propagation…
- TCS : proof of GPD sensitivities
- TCS and DVCS : universality of GPDs, complementarity of observables, higher twist sensitivity...

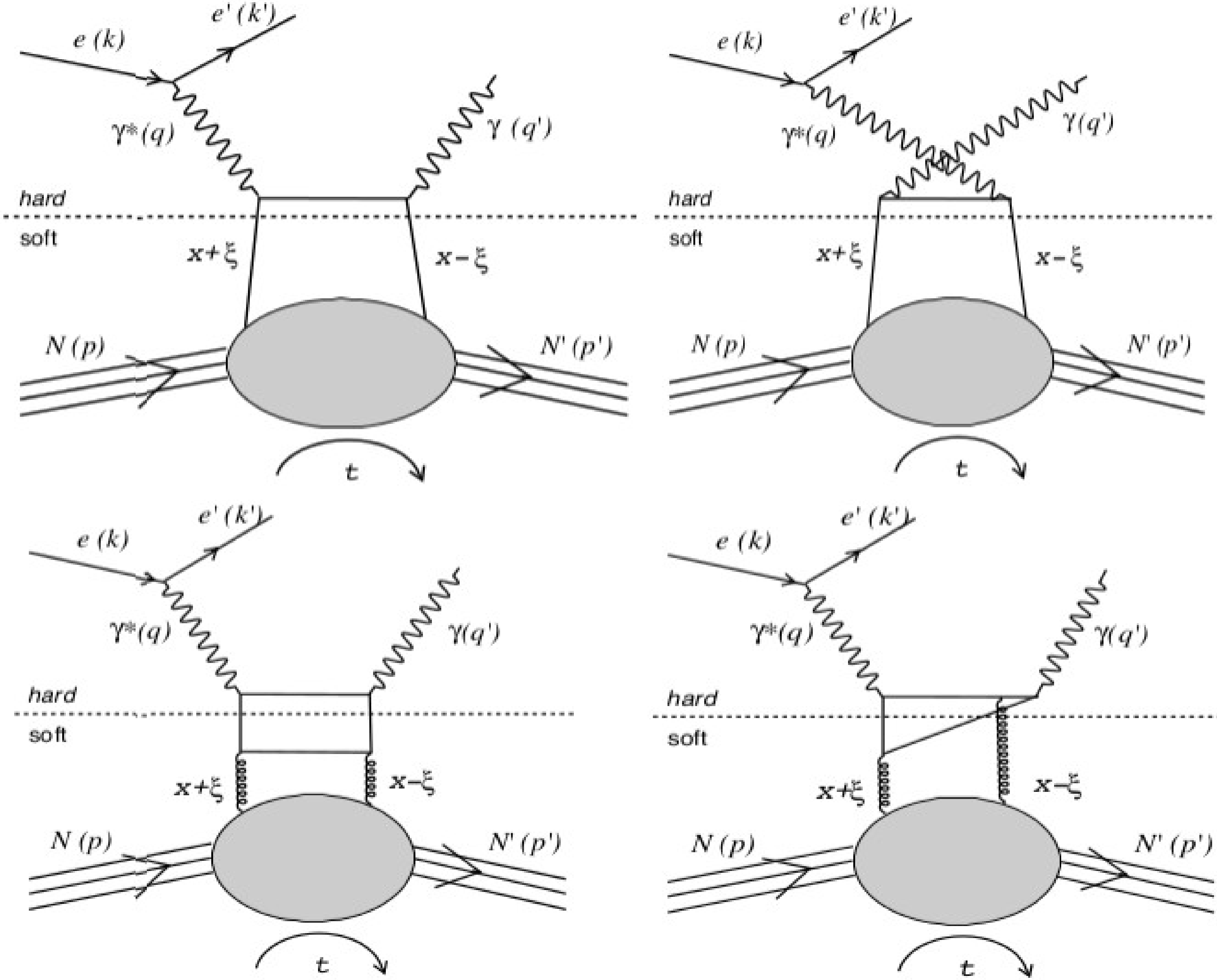
J.Phys. G42 (2015) 3, 034023

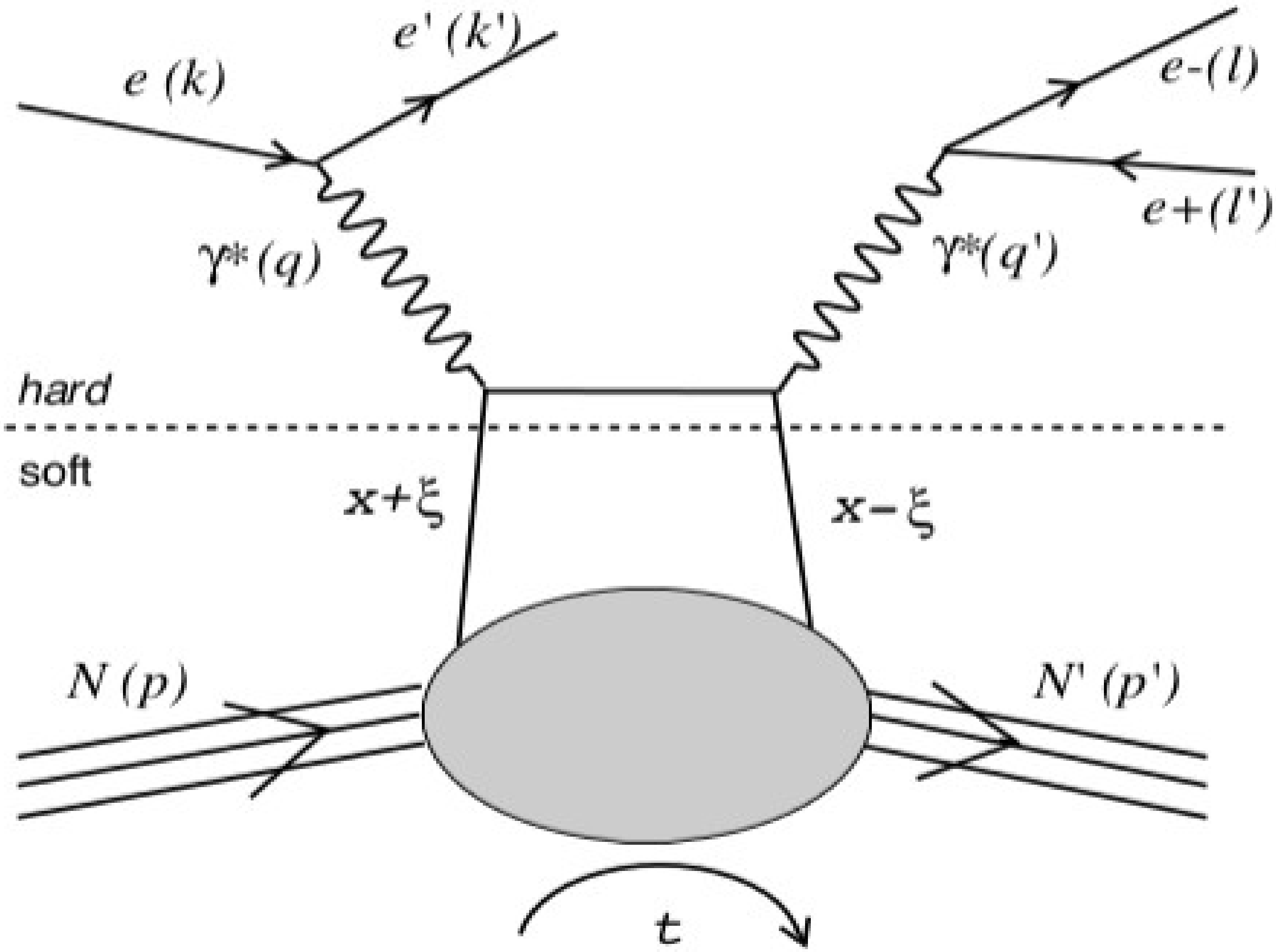
(paper in preparation)

V. Experimental perspectives for TCS and DDVCS at JLab at 12 GeV

- TCS : proposal for Hall B CLAS12 (E12-12-001 (2012))
- TCS, submitted in 2015 : **run group proposal for Hall A SoLID and LOI for Hall C NPS**
- DDVCS, submitted in 2015 : **LOI for Hall A SoLID**
- future : DDVCS in Hall B CLAS12

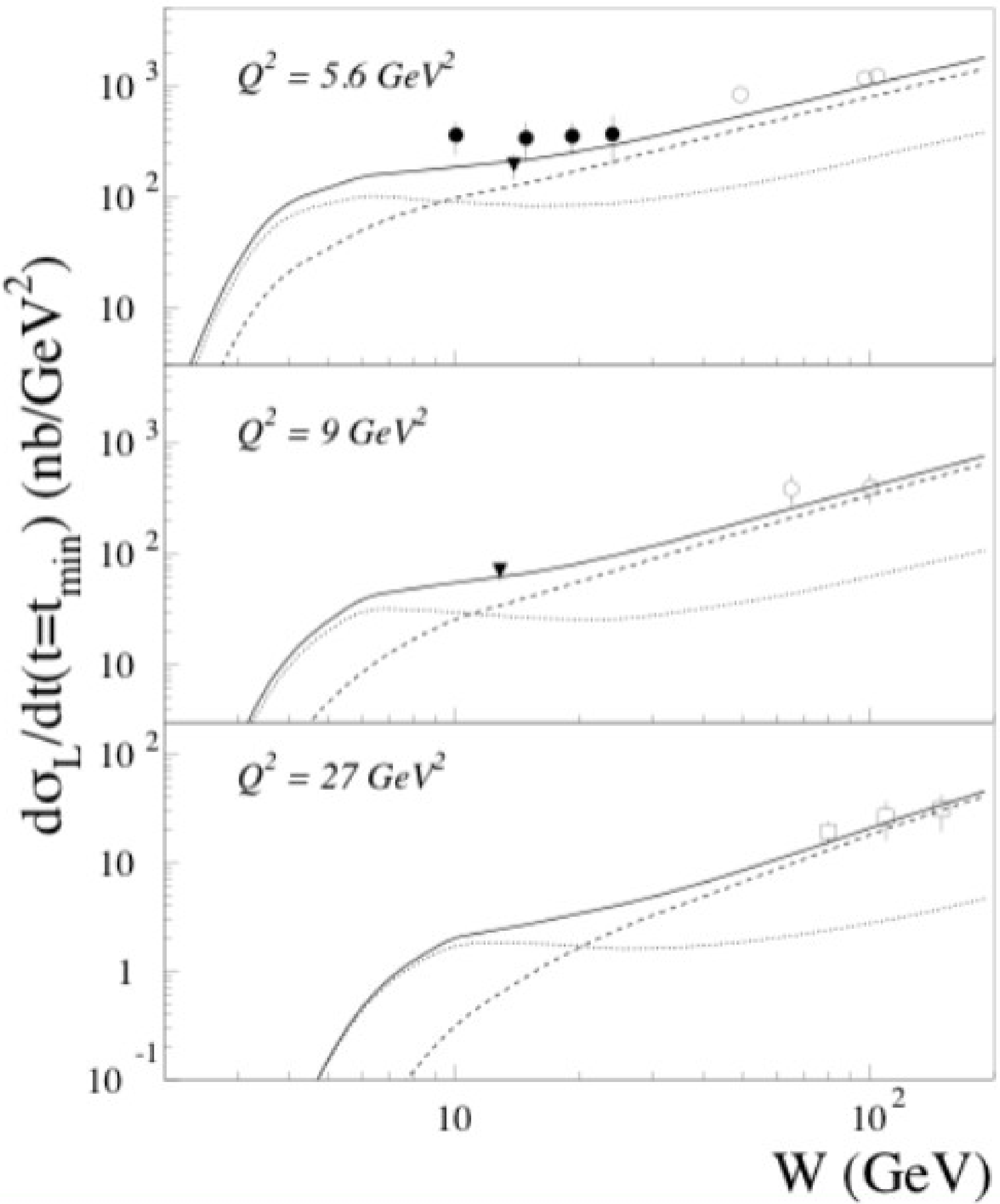
Submitted to PAC43 (2015) :
- proposal E12-12-006A (accepted in 2015, July)
- LOI12-15-007
- LOI12-15-005


e (k)
e' (k')
γ* (q)
γ (q')
hard
soft
x+ξ
x−ξ
N (p)
N' (p')
t
e (k)
e' (k')
γ*(q)
γ(q')
hard
soft
x+ξ
x−ξ
N (p)
N' (p')
t
e (k)
e' (k')
γ*(q)
γ(q')
hard
soft
x+ξ
x−ξ
N (p)
N' (p')
t
e (k)
e' (k')
γ*(q)
γ(q')
hard
soft
x+ξ
x−ξ
N (p)
N' (p')
t



e (k)
e' (k')
e-(l)
e+(l')
γ*(q)
γ*(q')
hard
soft
x+ξ
x−ξ
N (p)
N' (p')
t

$\gamma^* + p \rightarrow \rho_L^0 + p$



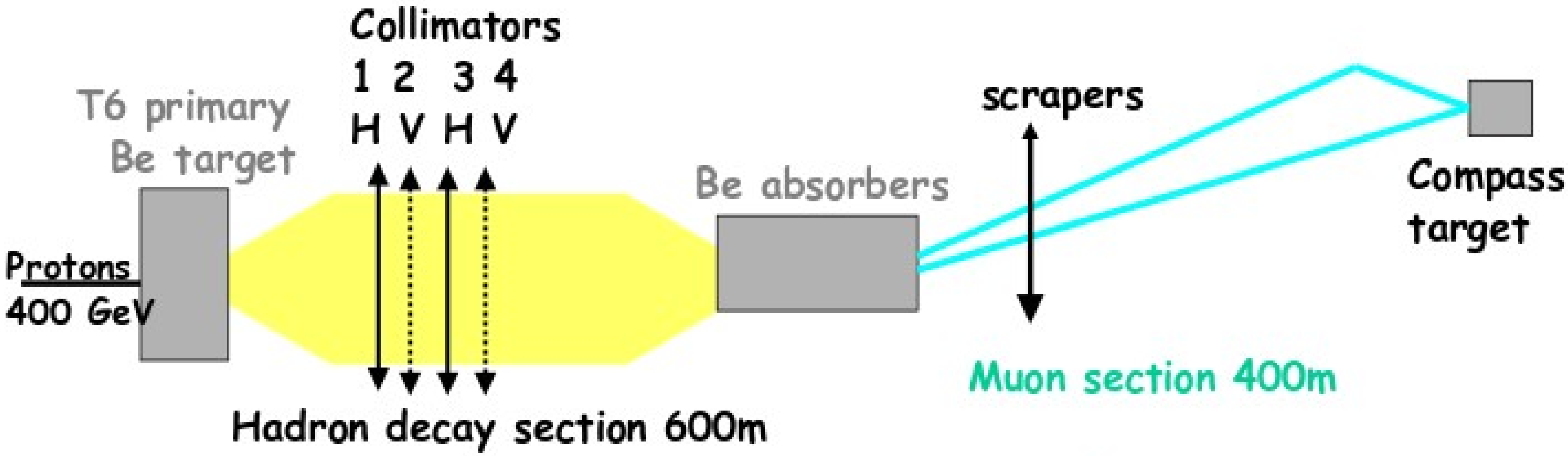
— somme
...... échange g
----- échange q

Vanderharghen, Guidal, Guidal,
PRD 60 (1999) 094017

Polarized muon beam

proton extraction → secondary pion beam → polarized muon beam (80%)

SPS
M2
beam line



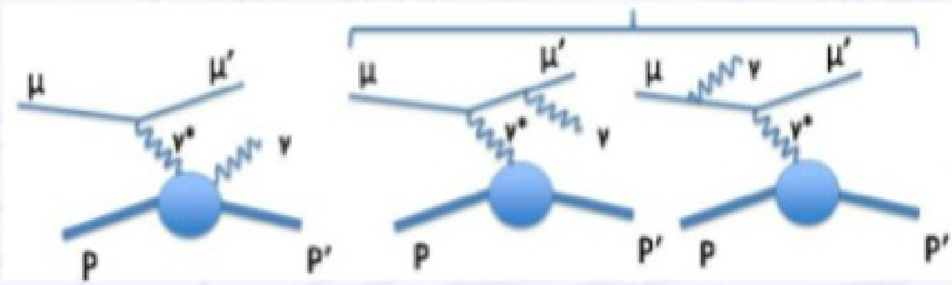
~ 10^{12} protons/second

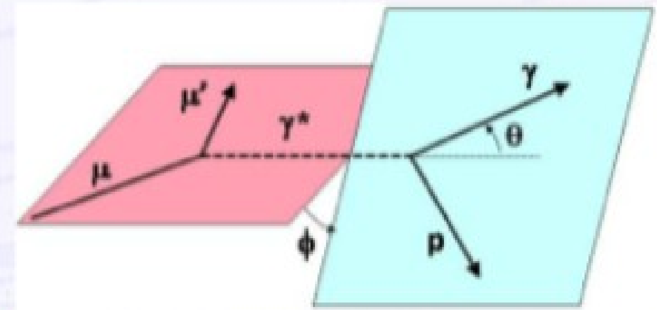
4. 10^{7} muons/second

COMPASS muon beam in 2009 :
- 1 week for DVCS test run
- 160 GeV muons (μ^{+} and μ^{-})
- 10 second beam / 45 sec. (spills)

Extraction of GPDs with COMPASS measurements

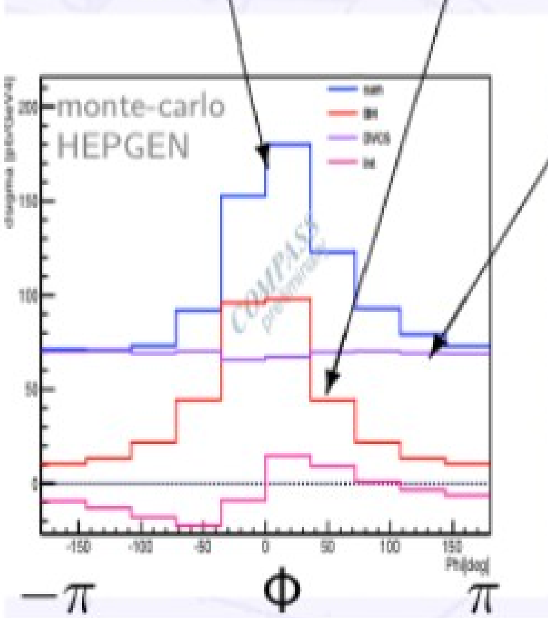
Production "exclusive" d'un γ= DVCS+Bethe-Heitler+Int.





COMPASS = $\mu^{+\leftarrow}$ et $\mu^{-\rightarrow}$ $\quad$ e_ℓ : *charge* ℓ, P_ℓ: hélicité ℓ

$$\left.\frac{d^4\sigma(\ell P \rightarrow \ell' P' \gamma)}{dx_{bj}\,dQ^2\,d|t|\,d\phi}\right/_{E_\ell} = d\sigma^{BH} + (d\sigma^{DVCS}_{unpol} + P_\ell\, d\sigma^{DVCS}_{pol}) + e_\ell(\mathcal{R}e\ Int. + P_\ell\, \mathcal{I}m\ Int.)$$



$$d\sigma_\gamma^{\mu^{+\leftarrow},u} + d\sigma_\gamma^{\mu^{-\rightarrow},u}$$

$$\propto BH + DVCS_{unpol} + \mathcal{I}m(Int)$$

$$\mathcal{I}m(Int) = \ldots\ sin\Phi$$

$$\int d\Phi \quad \frac{d\sigma^{DVCS}}{dt} \rightarrow \boxed{r_\perp}$$

$$\mathcal{I}m\,\mathcal{H} \propto \boxed{\mathbf{H}(\xi,\xi,t)\ldots}$$

$$d\sigma_\gamma^{\mu^{+\leftarrow},u} - d\sigma_\gamma^{\mu^{-\rightarrow},u}$$

$$\propto DVCS_{pol} + \mathcal{R}e(Int)$$

$$\mathcal{R}e(Int) = \ldots\ cos\Phi$$

$$\mathcal{R}e\,\mathcal{H} \propto \boxed{\int dx\mathbf{H}(x,\xi,t)\left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right)}$$

Faisceau polarisé 80%(4%)
160 GeV $\mu^{+\leftarrow}$ et $\mu^{-\rightarrow}$

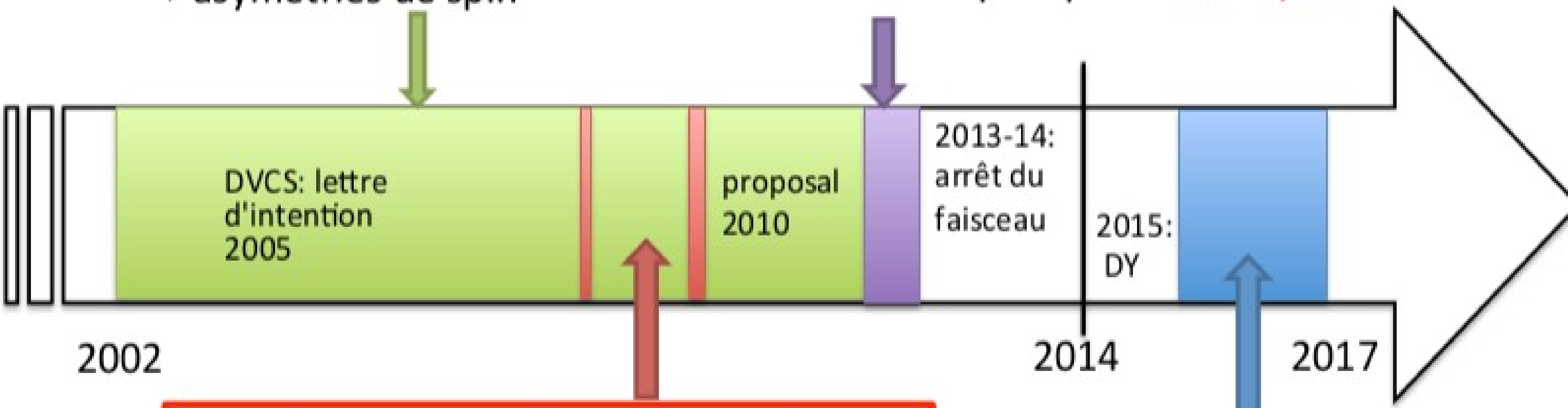
objectifs:
mesures σ(3%)

$d\sigma_\gamma^{\mu^{+\leftarrow},u} + d\sigma_\gamma^{\mu^{-\rightarrow},u}$ $\Longrightarrow$ Im (CFF) et dσ / dt

$d\sigma_\gamma^{\mu^{+\leftarrow},u} - d\sigma_\gamma^{\mu^{-\rightarrow},u}$ $\Longrightarrow$ Re (CFF)

Mésons vecteurs (2002-2011)
cible H et D polarisée // et ⊥
$\Longrightarrow$ asymétries de spin

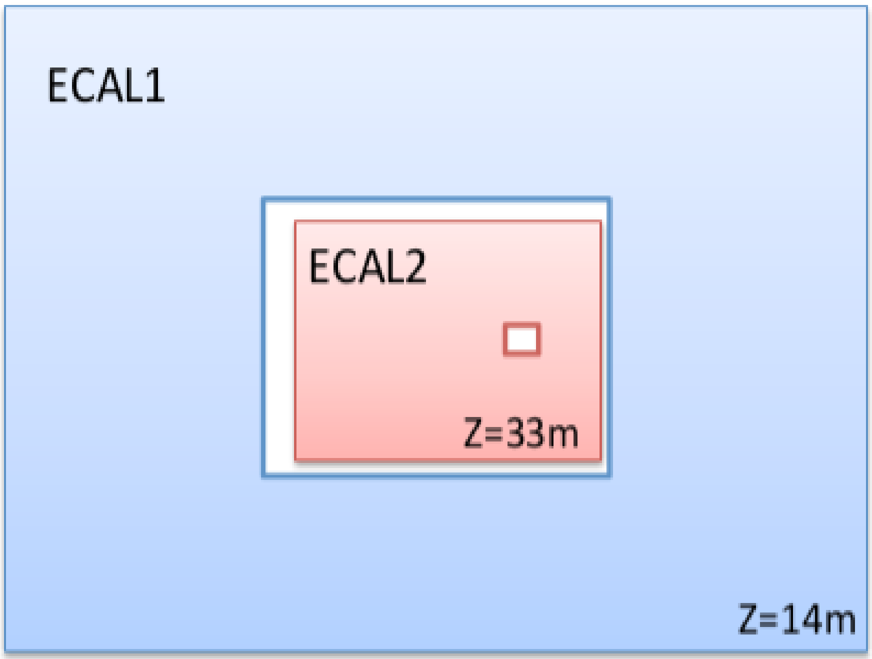
DVCS: "test run" 2012 (1 mois, dispositif final)
cible 2.5 m H_2, détecteur de recul dédié,
faisceau μ^+ & μ^- $\Longrightarrow$ $d\sigma^{DVCS}/dt$



DVCS: "test runs" 2008, 2009 (1 semaine)
cible 40 cm H_2, détecteur de recul,
test de faisabilité programme DVCS,
première mesure $\sigma^{BH+DVCS}$

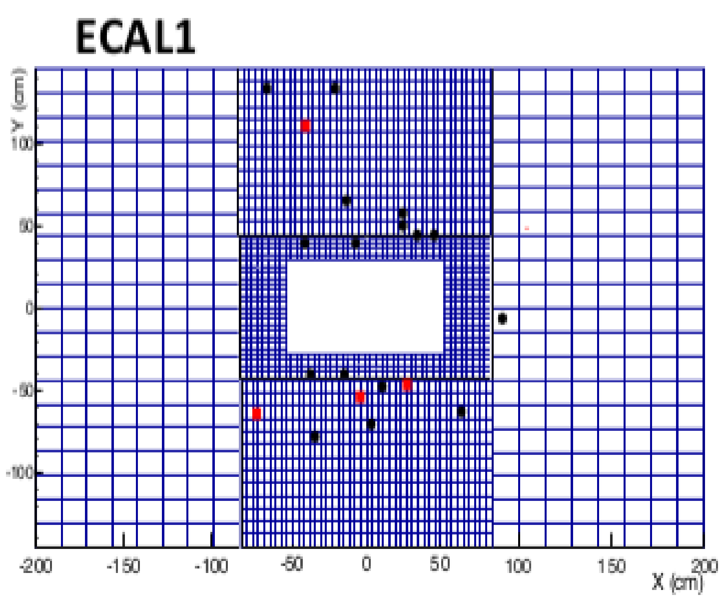
Expérience DVCS approuvée
2016-2017 (2x6 mois)
$\Longrightarrow$ accès à la GPD H
objectif: erreur 3% sur $\sigma^{\mu P \rightarrow \mu P \gamma}$

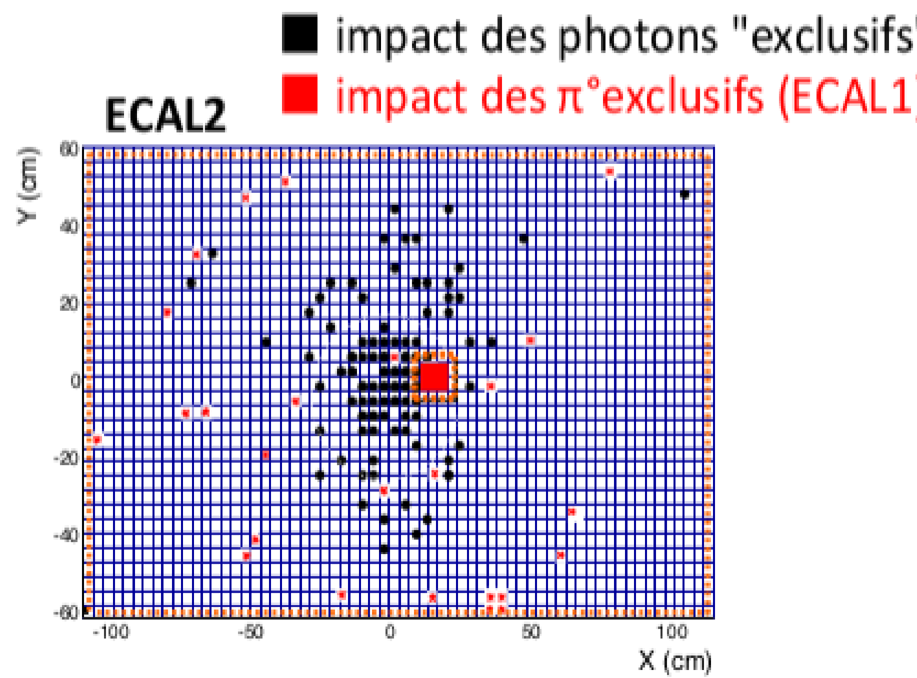
Electromagnetic Calorimeters



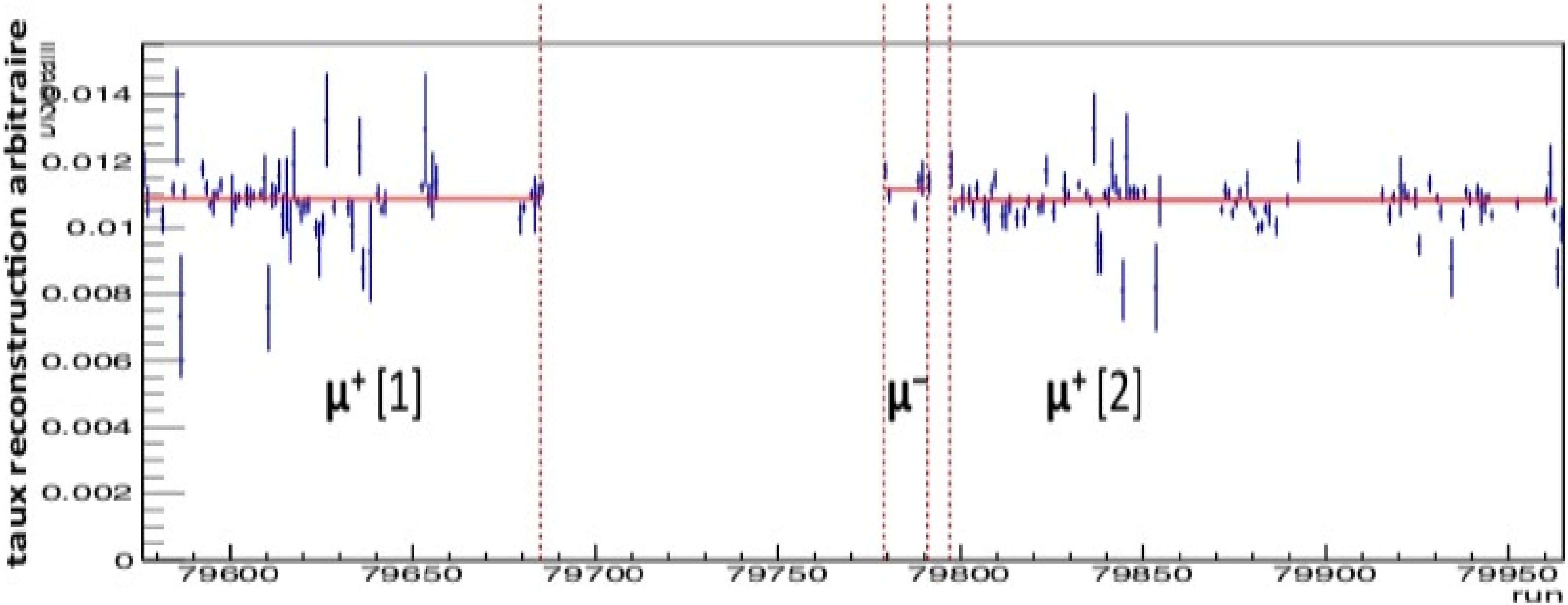
ECAL1 "grand angle"
Verre au Pb,
5 GeV < $E_\gamma \lesssim$ 25 GeV

ECAL2 "petit angle"
Verre au Pb + "Shashlik",
10 GeV < $E_\gamma \lesssim$ 140 GeV

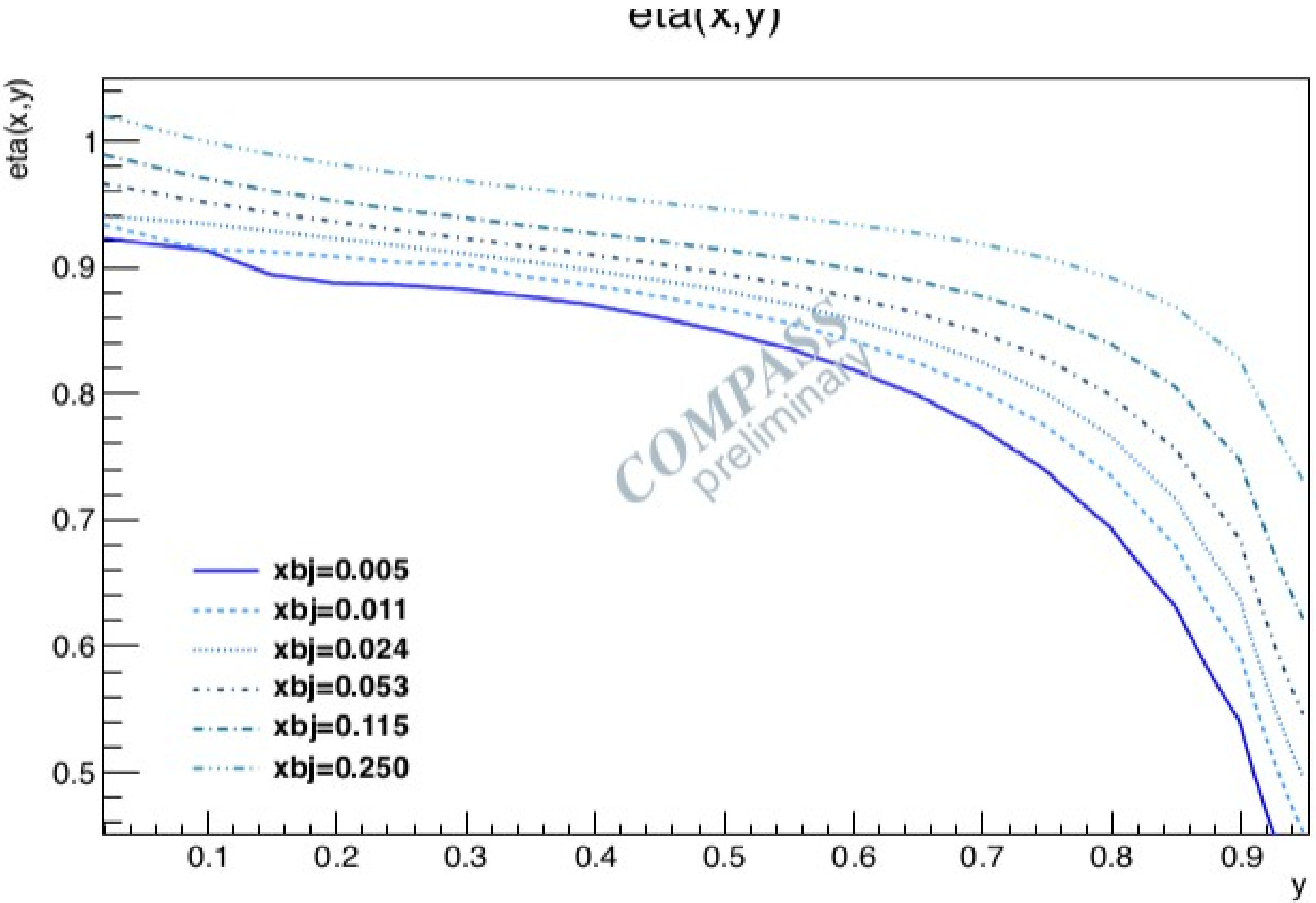




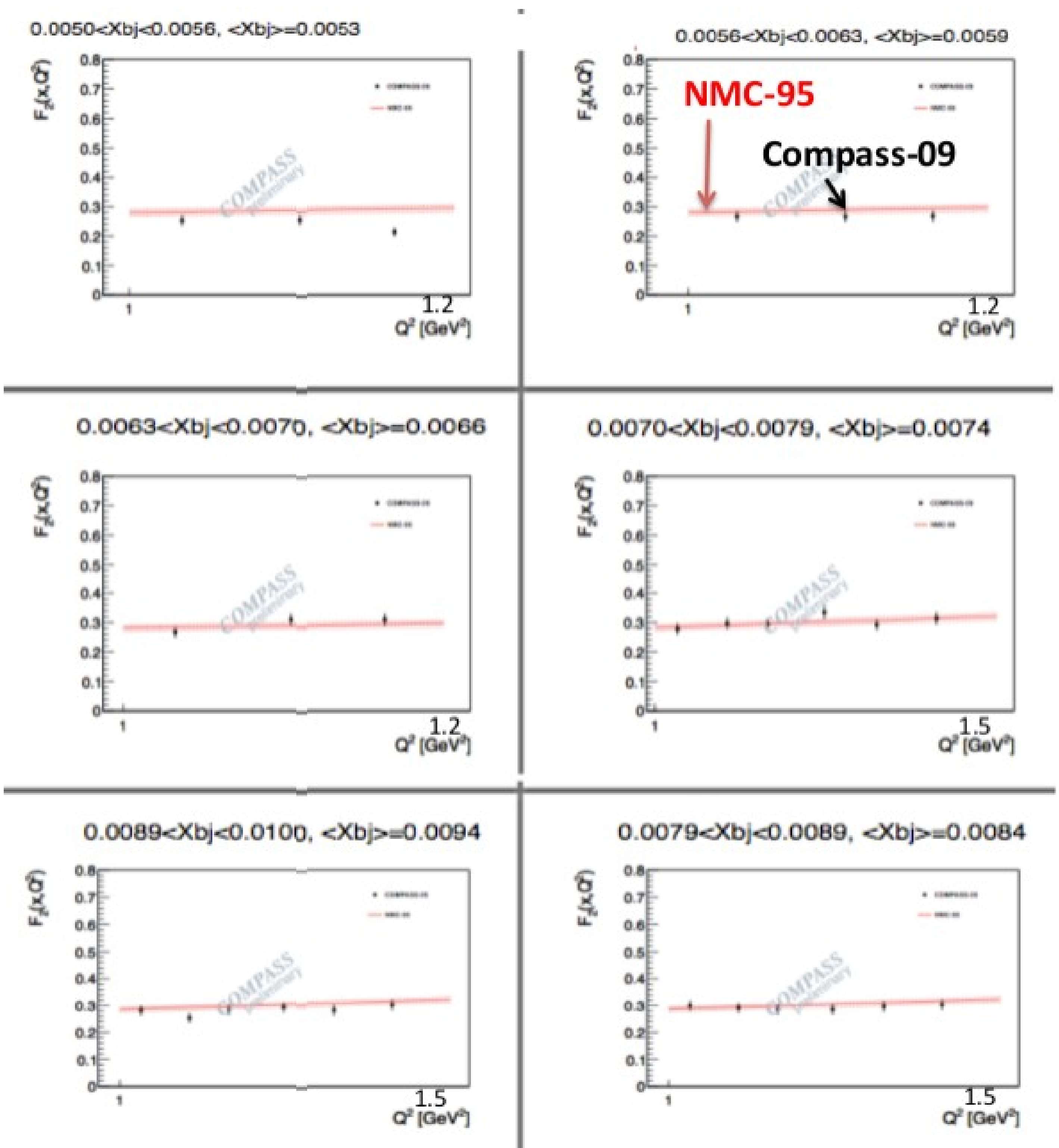
DIS stability run/run



COMPASS : radiative corrections



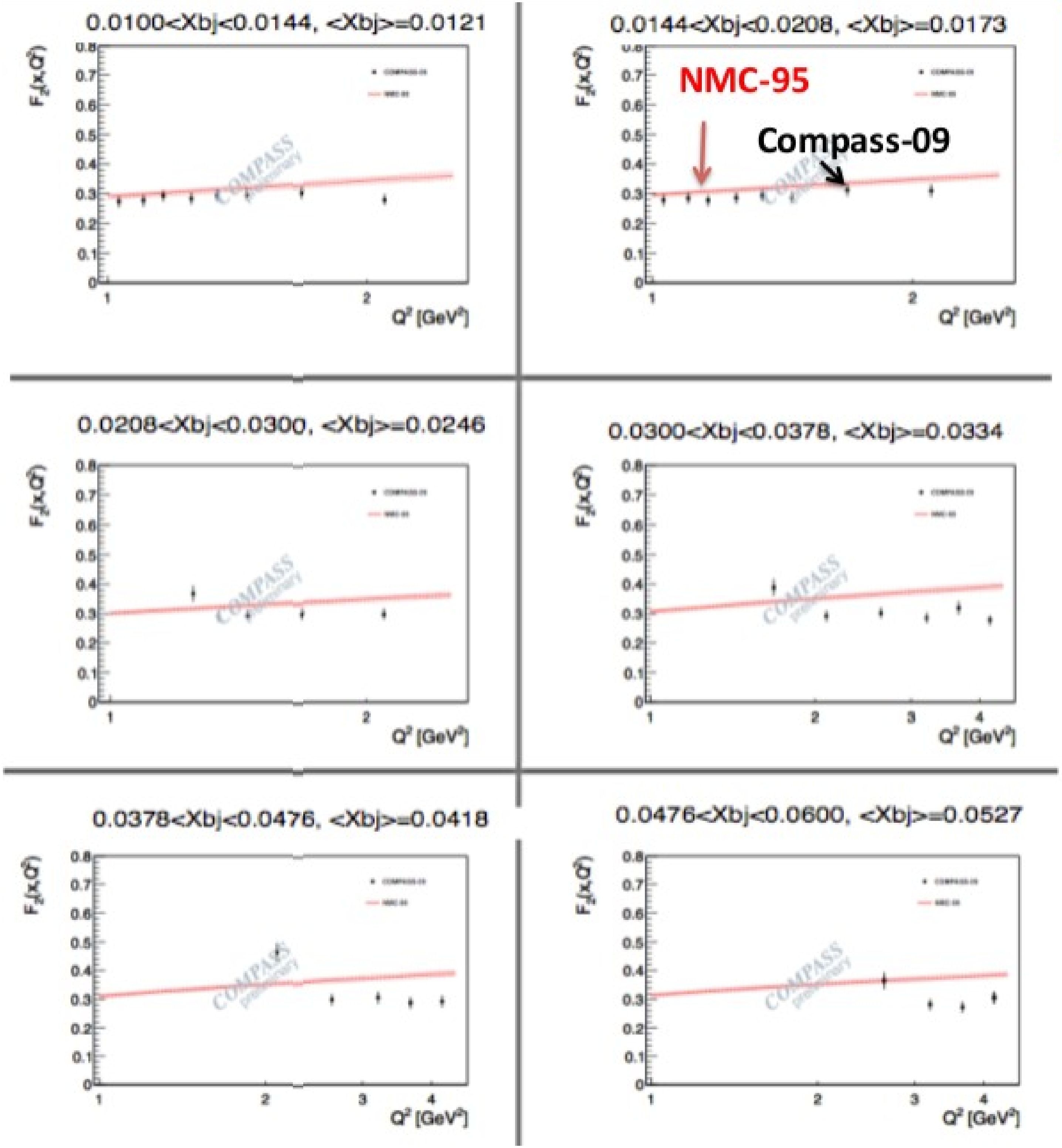
$F2(x,Q^2)$ vs Q^2 in 12 xbj bins (1/2)



= 2 first x_{bj} bins for exclusive photon

Good agreement with NMC parameterization

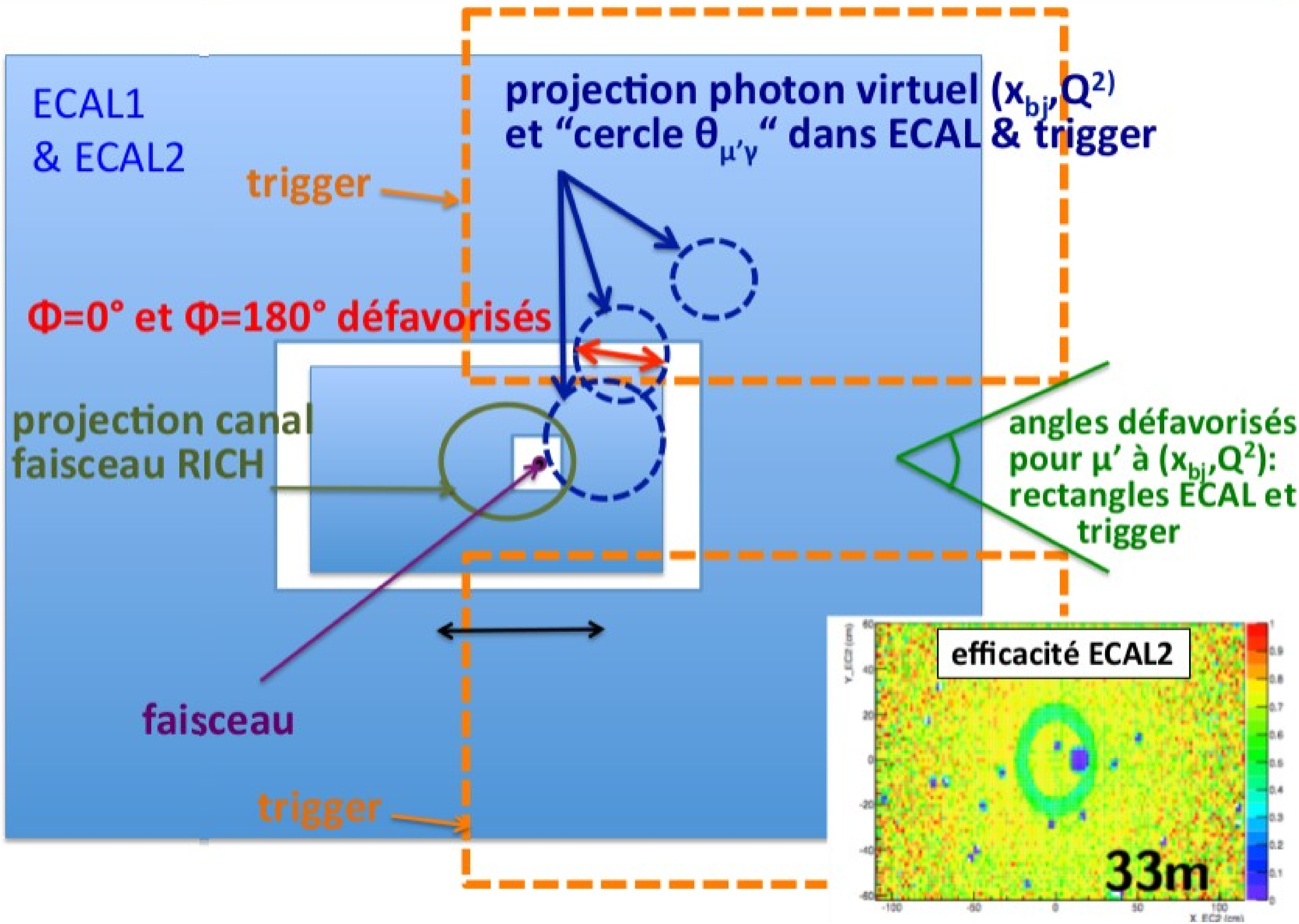
F2(x,Q^2) vs Q^2 in 12 xbj bins (2/2)



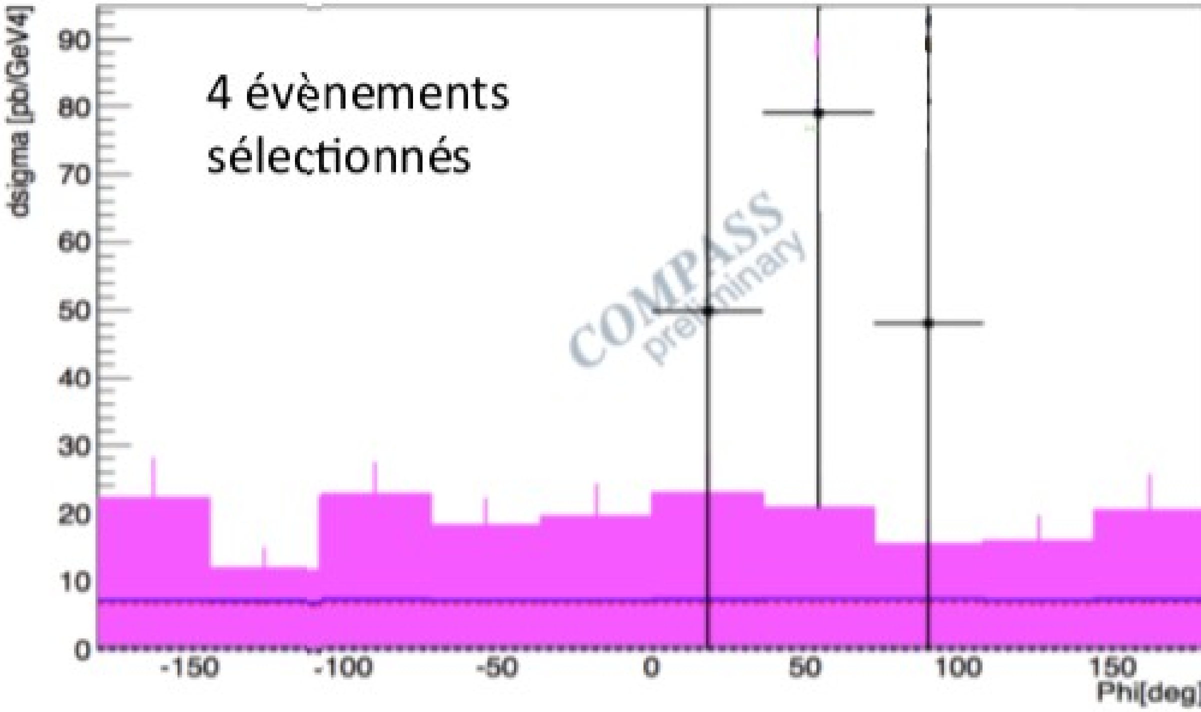
= 2 last x_{bj} bins for exclusive photon

Good agreement with NMC parameterization for xbj<0.03, some deviations at xbj>0.06

Interprétation des acceptances



Exclusive pi°



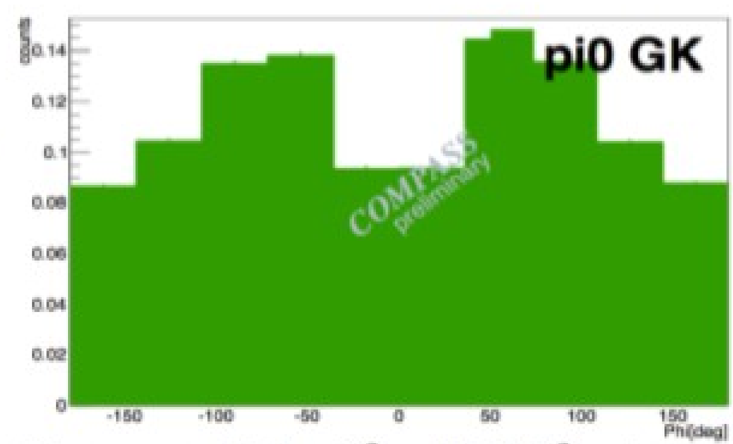
$.03 < x_{bj} < .06; 1 < Q^2 < 4.5\ \mathrm{GeV}^2; -t \in [.06; .8]\ \mathrm{GeV}^2$

Section efficace:
<20 pb.GeV^{-4} (1σ)

bruit semi-inclusif (LEPTO)
≈ 4 évènements

modèle GK

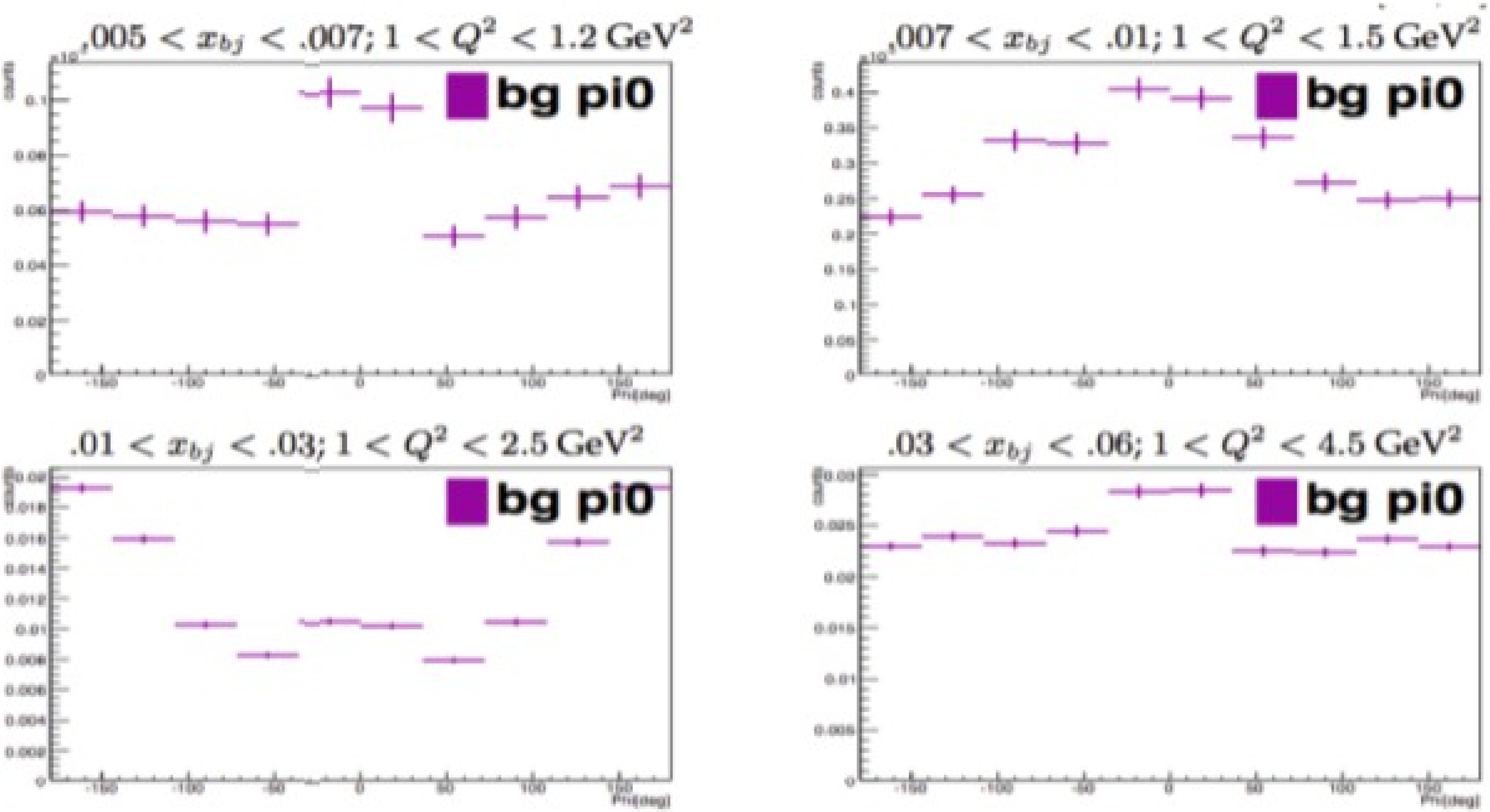
compatible GK: σ = 7.8 pb.GeV^{-4}
prédiction taux de comptage
à la luminosité 2009



$.03 < x_{bj} < .06; 1 < Q^2 < 4.5\ \mathrm{GeV}^2; -t \in [.06; .8]\ \mathrm{GeV}^2$

Permet aussi d'accéder aux GPDs
Plus de statistique requise pour cette mesure
Section efficace faible aux énergies de COMPASS

Exclusive pi° background in DVCS

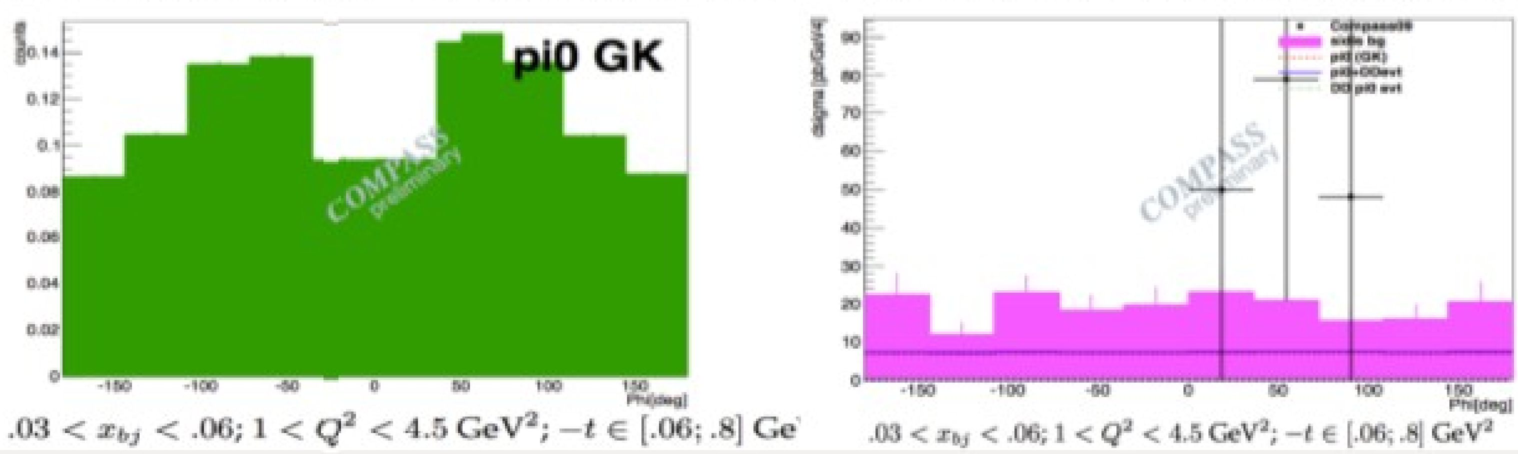


predicted counting rates in DVCS (1 gamma loss)

from GK model

small xbj ≈0
last bin <2%

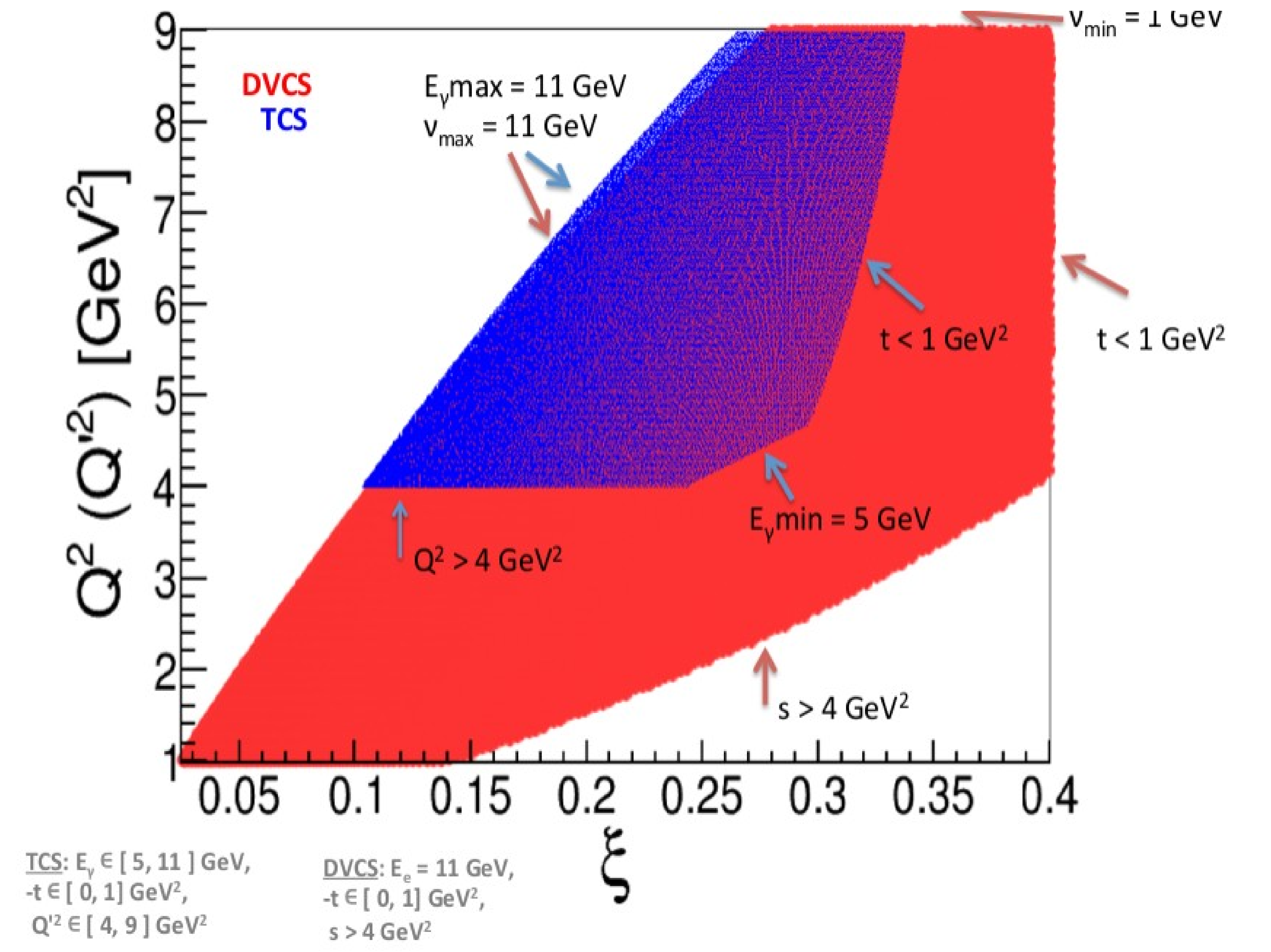
<u>check this rate</u>: π° cross section but: ≈1 event and ≈3 background at 2009 lumi (simulations)



Mesured x-section: <20 pb.GeV-4 (1σ)

GK: 7.8 pb.GeV^{-4}

<u>=> bg normalized to GK</u>



DVCS
TCS
$E_\gamma max = 11$ GeV
$\nu_{max} = 11$ GeV
$\nu_{min} = 1$ GeV
$t < 1$ GeV^2
$t < 1$ GeV^2
$Q^2 > 4$ GeV^2
$E_\gamma min = 5$ GeV
$s > 4$ GeV^2
Q^2 (Q'^2) [GeV^2]
ξ
TCS: $E_\gamma \in [5, 11]$ GeV, $-t \in [0, 1]$ GeV^2, $Q'^2 \in [4, 9]$ GeV^2
DVCS: $E_e = 11$ GeV, $-t \in [0, 1]$ GeV^2, $s > 4$ GeV^2

Corrections en masse avec ξ

"cône de lumière"

$$\tilde{\xi} = \xi \cdot \frac{1+\tilde{\xi}'^2 \frac{\bar{M}^2}{\bar{q}^2}}{1-\tilde{\xi}'^2 \frac{\bar{M}^2}{\bar{q}^2}}$$

$$\tilde{\xi}' = \xi' \cdot \frac{2}{1+\sqrt{1-4\xi'^2 \frac{\bar{M}^2}{\bar{q}^2}}}$$

Variables cinématiques accessibles expérimentalement

$$\xi' = -\frac{\bar{q}^2}{2P.\bar{q}} = \frac{-Q'^2 + \Delta^2/2}{2(s-m_N^2)+\Delta^2-Q'^2}$$

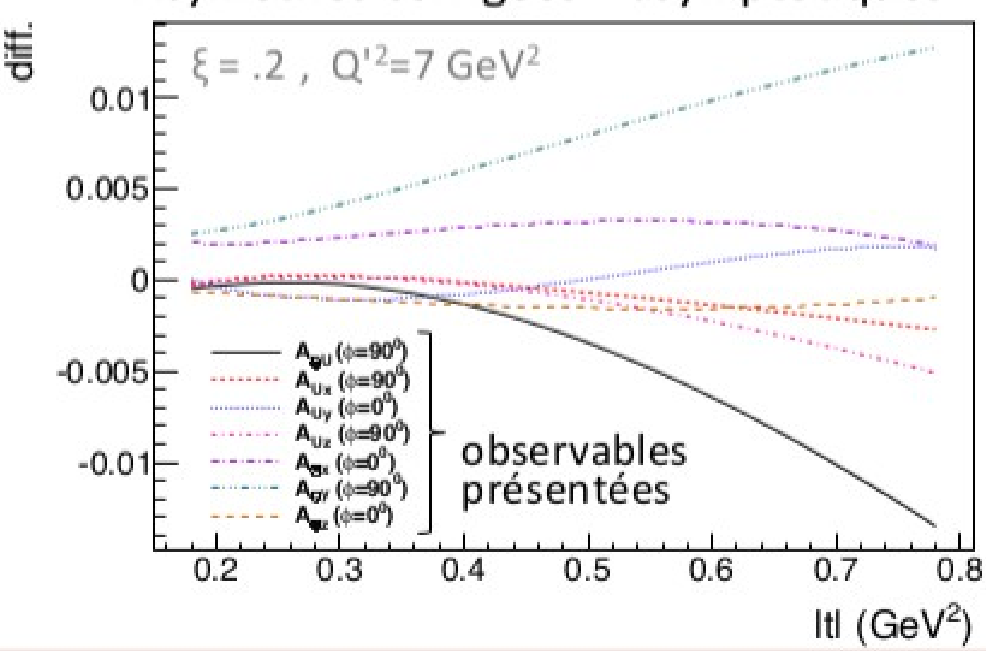
$$\xi = -\frac{\Delta.\bar{q}}{2P.\bar{q}} = \frac{Q'^2}{2(s-m_N^2)+\Delta^2-Q'^2}$$

Limite asymptotique (twist 2)
Δ^2/Q^2 et $M^2/Q^2 \ll 1$

$$\tilde{\xi} = \xi = -\tilde{\xi}' = -\xi' = \frac{Q'^2}{2s-Q'^2}$$

Correction en "masse": levée des approximations avec $\tilde{\xi}' \neq -\xi$

Asymétries corrigées – asymptotiques



Corrections sur les asymétries: <0.01 vs 0.10 à 0.30, sections efficaces: <5%

Restauration de l'invariance de jauge

Condition d'invariance de jauge : $q_\mu H^{\mu\nu} = q_\nu H^{\mu\nu} \equiv 0$

Amplitudes au twist 2 non invariantes de jauge

Or $\rightsquigarrow q_\mu H^{\mu\nu}_{LO} = \frac{1}{2}(\Delta_\perp)_\kappa H^{\kappa\nu}_{LO}$ et $q'_\nu H^{\mu\nu}_{LO} = -\frac{1}{2}(\Delta_\perp)_\lambda H^{\kappa\lambda}_{LO}$

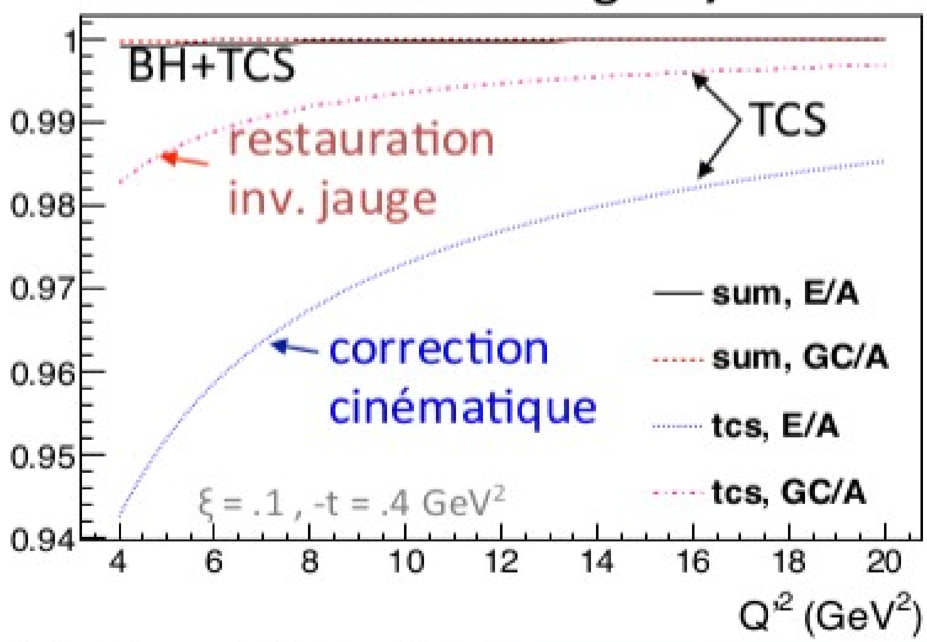
Nous restaurons l'invariance de jauge avec la correction[1]:

$$H^{\mu\nu} = \underbrace{H^{\mu\nu}_{LO}}_{\text{twist 2 (ordre le plus bas en 1/Q') partie vecteur}} - \frac{P^\mu}{2P\cdot\bar{q}}\cdot(\Delta_\perp)_\kappa \cdot H^{\kappa\nu}_{LO} + \frac{P^\nu}{2P\cdot\bar{q}}\cdot(\Delta_\perp)_\lambda \cdot H^{\mu\lambda}_{LO} - \frac{P^\mu P^\nu}{4(P\cdot\bar{q})^2}\cdot(\Delta_\perp)_\kappa\cdot(\Delta_\perp)_\lambda\cdot H^{\kappa\lambda}_{LO}$$

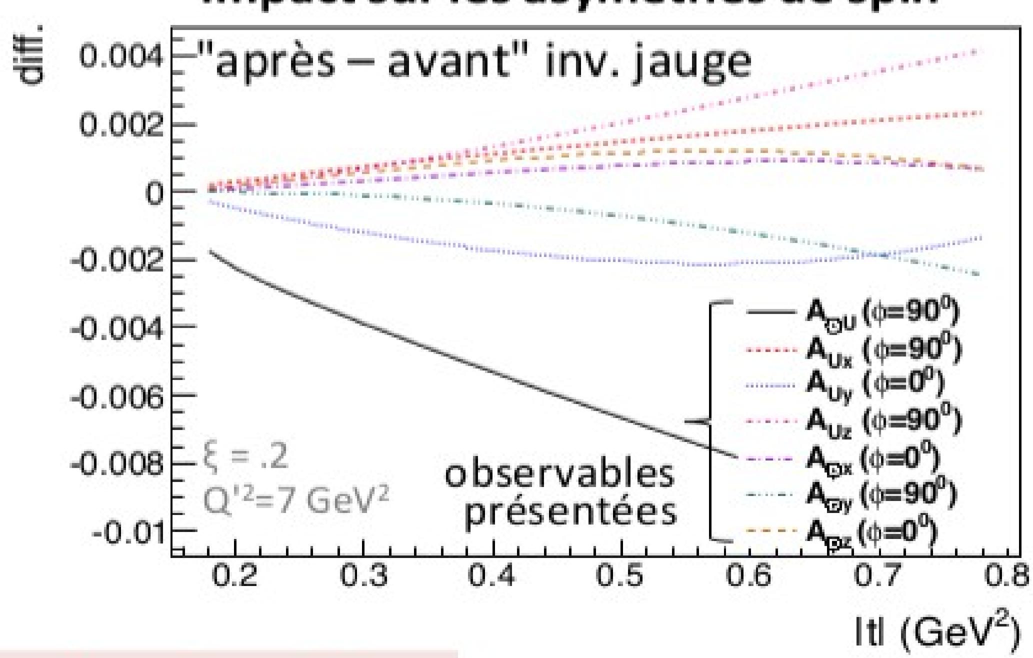
twist 2 (ordre le plus bas en 1/Q')
partie vecteur

termes additionnels

Sections efficaces corrigées / "avant"



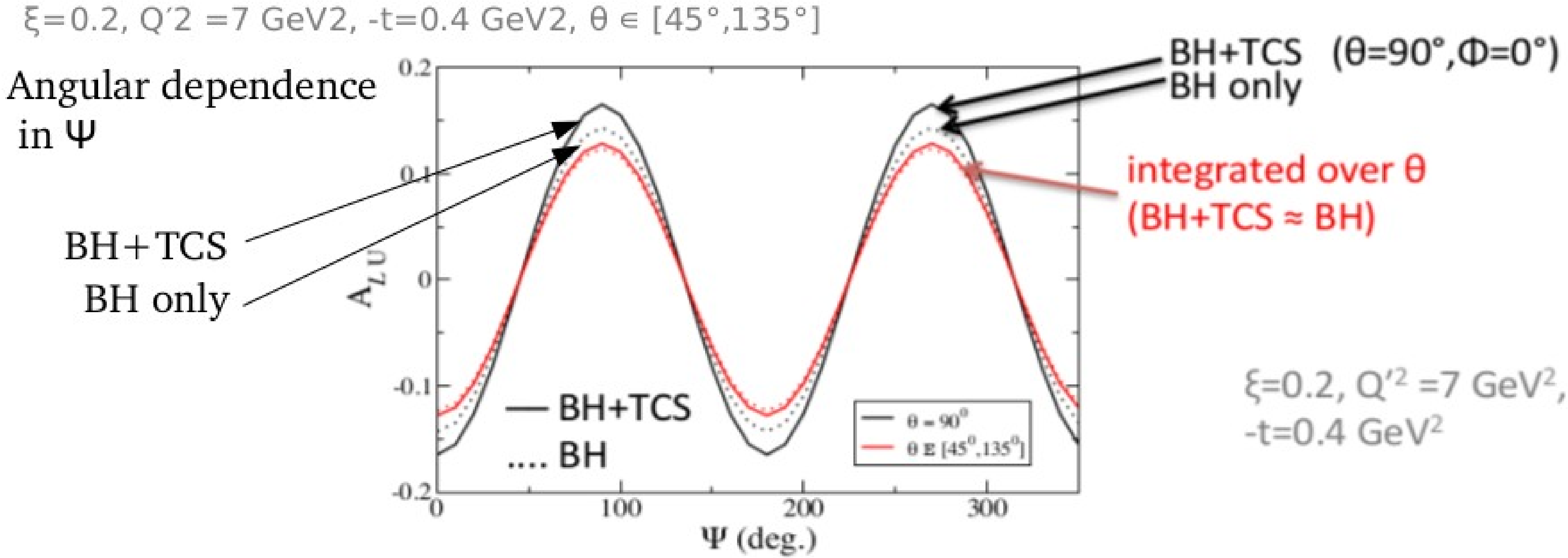
Impact sur les asymétries de spin



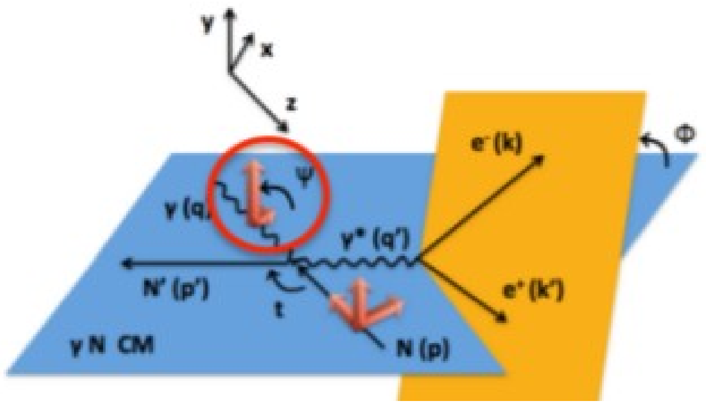
[1] Vanderhaeghen, Guichon, Guidal, PRD 60 (1999) 094017

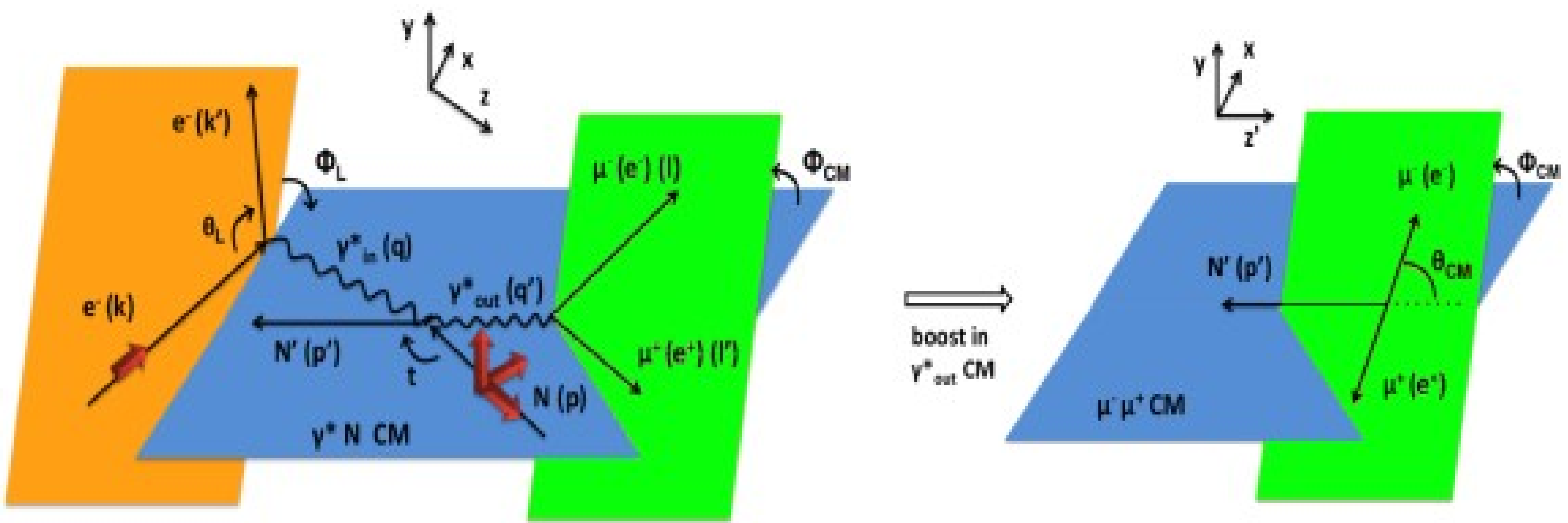
corrections ≪ valeurs des observables

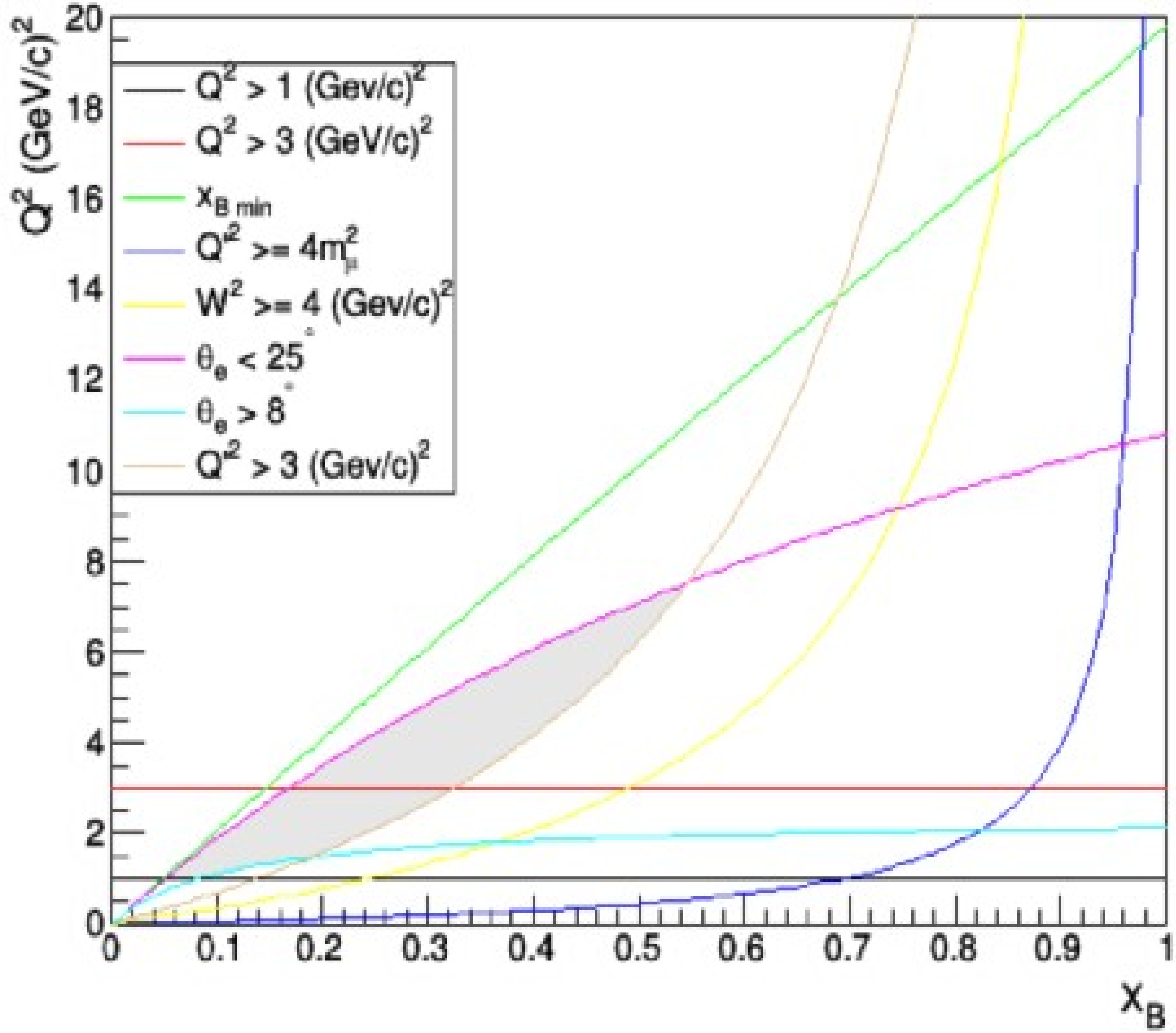
Linearly polarized Beam Spin Asymmetries



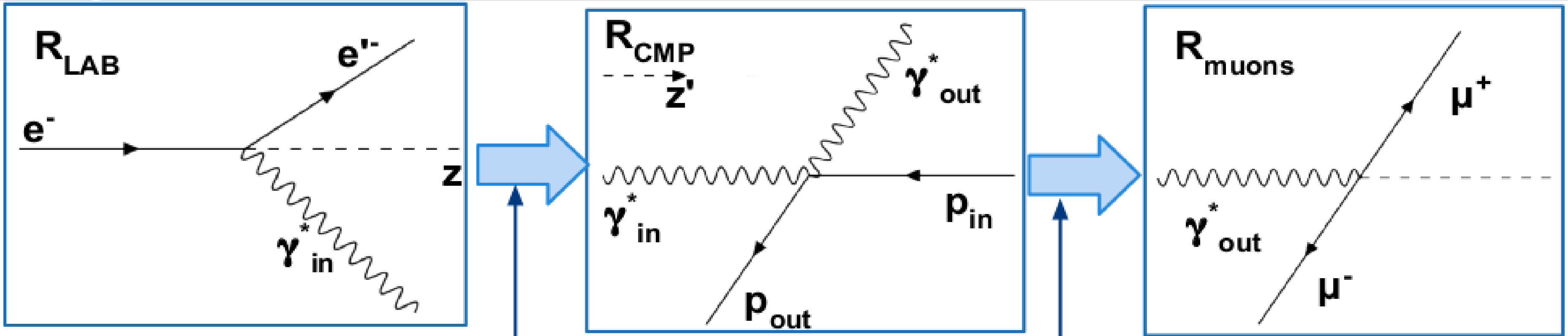
- Real part of amplitudes ⟹ BH only ≠ 0
- Small deviation due to TCS, small sensitivity to the GPDs
- Bins in ϕ and θ required




y
x
z
e⁻ (k′)
Φ_L
θ_L
γ*_in (q)
e⁻ (k)
γ*_out (q′)
N′ (p′)
t
N (p)
γ* N CM
μ⁻ (e⁻) (l)
μ⁺ (e⁺) (l′)
Φ_CM
boost in
γ*_out CM
y
x
z′
μ⁻ (e⁻)
Φ_CM
N′ (p′)
θ_CM
μ⁺ (e⁺)
μ⁻ μ⁺ CM



Q^2 (GeV/c)^2
Q^2 > 1 (Gev/c)^2
Q^2 > 3 (GeV/c)^2
$x_{B\ min}$
Q^2 >= $4m_\mu^2$
W^2 >= 4 (Gev/c)^2
θ_e < 25°
θ_e > 8°
Q^2 > 3 (Gev/c)^2
0
2
4
6
8
10
12
14
16
18
20
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
X_B



Boost dans le reférentiel du centre de masse $[\gamma^*_{in}, p_{in}]$

Boost dans le référentiel de la création de la paire de muons

Enfin, on ramène les 4-vecteurs de toutes les particules finales dans R_{LAB}

0	0	0	0	...
0	0	0	0.1	...
0.1	0.2	0.1	0.2	...
0.2	0.4	0.2	0.6	...
...	...	...	...	...

Tables de sections efficaces précalculées en fonction des modèles

Générateur

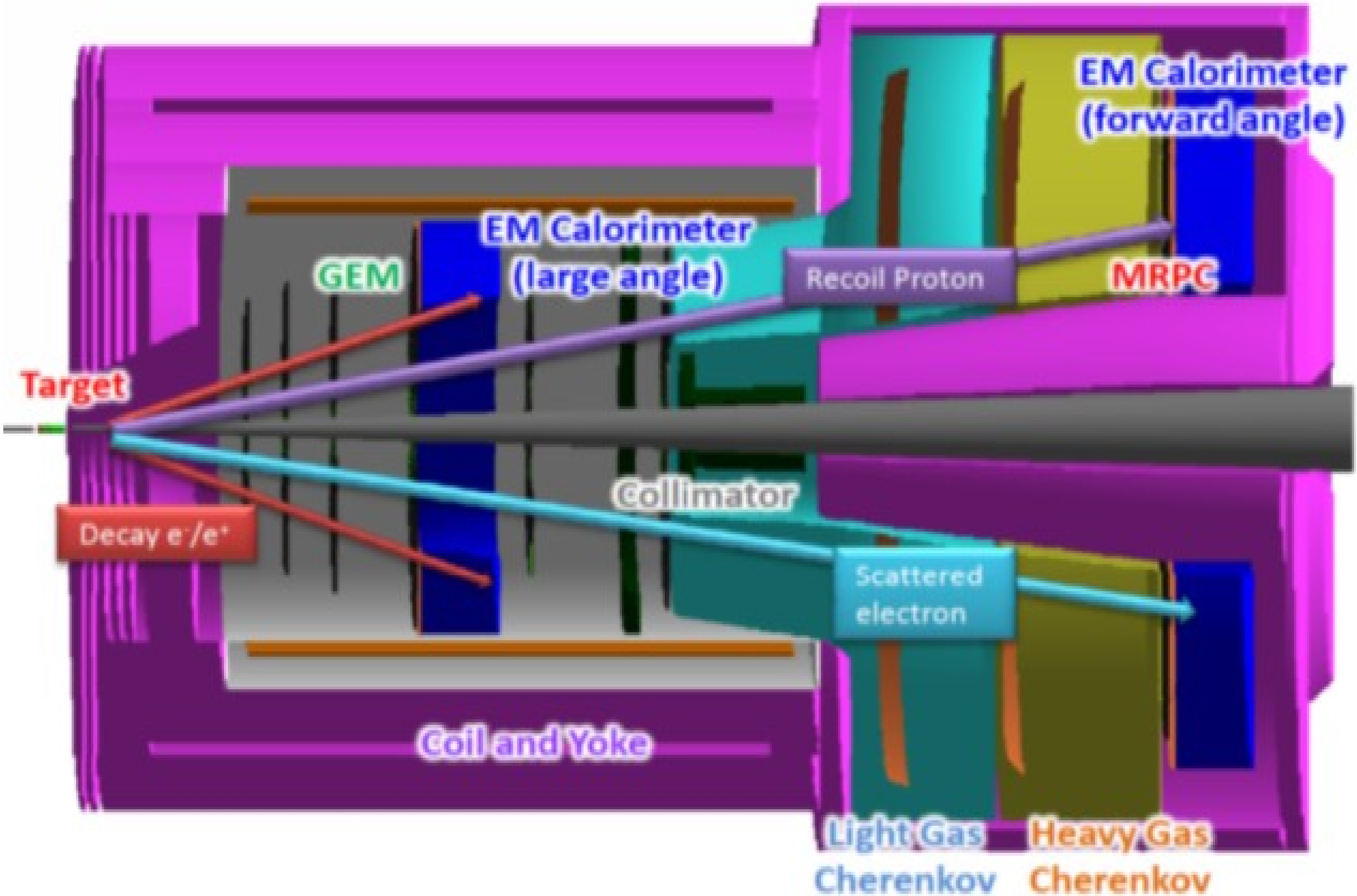
Génération aléatoire des variables cinématiques

Calcul des 4-vecteurs des particules de l'état final dans l'espace de phase

Pondération des évènements en fonction des sections efficaces

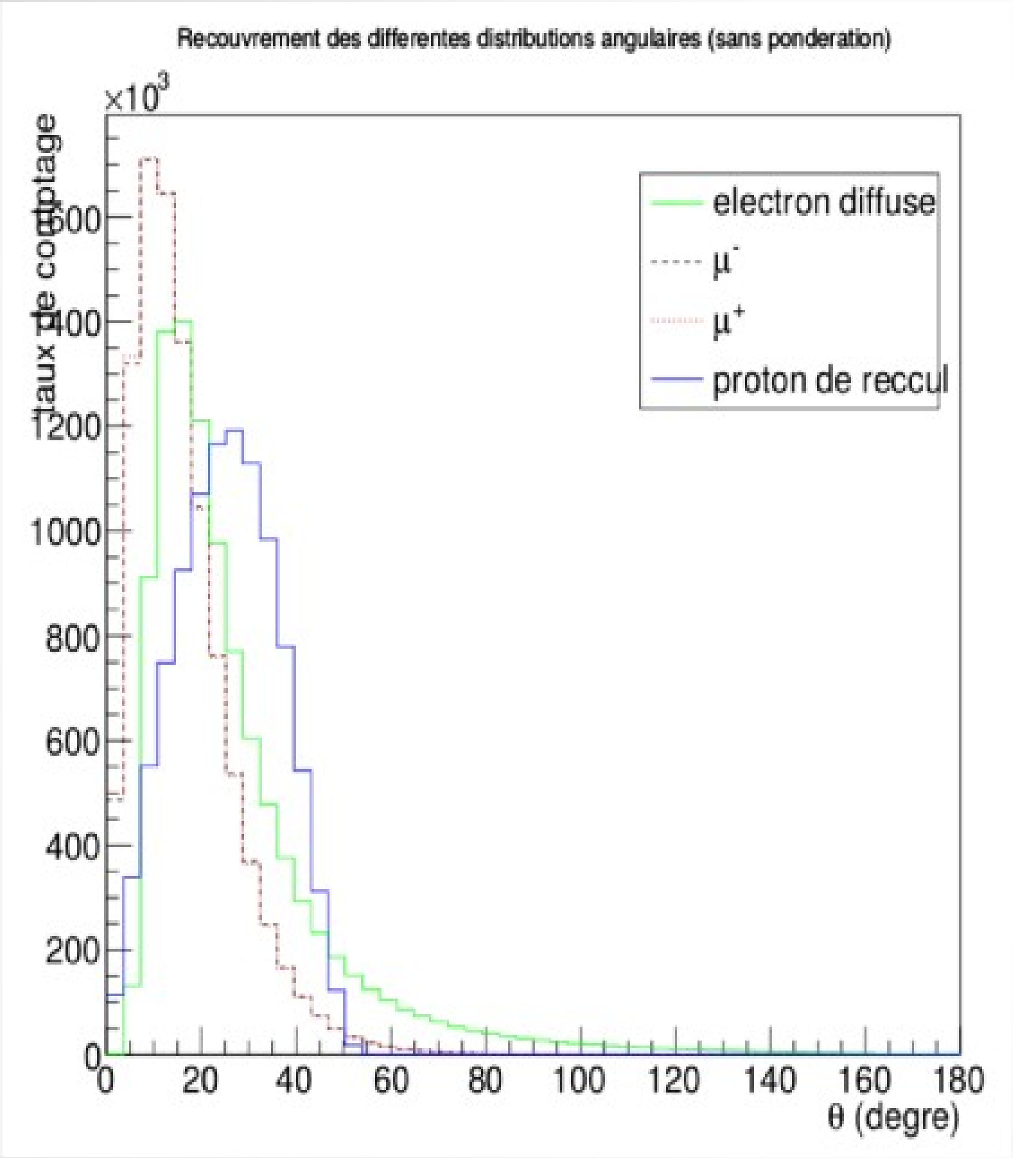
Évènements générés

From R. Lustrat



EM Calorimeter
(forward angle)
EM Calorimeter
(large angle)
GEM
Recoil Proton
MRPC
Target
Collimator
Decay e⁻/e⁺
Scattered
electron
Coil and Yoke
Light Gas
Cherenkov
Heavy Gas
Cherenkov

Distributions angulaires



Particule détectée	Détection (provisoire)
électron	16-25° et 8-14.5°
muons	0-20°
proton	16-25° et 8-14.5°

➪ **La configuration actuelle du détecteur est apte à la détection des produits de réaction.**

➪ **Canal e^+/e^-: fort recouvrement entre e^- de la paire et e^- du faisceau → difficultés pour définir les variables cinématiques.**

From A. Luboz