Timelike Compton Scattering off transversely polarized proton

C12-18-005

PAC 48, August 13th, 2020

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Proposal for Hall C, with NPS and CPS collaborations

This proposal

Following E12-18-005 conditionally approved (C2) in 2018

Main TAC concerns in 2018

- high rates in hodoscopes
- proton tracking accuracy

Main updates:

- hodoscopes replaced by GEM+scintillators hodoscopes for proton detection and tracking
- trigger with GEM+scintillators+calorimeter
- improved background and tracking studies

This presentation:

1) New additions to the setup

2) Other parts of the experimental setup

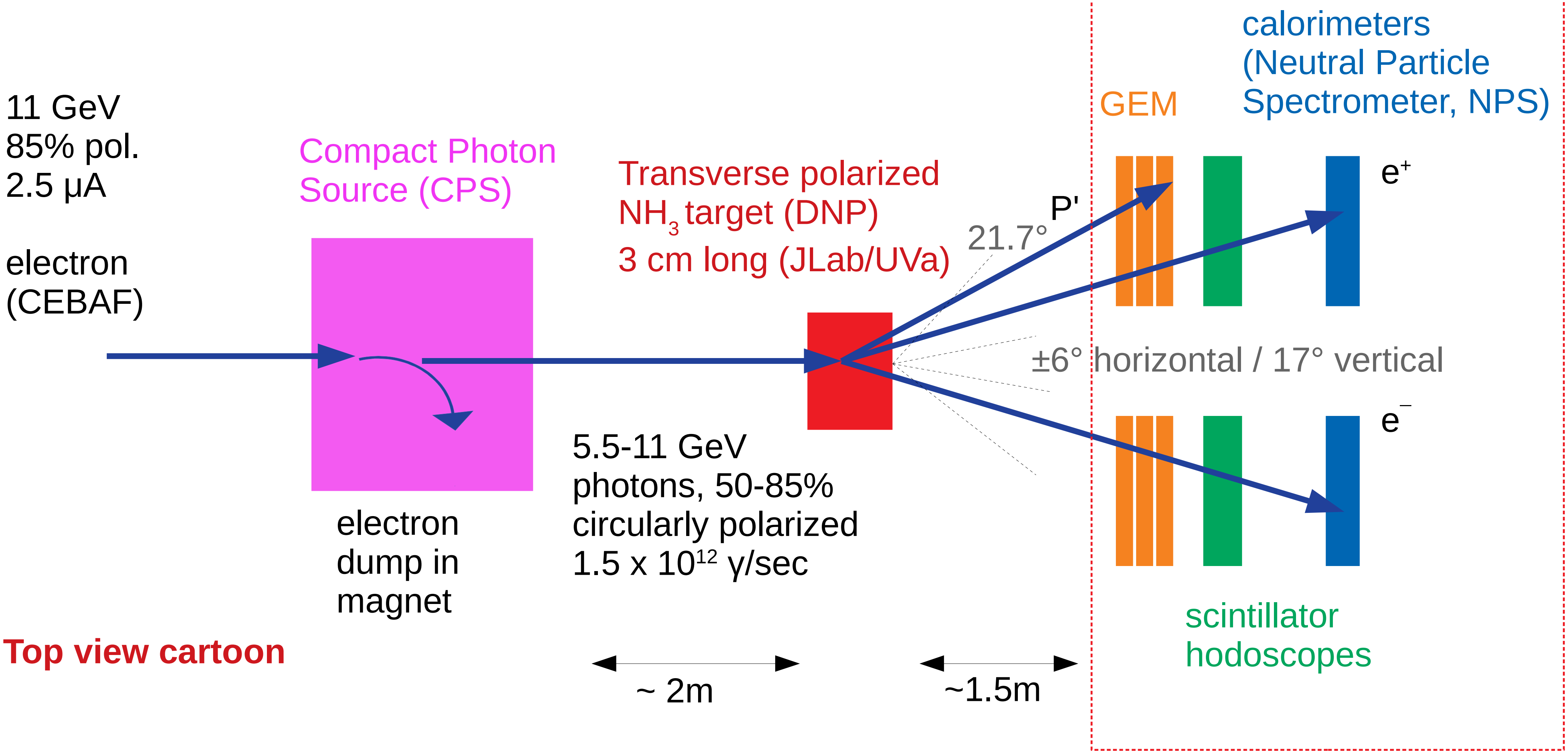
3) Physics goals of our experiment

4) Analysis and what is expected

Experimental setup

γ P → e^+ e^- P'

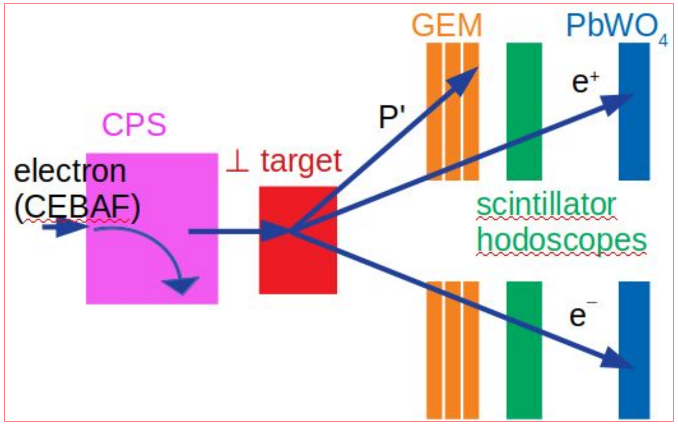
All 3 final particles in coincidence detected



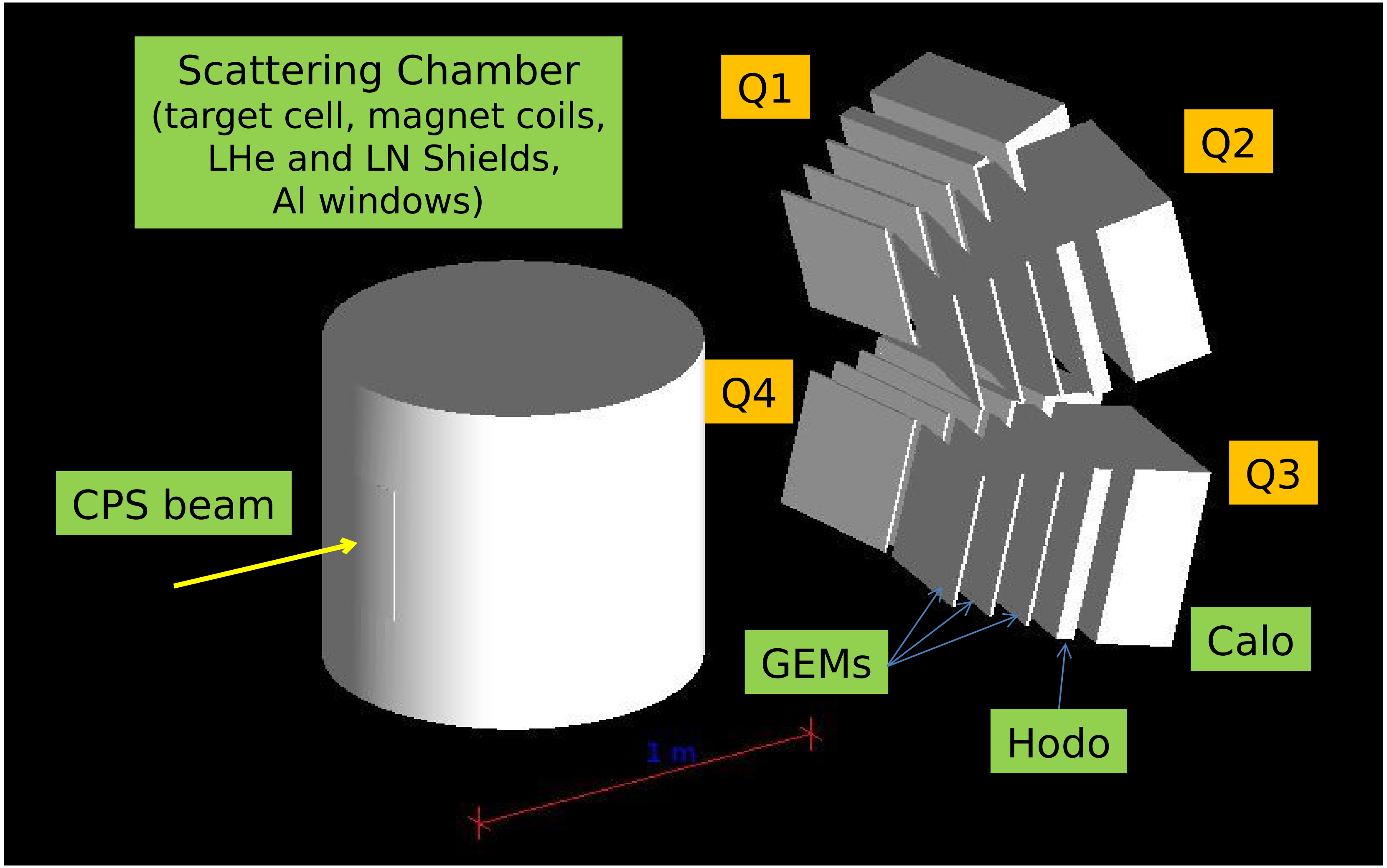
Trigger: GEMs, hodoscopes, calorimeters (all 3 particles)

Integrated luminosity: 5.85 x 10^5 pb^{-1} for 30 PAC days of "physics"

Experimental setup



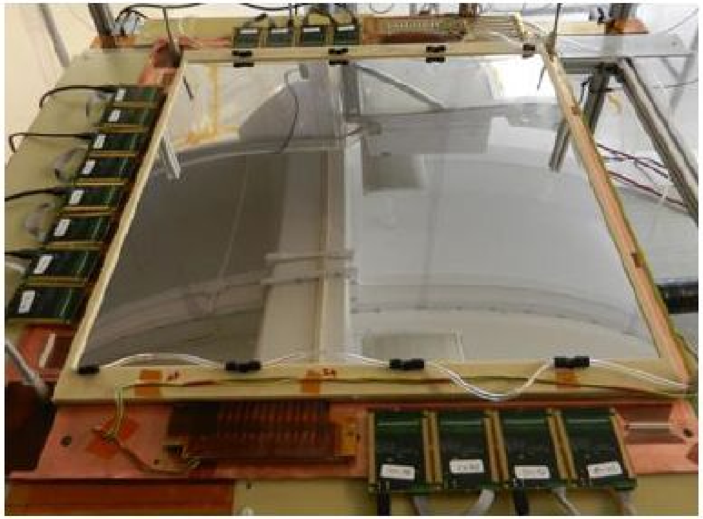
- Radiator: Compact Photon Source
- Target: ⊥ polarization, NH_3
- GEMs (new), scintillator hodoscopes
- Calorimeters: $PbWO_4$
- Trigger: 3 particles, GEM+hodoscope+calorimeter



Trackers: GEM

Main addition to our setup since 2018

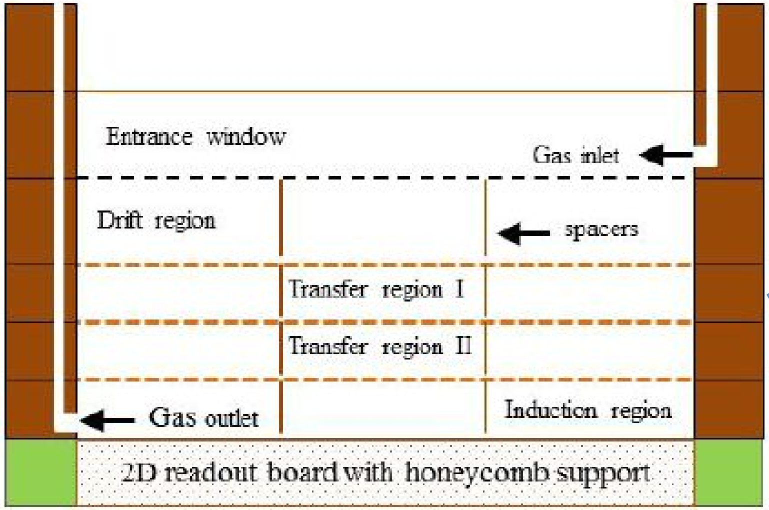
SBS BT GEM prototype

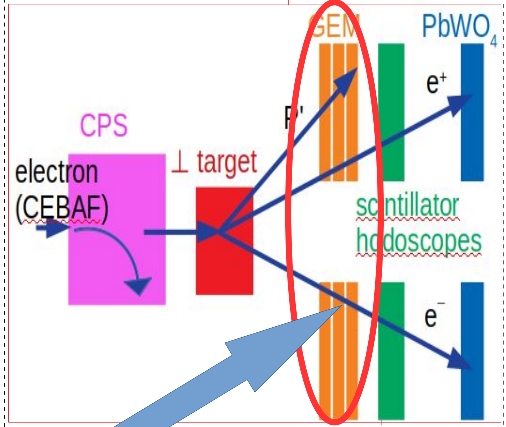


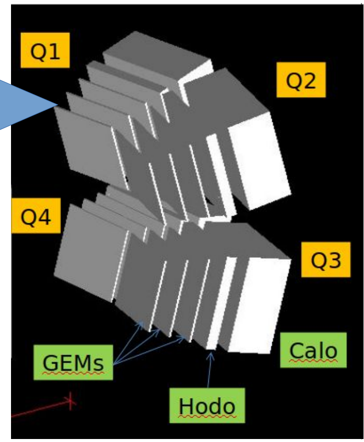
from: Gnanvo et al. NIM. A 782 (2015)

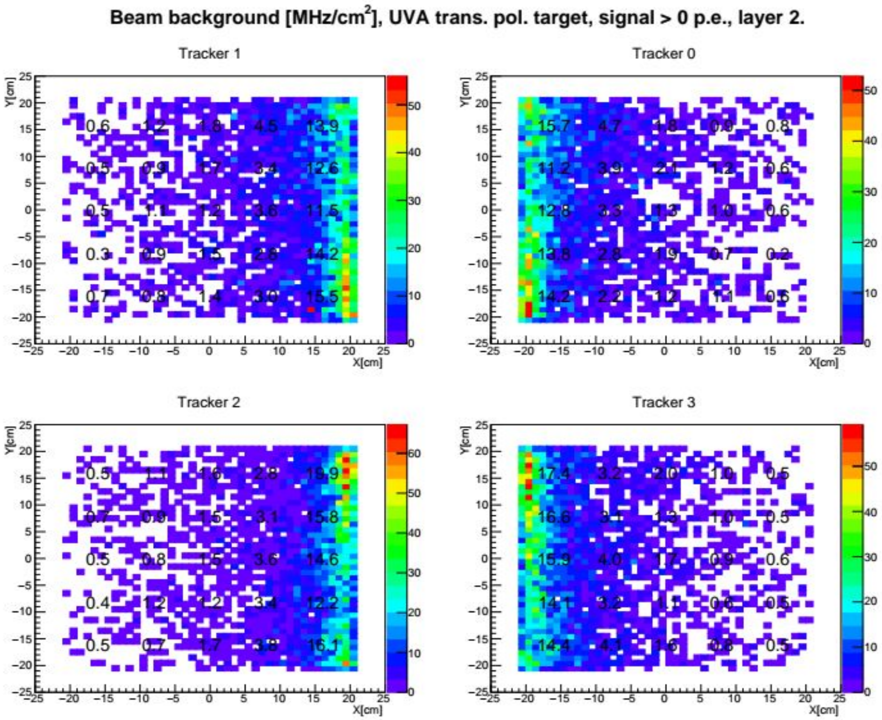
4 groups, 3 layers

SBS BT GEM module







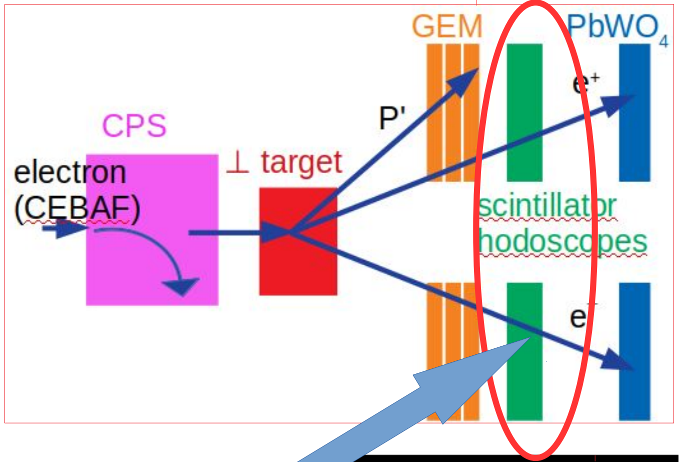


- Tolerance rate 10^6 Hz/mm²
- Tracking accuracy: ~ 100 μm
- Tolerance to magnetic field: 1.4 T [as tested with BONUS]
- 3 parallel layers, split in 4 symmetric quadrants 50x50 cm

As per several Hall A experiments using SBS, PRad, SoLID

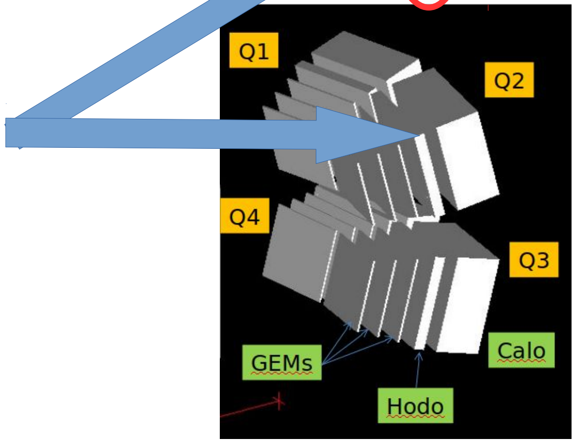
Trackers: scintillator hodoscopes

Modification to our setup since 2018

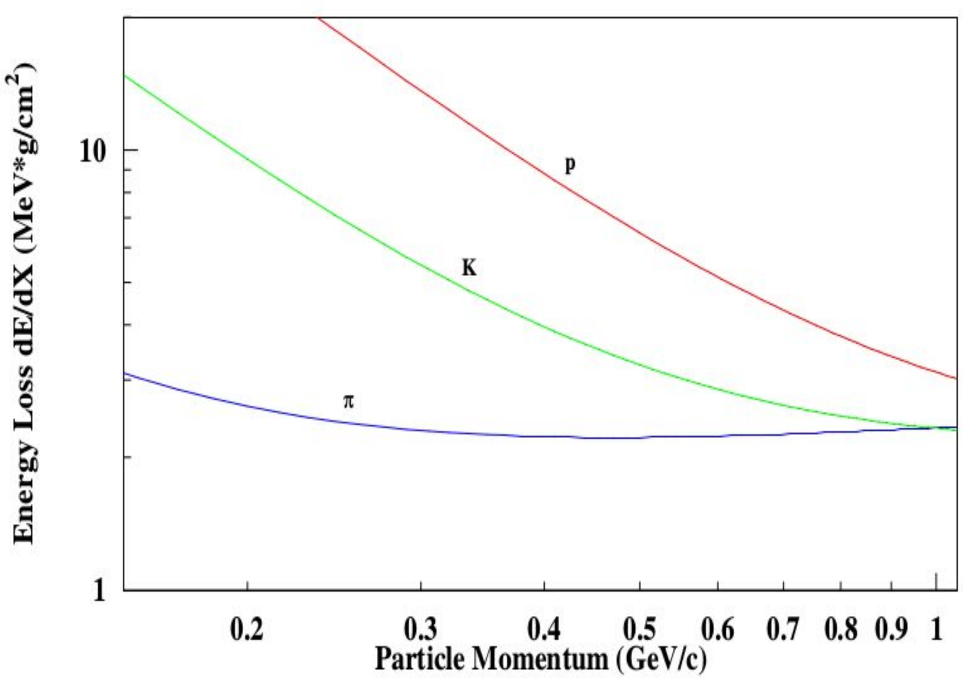


- 2x2x5 cm³ active elements scintillators with light detectors on the rear
- Along particle trajectory
- dE/dX for low momentum protons, complete tracking

4 groups

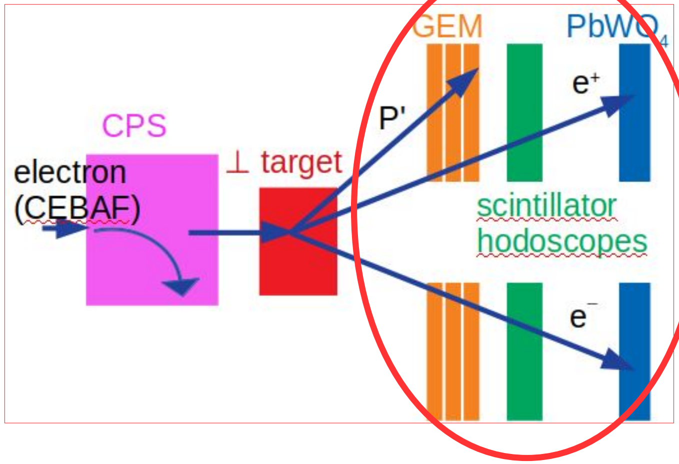


dE/dx for protons, π and K vs momentum



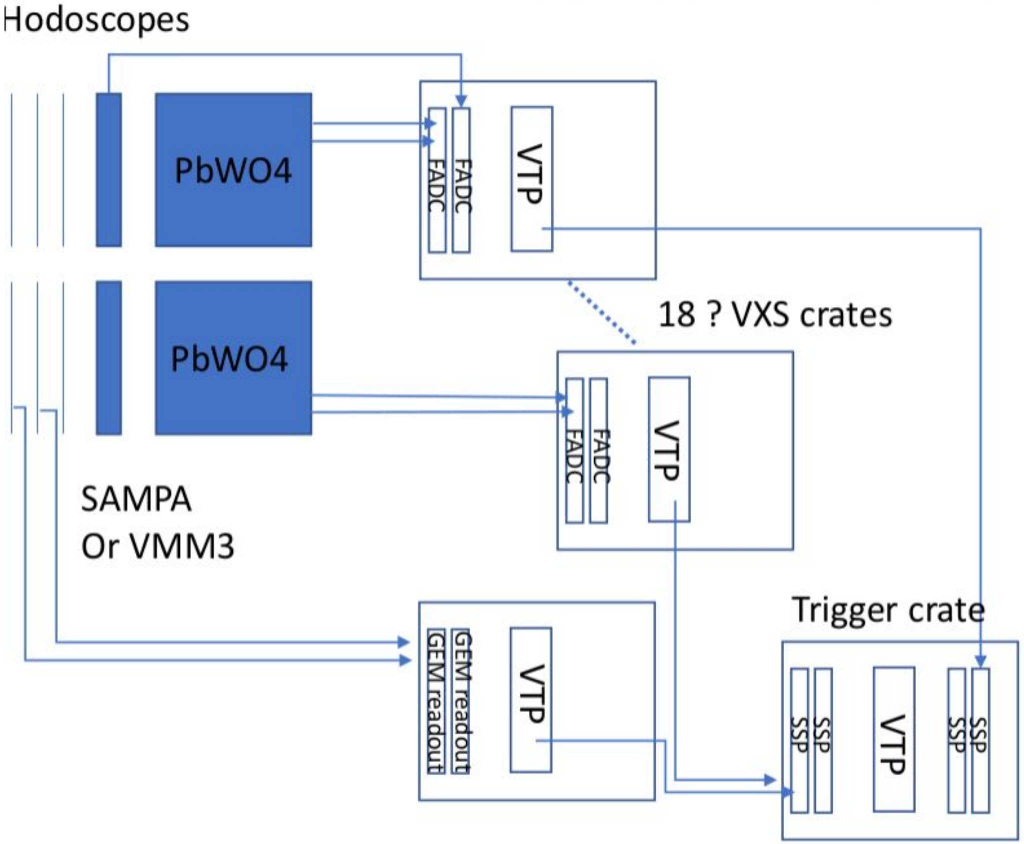
Note:
particles bended by target magnetic field

Trigger and DAQ



Main modification to our setup since 2018

γ P → e+ e- P' 3 final particle in trigger



4 x 23x23 crystals and scintillators
= 2116 x 2 = 4,232 fADC
4 x (5 layers of GEM chambers 50 cm x 50 cm)
= 16 x 2 x 500/0.4 = 50,000 channels of VMM3

VTP : VXS Trigger Processor

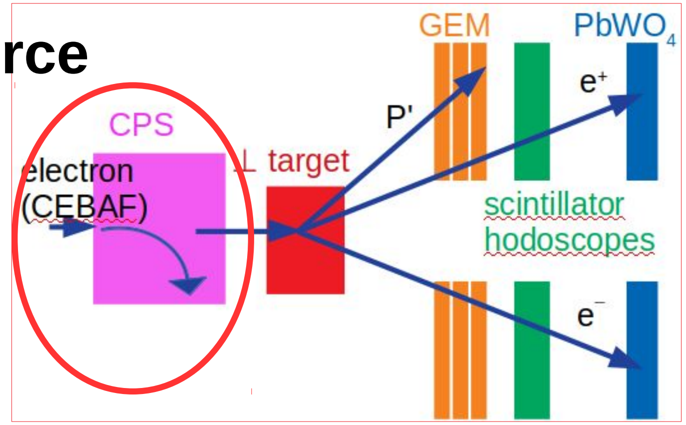
Trigger level 1

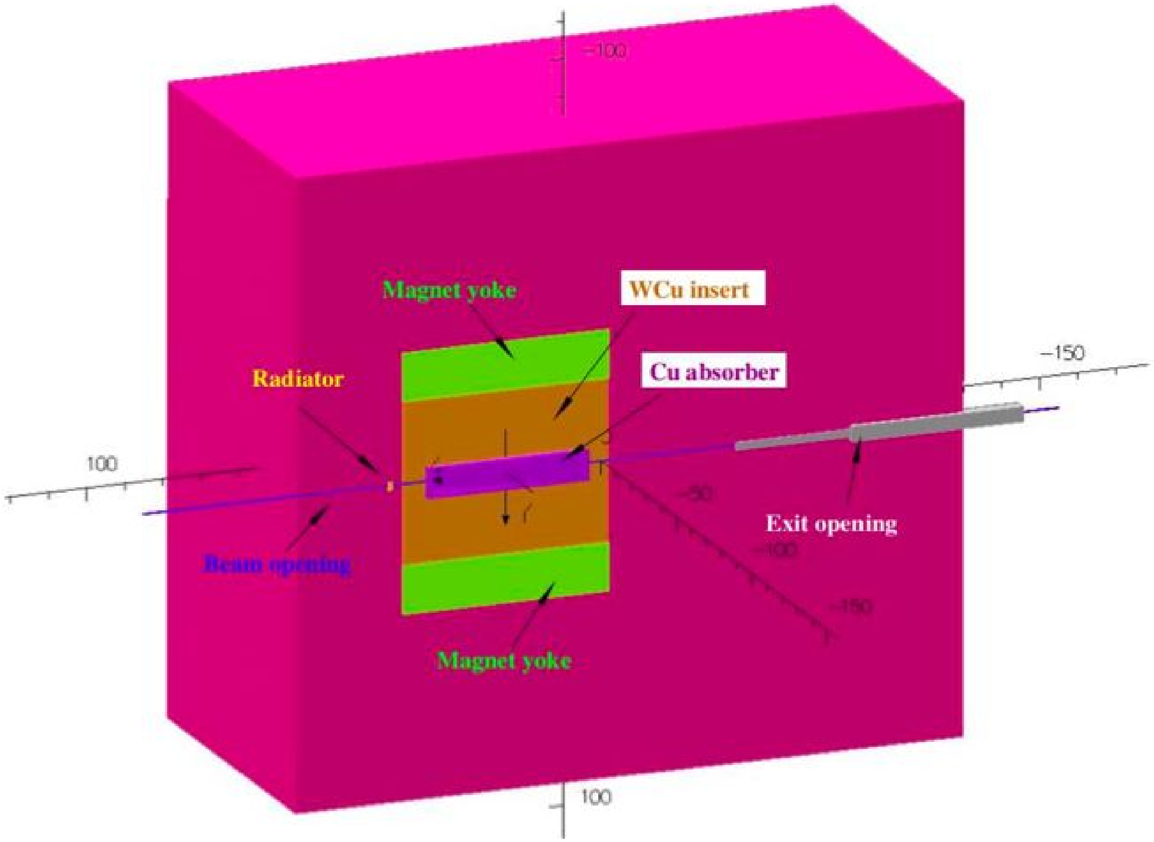
1. Request 2 strongest clusters in the calorimeters, in the opposite quadrants, with energy > 1 GeV each, with combined energy > 5 GeV
2. Request energy depositions in 2 hodoscope blocks, correlated in time and location with the calorimeter clusters.

Trigger level 2

3. Request 2 coincident clusters in the calorimeters (e+, e-)
4. Request hit in scintillator (recoil proton) correlated in time with the calorimeter clusters, and corresponding 2 hits out of 3 in GEM-s.

Radiator: Compact Photon Source



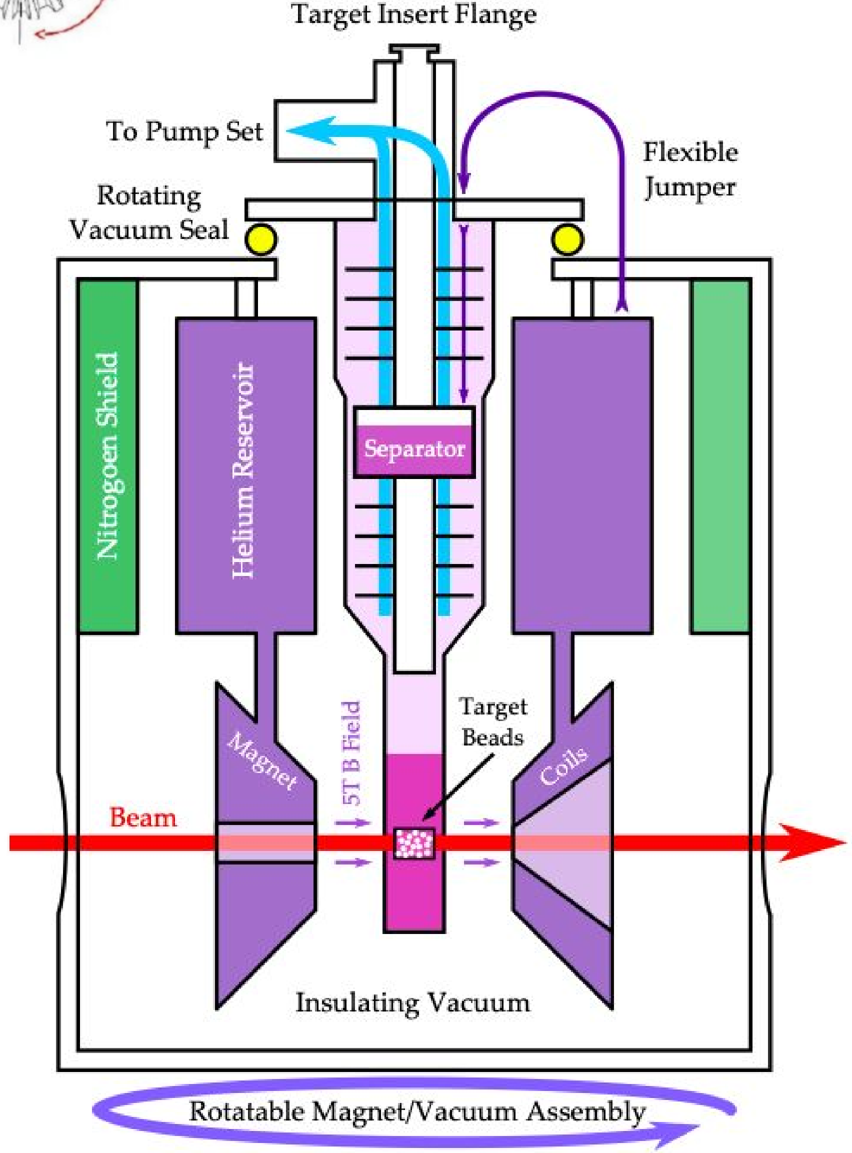


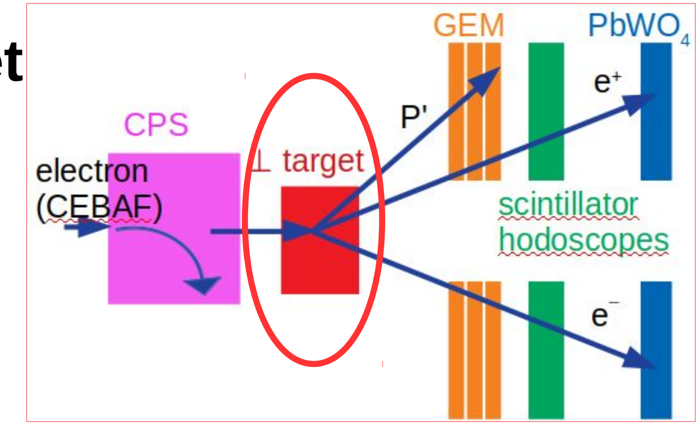
- 10% Cu radiator
- used for beam dump with 3.2 T warm magnet
- W/Cu shielding: minimal radiation, negligible interference with target field
- 1.5×10^{12} γ/s at 2.5 μA, 5.5 to 11 GeV (5.8×10^{5} pb^{-1} integrated luminosity)
- ~1 mm spot size at 2m

used for WACS approved experiment, in development

Transverse JLab/UVa polarized target

rotating cell,
beam "spiral"



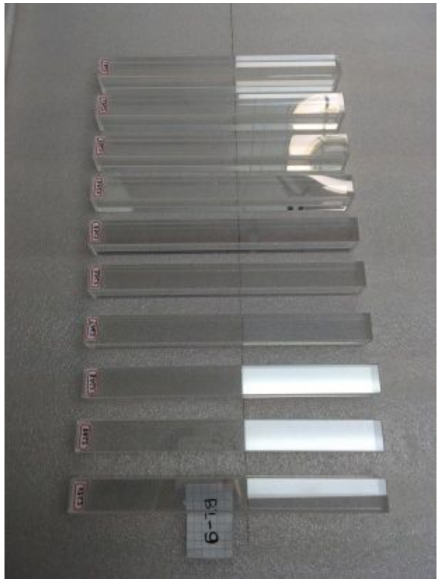


- Target: $^{15}NH_3$ in ^4He at 1K, 0.6 packing fraction
- DNP at 140 GHz; 20 W RF field
- **5T magnetic field by superconducting Helmhotz coils used for bending particles in spectrometer**
- "live" polarization monitoring by NMR
- Acceptance: ±17° horizontal, ±(6°-21.7°) vertical
- Up/down (~10 mm) and 1 Hz rotation of target cup to avoid radiation damage and depolarization effects
- Dilution factor (from MC) for our reaction ~20%
- Rotation 90° of magnet and scattering chamber for ⊥

used for several other 6/12 GeV experiments

Target magnetic field for tracking: mapping before/during commissioning

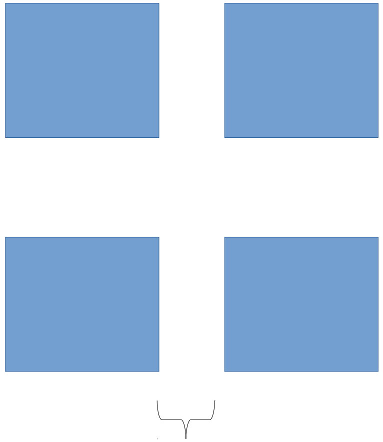
Calorimeters



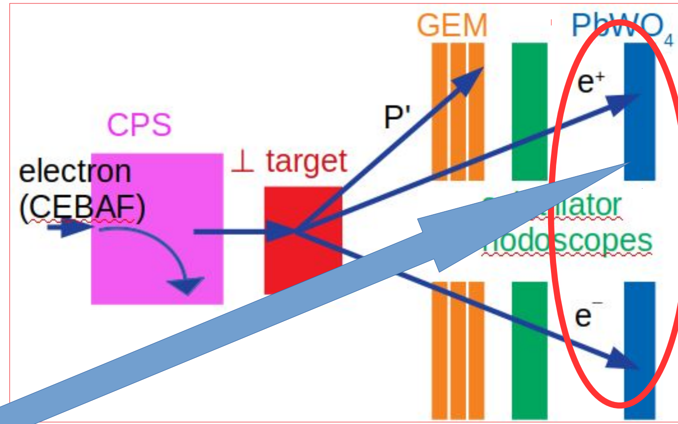
crystals (NPS collaboration)

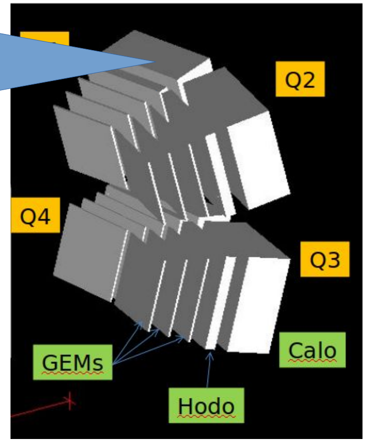
half crystals used for other experiments: DVCS...

4 symmetrical parts:



vertical gap

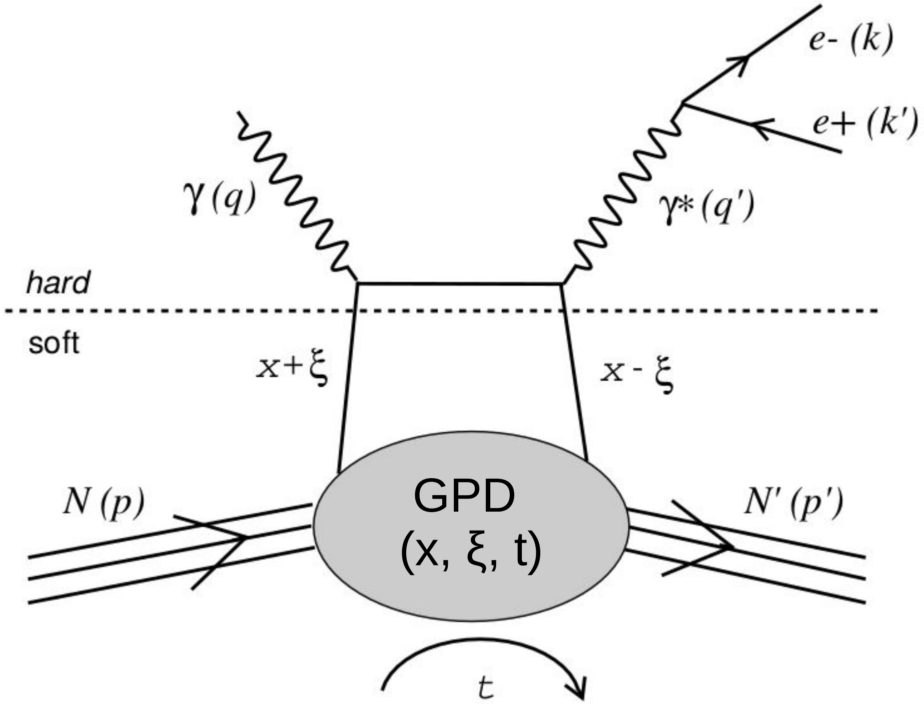


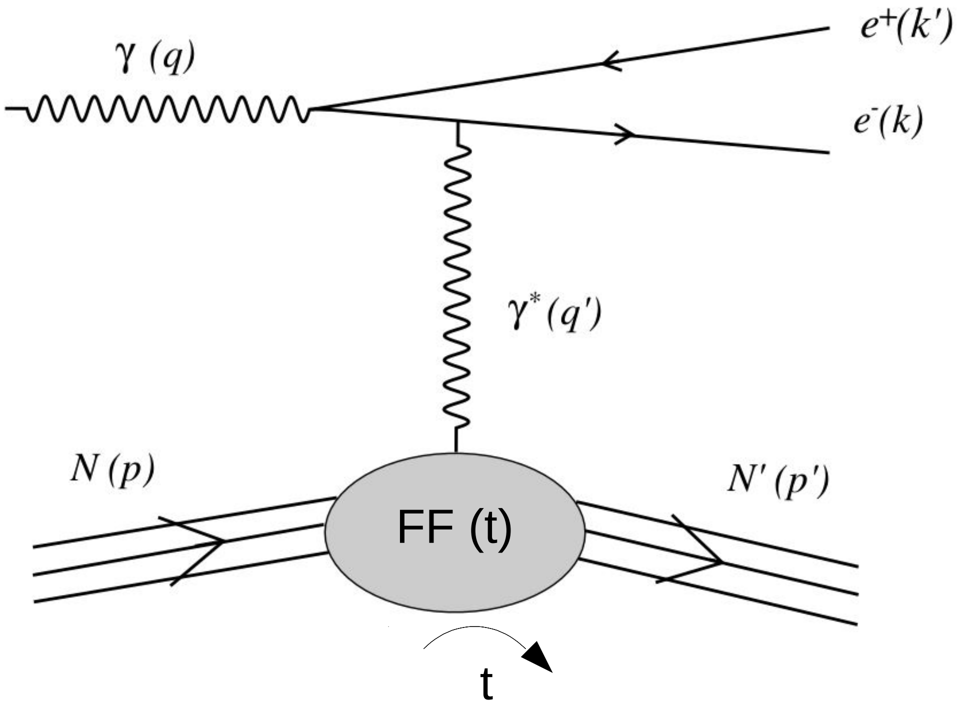


- 2x2x20 $PbWO_4$ calorimeters: 2116 blocks total divided in 4 groups of 23x23 matrix (active area .74m²)
- Hamamatsu R4125 PMTs (3/4" diameter bialkali photocathode)
- 22.5 radiation lengths deep
- Vertical aperture θ = ±1.6°: region affected by high rates from transverse magnetic field [BH region]
- Resolutions 2.5/√E +1%, $\sigma_x \approx$ 3mm at 1 GeV
- In-situ calibration using π° electroproduction

Timelike Compton Scattering

$\gamma P \rightarrow e^+e^- P'$ = TCS + Bethe-Heitler



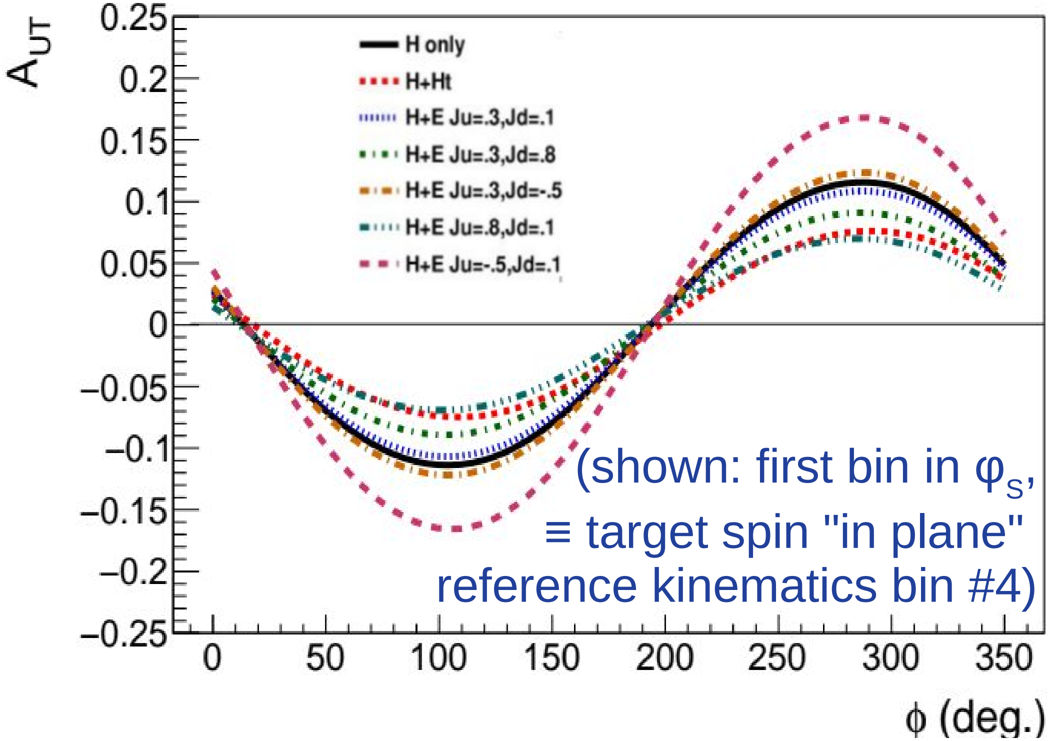


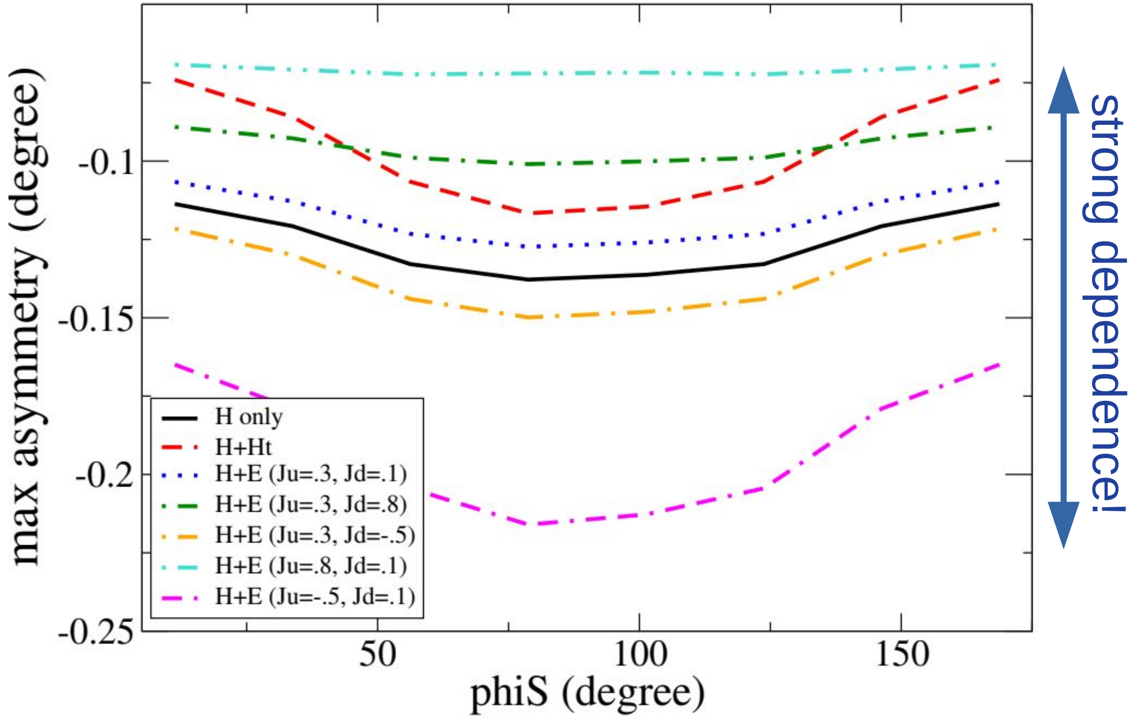
Why measuring TCS off a transversely polarized proton?

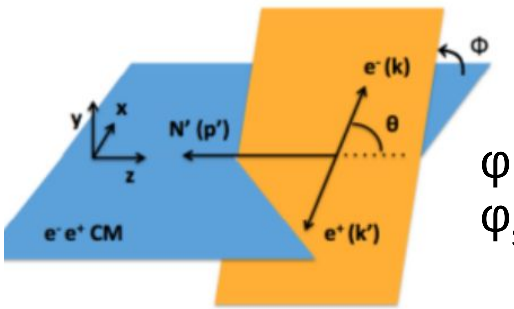
- **Unique access to GPD E of the proton**
- **GPD universality studies (TCS vs DVCS)**
- **Independent observables for GPD data sets and global fits in valence region**
- **Most knowledge on GPDs from DVCS: complex conjugate, TCS access same information**

Transverse target spin asymmetries

Dependence in GPD parametrization and J_u, J_d (VGG model) vs φ and φ_S







φ: e^- vs reaction plane
φ_S: P spin vs reaction plane

θ: polar angle (integrated)
E_γ ($\rightarrow \xi$), t, Q'^2

calculations based on Boër, Guidal, Vanderhaeghen
GPDs from Vanderhaeghen, Guidal, Guichon (VGG)

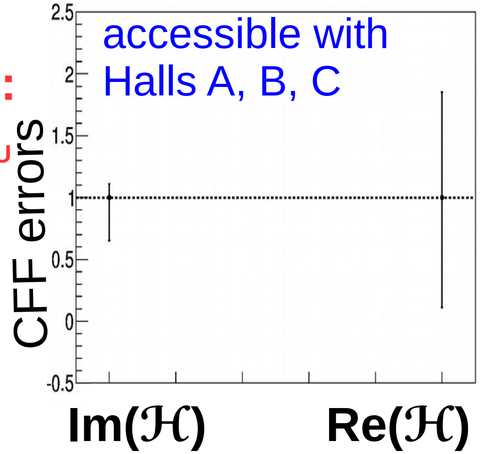
- **TCS contribution through interference**
  → purely imaginary, BH cancels
- **Sensitive to GPD parametrization**
- **Angular momenta J_u, J_d and GPD E**

Need of experimental data!

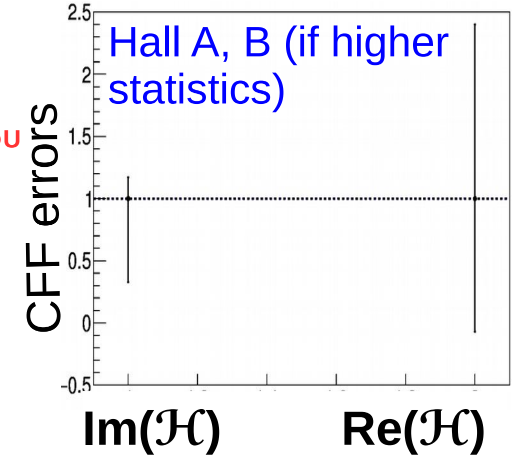
Compton Form Factors from DVCS and TCS

[fit of simulations with same errors]

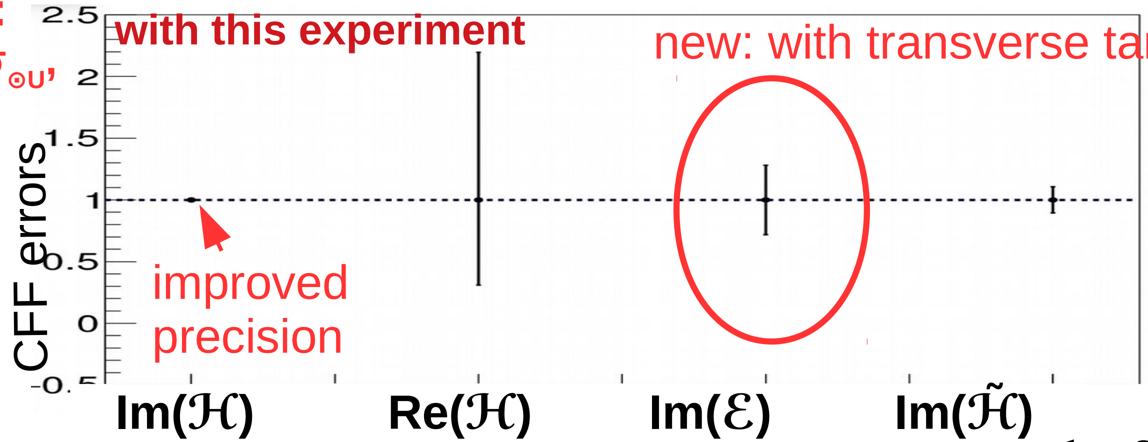
DVCS:
σ, $\Delta\sigma_{LU}$



TCS:
σ, $\Delta\sigma_{\odot U}$



TCS:
σ, $\Delta\sigma_{\odot U}$, $\Delta\sigma_{UX}$, $\Delta\sigma_{UY}$



← extracted CFFs (generated at value=1)

- **CFFs from TCS can be extracted at same level than DVCS**
- **Im($\mathcal{E}$) extracted thanks to transverse target**
- **Precision on H greatly improved with new constraints**

Main goal: **GPD E (proton) → unique**, **not measured in other exp.**

Secondary goal: **complement universality studies**

→ universality or breaking? Higher twist/NLO effects?

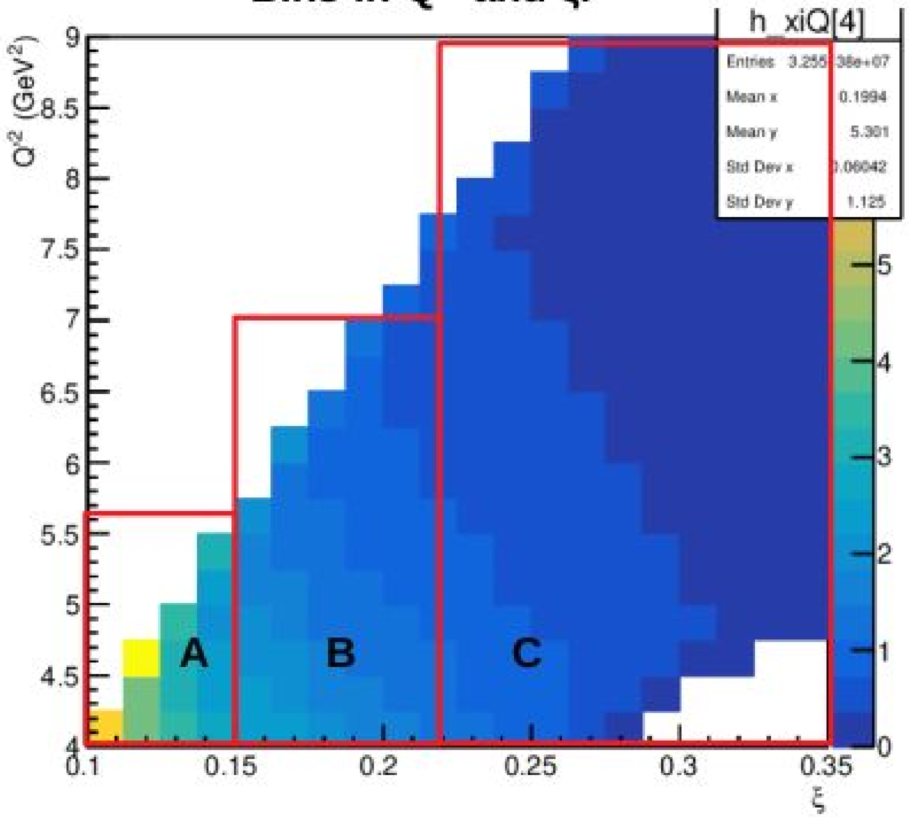
- Studied with Q^2 evolution in other experiments
- Comparison of fit results DVCS only, TCS, TCS+DVCS

→ **interpretation depends on size of observed effects**

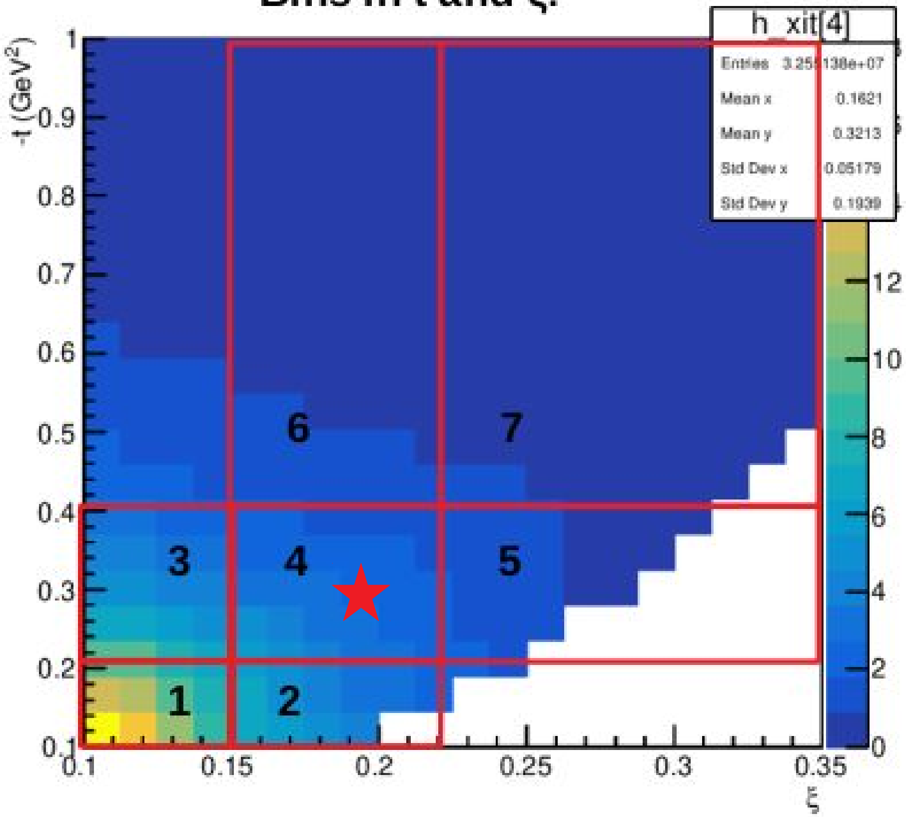
Caveat: for comparison purpose and sensitivity studies; assuming same uncertainties for all cases (based on Boër, Guidal...)

Phase Space

Bins in Q'² and ξ:



Bins in t and ξ:



A: .10 < ξ < .15 ; 4 < Q'² < 5.5 GeV²
B: .15 < ξ < .22 ; 4 < Q'² < 7 GeV²
C: .22 < ξ < .35 ; 4 < Q'² < 9 GeV²

1, 2: .1 < -t < .2 GeV²
3, 4, 5: .2 < -t < .35 GeV²
6, 7: .35 < -t < .7 GeV²

★ reference bin

also 16 bins in φ x 16 bins in $φ_S$, integrated over θ

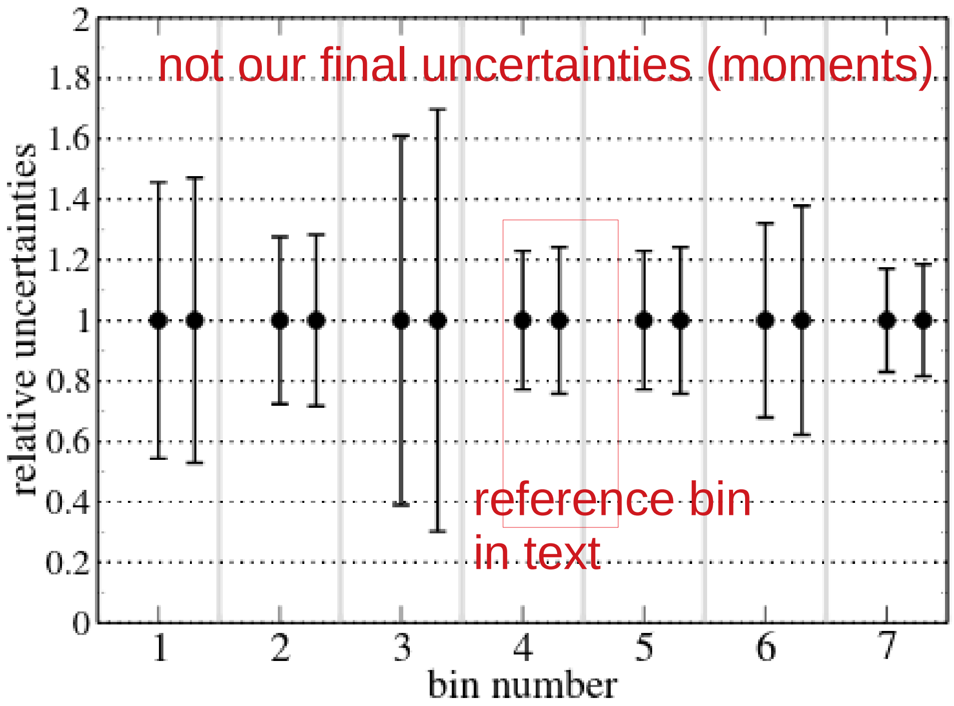
Main cuts:
- triple coincidence: 2 leptons, 1 proton
- Physics: cut out regions near BH peaks by (E, θ, Q'²) φ and θ dependent cut
- Trigger thresholds: triple coincidence, minimum 1 GeV/lepton and 5 GeV/2 leptons in calorimeter
- Exclusivity: momentum/energy/missing mass balance

Analysis: exclusivity cuts and/or machine learning for better background rejection ($\pi^+\pi^-$...)

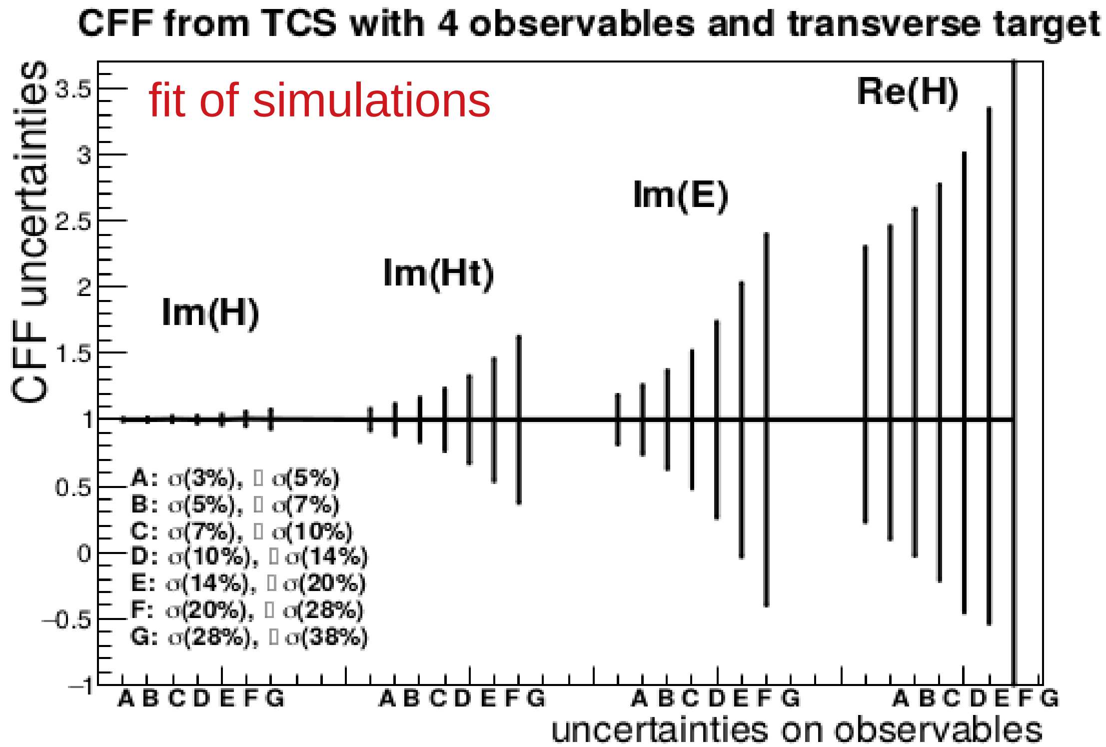
Anticipated results on CFFs

Mostly dominated by complementary unpolarized experiments, due to correlation with GPD H

(illustration) **combined errors** on 2 orthogonal $\perp$ asymmetries for first sinus moment, for all bins (to be compared with size of asymmetries vs φ_S)



CFFs uncertainties vs experimental errors
fits on simulations using VGG parametrization



- **Im(H), Re(H), Im(H̃), Im(E) extracted even with very large experimental uncertainties (E, F, G)**
- **Results mostly depend on unpolarized cross section errors (other experiments off LH2)**
- **Our experiment will put constraints on GPD E, J_u & J_d, and reduce errors on Im+Re(H)**

Beam time request

setup and installation	2.5 (PAC days)
signal and electronic checkout	2.5
gain matching of the detector's channels	0.5
Decomissioning	1.5
Overhead	7.5
commissioning with beam	**5**
physics	**30**

Total: 49.5 PAC days, 35 days with beam

Overhead	Number	Time Per (hr)	total (hr)
Polarization/depolarization	60	2.0	120
Target Anneals	15	4.0	60
Target T.E. Calibrations	10	4	28
Packing fraction/Dilution runs	6	2	12
Target Material Change	8	4	32
NPS Crystal Recovery	1	24	24
BCM/BPM Calibration	8	2	16
Moller Measurements	1	1	42
Total Overhead			346 (14.4 days)

Projections:
30 physics PAC day, L=5.85x10^5 pb^{-1} with 11 GeV e$^-$ beam and CPS (1.5x10^{12} γ/s or 10^{35} γ/cm²/s)

Summary

Physics

- Unique access to **GPD E** of the proton
- **Extraction of CFFs** from transverse polarized asymmetries + complementary TCS measurements

Reduce correlation uncertainties by ~x10 compared to only unpolarized+beam polarized experiments

- Contribution to GPD data sets, **universality studies** with complementary TCS / DVCS experiments

Experimental setup

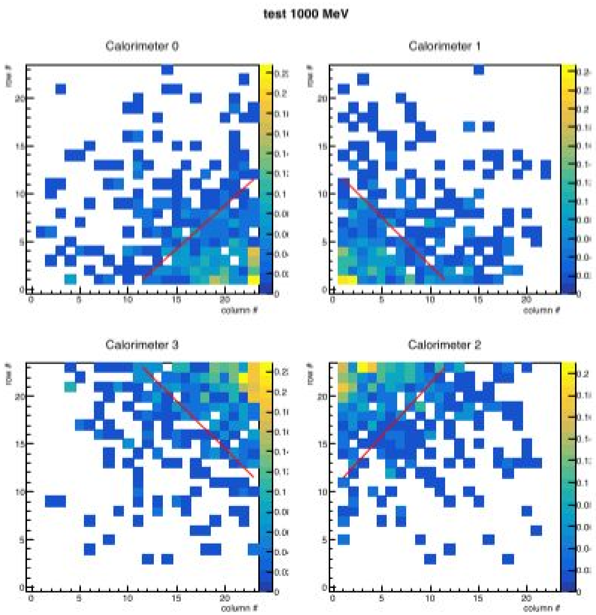
- New: Tracking with **GEM detectors**, to handle high background rates + scintillator hodoscopes
- New: **Trigger with calorimeters +GEMs, triple coincidence**, high thresholds (> 1 GeV /lepton)
- High intensity **real photon beam** from radiator (CPS collaboration)
- 2 splits $PbWO_4$ electromagnetic **calorimeters** (NPS collaboration)
- **Transversely polarized DNP target**, ammonia (JLab/UVA target)

Main advantages of this experiment and dedicated setup: GPD E, high intensity real photons

backup

Trigger details

- Each of four quadrants will provide in pipeline (2-3 micro seconds delay) parameters per cluster
  - Location, time, and energy of two strongest clusters in the calorimeter,
  - Energy deposition in the scintillator block correlated in time and location
- VTP (VXS trigger processor) will use the combined energy (> 5 GeV) for the trigger level 1
  - Search for proton signals in the scintillator hodoscope correlated in time to e+/e-
  - Initiate readout of GEM DAQ
- Preliminary proton tracking using GEM information in VMM3 (modern GEM chamber chip, an implementation under development for the SOLID preRD)



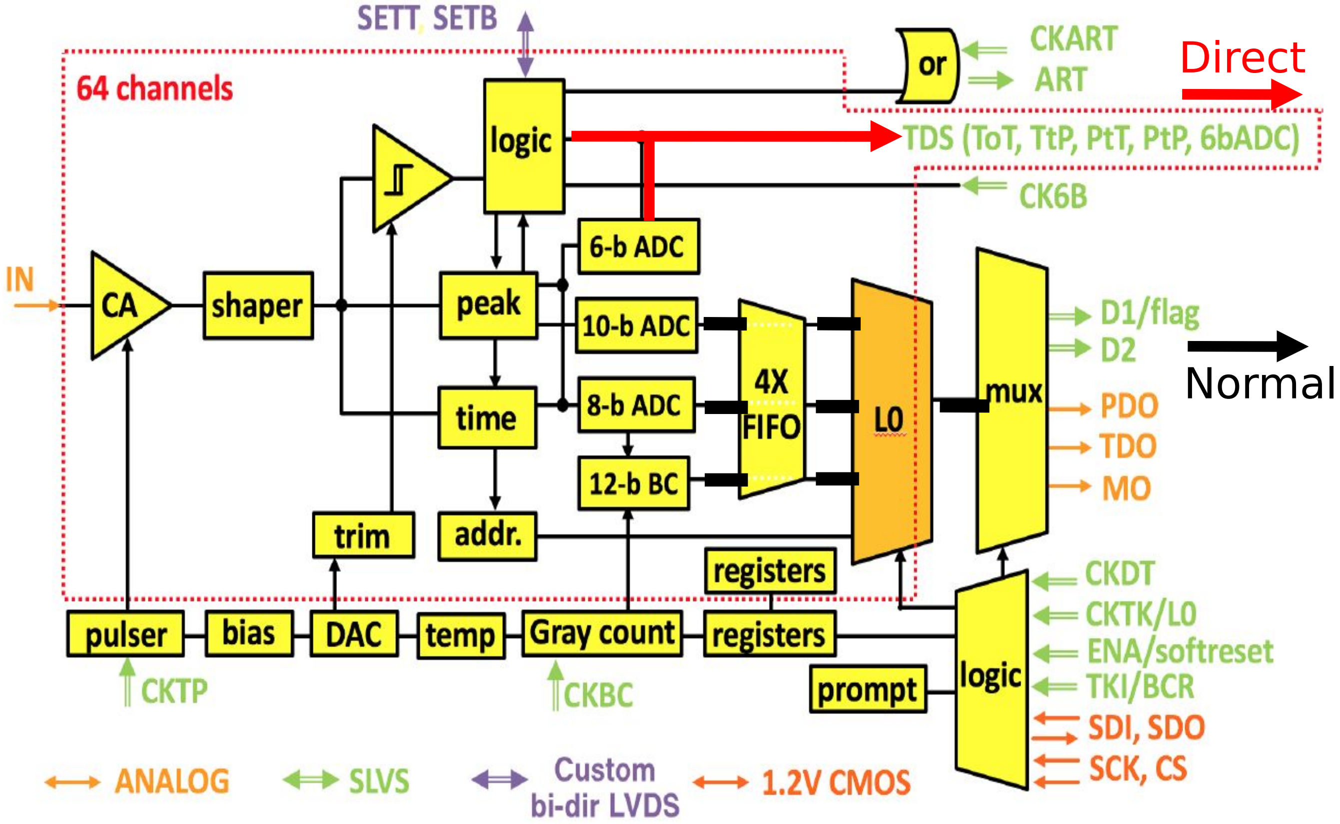
Calorimeter cluster trigger

- Compute all 4x4 sums, one sum above threshold
- Request "seed" energy > 1 GeV, 2 quadrant combined energy > 5 GeV

- ✓ Exclude hot blocks (1/8 fraction) close to beam pipe (~23% reduction of useful events)
- ✓ ~3 MHZ integral hit rate in each quadrant (energy above1 GeV), reasonable for trigger formation
- ✓ 38 kHZ background trigger rate , reasonable for trigger formation
- ✓ At least 90% efficiency for TCS events (estimate with no background)

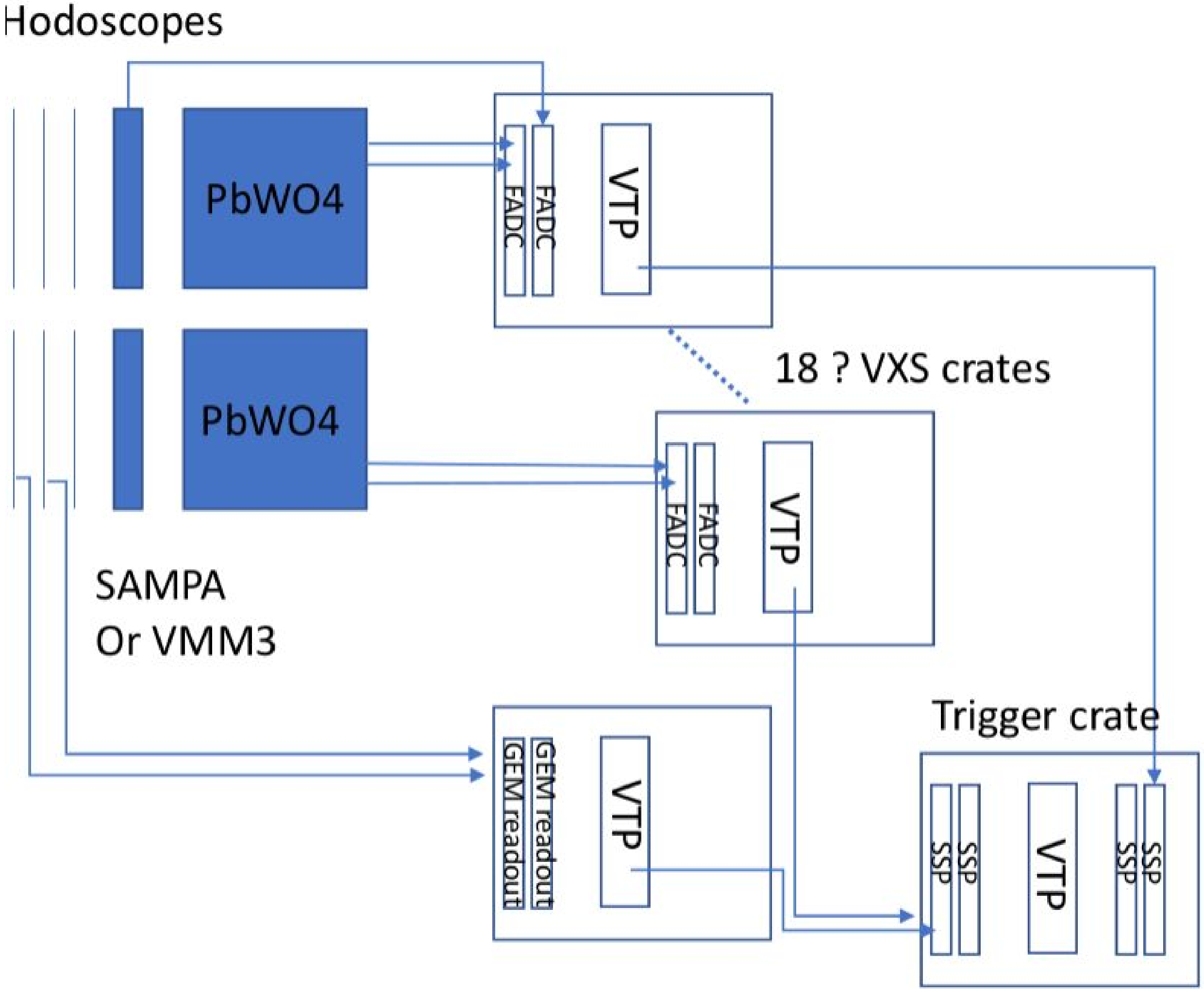
VMM3 chip

VMM3 block diagram



- ASIC for ATLAS New Small Wheel
- Radiation hard similar to APV25 : > 100 Mrad
- 64 channels
- Low noise over wide range of input capacitance (<1 pF to ~1 nF)
- Shaping times : **25 ns**, 50 ns, 100 ns, 200 ns
- Pulse amplitude proportional to charge at input
- Gains : 0.5, 1, 3, 4.5, 6, 9, 12, 16 mV/fC
- **6 bit ADC (25 ns conversion)** and **10 bit ADC (250 ns conversion)**, 8 bits TDC (1 ns resolution), 12 bits Beam Crossing time stamp
- 4 MHz of rate per channel thanks to multilevel FIFO
- Continuous or triggered readout on normal data path
- Latency up to 16 ms in triggered mode
- **Fast direct outputs (64 channels) for ATLAS trigger (6b ADC, ToT)**
- Normal data link up to 320 Mb/s

Scheme of DAQ



4 x 23x23 crystals and scintillators
= 2116 x 2 = 4,232 fADC
4 x (5 layers of GEM chambers 50 cm x 50 cm)
= 16 x 2 x 500/0.4 = 50,000 MVV3

VTP : VXS Trigger Processor

Inclusion of GEM in trigger will be developed

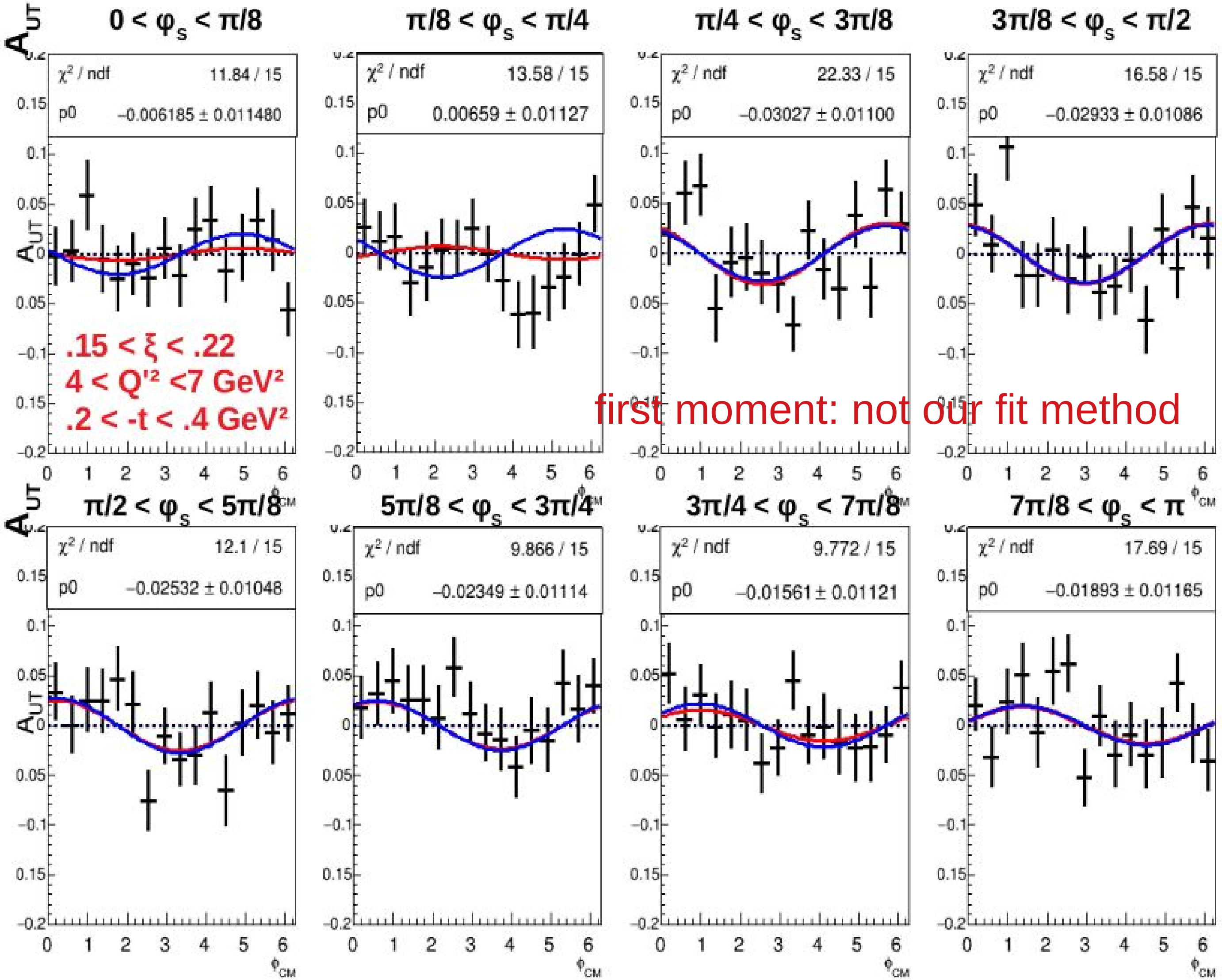
Extracting spin asymmetry

Here (also in proposal): fit of first moment - for illustration

<u>Method that will be used</u>: direct fits of CFFs on full asymmetries combined with unpolarized and beam polarized cross sections → takes all moments into account and reduce CFFs correlations

Error on CFFs will be dominated by complementary unpolarized experiments

sin(φ-φ_s) fitting of kinematic bin 4th, vs φ, 8 bins in φ_s



+ smeared simulations (with dilution factors+errors)

- ideal fit (on unsmeared data)
- 1 attempt fit (on smeared data)

Systematic uncertainties

SOURCE	VALUE	COMMENTS
target polarization	0.05	NMR measurement
packing fraction	0.03	target spec
target dilution factor	≈ 0.02	depend on analysis cuts / possibility of run off frozen N similar target
interaction with target material	negligible	with vertex reconstruction, exclusivity
background subtraction ($\pi^{\pm}$, accidental)	0.03	measurements other Halls and MC
proton resonances	< 0.01	thanks to proton detection
trigger and tracking efficiency	0.01	from MC
beam polarization (for $A_{\odot U}$)	0.01	measured (not main measurements)
luminosity (for σ and $\sigma_{\odot U}$)	-	(not main measurement, in development)

Total ~ 0.07

Measurements dominated by statistic uncertainties and corrections to dilution factors

Impact of dynamic twist corrections on DVCS+TCS fits

- **Corrections applied**: **target mass and restauration of gauge invariance**
- **Impact on CFFs**: **~10% on Re, ~1% on Im, opposite sign in DVCS and TCS**
- **Impact on DVCS+TCS fits: between "twist 2" and "DVCS" results; 1% (Im) to 10% (Re)**

→ **below uncertainties on CFFs**

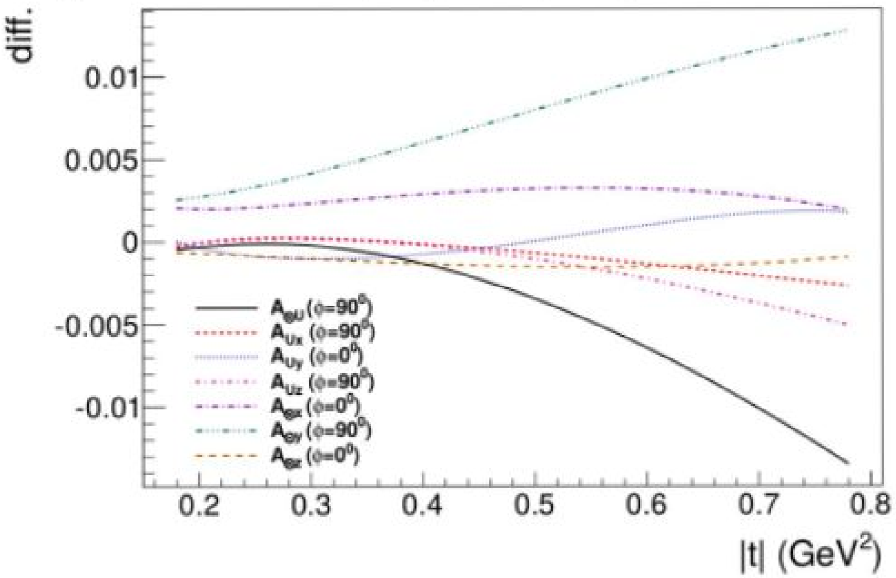
Corrections

mass and Δ=(p-p') in skewness variable:

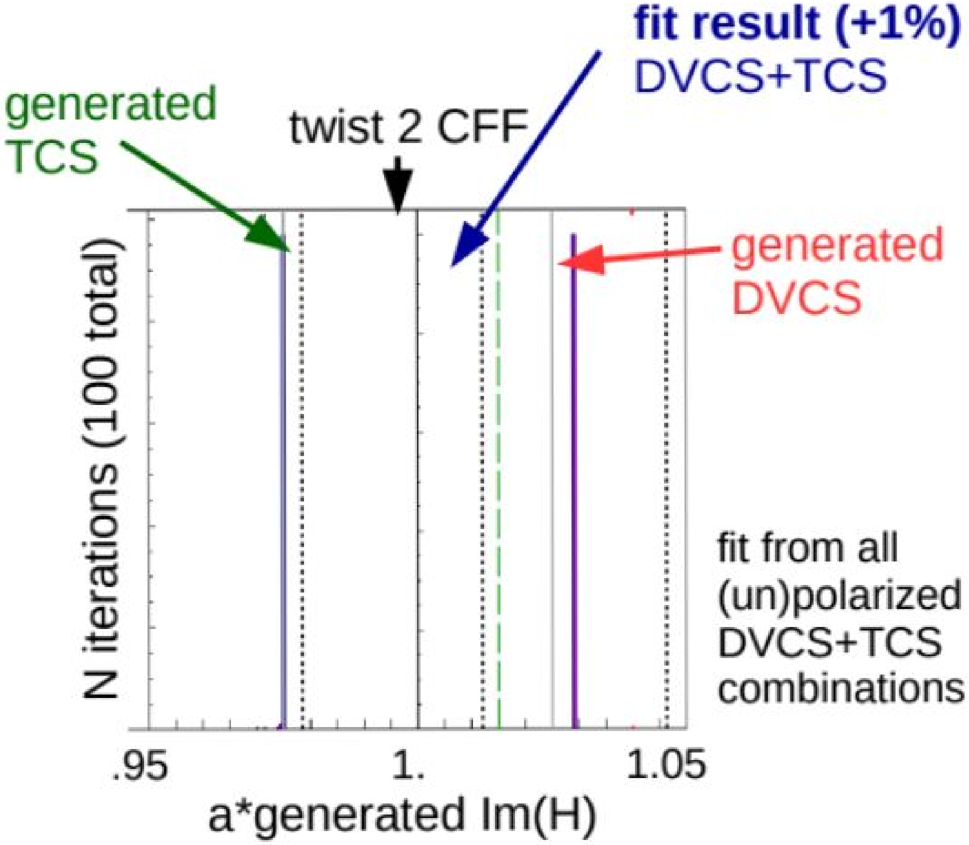
$$\xi' = -\frac{\bar{q}^2}{2P\cdot\bar{q}} = \frac{-Q'^2 + \Delta^2/2}{2(s-m^2)+\Delta^2-Q'^2}$$

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

(corrected - asymptotic) asymmetries



Fit results



fit from all (un)polarized DVCS+TCS combinations

Dynamic twist corrections for TCS

- leading-twist TCS hadronic part of amplitude with "Ji's" GPDs decomposition

$$H_{\mu\nu}^{\mathrm{TCS}} =$$
$$\frac{1}{2}(-g_{\mu\nu})_\perp \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{x-\xi-i\epsilon} + \frac{1}{x+\xi+i\epsilon}\right)$$
$$\cdot \left(H(x,\xi,t)\bar{u}(p')\not{n}u(p) + E(x,\xi,t)\bar{u}(p')i\sigma^{\alpha\beta}n_\alpha \frac{\Delta_\beta}{2m}u(p)\right)$$
$$-\frac{i}{2}(\epsilon_{\nu\mu})_\perp \int_{-1}^{1} \mathrm{d}x \left(\frac{1}{x-\xi-i\epsilon} - \frac{1}{x+\xi+i\epsilon}\right)$$
$$\cdot \left(\tilde{H}(x,\xi,t)\bar{u}(p')\not{n}\gamma_5 u(p) + \tilde{E}(x,\xi,t)\bar{u}(p')\gamma_5 \frac{\Delta\cdot n}{2m}u(p)\right)$$

$$\Delta = (p' - p)$$

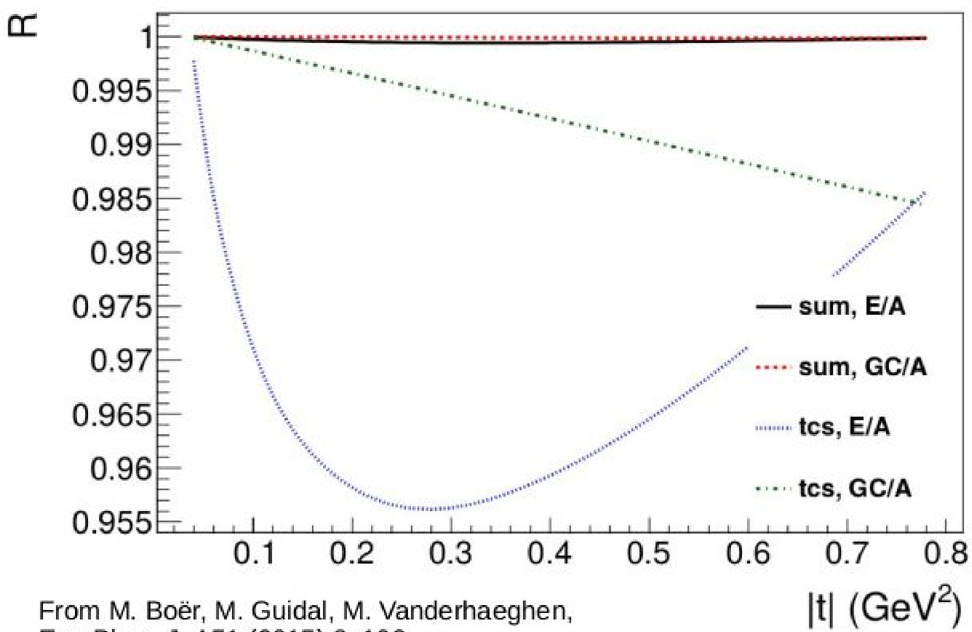
- ad-hoc twist 3 corrections for gauge-invariance

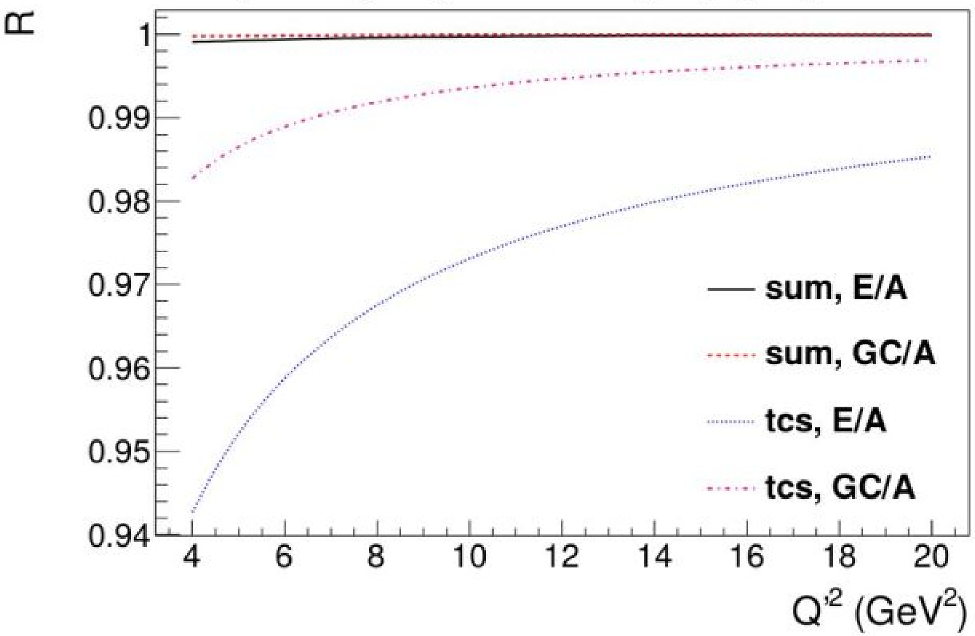
$$H^{\mu\nu} = H_{LO}^{\mu\nu} - \frac{P^\mu}{2P\cdot\bar{q}}\cdot(\Delta_\perp)_\kappa \cdot H_{LO}^{\kappa\nu} + \frac{P^\nu}{2P\cdot\bar{q}}\cdot(\Delta_\perp)_\lambda \cdot H_{LO}^{\mu\lambda} - \frac{P^\mu P^\nu}{4(P\cdot\bar{q})^2}\cdot(\Delta_\perp)_\kappa\cdot(\Delta_\perp)_\lambda \cdot H_{LO}^{\kappa\lambda}$$

- mass and Δ terms in skewness variables, related to light cone momentum fractions

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

R = corrected / asymptotic unpolarized cross sections, vs t (left) and vs Q'² (right)





From M. Boër, M. Guidal, M. Vanderhaeghen, Eur. Phys. J. A51 (2015) 8, 103

Experimental setup (simplified pic)