The DVCS Physics Program at COMPASS

P. Jörg (ALU Freiburg)

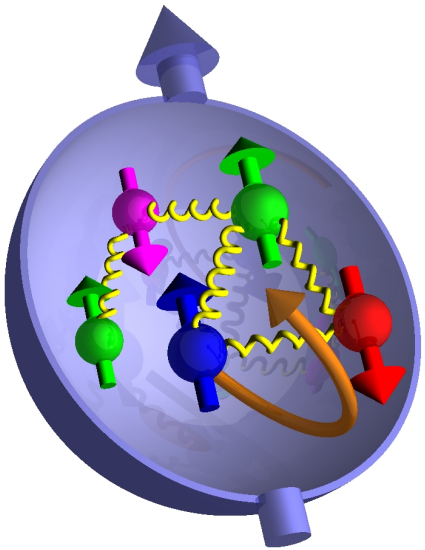
on behalf of the COMPASS Collaboration

DIS2015 - Dallas (Texas), 29/04/2015

SEVENTH FRAMEWORK PROGRAMME

bmb+f - Förderschwerpunkt COMPASS Großgeräte der physikalischen Grundlagenforschung

The Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathscr{L}$$

(Jaffe&Manohar Nucl.Phys.B337 (1990))

- $\frac{1}{2}\Delta\Sigma \sim 0.15$ well known from DIS/SIDIS
- $|\Delta G| \sim 0.2$ known from DIS/pp
- $\mathscr{L}$ unknown

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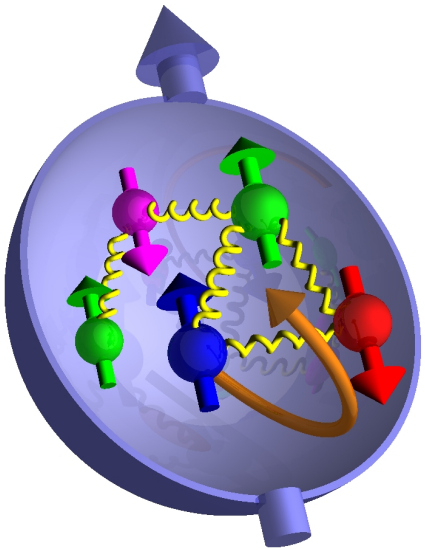

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The **Ji sum rule** connects the Generalized Parton Distributions (GPDs) H and E, measured in exclusive reactions, with the total angular momentum $J^{q,g}$, e.g.

$$J^q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{+1} x[H^q + E^q]dx$$

(Phys.Rev.Lett.78 (1997))

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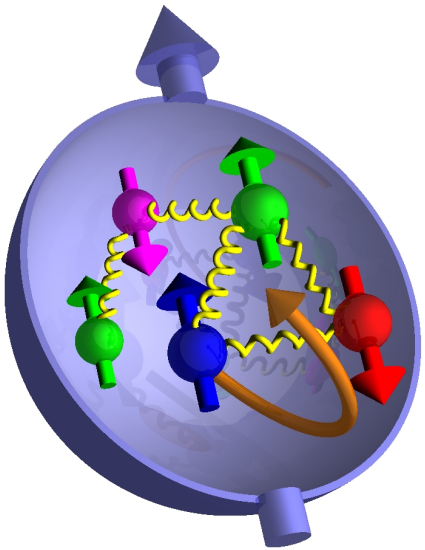

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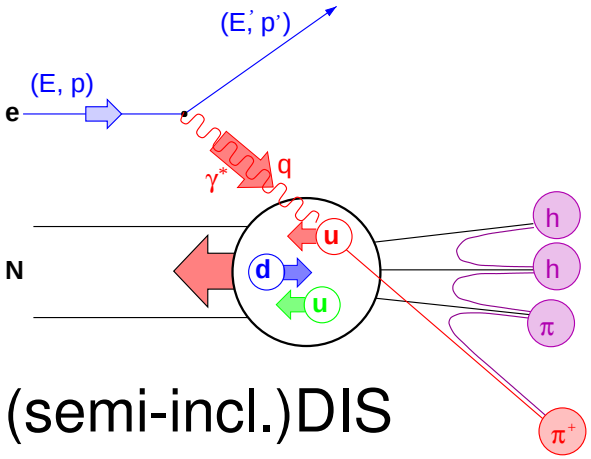
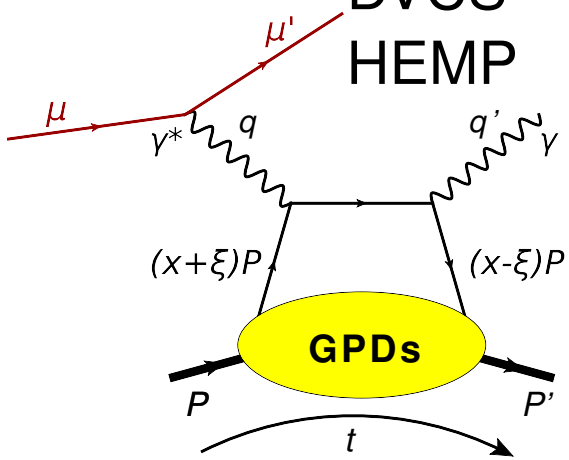
COMPASS experimental tools:

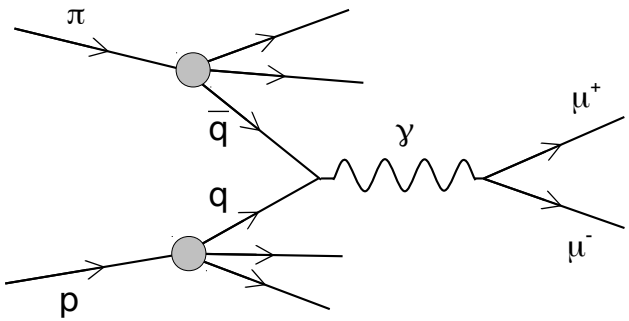


(semi-incl.)DIS

DVCS
HEMP



Pol. Drell-Yan



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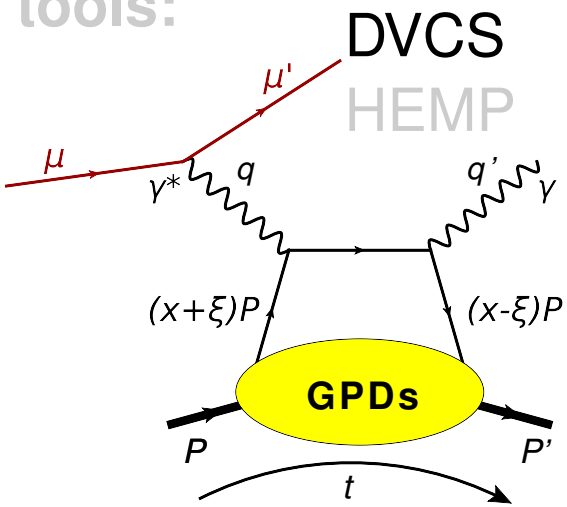
This talk:

COMPASS experimental tools:

(semi-incl.)DIS

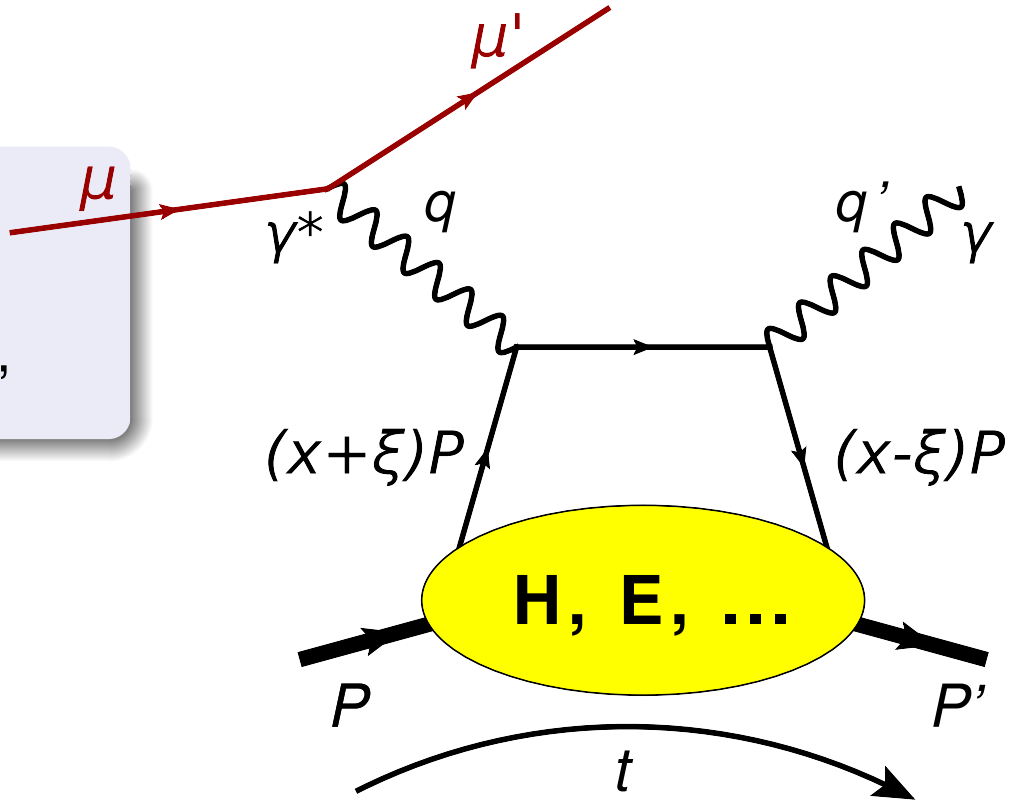


Pol. Drell-Yan

Meson production:
see **Pawel Sznajder's**
talk in the
Spin Physics Session 2
(today 11:10)

Introduction to GPDs

"GPDs are **non-perturbative** objects entering the description of **hard exclusive** electroproduction"



Definition of variables:

- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2-x_B)$
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

Introduction to GPDs

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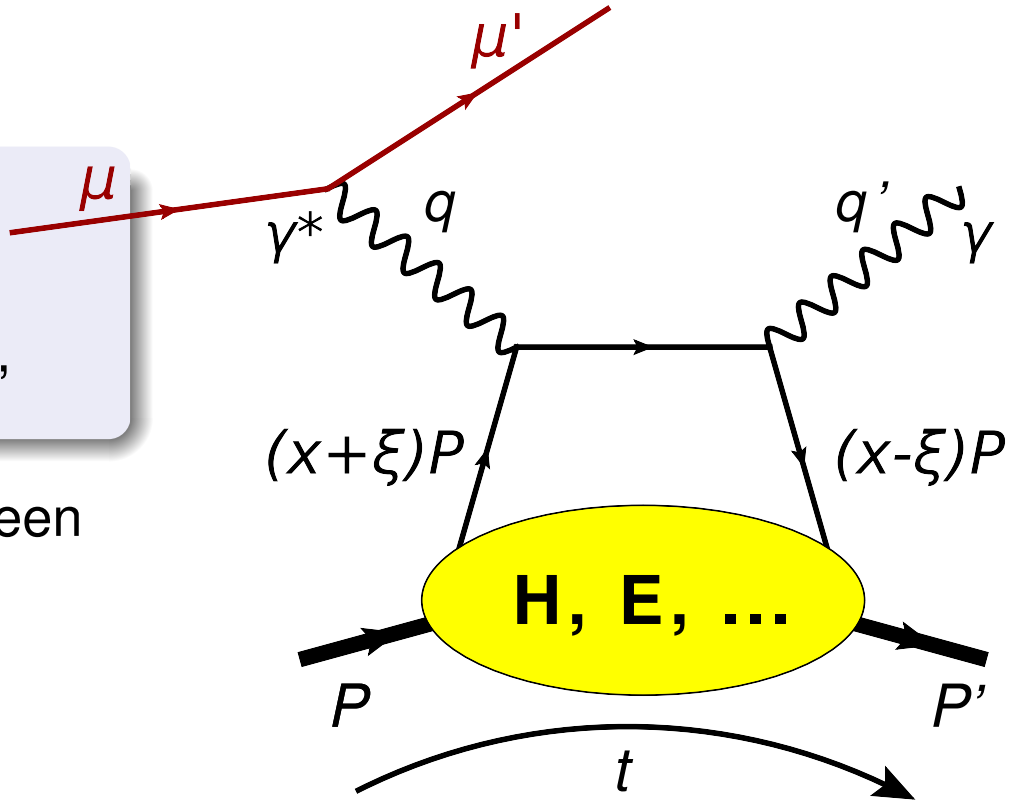
They encode **CORRELATIONS** between the long. mom. **x** and the transv. position $\mathbf{b}_\perp$ of partons



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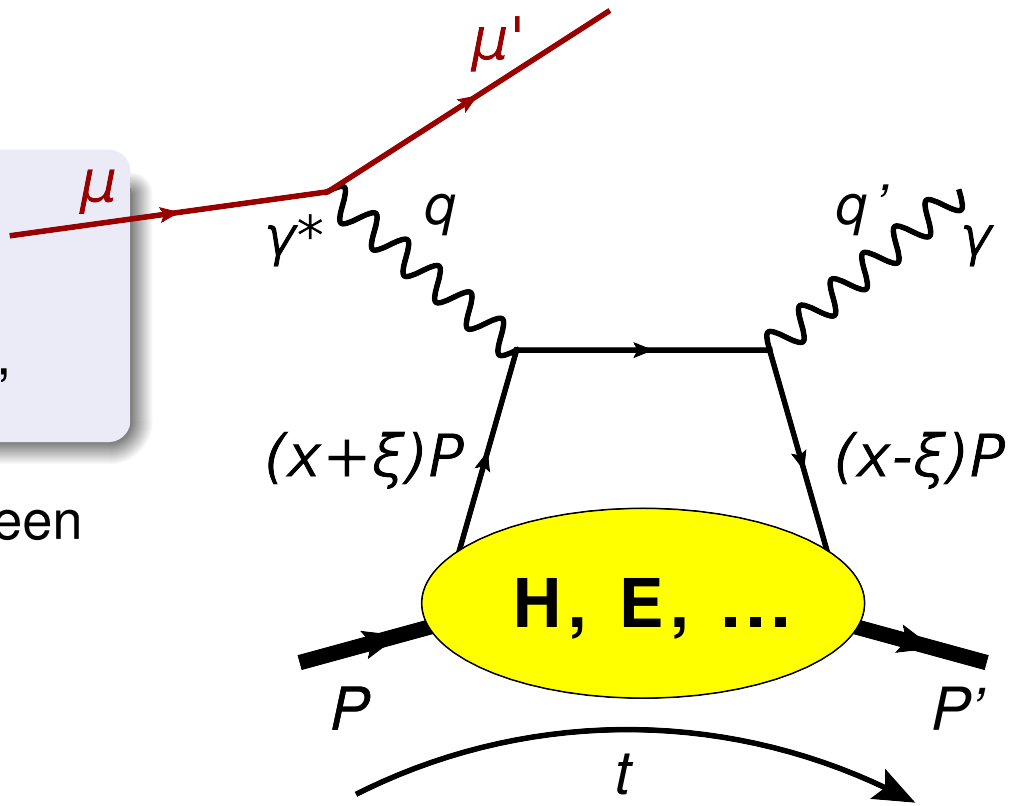

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Experimentally accessible through Compton Form Factors (CFFs):

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

$$\mathbf{Re}\mathcal{H}(\xi,\mathbf{t}) = \int \frac{\mathbf{dx\ H}(\mathbf{x},\mathbf{x},\mathbf{t})}{(\mathbf{x}-\xi)} + \mathbf{Dterm}$$

Definition of variables:

- x: average long. momentum - NOT ACCESSIBLE
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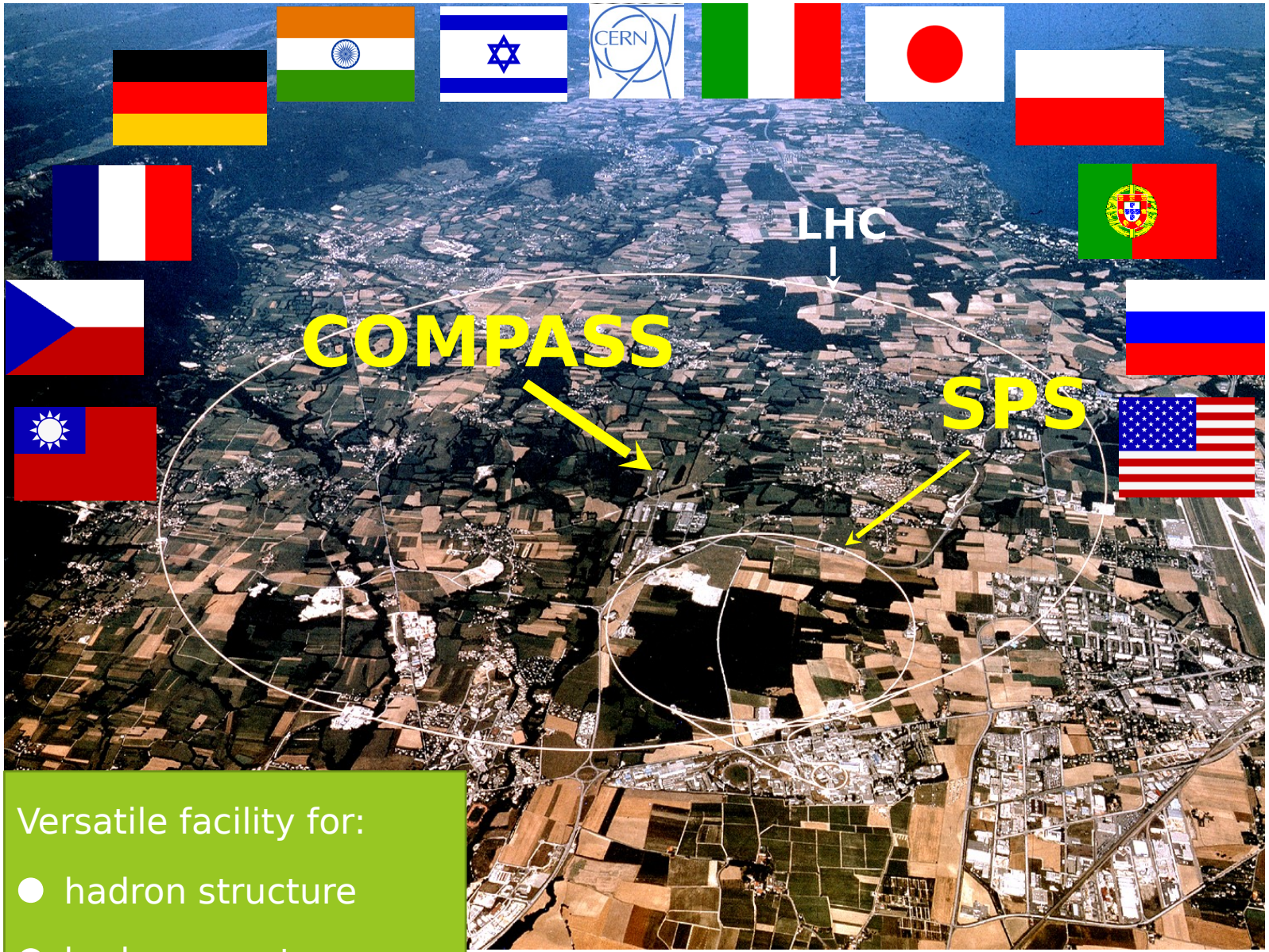
The COMPASS Experiment

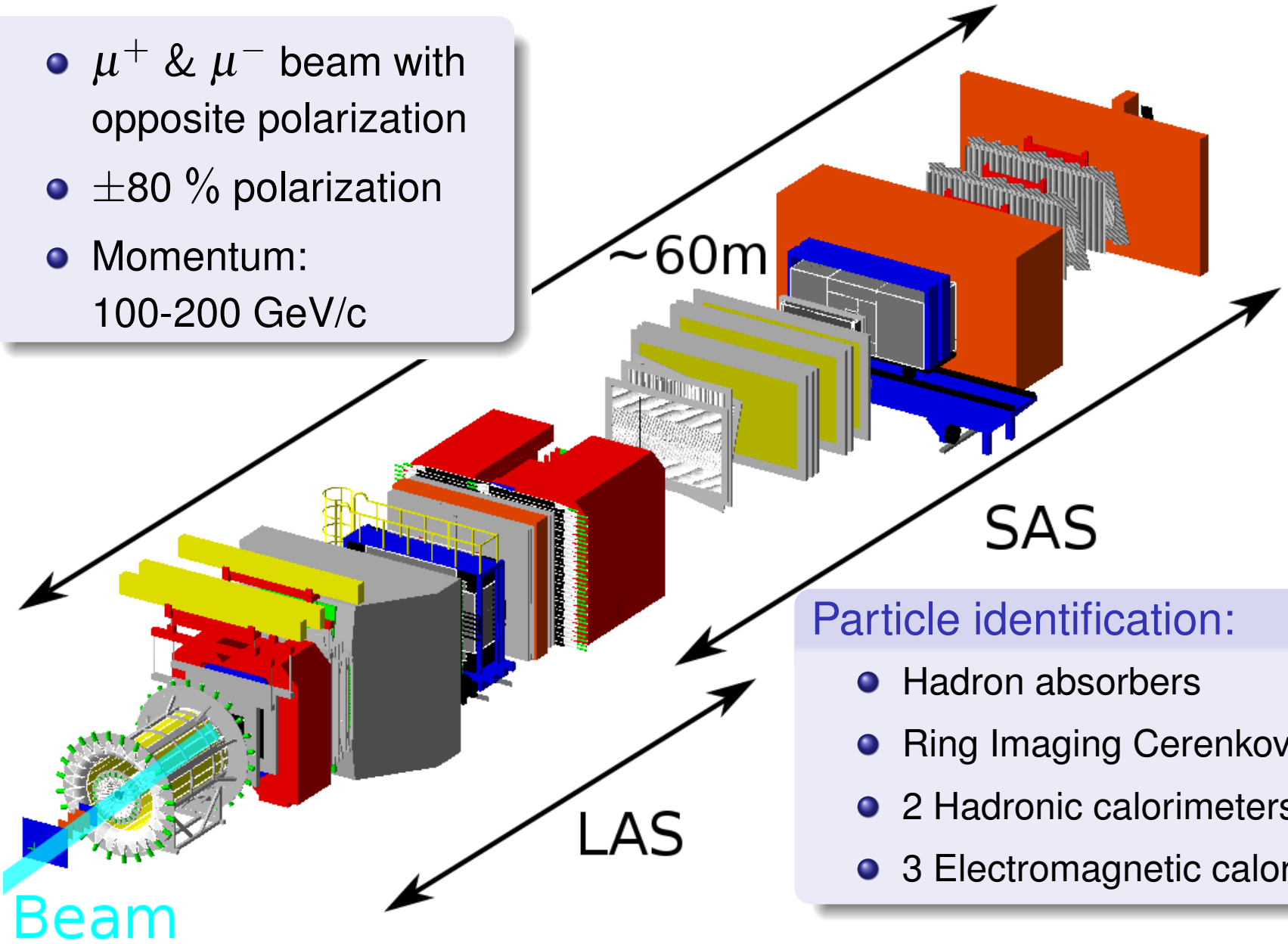


Versatile facility for:

- hadron structure
- hadron spectroscopy

The COMPASS II Spectrometer

- μ^+ & μ^- beam with opposite polarization
- ± 80 % polarization
- Momentum: 100-200 GeV/c



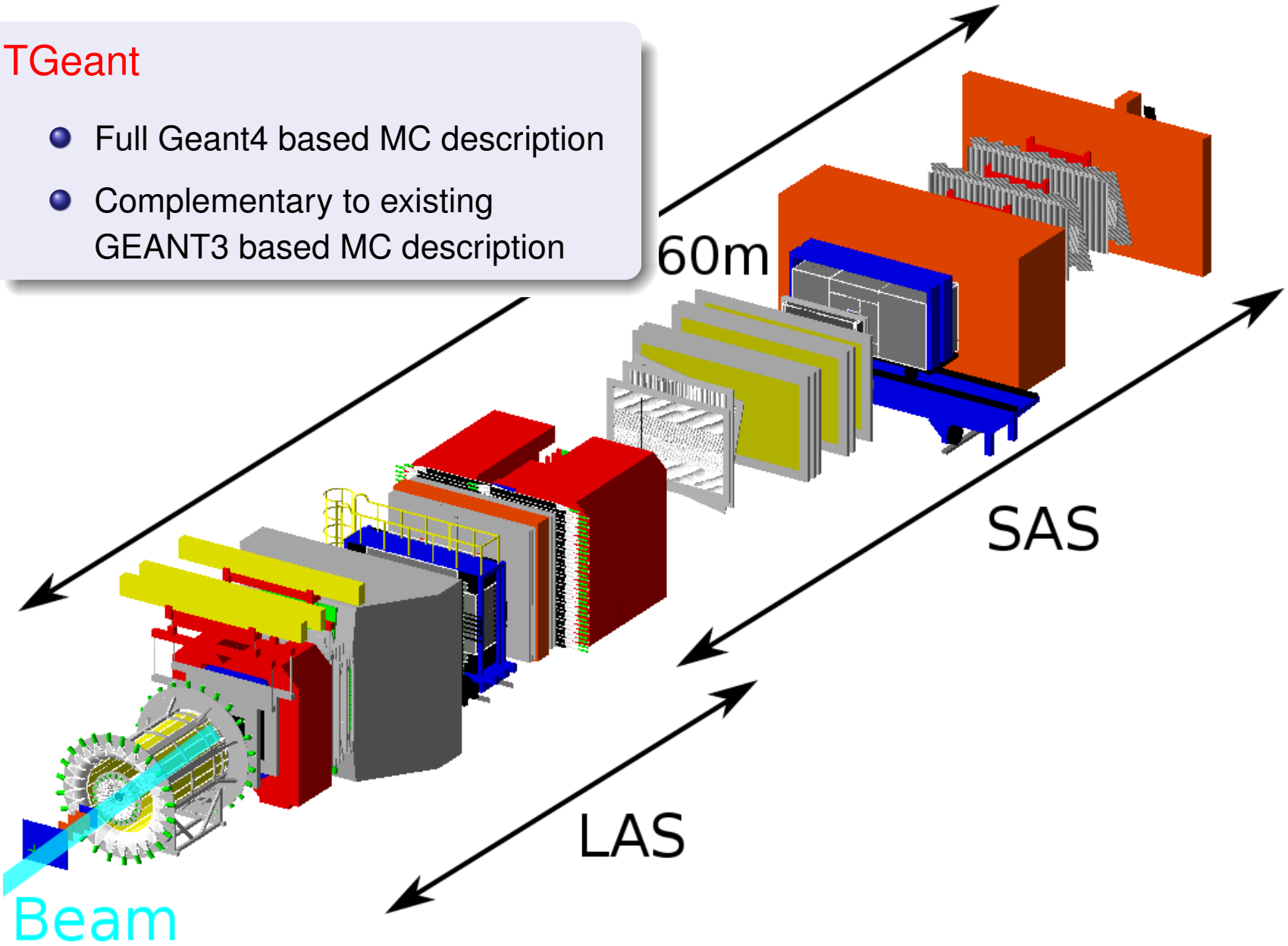
Particle identification:

- Hadron absorbers
- Ring Imaging Cerenkov Counter
- 2 Hadronic calorimeters
- 3 Electromagnetic calorimeters

Upgrades for the DVCS Program

TGeant

- Full Geant4 based MC description
- Complementary to existing GEANT3 based MC description



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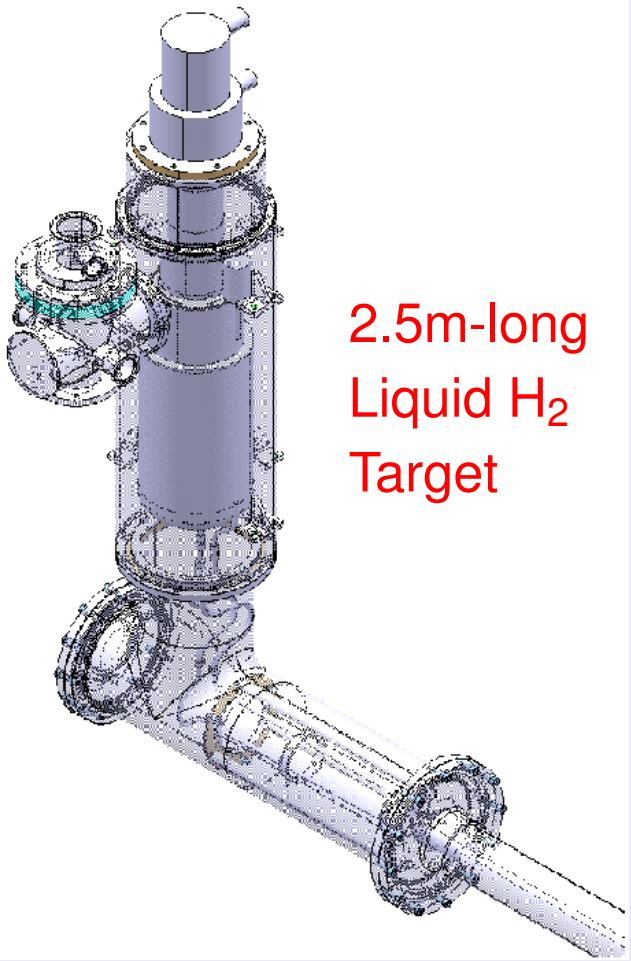


2.5m-long Liquid H_2 Target

SAS

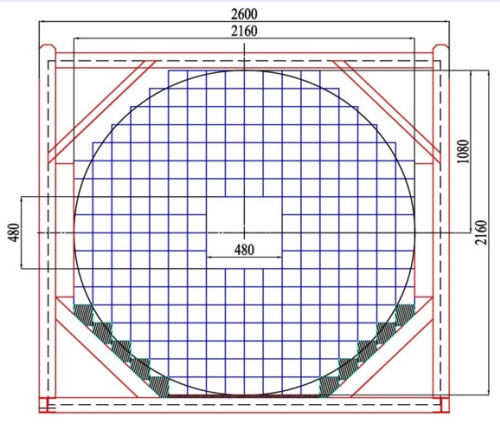
Beam

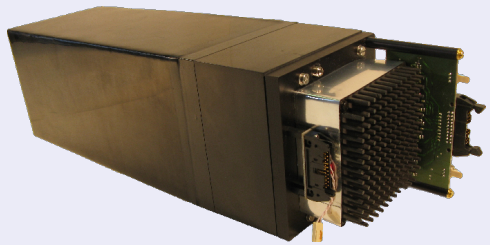
Upgrades for the DVCS Program

ECAL0 Calorimeter

Shashlyk modules + MAPD readout

$\sim 2 \times 2\ m^2$, $\sim$2200 ch.





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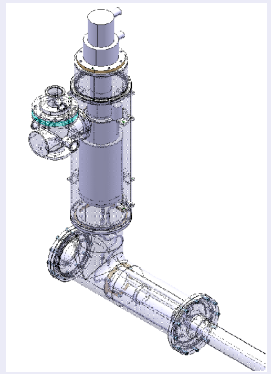

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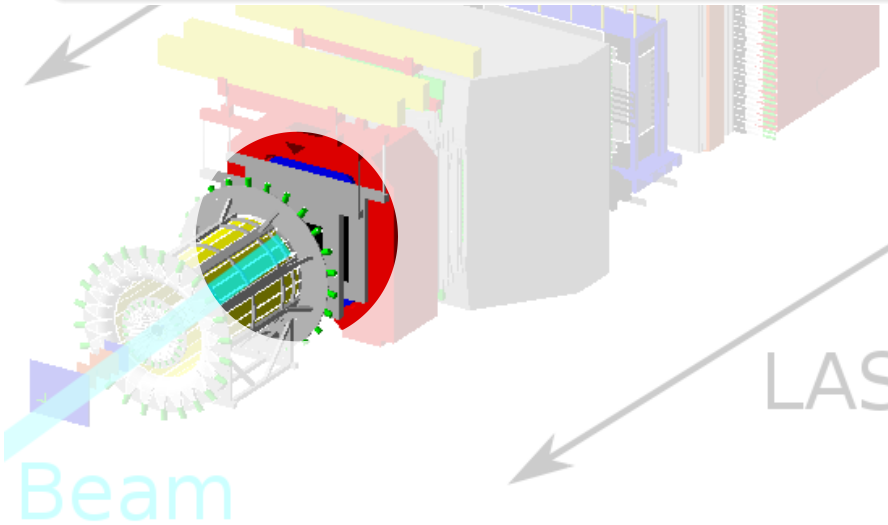

Upgrades for the DVCS Program

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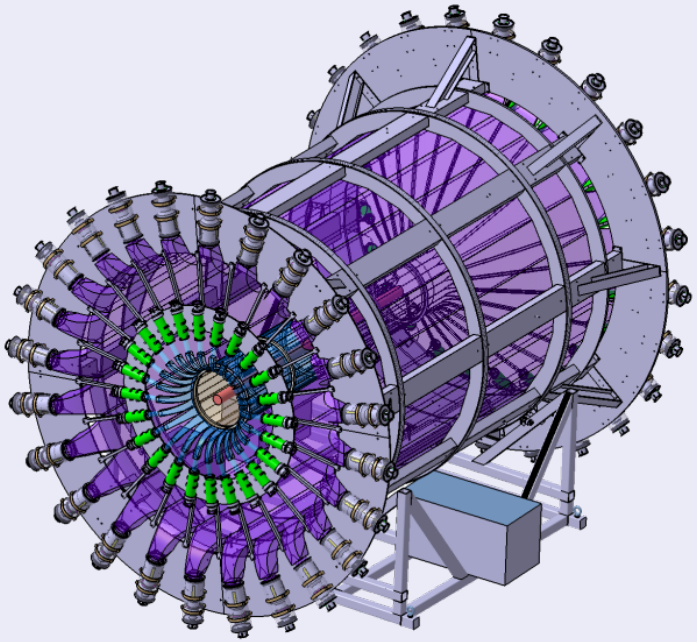
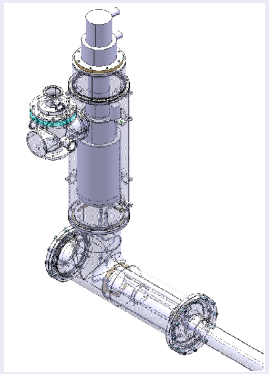
Target ToF System

24 inner & outer scintillators

1 GHz SADC readout

Goal: **310 ps** ToF resol.





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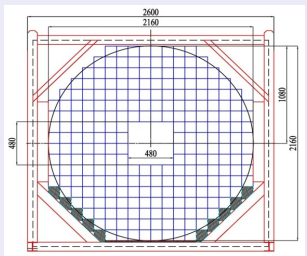
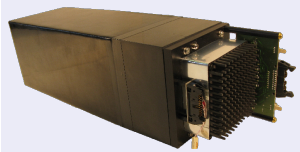
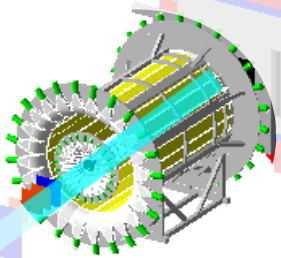
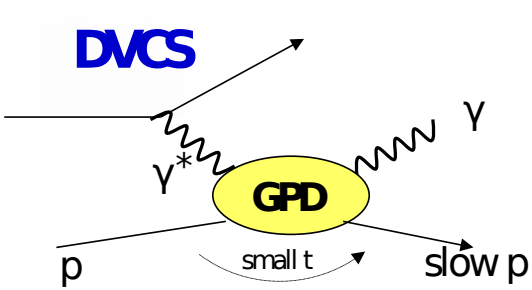
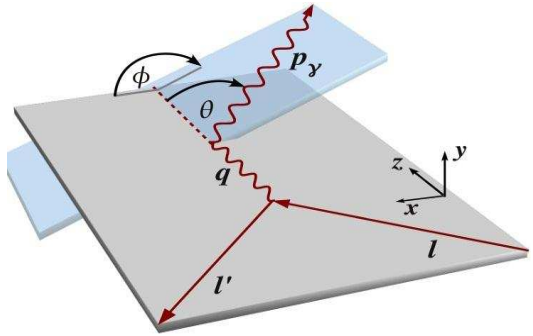
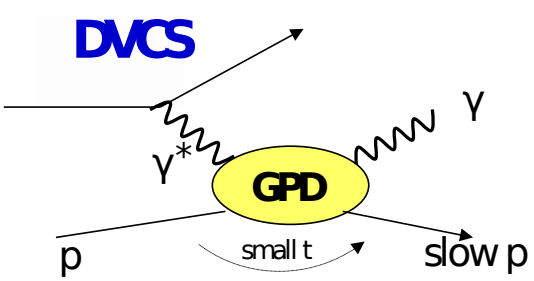


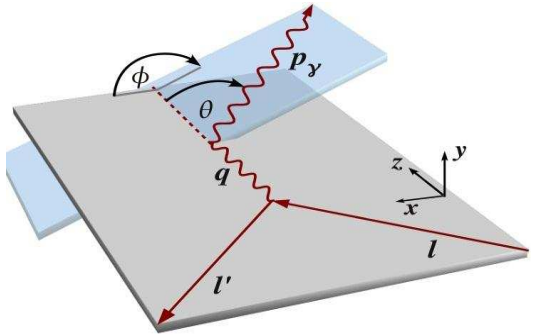





DVCS
γ*
γ
GPD
p
small t
slow p

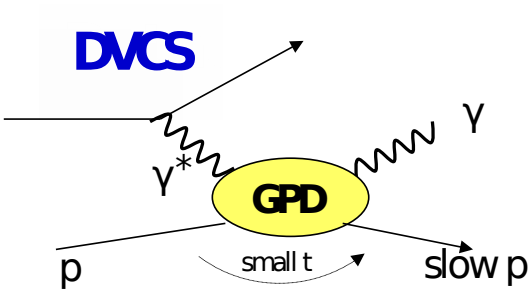

ϕ
θ
p_γ
q
z
y
x
l
l'

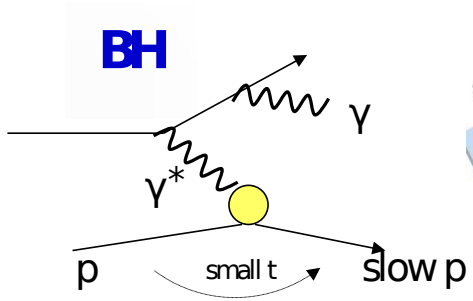


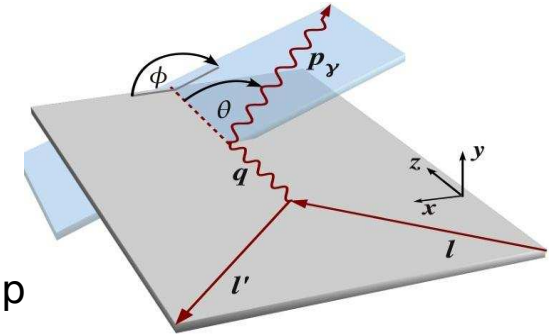


$$d\sigma \propto \underbrace{|T_{DVCS}|^2}$$

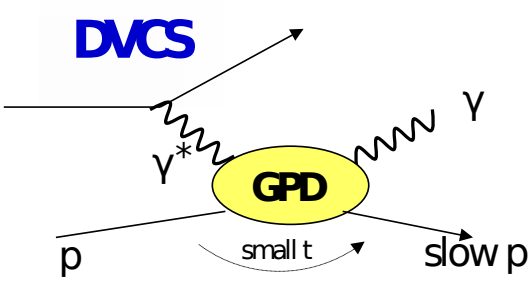
bilinear combination of GPDs

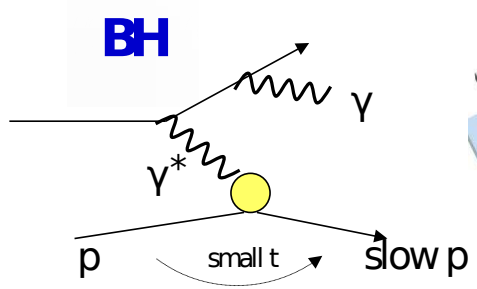


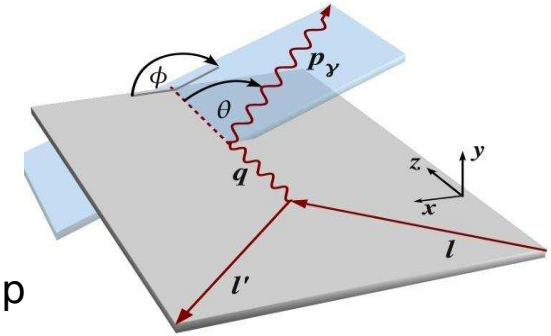




$$d\sigma \propto \underbrace{|T_{DVCS}|^2}_{\text{bilinear combination of GPDs}} + \underbrace{|T_{BH}|^2}_{\text{known to 1 \%}} + \underbrace{\text{interference term}}_{\text{linear combination of GPDs}}$$







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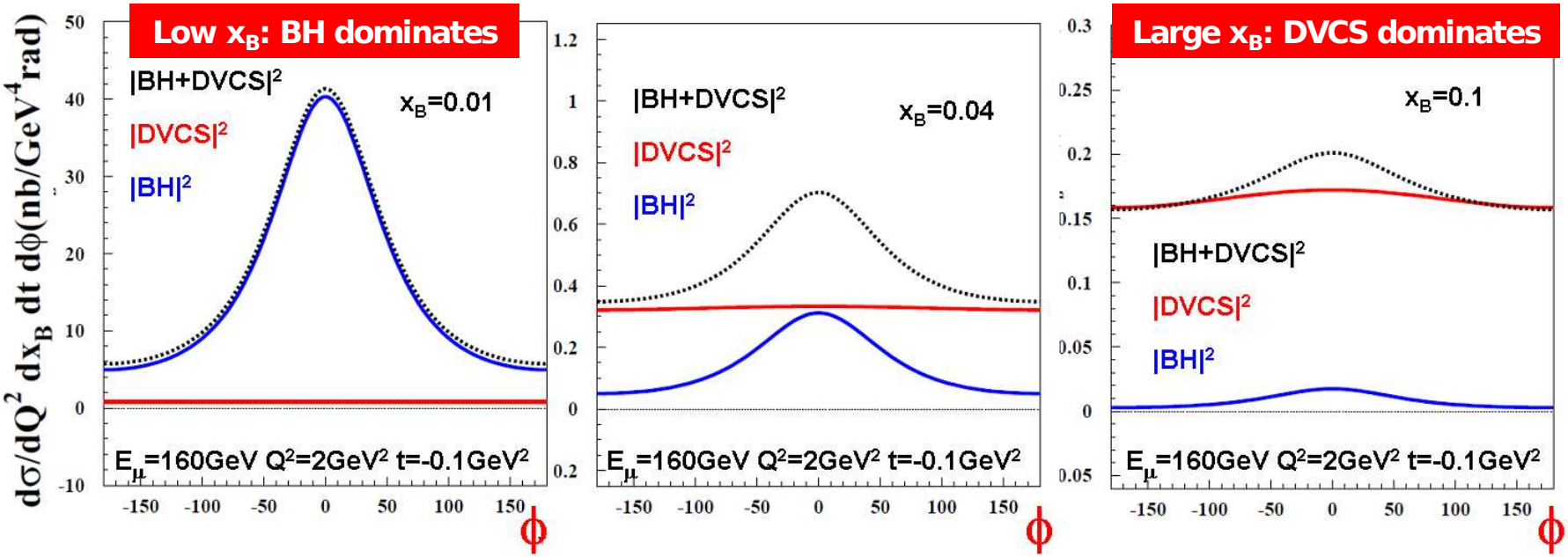

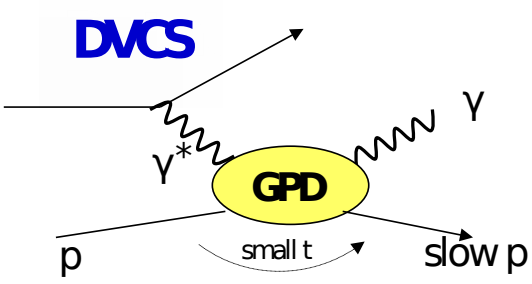

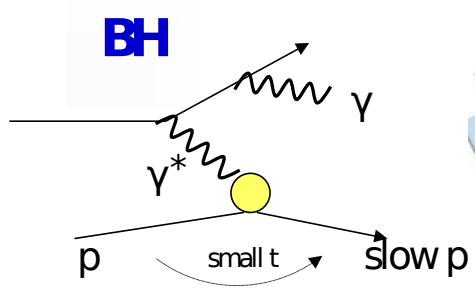

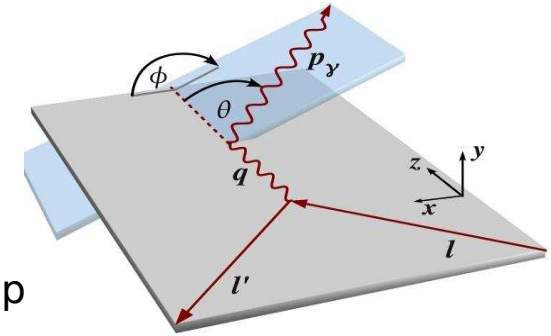

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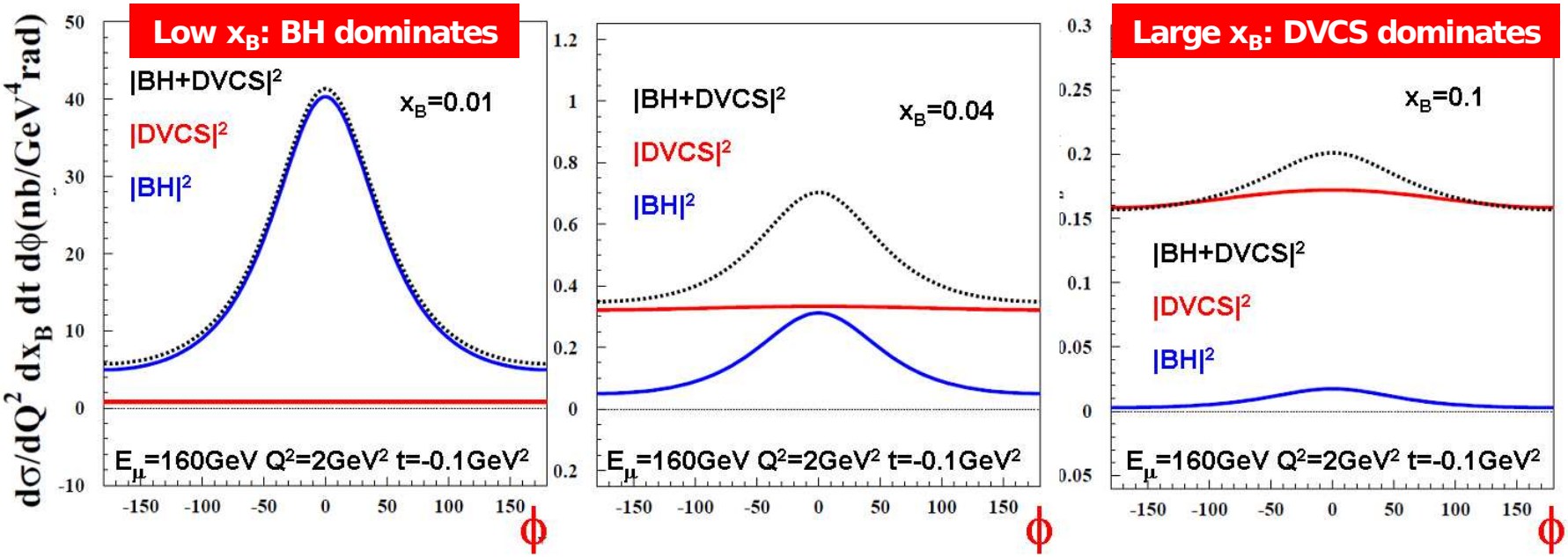
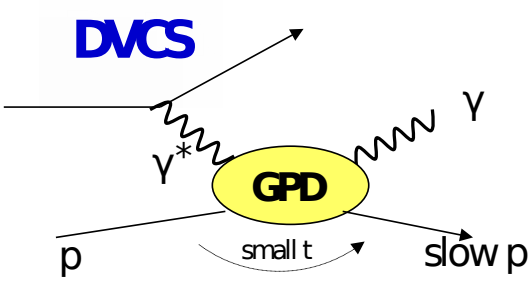
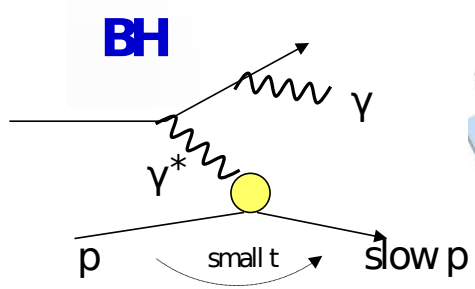
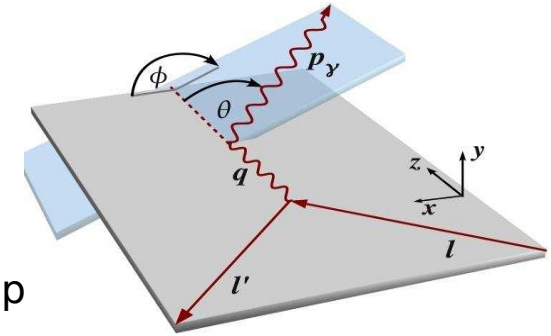


reference from
almost pure
Bethe-Heitler







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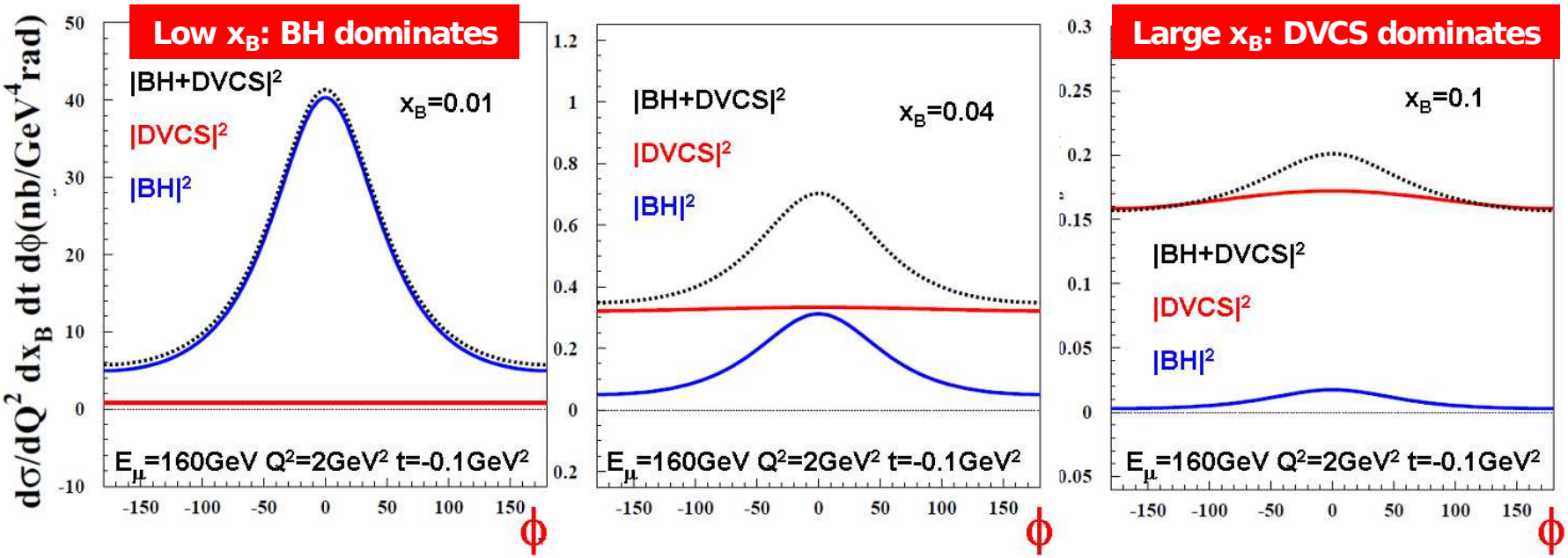
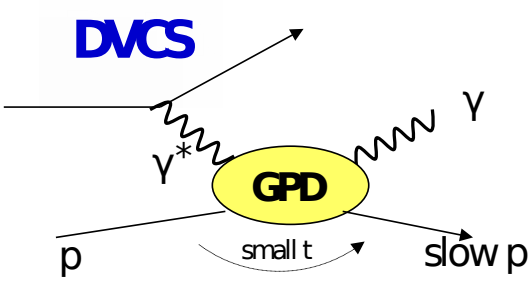
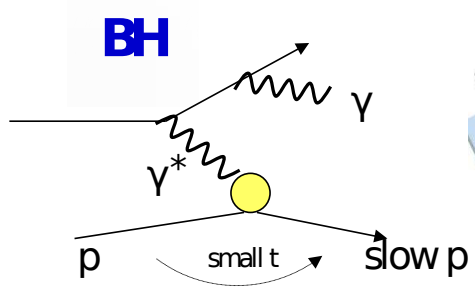
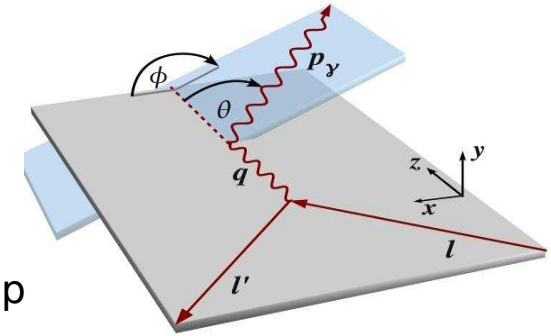


reference from almost pure Bethe-Heitler

Study DVCS with:
$\Re(T^{DVCS})$ & $\Im(T^{DVCS})$
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$







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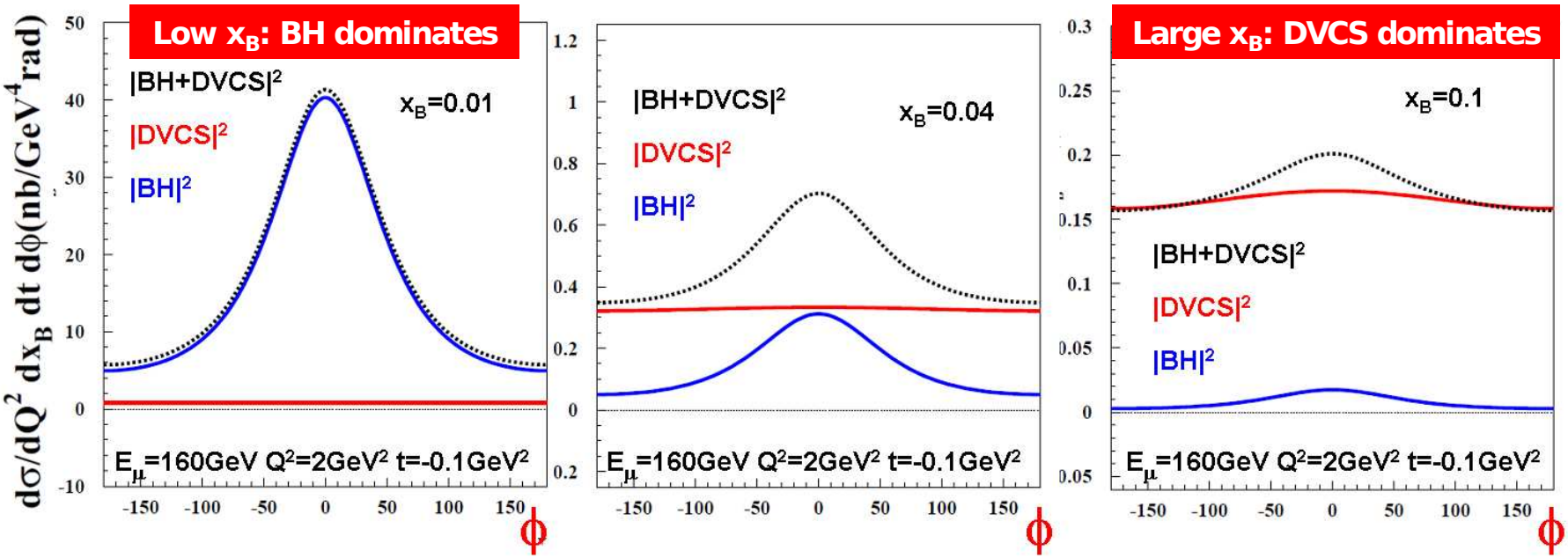

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Study DVCS with:
$\Re(T^{DVCS})$ & $\Im(T^{DVCS})$
via $(d\sigma^{+\leftarrow} \pm d\sigma^{-\rightarrow})$

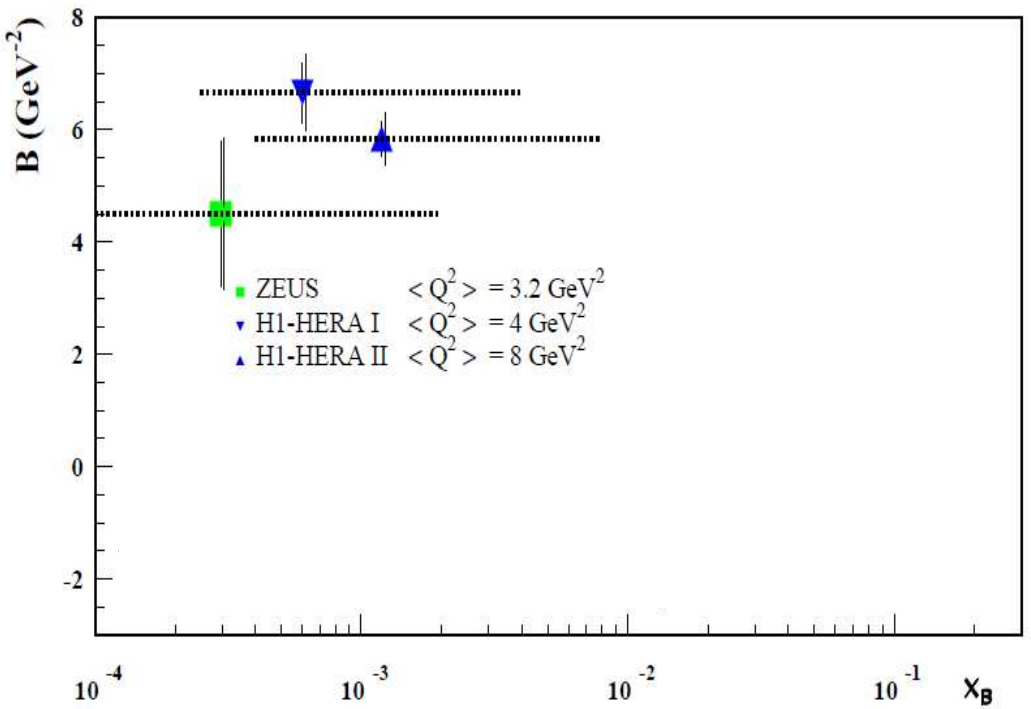
Transverse Imaging:
$d\sigma^{DVCS}/dt$
via $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$

- Using: $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Integrate over ϕ
- Subtract Bethe-Heitler

$$\frac{d\sigma}{d|t|} \propto e^{-B|t|}; < r_{\perp}^{2} > \sim 2B(x_{Bj})$$

- Using: $(d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow})$
- Integrate over ϕ
- Subtract Bethe-Heitler

$$\frac{d\sigma}{d|t|} \propto e^{-B|t|}; < r_{\perp}^2 > \sim 2B(x_{Bj})$$



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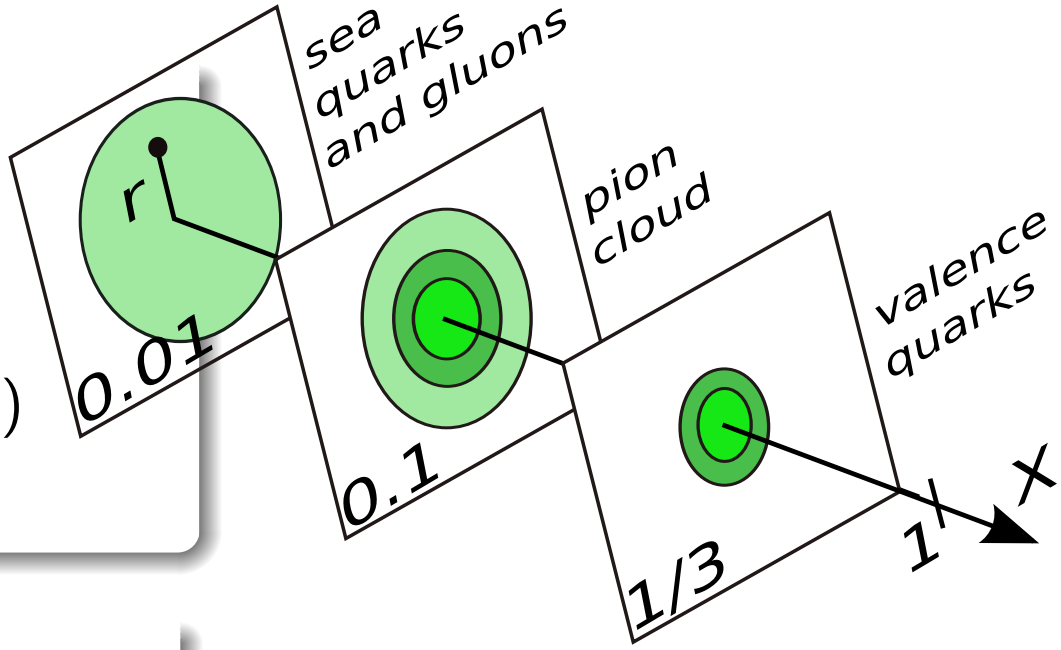
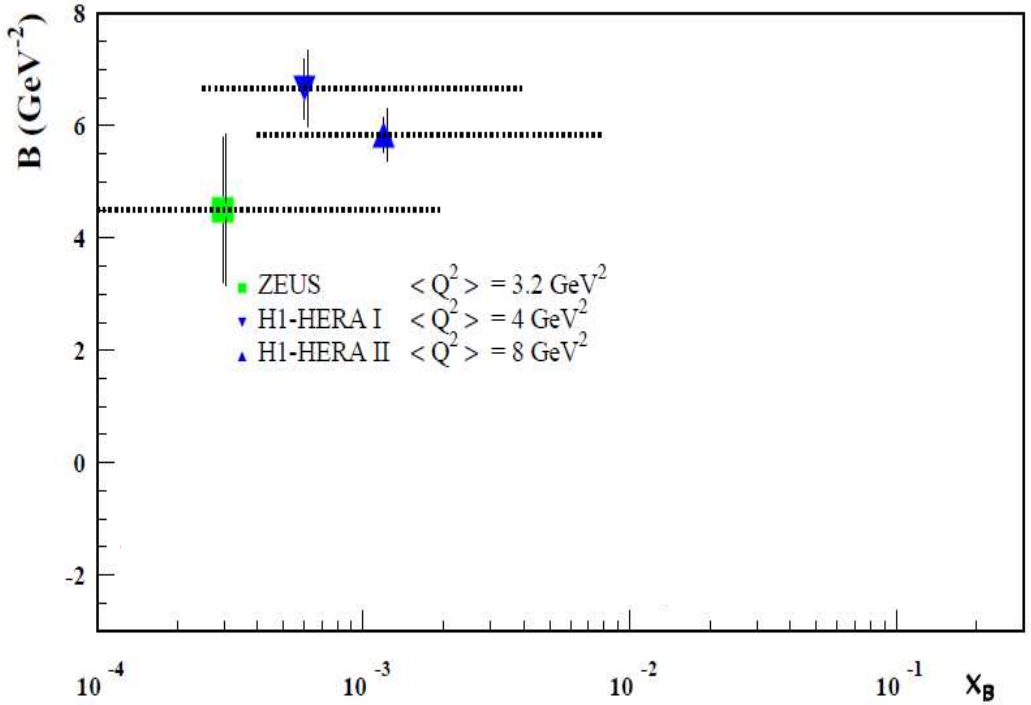
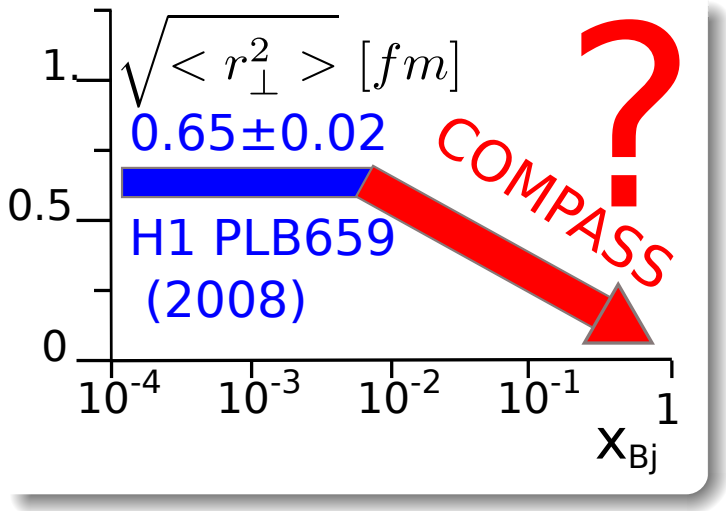
$$\frac{d\sigma}{d|t|} \propto e^{-B|t|}; < r_\perp^2 > \sim 2B(x_{Bj})$$







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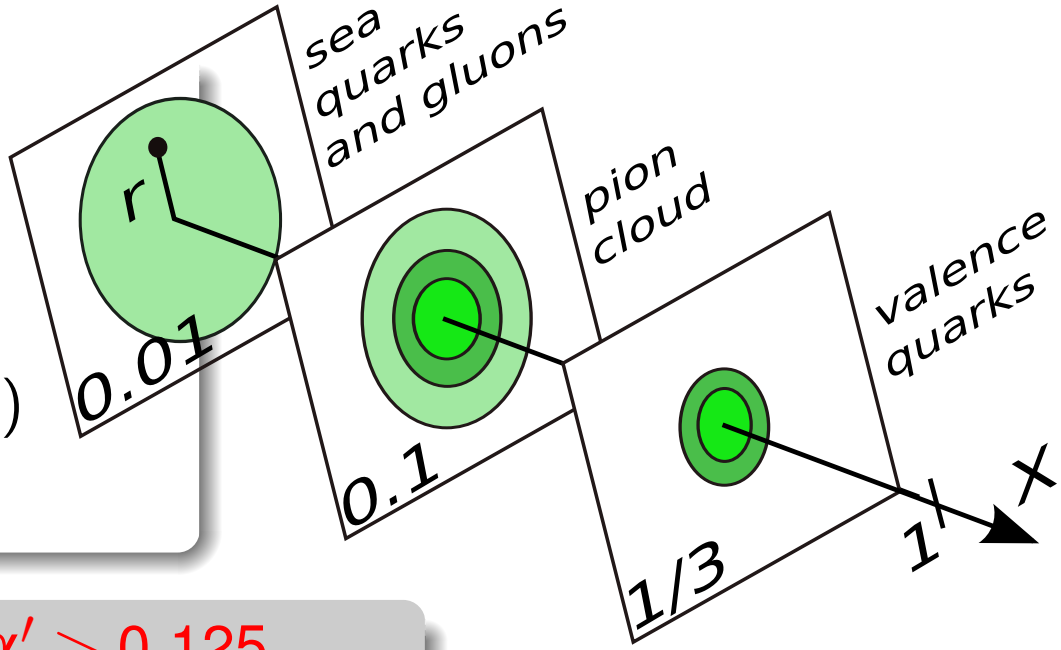
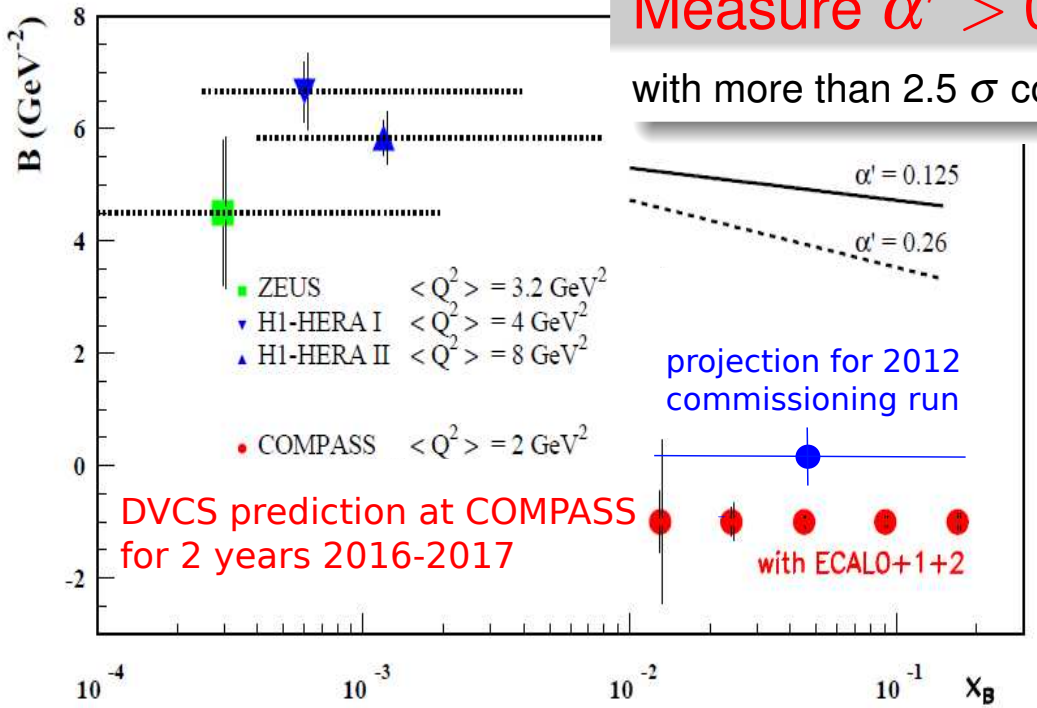
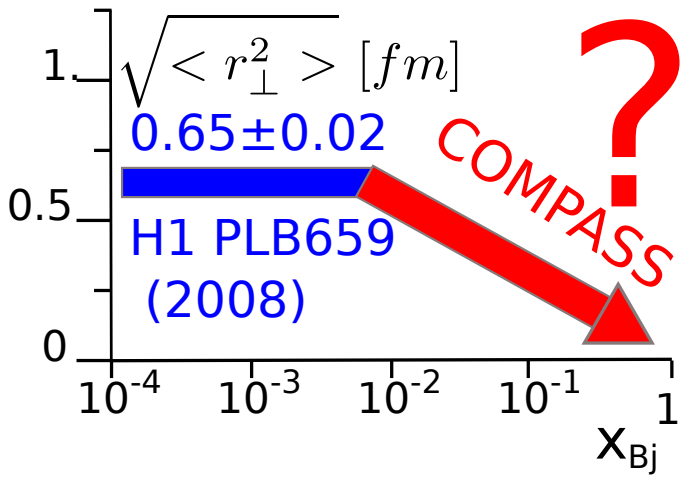
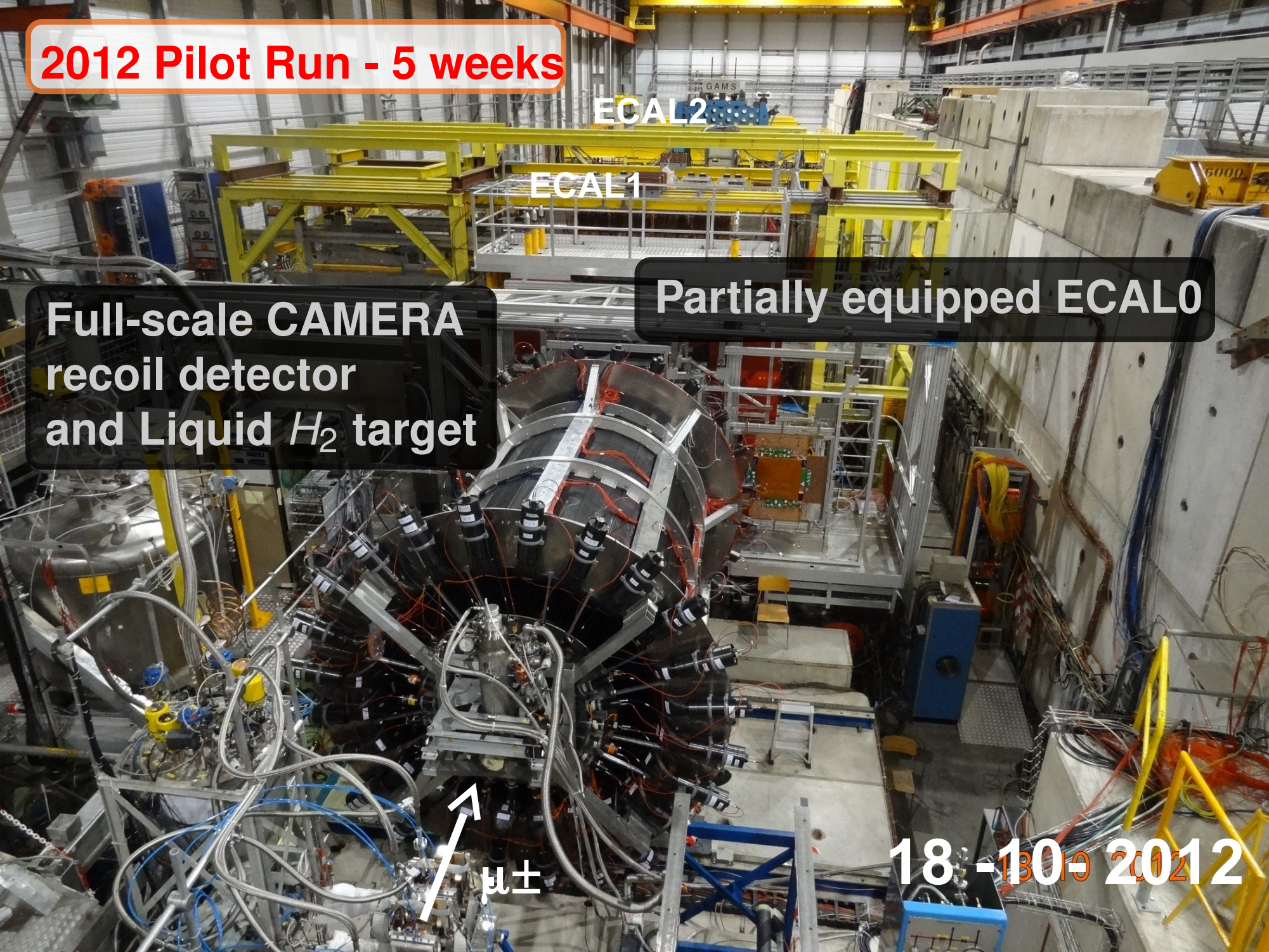


Measure $\alpha' > 0.125$

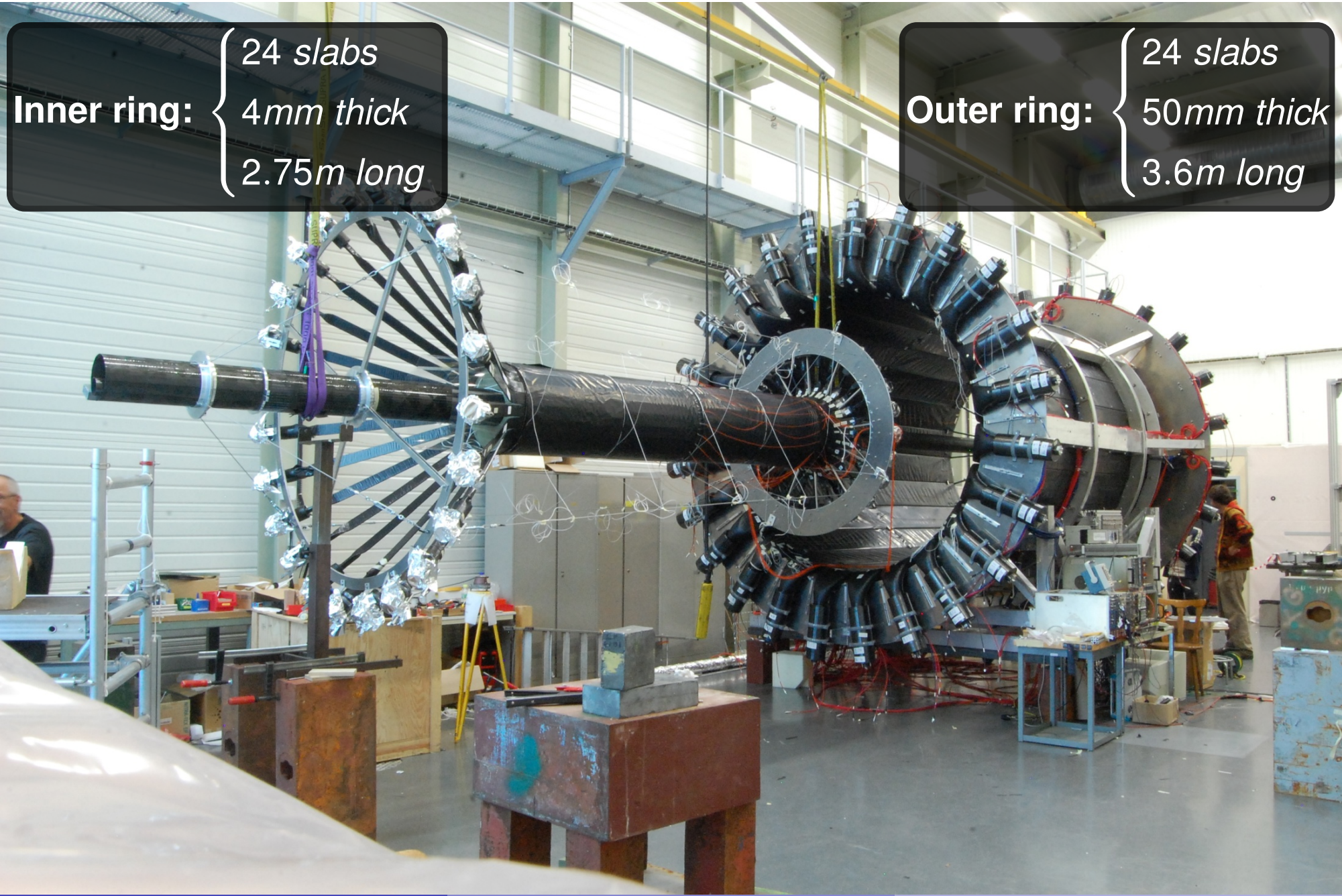
with more than 2.5 σ confidence level






2012 Pilot Run - 5 weeks
ECAL2
ECAL1
Partially equipped ECAL0
Full-scale CAMERA
recoil detector
and Liquid H_2 target
μ±
18 -10- 2012

The Recoil ToF Detector CAMERA

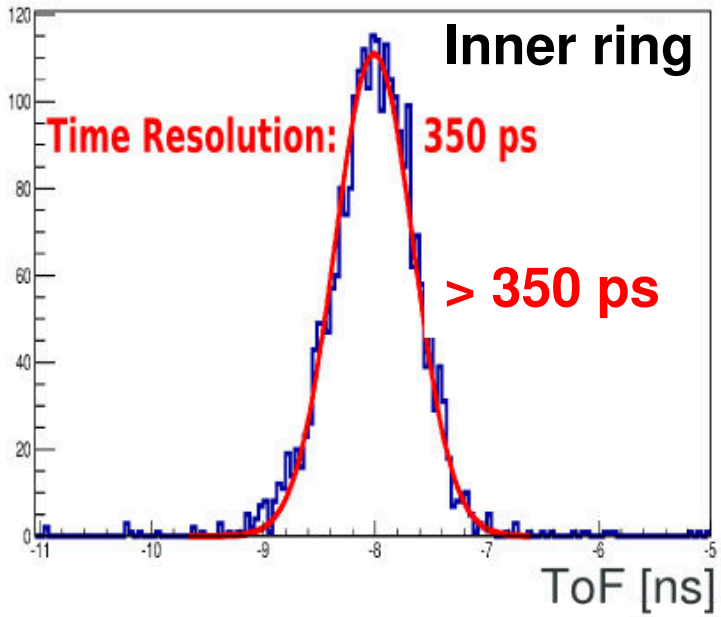


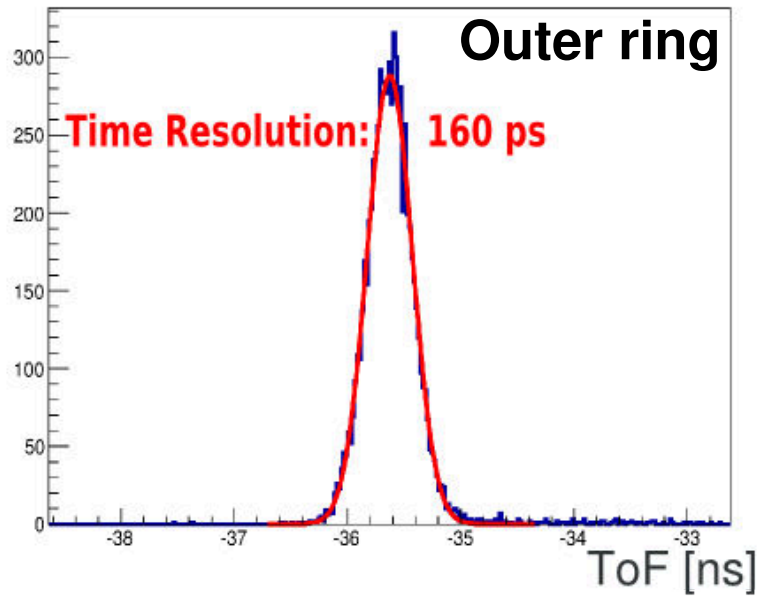
The Recoil ToF Detector CAMERA

Inner ring: 24 *slabs*, 4*mm thick*, 2.75*m long*

Outer ring: 24 *slabs*, 50*mm thick*, 3.6*m long*

Time resolution measurement with cosmics





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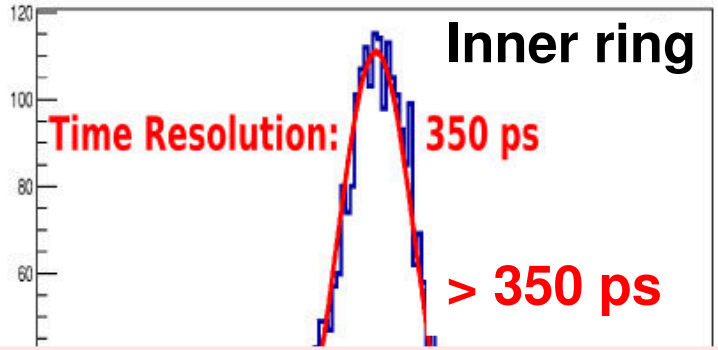
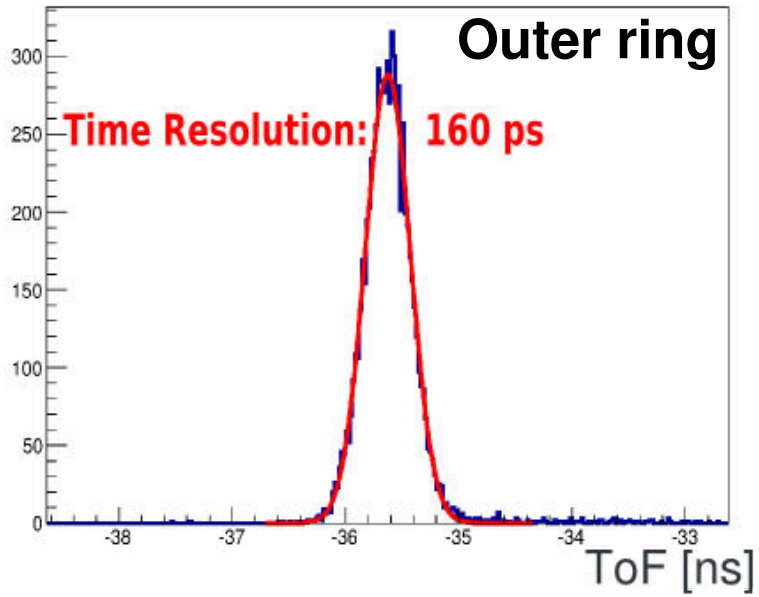




Bad scintillator quality!

Replacement in 2016

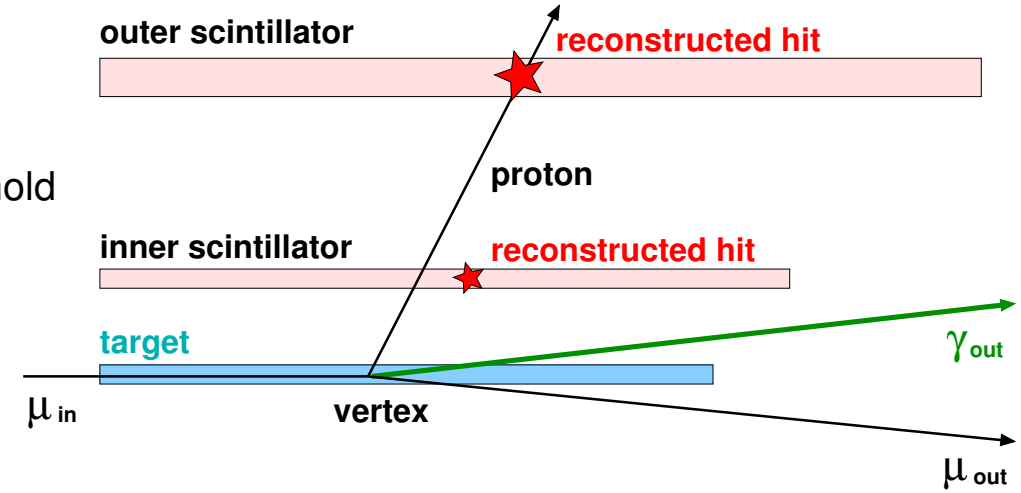
Exclusive Photon Events Selection

Reconstructed interaction vertex in **target volume**

One single photon above DVCS production threshold

$Q^2 > 1$ (GeV/c)^2, $\quad 0.05 < y < 0.9$,

0.06 (GeV/c)$^2 < t < 0.64$ (GeV/c)^2



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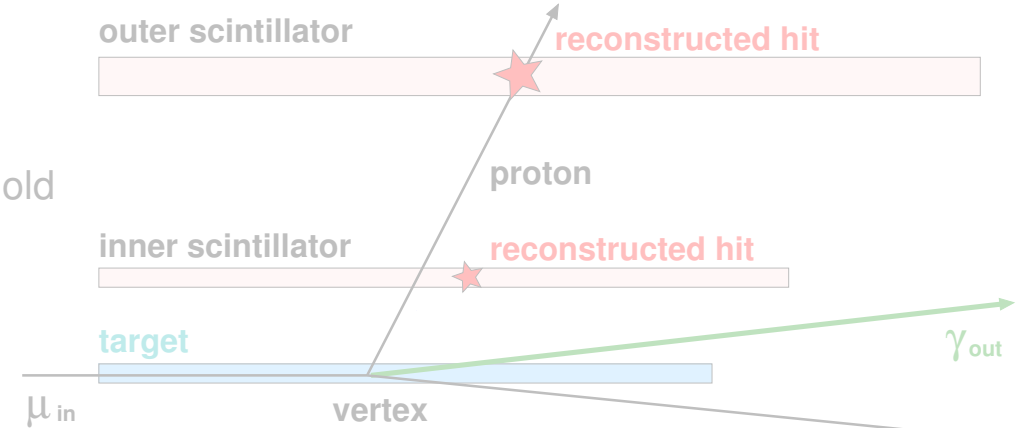
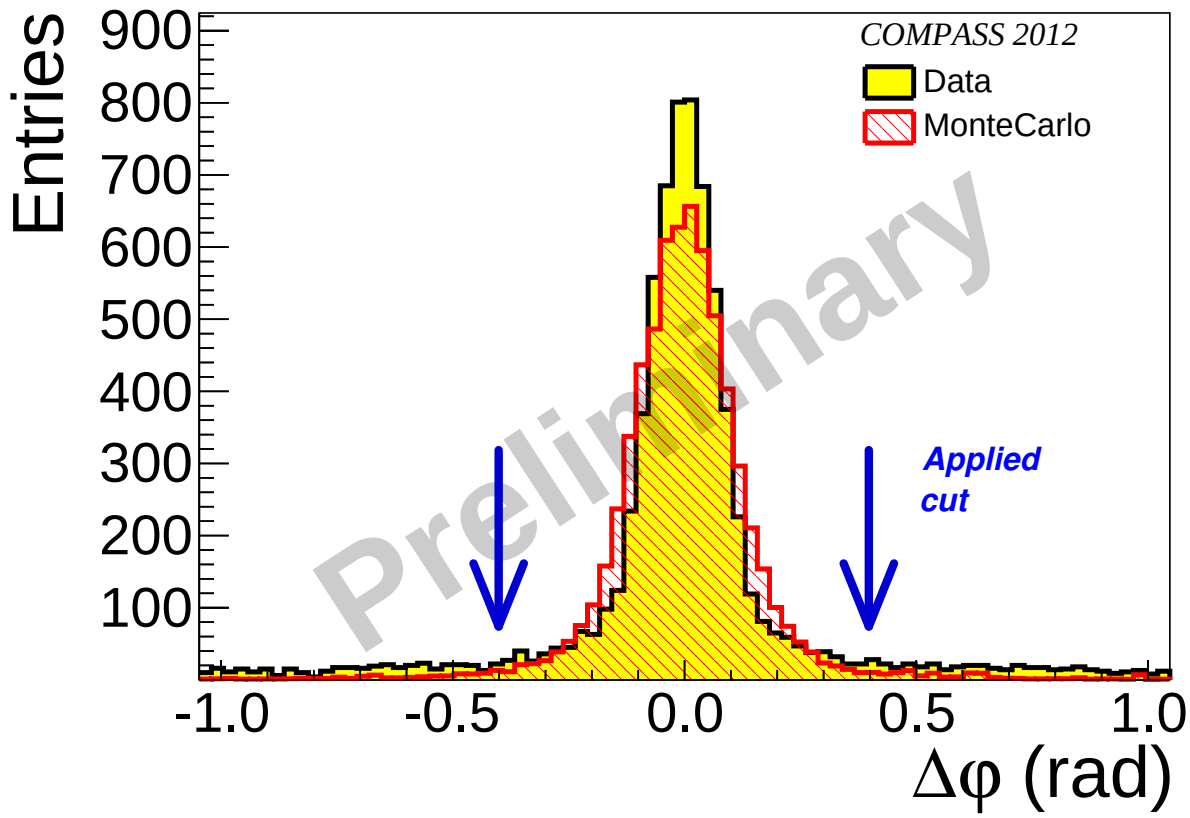
- Transv. momentum balance:
  $\Delta p_\perp = p^{proton}_{\perp,meas} - p^{proton}_{\perp,reco}$
- Four-momentum balance:
  $M_X^2 = (p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_{p_{out}}$
- Missing energy:
  $E_{miss} = ((p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_\gamma)$





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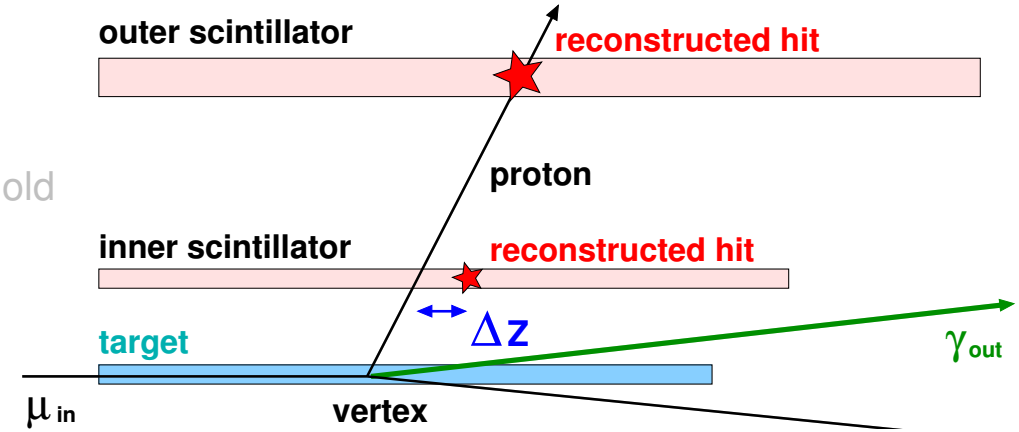

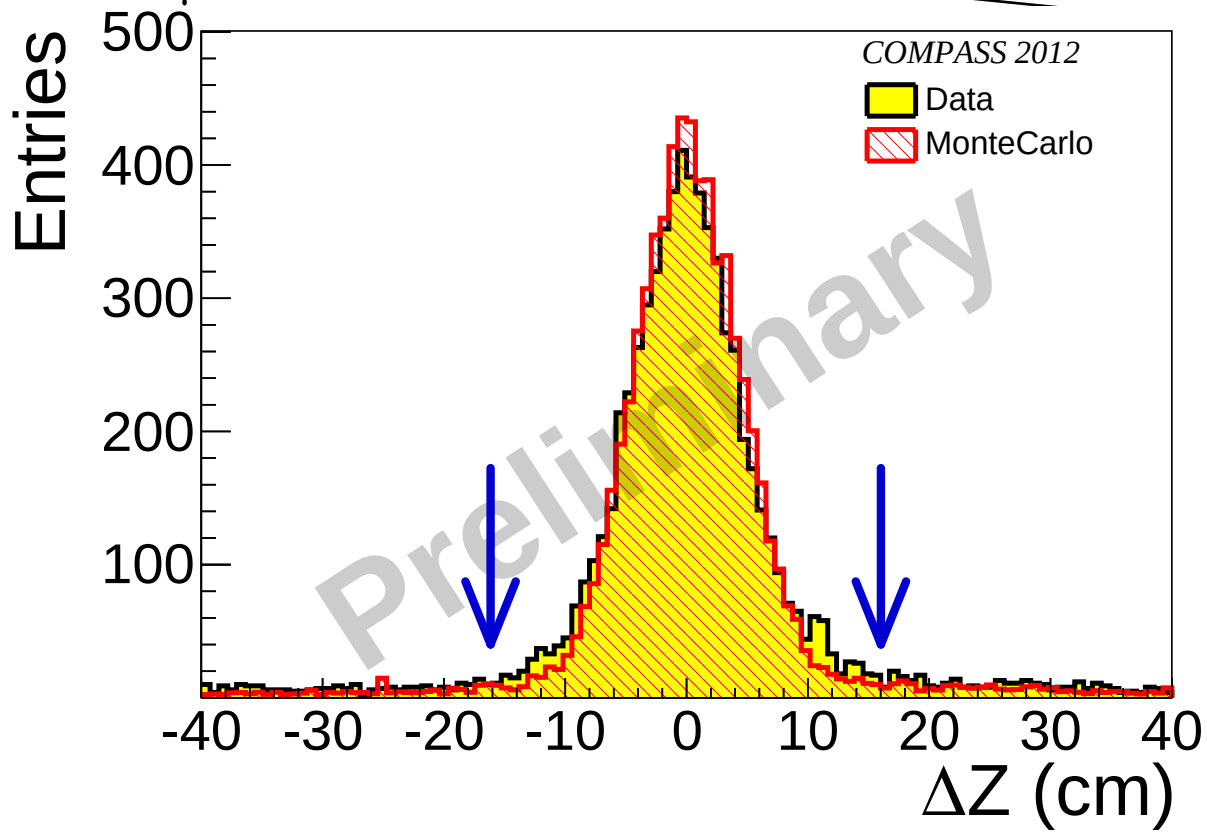

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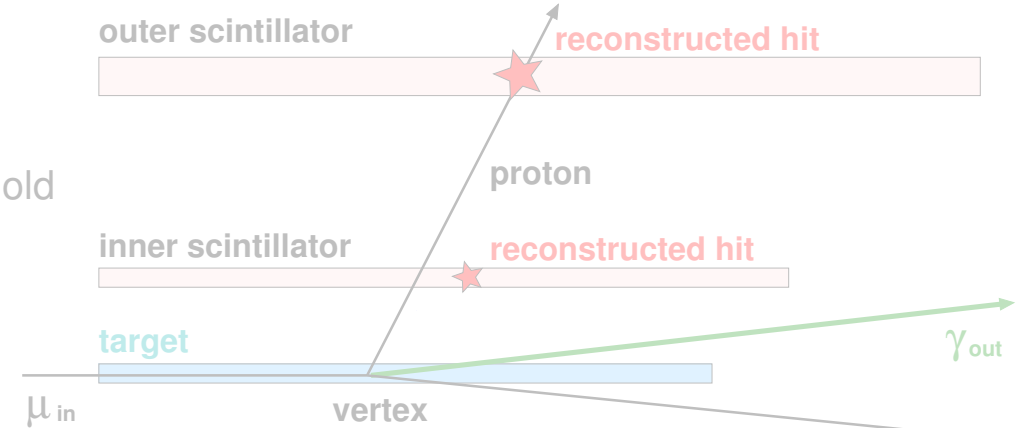

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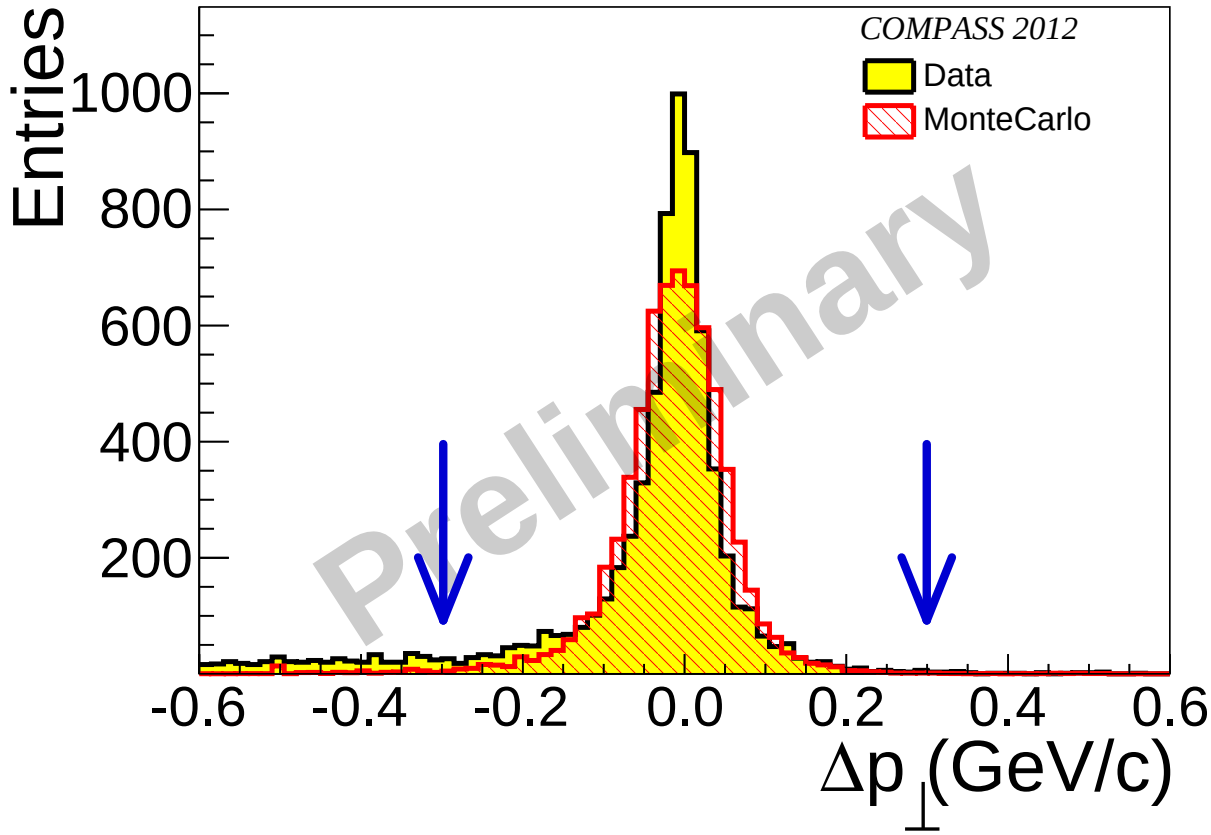

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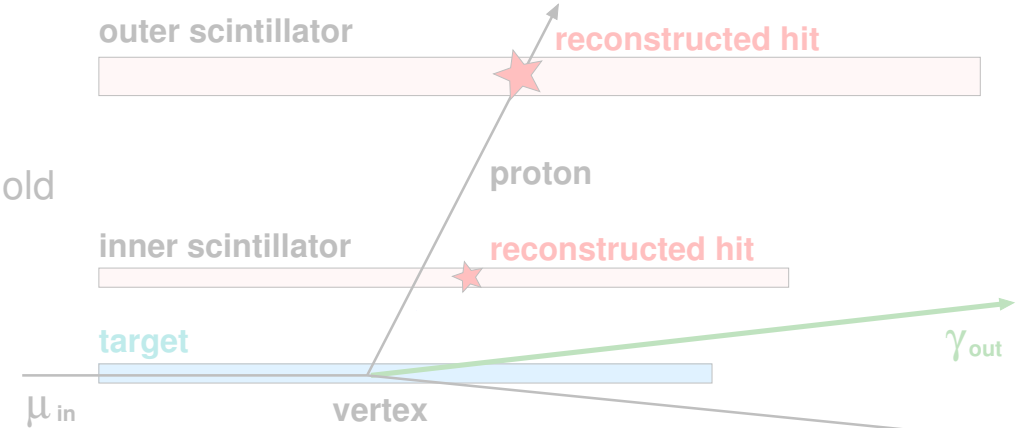

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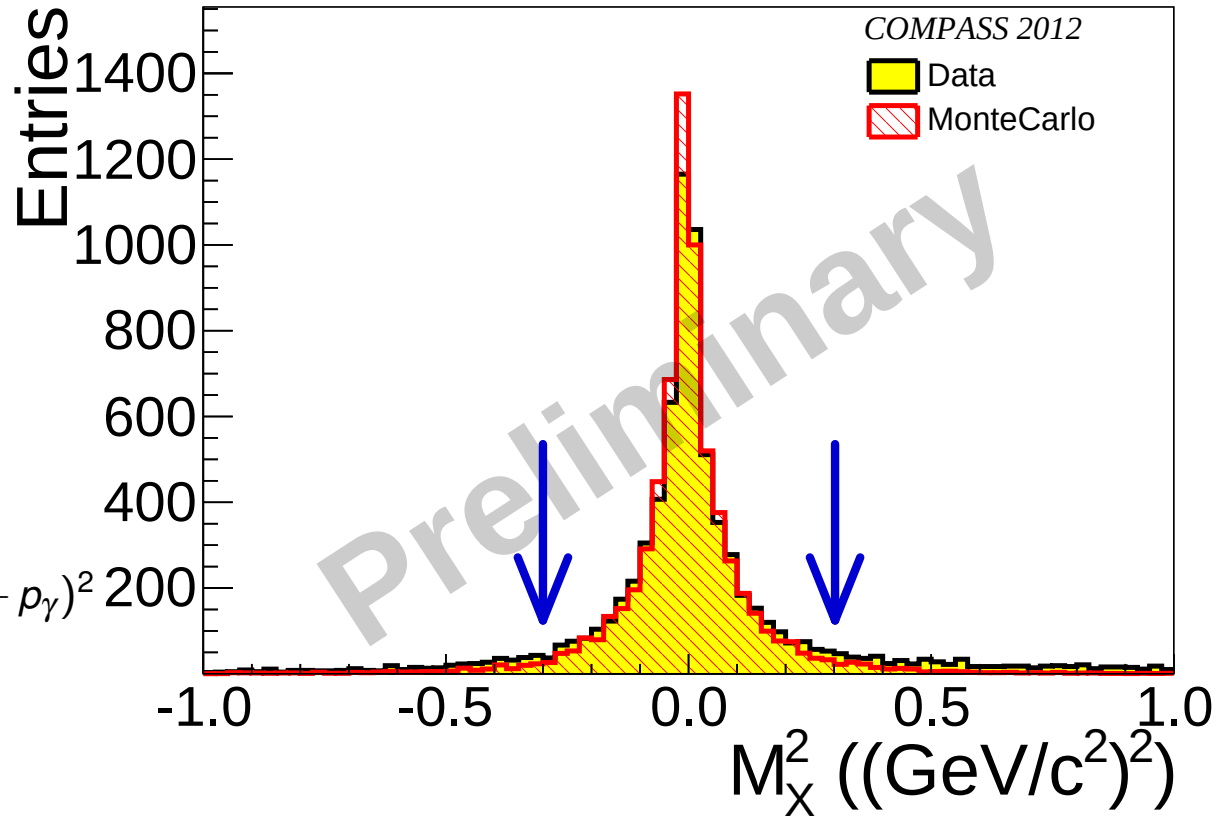
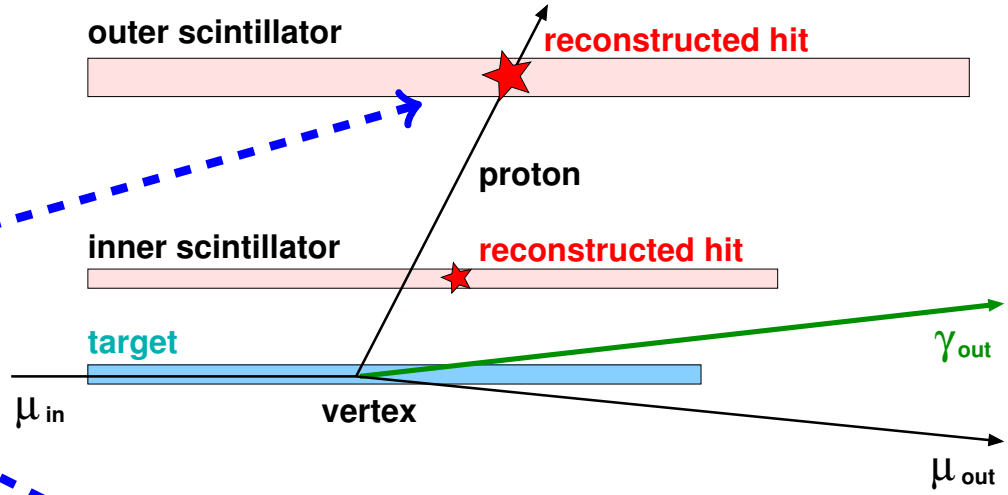


Exclusive Photon Events Selection

Signal amplitude in outer scintillators vs. β of recoiling particle

Proton signature clearly visible after all exclusivity conditions



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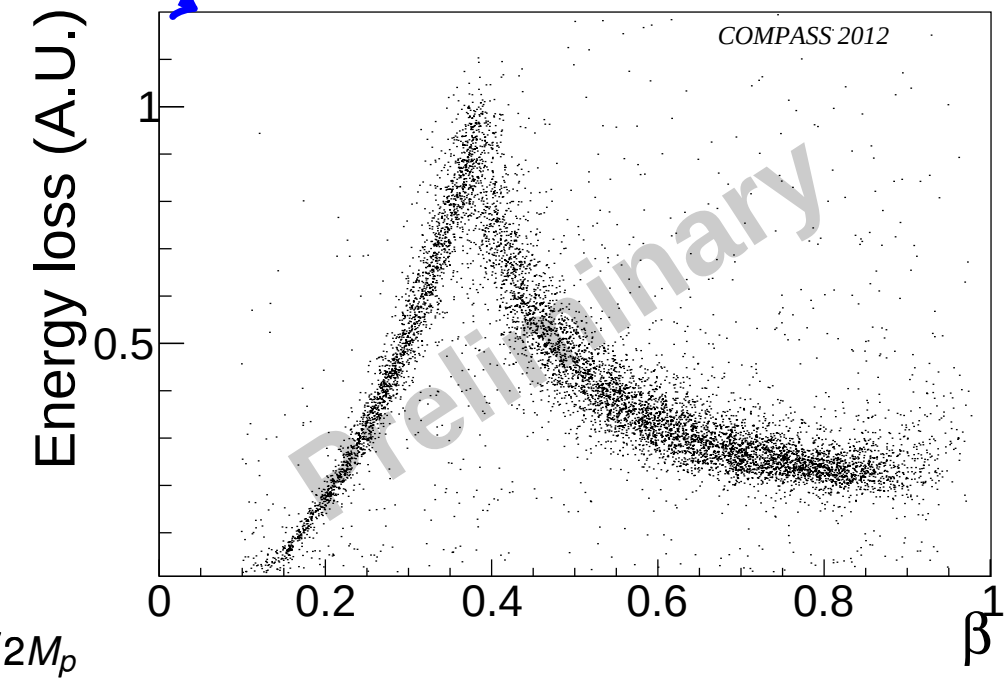
- Missing energy:
  $E_{miss} = ((p_{\mu_{in}} + p_{p_{in}} - p_{\mu_{out}} - p_\gamma)^2 - M_p^2)/2M_p$

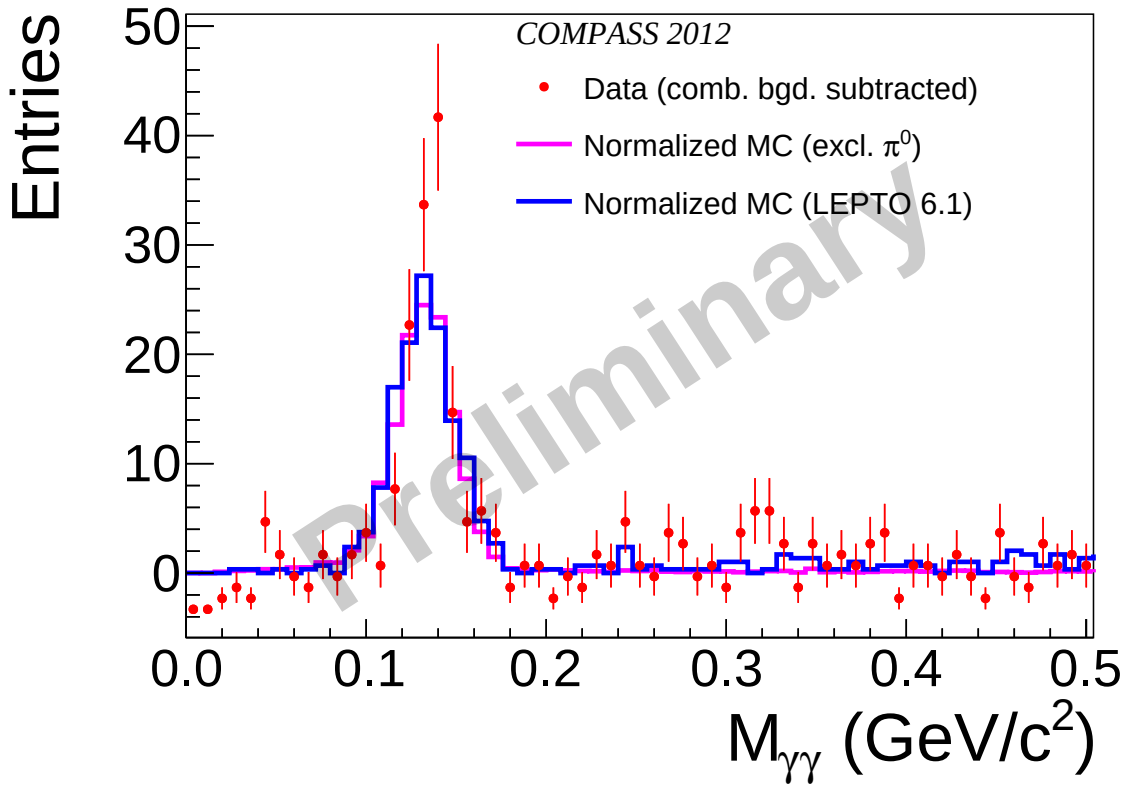


π^0 Background Estimation

Major background source for exclusive photon events

Two cases:

- **Visible** (both γ detected, easy to reject)
- **Invisible** (one γ "lost", estimated with MC)



$M_{\gamma\gamma}$ distribution ("Visible" π^0) „Exclusive" γ + one below energy threshold

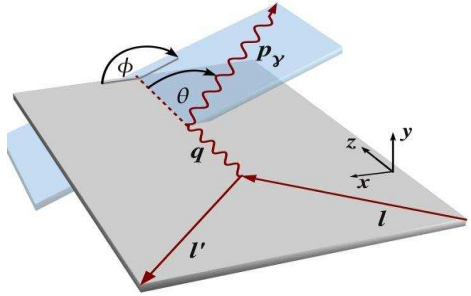
Semiinclusive LEPTO MC

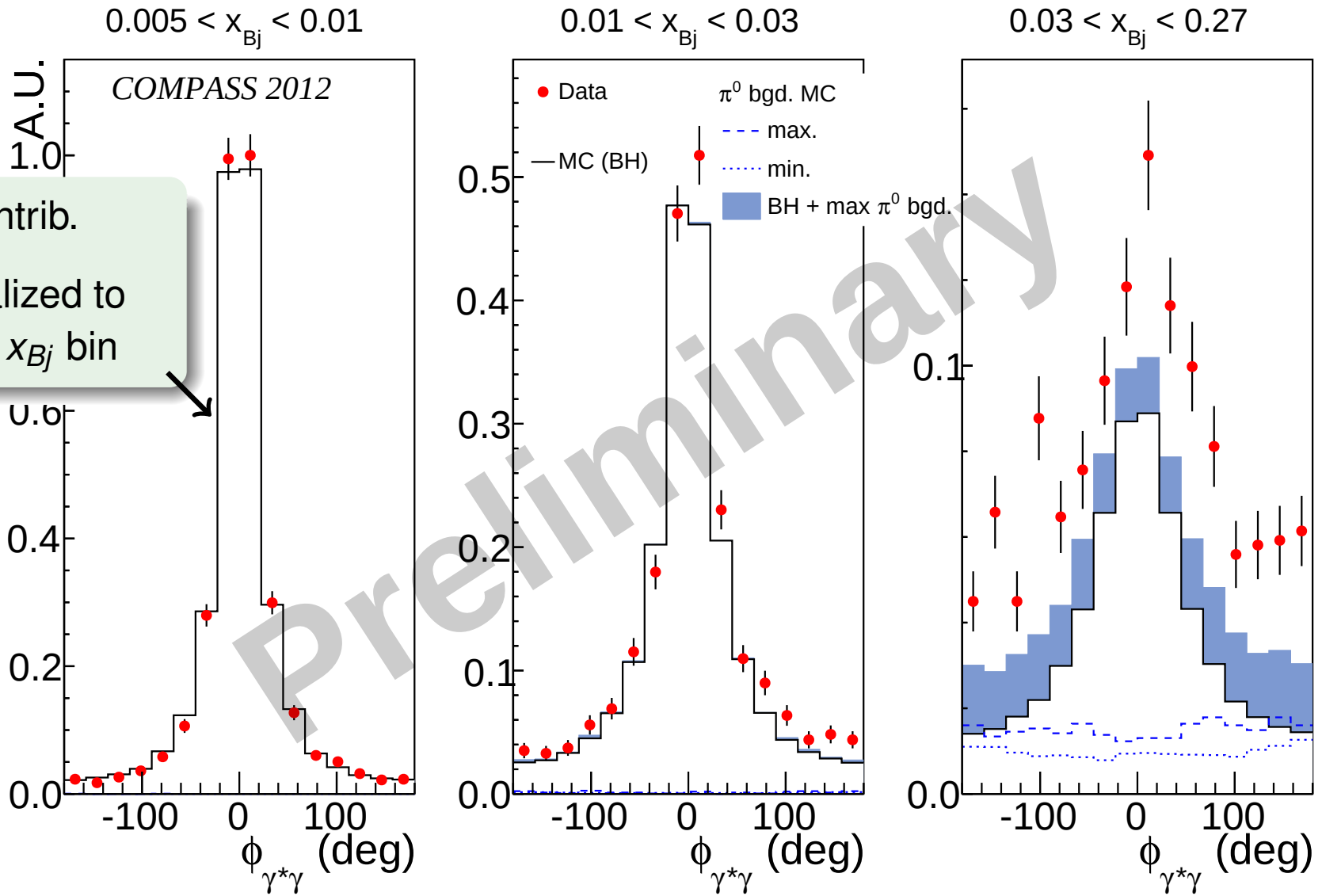
or

exclusive Hepgen MC (Golosgokov & Kroll model)

π^0 contribution normalized to $M_{\gamma\gamma}$ peak from real data

Exclusive γ Azimuthal Distribution

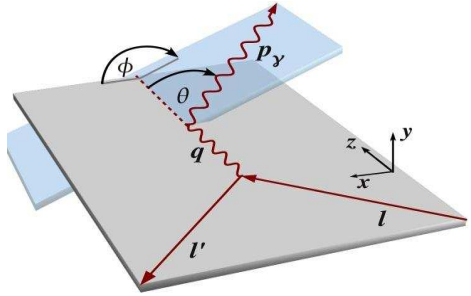




BH contrib.

Normalized to lowest x_{Bj} bin

Exclusive γ Azimuthal Distribution



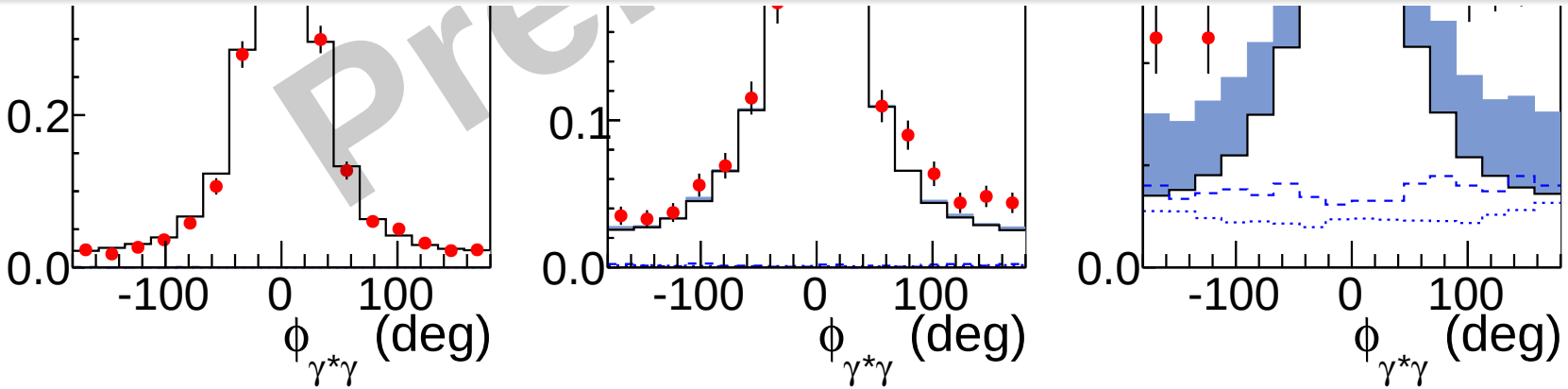
$0.005 < x_{Bj} < 0.01$ $0.01 < x_{Bj} < 0.03$ $0.03 < x_{Bj} < 0.27$

Dominant **Bethe-Heitler** process clearly visible at small x_{Bj}

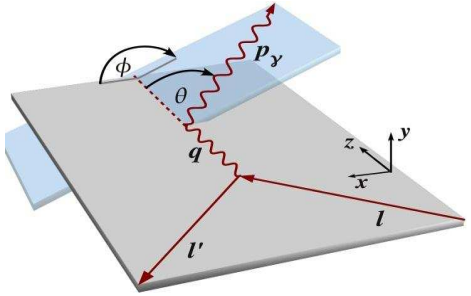
$\phi_{\gamma^*\gamma}$ shape well reproduced by MC simulation

First estimation of π^0 **background** at large x_{Bj}

Data at large x_{Bj} show an **excess** compared to BH+background



Exclusive γ Azimuthal Distribution



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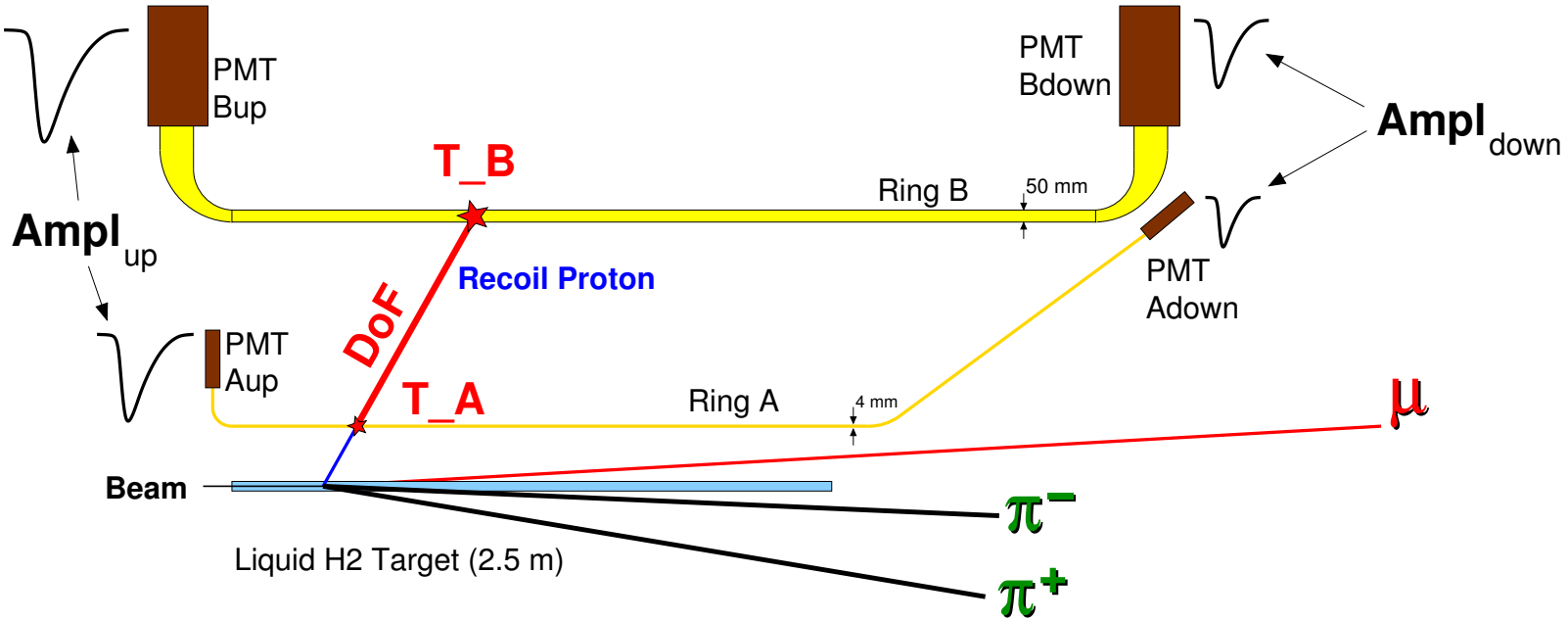
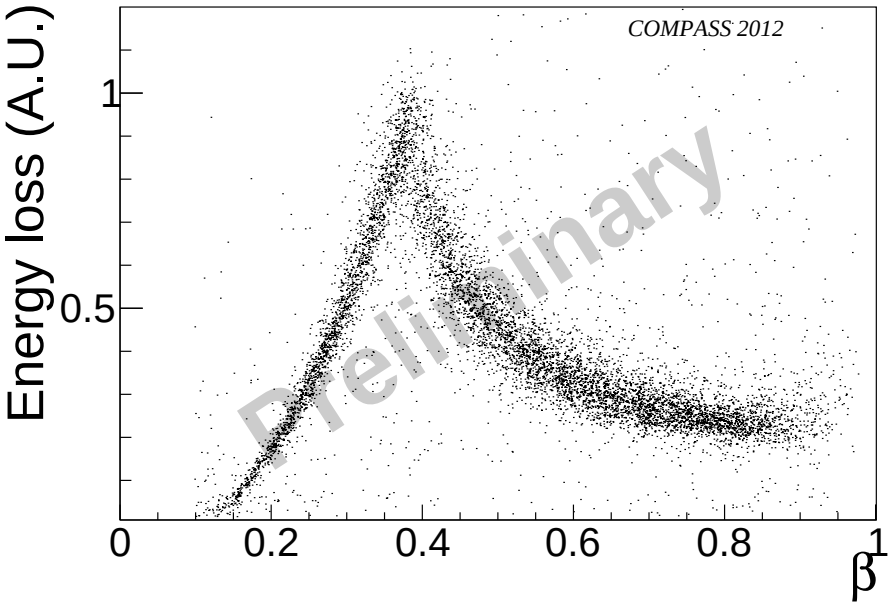
Next steps:

- **t-slope** extraction $\rightarrow$ nucleon tomography
- **Beam charge difference extraction**
- **Dedicated beam time for DVCS 2016-2018**

Recoil particle Measurement in CAMERA





$$E_{loss} \sim \sqrt{Ampl_{up} * Ampl_{down}}$$

$$\textbf{TOF} \rightarrow (t_{up} + t_{down})_{A,B}$$

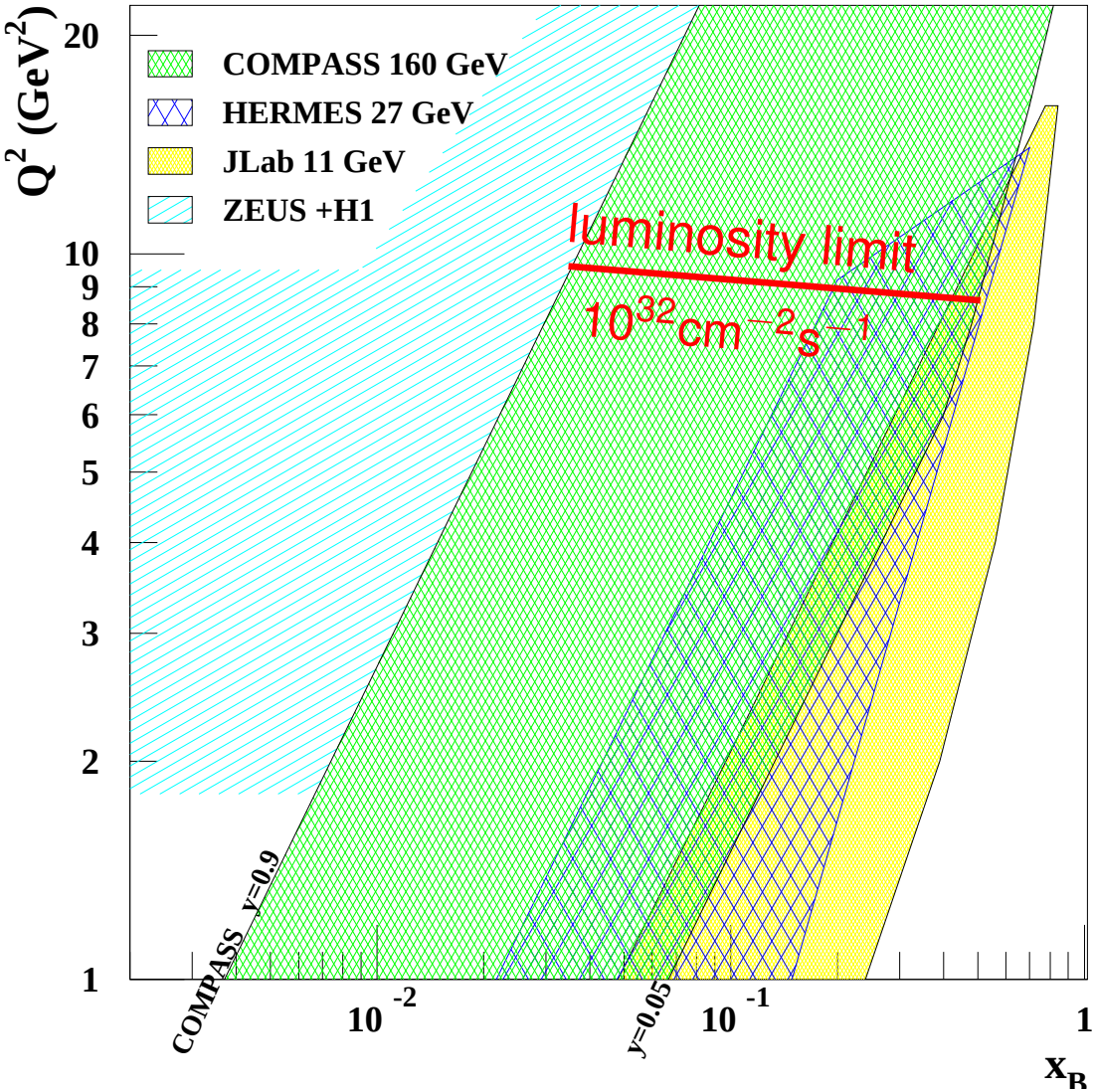
$$\textbf{z} \rightarrow t_{up} - t_{down}$$

Count rates: > 5 MHz in ring A

~1 MHz in ring B

What Makes COMPASS Unique?

COMPASS covers the unexplored region between collider (H1+Zeus) and low-energy fixed target (Hermes+JLab) experiments

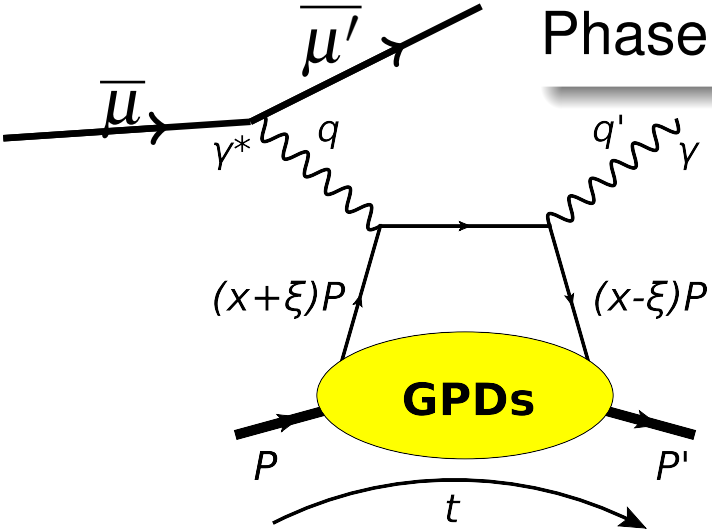


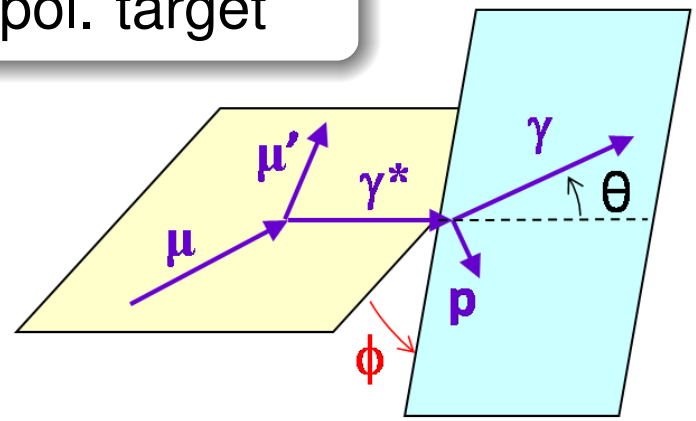
- μ^+ and μ^- beams
- momentum: $100 - 190\,\mathrm{GeV}/c$
- beam polarization: 80 %
  opposite for μ^+ and μ^-
- coverage of intermediate x_B
  - $\rightarrow$ low x_B: **pure BH**
    useful for normalization
  - $\rightarrow$ high x_B: **DVCS predominar**

$\rightsquigarrow$ **unexplored region between ZEUS+H1 and HERMES+JLab**

DVCS: What Can We Learn?

Phase 1: Polarized beam, unpol. target

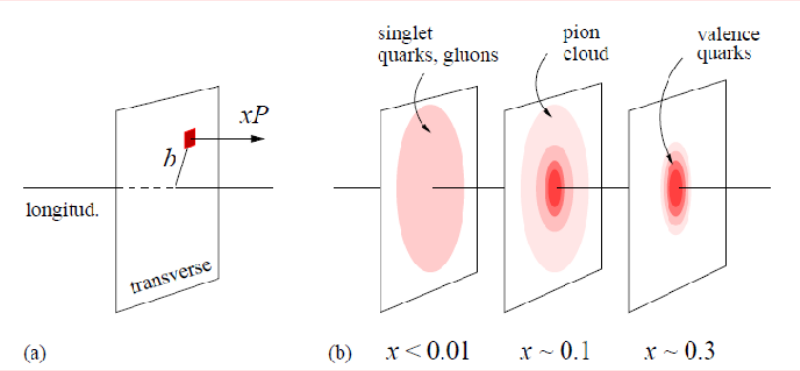




DVCS dominance at large x_B

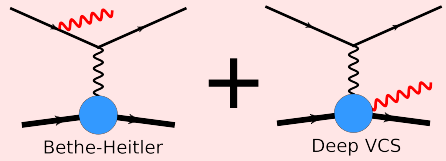
BH/DVCS interf. at intermediate x_B

x_B-dependent transv. size of nucleon



$\mathbf{r}_\perp$ parameter from slope of $d\sigma^{DVCS}/dt$

Interference between BH and DVCS



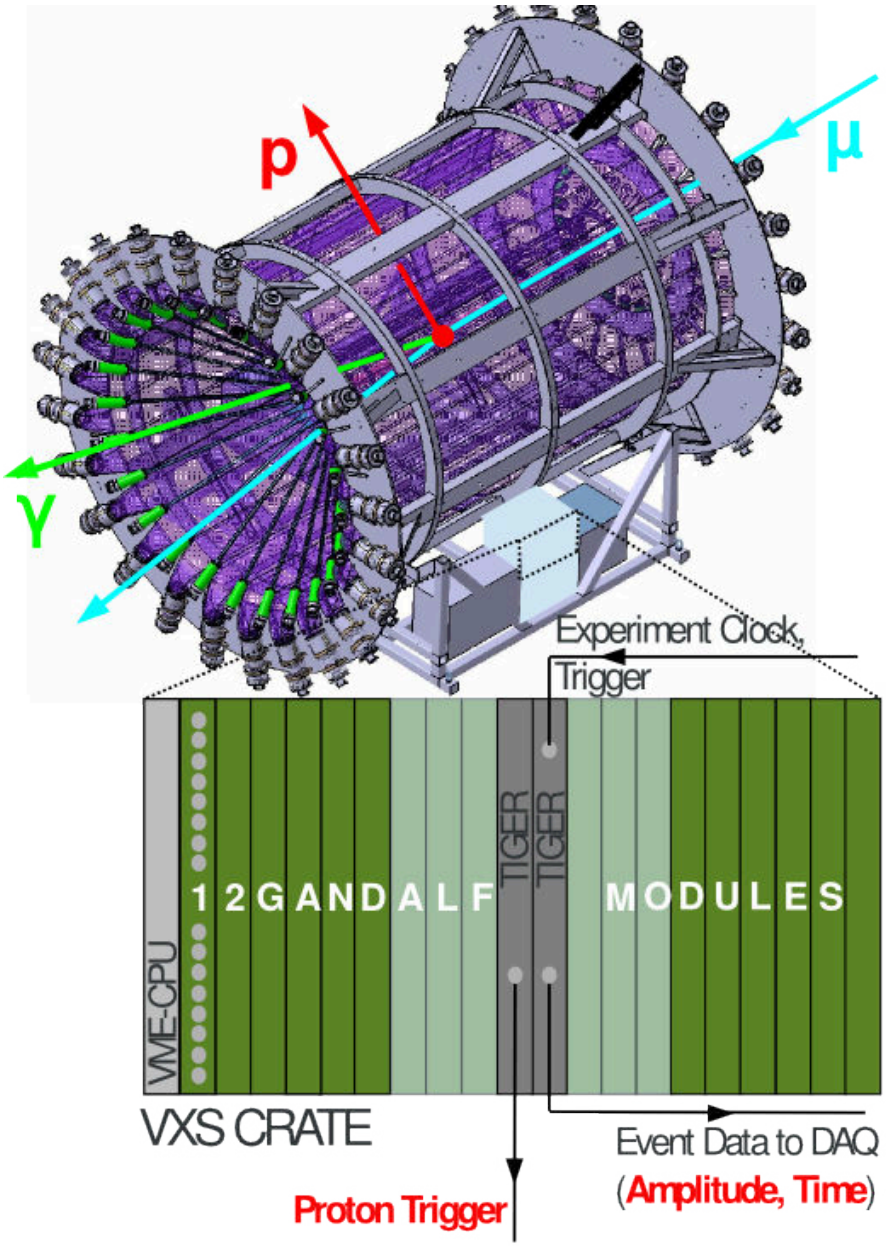
"Boost" of DVCS through int. term

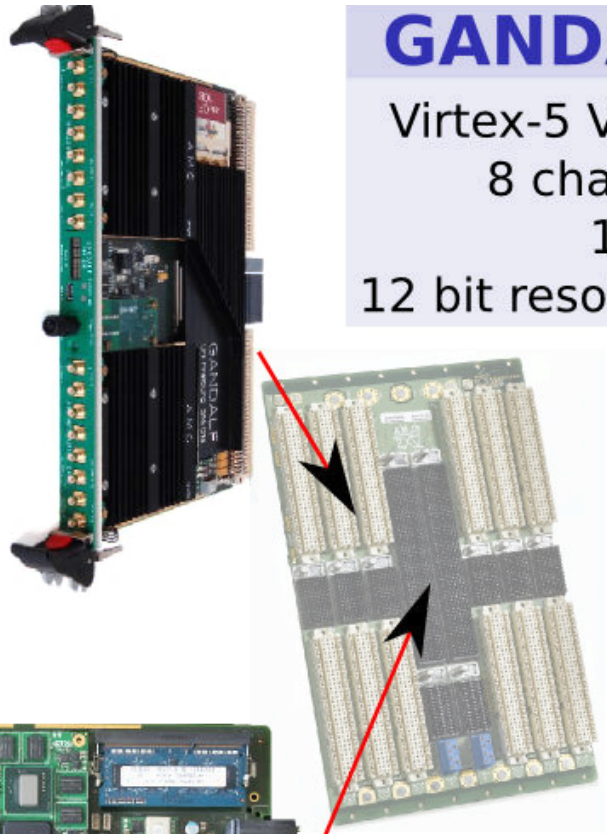
Measurement of $Re\mathcal{H}(\xi,t)$ and $Im\mathcal{H}(\xi,t)$ via ϕ-modulation of cross section

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

Exp. constrain to GPD H

CAMERA Readout





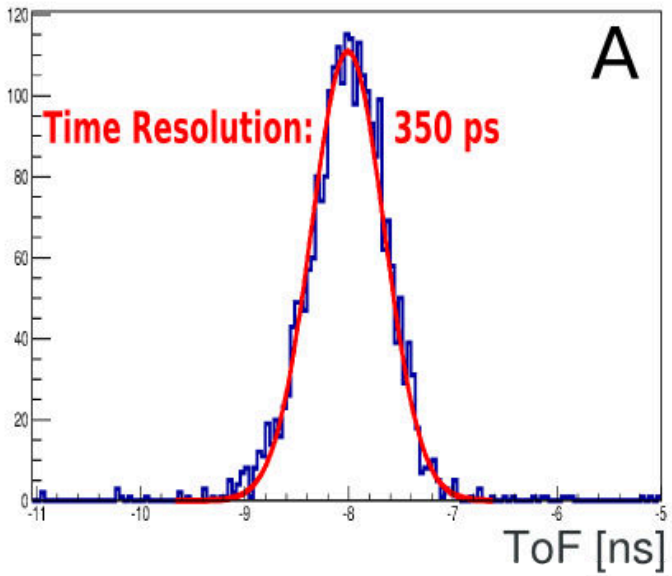
GANDALF

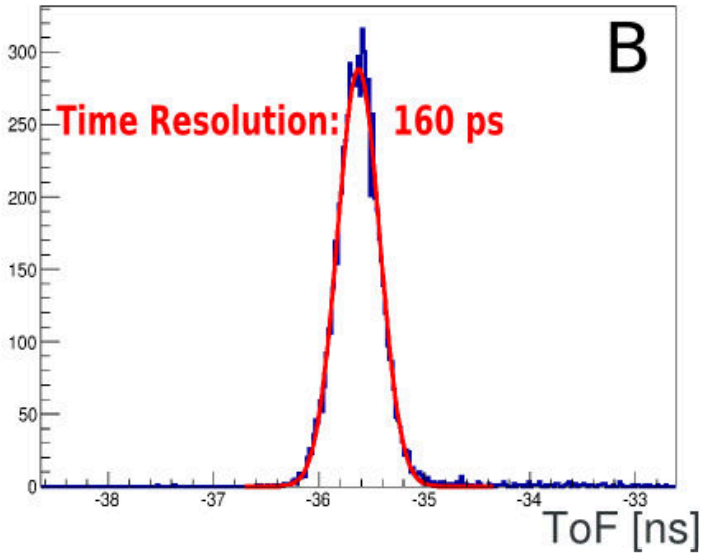
Virtex-5 VSX95
8 channels
1 GS/s
12 bit resolution

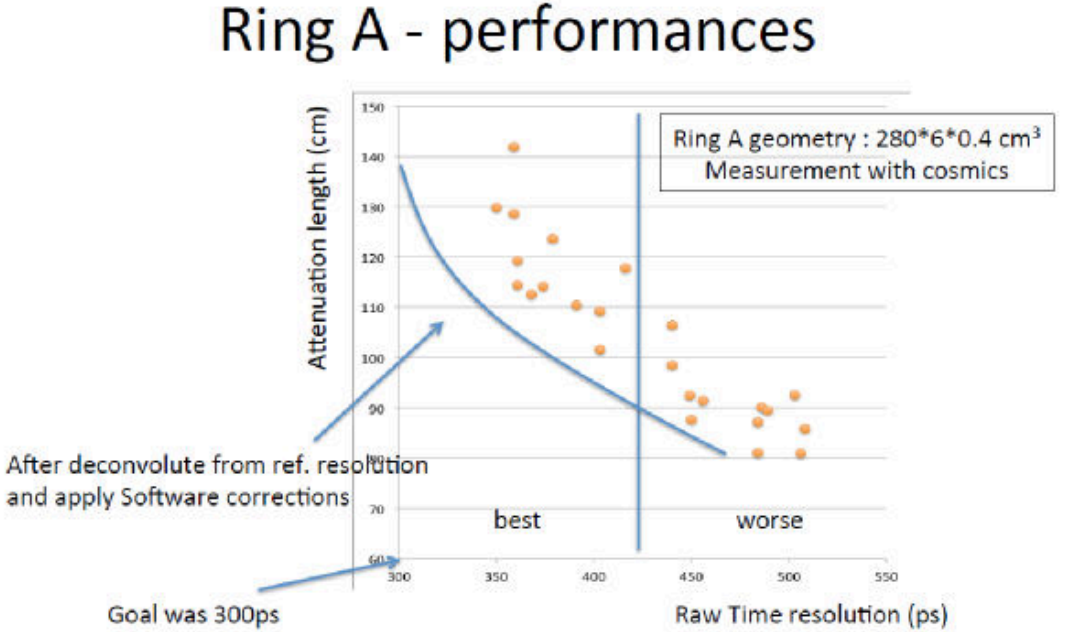
TIGER

Virtex-6 VLX365
onBoard GPU
2x SFP+
COM Express

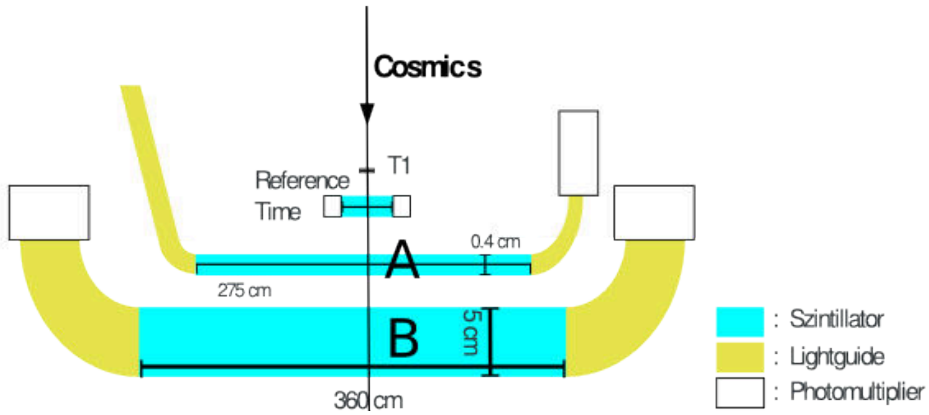
Time Resolutions Measured with Cosmics





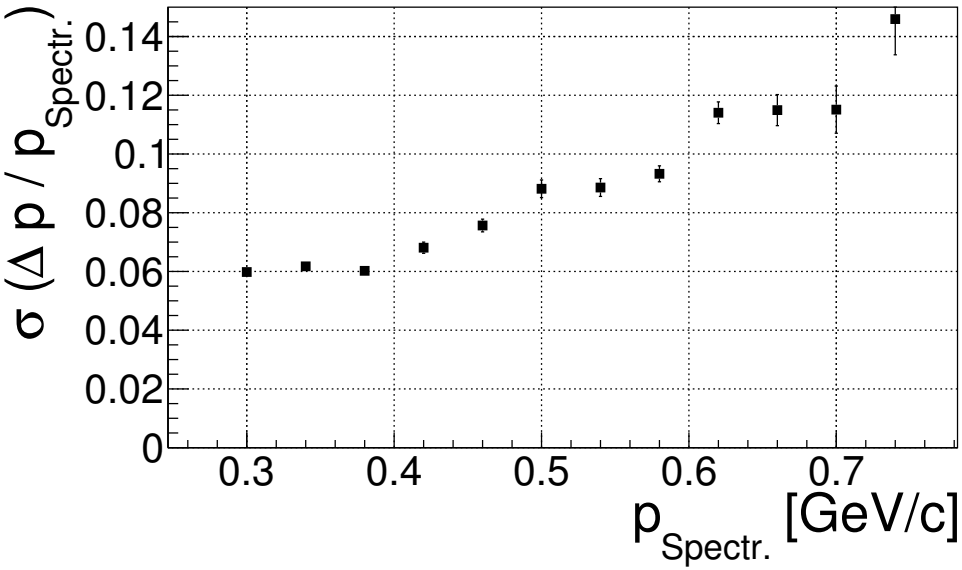


Att length better than 200 cm was expected

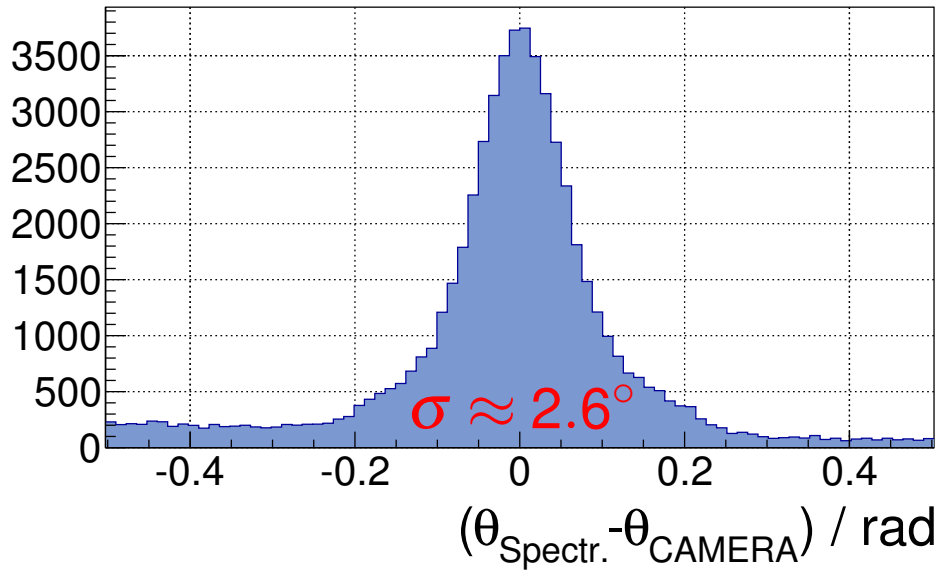


Summary of Present CAMERA Performances

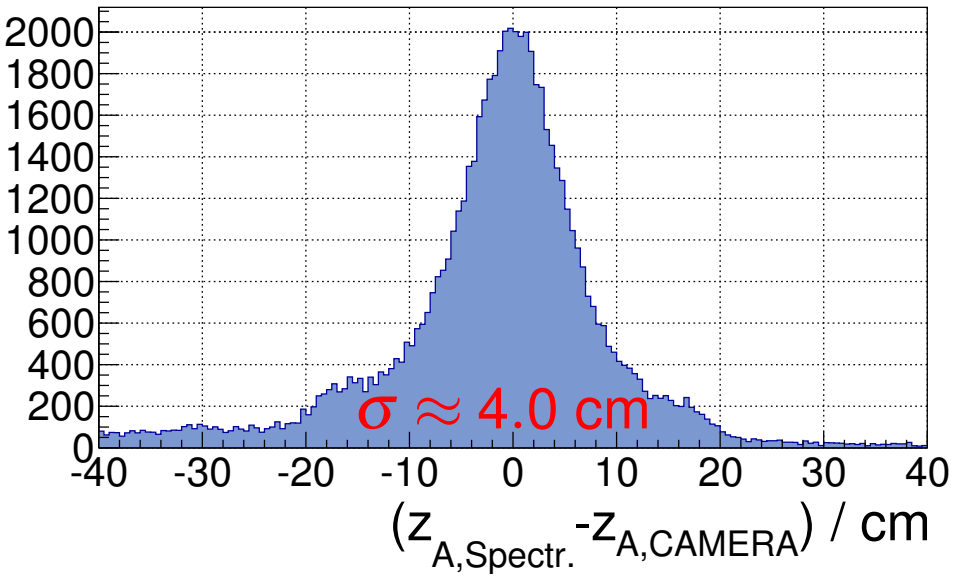
momentum resolution



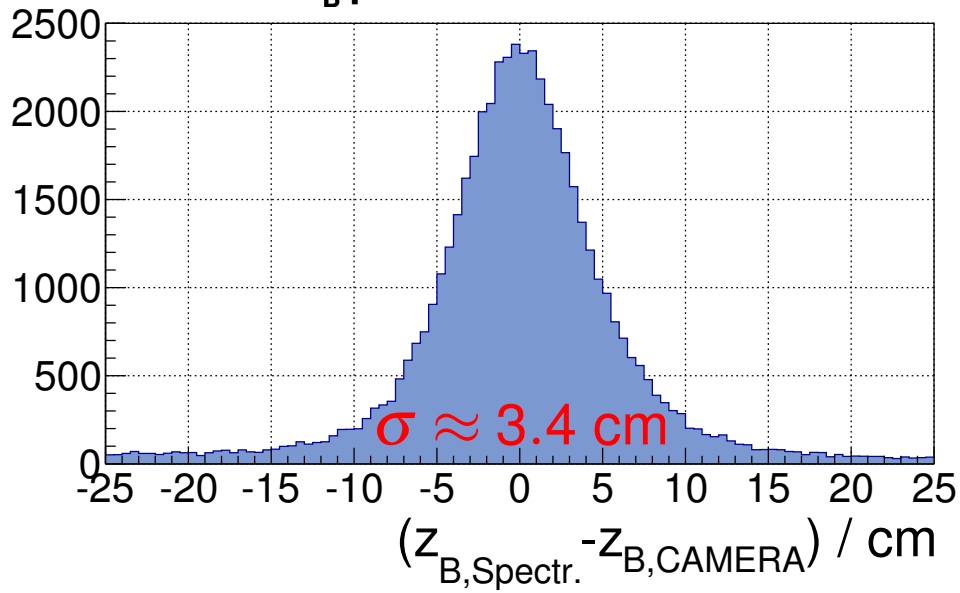
polar angle resolution



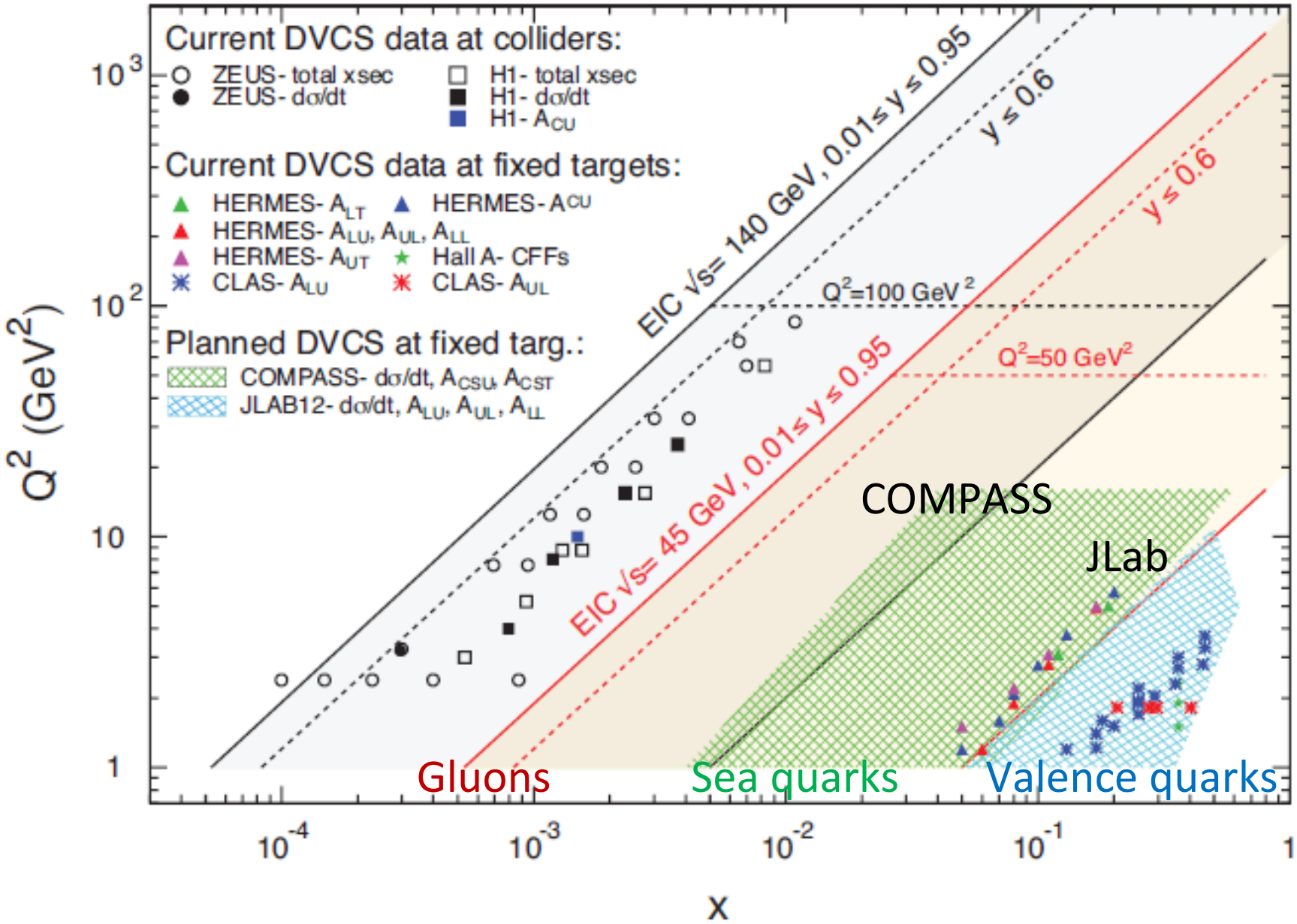
z_A position resolution



z_B position resolution



Past, Present and Future GPD Experiments



Measurements of DVCS and BH Cross-sections

cross-sections on proton for $\mu^{+\downarrow}$, $\mu^{-\uparrow}$ beam with opposite charge & spin (e_μ & P_μ)

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

Charge & Spin Difference and Sum:

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

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

$$c_1^{Int} \propto \mathcal{R}e\left(F_1\,\mathcal{H} + \xi(F_1+F_2)\,\tilde{\mathcal{H}} - t/4m^2\, F_2\mathcal{E}\right)$$

NOTE: ✓ dominance of $\mathcal{H}$ with a proton target at COMPASS kinematics
✓ only leading twist and LO