Physics from πN and μN scattering at COMPASS-II

- COMPASS-II
- $\pi^- p^{\uparrow\downarrow} \rightarrow \mu\mu X$: TMDs from polarized DY
- $\mu^{\pm\leftrightarrows} p \rightarrow \mu h X$: FFs and TMDs from SIDIS
- $\mu^{\pm\leftrightarrows} p \rightarrow \mu p \gamma$ or $\mu p M$: GPDs from hard exclusive reactions
- Outlook

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On behalf of the COMPASS collaboration

NSF

QCD Frontier

Jefferson Lab
Newport News, Virginia, USA
October 21-22, 2013

COMPASS

= COmmon Muon and Proton Apparatus for Structure and Spectroscopy

A multi-purpose facility

Bird view of CERN
European Organization for Nuclear Research

Large Hadron Collider

COMPASS

data taking since 2002

218 physicists from
24 institutions and
12 countries + CERN

SPS

Main CERN site

COMPASS-II

Beams

400 GeV SPS protons onto conversion target
⇒ mesons with intensity up to 10^8 particles/s

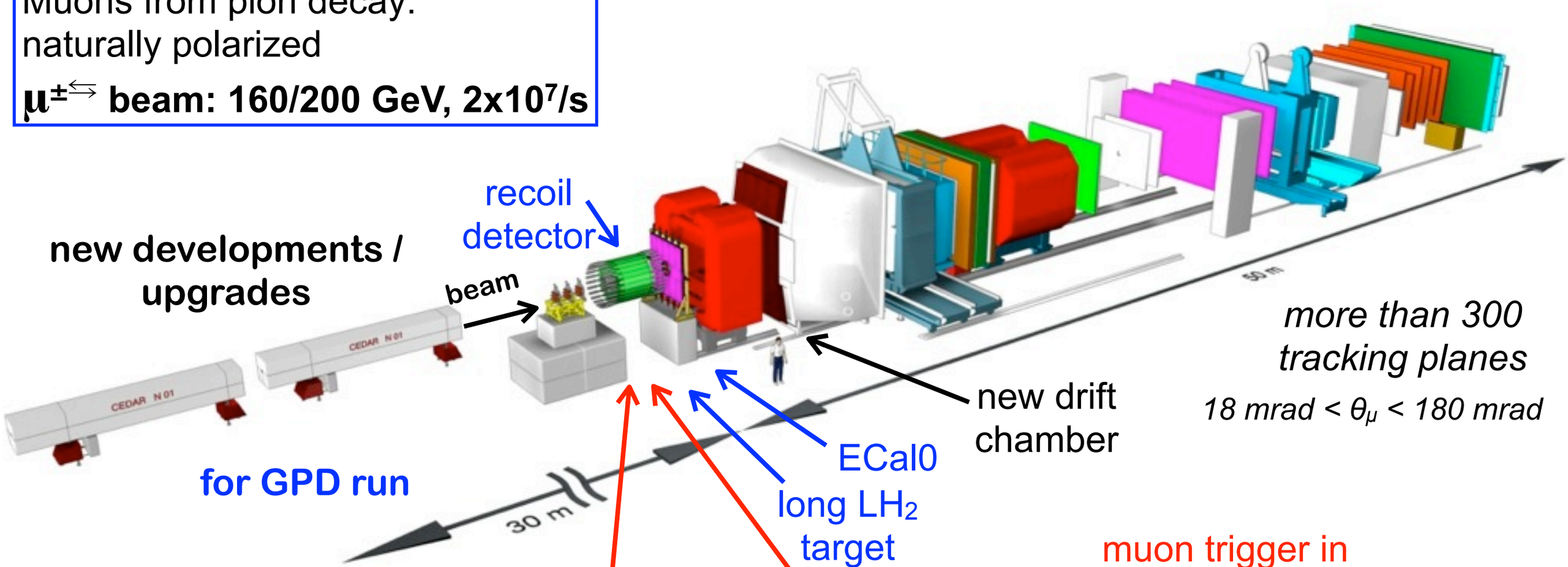
h^- beam: 190 GeV, π/K/p 97/2/1%

Muons from pion decay:
naturally polarized

$\mu^{\pm\leftrightarrows}$ beam: 160/200 GeV, 2x10^7/s

TMD run (Drell-Yan): 2015
on transversely polarized NH_3 target
commissioning run end of 2014

GPD run (with SIDIS): 2016/17
on unpolarized liquid hydrogen target



new developments / upgrades

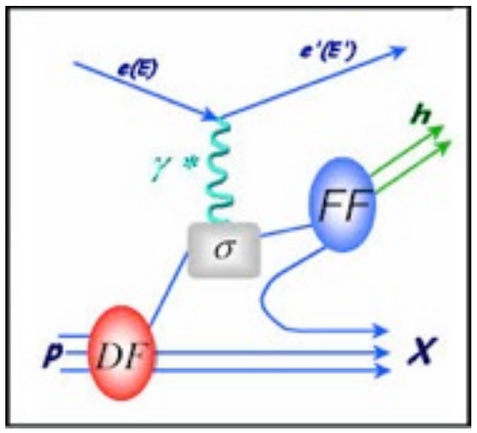
for GPD run

for TMD run

more than 300 tracking planes

18 mrad < θ_μ < 180 mrad

Probing the partonic structure of hadrons

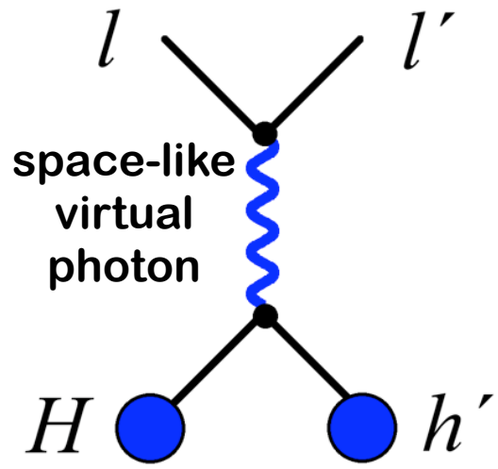


Probe universality

Assumption: factorization applies
Caveat: might break down @high-x

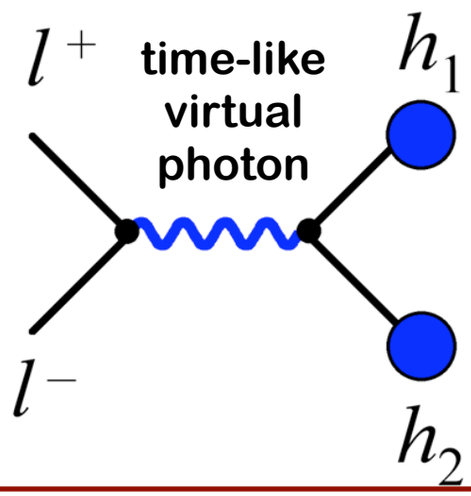
(SI)DIS

$DF \otimes FF$



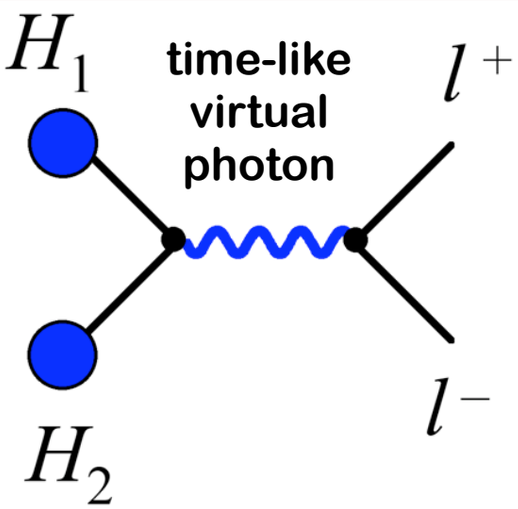
electron-positron annihilation

$FF \otimes FF$

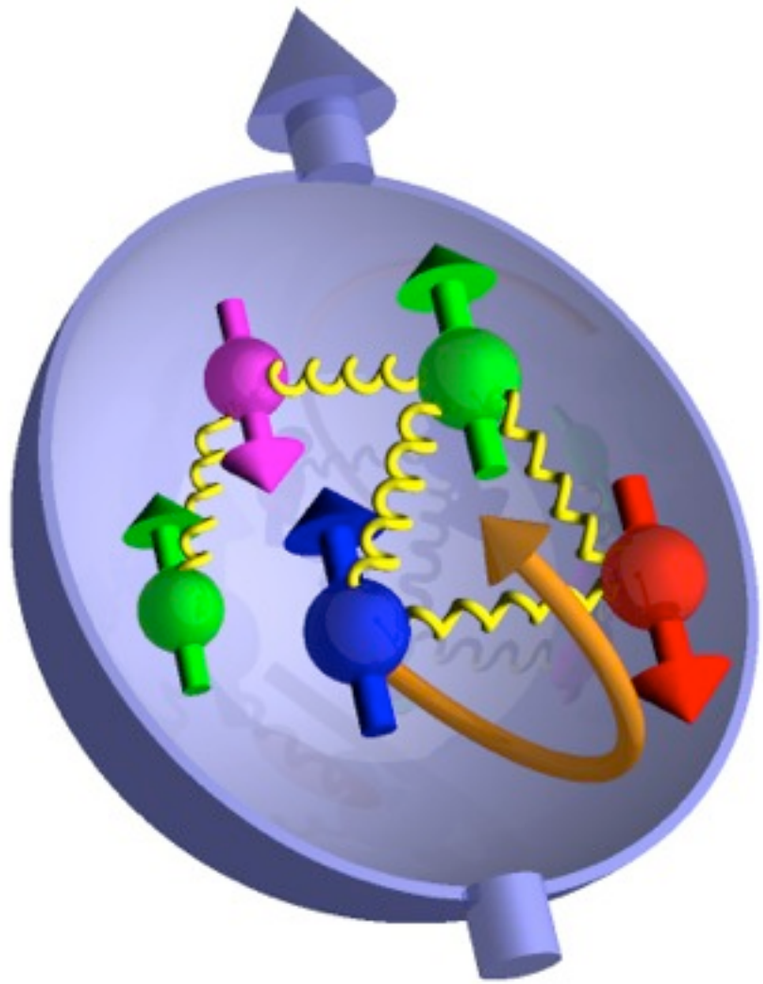


Drell-Yan (DY)

$DF \otimes DF$

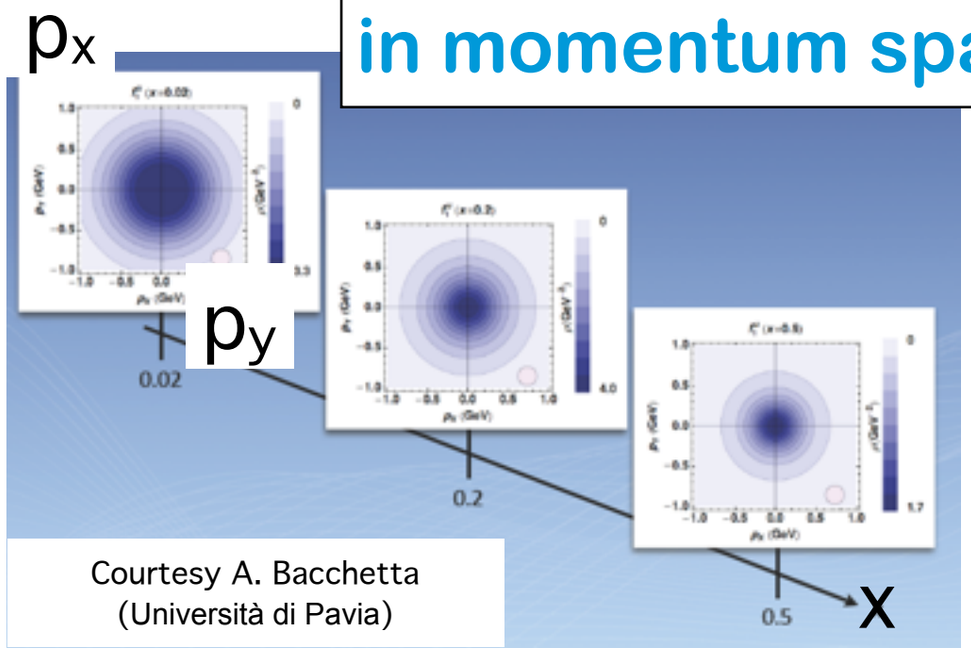


time



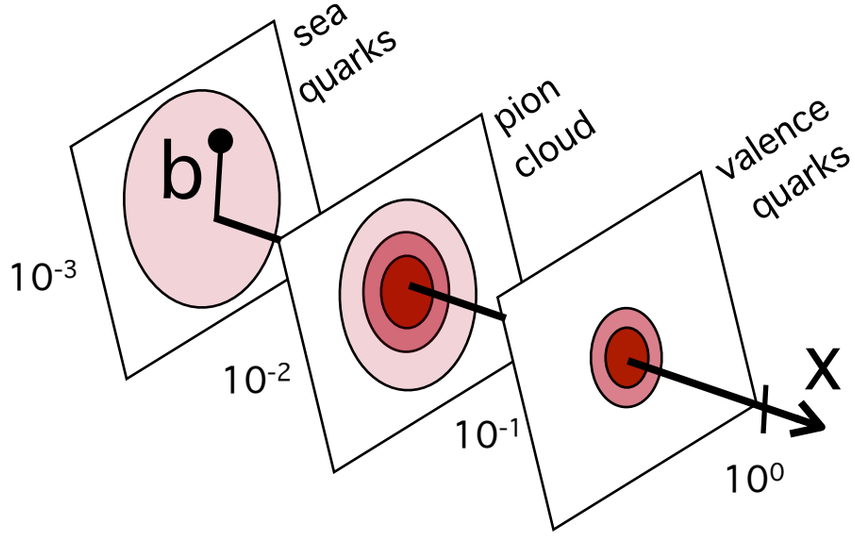
Nucleon Tomography

in momentum space



Courtesy A. Bacchetta
(Università di Pavia)

in position space



Correlation between ***spin*** *and* ***transverse momentum*** *?*

Correlation between ***longitudinal momentum*** *and* ***transverse position*** *?*

Transverse Momentum dependent PDFs

TMDs
$f(x,k_\perp)$

GPDs
$H(x,b_\perp)$
$\leftrightarrow$ FT $\leftrightarrow$ $H(x,\xi,t)$

Generalized Parton Distributions

$k_\perp$**-integration**

Drell-Yan

SIDIS

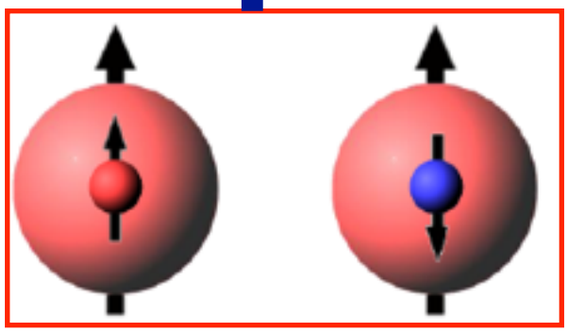
PDFs q(x), 1D:
Parton Distribution Functions

inclusive DIS

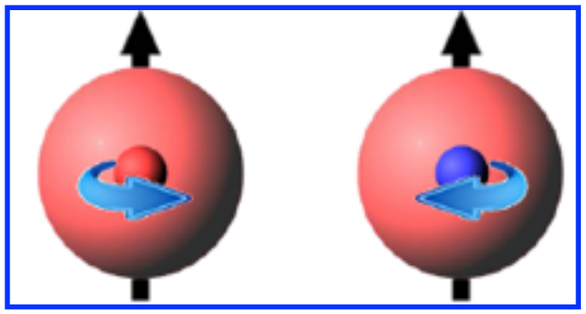
$\xi=0, t=0$

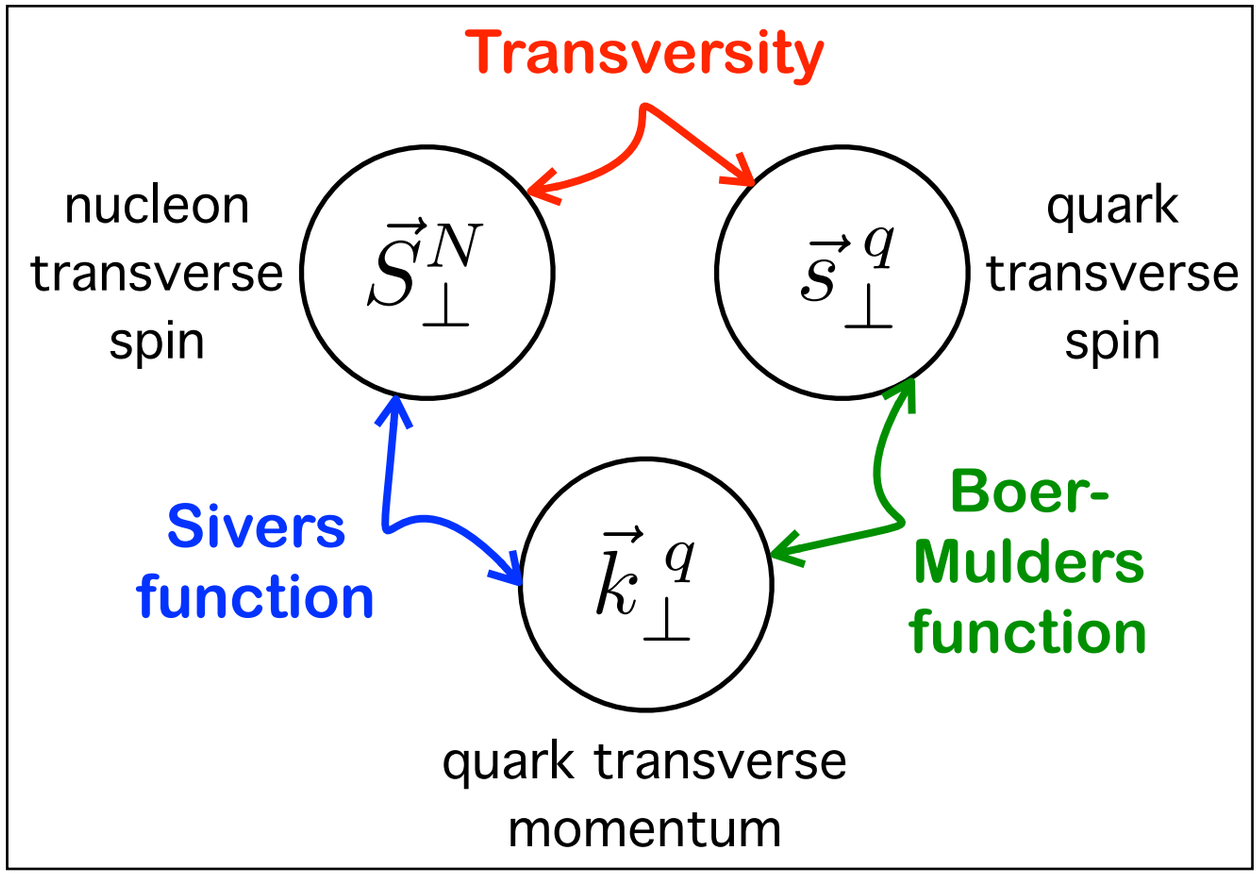
hard exclusive reactions

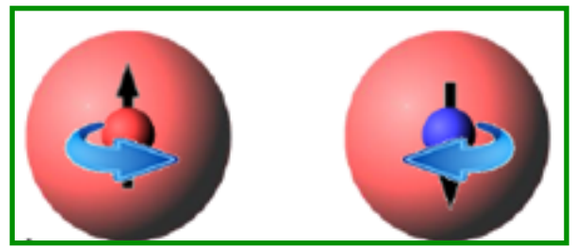
TMDs in spin-dependent Drell-Yan



The missing spin program







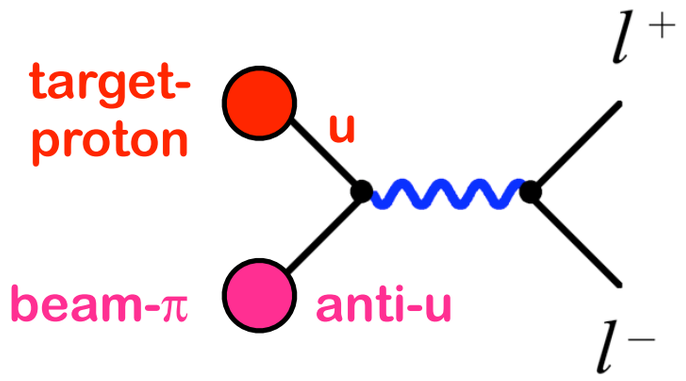
- Are Sivers and Boer-Mulders **universal**?
  - Expect **sign switch** of these naïve time-reversal-odd TMDs in DY wrt SIDIS: fundamental QCD prediction due to gauge invariance

- Experimental verification: crucial test of non-perturbative QCD and TMD physics
  - Origin of large Single Spin Asymmetries $p^{\uparrow}p \rightarrow \pi X$ at FNAL and BNL?
  - Validity of QCD factorization?

Angular dependence of Drell-Yan cross section

Drell-Yan $\boxed{\mathrm{DF} \otimes \mathrm{DF}}$

$$\sigma^{\mathrm{DY}} \propto f_{\overline{u}|\pi} \otimes f_{u|p}$$



dominated by u anti-u annihilation

probe valence-quark region

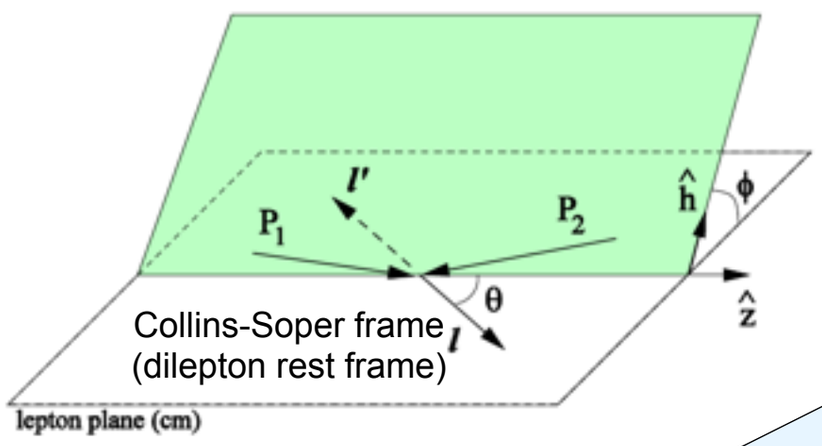
Spin-integrated cross section:

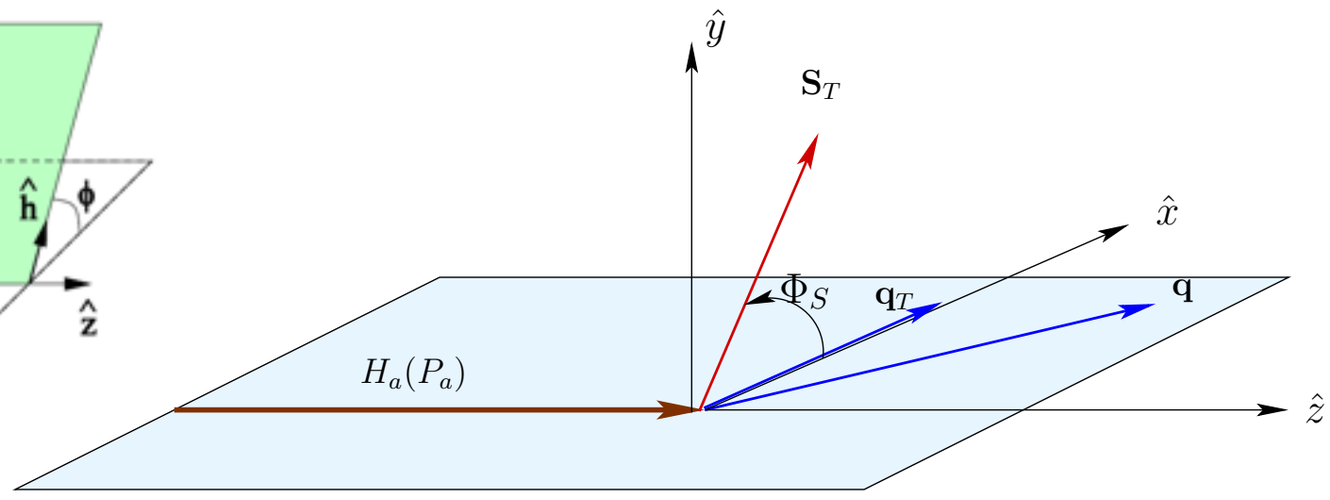
"Naive Drell-Yan" in collinear (k_T=0) qqbar annihilation $\quad \dfrac{d\sigma}{d\Omega} \propto 1 + \cos^2\theta$

+ k_T + higher O(α_S): $\quad \dfrac{d\sigma}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin(2\theta)\cos\phi + \dfrac{\nu}{2}\sin^2\theta\cos(2\phi)$

$1 - \lambda = 2\nu$ Lam-Tung relation

Boer-Mulders (BM) modulation



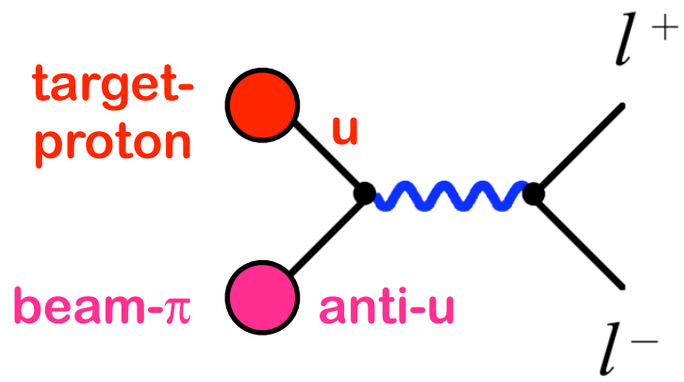


Measure magnitude of azimuthal modulations in cross section: **"Single-Spin Asymmetries" SSA**

Angular dependence of Drell-Yan cross section

Drell-Yan $\boxed{\mathrm{DF} \otimes \mathrm{DF}}$

$$\sigma^{\mathrm{DY}} \propto f_{\overline{u}|\pi} \otimes f_{u|p}$$



dominated by u anti-u annihilation

probe valence-quark region

$$\mathrm{d}\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X) = 1 + \boxed{\overline{h}_1^\perp} \otimes \boxed{h_1^\perp} \cos(2\phi)$$

$$+ |S_T| \Big[\boxed{\overline{f}_1} \otimes \boxed{\overline{f}_{1T}^\perp} \sin\phi_S$$

$$+ \boxed{\overline{h}_1^\perp} \otimes \boxed{h_{1T}^\perp} \sin(2\phi + \phi_S)$$

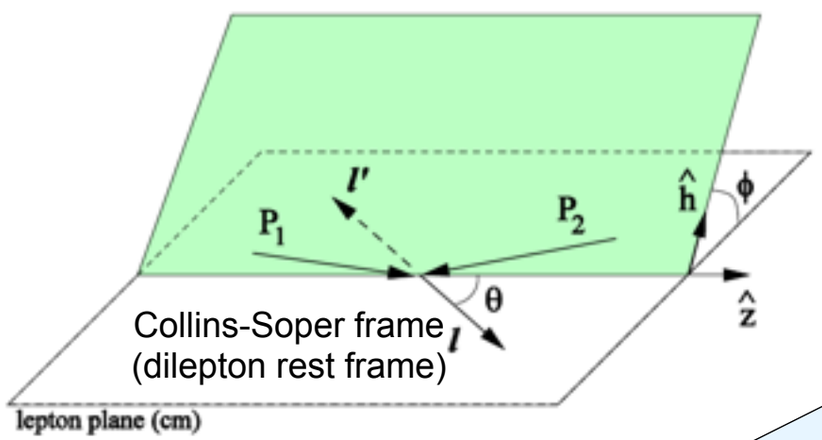
$$+ \boxed{\overline{h}_1^\perp} \otimes \boxed{h_1} \sin(2\phi - \phi_S) \Big]$$

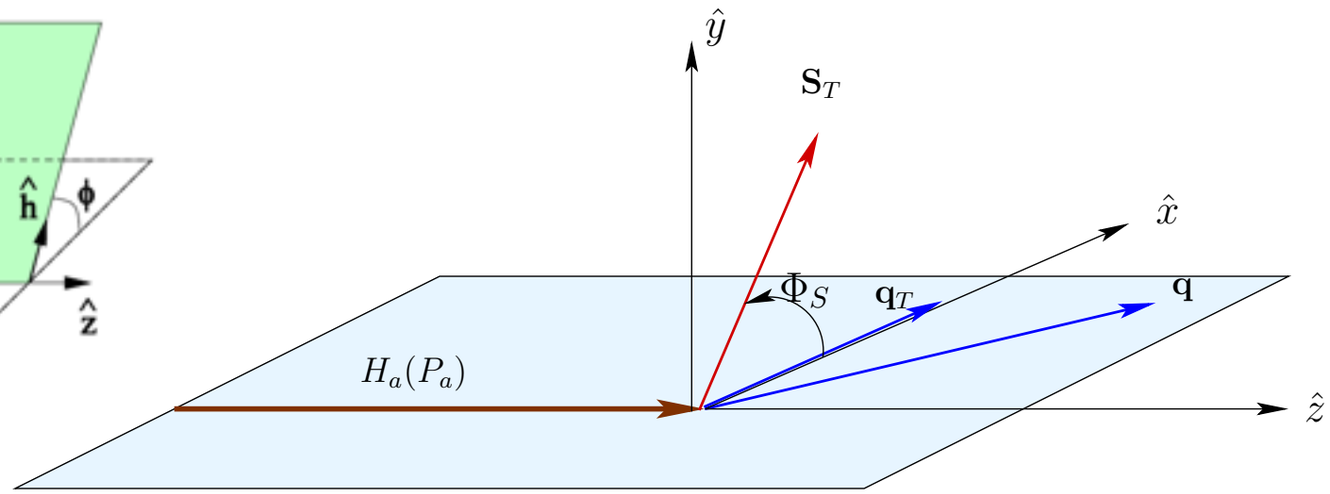
$(BM)_\pi \otimes (BM)_p$

$(f_1)_\pi \otimes (Sivers)_p$

$(BM)_\pi \otimes (Pretzelosity)_p$

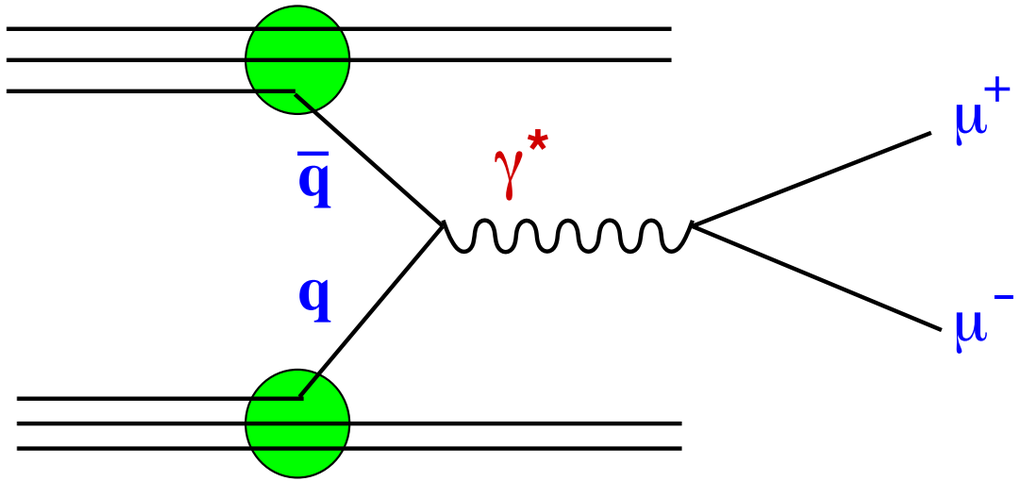
$(BM)_\pi \otimes (Transversity)_p$





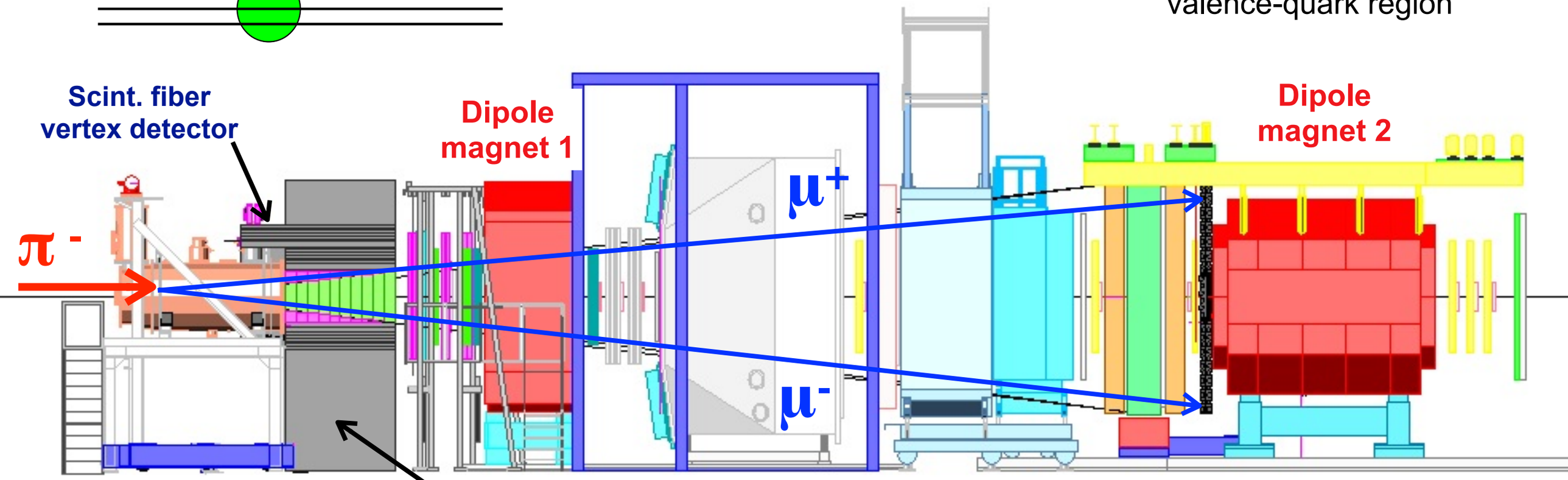
Measure magnitude of azimuthal modulations in cross section: **"Single-Spin Asymmetries" SSA**

Pion-induced Drell-Yan at COMPASS-II

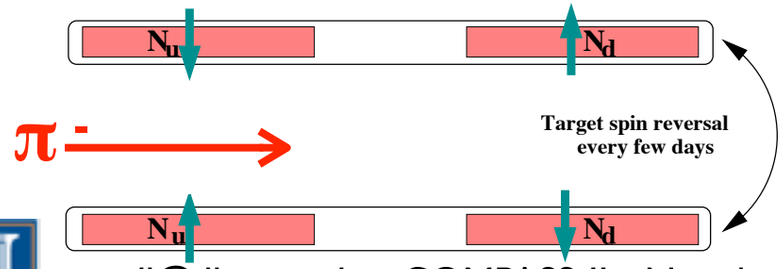


Small cross section ➜ need high-intensity hadron beam

Tracking system - **Large**- and Small-Angle Spectrometer
➜ large acceptance for valence-quark region



Transversely polarized NH_3 target



RICH-I hadron ID

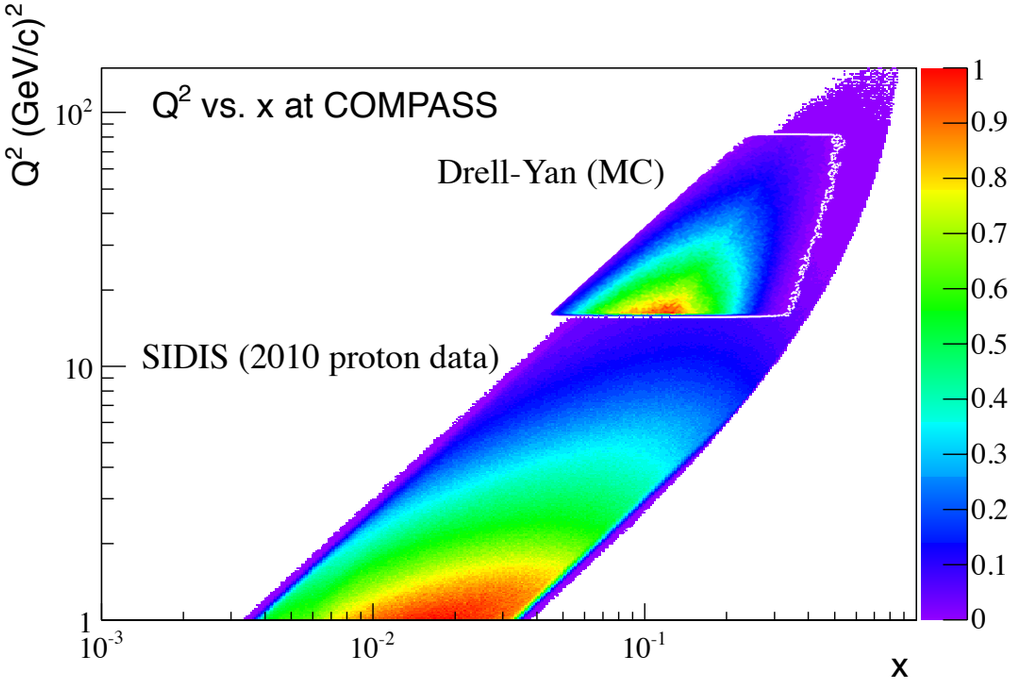
Calorimetry

μ ID

240cm Al_2O_3 **hadron absorber** and 120cm Tungsten **beam plug**

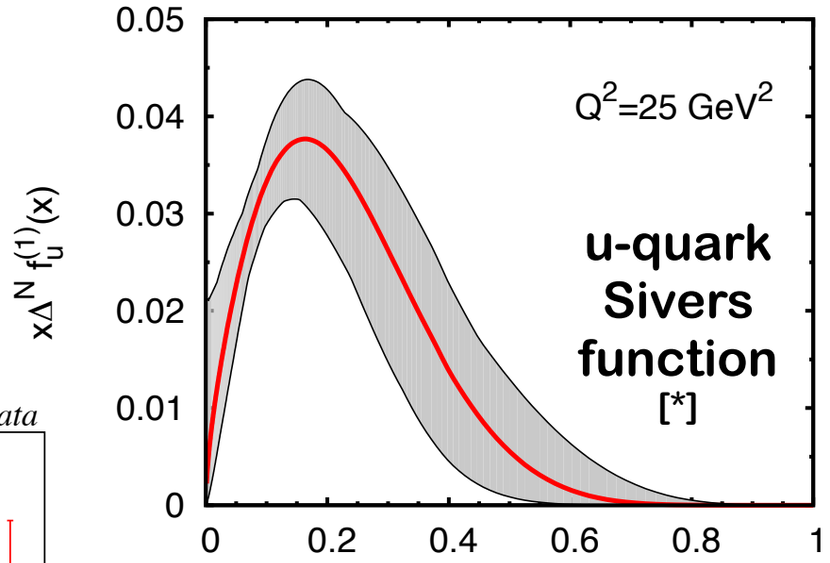
Muon trigger 1st spectrometer

Phase space of COMPASS-II Drell-Yan data



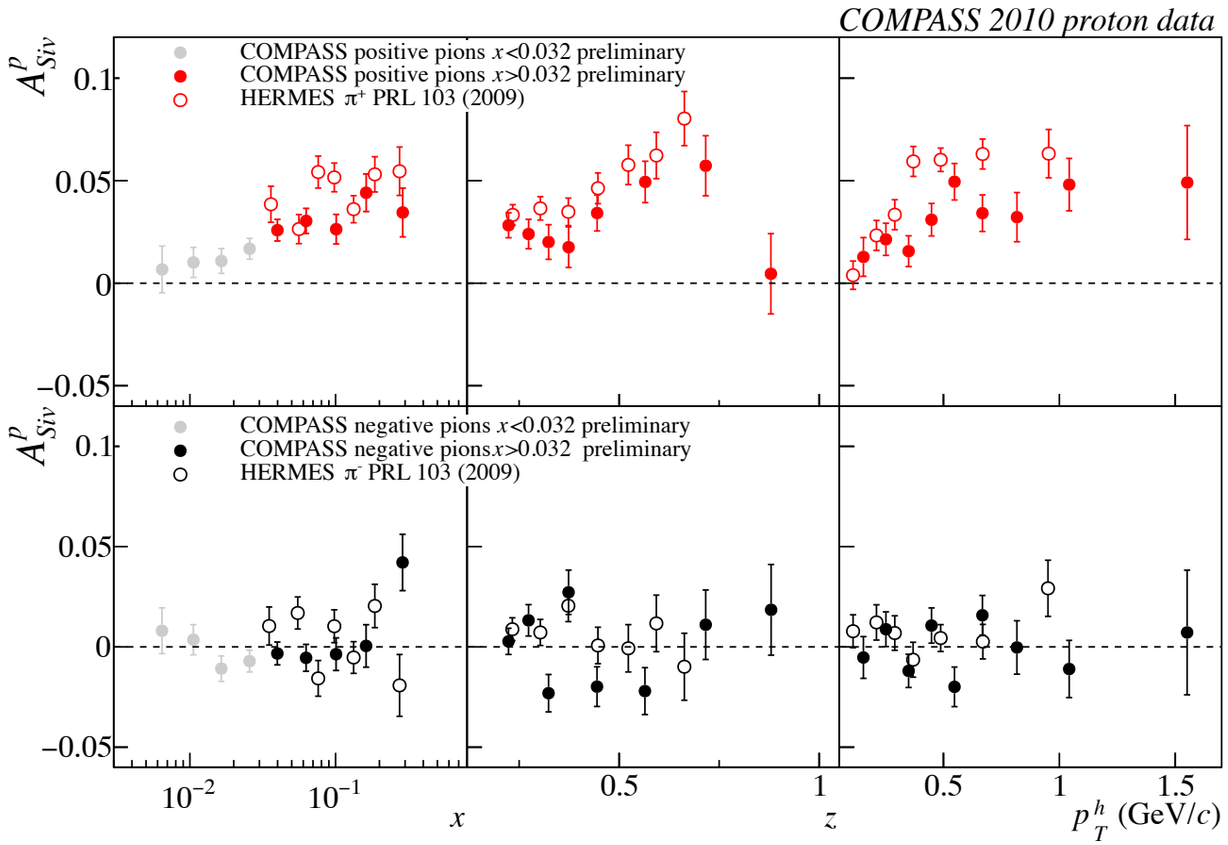
Kinematic overlap of DY and SIDIS data for clear answer on sign-change question

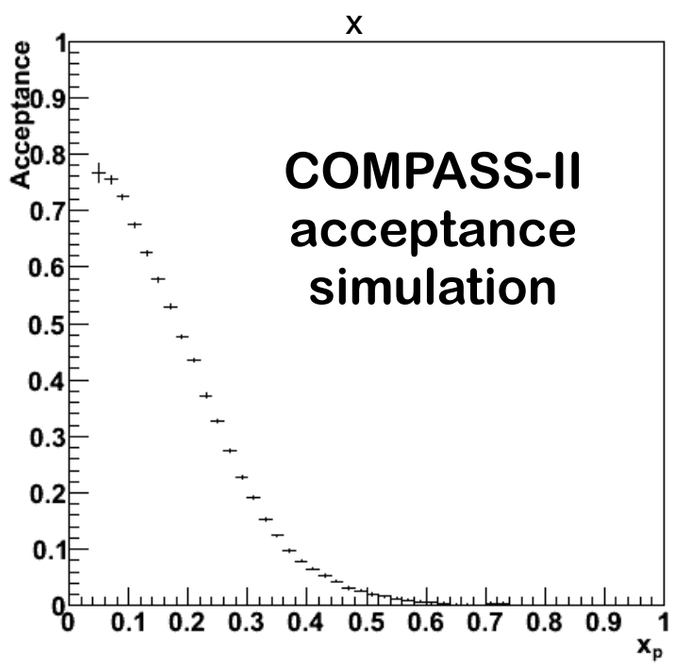
Will probe **valence-quark region** → Sivers function of large magnitude.



Sivers asymmetry in **SIDIS** measured to be clearly different from zero!

COMPASS ●
HERMES ○

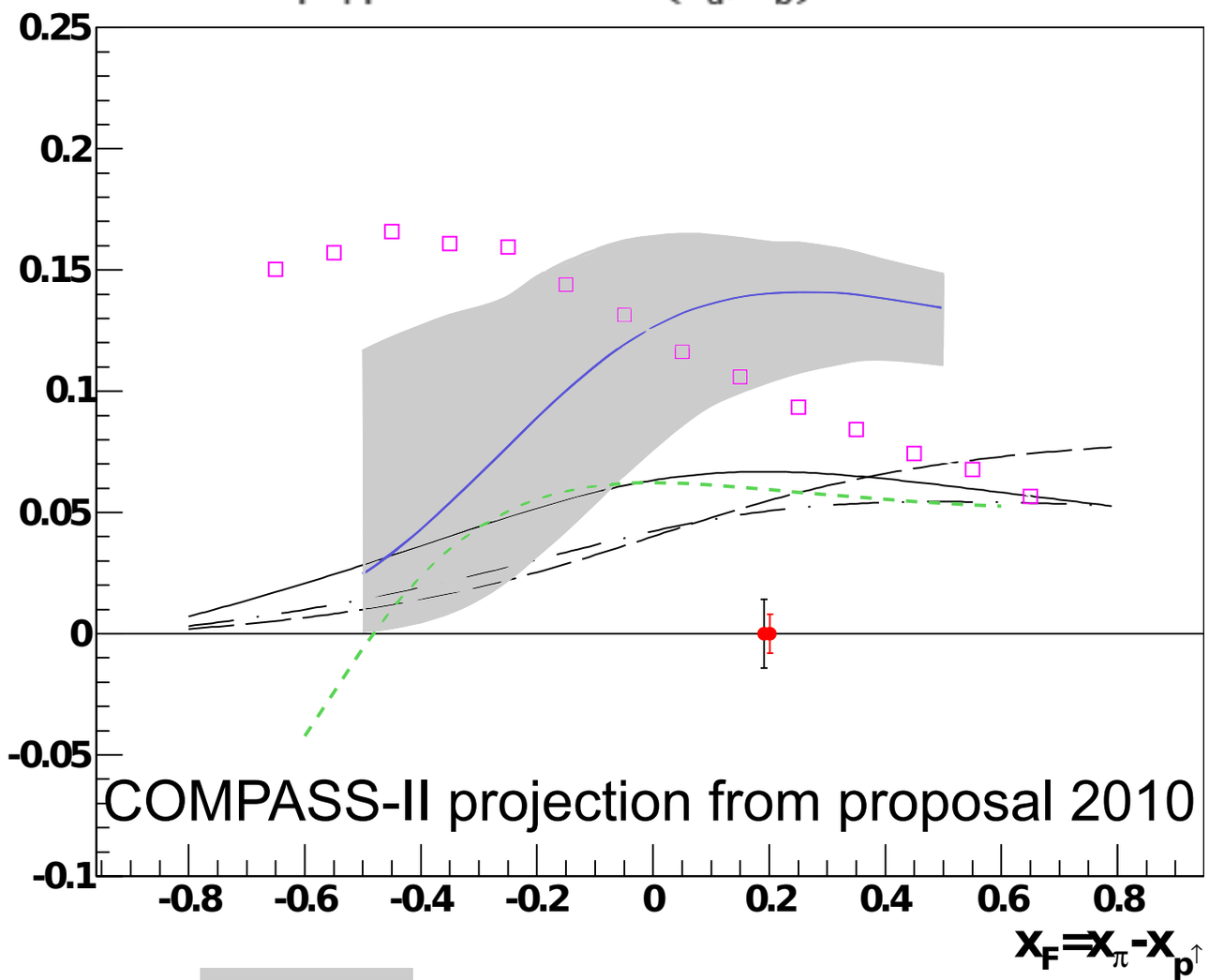


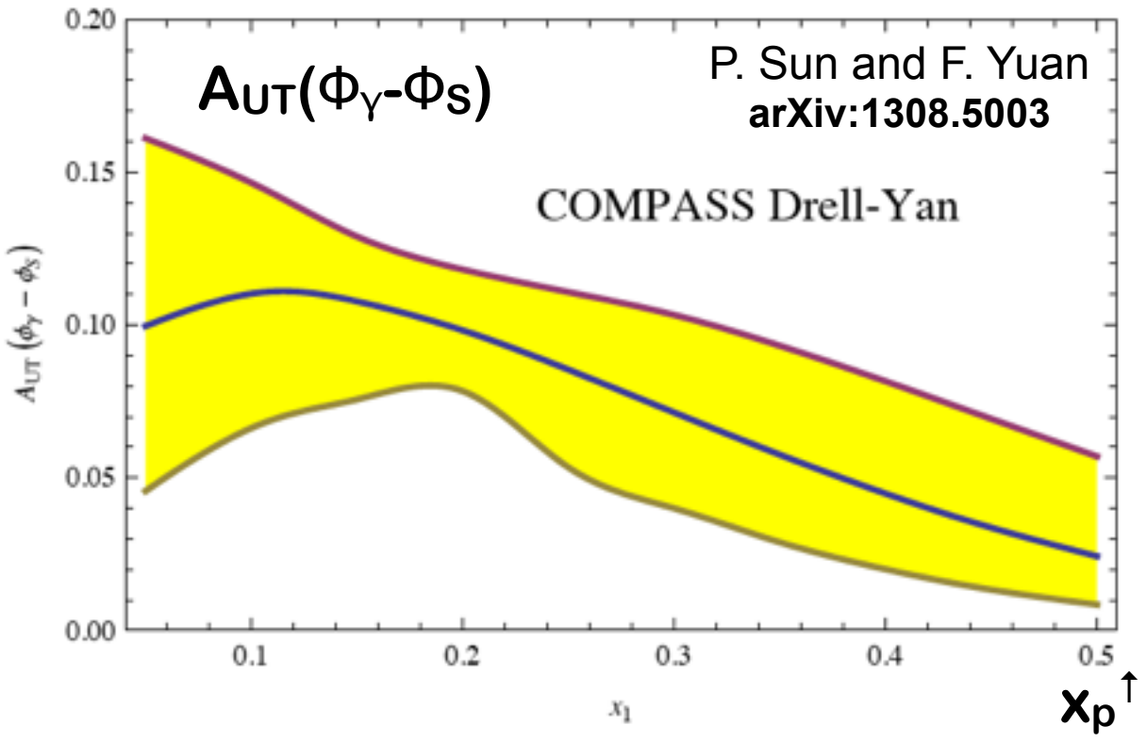


[*] M. Anselmino et al., Eur. Phys. J. A39 (2009) 89.

Sivers asymmetry: predictions

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

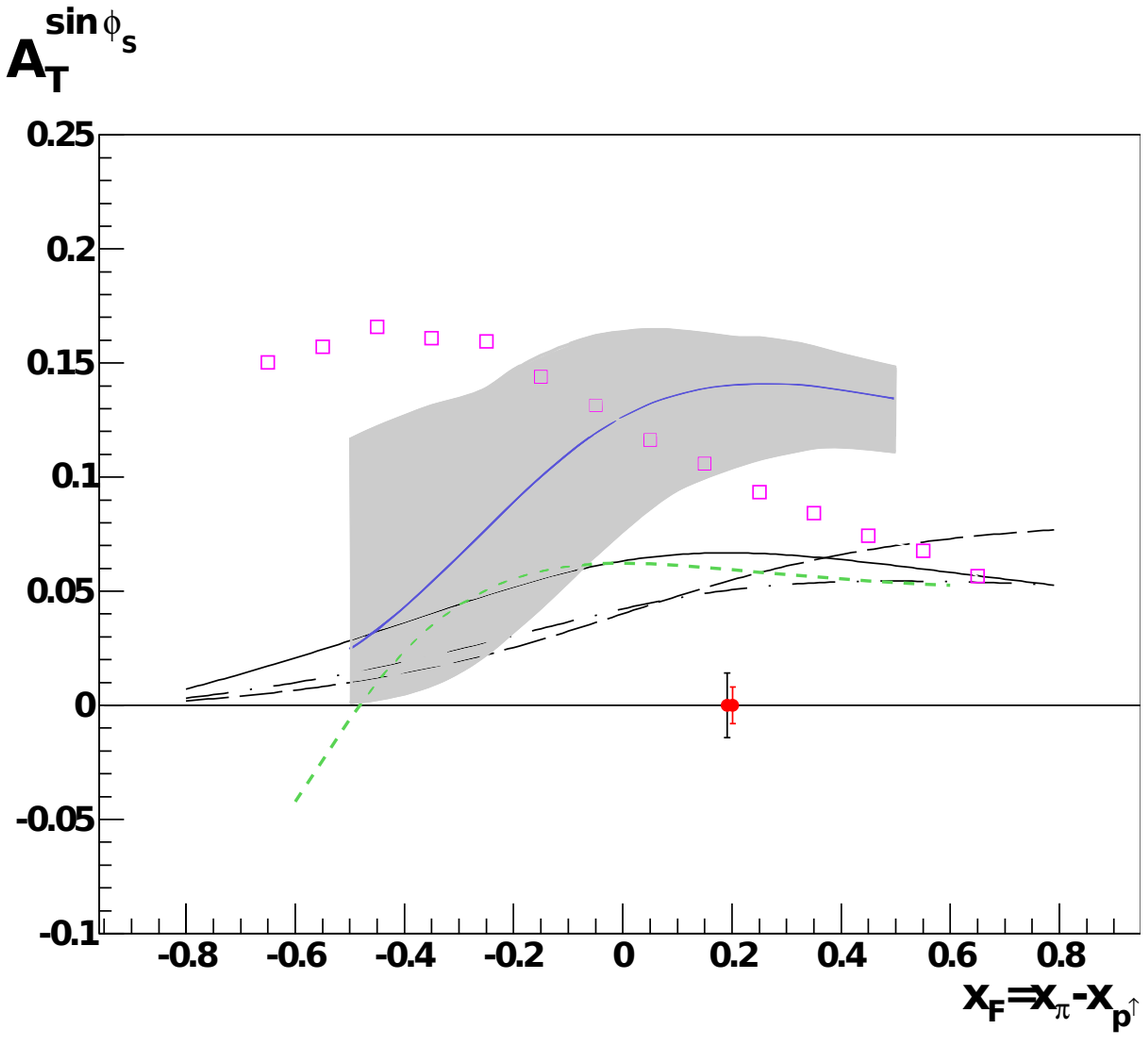




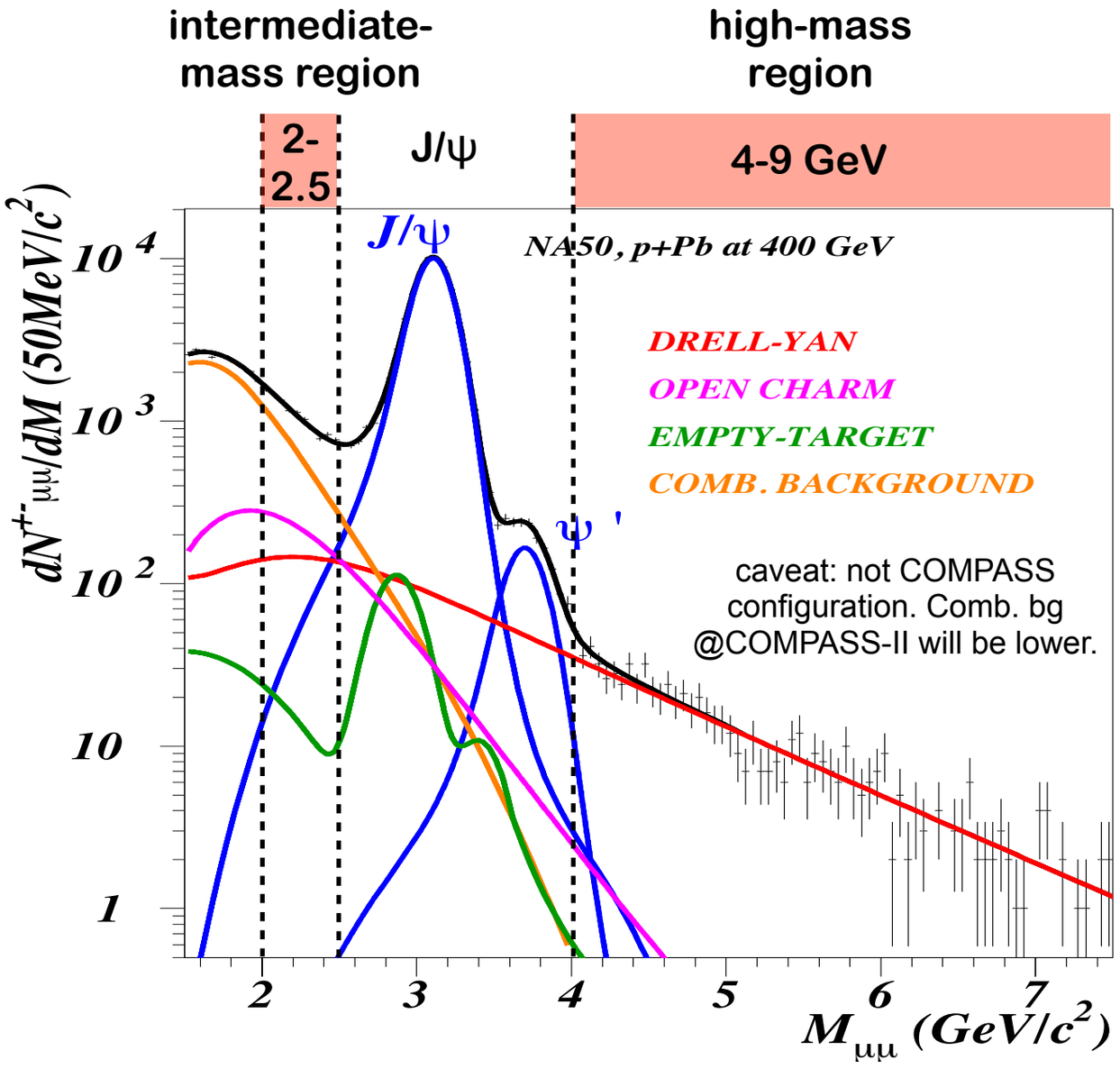
COMPASS polarized Drell-Yan: projections

(all numbers from 2010 COMPASS-II proposal)

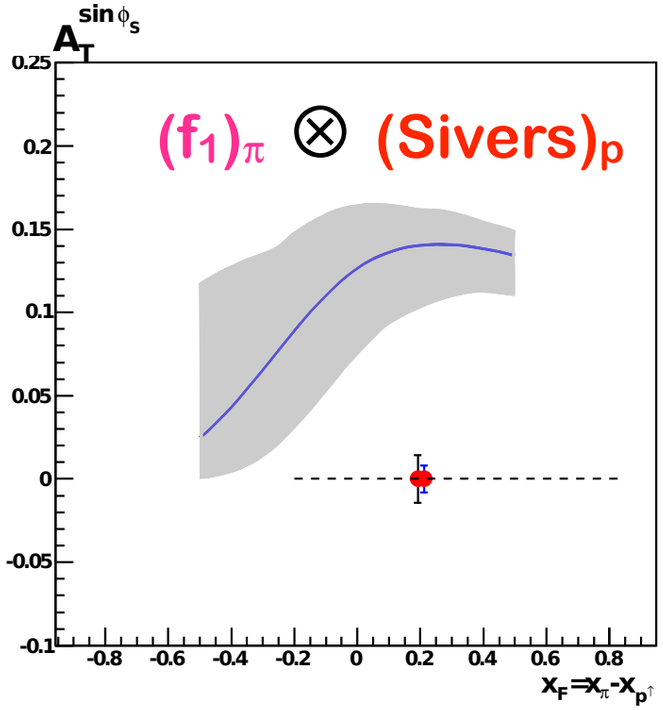
$6 \cdot 10^8$ π/spill (duration 9.6s every 48s)
1.1m trans. pol. target
Lumi=$1.2 \cdot 10^{32}$ $cm^{-2}s^{-1}$
beam energy = 190 GeV

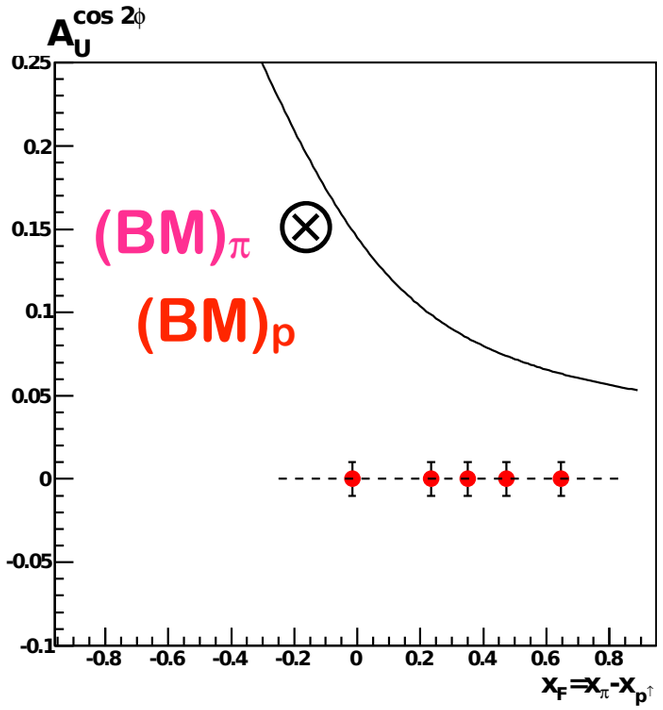


Projection: 2 years running (140 days/a)
- 230k DY events 4 GeV < $M_{\mu\mu}$ < 9 GeV
- 1.4 M DY events 2 GeV < $M_{\mu\mu}$ < 2.5 GeV



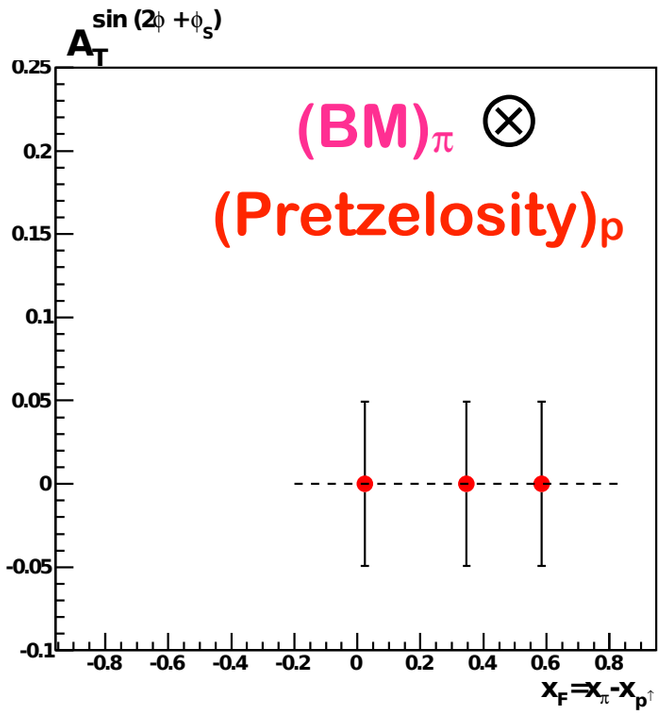
COMPASS-II projections and beam test

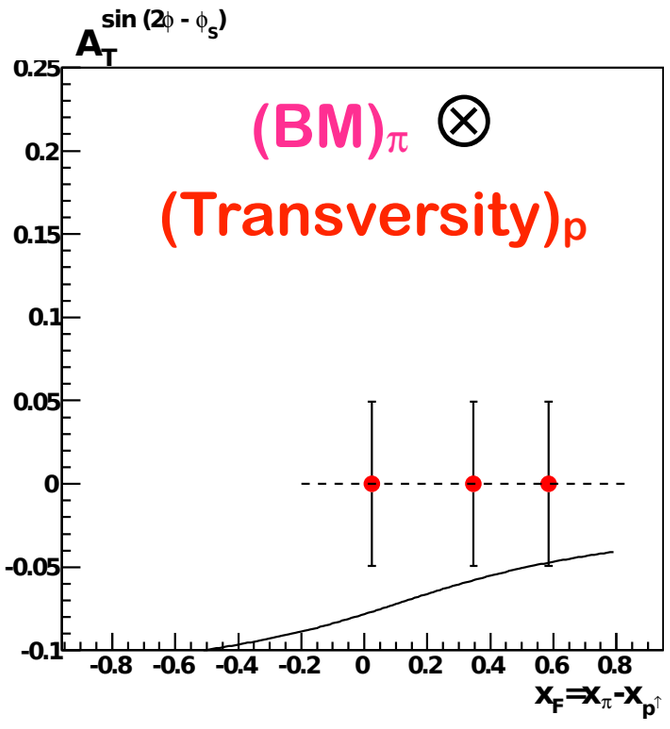


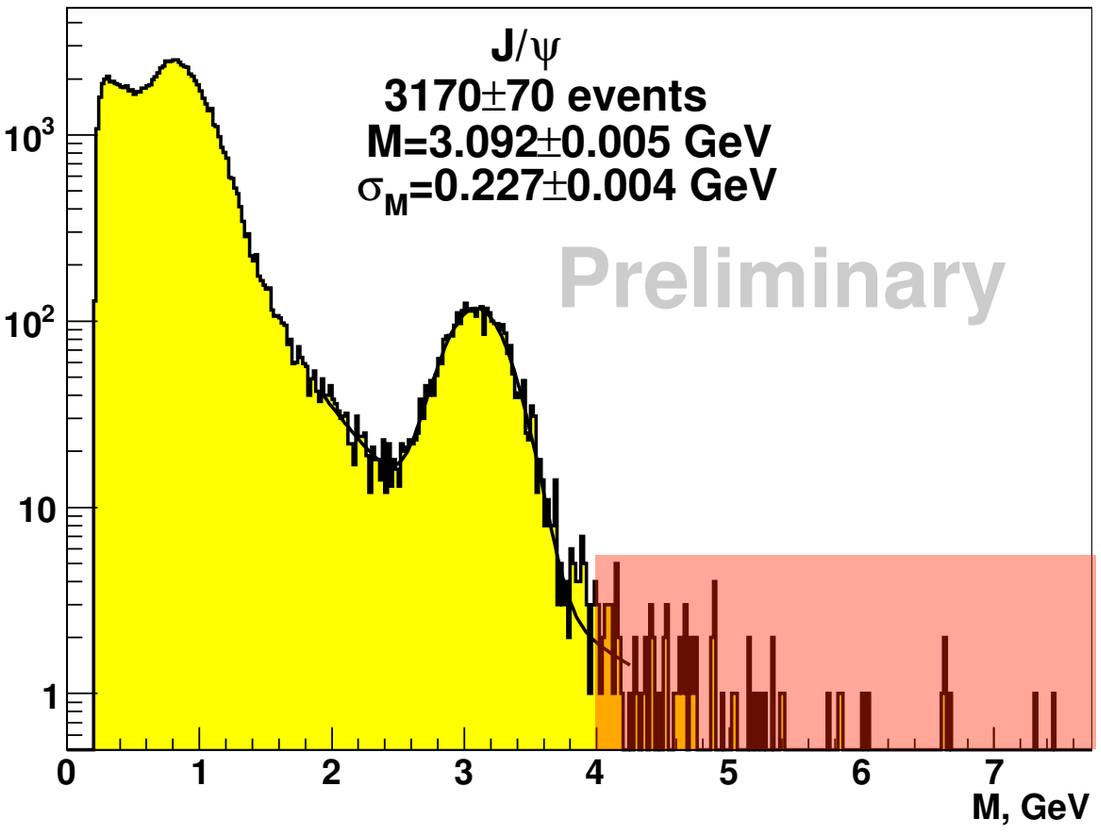


$$\mathrm{d}\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X)$$

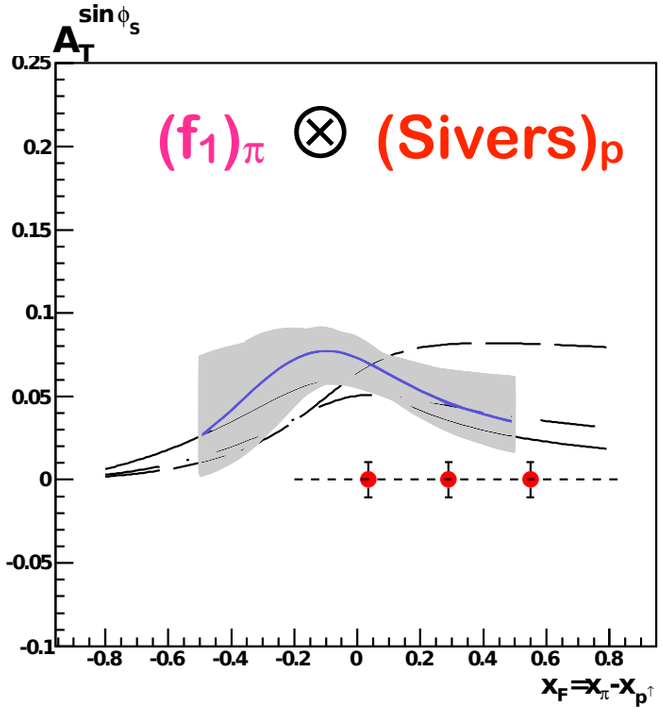
High-mass region
beyond J/ψ threshold
- high signal/background
- but low cross section

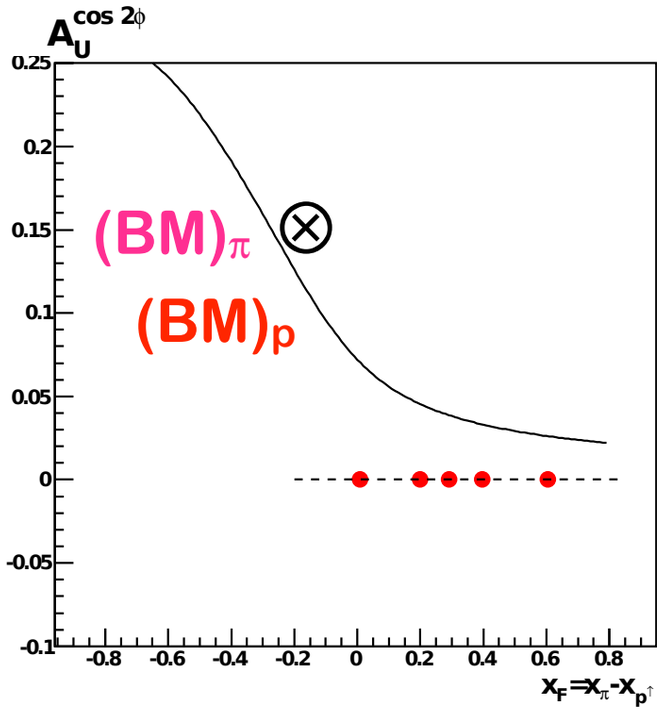


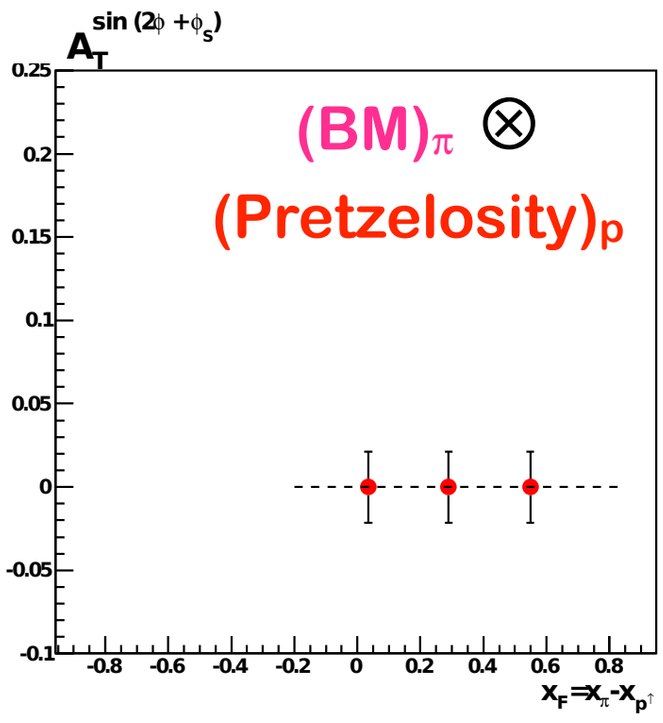


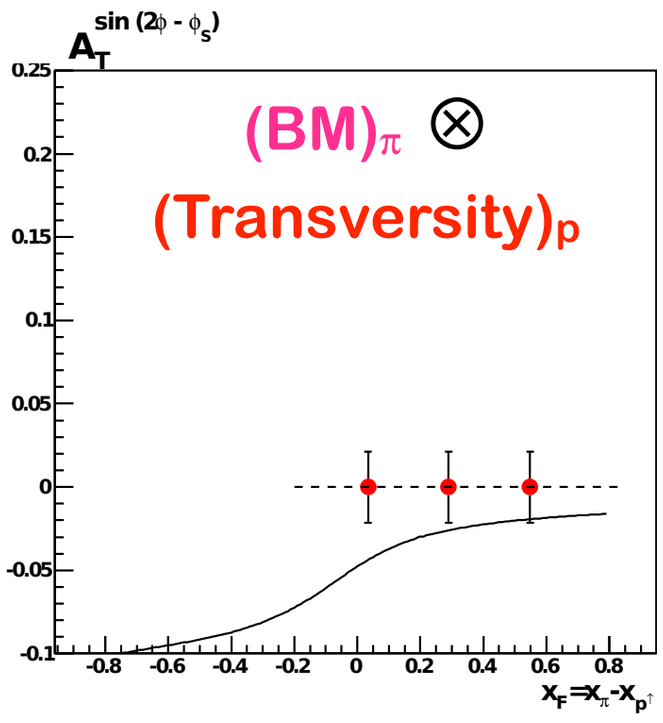


COMPASS-II projections and beam test





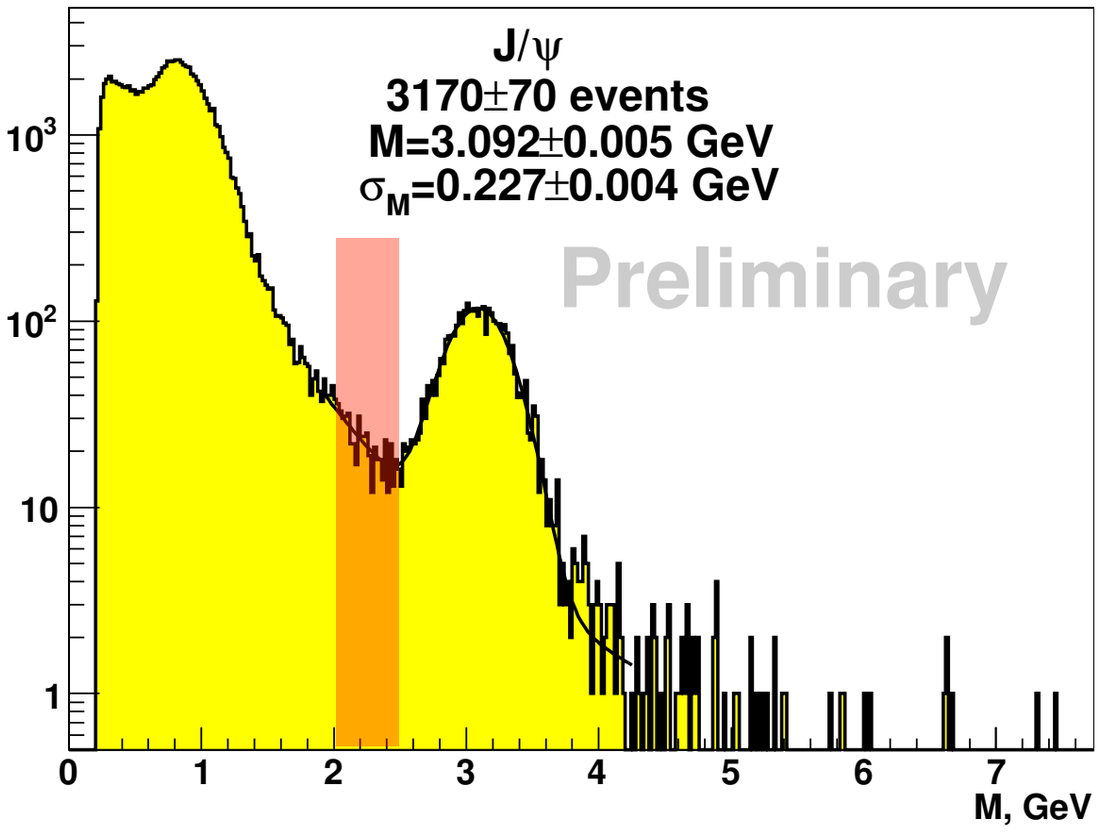




$$\mathrm{d}\sigma(\pi^- p^\uparrow \to \mu^+\mu^- X)$$

Intermediate-mass region
- high cross section
- but low signal/background

COMPASS DY beam test 2009



Beam test 2009: 190 GeV π^- beam
($8\cdot 10^7$ π^-/spill) on 2 40cm-CH_2 cells

COMPASS-II SIDIS program

- Previously (2002-2011): SIDIS with polarized targets
  To come (2016/17): SIDIS with unpolarized target
  (long liquid hydrogen) in parallel to GPD run

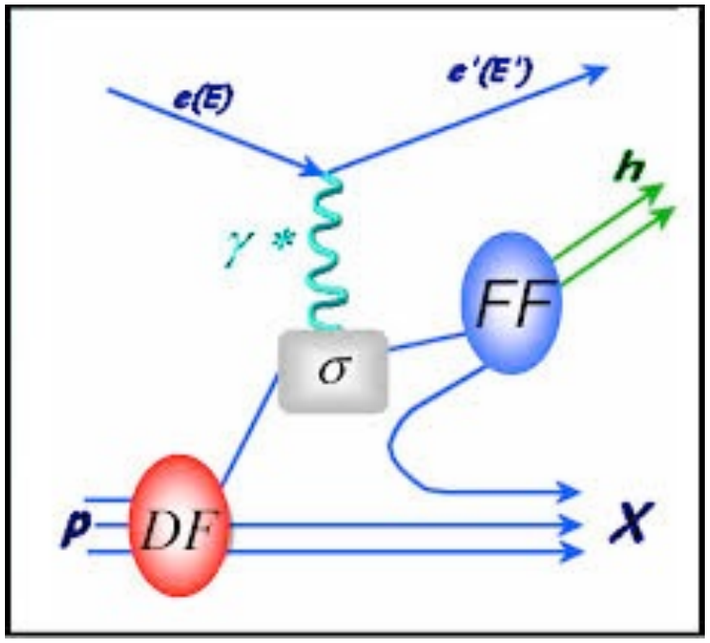
- Flavor separation: proton + deuteron data and advanced hadron PID.

- Precise mapping in 4 dimensions: x, Q^2, p_T^2, z

- Global QCD analyses to constrain unpolarized **PDFs** and quark **Fragmentation Functions**

- Strange-quark **Distribution Function** s(x)
  - So far uncovered region 0.001 <x < 0.2
  - Higher average Q^2 and W than existing HERMES data

- **TMDs in SIDIS**: BM and Cahn-effect
  depending on k_T, the intrinsic transverse momentum of quarks



$DF(x) \otimes FF(z)$

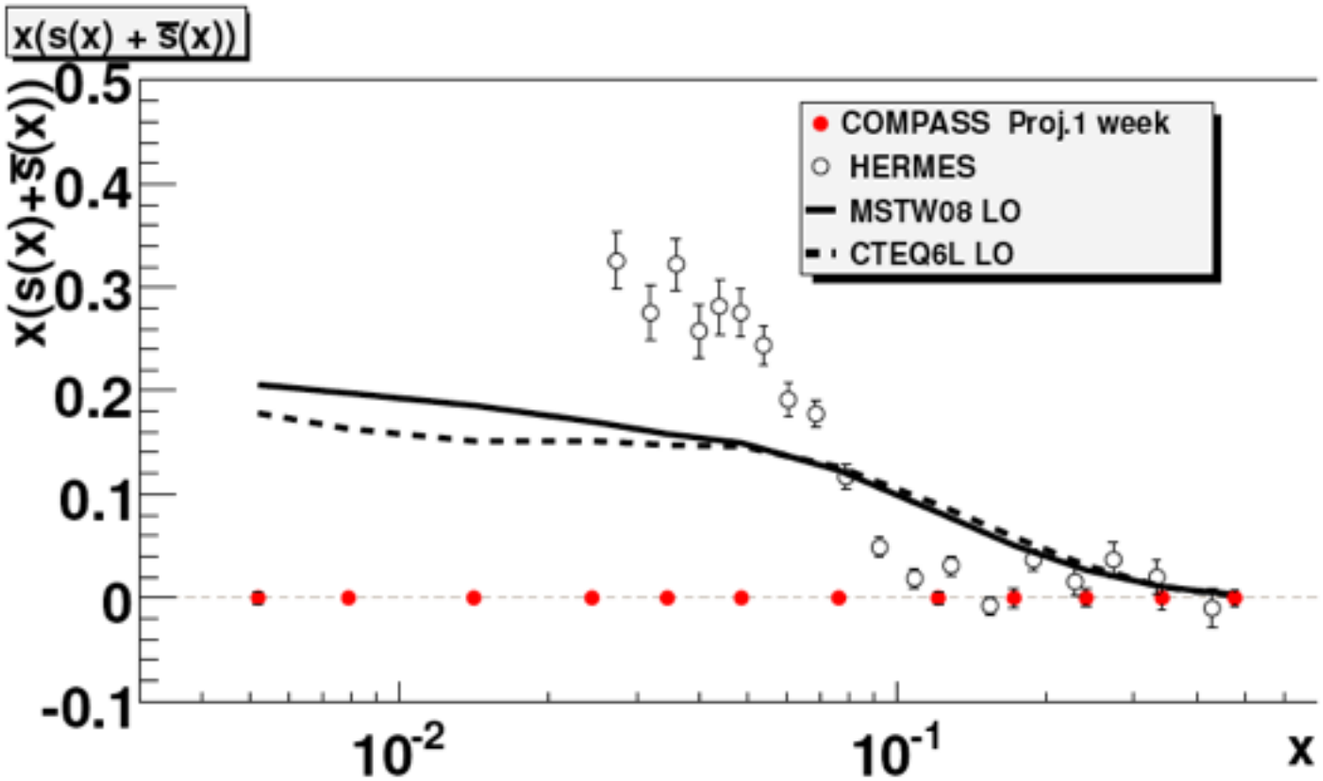
(SI)DIS

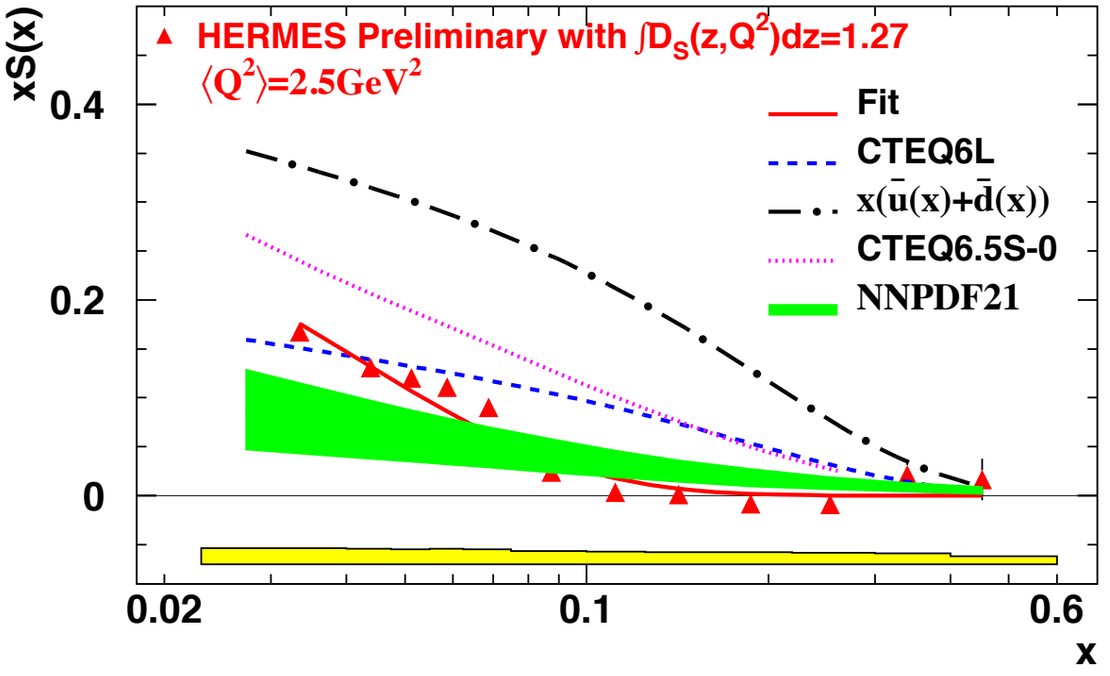
Strange-quark distribution in the proton

Multiplicity for hadron type $h = \pi^+, \pi^-, \pi^0, K^+, K^-, K^0, \Lambda, \overline{\Lambda}$

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

DF(x) ⊗ FF(z)

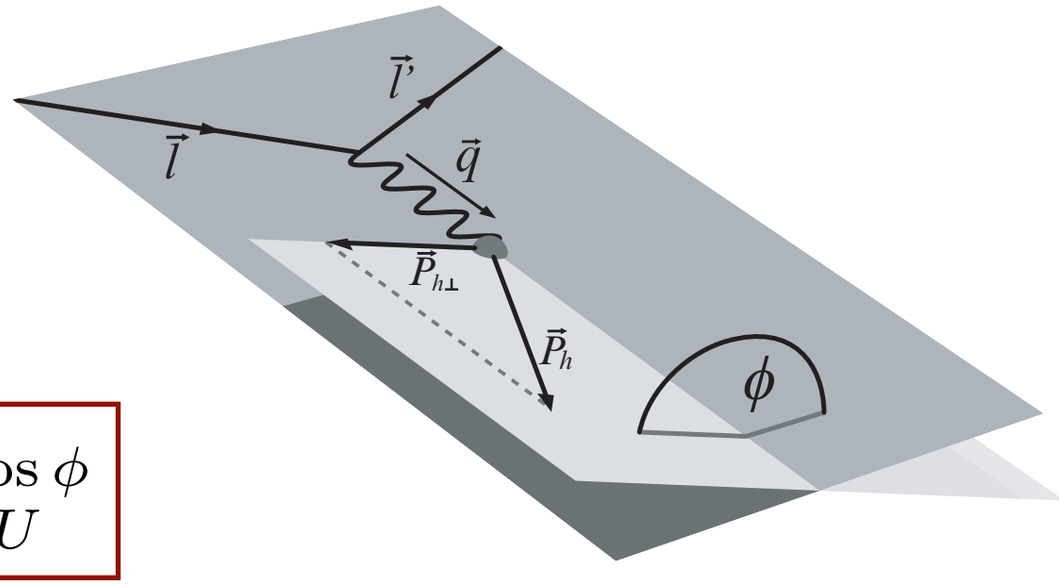




Re-evaluation. Details see Hal Jackson at DIS13

Cosine modulations in hadrons off the unpolarized proton

TMDs in SIDIS



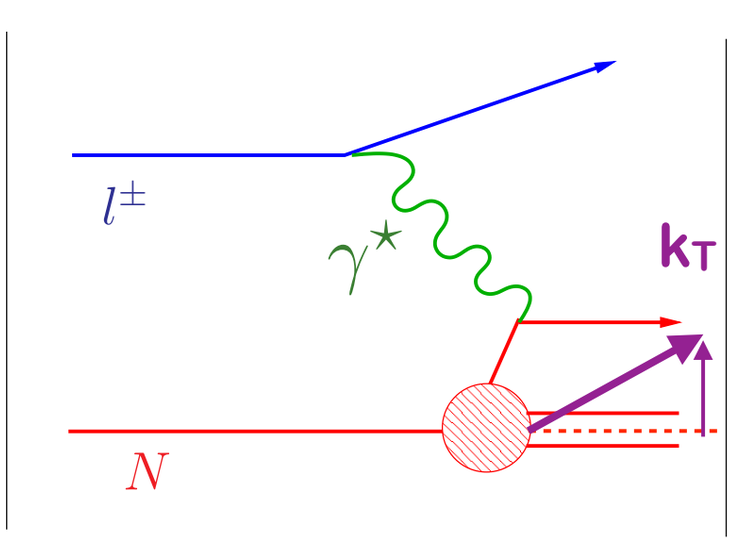
Cahn-effect + BM ⊗ Collins

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}\phi}(\vec{l}p \to lhX) \propto F_{UU} + \epsilon_1 \cos\phi F_{UU}^{\cos\phi}$$

$$+\epsilon_2 \cos(2\phi) F_{UU}^{\cos(2\phi)} + P_l \epsilon_3 \sin\phi F_{LU}^{\sin\phi}$$

BM ⊗ Collins

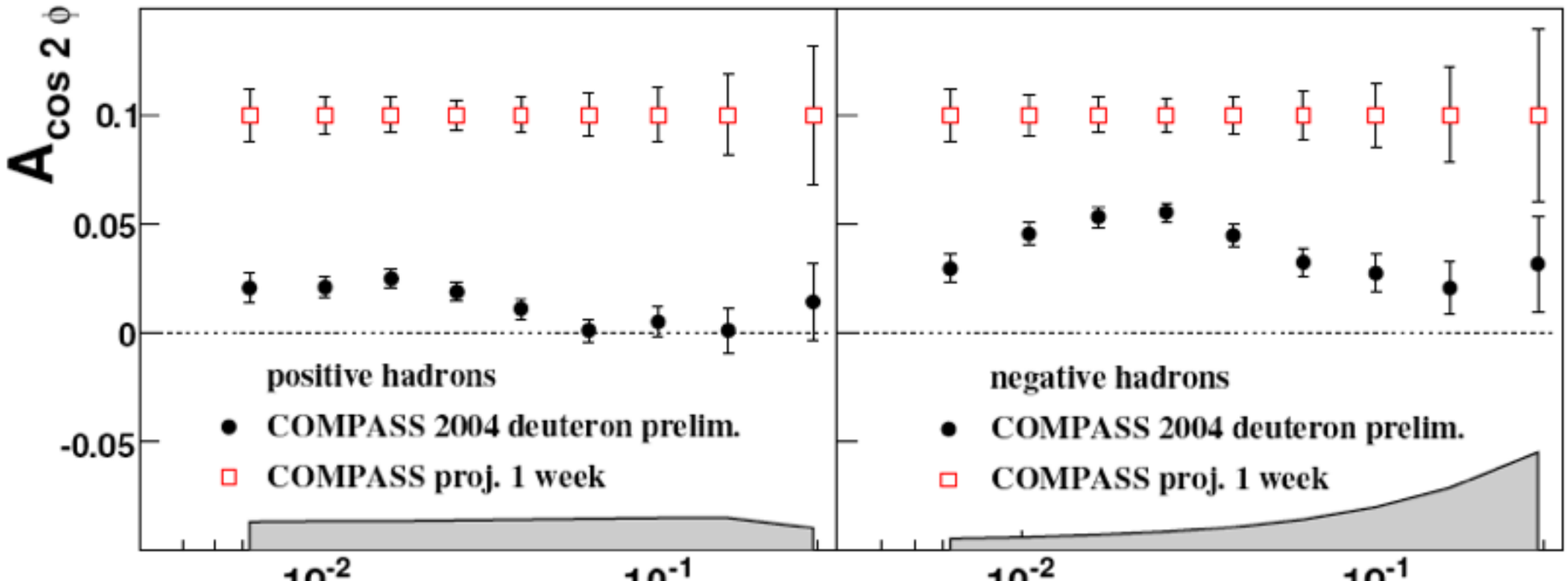
Beyond collinear approximation:



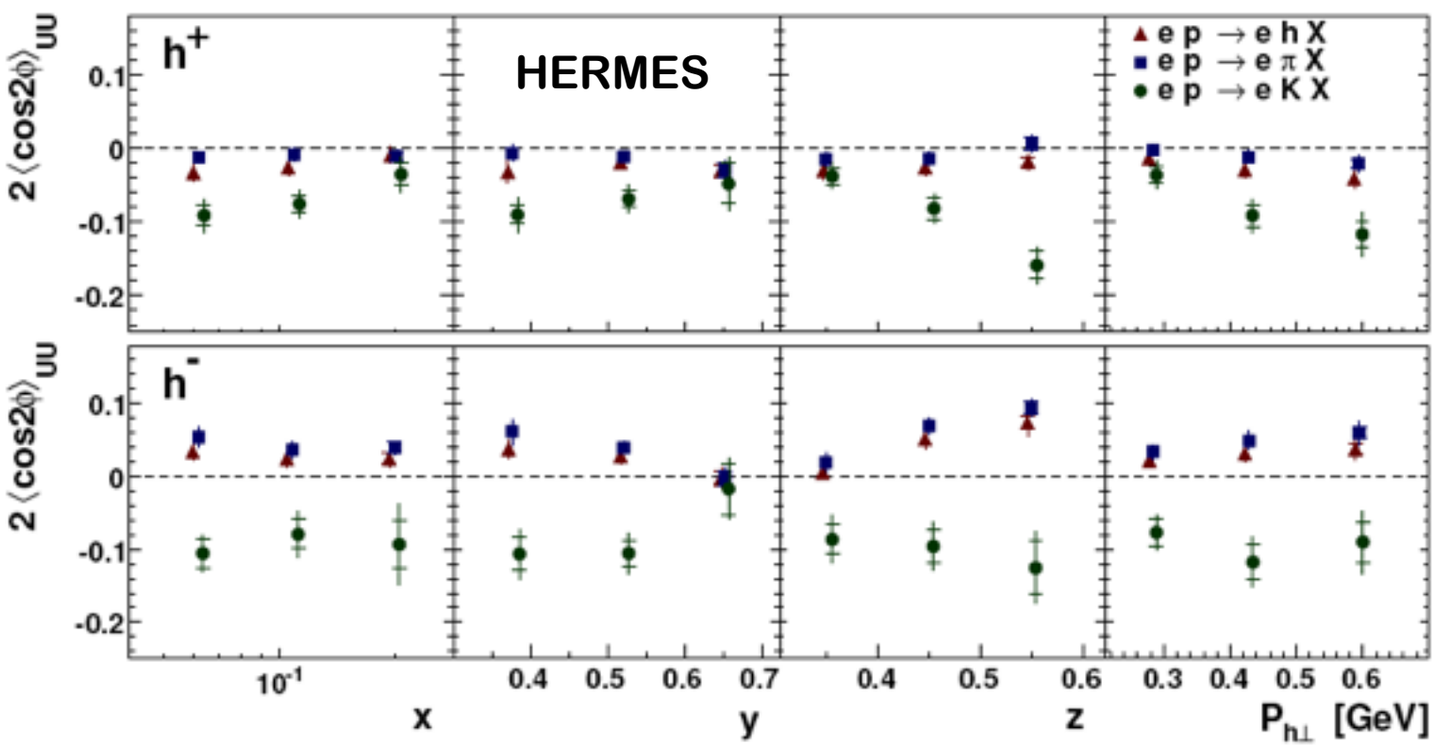
Cahn effect: information on average transverse momentum carried by unpolarized quarks in the unpolarized nucleon

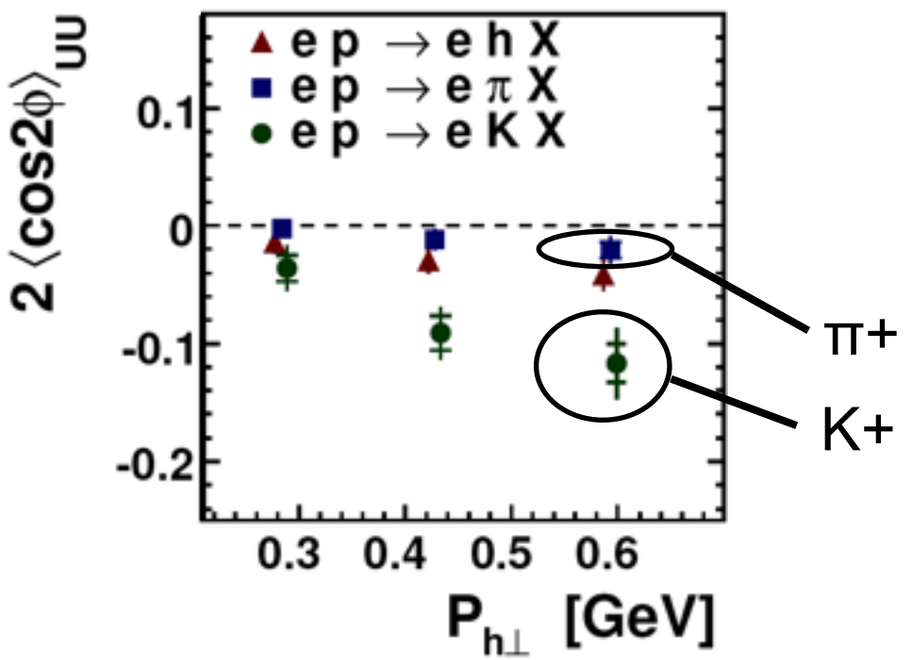
SIDIS cos(2Φ)-modulation

BM ⊗ Collins



Hadron ID will be very interesting!

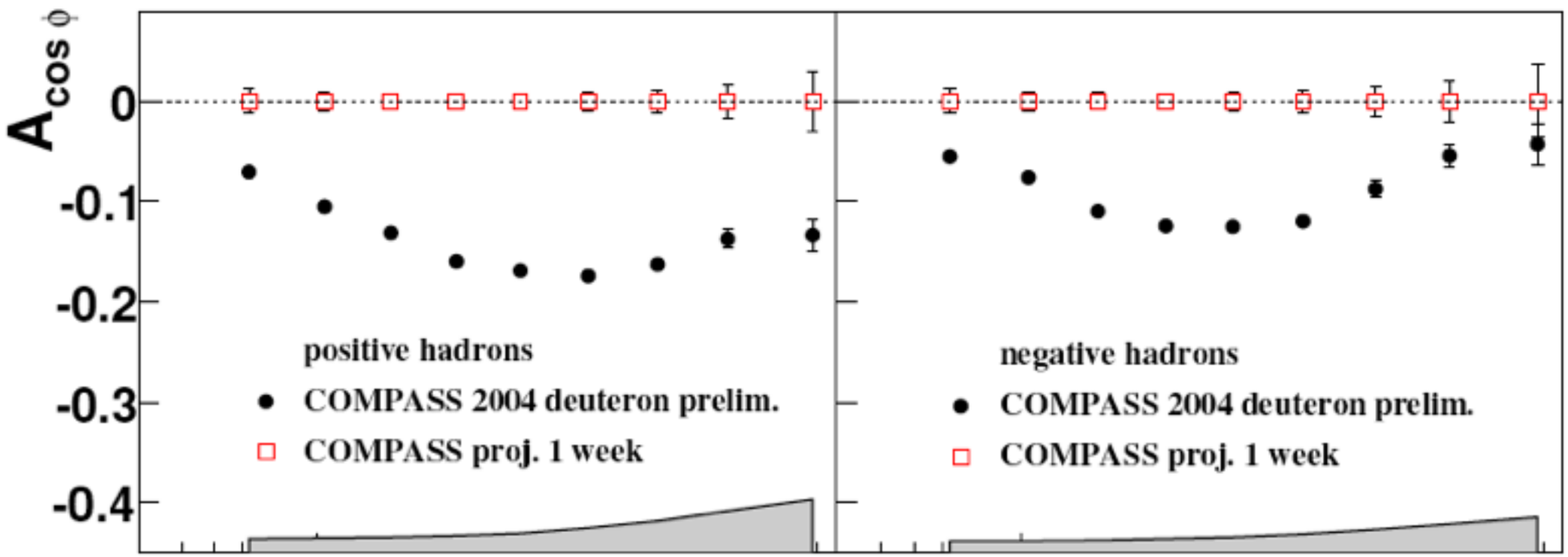


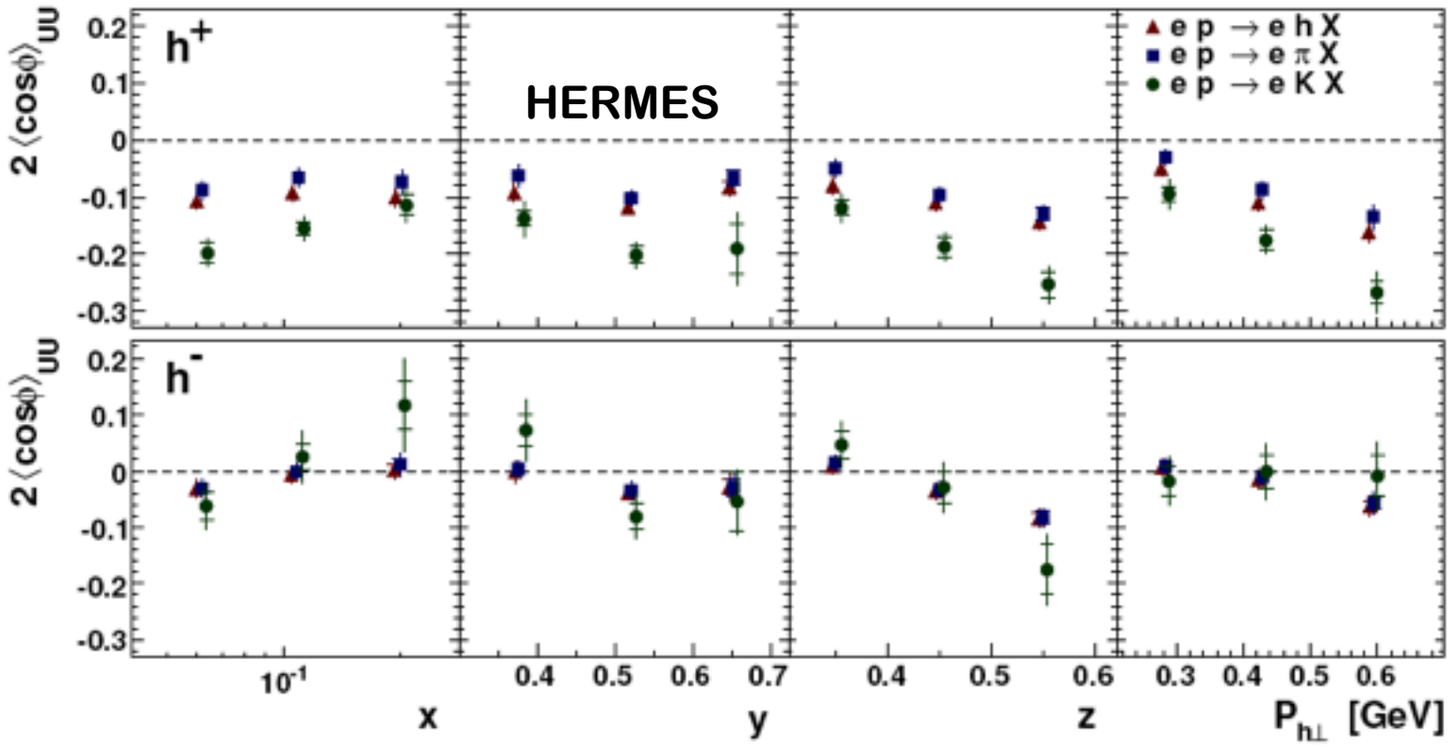


HERMES Phys. Rev. D 87 (2013) 012010

SIDIS cosΦ-modulation

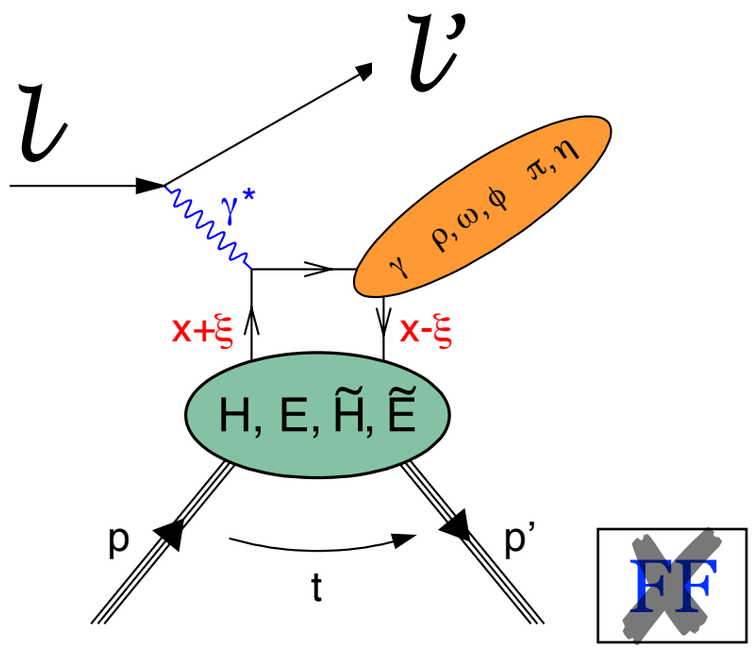
Cahn-effect +
BM ⊗ Collins





HERMES Phys. Rev. D 87 (2013) 012010

Hard-exclusive reactions



$lp \to lp\gamma$ Deeply Virtual Compton Scattering (**DVCS**)

$lp \to lpM$ Deeply Virtual Meson Production (**DVMP**)

Generalized Parton Distributions

4 chiral-even quark GPDs	flips nucleon helicity	conserves nucleon helicity
does not depend on quark helicity	**E** ↔ Sivers	**H** →q(x) (forward limit)
depends on quark helicity	$\tilde{\mathbf{E}}$	$\tilde{\mathbf{H}}$ →Δq(x)

@leading twist for a spin-½ target

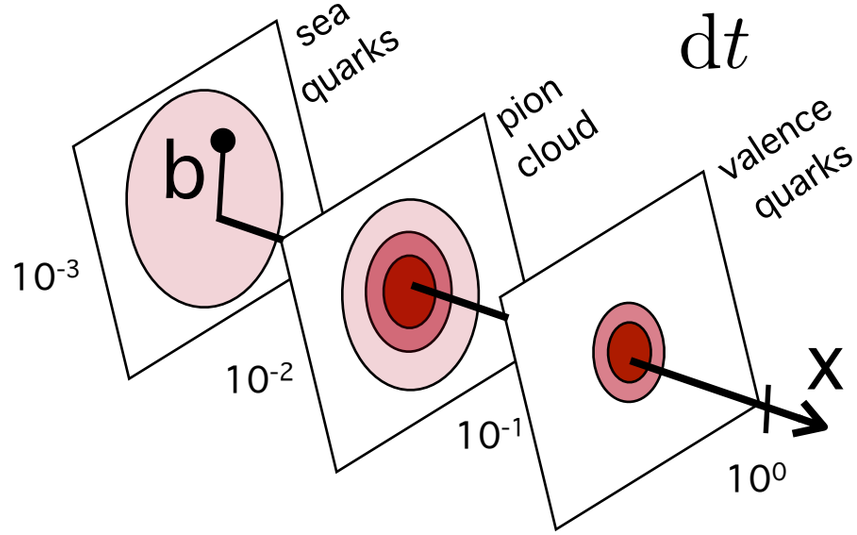
4 chiral-odd quark GPDs
H_T ↔ **transversity**
$2\tilde{H}_T + E_T$ ↔ **Boer-Mulders**
$\tilde{E}_T$

GPD E and Sivers function involve switch of nucleon helicity: related to OAM

Transverse imaging: transverse size of nucleus

b = "t-slope" = average impact parameter

$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}}{\mathrm{d}t} \propto e^{-b|t|}$$

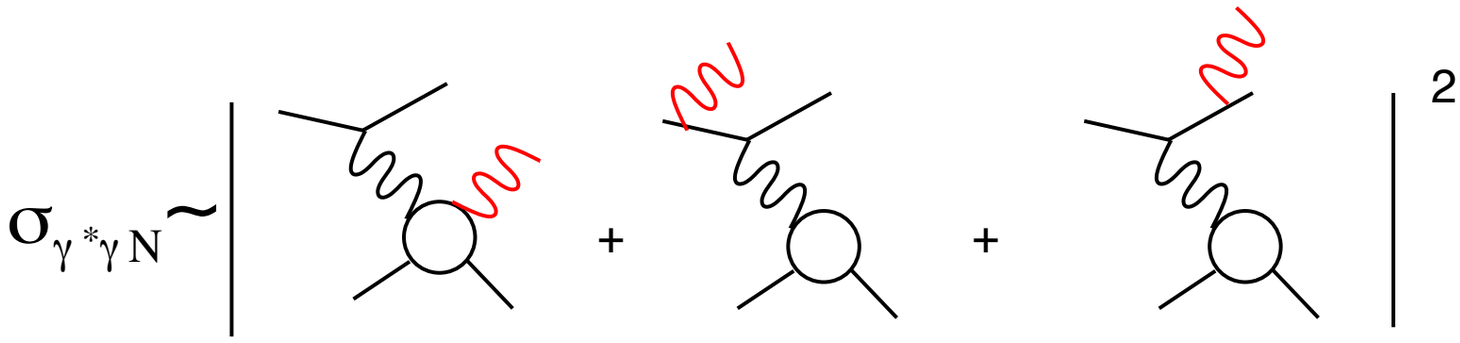


"tomographic images" of the nucleon

impact-parameter representation: $q^f(x, \boldsymbol{b}_\perp) = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_\perp}{(2\pi)^2} e^{-i\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} H^f(x, 0, -\boldsymbol{\Delta}_\perp^2)$

Burkardt, Int. J. Mod. Phys. A18 (2003) 173

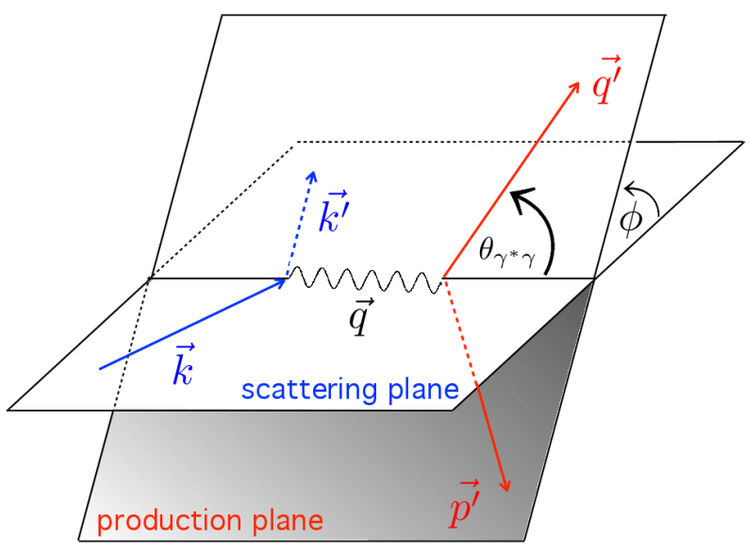
DVCS at COMPASS

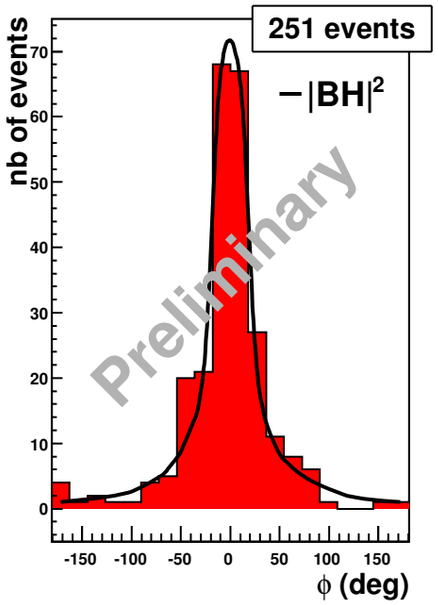


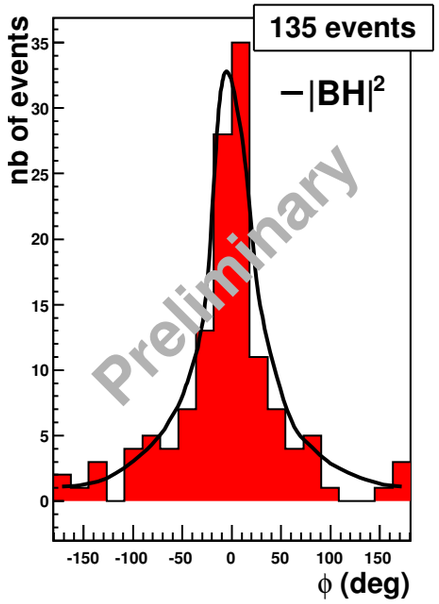
interference

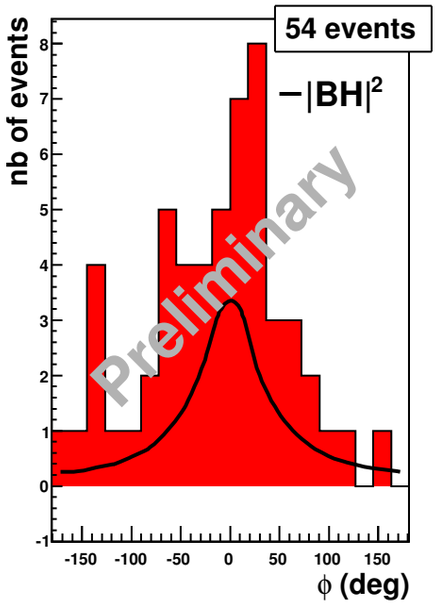
$$= |\mathcal{T}_{\mathrm{BH}}|^2 + (\mathcal{T}_{\mathrm{DVCS}}\mathcal{T}^*_{\mathrm{BH}} + \mathcal{T}^*_{\mathrm{DVCS}}\mathcal{T}_{\mathrm{BH}}) + |\mathcal{T}_{\mathrm{DVCS}}|^2$$

0.005<x_B<0.01 **0.01<x_B<0.03** **0.03<x_B**









2009 DVCS test run with short recoil (re-analyzed)

BH reference yield

DVCS amplitude: Φ-modulations in cross section

Transverse imaging: Φ-integrated cross section

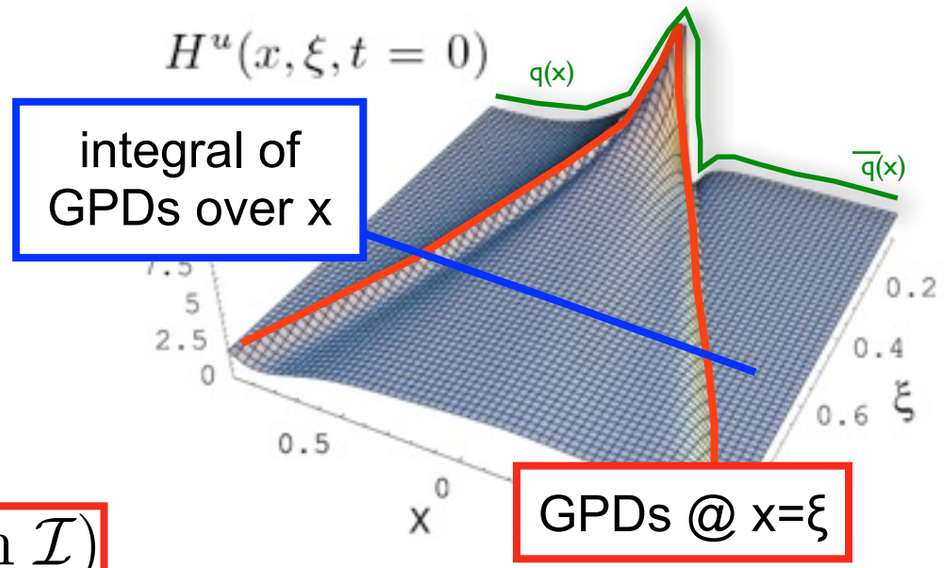
pure DVCS cross section after subtraction of BH

GPD program at COMPASS-II

- **2016/17 (phase 1)**: LH_2 target + long recoil detector
  - transverse imaging from DVCS and DVMP
  - GPD H from DVCS

$$\mathcal{S}_{CS,U} \equiv \mathrm{d}\sigma^{\overleftarrow{+}} + \mathrm{d}\sigma^{\overrightarrow{-}} = 2(\mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + e_\mu P_\mu \boxed{\mathrm{Im}\,\mathcal{I}})$$

$$\mathcal{D}_{CS,U} \equiv \mathrm{d}\sigma^{\overleftarrow{+}} - \mathrm{d}\sigma^{\overrightarrow{-}} = 2(P_\mu \mathrm{d}\sigma^{\mathrm{DVCS}}_{\mathrm{pol}} + e_\mu \boxed{\mathrm{Re}\,\mathcal{I}})$$



DVCS is special: allows separation of real and imaginary parts of DVC scattering amplitude

@COMPASS: H-dominance

$$\boxed{\mathrm{Im}\,\mathcal{H}(\xi,t,Q^2) \overset{\mathrm{LO}}{=} \pi \sum_f e_f^2 \left(H^f(\xi,\xi,t,Q^2) \mp H^f(-\xi,\xi,t,Q^2)\right)}$$

$$\boxed{\mathrm{Re}\,\mathcal{H}(\xi,t,Q^2) \overset{\mathrm{LO}}{=} \sum_f e_q^2 \left[\mathcal{P}\int_{-1}^{1} \mathrm{d}x\; H^f(x,\xi,t,Q^2)\left(\frac{1}{x-\xi} \mp \frac{1}{x+\xi}\right)\right]}$$

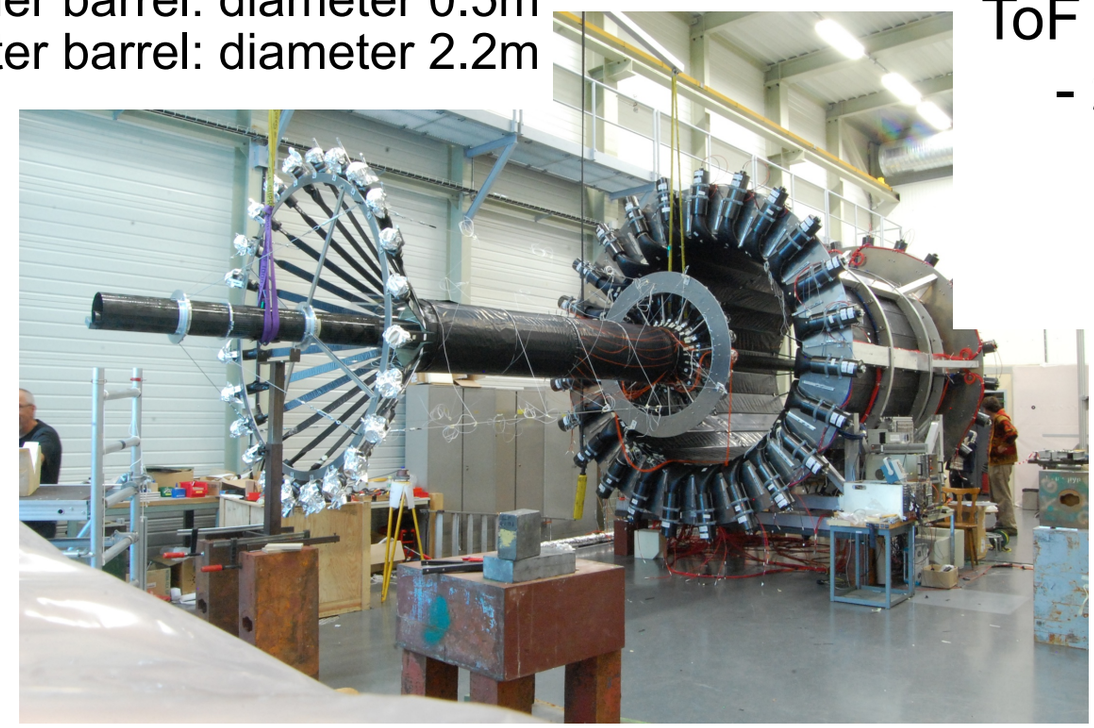
+ link to D-term

- **>2017 (phase 2 (?))**: $NH_3\uparrow$ target + recoil detector
  - GPD E from DVCS
  - GPD E and chiral-odd GPDs from DVMP
    - vector mesons ρ^0, ρ^+, ω, Φ
    - pseudoscalar mesons π^0
  - Mesons allow access to different GPD combinations

For ρ^0 mesons, selection of exclusive data sample feasible without recoil-proton detection. Results exist from 2007-2010 transversely polarized data.

Detector upgrades for GPD run

inner barrel: diameter 0.5m
outer barrel: diameter 2.2m



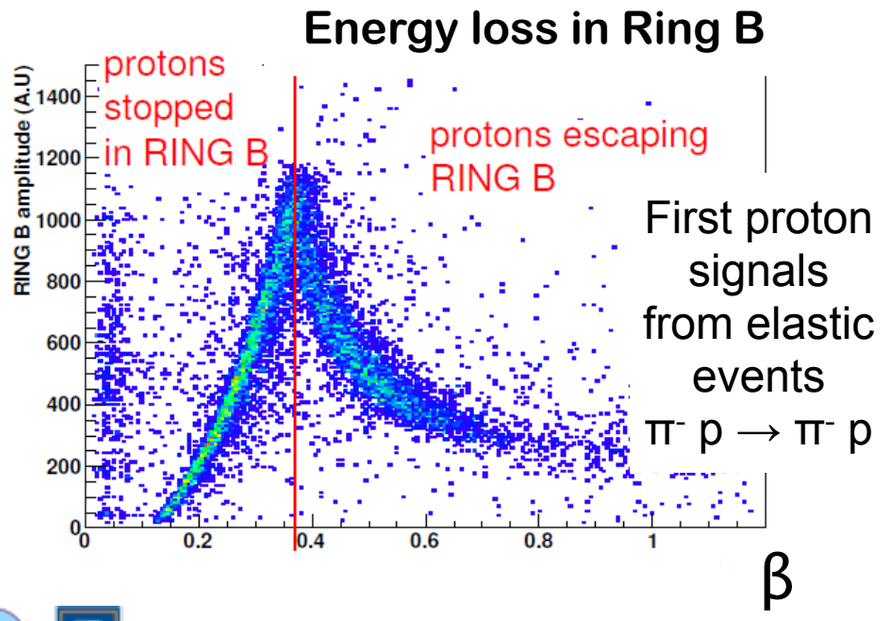
Long recoil detector CAMERA

ToF between 2 rings of scintillators

- 24 inner and 24 outer scintillators
- ToF resolution 300 ps
- p_{min}=260 MeV

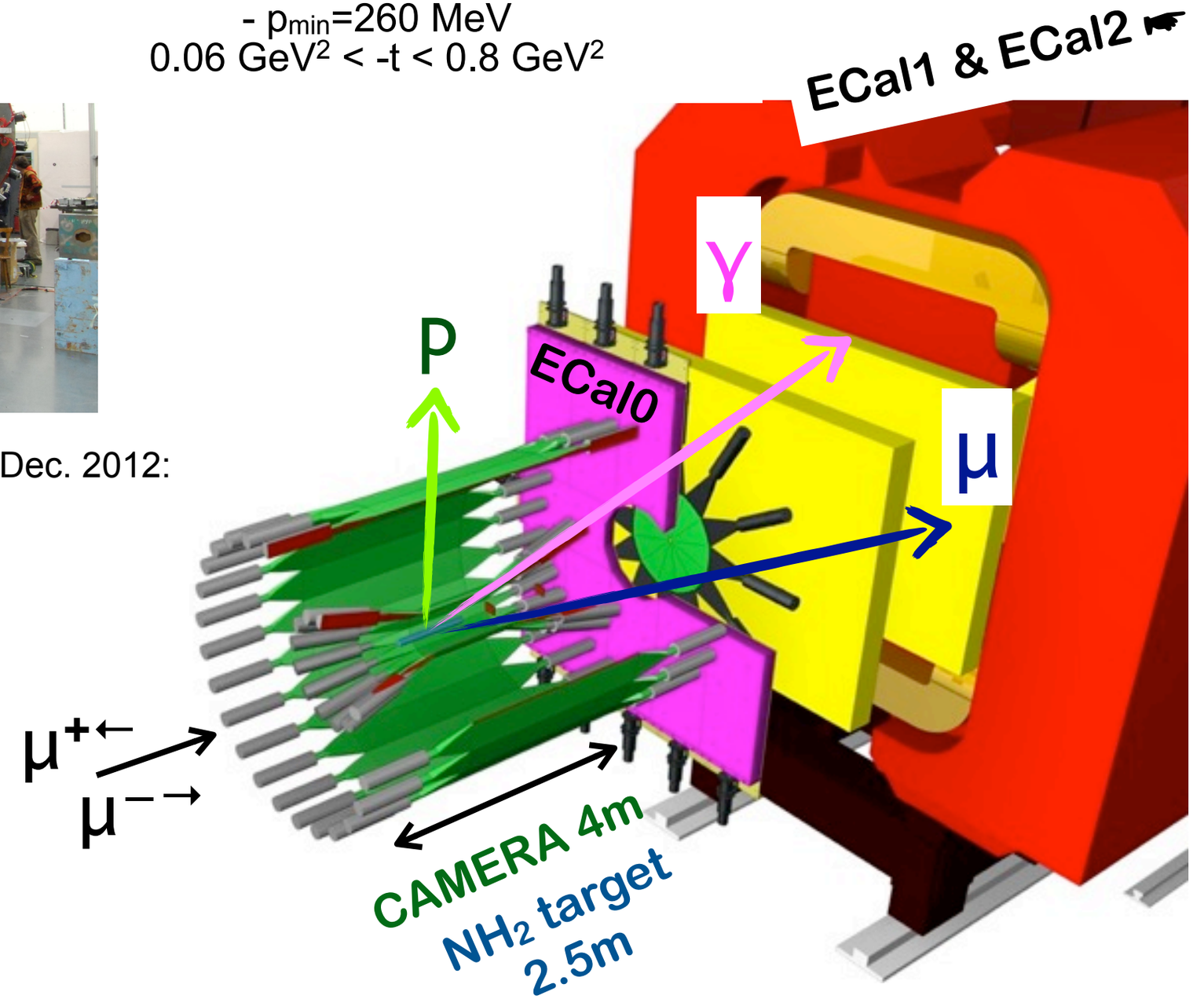
0.06 GeV^2 < -t < 0.8 GeV^2

First DVCS run Sept 26, 2012 with CAMERA until Dec. 2012:



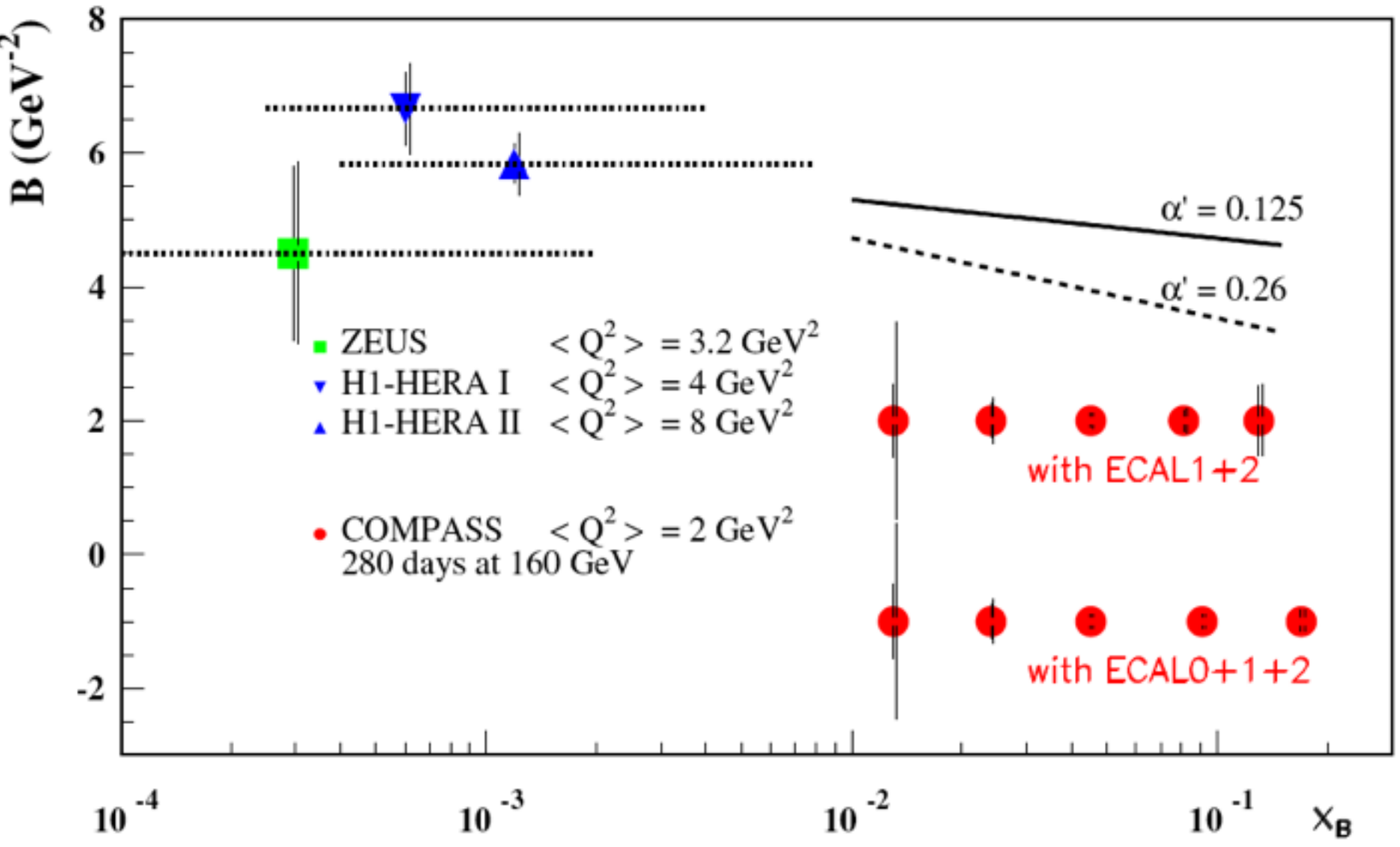
First proton signals from elastic events

$\pi^- p \rightarrow \pi^- p$



COMPASS-II projection for t-slope

$$\frac{\mathrm{d}\sigma^{\mathrm{DVCS}}}{\mathrm{d}t} \propto e^{-b|t|}$$



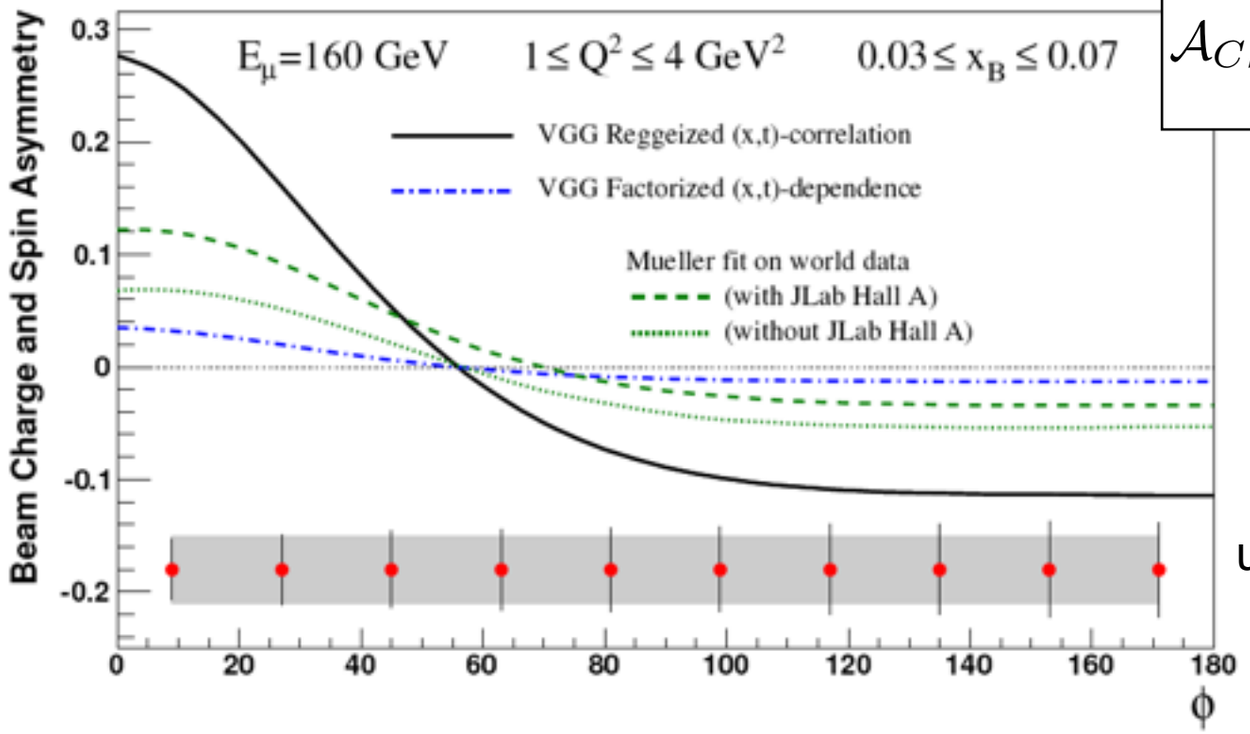
2 years of data
beam energy 160 GeV
$4 \cdot 10^8$ μ^+/spill (μ^- 2.6x less)
duration 9.6s every 48s
2.5m target
Lumi=10^{32} cm^{-2}s^{-1}
ε_{global} =10%

Regge-trajectory ansatz
$b(x_B) = b_0 + 2\alpha' \ln(x_0/x_B)$

$\alpha' \simeq 0.25$ GeV^{-2}
soft pomeron

1-bin-extraction already possible from DVCS test in 2012

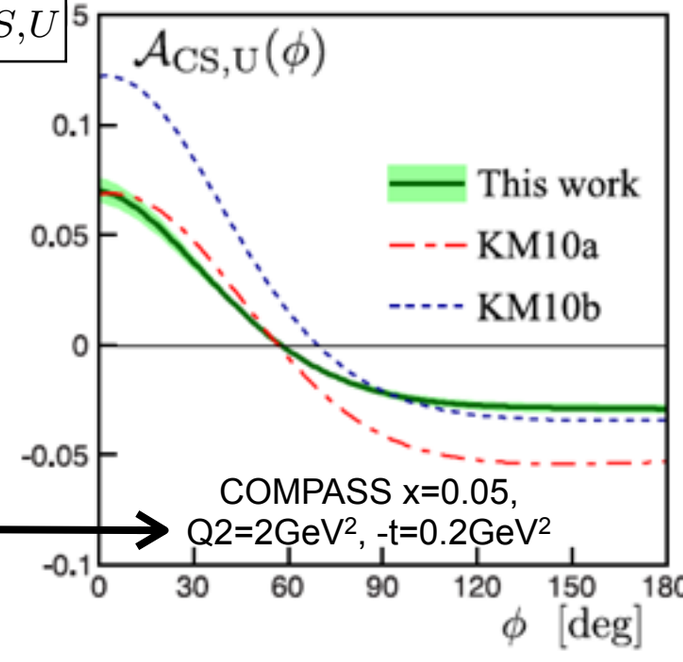
COMPASS-II projections for spin & charge asym.



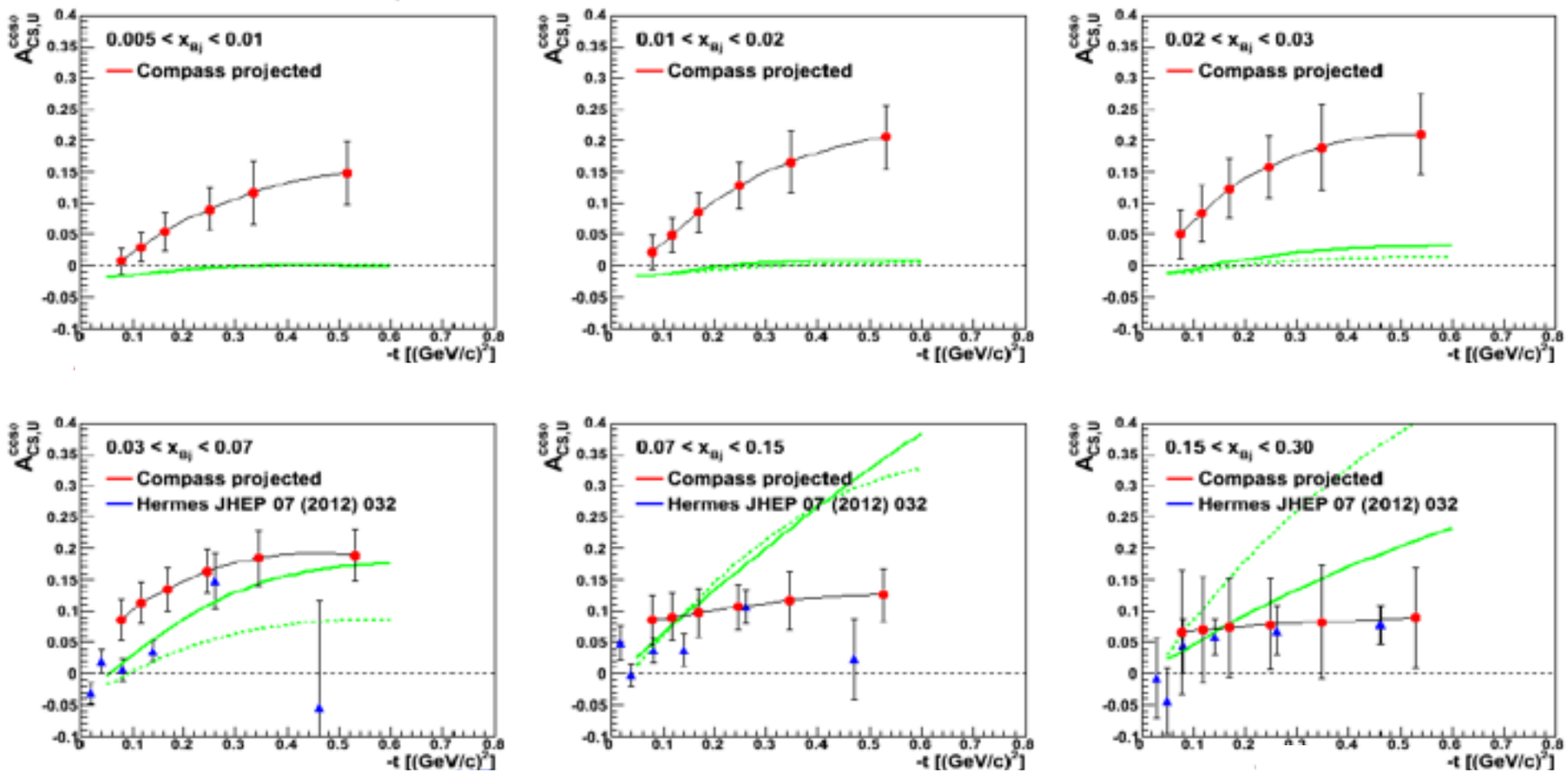
$$\mathcal{A}_{CS,U} \equiv \frac{\mathrm{d}\sigma^{\overleftarrow{+}} - \mathrm{d}\sigma^{\overrightarrow{-}}}{\mathrm{d}\sigma^{\overleftarrow{+}} + \mathrm{d}\sigma^{\overrightarrow{-}}} = \frac{\mathcal{D}_{CS,U}}{\mathcal{S}_{CS,U}}$$

Kroll, Moutarde, Sabatié, arXiv:1210.6975

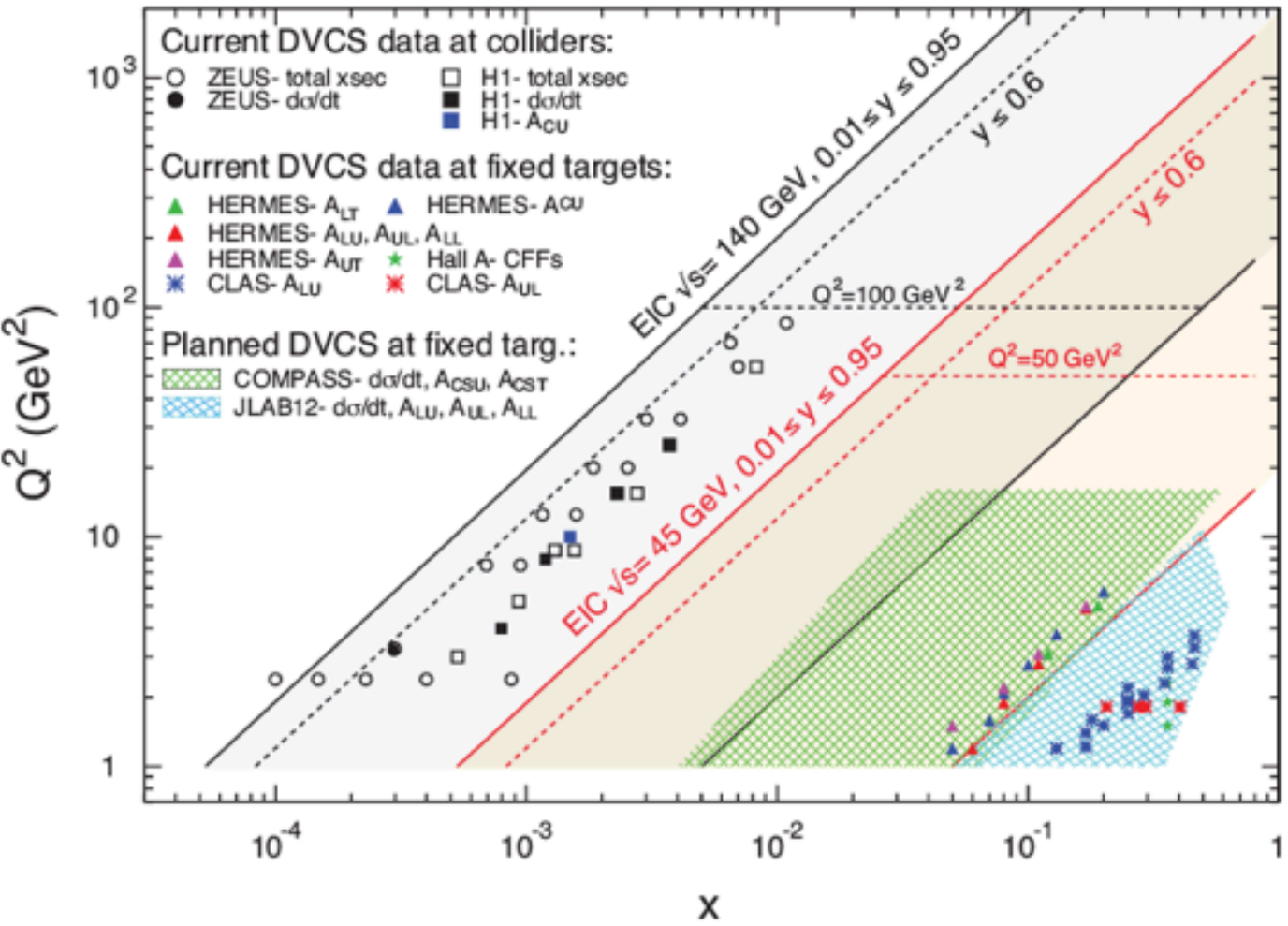
Check of GPD universality: use DVMP data to constrain GPD params



- Projection compared with HERMES beam-charge asymmetry's cosΦ-modulation
- Question: magnitude of cosΦ-modulation in COMPASS data?
- Changes sign in between H1 and HERMES!



Global analysis of DVCS data

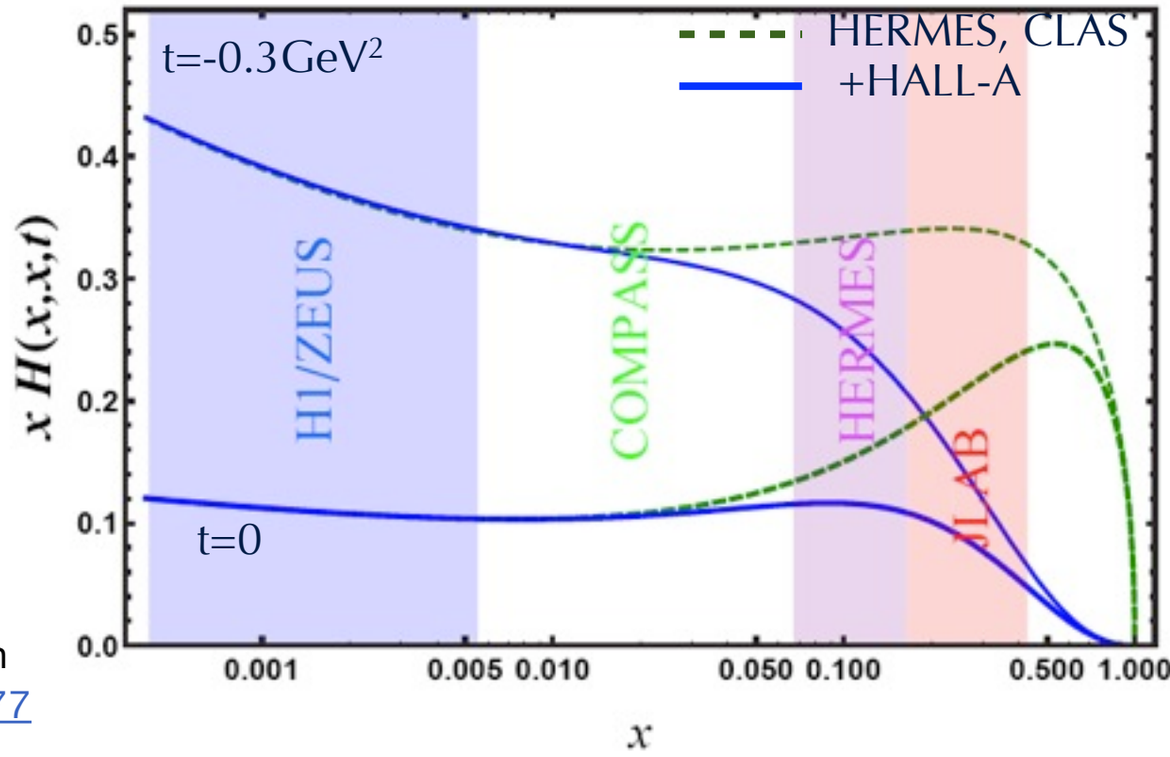


"Deeply Virtual Compton Scattering at a Proposed High-Luminosity Electron-Ion Collider", E.-C. Aschenauer, S. Fazio, K. Kumericki and D. Mueller, arXiv:1304.0077

Global fit to H(x,ξ=x,t) from DVCS data (NNLO)

Kumericki, Müller Nucl. Phys. **B**841 (2010) 1-58

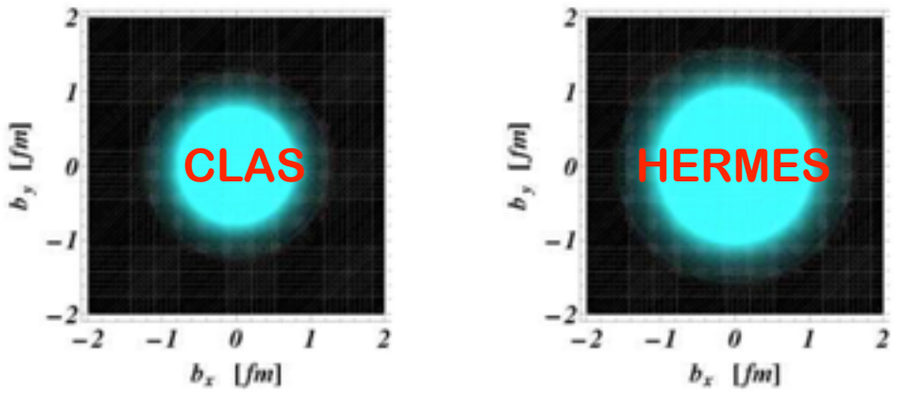
- **HERMES** A_C , **CLAS** A_{LU} and **Hall A** x-section.
- Small-x behavior from **HERA collider** data.



From Compton Form Factors to spatial charge densities

$$H(x,b_\perp) = \int_0^\infty \frac{d\Delta_\perp}{2\pi}\,\Delta_\perp\, J_0(b_\perp\Delta_\perp)\, H(x,0,-\Delta_\perp^2)$$

M. Guidal, H. Moutarde, M. Vanderhaeghen, arxiv.org:1303.6600



Outlook: COMPASS-II

Pion-induced Drell-Yan:

- Pions as alternative probe to test nuclear models and meson structure (not accessible in DIS)
- Flavor dependence: pion (or meson in general) is specific qqbar compound

W.-C. Chang and D. Dutta, The pionic Drell-Yan process: a brief survey. International Journal of Modern Physics E, Vol. 22, No. 8 (2013) 1330020. arXiv:1306.3971

Beyond 2017?

- **Drell-Yan**
  - Universality of TMDs (higher statistics $p^{\uparrow}$)
  - Flavor dependence ($d^{\uparrow}$)
  - Test of Lam-Tung relation (p)
  - EMC effect in DY (nuclear targets) *maybe earlier!*
- **SIDIS**
  - d-quark transversity with same precision as u-quark transversity ($d^{\uparrow}$)
  - Sivers-function evolution (lower beam energy of 100 GeV)
- **GPD**
  GPD E ($p^{\uparrow}$ with recoil detector)

Not approved (yet).
Not decided (yet).

Summary: COMPASS-II

- 2015: **Drell-Yan**
  First polarized Drell-Yan measurement ever!
  Also first and only meson-induced DY since more than 25 years.
  - **TMD universality** in Drell-Yan vs. SIDIS?
  - **Sign switch** of time-reversal-odd TMDs?

- 2016/17: **SIDIS**
  - High-statistics data acquisition for constraints of unpol. PDFs and quark FFs
  - Effects of quark transverse momentum in the unpolarized nucleon

- 2016/17: **GPDs**
  - **GPD H** from helicity-dependent and -averaged cross section
  - **Transverse imaging**

- **Outlook:** measure Drell-Yan on nuclear targets?
  Beyond 2017: plans for 2nd Drell-Yan run. Possibly measure GPD E.

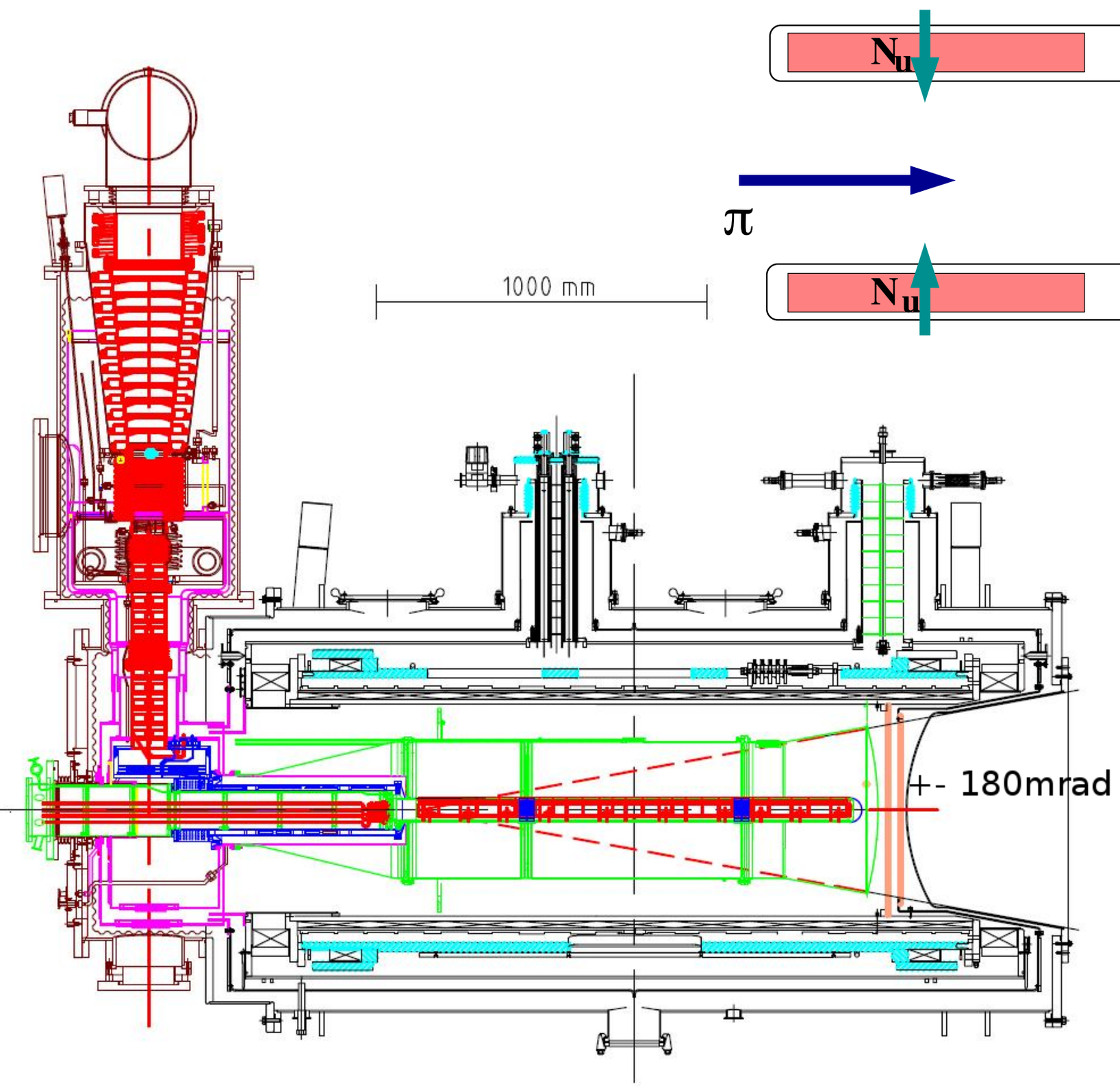
COMPASS-II 2010 **proposal** recommended by SPSC and approved by the Research Board for a first period of **3 years** including 1 year for **Drell-Yan** and 2 years for **GPDs.**

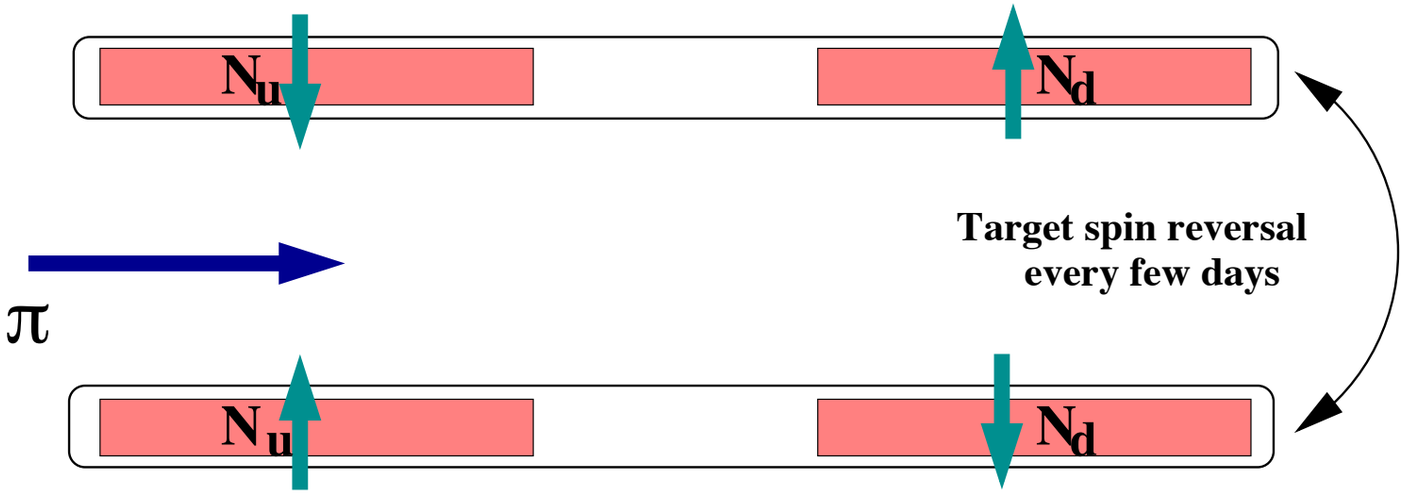
http://wwwcompass.cern.ch/compass/proposal/compass-II_proposal/compass-II_proposal.pdf

Thank you for material to: A. Ferrero, O. Denisov, C. Quintans, E. Zemlyanichkina, N. D'Hose!

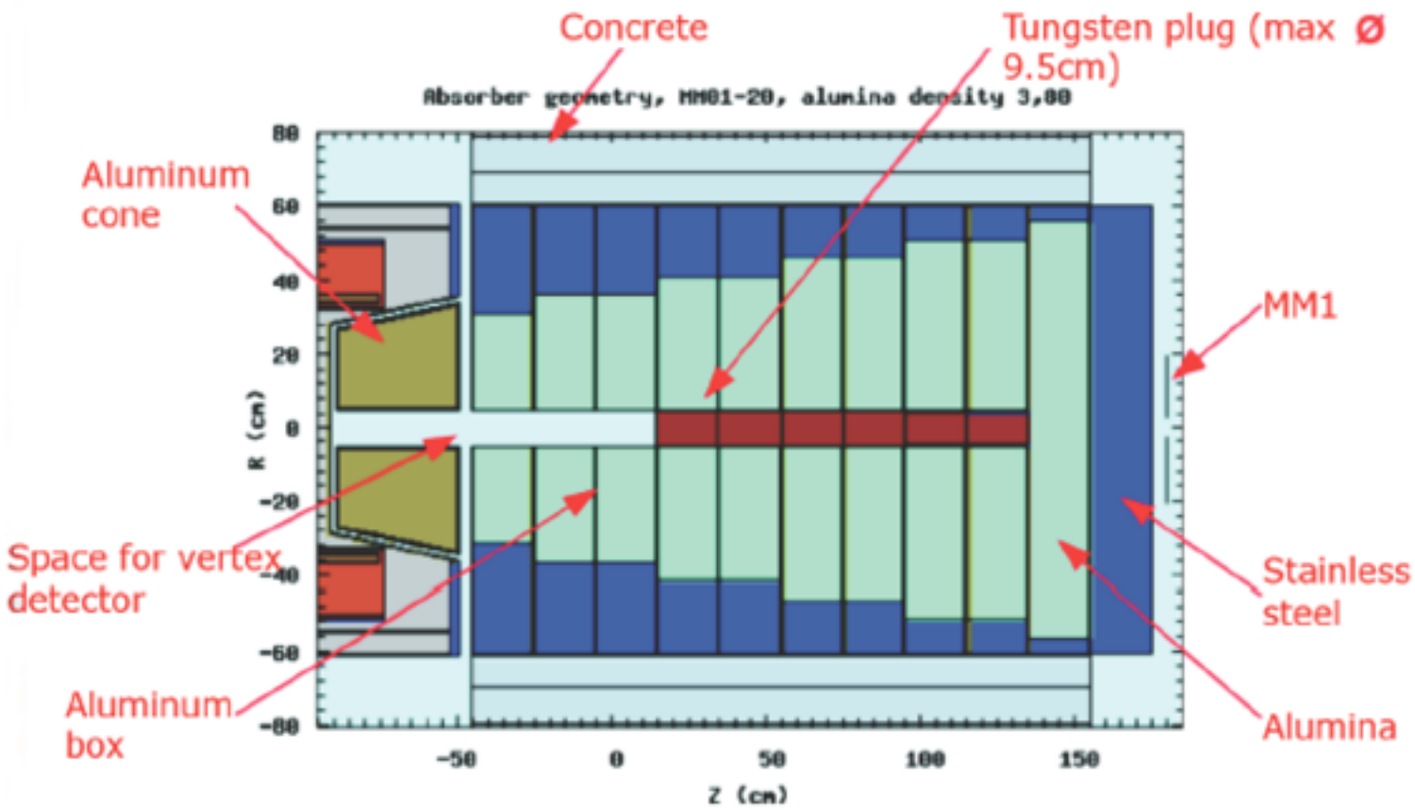
Backup

The transversely polarized NH_3 target





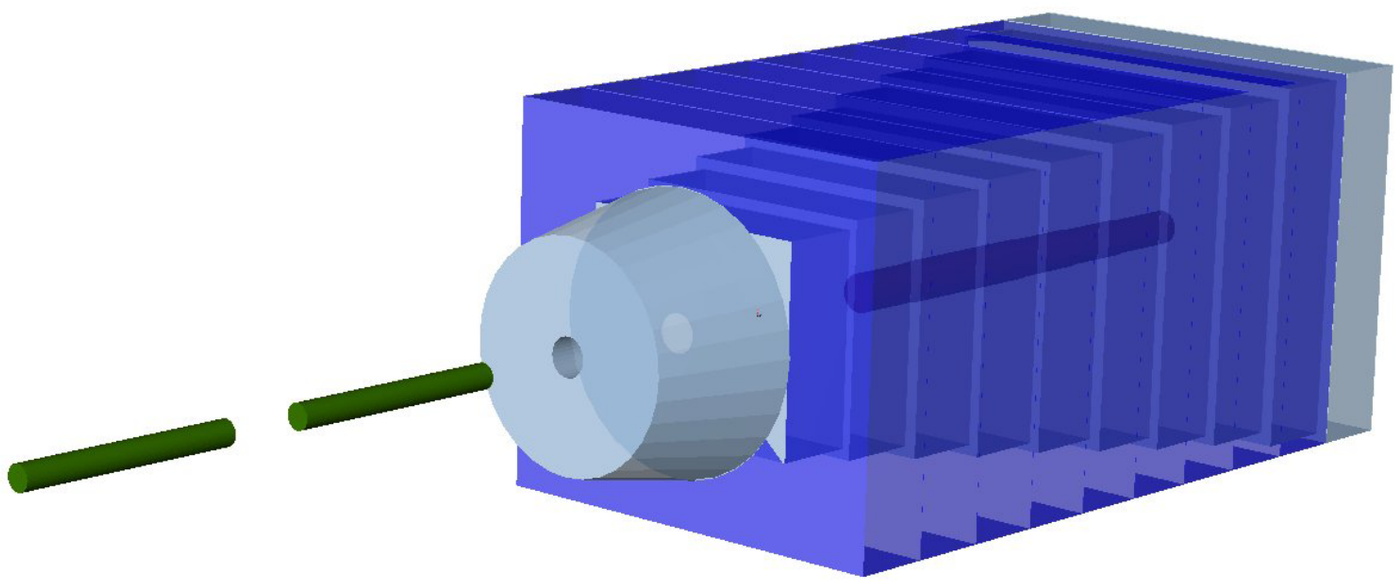
The hadron absorber



Structure of the hadron absorber:

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

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



Minimize multiple scattering of muons and maximize stopping power for hadrons.

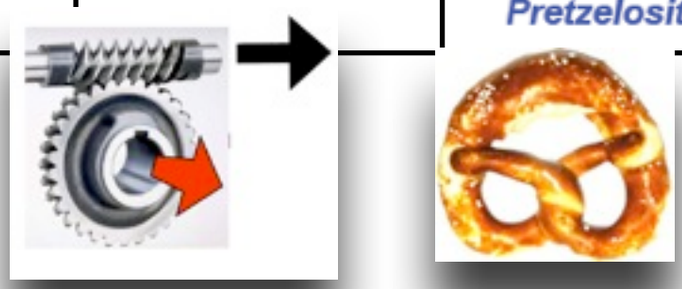
Transverse-Momentum Dependent PDFs (TMDs)

Distribution Functions (DF)

Diagonal 'survives' integration over transverse momentum k_T. "Collinear analysis"

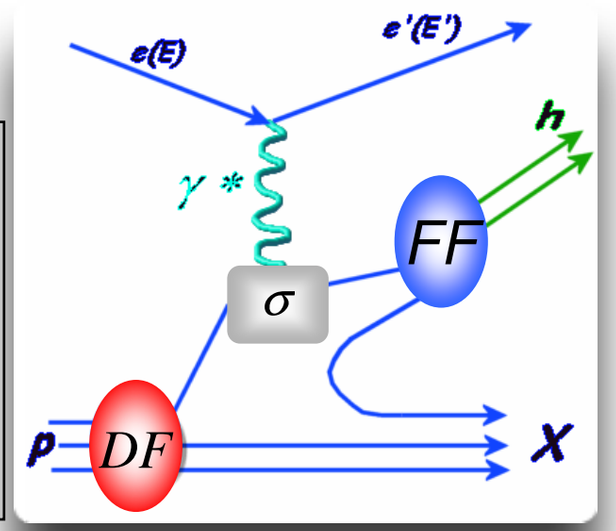
nucleon \ quark polarization	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity, $h_{1T}^\perp$ Pretzelosity

chiral odd



factorization

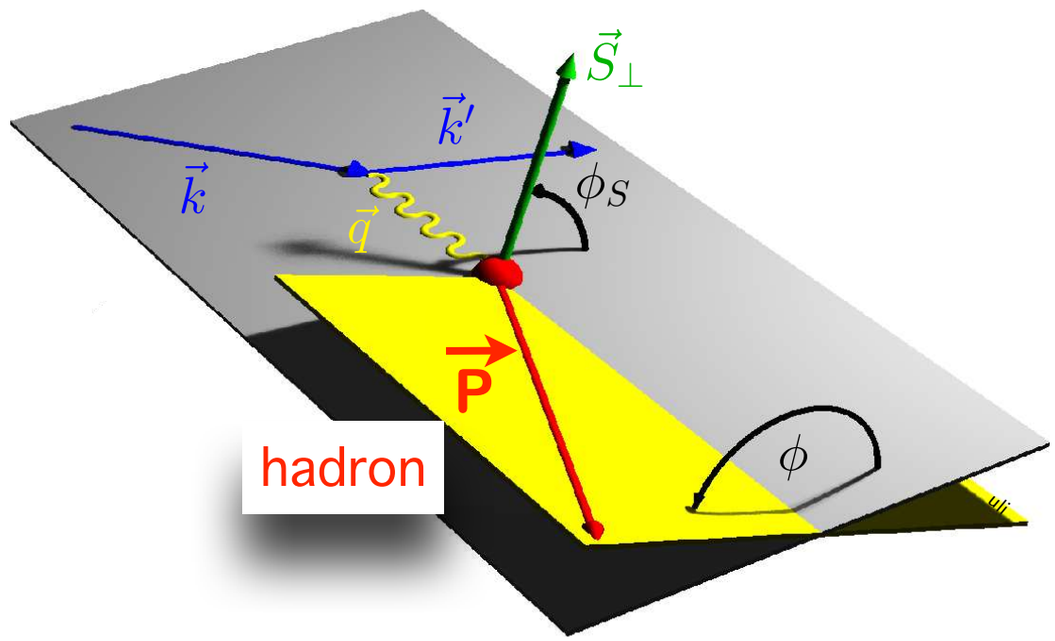
$\sigma^{ep\to ehX} = \Sigma_q$ (FF $\otimes$ $\sigma^{eq\to eq}$ $\otimes$ DF)



Fragmentation Function (FF)

☛ TMDs depend on the longitudinal and transverse momentum of a parton inside a hadron.

☛ Describe strength of various spin-spin or spin-orbit correlations of the parton-hadron system.



Future Drell-Yan experiments

- Programs for future Drell-Yan measurements:
  nucleon-nucleon at
    - SeaQuest (Fermilab)
    - RHIC (Brookhaven)
    - J-PARC (KEK)
    - IHEP (Protvino)
    - JINR (Dubna)
  anti(p)-nucleon at
    - FAIR (GSI)
  pion-nucleon at
    - COMPASS (CERN)

    Only existing meson plan!

- Past measurements exclusively considered the unpolarized cross section, future ones also aim for polarization measurements.
  - transversely polarized DY: spin-dependent TMDs
  - longitudinally polarized DY: quark helicity