YAMAGATA UNIVERSITY

COMPASS experiment

Yoshiyuki Miyachi, Yamagata University
on behalf of the COMPASS Collaboration

Contents

YAMAGATA UNIVERSITY

- COMPASS I
  - COMPASS Experiment
  - Longitudinal spin structure of the proton
  - Transverse spin structure of the proton: TMD
- COMPASS II
  - Drell-Yan Program
  - GPD Program
- Summary

COMPASS Spectrometer

YAMAGATA UNIVERSITY

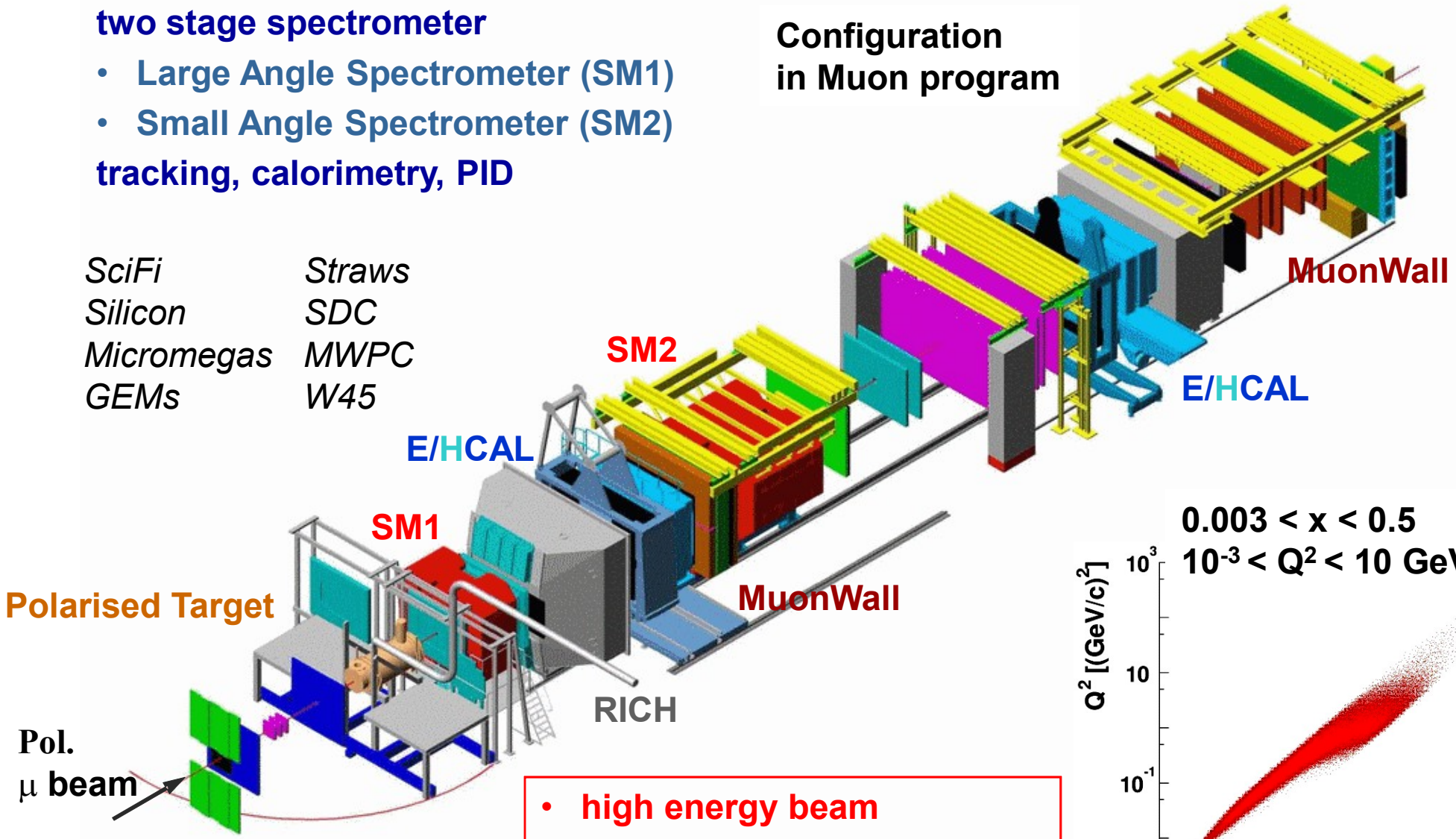
two stage spectrometer

- **Large Angle Spectrometer (SM1)**
- **Small Angle Spectrometer (SM2)**

tracking, calorimetry, PID

SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*

Configuration in Muon program



160GeV, pol. 80%

- **high energy beam**
- **broad kinematical range**
- **large angular acceptance**

$0.003 < x < 0.5$
$10^{-3} < Q^2 < 10$ GeV^2

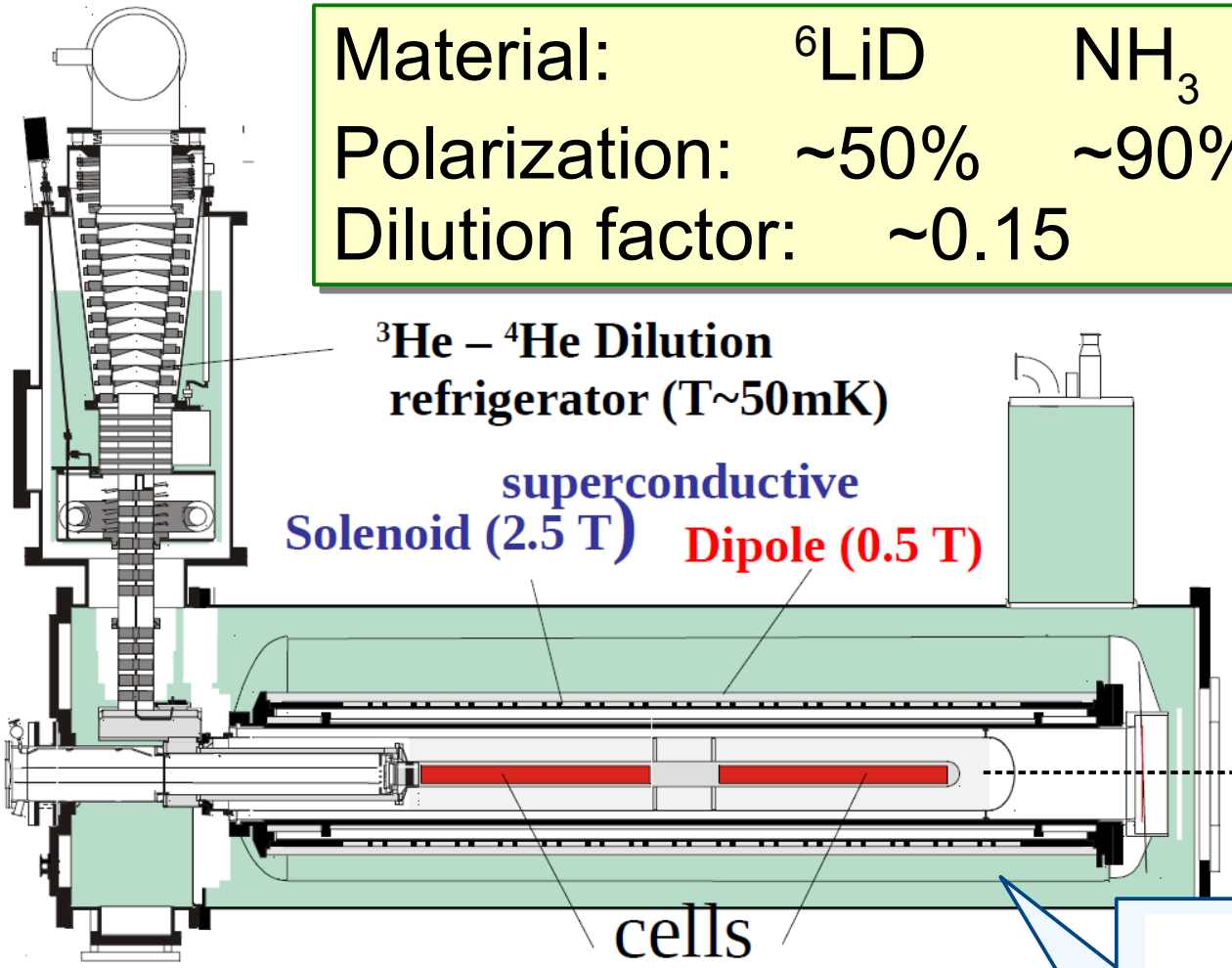
COMPASS polarized target

YAMAGATA UNIVERSITY

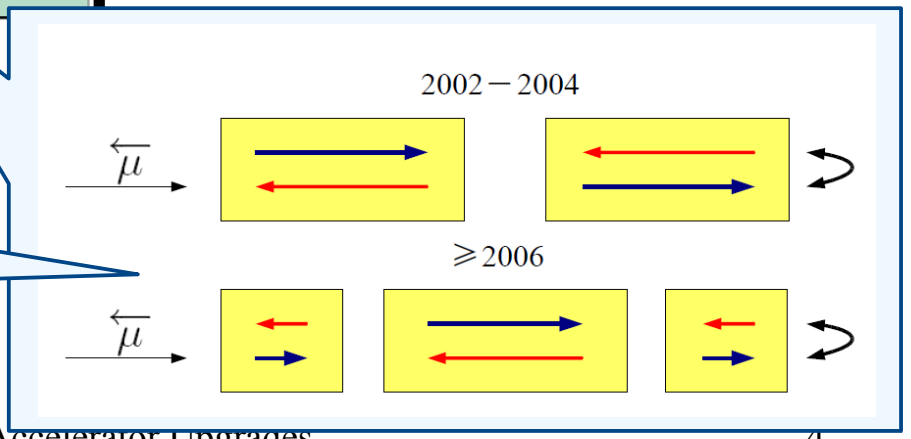
Material: ^{6}LiD NH_3

Polarization: ~50% ~90%

Dilution factor: ~0.15



Year	Material	Polarization
2002	^{6}LiD	L, T
2003		
2004		
2005		
2006		L
2007	NH_3	L, T
2008	hadron program	
2009		
2010	NH_3	T
2011		L



Spin flip: Field rotation & DNP

COMPASS I: 2002~2011, μ-program

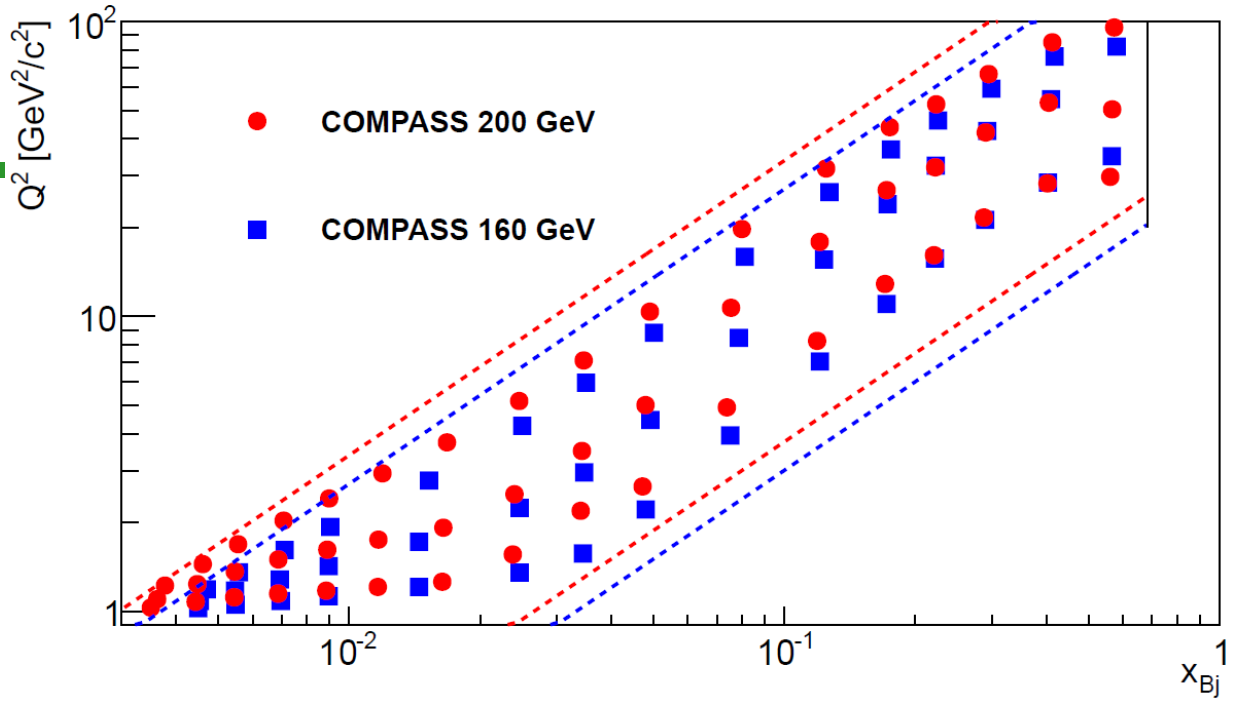
YAMAGATA UNIVERSITY

Year	Material	Polarization
2002	^{6}LiD	L, T
2003		
2004		
2005		
2006		L
2007	NH_3	L, T
2008	hadron program	
2009		
2010	NH_3	T
2011		L

Polarized DIS & SIDIS
- Spin structure function: g_1
- SIDIS asymmetry: A_1^h
- SSA with T-pol. Target
- ...

Hard exclusive ρ^0 production
- A_{UT}, A_{LT}

Unpol. SIDIS
- Hadron multiplicity
- Azimuthal amplitudes
- ...



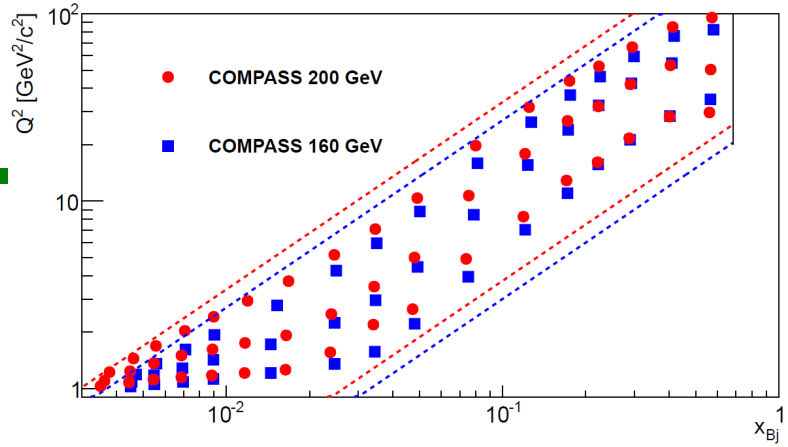
Year	Material	Polarization
2002	^{6}LiD	L, T
2003		
2004		
2005		
2006		L
2007	NH_3	L, T
2008	hadron program	
2009		
2010	NH_3	T
2011		L

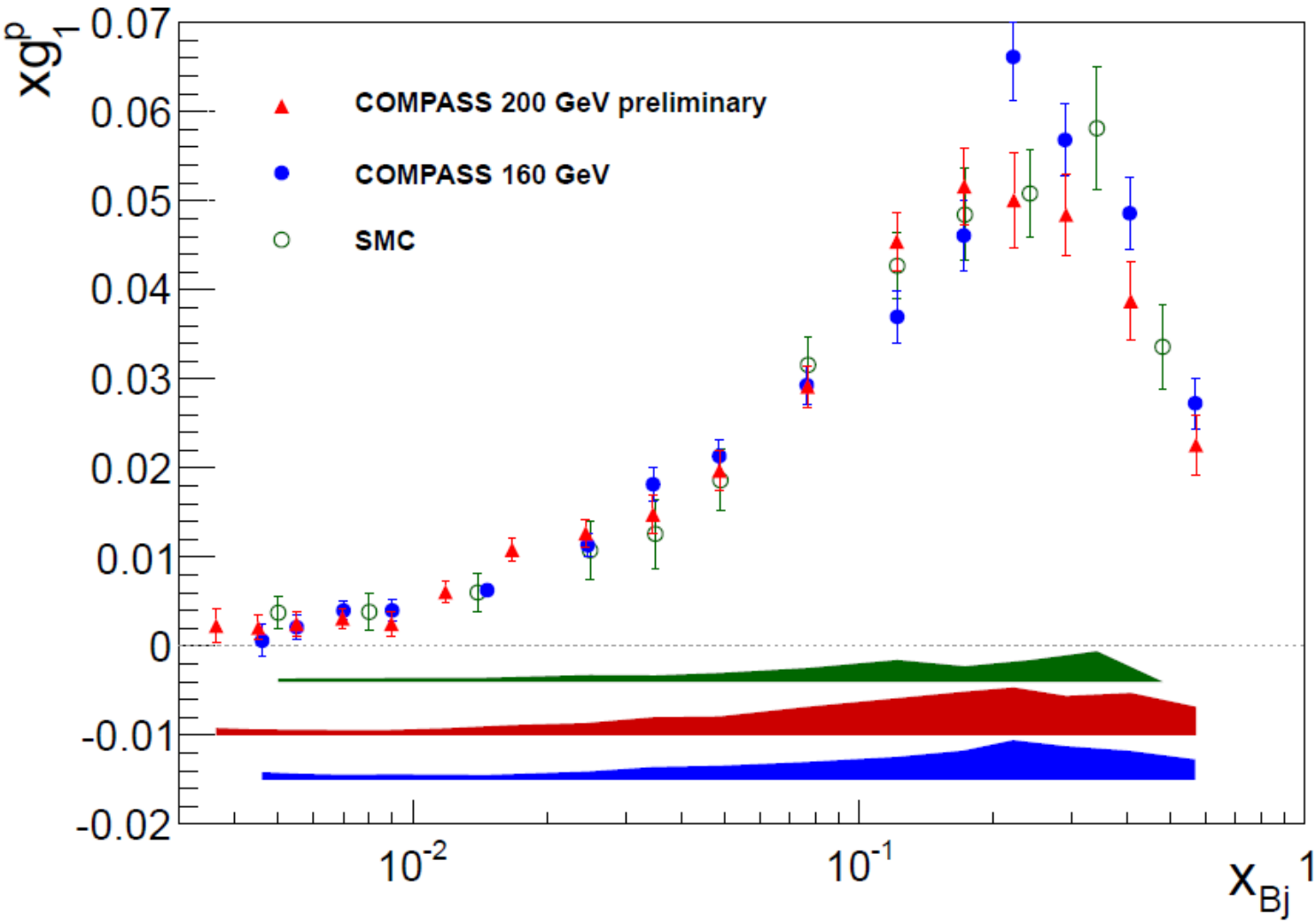
Beam

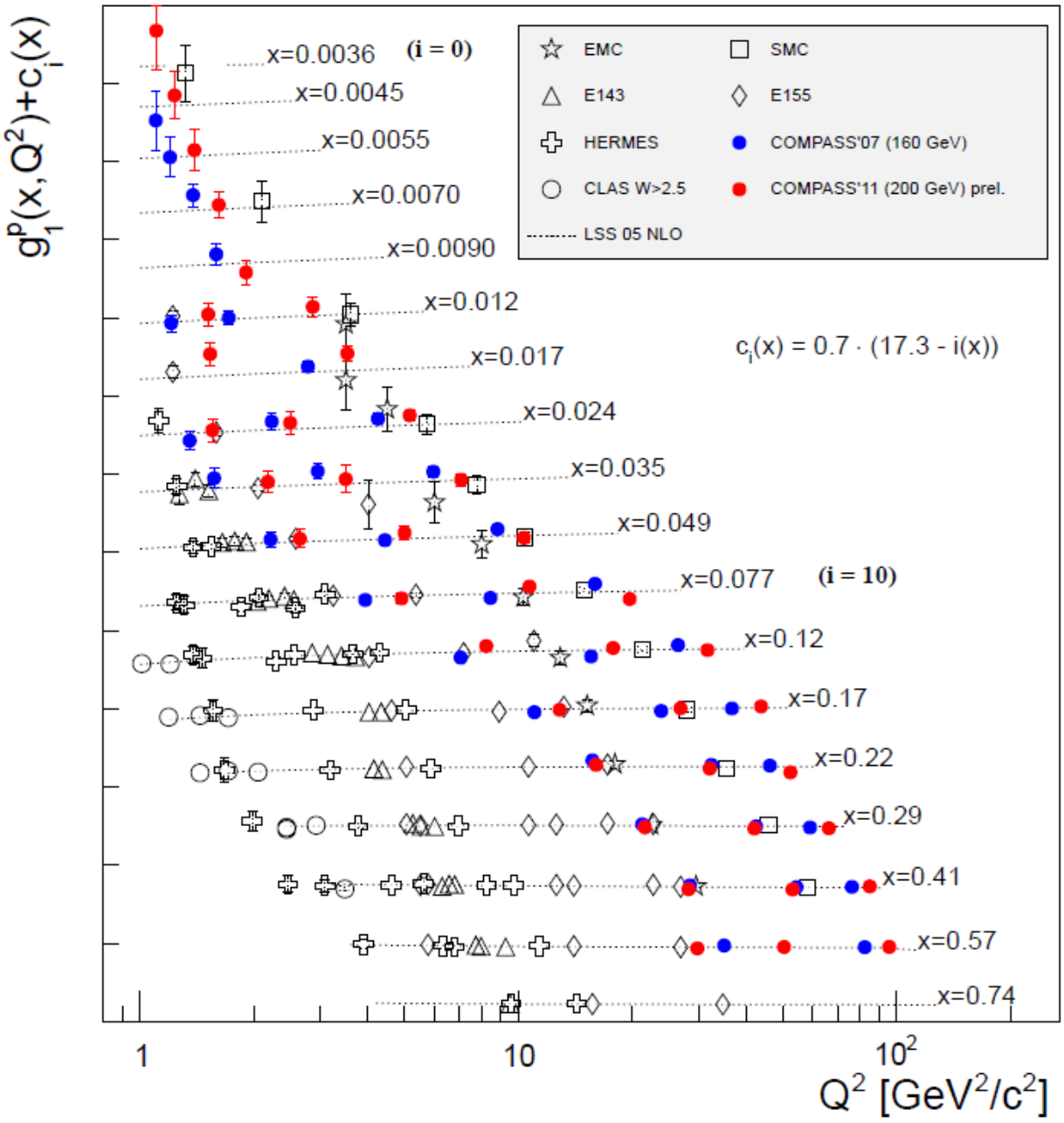
160 GeV

200 GeV

g_1^p: PLB690(2010)466


Q^2 [GeV^2/c^2]
10^2
10
1
COMPASS 200 GeV
COMPASS 160 GeV
10^{-2}
10^{-1}
1
x_{Bj}


xg_1^p
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
COMPASS 200 GeV preliminary
COMPASS 160 GeV
SMC
10^{-2}
10^{-1}
1
x_{Bj}

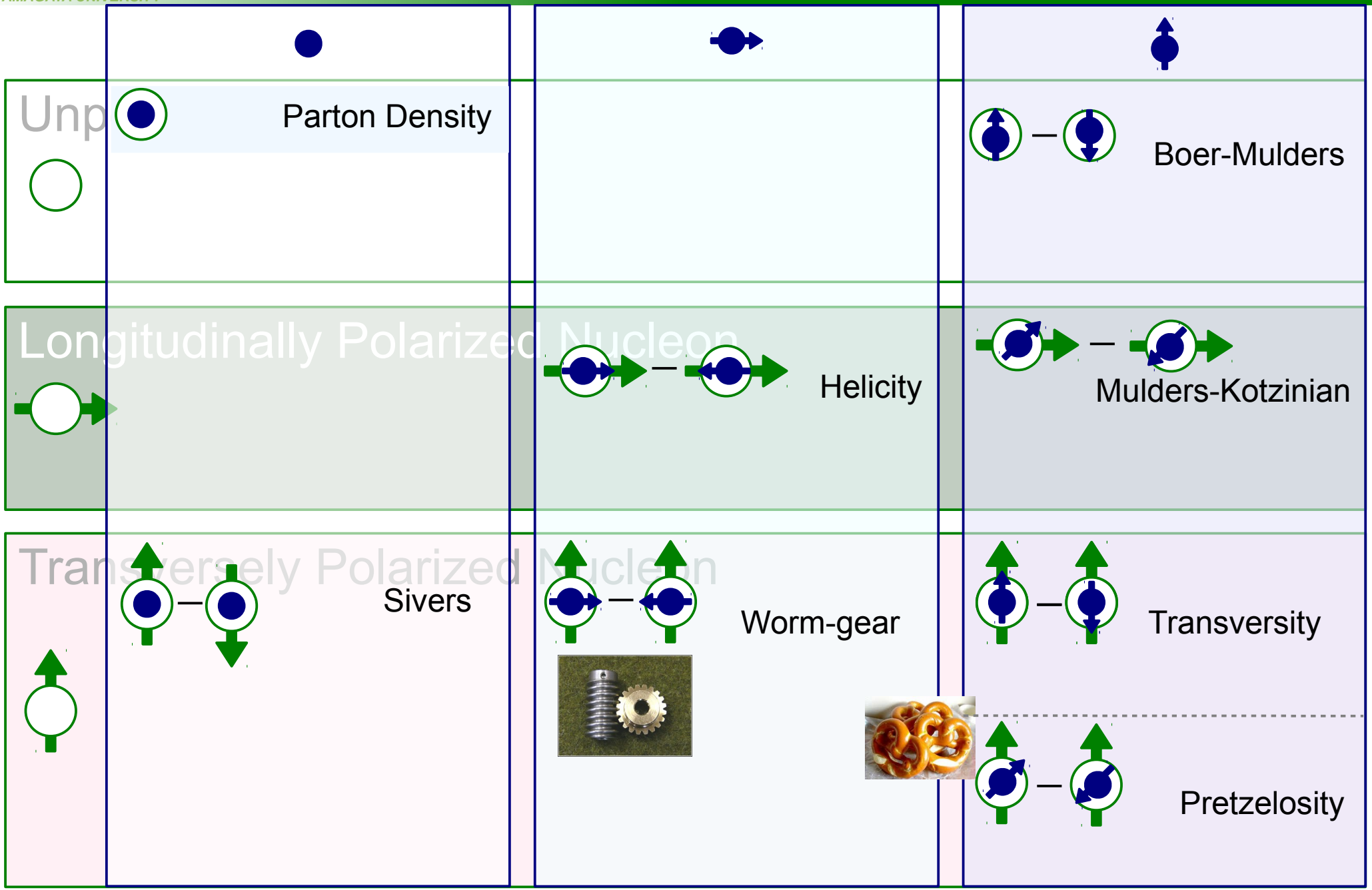


Global analysis

TMDs in COMPASS

Twist-2 TMD

YAMAGATA UNIVERSITY



SIDIS with T-pol. target

YAMAGATA UNIVERSITY

Year	Material	Polarization
2002	^{6}LiD	L, T
2003		
2004		
2005		
2006		L
2007	NH_3	L, T
2008	hadron program	
2009		
2010	NH_3	T
2011		L

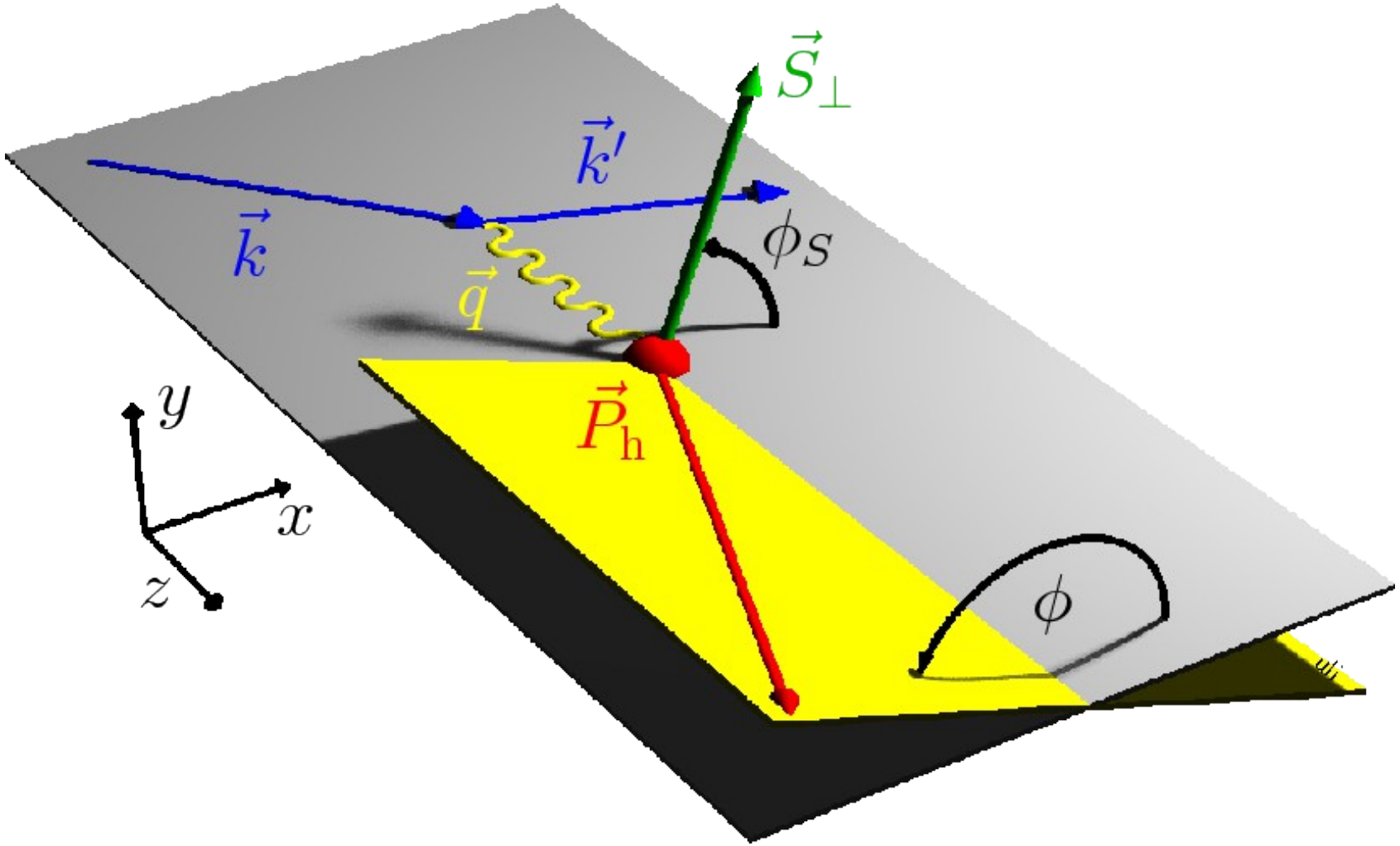
Target \ Parton	U	L	T
U	Density		Boer-Mulders
L		Helicity	Mulders-Kotzinian
T	Sivers	Worm-Gear	Transversity
			Pretzelosity

with pol. beam

Azimuthal angles in SIDIS

YAMAGATA UNIVERSITY

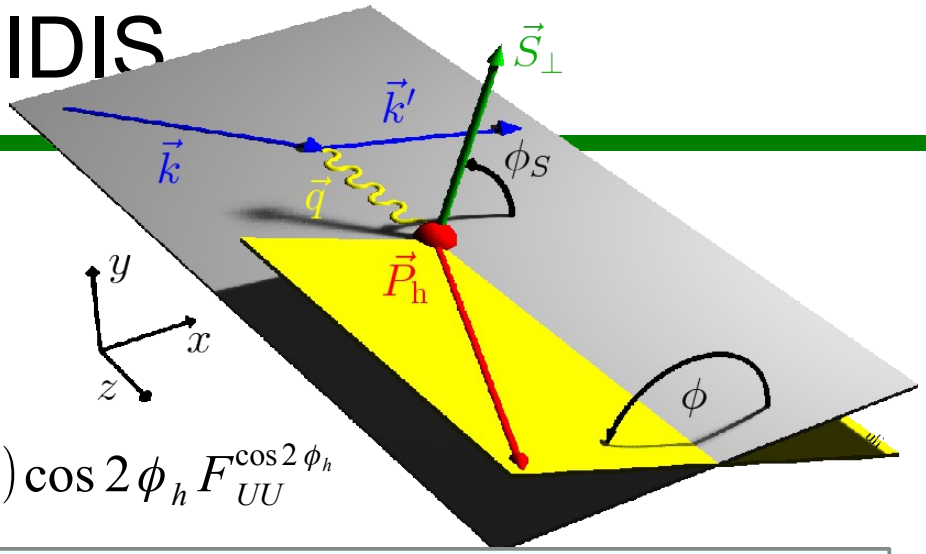
$$l + N \rightarrow l' + h + X$$



Azimuthal amplitudes in SIDIS

YAMAGATA UNIVERSITY

$$l + N \rightarrow l' + h + X$$



$$d\sigma \propto$$

$$\frac{1+(1-y)^2}{2} F_{UU} + (2-y)\sqrt{1-y}\cos\phi_h F_{UU}^{\cos\phi_h} + (1-y)\cos 2\phi_h F_{UU}^{\cos 2\phi_h}$$

$$+ S_L\left[(1-y)\sin 2\phi_h F_{UL}^{\sin 2\phi_h} + (2-y)\sqrt{1-y}\sin\phi_h F_{UL}^{\sin\phi_h}\right]$$

$$+ S_L P_z^l\left[\frac{1-(1-y)^2}{2} F_{LL} + y\sqrt{1-y}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

$$+ S_T\left[\frac{1+(1-y)^2}{2}\sin(\phi_h - \phi_S) F_{UT}^{\sin(\phi_h-\phi_S)}\right.$$
$$+ (1-y)\left(\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}\right)$$
$$\left. + (2-y)\sqrt{1-y}\left(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi - \phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\right)\right]$$

$$+ S_T P_z^l\left[\frac{1-(1-y)^2}{2}\cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + y\sqrt{1-y}\left(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi - \phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\right)\right]$$

TMD in SIDIS

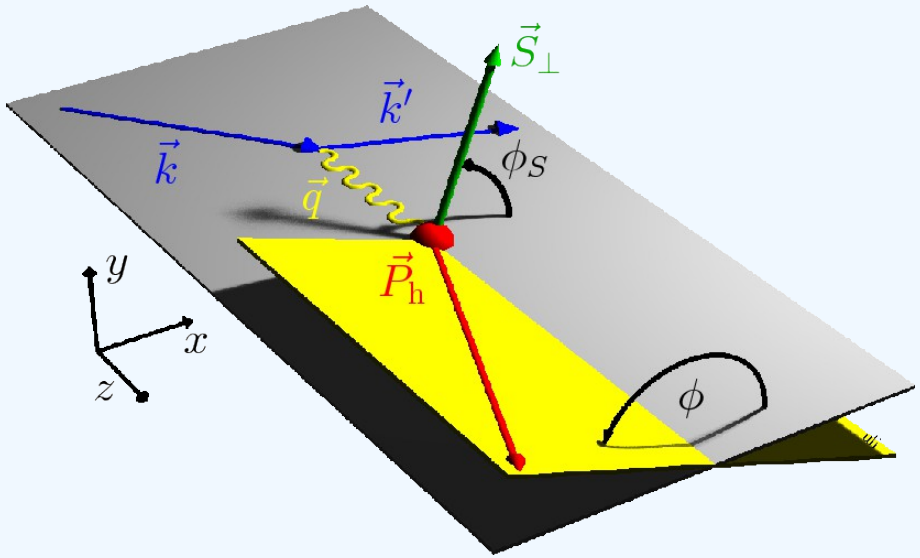
YAMAGATA UNIVERSITY

with pol. beam

Unp

Lon

Transversely Polarized Nucleon



$h_1^\perp$ Boer-Mulders

$h_1^\perp \otimes H_1^\perp \sim \cos 2\phi$

Mulders-Kotzinian

$h_{1L}^\perp \otimes H_1^\perp \sim \sin 2\phi$

Sivers

$f_{1T}^\perp \otimes D_1 \sim \sin(\phi - \phi_S)$

Worm-gear

$g_{1T} \otimes D_1 \sim \cos(\phi - \phi_S)$

Transversity

$h_{1T} \otimes H_1^\perp \sim \sin(\phi + \phi_S)$

Pretzelosity

$h_{1T}^\perp \otimes H_1^\perp \sim \sin(3\phi - \phi_S)$

TMD related publication from

YAMAGATA UNIVERSITY

Year	Material	Polarization
2002	^{6}LiD	L, T
2003		
2004		
2005		
2006		L
2007	NH_3	L, T
2008	hadron program	
2009		
2010	NH_3	T
2011		L

Other azimuthal asymmetries:
PLB 713 (2012) 10

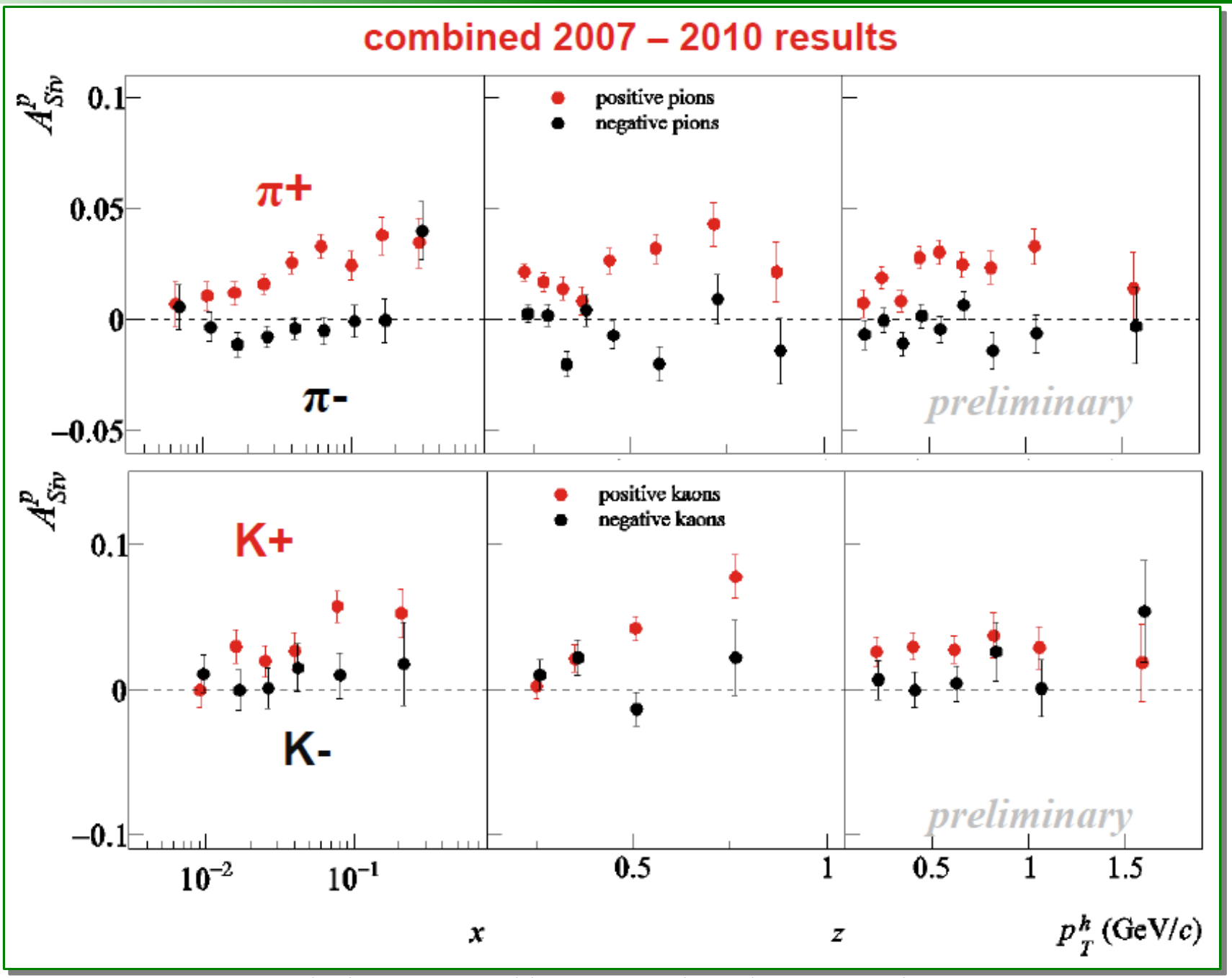
h-pair: PLB 713 (2012) 10

A_{siv}, A_{coll}: $\pi^{+,-}$, $K^{+,-}$
PLB 673 (2009) 127–135

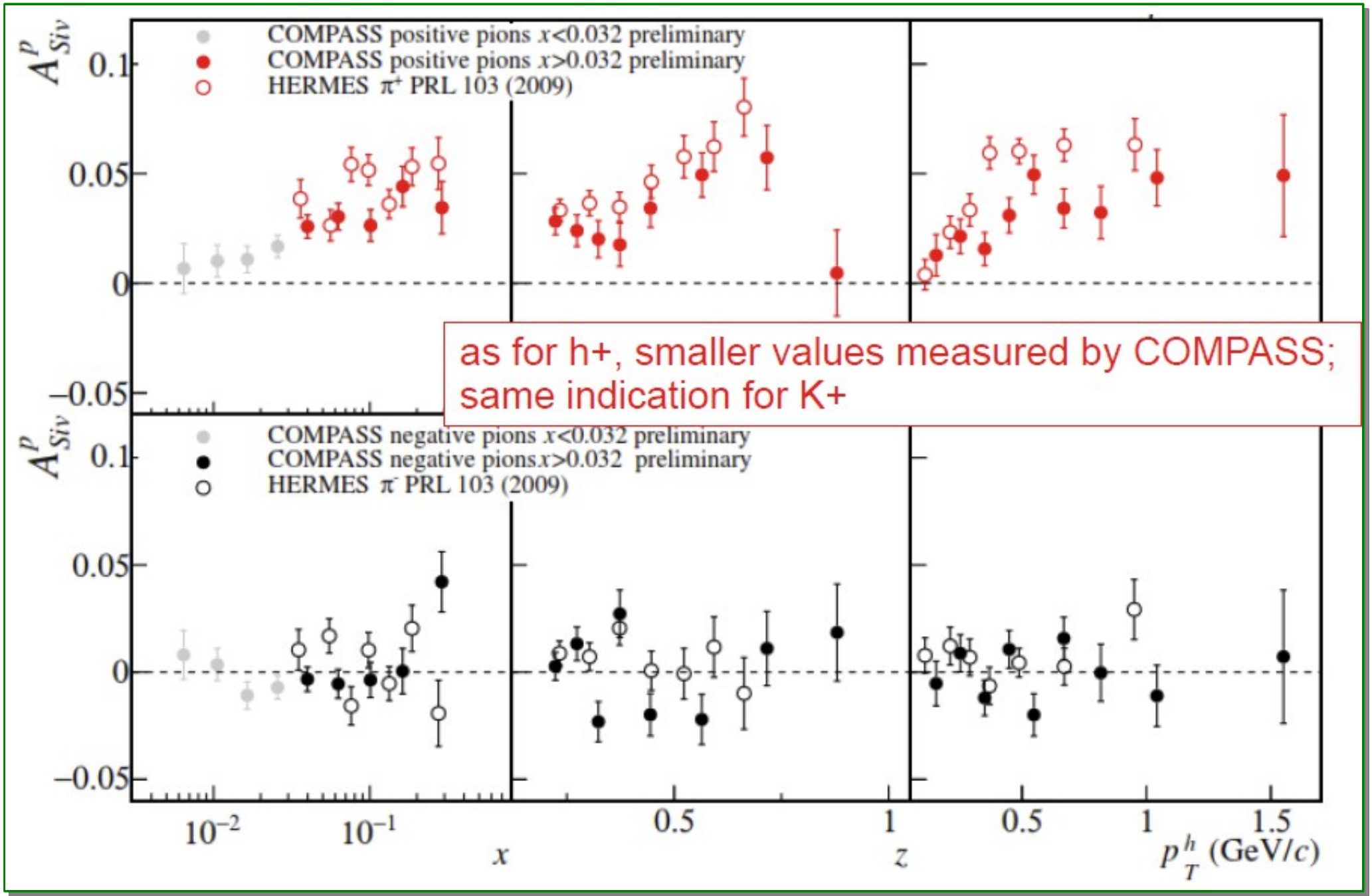
A_{siv}, A_{col} :$h^{+,-}$ PLB 692 (2010) 240–246

A_{Siv}: $h^{+,-}$ PLB 717 (2012) 383
$A_{coll:}$: $h^{+,-}$ PLB 717 (2012) 376

Sivers asymmetry

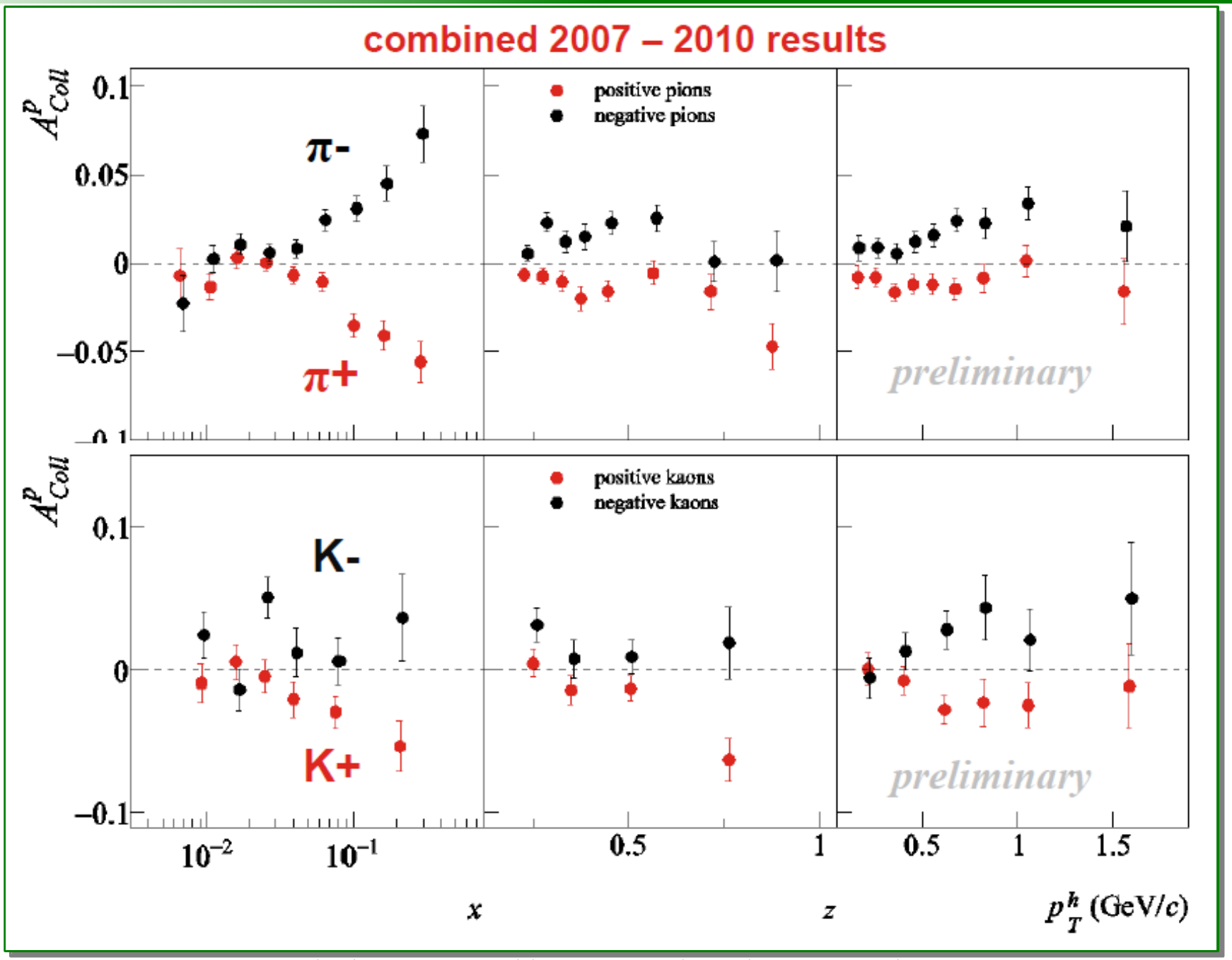


Sivers asymmetry

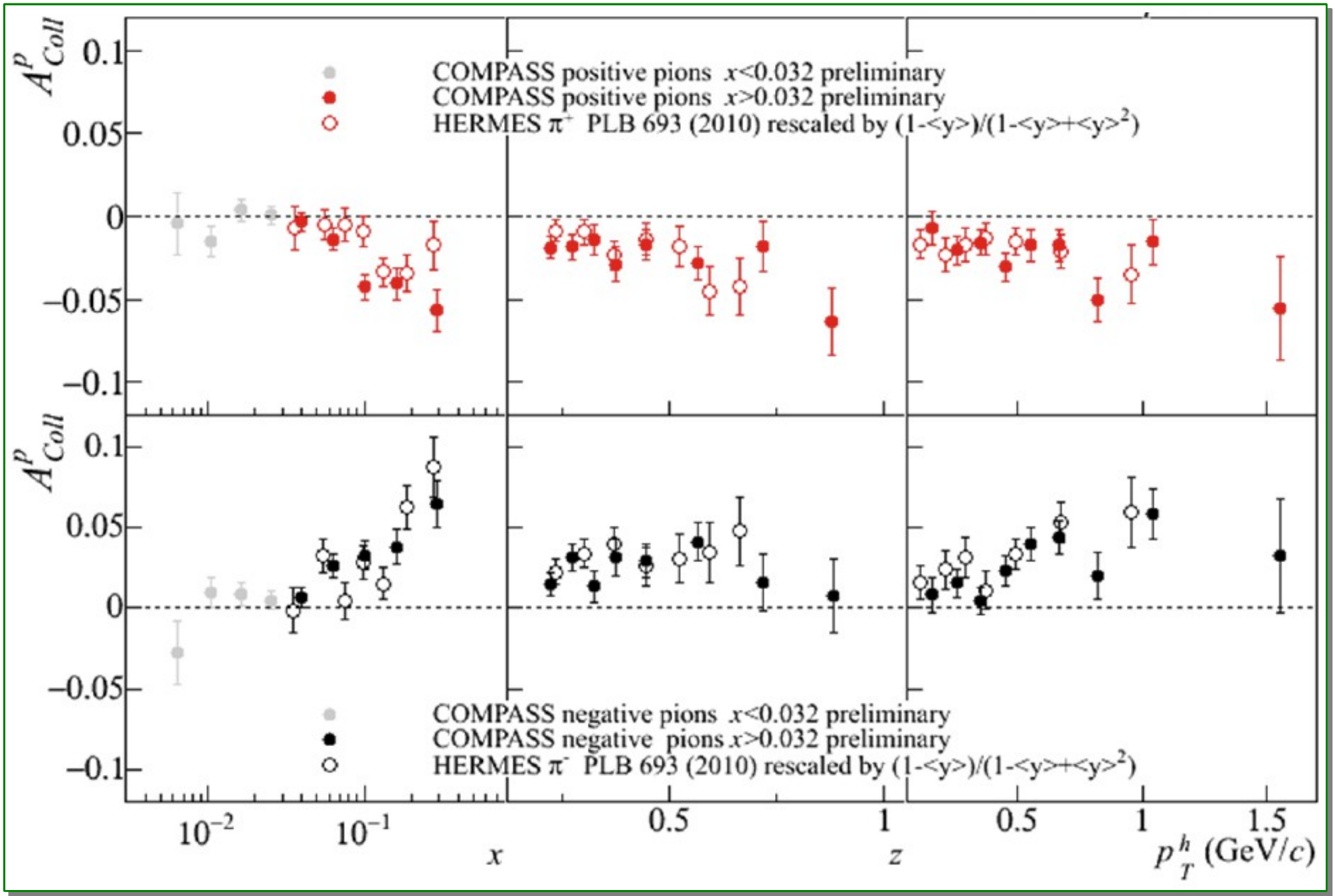


as for h+, smaller values measured by COMPASS; same indication for K+

Collins asymmetry



Collins asymmetry



Extraction of transversity

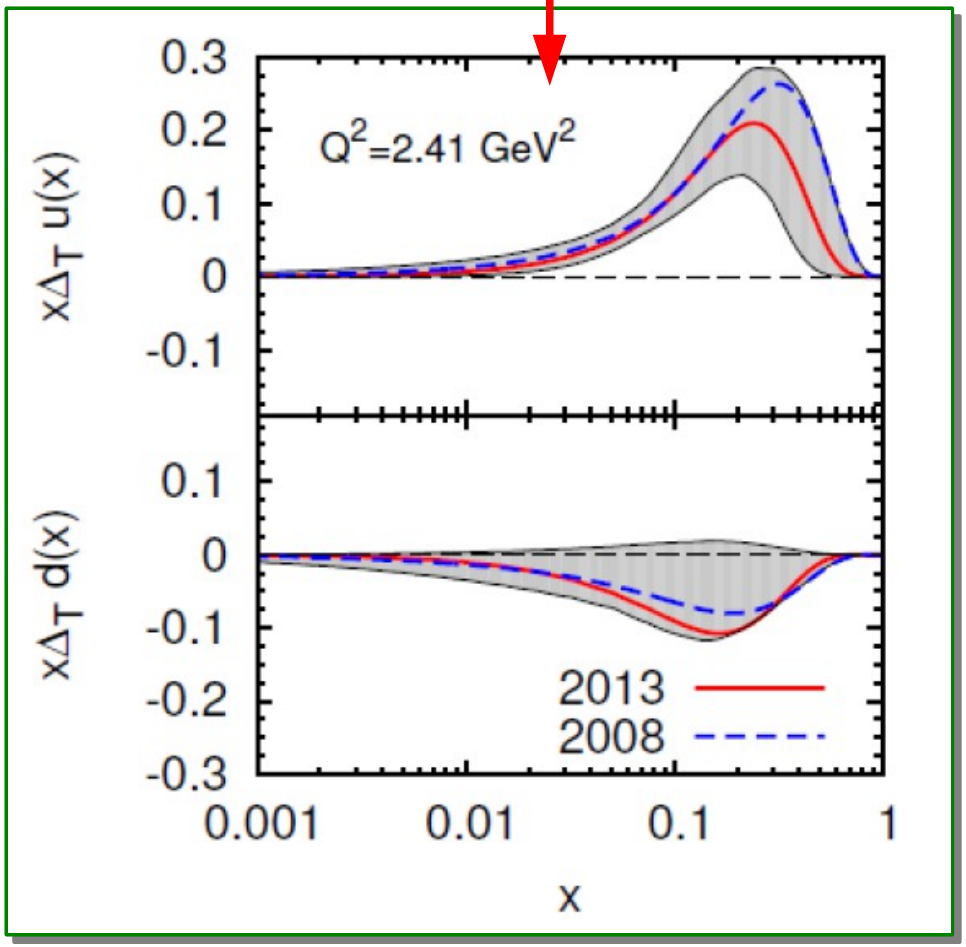
YAMAGATA UNIVERSITY

M. Anselmino et al., arXiv:1303.3822

HERMES, COMPASS

$$A_{UT}^{\sin(\phi+\phi_S)} \sim h_{1T} \otimes H_1^{\perp}$$

Belle

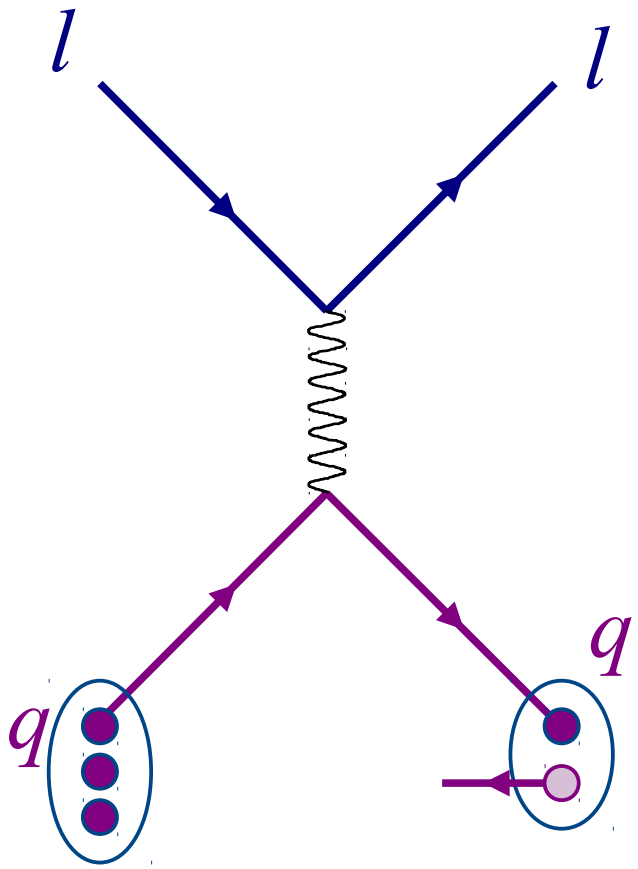


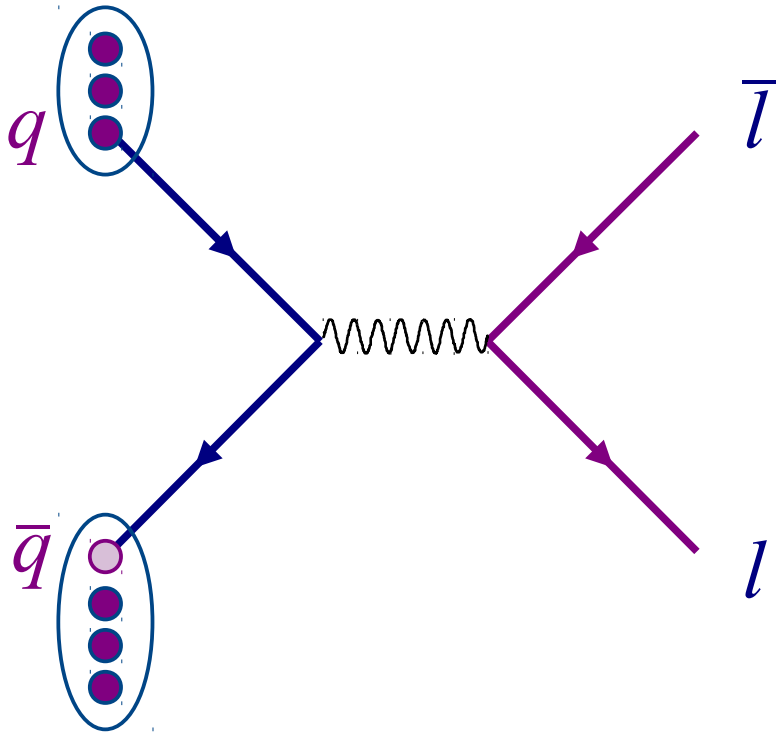
COMPASS II

2012 ~ 2016

SIDIS and Drell-Yan

YAMAGATA UNIVERSITY





Chiral-odd TMD in SIDIS and Drell-Yan

Azimuthal amplitudes (Single T-pol. DY)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4q\,\mathrm{d}\Omega} = \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U\Big\{\Big(1 + D_{[\sin^2\theta]}\,A_U^{\cos 2\phi}\cos 2\phi\Big)$$

$$\overset{\text{LO}}{=} \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U\Big\{\Big(1 + D_{[\sin^2\theta]}\,A_U^{\cos 2\phi}\cos 2\phi\Big)$$

$$+ |\mathbf{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)$$

$$+ A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\},$$

$$+ D_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) + A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\}$$

In LO QCD parton model

COMPASS II (DY)

π induced DY with T-pol. target

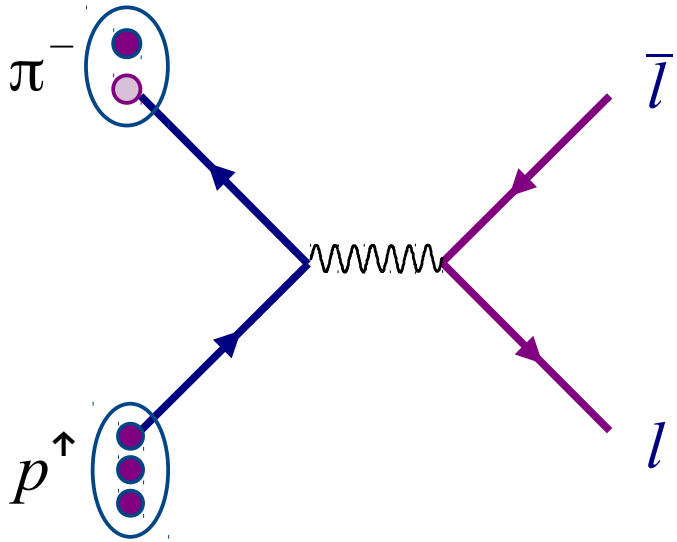
$$\pi^- + p^\uparrow \rightarrow \mu^+ + \mu^- + X$$

TMDs in COMPASS II (DY)

YAMAGATA UNIVERSITY

$$\pi^- + p^\uparrow \rightarrow \mu^+ + \mu^- + X$$

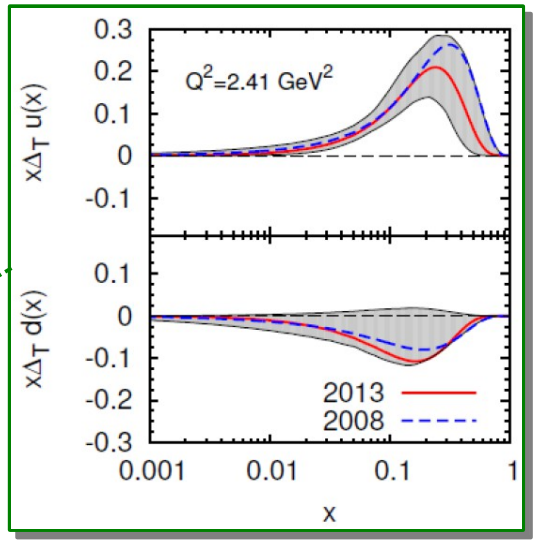
$$\begin{aligned}\frac{d\sigma}{d^4q\,d\Omega} \overset{LO}{=} & \frac{\alpha_{em}^2}{F\,q^2}\hat{\sigma}_U\Big\{\Big(1 + D_{[\sin^2\theta]}\,A_U^{\cos 2\phi}\cos 2\phi\Big) \\ & + |\mathbf{S}_T|\Big[A_T^{\sin\phi_S}\sin\phi_S + D_{[\sin^2\theta]}\Big(A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S) \\ & + A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\Big)\Big]\Big\},\end{aligned}$$



From DY, SIDIS

PDF set (MRSS,GRVPI)

- $A_U^{\cos 2\phi} : (BM)_\pi \otimes (BM)_P$
- $A_T^{\sin\phi_S} : (f_1)_\pi \otimes (Sivers)_P$
- $A_T^{\sin(2\phi+\phi_S)} : (BM)_\pi \otimes (Pretz.)_P$
- $A_T^{\sin(2\phi-\phi_S)} : (BM)_\pi \otimes (Trans.)_P$



TMDs in COMPASS-DY

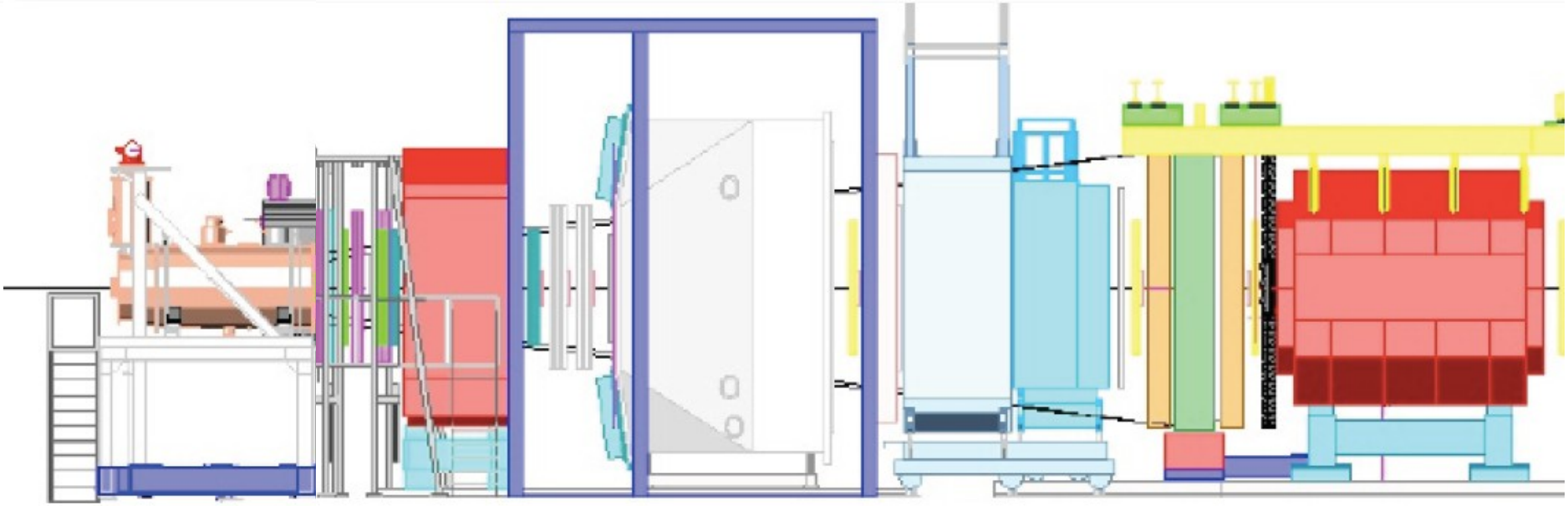
- $A_U^{\cos 2\phi} : (BM)_\pi \otimes (BM)_P$
- $A_T^{\sin \phi_S} : (f_1)_\pi \otimes (Sivers)_P$
- $A_T^{\sin(2\phi+\phi_S)} : (BM)_\pi \otimes (\mathrm{Pr}etz.)_P$
- $A_T^{\sin(2\phi-\phi_S)} : (BM)_\pi \otimes (Trans.)_P$

Sign of naïve T-odd TMD

$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$$
$$h_1^{\perp}(DY) = -h_1^{\perp}(SIDIS)$$

COMPASS II: Drell-Yan set-up

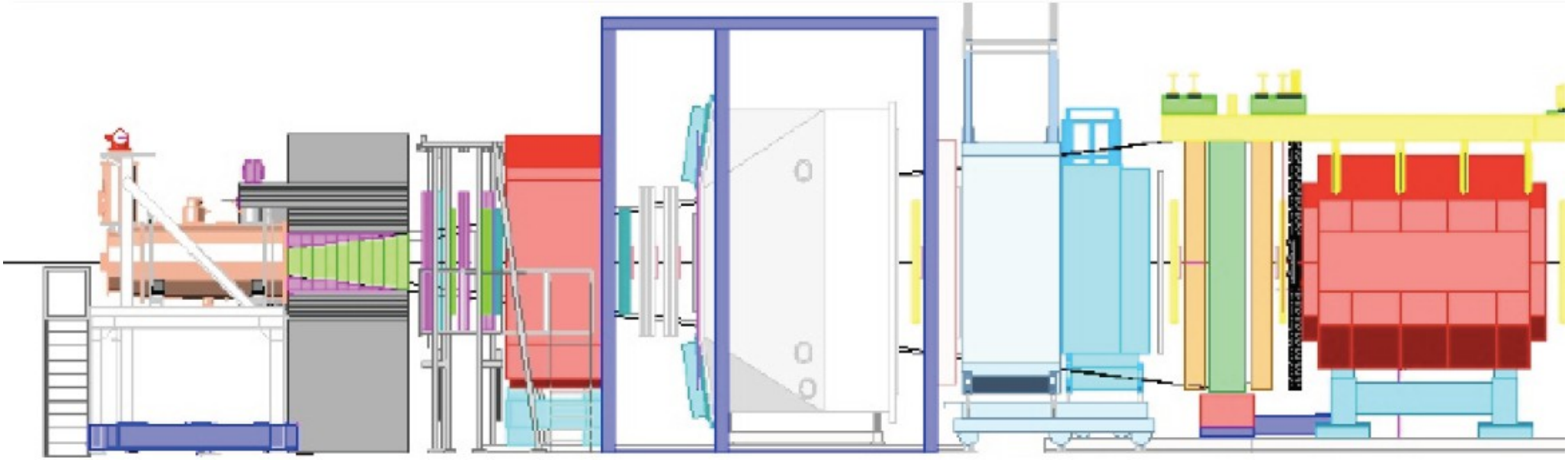
YAMAGATA UNIVERSITY



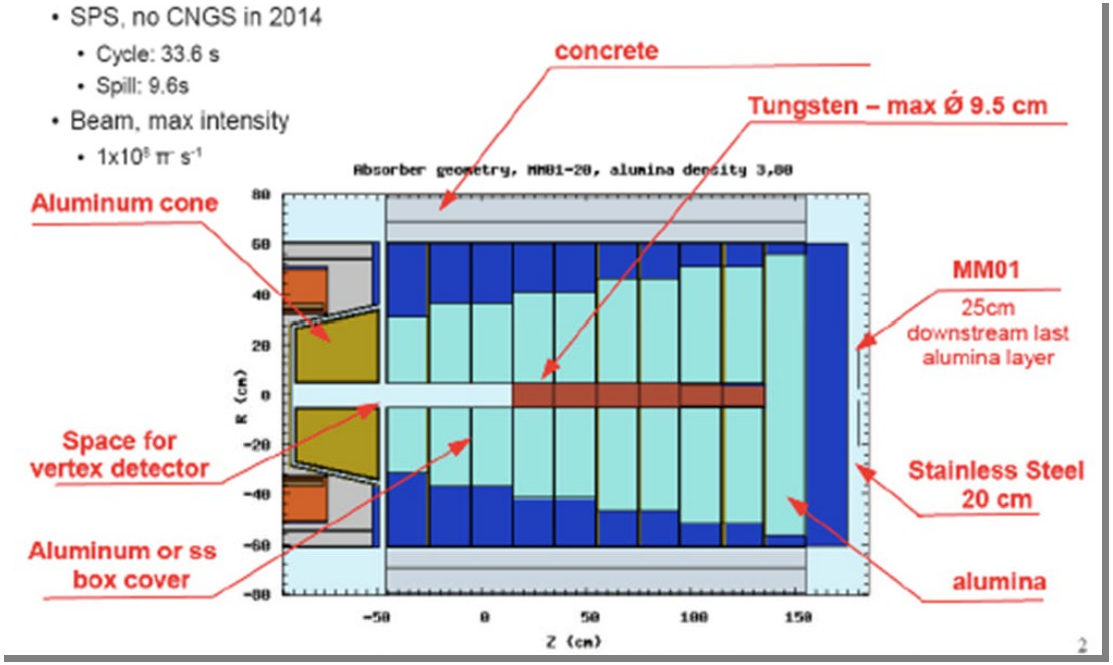
- 160 GeV π^-, ~ 10^8 particles/s
- T-pol. NH_3 in the frozen spin mode
  has to be moved upstream, by 2.2 m.
- hadron absorber in the gap
- New SciFi trackers: beam telescope & vertex

Hadron absorber

YAMAGATA UNIVERSITY



- SPS, no CNGS in 2014
  - Cycle: 33.6 s
  - Spill: 9.6s
- Beam, max intensity
  - $1x10^{3}$ π^{-} s^{-1}

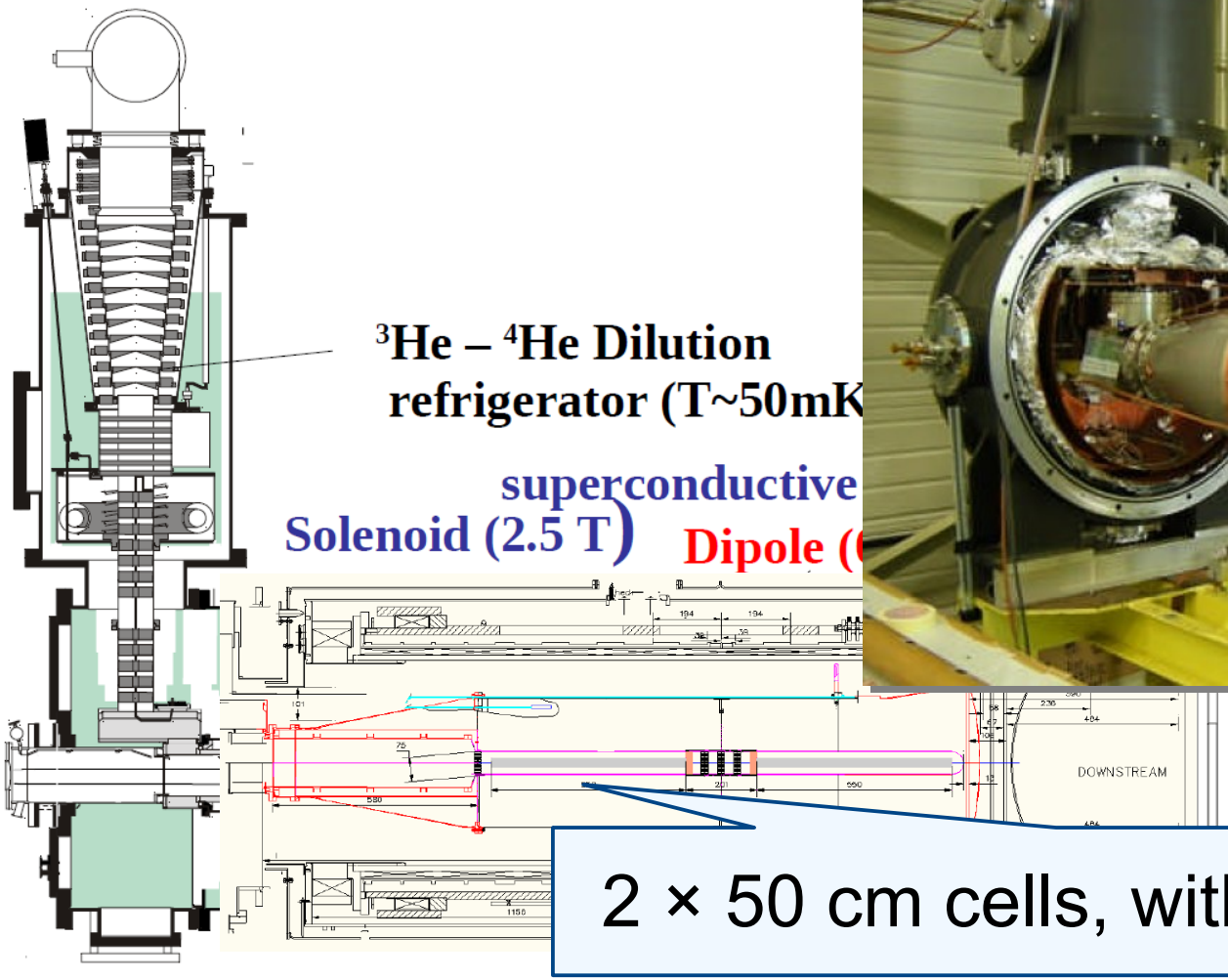


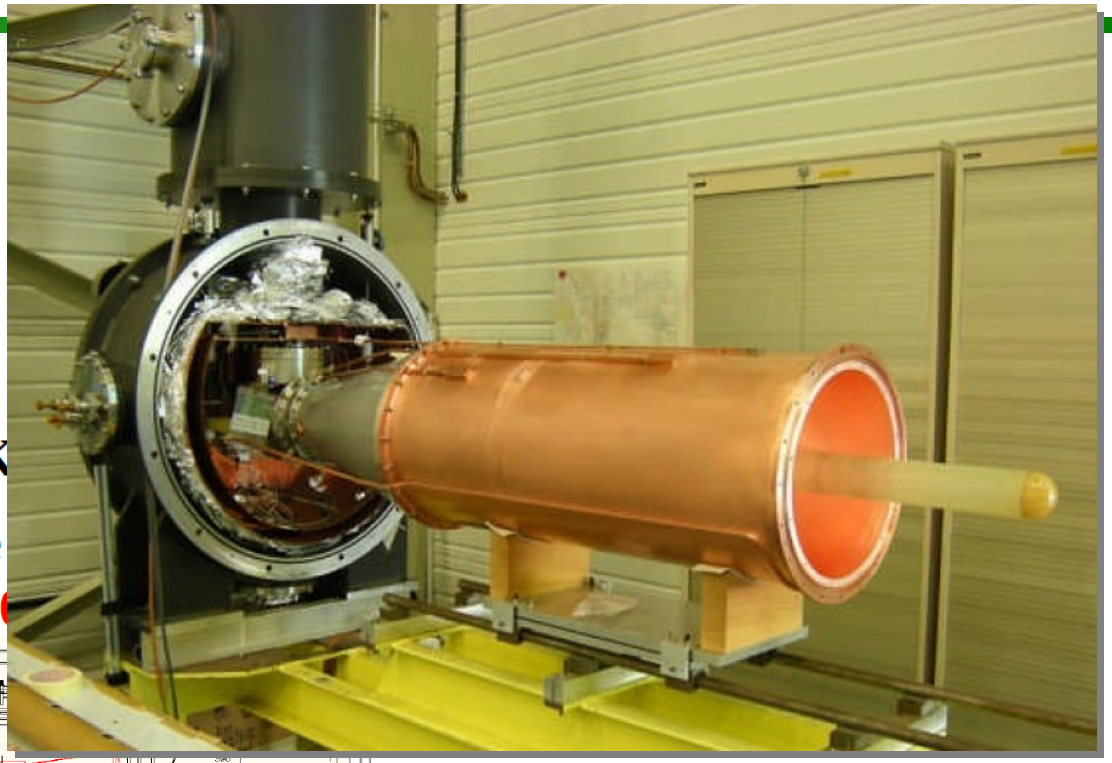
Structure of the hadron absorber:

- 120 cm tungsten beam plug
- aluminium conical part
- 200 cm alumina (Al_2O_3)
- non-magnetic stainless steel peripheral part

COMPASS II: Pol. Target for DY

YAMAGATA UNIVERSITY





2 × 50 cm cells, with 20 cm space.

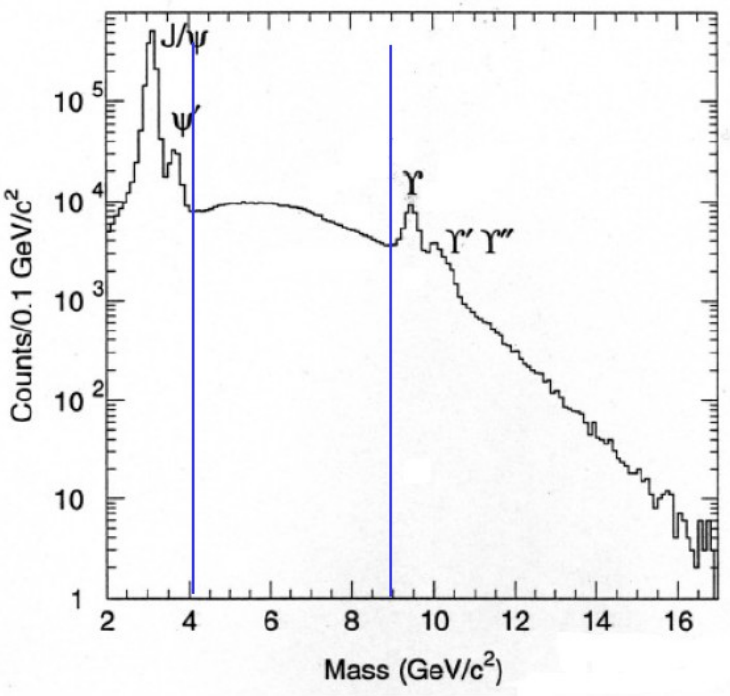
⇨ New target cell, μ-wave guide & cabity

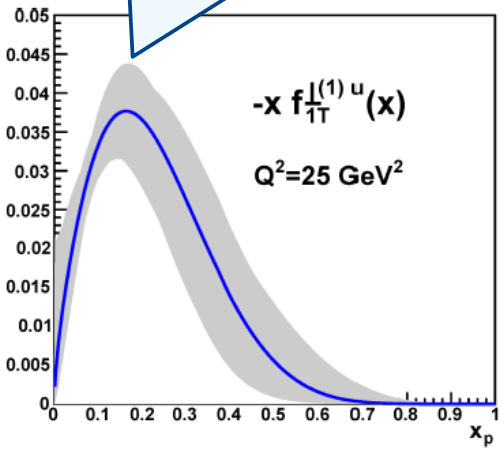
COMPASS II: DY acceptance

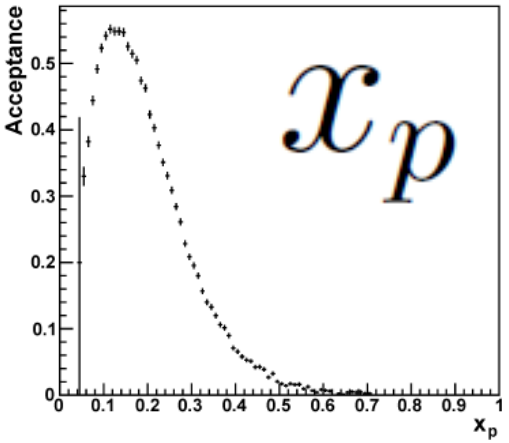
YAMAGATA UNIVERSITY

M. Anselmino et al., EPJ A39 (2009) 89

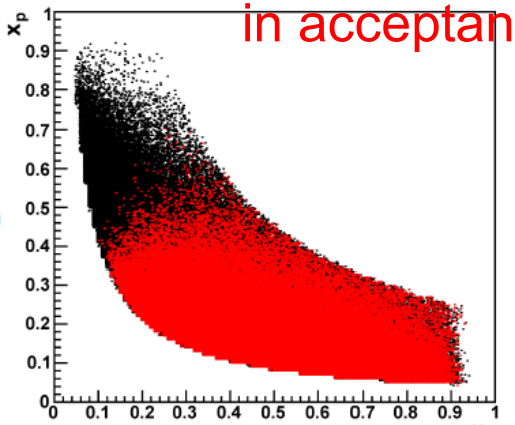
$P_\pi = 190$ GeV/c



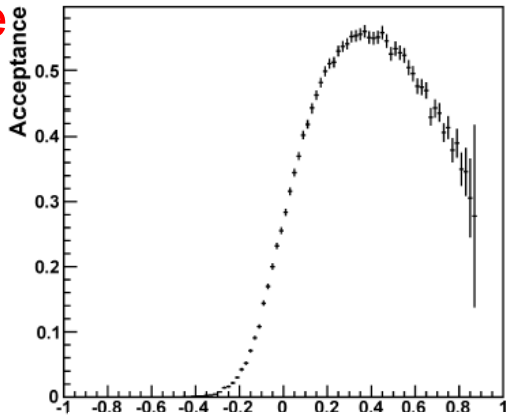




x_p



in acceptance



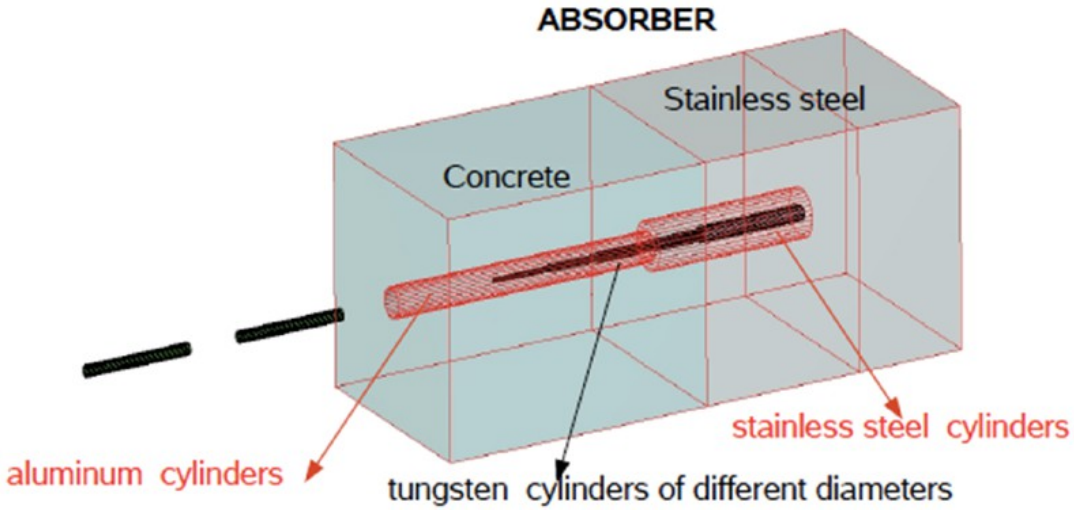
x_π

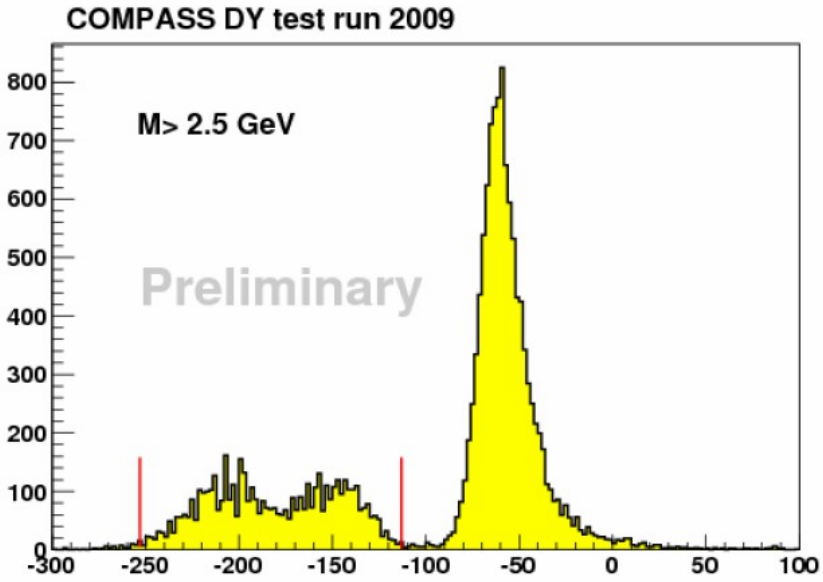
$x_F = x_\pi - x_p$

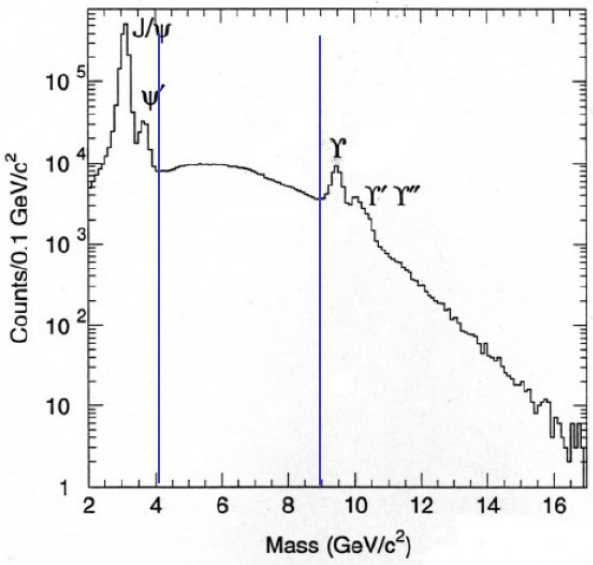
$4\ \mathrm{GeV}/c^2 < M_{\mu^+\mu^-} < 9\ \mathrm{GeV}/c^2$

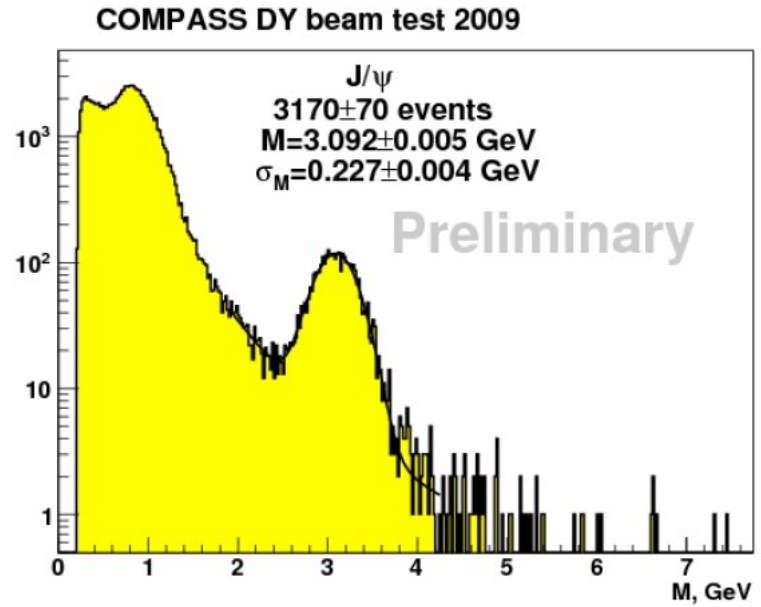
COMPASS II: DY test run in 2009

YAMAGATA UNIVERSITY



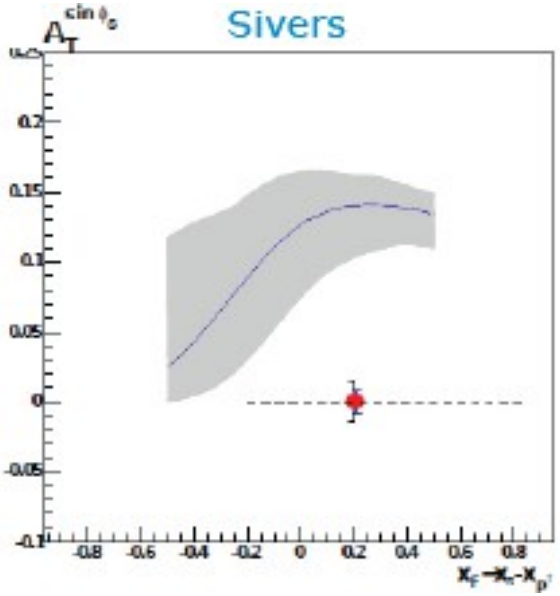


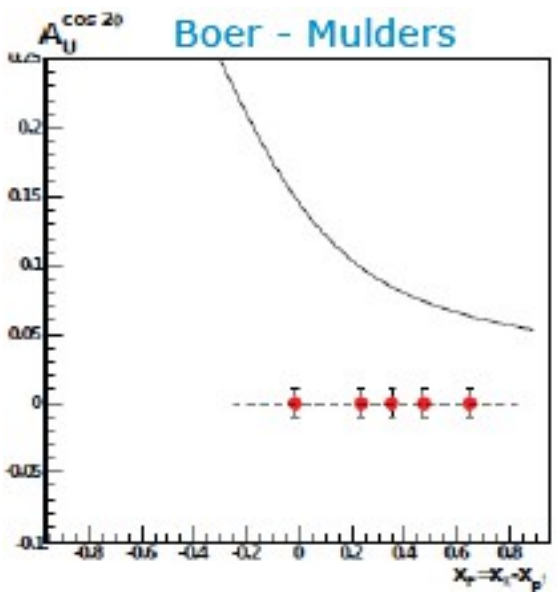




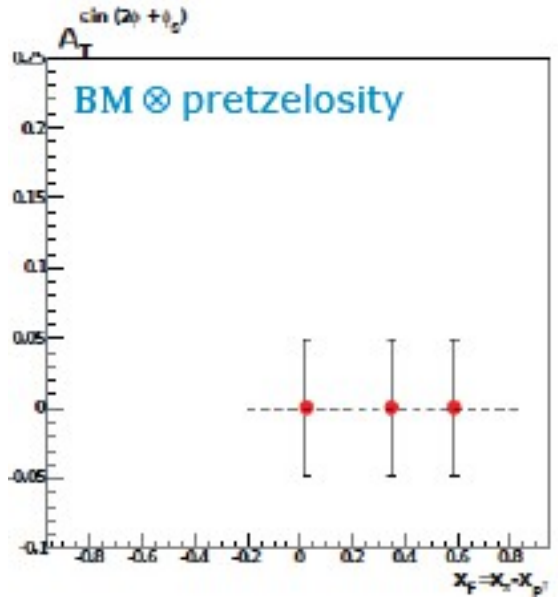
COMPASS II: Drell-Yan program

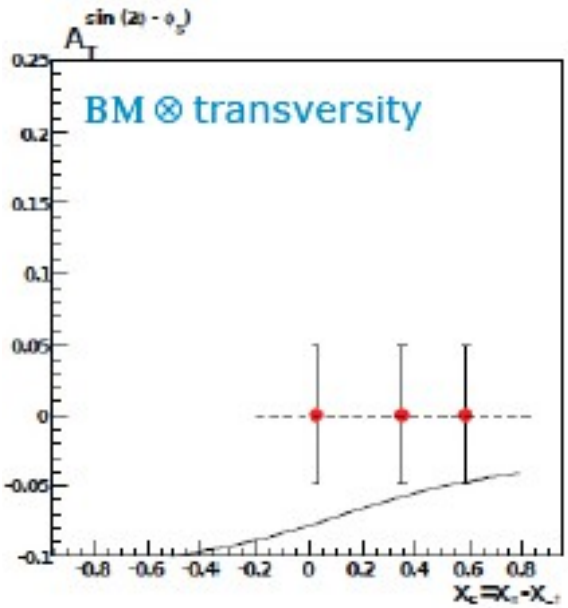
YAMAGATA UNIVERSITY





2 years of data taking
DY 4.-9. GeV/c^2





- 1 year beam time (2014 – 2015)

List of pol. Drell-Yan programs

YAMAGATA UNIVERSITY

Facility	Type		s (GeV^2)	Timeline
COMPASS	fixed target	$\pi^{\pm} p^{\Uparrow}$	357	2014
RHIC (STAR,PHENIX)	collider	$p^{\Uparrow} p$	200^2	>2016
Fermilab (SeaQuest)	fixed target	$p^{\Uparrow\Rightarrow} H$, $pH^{\Uparrow\Rightarrow}$	234	>2015
J-PARC	fixed target	$pp^{\Uparrow}$, $\pi p^{\Uparrow}$	$60-100$	>2018
Fair (PAX)	collider	$\overline{p}^{\Uparrow} p^{\Uparrow}$	200	>2018
NICA	collider	$p^{\Uparrow} p^{\Uparrow}$, $d^{\Uparrow} d^{\Uparrow}$	144, 676	>2018

New programs (COMPASS II)

approved by CERN Research B

2014 – 2015
(1y beam time)

- Polarized Drell-Yan measurement
  TMD PDFs
  π^- beam with polarized proton target
- GPD measurement
  Transverse imaging
  $\mu^+ \mu^-$ beam with liquid hydrogen target
- Pion and Kaon polarizability
  Chiral perturbation theory
  π^-, K^- (μ^-) beam with nucleus target

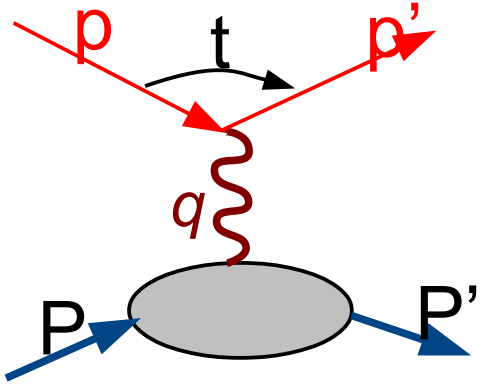
2016 – 2017
(2y beam time)

With a upgraded COMPASS spectrometer

Hard exclusive production & GPD

YAMAGATA UNIVERSITY

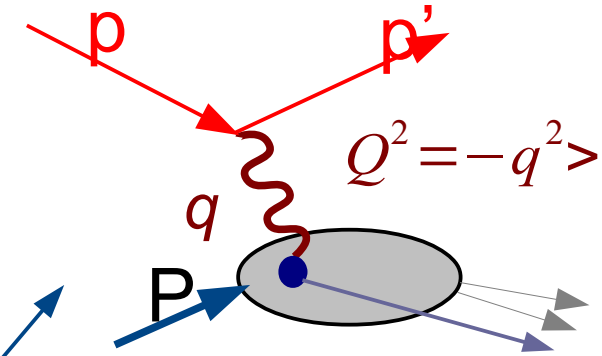
Elastic scattering



Form Factor: F(t), G(t)

$$\int_{-1}^{1} dx$$

Deep Inelastic Scattering

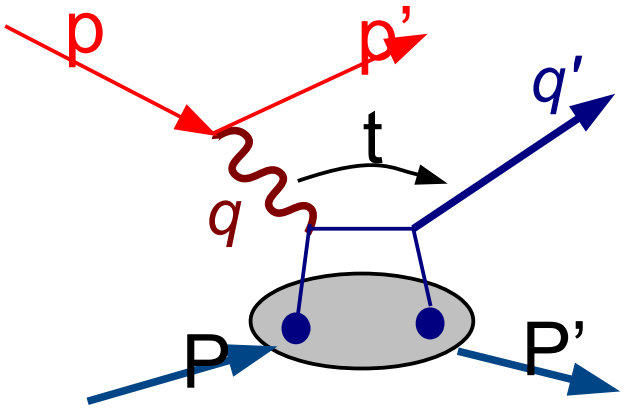


$Q^2 = -q^2 > 1\ \mathrm{GeV}^2$

Parton distribution: **q(x), Δq(x)**

Forward limit

Hard Exclusive Production:



$$e + N \rightarrow e' + N' + \{\gamma,\ \rho,\ \pi, \ldots\}$$

Generalized Parton Distribution:

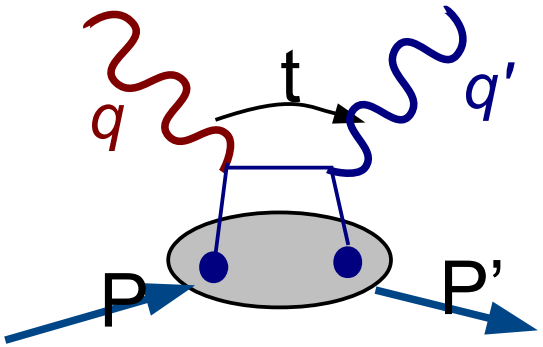
Hard Exclusive Production and GPD

YAMAGATA UNIVERSITY

Deeply Virtual Compton Scattering:

$$e + N \rightarrow e' + N' + \gamma$$

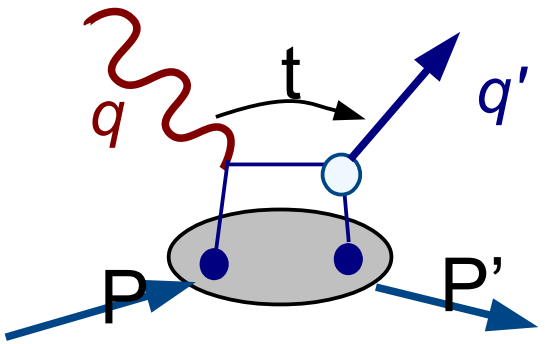
Involved GPDs: H, E, $\tilde{H}$, $\tilde{E}$
clean reaction



Hard exclusive meson production:

$$e + N \rightarrow e' + N' + \{\rho,\ \pi, \ldots\}$$

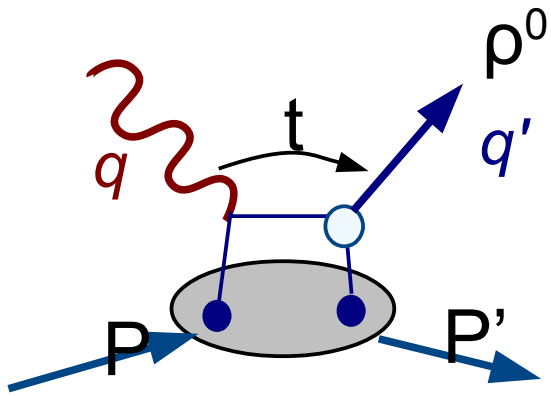
vector meson: H, E
pseudo-scalar meson: $\tilde{H}$, $\tilde{E}$
Meson amplitude involved



Exclusive ρ^0 production: COMPASS I

YAMAGATA UNIVERSITY

Year	Material	Polarization
2002	^{6}LiD	L, T
2003		
2004		
2005		
2006		L
2007	NH_3	L, T
2008	hadron program	
2009		
2010	NH_3	T
2011		L



$$A_{UT}^{\sin(\phi-\phi_S)} \Rightarrow E^u \text{ and } E^d$$

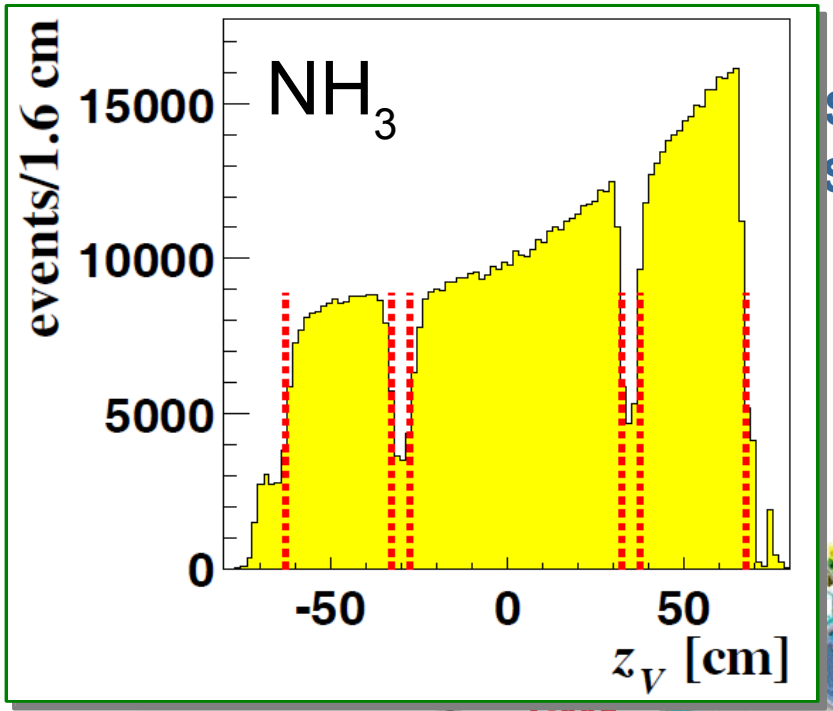
NPB 865 (2012) 1

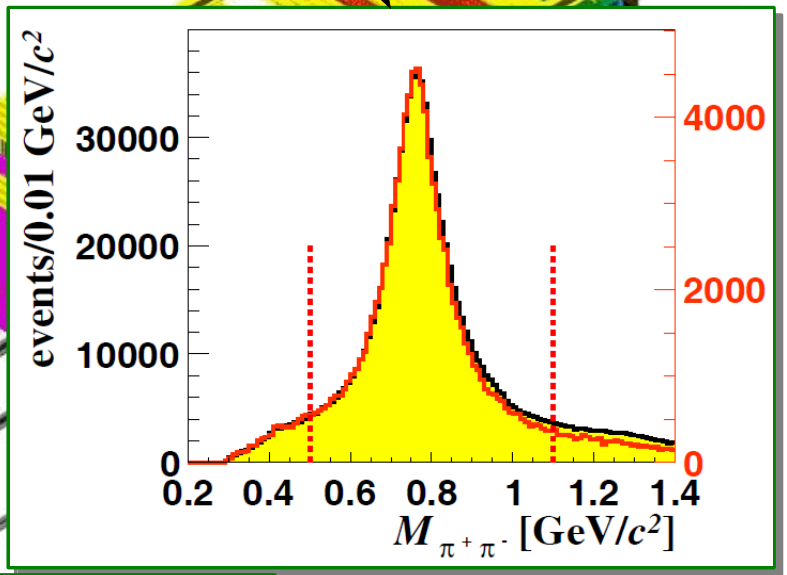
Exclusive ρ^0 production:

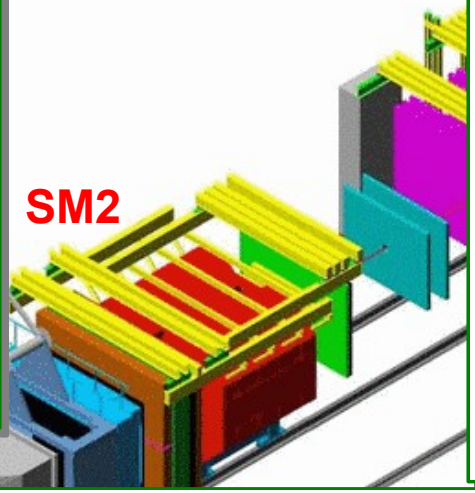
NPB 865 (2012) 1

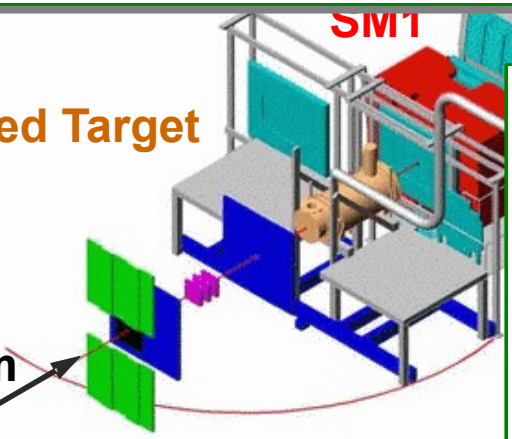
YAMAGATA UNIVERSITY

$$\mu + N \rightarrow \mu' + \pi^+ + \pi^- + X$$

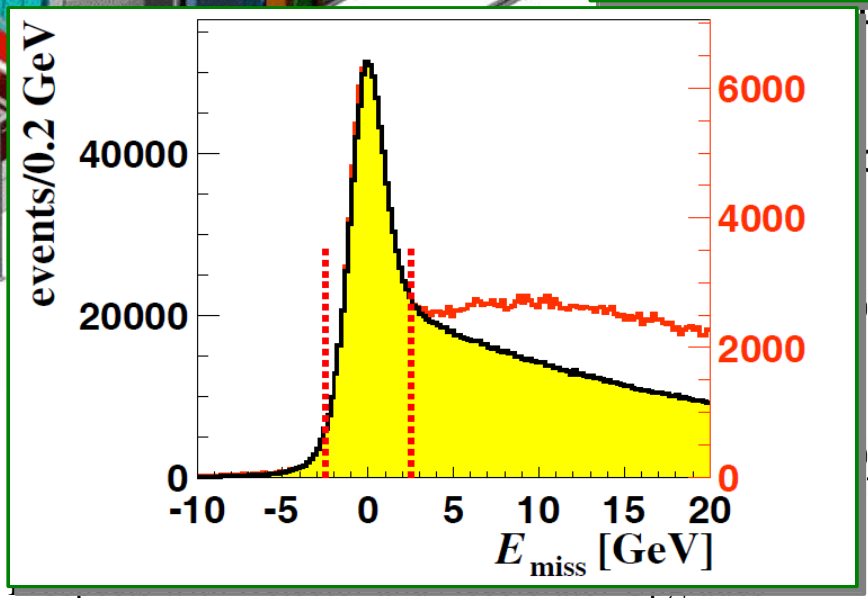


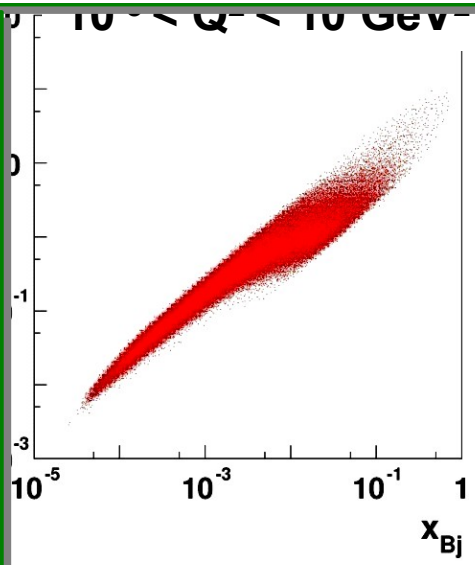




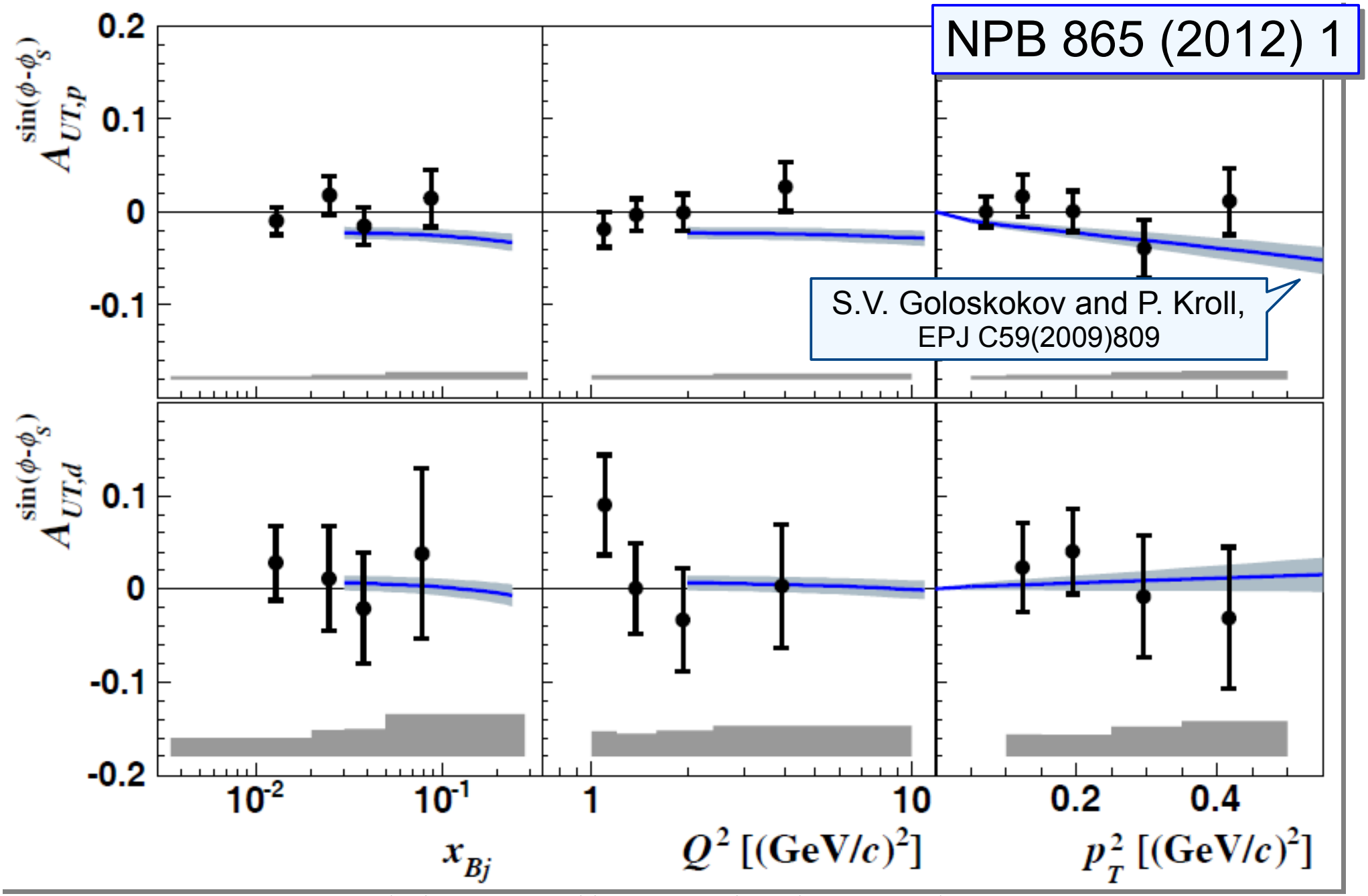


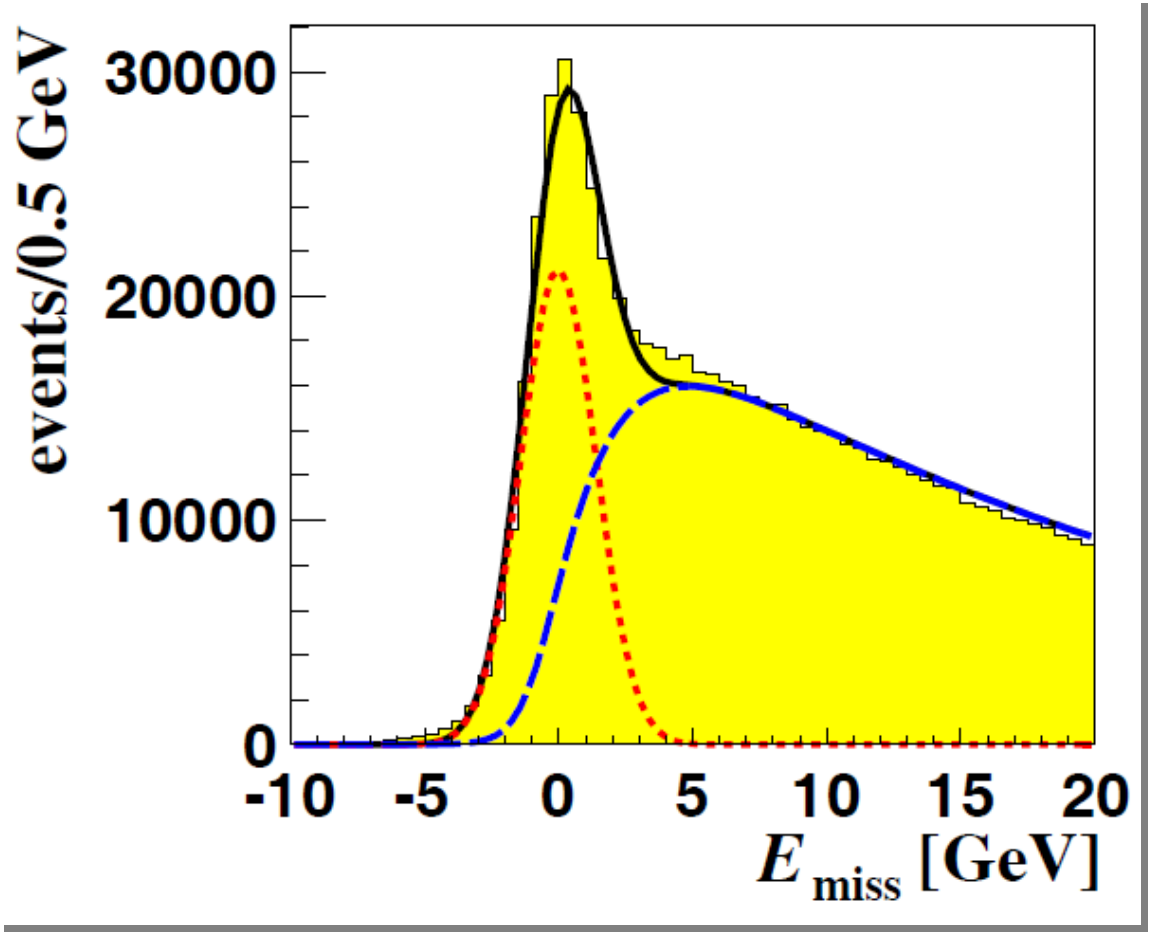
160GeV,
pol. 80%





SSA in exclusive ρ^0 production

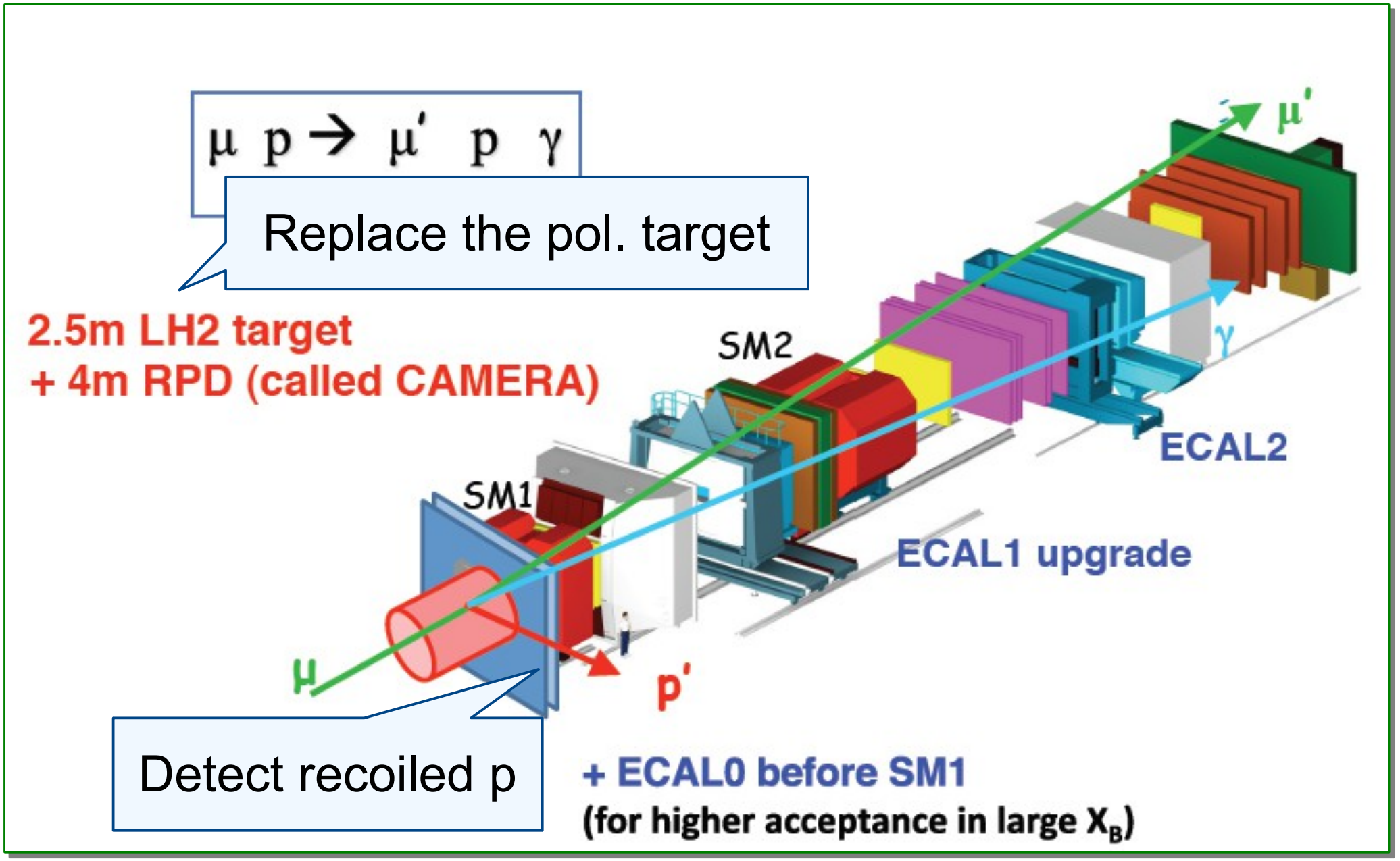




5 ~ 40% background from SIDIS

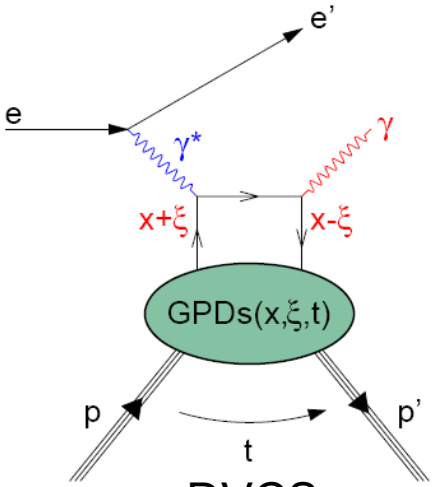
COMPASS II: GPD setup

YAMAGATA UNIVERSITY



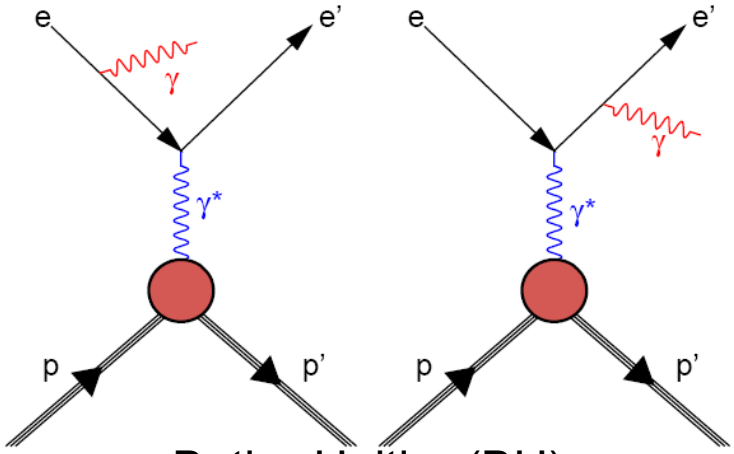
DVCS vs Bethe-Heitler

YAMAGATA UNIVERSITY



DVCS

@HERMES, JLab



Bethe-Heitler (BH)

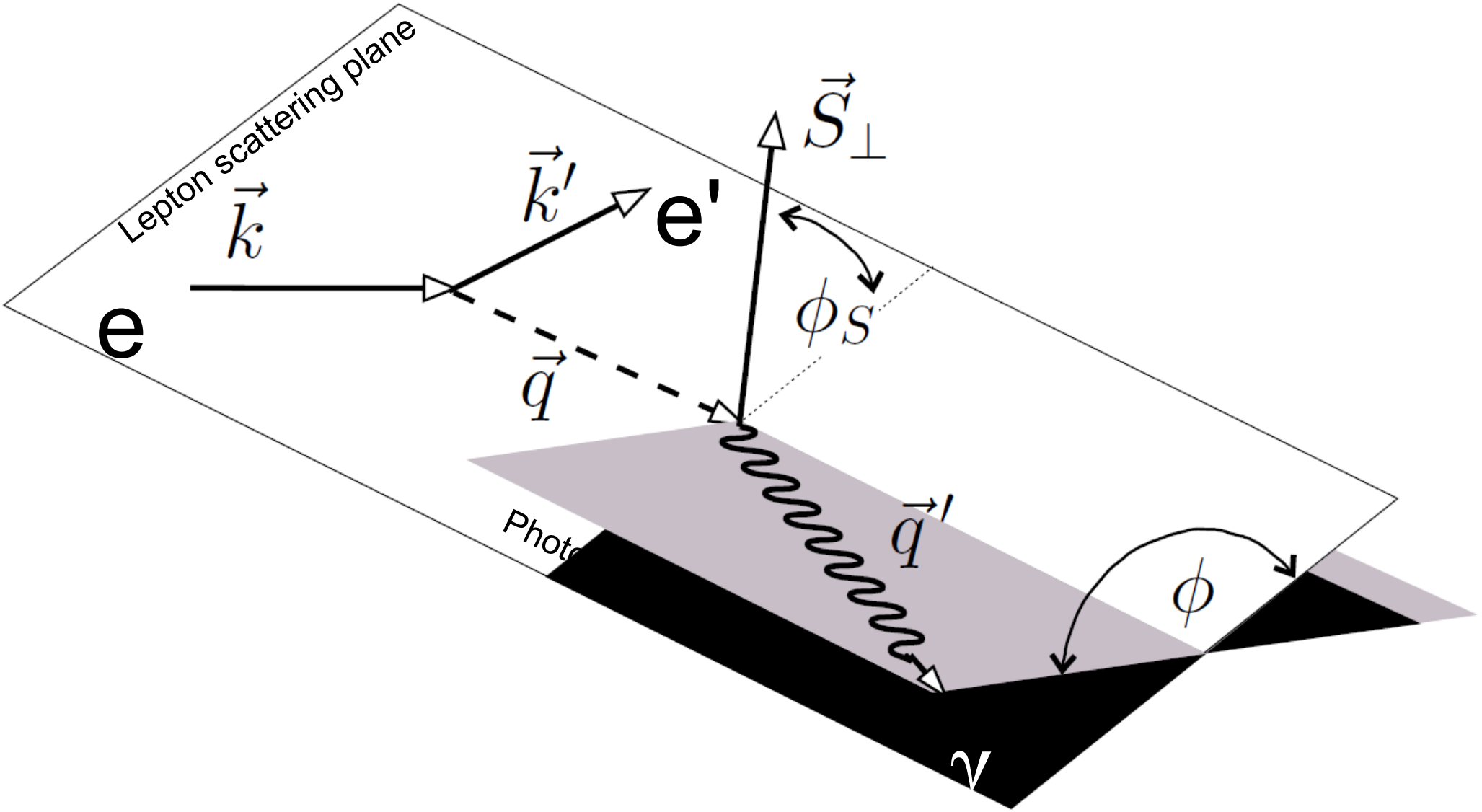
$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}Q^2\,\mathrm{d}x_\mathrm{B}\,\mathrm{d}t\,\mathrm{d}\phi} = \frac{x_\mathrm{B}e^6}{32(2\pi)^4Q^4\sqrt{1+\epsilon^2}}\left|\mathcal{T}_{ep\to ep\gamma}\right|^2,$$

$$\left|\mathcal{T}_{ep\to ep\gamma}\right|^2 = \left|\mathcal{T}_\mathrm{BH}\right|^2 + \left|\mathcal{T}_\mathrm{DVCS}\right|^2 + \mathcal{I},$$

$$\mathcal{I} = \mathcal{T}_\mathrm{BH}\mathcal{T}^*_\mathrm{DVCS} + \mathcal{T}_\mathrm{DVCS}\mathcal{T}^*_\mathrm{BH}.$$

Azimuthal angles in DVCS

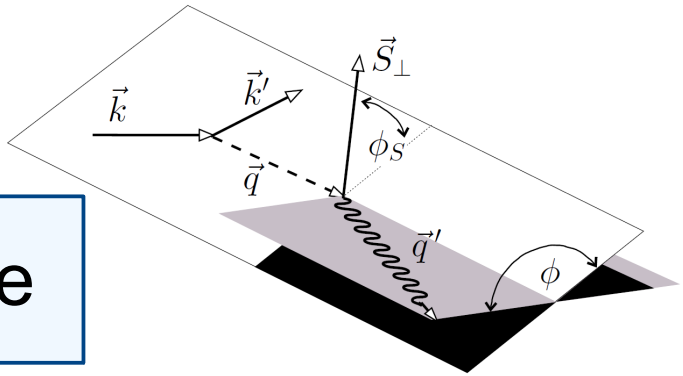
YAMAGATA UNIVERSITY



DVCS cross section

Unpol. target

$$|\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \mathcal{I},$$



Azimuthal angle dependence

$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left(c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH}\cos(n\phi)\right),$$

$$|\mathcal{T}_{\rm DVCS}|^2 = K_{\rm DVCS}\left(c_0^{\rm DVCS} + \sum_{n=1}^{2} c_n^{\rm DVCS}\cos(n\phi) + \lambda s_1^{\rm DVCS}\sin\phi\right),$$

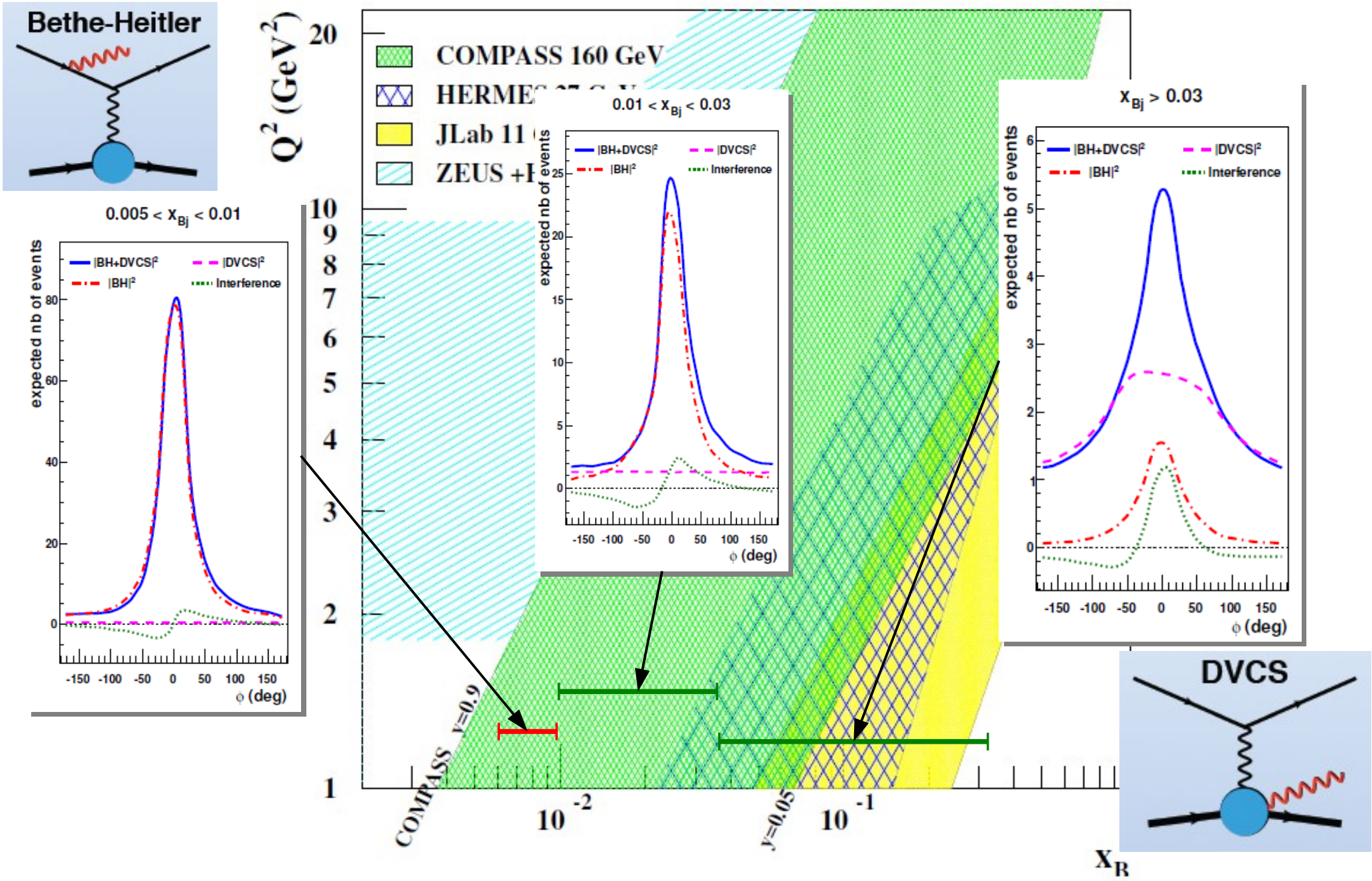
$$\mathcal{I} = \frac{-e_\ell K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left(c_0^{\mathcal{I}} + \sum_{n=1}^{3} c_n^{\mathcal{I}}\cos(n\phi) + \lambda\sum_{n=1}^{2} s_n^{\mathcal{I}}\sin(n\phi)\right).$$

Beam Charge

Beam helicity

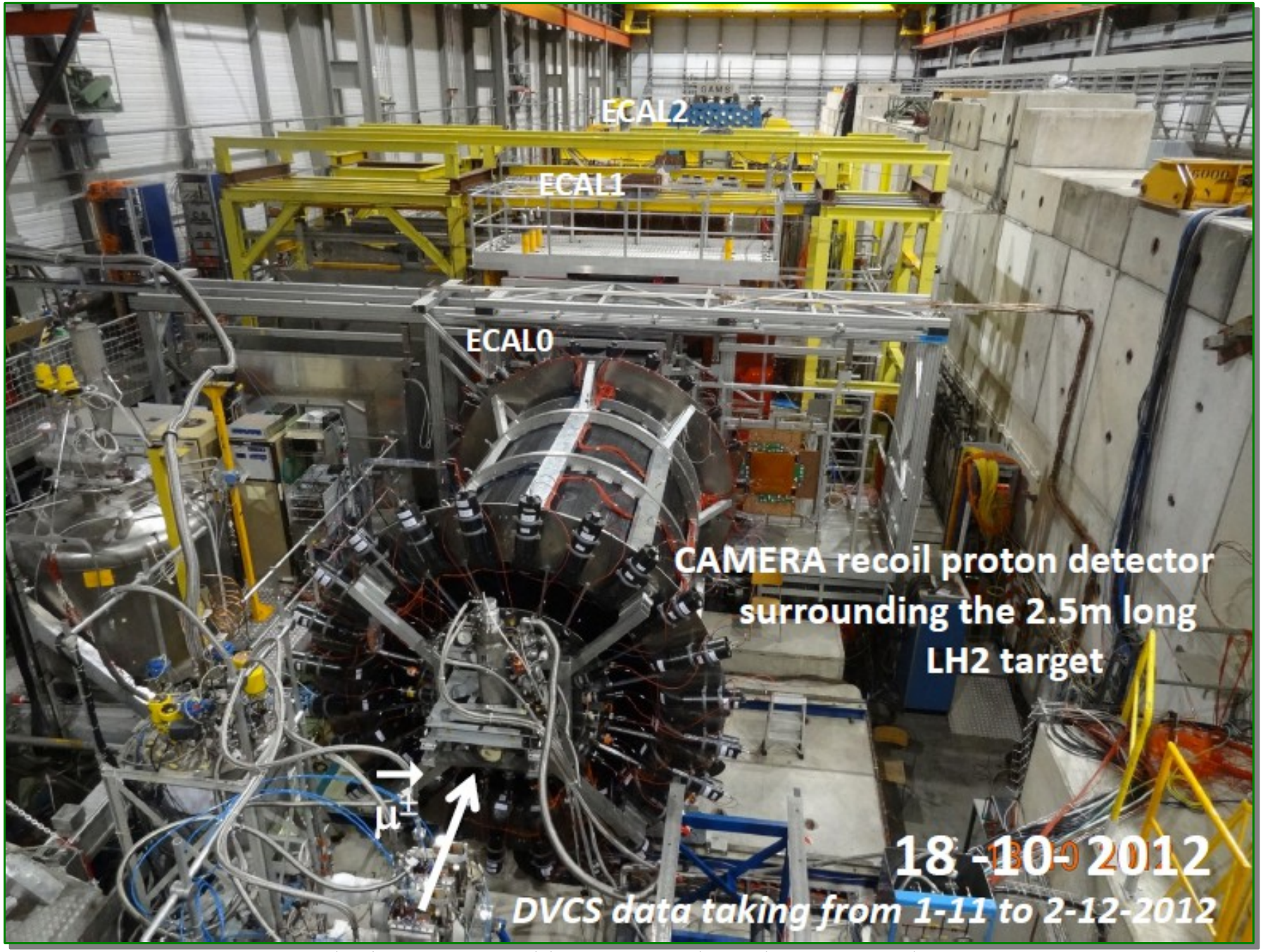
COMPASS II : DVCS kinematics

YAMAGATA UNIVERSITY



COMPASS II: GPD 2012 “short” RUN

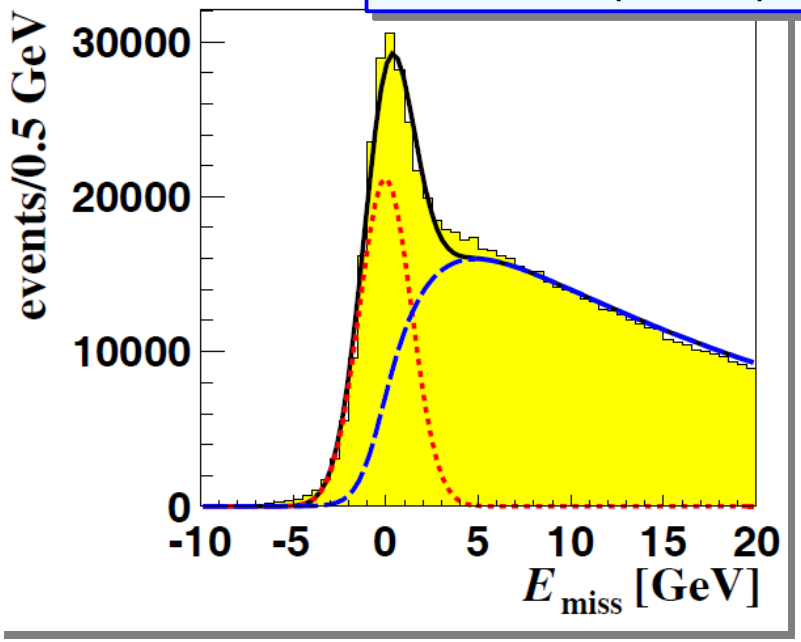
YAMAGATA UNIVERSITY

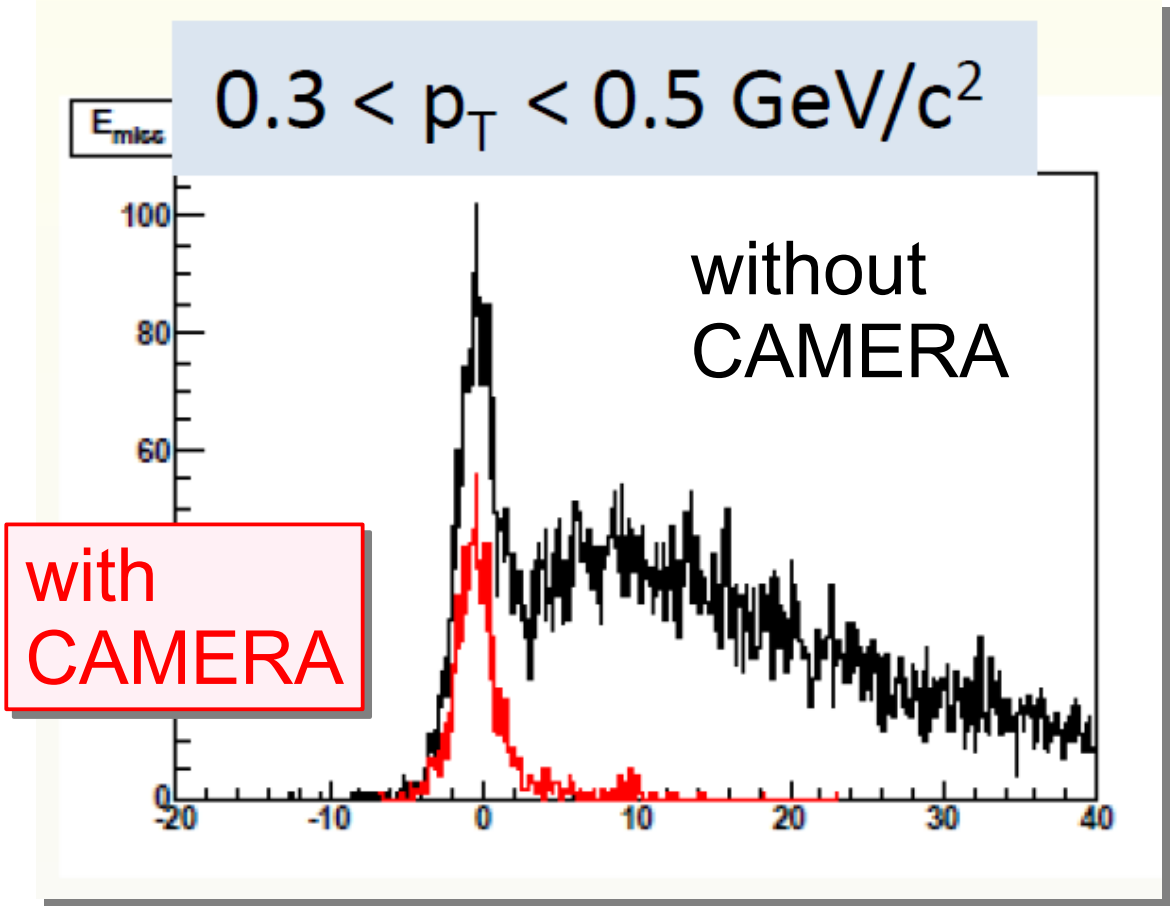


CAMERA study: with exclusive ρ^0

YAMAGATA UNIVERSITY

NPB865(2012)1





COMPASS II: DVCS analysis

(1) The beam charge & spin sum of cross sections

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

(2) The beam charge & spin difference of cross sections

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

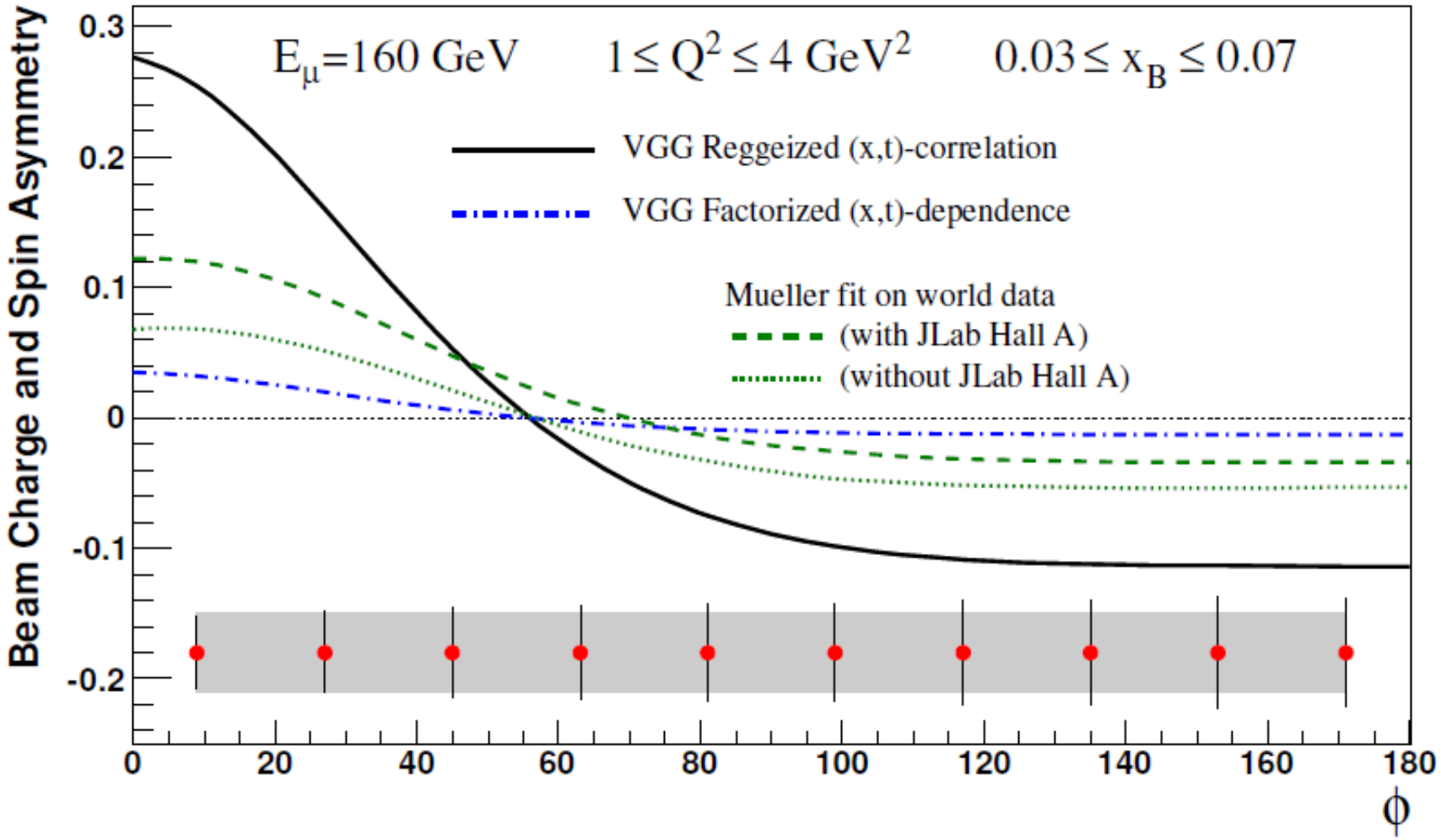
(3) The beam charge & spin asymmetry of cross sections

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

COMPASS II: GPD, expected asymmetry

YAMAGATA UNIVERSITY

2016 - 2017



SF

$$c_1^I \propto \mathrm{Re}\left(F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E} \right)$$

Summary

YAMAGATA UNIVERSITY

- COMPASS I: 2002 ~ 2011
  - Longitudinal & Transverse spin structure of the proton
  - GPD with exclusive ρ^0 production
- COMPASS II
  - Drell-Yan Program: 2014 – 2015
    - Target modification, Hadron absorber, new SciFi detector
    - Pol DY for the first time
    - Sign change of T-odd TMDs in SIDIS & DY
  - GPD Program: 2012, 2016 – 2017
    - CAMERA was installed and tested in 2001
    -