WG6 Highlights: Spin Physics

Yann Bedfer, Barbara Pasquini, Ernst Sichtermann

DIS2014 - WG6: Spin Physics

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Ken BARISH
Catarina QUINTANS
Salvatore FAZIO

43 talks:

14 theory / phenomenology
29 experiment / future

11 Quark and gluon helicity
13 TMD
10 GPD
9 multiple, other

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Thank you to all Speakers!

Our apologies where we omitted your favorite topic...

DIS 2014 - WG6: Spin Physics

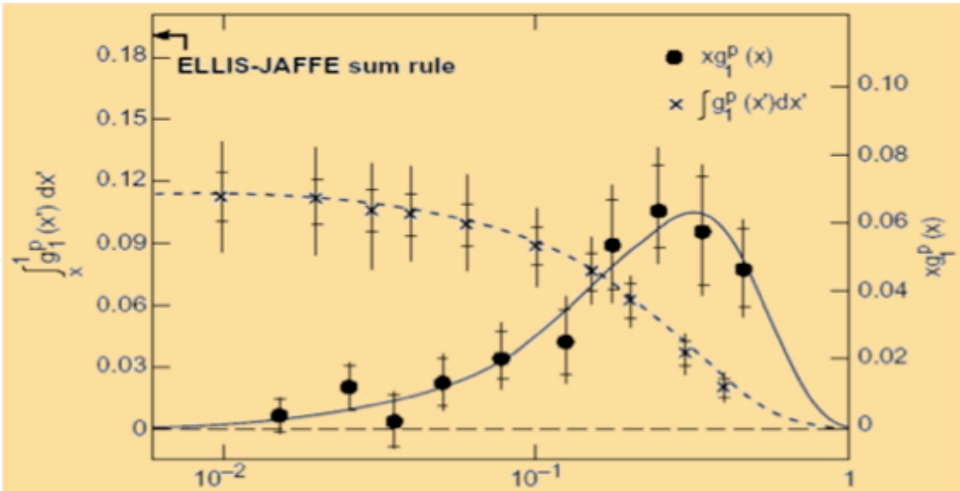
How is the nucleon spin carried by quark and gluon spins and orbital momenta?

What is the role of spin in QCD?

Jianwei QIU, plenary

The Past

- EMC (European Muon Collaboration '87) – "the Plot":



$$g_1(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x) + \Delta\bar{q}(x)\right] + \mathcal{O}(\alpha_s) + \mathcal{O}(1/Q)$$

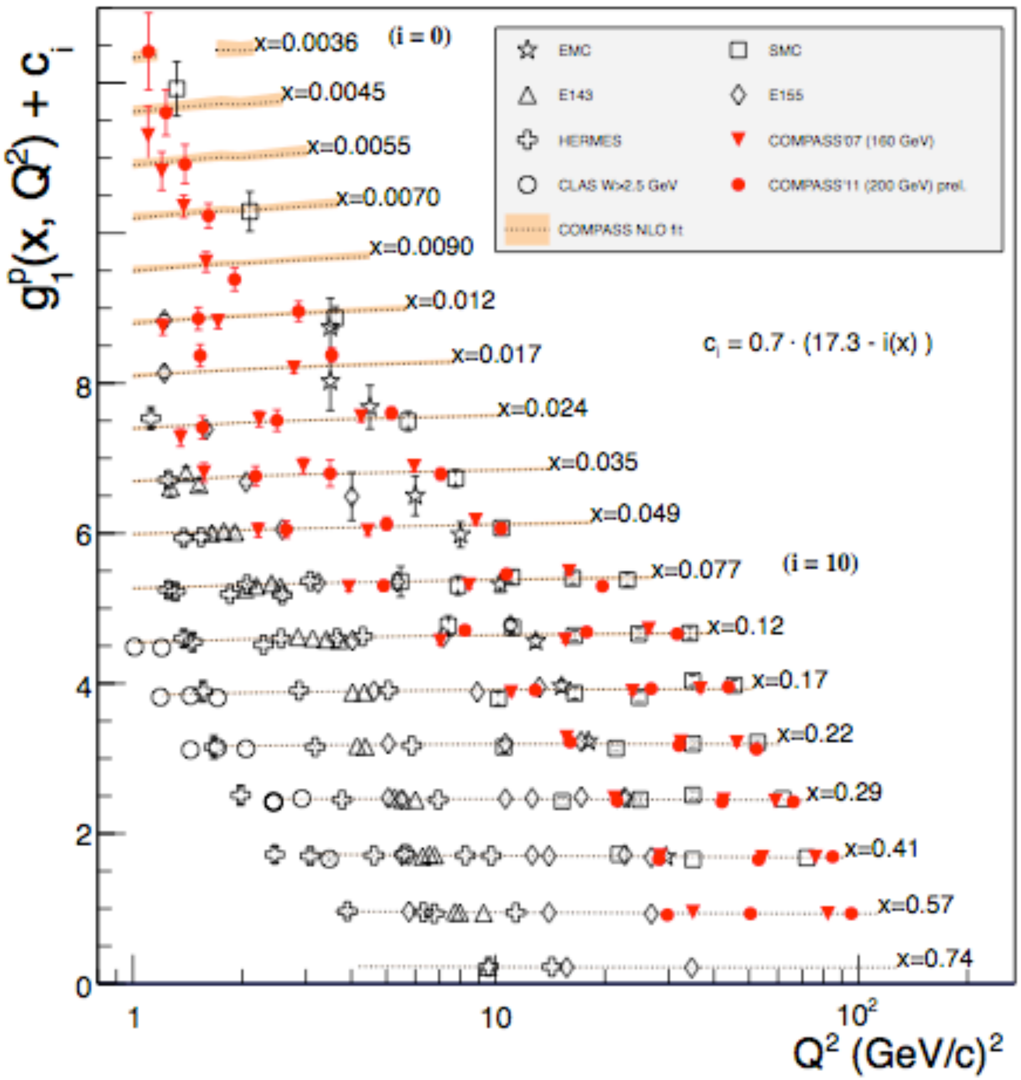
- Combined with earlier SLAC data: $\int_0^1 g_1^p(x)dx = 0.126 \pm 0.018$
- Combined with: $g_A^3 = \Delta u - \Delta d$ and $g_A^8 = \Delta u + \Delta d - 2\Delta s$
  from low energy neutron & hyperon β decay

$$\Rightarrow \quad \Delta\Sigma = \sum_q\left[\Delta q + \Delta\bar{q}\right] = 0.12 \pm 0.17$$

- "Spin crisis" or puzzle:
  - Strange sea polarization is sizable & negative
  - Very little of the proton spin is carried by quarks

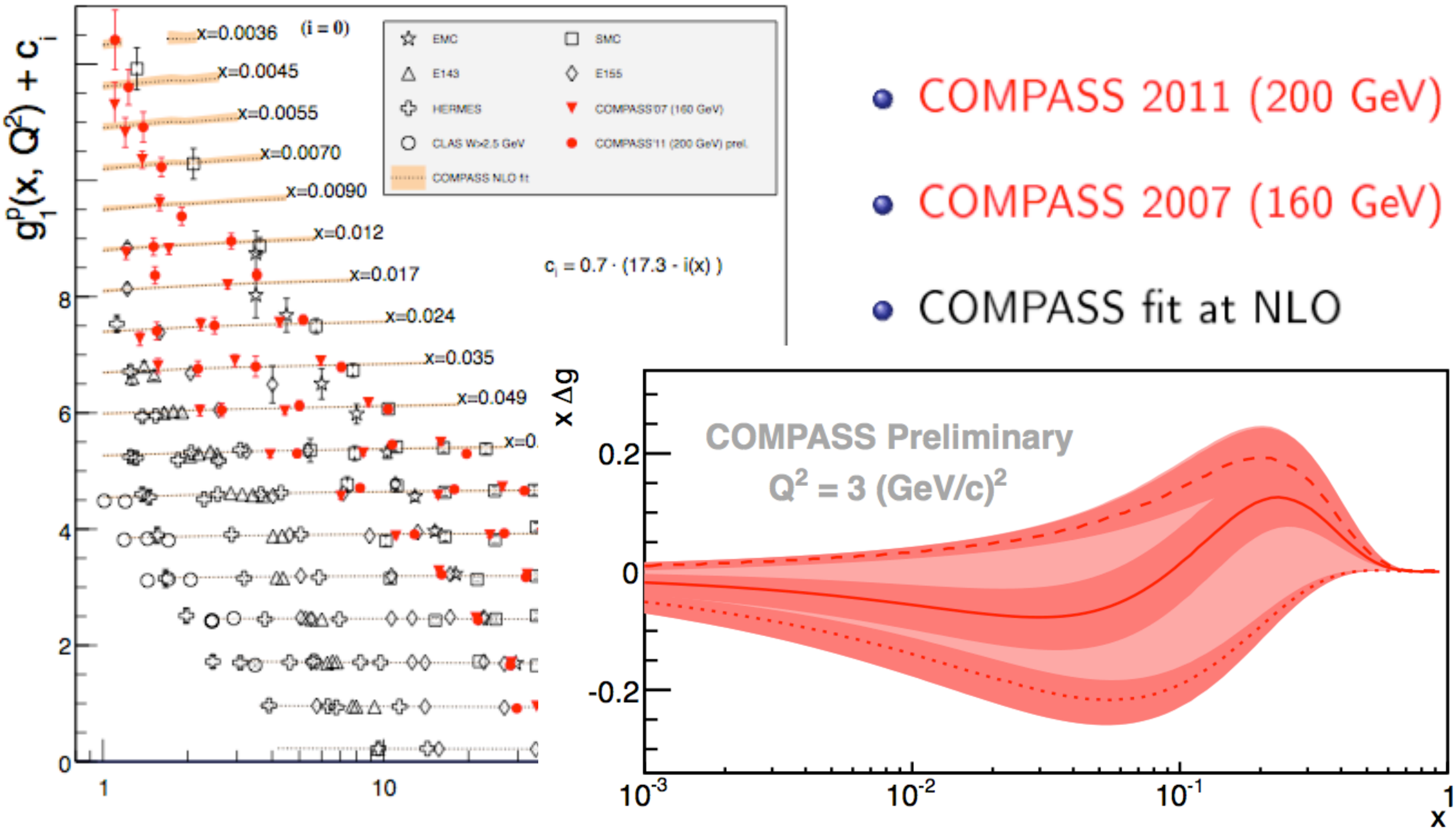
→ New era of spin physics

Malte WILFERT



- COMPASS 2011 (200 GeV)
- COMPASS 2007 (160 GeV)
- COMPASS fit at NLO
- New data point at very low x
- New input for global QCD fit
- Indirect ΔG extraction

Malte WILFERT



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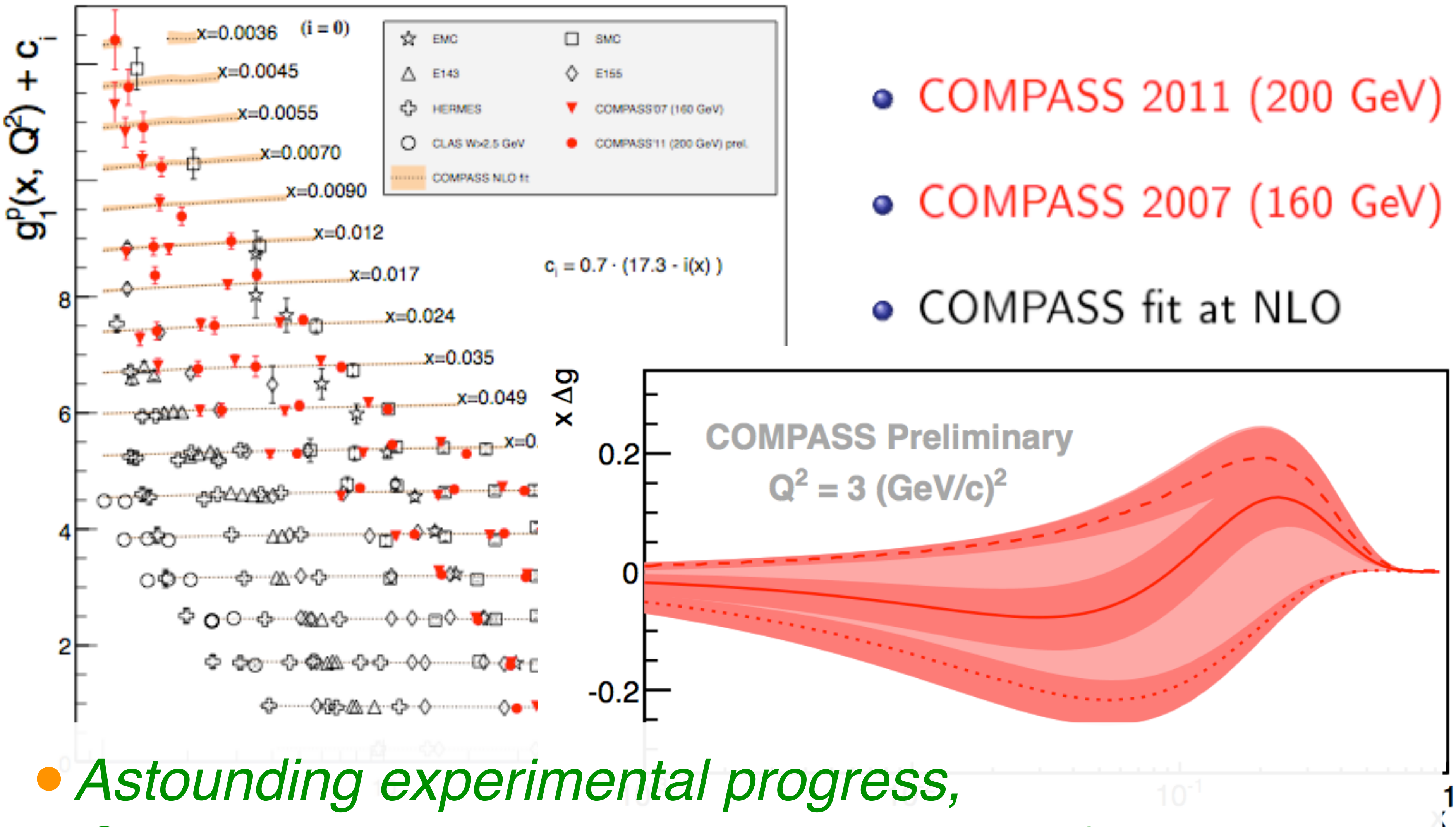
Malte WILFERT

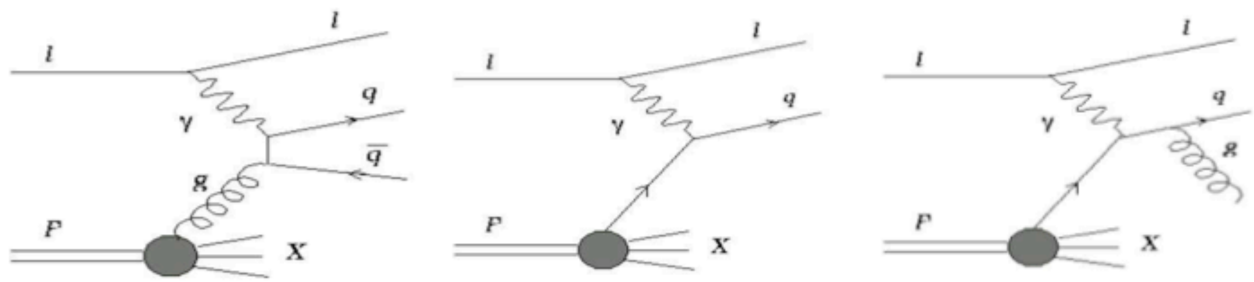


- COMPASS 2011 (200 GeV)
- COMPASS 2007 (160 GeV)
- COMPASS fit at NLO

- *Astounding experimental progress,*
- *Gluon polarization, in particular, needs further help...*

The Analysis Method of High-p_T Events in the DIS Region

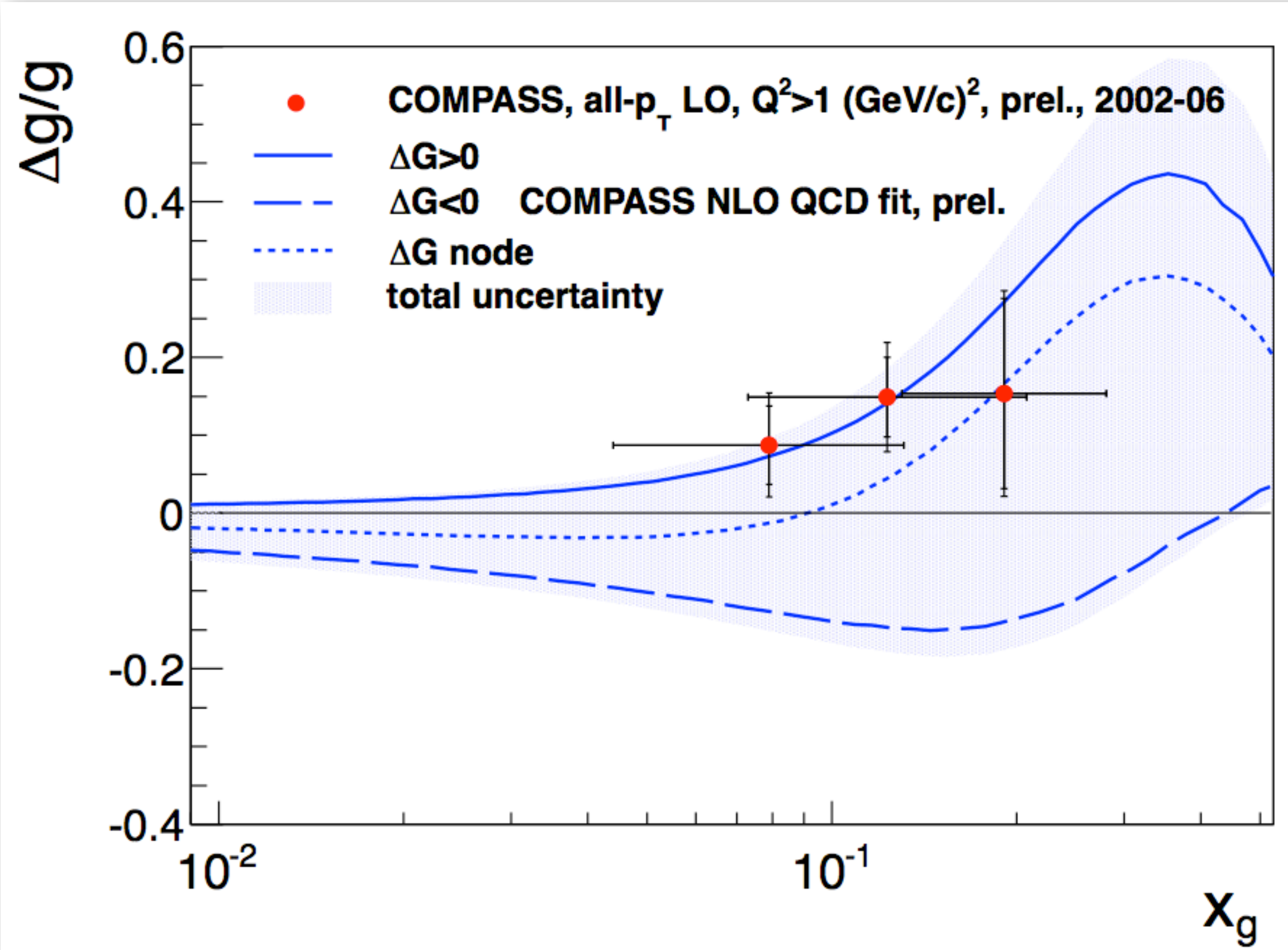
- Contribution from 3 processes to the observed asymmetry is assumed:



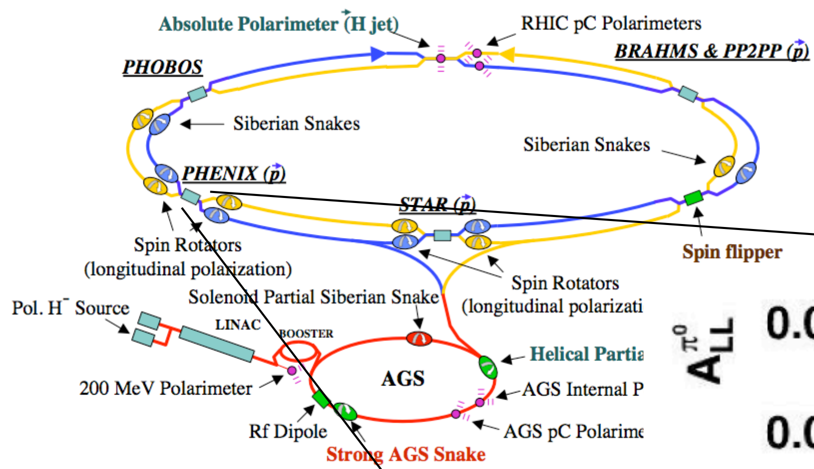
PGF LP QCDC

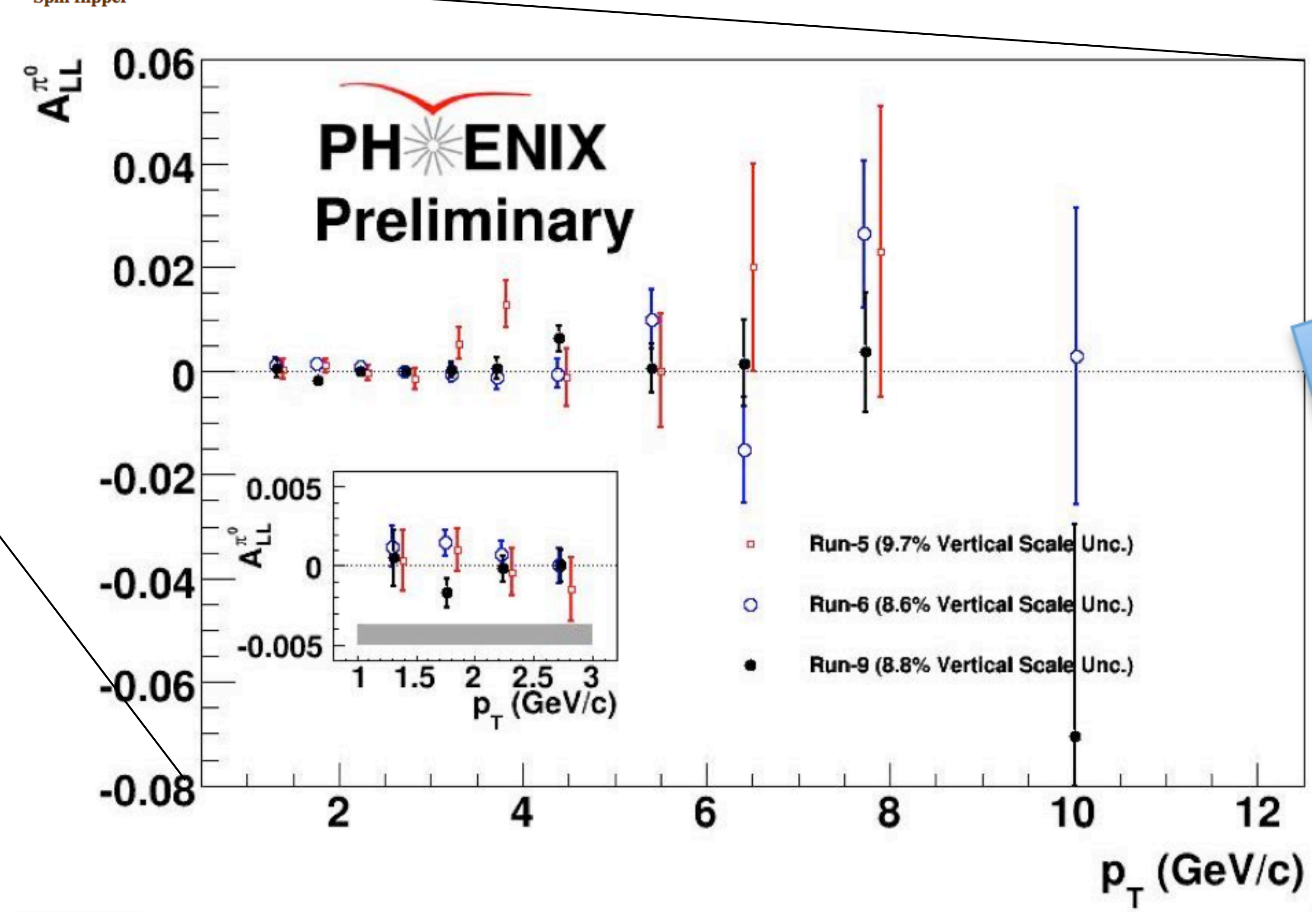
- $A^h_{LL}(x_{Bj}) = R_{PGF} a^{PGF}_{LL} \Delta g/g(x_G) + R_{LP} D A^{LO}_1(x_{Bj}) + R_{QCDC} a^{QCDC}_{LL} A^{LO}_1(x_C)$
  where:
  - $A^{LO}_1 \equiv \frac{\sum_i e_i^2 \Delta q_i}{\sum_i e_i^2 q_i}$
  - the fraction of the processes (R_i) and partonic cross-section asymmetries (a^i_{LL}) are obtained from MC and parametrized by NN
- Idea: larger p_T → larger R_{PGF} → larger sensitivity to $\Delta g/g$

Marcin STOLARSKI



Itaru NAKAGAWA





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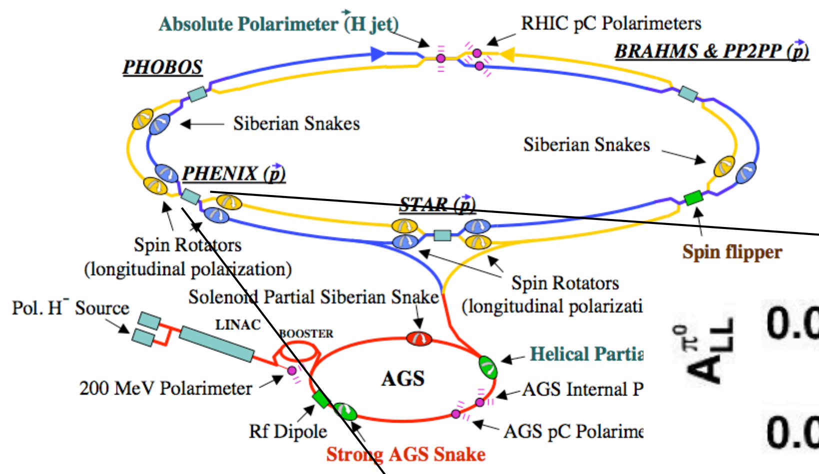
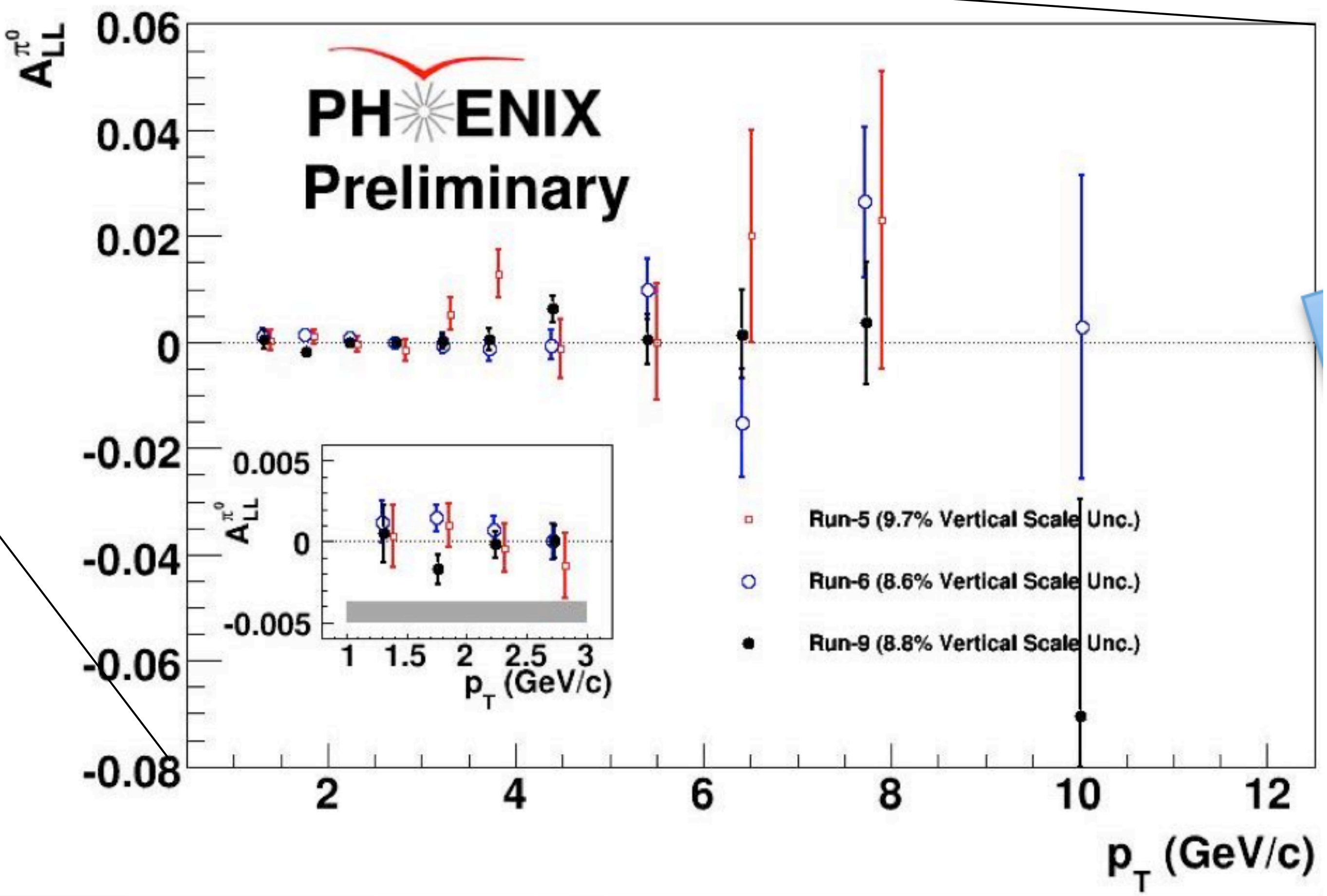
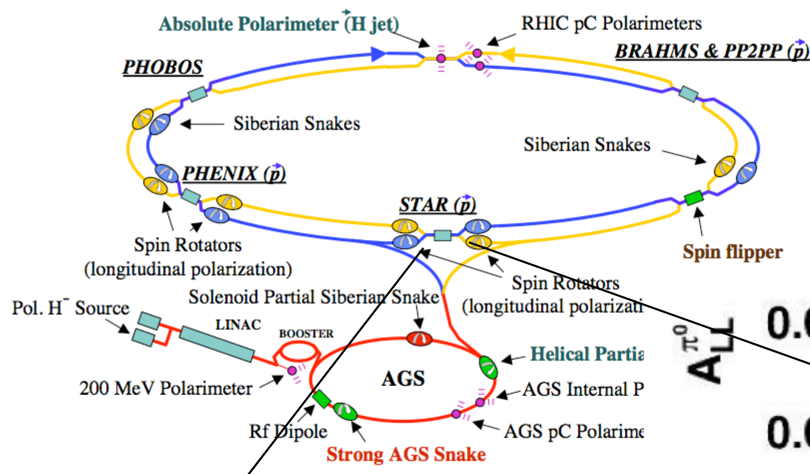
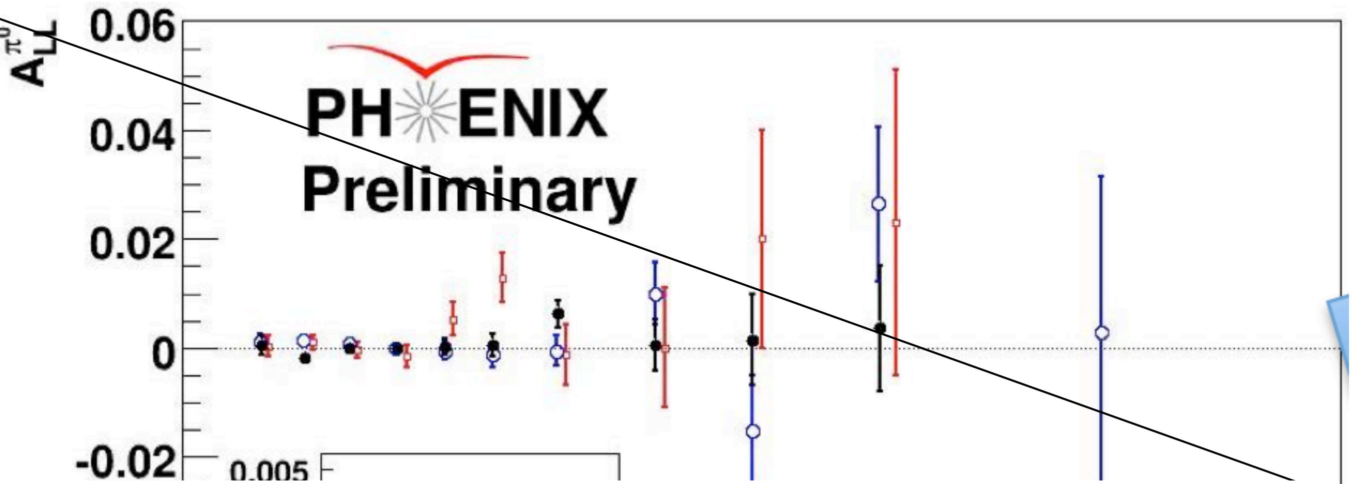


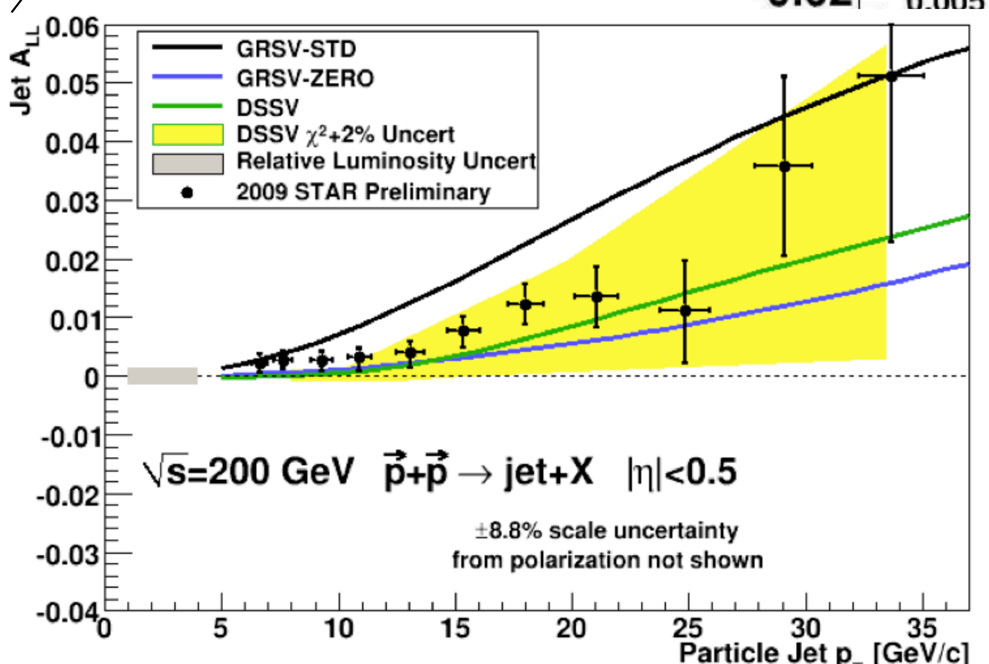


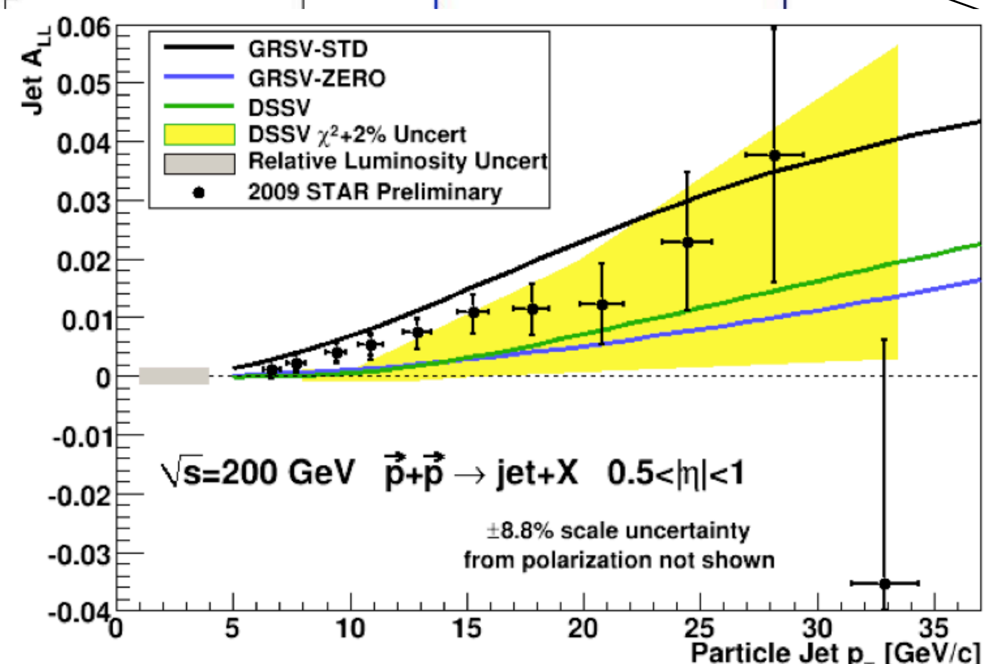
- *Additional channels: π^+, π^-, e, π^0-π^0 correlations, forward π^0, clusters*

Itaru NAKAGAWA
Justin STEVENS

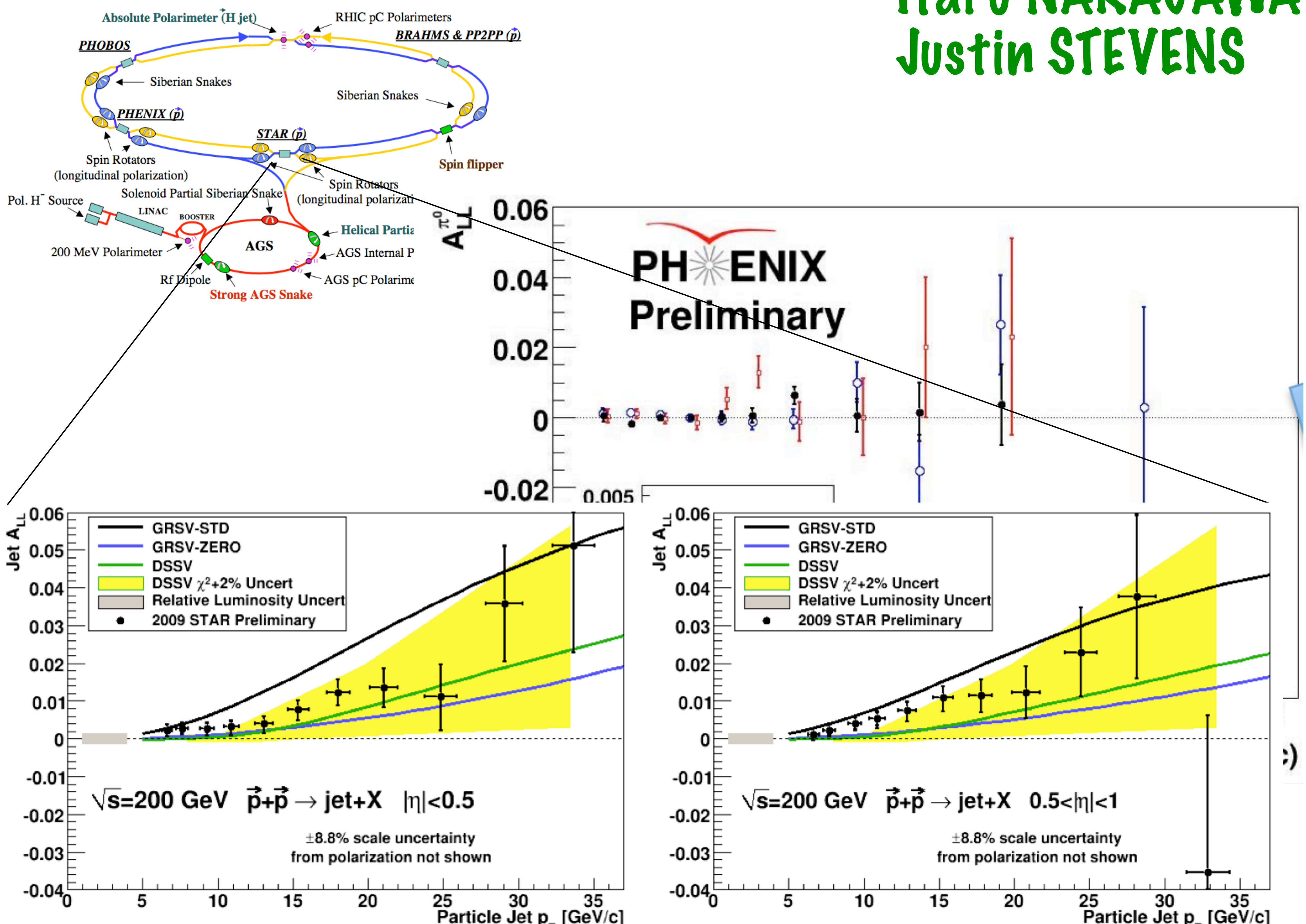






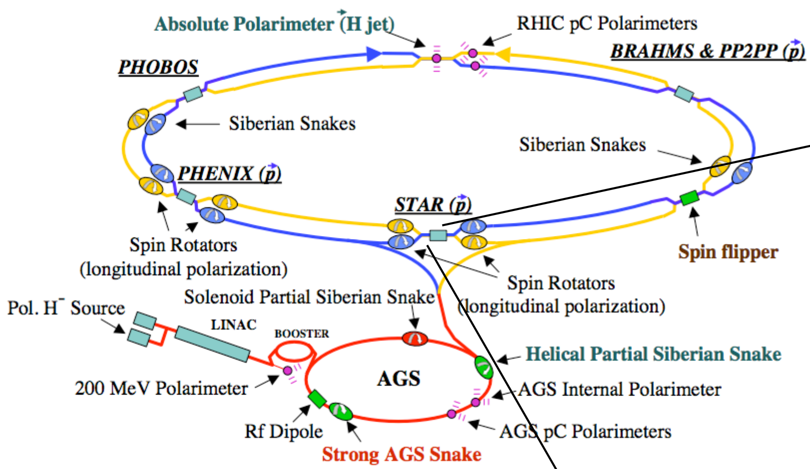


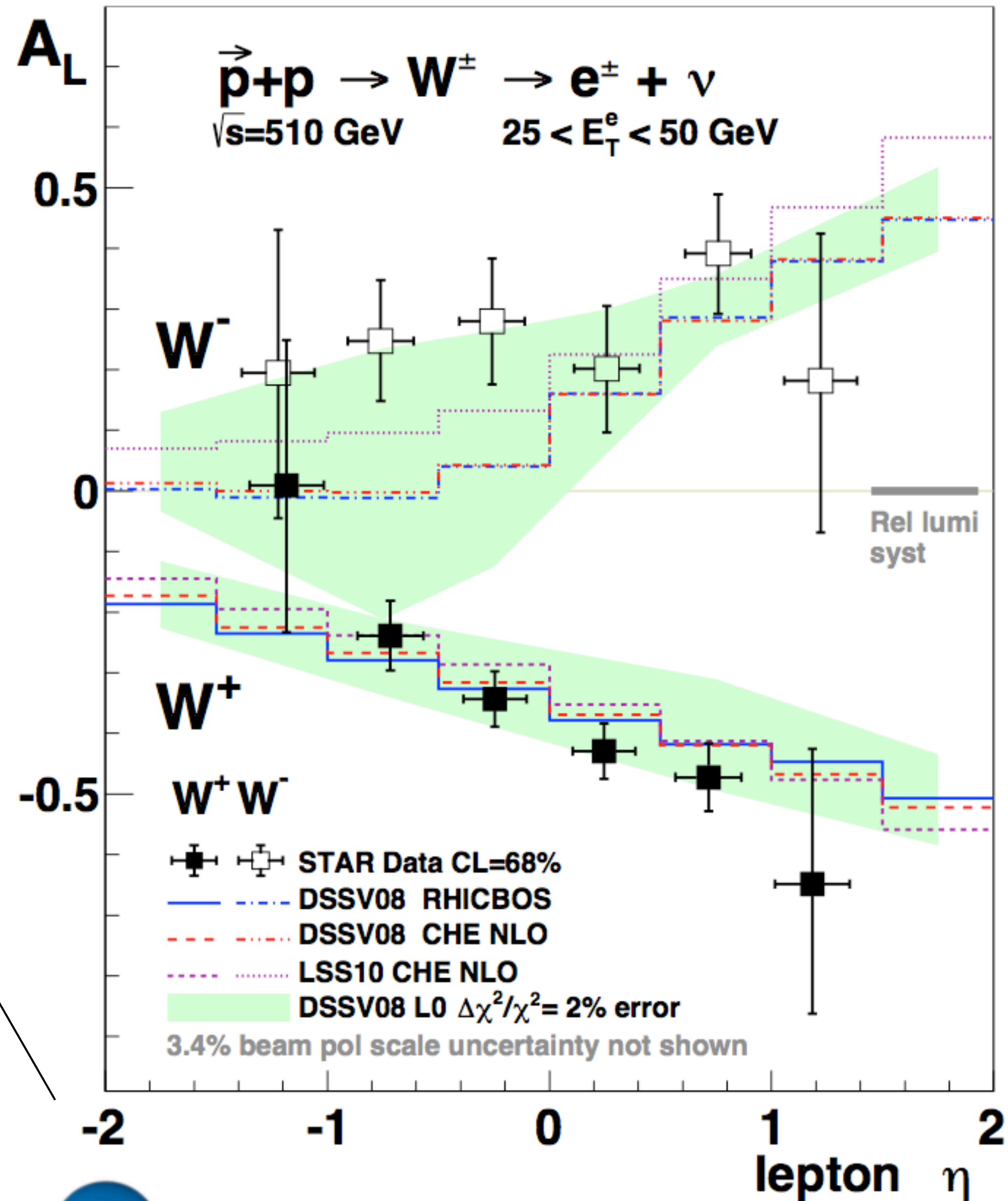
Itaru NAKAGAWA
Justin STEVENS



- *prospects √s = 500 GeV (Stevens), forward di-jets (Surrow, WG6+7)*

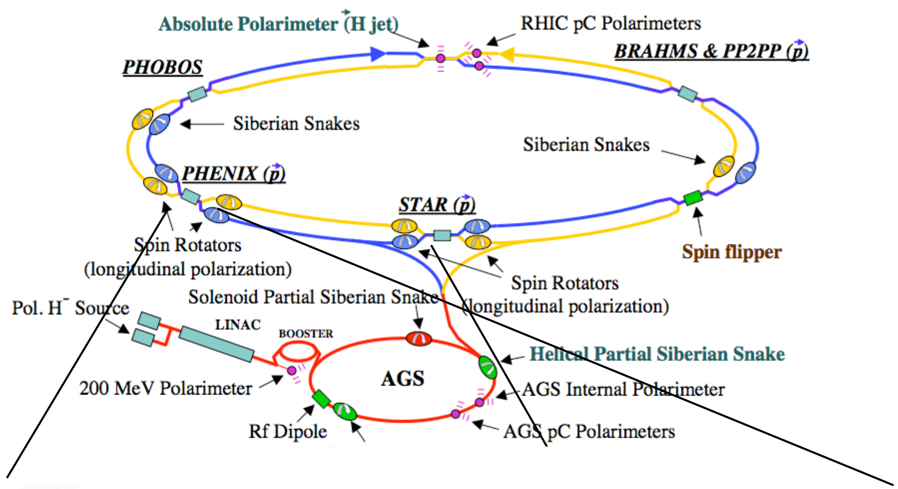
Justin STEVENS

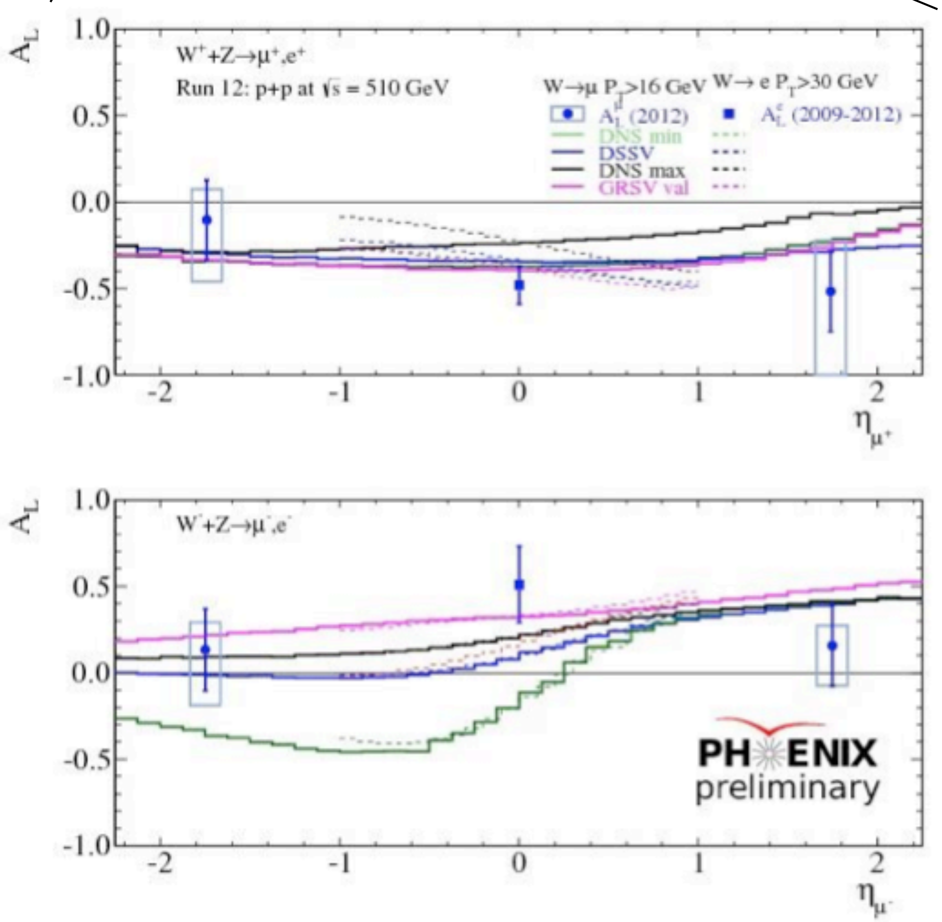


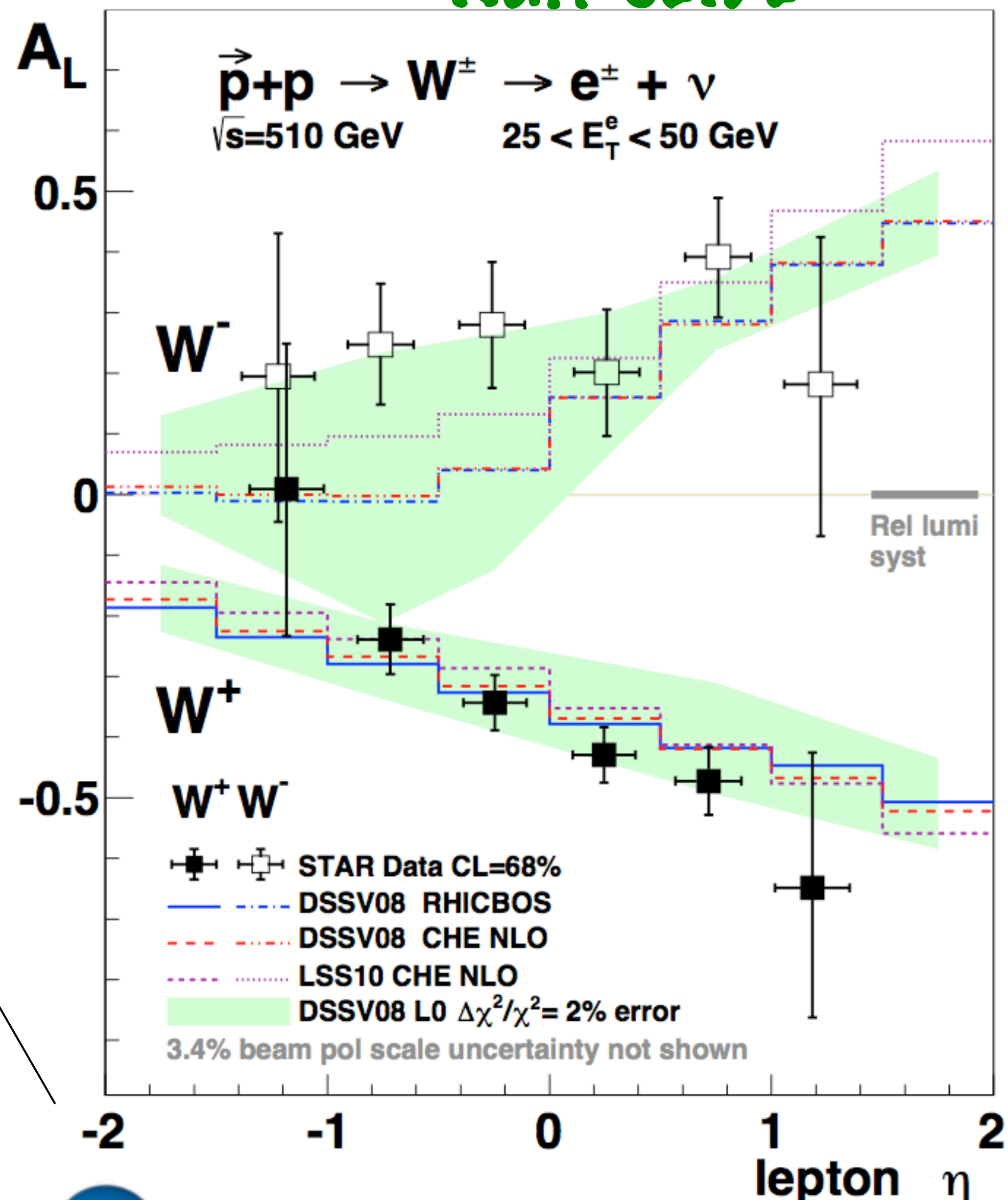


NEW arXiv:1404.6880

Justin STEVENS
Ralf SEIDL







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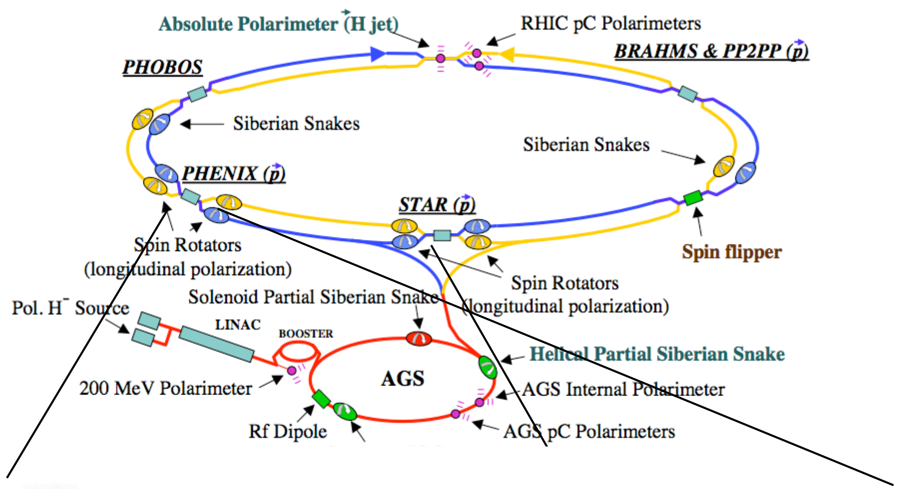
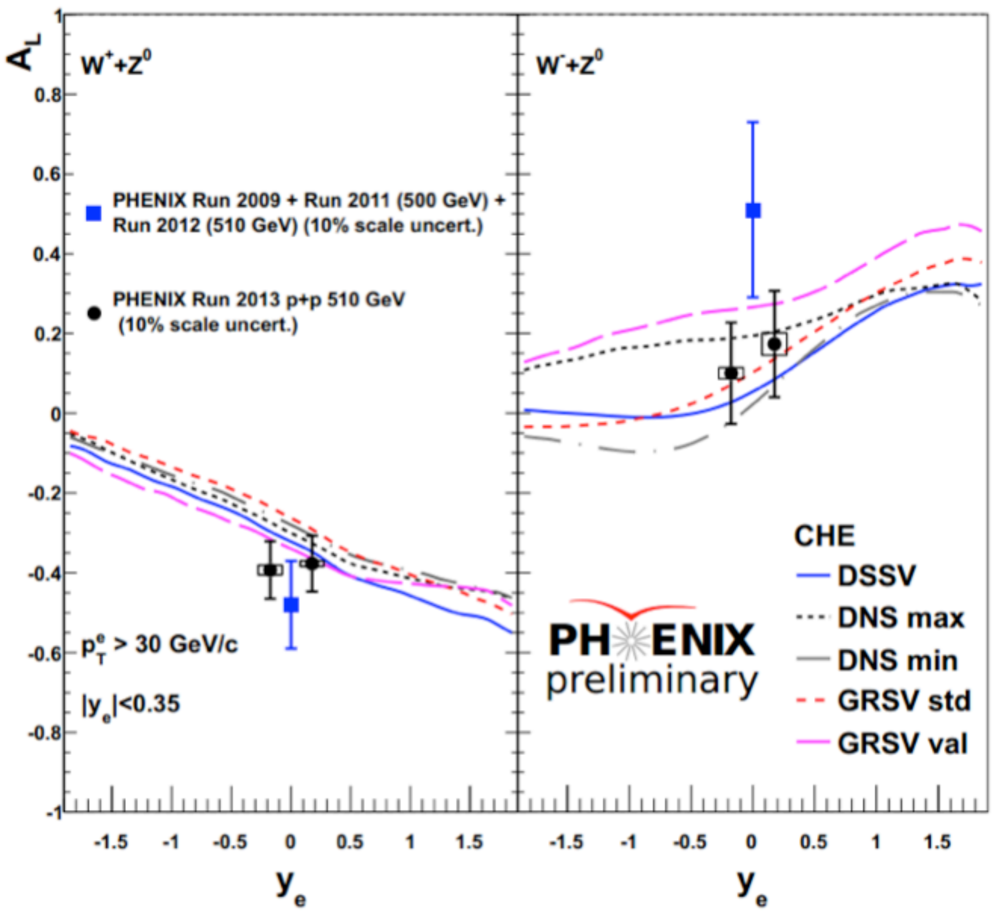
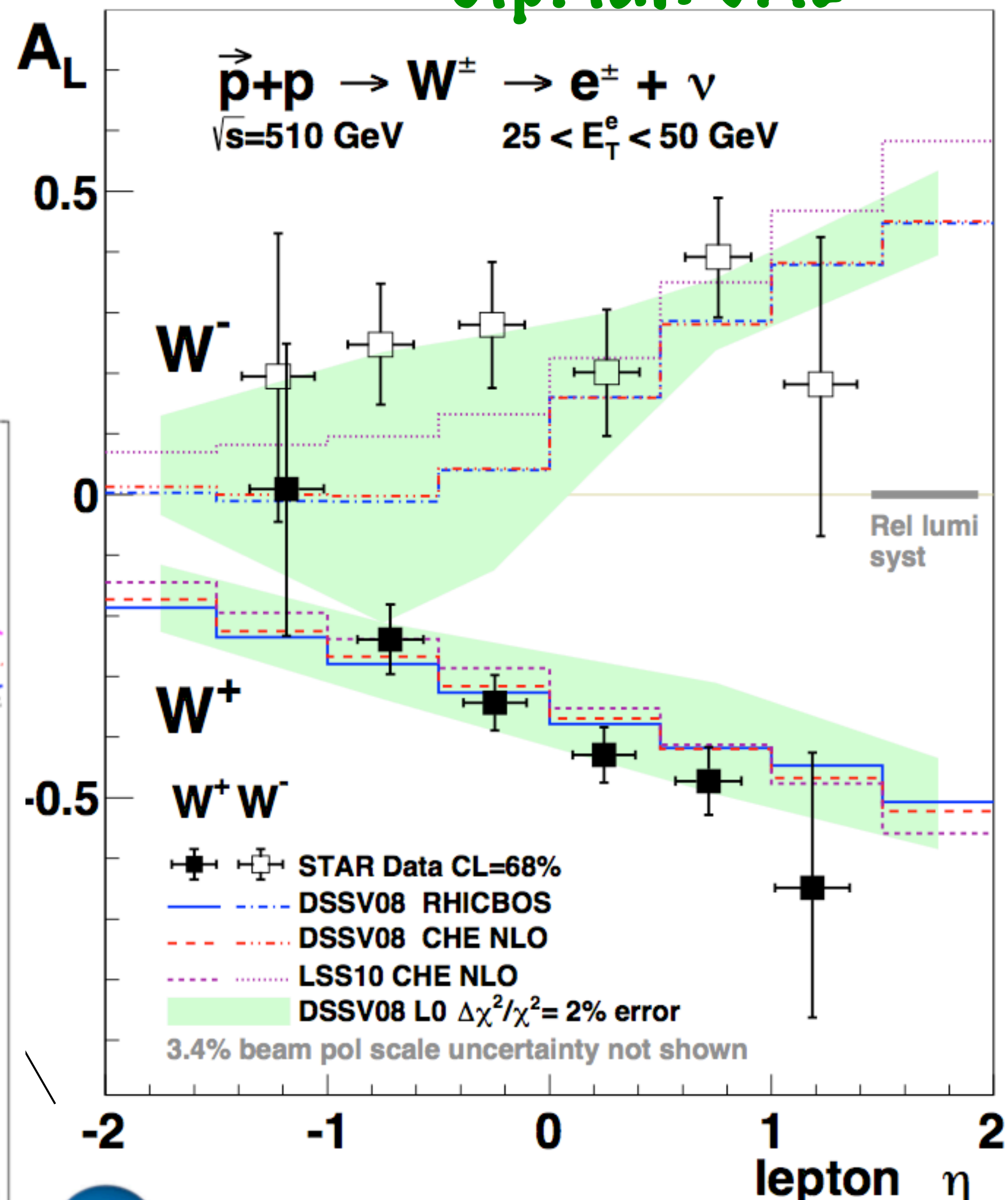
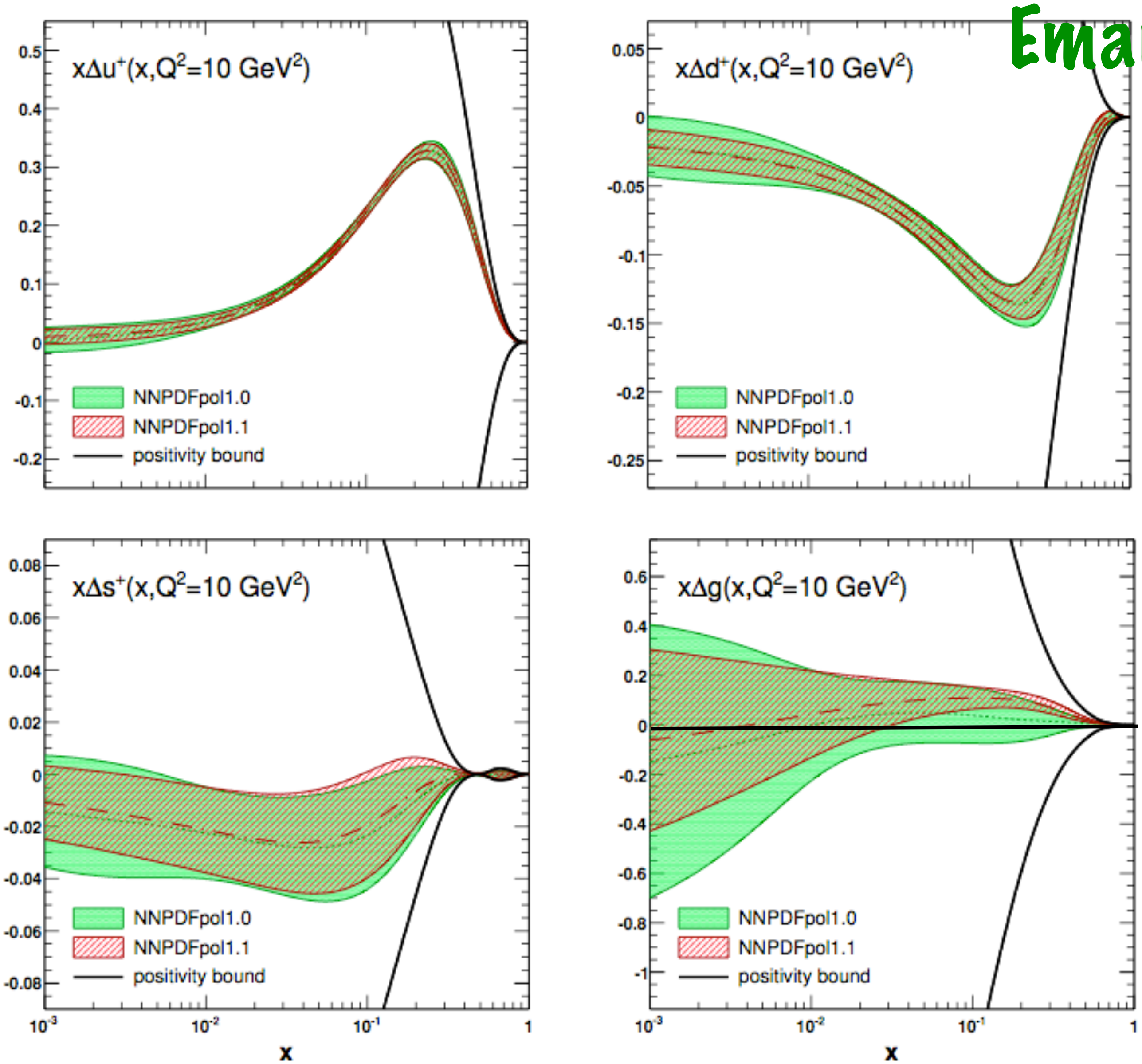
Ciprian GAL







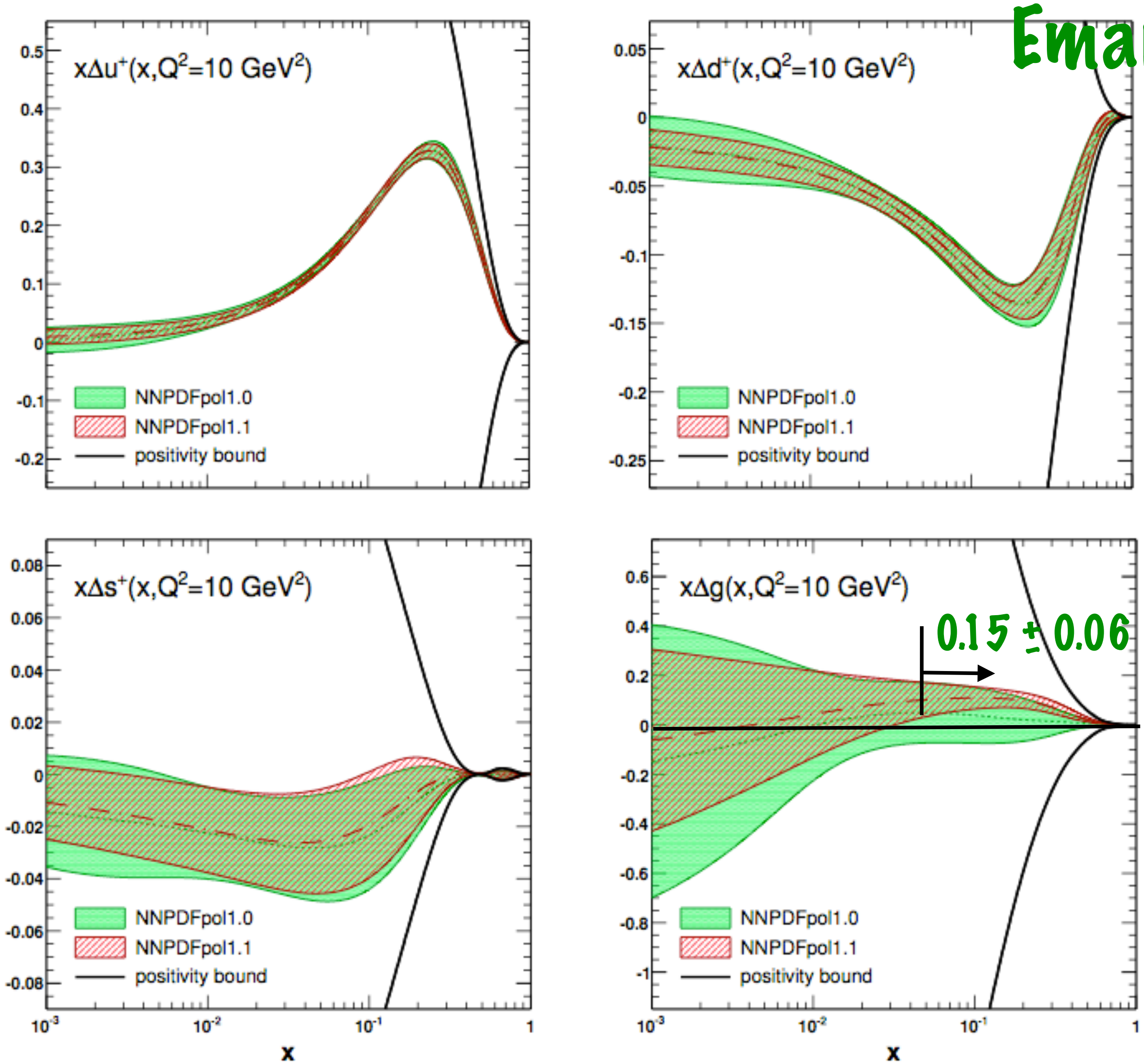
Emanuele NOCERA



- $\Delta q^+ \equiv \Delta q + \Delta\bar{q}$, $q = u, d$ are statistically equivalent in the two parton sets
- Δs^+ is almost unaffected by W data (unlike in the unpolarized case)
- the underlying probability distributions for Δg in the two determinations differ up to one sigma in the region covered by jet data, $0.05 \lesssim x \lesssim 0.2$
- Δg from NNPDFpol1.1 is definitely positive in the data region and its uncertainty is reduced up to a factor three w.r.t. NNPDFpol1.0

Emanuele NOCERA

Prospects CC pDIS at EIC (Burton,WG6+7)



Evidence also from:
- JAM (Accardi)
- DSSV (arXiv 1404.4293)

Prospects:
- photoproduction of high-p_T hadrons (Levillain, COMPASS)
- forward, 500 GeV RHIC data (Nakagawa, Surrow)

- $\Delta q^+ \equiv \Delta q + \Delta\bar{q}$, $q = u, d$ are statistically equivalent in the two parton sets
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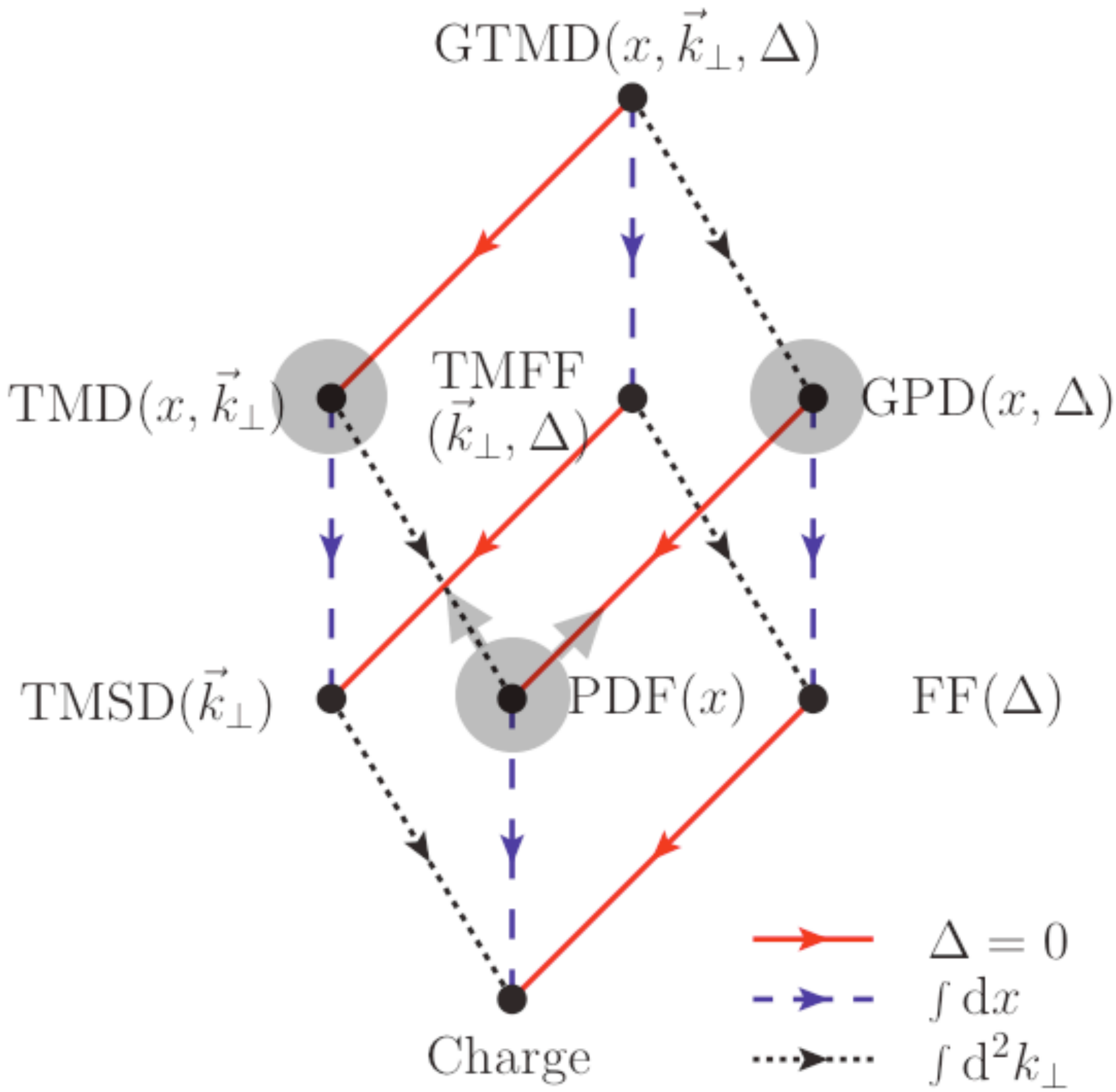


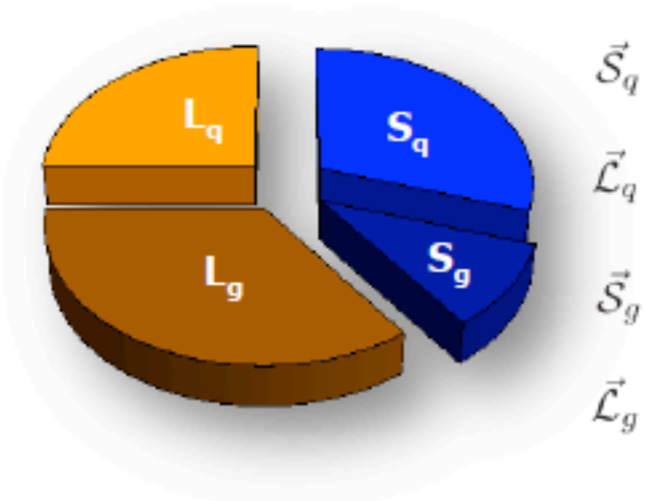
Angular Momentum Decomposition

C. Lorcé

Canonical

$\vec{p} = \frac{\partial L}{\partial \vec{v}}$

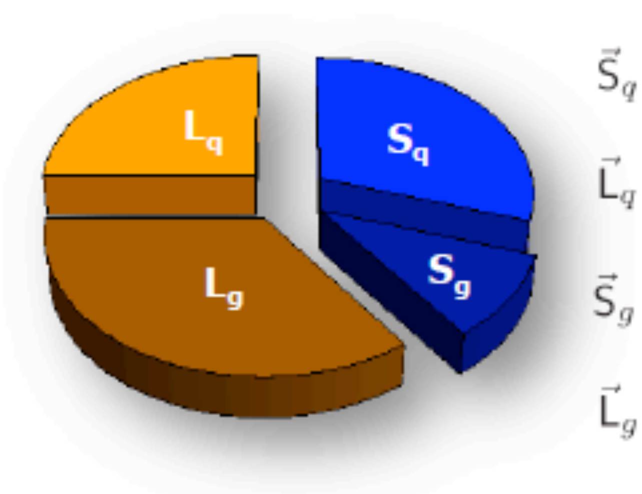
[Jaffe-Manohar (1990)]



$$\vec{S}_q = \frac{1}{2}\int \mathrm{d}^3r\, \psi^\dagger \vec{\Sigma} \psi$$
$$\vec{\mathcal{L}}_q = \int \mathrm{d}^3r\, \psi^\dagger \vec{r} \times (-i\vec{\nabla})\psi$$
$$\vec{S}_g = \int \mathrm{d}^3r\, \vec{E}^a \times \vec{A}^a$$
$$\vec{\mathcal{L}}_g = \int \mathrm{d}^3r\, E^{ai} \vec{r} \times \vec{\nabla} A^{ai}$$

Gauge non-invariant!

[Chen *et al.* (2008)] $A = A_{\text{pure}} + A_{\text{phys}}$



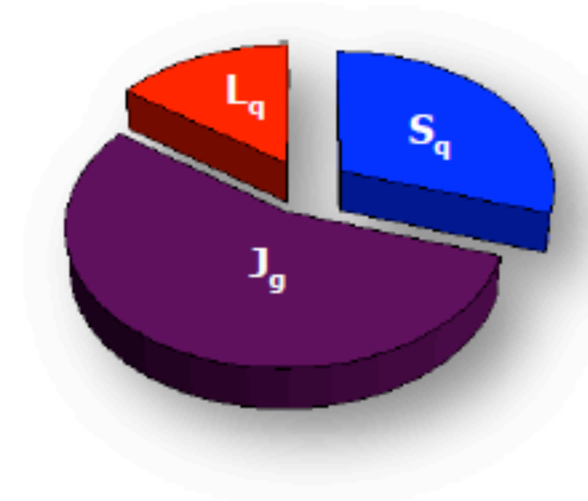
$$\vec{S}_q = \frac{1}{2}\int \mathrm{d}^3r\, \psi^\dagger \vec{\Sigma} \psi$$
$$\vec{L}_q = \int \mathrm{d}^3r\, \psi^\dagger \vec{r} \times (-i\vec{D}_{\text{pure}})\psi$$
$$\vec{S}_g = \int \mathrm{d}^3r\, \vec{E}^a \times \vec{A}^a_{\text{phys}}$$
$$\vec{L}_g = \int \mathrm{d}^3r\, E^{ai} \vec{r} \times \vec{\mathcal{D}}_{\text{pure}} A^{ai}_{\text{phys}}$$

Gauge-invariant extension (GIE)

Kinetic

$\vec{\pi} = m\vec{v} = \vec{p} + g\vec{A}$

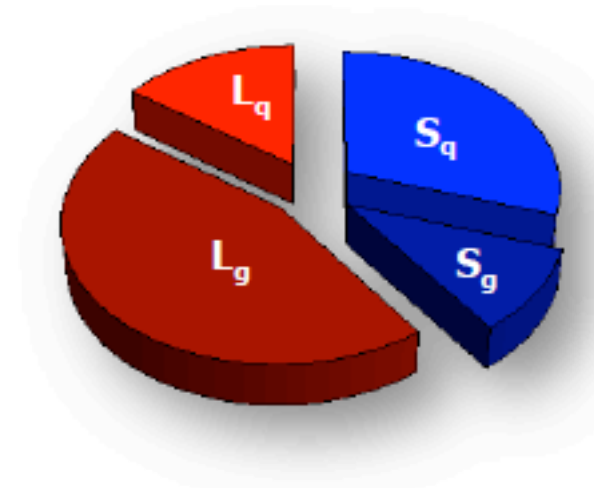
[Ji (1997)] $\vec{D} = \vec{\nabla} + ig\vec{A}$



$$\vec{S}_q = \frac{1}{2}\int \mathrm{d}^3r\, \psi^\dagger \vec{\Sigma} \psi$$
$$\vec{L}_q = \int \mathrm{d}^3r\, \psi^\dagger \vec{r} \times (-i\vec{D})\psi$$
$$\vec{J}_g = \int \mathrm{d}^3r\, \vec{r} \times (\vec{E}^a \times \vec{B}^a)$$

Gauge invariant

[Wakamatsu (2010)] $A = A_{\text{pure}} + A_{\text{phys}}$



$$\vec{S}_q = \frac{1}{2}\int \mathrm{d}^3r\, \psi^\dagger \vec{\Sigma} \psi$$
$$\vec{L}_q = \int \mathrm{d}^3r\, \psi^\dagger \vec{r} \times (-i\vec{D})\psi$$
$$\vec{S}_g = \int \mathrm{d}^3r\, \vec{E}^a \times \vec{A}^a_{\text{phys}}$$
$$\vec{L}_g = \int \mathrm{d}^3r\, \vec{r} \times (\vec{E}^a \times \vec{B}^a) - \int \mathrm{d}^3r\, \vec{E}^a \times \vec{A}^a_{\text{phys}}$$

No fundamental reason for insisting that the physical interpretation of a measurable quantity be gauge-invariant

C. Lorcé

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The relevant question is to whether a gauge non-invariant quantity with clear physical interpretation can be associated with a measurable quantity

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C. Lorcé

Sum rule for longitudinally polarized nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

PDF GPDs

No fundamental reason for insisting that the physical interpretation of a measurable quantity be gauge-invariant

The relevant question is to whether a gauge non-invariant quantity with clear physical interpretation can be associated with a measurable quantity

C. Lorcé

Sum rule for longitudinally polarized nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

PDF GPDs

K. Tanaka

Sum rule for transversely polarized nucleon

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma_T + \Delta G_T + L_T$$

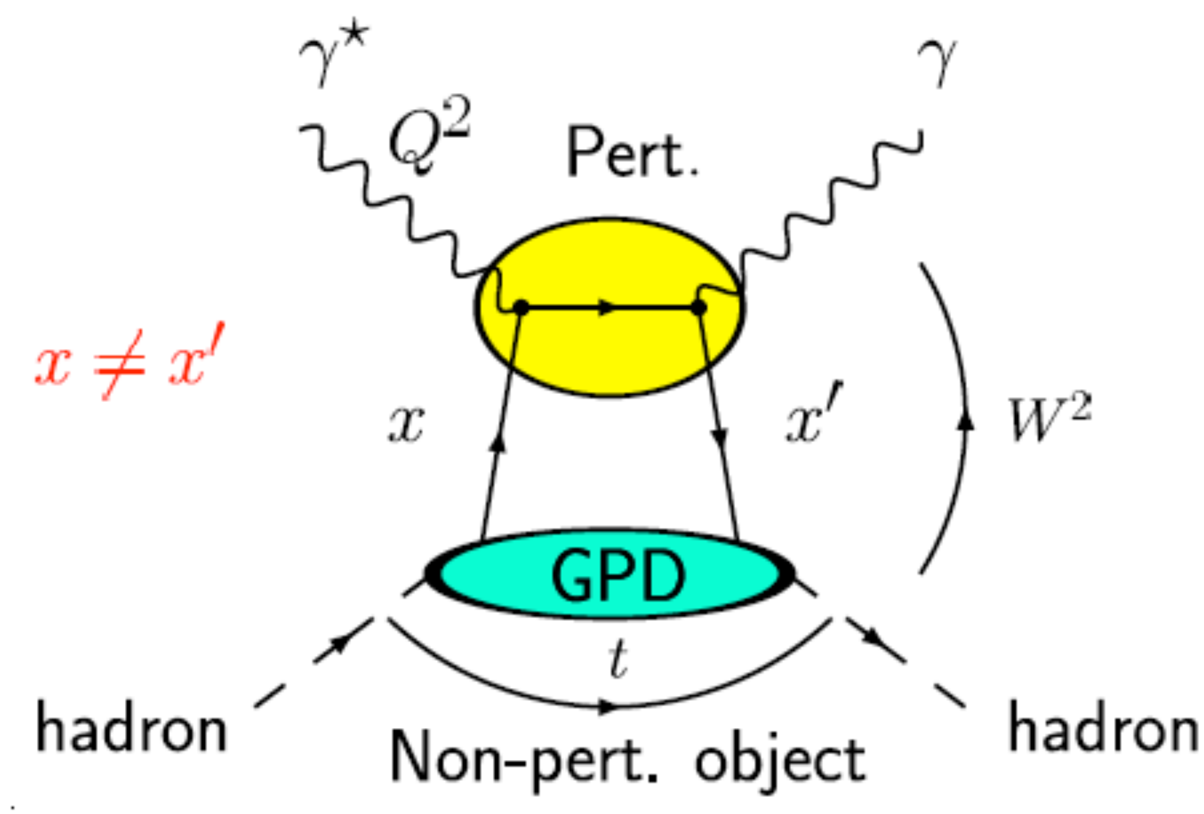
$$\Delta\Sigma_T = \int \mathrm{d}x\, g_T(x) = \Delta\Sigma$$

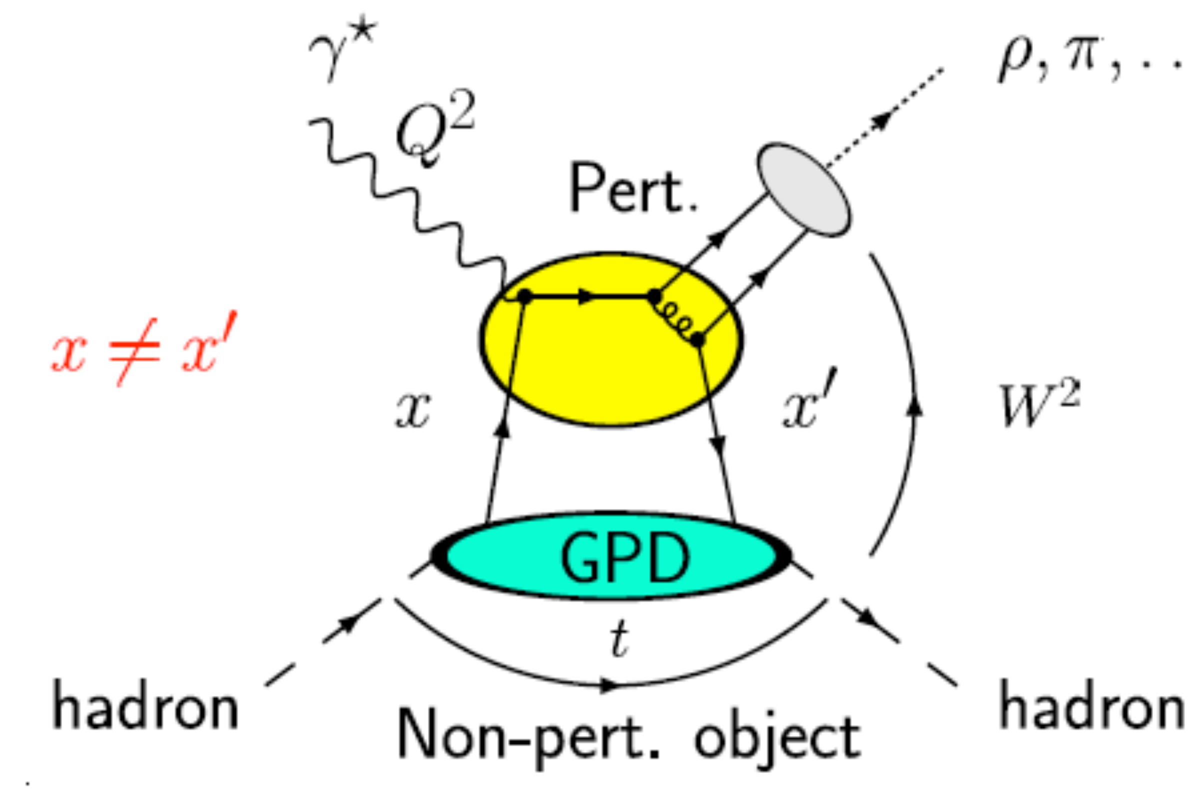
twist-3 PDF

$$\Delta G_T = \int \mathrm{d}x\, G_T(x) = \Delta G$$

no-decomposition of OAM $L_T \neq L_T^q + L_T^g$

Generalized Parton Distributions





- accessible in exclusive reactions
- factorization for large Q^2, $|t| << Q^2$
- depend on 3 variables: $\bar{x}, \xi, t$

Compton Form Factors

$$\mathrm{Im}\,\mathcal{H}(\xi, t) \stackrel{\mathrm{LO}}{=} H(\xi, \xi, t)$$

$$\mathrm{Re}\,\mathcal{H}(\xi, t) \stackrel{\mathrm{LO}}{=} \mathcal{P} \int_{-1}^{1} \mathrm{d}x\ \mathrm{H}(\bar{x}, \xi, t) \frac{1}{\bar{x} - \xi}$$

Measurements of
deeply virtual Compton scattering and hard exclusive meson production at

JLab HERMES COMPASS

DVCS at JLab

F. Sabatié

cross section at JLab mostly sensitive to CFF $\mathcal{H}$

$A_{X\,Y}$: X → beam, Y → target

Experiment	Observable	Normalized CFF dependence
CLAS	$A_{\mathrm{LU}}^{-,\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.06\mathrm{Im}\mathcal{E} + 0.21\mathrm{Im}\widetilde{\mathcal{H}}$
	$A_{\mathrm{UL}}^{-,\sin\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} + 0.12\mathrm{Im}\mathcal{H} + 0.04\mathrm{Im}\mathcal{E}$
	$A_{\mathrm{UL}}^{-,\sin 2\phi}$	$\mathrm{Im}\widetilde{\mathcal{H}} - 0.79\mathrm{Im}\mathcal{H} + 0.30\mathrm{Im}\mathcal{E} - 0.05\mathrm{Im}\widetilde{\mathcal{E}}$
HALL A	$\Delta\sigma^{\sin\phi}$	$\mathrm{Im}\mathcal{H} + 0.07\mathrm{Im}\mathcal{E} + 0.47\mathrm{Im}\widetilde{\mathcal{H}}$
	$\sigma^{\cos 0\phi}$	$1 + 0.05\mathrm{Re}\mathcal{H} + 0.007\mathcal{H}\mathcal{H}^*$
	$\sigma^{\cos\phi}$	$1 + 0.12\mathrm{Re}\mathcal{H} + 0.05\mathrm{Re}\widetilde{\mathcal{H}}$

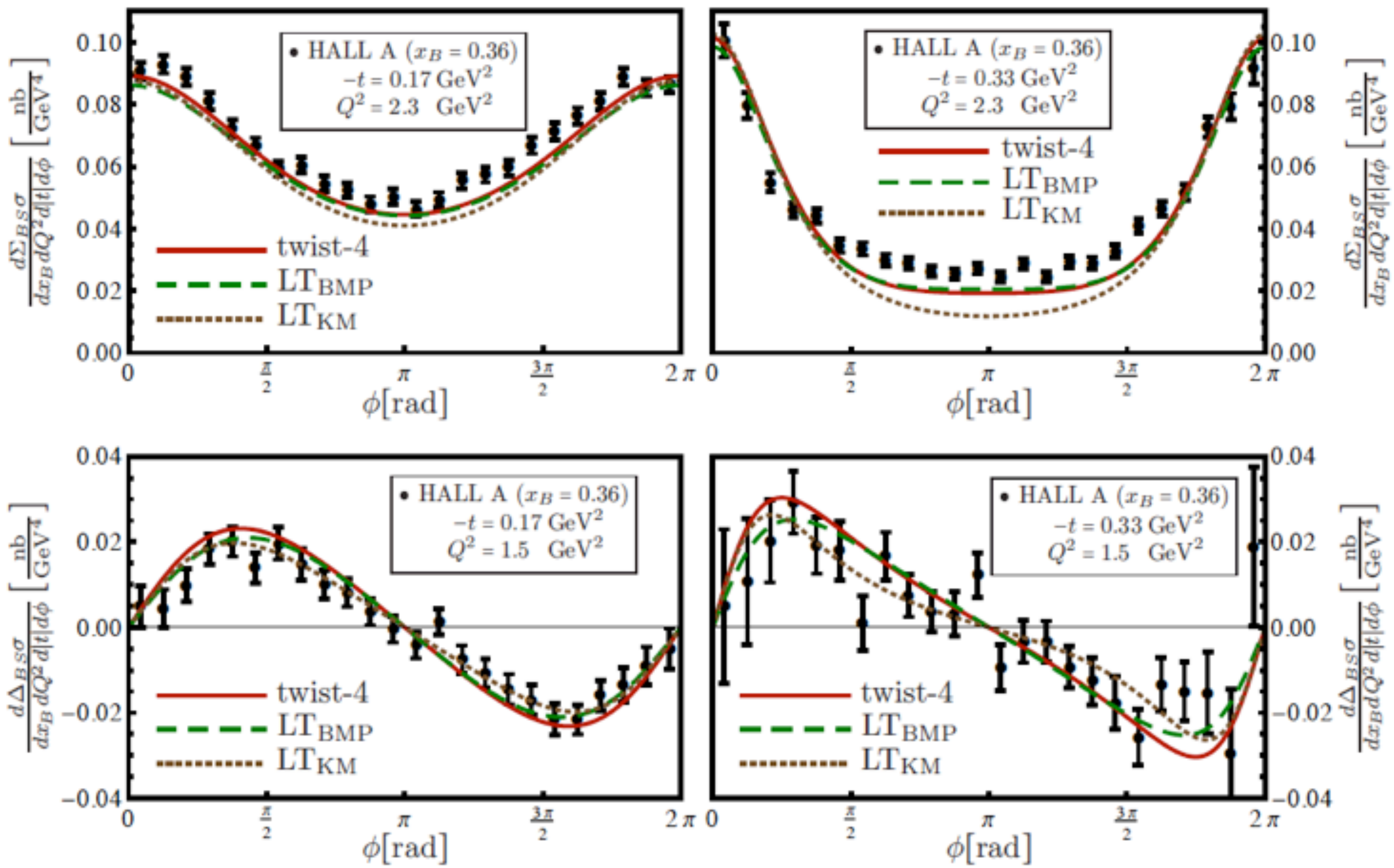
Kroll, Moutarde, F.S., EPJC73 2278 (2013)

New data and/or analysis from Hall A and CLAS for DVCS unpolarized cross section and helicity-difference cross sections

Hall A pioneering results (proton target)

First complete calculation of kinematics power corrections ~t/Q² and ~m²/Q² to twist-4 accuracy

V. Braun

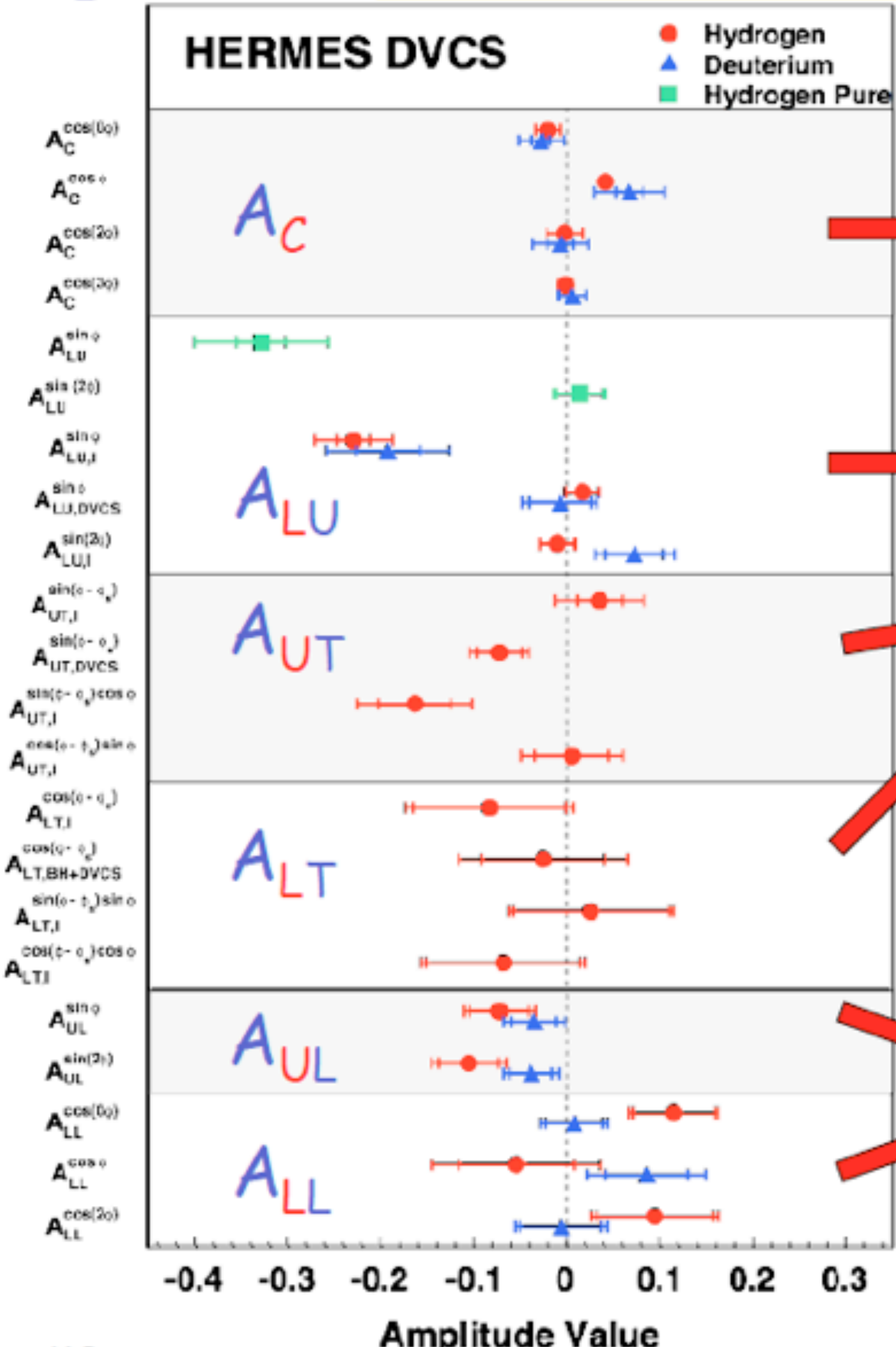


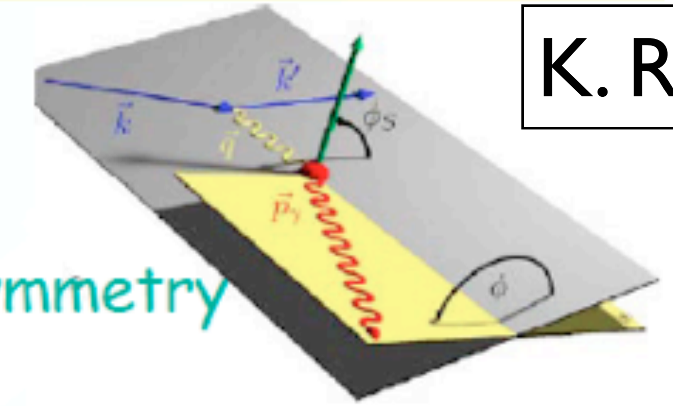
- Preliminary results from re-analysis of data show even better agreement with calculation including target mass and finite-t corrections

F. Sabatié

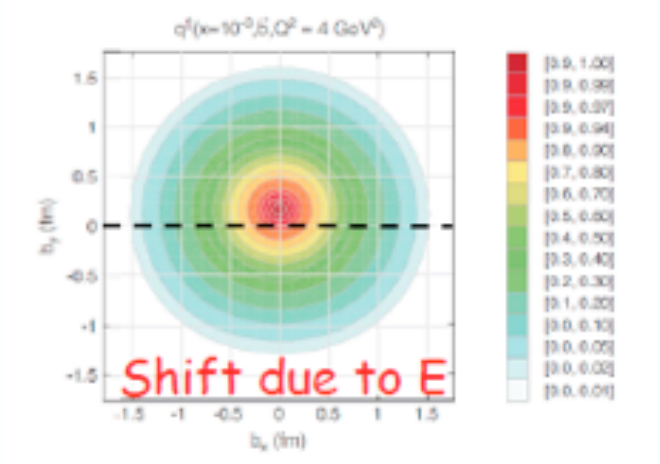
DVCS asymmetries measured @ HERMES

K. Rith





- Beam charge asymmetry
  GPD H
- Beam helicity asymmetry
  GPD H
- Transverse target-spin asymmetries
  GPD E

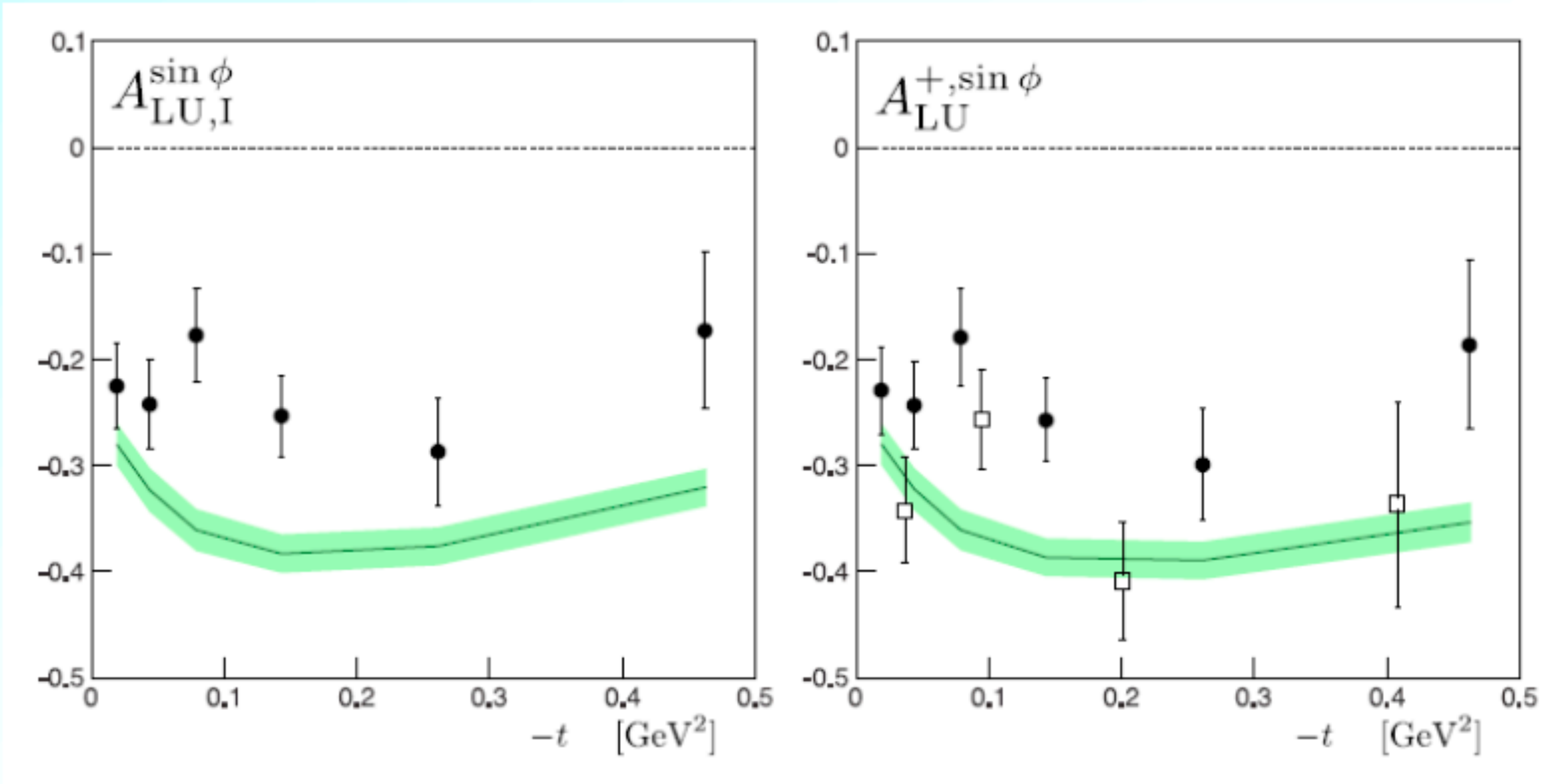


- Longitudinal target spin asymmetries
  GPD $\tilde{H}$

$$\Delta q = \lim_{\zeta,t\to 0} \int_{-1}^{+1} dx \; x \; [\tilde{H}^q(x,\zeta,t)$$

Single-charge BSA with recoil proton

K. Rith



● HERMES (without Recoil) □ HERMES (with Recoil)

Derived from GPDs, which are extracted from HEMP

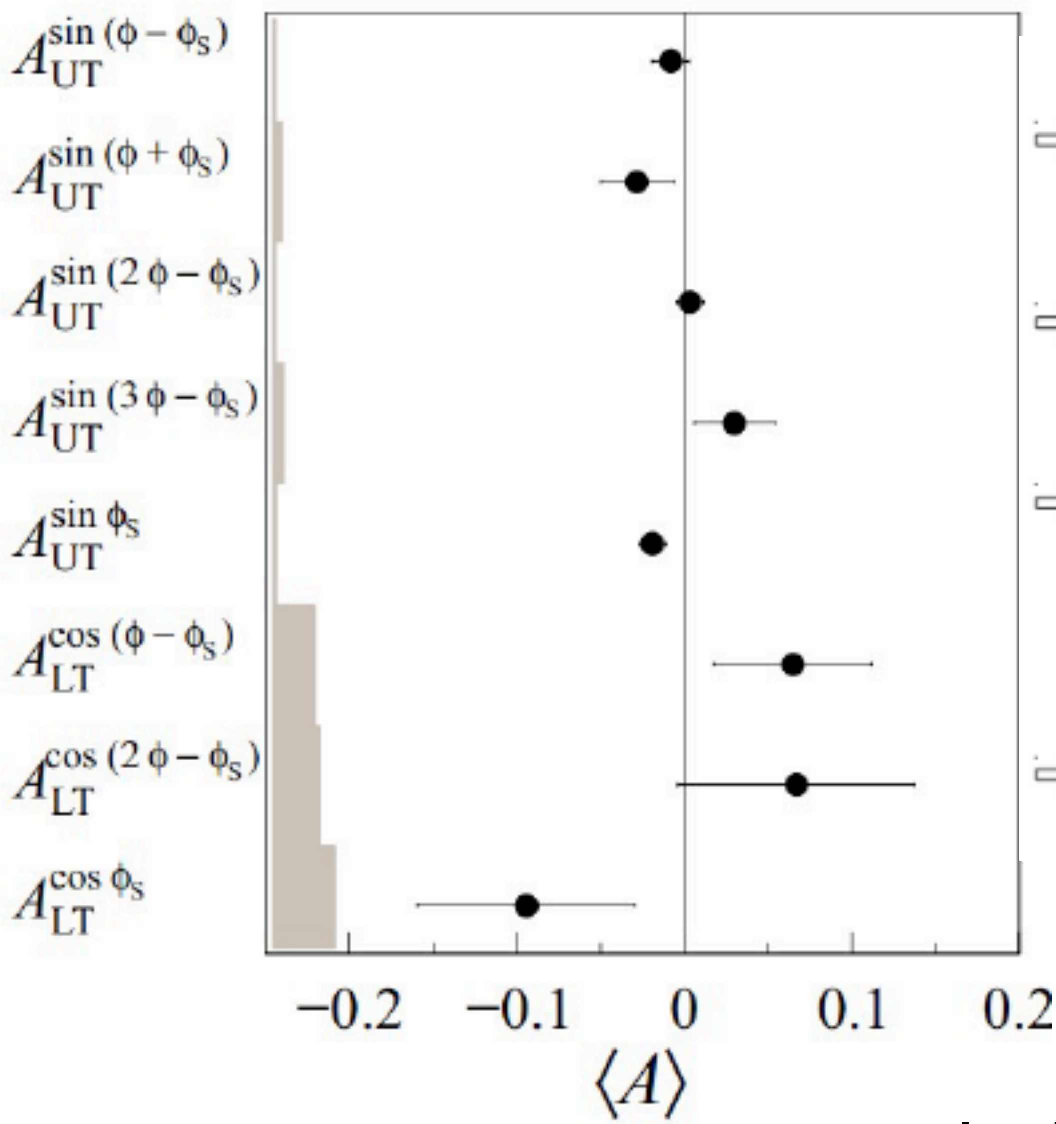
P. Kroll, H. Moutarde, F. Sabatié, Eur. Phys. J. C (2013) 73:2278

Recoil data leads to a significantly better overlap with HEMP data

Exclusive ρ^0 production at COMPASS

access to chiral-odd GPDs

P. Sznajder



$\langle x_B \rangle \approx 0.039$

$\langle Q^2 \rangle \approx 2.0\ (GeV/c)^2$

$\langle p_T^2 \rangle \approx 0.18\ (GeV/c)^2$

~E, ~H, ~E, ~H, ~H_T, ~$\bar{E}_T$

$$\Rightarrow A_{UT}^{\sin(\varphi-\varphi_s)}\sigma_0 = -2\,Im[\epsilon M^*_{0-,0+} M_{0+,0+} + M^*_{+-,++} M_{++,++} + \frac{1}{2} M^*_{0-,++} M_{0+,++}]$$

~$\bar{E}_T$, ~E

$$\Rightarrow A_{UT}^{\sin(2\varphi-\varphi_s)}\sigma_0 = -Im[M^*_{0+,++} M_{0-,0+}]$$

$\bar{E}_T = 2\tilde{H}_T - E_T$

~H_T, ~H, ~$\bar{E}_T$, ~E

$$\Rightarrow A_{UT}^{\sin(\varphi_s)}\sigma_0 = -Im[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}]$$

~H_T, ~H, ~$\bar{E}_T$, ~E

$$\Rightarrow A_{LT}^{\cos(\varphi_s)}\sigma_0 = -Re[M^*_{0-,++} M_{0+,0+} - M^*_{0+,++} M_{0-,0+}]$$

Indication of contribution from H_T
which is the non-forward generalization of transversity

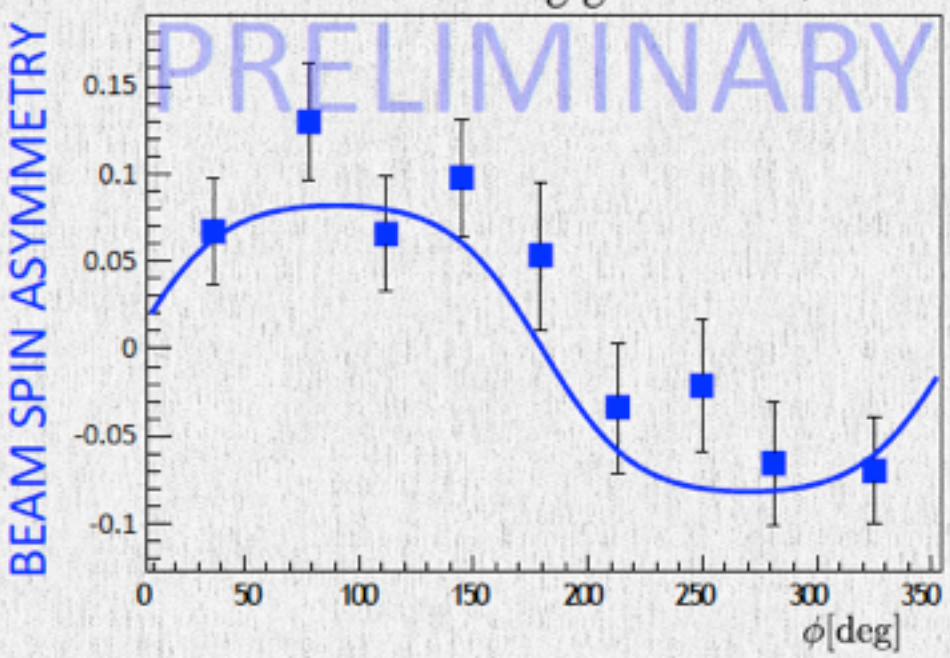
Study of exclusive meson production will be continued at COMPASS-II

E. Kabuss in the summary talk of WG7

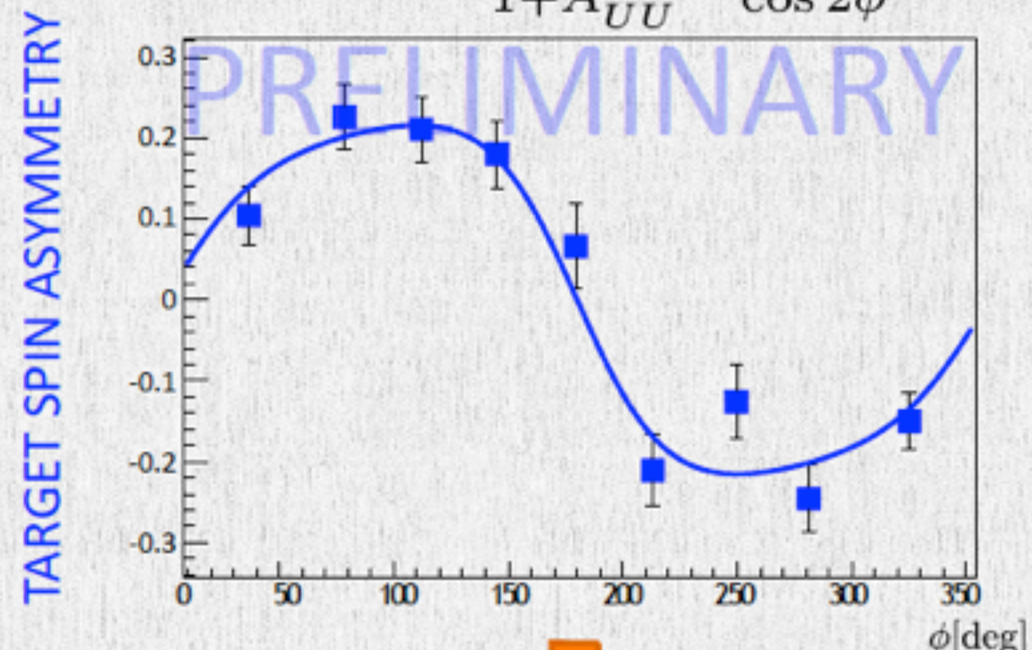
Exclusive π^0 production at CLAS

A. Kim

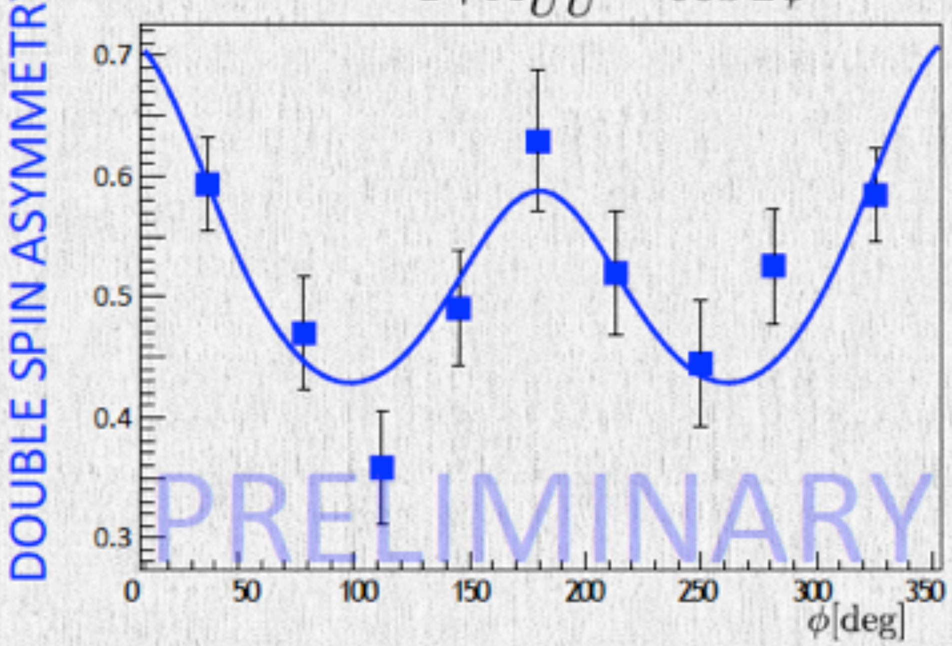
$$A_{LU}=\frac{A_{LU}^{\sin\phi}\sin\phi}{1+A_{UU}^{\cos 2\phi}\cos 2\phi}$$



$$A_{UL}=\frac{A_{UL}^{\sin\phi}\sin\phi+A_{UL}^{\sin 2\phi}\sin 2\phi}{1+A_{UU}^{\cos 2\phi}\cos 2\phi}$$



$$A_{LL}=\frac{A_{LL}^{const}+A_{LL}^{\cos\phi}\cos\phi}{1+A_{UU}^{\cos 2\phi}\cos 2\phi}$$



The data were **fitted simultaneously** with 6 parameters:

1. $A_{UU}^{\cos 2\phi}$
2. $A_{LU}^{\sin\phi}$
3. $A_{UL}^{\sin\phi}$
4. $A_{UL}^{\sin 2\phi}$
5. A_{LL}^{const}
6. $A_{LL}^{\cos\phi}$

The data were integrated over wide range of Q^2, x_B and t'

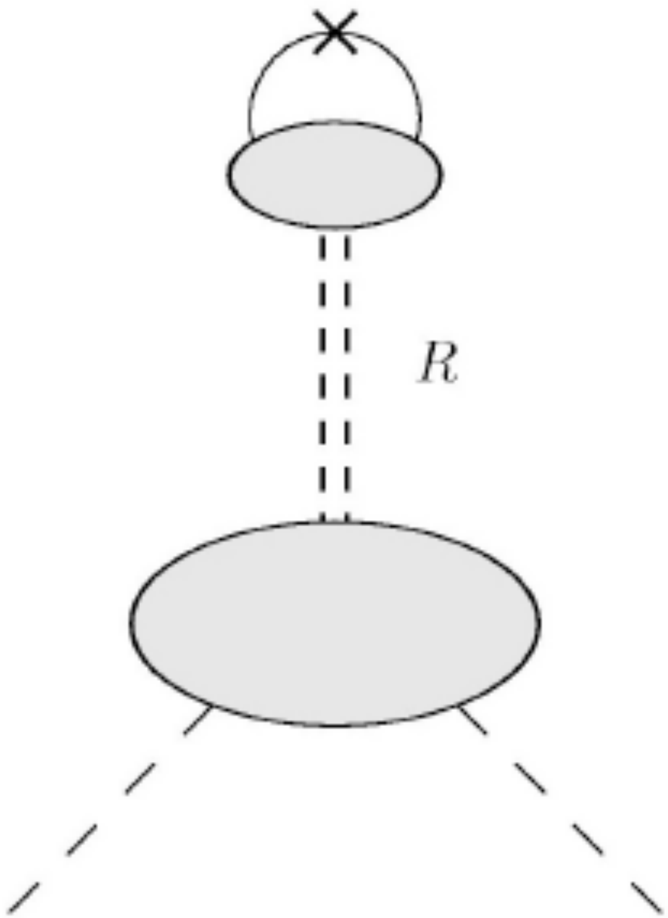
From theory: need of more phenomenological studies for chiral-odd GPDs

New representation for Chiral-odd GPDs

K. Semenov-Tian-Shansky

- GPD modeling can be done in various representations:
  double-distribution (most common)
  conformal PW expansion (dual representation)

- Aim: get more insights from considering GPD properties within different representations



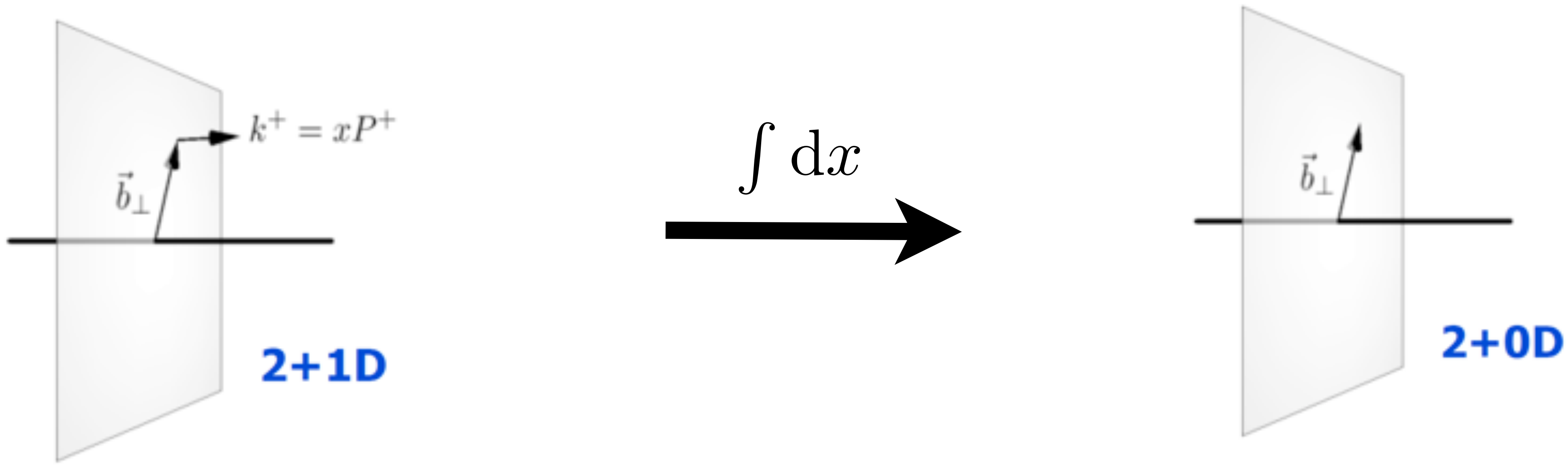
Dual representation:
GPDs are presented as infinite series of t-channel Regge exchanges

Theoretical framework extended to chiral-odd GPDs and phenomenological applications are under study

- New classification of chiral-odd pion GPDs beyond leading twist

S. Wallon

GPDs | Transverse densities

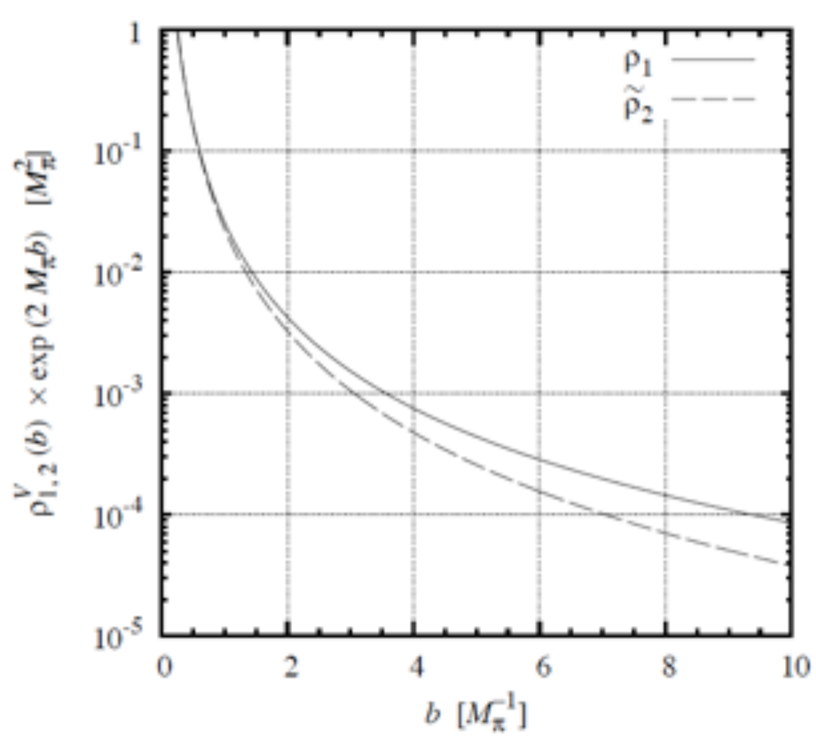


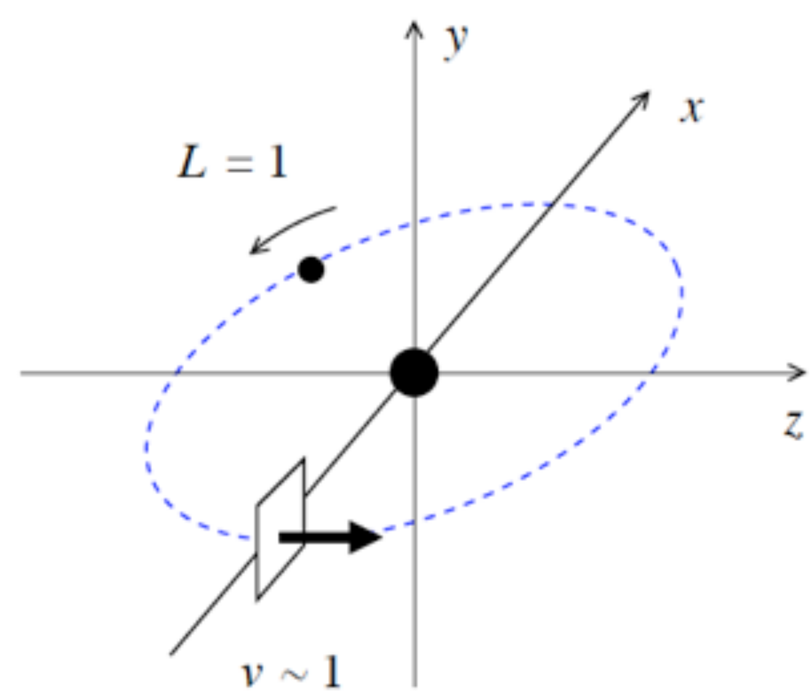
transverse charge and magnetization densities

C. Granados

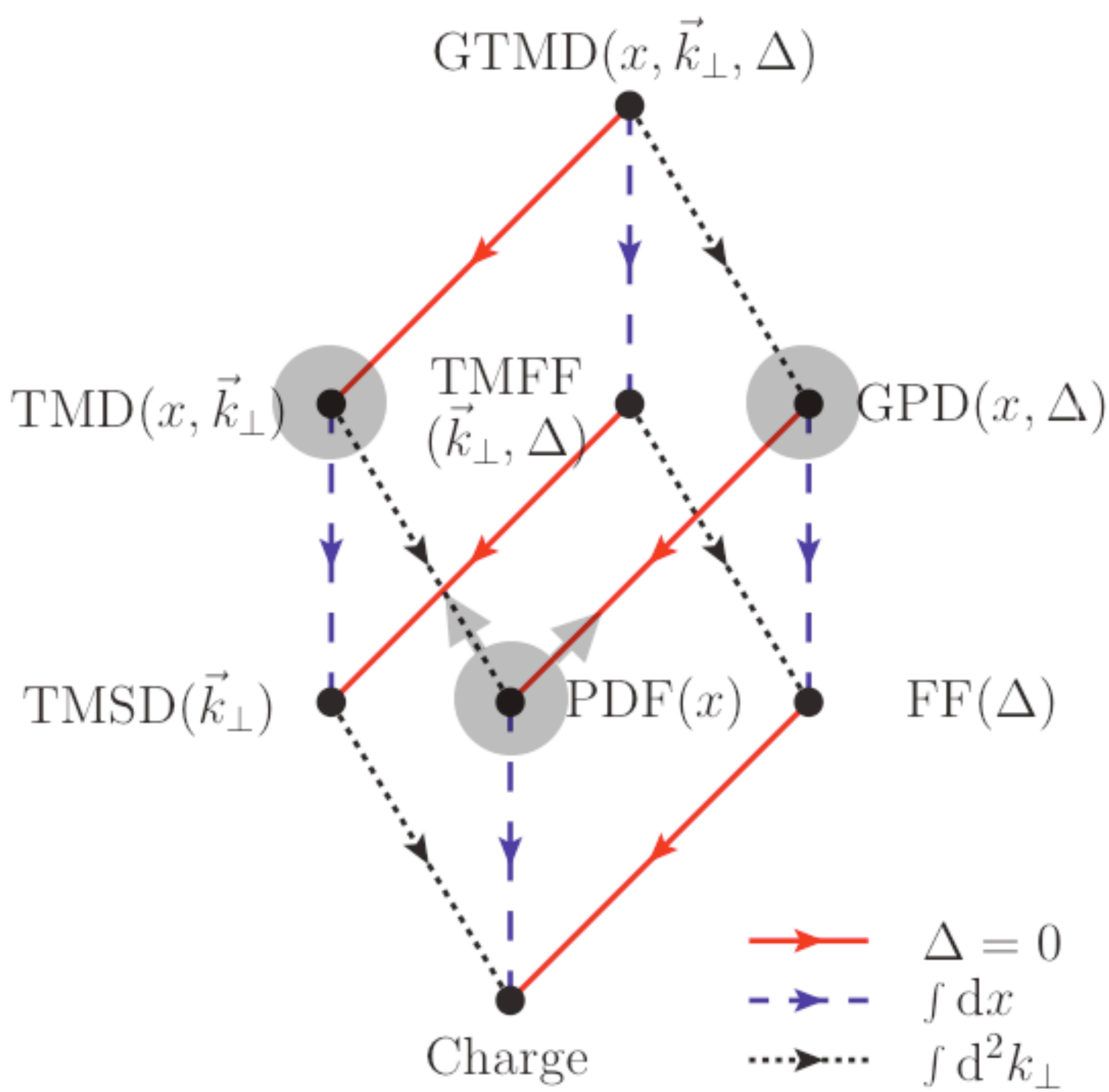
$$\rho_{1,2}(b) \quad = \quad \int \frac{d^2\Delta_T}{(2\pi)^2}\, e^{-i\boldsymbol{\Delta}_T \boldsymbol{b}}\, F_{1,2}(t = -\boldsymbol{\Delta}_T^2)$$

peripheral transverse densities from chiral effective field theory





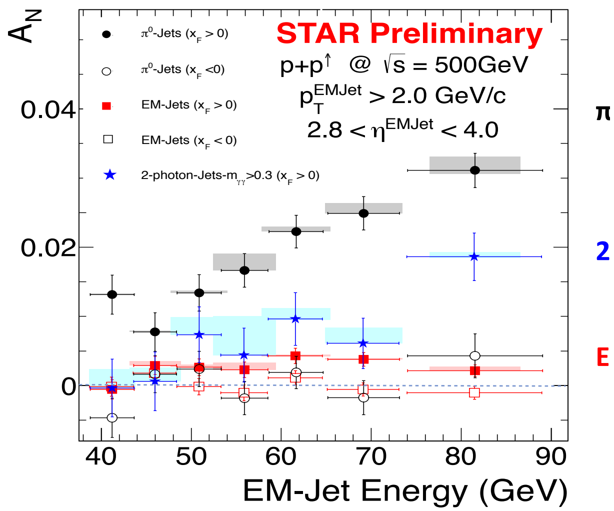
DIS2014 - WG6: Spin Physics

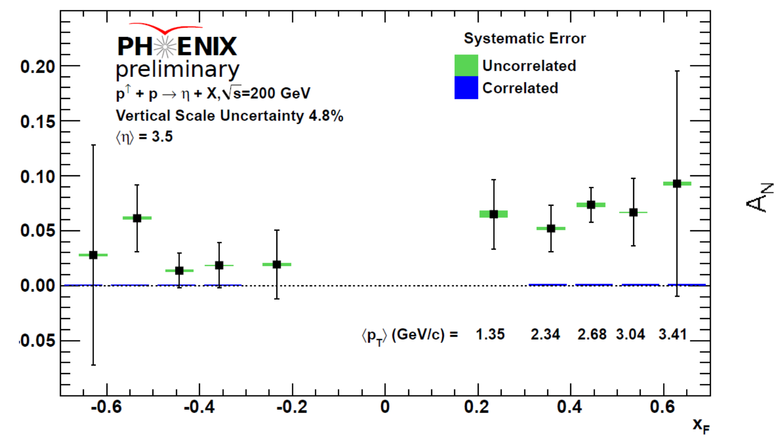


Transverse Single Spin Asymmetry

- Incompleteness of the integrated PDF: 2nd piece of (experimental) evidence
- First evidence E704 @ FNAL. TMDs have emerged as the prime explanation.

- Significant asymmetries already measured @ RHIC for $x_F > 0$ $(p\uparrow)$
- **Enriched measurement set from runs 2011/2** **K. Barish, M. Mondal**





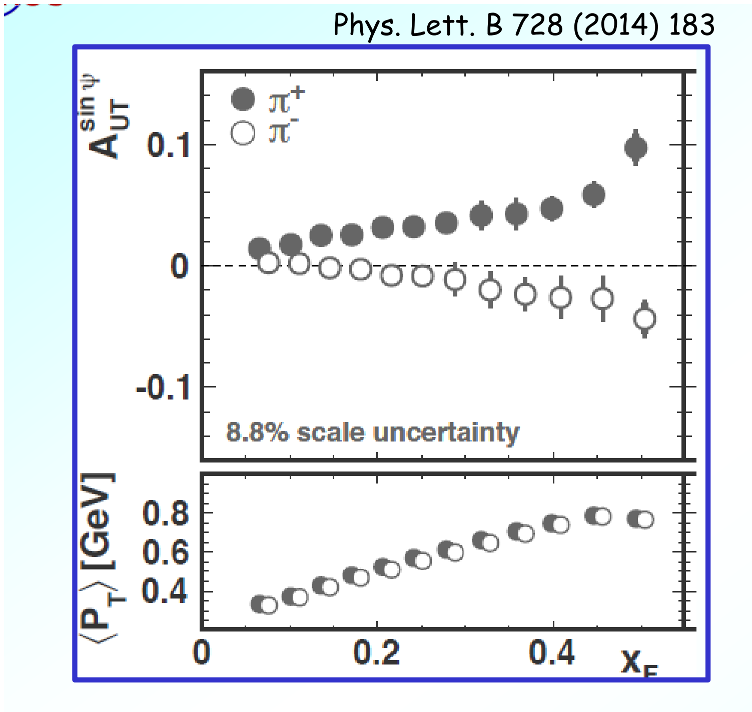
- PHENIX: A_N for extended set of FS: π^0, η and (compatible w/ 0) $\mu, J/\psi$
  $\Rightarrow$ Explore difference in fragmentation mass, strangeness, isospin

  Upgrades planned. Will significantly extend physics capabilities

- STAR: EM jets: complex behaviour upon jet topology
  $\Rightarrow$ Challenging for the TMD-based interpretation.

TSSA in $l + p^{\uparrow} \rightarrow h + X$

○ TSSA @ HERMES — K. Rith



- Substantial asymmetries for π^+ and K (*not shown*)
- x_F (l) reminiscent of hadron collisions. . .
  . . . Turns out to be a reflexion of the underlying p_T dependence
- Complicated p_T dependence of subsamples (*not shown*)

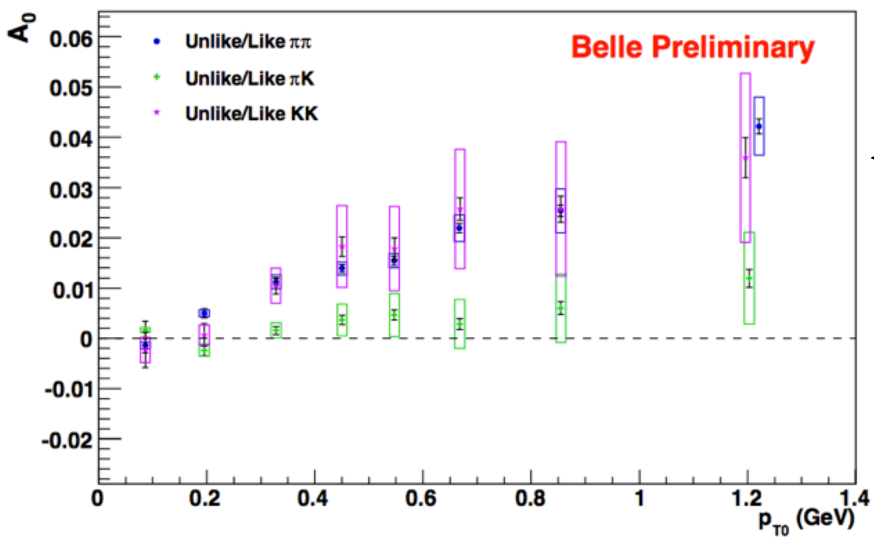
○ TMD phenomenology — U. D'Alesio

- Reproduces some of HERMES subsamples (SIDIS, high-p_T)
- Predicts significant asymmetries for EIC.

TMDFFs

◦ TMDFF @ Belle F. Giordano

- Collins FF, $H_1^\perp$: Correlation between parton transverse spin and direction of the final hadron
- SIDIS: Convolutes w/ transversity TMD
  A_{UT} , $A_{UU} \propto h_1^\perp \bigotimes H_1^\perp$



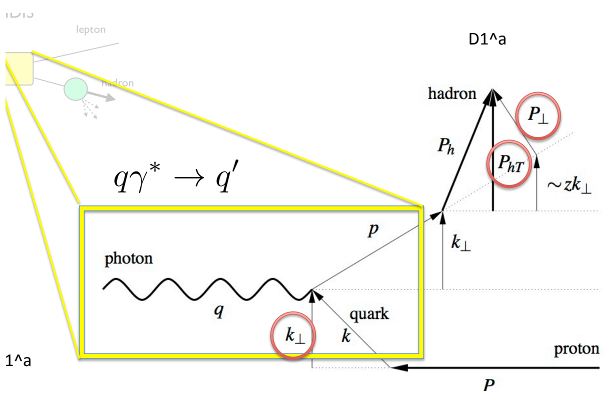
$\Longleftarrow$

- Correlation between two hadrons
  E.g. h_1 modulation w.r.t. h_2 scat. plane
- Access $H_1^\perp(z_1)H_1^\perp(z_2)$ / $D_1^\perp(z_1)D_1^\perp(z_2)$ (worked out by D. Boer)
- New: KK and πK pairs

- Disentangling the flavor dependent fragmentation contributions challenging.

Extract TMDs from data: (global) fit

- Fit of unpolarized SIDIS multiplicity $vs.$ p_T data TMDPDF $\otimes$ TMDFF



- **Fit of HERMES multiplicities** **A. Signori**
  - Gaussian widths ($modeling\ k_\perp, p_\perp\ dependence$) specified *per* flavor

$\Rightarrow$ Clear indication of a flavor dependence
($e.g.$) D_q^π favored width < unfavored & D_q^K favored

- **Attempt at fitting of HERMES + COMPASS** **J. O. Gonzalez Hernandez**

$\Rightarrow$ Unsuccessful: large tension between/within sets. Whether to data or oversimplistic model?

- Upcoming: global fits, using TMD evolution

TMD Evolution I. Scimeni

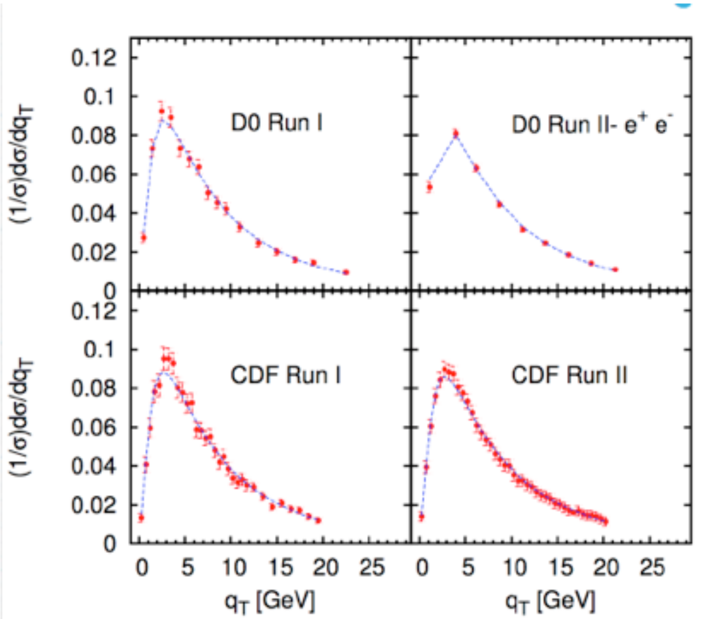
$$\tilde{F}^{[\Gamma]}_{f/N}(x, \mathbf{b}_\perp, S; \zeta_{F,f}, \mu_f^2) = \tilde{F}^{[\Gamma]}_{f/N}(x, \mathbf{b}_\perp, S; \zeta_{F,i}, \mu_i^2)\, \tilde{R}\left(b_T; \zeta_{F,i}, \mu_i^2, \zeta_{F,f}, \mu_f^2\right),$$

$$\tilde{D}^{[\Gamma]}_{h/f}(z, \mathbf{b}_\perp, S_h; \zeta_{D,f}, \mu_f^2) = \tilde{D}^{[\Gamma]}_{h/f}(z, \mathbf{b}_\perp, S_h; \zeta_{D,i}, \mu_i^2)\, \tilde{R}\left(b_T; \zeta_{D,i}, \mu_i^2, \zeta_{D,f}, \mu_f^2\right),$$

$$\tilde{R}(b; \zeta_i, \mu_i^2, \zeta_f, \mu_f^2) = \exp\left\{ \int_{\mu_i}^{\mu_f} \frac{d\bar{\mu}}{\bar{\mu}} \gamma\left(\alpha_s(\bar{\mu}), \ln \frac{\zeta_f}{\bar{\mu}^2}\right) \right\} \left(\frac{\zeta_f}{\zeta_i}\right)^{-D(b_T;\mu_i)}$$

Evolution of all TMDs is universal (alike PDFs and FFs it is process independent)

Evolution of all TMDs is spin independent and it is the same for TMDs and TMDFF



First fits for unpolarized TMD in DY.
Data with 4 < Q<10 GeV can fix non-perturbative parameters which have some impact on vector boson production and DY processes at LHC.

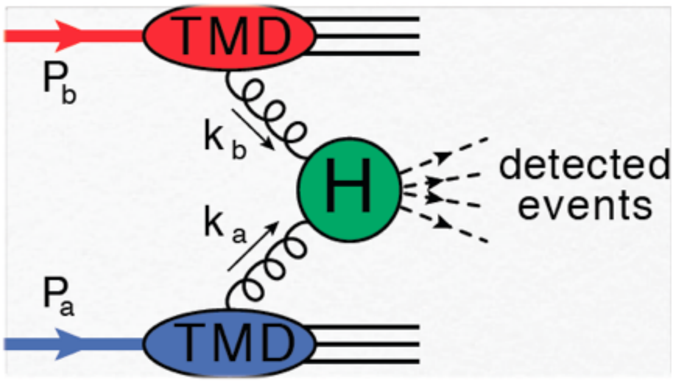
TMD non-perturbative QCD effects should be included in high precision LHC observables

(*courtesy of B. Pasquini*)

Application of TMDs: Gluon TMDs and Higgs Boson Production

M. Schlegel

$pp \to \gamma\gamma X$

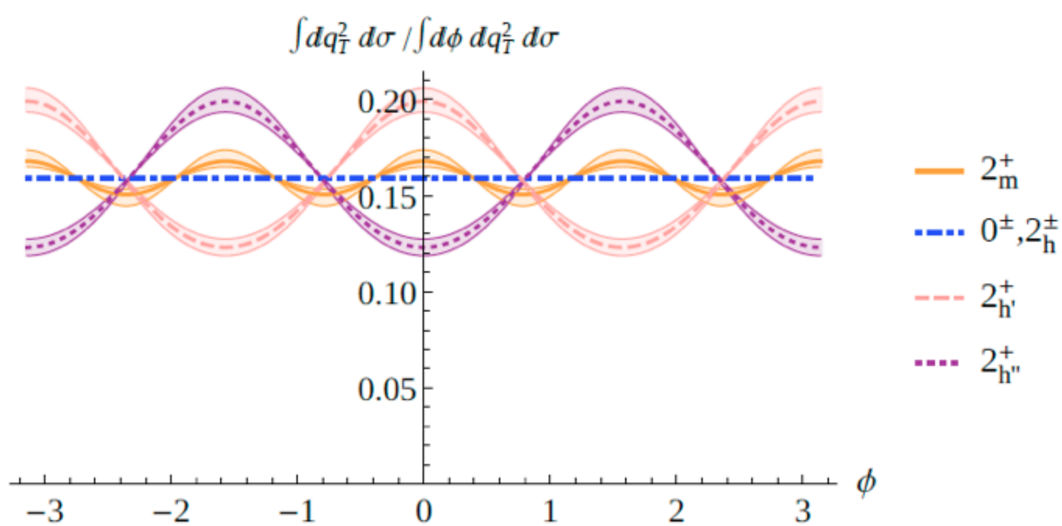


TMD Factorization:

cross section is split into a partonic

$gg \to \gamma\gamma$ cross section

and two TMD gluon correlators $(f_1^g,\ h_1^{\perp\,g}$

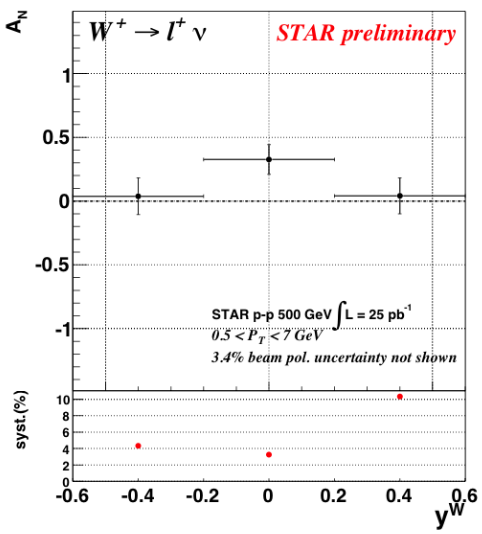


(courtesy of B. Pasquini)

Prospects

- Mapping of GPD H from JLab $\to$ HERA (**F. Sabatie**)
- TCS @ JLab (**J. Wagner**)
- DVCS/MP @ COMPASS in 1916 (**E.M. Kabuß**)

- **Sign change between SIDIS and Drell-Yan or W or Z**
  - Important test of pQCD
  - **$W\pm$ and $Z0$ production @ RHIC** **S. Fazio**



- Test measurement of A_N for $Z0$ and $W\pm$
- Systematics under control. Up to 900 pb^{-1}

$\Rightarrow$ Proof of principle:
Stat. significant sign change measurement

- **Polarized Drell-Yan @ COMPASS** **C. Quintans**
  - Expected stat. error in the Sivers asymmetry $\simeq 1\%$.
  - Direct Drell-Yan *vs.* SIDIS comparison in overlapping kinematical domain.