Nucleon spin: longitudinal, transverse, and evolution

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- How do quarks and gluons carry the proton spin?
  - What is the role of gluons?
  - What is the role of sea quarks?

- What are the origins of the transverse spin phenomena in QCD?

- What are the underlying mechanism and how do we the associated QCD dynamics?

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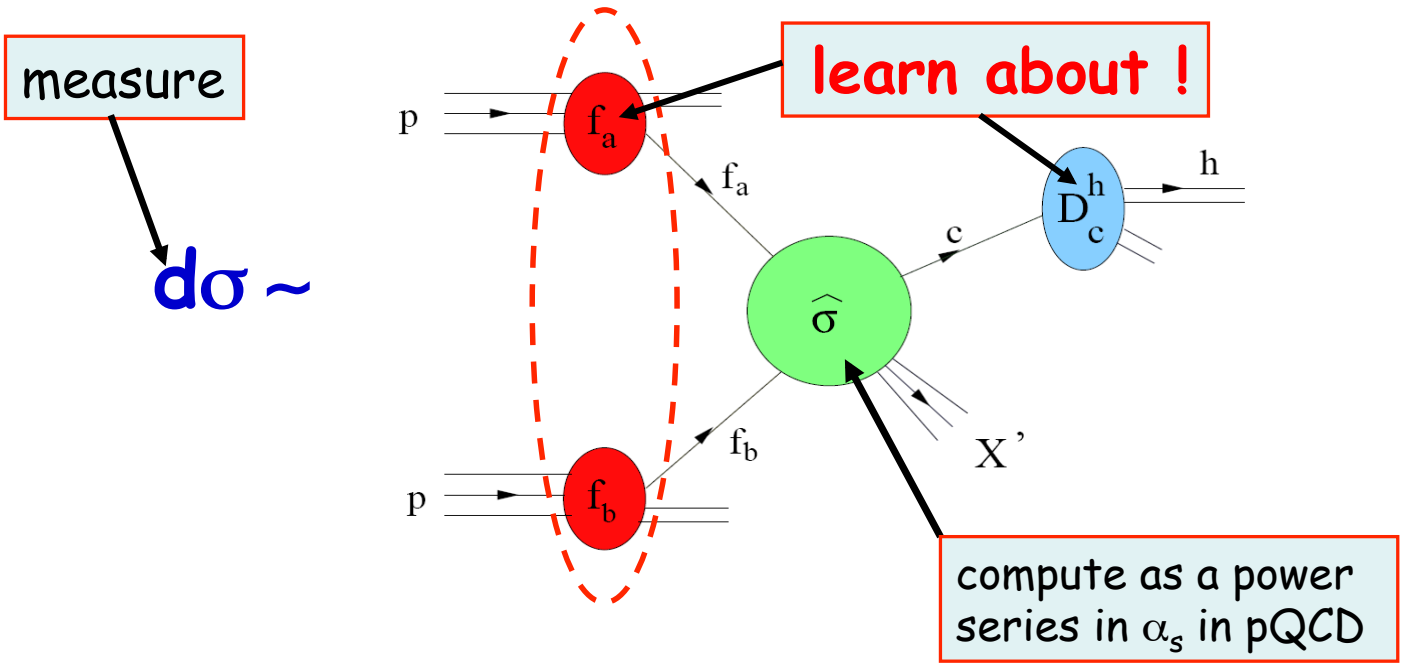
Mechanism and Evolution

QCD factorization

- Factorization of short-distance and long-distance physics

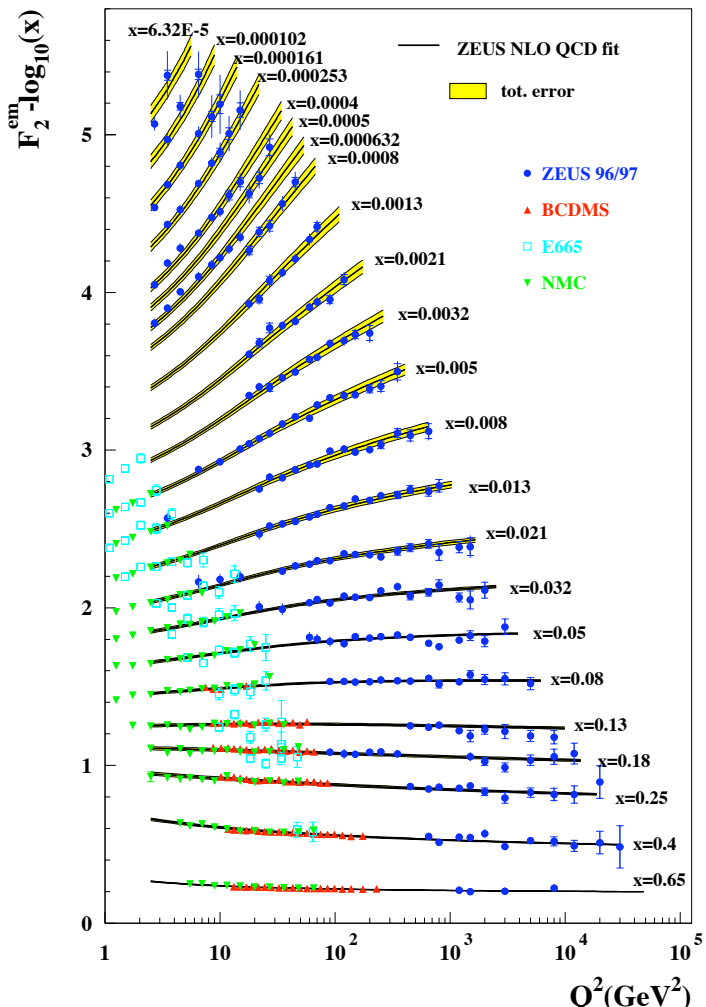


$$\sigma(P_h, S) \propto f_a(x_a, \mu^2) \otimes f_b(x_b, \mu^2) \otimes \hat{\sigma}_{ab\to c} \otimes D_{h/c}(z_c, \mu^2)$$

Universal Universal calculable Universal

Success of QCD factorization

- Universality of PDFs: mapped in one process (say DIS), used in other process



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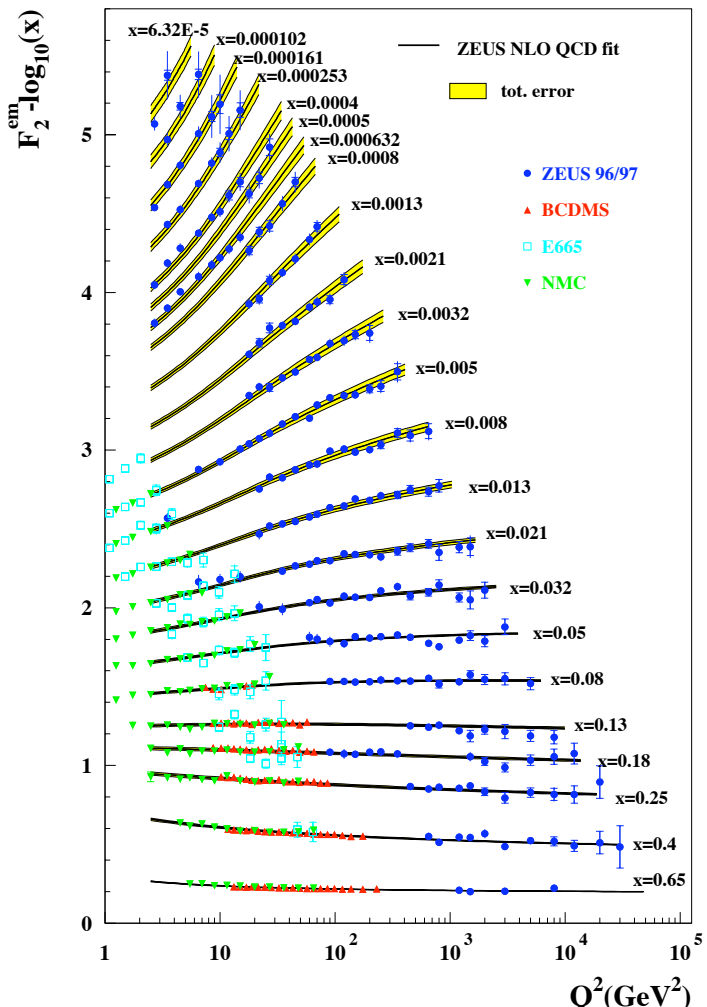

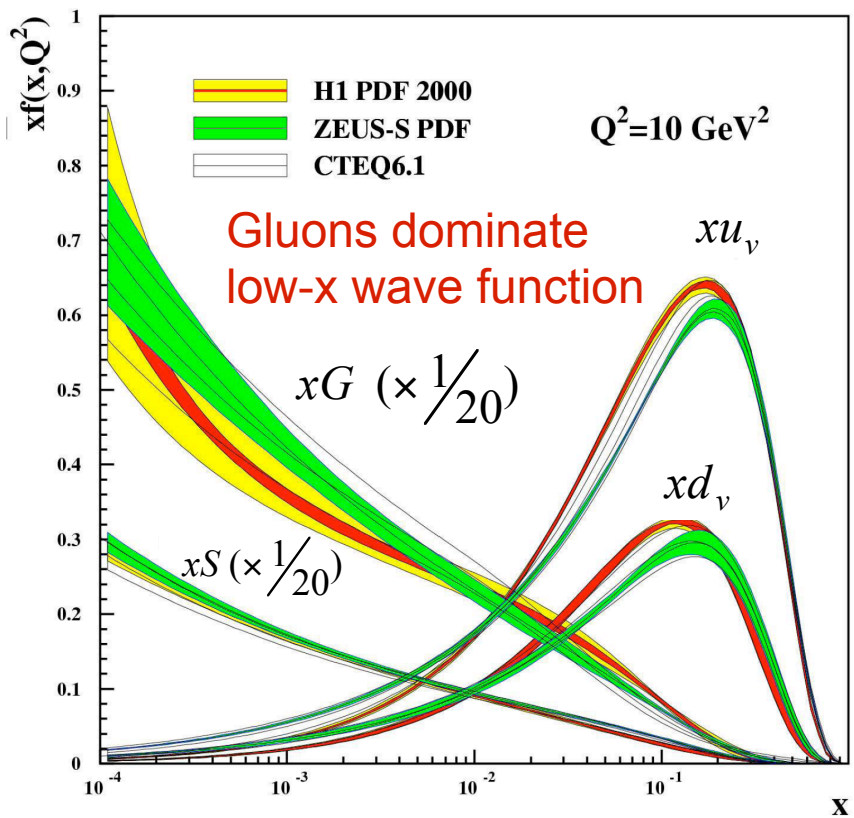

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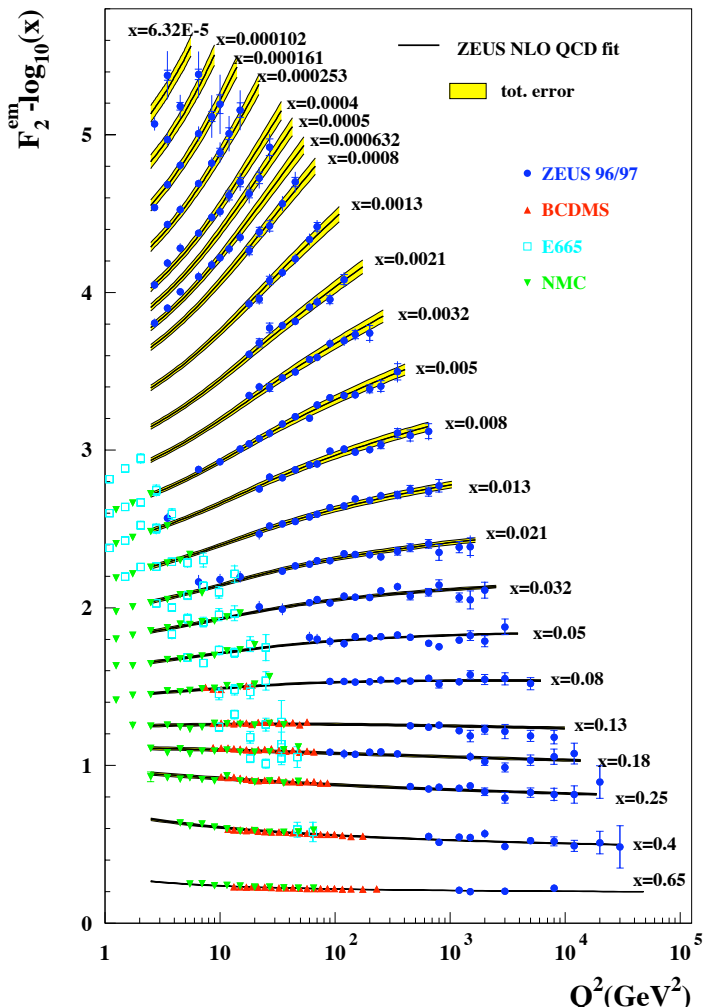

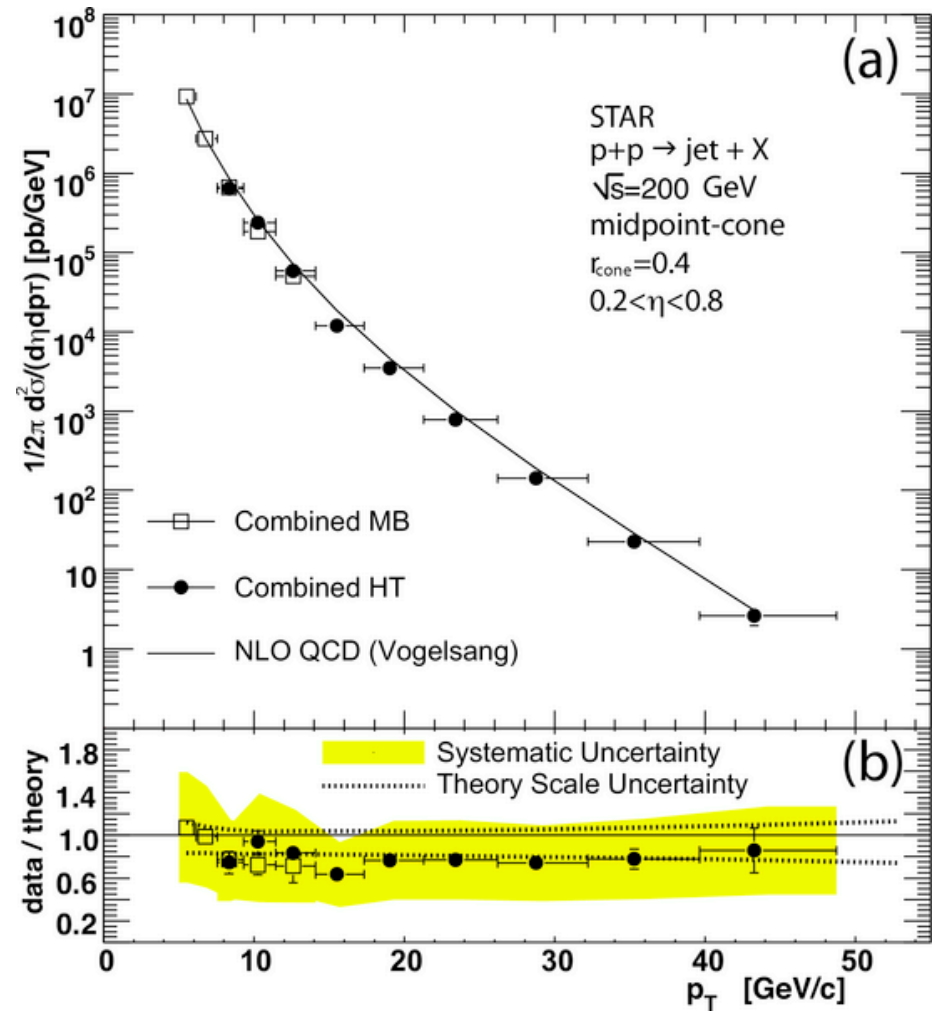

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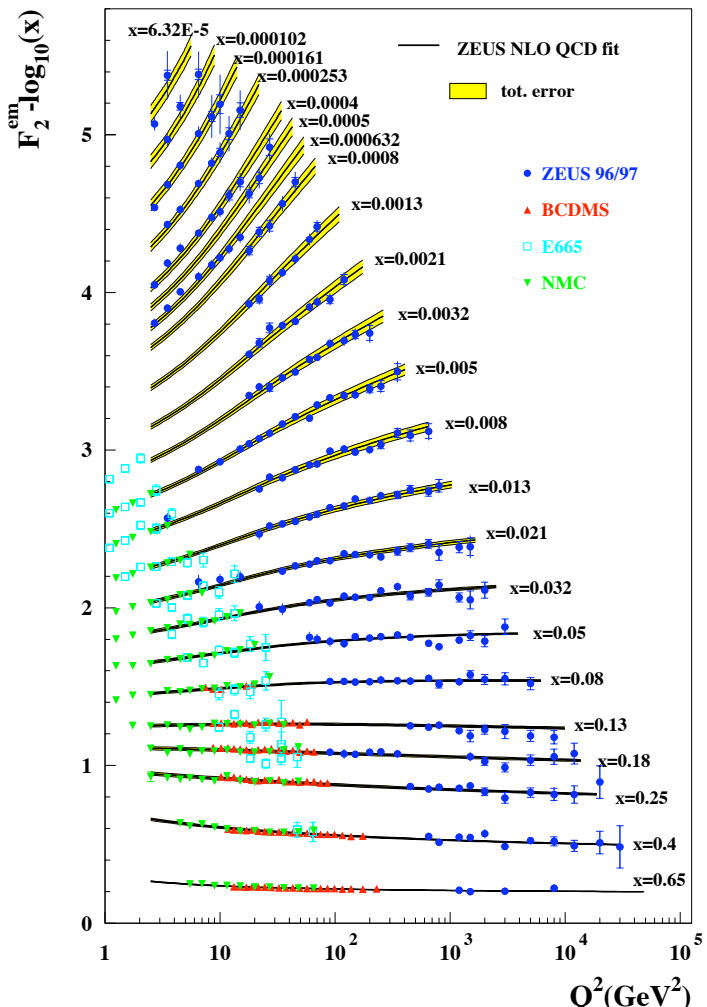

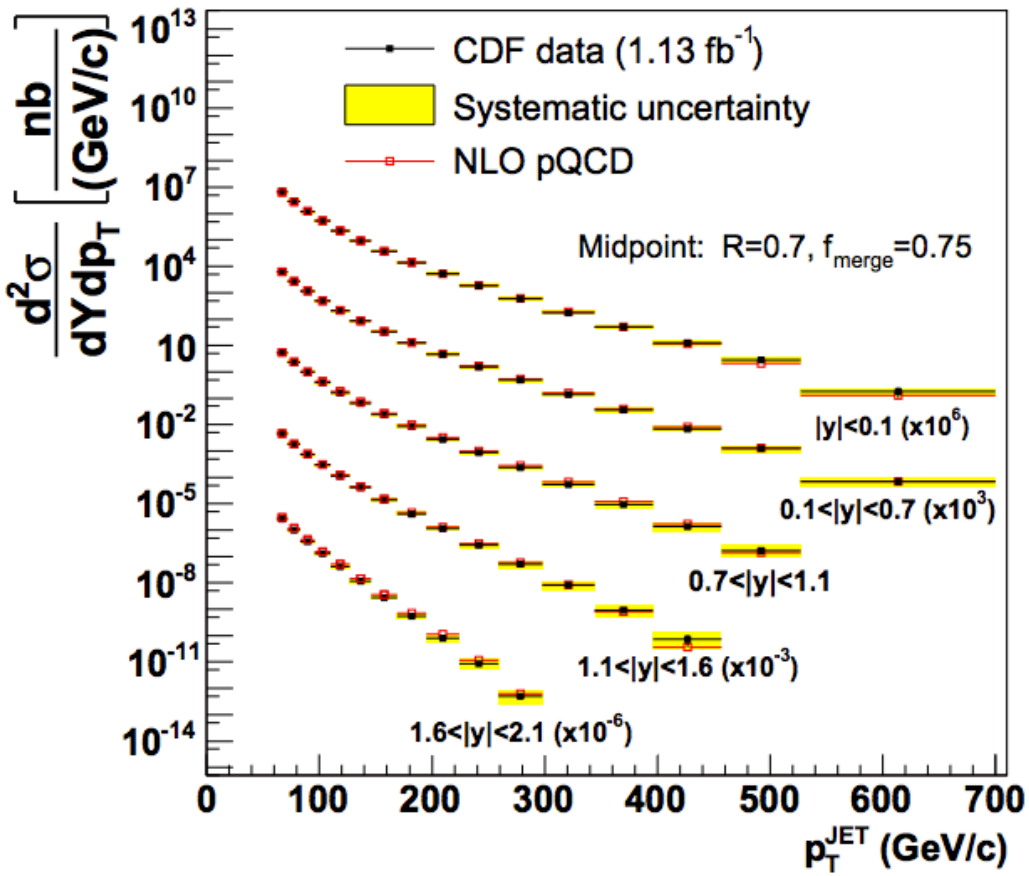

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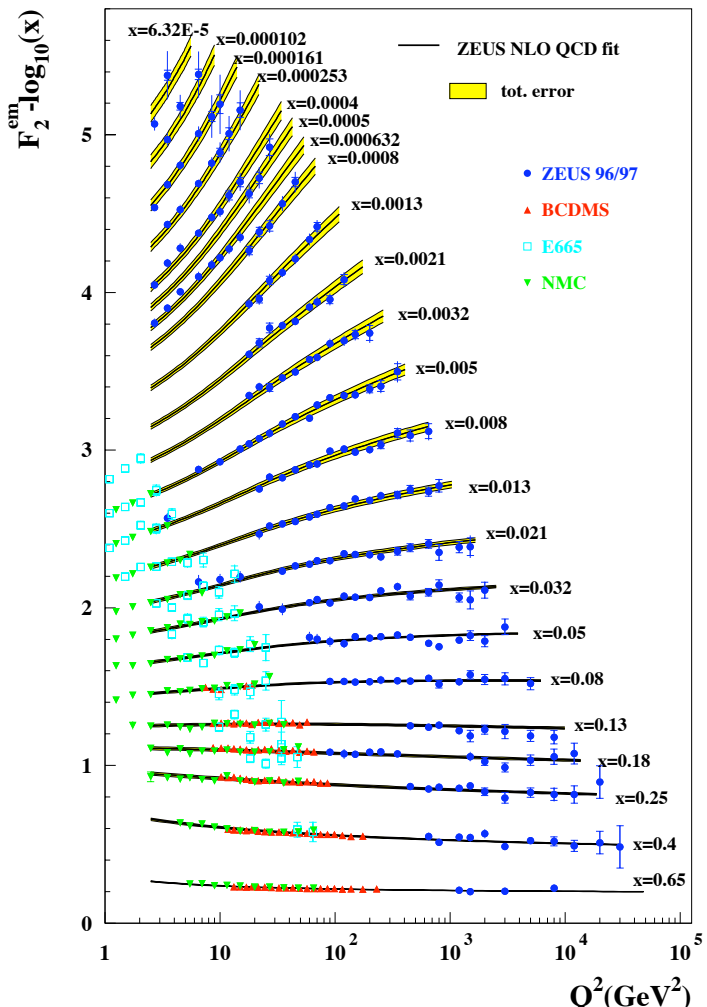
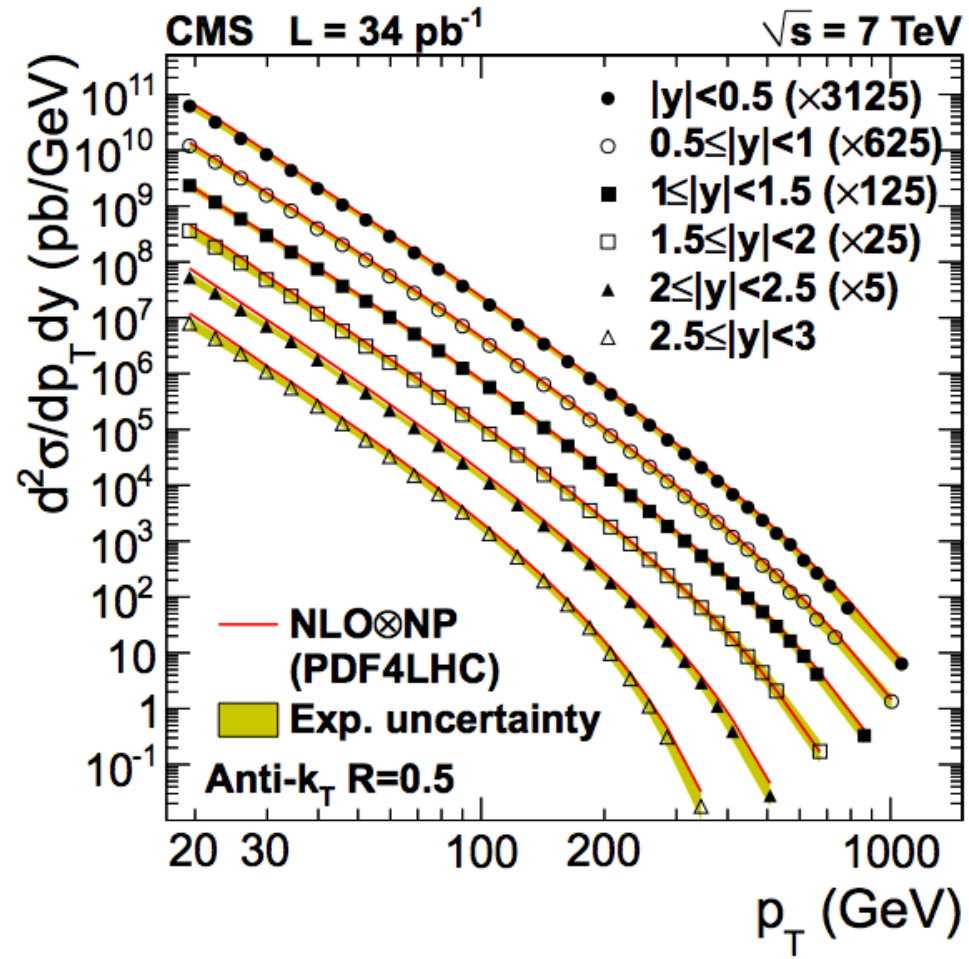


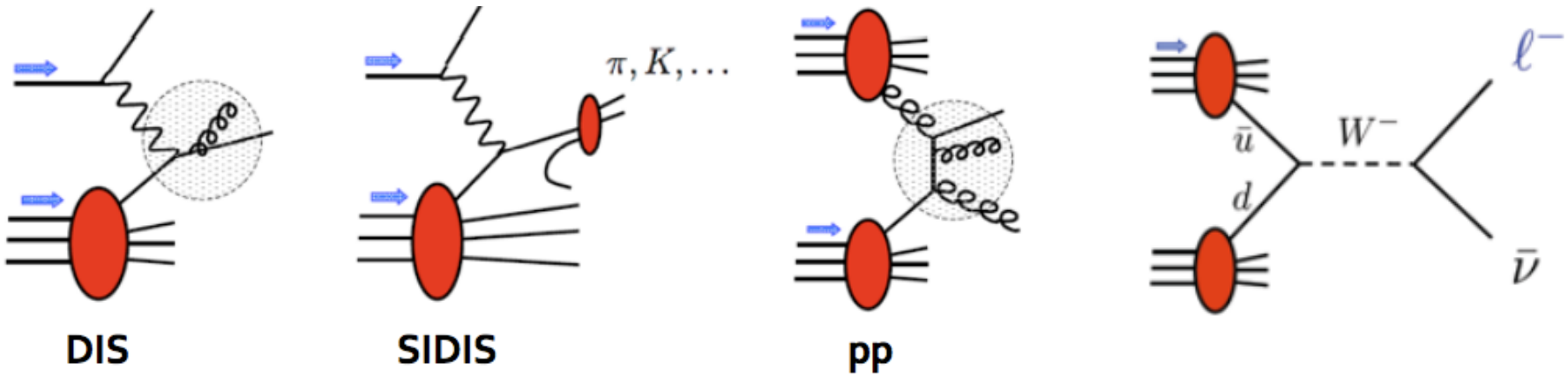


LONGITUDINAL SPIN

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

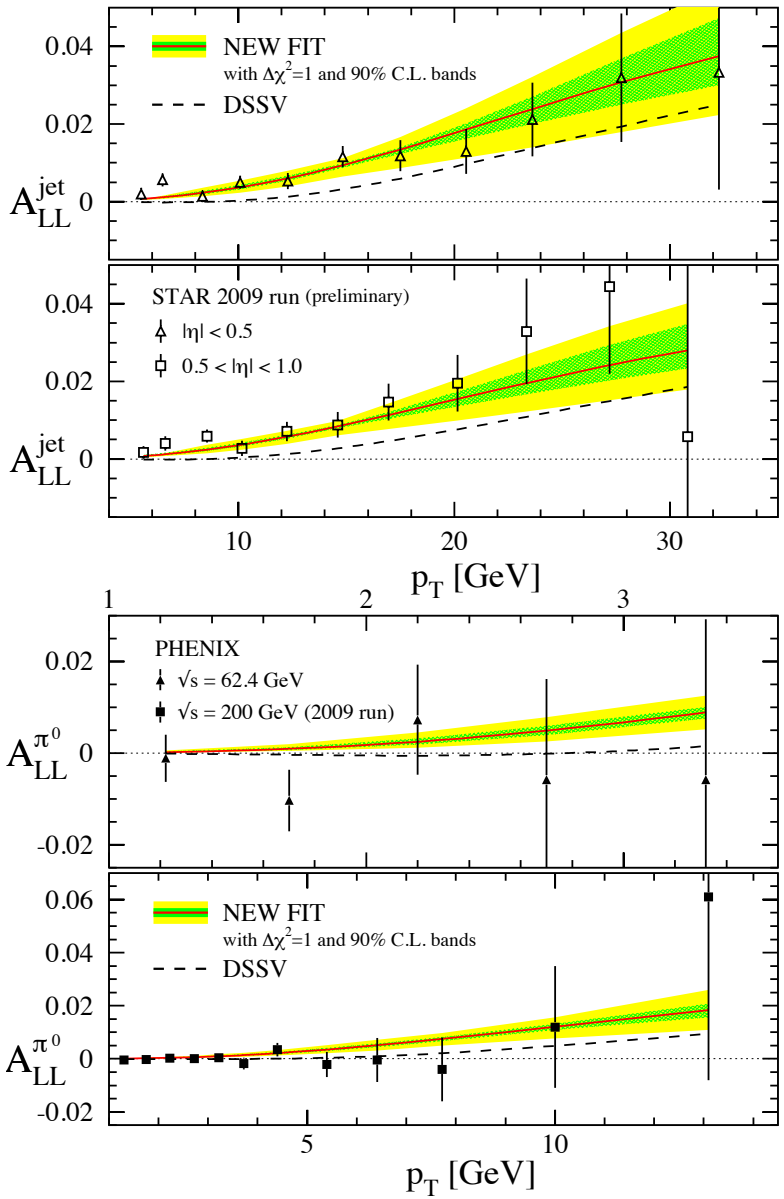
Probes of nucleon helicity structure

- Hadronic type final states (jet, hadron) in p+p collisions are sensitive to the gluon helicity distribution



- Weak interaction (W boson) has flavor separation, can map out sea quark helicity distribution

Recent progress: $\Delta G \neq 0$



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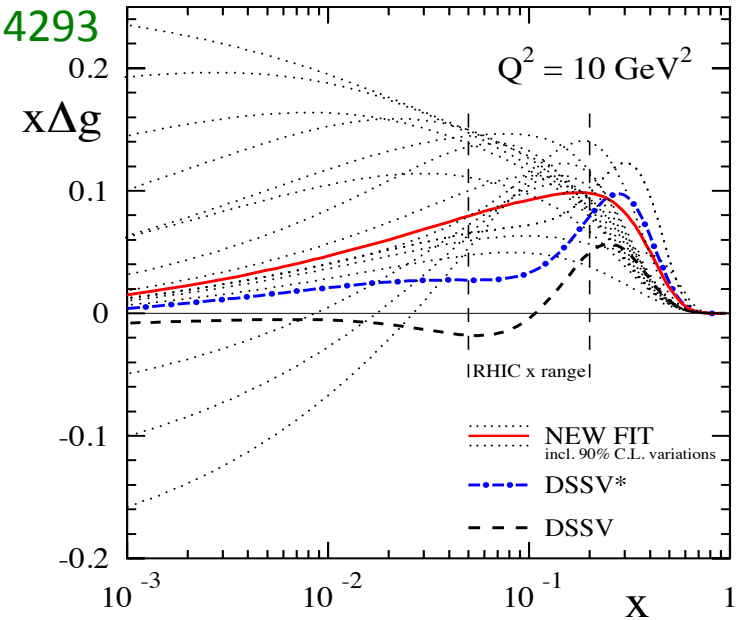


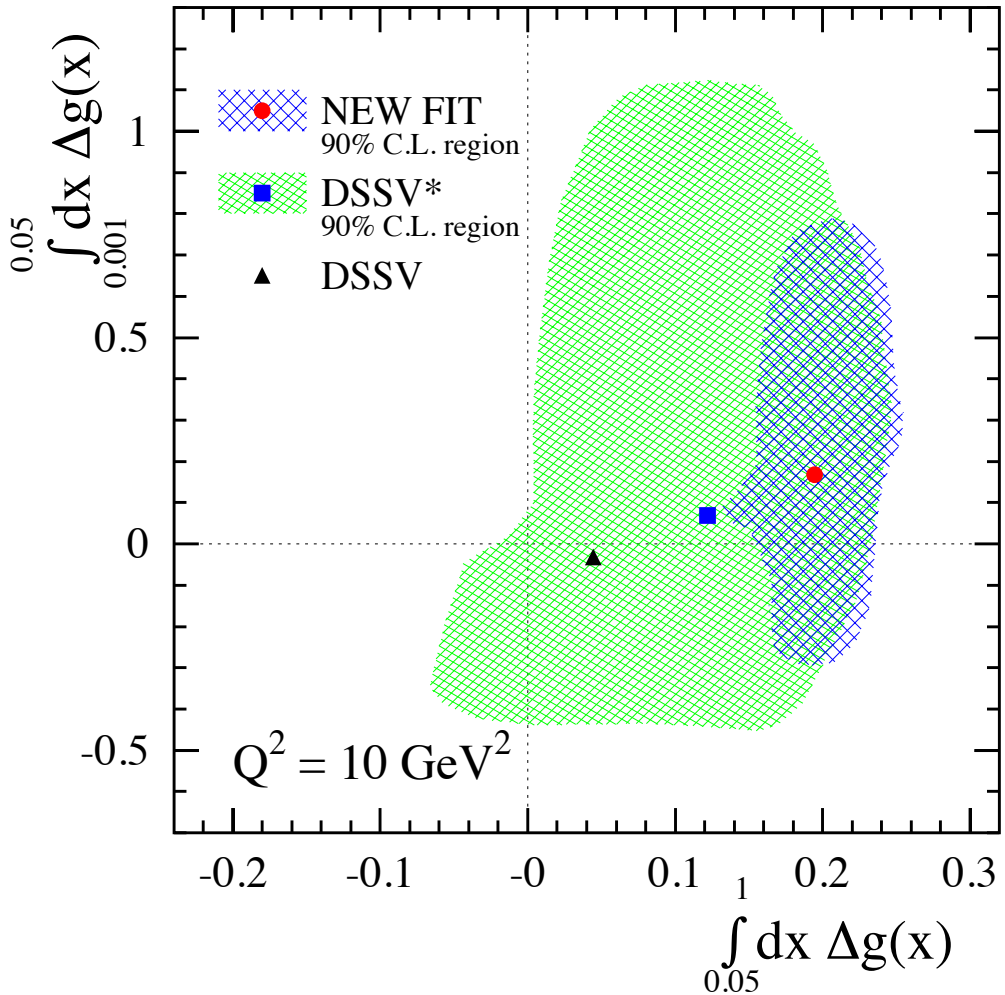
New Fit: DSSV + all new SIDIS + RHIC 2009

DSSV: $$\Delta G = \int_{0.05}^{0.2} dx \Delta g(x) = 0.006 \pm 0.06$$

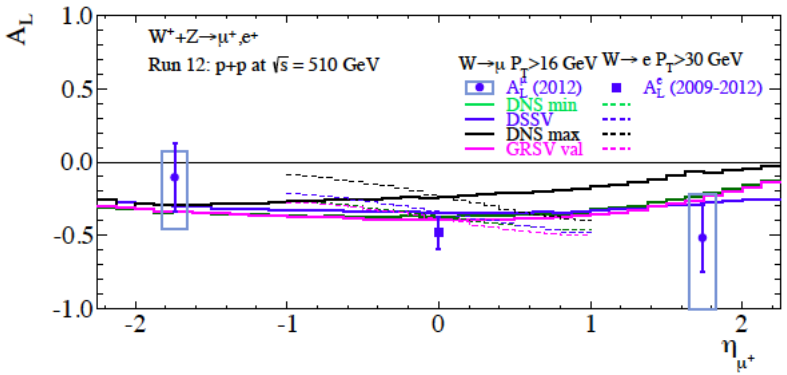
New Fit: $$\Delta G = \int_{0.05}^{0.2} dx \Delta g(x) = 0.2 \pm^{0.06}_{0.07}$$

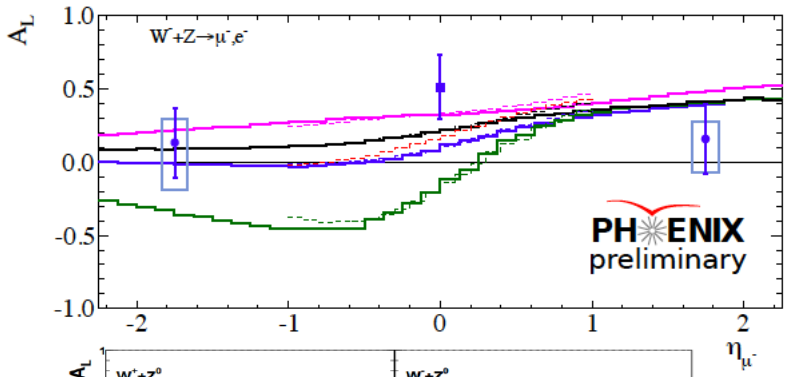
Recent progress: large uncertainty for $\Delta g(x)$ at small x

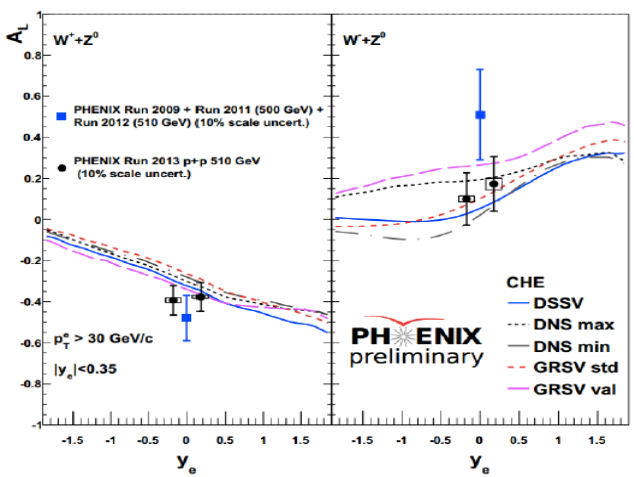
- Need observables which probes small x region: dijet in forward direction

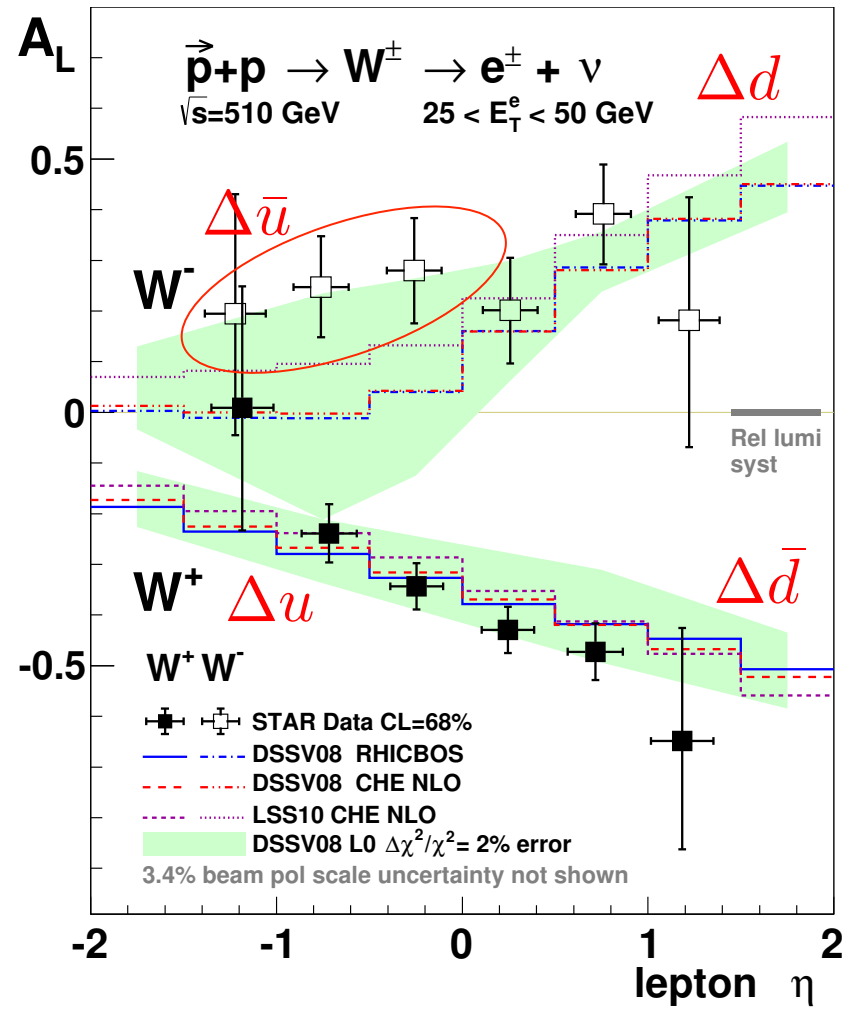


Recent progress: W



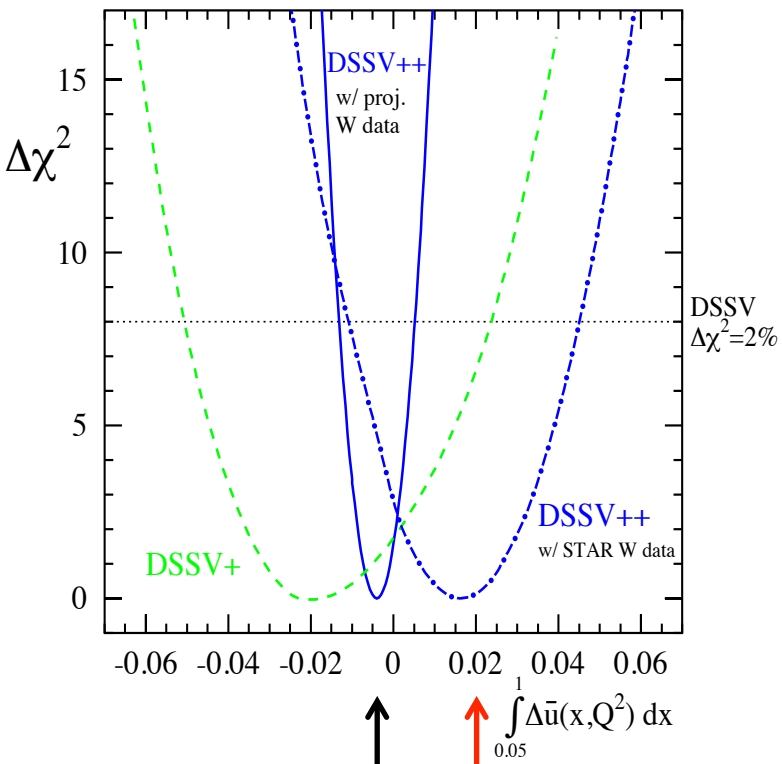




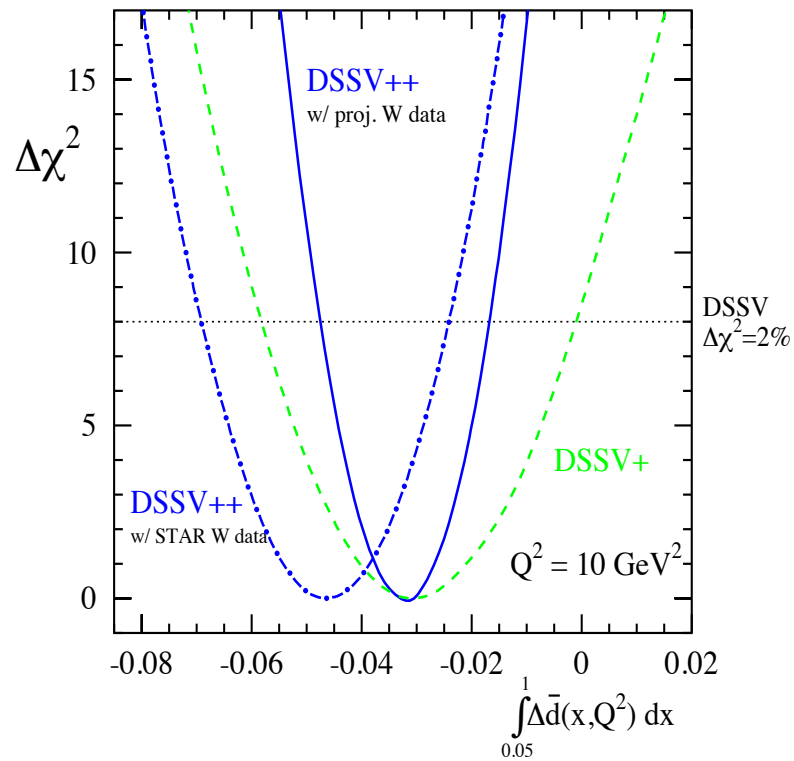


Positive anti-u quark

$\Delta\bar{u}$



$\Delta\bar{d}$

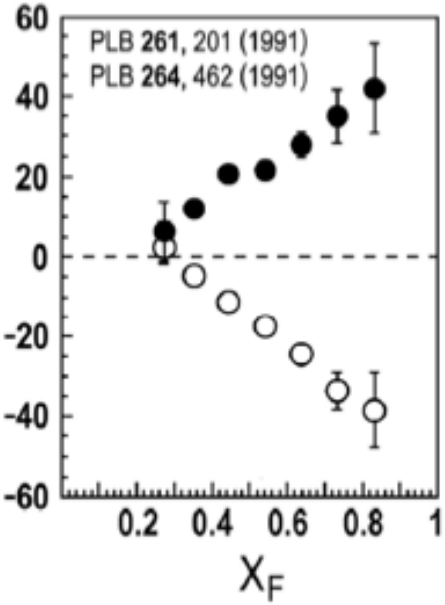


DSSV New Fit

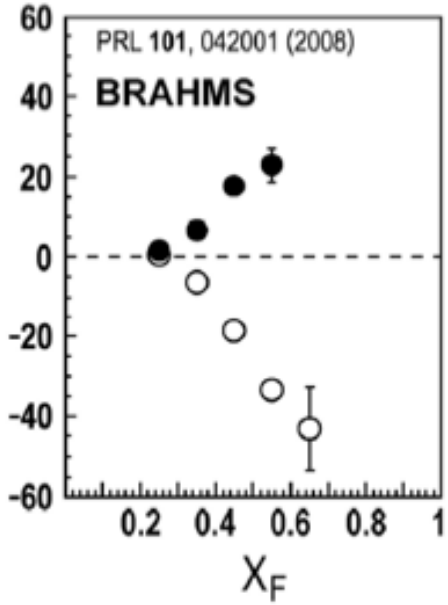
TRANSVERSE SPIN

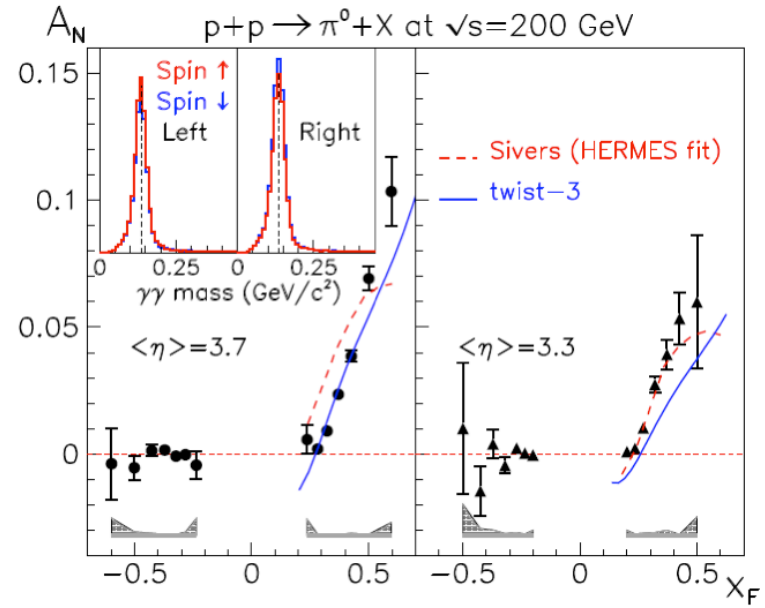
Mysterious transverse spin asymmetry

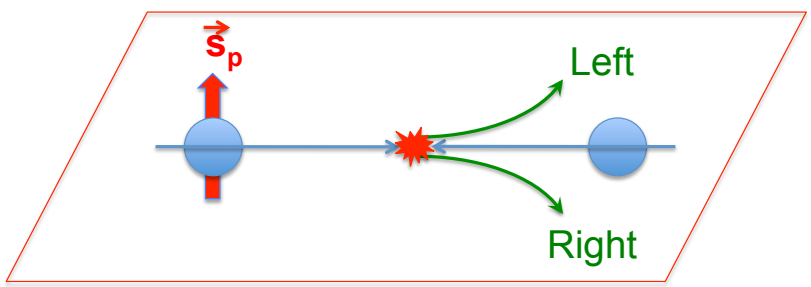
√s=19.4 GeV



√s=62.4 GeV







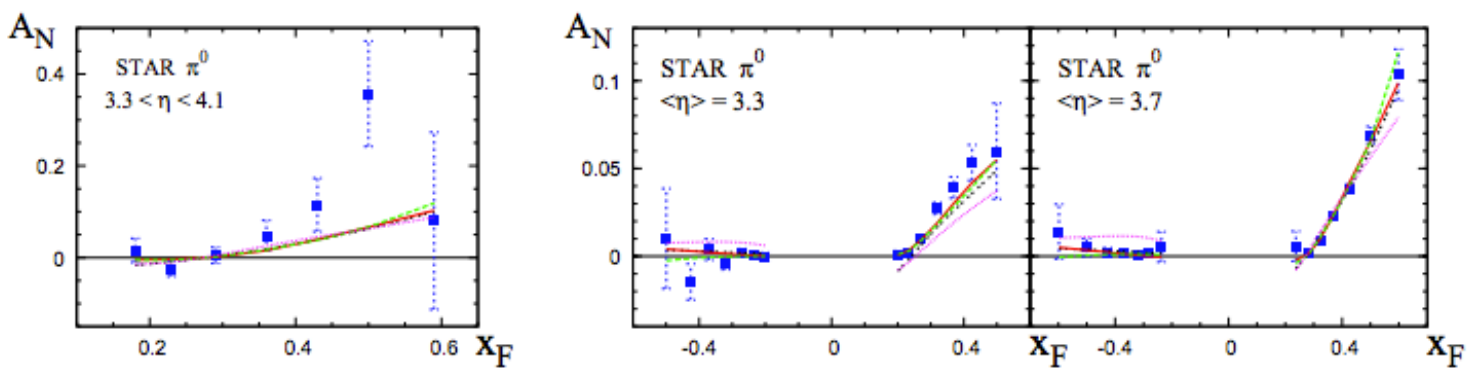
Observed everywhere?
What's the origin?

First attempt to understand

- Sivers type effect (twist-3 Qiu-Sterman) mechanism: close your eye, fit $T_F(x_1, x_2)$, gets good description of data

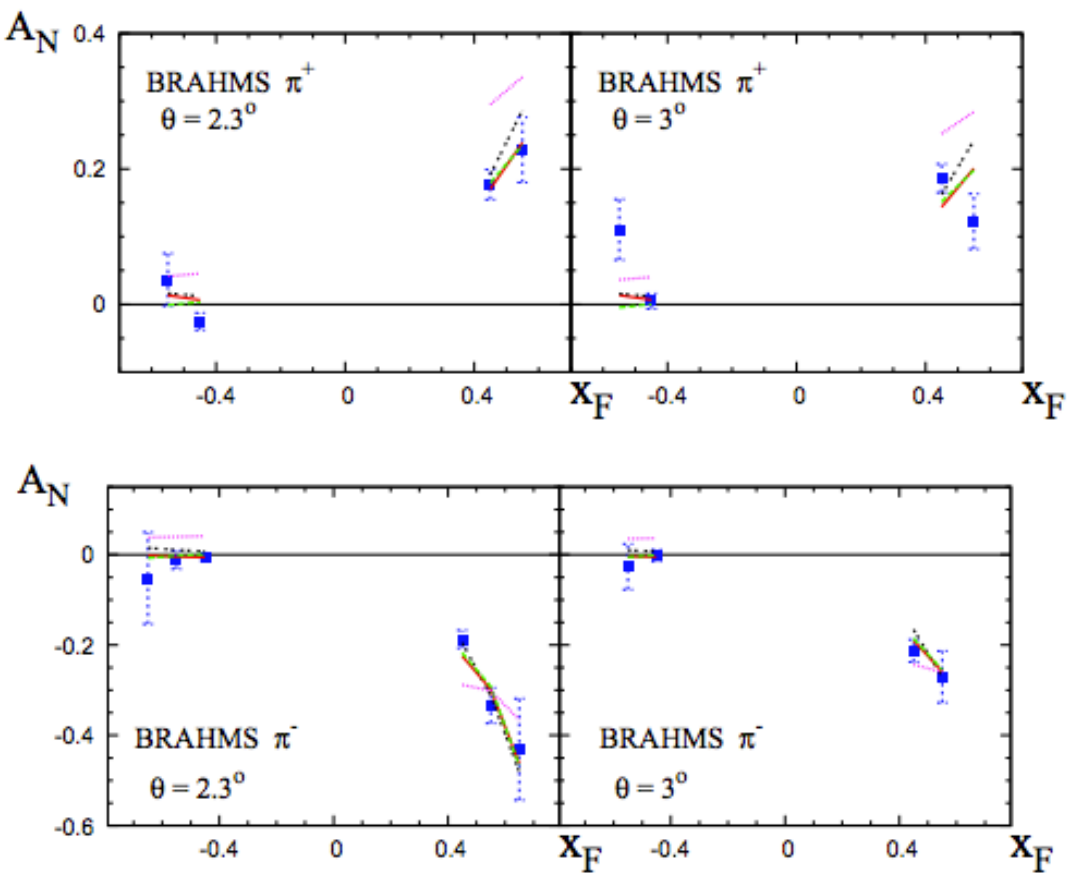
STAR $\sqrt{s} = 200$ GeV

1005.1468



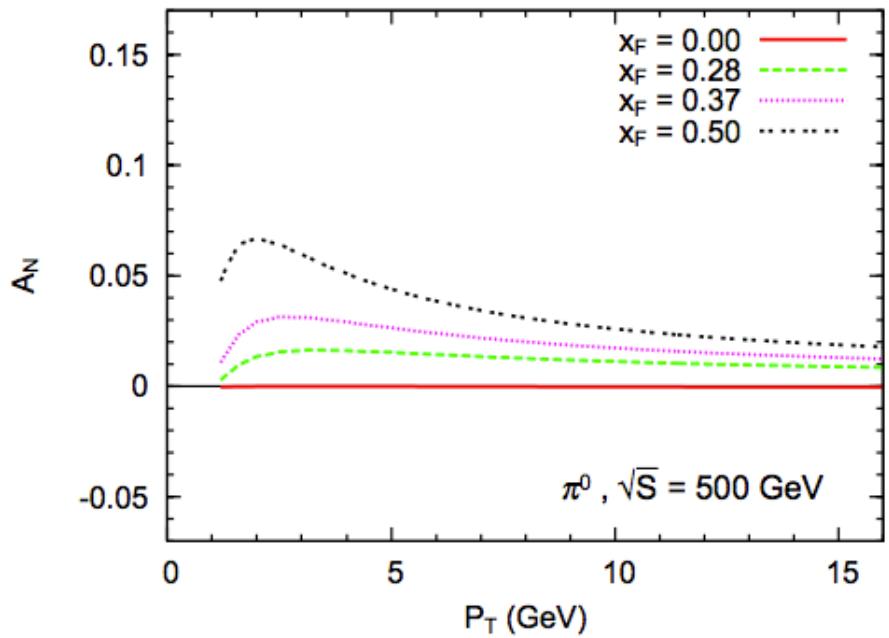
BRAHMS $\sqrt{s} = 62.4$ GeV

1005.1468



Even the pt dependence

- 1/pt is only the power counting: the actual formalism is more complicated than that

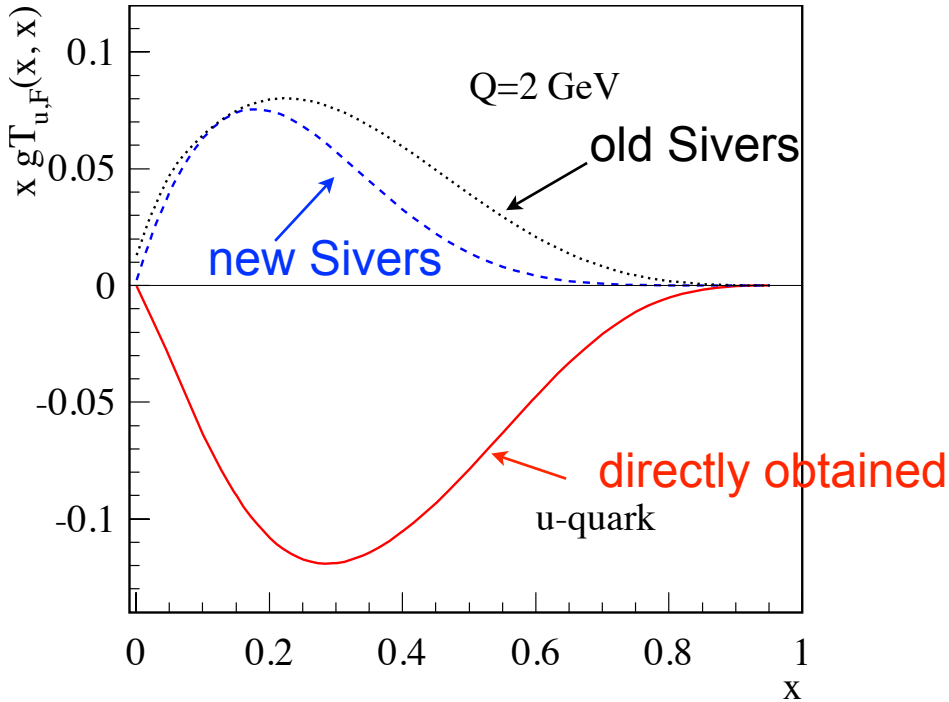


1104.0117

- Then one starts to compare pp and SIDIS data to hopefully better constrain Qiu-Sterman function, we found "sign mismatch" problem

Lesson learned

- Has to independently constrain "the fitted functions" in at least two processes, and cross check them



Kang-Qiu-Vogelsang-Yuan, 1103.1591

Solving "sign mismatch"

- The solution seems to be naturally on the fragmentation side (Collins or new twist-3 fragmentation functions)

$$d\sigma = H \otimes f_{a/A(3)} \otimes f_{b/B(2)} \otimes D_{c/C(2)}$$

$$+ H' \otimes f_{a/A(2)} \otimes f_{b/B(3)} \otimes D_{c/C(2)}$$

$$+ H'' \otimes f_{a/A(2)} \otimes f_{b/B(2)} \otimes D_{C/c(3)}$$

Twist-3 Qiu-Sterman

→ Negligible (Kanazawa and Koike (2000))

Twist-3 fragmentation function

Metz and Pitonyak result

- Calculation of twist-3 fragmentation term (Metz and DP - PLB **723** (2013))

$$\frac{P_h^0 d\sigma_{pol}}{d^3\vec{P}_h} = -\frac{2\alpha_s^2 M_h}{S}\,\epsilon_{\perp\mu\nu}\,S_\perp^\mu P_{h\perp}^\nu \sum_i \sum_{a,b,c} \int_{z_{min}}^1 \frac{dz}{z^3} \int_{x'_{min}}^1 \frac{dx'}{x'}\,\frac{1}{x'S+T/z}\,\frac{1}{-x\hat{u}-x'\hat{t}}$$

$$\times\,\frac{1}{x}\,h_1^a(x)\,f_1^b(x')\left\{\left(\hat{H}^{C/c}(z) - z\frac{d\hat{H}^{C/c}(z)}{dz}\right)S_{\hat{H}}^i + \frac{1}{z}\,H^{C/c}(z)\,S_H^i\right.$$

$$\left. + 2z^2 \int \frac{dz_1}{z_1^2}\,PV\,\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\,\hat{H}_{FU}^{C/c,\Im}(z,z_1)\,\frac{1}{\xi}\,S_{\hat{H}_{FU}}^i\right\}$$

➡ "Derivative term" has been calculated previously (Kang, Yuan, Zhou (2010))

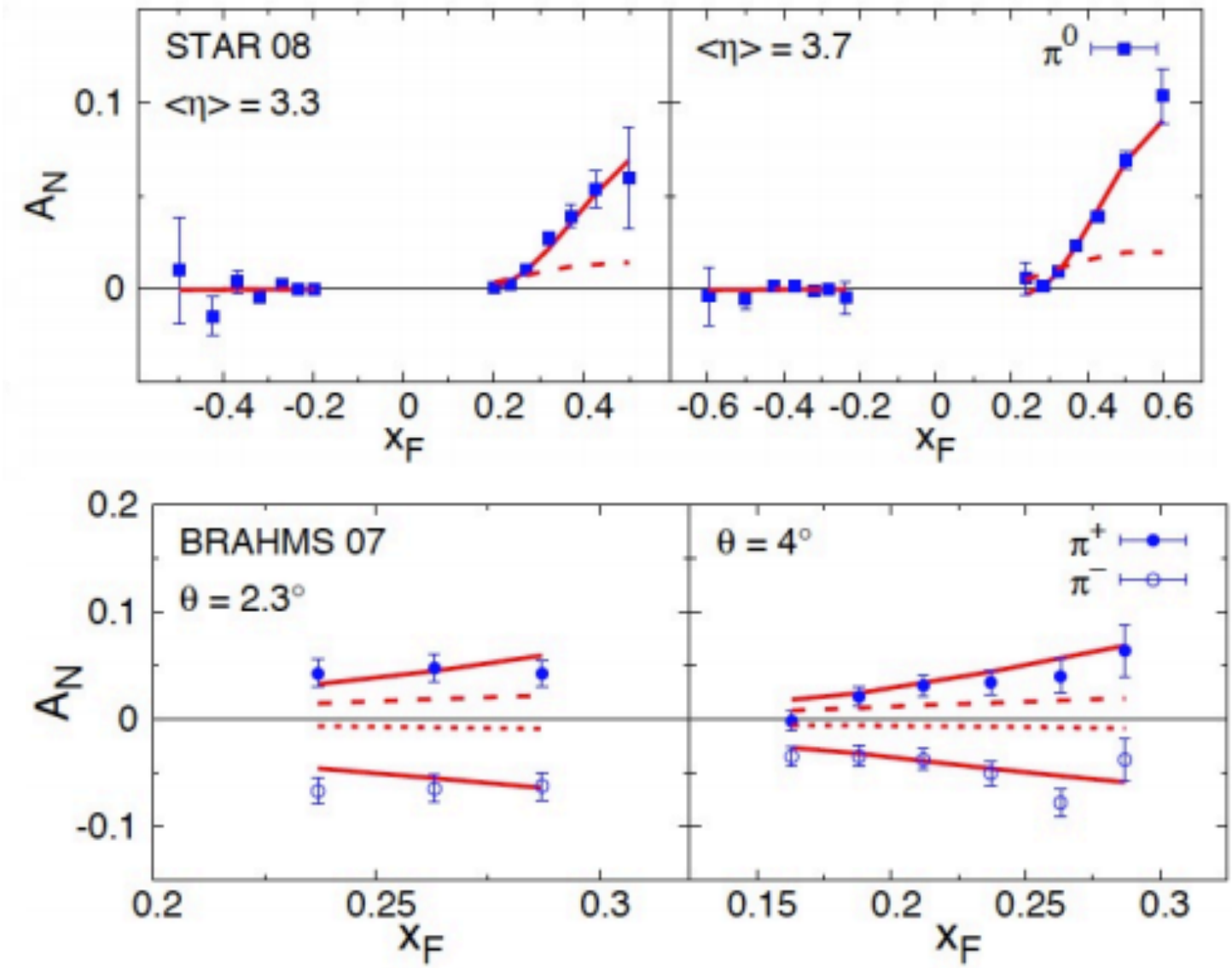
➡ First time we have a complete pQCD result for this term in *pp* within the collinear twist-3 approach

$$\hat{H}^{h/q}(z) = z^2 \int d^2\vec{k}_\perp\,\frac{\vec{k}_\perp^2}{2M_h^2}\,H_1^{\perp\,h/q}(z, z^2\vec{k}_\perp^2)$$ Collins-type function

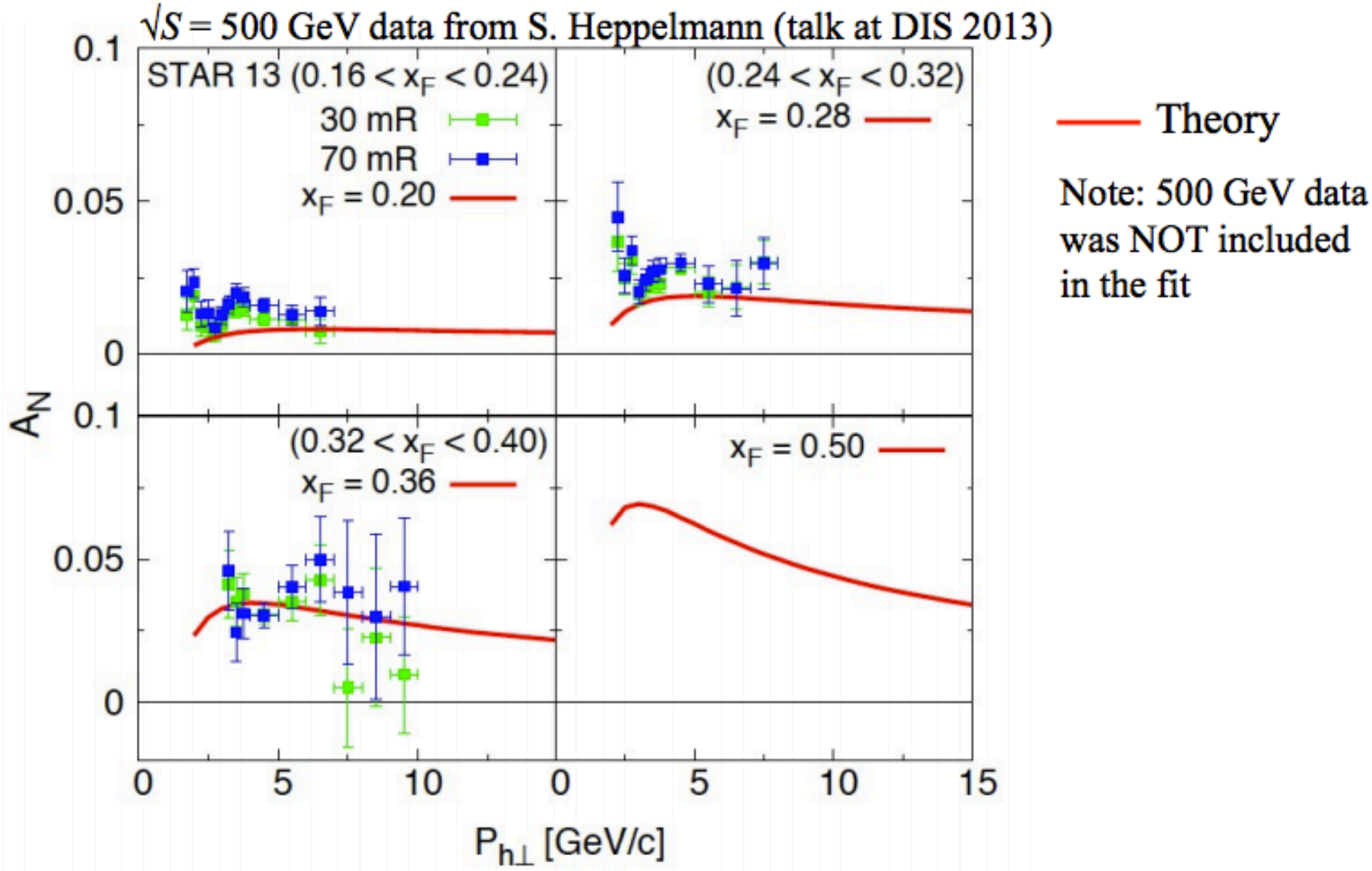
$$2z^3 \int_z^\infty \frac{dz_1}{z_1^2}\,\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\,\hat{H}_{FU}^{h/q,\Im}(z,z_1) = H^{h/q}(z) + 2z\hat{H}^{h/q}(z)$$ 3-parton correlator

Fit the unknown twist-3 FFs

1404.1033



Also pt dependence



Solved "sign mismatch" already?

- Learn from history
  - Not so fast. Remember to cross check "the fitted twist-3 FFs" from two independent sources
- Not so easy to find such a process
  - A candidate: e+p→h+X Gamberg-Kang-Metz-Pitonyak-Prokudin, to appear

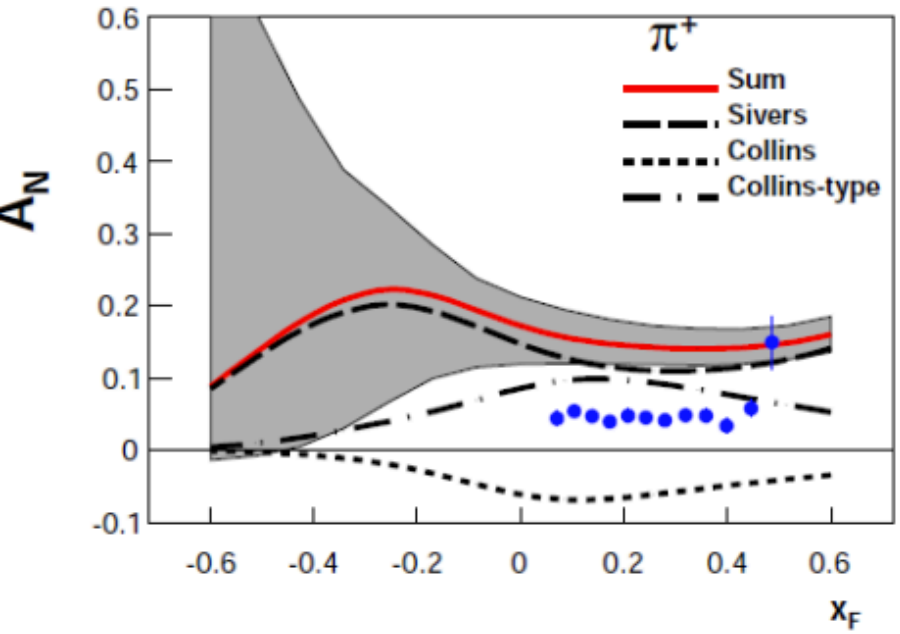
$$P_h^0 \frac{d\sigma_{UT}}{d^3\vec{P}_h} = -\frac{8\alpha_{\rm em}^2}{S}\,\varepsilon_{\perp\mu\nu}\,S_\perp^\mu\,P_{h\perp}^\nu \sum_q e_q^2 \int_{z_{\min}}^1 \frac{dz}{z^3}\,\frac{1}{S+T/z}\,\frac{1}{x}$$

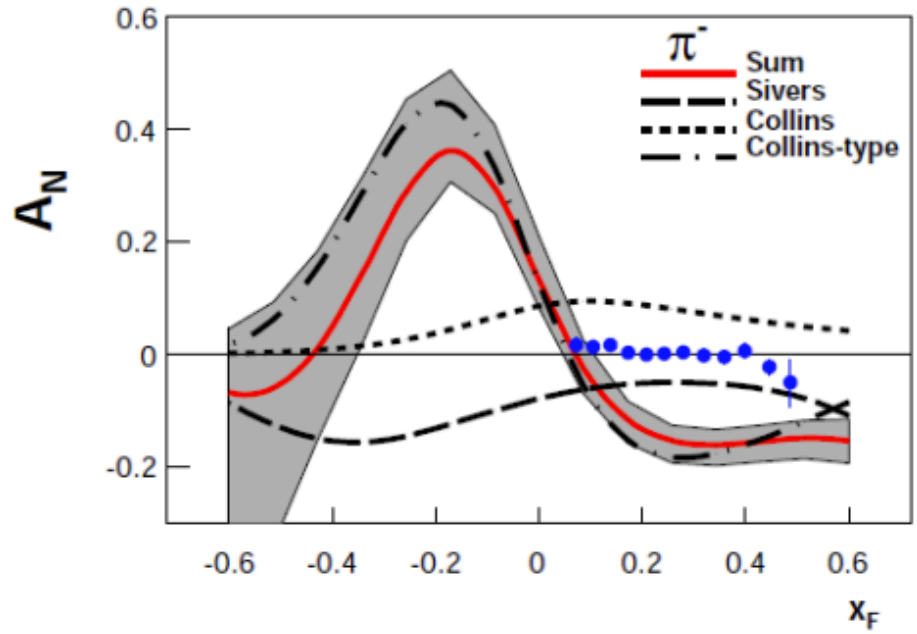
$$\times\Bigg\{-\frac{\pi M}{\hat{u}}\,D_1^{h/q}(z)\left(F_{FT}^q(x,x) - x\frac{dF_{FT}^q(x,x)}{dx}\right)\left[\frac{\hat{s}(\hat{s}^2+\hat{u}^2)}{2\hat{t}^3}\right]$$ "Sivers"

$$+\frac{M_h}{-x\hat{u}-\hat{t}}\,h_1^q(x)\Bigg\{\left(\hat{H}^{h/q}(z) - z\frac{d\hat{H}^{h/q}(z)}{dz}\right)\left[\frac{(1-x)\hat{s}\hat{u}}{\hat{t}^2}\right]$$ "Collins"

$$+\frac{1}{z}H^{h/q}(z)\left[\frac{\hat{s}(\hat{s}^2+(x-1)\hat{u}^2)}{\hat{t}^3}\right] + 2z^2\int_z^\infty \frac{dz_1}{z_1^2}\,PV\frac{1}{\frac{1}{z}-\frac{1}{z_1}}\,\hat{H}_{FU}^{h/q,\Im}(z,z_1)\left[\frac{x\hat{s}^2\hat{u}}{\xi_z\,\hat{t}^3}\right]\Bigg\}\Bigg\}$$ "Collins-type"

LO formula Compare to HERMES data





Forward region $x_F < 0$

Collins contribution is suppressed, Sivers dominates for π^+

Sivers extraction 2009 with DSS FF. π^- dominated by “Collins-type” contribution.

Constrain twist-3 FFs

- In principle it could be used to constrain twist-3 FFs
  - Need to study NLO corrections for e+p collisions, potentially large (resolved photon contribution)
  - Need to explore the asymmetry in the overlap xF regions for e+p and p+p
- Need further evidence/work to resolve “sign mismatch”

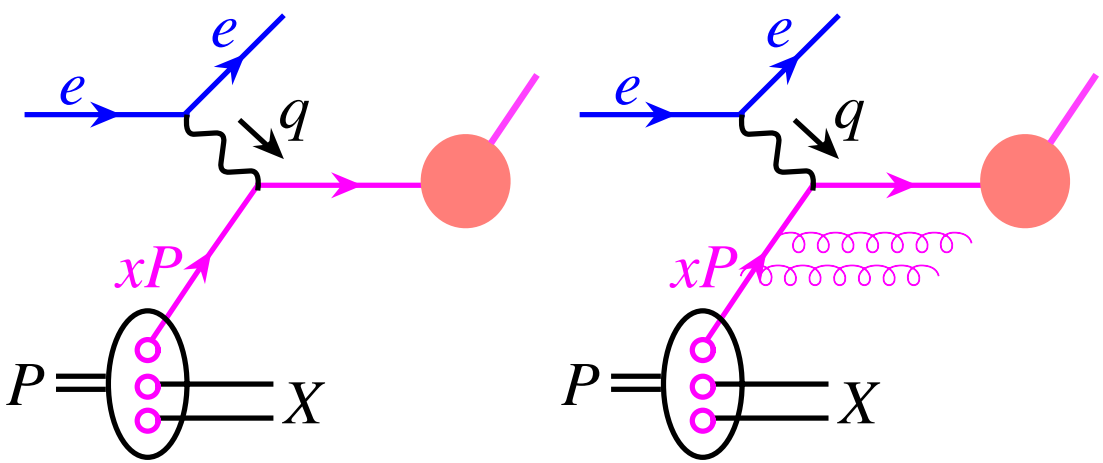
Most active subject: TMD evolution

- Recently one of the most active topics on the theory side is to study and constrain TMD evolution

Evolution

QCD evolution: TMDs

- TMD factorization works in the situation where there are two observed momenta in the process, such as SIDIS, DY, W/Z production at low qt << Q
- Evolution = sum all the large perturbative corrections
- Naturally if Q~qt, no large corrections, so no TMD evolution



$$\left(\alpha_s \ln^2 \frac{Q^2}{q_T^2}\right)^n$$

What's the complication in TMD evolution?

- TMD evolution kernel is NOT entirely perturbative (collinear evolution kernel is purely perturbative)
- We have a TMD distribution F(x, kt; Q) measured at a scale Q
  - It is easy to deal in the Fourier transformed space

$$F(x,b;Q) = \int d^2k_\perp e^{-ik_\perp \cdot b} F(x,k_\perp;Q)$$

  - Perturbatively it evolves from an initial scale $c = 2e^{-\gamma_E} \sim O(1)$

$$F(x,b;Q) = F(x,b;c/b) \exp\left\{ -\int_{c/b}^{Q} \frac{d\mu}{\mu} \left(A \ln \frac{Q^2}{\mu^2} + B \right) \right\}$$

$$A = \sum_{n=1} A^{(n)} \left(\frac{\alpha_s}{\pi}\right)^n, \qquad B = \sum_{n=1} B^{(n)} \left(\frac{\alpha_s}{\pi}\right)^n$$

Fourier transform to kt space

- Fourier transform back to the momentum space, one needs the whole b region (also large b) and in turn needs some non-perturbative extrapolation

$$F(x, k_\perp; Q) = \frac{1}{(2\pi)^2} \int d^2 b e^{i k_\perp \cdot b} F(x, b; Q)$$
$$= \frac{1}{2\pi} \int_0^\infty db\, b J_0(k_\perp b) F(x, b; Q)$$

- Non-perturbative extrapolation can only been fitted from the data
  - Current wisdom: use the unpolarized cross section to constrain it as much as possible

Lots of progress

Transversity 2014

Stefano Melis

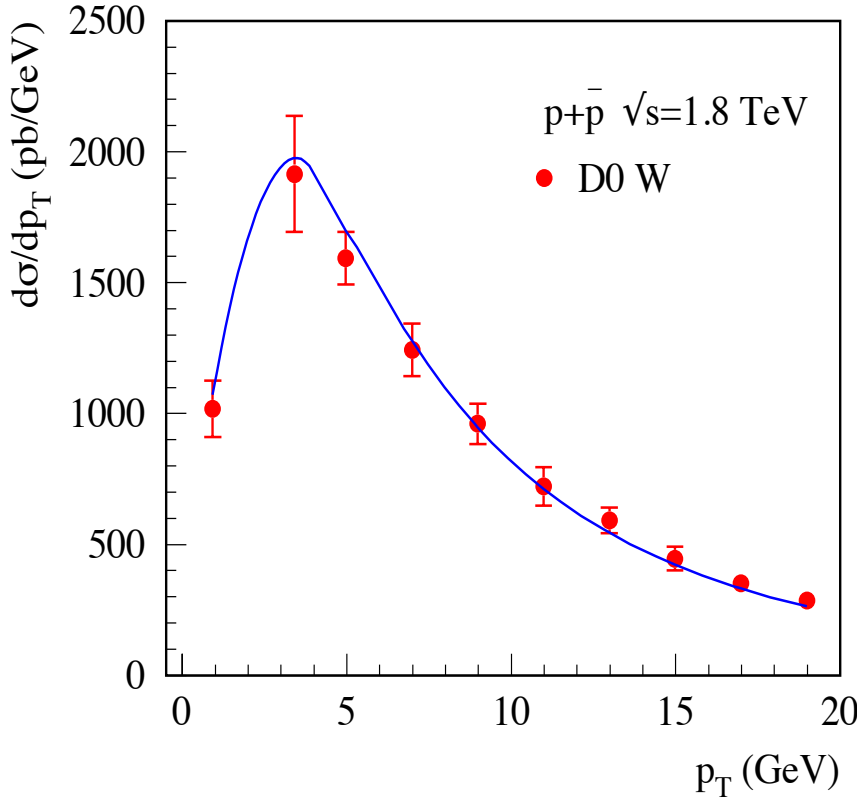
	Can describe unpolarized **SIDIS**	**DY**
➢Aybat-Roger-Prokudin: TMD EVO I/O	No	No
➢Anselmino-Boglione-Melis: Gaussian	Maybe	Maybe No High energy
➢Anselmino-Boglione-Melis: TMD EVO I/O	No	No
➢Sun-Yuan: TMD EVO IO+ Modified Sudakov	No Hermes YES/Maybe COMPASS	Yes low energy No High energy
➢EIKV*: TMD Evo a la CSS+ C at LO	No Hermes YES/Maybe COMPASS	YES

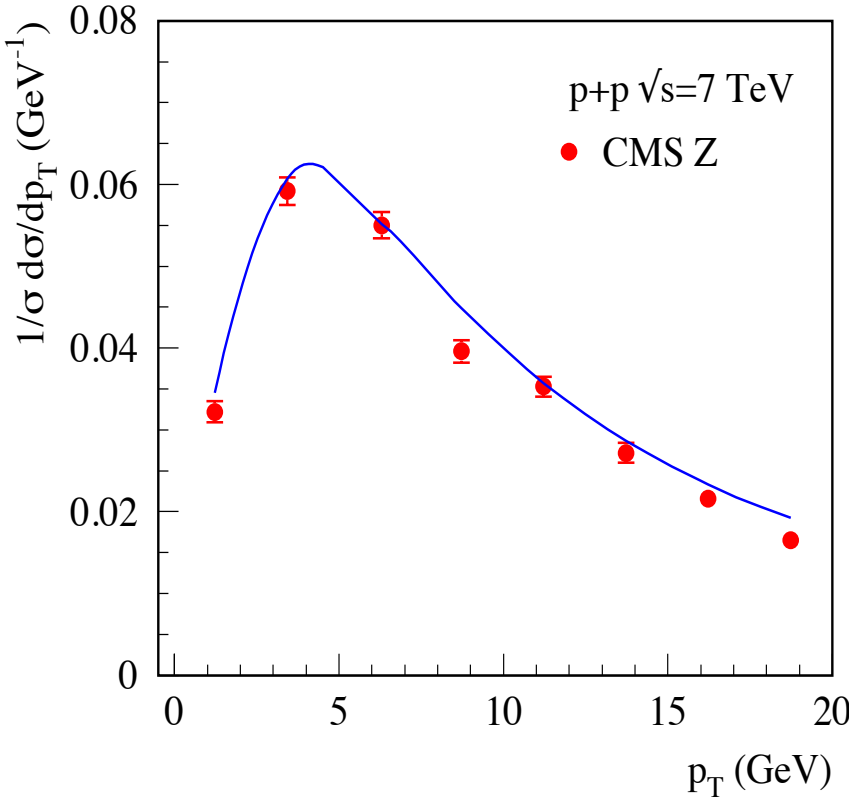
*Echivarria-Idilbi-Kang-Vitev

From our recent work

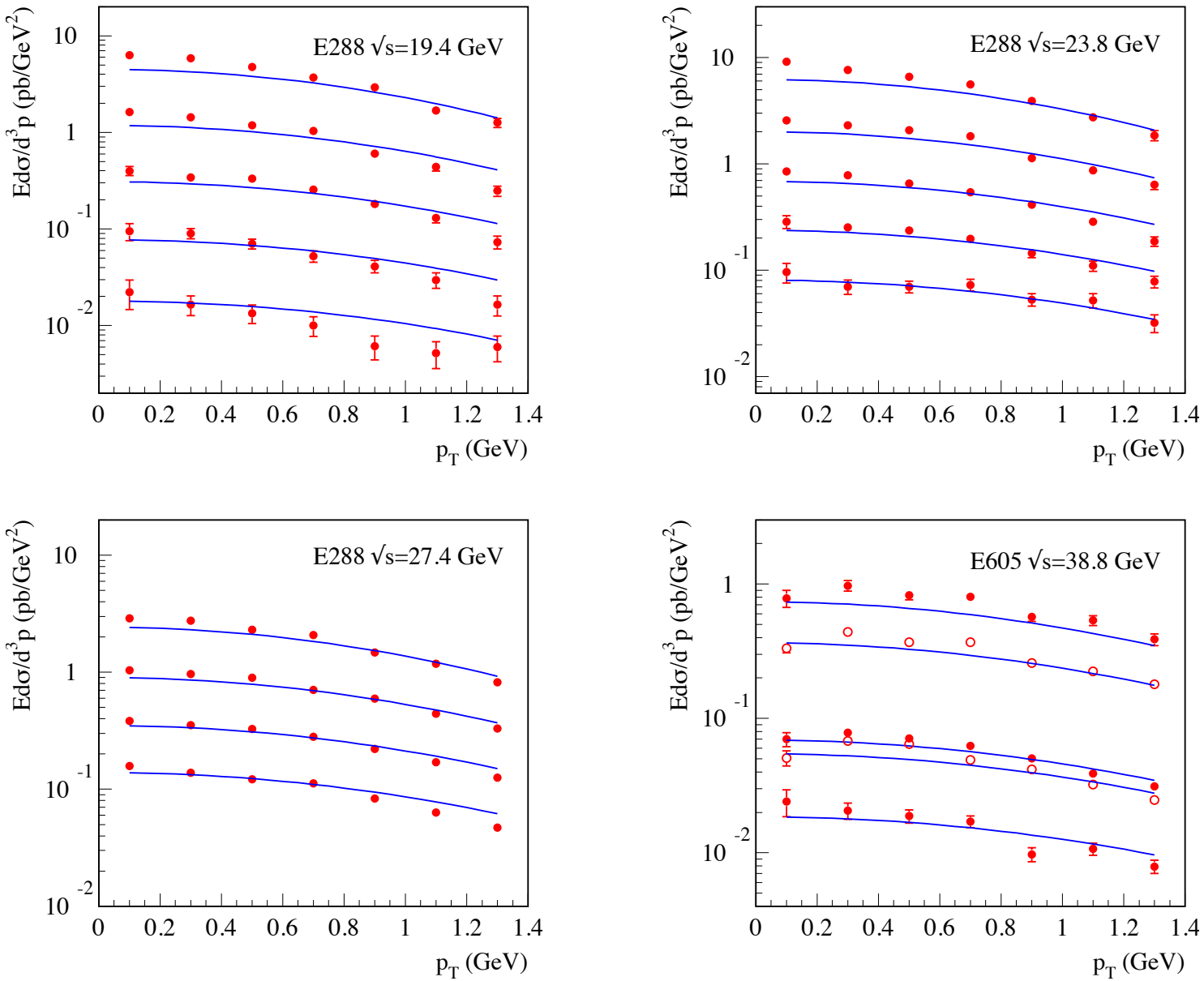
- Description of W/Z data at Tevatron and LHC: not a fit, but a reasonable "tune"

Echevarria-Idilbi-Kang-Vitev, 1401.5078





Drell-Yan production



SIDIS: COMPASS

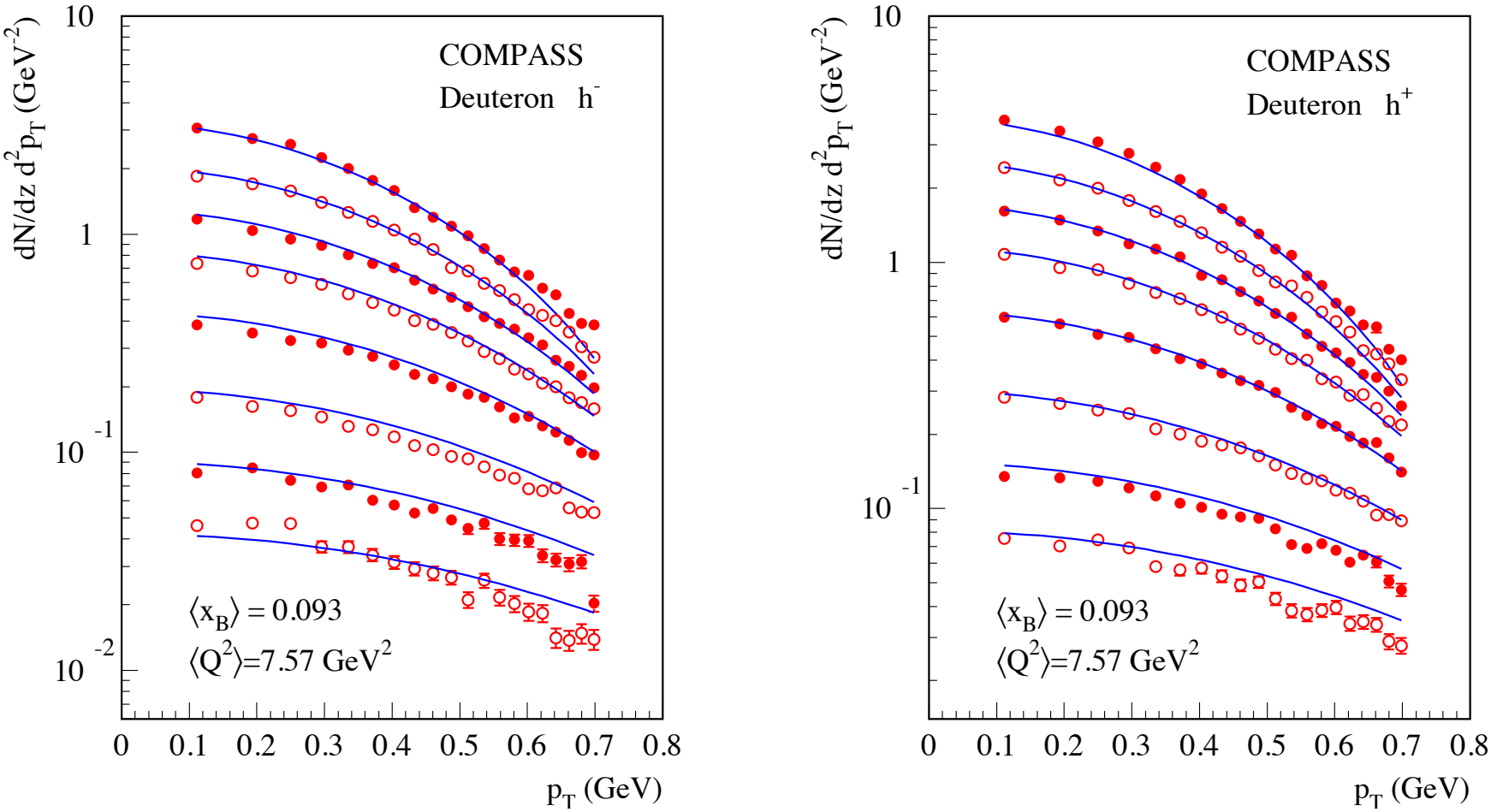
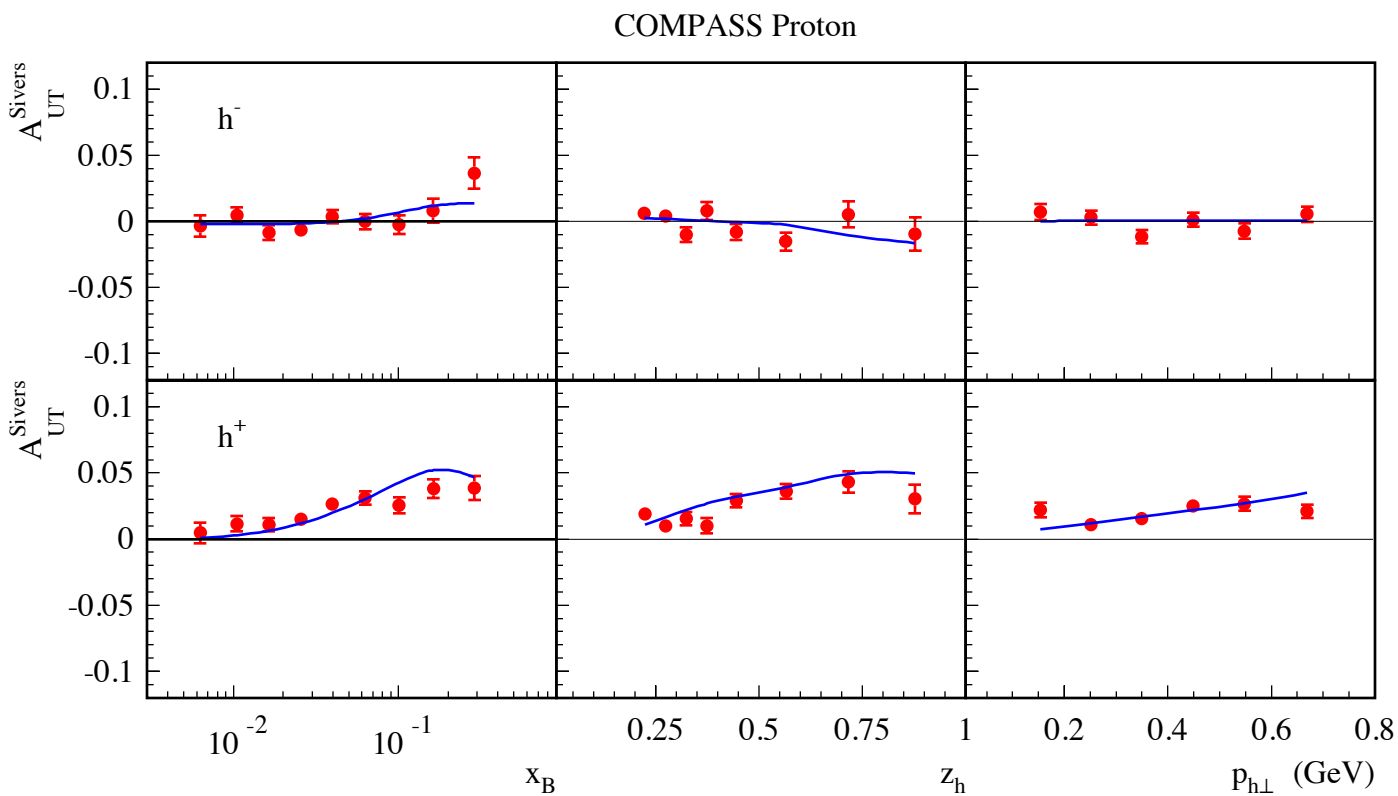


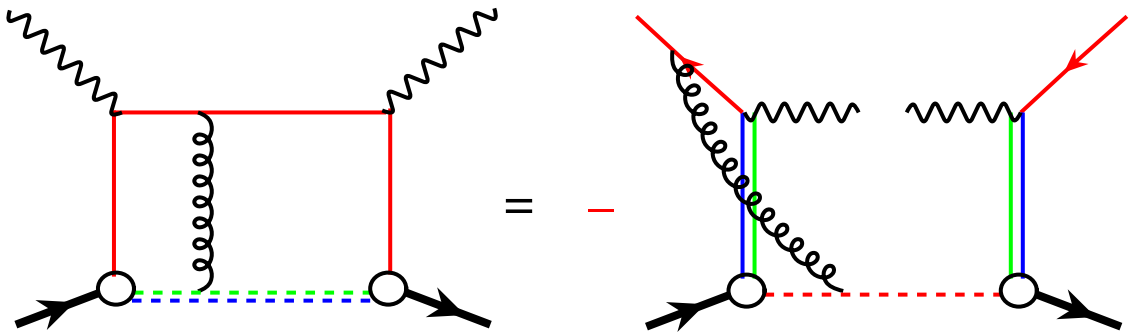
FIG. 2. The comparison with the COMPASS data (deuteron target) [7] at $\langle Q^2 \rangle = 7.57$ GeV^2 and $\langle x_B \rangle = 0.093$. The data points from top to bottom correspond to different z region: $[0.2, 0.25]$, $[0.25, 0.3]$, $[0.3, 0.35]$, $[0.35, 0.4]$, $[0.4, 0.5]$, $[0.5, 0.6]$, $[0.6, 0.7]$, and $[0.7, 0.8]$.

Sivers effect: fit

- Once the non-perturbative part is constrained, use the same formalism to describe the Sivers effect



Sign change of Sivers function

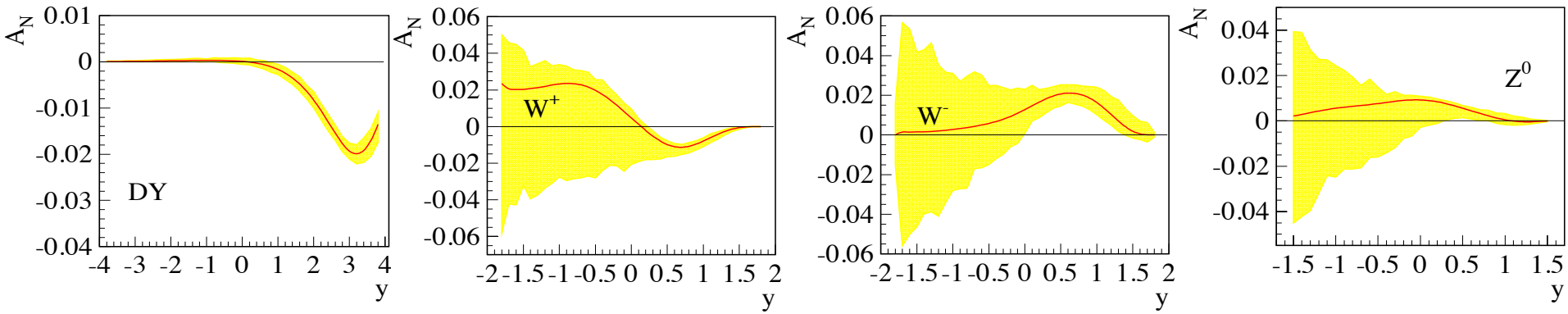


SIDIS = – DY

$$\Delta^N f^{\rm DIS}_{q/h^\uparrow}(x,k_\perp) = -\Delta^N f^{\rm DY}_{q/h^\uparrow}(x,k_\perp)$$

Predictions for DY, W/Z

- At 510 GeV RHIC energy

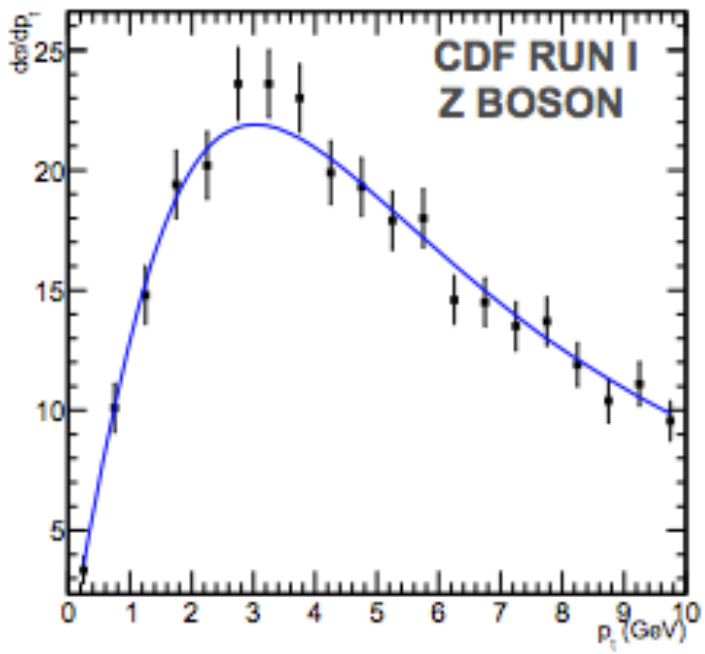


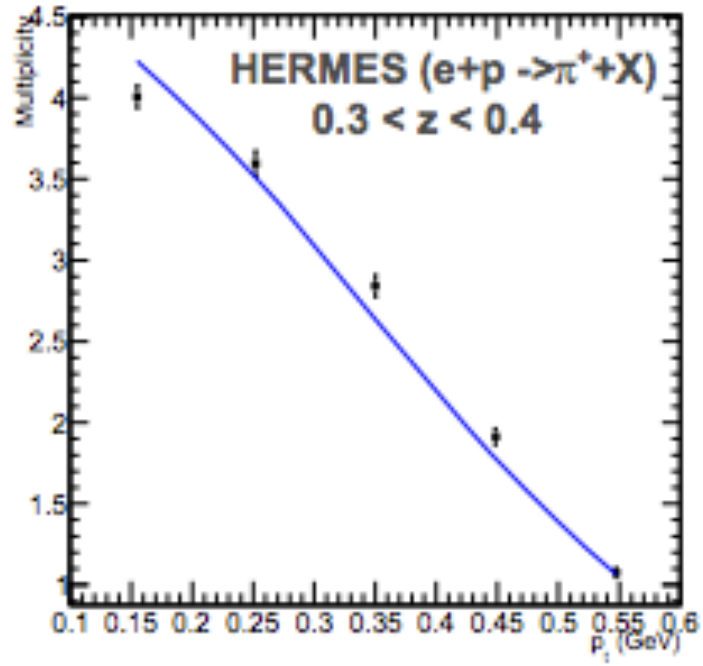
- DY plot has to be updated (negative y region)
- Note: sea quark Sivers functions are not constrained from the current SIDIS data, so the backward has large uncertainty

Could we do better

- A new fit for DY seems also describe SIDIS data

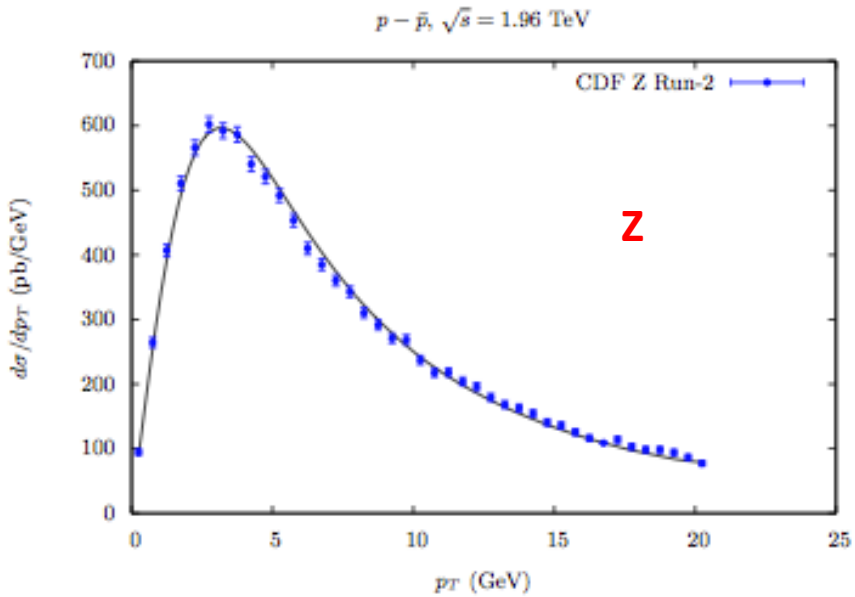
Sun-Isaacson-Yuan-Yuan,1406.3073

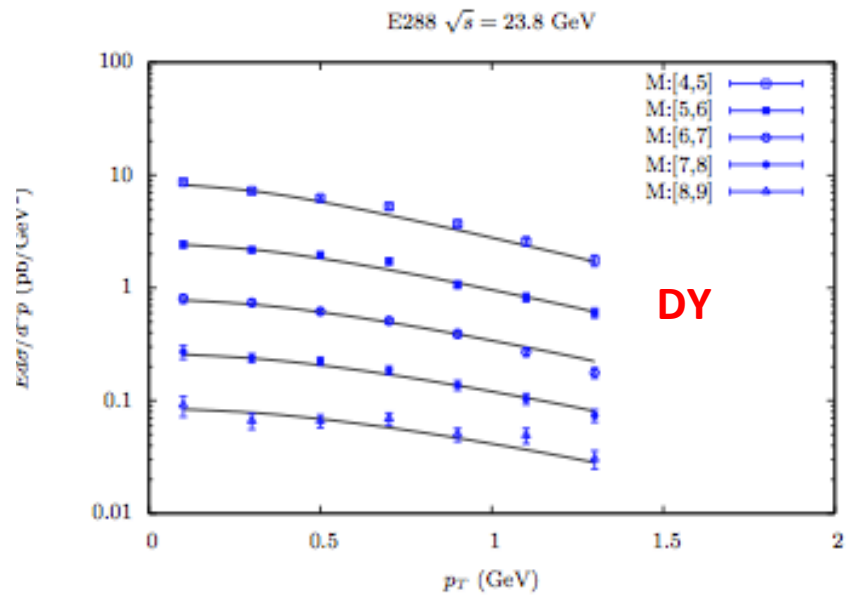


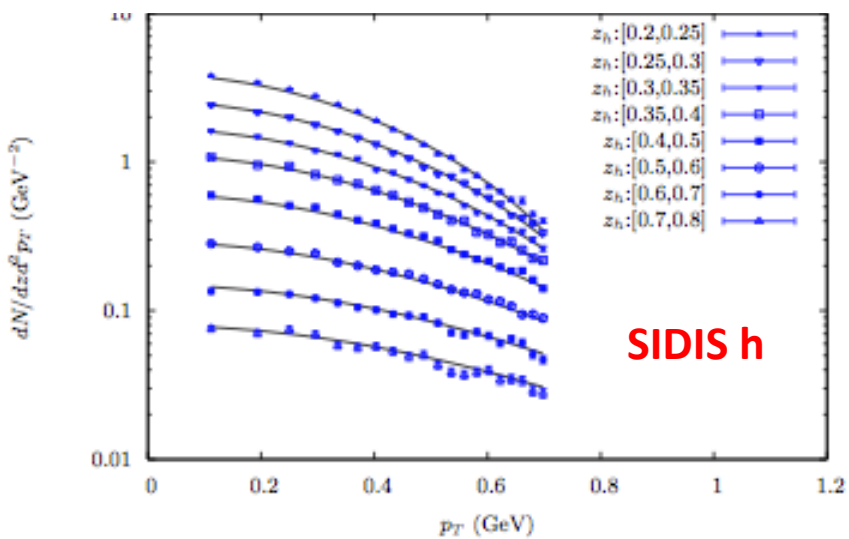


$$\exp\left(-g_2 b^2 \ln Q^2 + \cdots\right) \qquad \exp\left(-g_2 \ln b \ln Q^2 + \cdots\right)$$

A true global fit of SIDIS, DY and W/Z







Chi2/d.o.f ~ 2.2

Echevarria-Idilbi-Kang, et.al. preliminary

Summary

- We have made lots of progress recently
- Need more data to further understand the mechanism for single transverse spin asymmetry
- TMD evolution is very important, different groups start to converge

So what questions

- If we have measured collinear unpolarized PDFs up to enough accuracy, so what?
  - Asked by Kang at INT workshop 2010 to PDFs working group
- If we have measured TMDs, spin asymmetries up to 1% accuracy, so what?
- If we have understood all TMD evolution, and extract all distributions and fragmentation functions up to enough accuracy, so what?
  - Asked by Roberts at ANL to Kang