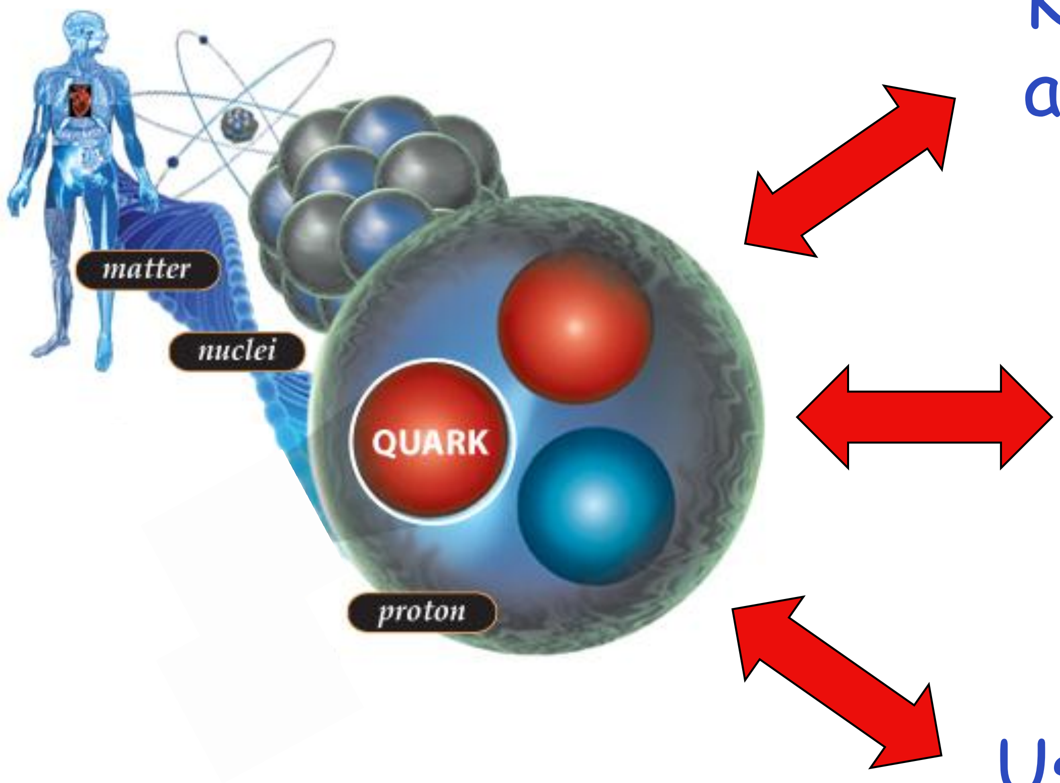
QCD Spin Physics: Some Recent Highlights

Werner Vogelsang

Tübingen University

IWHSS12, Lisboa, 04/16/2012

Exploring the nucleon: a fundamental quest



Know what we are made of !

Understand the strong force: "QCD"

Use protons as tool for discovery (e.g. LHC)

25 years since the "proton spin crisis":

$$\Delta\Sigma \sim 0.25 \ll 1$$

We have come a long way …

- what role do gluons play for the proton spin ?
- and strangeness ?
- what orbital angular momenta do partons carry ?
- what's the 3D image of the nucleon in terms of quarks and gluons
  - spacially (→ GPDs) ?
  - in momentum (→TMDs) ?

A far-developed theory framework to address this

Plus, first-rate experimental facilities

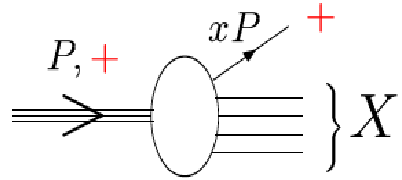
Today's talk :

Not a comprehensive review – a collection of recent results with emphasis on relevance for COMPASS

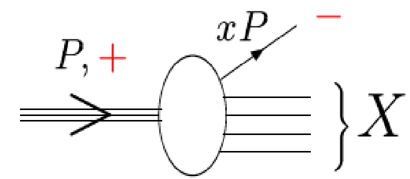
- Nucleon helicity PDFs
  - status, latest results
  - theory efforts
- Role of fragmentation functions
- Transverse-spin phenomena

Nucleon Helicity Parton Distributions

$\Delta q(x) = \Big|$

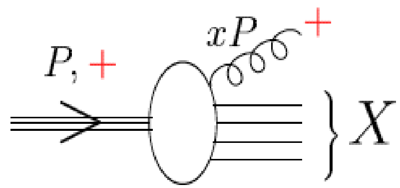


$\Big|^2 - \Big|$

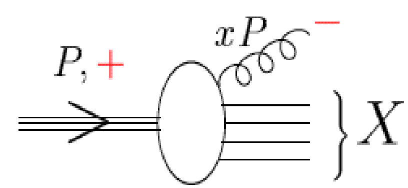


$\Big|^2$

$\Delta g(x) = \Big|$



$\Big|^2 - \Big|$



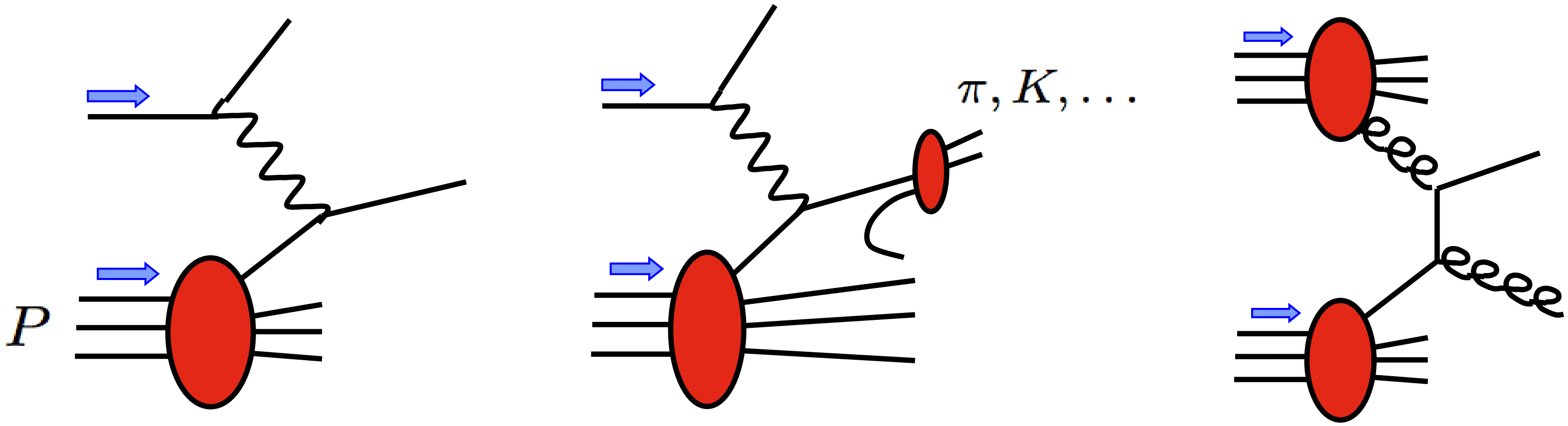
$\Big|^2$

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

$$\Delta\Sigma(Q^2) = \int_0^1 dx \left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right](x, Q^2)$$

$$\Delta G(Q^2) = \int_0^1 dx\, \Delta g(x, Q^2)$$

Probes of nucleon helicity structure:



$$\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx \, \Delta f(x, Q^2) \, \Delta\hat{\sigma}^f (xP, \alpha_s(Q^2)) + \ldots$$

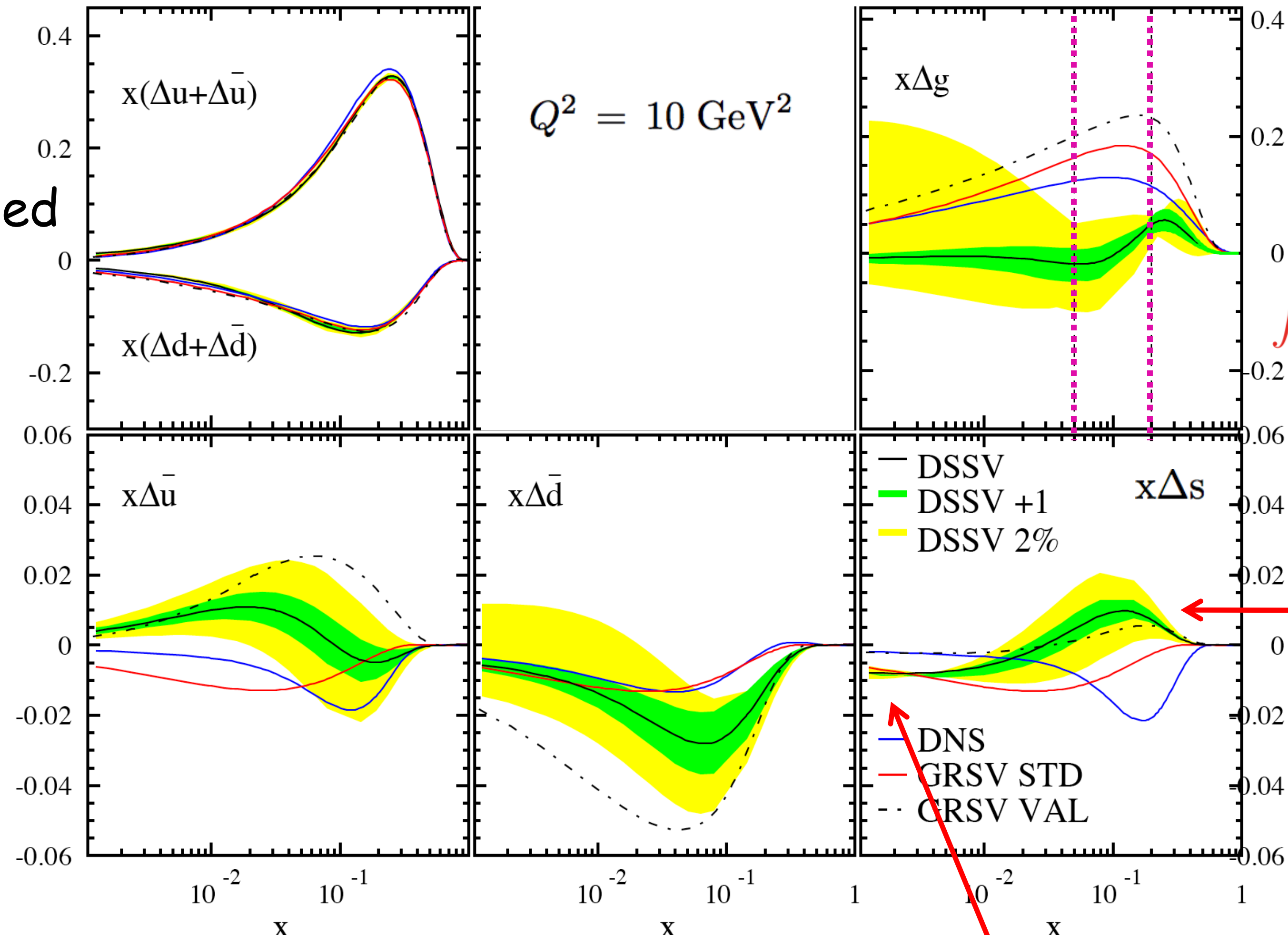
$$\Delta\sigma = \sum_{a,b=q,\bar{q},g} \int dx_a \, \Delta f_a(x_a, p_\perp^2) \int dx_b \, \Delta f_b(x_b, p_\perp^2) \Delta\hat{\sigma}^{ab}(x_a P, x_b P', \alpha_s(p_\perp^2)) + \ldots$$

- NLO ($\overline{\text{MS}}$) "global analysis" de Florian, Sassot, Stratmann, WV

Status ~ 2009 :

de Florian, Sassot, Stratmann, WV

best constrained



small in measured regime !

$$\int_{0.05}^{0.2} dx\, \Delta g \approx 0$$

driven by SIDIS

SIDIS

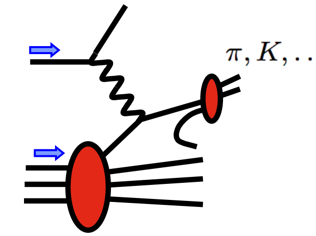
indications for $\Delta\bar{u} > 0$ $\Delta\bar{d} < 0$

DIS + SU(3)

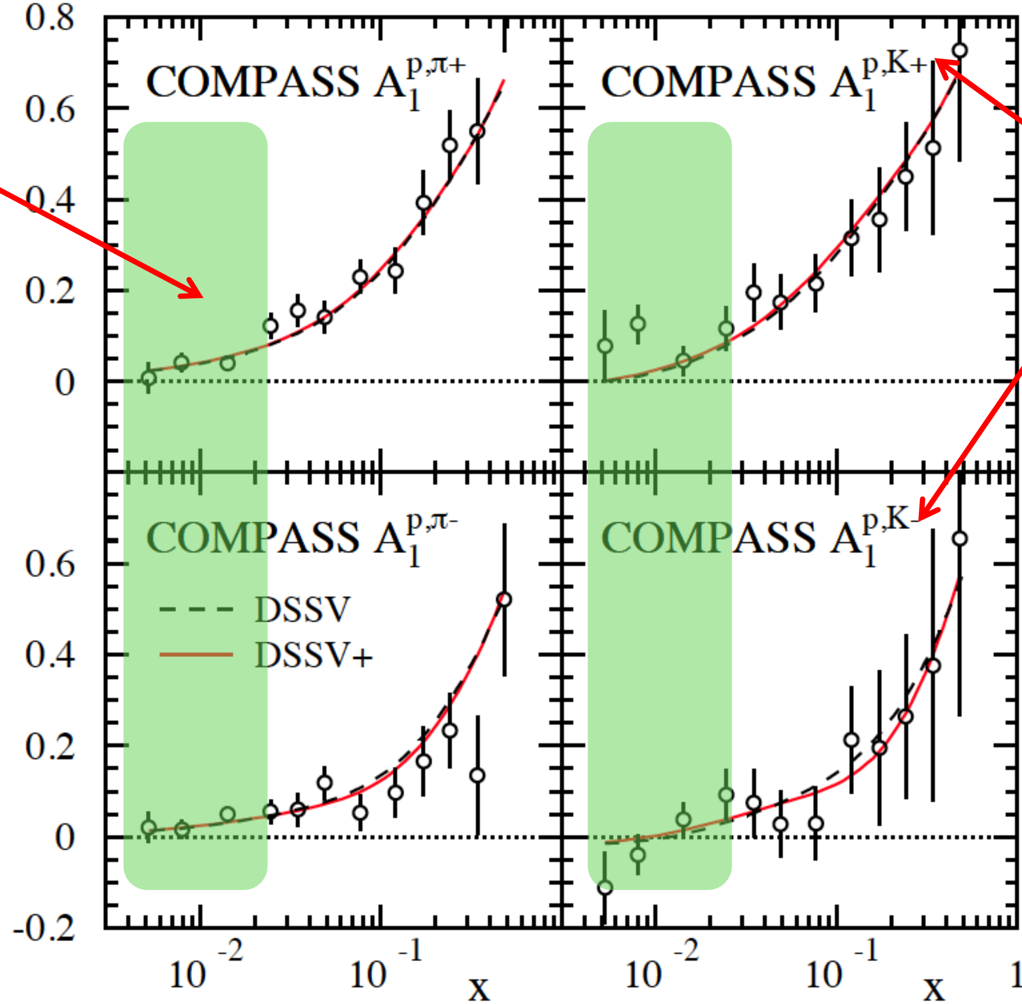
strangeness puzzle?

Recent developments:
new input from experiments

- recent COMPASS semi-inclusive data:



not covered by HERMES

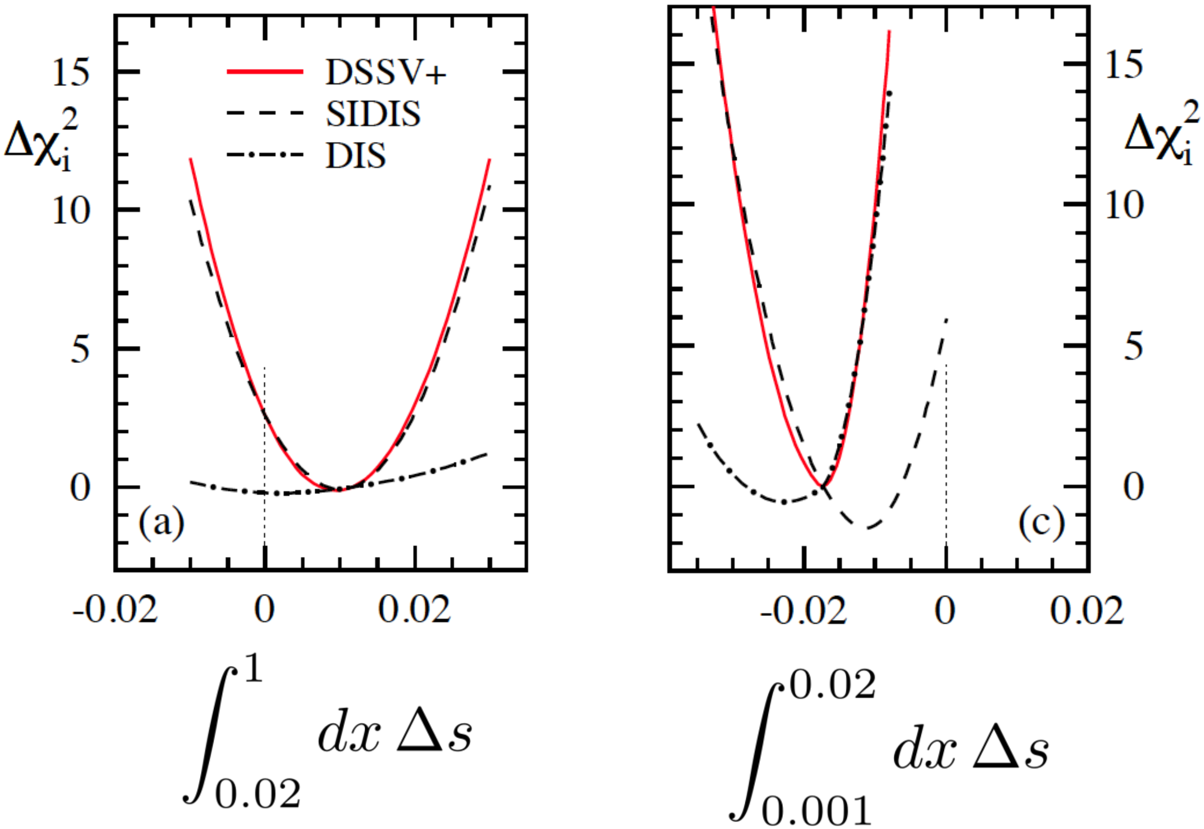


not available from HERMES

DSSV+ (Stratmann,Sassot)

- implications for Δs ?

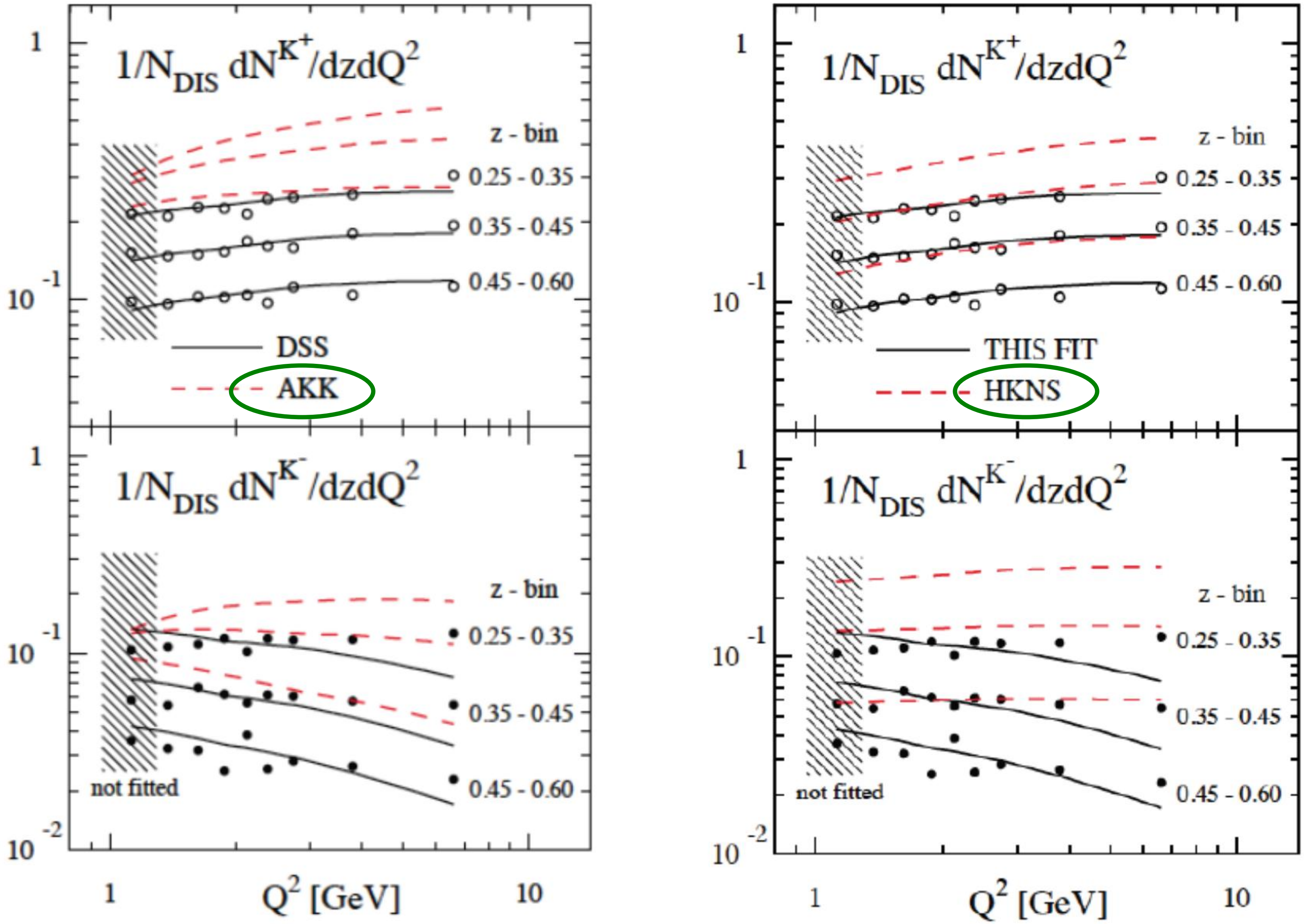
Stratmann @ DIS2011



- tendency toward negative low-x Δs also from SIDIS ?
- heavily relies on kaon fragmentation

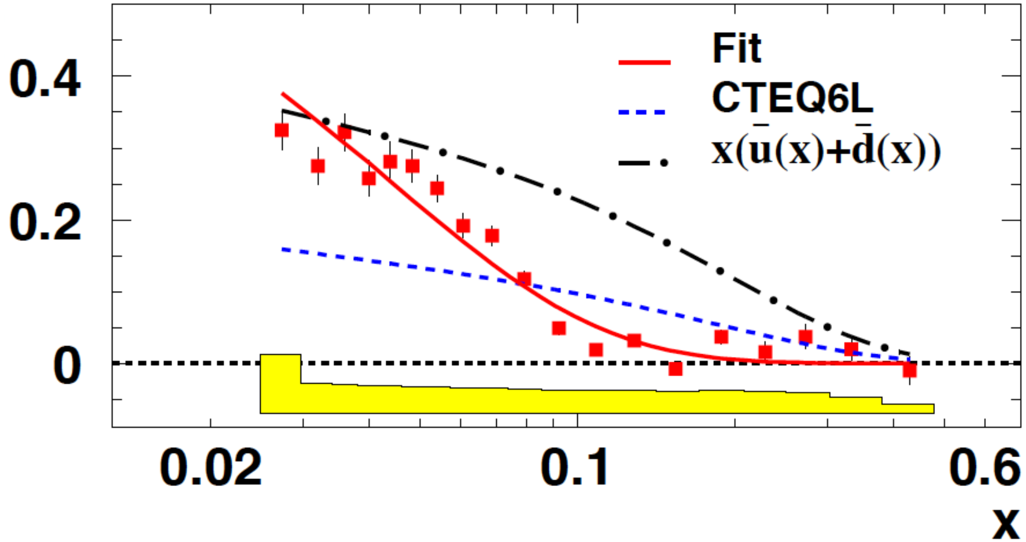
Leader,Sidorov,Stamenov

Stratmann at DIS 2011

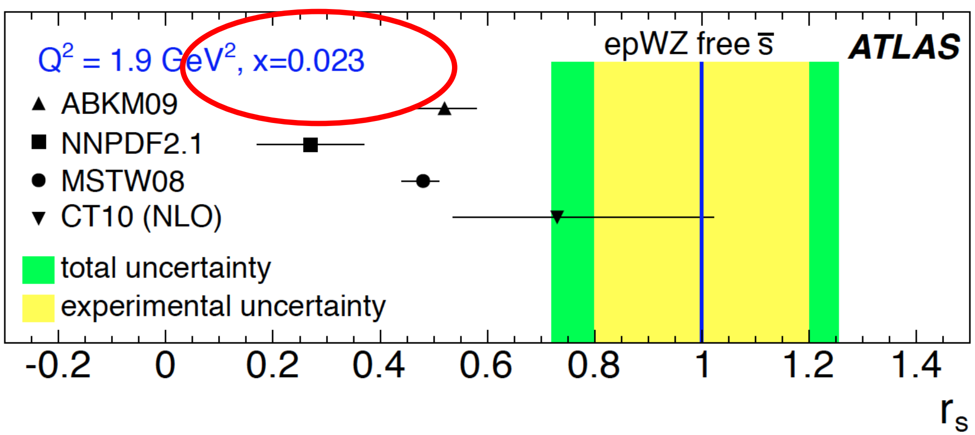


- still have a lot to learn about strangeness:

$x(s+\bar{s})$



HERMES

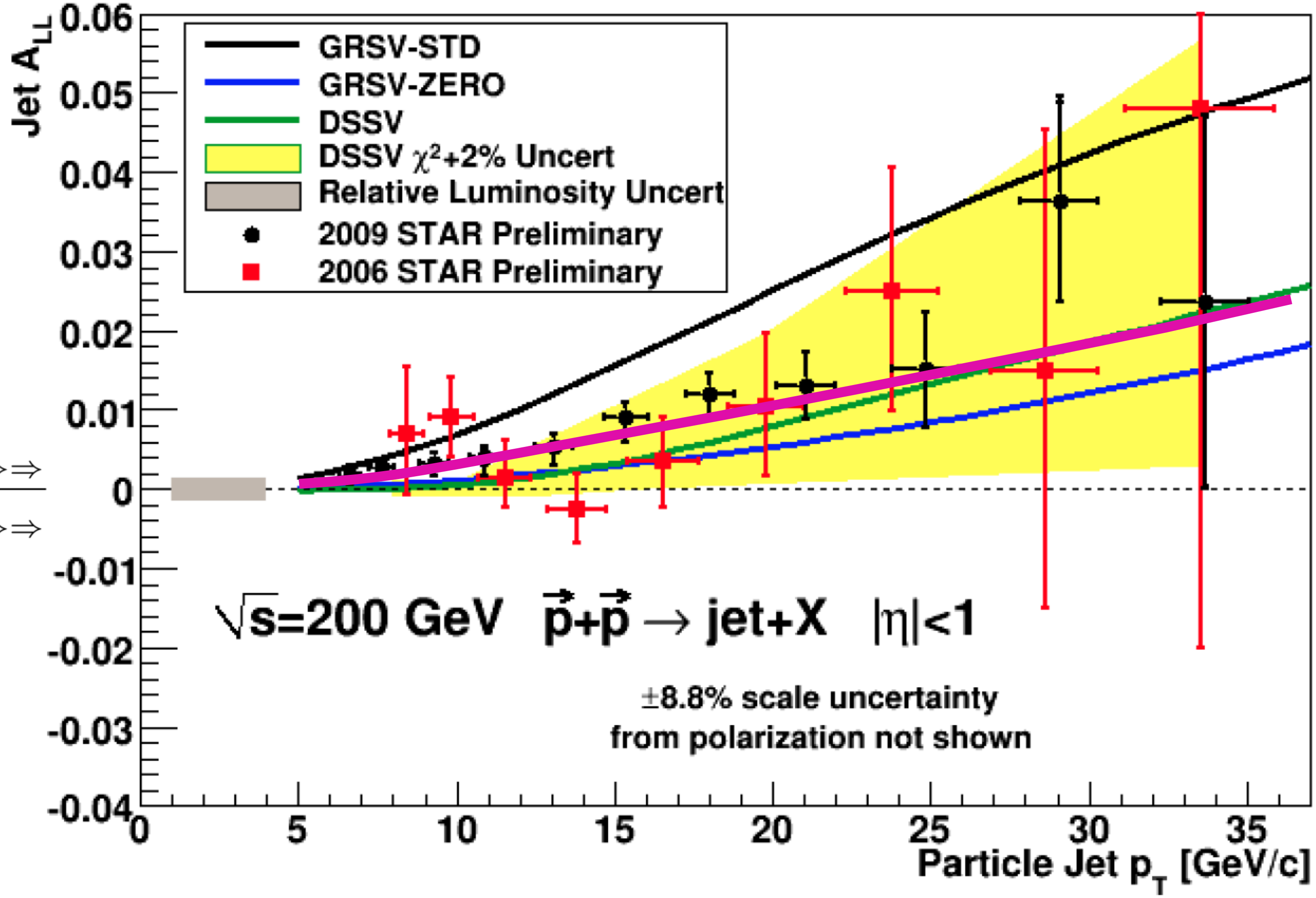


ATLAS

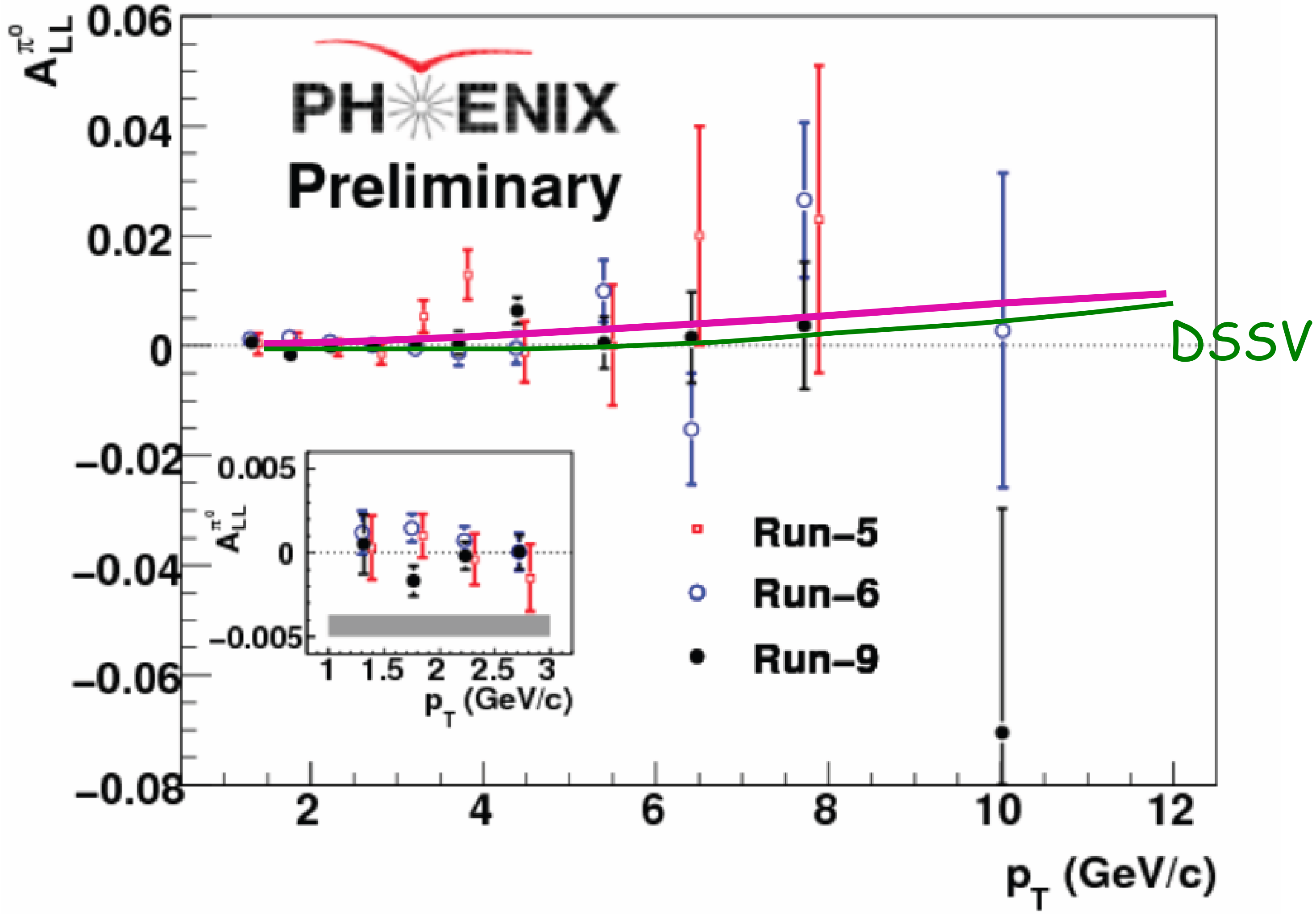
$$r_s = 0.5\,\frac{s+\bar{s}}{\bar{d}}$$

New devlopments on Δg :

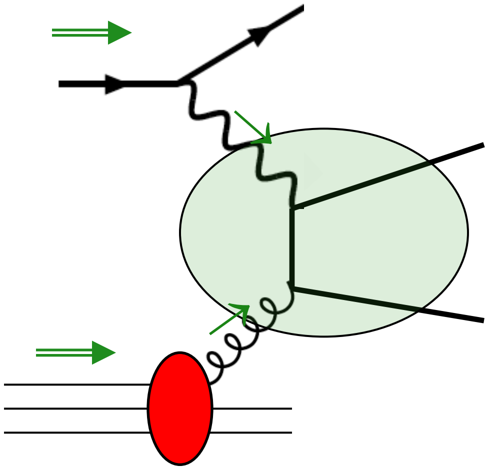
$$A_{LL} = \frac{\sigma_{\Rightarrow\Leftarrow} - \sigma_{\Rightarrow\Rightarrow}}{\sigma_{\Rightarrow\Leftarrow} + \sigma_{\Rightarrow\Rightarrow}}$$

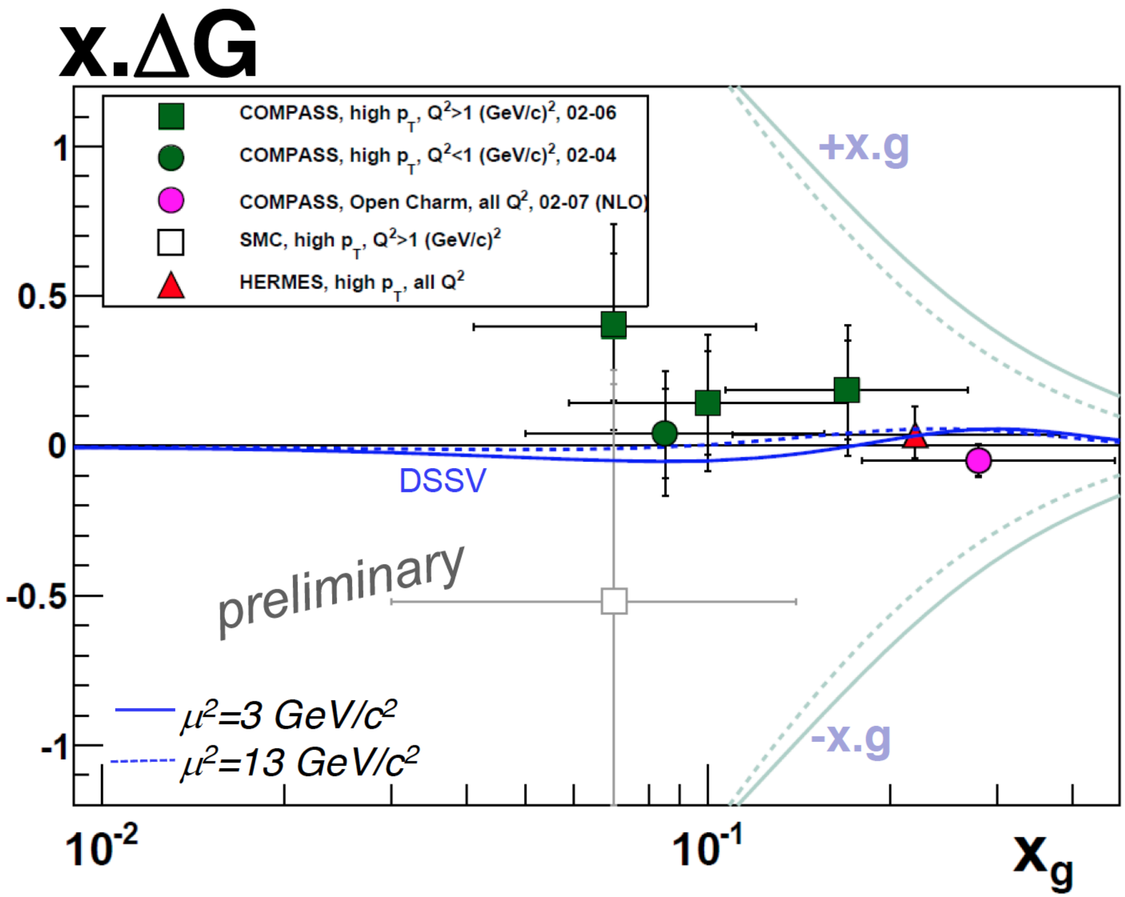


- gives gluon with $\int_{0.05}^{0.2} dx\, \Delta g \approx 0.1$


PHENIX
Preliminary
DSSV
Run–5
Run–6
Run–9
$A_{LL}^{\pi^0}$
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
2
4
6
8
10
12
p_T (GeV/c)
0.005
0
−0.005
1
1.5
2
2.5
3

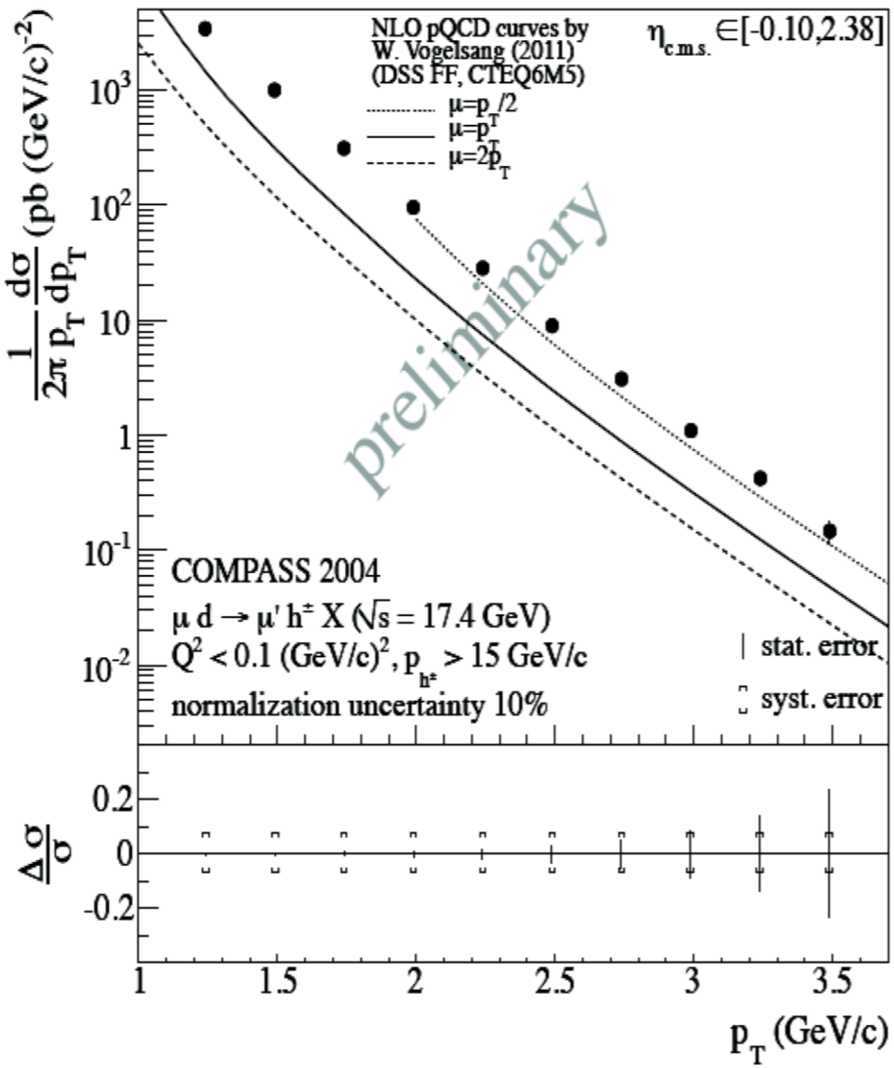
Lepton scattering:





(yet to be included in global analysis)

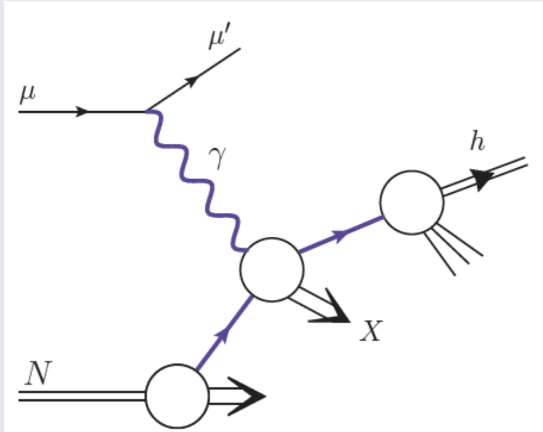
COMPASS cross section for $\gamma d \to h^{\pm} X$



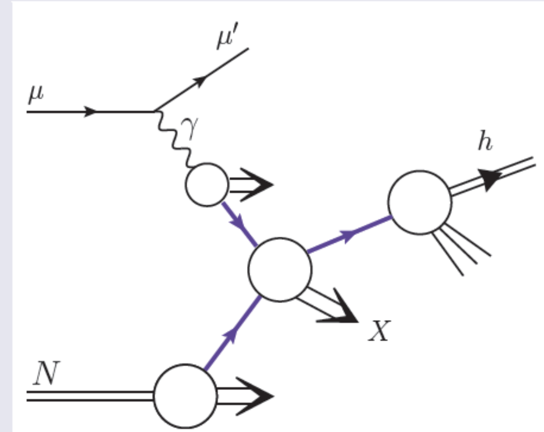
NLO: Jäger, Stratmann, WV

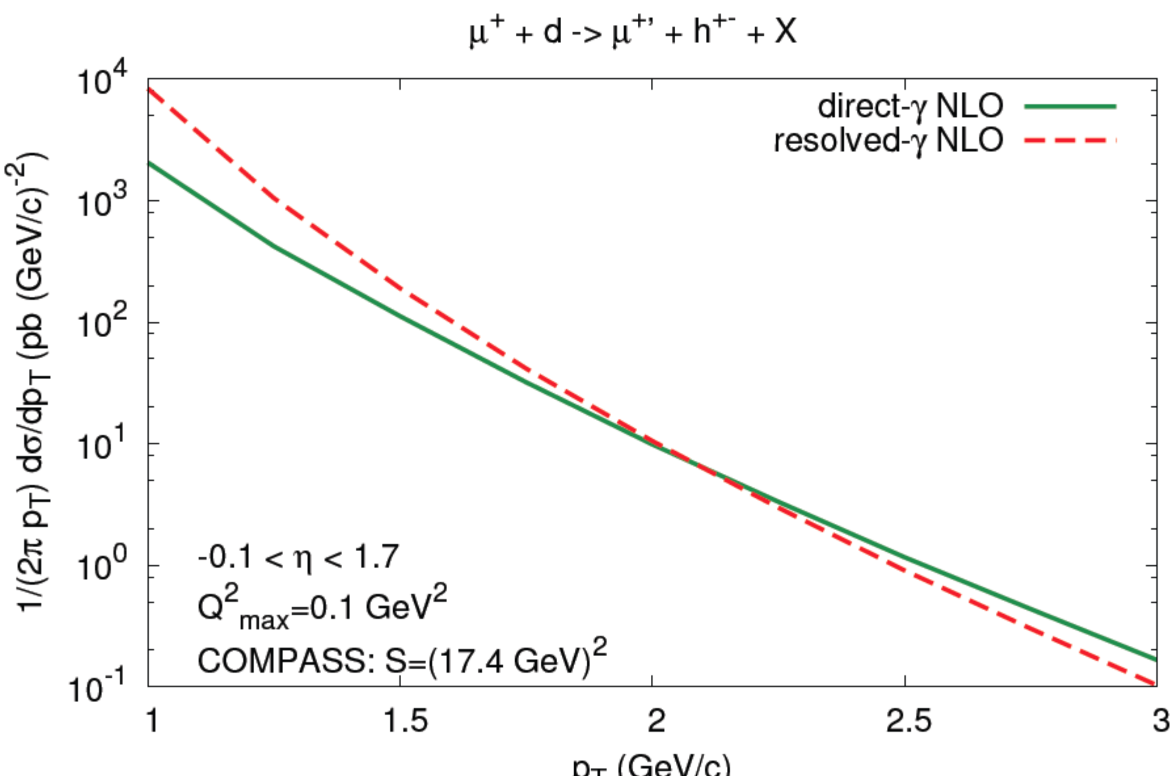
thesis C. Hoeppner / A. Morreale

direct-γ-contribution

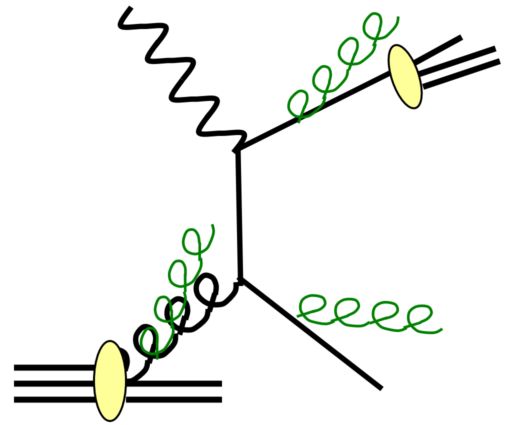


resolved-γ-contribution





Fixed-target regime:
Large logarithmic terms

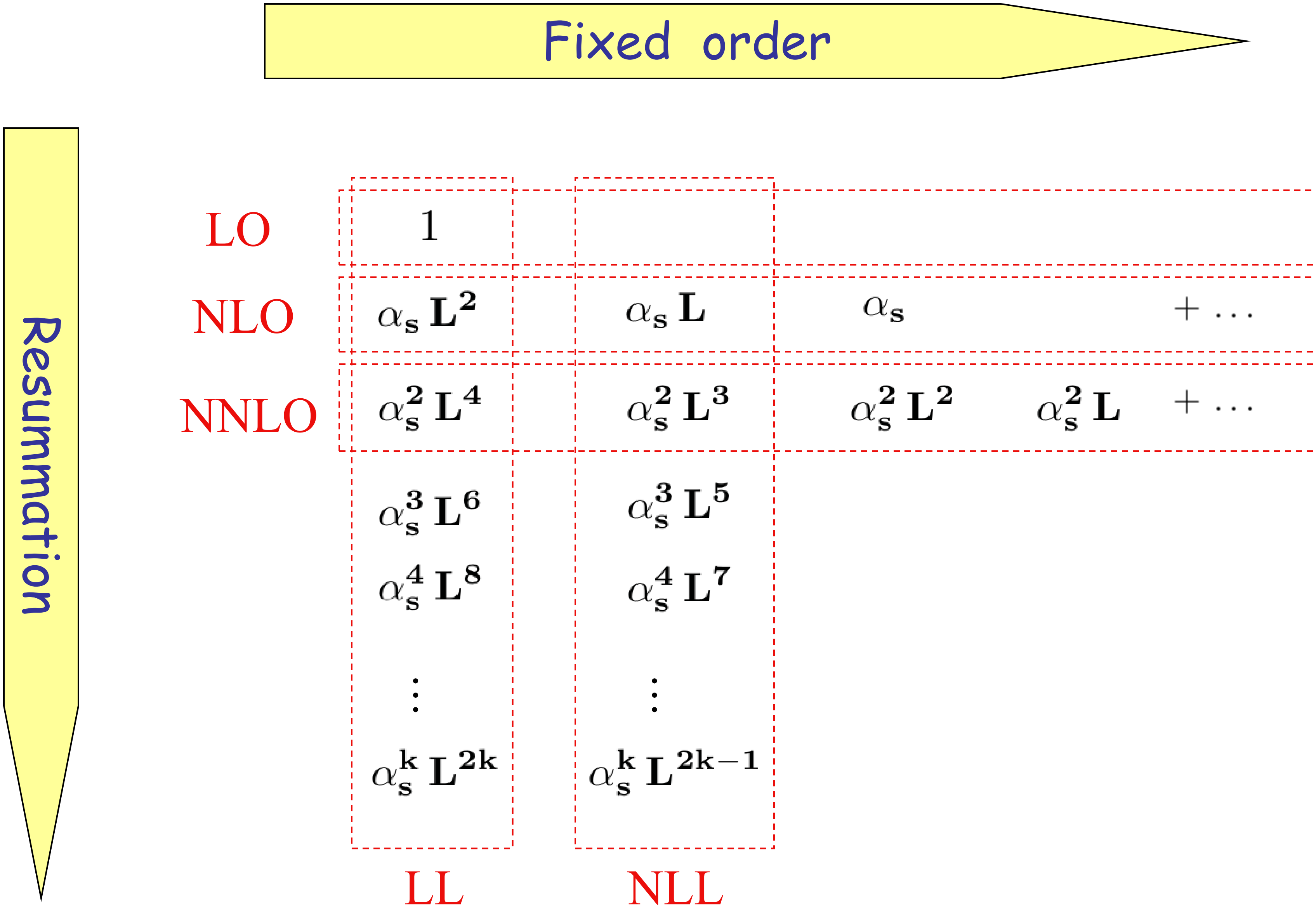


$$p_T^3 \frac{d\hat{\sigma}_{ab}}{dp_T} = p_T^3 \frac{d\hat{\sigma}_{ab}^{\text{Born}}}{dp_T} \left[1 + \underbrace{\mathcal{A}_1 \alpha_s \ln^2\left(1-\hat{x}_T^2\right) + \mathcal{B}_1 \alpha_s \ln\left(1-\hat{x}_T^2\right)}_{\text{NLO}} + \ldots + \mathcal{A}_k \alpha_s^k \ln^{2k}\left(1-\hat{x}_T^2\right) + \ldots \right] + \ldots$$

$$\hat{x}_T \equiv \frac{2p_T}{\sqrt{\hat{s}}}$$

$\hat{x}_T \rightarrow 1$: only soft/collinear gluons allowed

→ all-order resummation relevant

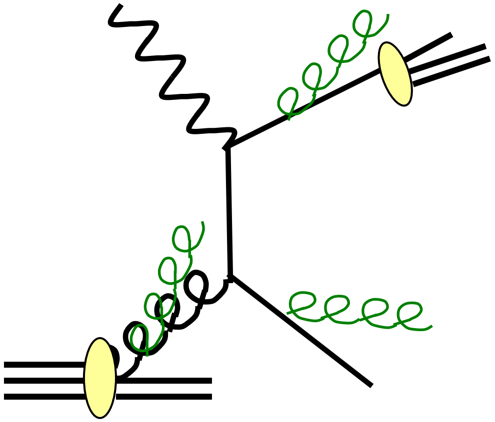

Fixed order
Resummation
LO
NLO
NNLO
1
$\alpha_s L^2$
$\alpha_s L$
α_s
$+ \ldots$
$\alpha_s^2 L^4$
$\alpha_s^2 L^3$
$\alpha_s^2 L^2$
$\alpha_s^2 L$
$+ \ldots$
$\alpha_s^3 L^6$
$\alpha_s^3 L^5$
$\alpha_s^4 L^8$
$\alpha_s^4 L^7$
$\vdots$
$\vdots$
$\alpha_s^k L^{2k}$
$\alpha_s^k L^{2k-1}$
LL
NLL

All-order resummation:

Laenen, Oderda, Sterman; Catani et al.;
Kidonakis, Sterman; Bonciani et al.;
de Florian, WV;
Almeida, Sterman, WV

- soft-gluon effects exponentiate :

$$\gamma g \to qg$$

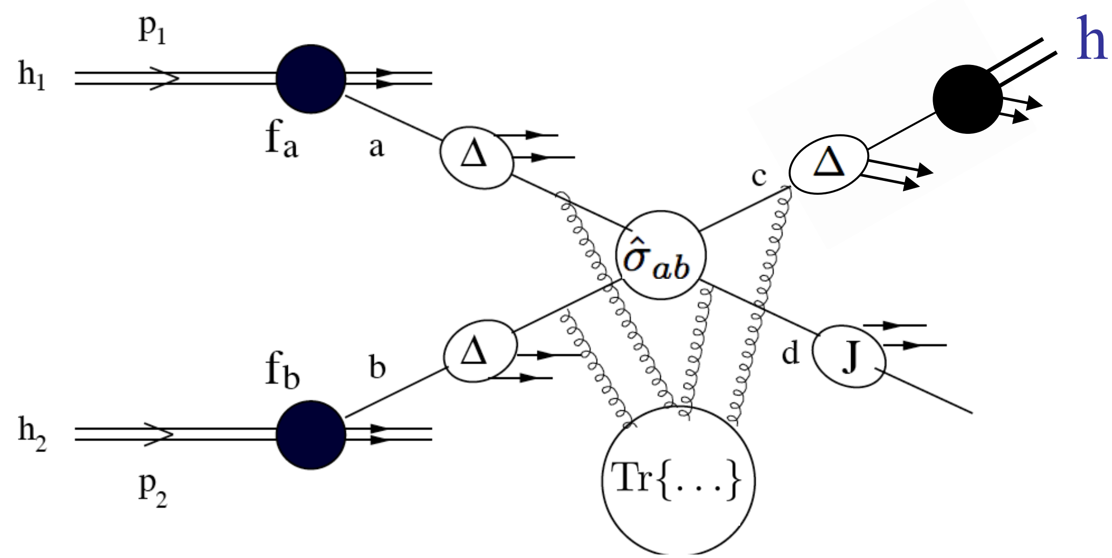


Leading logarithms:

Mellin moment in $\hat{\mathbf{x}}_{\mathbf{T}}^{\mathbf{2}}$

$$\sigma_{\rm res}^{\gamma g} \sim \exp\left[\left(C_A + C_F - \frac{1}{2}C_F\right)\frac{\alpha_s}{\pi}\ln^2 N\right]$$

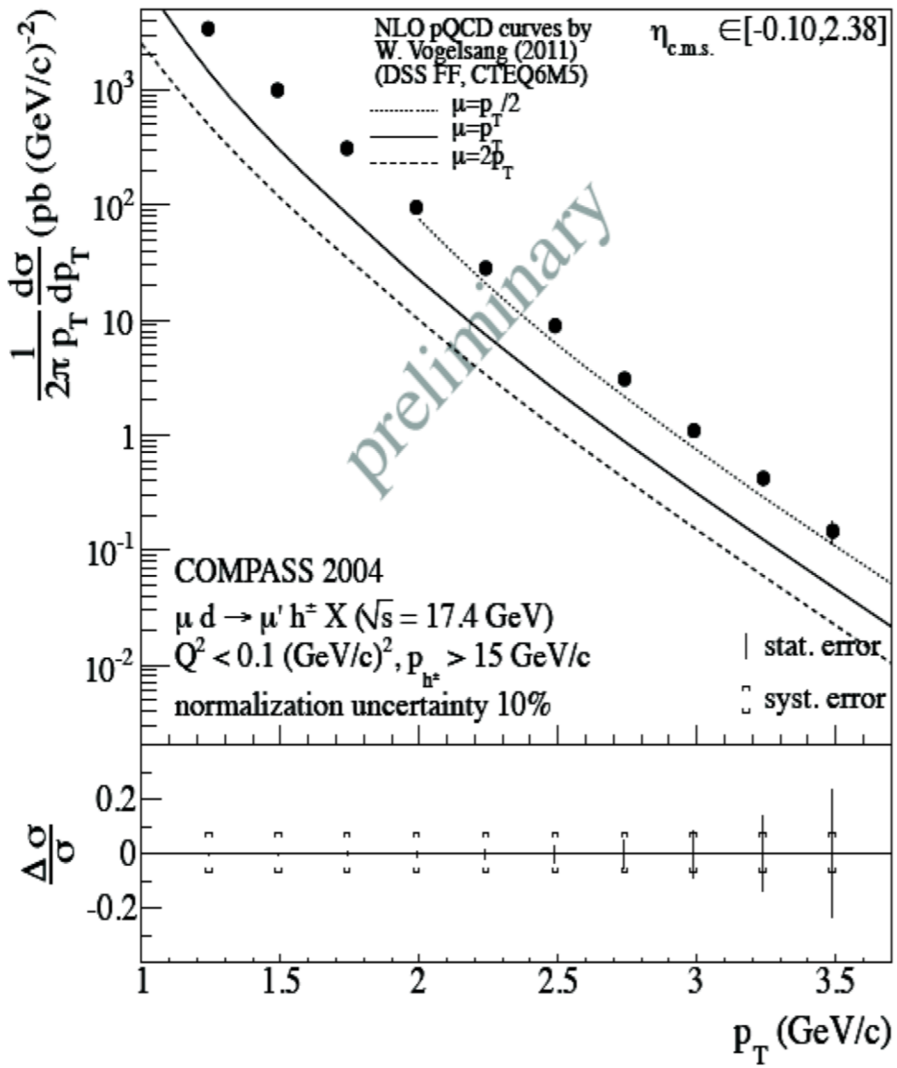
Beyond leading logs:

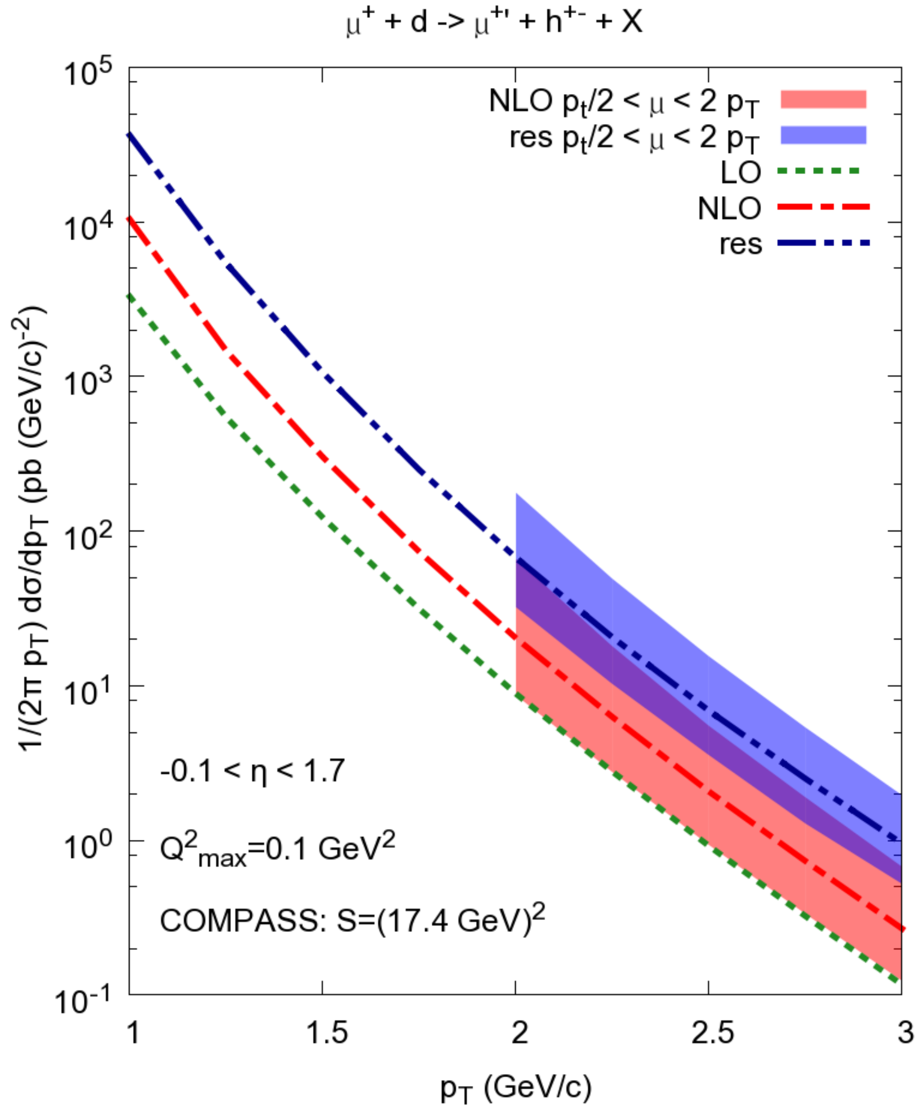


$$\hat{\sigma}^{(\mathrm{res})} = C_{ab\to cd}\,\Delta^{a}_{N_a}\,\Delta^{b}_{N_b}\,\Delta^{c}_{N}\,J^{d}_{N}\,\mathrm{Tr}\left\{H\mathcal{S}^{\dagger}_{N}S\mathcal{S}_{N}\right\}\hat{\sigma}^{B}_{ab\to cd}(N)$$

soft & coll.
gluons (LL)

large-angle
soft gluons (NLL)



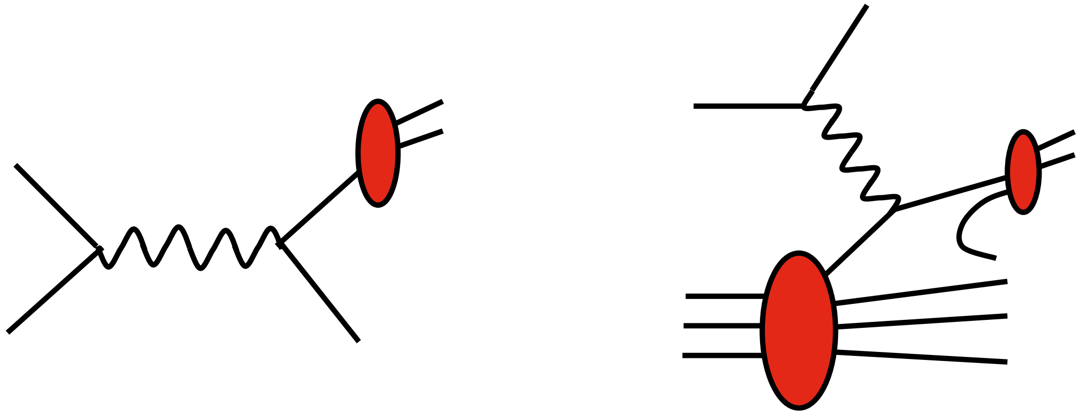


de Florian, Pfeuffer, Schäfer, WV (prel.)

News on fragmentation functions

Fragmentation functions $D_q^h(z)$:

- crucial for pQCD description of hadron-production data: $e^+e^- \to hX, \;\; ep \to hX, \;\; pp \to hX$

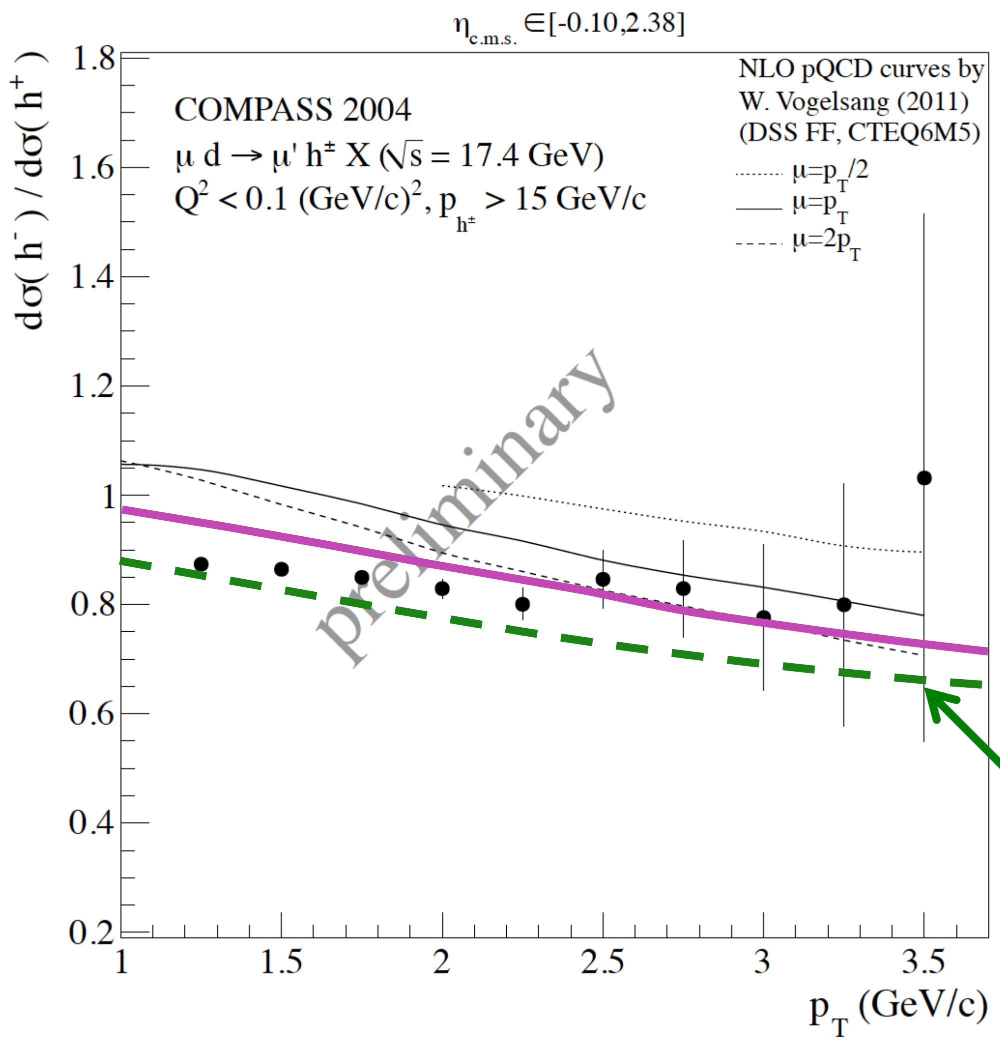


- encode hadronization in hard-scattering reactions
- universality / factorization
- global analyses with uncertainty estimates:

  de Florian, Stratmann, Sassot (DSS) e^+e^-, ep, pp

  Albino, Kniehl, Kramer (AKK) e^+e^-, pp

  Hirai, Kumano, Nagai. Sudoh (HKNS) e^+e^-



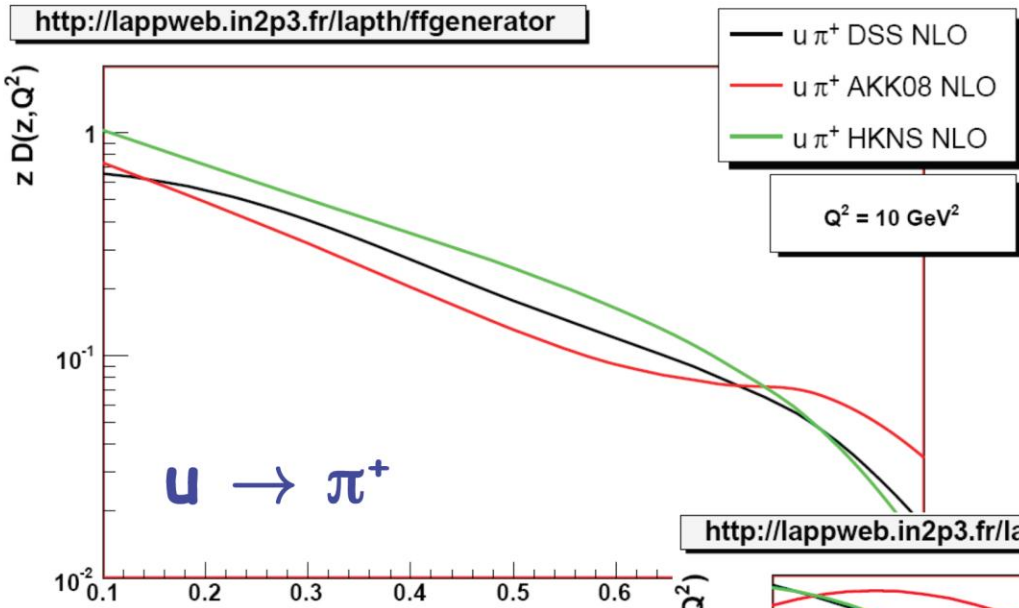
corrected mistake in NLO calculation !

direct only

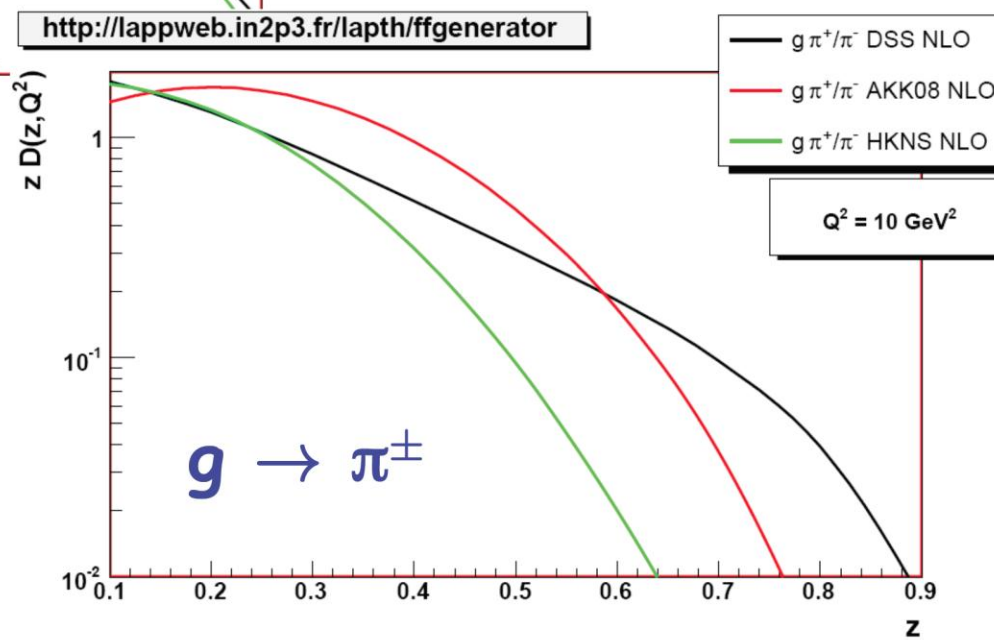
thesis C. Hoeppner

(M. Stratmann at INT workshop 02/2012)

comparison of pion FFs

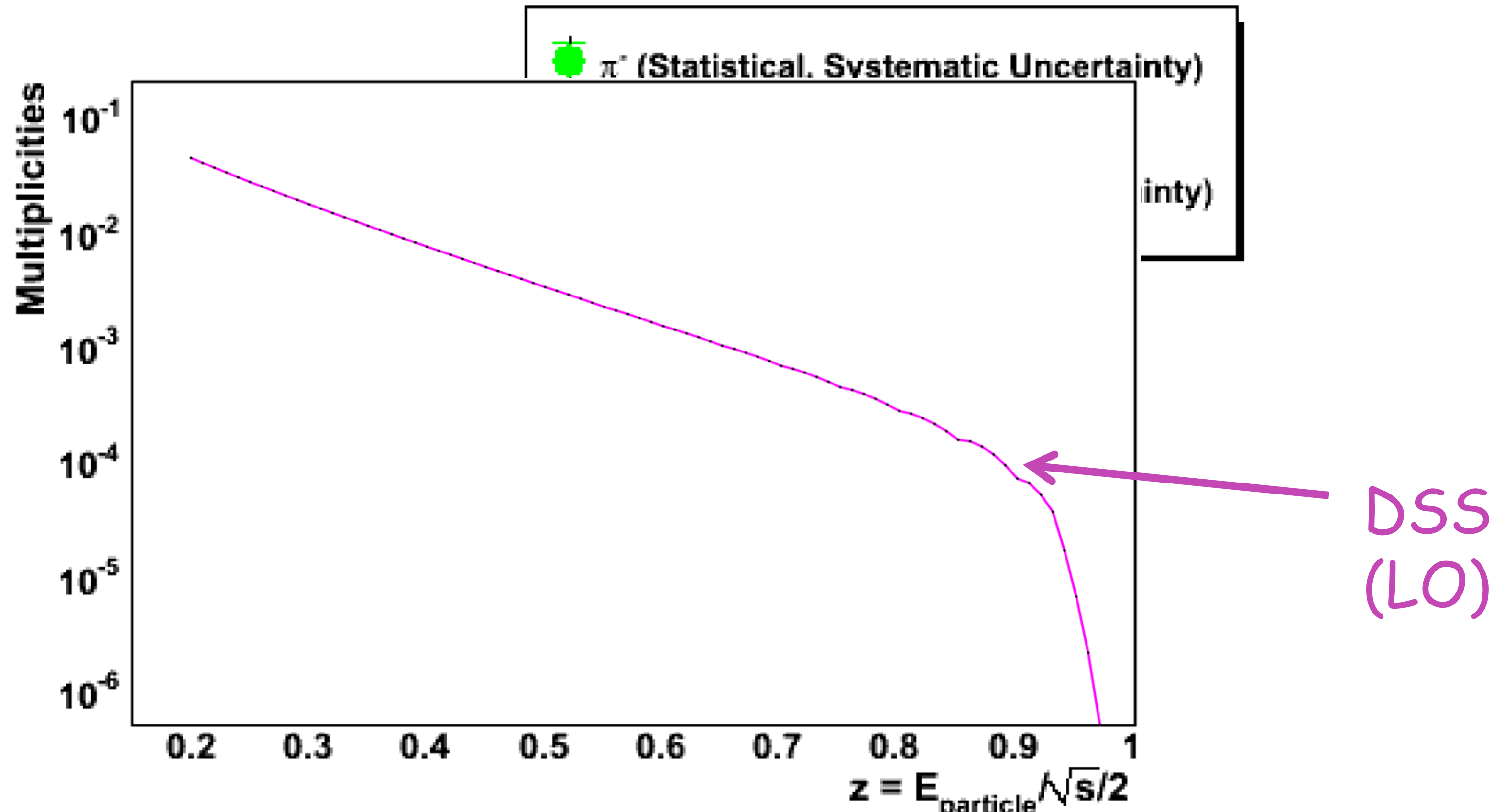


LEP data mostly fix singlet !



recall: DSS, AKK08, HKNS
are based on different data sets
and assumptions

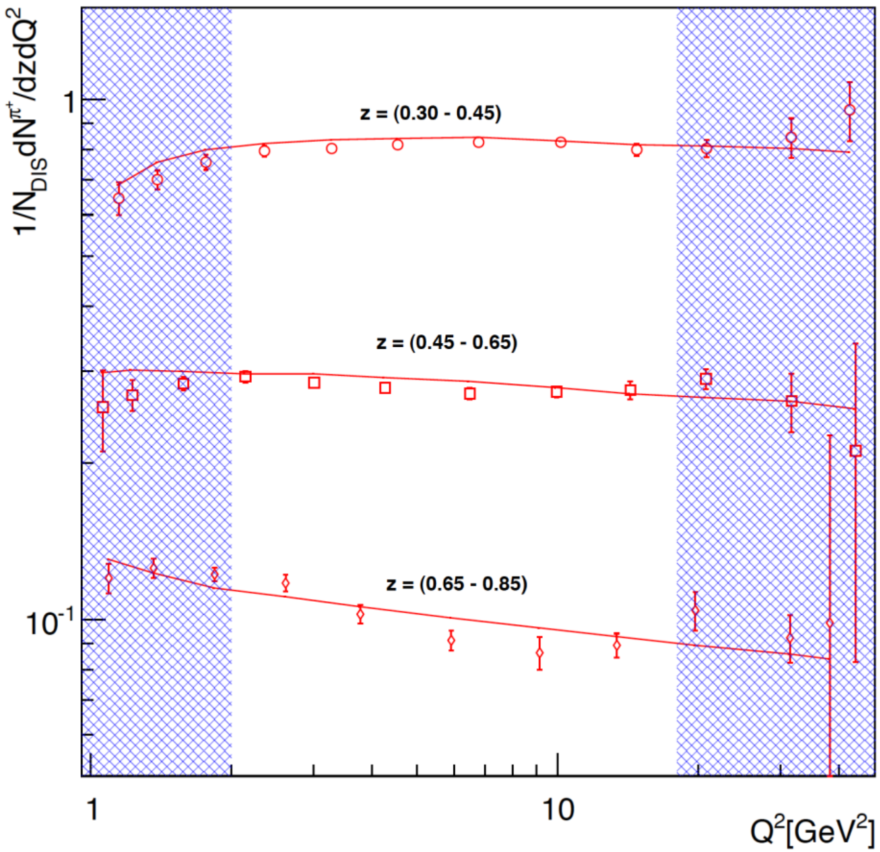
BELLE (M. Leitgab at DIS 2012)

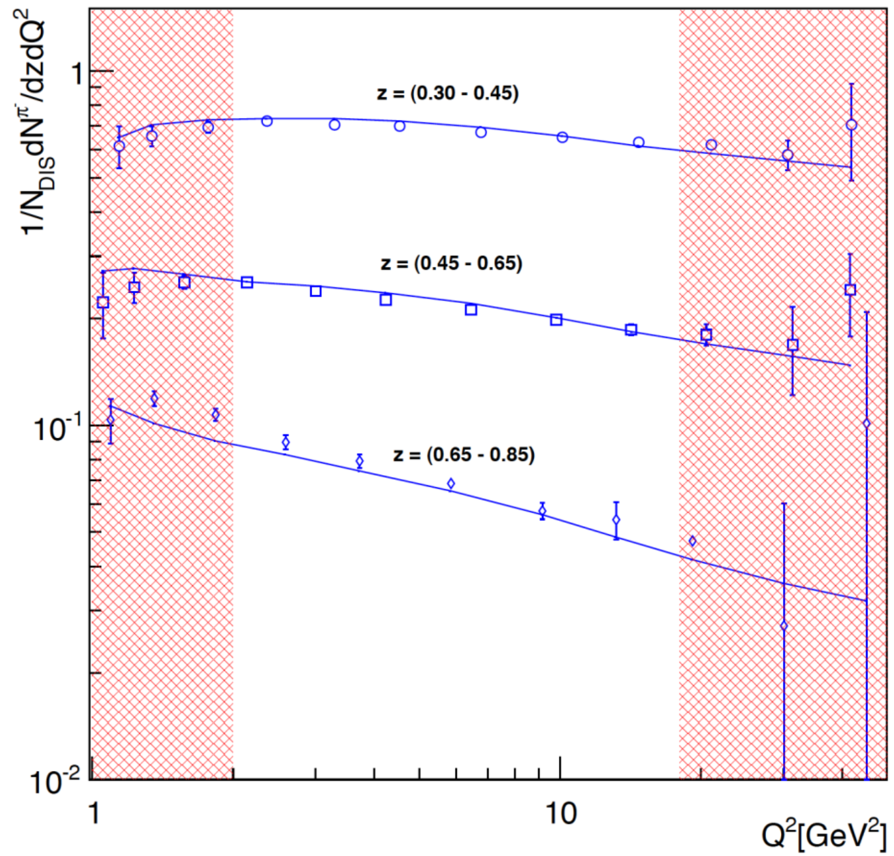


Belle experimental data, ~220M events

- marks new era of precision fragmentation functions.
  Evolution → D_g^h e^+e^- vs. RHIC(pp)
- beware of large-z effects / power corrections !

$\pi^{\pm}$



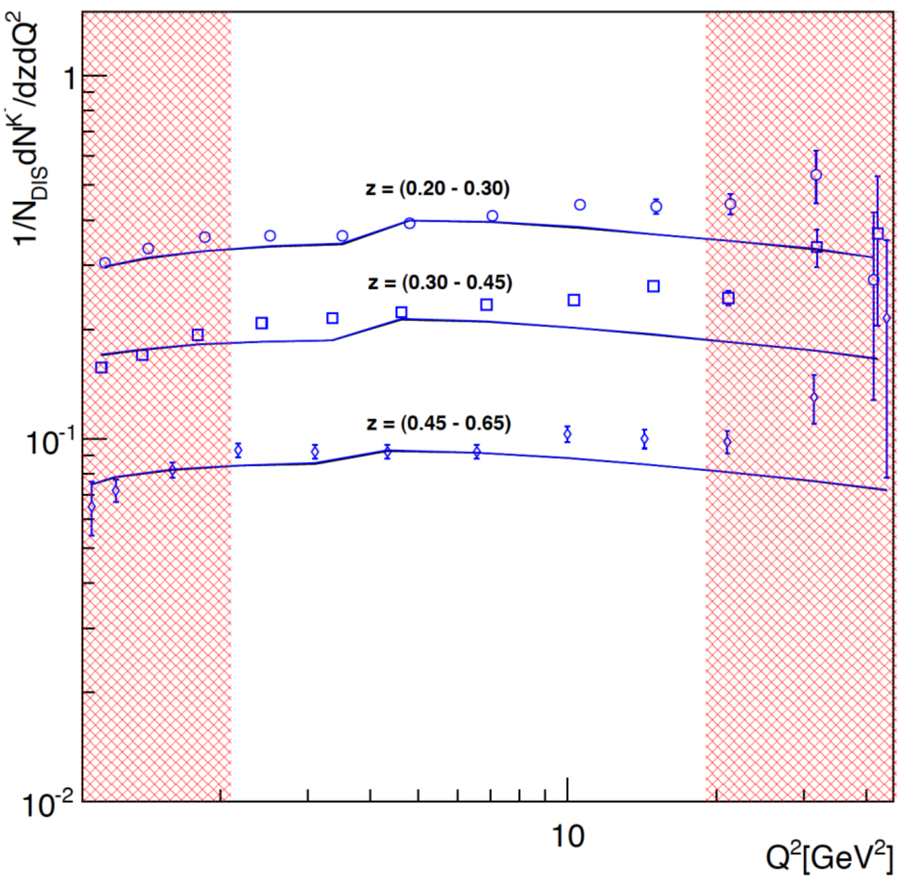


courtesy de Florian,Pinto,Sassot,Stratmann

(w/o HERMES data)

$K^{\pm}$

Preliminary fit to COMPASS data



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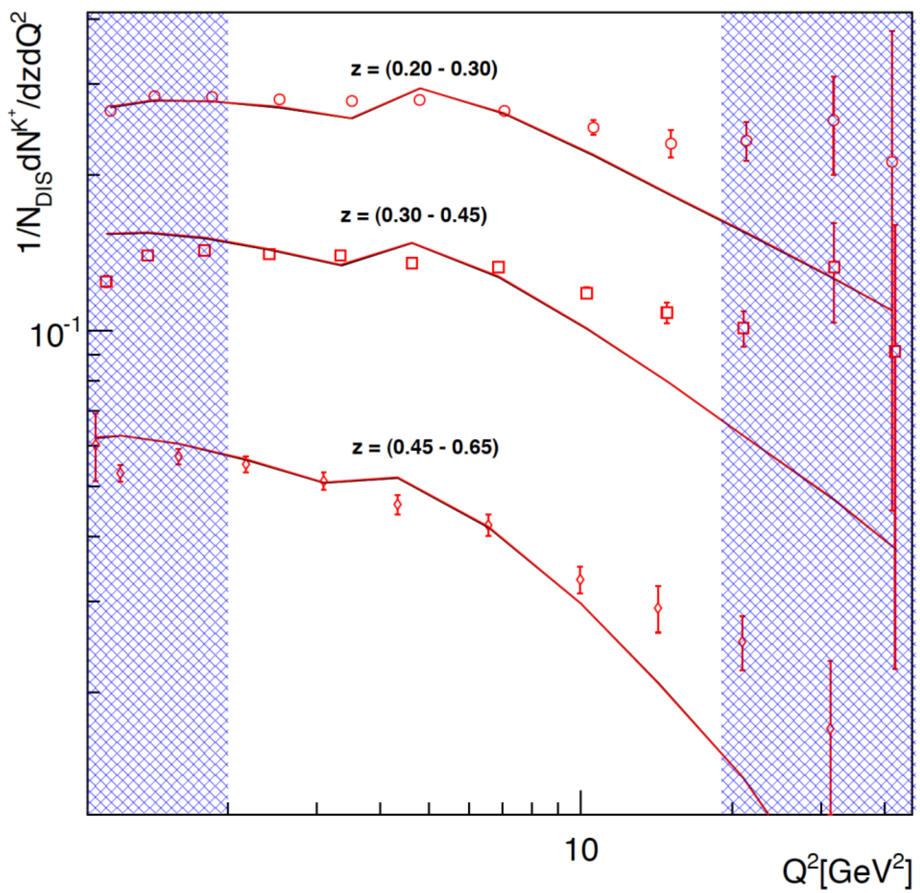
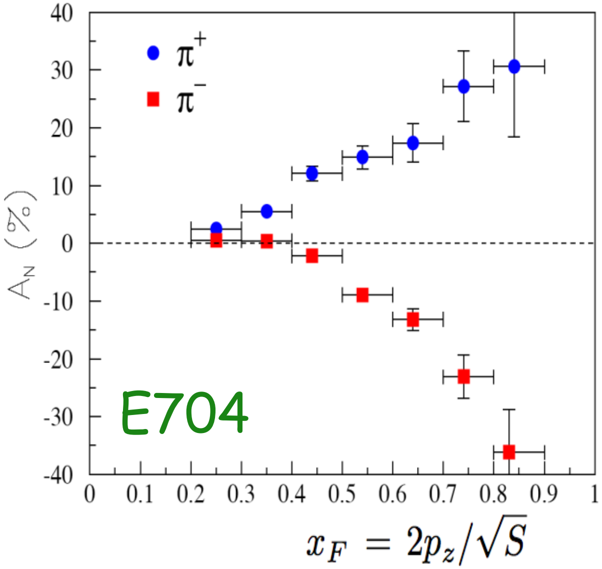
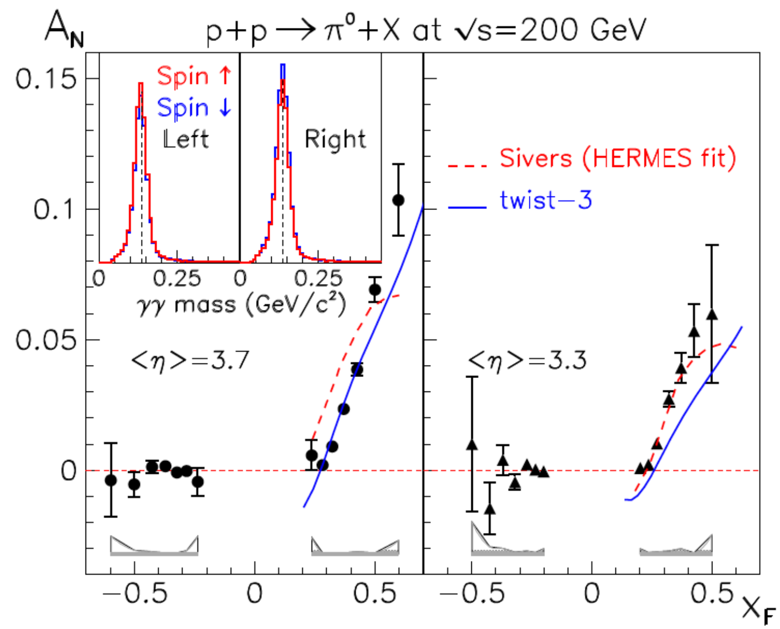


(w/o HERMES data)

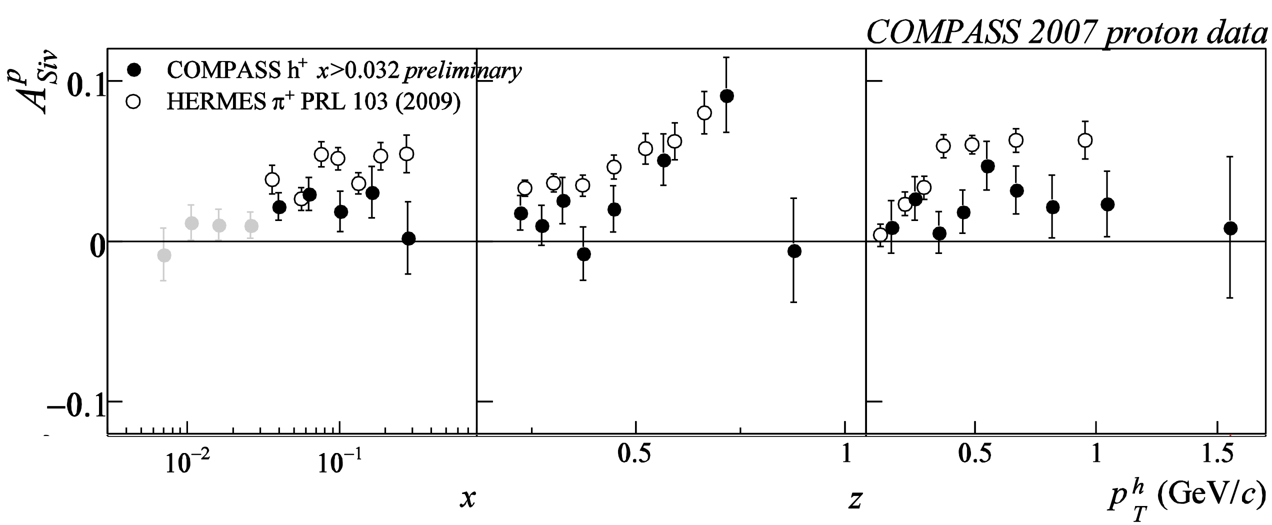
courtesy de Florian,Pinto,Sassot,Stratmann

Transverse-spin phenomena



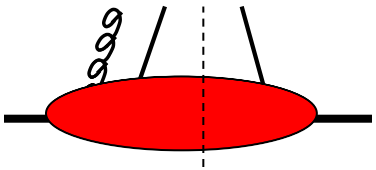


STAR, BRAHMS, PHENIX



HERMES, COMPASS, JLab

- *single-inclusive* processes, e.g. $pp \to \pi X$
  - single large scale $p_\perp$
  - power-suppressed ~$1/p_\perp$ in QCD
  - collinear factorization
  - probe qqg correlations, e.g. $T_F \sim \langle P,S|\,\bar{q}\,F\,q\,|P,S\rangle$



- *two-scale* processes: small & measured $q_\perp \ll Q$
  - SIDIS at HERMES,COMPASS
  - TMD factorization for simplest observables, e.g. Sivers $f_{1T}^{\perp q}$
  - crucial role of gauge links / non-universality
  - spin-orbit correlations, "lensing", 3D imaging

TMDs and twist-3 functions are closely related:

- at operator level:

Boer,Mulders,Pijlman,
Ji, Qiu,WV,Yuan; Koike,WV,Yuan
Zhou,Yuan,Liang
Bacchetta,Boer,Diehl,Mulders

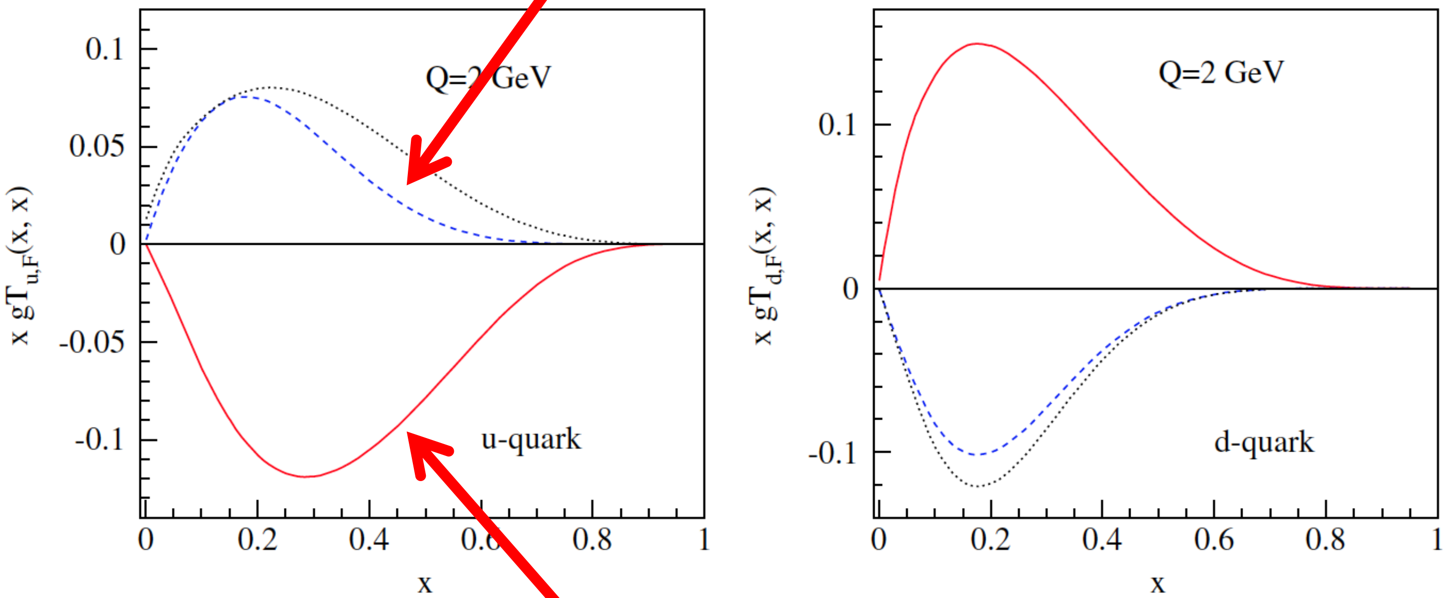
$$T_F(x,x) = -\int \frac{d^2\vec{k}_\perp}{2\pi} \frac{\vec{k}_\perp^2}{M^2} \left(f_{1T}^\perp(x,k_\perp)\right)_{\rm DIS}$$

- it means we can confront SIDIS and RHIC data

→ a sign puzzle

Kang,Qiu,Yuan,WV

from $-\int \frac{d^2\vec{k}_\perp}{2\pi} \frac{\vec{k}_\perp^2}{M^2} \left(f_{1T}^\perp(x, k_\perp)\right)_{\rm DIS}$



Kang,Qiu,Yuan,WV

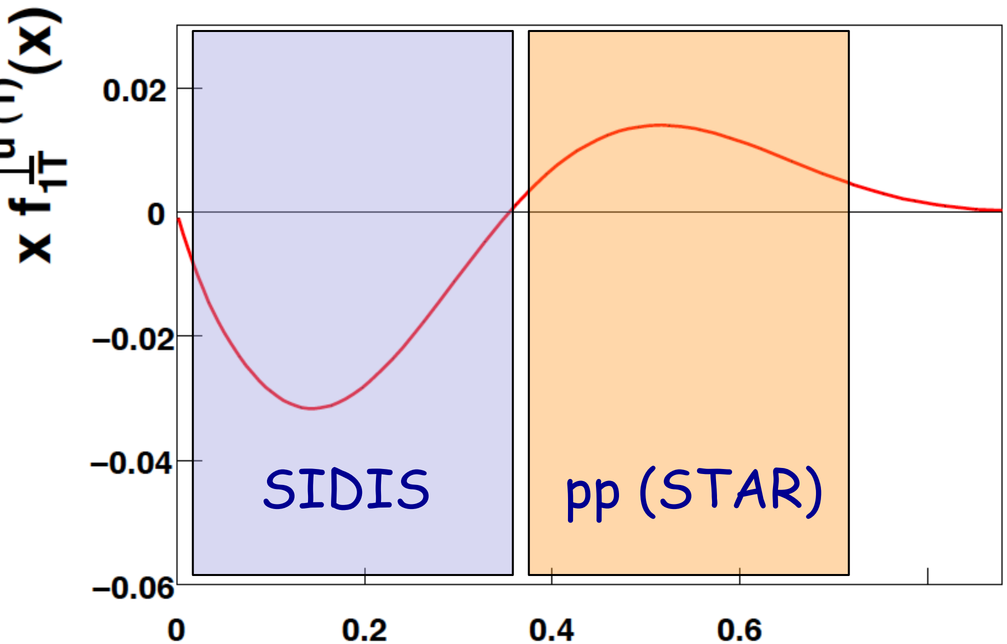
$T_F(x,x)$ from pp

What to conclude ?

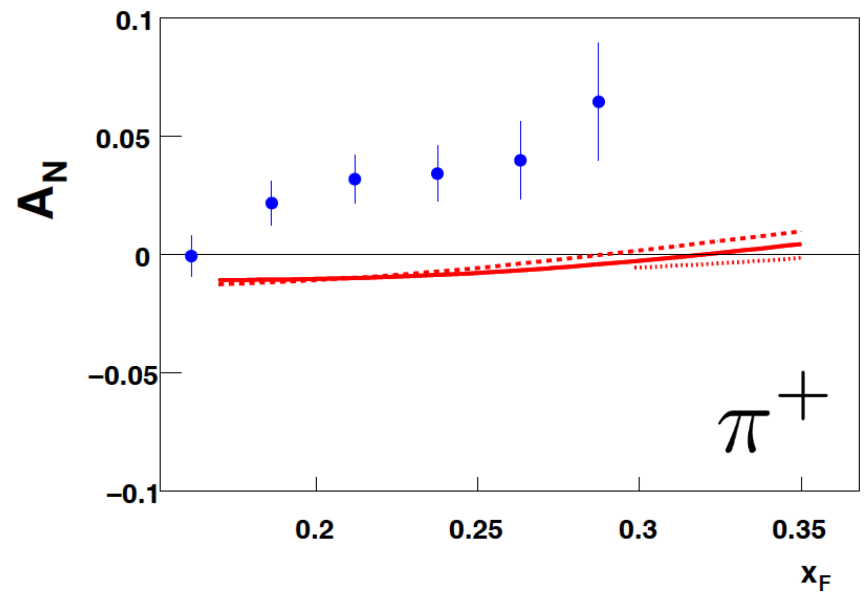
- inconsistency in QCD formalism for single-spin ?
- Collins-type effect dominant in $pp \to \pi X$?
- more mundane : can one get away with nodes in x / k_T?

Joint fit to SIDIS and pp data:

Kang,Prokudin

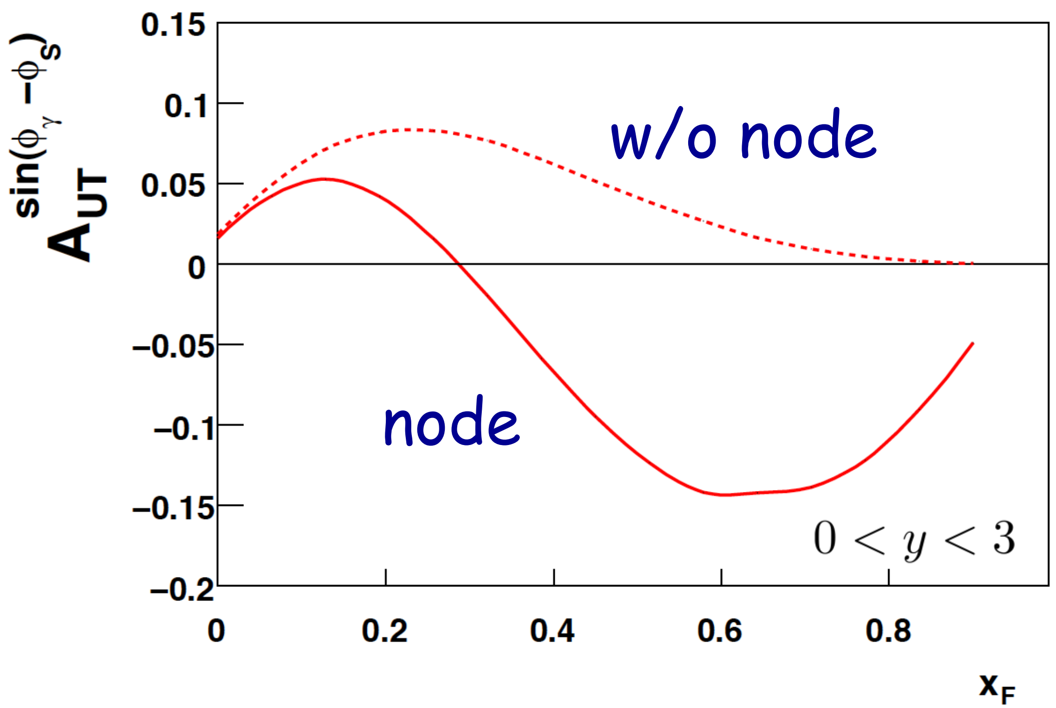


Works (reasonably) well for SIDIS and STAR, but fails For BRAHMS!



Has ramifications for DY spin asymmetry:

Kang,Prokudin

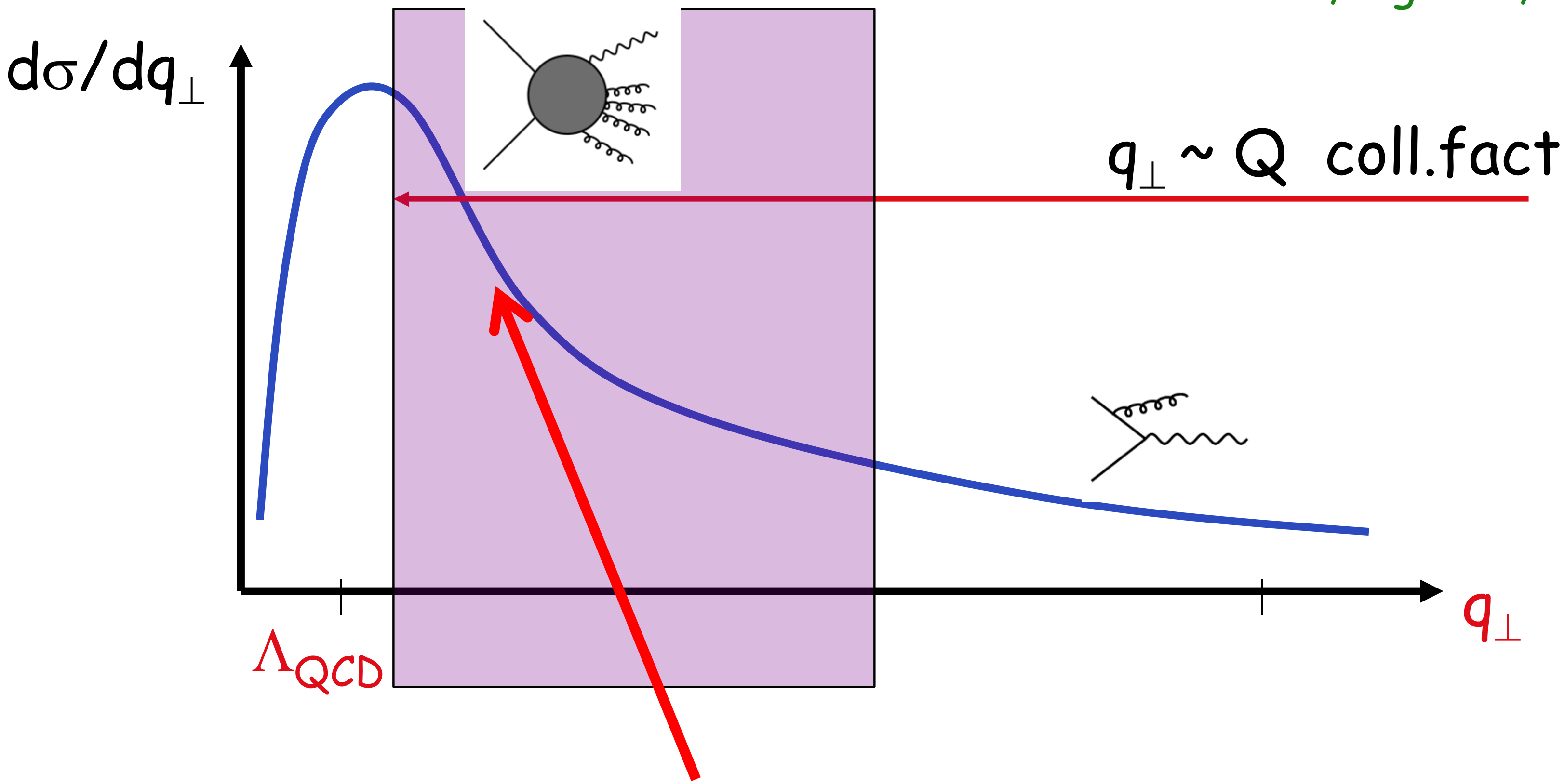


Strengthens case for study of DY "sign change" !

AnDY, COMPASS, E906,W bosons at RHIC

QCD evolution of TMDs

Collins,Aybat,Rogers,Qiu
Kang,Xiao,Yuan
Aybat,Prokudin,Rogers
Anselmino,Boglione,Melis



well-known feature: emergence of Sudakov logarithms

$$\alpha_s^k \frac{\log^{2k-1}\left(\frac{Q^2}{q_\perp^2}\right)}{q_\perp^2}$$

- can be resummed to all orders in strong coupling

(e.g. Drell-Yan, simplified)

Collins,Soper,Sterman;...
Koike, Nagashima,WV
Kang,Xiao,Yuan

$$\frac{d\sigma}{d^2q_\perp} \sim \sigma_0 \int d^2b\, \mathrm{e}^{-i\vec{b}\cdot\vec{q}_\perp}\, q(x_1,1/b)\otimes\bar{q}(x_2,1/b)\ \mathrm{e}^{\underbrace{-\frac{C_F}{\pi}\int_{1/b^2}^{Q^2}\frac{dk_\perp^2}{k_\perp^2}\left(\alpha_s(k_\perp^2)\log\frac{Q^2}{k_\perp^2}+\ldots\right)}_{\text{Sudakov exponent}}}$$

- can be formulated to give evolution of TMDs in terms of

$$\frac{d\sigma}{dq_\perp^2} \sim \sigma_0 \int d^2k_{\perp,1} \int d^2k_{\perp,2}\, F(x_1,k_{\perp,1},Q)\,\bar{F}(x_2,k_{\perp,2},Q)\,\delta^{(2)}(\vec{k}_{\perp,1}+\vec{k}_{\perp,2}-\vec{q}_\perp)$$

Mert Aybat,Rogers,
Collins,Qiu
Kang,Xiao,Yuan

- for Sivers function obtain (~ Sudakov)

$$f_{1T}^{\perp f}(x,k_\perp;Q) = \frac{-1}{2\pi k_\perp}\int_0^\infty \mathrm{d}b_T\, b_T\, J_1(k_\perp b_T)\, \tilde{F}_{1T}^{\prime\perp f}(x,b_T;Q,\zeta_F)$$

where

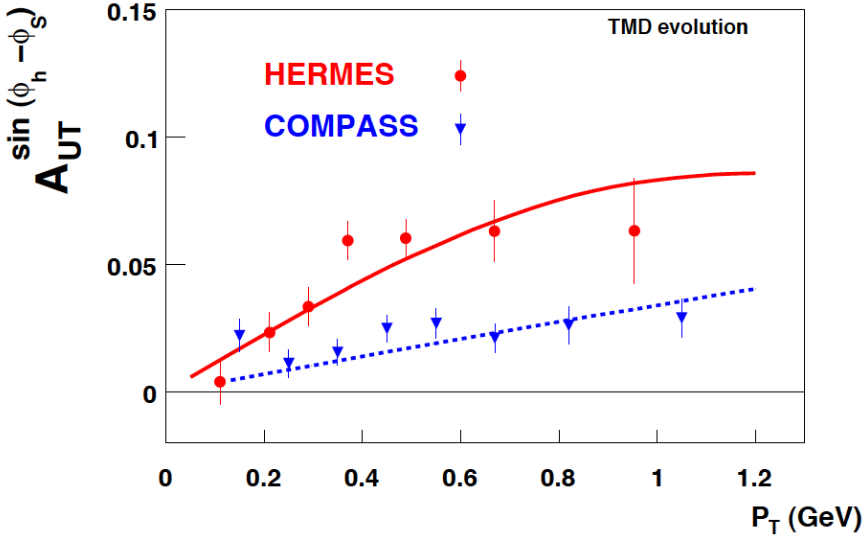
$$\tilde{F}_{1T}^{\prime\perp f}(x,b_T;Q,\zeta_F) = \tilde{F}_{1T}^{\prime\perp f}(x,b_T;Q_0,Q_0^2)$$
$$\times\exp\left\{\ln\frac{Q}{Q_0}\tilde{K}(b_*;\mu_b) + \int_{Q_0}^{Q}\frac{d\mu'}{\mu'}\left[\gamma_F(g(\mu');1) - \ln\frac{Q}{\mu'}\gamma_K(g(\mu'))\right]\right.$$
$$\left. + \int_{Q_0}^{\mu_b}\frac{d\mu'}{\mu'}\ln\frac{Q}{Q_0}\gamma_K(g(\mu')) - g_K(b_T)\ln\frac{Q}{Q_0}\right\}$$

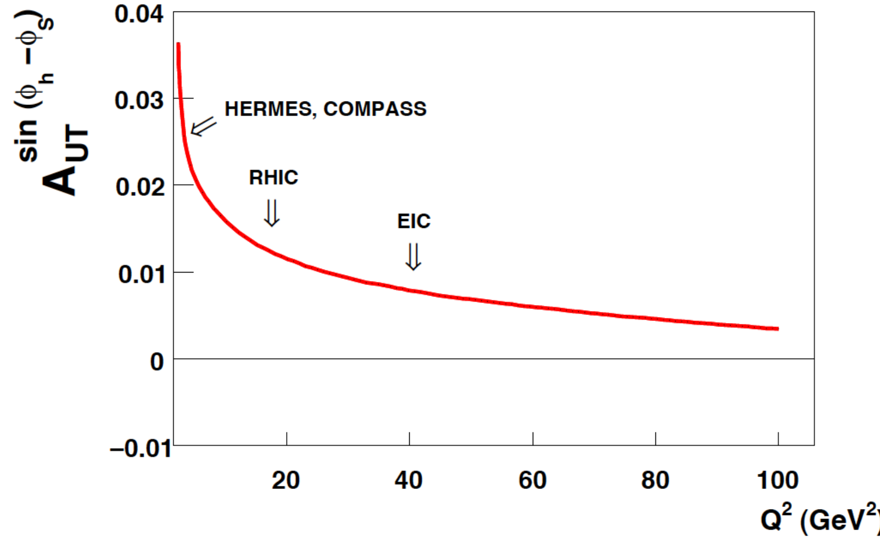
non-pert. piece

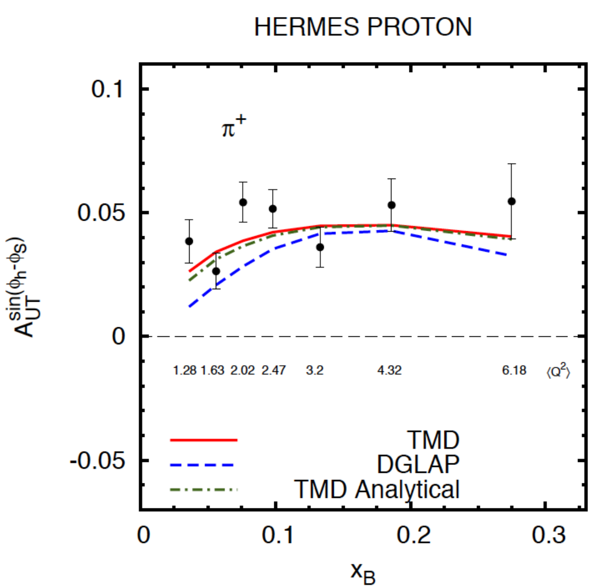
$$\mu_b \sim 1/b_* \qquad b_* = \frac{b_T}{\sqrt{1 + b_T^2/b_{\max}^2}}$$

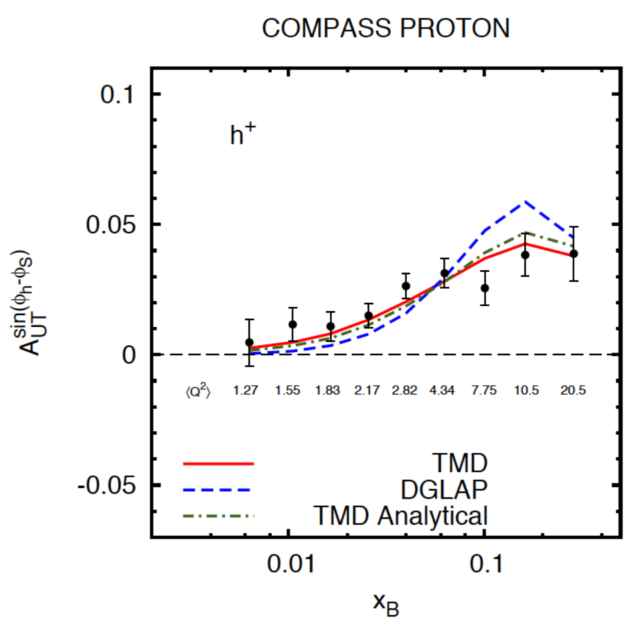
- initial phenomenology very encouraging

Aybat,Prokudin,Rogers









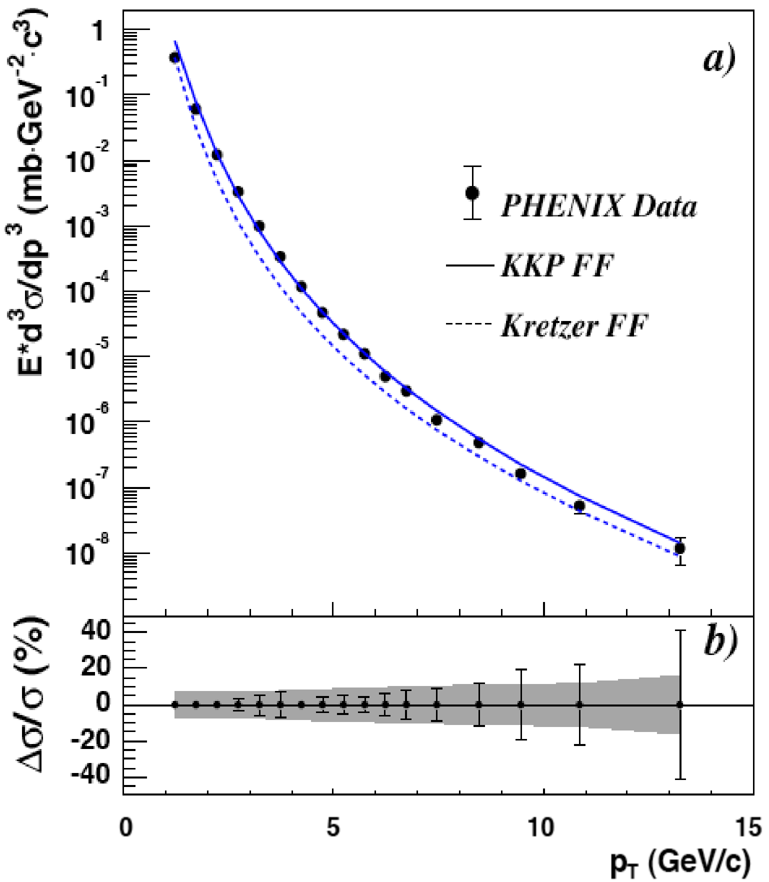
Anselmino,
Boglione,
Melis

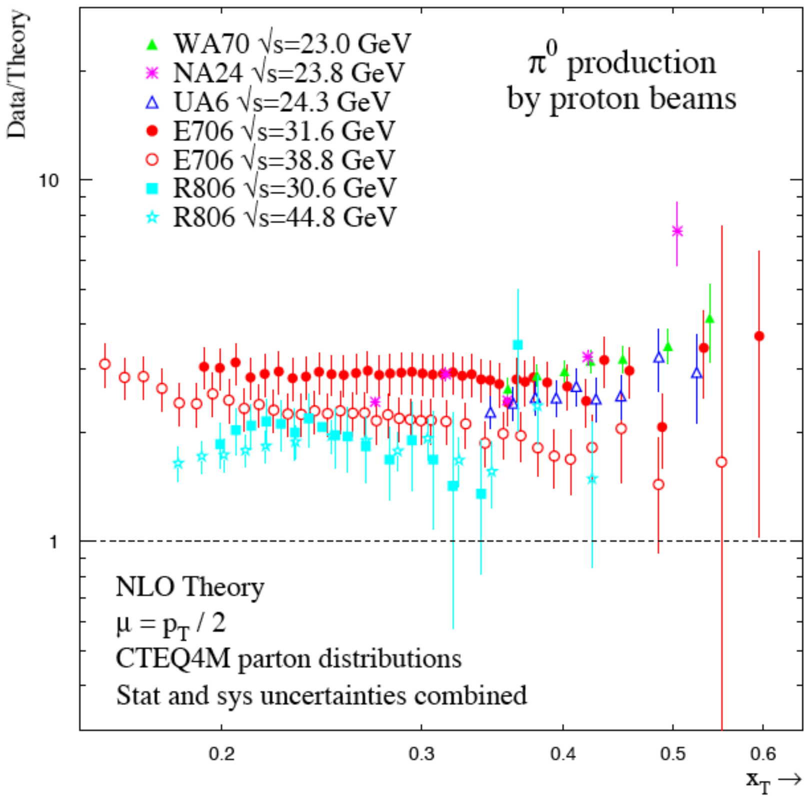
Takes this field to new level !

However, a number of caveats:

- various simplifying assumptions
- results will depend on large-b prescription:
  b_* only one possible choice
  choice of parameters such as g_2, b_{max}
- matching to large-k_T tail ("Y-term" / T_F)
- so far "just" leading log

Enjoy IWHSS12 !





…well described by NLO at RHIC

…but data much higher than NLO at fixed-target energies !

News

- spin sum rule / orbital angular momentum: a long-standing debate

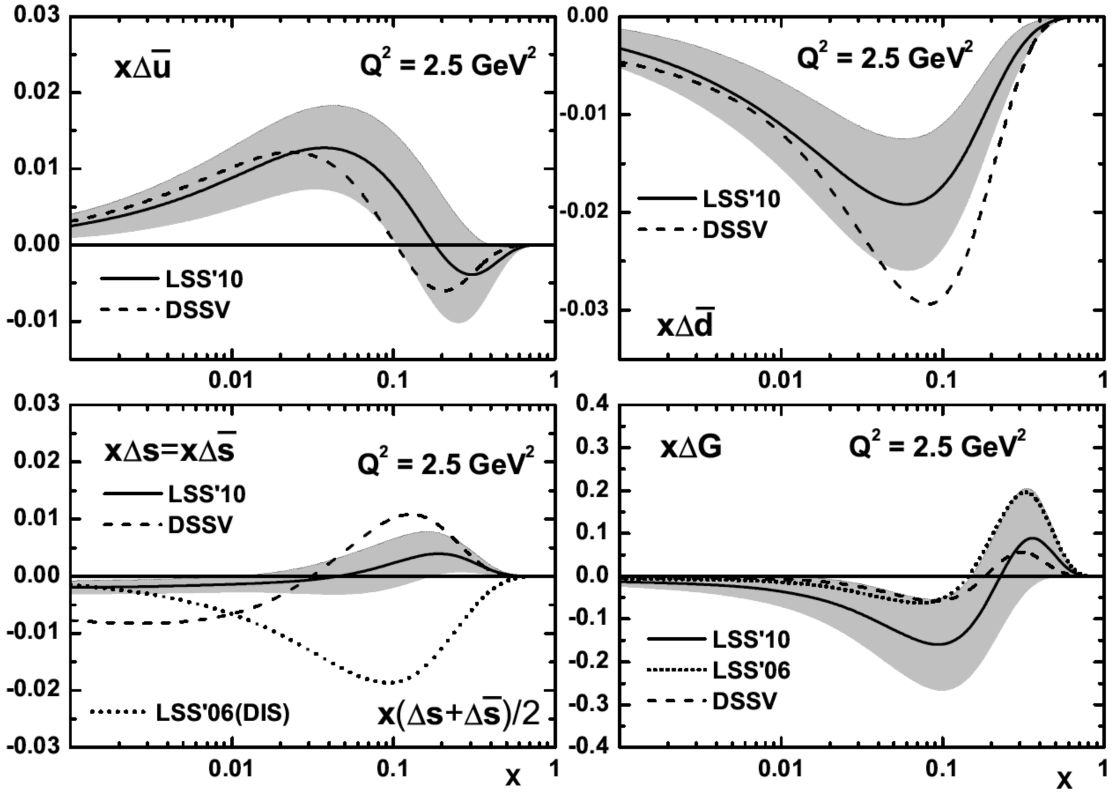
$$\boldsymbol{J}_{QCD} = \boldsymbol{S}^q + \boldsymbol{L}^q + \boldsymbol{S}^g + \boldsymbol{L}^g$$

$$\begin{aligned}
\boldsymbol{S}^q &= \int \psi^\dagger \frac{1}{2} \boldsymbol{\Sigma}\, \psi\, d^3x, \\
\boldsymbol{L}^q &= \int \psi\, \boldsymbol{x} \times (\boldsymbol{p} - g\, \boldsymbol{A})\, \psi\, d^3x, \\
\boldsymbol{S}^g &= \int \boldsymbol{E}^a \times \boldsymbol{A}^a_{phys}\, d^3x, \\
\boldsymbol{L}^g &= \int E^{aj}\, (\boldsymbol{x} \times \nabla)\, A^{aj}_{phys}\, d^3x \;+\; g \int \psi^\dagger\, \boldsymbol{x} \times \boldsymbol{A}_{phys}\, \psi\, d^3x
\end{aligned}$$

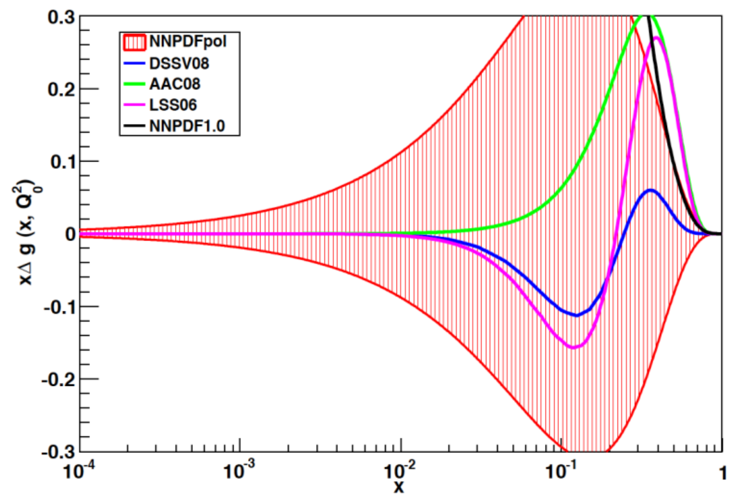
$$\begin{aligned}
A^\mu_{phys}(x) &\to U(x)\, A^\mu_{phys}(x)\, U^{-1}(x), \\
A^\mu_{pure}(x) &\to U(x) \left(A^\mu_{pure}(x) - \frac{i}{g}\, \partial^\mu \right) U^{-1}(x)
\end{aligned}$$

Recently:
Wakamatsu
Chen et al.
Leader

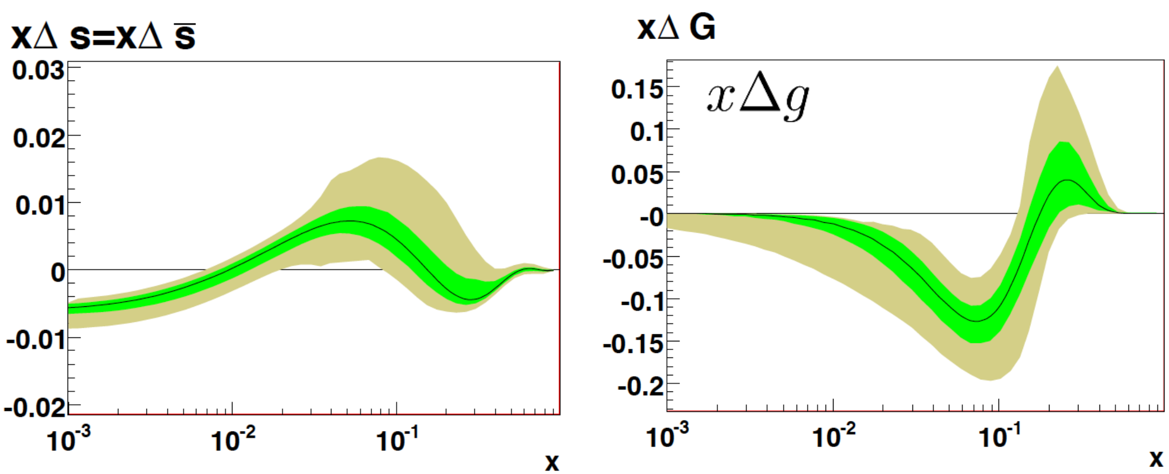
- other "contemporary" analyses of polarized (SI)DIS data:



Leader,Sidorov,Stamenov



Forte et al. (NNPDF)



Sissakian, Shevchenko, Ivanov

There are many observables that are sensitive to OAM. Question is connection to spin sum rule

News

Sivers <-> OAM in a quantitative way ?

Bacchetta,Radici

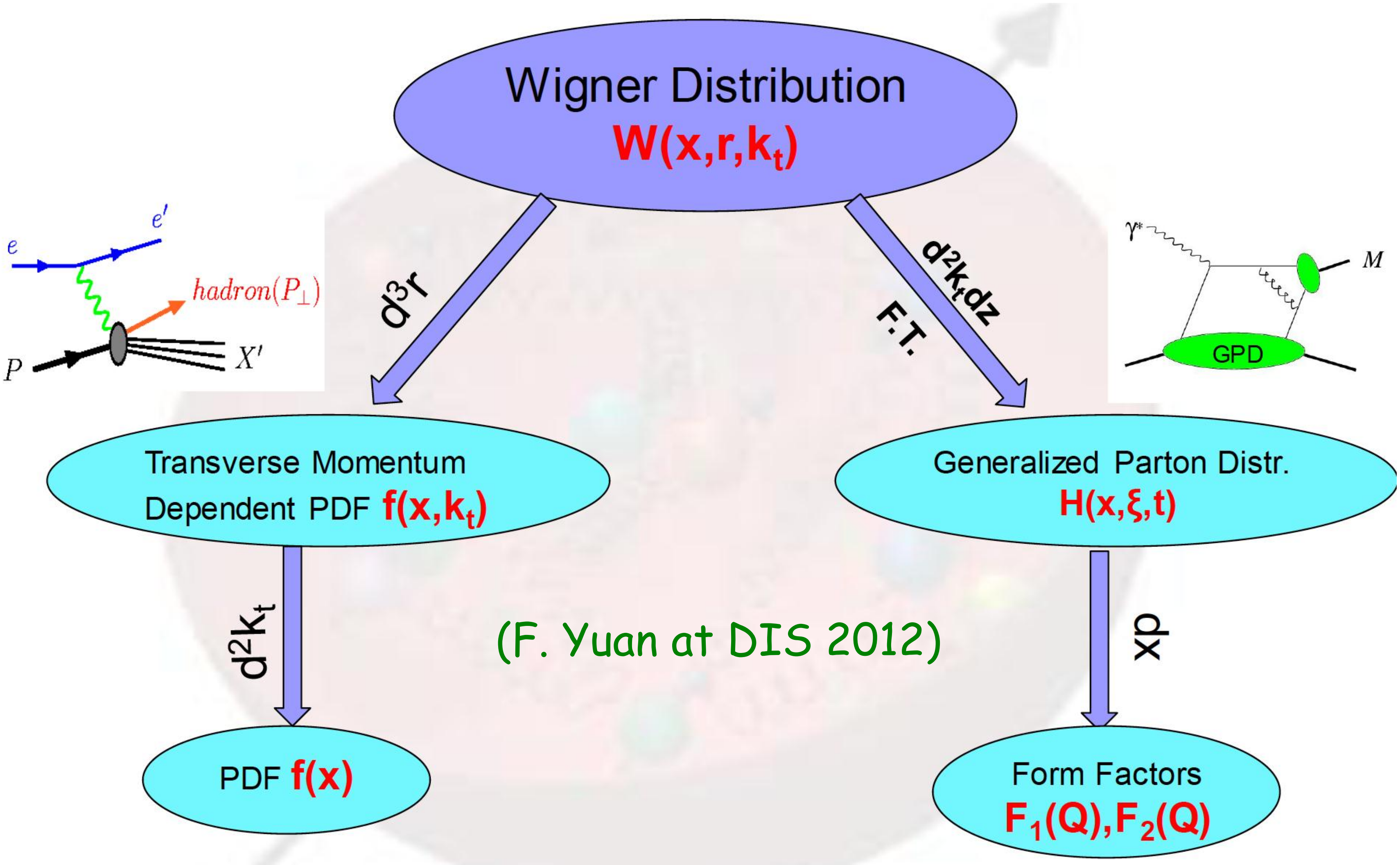
- combines:
  - Ji's expression for J_q in terms of GPDs
  - connection between moment of $f_{1T}^{\perp}$ and GPD $\mathcal{E}$ (Burkardt's lensing idea)
  - joint fit of SIDIS Sivers asymmetries and magnetic moments

- OAM from Wigner distributions ? Lorce,Pasquini

$$\rho^{[\Gamma]}(\vec{b}_\perp, \vec{k}_\perp, x, \vec{S}) \equiv \int \frac{d^2\Delta_\perp}{(2\pi)^2} \left\langle p^+, \frac{\vec{\Delta}_\perp}{2}, \vec{S} \,\middle|\, \hat{W}^{[\Gamma]}(\vec{b}_\perp, \vec{k}_\perp, x) \,\middle|\, p^+, -\frac{\vec{\Delta}_\perp}{2}, \vec{S} \right\rangle$$

$$\ell_z^q = \int dx d^2k_\perp d^2b_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z \rho^{[\gamma^+]q}(\vec{b}_\perp, \vec{k}_\perp, x, \vec{e}_z)$$

A far-developed theory framework to address this:



(F. Yuan at DIS 2012)

plus, first-rate experimental facilities

- connection to hyperon β-decays, SU(3)

$$\Delta\Sigma_q \equiv \int_0^1 dx\,(\Delta q + \Delta\bar{q})\,(x, Q^2) \;\propto\; \langle\, P, s \,|\, \bar{\psi}_q\, \gamma^\mu \gamma_5\, \psi_q \,|\, P, s \,\rangle$$

(axial charges)

Bjorken;
Ellis, Jaffe;
Sehgal;
Karliner, Lipkin;
Ratcliffe;...

$$\Delta\Sigma_u - \Delta\Sigma_d \;=\; g_A = 1.257 \pm \ldots$$

$$\Delta\Sigma_u + \Delta\Sigma_d - 2\Delta\Sigma_s \;=\; 3F - D \;=\; 0.58 \pm 0.03 \quad ?$$

- strangeness?

$$\Delta\Sigma \;=\; \Delta\Sigma_u + \Delta\Sigma_d + \Delta\Sigma_s \;=\; 3F - D \,+\, 3\Delta\Sigma_s$$