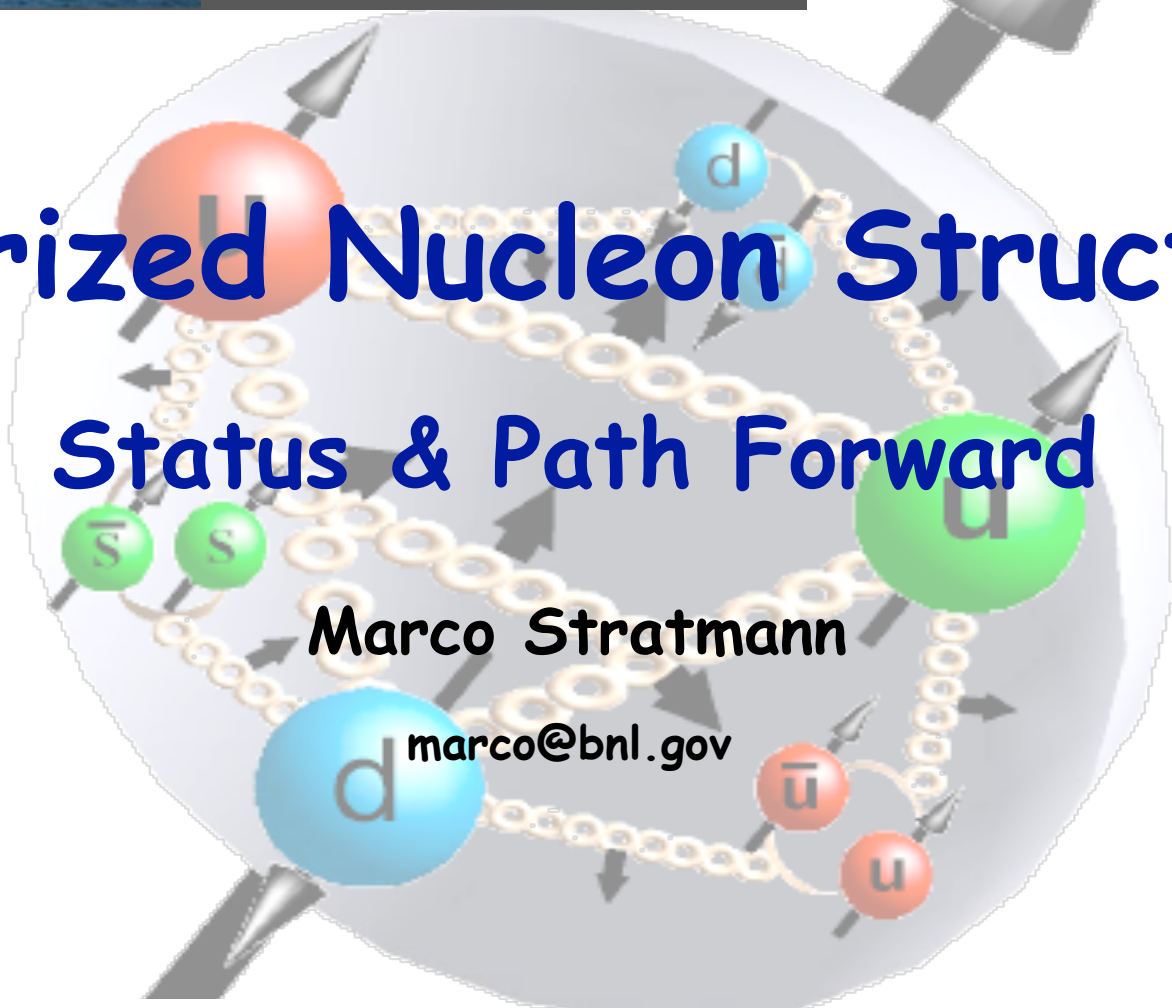




**D** XXI INTERNATIONAL WORKSHOP ON  
**I** DEEP-INELASTIC SCATTERING AND  
**S** RELATED SUBJECTS  
April 22-26 2013  
France - Marseille Congress Centre  
Proton Structure ■ Electroweak and Searches ■ Diffraction and Vector Mesons ■  
Hadronic Final States ■ Heavy Flavours ■ Spin Physics ■ Future Experiments ■

April 22<sup>nd</sup>, 2013

# Polarized Nucleon Structure Status & Path Forward



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U.S. DEPARTMENT OF  
**ENERGY**

Office of  
Science

**BROOKHAVEN**  
NATIONAL LABORATORY



# the cookies we crumble: fundamental questions driving spin physics



## how do quarks and gluons carry the proton spin



$$\Delta f(x) \equiv f \begin{matrix} \rightarrow \\ \rightarrow \end{matrix} (x) - f \begin{matrix} \rightarrow \\ \leftarrow \end{matrix} (x)$$

- what is the role of gluons and sea quarks
- what is the role of orbital angular momentum
- how does it compare to models/lattice QCD



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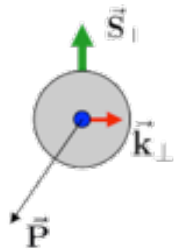
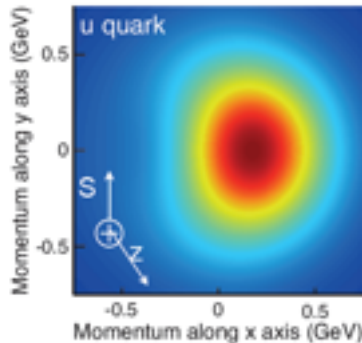


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## reveal mechanisms behind transverse spin phenomena



- further develop TMD framework / evolution
- role of multi-parton correlations & their matching to TMD's
- explore connections to unintegrated PDFs



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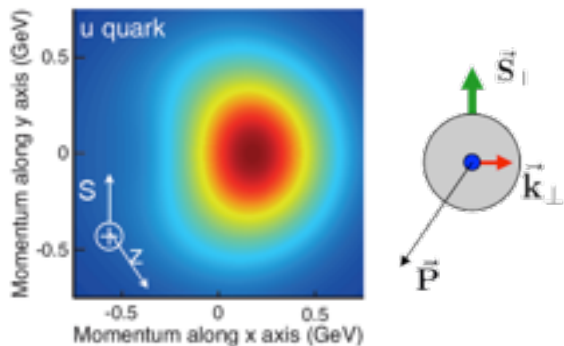


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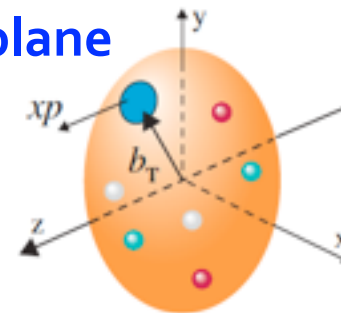


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## what is the distribution of partons in the transverse plane

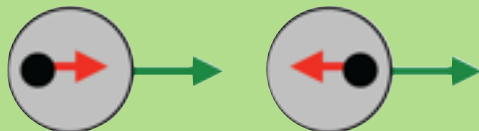
- physics of exclusive processes & generalized parton distributions
- possible access to quark and gluon angular momentum
- high-level connections of TMDs & GPDs to Wigner functions





# the cookies we crumble: fundamental questions driving spin physics

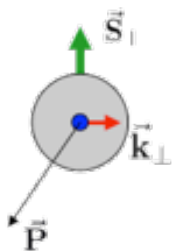
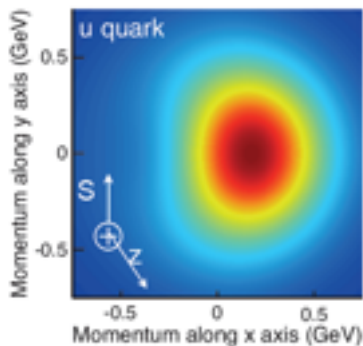
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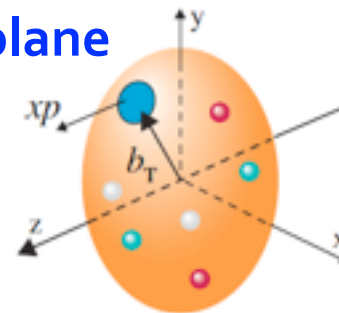
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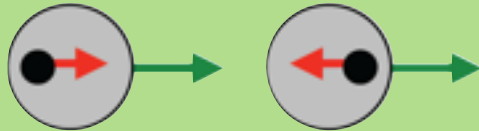
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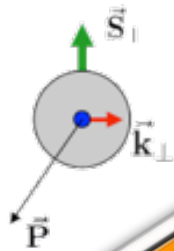
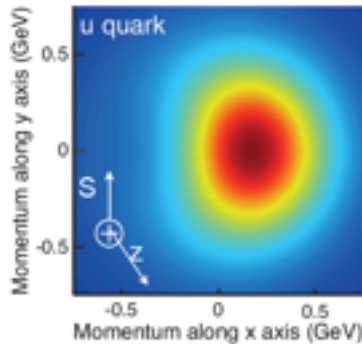
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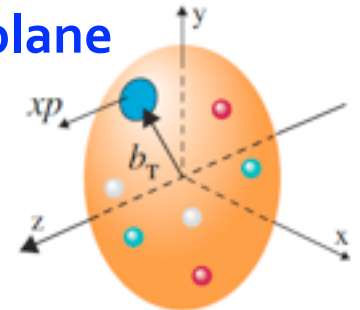


- further development of parton / evolution
- role of ... & their matching to TMD's
- ... integrated PDFs

briefly touch on some aspects  
largely leave to **Spin Summary on Friday**

## what is the difference between ... in the transverse plane

- physics ... generalized parton distributions
- possible ... and gluon angular momentum
- high-level ... of TMDs & GPDs to Wigner functions




1

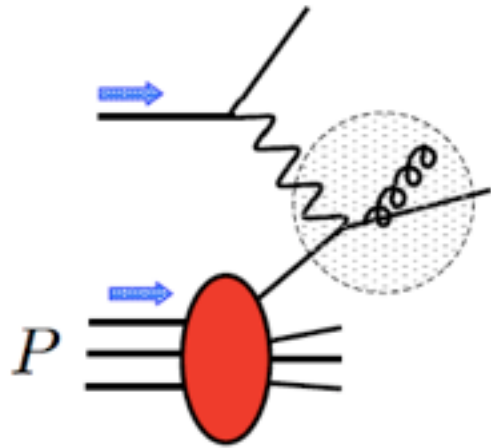


status of proton's helicity structure

# probes of nucleon helicity structure

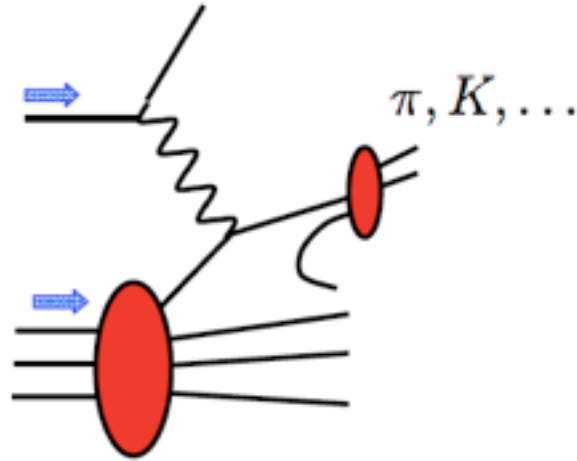


$$\Delta f(x) = f_{\rightarrow}(x) - f_{\leftarrow}(x)$$



DIS

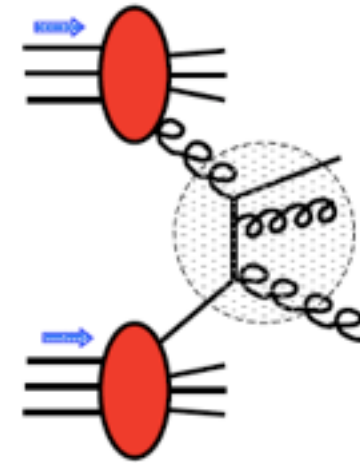
$$\Delta q + \Delta \bar{q}$$



SIDIS

$$\Delta q, \Delta \bar{q} \quad \text{pions, kaons}$$

$$\Delta g \quad \text{charm, 2-hadrons}$$



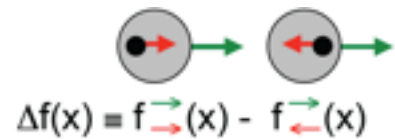
pp

$$\Delta g \quad \text{1-jet, 1-hadron}$$

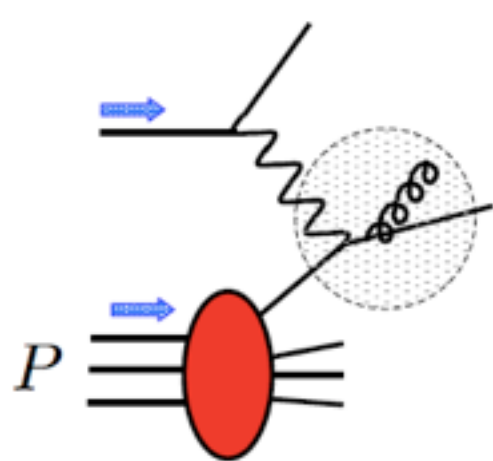
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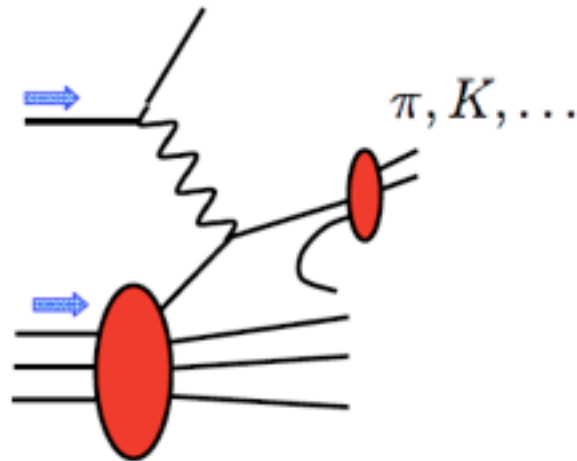


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DIS

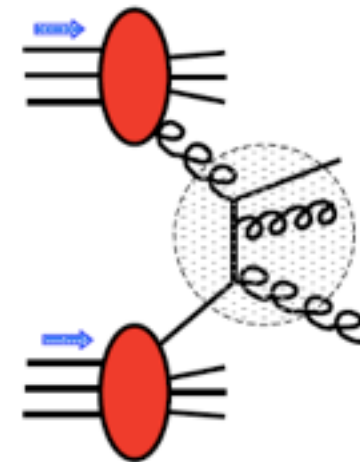
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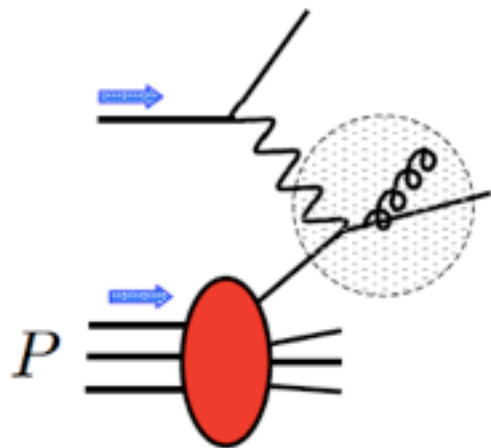
guiding principle: **factorization**

e.g. **DIS** 
$$d\Delta\sigma = \sum_{f=q,\bar{q},g} \int dx \Delta f(x, Q^2) d\Delta\hat{\sigma}_{\gamma^* f}(xP, \alpha_s(Q^2))$$

essential: QCD corrections 
$$d\Delta\hat{\sigma} = d\Delta\hat{\sigma}^{\text{LO}} + \alpha_s d\Delta\hat{\sigma}^{\text{NLO}} + \dots$$

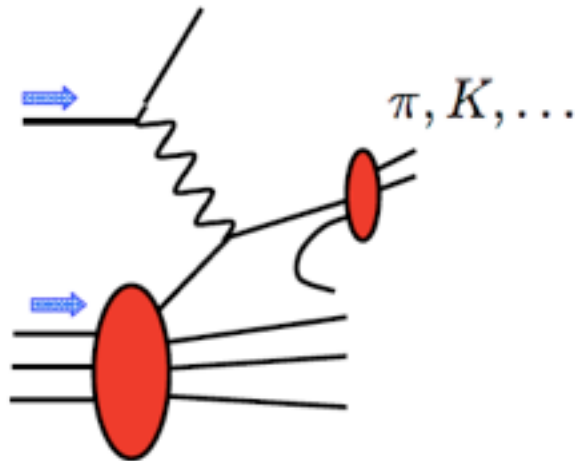
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DIS

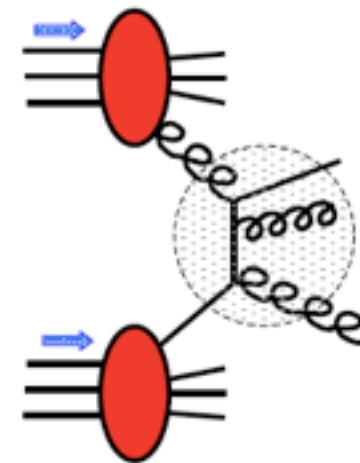
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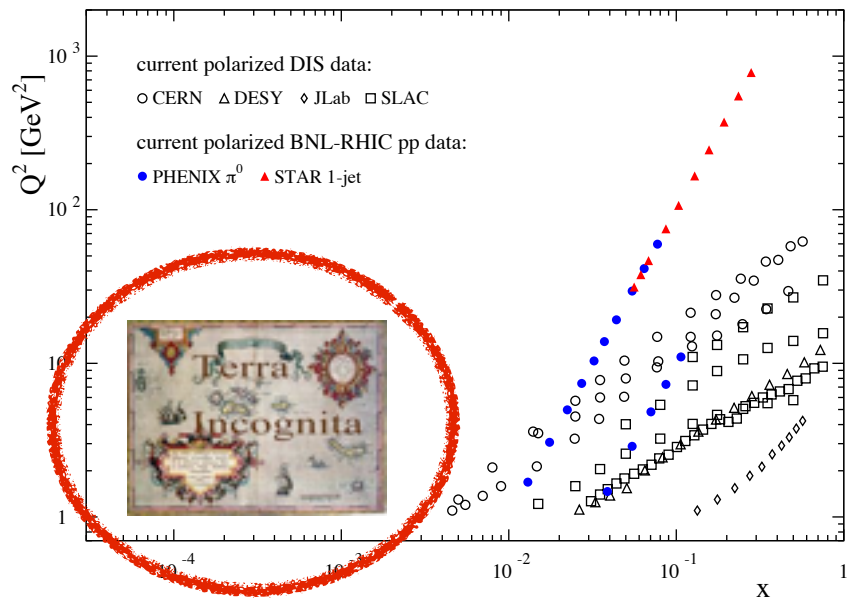
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**need DIS + SIDIS + pp to constrain all aspects of PDFs (a way to test factorization)**

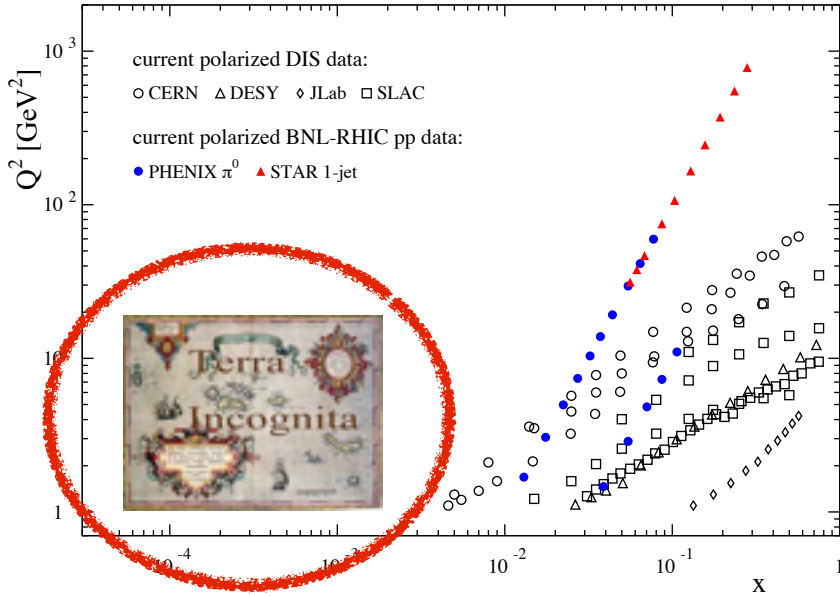
# challenges compared to unpolarized PDF fits



## □ rather limited $x$ - $Q^2$ coverage

- difficult to get  $\Delta g$  from scaling violations
  - ▶ need to rely on "direct probes" for  $\Delta g$
- need to use data down to  $Q^2 = 1 \text{ GeV}^2$ 
  - ▶ applicability of pQCD? higher twist?

# challenges compared to unpolarized PDF fits

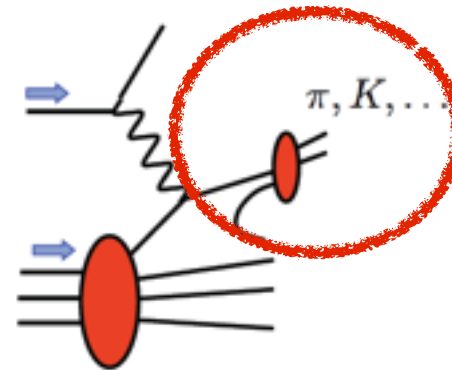


## □ no neutrino DIS data

- no quark/anti-quark separation from DIS
  - ▶ largely rely on SIDIS for flavor separation
  - ▶ need fragmentation functions to analyze data

## □ rather limited x- $Q^2$ coverage

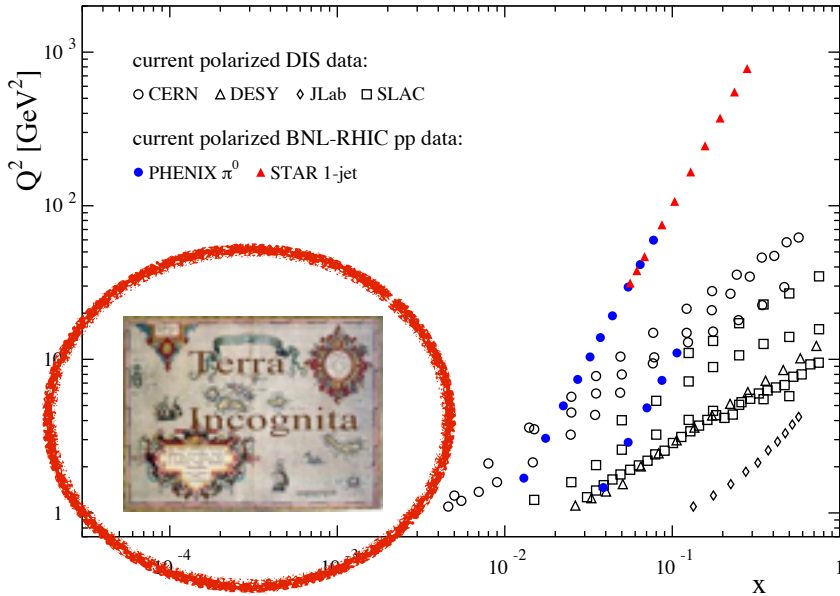
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extra source of uncertainties

new data:  
ALICE, BELLE,  
COMPASS, HERMES

# challenges compared to unpolarized PDF fits

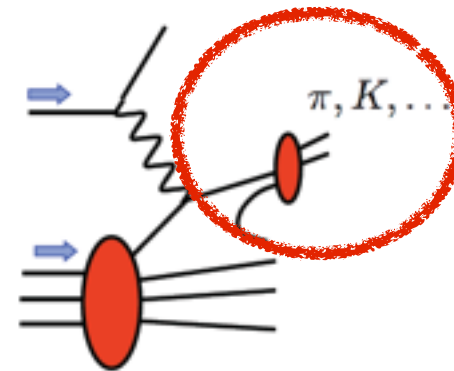


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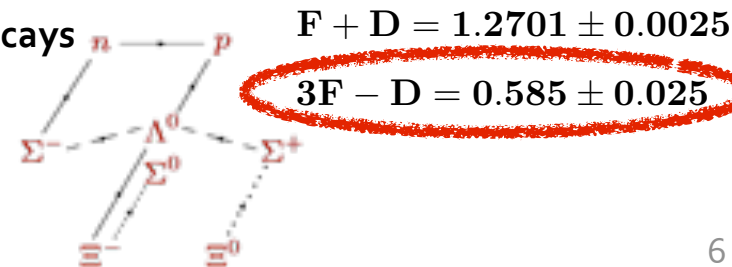


extra source of uncertainties

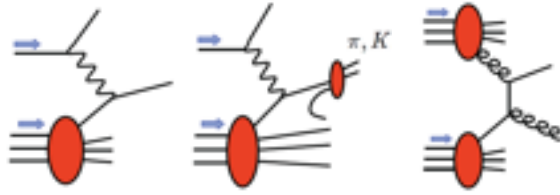
new data:  
 ALICE, BELLE,  
 COMPASS, HERMES

## sum rules on shaky (?) grounds

- 1<sup>st</sup> moments of non-singlet combinations  $\leftrightarrow$  hyperon decays
  - ▶ constraint on unmeasured small-x behavior of  $\Delta s$  and  $\Delta \Sigma$
  - ▶ doubts, however, on applicability of SU(3) relation  
 Savage, Walden; ... ; Bali et al. 1112.3354 (lattice)



# overview of recent helicity PDF fits @ NLO



uncertainties

last update

## NNPDF

Ball, Forte, Guffanti, Nocera, Rodolfi, Rojo



100 replicas  
stat. approach

1303.7236

Nocera (Tue)

## DSSV

de Florian, Sassot, MS, Vogelsang



L.M.  $\Delta\chi^2 = 8$  (1)  
(Hessian  $\Delta\chi^2 = 1$ )

0904.3821

[DSSV+/++: 1112.0904  
1304.0079]

## LSS

Leader, Sidorov, Stamenov



Hessian  $\Delta\chi^2 = 1$

1010.0574

## BB

Blumlein, Bottcher



Hessian  $\Delta\chi^2 = 1$

1010.3113

⋮

## GRSV

Gluck, Reya, MS, Vogelsang



1<sup>st</sup> NLO analysis  
9508347

# some highlights of the NNPDF analysis

Nocera (Tue)

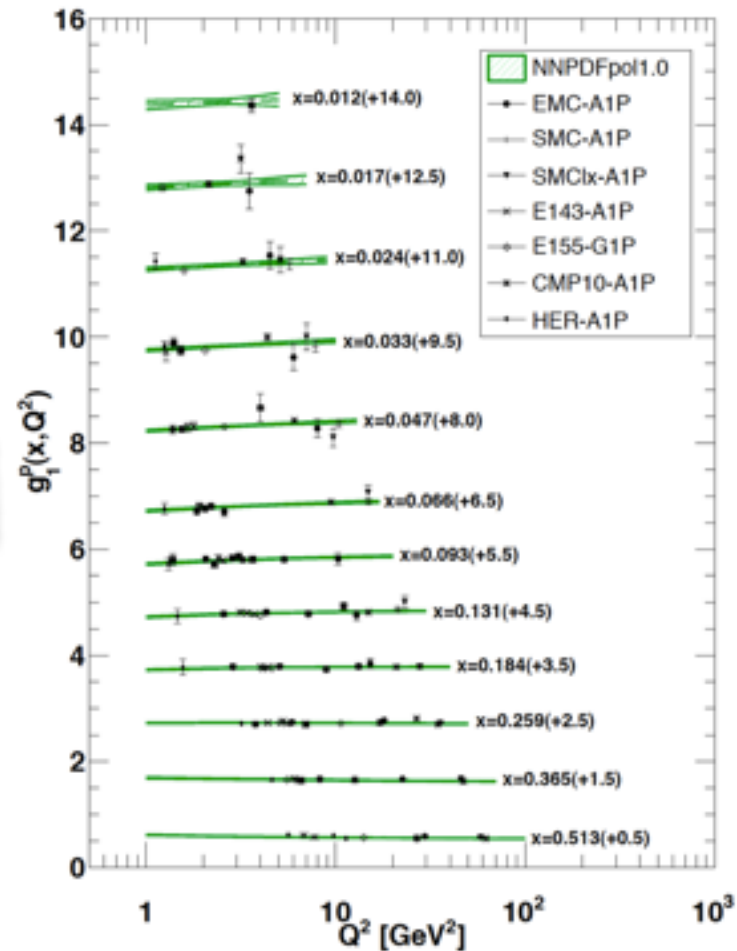
✓ **DIS only** (so far):  
determine  $\Delta u + \Delta \bar{u}, \Delta d + \Delta \bar{d}, \Delta s + \Delta \bar{s}, \Delta g$

✓ use all available correlated systematic uncertainties

✓ target mass corrections have no impact on fit  
all high  $x$ , low  $Q^2$  JLab data excluded by cut on  $W^2$

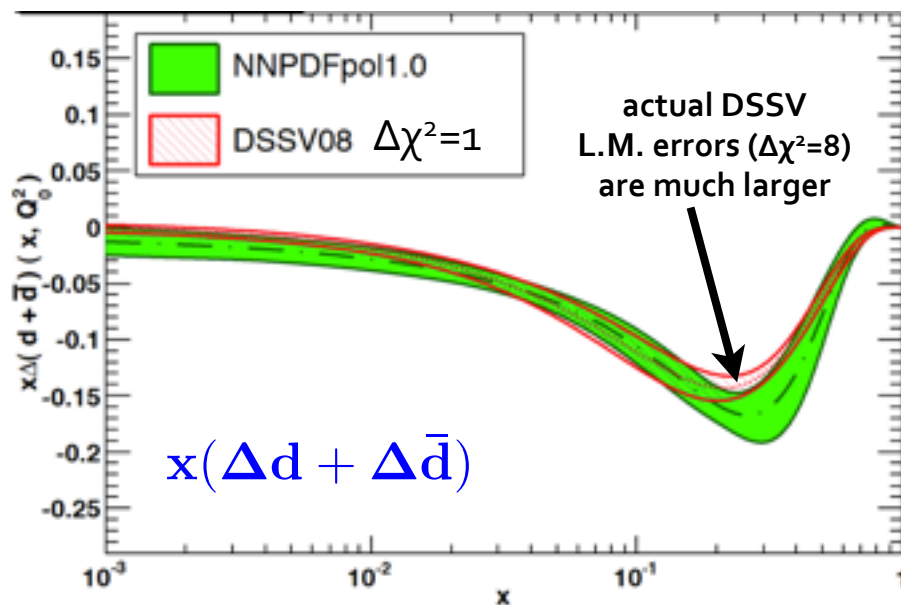
Accardi (Tue)  
new JAM analysis

✓ agrees best with global DSSV fit



Andrieux (Tue)  
new COMPASS  $g_1^P$

Kang (Tue)  
JLab data

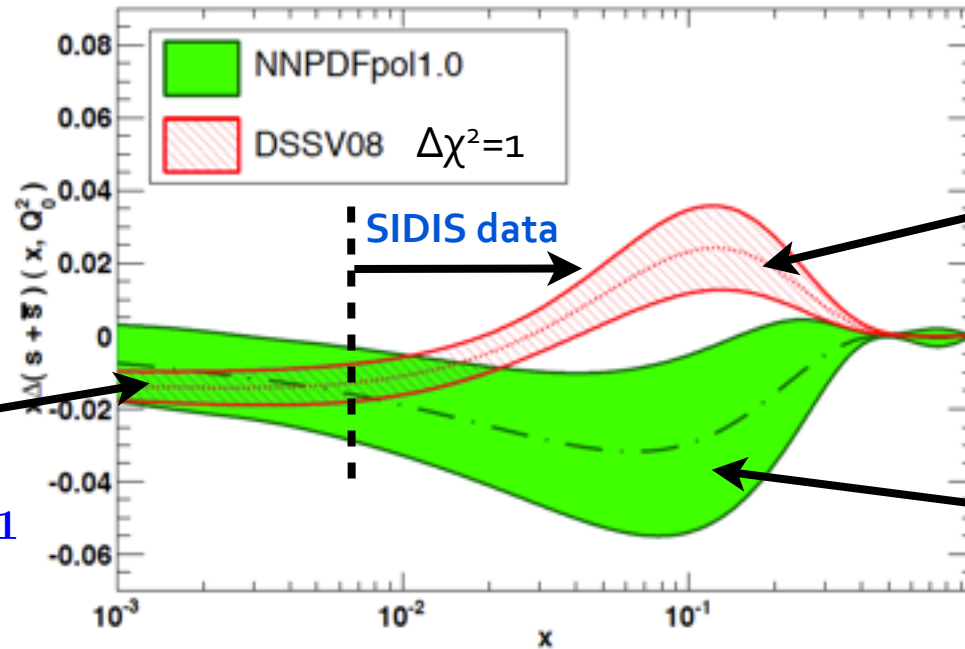


# strangeness conundrum

mounting tension between DIS and SIDIS kaon data?

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

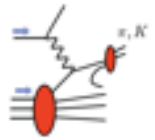
NNPDF 1303.7236



1<sup>st</sup> moment constrained by 3F-D

$$\int_0^1 dx [\Delta s + \Delta \bar{s}](x) \simeq -0.1$$

directly from SIDIS kaon data



indirectly from DIS data

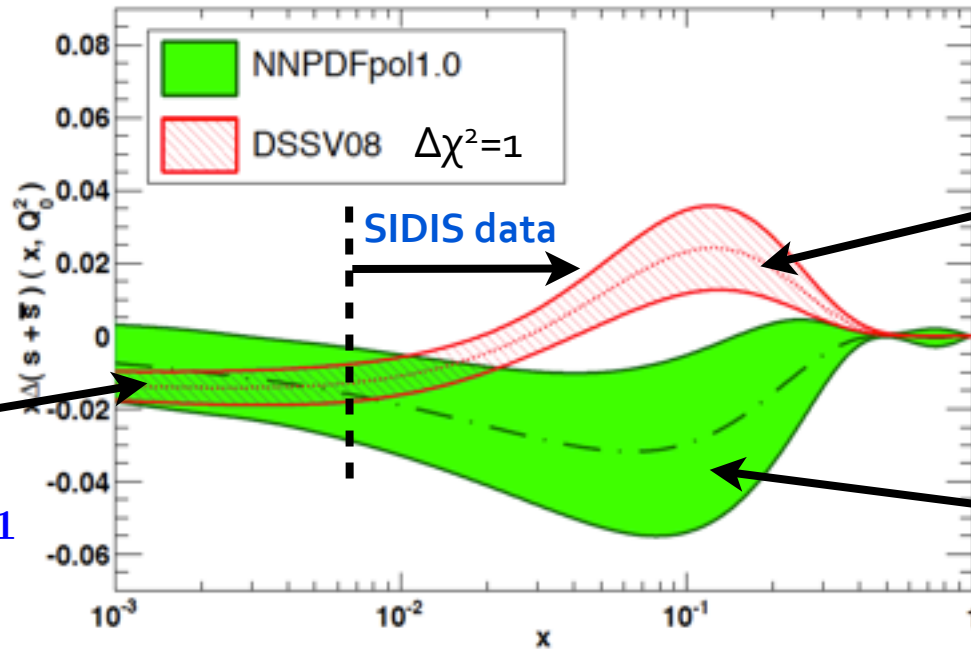




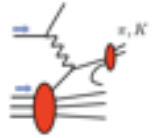
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## remarks/caveats:

- SIDIS analysis depends on s→K fragmentation
- DSSV global fit finds no tension between DIS and SIDIS
- NNPDF allows for 30% error on 3F-D → no big impact
- how well do we know the unpolarized s(x)?
- lattice finds small strangeness  $\int_0^1 dx [\Delta s + \Delta \bar{s}](x) \simeq -0.020(10)(1)$   
 ↔ large breaking of 3F-D relation

Bali et al. 1112.3354

van Hulse; Karyan; Makke (Tue)  
multiplicity data

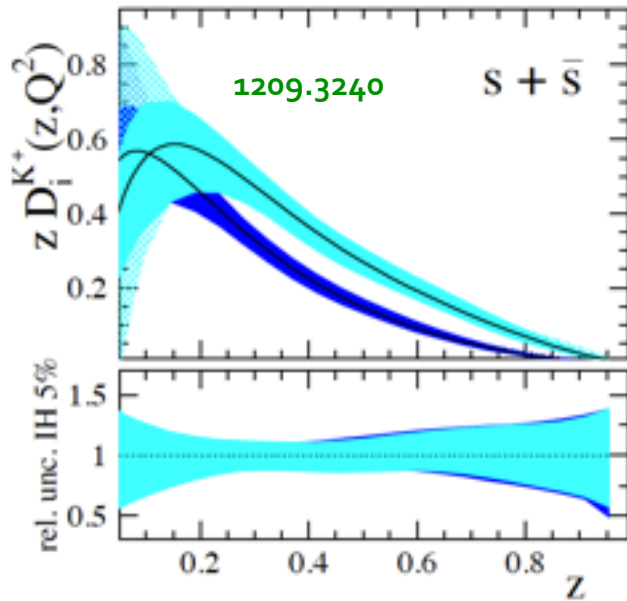
Jackson (Tue)  
s(x) from HERMES

2



impact of latest experimental results

# detour: hadron multiplicities & fragmentation



✓ FFs extracted from global fits @ NLO ( $e^+e^-$ , ep, pp data)

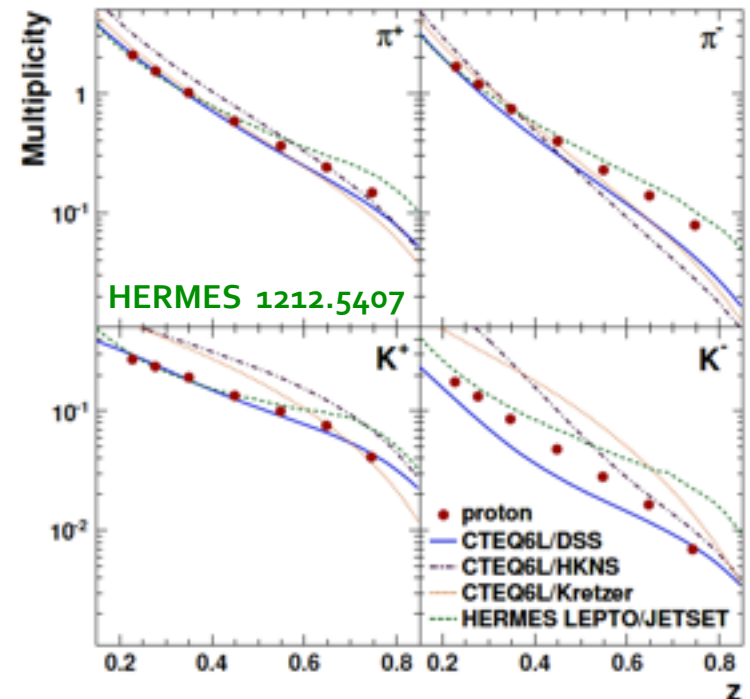
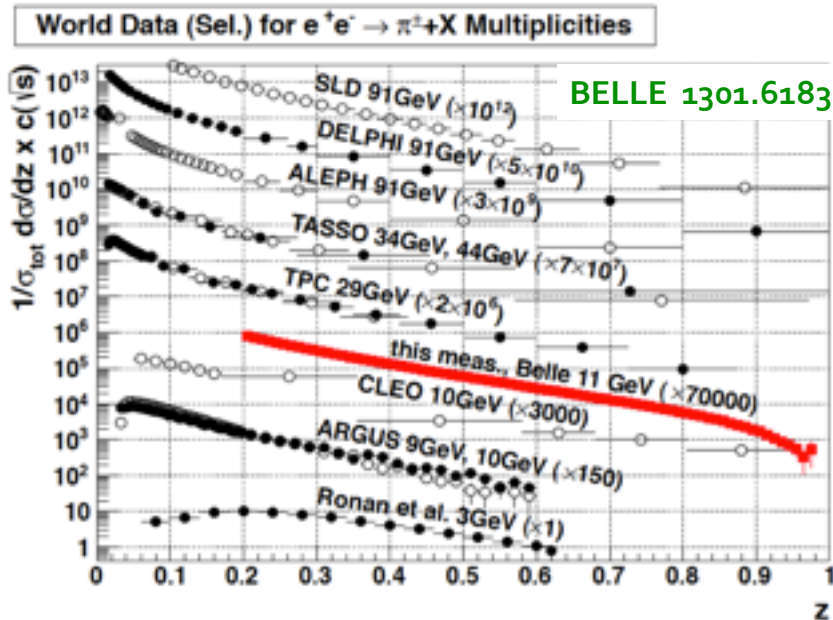
DSS: de Florian, Sassot, MS; AKK: Albino, Kniehl, Kramer ( $e^+e^-$  & pp only); ...

✓ recent study of uncertainties (within DSS framework)

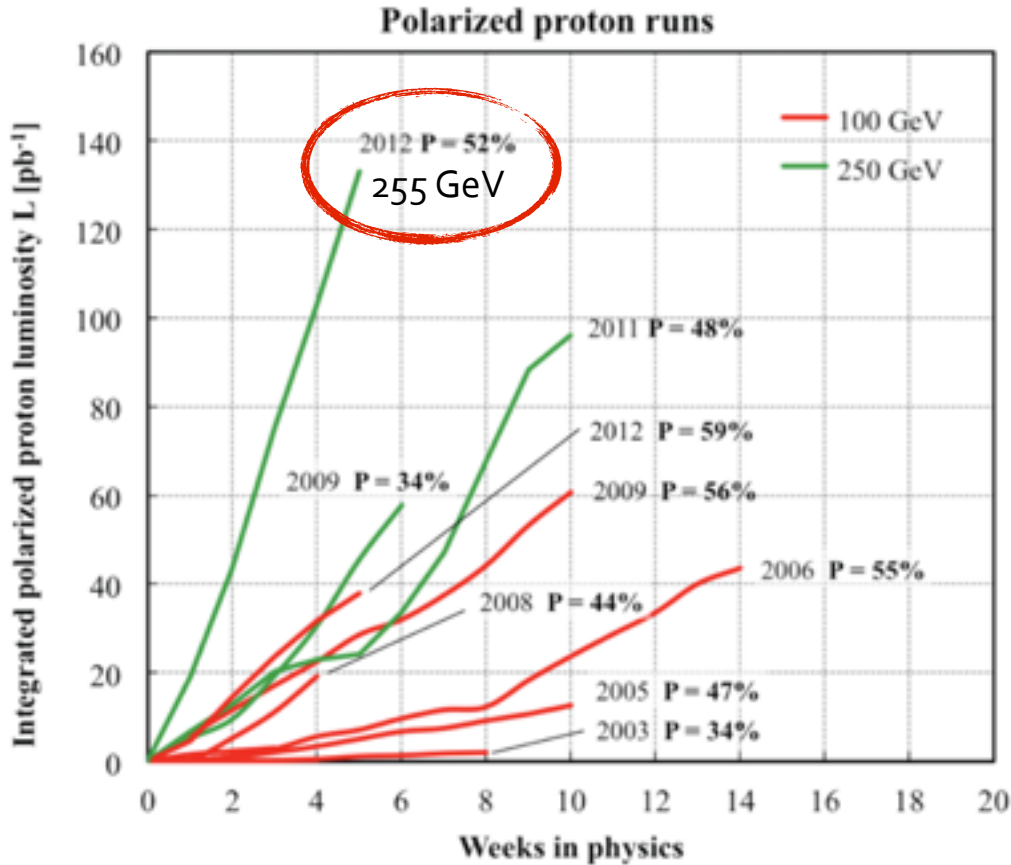
Epele, Lubaroff, Sassot, MS: 1209.3240

plenty of new data to play with  
ALICE, BELLE, COMPASS, HERMES  
expect updated fits soon

van Hulse; Karyan;  
Makke (Tue)  
new multiplicity data



# RHIC spin program

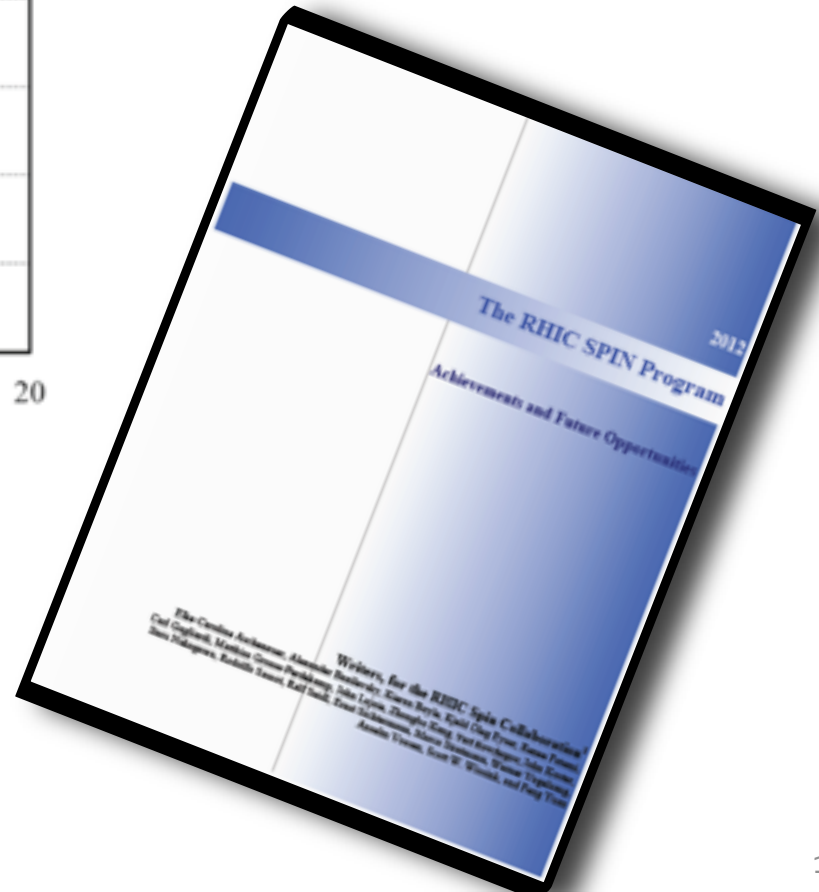


still a very vibrant program

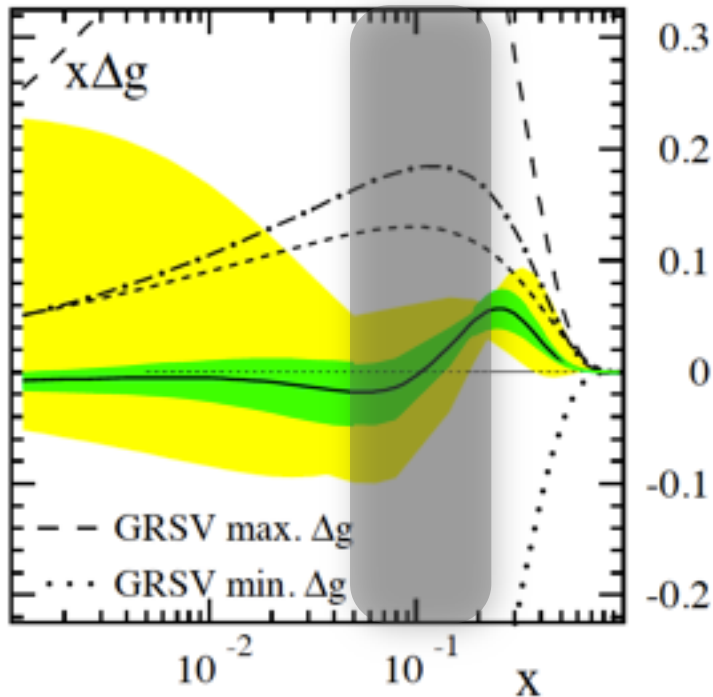
- run-12 was the best so far
- another long spin run ongoing

Chiu, Eyser, Gliske, Heppelmann,  
Gagliardi, Park, Sarsour, Surrow, Webb  
RHIC results (Tue/Thu)

latest results & outlook summarized in  
[arXiv:1304.0079](https://arxiv.org/abs/1304.0079)



# $\Delta g$ from RHIC - the story so far



✓ 200 GeV data mainly probe gluon in  $x=0.05-0.2$

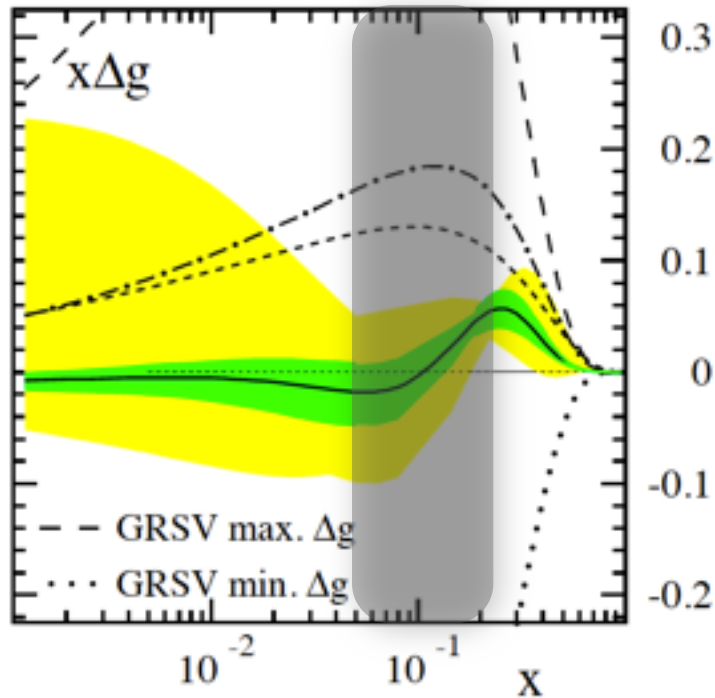
✓ found to be small, but uncertainties still large

$$\int_{0.05}^{0.2} dx \Delta g(x, Q^2 = 10 \text{ GeV}^2) = 0.005^{+0.129}_{-0.164}$$

from DSSV 2008/09 analysis

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$\Delta g$



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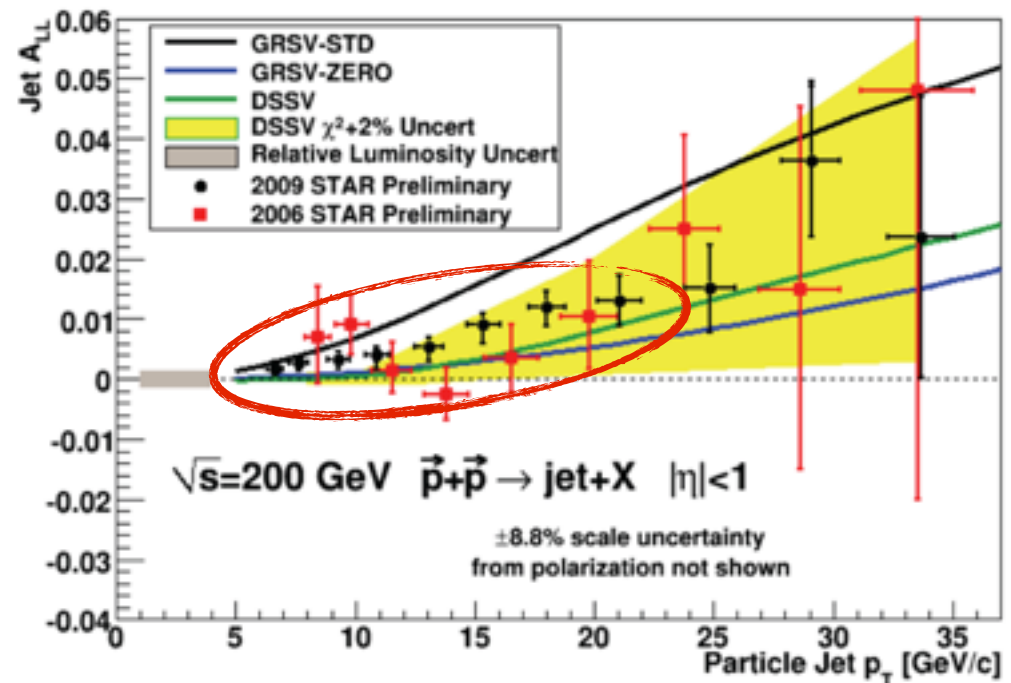
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from DSSV 2008/09 analysis

Chiu, Gagliardi  
 $\Delta g$  from RHIC (Tue)

- new data consistently above DSSV
- considerably smaller errors

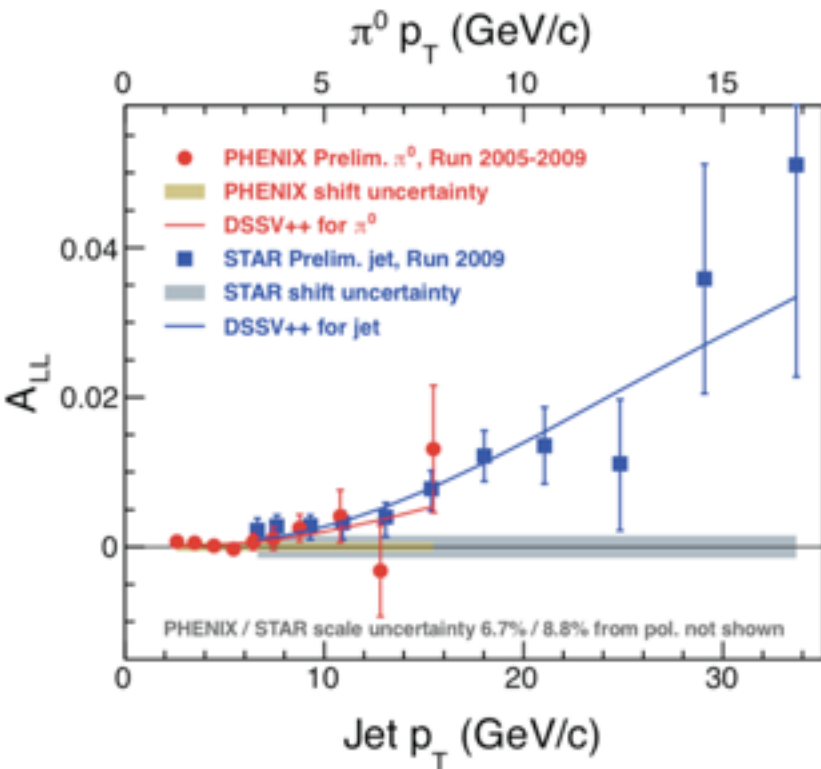
what's the impact?



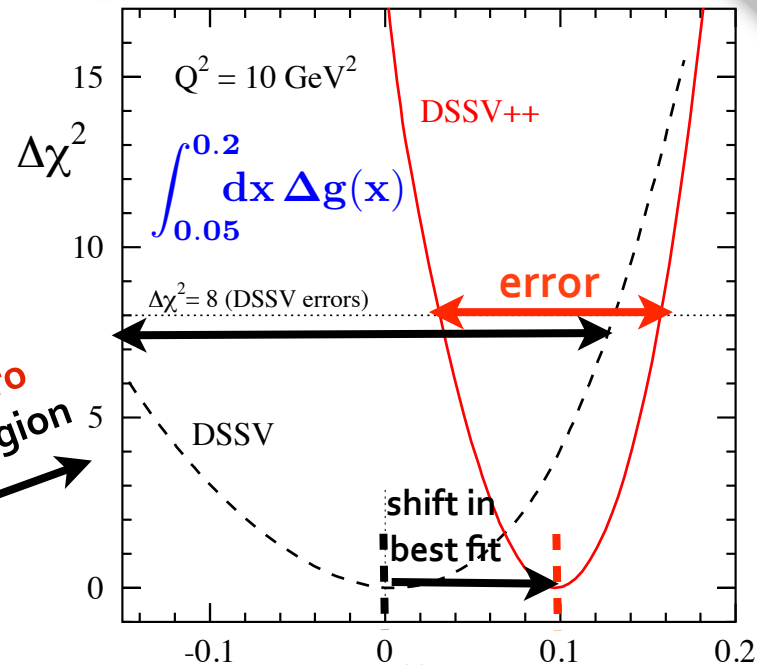
# $\Delta g$ from RHIC - gaining weight

$\Delta g$

new RHIC data included in **DSSV++**



lead to **non-zero**  
 $\Delta g$  in RHIC x-region



$$\int_{0.05}^{0.2} dx \Delta g(x, Q^2 = 10 \text{ GeV}^2) = 0.1^{+0.06}_{-0.07}$$

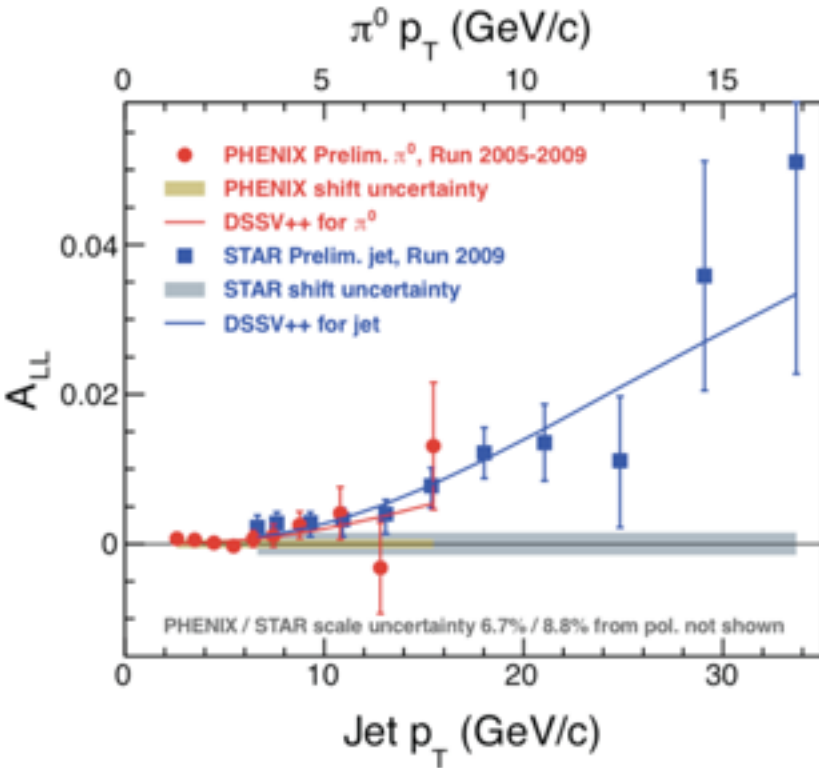
fully compatible with old DSSV error estimate

Chiu, Gagliardi  
 $\Delta g$  from RHIC (Tue)

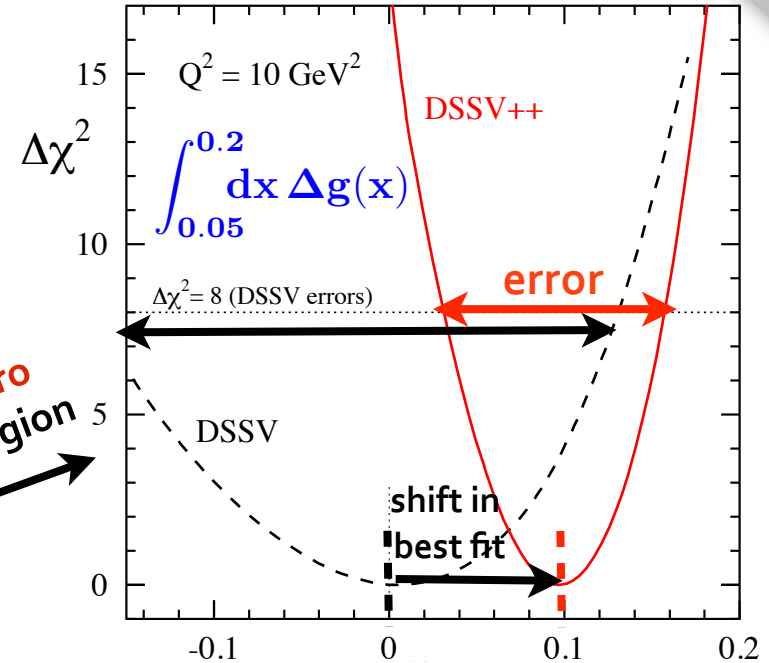
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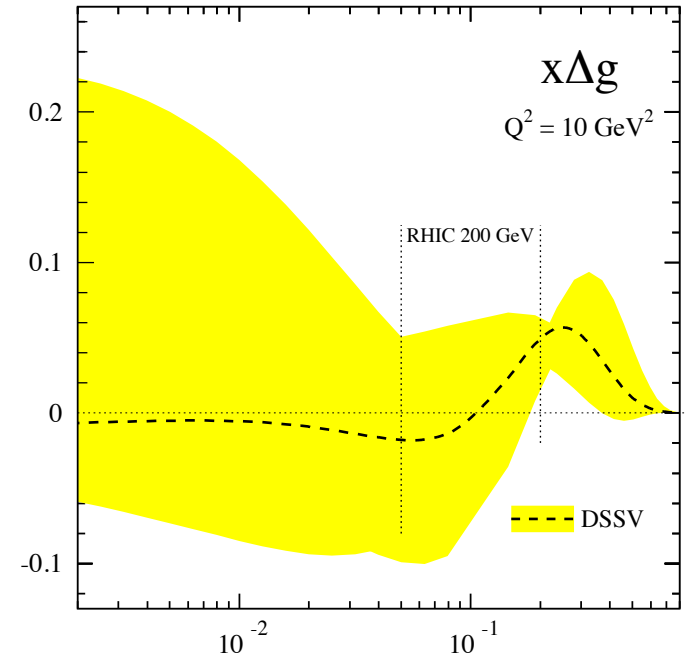
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Chiu, Gagliardi  
 $\Delta g$  from RHIC (Tue)

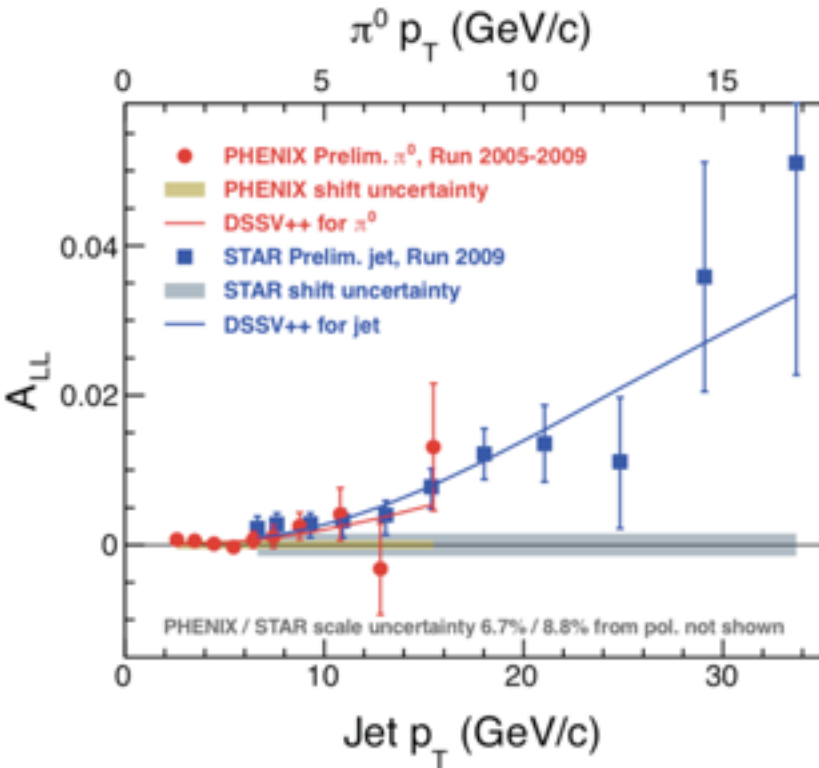




# $\Delta g$ from RHIC - gaining weight

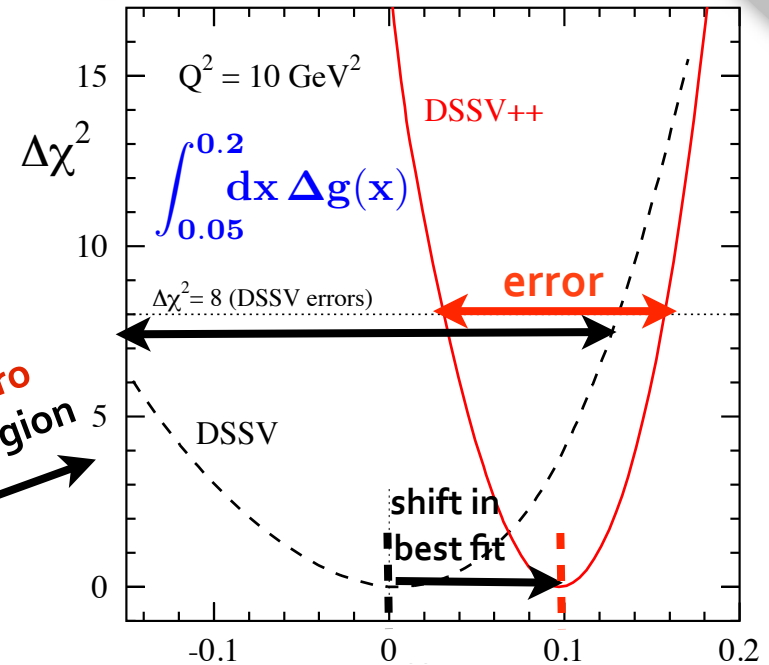
$\Delta g$

new RHIC data included in **DSSV++**



lead to **non-zero**  
 $\Delta g$  in RHIC x-region

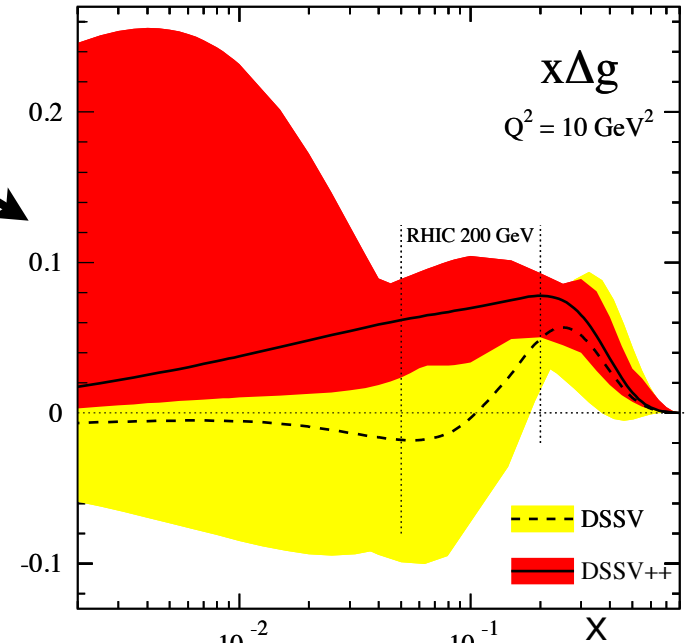
**positive  $\Delta g$**   
in RHIC x-region



$$\int_{0.05}^{0.2} dx \Delta g(x, Q^2 = 10 \text{ GeV}^2) = 0.1^{+0.06}_{-0.07}$$

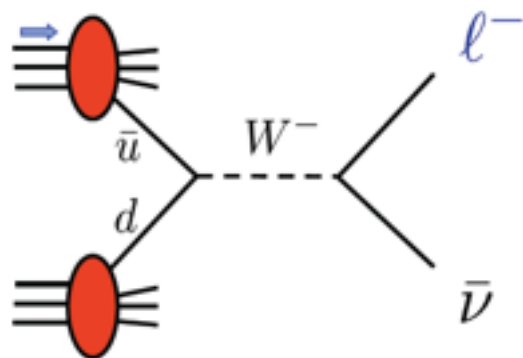
fully compatible with old DSSV error estimate

Chiu, Gagliardi  
 $\Delta g$  from RHIC (Tue)



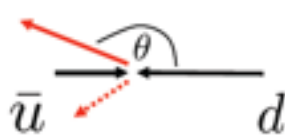
# more exciting new results: W boson asymmetry $\Delta\bar{u}$ $\Delta\bar{d}$

## key measurement at RHIC

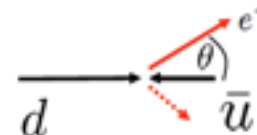


neat idea: measure parity-violating single-spin asymmetry

$$A_L^{e^-} \sim \frac{\Delta\bar{u}(x_1)d(x_2)(1 - \cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1 + \cos\theta)^2}{\bar{u}(x_1)d(x_2)(1 - \cos\theta)^2 + d(x_1)\bar{u}(x_2)(1 + \cos\theta)^2}$$



backward lepton rapidity



forward lepton rapidity

✓ repeat for  $W^+$  to get  $\Delta u/u$ ,  $\Delta\bar{d}/\bar{d}$

✓ leads to flavor separation at  $Q = M_W$  free of fragmentation uncertainties

✓ accessible x-range at RHIC limited to  $\langle x_{1,2} \rangle \simeq \frac{M_W}{\sqrt{S}} e^{\pm\eta/2} \simeq 0.04 \div 0.4$

@  $Q=M_W$   
evolution!

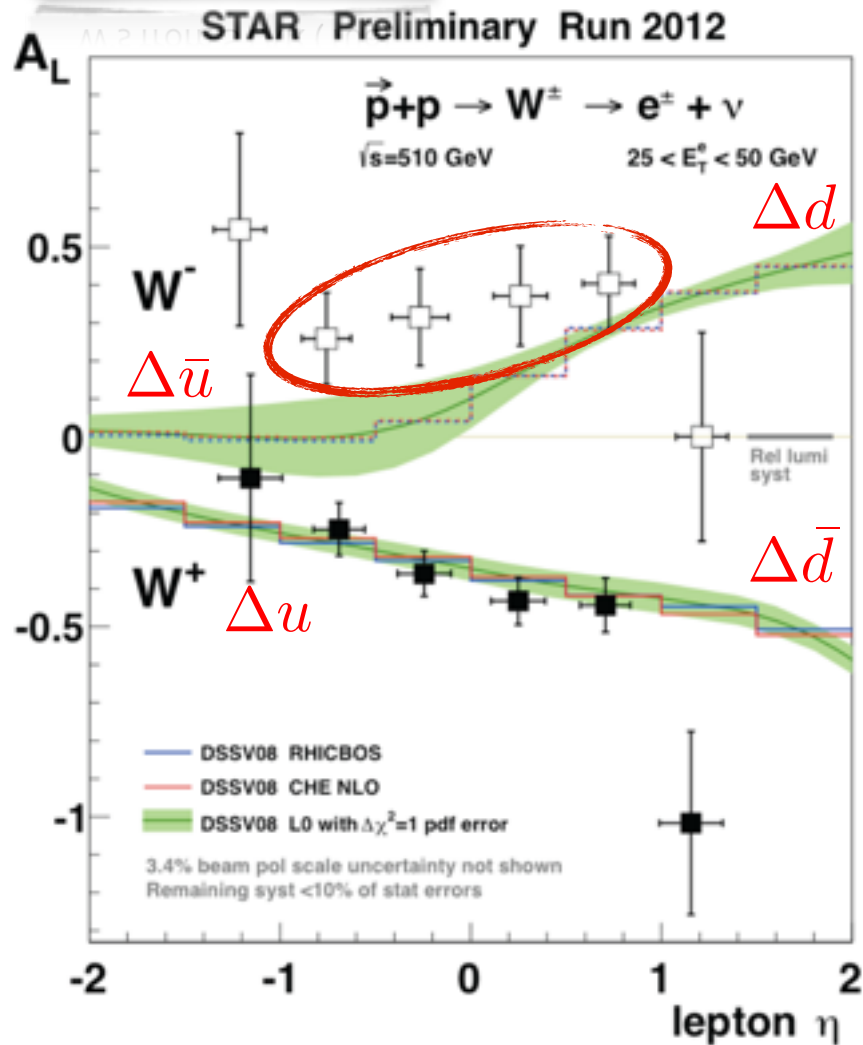
✓ no access to strangeness (would require  $W^+$ charm)

Park, Surov  
W's from RHIC (Tue)

# preliminary 2012 STAR data & impact

$\Delta \bar{u}$   
 $\Delta \bar{d}$

Surrow  
W's from STAR (Tue)

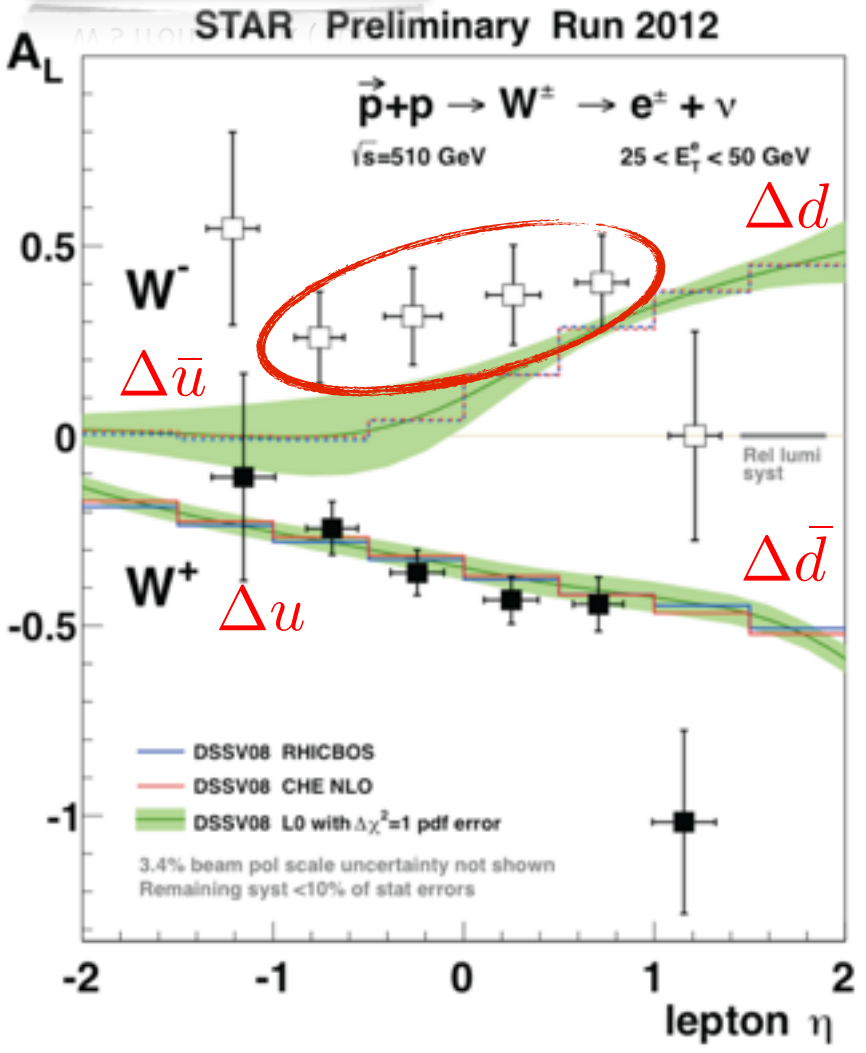


much more to come from current RHIC run

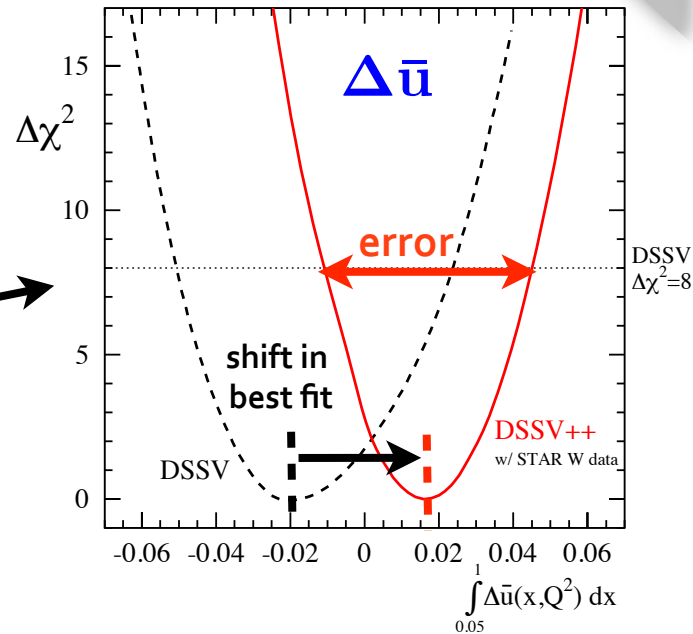
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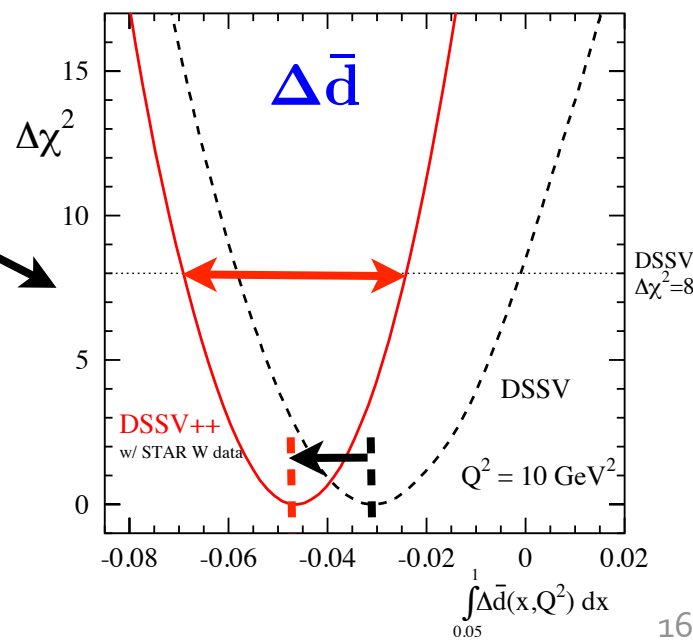
Surrow  
W's from STAR (Tue)



run 12 data already have a significant impact



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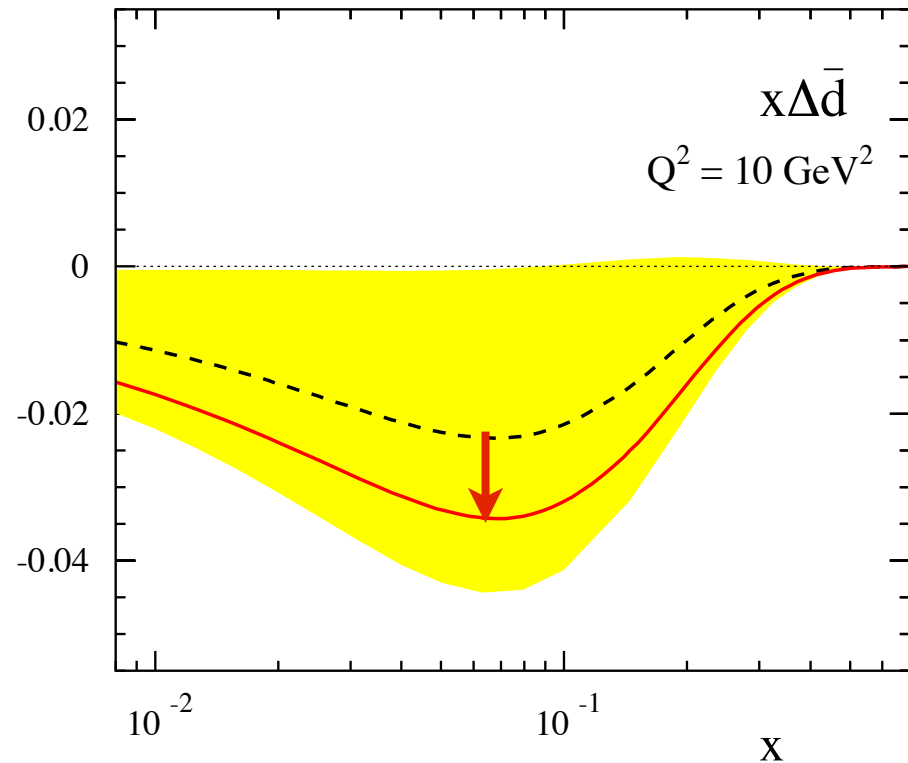
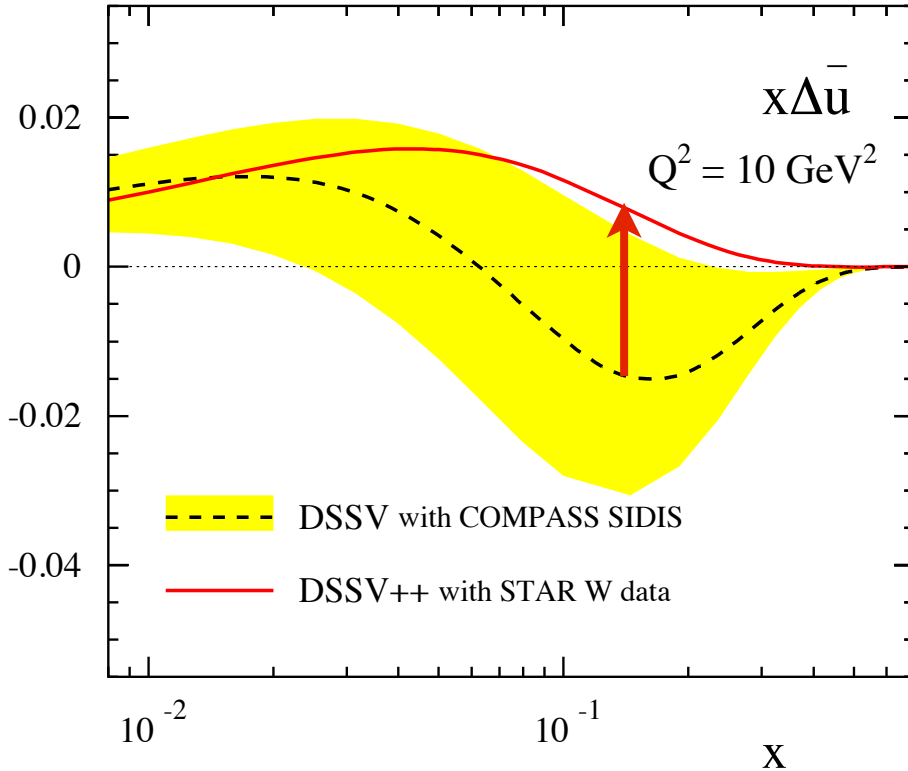


much more to come from current RHIC run

# impact in terms of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$

$\Delta\bar{u}$   
 $\Delta\bar{d}$

still very preliminary !



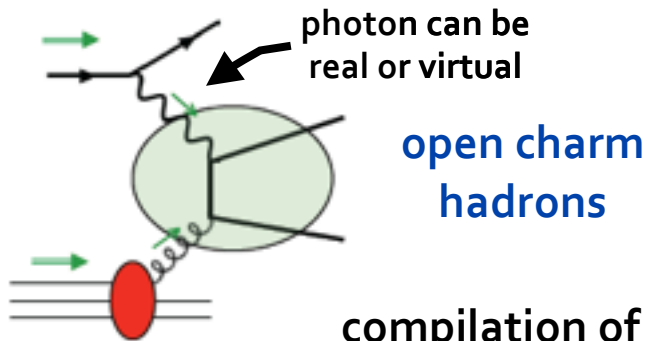
☑ starts to test of what we know about sea quarks from SIDIS with pions

☑ new fit points towards rather sizable  $\Delta\bar{u}(x) - \Delta\bar{d}(x)$  of interest for models

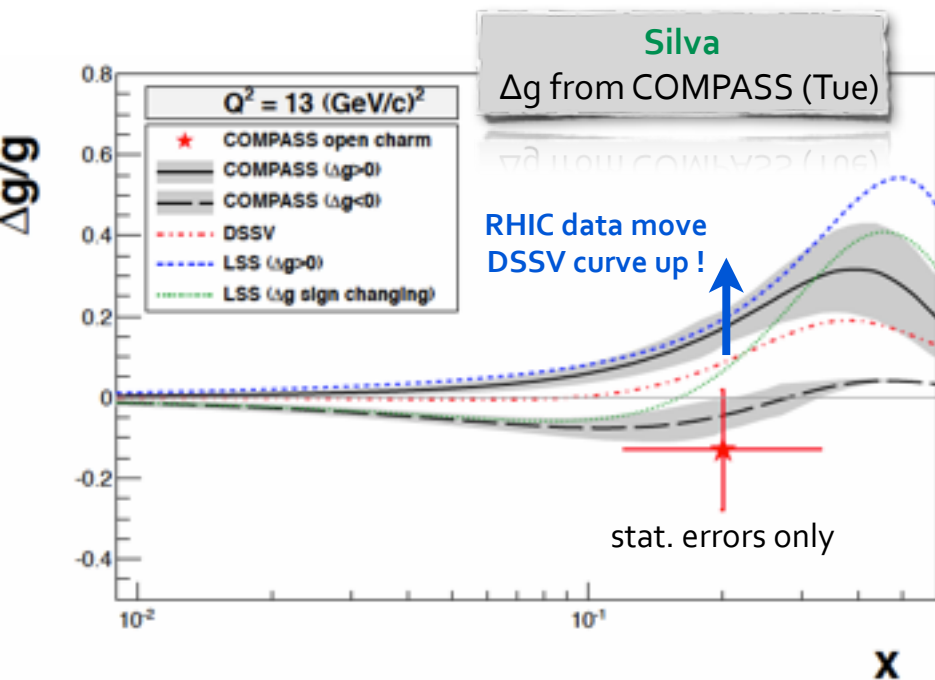
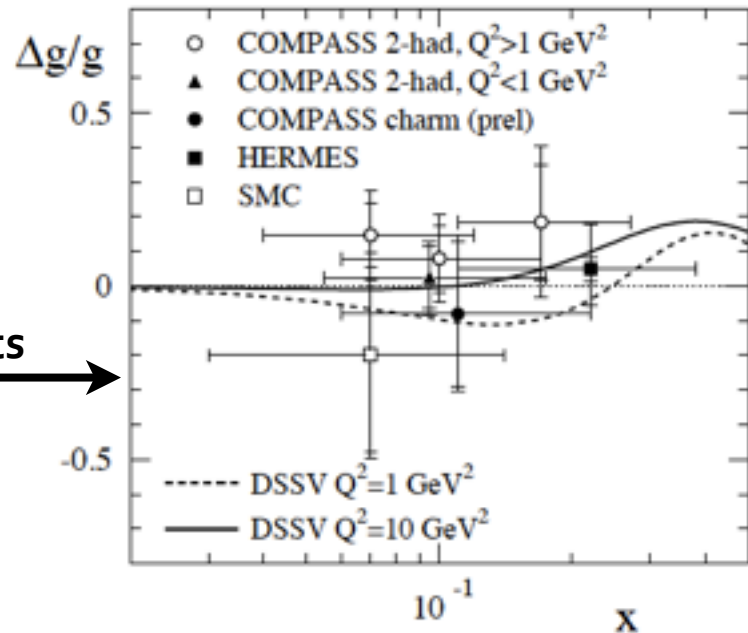
looming (mild ?) tension with SIDIS data

# update on $\Delta g$ from fixed-target experiments

idea: processes with (dominant) contributions from  $\gamma g$ -fusion



compilation of existing results



Silva  
 $\Delta g$  from COMPASS (Tue)

new result

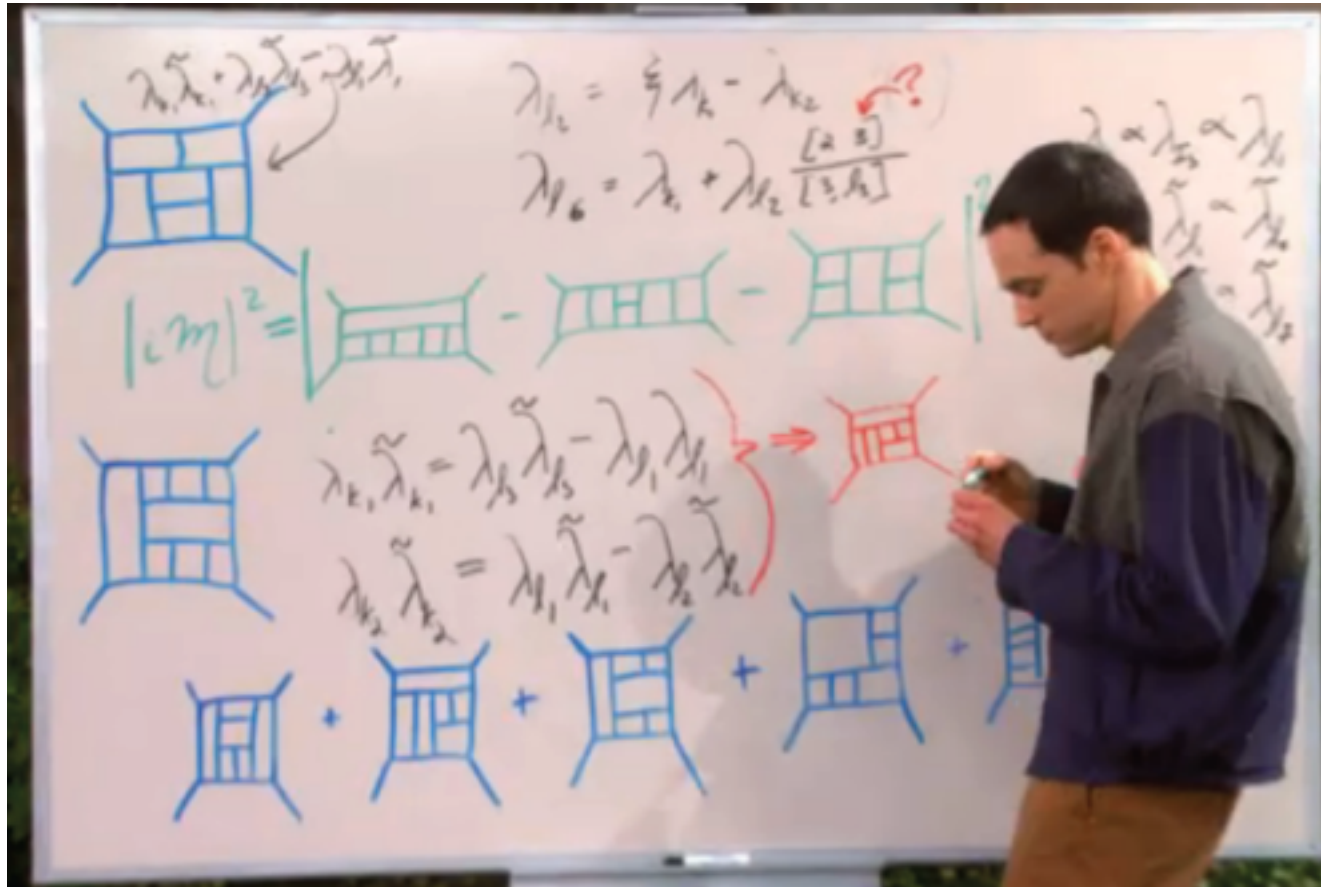
1211.6849

$$\left\langle \frac{\Delta g}{g} \right\rangle = -0.13 \pm 0.15 \pm 0.15$$

$$\langle x \rangle = 0.2 \quad \langle \mu^2 \rangle = 13 \text{ GeV}^2$$

from some "hybrid MC/NLO" extraction

# 3



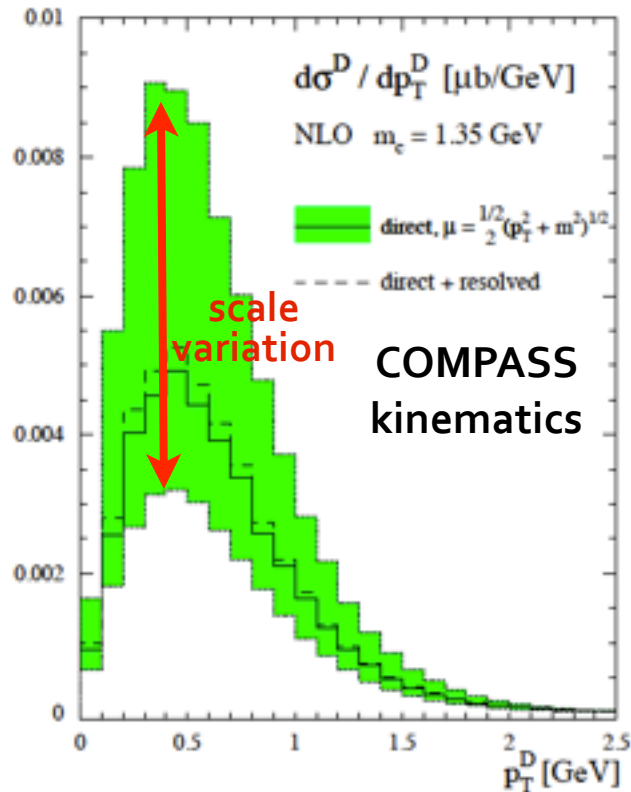
recent theoretical results

[since DIS 2012]

# progress on NLO calculations

## photoproduction of heavy quarks

J. Riedl, A. Schafer, MS, 1212.1319



- large scale & mass uncertainties
- large NLO corrections to  $A_{LL}$

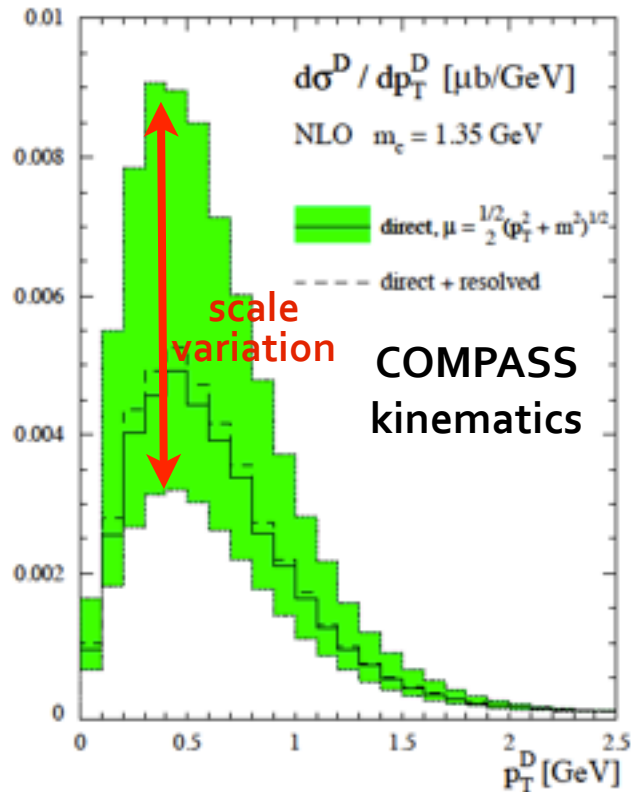
limited sensitivity to  $\Delta g$



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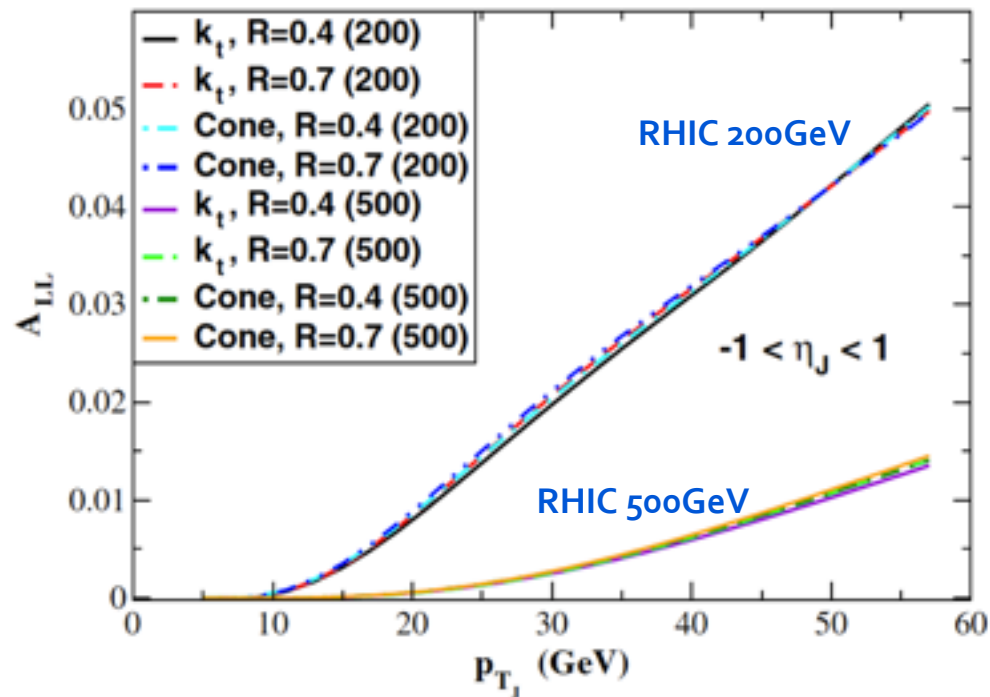
- large scale & mass uncertainties
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limited sensitivity to  $\Delta g$

## 1-jet in narrow jet approximation

A. Mukherjee, W. Vogelsang, 1209.1785

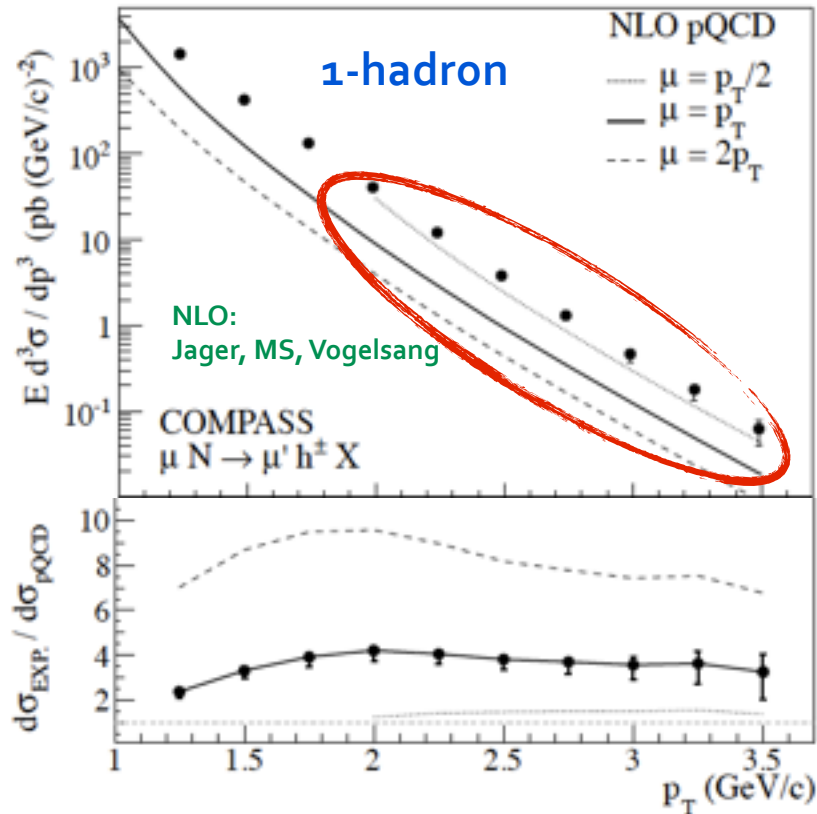
- extends analytical calculation for small cone to arbitrary jet algorithms Jager, Schafer, MS, Vogelsang
- used to analyze STAR jet data (anti- $k_T$ )
- jet algorithm largely cancels in spin asymmetry



# progress on all-order resummations

trend for NLO to fall short of data at low  $\sqrt{S}$

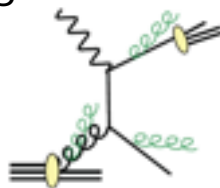
latest example from COMPASS 1207.2022



lesson: resum large threshold logs  
(soft gluons) to all orders

✓ pp de Florian, Vogelsang

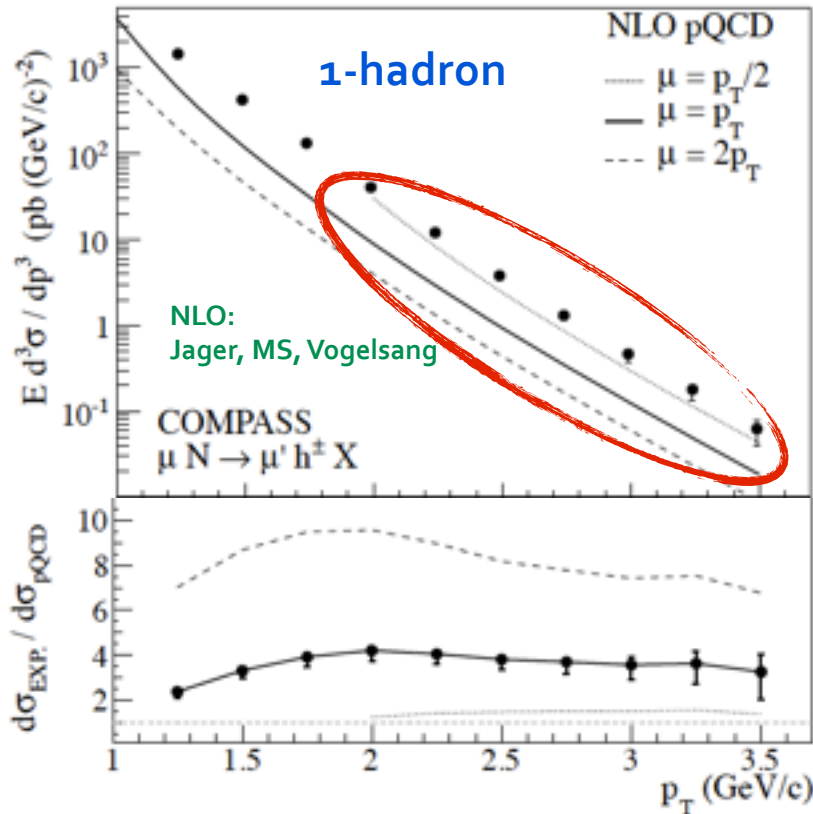
✗ lp not quite there yet



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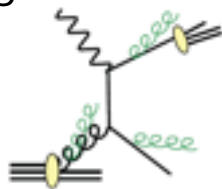
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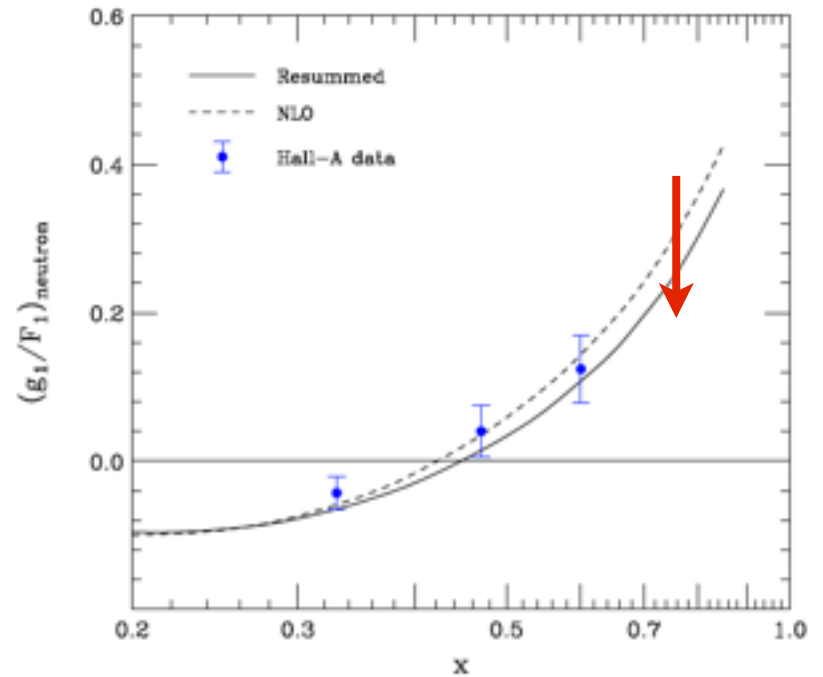
✗ lp not quite there yet



## threshold resummations for (SI)DIS

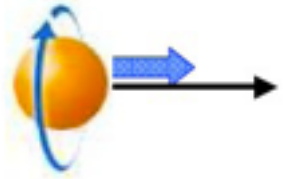
Anderle, Ringer, Vogelsang 1304.1373

- (modest) decrease of spin asymmetries
- most relevant for JLab kinematics



- important for future high statistics JLab-12

# status of proton spin sum rule



$$\frac{1}{2} = \langle P, \frac{1}{2} | \hat{J}_z | P, \frac{1}{2} \rangle$$

raging controversy in past 2 years  
(often semantics)

Jaffe, Manohar; Ji; ...; Chen et al.;  
Wakamatsu; Leader; Lorce;  
Hatta, Yoshida; Leader; Ji, Xiong, Yuan; ...

in a nutshell

Ji  $\frac{1}{2} = \frac{1}{2} \Delta\Sigma + L_q + J_g$

gauge invariant

↙ same  
↘ "number"

Jaffe  
Manohar  $\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta g + \mathcal{L}_q + \mathcal{L}_g$

"partonic"  $A^+=0$  gauge

all quantities depend on scale Q & factorization scheme

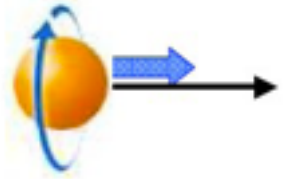
✓  $\Delta\Sigma = \sum_q \int_0^1 dx [\Delta q(x) + \Delta \bar{q}(x)]$

✓  $J_{q,g} \leftrightarrow$  GPD's (exclusive processes)

✓  $\Delta g = \int_0^1 dx \Delta g(x)$

✓ ✗  $\mathcal{L}_{q,g} \leftrightarrow$  twist-3 GPD's  
Ji, Xiong, Yuan

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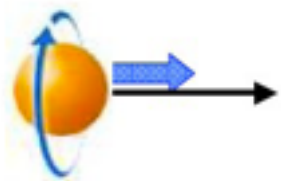
where do we stand on  $\Delta\Sigma$  and  $\Delta g$  ?

- all fits find  $\Delta\Sigma \approx 0.25$   
beware of **LARGE** small x & 3F-D **uncertainties**
- $\Delta g$  is anybody's guess (apart from  $x=0.05-0.2$  region)
- even non-singlet BJ sum has large errors

$$\Delta u + \Delta \bar{u} - (\Delta d + \Delta \bar{d}) = 1.19 \pm 0.22$$

NNPDF

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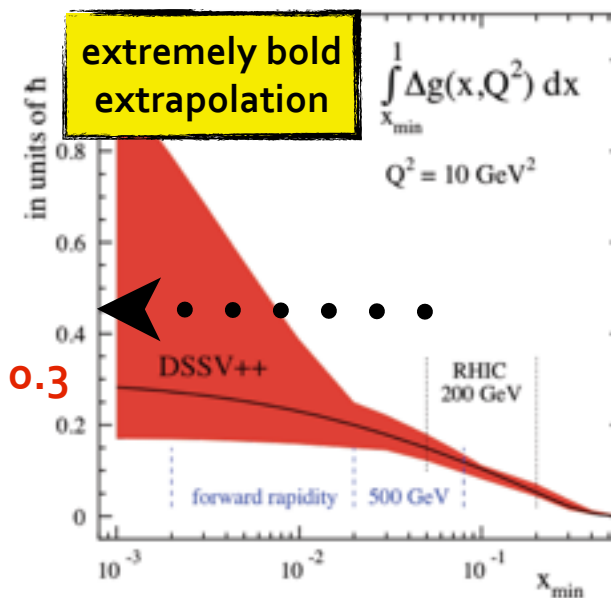
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NNPDF



little  
room  
for  
OAM ?



4

**the path forward**

# the path forward

COMPASS, JLab-12, RHIC have vibrant spin programs

Burtin, Chiosso, Keppel  
future/upgrades (Wed)

**BUT**

we need to explore small  $x$  region to determine  $\Delta\Sigma$ ,  $\Delta g$ , Bjorken sum, ....



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**What facility do we need to achieve that?**

- kinematic reach --> high-energy collider
- precision of electromagnetic probes  
--> electron beams
- spin --> polarized hadron beams
- versatility --> heavy ion beams

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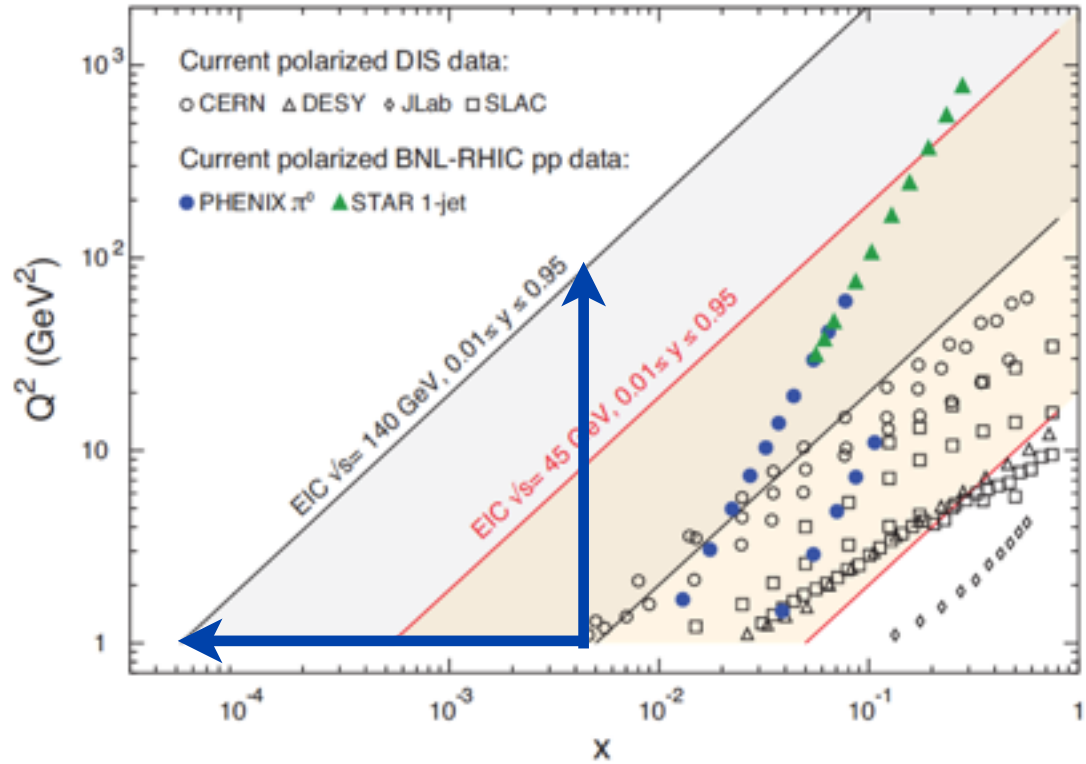
- kinematic reach --> high-energy collider
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in short: an **Electron-Ion Collider**

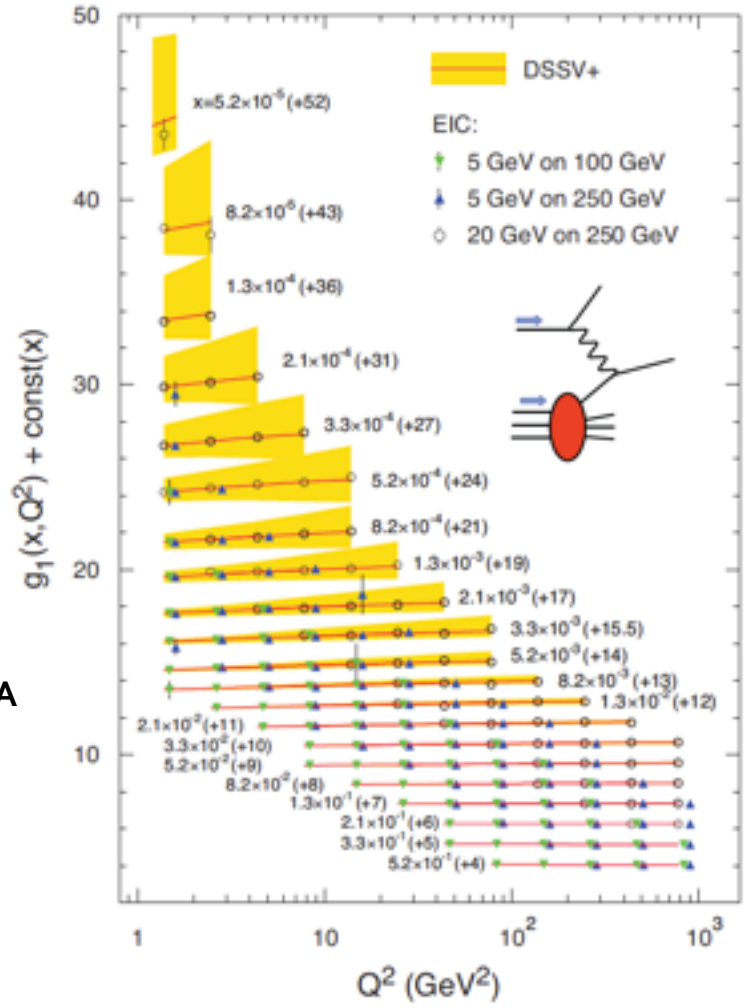
Aschenauer, Dehmelt,  
Deshpande, Lamont, Nadel-  
Turonski, Zhang EIC (Wed)



# kinematic reach and potential impact



simulated pseudo-data for DIS  
 similar coverage for SIDIS



✓ gain two decades in  $x$ , large  $Q^2$  coverage  
 also: lumi = 100-1000 x HERA

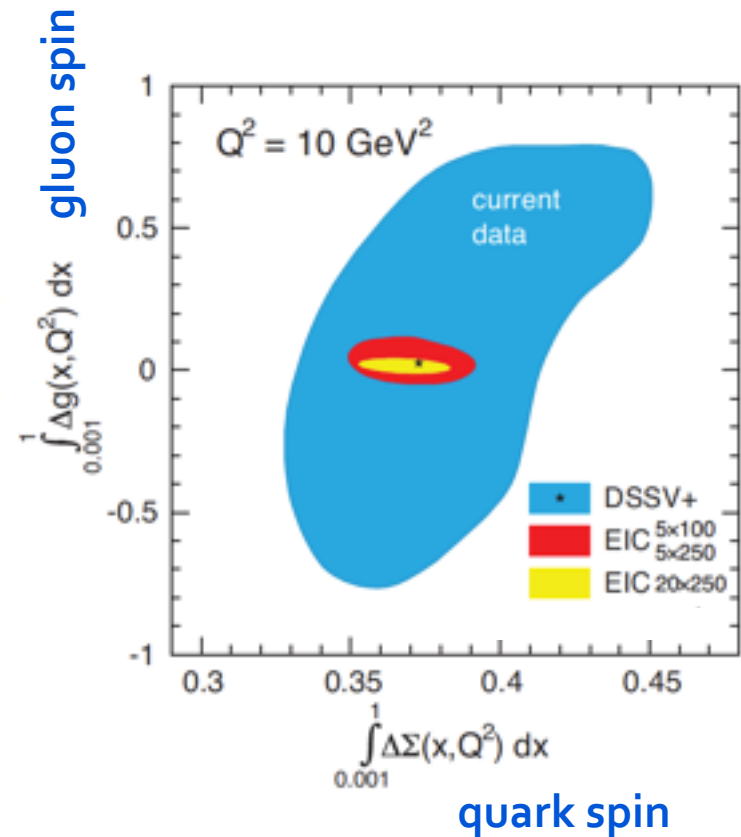
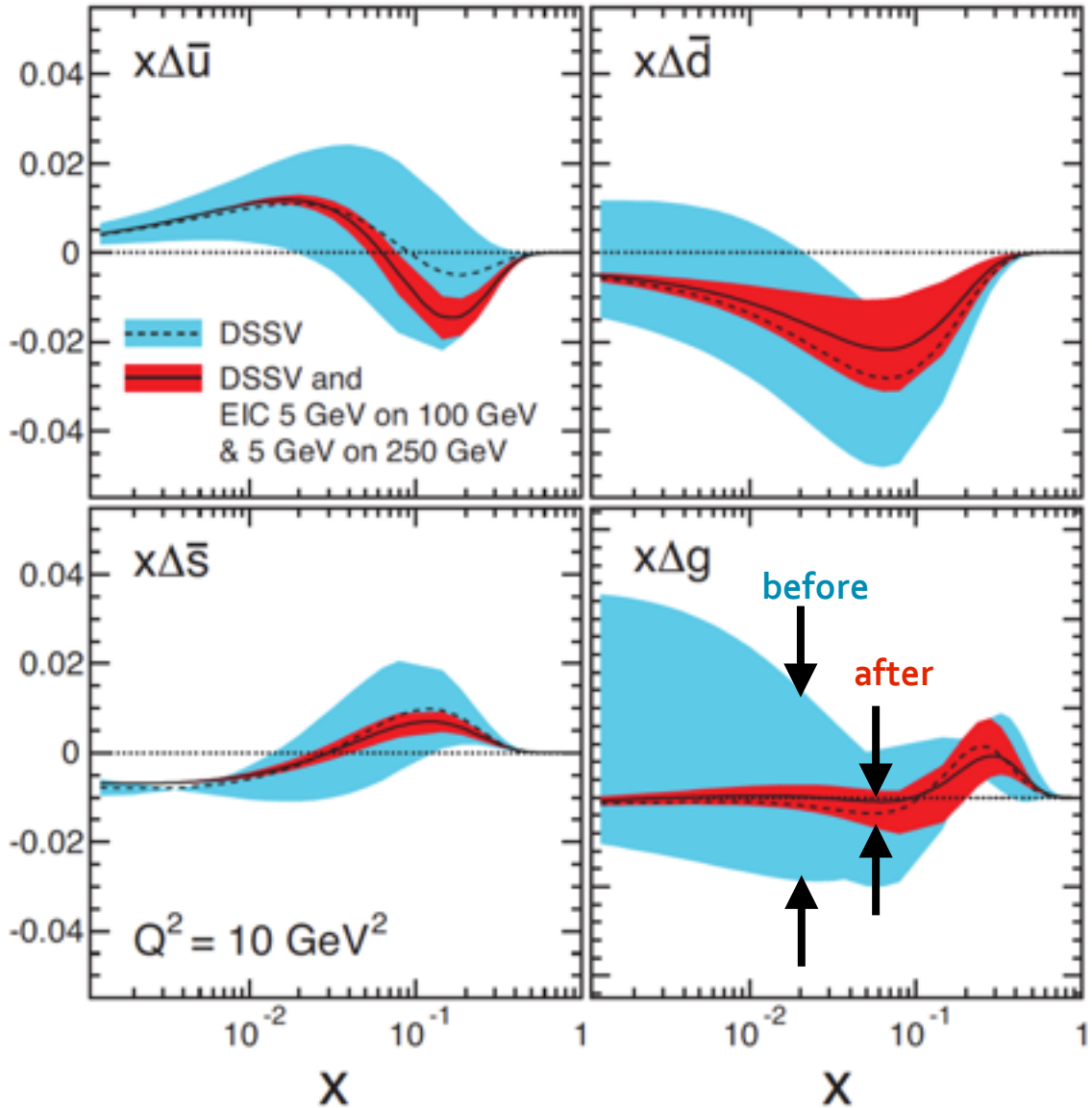
- $\Delta g$  from scaling violations a la HERA
- access to e-w effects in polarized DIS

recent NLO study on e-w SIDIS:  
 de Florian, Rotstein Harbanau 1210.7203

# expectations for helicity PDFs

only uses DIS + SIDIS data up to  $\sqrt{S} \simeq 70$  GeV and  $Q^2 > 2$  GeV<sup>2</sup>

Aschenauer, Sassot, MS 1209.3240



only relative improvement of uncertainties matters

# big picture: the 3-D experience

standard PDFs do not resolve transverse positions in the nucleon



## compelling questions

- how are quarks and gluons spatially distributed
- how do they move in the transverse plane
- do they orbit and do we have access to spin-orbit correlations

# big picture: the 3-D experience

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$$f(\mathbf{x}, \mathbf{k}_T)$$

3-D  
transv. mom. dep. PDF  
*semi-inclusive DIS*

$$\int d^2\mathbf{k}_T$$

1-D  
 $f(\mathbf{x})$   
parton densities

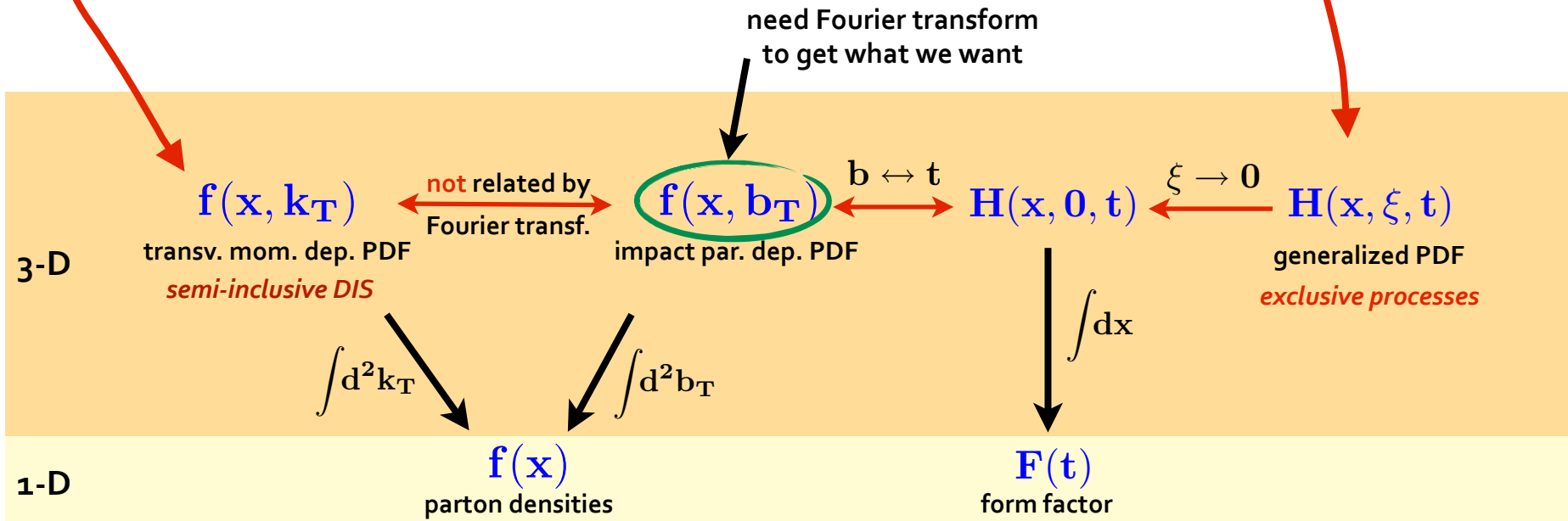
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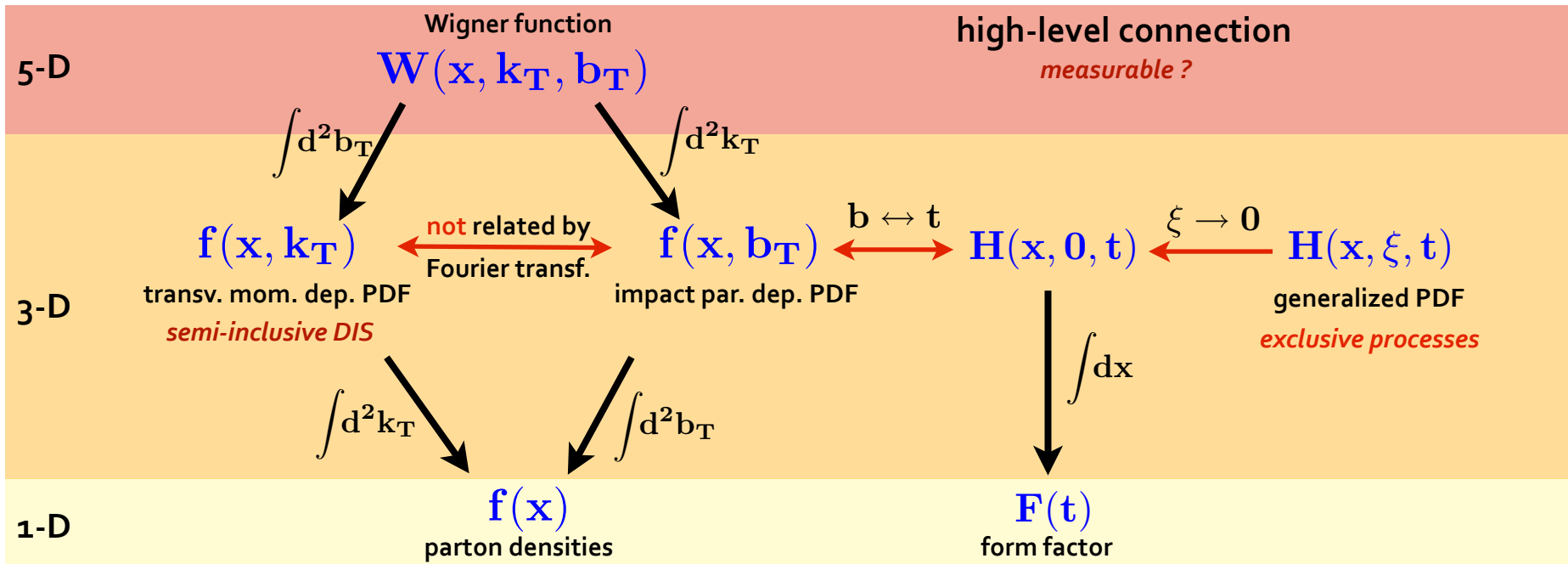
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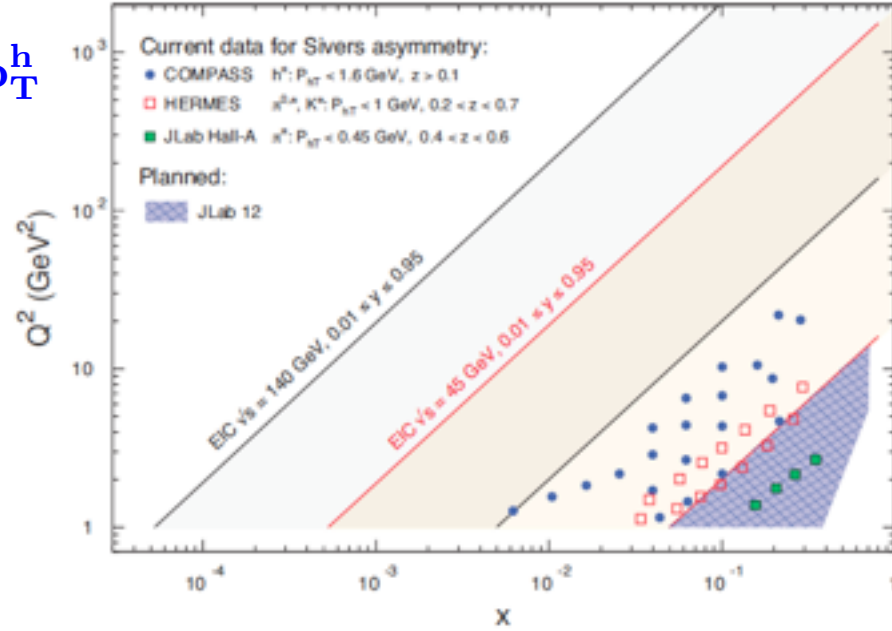




# physics of TMDs

- theoretically interesting multi-scale problem:  $Q^2, p_T^h$
- TMD framework applicable for  $Q^2 \gg p_T^h$
- studied only in fixed target regime  
**nothing known yet about sea quarks and gluons**

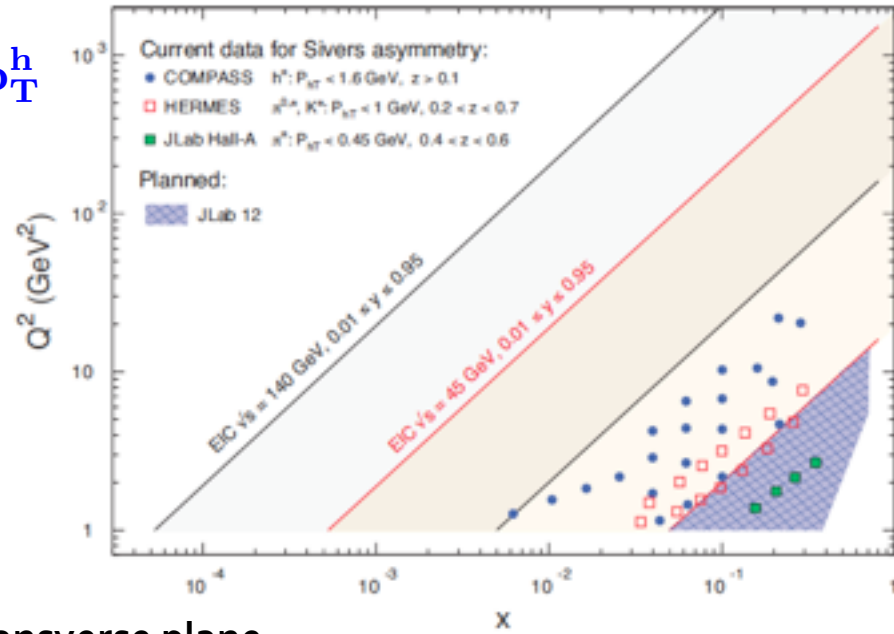
Anulli, Aghasyan, Braun, Eyser,  
Heppelmann, Martin, Parsamyan,  
Sbrizzai, Rith exp. results (Wed/Thu)



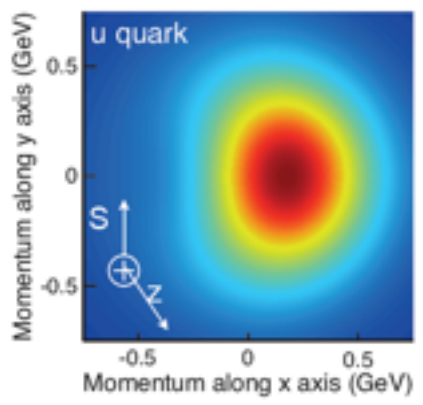
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Anulli, Aghasyan, Braun, Eyser, Heppelmann, Martin, Parsamyan, Sbrizzai, Rith exp. results (Wed/Thu)



- yields momentum distribution of partons in the transverse plane



$$f_{q/P^\uparrow}(x, \mathbf{k}_\perp, S) = f_1(x, \mathbf{k}_\perp^2) - \frac{\mathbf{S} \cdot (\hat{\mathbf{P}} \times \mathbf{k}_\perp)}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2)$$

unintegrated PDFs  $f_1$   $f_{1T}^\perp$  Sivers effect

anisotropy due to transverse proton polarization in y direction

- deeply linked with color gauge invariance of QCD
- issues with factorization in pp

Buffing, Kanazawa, Lu, Prokudin, Schimemi theory aspects (Wed)

# physics of GPDs

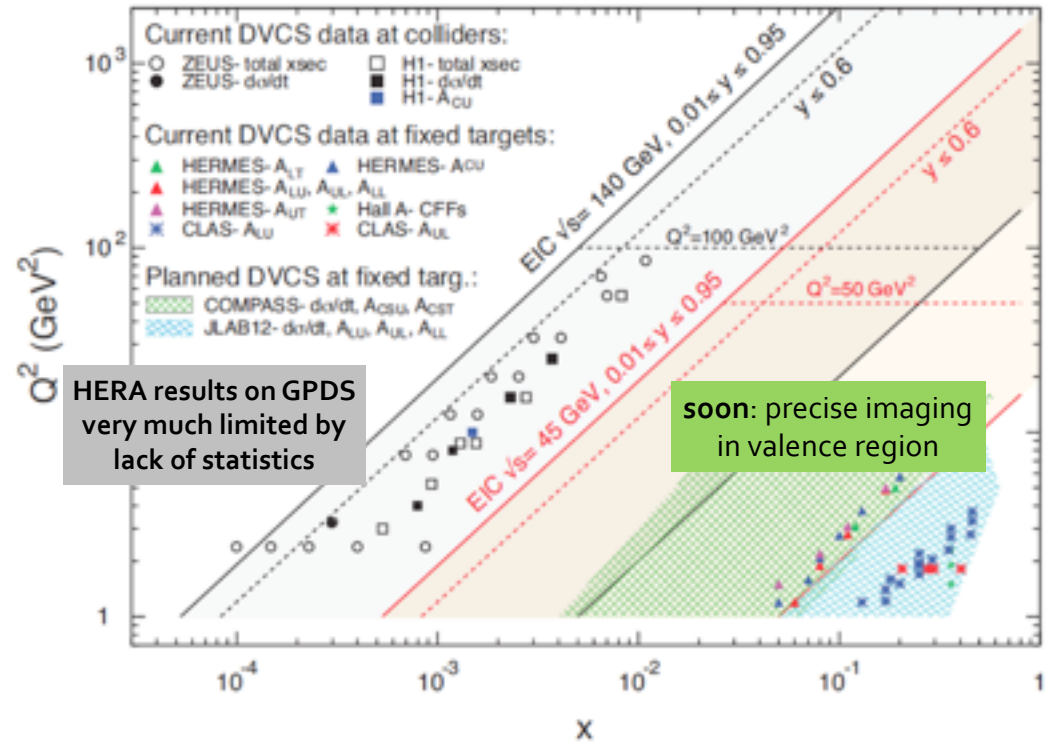
GPDs describe exclusive processes

DVCS



- theory well understood
- link to total angular momentum  $J_{q,g}$

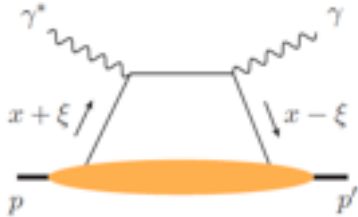
Yaschenko, Schmidt, Marianski  
data (Wed)



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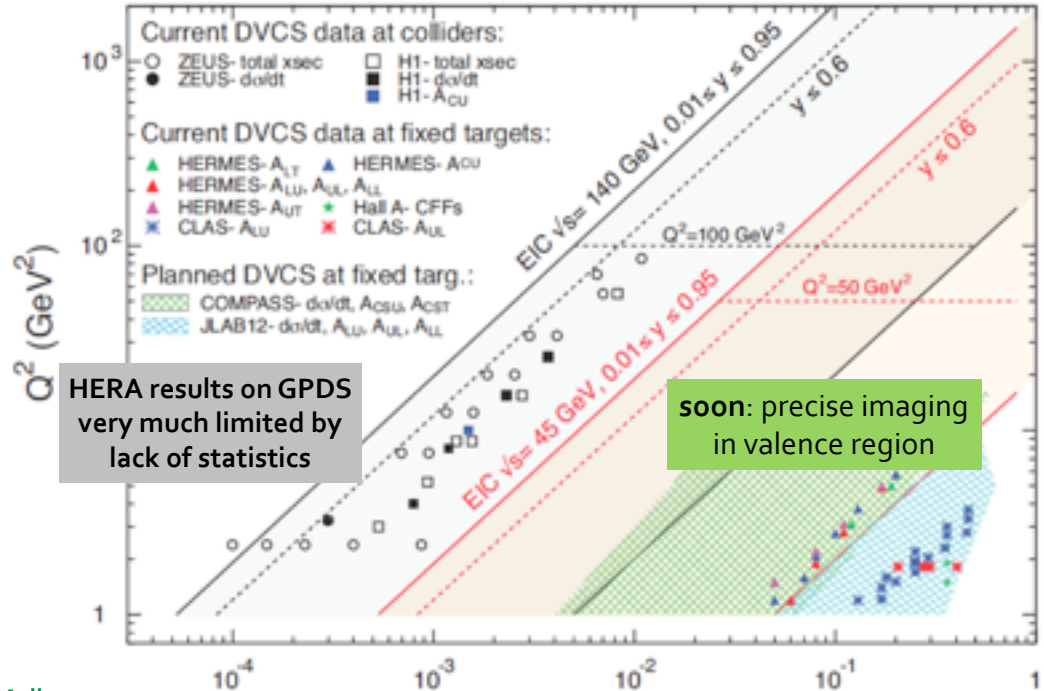
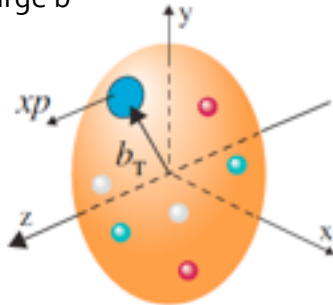
Yaschenko, Schmidt, Marianski data (Wed)

## roadmap to imaging at an EIC

Aschenauer, Fazio, Kumericki, Muller 1304.0077

- ▶ global analysis of DVCS and vector meson data  
angular & polarization observables to disentangle different GPDs
- ▶ Fourier transform  $t$  dependence to obtain  $b$ -space image  
need large  $t$  range to resolve small/large  $b$

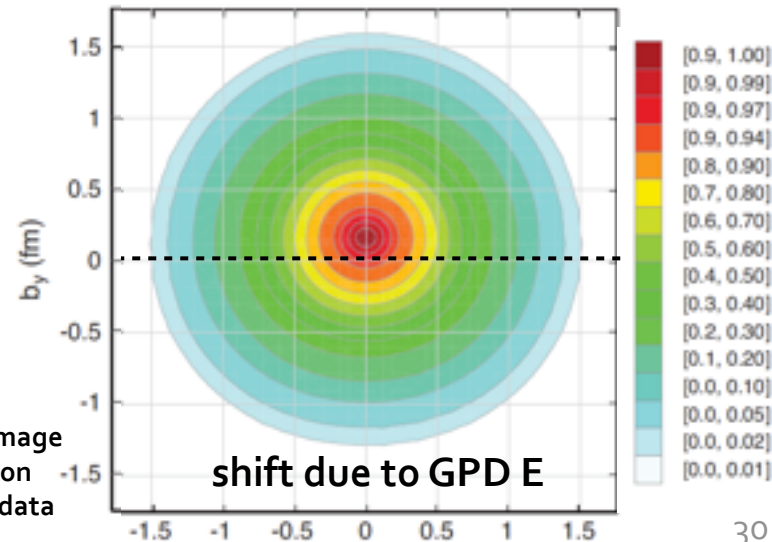
Diehl, Siddikov, Wagner, Wallon theory (Wed)



HERA results on GPDs very much limited by lack of statistics

soon: precise imaging in valence region

$q^1(x=10^{-3}, \vec{b}, Q^2 = 4 \text{ GeV}^2)$



sample image based on pseudo-data

shift due to GPD E

# take away message



**spin experiments continue to produce high impact results**

theory efforts & global QCD fits try to keep up interesting physics questions in gluon/sea quark regime

to close the chapter on the proton spin

&

to have the real 3-D experience of the proton

**an EIC is the only option**

