June 25th, 2013

Spin Physics
Theory Overview

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BROOKHAVEN NATIONAL LABORATORY

the cookies we crumble: fundamental questions driving spin physics

how do quarks and gluons carry the proton spin

$$\Delta f(x) \equiv f_{\rightrightarrows}(x) - f_{\rightleftarrows}(x)$$

- 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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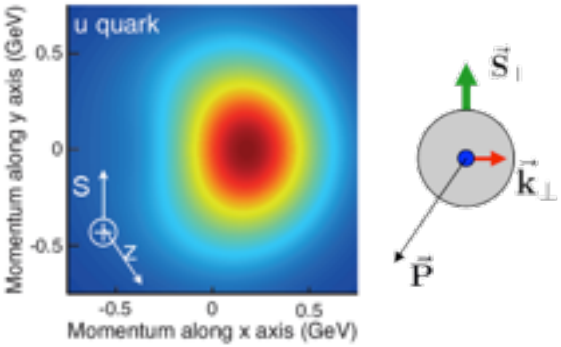
reveal mechanisms behind transverse spin phenomena



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

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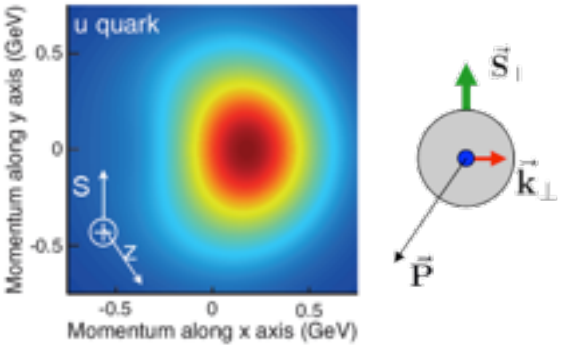

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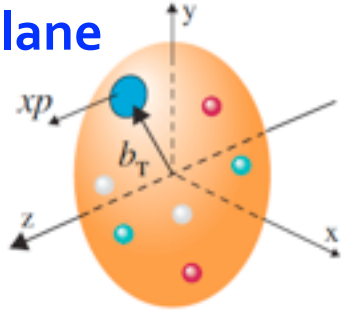
what is the distribution of partons in the transverse plane

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



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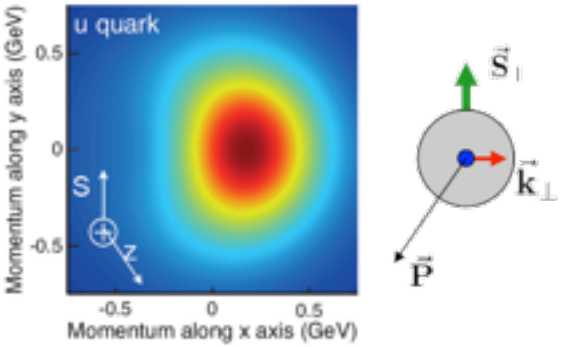

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--> Mauro's & Yuri's talks earlier today

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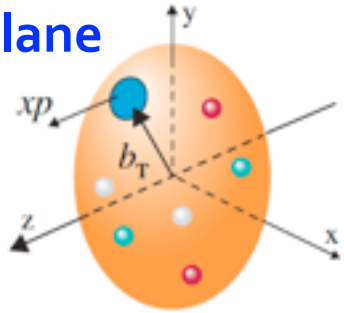
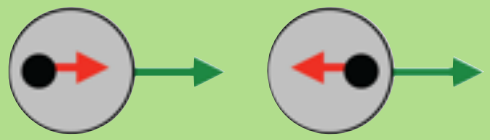


the cookies we crumble: fundamental questions driving spin physics

how do quarks and gluons carry the proton spin



$$\Delta f(x) \equiv f_{\rightrightarrows}(x) - f_{\rightleftarrows}(x)$$

- what is th… and sea quarks
- wha… angular momentum
- … to models/lattice QCD

major contributions from RHIC program
single-/double-spin asymmetries

reveal mechanisms behi… pin phenomena

- develop TMD framework / evolution
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- explore connections to unintegrated PDFs

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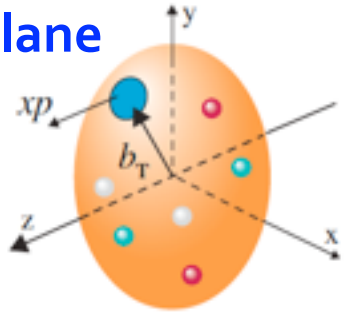

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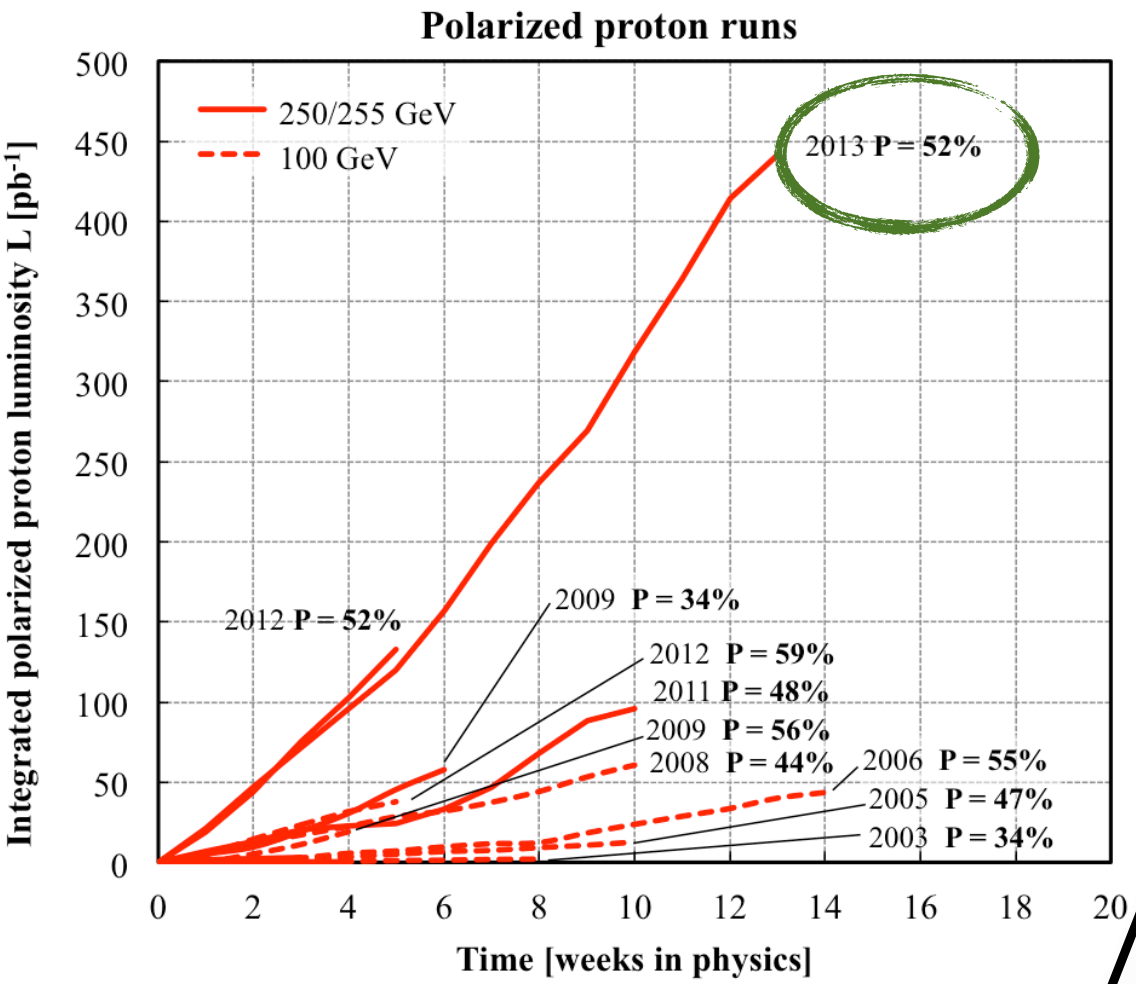
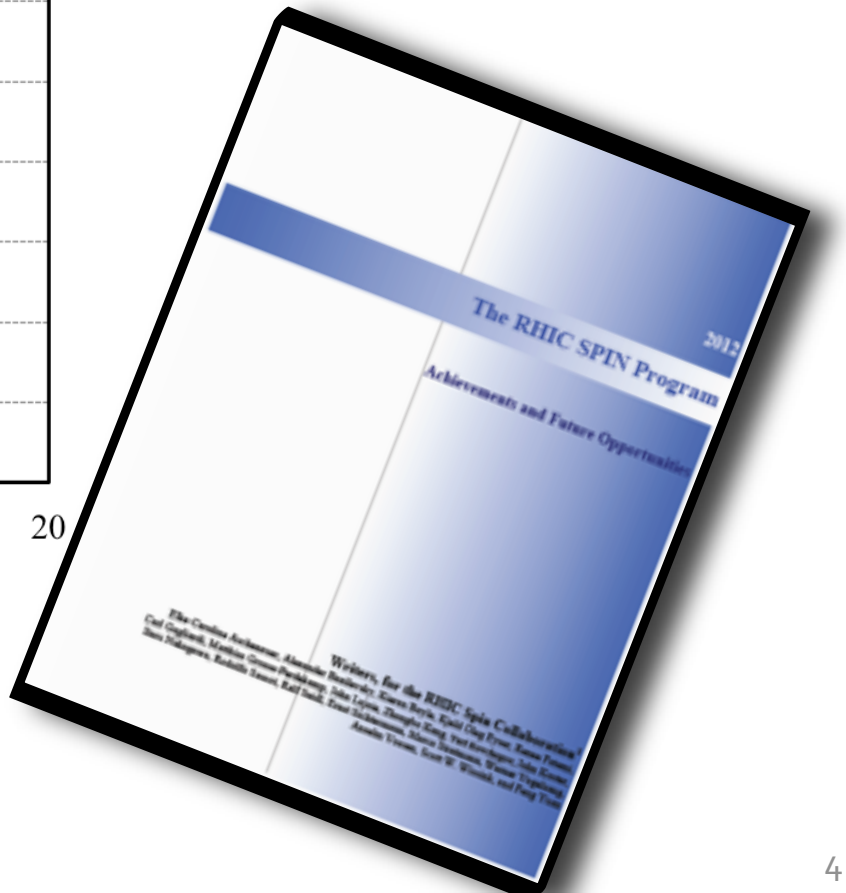
RHIC spin program



still a very vibrant program



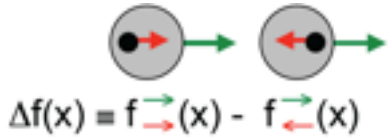
latest results & outlook summarized in

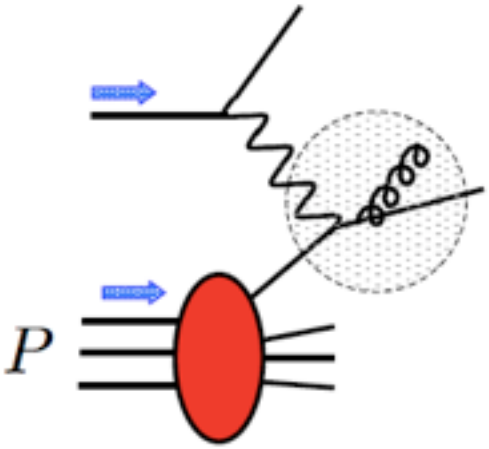
arXiv:1304.0079

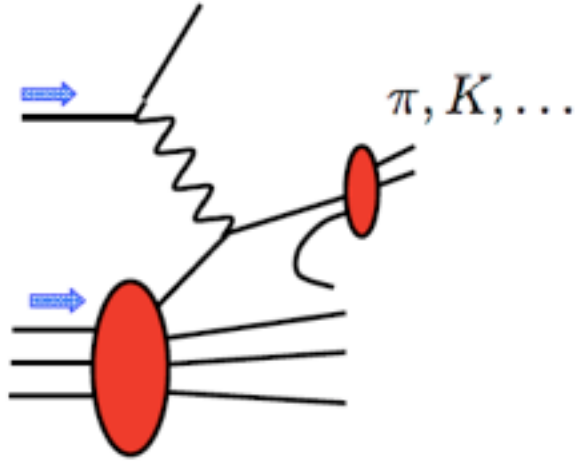
1

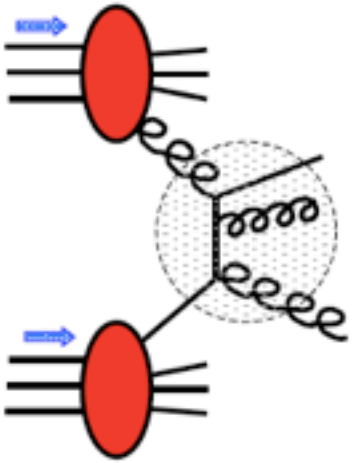
status of proton's helicity structure

probes of nucleon helicity structure









DIS

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

SIDIS

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

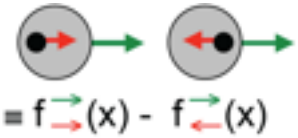
Δg charm, 2-hadrons

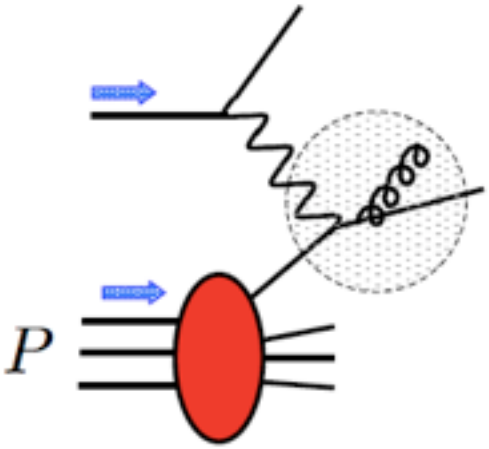
pp

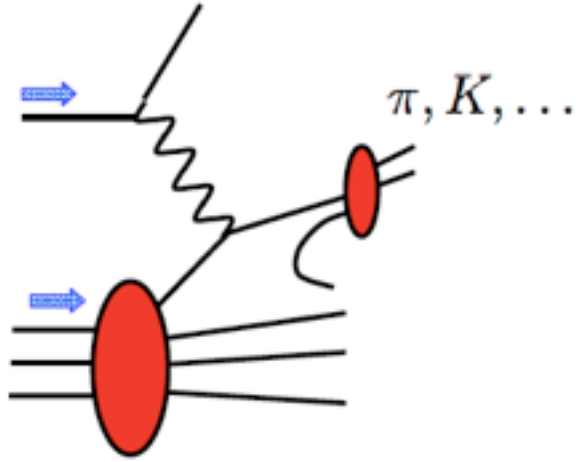
Δg 1-jet, 1-hadron

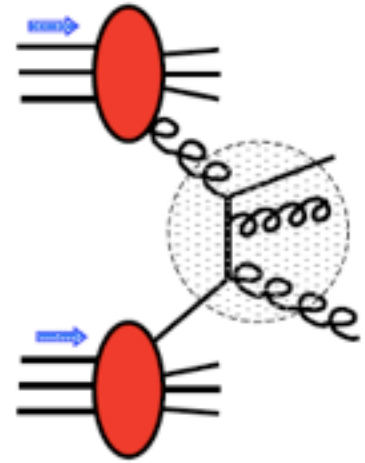
$\Delta q, \Delta \bar{q}$ $W^{+/-}$ bosons

probes of nucleon helicity structure









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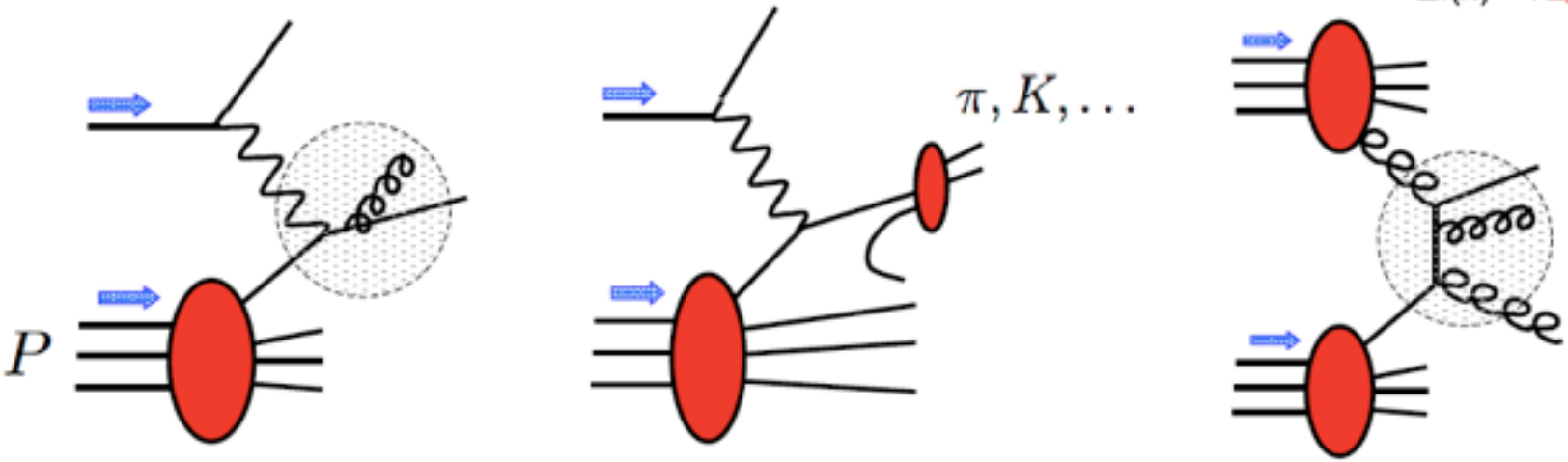
guiding principle: **factorization**

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 $d\Delta\hat{\sigma} = d\Delta\hat{\sigma}^{\mathrm{LO}} + \alpha_s\, d\Delta\hat{\sigma}^{\mathrm{NLO}} + \ldots$

probes of nucleon helicity structure

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



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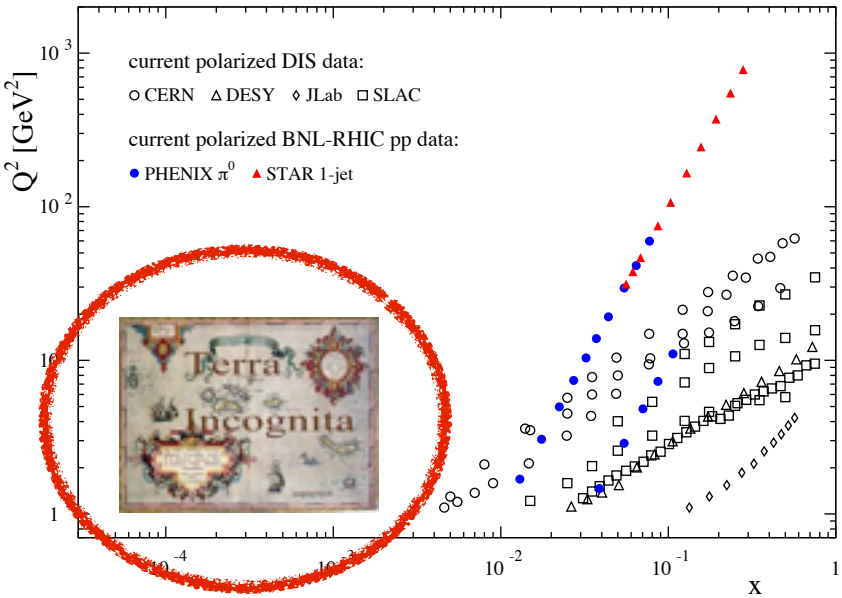
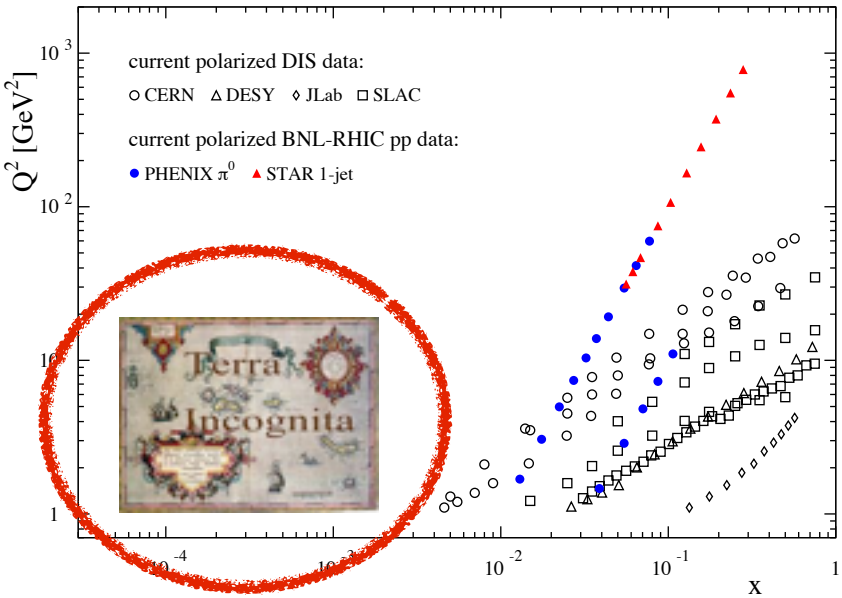
need DIS + SIDIS + pp to constrain all aspects of PDFs (a way to test factorization)

challenges compared to unpolarized PDF fits



- **rather limited x-Q² coverage**
  - **difficult to get Δg from scaling violations**
    - need to rely on "direct probes" for Δg
  - **need to use data down to Q² = 1 GeV²**
    - applicability of pQCD ? higher twist ?

challenges compared to unpolarized PDF fits



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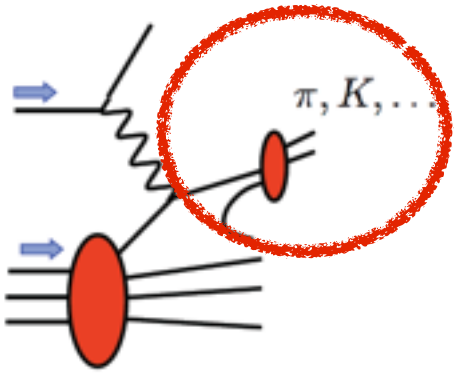
- **no neutrino DIS data**
  - **no quark/anti-quark separation from DIS**
    - largely rely on SIDIS for flavor separation
    - need fragmentation functions to analyze data



extra source of uncertainties

new data:
ALICE, BABAR, BELLE, COMPASS, HERMES

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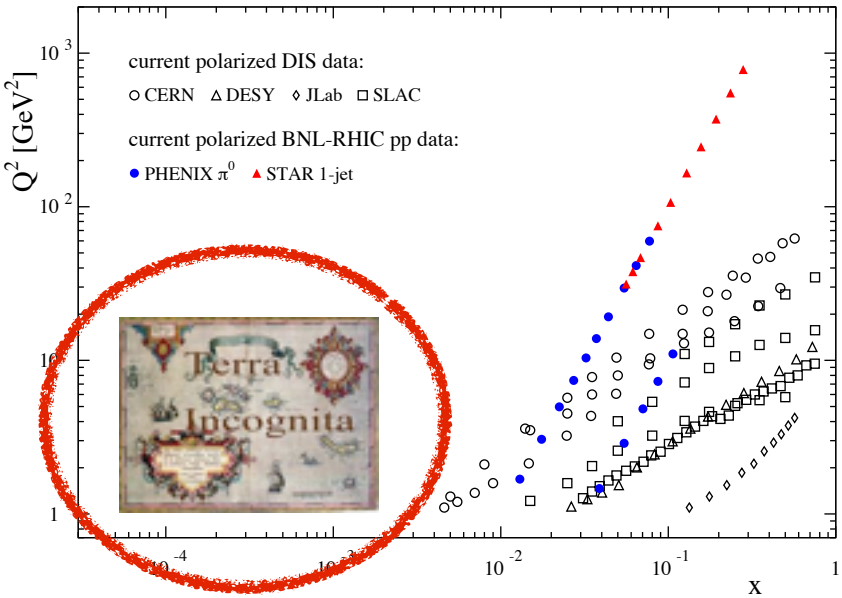

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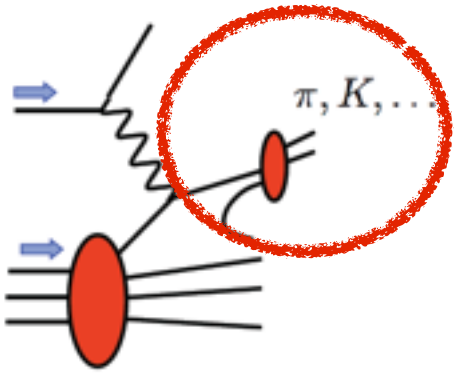

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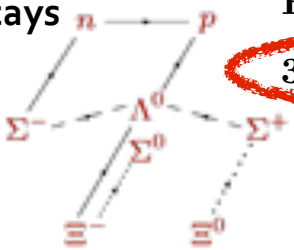
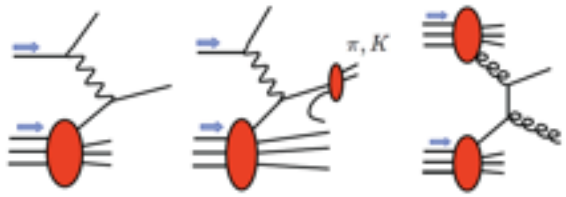
- **sum rules on shaky (?) grounds**
  - **1st moments of non-singlet combinations <-> hyperon decays**
    - constraint on unmeasured small-x behavior of Δs and ΔΣ
    - doubts, however, on applicability of SU(3) relation
      Savage, Walden; … ; Bali et al. 1112.3354 (lattice)



$$F + D = 1.2701 \pm 0.0025$$

$$3F - D = 0.585 \pm 0.025$$

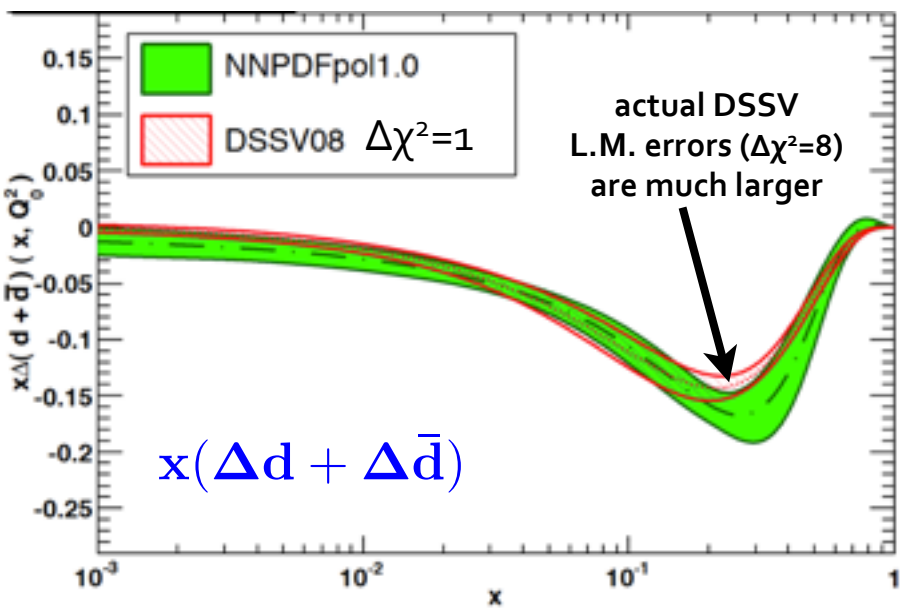
overview of recent helicity PDF fits @ NLO

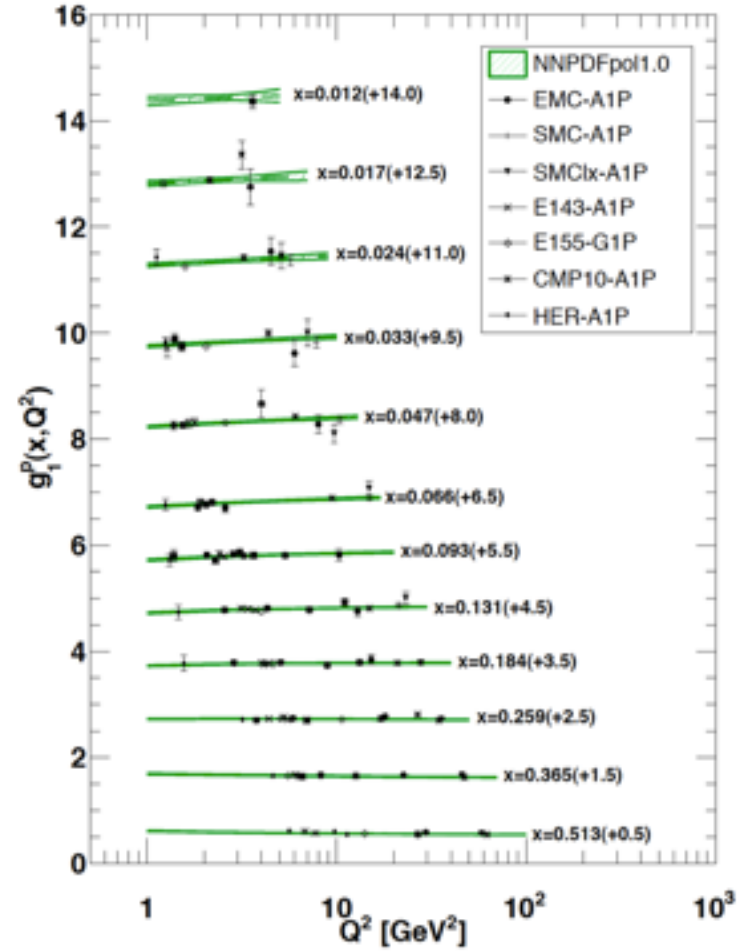


				uncertainties	last update
NNPDF Ball, Forte, Guffanti, Nocera, Rodolfi,Rojo	✓	✗	✗	100 replicas stat. approach	1303.7236
DSSV de Florian, Sassot, MS, Vogelsang	✓	✓	✓	L.M. $\Delta\chi^2 = 8$ (1) (Hessian $\Delta\chi^2 = 1$)	0904.3821 [DSSV+/++: 1112.0904 1304.0079]
LSS Leader, Sidorov, Stamenov	✓	✓	✗	Hessian $\Delta\chi^2 = 1$	1010.0574
BB Blumlein, Bottcher	✓	✗	✗	Hessian $\Delta\chi^2 = 1$	1010.3113
⋮		⋮			⋮
GRSV Gluck, Reya, MS, Vogelsang	✓	✗	✗	✗	1st NLO analysis 9508347

some highlights of the NNPDF analysis

- **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
- agrees best with global DSSV fit





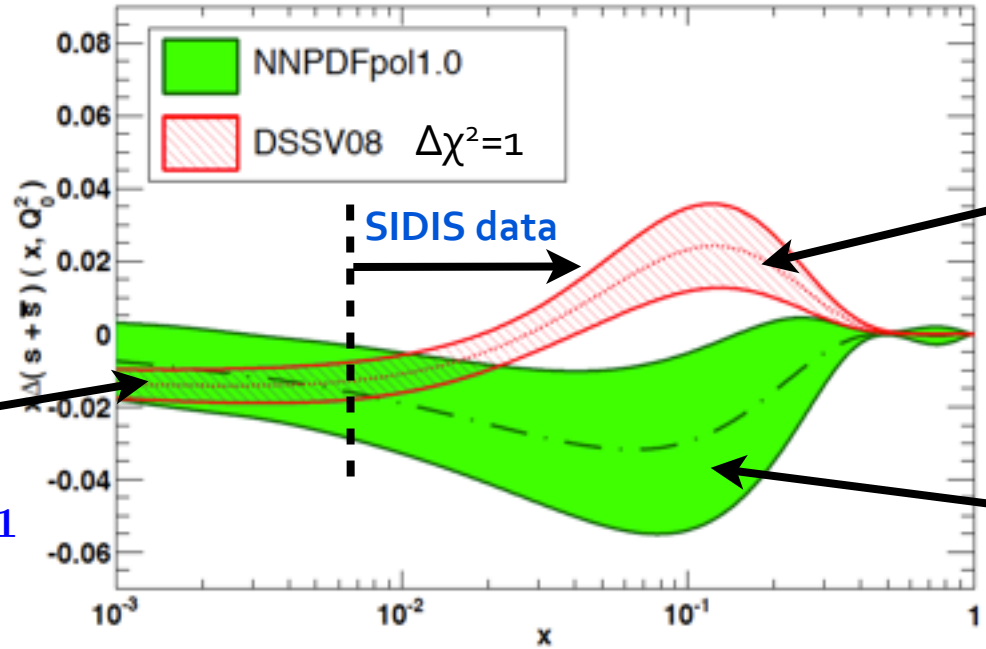
work towards including RHIC data

strangeness conundrum

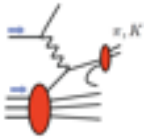
mounting tension between DIS and SIDIS kaon data?

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

NNPDF 1303.7236



directly from SIDIS kaon data



indirectly from DIS data

1st moment constrained by 3F-D

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

strangeness conundrum

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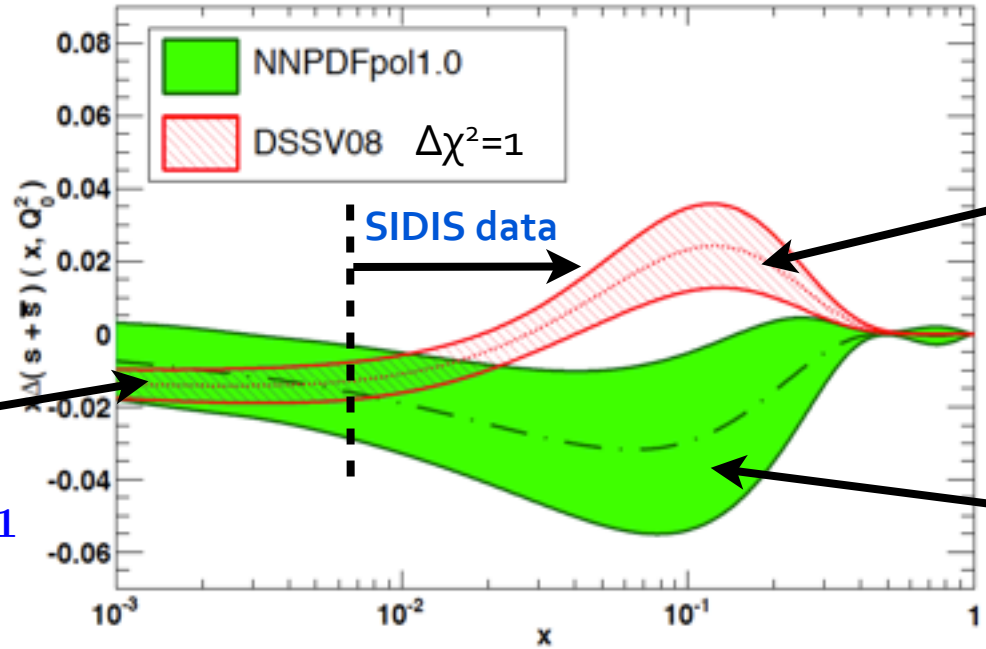
$x(\Delta s + \Delta\bar{s})$ NNPDF 1303.7236



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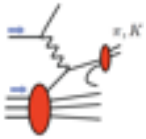

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remarks/caveats:

- 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

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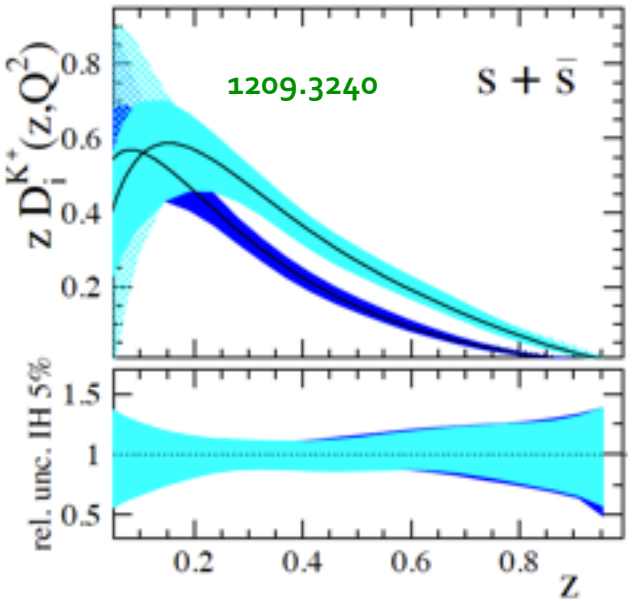
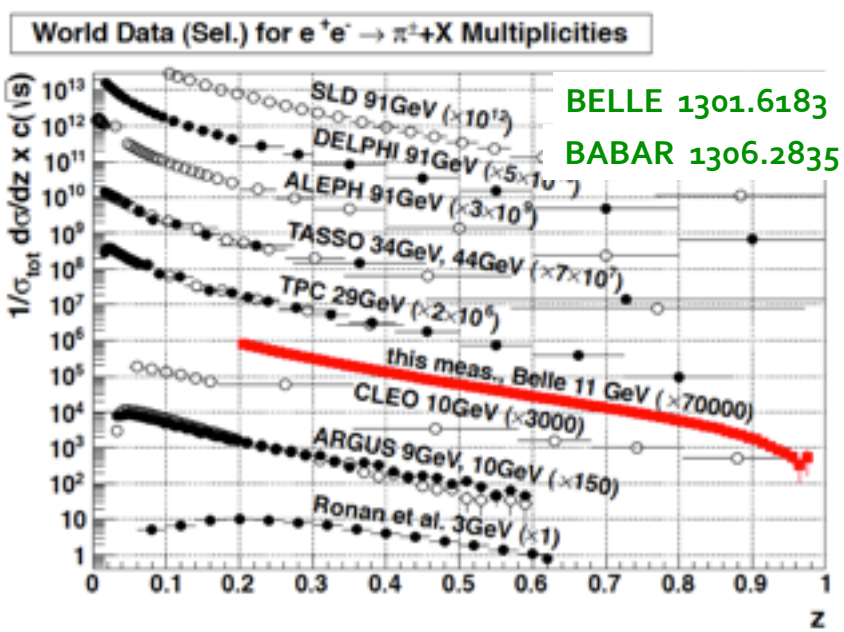
impact of latest experimental results

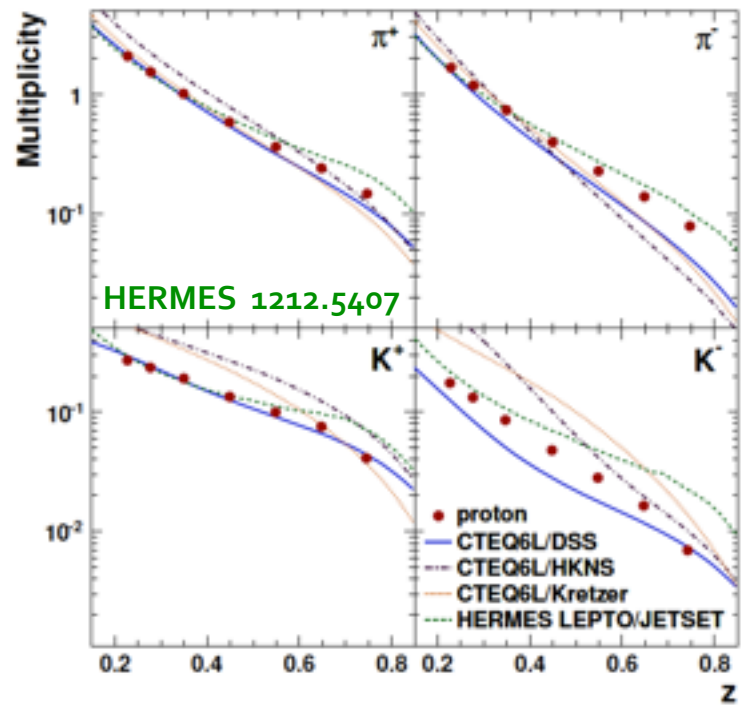
detour: hadron multiplicities & fragmentation



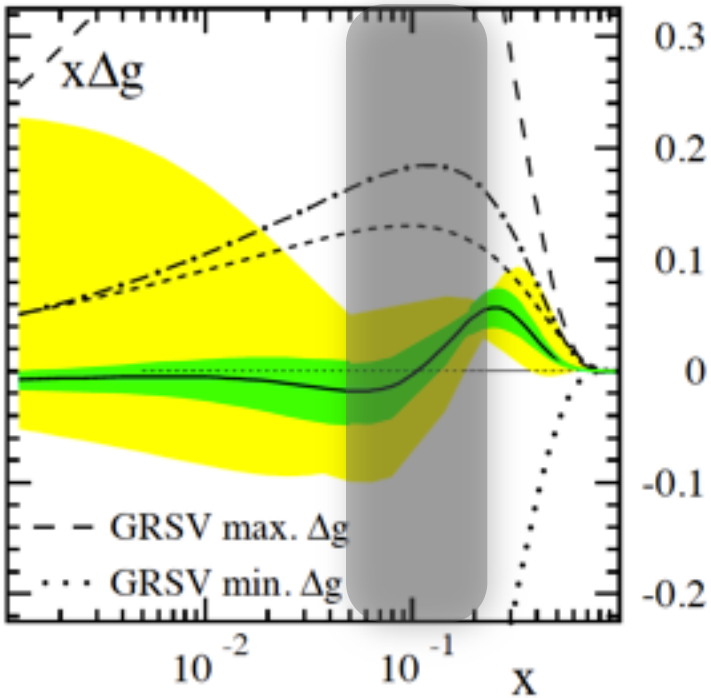
- ☑ **FFs extracted from global fits @ NLO** (e^+e^-, ep, pp data)
  DSS: de Florian, Sassot, MS; AKK: Albino, Kniehl, Kramer (e^+e^- & pp only); ...
- ☑ recent study of uncertainties (within DSS framework)
  Epele, Llubaroff, Sassot, MS: 1209.3240

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





Δg 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

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

from DSSV 2008/09 analysis

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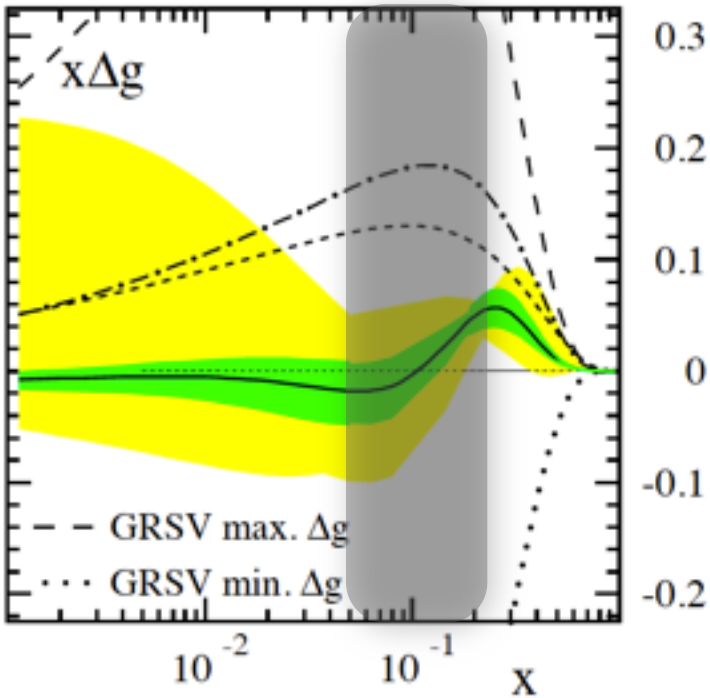

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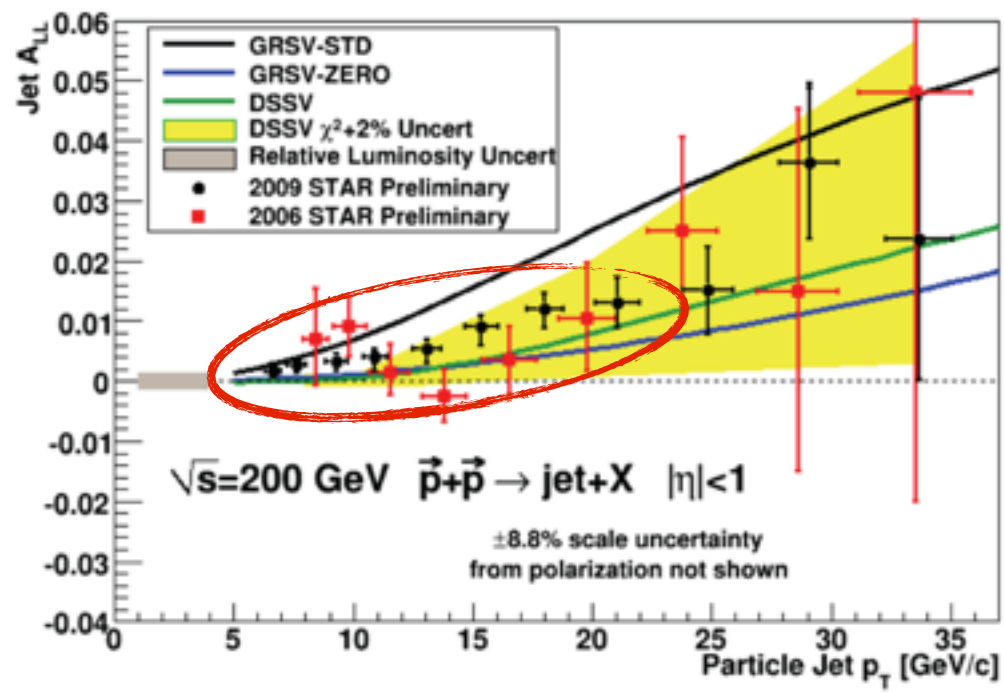
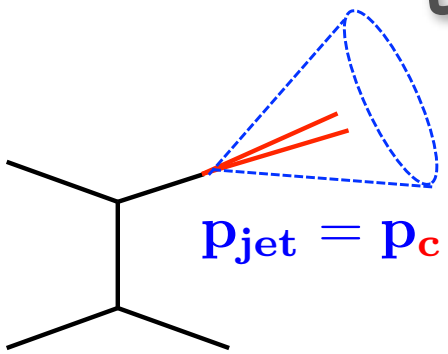


- ☑ new data consistently above DSSV
- ☑ considerably smaller errors

what's the impact?

update on jet analysis



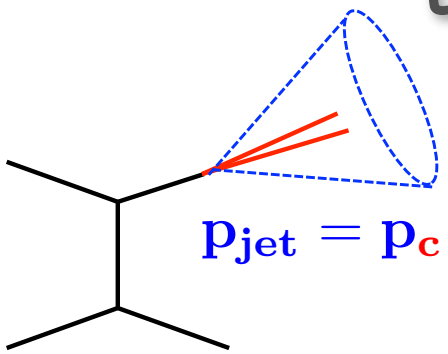
$$\mathbf{p_{jet}} = \mathbf{p_c} + \mathbf{p_d}$$

cone type distance of each parton to jet direction constrained

k_T type distance between two partons constrained by algorithm

☑ STAR has switched to anti-k_T algorithm for run-9 --> adopt this in our analysis as well

update on jet analysis



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cone type distance of each parton to jet direction constrained

k_T type distance between two partons constrained by algorithm

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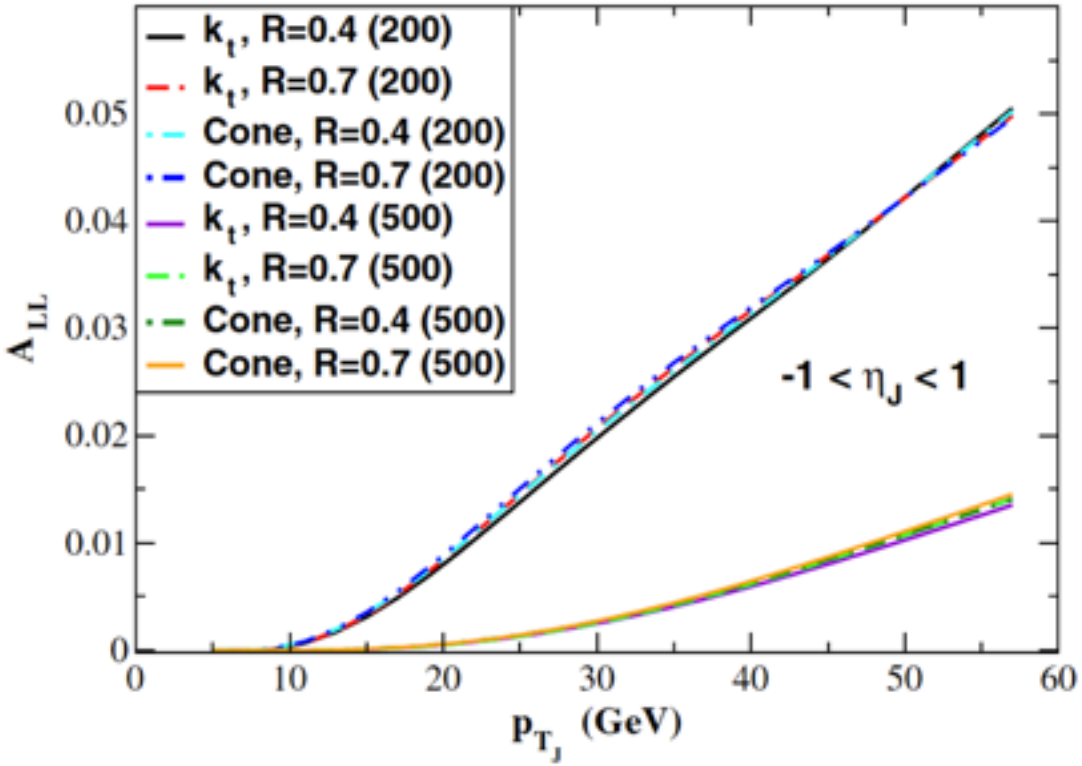
- ☑ very little impact on spin asymmetries though:

Mukherjee, Vogelsang



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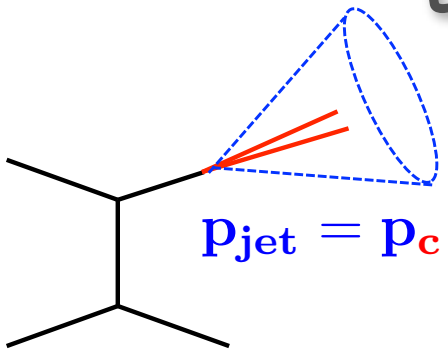

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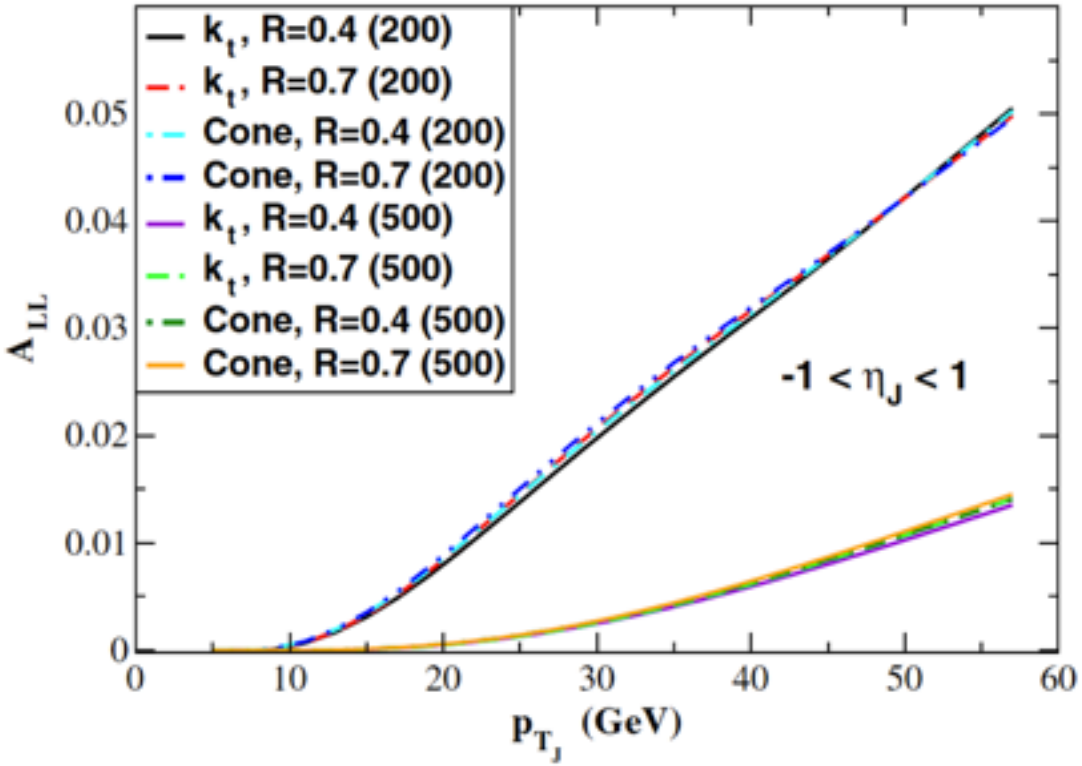


aside:

in narrow jet approximation

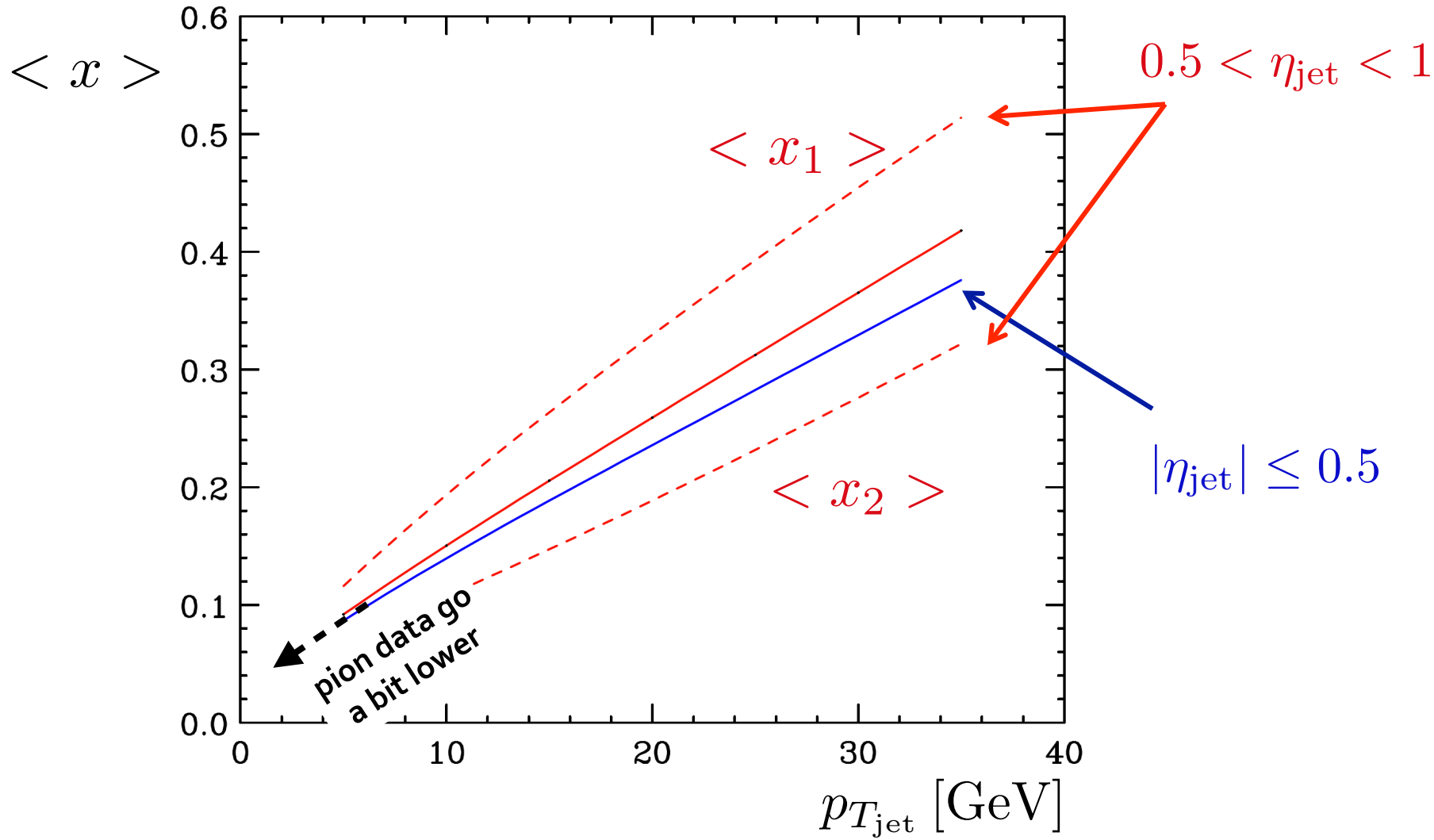
$$d\sigma \simeq \boxed{\mathbf{A}\log(\mathbf{R}) + \mathbf{B}} + \mathcal{O}(\mathbf{R}^2)$$

calculated

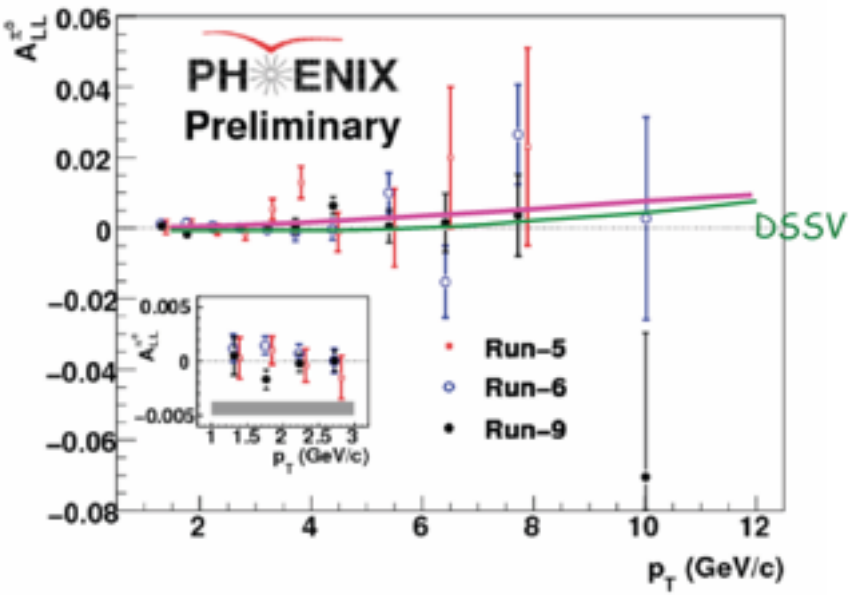
--> **R should be small** (0.7 still works fine)

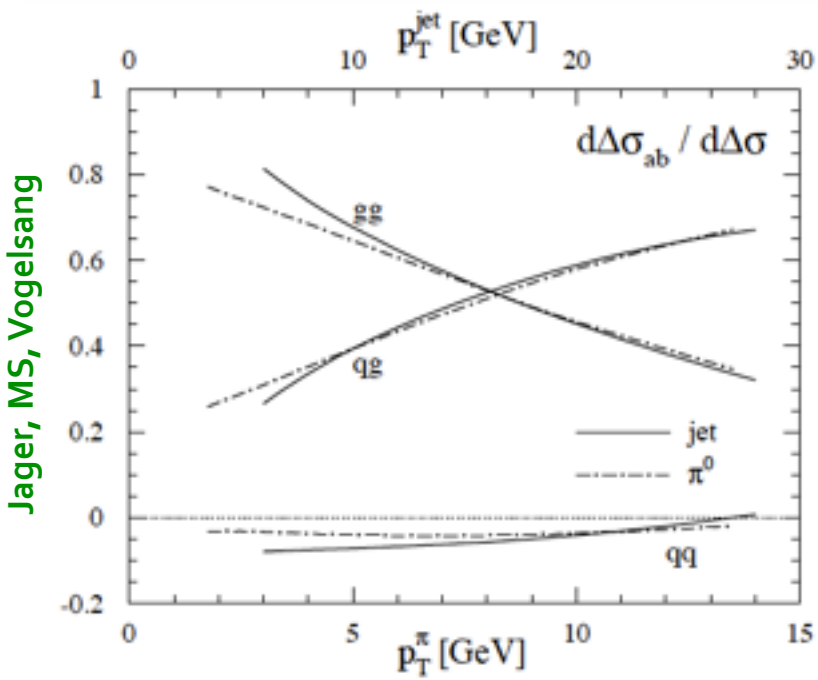
x-range probed in jet analysis

where does the estimate for the "RHIC x-range **[0.05-0.2]** " come from ?



consistency of STAR and PHENIX data





- mid rapidity π^0 and jet data closely related
- π's carry approx. 1/2 of parton's momentum

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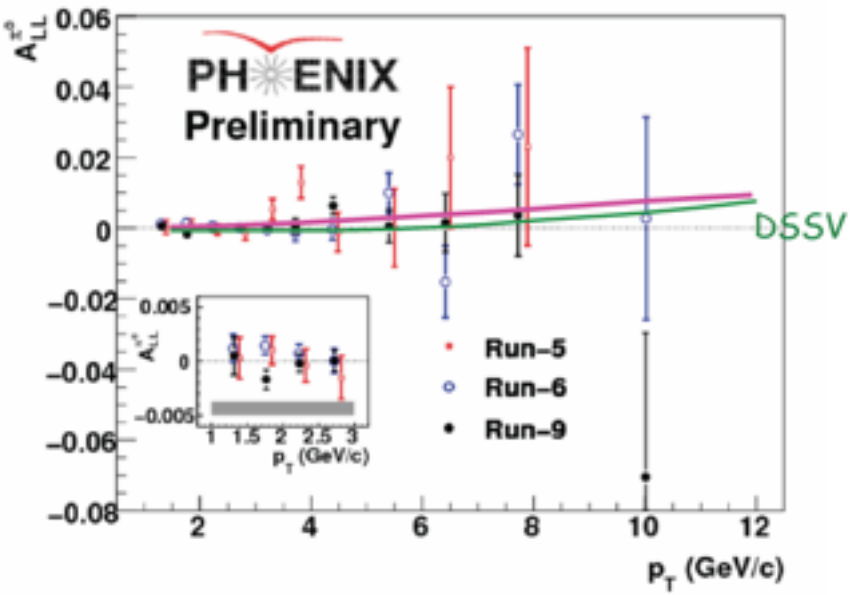
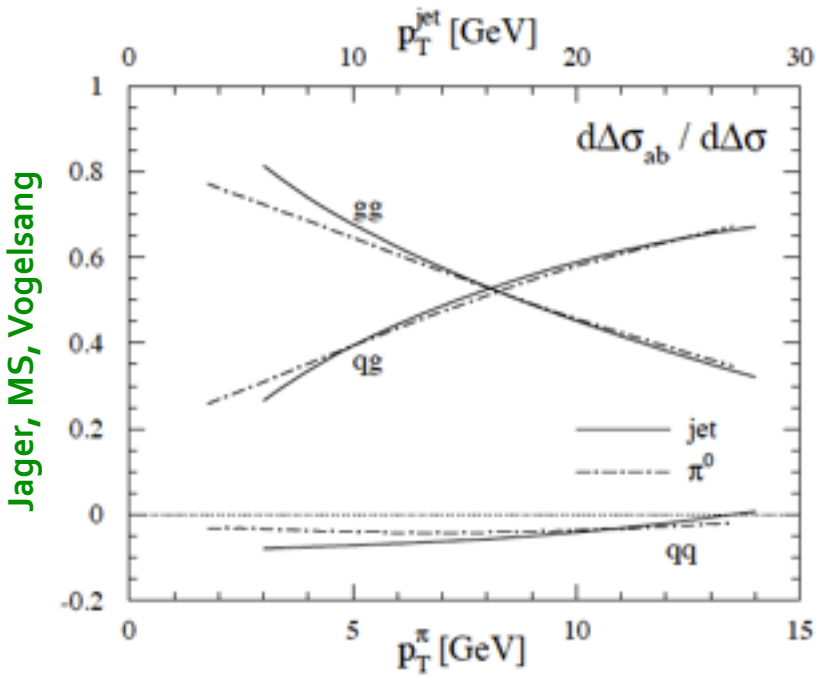
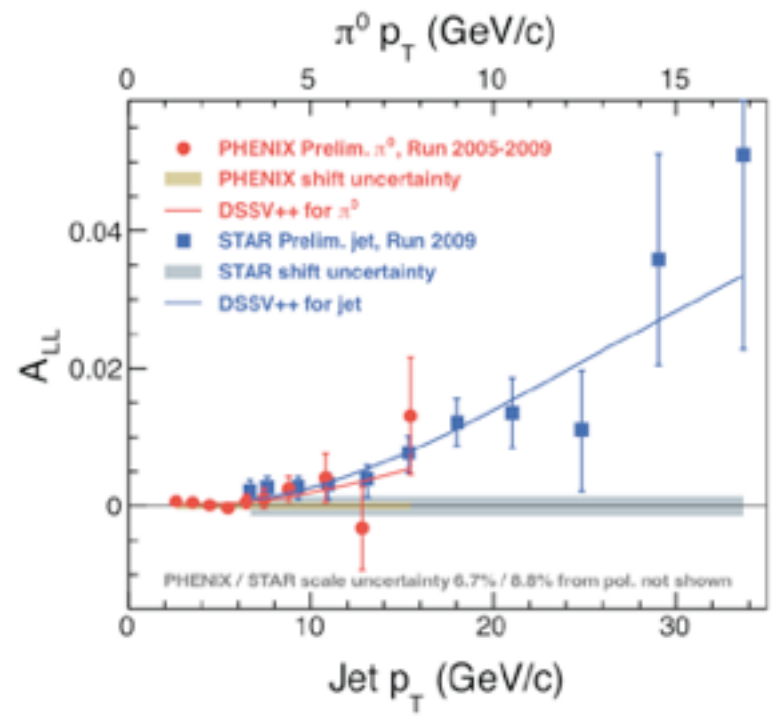


- mid rapidity π^0 and jet data closely related
- π's carry approx. 1/2 of parton's momentum

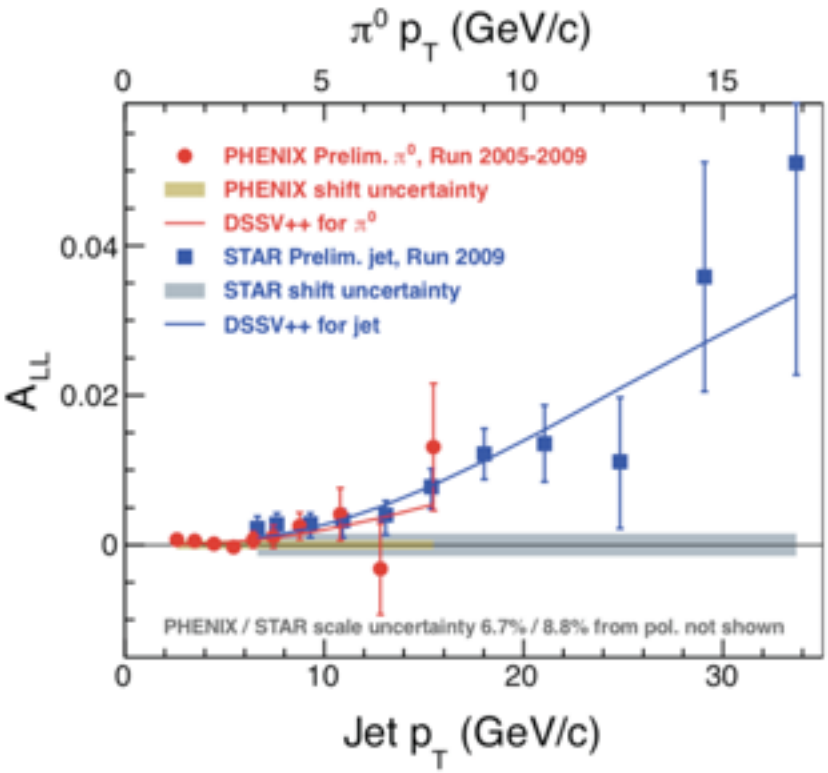
- jet and π^0 data can be put into one plot
- PHENIX probes lower p_T (slightly lower x)



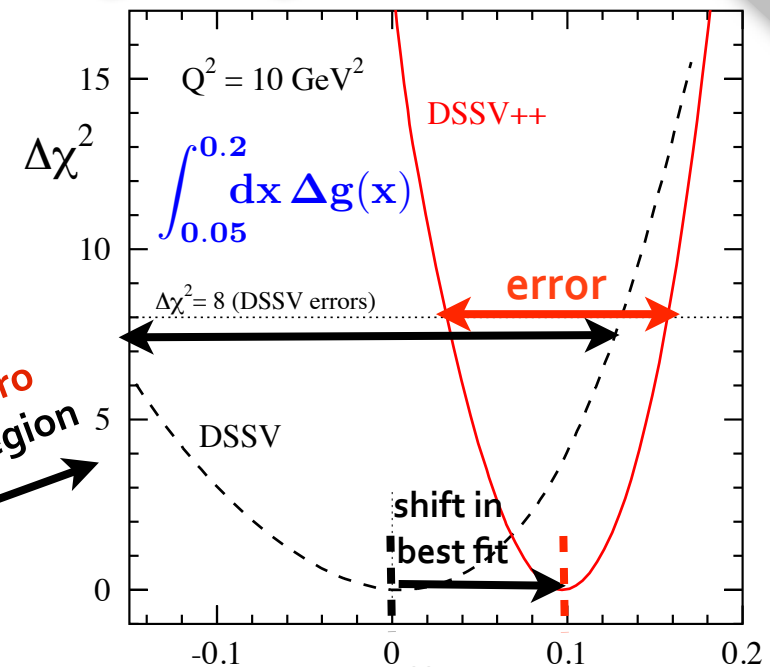


Δg from RHIC - gaining weight

new RHIC data included in DSSV++



lead to non-zero Δg in RHIC x-region



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

fully compatible with old DSSV error estimate

Δg from RHIC - gaining weight

Δg

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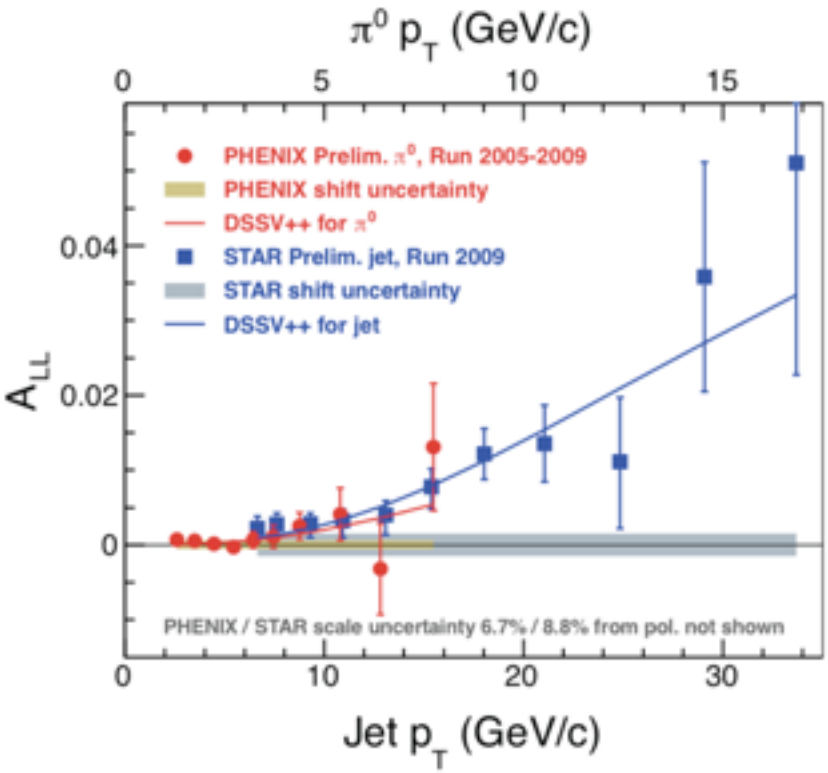

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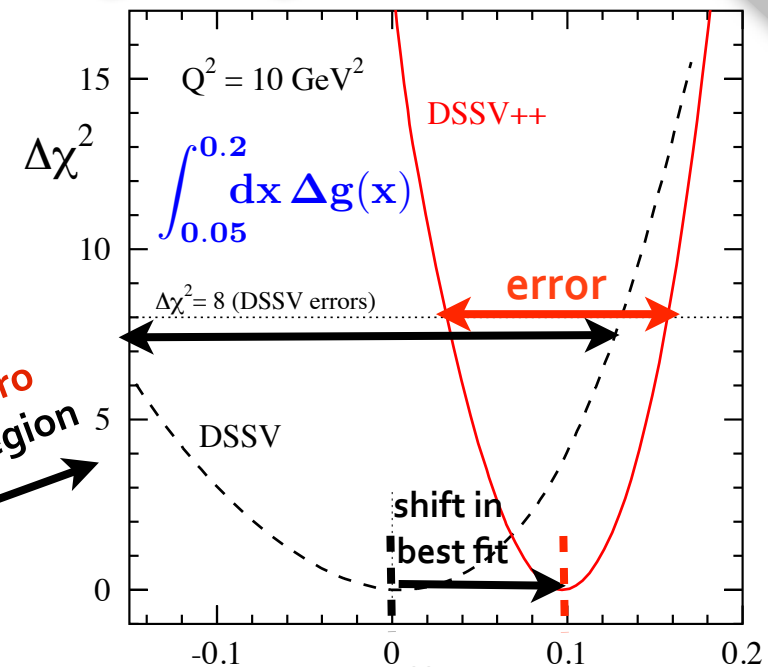

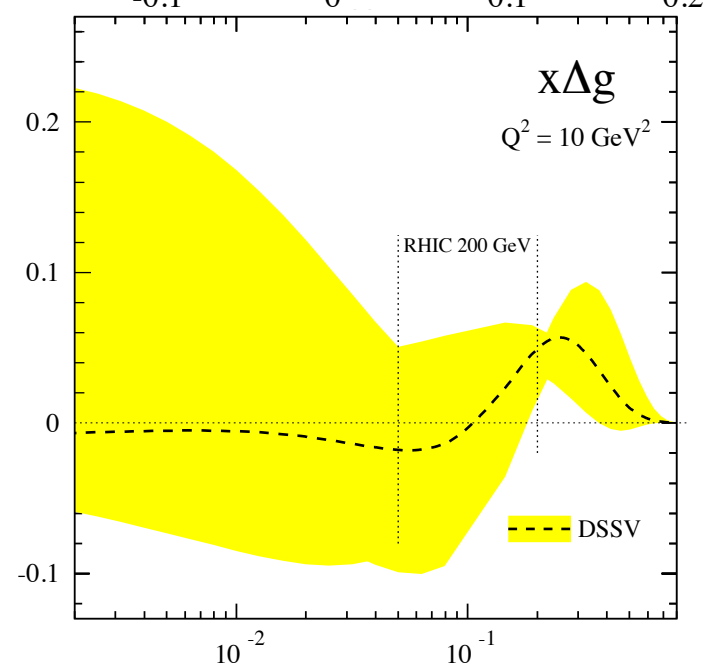

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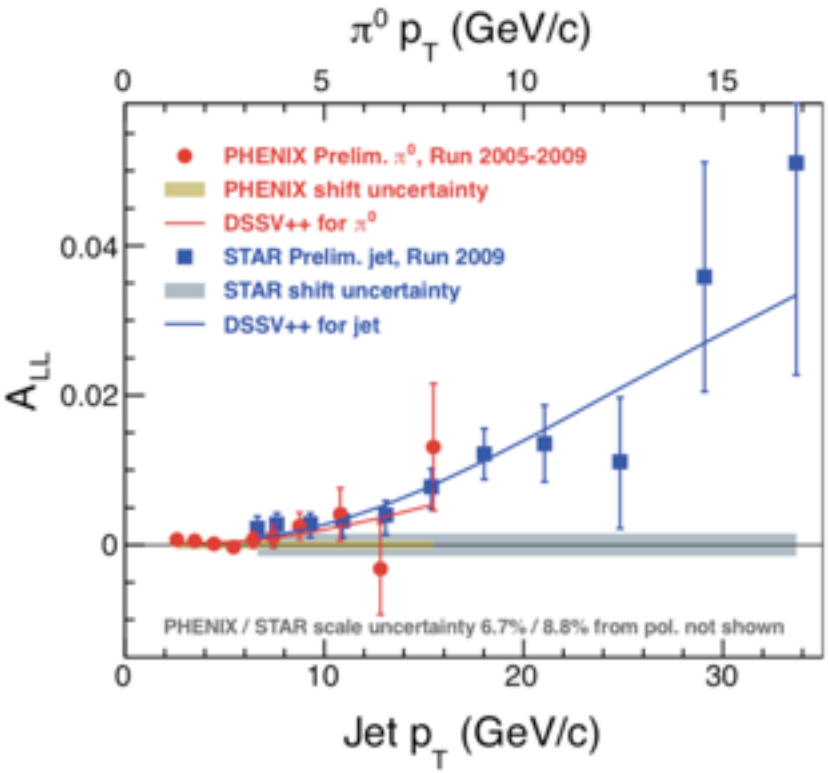

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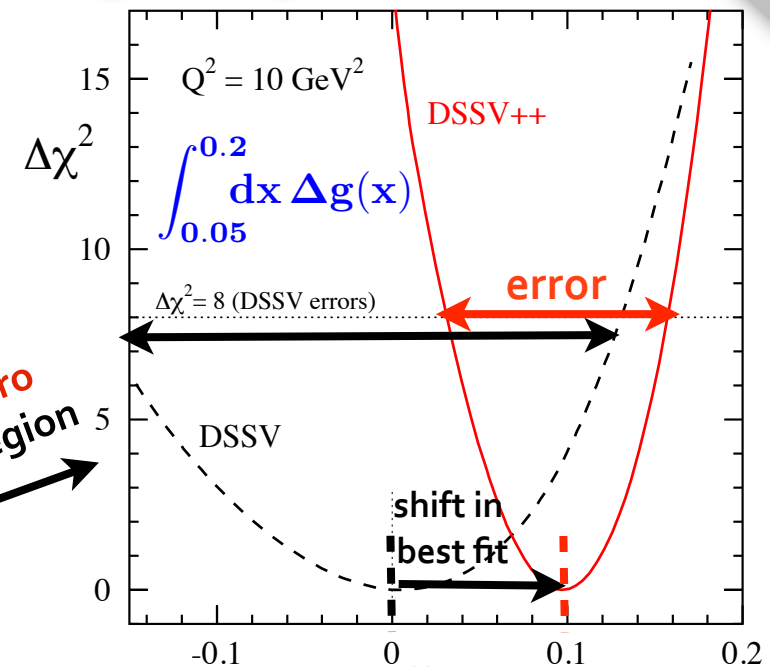
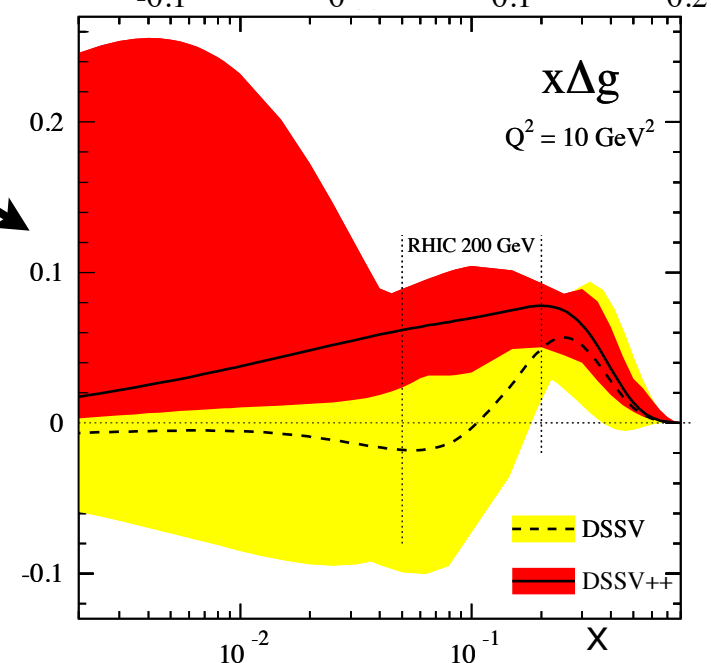


positive Δg in RHIC x-region



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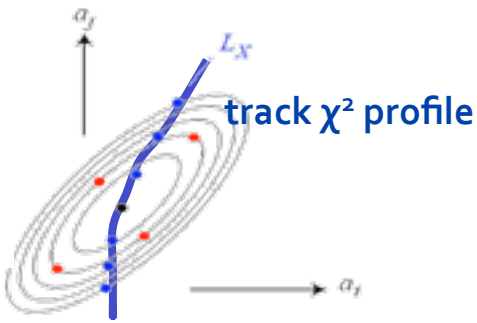
uncertainty estimates in DSSV analysis

- Lagrange multipliers as main method for uncertainty estimates
- use $\int_{x_{min}}^{x_{max}} \Delta f(x, Q^2) dx$ as proxy for uncertainty studies

Lagrange multiplier

idea: force observables to take certain fixed values and map out χ^2 profile



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- no approximations
- not suitable for "end user"
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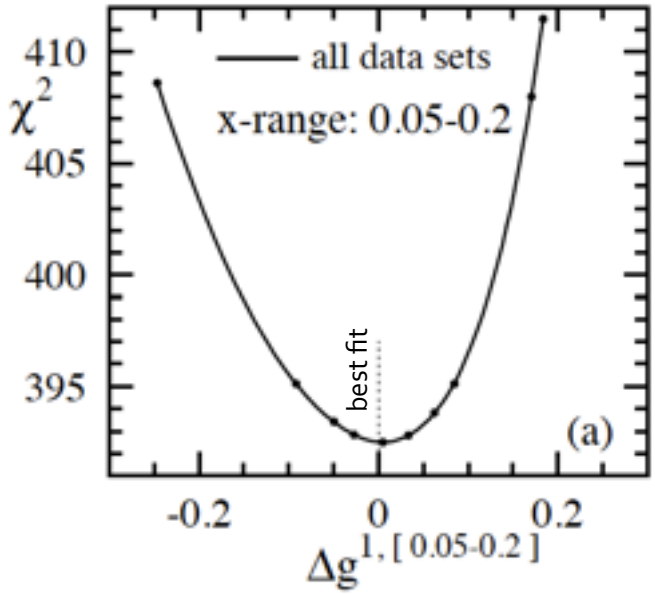

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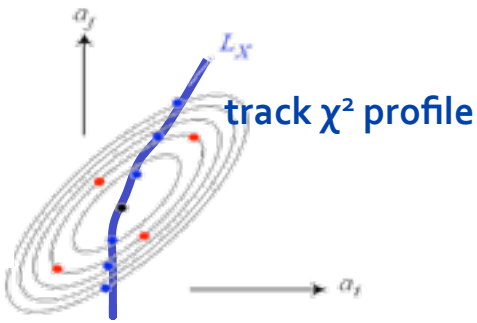

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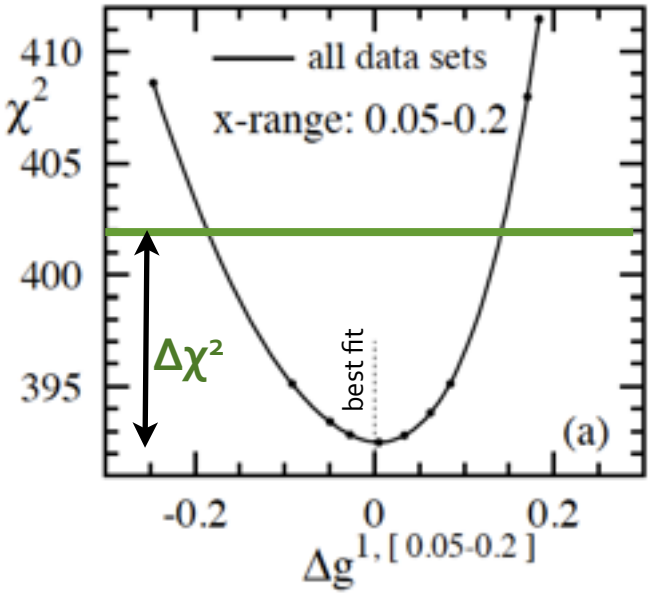

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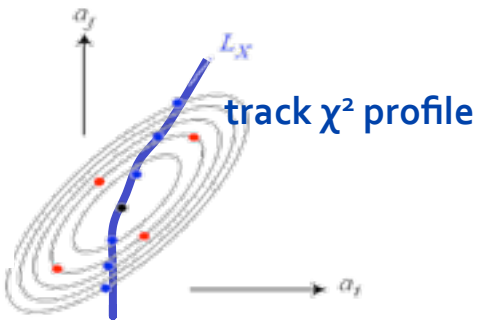

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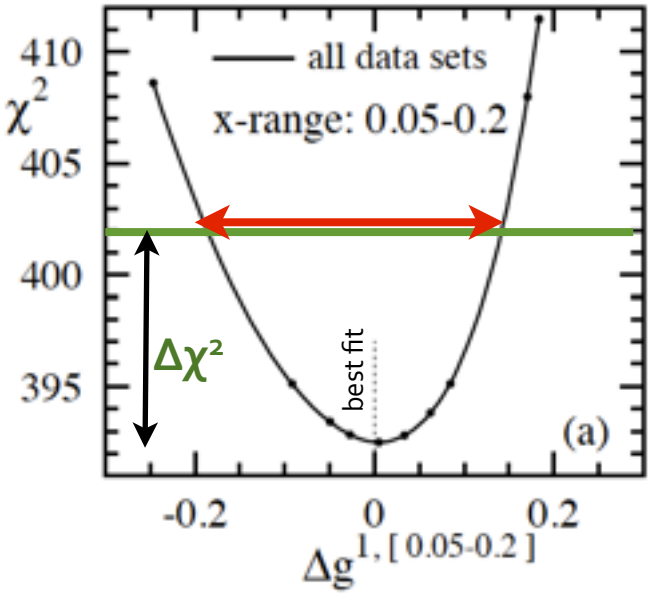

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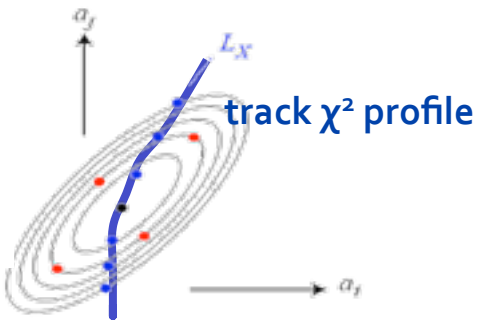

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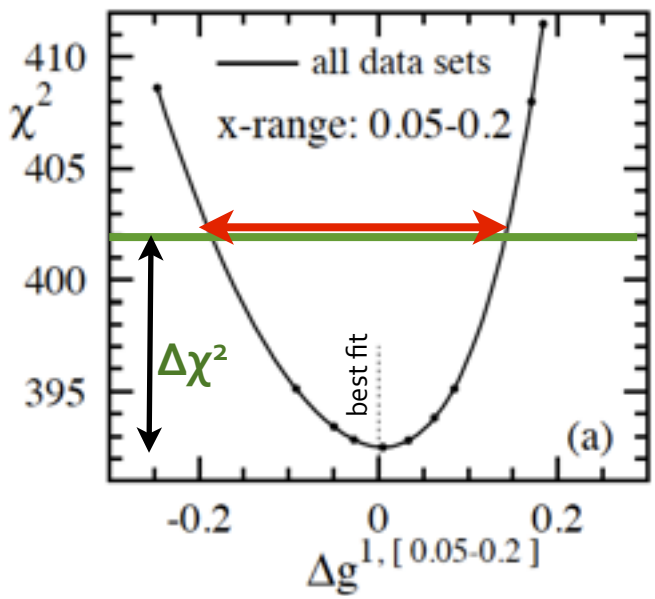

- in this way we find

	$x_{min} = 0$ best fit	$x_{min} = 0.001$ $\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
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Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

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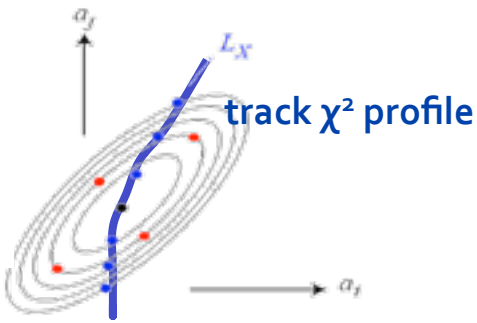

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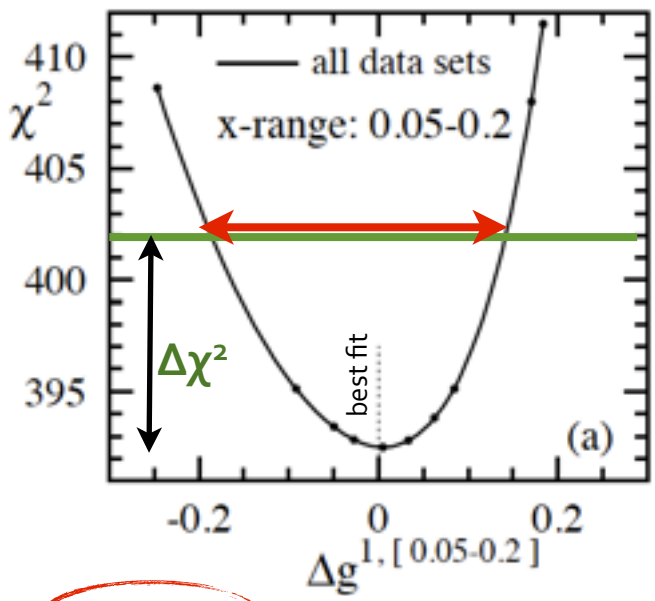

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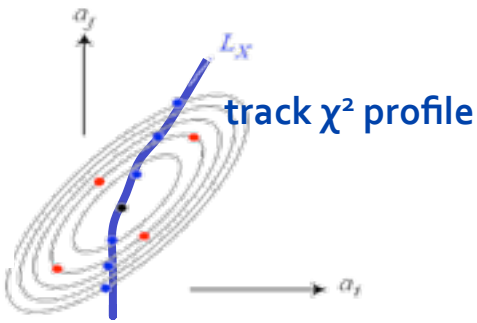

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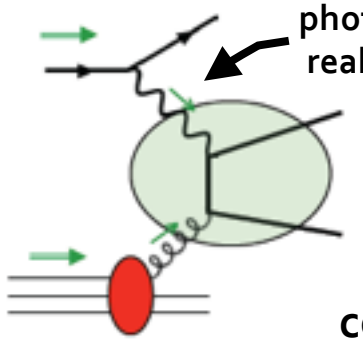
ser"

we do not provide uncertainties for the full 1st moments
due to unmeasured small x region

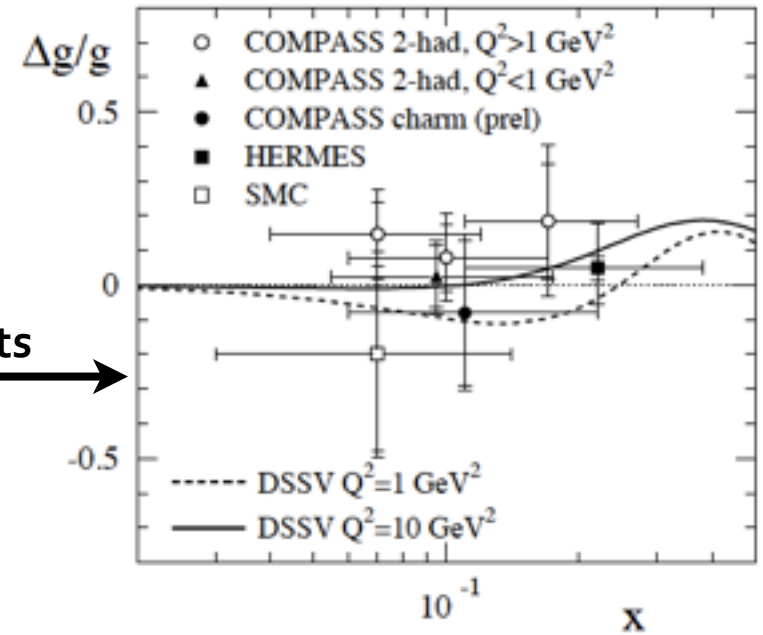
update on Δg from fixed-target experiments

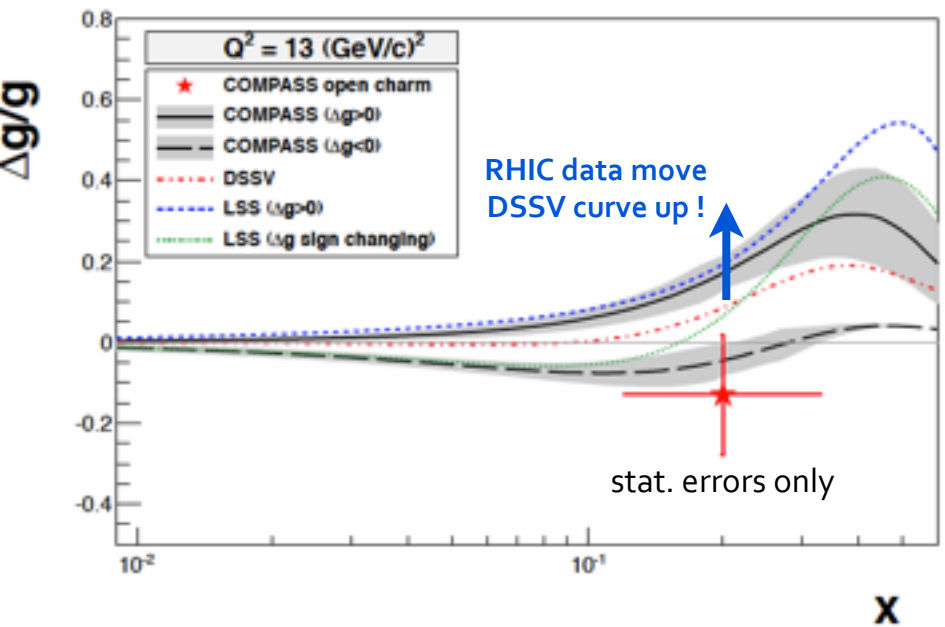
idea: processes with (dominant) contributions from γg-fusion



open charm
hadrons

compilation of existing results





new result

1211.6849

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

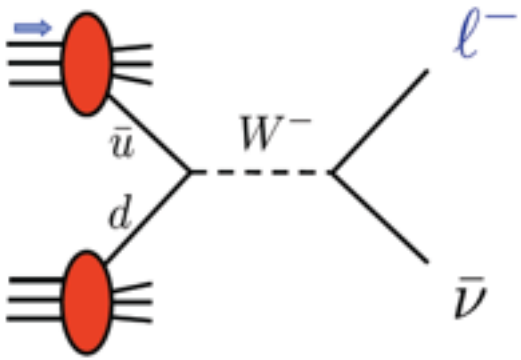
$$\langle x \rangle = 0.2 \quad \langle \mu^2 \rangle = 13\,\mathrm{GeV}^2$$

from some "hybrid MC/NLO" extraction

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

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

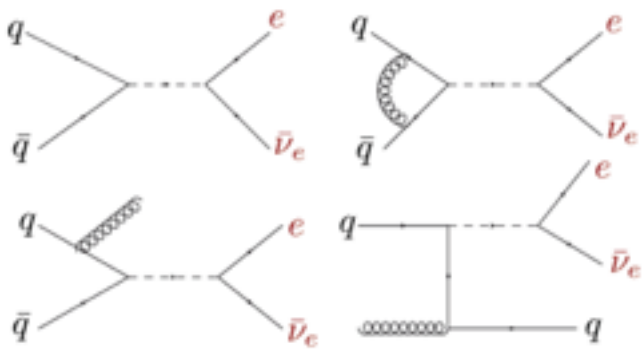
backward lepton rapidity forward lepton rapidity

- ☑ 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 $\langle x_{1,2}\rangle \simeq \frac{M_W}{\sqrt{S}} e^{\pm\eta_l/2} \simeq 0.04 \div 0.4$ **@ $Q=M_W$ evolution!**
- ☑ no access to strangeness (would require W+charm)

NLO calculation of A_L what does it take?

new channels in NLO

$$\Delta\bar{q}\, q \rightarrow e\,\bar{\nu}_e$$
$$\Delta q\, \bar{q} \rightarrow e\,\bar{\nu}_e$$
$$\Delta\bar{q}\, g \rightarrow e\,\bar{\nu}_e\,\bar{q}$$
$$\Delta g\, \bar{q} \rightarrow e\,\bar{\nu}_e\,\bar{q}$$
$$\Delta q\, g \rightarrow e\,\bar{\nu}_e\, g$$
$$\Delta g\, q \rightarrow e\,\bar{\nu}_e\, g$$

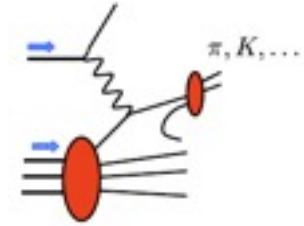


all incorporated in versatile & fast parton-level MC "CHE"

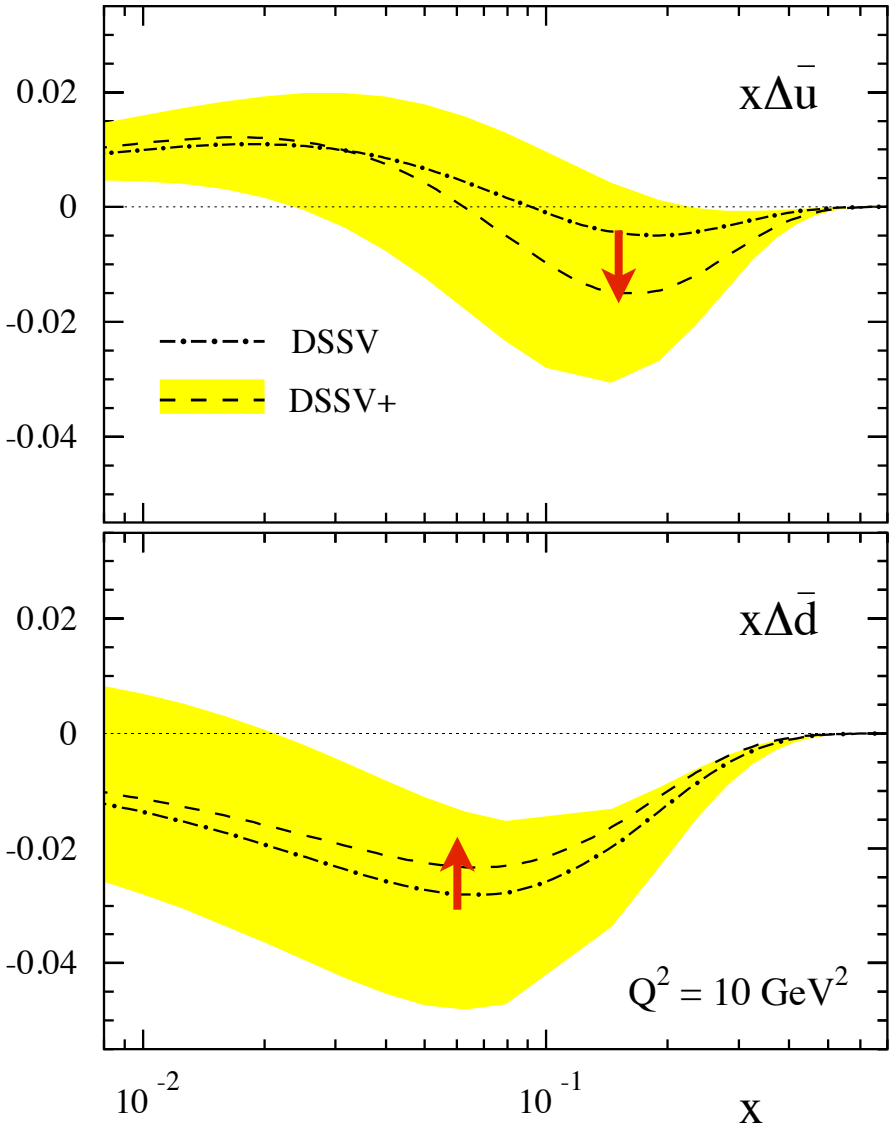
de Florian, Vogelsang, arXiv:1003.4533

- includes "background" contributions from $Z/\gamma \rightarrow l^+l^-$
  - large Z contribution to unpol. W^- cross section; grows with rapidity
  - much less relevant in $d\Delta\sigma$ but "dilutes" A_L
  - veto on lepton pairs?
  - statistics for A_L for identified Z's presumably too small ?!

impact of new SIDIS data on $\Delta\bar{u}$ and $\Delta\bar{d}$



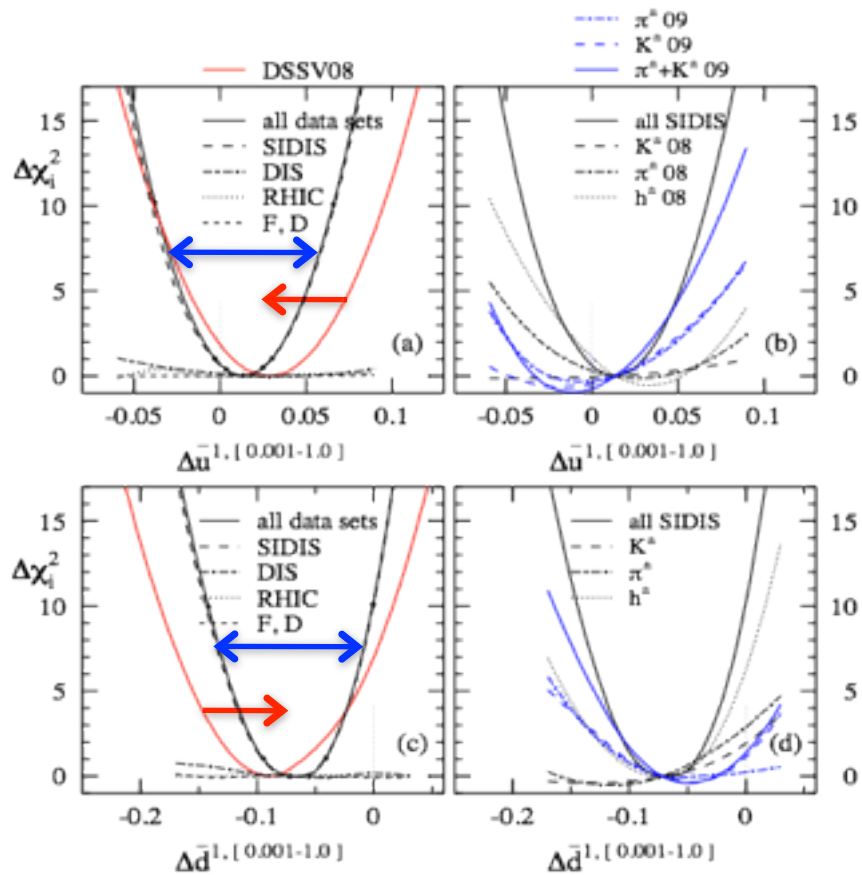
COMPASS data from 2009/10



less net polarization of sea quarks

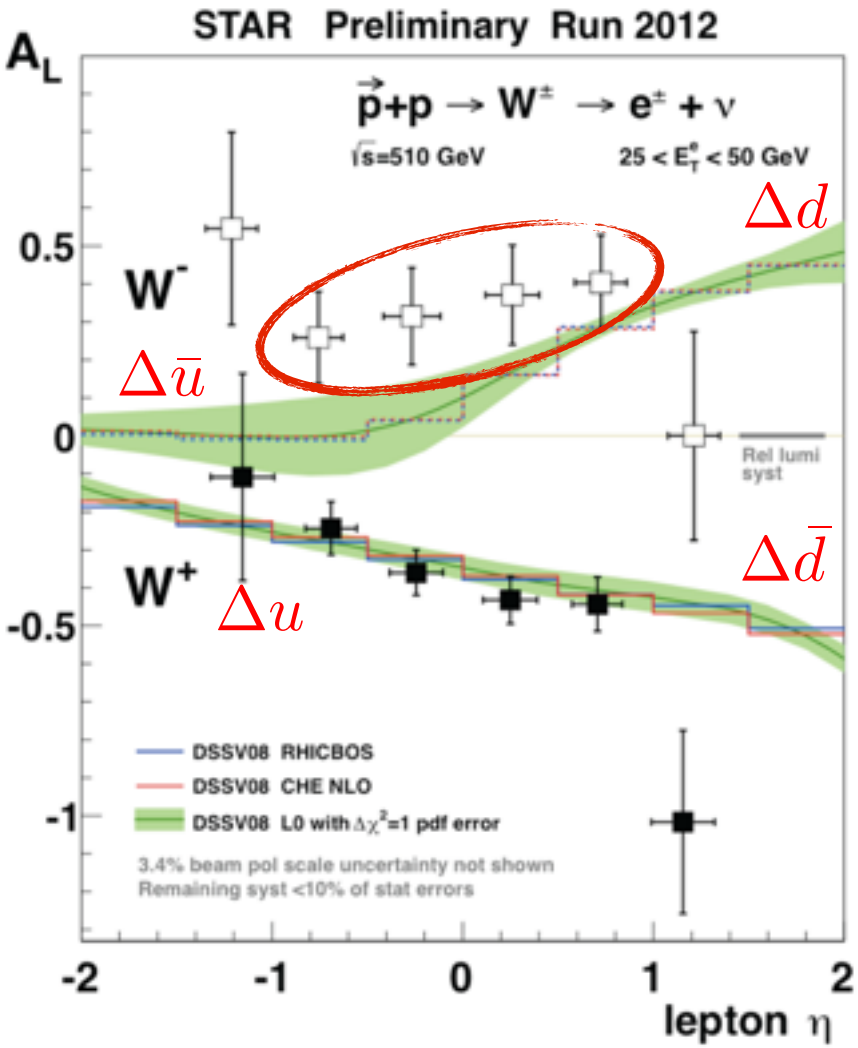
also, smaller $\Delta\bar{u}(x) - \Delta\bar{d}(x)$

and smaller uncertainties



preliminary 2012 STAR W data & impact

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



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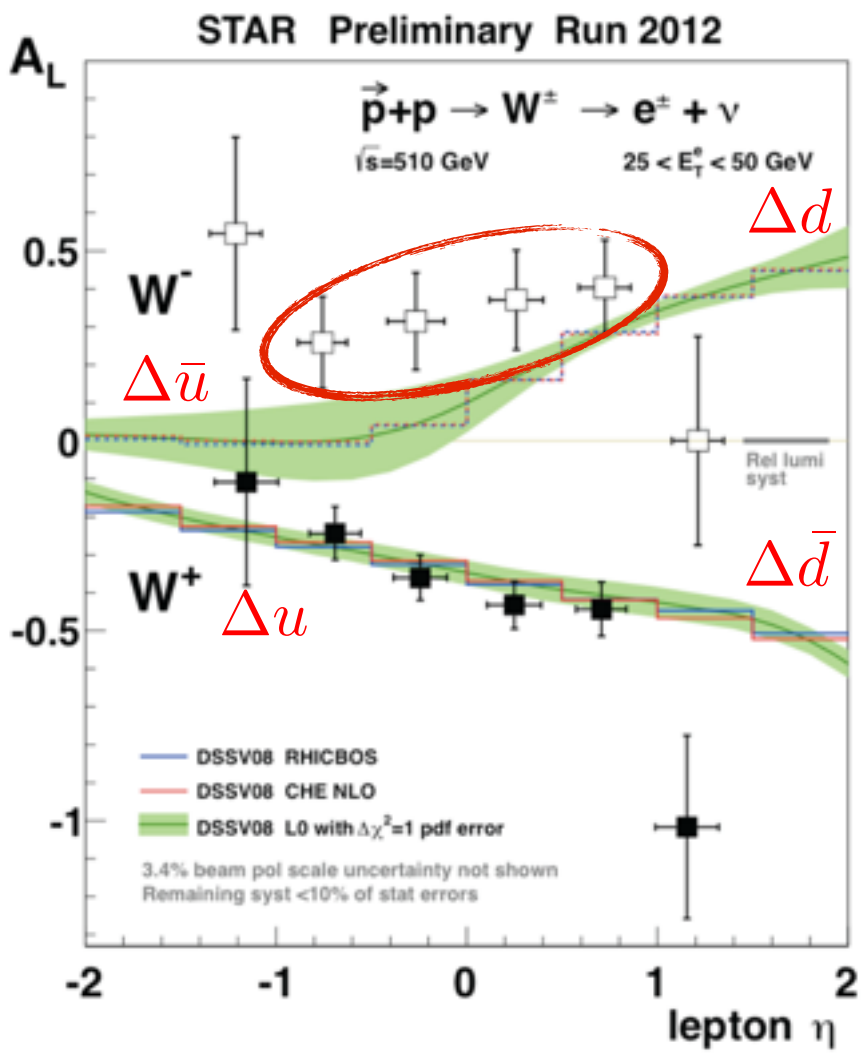
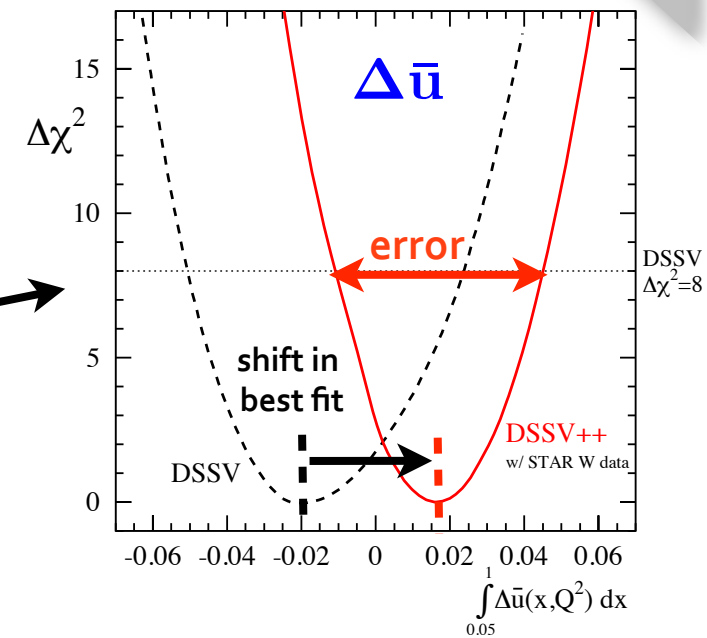
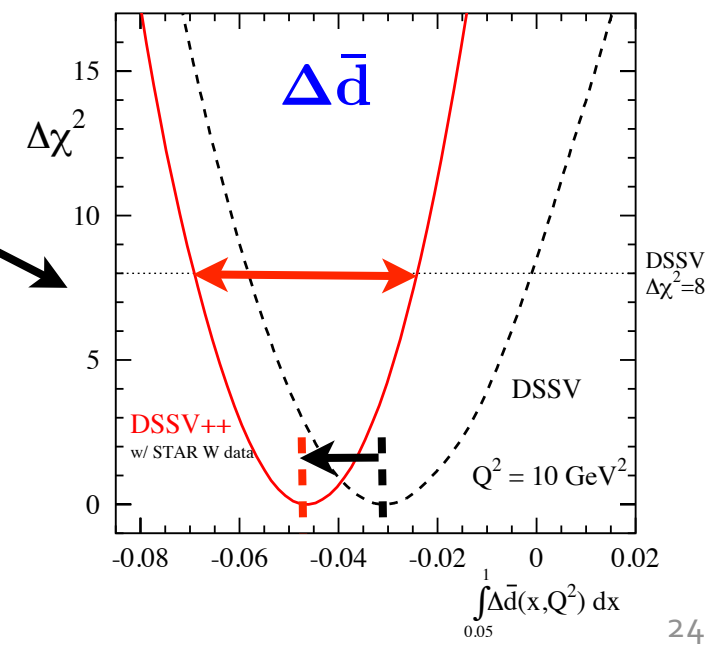
$\Delta\bar{u}$
$\Delta\bar{d}$



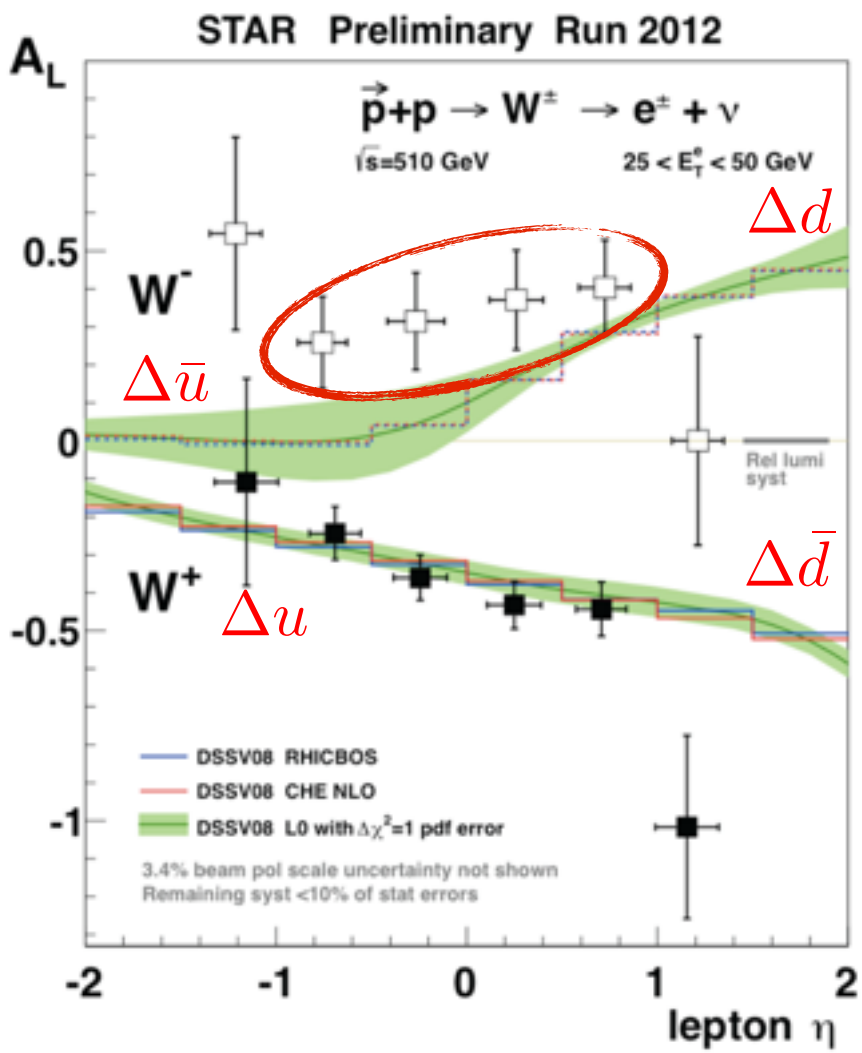
run 12 data already have a significant impact





preliminary 2012 STAR W data & impact

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



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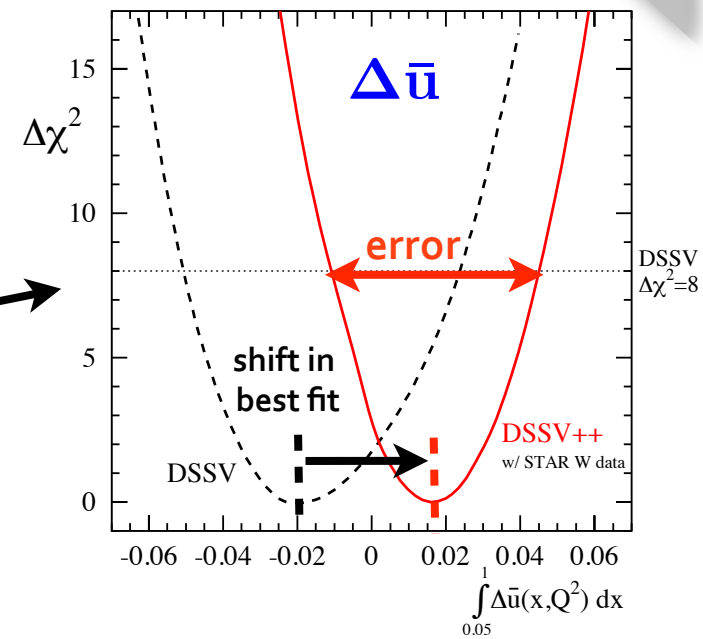
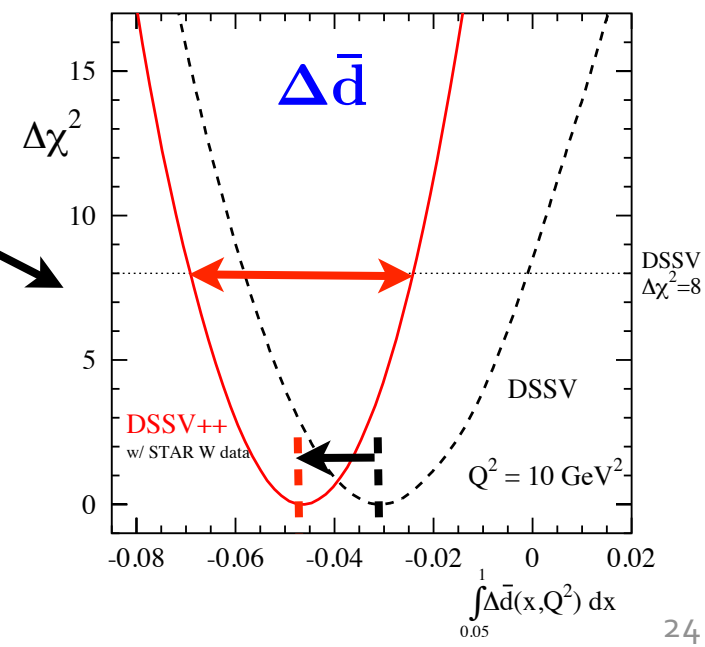




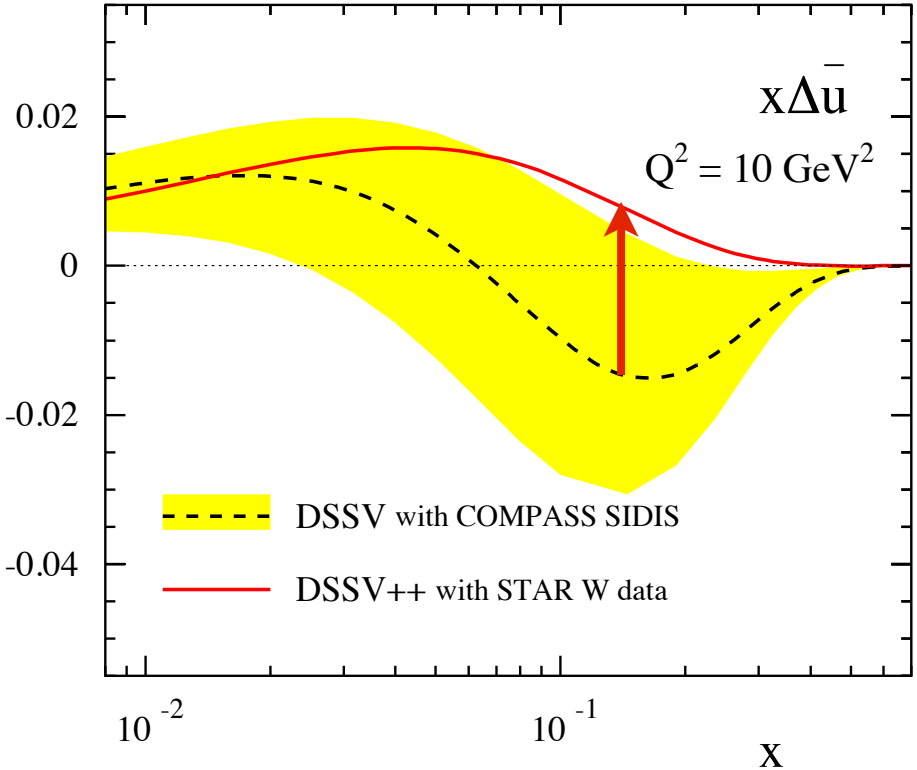
much more to come from RHIC run-13

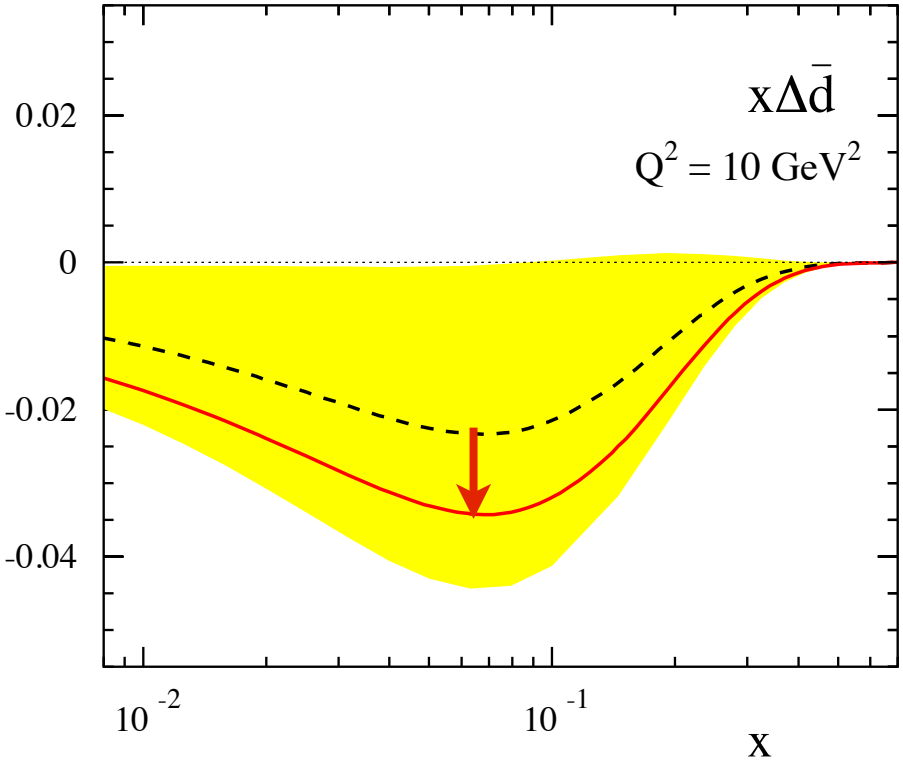
✔ DOE milestone for 2013

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

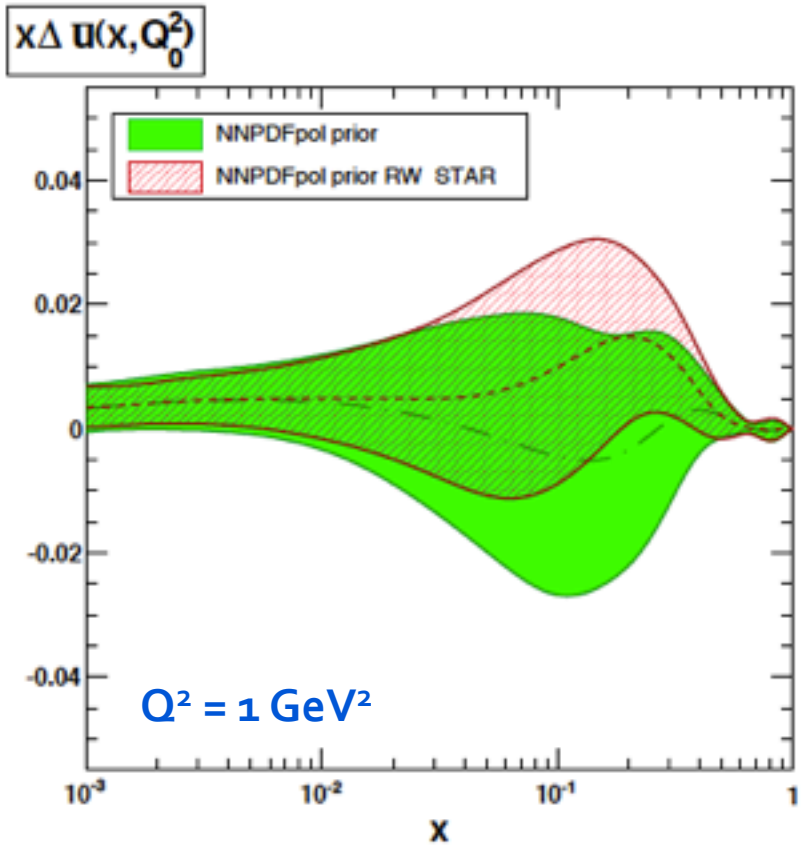
looming (mild ?) tension with SIDIS data

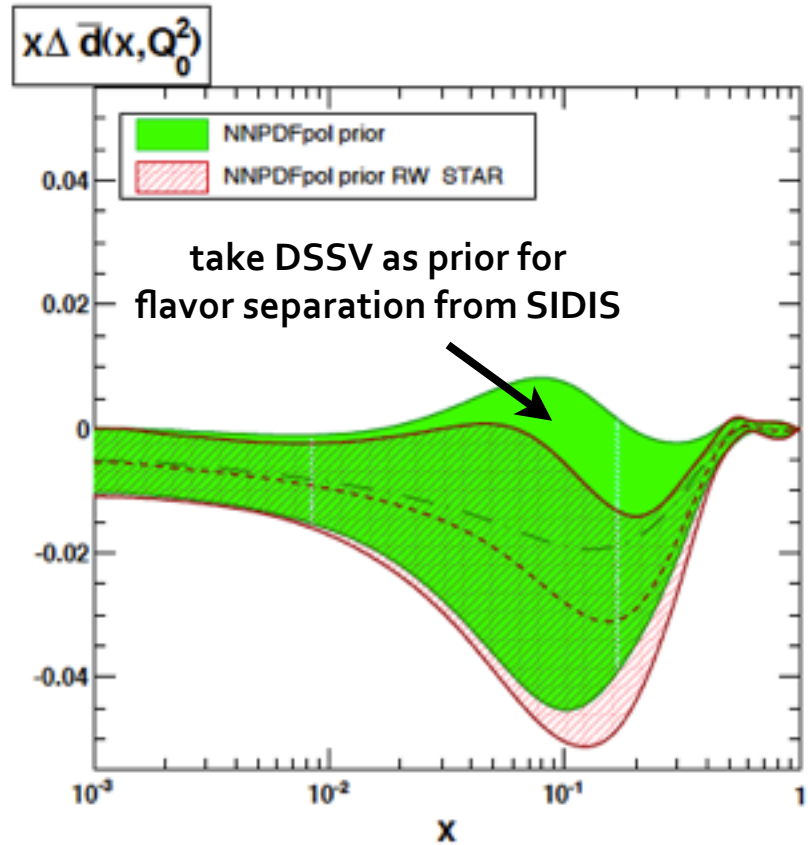
impact of W data in NNPDF analysis

E. Nocera @ DIS'13

use method of **Bayesian reweighting** to incorporate new data (no re-fit needed)

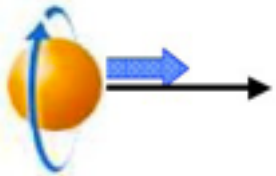
- assign relative weight to each replica set based on χ^2 for new data
- new replicas are no longer equally probable; use to compute new expectation values





observe similar modifications in shape than in DSSV

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 $\quad \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$ $\quad$ gauge invariant

same "number"

Jaffe Manohar $\quad \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + \mathcal{L}_q + \mathcal{L}_g$ $\quad$ "partonic" $A^+=0$ gauge

all quantities depend on scale Q & factorization scheme

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

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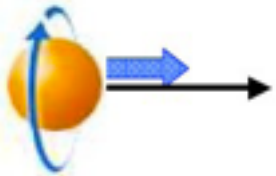

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where do we stand on ΔΣ and Δg ?

- all fits find $\Delta\Sigma \approx 0.25$
  beware of LARGE small x & 3F-D uncertainties
- Δg is anybody's guess (apart from x=0.05-0.2 region)
- even non-singlet BJ sum has large errors
  $\Delta u + \Delta\bar{u} - (\Delta d + \Delta\bar{d}) = 1.19 \pm 0.22$
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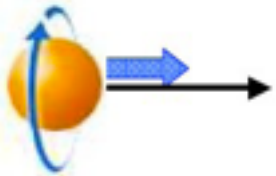

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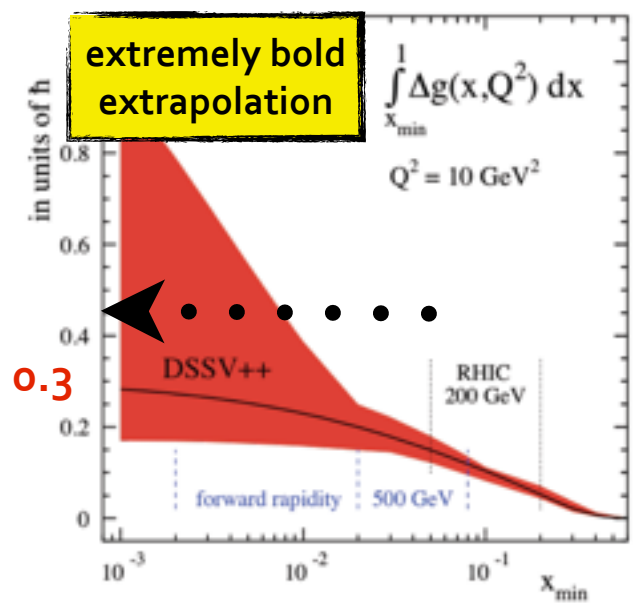

little room for OAM ?

3

future avenues at RHIC

more on Δg from single-inclusive probes

Q-1: can we further shrink the errors in the RHIC x-region?

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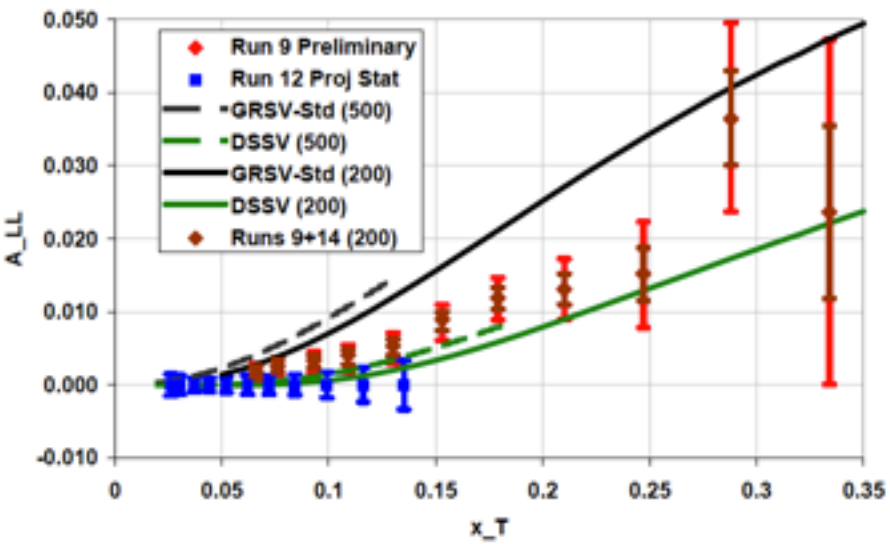
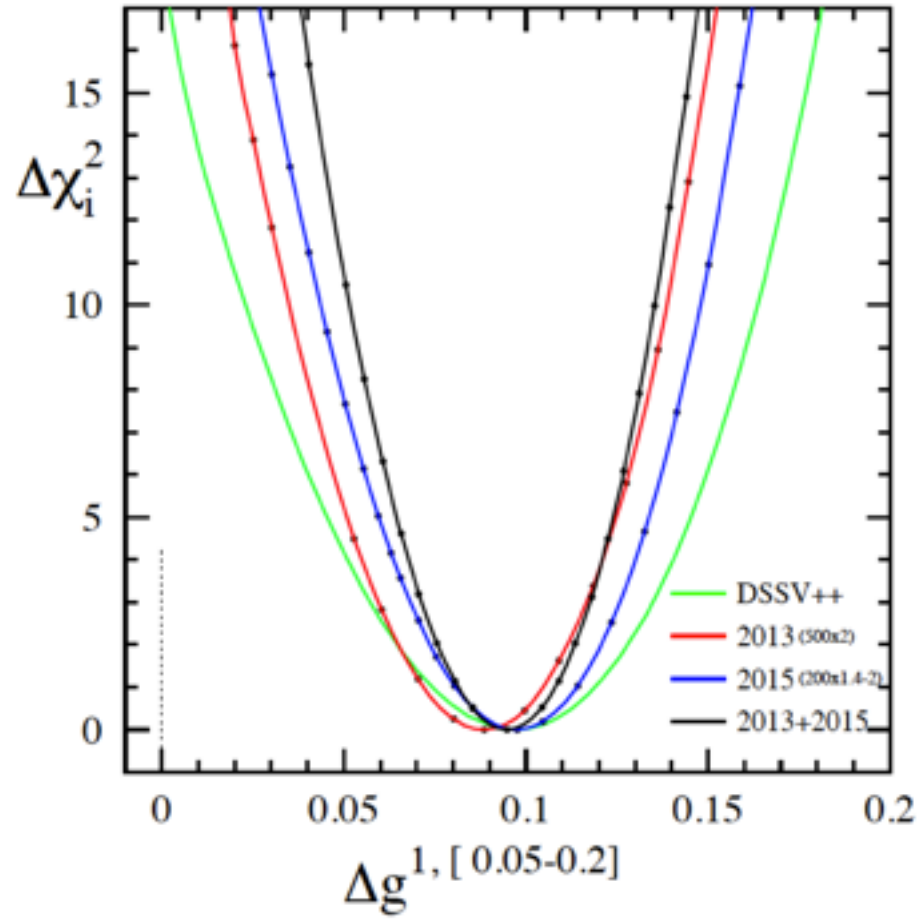
projection for STAR mid rapidity jets

taken from STAR BUP



impact study in DSSV framework



expect to reduce uncertainties by about a factor of 2 by end of run-15

more on Δg from single-inclusive probes

Q-2: can we further extend the x-reach towards smaller values?

more on Δg from single-inclusive probes

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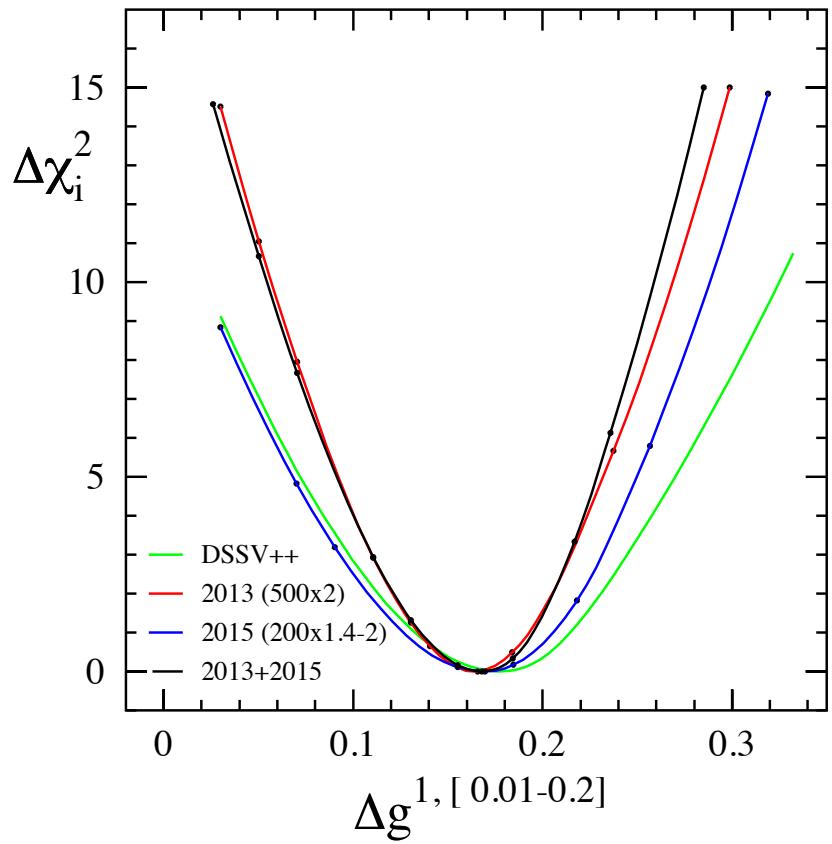
expect some impact from 500 GeV mid rapidity jet data



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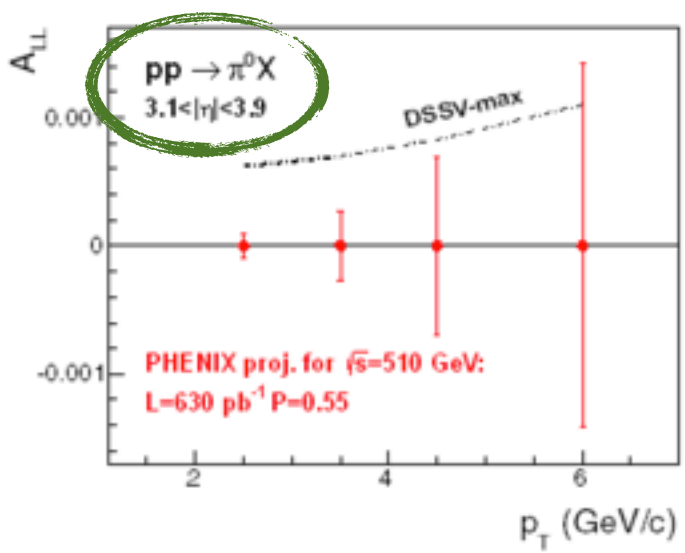
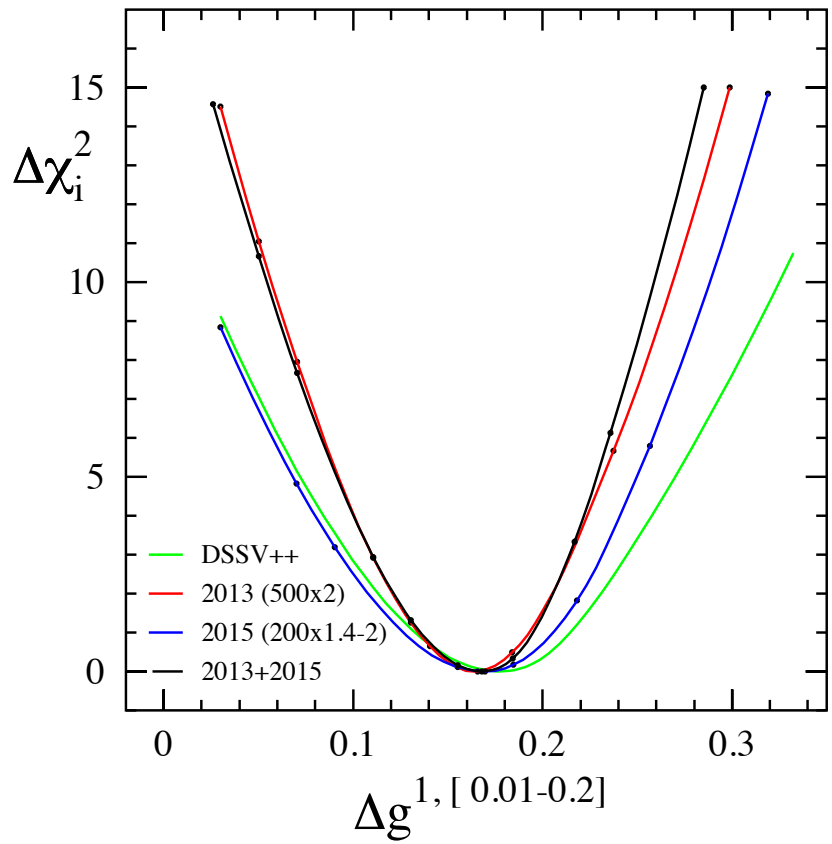


expectations from PHENIX



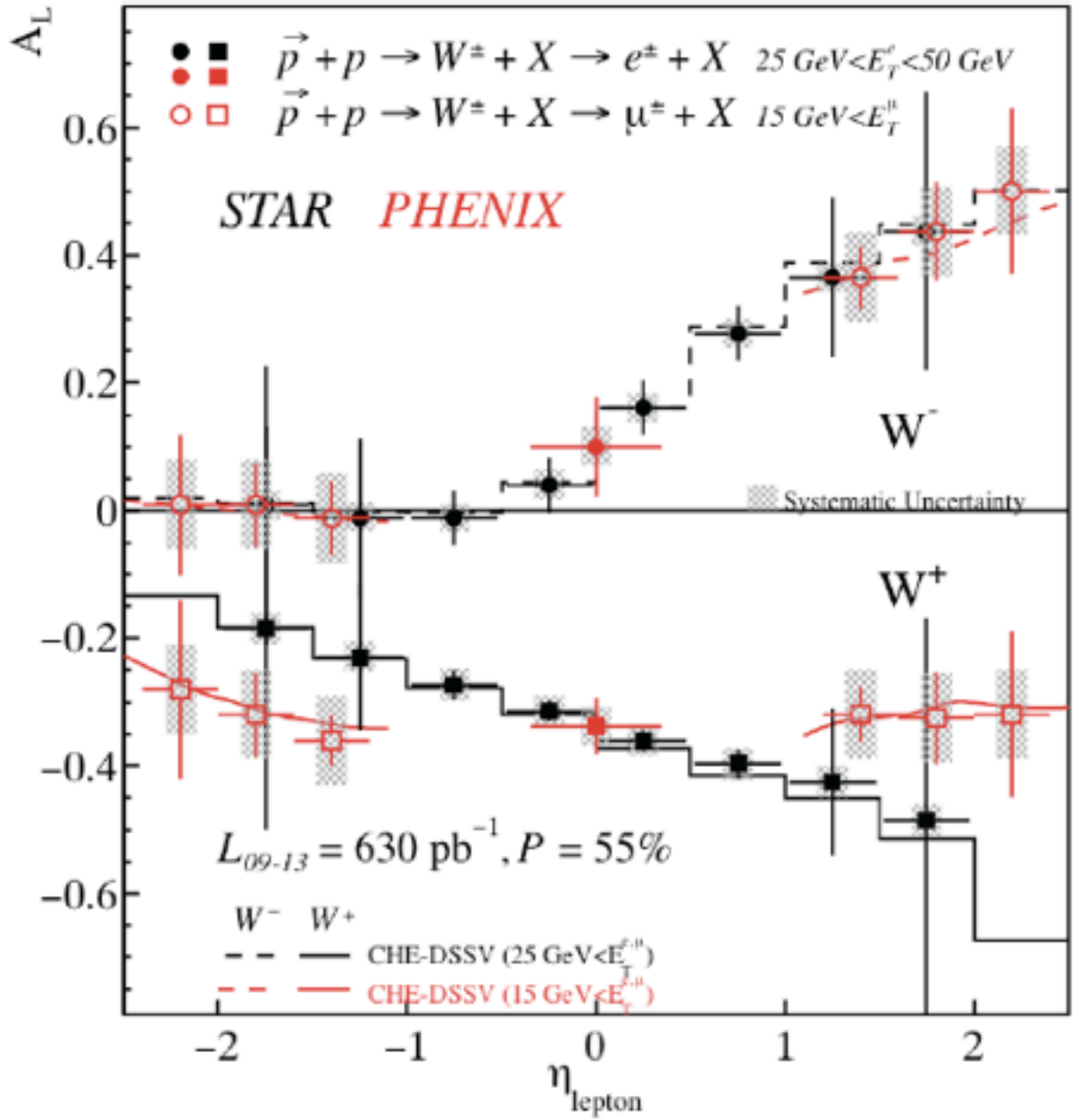
better should be **data at forward rapidities**:

- qg scattering relevant
- smaller x probed

no simulations with pseudo-data yet

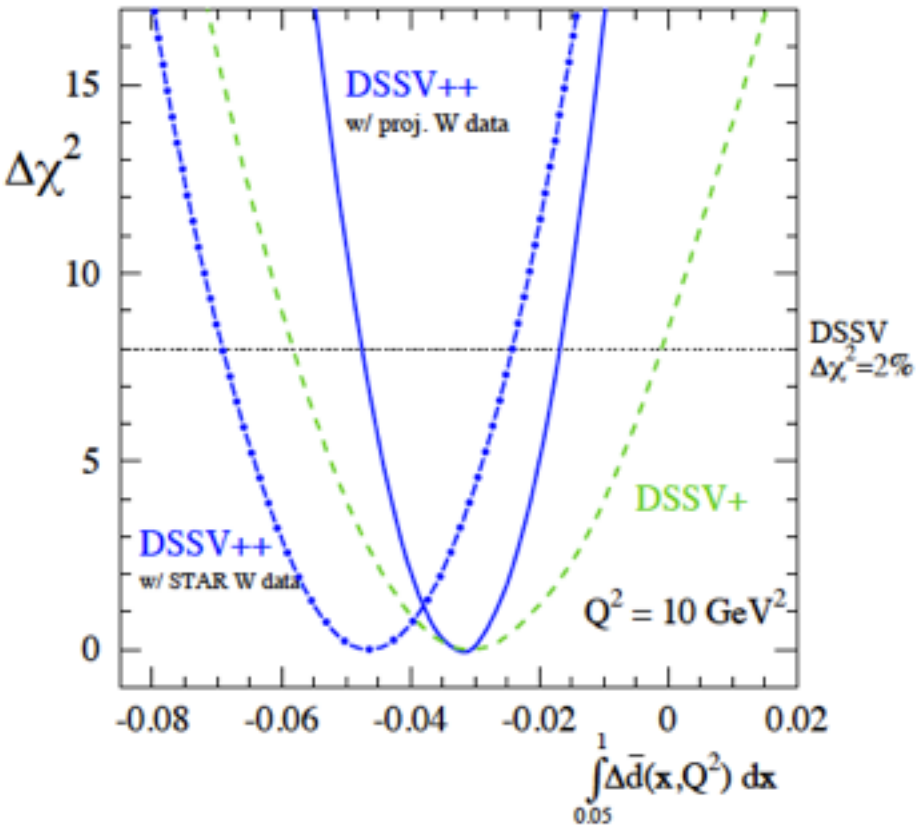
what to expect from 2013 W data ?

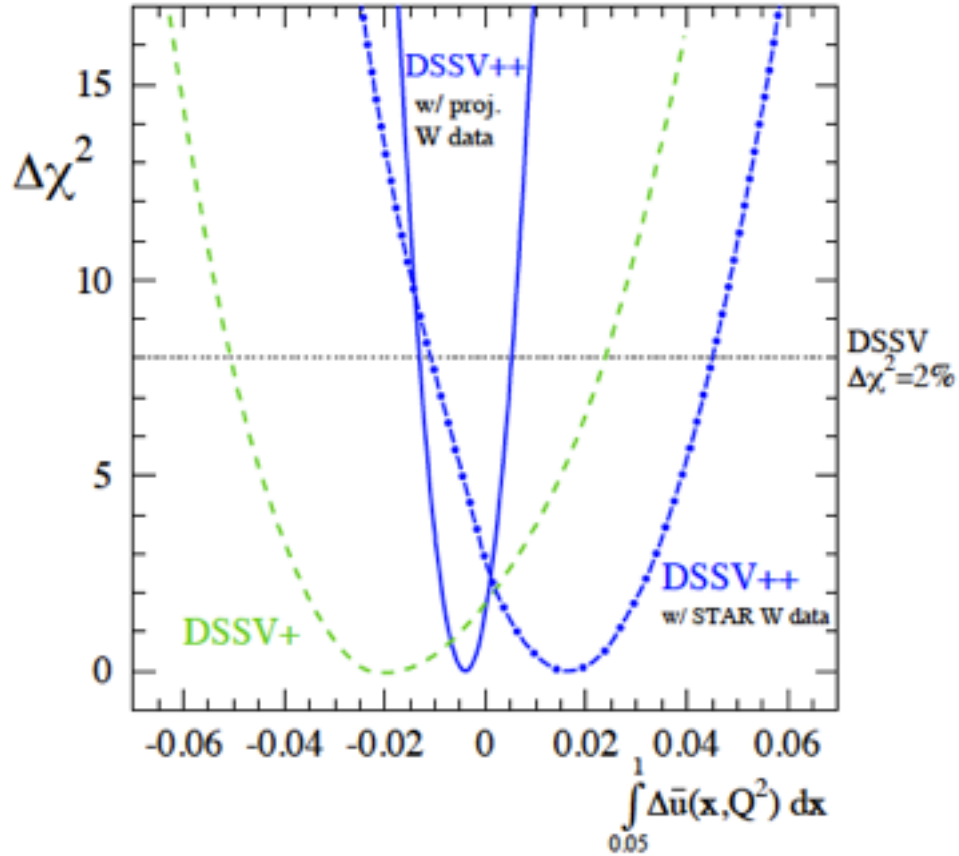
projections



expected impact in probed x-region

- more than a factor of 2 reduction in uncertainties

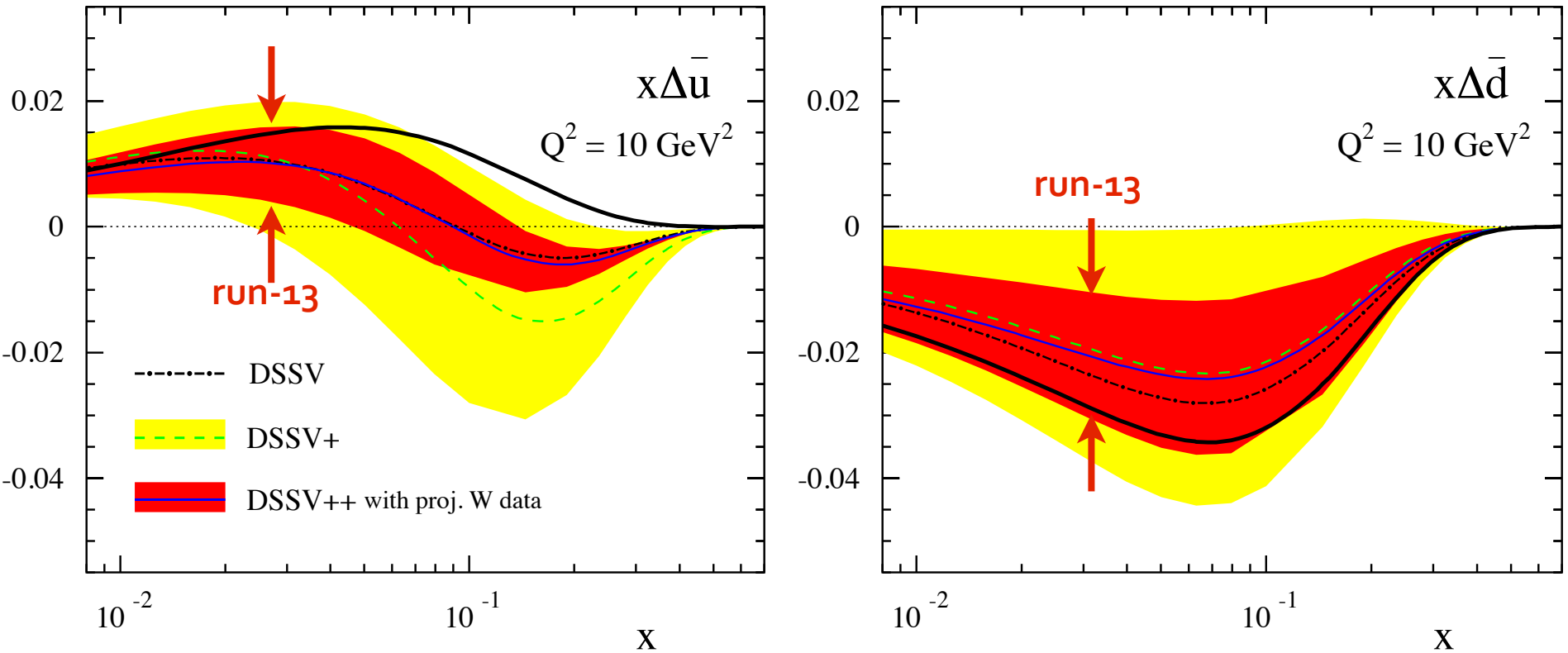




compatibility with SIDIS data can be tested

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

preliminary study!

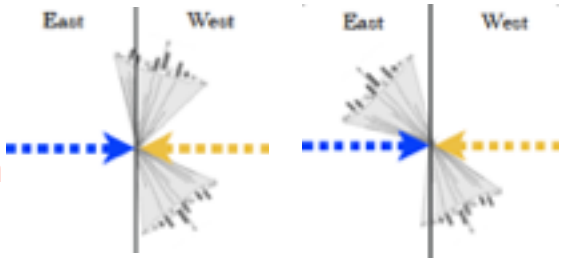


compatibility with SIDIS data can be tested

DSSV – readiness for other new observables

- **general policy:** NLO must be known for an observable to be included in fit
- use of **improved Mellin technique** allows us to included *any* observable consistently at NLO accuracy without the usual cheating ("K-factors", etc)

promising future avenues at RHIC (doable ?) to further our knowledge of helicity PDFs



focus on

- **particle correlations**, like di-jets
  better control on probed x-range; **expect data soon**

Δg

- **rare probes** (prompt photons, heavy flavors) **NEEDS L > 1-2 fb^{-1}**
  probe *different* aspects of hard scattering dynamics (**test of factorization/universality**)

Δg

- **polarized Λ baryon** production
  perhaps the only probe of strangeness at RHIC; STAR has some results already

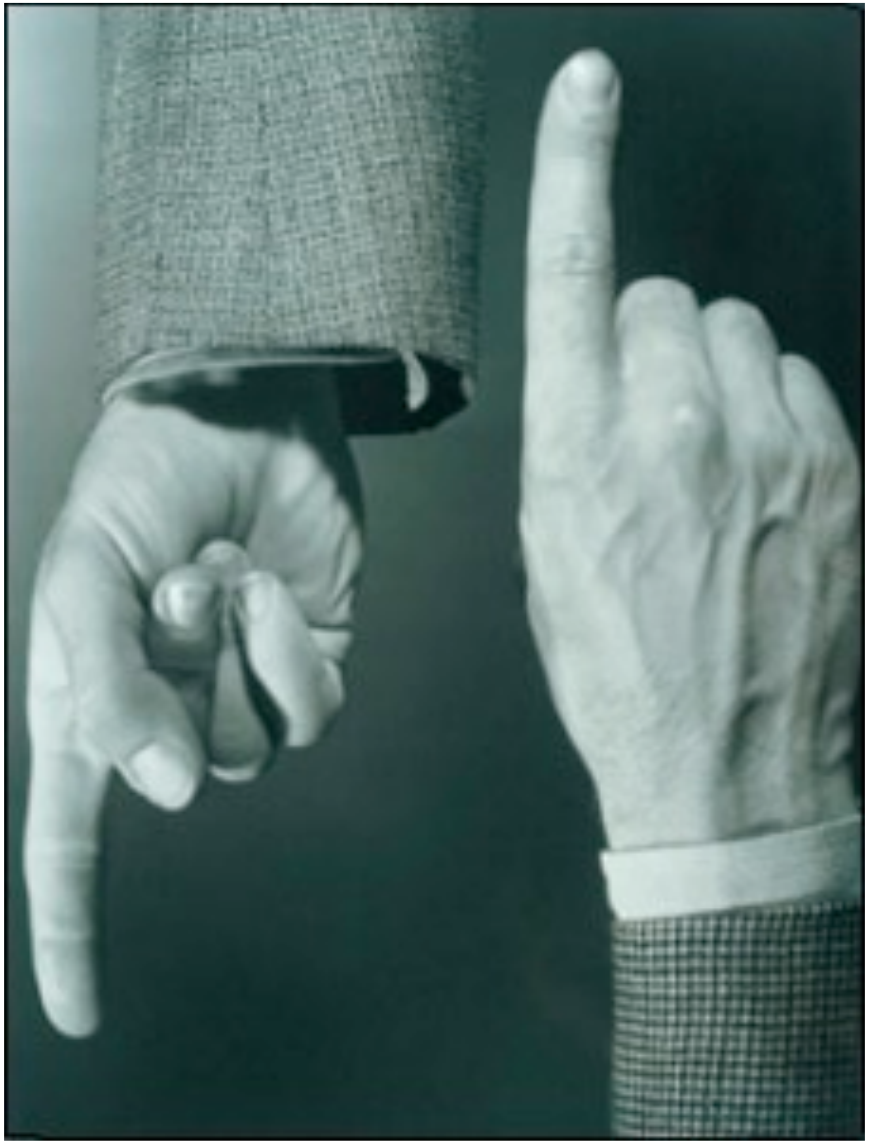
Δs

4

transverse spin (very briefly)

--> Mauro's & Yuri's talks earlier today

4



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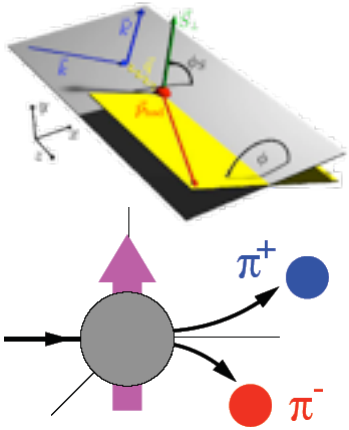
main objective

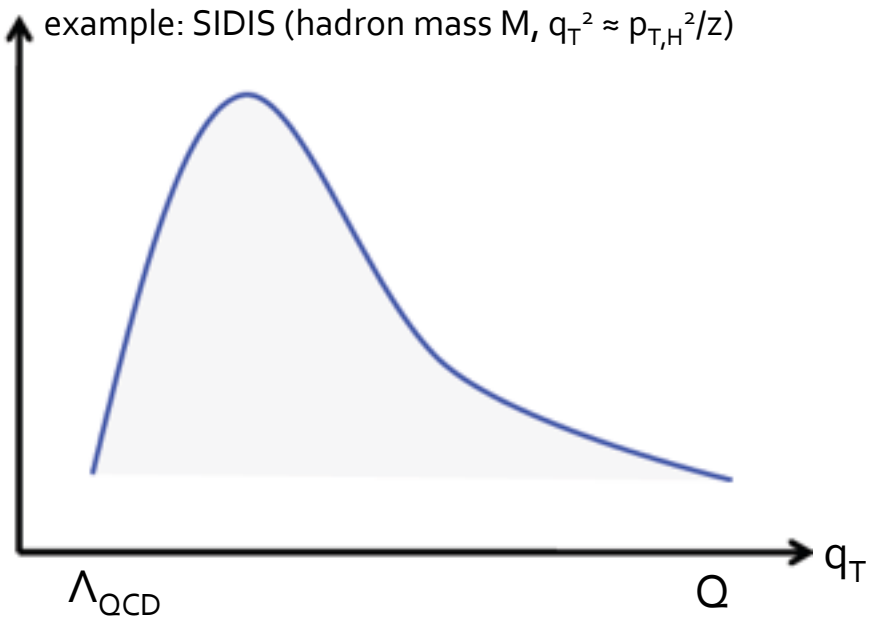
basic observables are azimuthal modulations/asymmetries of the produced hadrons



- **SIDIS A_{UT}, …** : two scale process with large Q^2 and small p_T
- **pp A_N**: one scale process depending on p_T

large asymmetries have been observed throughout

two mechanisms have been conceived to provide a theoretical framework



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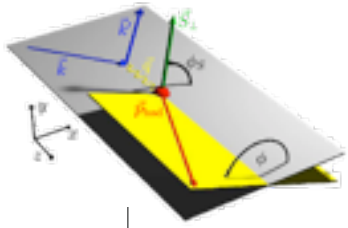

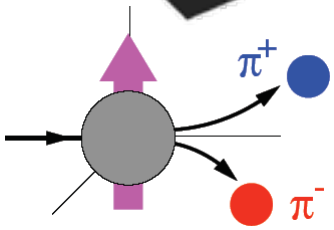

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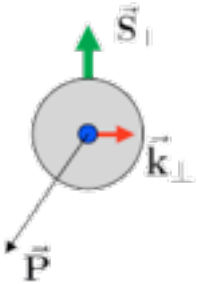
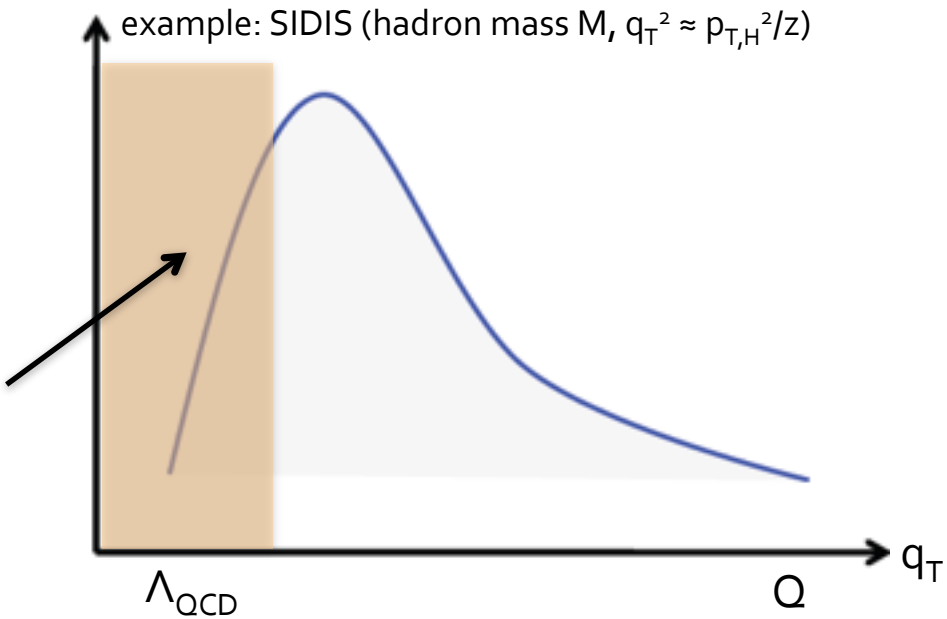
$$\Lambda_{QCD} \lesssim q_T \ll Q$$

TMD "factorization"

Sivers effect





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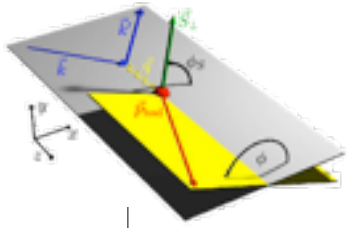

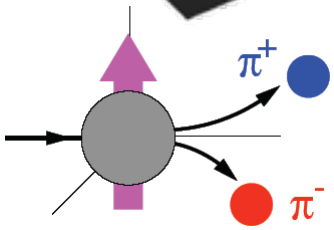

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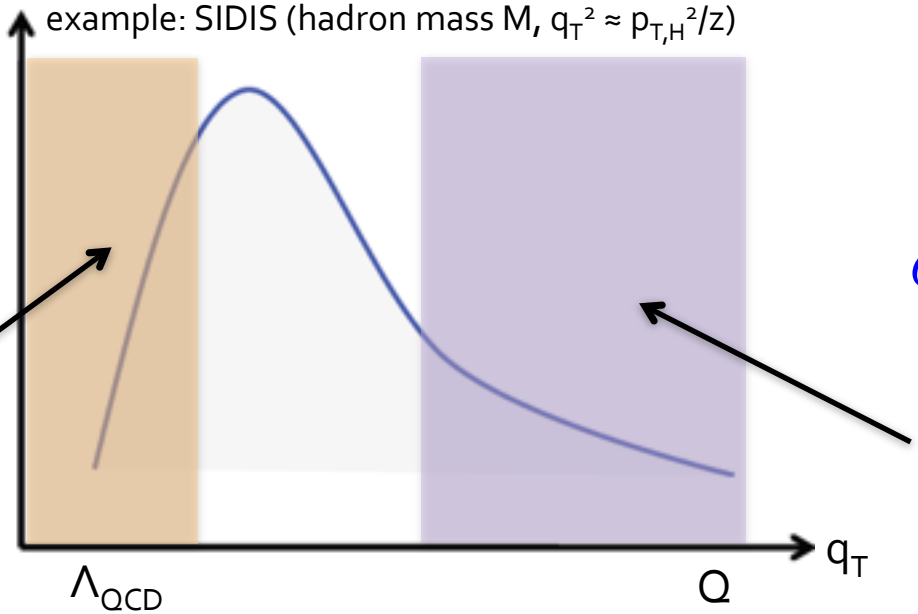

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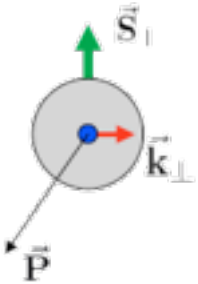

$Q, Q_T \gg \Lambda_{QCD}$

collinear twist-3 approach

Efremov, Teryaev; Qiu, Sterman

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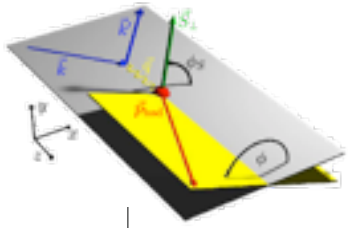

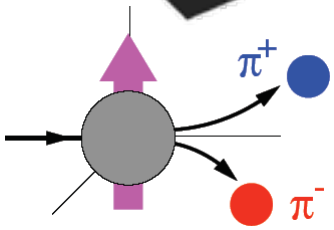

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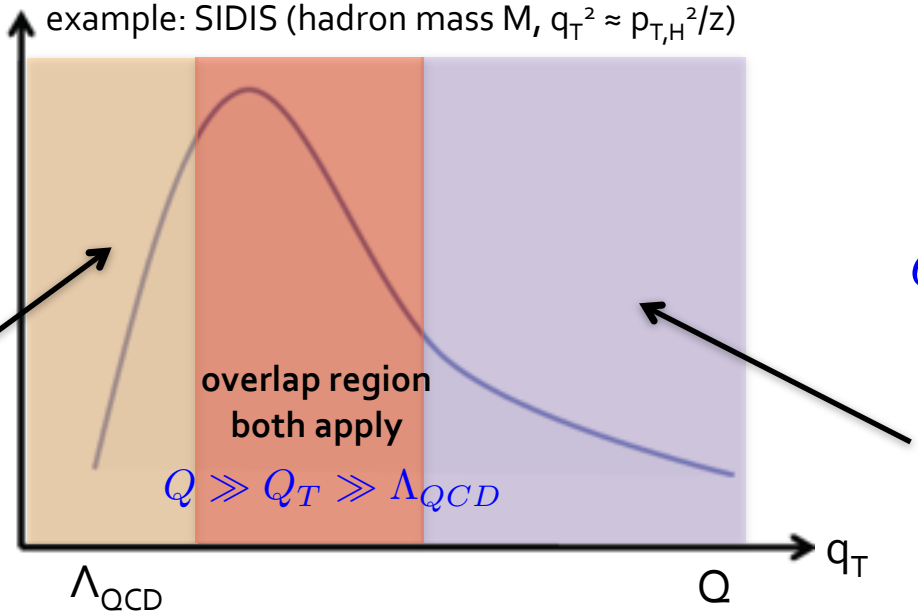

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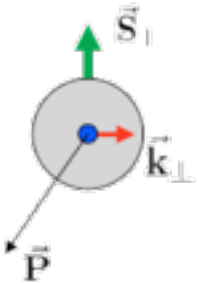

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Efremov, Teryaev; Qiu, Sterman

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- TMD framework encodes physics for small p_T ($\ll Q^2$) [or p_T differences]
- entire zoo of TMD parton distribution and fragmentation functions

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

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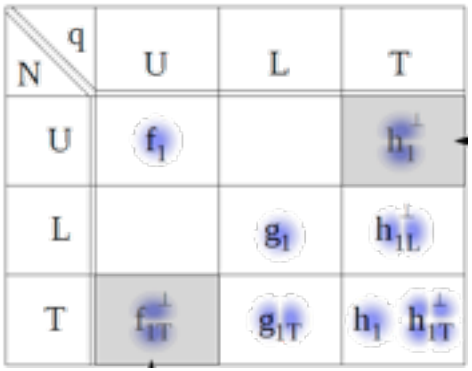

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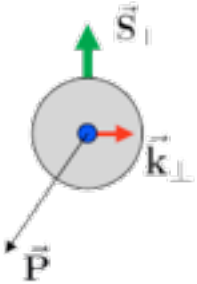
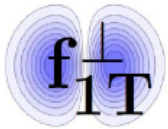


correlation of transverse spin of proton with k_T of an unpolarized quark

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



Sivers effect

- clearly established for quarks in SIDIS **HERMES, COMPASS**
- **non universal function (factorization in pp processes ??)**

Rogers, Mulders; Rogers; ....

access to 3D imaging in momentum space

non-trivial role of Wilson lines

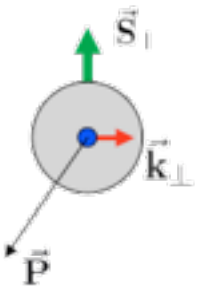
role of spin-orbit correlations & OAM

physics of TMDs

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

- TMD framework encodes physics for small p_T (<< Q^2) [or p_T differences]
- entire zoo of TMD parton distribution and fragmentation functions

Sivers effect



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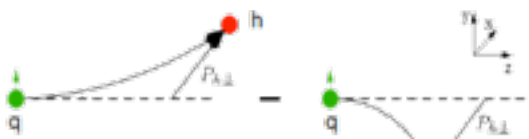
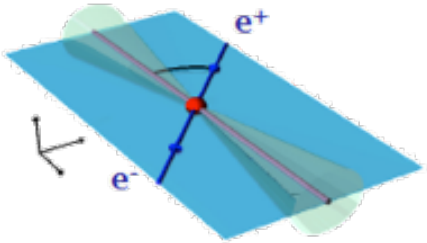
Collins effect



$$s_q \cdot (p_q \times P_T^h)$$

correlation of transverse spin of fragmenting quark and hadron p_T

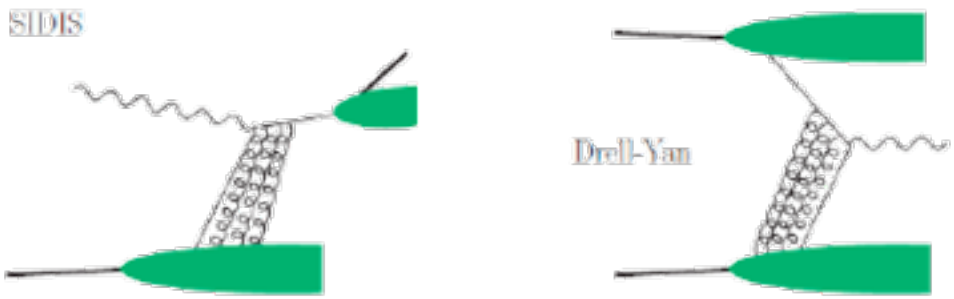
- clearly established in SIDIS HERMES, COMPASS
- Collins function extracted in e^+e^- BELLE, BABAR
- **universal function**



$$e^+e^- \to \pi^+_{jet1}\, \pi^-_{jet2}\, X$$

Sivers function: sign and sign mismatches

- **profound consequence of gauge invariance:** colored partons "surrounded" by gluons (technically realized by Wilson lines)



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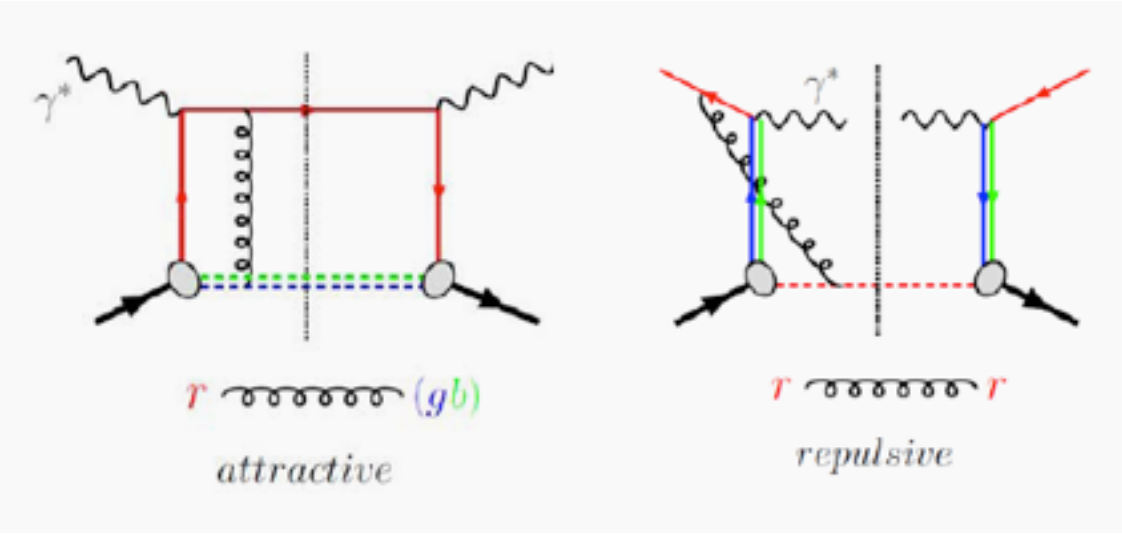

$$f_{1T}^{\perp \mathrm{SIDIS}} = -f_{1T}^{\perp \mathrm{DY}}$$

Sivers fct. has **opposite sign** when gluons couple "after" quark scatters (SIDIS) or "before" quark annihilates (DY) (and would be zero without gluons)

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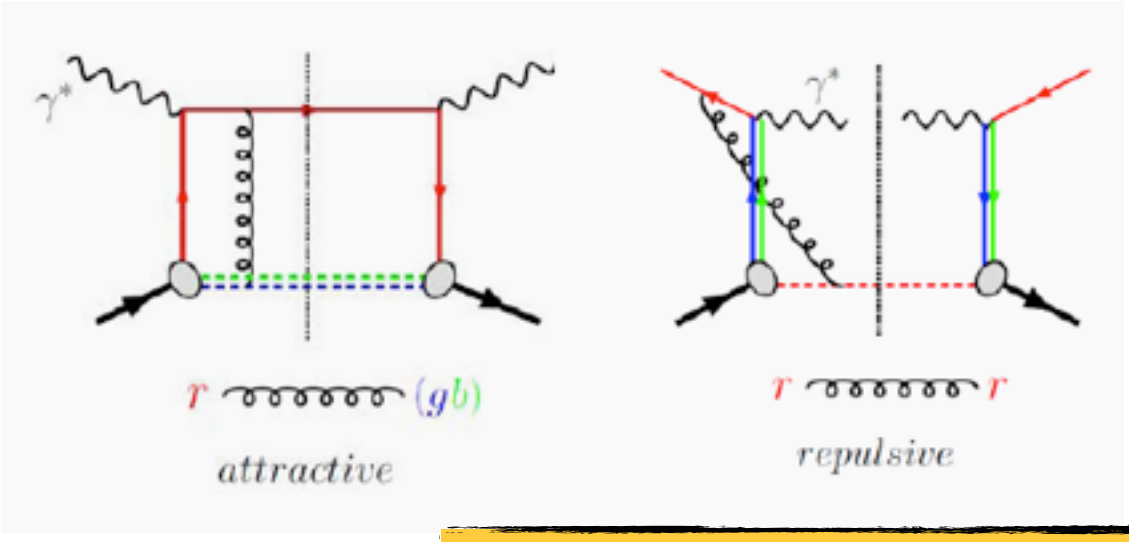

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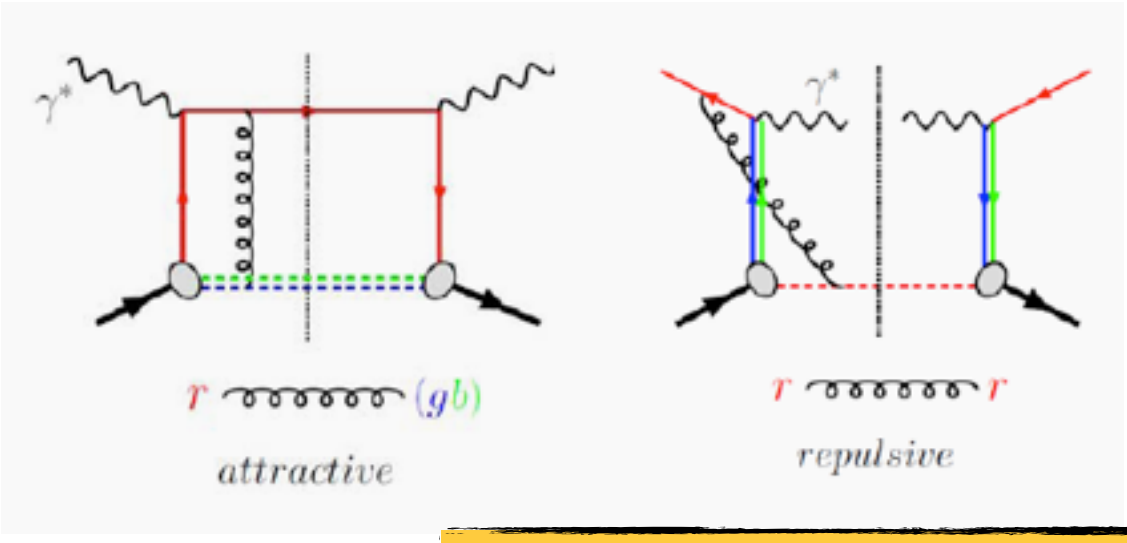

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still awaits experimental verification

- **1st k_T moment of Sivers fct and twist-3 analogue related at operator level**

Boer, Mulders, Pijlman;
Ji, Qiu, Vogelsang, Yuan

$$g_s T_{q,F}(x,x) = -\int d^2k_T \frac{|k_T|^2}{M} f_{1T}^{\perp}(x,k_T^2)|_{\mathrm{SIDIS}}$$

both sides have been extracted from data

find: similar magnitude ✓ but wrong sign ✖

Kang, Qiu, Vogelsang, Yuan; ...

who ordered that?

progress on theoretical calculations

- **energy dependence of TMDs governed by CSS-type evolution** Collins, Soper, Sterman
  two-scale problem -> need to resum large double-logs

- **recently incorporated in TMD analyses** Idilbi, Ji, Ma, Yuan; Kang, Xiao, Yuan; Collins; Aybat, Collins, Rogers, Qiu; Aybat, Prokudin, Rogers; Boer; Sun, Yuan; ....

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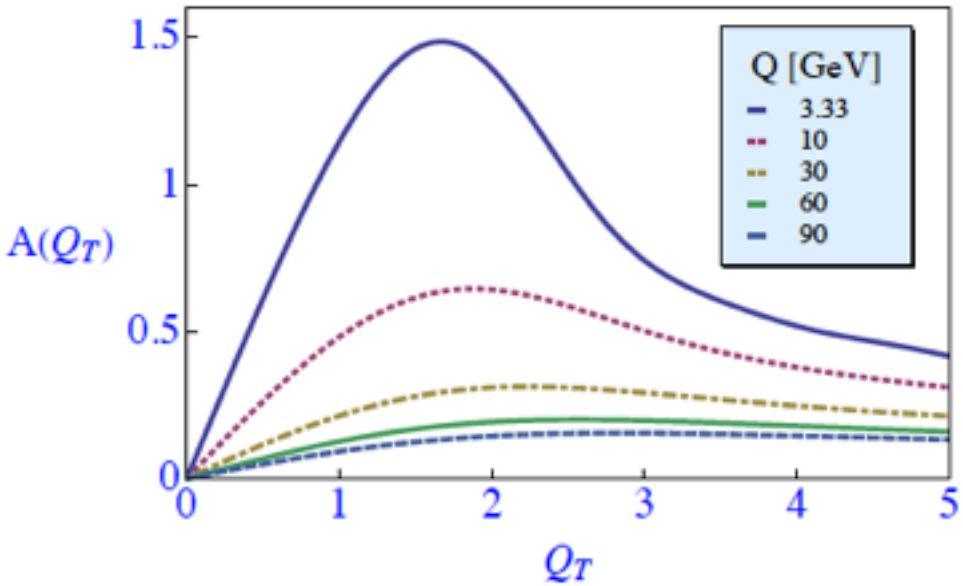
example from Boer, arXiv:1304.5387



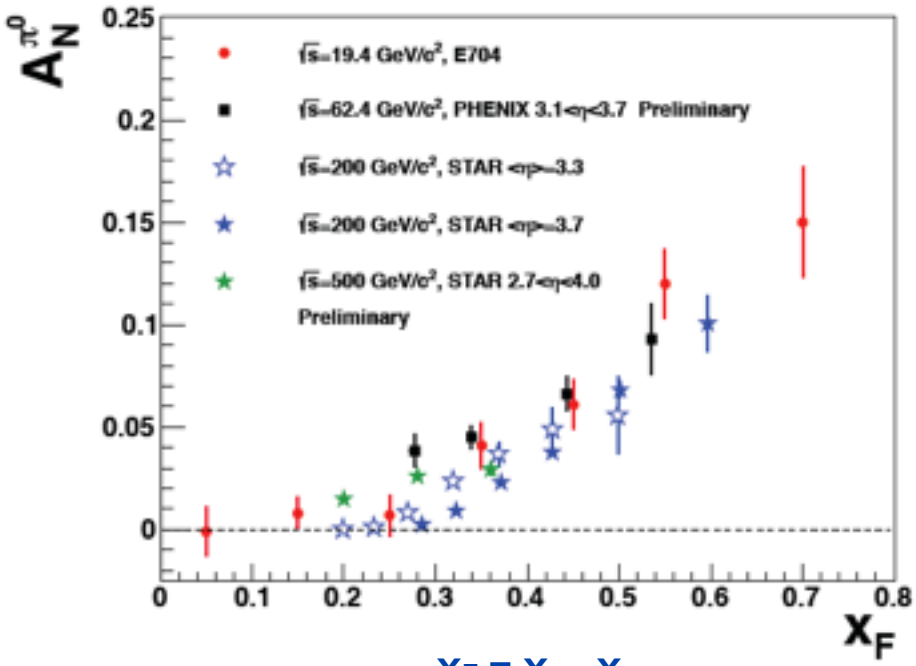
find:

- amount of suppression from evolution very much depends on details of setup
  [choice of NP Sudakov term, ...]

- important to understand for future phenomenology:
  Drell Yan; SIDIS at large Q^2 @ eRHIC; ...

devil is still in the details

RHIC's contributions



$x_F = x_1 - x_2$

- sizable A_N largely independent of energy
- relatively large p_T scale:
  twist-3 formalism should be applicable
  [A_N nevertheless analyzed with TMDs;
  issues with factorization in pp !]
- various mechanisms can contribute:
  Sivers-type, Collins-type

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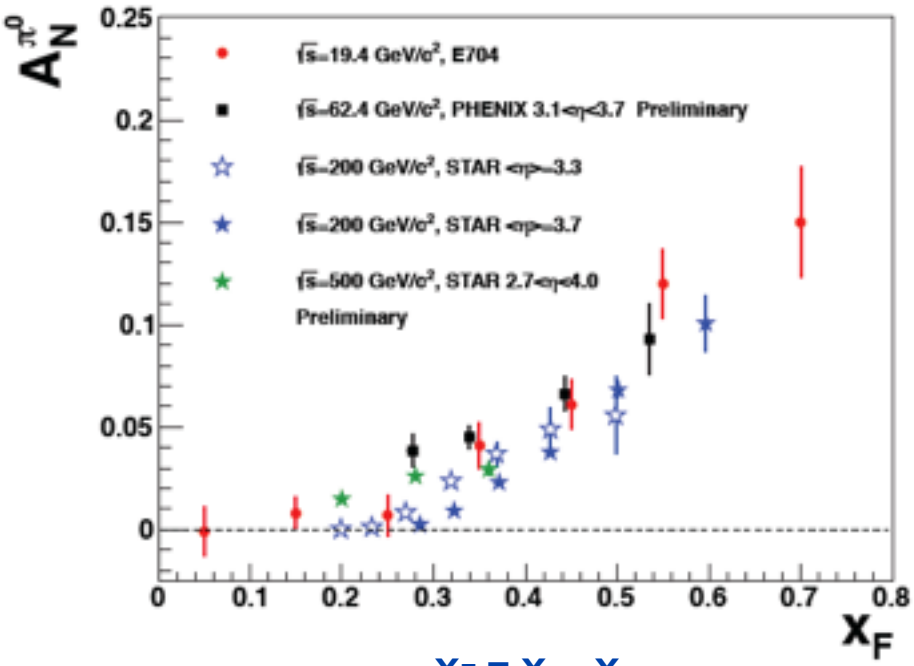

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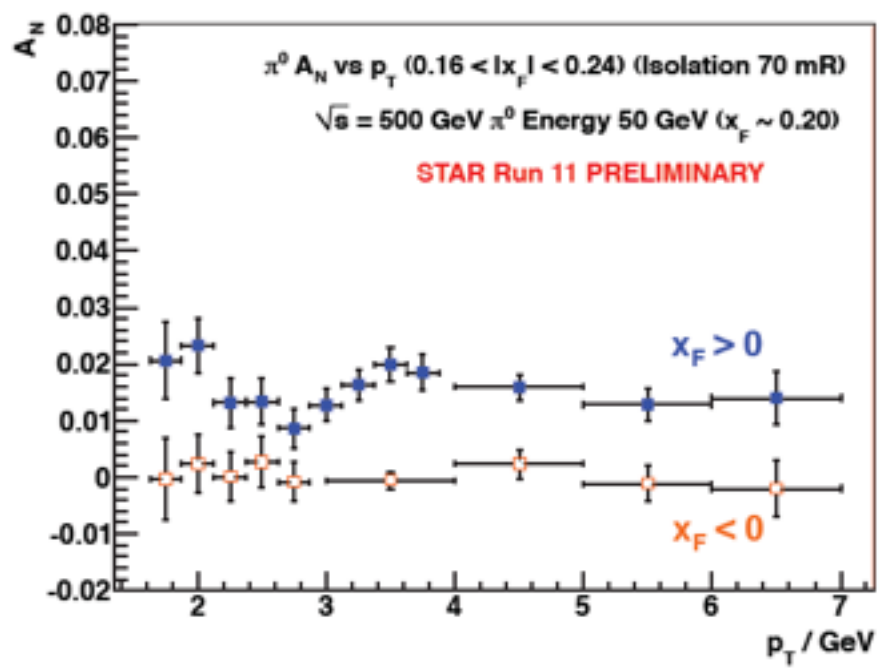

- small A_N at x_F<o or mid rapidity
  --> constraint on gluonic contributions
- A_N at x_F>o does not (?) drop with p_T

RHIC's contributions - cont'd

recent A_NDY measurement of A_N for jets arXiv:1304.1454

- jets = energy deposit: no fragmentation -> no Collins-type contribution
- jets contain π^+, π^-, and π^0: expect some cancelations in A_N(jet) [as $A_N(\pi^+) \approx A_N(\pi^-)$]

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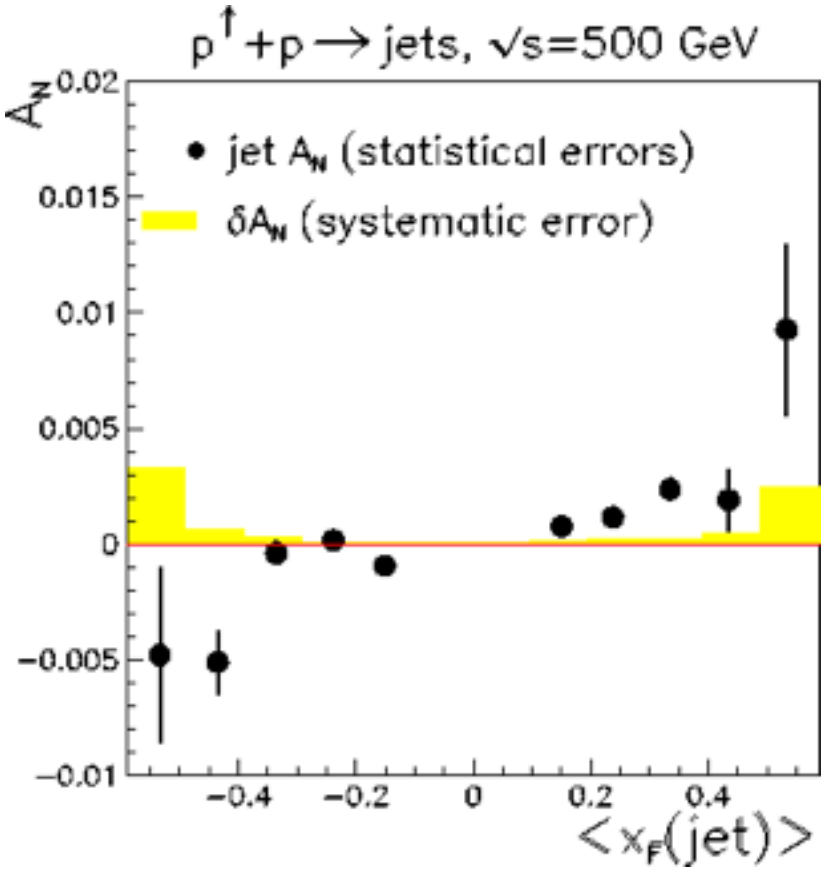


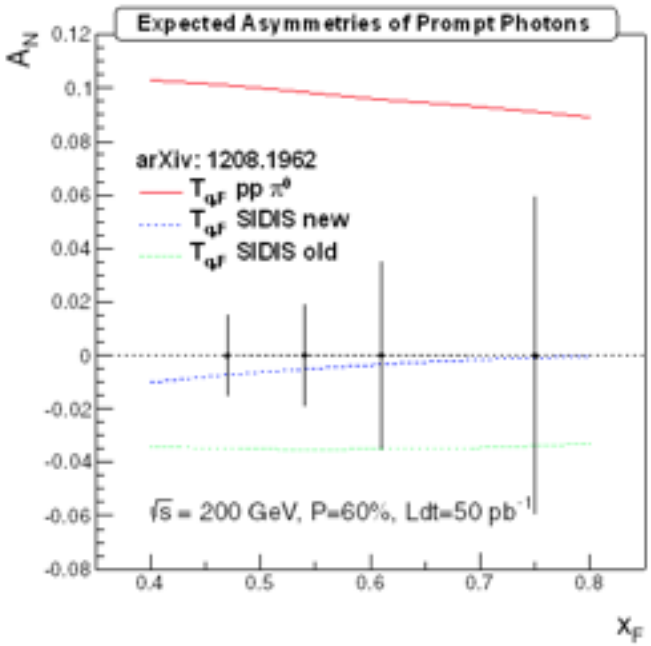
find

- forward kinematics matches with SIDIS
  [probed x range in polarized proton]
- measured A_N(jet) agrees with expectations
  Gamberg, Kang, Prokudin
- small but non-zero analyzing power
  [important for future Drell-Yan studies]

moving ahead: future plans

A_N for prompt photons using forward detectors at PHENIX and STAR

- shed more light on underlying mechanism
  [and TMD "factorization" in pp]



PHENIX MPC-EX proposal

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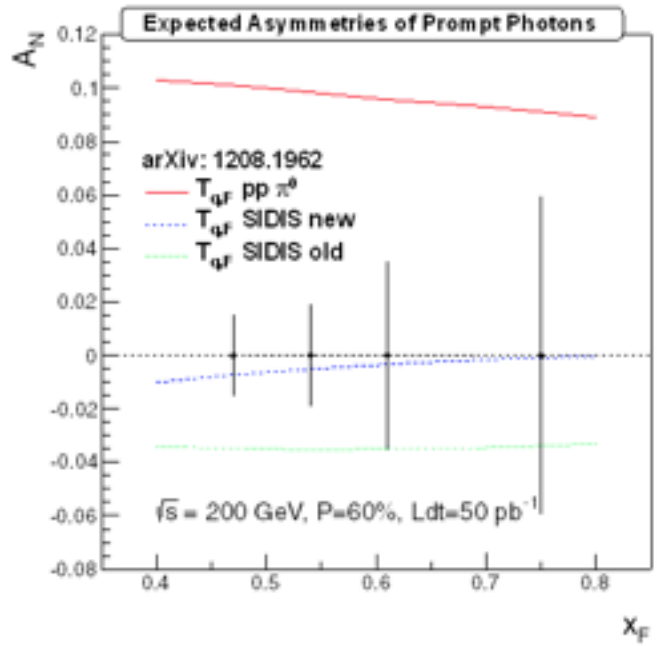
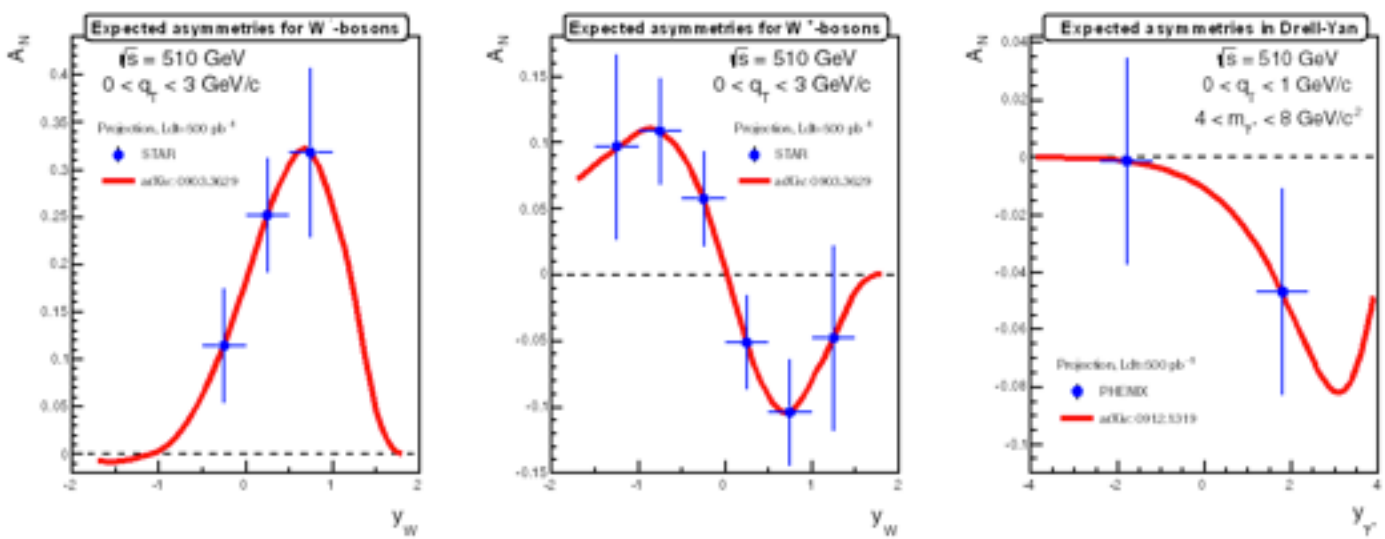


PHENIX MPC-EX proposal

A_N in Drell-Yan like reactions (γ^*, $W^{+/-}$, Z) to test sign change in Sivers TMD



curves by Kang, Qiu
no evolution included !

5

the path forward beyond RHIC

the path forward

COMPASS, JLab-12, RHIC have vibrant spin programs

BUT

we need to explore small x region to determine ΔΣ, Δg, Bjorken sum, ...

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BUT

we need to explore small x region to determine ΔΣ, Δg, Bjorken sum, ...

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

the path forward

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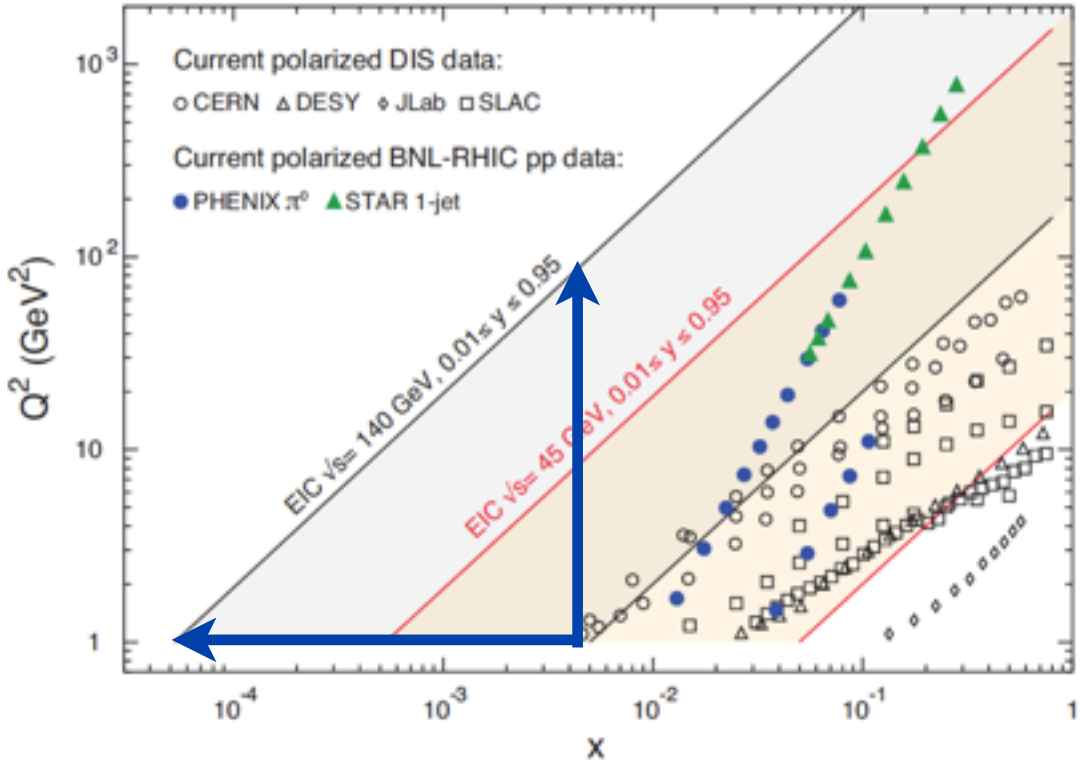
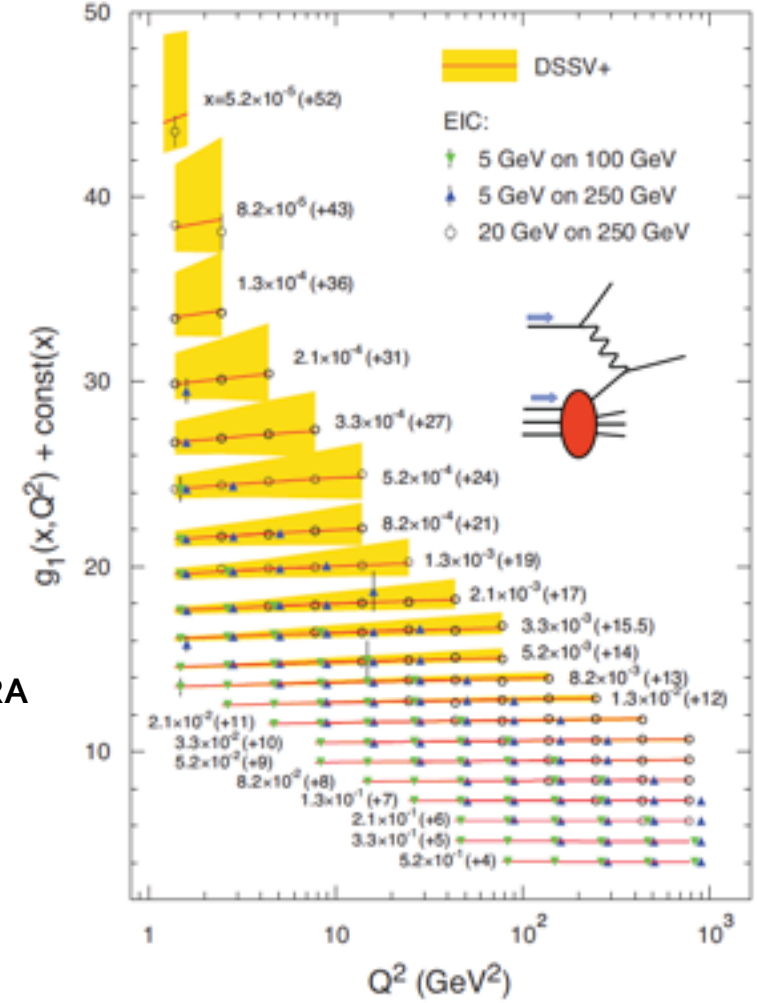
in short: an **Electron-Ion Collider**

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

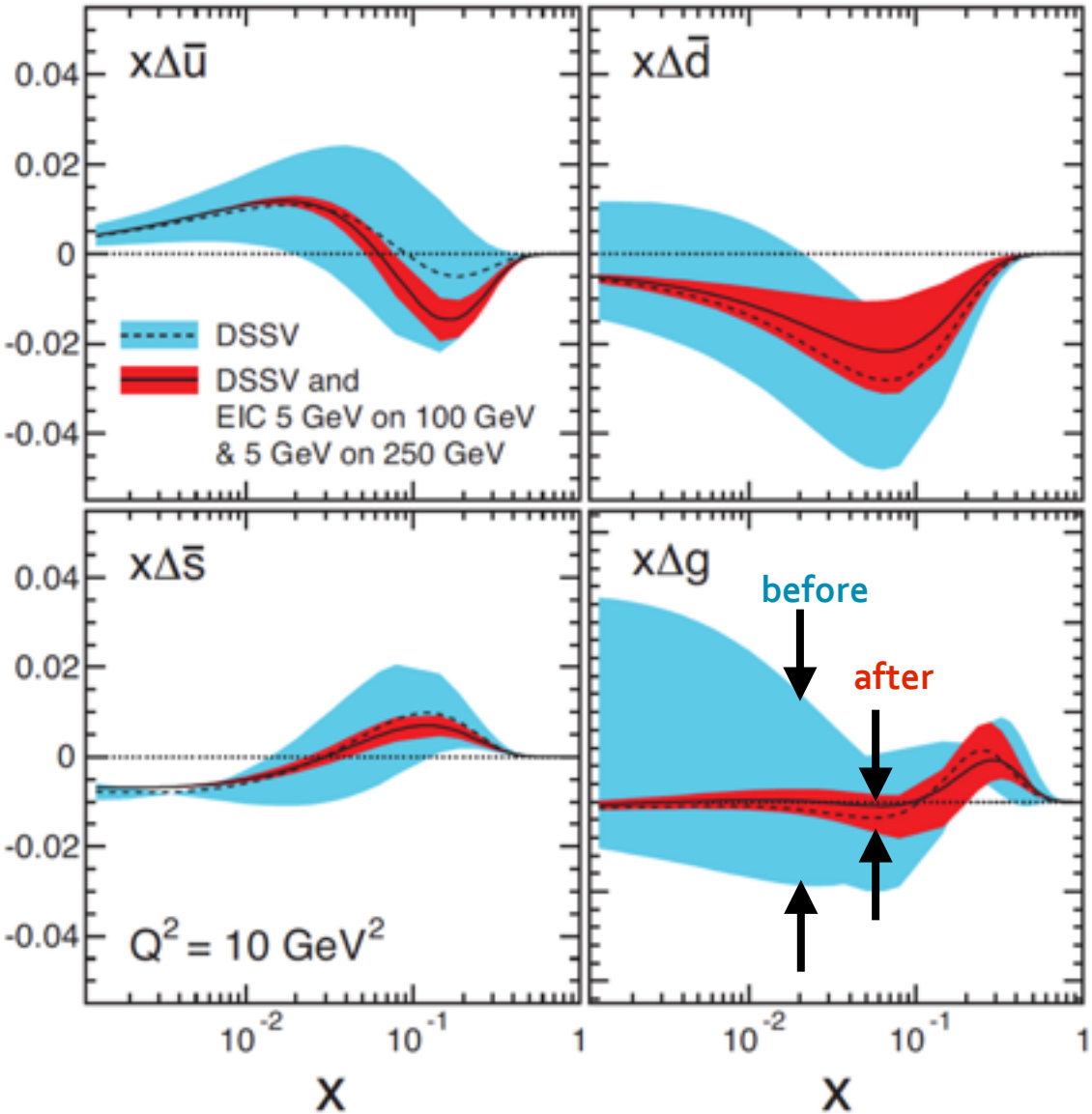
- Δg from scaling violations a la HERA
- access to e-w effects in polarized DIS

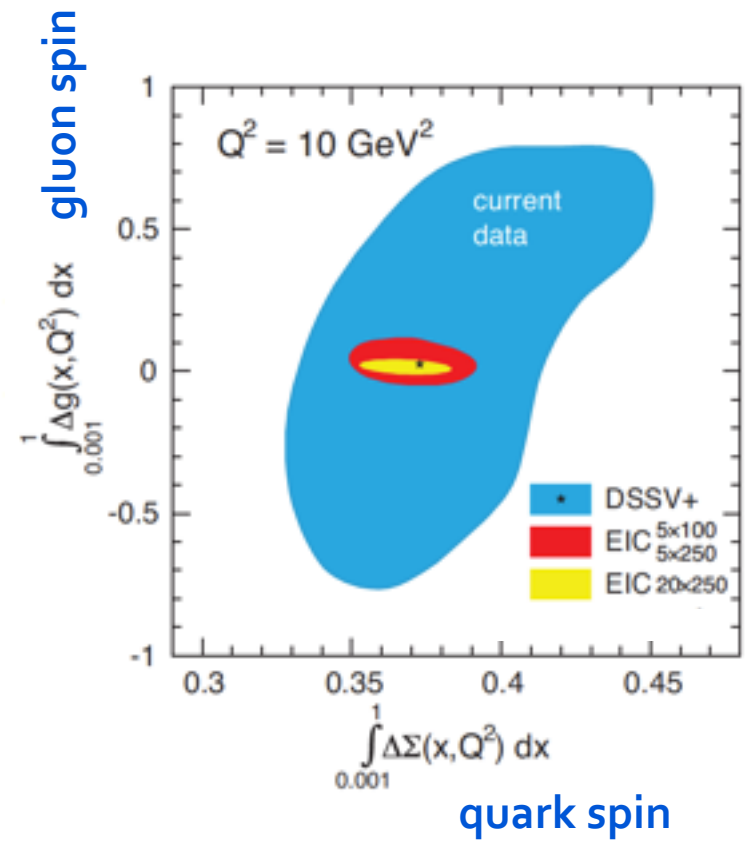
recent NLO study on e-w SIDIS:
de Florian, Rotstein Harbanau 1210.7203

expectations for helicity PDFs

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

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

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3-D

$$\mathbf{f(x, k_T)}$$

transv. mom. dep. PDF

semi-inclusive DIS

$$\int d^2 k_T$$

1-D

$$\mathbf{f(x)}$$

parton densities

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need Fourier transform to get what we want

3-D

$f(x, k_T)$ — transv. mom. dep. PDF — *semi-inclusive DIS*

not related by Fourier transf.

$f(x, b_T)$ — impact par. dep. PDF

$b \leftrightarrow t$

$H(x, 0, t)$

$\xi \to 0$

$H(x, \xi, t)$ — generalized PDF — *exclusive processes*

$\int d^2k_T$

$\int d^2b_T$

$\int dx$

1-D

$f(x)$ — parton densities

$F(t)$ — form factor

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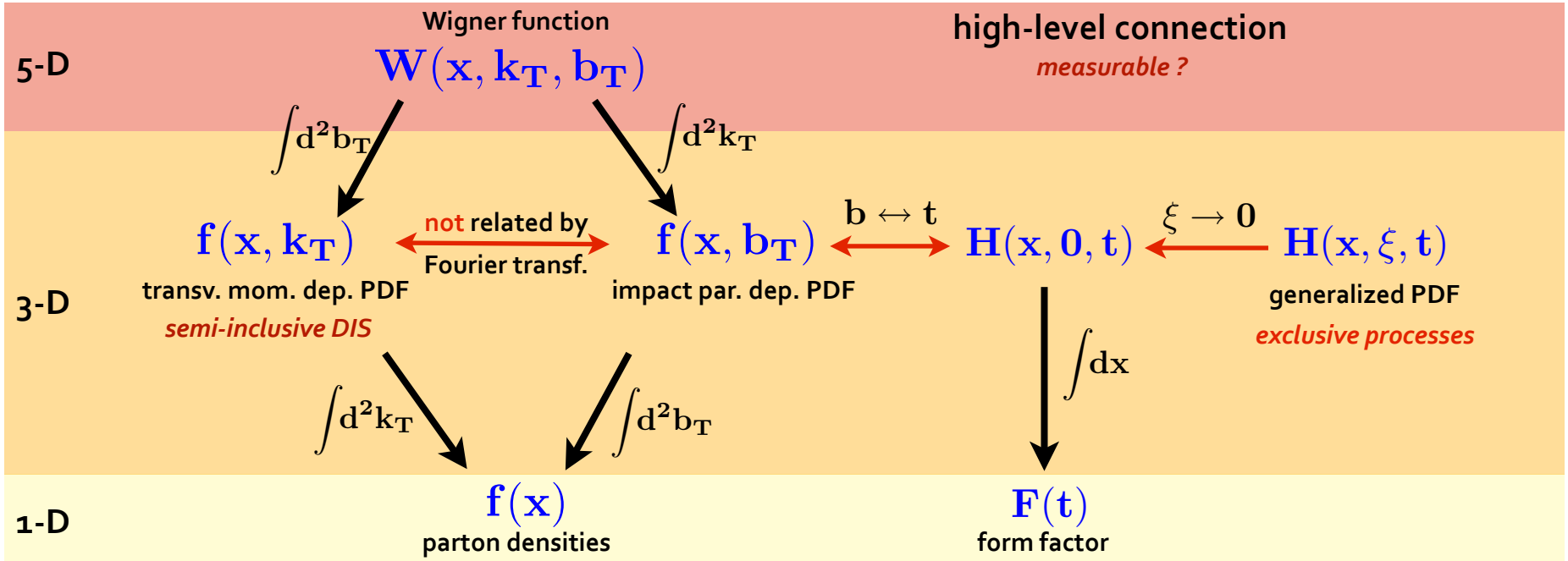

take away message

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

eRHIC is the only option