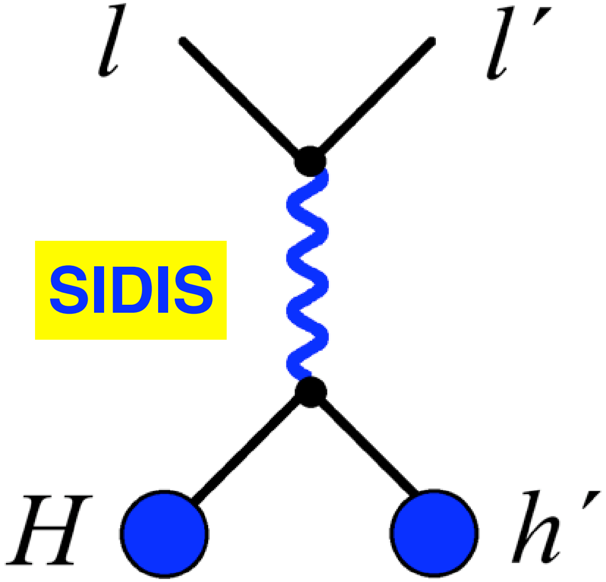
Drell-Yan:
The Missing Spin Programme

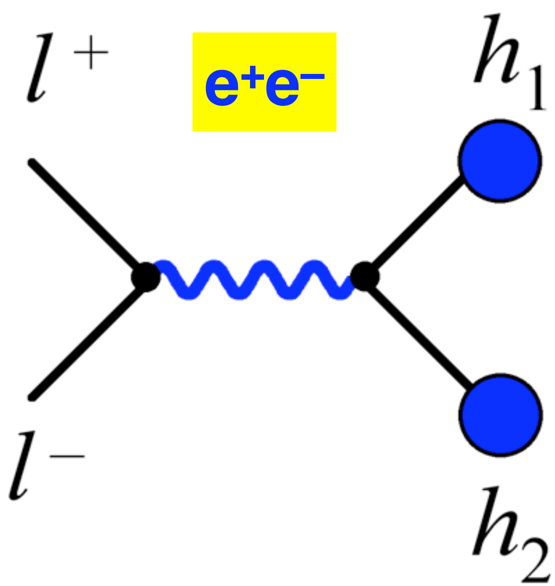
Leptons: clean, surgical tools



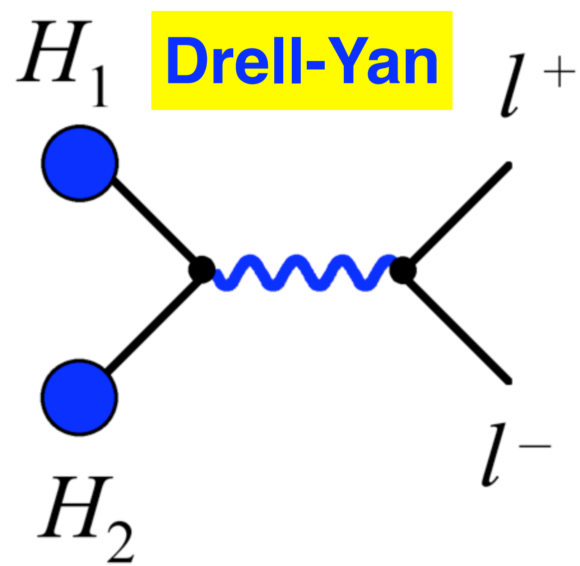
$$\sum_q e_q^2\ \mathbf{f_q^{(H)}}(x)\ \mathbf{D_q^{h'}}(z)$$

- *Disentangle **distribution** (f) and **fragmentation** (D) functions → measure **<u>all process</u>***
  - *Disentangle **quark flavours** q → measure as many **<u>hadron species</u>** H,h as possible*

These are the **only** processes where TMD factorization is proven



$$\sum_q e_q^2\ \mathbf{D_q^{h_1}}(z_1)\ \mathbf{D_{\bar{q}}^{h_2}}(z_2)$$



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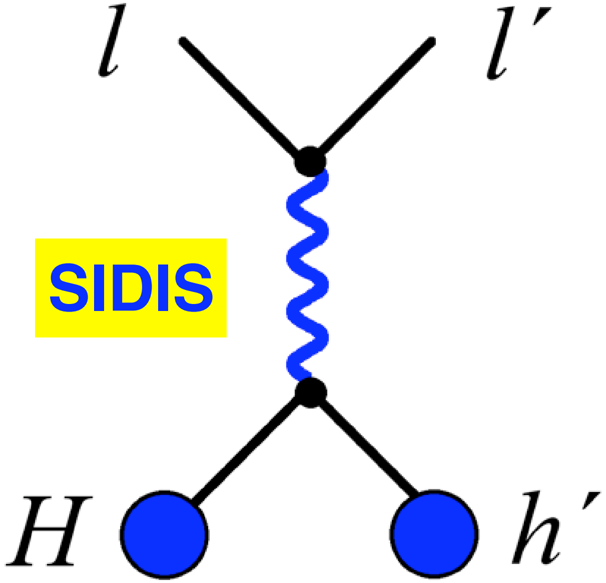
Leptons: clean, surgical tools



$$\sum_q e_q^2 \; \mathbf{f}_\mathbf{q}^{(\mathbf{H})}(x) \; \mathbf{D}_\mathbf{q}^{\mathbf{h}'}(z)$$

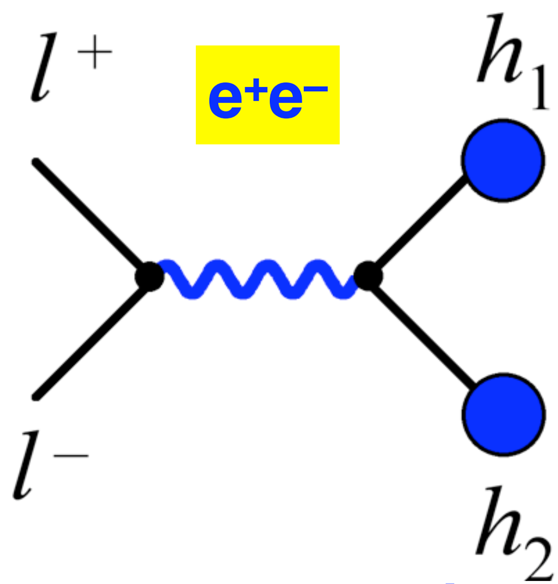
hermes

COMPASS

Jefferson Lab

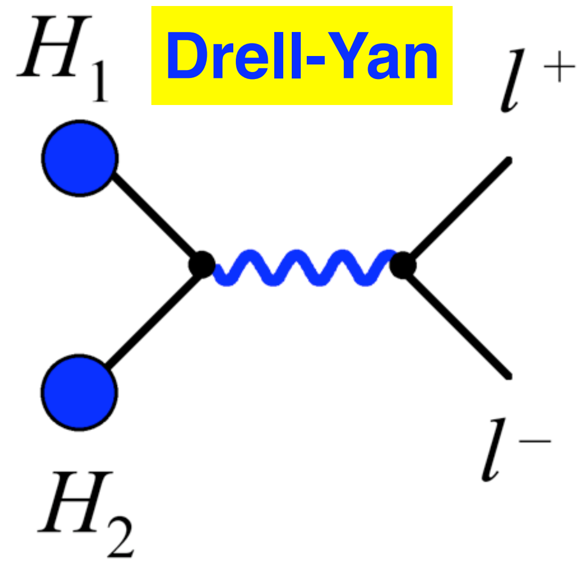
Exploring the Nature of Matter

Spin Programs



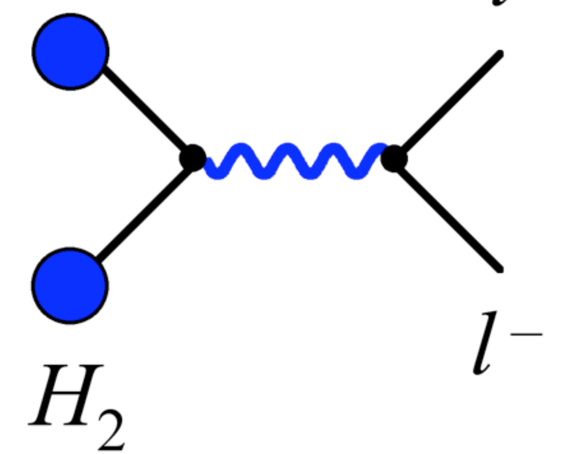
$$\sum_q e_q^2 \; \mathbf{D}_\mathbf{q}^{\mathbf{h_1}}(z_1) \; \mathbf{D}_{\bar{\mathbf{q}}}^{\mathbf{h_2}}(z_2)$$

BELLE



$$\sum_q e_q^2 \; \mathbf{f}_\mathbf{q}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$

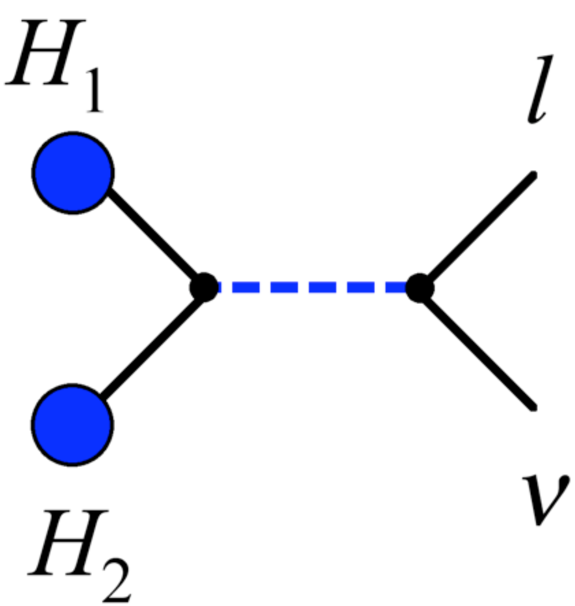
Drell-Yan



The Missing Spin Program: Drell-Yan

$$\sum_q e_q^2 \; \mathbf{f}_{\mathbf{q}}^{(\mathbf{H_1})}(x_1) \; \mathbf{f}_{\bar{\mathbf{q}}}^{(\mathbf{H_2})}(x_2)$$

W production



- Clean access to **sea quarks** e.g. $\Delta\bar{u}(x), \Delta\bar{d}(x)$ at RHIC
- Crucial test of **TMD formalism** → **sign change** of T-odd functions
- A **complete** spin program requires multiple hadron species → **nucleon & meson beams**


seaQuest
2032

Sea-Spin: The Final Frontier

- Baseline: **Sign Change** for T-Odd TMD(u)
  → as much **u-quark dominance** as possible
  → **COMPASS-II $\pi^- p\uparrow$** first: **approved** and
  best kinematic match to SIDIS
  → SeaQuest with beam↑ maybe next

- The Sea: **Sivers & Boer-Mulders** for **ubar**
  → **π^+ or p beam** at COMPASS-II
  → possible fixed target: **N↑ target**
  @ SeaQuest, PANDA
  → possible **collider**: RHIC, NICA

- **Full Programme** of Spin-DY: TMD ultimate global fit
  → **many beam species** (p, pbar, d, meson): flavor separation
  → **L and T** polarization: TMD separation

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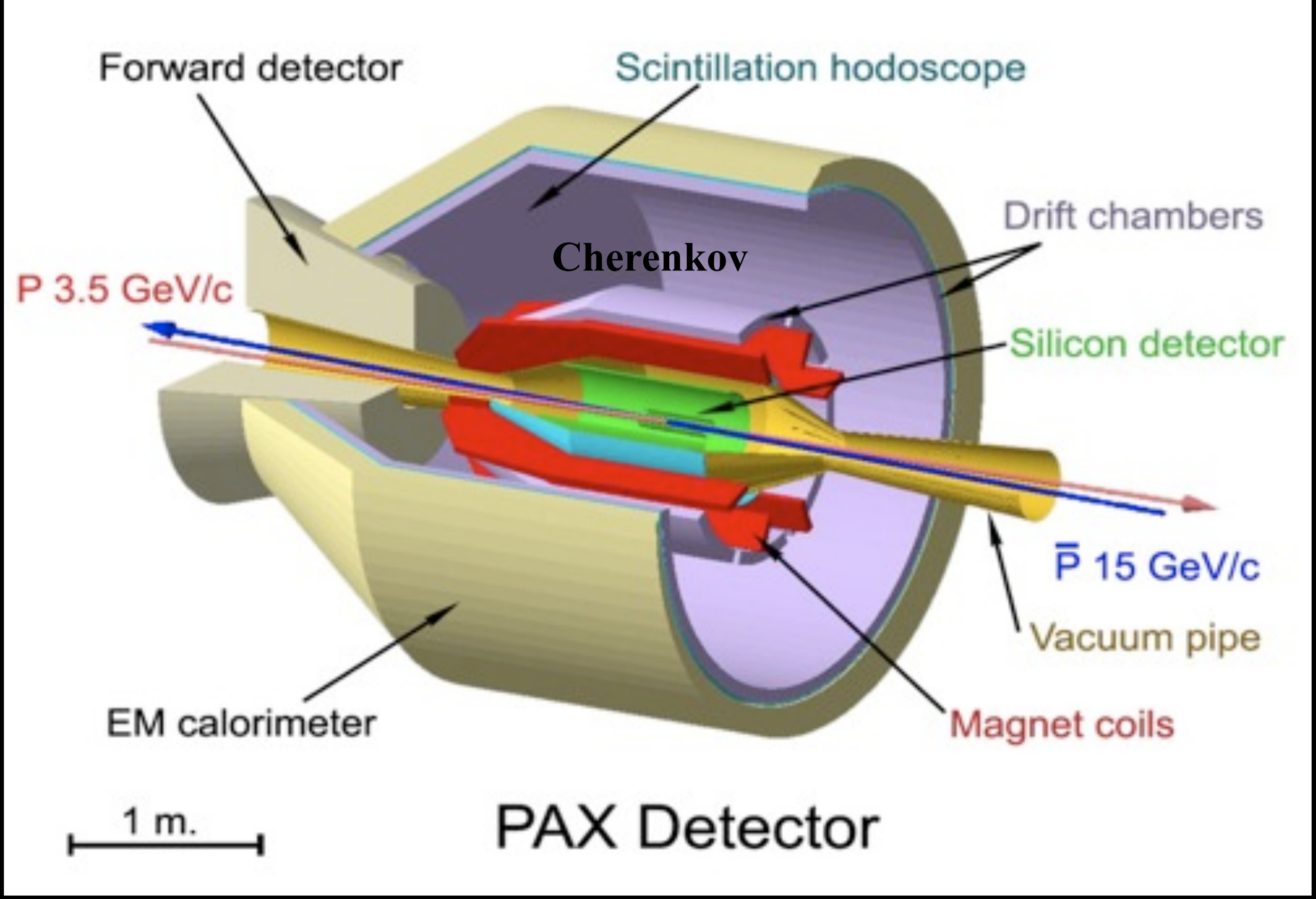
The Experiments



approved (solid line)
unpolarized (dotted line)

The Experiments

experiment		particles	energy	x_b or x_t	luminosity	timeline
COMPASS (CERN)	[22]	$\pi^{\pm} + p^{\uparrow}$	160 GeV $\sqrt{s} = 17.4$ GeV	$x_t = 0.2 - 0.3$	$1 \times 10^{32}\ cm^{-2}s^{-1}$	2014
PAX (GSI)	[23]	$p^{\uparrow} + \overline{p}$	collider $\sqrt{s} = 14$ GeV	$x_b = 0.1 - 0.9$	$2 \times 10^{30}\ cm^{-2}s^{-1}$	>2017
PANDA (GSI)	[24]	$\overline{p} + p^{\uparrow}$	15 GeV $\sqrt{s} = 5.5$ GeV	$x_t = 0.2 - 0.4$	$2 \times 10^{32}\ cm^{-2}s^{-1}$	>2016
NICA (JINR)	[25]	$p^{\uparrow} + p$	collider $\sqrt{s} = 20$ GeV	$x_b = 0.1 - 0.8$	$1 \times 10^{30}\ cm^{-2}s^{-1}$	>2014
PHENIX (BNL)	[26]	$p^{\uparrow} + p$	collider $\sqrt{s} = 200$ GeV	$x_b = 0.05 - 0.1$	$2 \times 10^{32}\ cm^{-2}s^{-1}$	>2018
RHIC internal target phase-1	[27]	$p^{\uparrow} + p$	250 GeV $\sqrt{s} = 22$ GeV	$x_b = 0.25 - 0.4$	$2 \times 10^{33}\ cm^{-2}s^{-1}$	>2015
RHIC internal target phase-2	[27]	$p^{\uparrow} + p$	250 GeV $\sqrt{s} = 22$ GeV	$x_b = 0.25 - 0.4$	$3 \times 10^{34}\ cm^{-2}s^{-1}$	>2018
E-906/SeaQuest (FNAL)	[12]	$p + p$	120 GeV $\sqrt{s} = 15$ GeV	$x_b = 0.3 - 0.9$ $x_t = 0.1 - 0.45$	$2.0 \times 10^{35}\ cm^{-2}s^{-1}$	2011
pol. SeaQuest (FNAL)		$p^{\uparrow} + p$	120 GeV $\sqrt{s} = 15$ GeV	$x_b = 0.3 - 0.9$	$1 \times 10^{36}\ cm^{-2}s^{-1}$	>2014

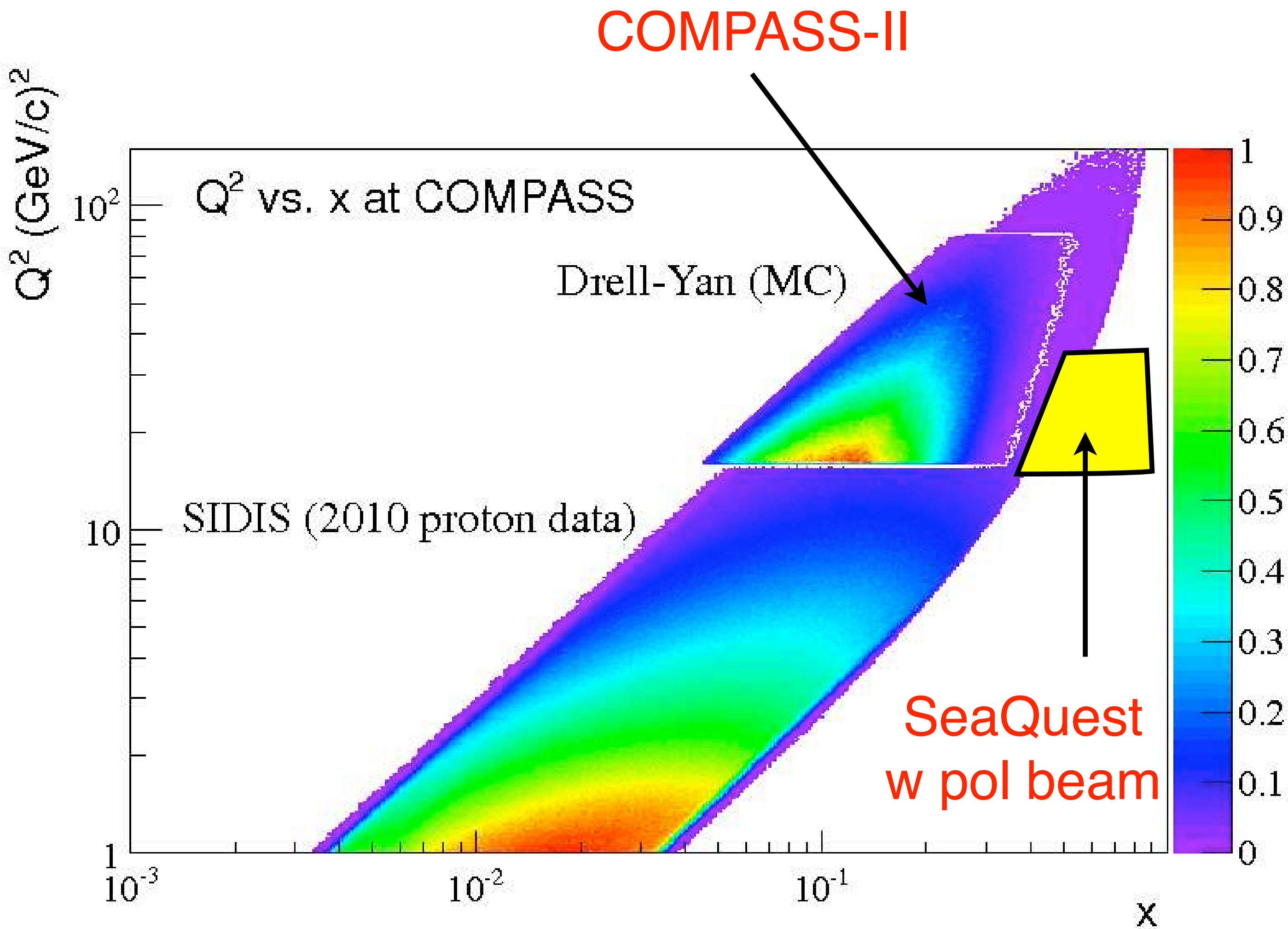
"valence" x
≈ 0.25
→ match to SIDIS

high √s
→ low x,
low lumi

low mass
$M_{\mu\mu} < 2.5$

"Valence x" → where the action is

SIDIS and DY



The COMPASS SIDIS and DY experimental measurements have an overlapping region.

AnDY - Staging

Polarized proton runs at √s = 500 GeV

2011 HCal + newly constructed BBC at IP2 to establish the impact of a 3rd IR operation and to demonstrate the calibration of HCal to get first data constraints on charged hadron backgrounds

2012 HCal + EmCal + neutral/charge veto + BBC for zero-field data sample with L_{int}≈150 pb^{-1} and P≈50% to observe di-leptons from J/ψ, Y, and intervening continuum.

2013 HCal + EmCal + neutral/charge veto + BBC + split-dipole for data sample with L_{int}≈ 150 pb^{-1} and P=50% to observe di-leptons from J/ψ, Y, and intervening continuum to address whether charge sign discrimination is required

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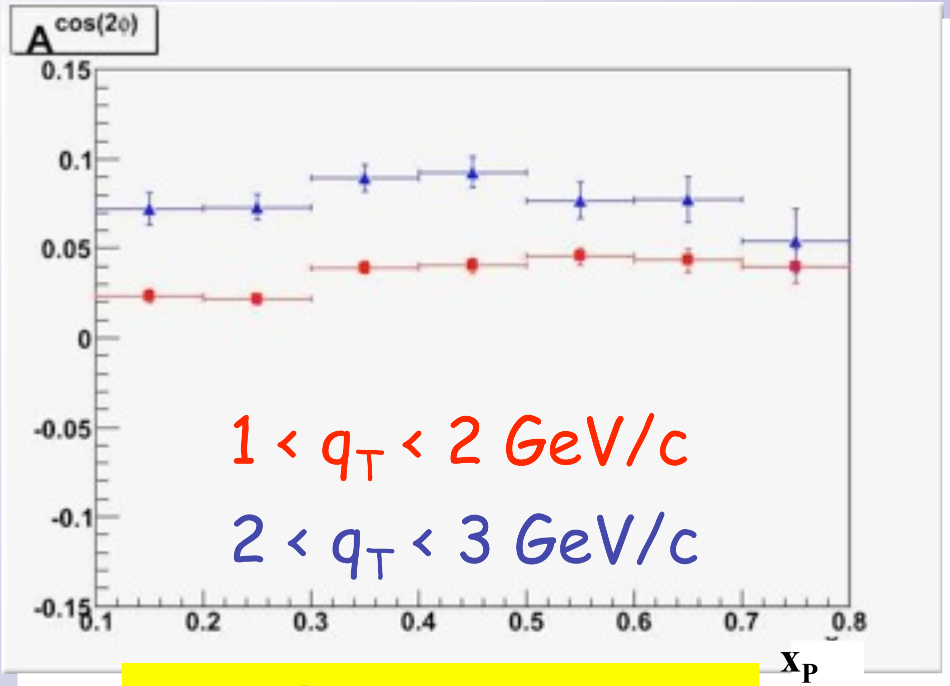
DY @ 15 GeV/c — $\bar{p}p \to \mu^+\mu^- X$ $\sqrt{s} = 5.5$ GeV

UNPOLARISED



Anti-proton beam!
PAX → polarize it ...

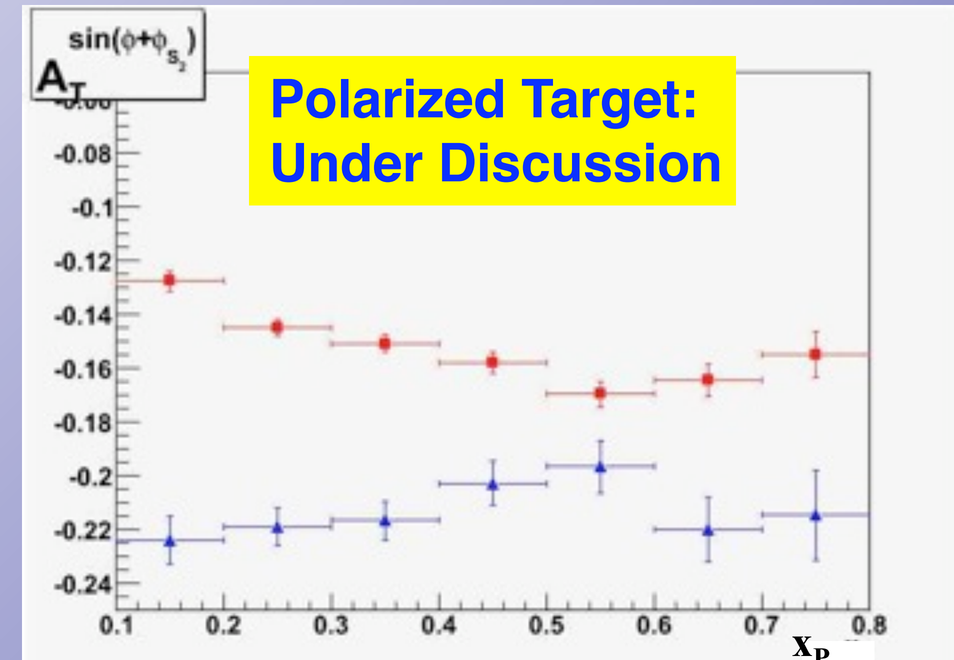
500KEv included in asymmetries

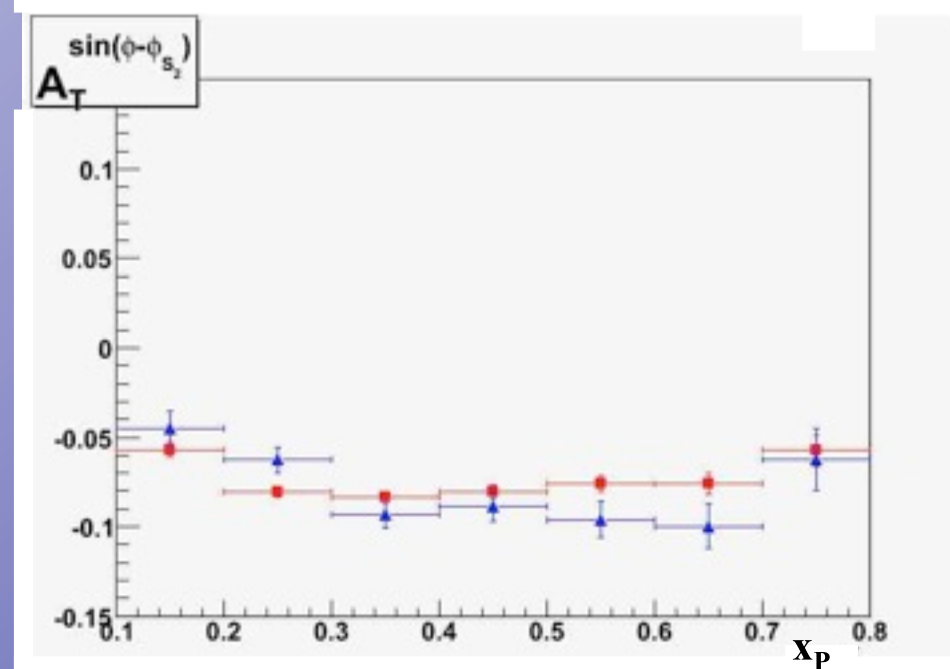
Acceptance corrections crucial!

Low-Mass $M_{\mu\mu} < 2.5$ GeV

SINGLE-POLARISED

Polarized Target: Under Discussion





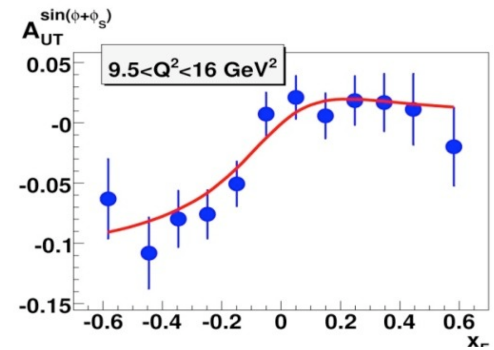
Physics Performance Report for PANDA arXiv:0903.3905

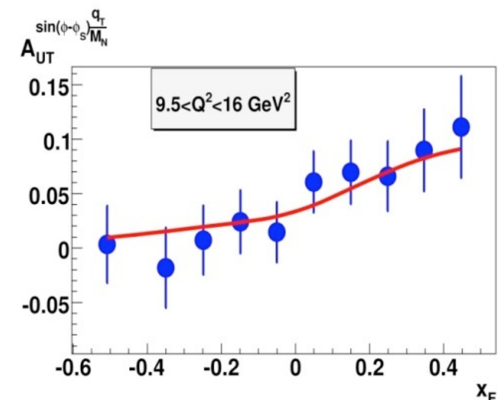
SPD EXPERIMENT AT NICA. PROPOSED MEASUREMENTS.

Extraction of unknown (poor known) parton distribution functions (PDFs):

$p(D)p(D) \to \gamma^* X \to l^+ l^- X$	Boer-Mulders PDF
$p^\uparrow(D^\uparrow)p(D) \to \gamma^* X \to l^+ l^- X$	Sivers PDFs (Efremov,... PLB 612 (2005), PRD 73(2006));
$p^\uparrow(D^\uparrow)p^\uparrow(D^\uparrow) \to \gamma^* X \to l^+ l^- X$	Transversity PDF (Anselmino, Efremov, ...)
$p^\uparrow(D^\uparrow)p(D) \to \gamma^* X \to l^+ l^- X$ $p(D)p(D) \to \gamma^* X \to l^+ l^- X$	Transversity and first moment of Boer-Mulders PFDs (Sissakian, Shevchenko, Nagaytsev , Ivanov, PRD 72(2005), EPJ C46 ,2006 C59, 2009)
$p^\rightarrow(D^\rightarrow)p^\leftarrow(D^\leftarrow) \to \gamma^* X \to l^+ l^- X$	Longitudinally polarized sea and strange PDFs and tenzor deuteron structure (Teryaev, ...)

The same PDFs from J/ψ production processes ($\sqrt{s} \le 10 GeV$).





"Polarization effects in Drell-Yan processes", Sissakian A. N.,Shevchenko O. Yu.,Nagaitsev A. P.,Ivanov O. N. Physics of Particles and Nuclei, Volume 41, Issue 1, pp.64-100, MAIK award for 2010.

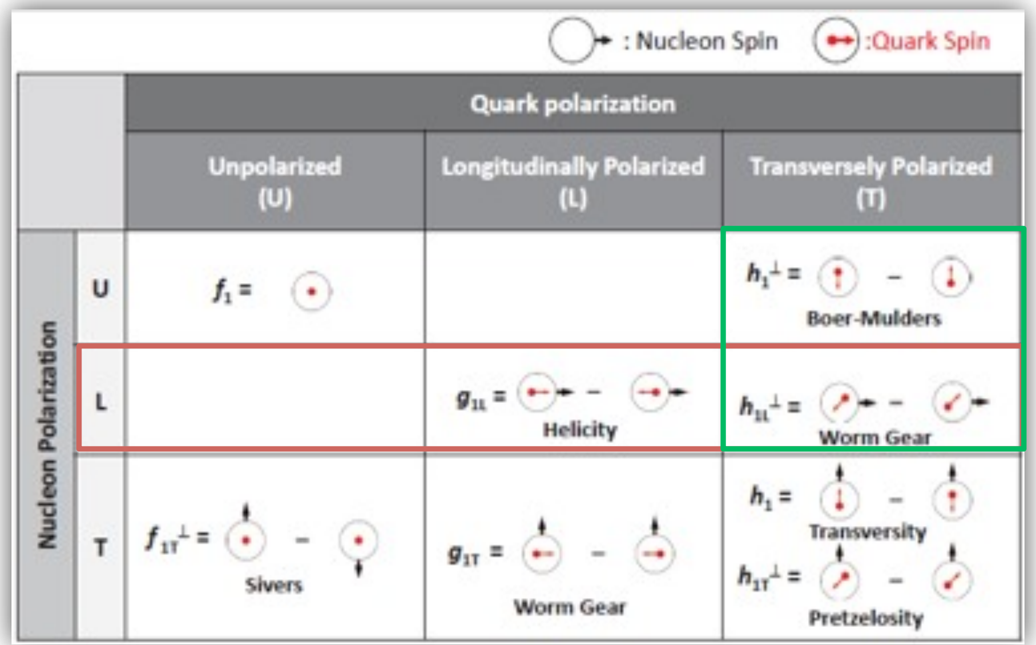
Low-Mass $M_{\mu\mu} < 2.5$ GeV

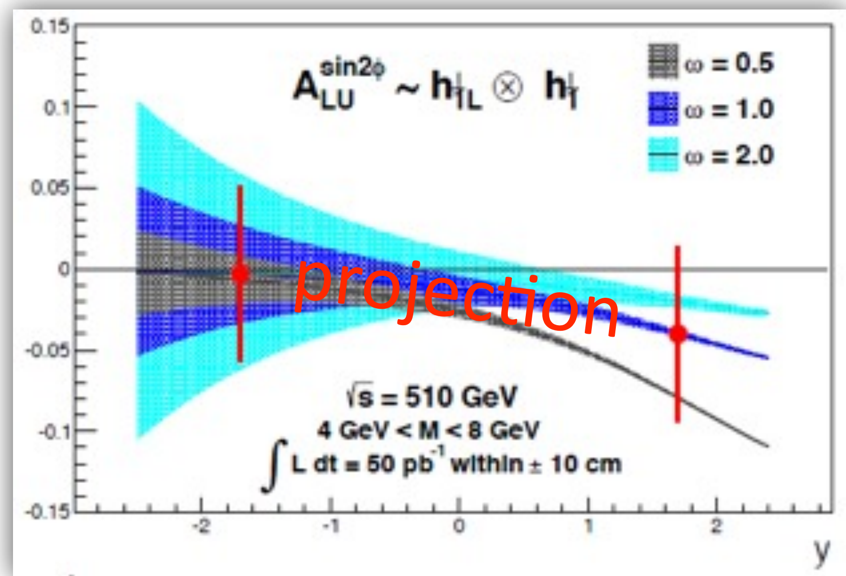
Polarized *everything!* Including *d!*

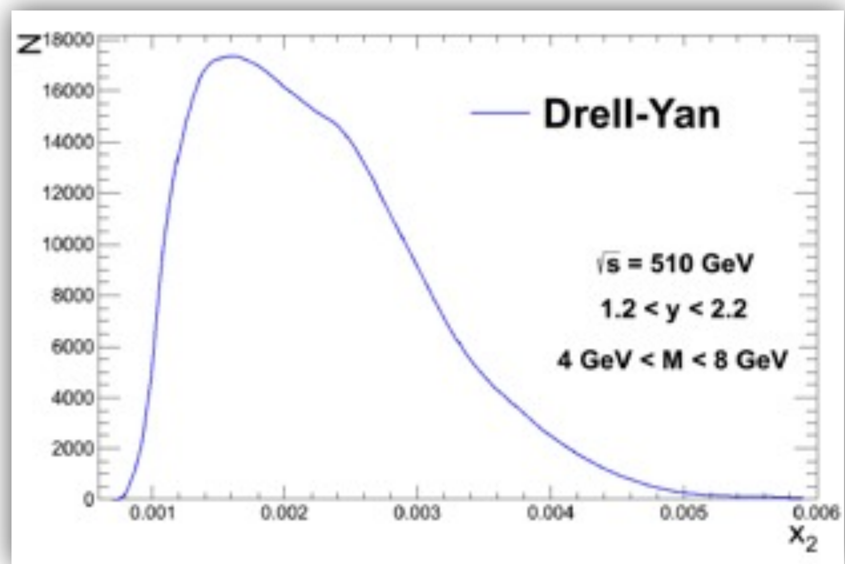
Highest √s polarized → RHIC collider

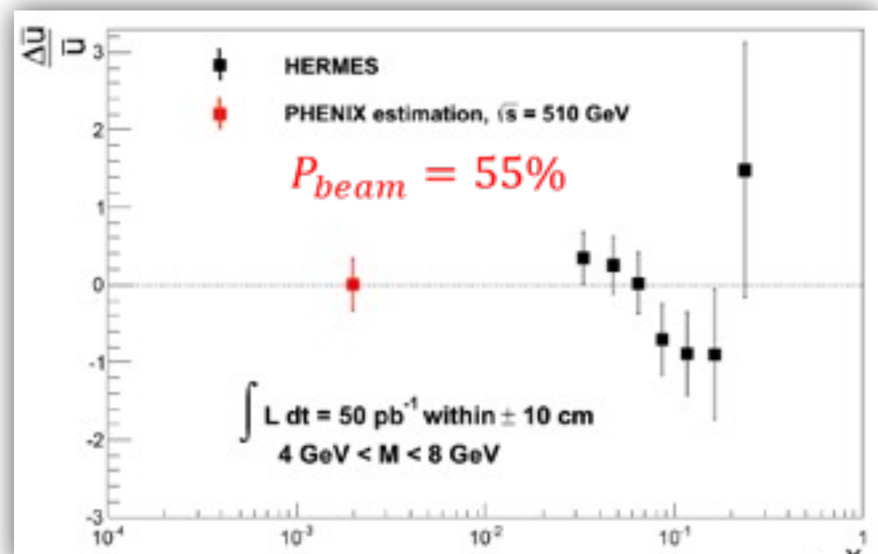
Polarized Drell-Yan with PHENIX?

arxive:1108.4974 (Lu, Ma, Zhu)



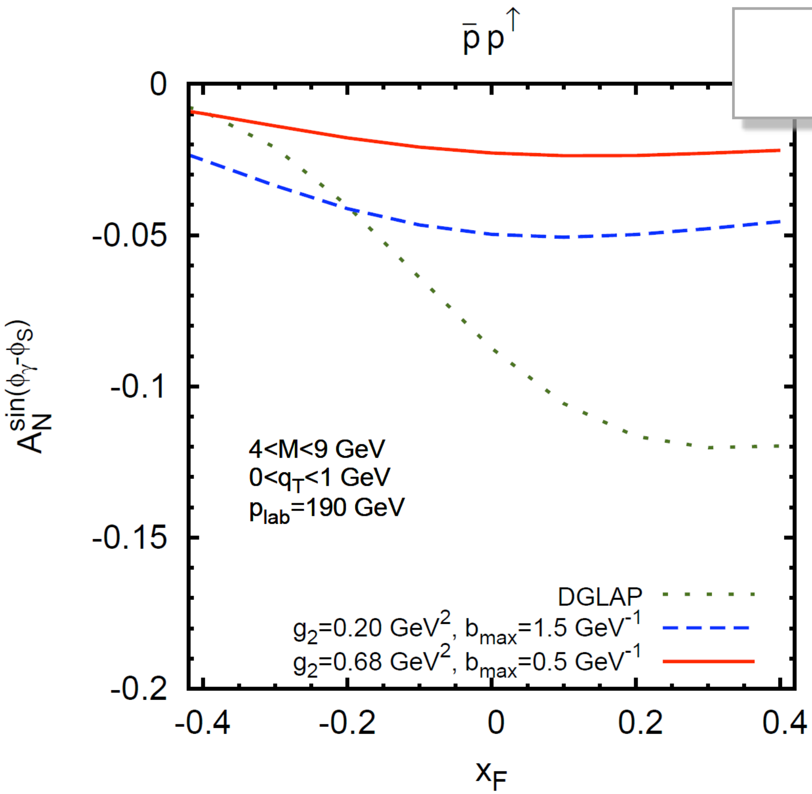


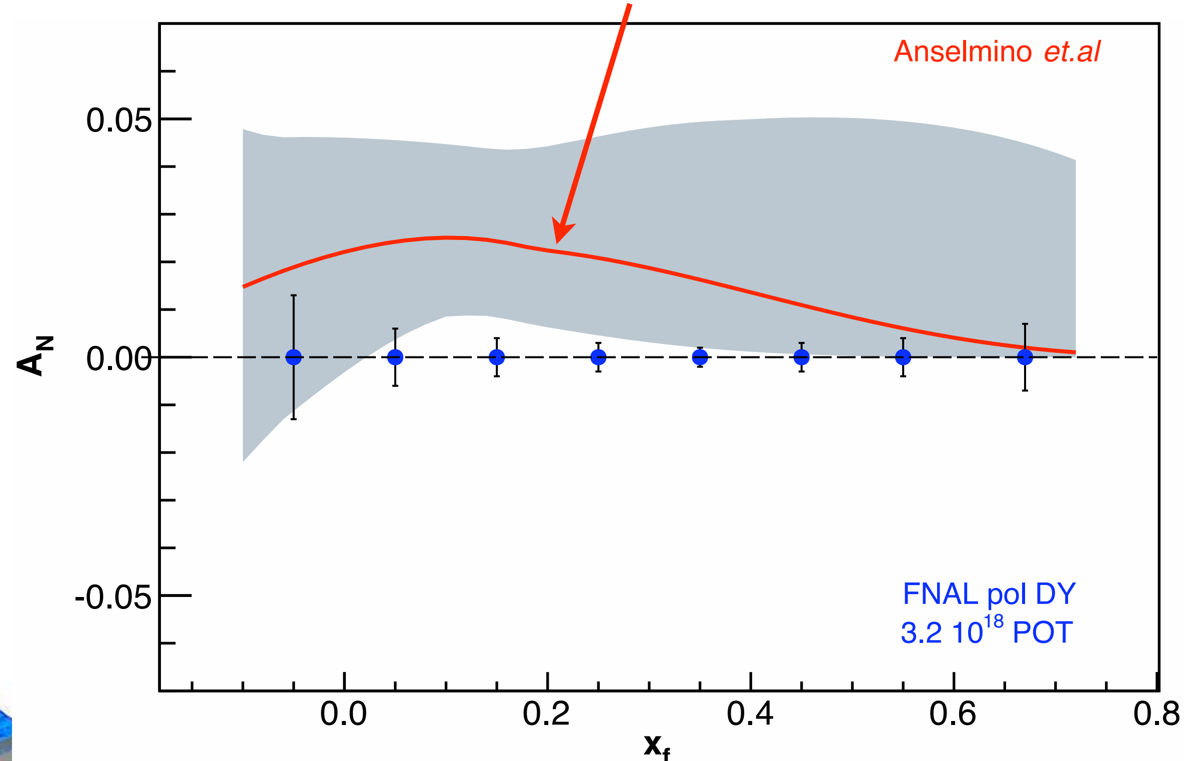


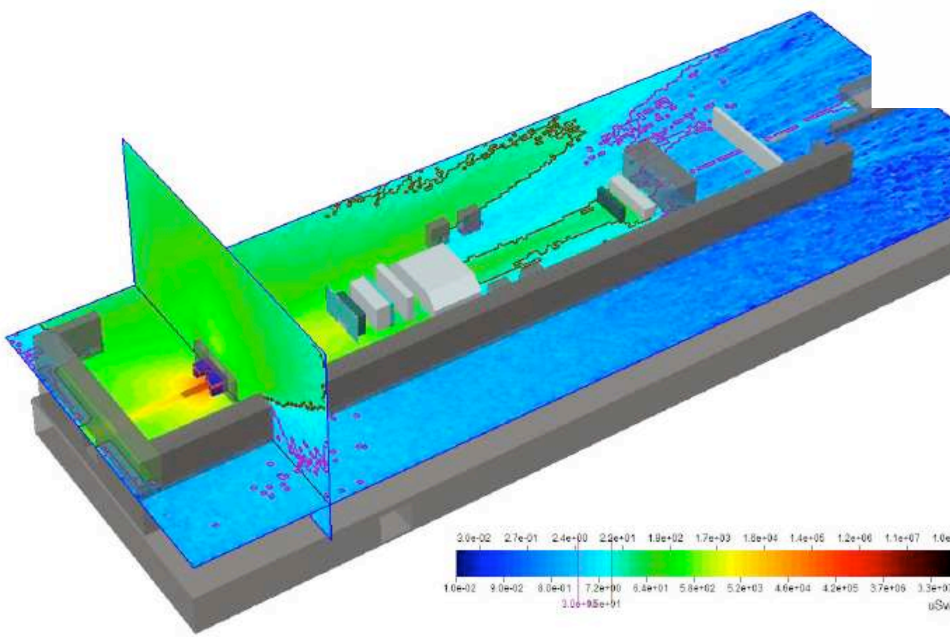


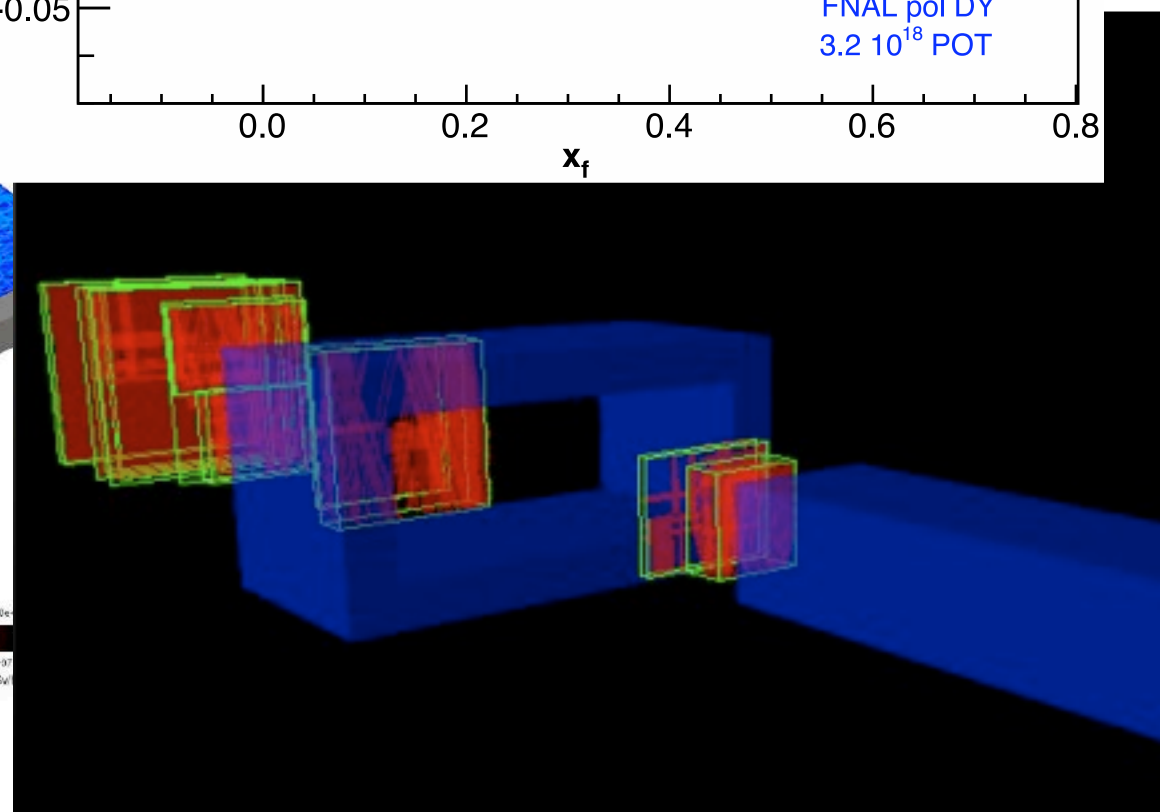
This Week

will get smaller

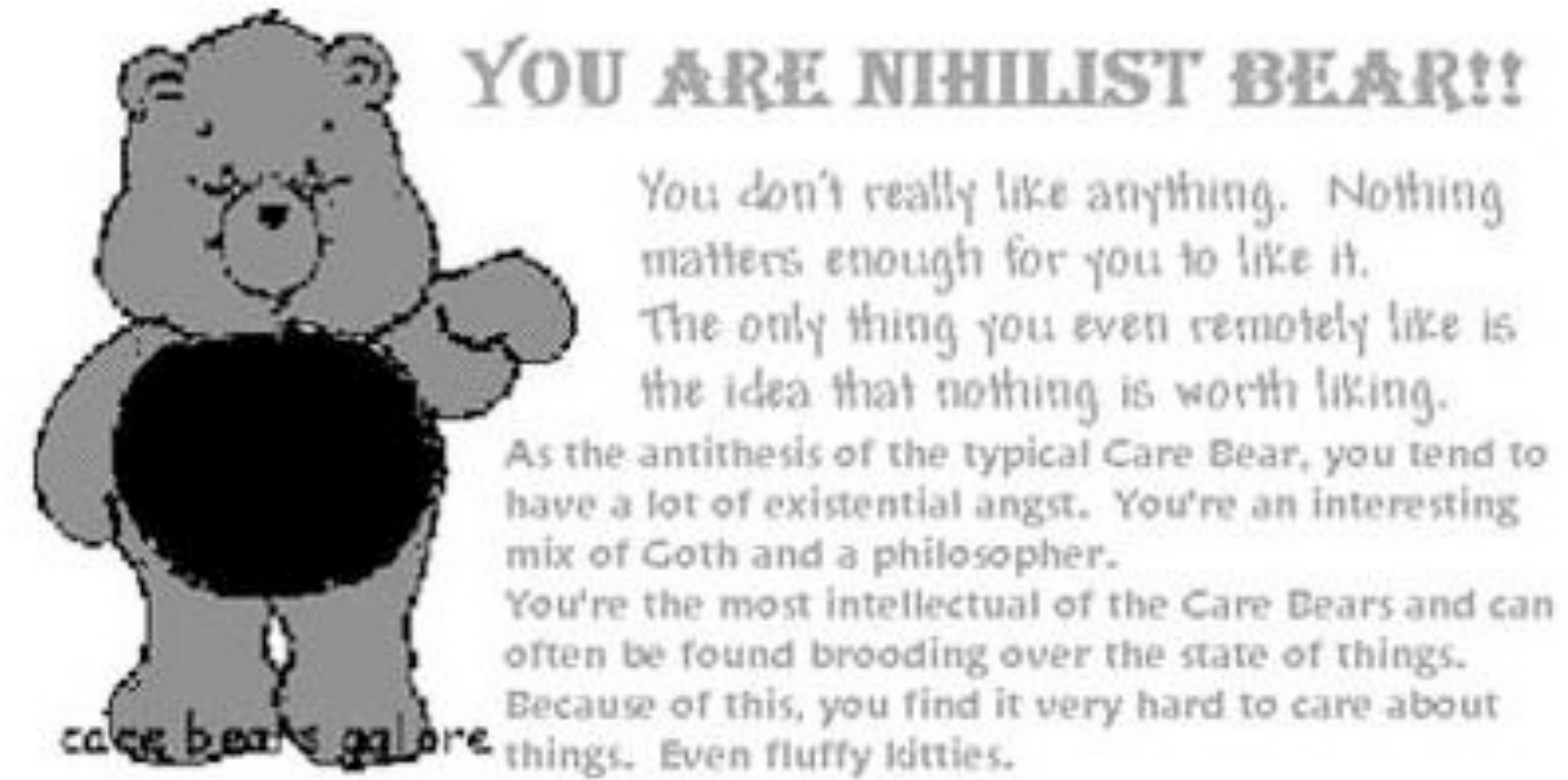








Which dysfunctional care bear are you?

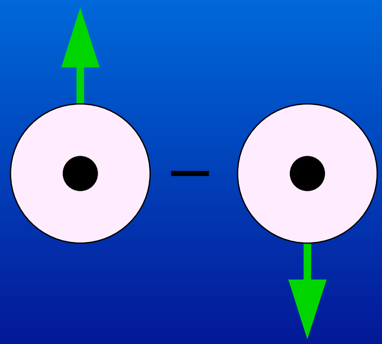


In Search of L*

TMDs + Models give

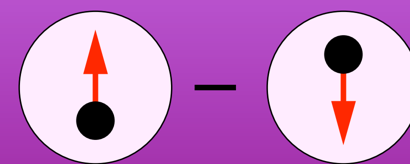
Sivers

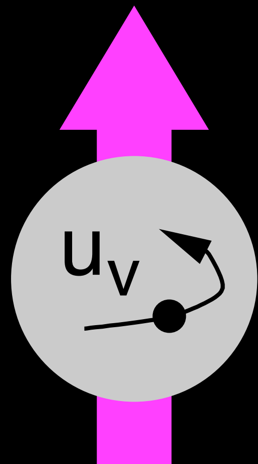
$$f_{1T}^{\perp}(x, k_T)$$



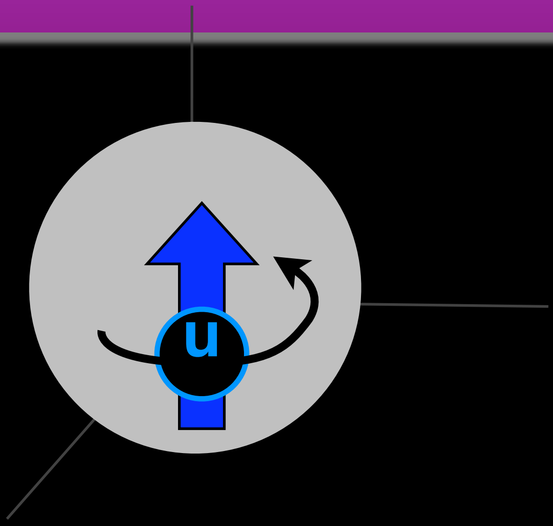
Boer-Mulders

$$h_1^{\perp}(x, k_T)$$



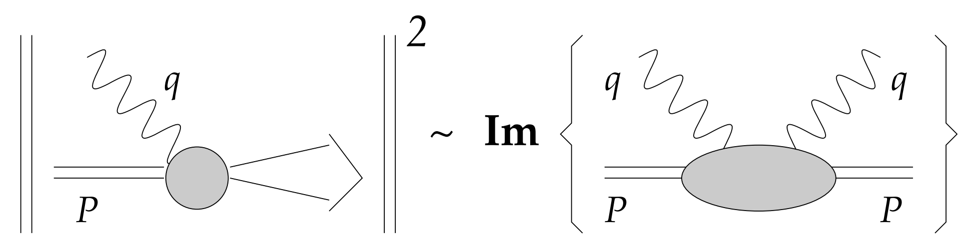


*undefined but beloved

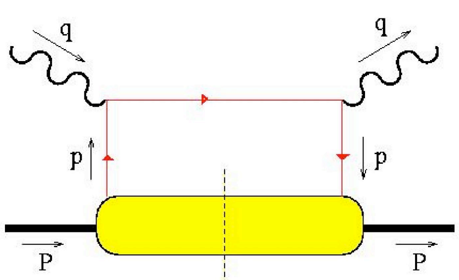


T-odd TMDs → gauge links and L

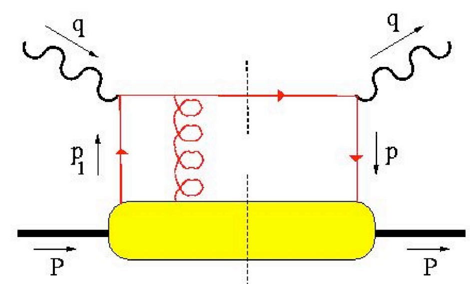
A T-odd function like $f_{1T}^{\perp}$ ***must*** arise from ***interference*** ... but a distribution function is just a forward scattering amplitude, how can it contain an interference?



Brodsky, Hwang, & Schmidt 2002



can interfere with

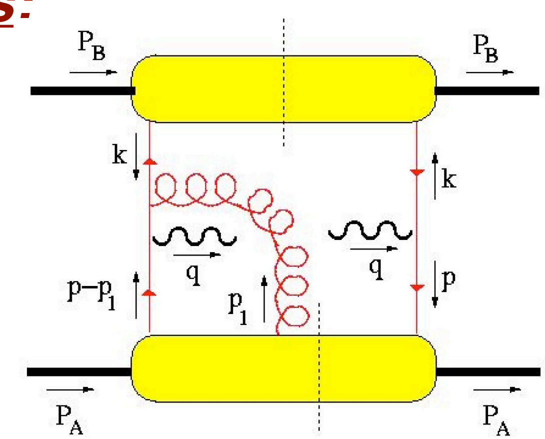


and produce a T-odd effect! (also need $L_z \neq 0$)

It looks like higher-twist ... but no, these are soft gluons: "gauge links" required for color gauge invariance

Such soft-gluon reinteractions with the soft wavefunction are ***final / initial state interactions*** ... and ***process-dependent*** ...

e.g. ***Drell-Yan***: → Sivers effect should have **opposite sign** cf. SIDIS

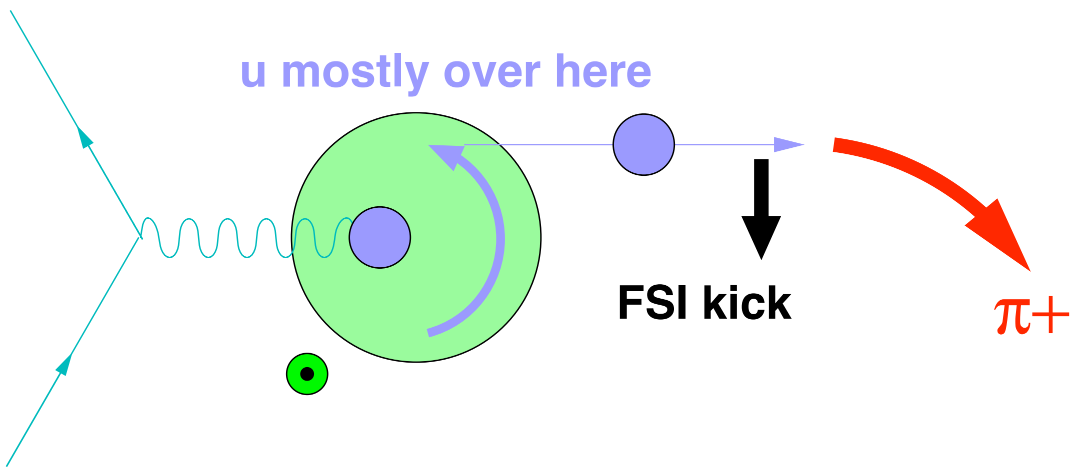


Phenomenology: Sivers Mechanism

Assuming $L_u > 0$ ...

M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ ***stronger for oncoming quarks***



We observe $\langle \sin(\phi_h^l - \phi_S^l) \rangle_{UT}^{\pi^+} > 0$

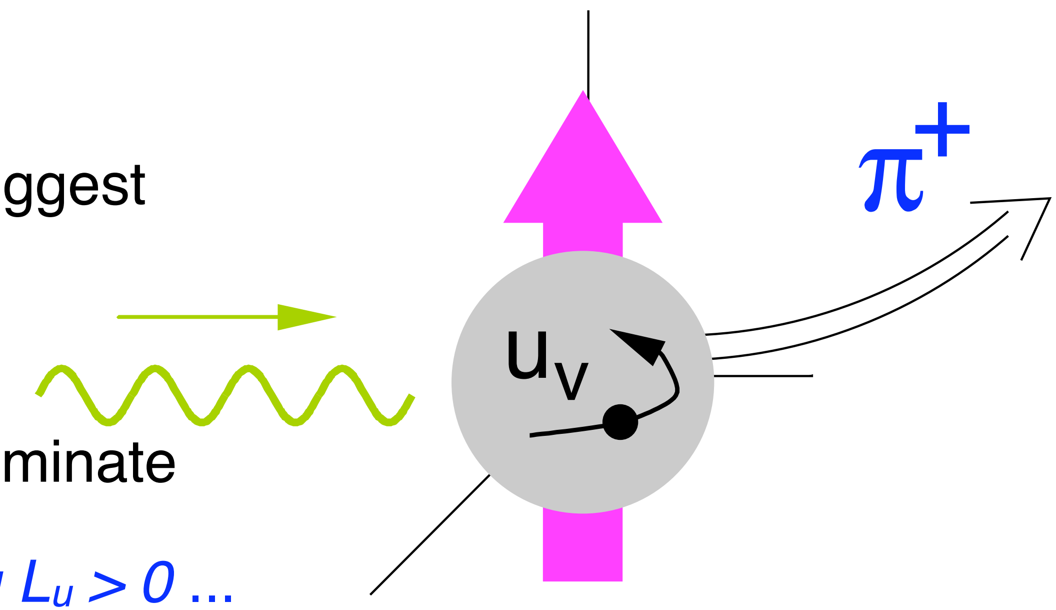
(and opposite for π^-)

$\therefore$ for $\phi_S^l = 0,\ \phi_h^l = \pi/2$ preferred

Model agrees!

D. Sivers: Jet Shadowing

Parton energy loss considerations suggest ***quenching of jets*** from ***"near" surface of target***



➡ quarks from "far" surface should dominate

Opposite sign to data … *assuming $L_u > 0$* ...

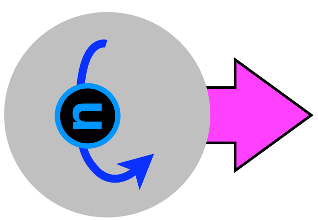
Transverse spin on the lattice

Hagler et al, PRL98 (2007)

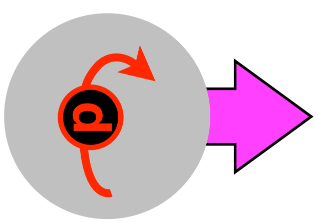
*Compute **quark densities** in **impact-parameter space** via GPD formalism*

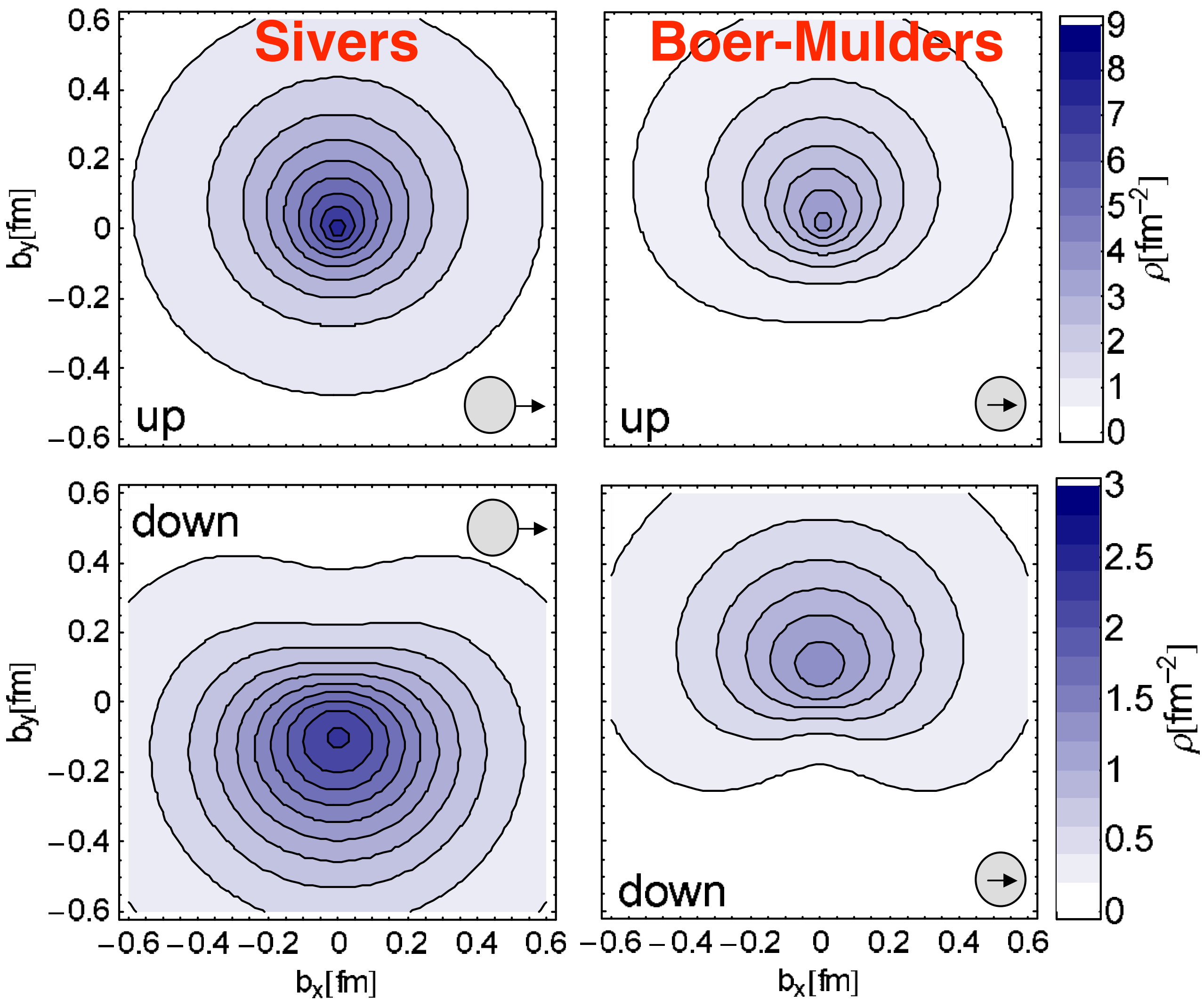
***nucleon** coming **out of page ...** observe spin-dependent **shifts** in quark densities:*

$L_u > 0$

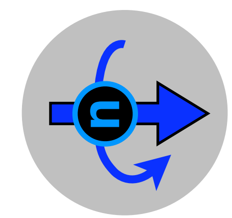


$L_d < 0$



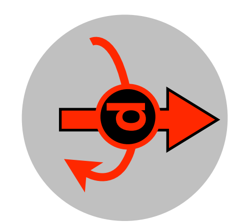


L_u // S_u



***Expected picture** from __quark models__ + __lensing__*

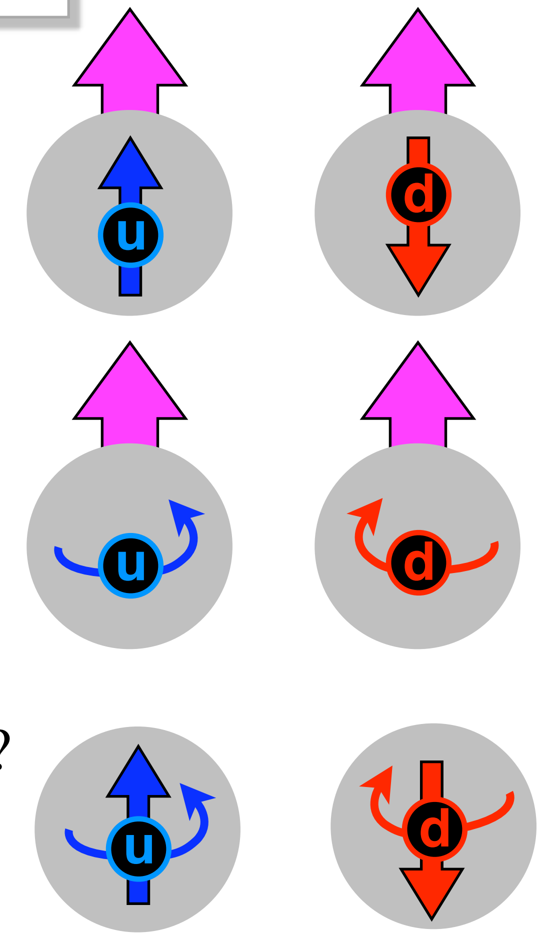
L_d // S_d



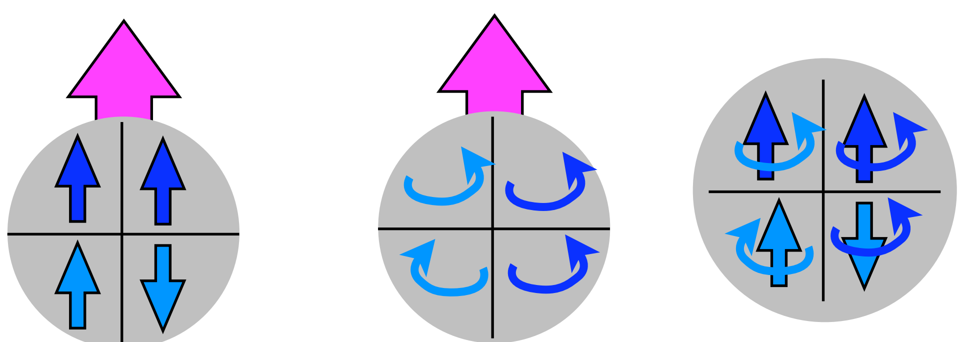
is it a HAPPY picture?

A Tantalizing Picture from SIDIS + Lensing Models

- **Transversity**: $h_{1,u} > 0 \quad h_{1,d} < 0$
  → same as $g_{1,u}$ and $g_{1,d}$ in NR limit
- **Sivers**: $f_{1T^{\perp},u} < 0 \quad f_{1T^{\perp},d} > 0$
  → relat^{n} to **anomalous magnetic moment***
  $f_{1T^{\perp},q} \sim \kappa_q$ where $\kappa_u \approx +1.67 \quad \kappa_d \approx -2.03$
  values achieve $\kappa^{p,n} = \Sigma_q e_q \kappa_q$ with u,d only
- **Boer-Mulders:** follows that $h_1{}^{\perp}{}_{,u}$ and $h_1{}^{\perp}{}_{,d} < 0$?
  → **results** on **$\langle\cos(2\Phi)\rangle_{UU}$** suggest yes:

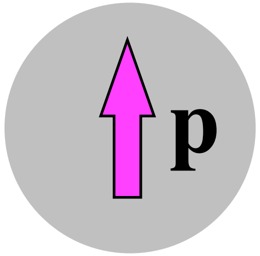


N.B. these TMDs are all ***independent***



$\langle \vec{s}_u \cdot \vec{S}_p \rangle = +0.5 \quad \langle \vec{l}_u \cdot \vec{S}_p \rangle = +0.5 \quad \langle \vec{s}_u \cdot \vec{l}_u \rangle = 0$

** Burkardt PRD72 (2005) 094020; Barone et al PRD78 (1008) 045022;*



Meson Cloud on an Envelope → It ORBITS

$|p\rangle = p + N\pi + \Delta\pi + \ldots$

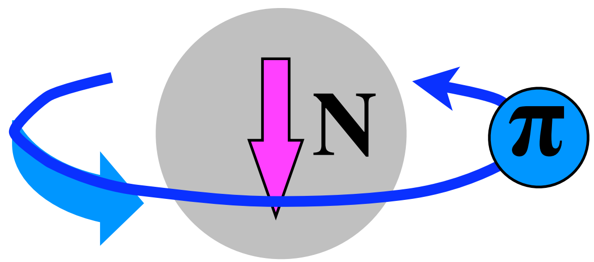
Pions have $J^P = 0^-$ = **negative parity** ...
→ **NEED L = 1** to get proton's $J^P = ½^+$

Nπ cloud:

u

2/3	$n\,\pi^+$
1/3	$p\,\pi^0$

⊗



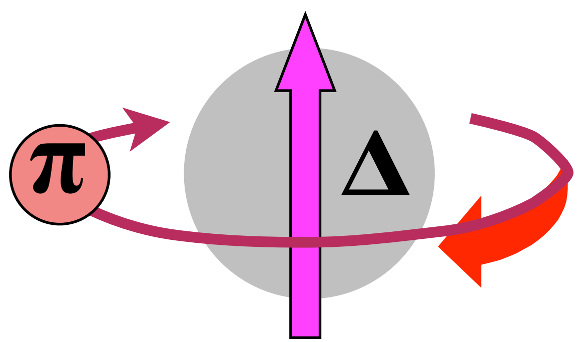
2/3	$L_z = +1$
1/3	$L_z = 0$

Δπ cloud:

d

1/2	$\Delta^{++}\,\pi^-$
1/3	$\Delta^+\,\pi^0$
1/6	$\Delta^0\,\pi^+$

⊗



1/2	$L_z = -1$
1/3	$L_z = 0$
1/6	$L_z = +1$

Dominant source of:

orbiting u: $n\,\pi^+$ with $L_z(\pi) > 0$
orbiting d: $\Delta^{++}\,\pi^-$ with $L_z(\pi) < 0$

⇒

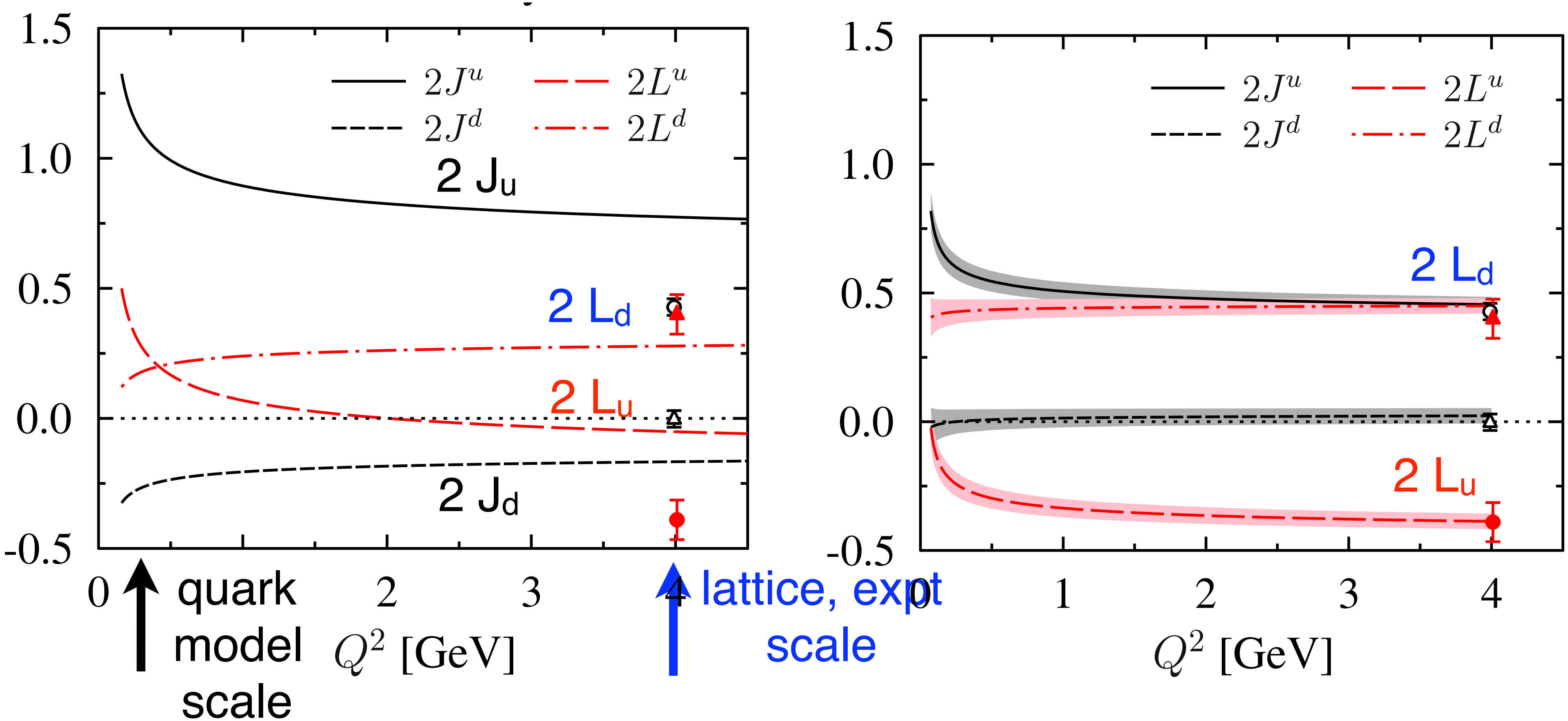
$L_u > 0$
$L_d < 0$
$L_{qbar} \neq 0$

Thomas, PRL101 (2008)

... and Longitudinal spin on the lattice ...

Wakamatsu, EPJA44 (2010)

Thomas: **cloudy bag model** evolved up to Q^2 of expt / lattice



→ ***lattice shows $L_u < 0$ and $L_d > 0$ in longitudinal case at expt'al scales!***

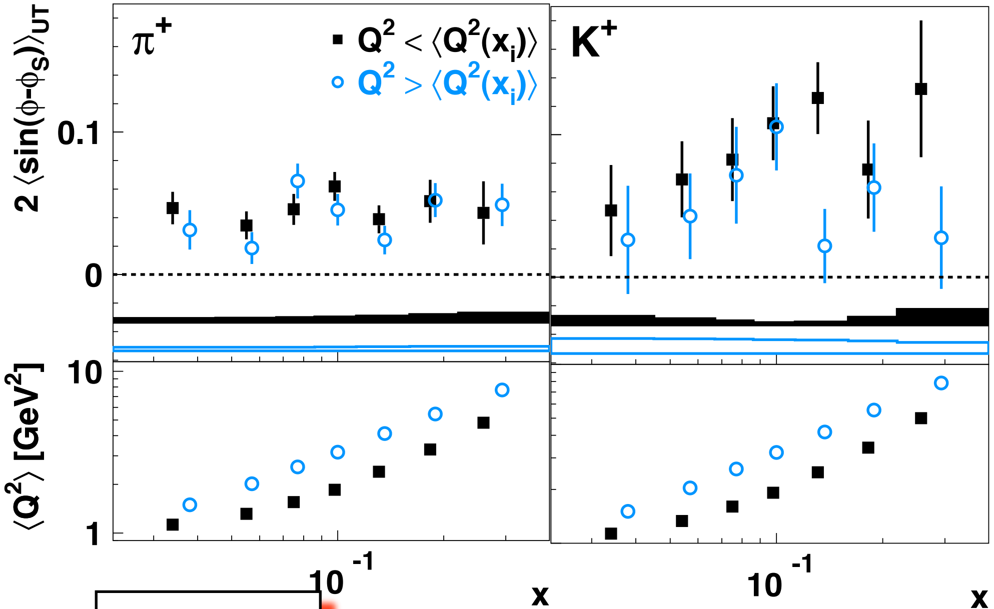
Evolution might explain disagreement with quark models ...

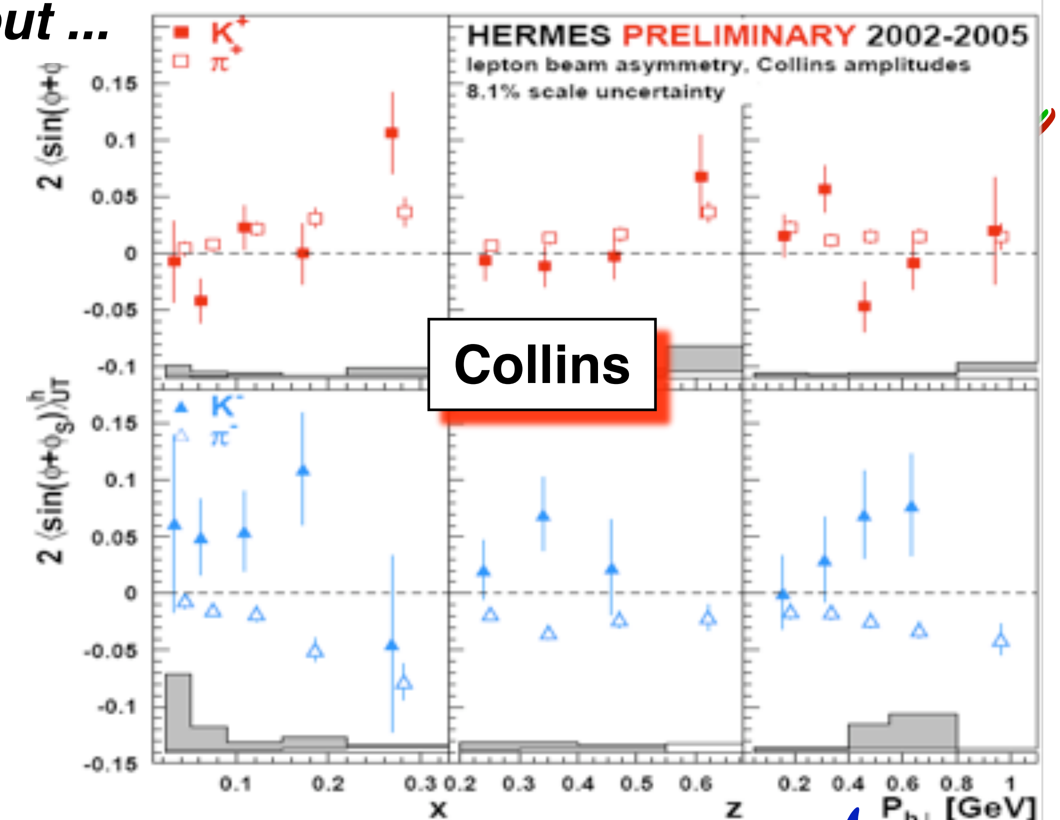
or not. *Wakamatsu evolves down → insensitive to uncertain scale of quark models*

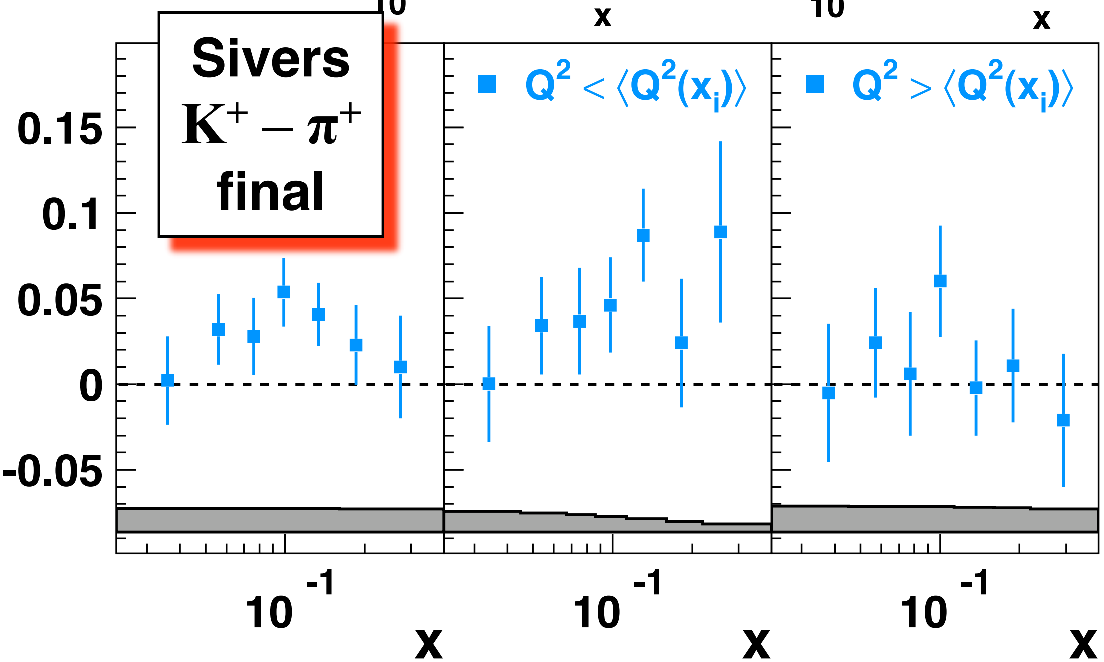
Enter the Sea

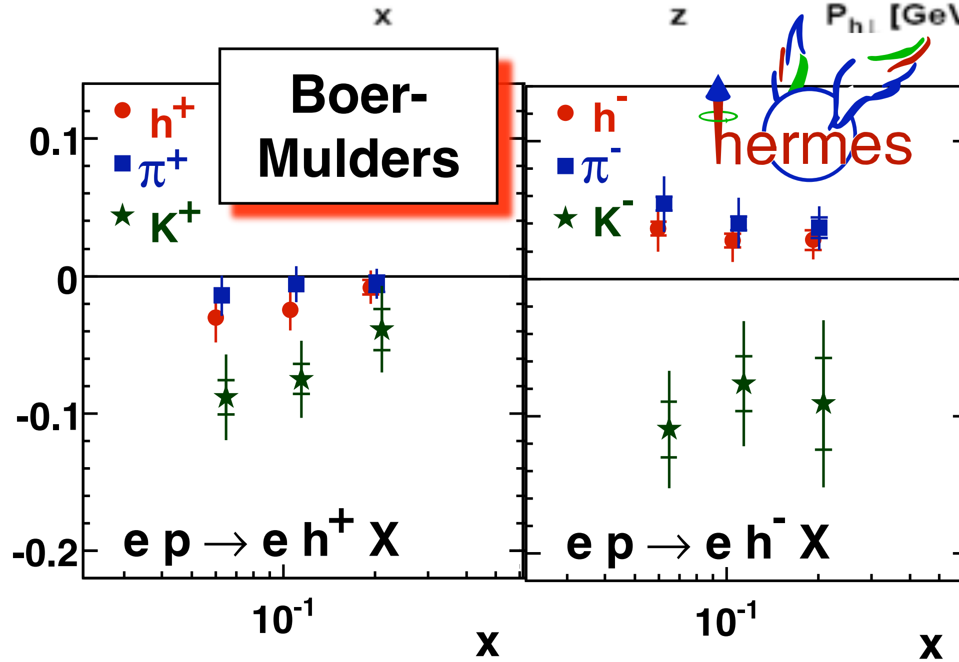
New Sivers fits give ≈0 for antiquarks, but ...

The Kaon Collection









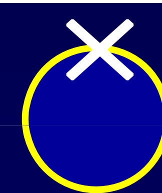
... and BRAHMS SSA's for kaons, never explained ...

Flavor-singlet g_A

KehFeh Liu,
INT Workshop, Feb 2012

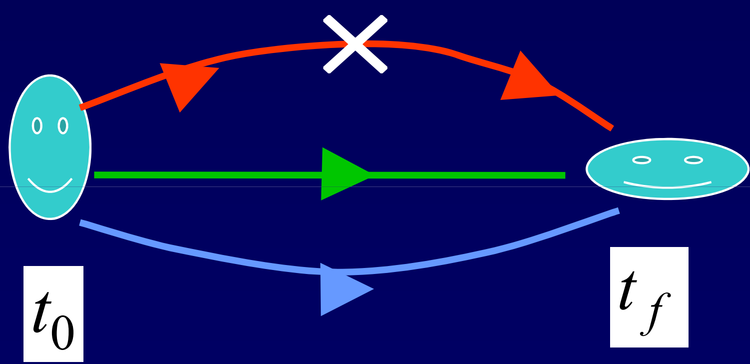
- Quark spin puzzle (dubbed `proton spin crisis')
  - $$g_A^0 = \Delta u + \Delta d + \Delta s = \begin{cases} 1 & \text{NRQM} \\ 0.75 & \text{RQM} \end{cases}$$
  - Experimentally (EMC, SMC, … $\Delta\Sigma = g_A^0 \sim 0.2 - 0.3$

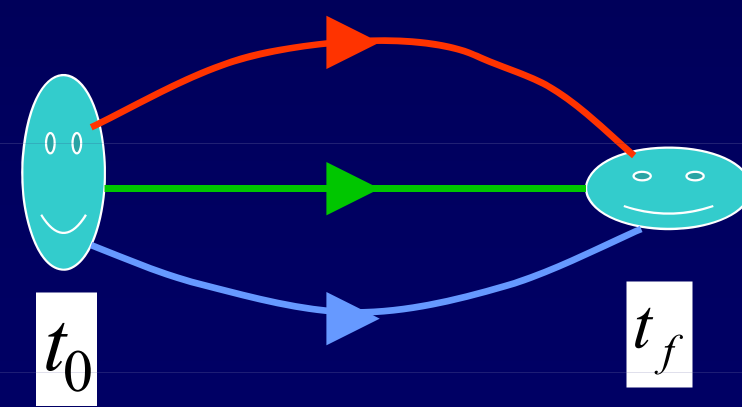
$$\overline{\Psi}\gamma_\mu\gamma_5\Psi(t)(u,d,s)$$



New: Disconnected Insertions → Sea

$$(\overline{u}\gamma_\mu\gamma_5 u + \overline{d}\gamma_\mu\gamma_5 d)(t)$$





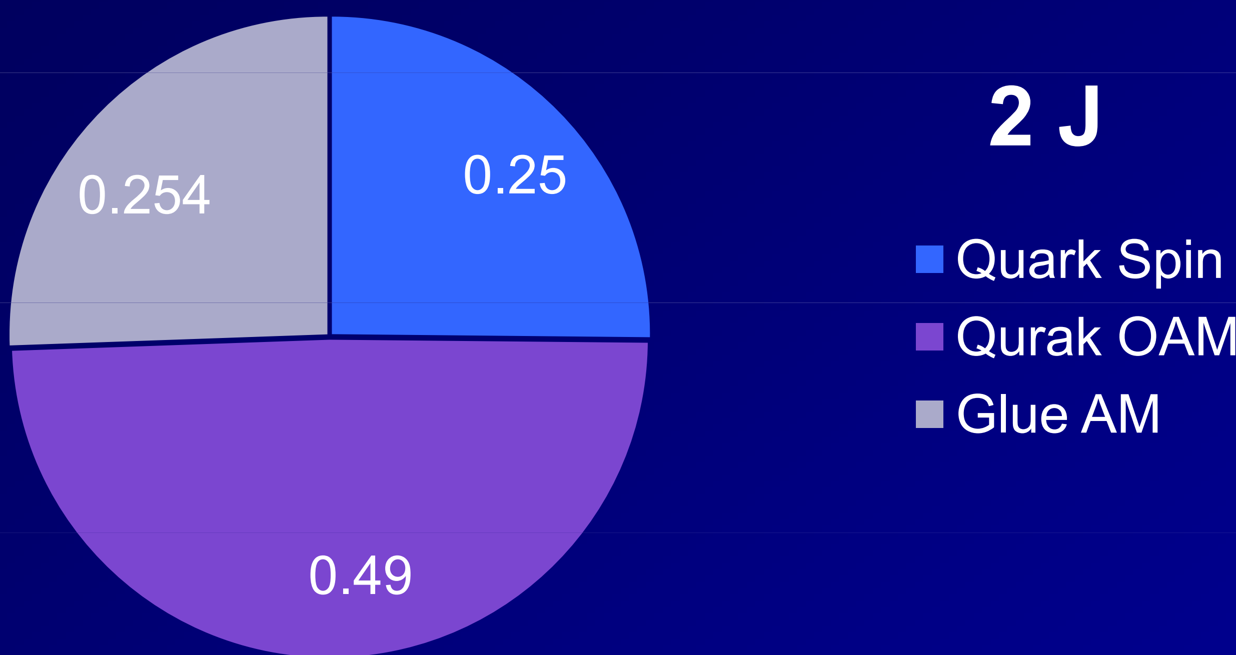
$$g^0_{A,con} = (\Delta u + \Delta d)_{con}$$

$$g^0_{A,dis} = (\Delta u + \Delta d + \Delta s)_{dis}$$

Renormalized results:

	CI(u)	CI(d)	CI(u+d)	DI(u/d)	DI(s)	Glue
2J	0.726 (128)	-.072 (82)	0.651 (51)	0.036 (7)	0.023 (7)	0.254 (76)
g_A	0.95 (11)	-0.32 (12)	0.65 (8)	-0.12 (1)	-0.12 (1)	
2 L	-0.25 (18)	0.26 (14)	0.00 (10)	0.17 (2)	0.15 (2)	

Quark Spin, Orbital Angular Momentum, and Gule Angular Momentum



The Sea is Orbiting!

$$\Delta q \approx 0.25;$$

$$2\ L_q \approx 0.49\ (0.0(\mathrm{CI}) + 0.49(\mathrm{DI}));$$

$$2\ \mathrm{J}_g \approx 0.25$$

Proton Spin Decompositions

$$J^{\mathrm{Ji}} = \frac{i}{2} q^\dagger (\vec{r} \times \vec{D})^z q + \frac{1}{2} q^\dagger \sigma^z q + 2\,\mathrm{Tr}\, E^j (\vec{r} \times \vec{D})^z A^j + \mathrm{Tr}(\vec{E} \times \vec{A})^z$$

L_q Δq L_g Δg

$$J^{\mathrm{Jaffe}} = \frac{1}{2} q_+^\dagger (\vec{r} \times i\vec{\nabla})^z q_+ + \frac{1}{2} q_+^\dagger \gamma_5 q_+ + 2\,\mathrm{Tr}\, F^{+j} (\vec{r} \times i\vec{\nabla})^z A^j + \varepsilon^{+-ij} \mathrm{Tr} \vec{F}^{+i} \vec{A}^j$$

Ji, PRL 78 (1997)

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Ji: ❸ gauge invariant Δq, L_q, J_g

✘ **access Δg**: no GI sep^n of Δg, L_g

✔ **measure L_q** (expt & lattice):
yes → via GPDs & DVCS

✘ **interpret L_q**: covariant derivative
$D^\mu = \partial^\mu + i g^\mu$ ← **gluon interac's**

Ji, PRL 78 (1997)

Proton Spin Decompositions

Jaffe & Bashinsky, NPB 536 (1998)

$$J^{\text{Ji}} = \frac{i}{2}q^\dagger(\vec{r}\times\vec{D})^z q + \frac{1}{2}q^\dagger\sigma^z q + 2\,\mathrm{Tr}\,E^j(\vec{r}\times\vec{D})^z A^j + \mathrm{Tr}(\vec{E}\times\vec{A})^z$$

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- ✔ **access Δg**: this is what's being measured at RHIC, COMPASS
- ✔ **interpret L_q**: $\vec{r}\times\vec{p}$ → field-free OAM ... in ∞ momentum frame
- ✘ **measure L_q** (expt & lattice): involves **non-local** operators except in **lightcone gauge** $A^+=0$

Proton Spin Decompositions

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$$\qquad L_q \qquad\qquad \Delta q \qquad\qquad L_g \qquad\qquad \Delta g$$

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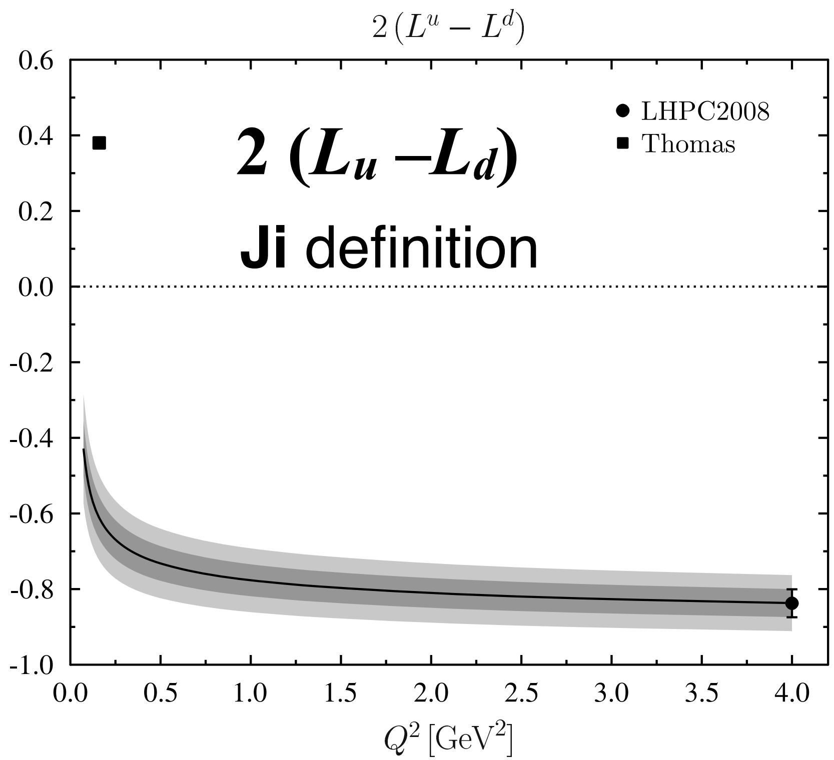
see ongoing work of **Wakamatsu** *PRD 81 (2010), 83 (2011)*
& **Chen** et al *PRL 100 (2008), 103 (2009)*

Insights from the χQSM

Wakamatsu, EPJA 44 (2010)

Theory: Ji's L_{u-d} is rock-solid & **negative**



$$2\,L_q^{\mathrm{Ji}} = \underbrace{\left[\langle x\rangle_q + E_q^{(2)}\right]}_{=J_q} - \Delta q$$

- $<x>_{u-d}$: well known
- $\Delta u - \Delta d = g_A$: well known
- $E^{(2)}_{u-d}$: **<u>all</u> lattice** calculat^{n}s **<u>and</u> XQSM** agree

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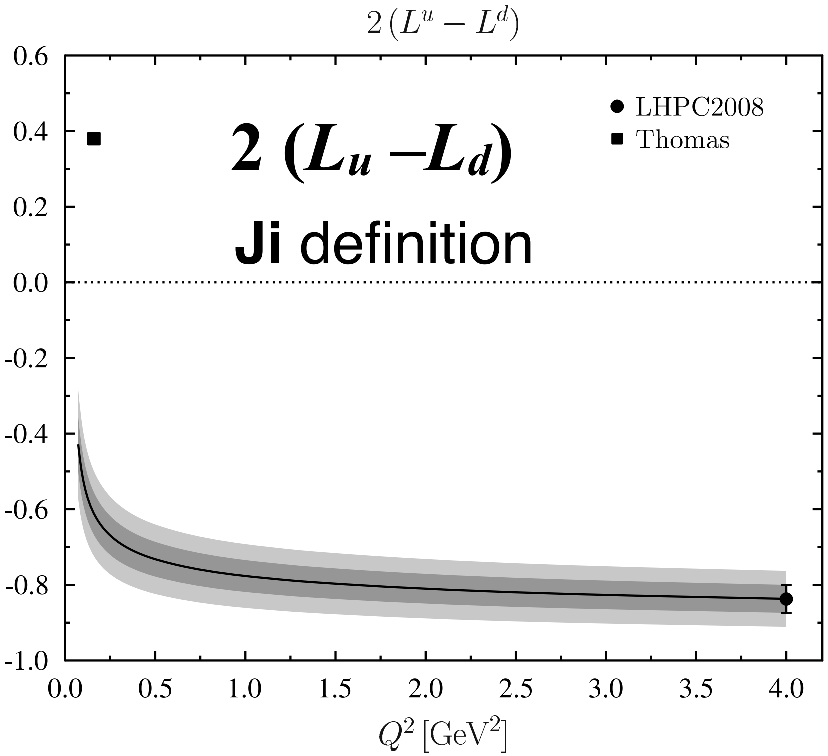

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Compare Jaffe & Ji

calculate explicitly in χQSM;
at quark-model scale:

	L_{u-d} Jaffe	L_{u-d} Ji
Valence	+0.147	–0.142
Sea	–0.265	–0.188
Total	–0.115	–0.330

Negative model value dominated by sea quark L !

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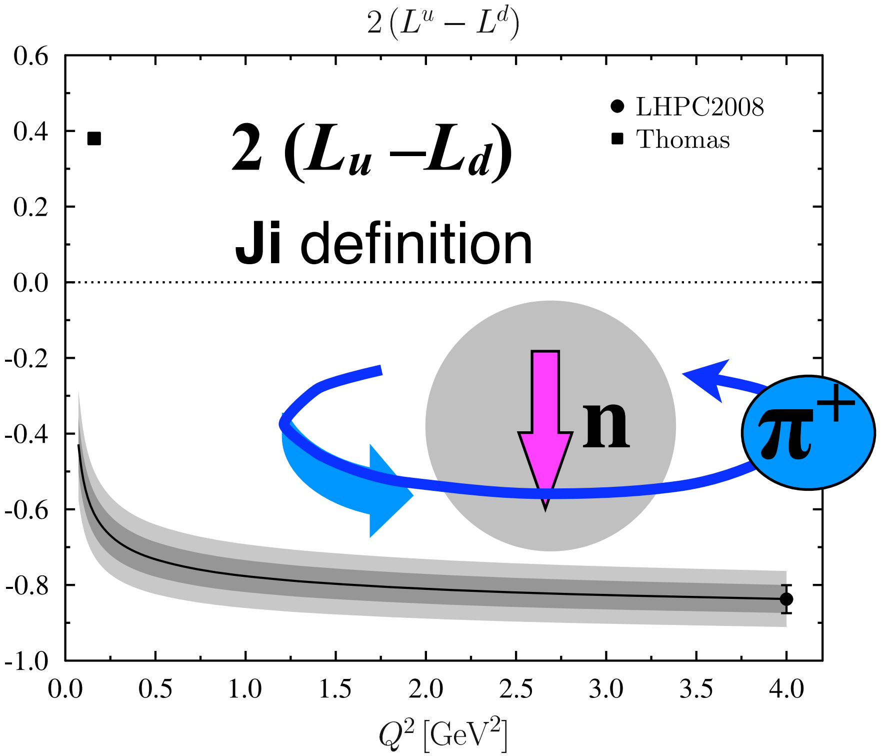

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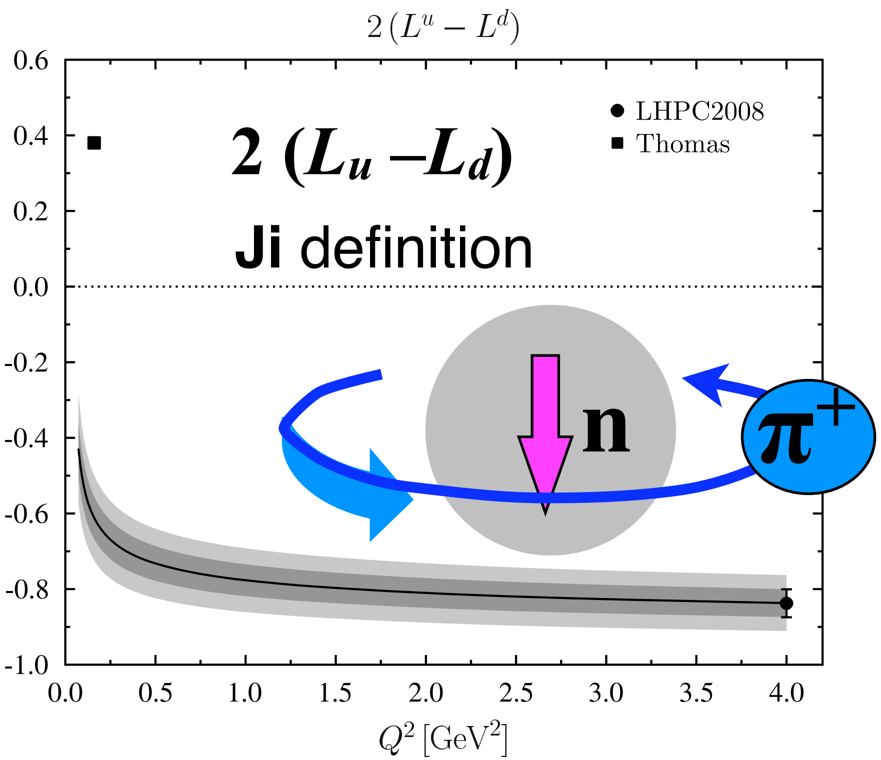

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Negative model value dominated by sea quark L !

Need direct measurement of Sivers for sea quarks:

Spin-dependent Drell-Yan with p or π^+ beam & pol'd target

TMD Evolution

Turin standard approach (DGLAP)

- Unpolarized TMDs are factorized in x and $k_\perp$. Only the collinear part evolves with DGLAP evolution equation. No evolution in the transverse momenta:

$$\widehat{f}_{q/p}(x, k_\perp; Q) = f_{q/p}(x; Q)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

Collinear PDF (DGLAP evolution)

Normalized Gaussian: no evolution

TMD evolution formalism*

*•J.C. Collins, Foundation of Perturbative QCD, Cambridge Monographs on Particle Physics, Nuclear Physics and Cosmology, No. 32, Cambridge University Press, 2011.

•S. M. Aybat and T. C. Rogers, Phys. Rev. D83, 114042 (2011), arXiv:1101.5057 [hep-ph]

•S. M. Aybat, J. C. Collins, J.-W. Qiu and T.C. Rogers, arXiv:1110.6428 [hep-ph]

R$_e^e$volution!

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TMD evolution formalism

- At LO the evolution equation can be summarized by the following expression:

$$\widetilde{F}(x, \boldsymbol{b}_T; Q) = \widetilde{F}(x, \boldsymbol{b}_T; Q_0)\, \widetilde{R}(Q, Q_0, b_T)\, \exp\left\{-g_K(b_T) \ln \frac{Q}{Q_0}\right\}$$

Output function at the scale **Q** in the impact parameter space

Input function at the scale $\mathbf{Q_0}$ in the impact parameter space

Evolution kernel

TMD evolution formalism

- At LO the evolution equation can be summarized by the following expression:

$$\widetilde{F}(x, \boldsymbol{b}_T; Q) = \widetilde{F}(x, \boldsymbol{b}_T; Q_0)\, \widetilde{R}(Q, Q_0, b_T)\, \exp\left\{-g_K(b_T) \ln \frac{Q}{Q_0}\right\}$$

- **Non Perturbative** (scale independent) part of the evolution kernel that needs to be empirically modeled

$$g_K(b_T) = \frac{1}{2}\, g_2\, b_T^2$$

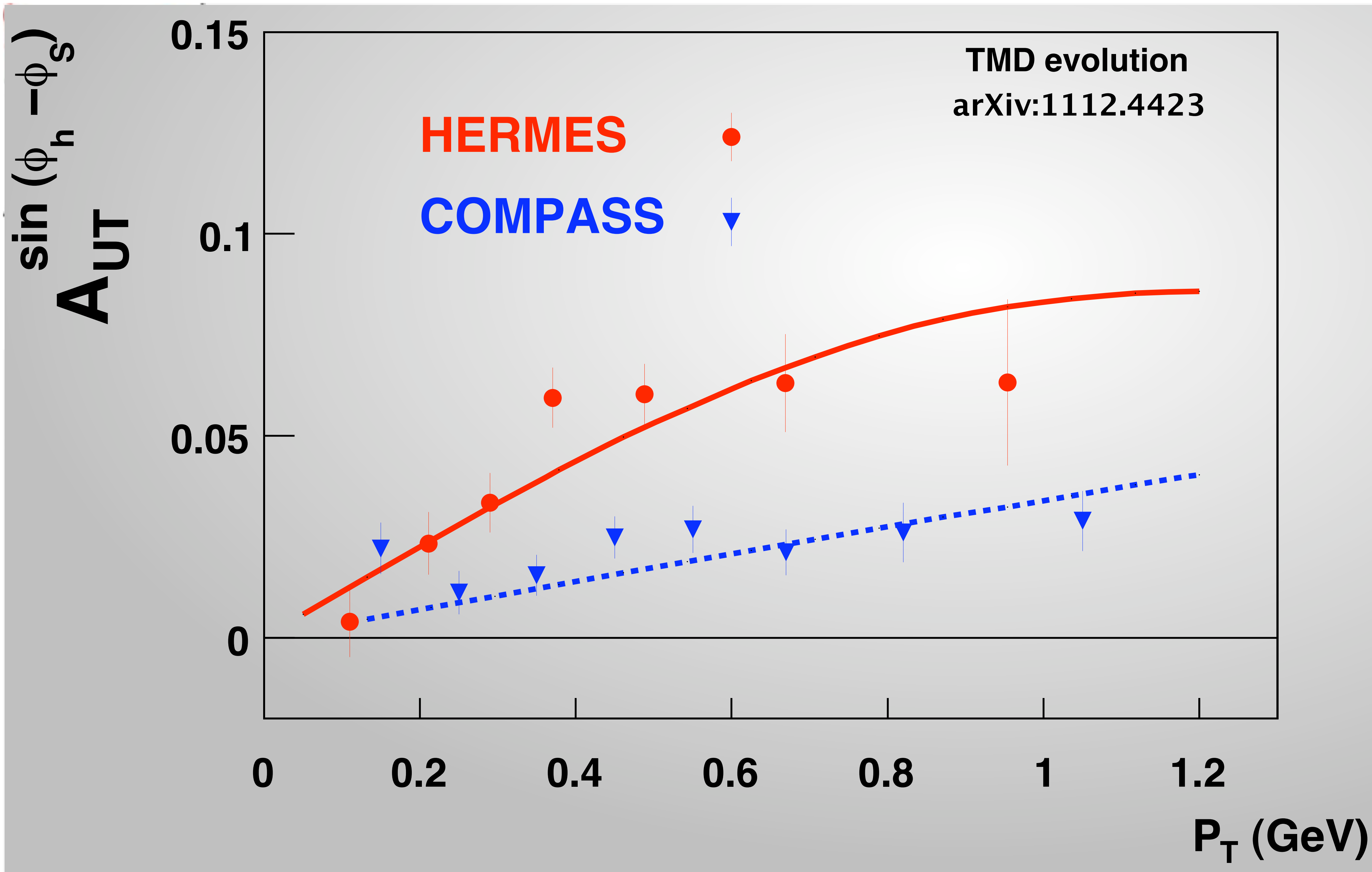
$$g_2 = 0.68\ \mathrm{GeV}^2$$

Common choice used in the unpolarized DY data analyses in the CSS formalism

Landry et al. Phys Rev D67, 073016

Crucial parameters: g_2 and $b_T$max

Great Success in bridging HERMES-COMPASS!



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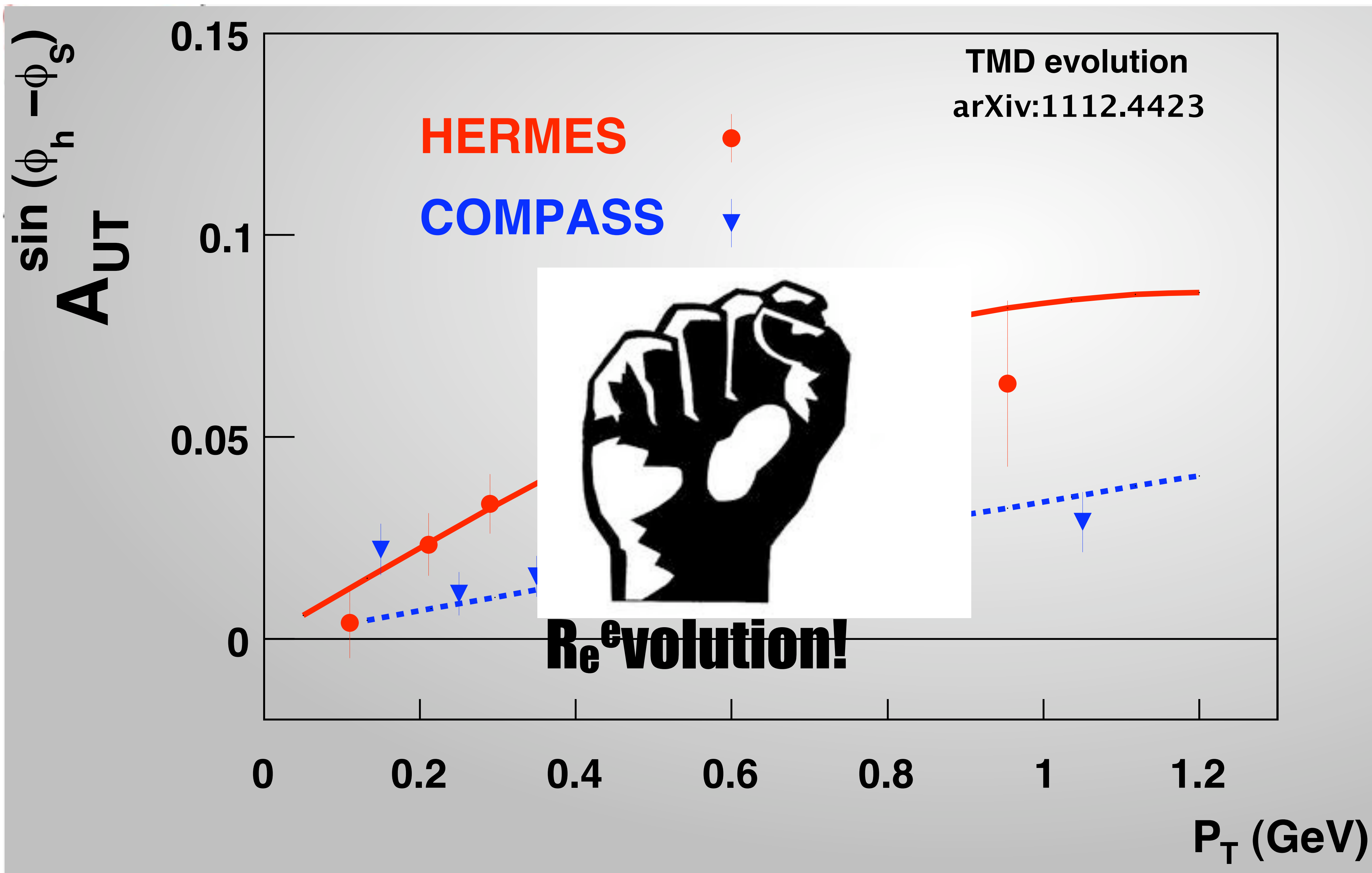
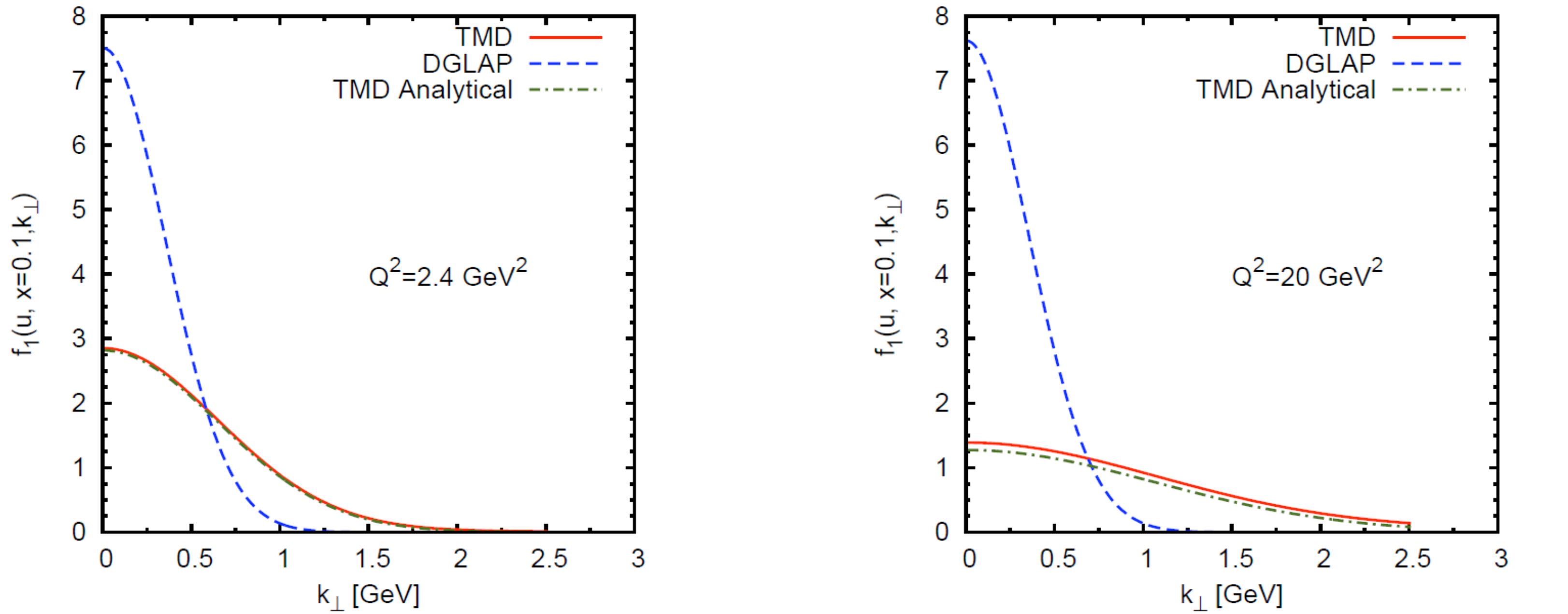


Comparative analysis of TMD evoultion equations

f1: huge effect!



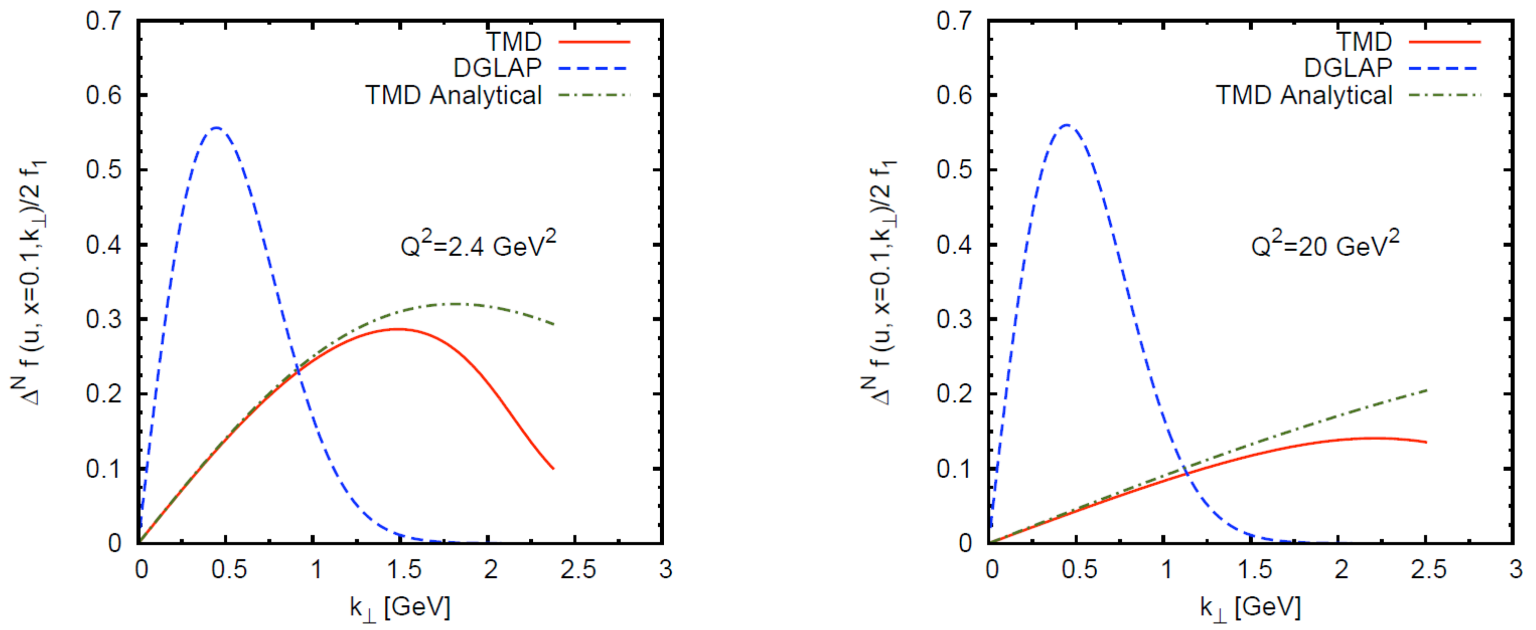
Starting scale Q_0=1 GeV
Same function at Q_0

DGLAP evolution is slow at moderate x and in this range of Q^2

For the unpolarized PDF, the analytical approximation holds up to large $k_\perp$

Comparative analysis of TMD evoultion equations

Sivers: huge effect!



Starting scale Q_0=1 GeV

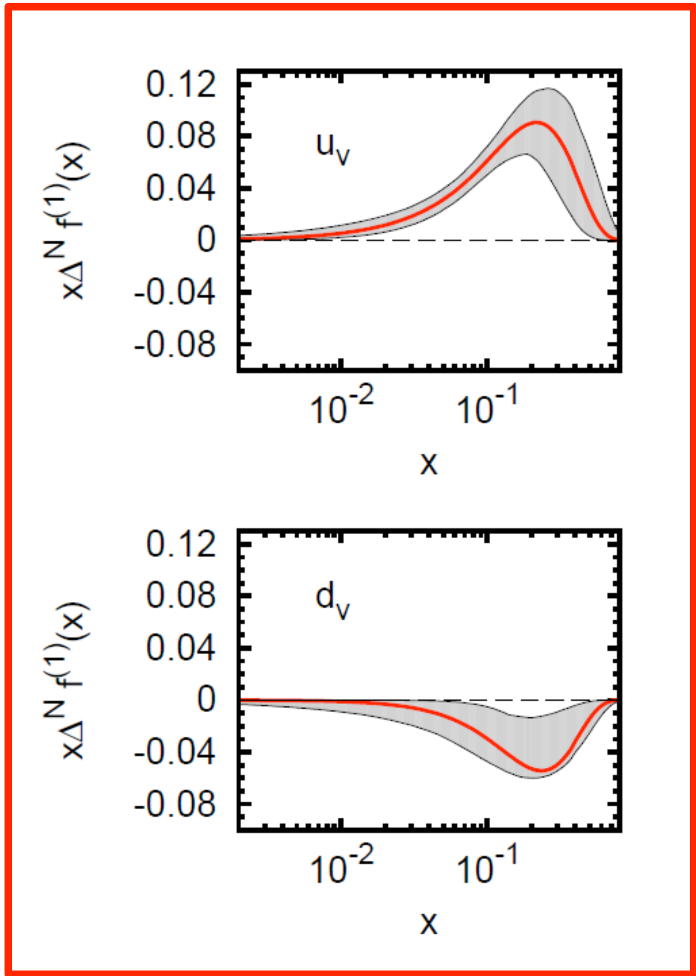
Same function at Q_0

For the Sivers function, the analytical approximation breaks down at large $k_\perp$ values

BIGGER Sivers function from SIDIS!

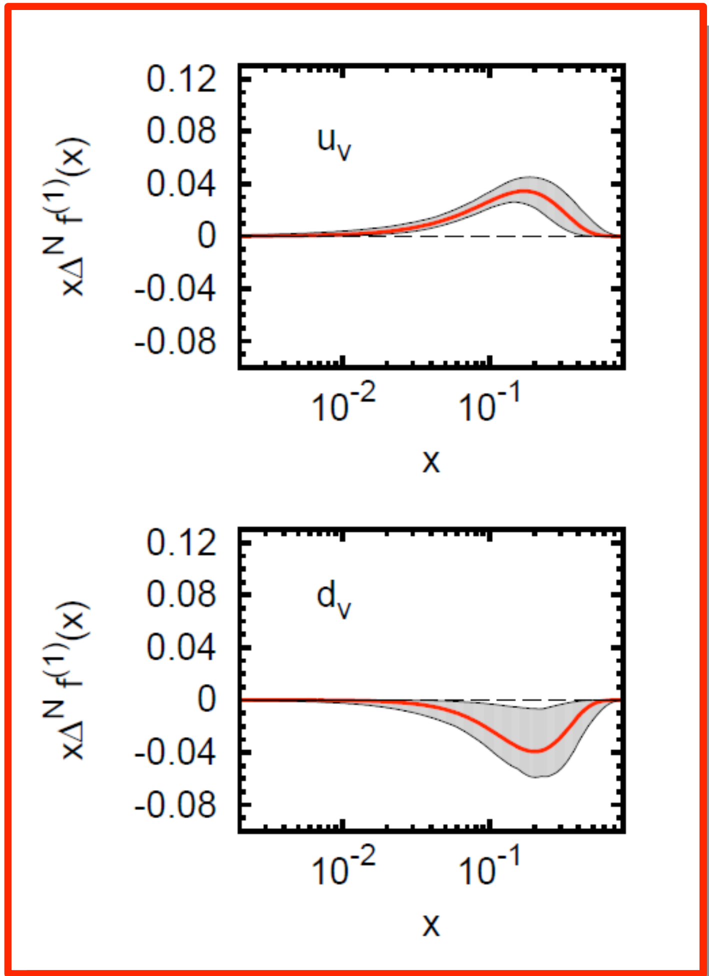
Fit of HERMES and COMPASS SIDIS data

TMD Evolution



Q_0=1 GeV

DGLAP Evolution



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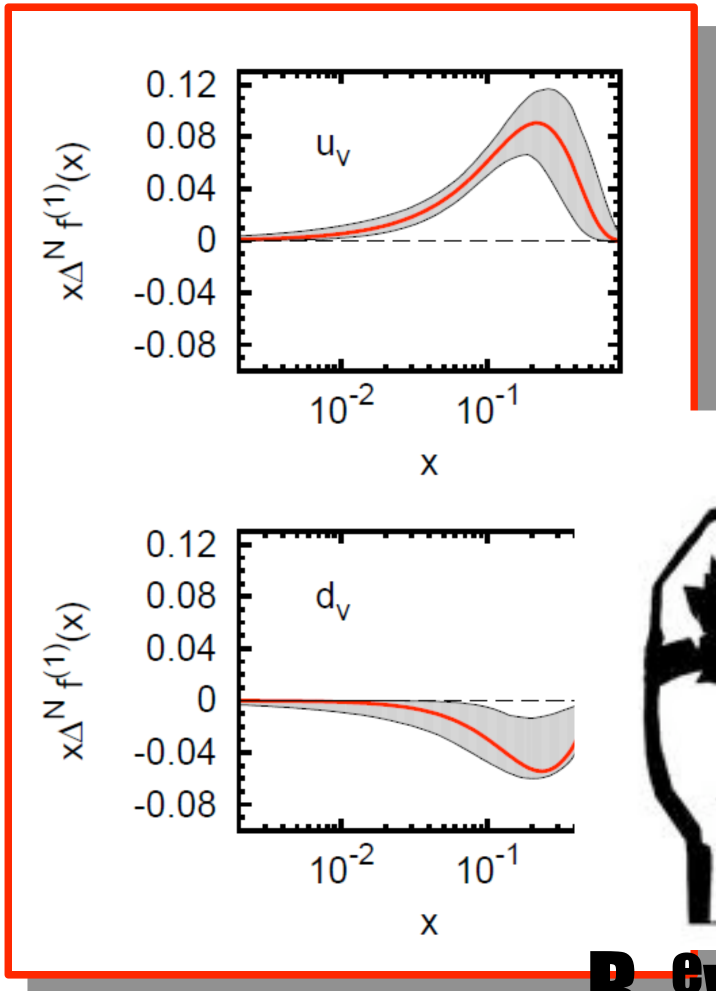
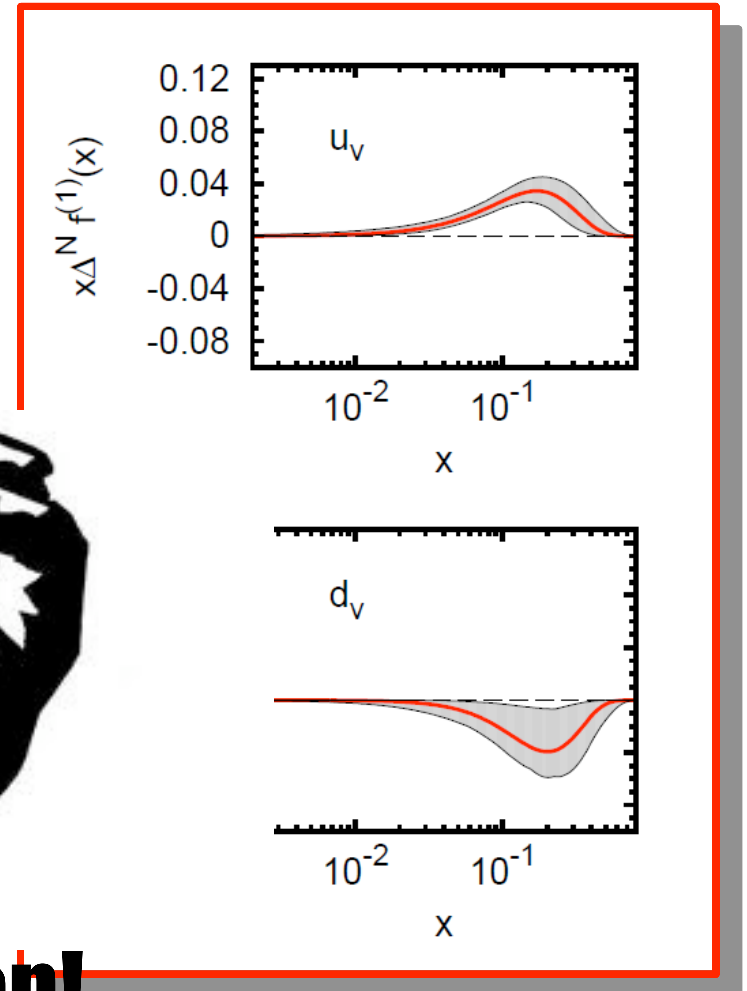


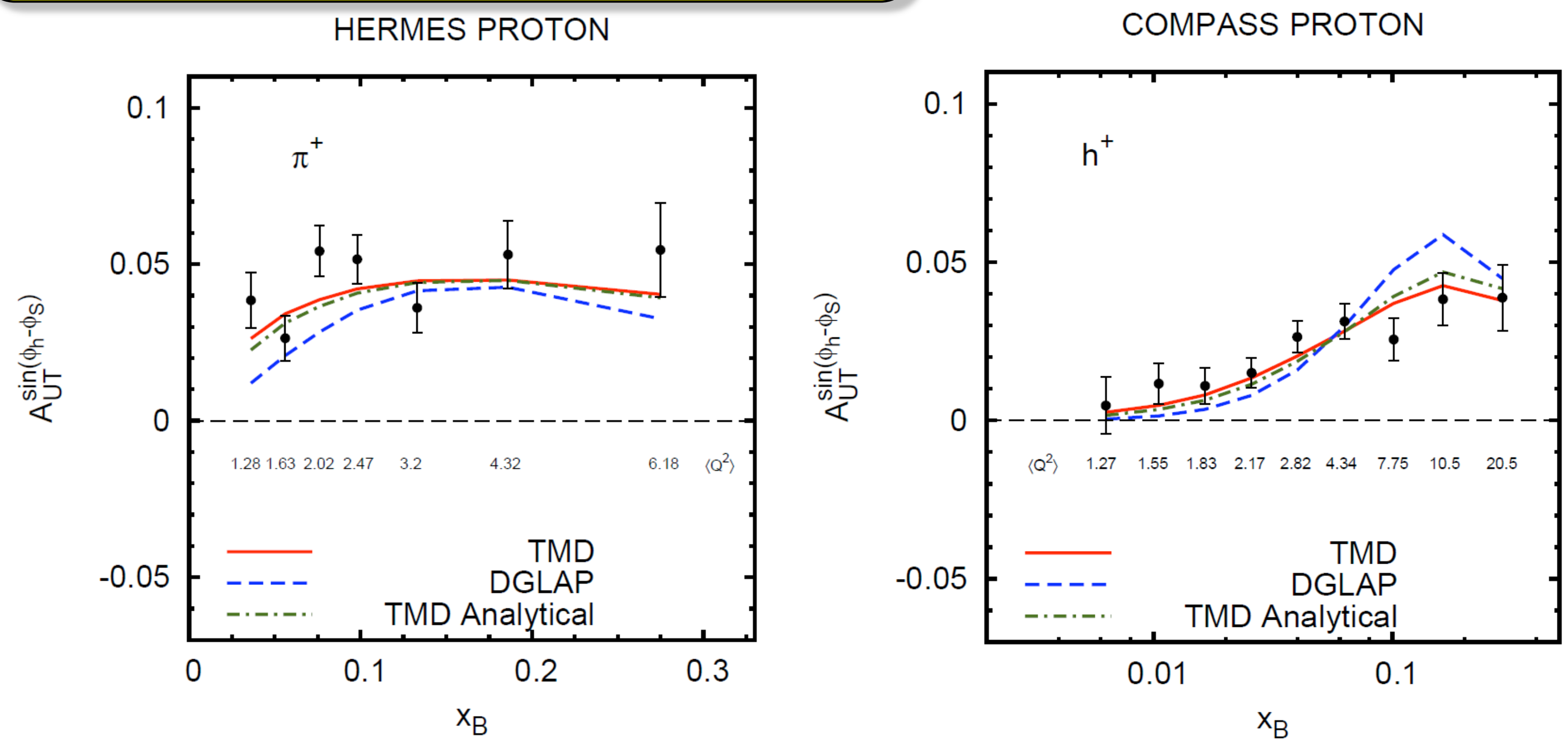
DGLAP Evolution



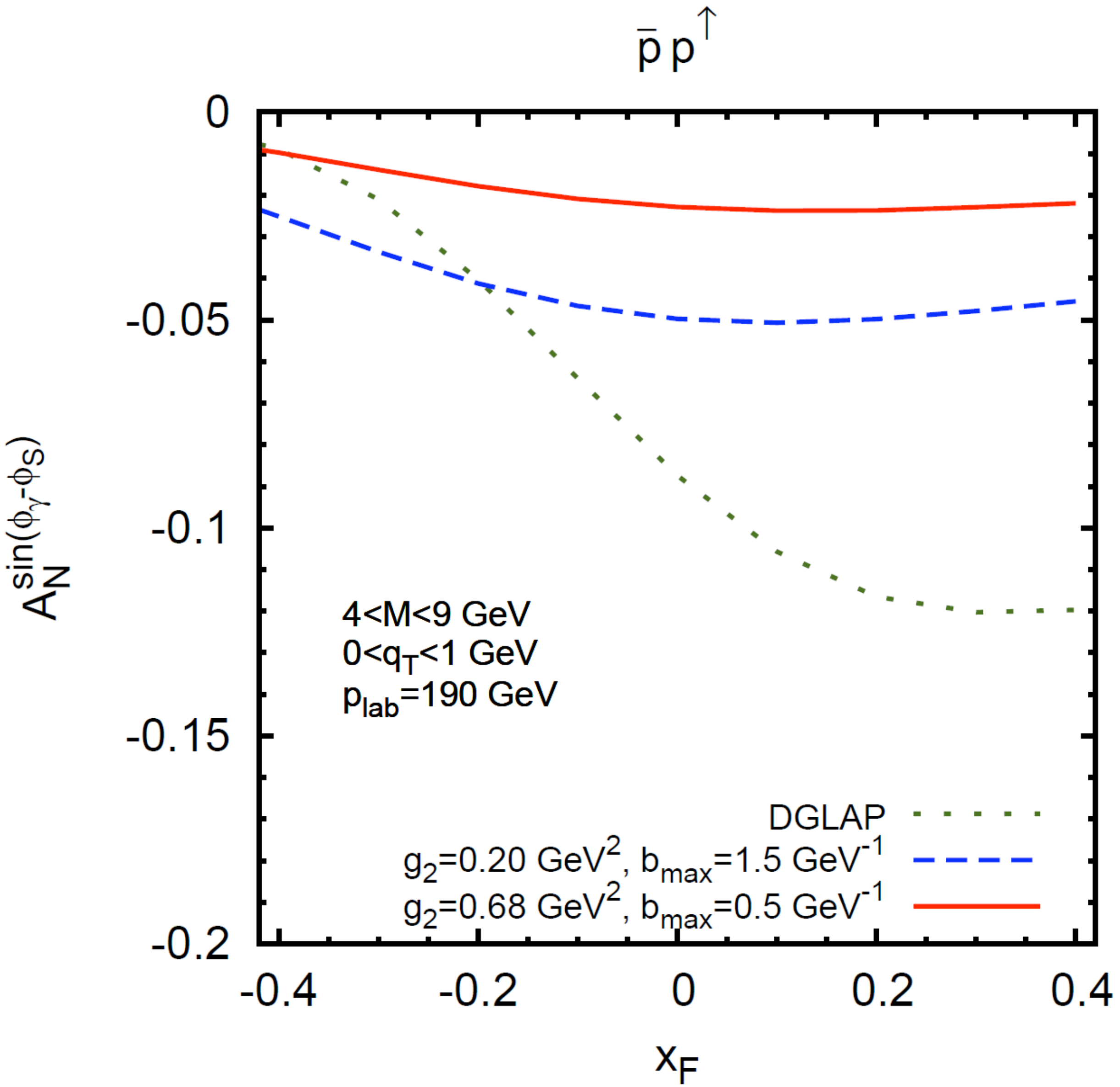
R$_{e}{}^{e}$volution!

Fit of HERMES and COMPASS SIDIS data

Sivers Asym: barely change in SIDIS



Sivers Asym: huge change in DY!



- smaller
- very dependent on g_2,b_{max}

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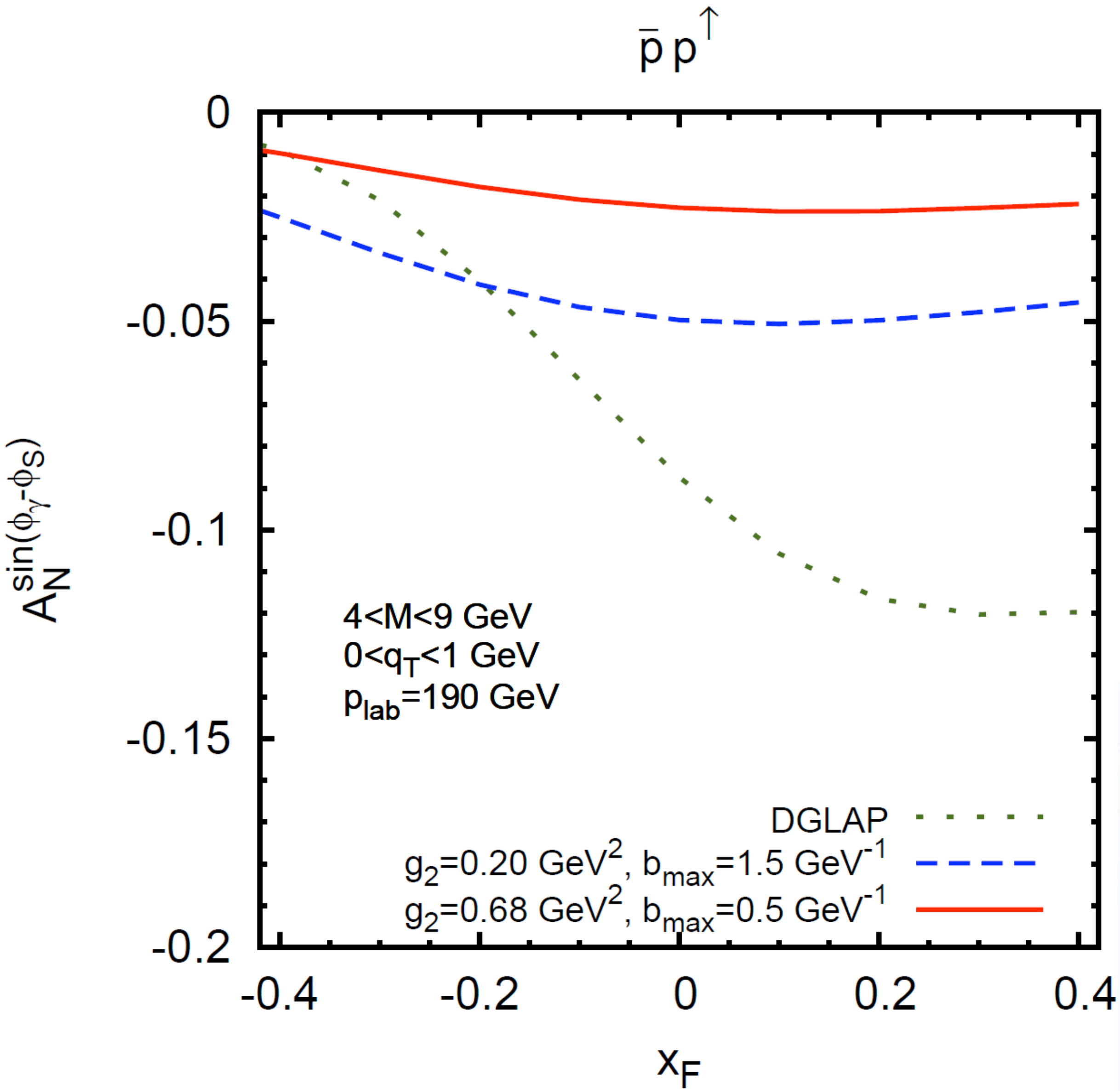
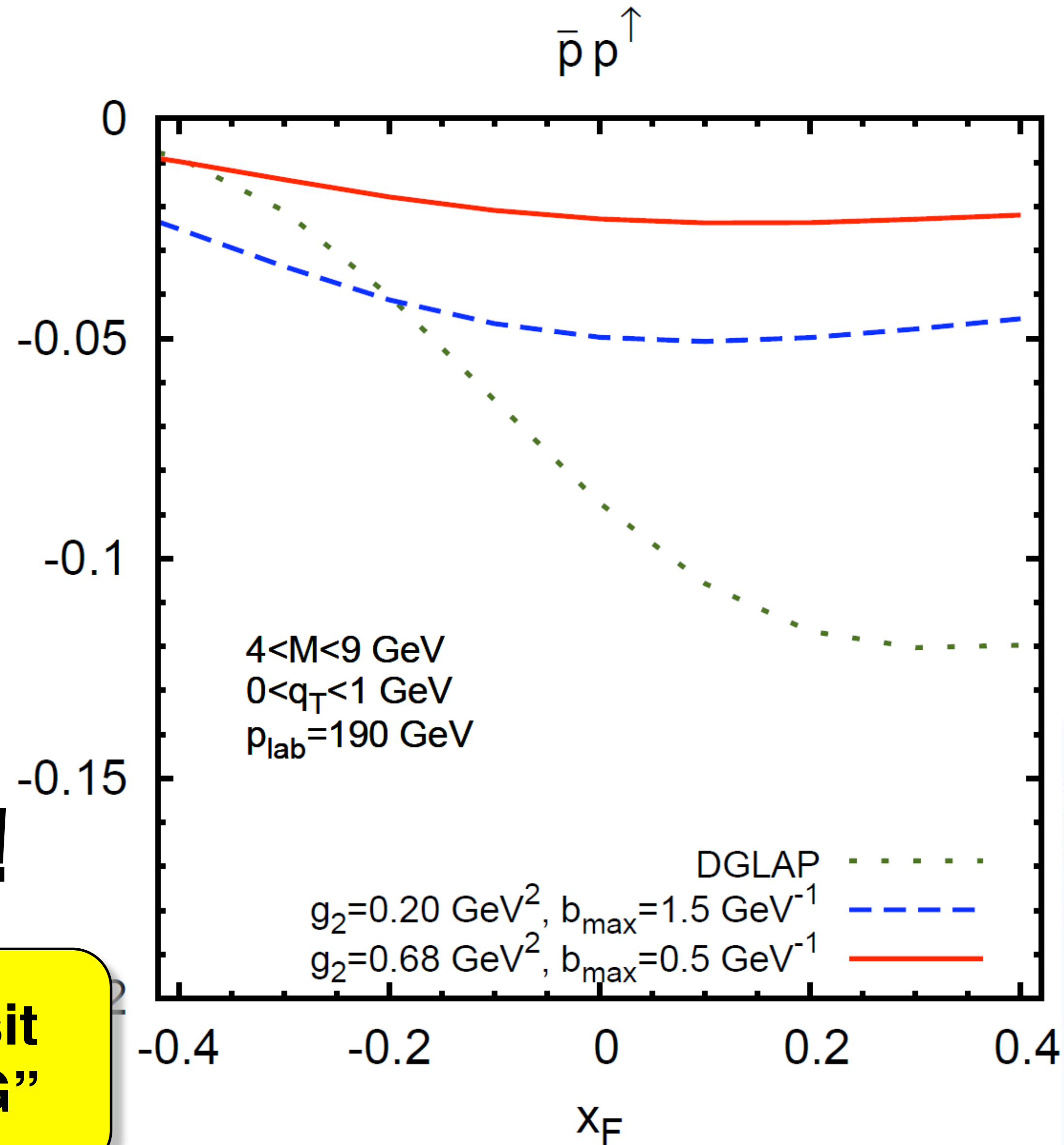


- smaller
- very dependent on g_2,b_{max}

Grumpy Bear

Sivers Asym: huge change in DY!

Re^e^volution!



- **smaller**
- **very dependent on g_2, b_{max}**

Melis: "Revisit EVERYTHING"

Grumpy Bear

$<k^2_\perp>$, Multi-D, and Global Fits

Boer-Mulders function in DY from fits

- Can we safely assume that the average transverse momentum is the same in SIDIS and in DY?

  - Gaussian smearing for unpolarized PDFs

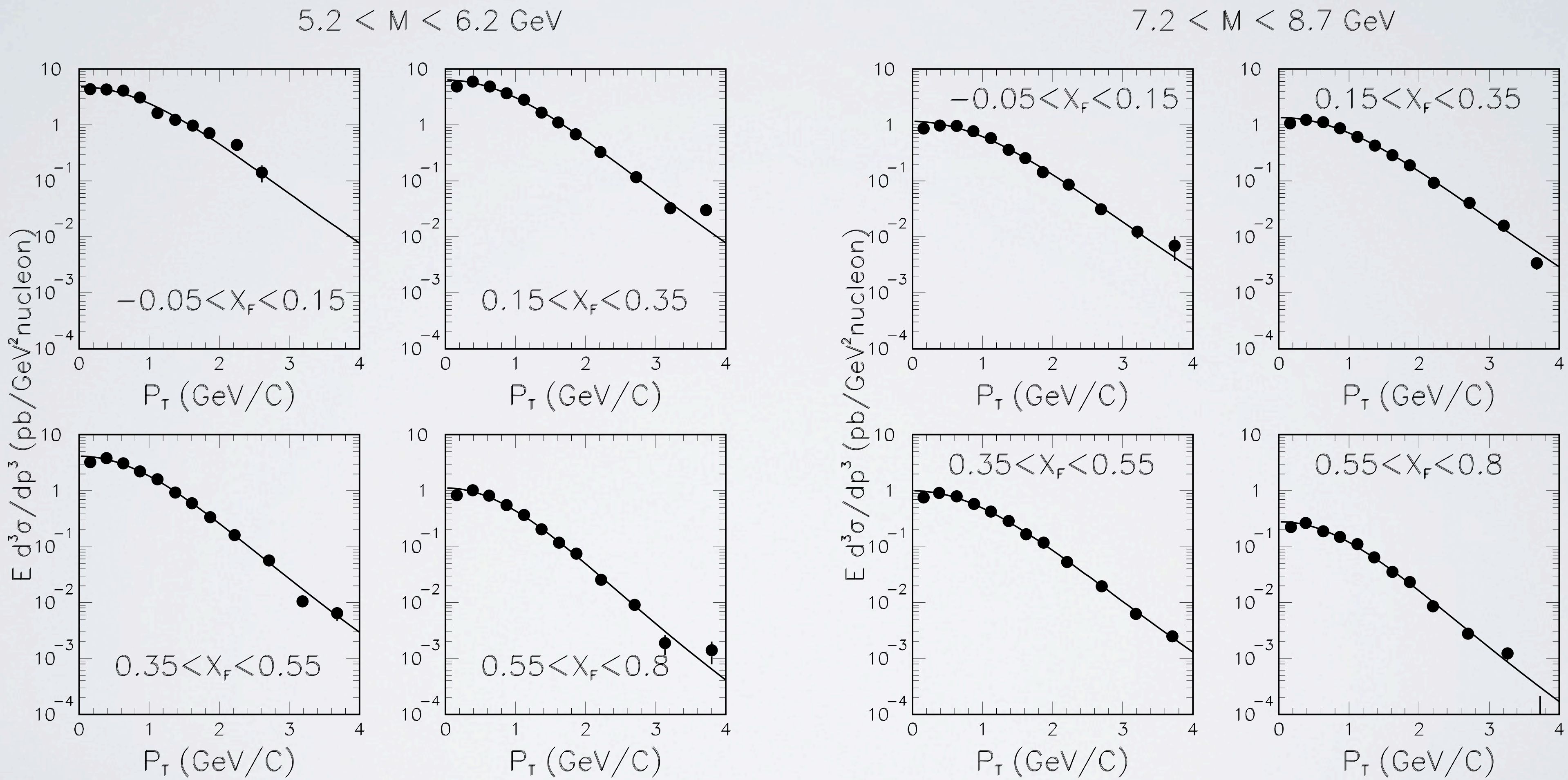
    - $f_{q/p}(x, k_\perp) = f_q(x)\, \frac{1}{\pi \langle k_\perp^2 \rangle}\, e^{-k_\perp^2/\langle k_\perp^2 \rangle}$

From SIDIS: $\langle k_\perp^2 \rangle = 0.25\ (\mathrm{GeV}/c)^2$

Typical DY : $\langle k_\perp^2 \rangle \simeq 0.5 - 1\ (\mathrm{GeV}/c)^2$

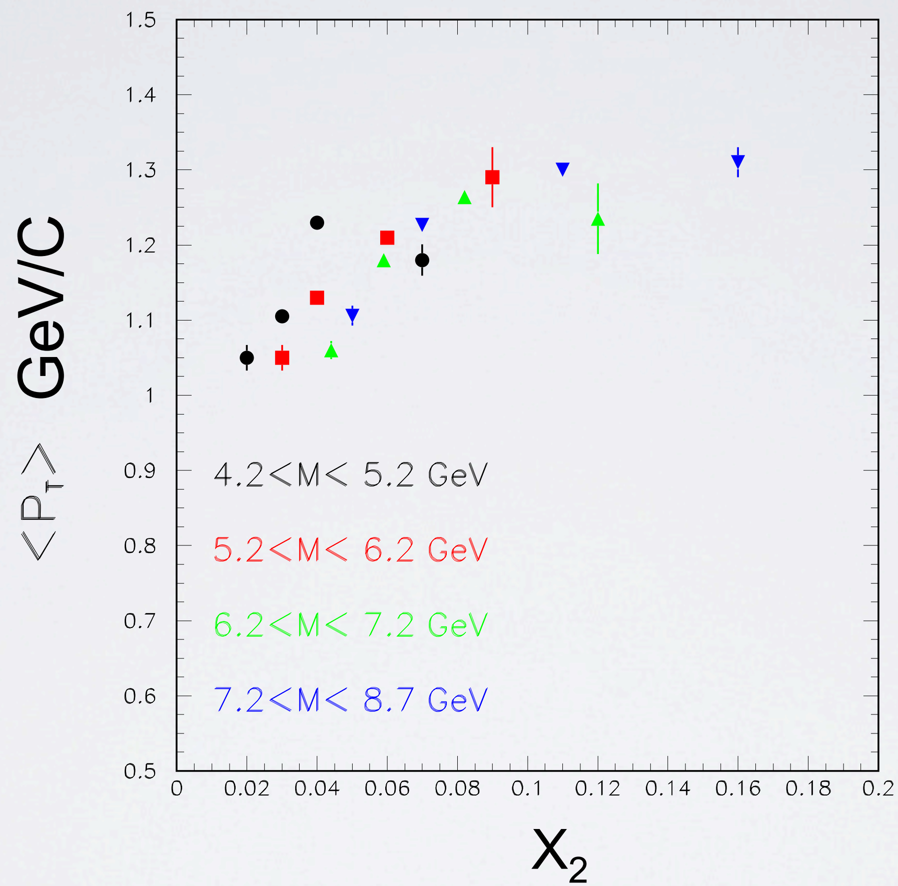
→ Let us try to change this value

Multidim. studies are needed



E866/NuSea preliminary,
talk by J.-C. Peng at DY@BNL workshop

New E866 data



Behavior opposite to BLNY fit

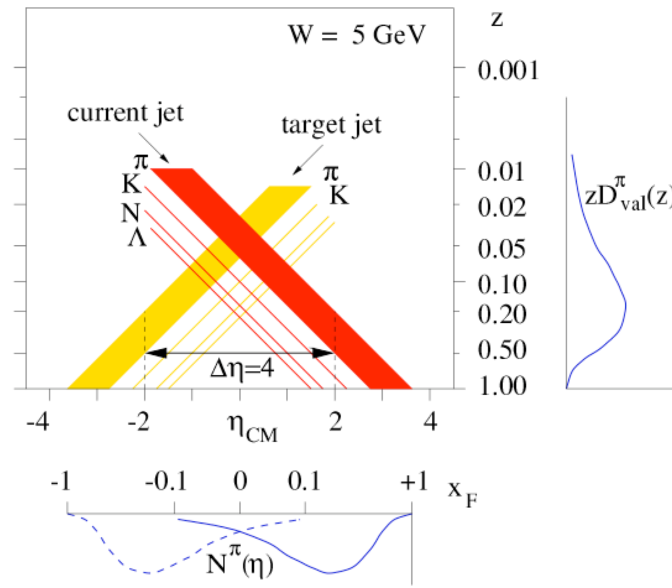
E866/NuSea preliminary,
talk by J.-C. Peng at DY@BNL workshop

multi-D SIDIS Multiplicities Coming → <k⊥> and <p⊥>

- How well do the **favored / disfavored** symmetries & **x-z factoriz^{n}** hold?
  ... assumed in ≈ all FF global fits & PDF extractions
  ... not exact at HERMES energies, acc to Lund MC

$$D_{\text{fav}} \equiv D_u^{\pi^+} = D_d^{\pi^-} = \ldots$$

$$D_{\text{disfav}} \equiv D_u^{\pi^-} = D_d^{\pi^+} = \ldots$$



- Are there **any** such FF symmetries for ***Kaons***?

- Does **intrinsic quark <k$_T$>** vary with ***x***?
  ... with ***flavor*** ? (holy grail!)

- Can the **Lund model** describe fragmentation at different **energies** / different **processes** (SIDIS vs e+e–) ***without retuning*** ?

hermes

paper permanently in progress

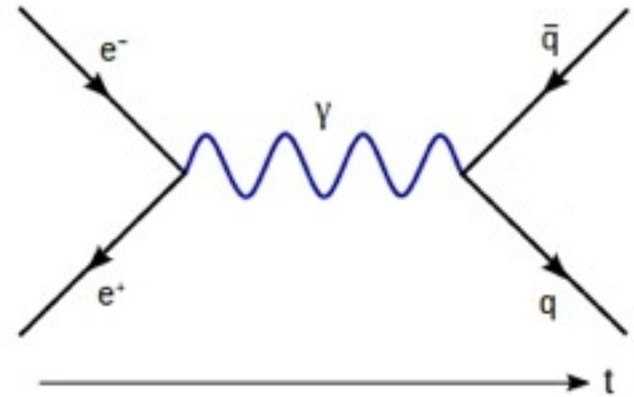
$d\sigma(x,z,p_T)$
$d\sigma(Q^2,z,p_T)$

for $\pi^{\pm}$, π^0,$K^{\pm}$, p, pbar

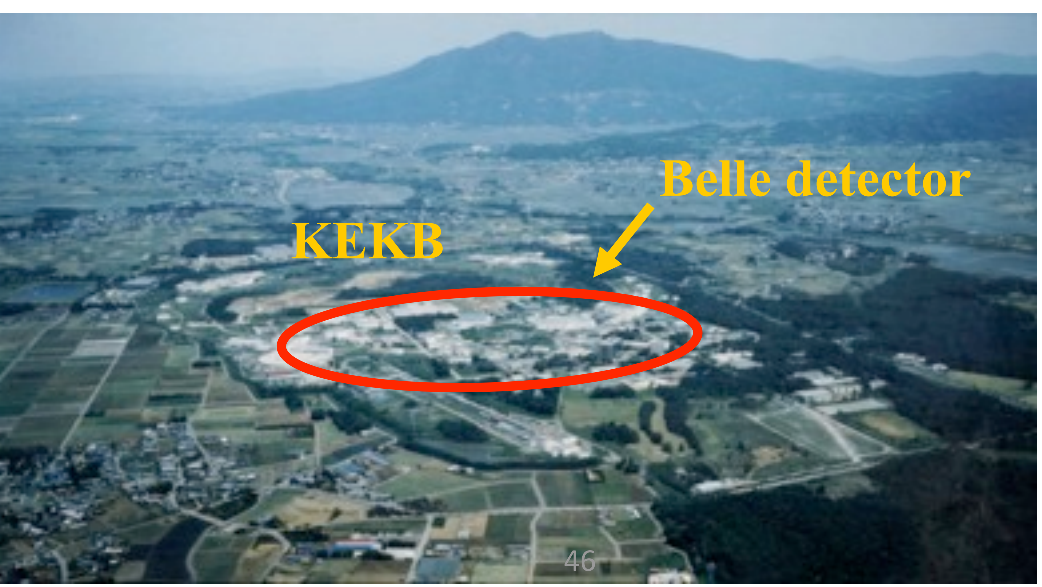
compare

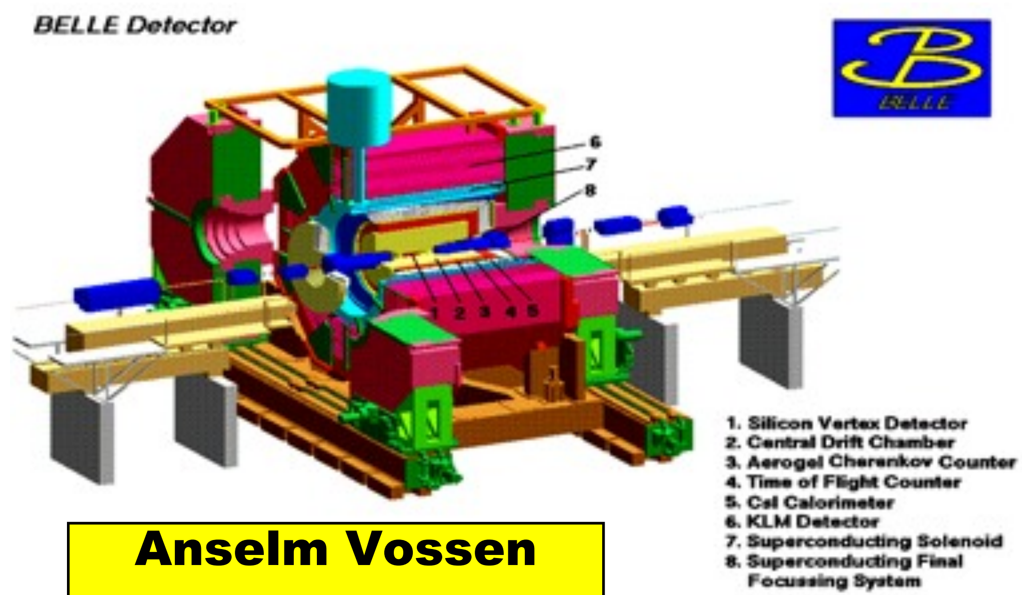
COMPASS-II $\mu^{\pm}$p
- pure LH2 target
- higher energy
- RICH upgrade
- full 4D binning

Measurements of Fragmentation Functions in e+e- at Belle



- KEK-B: asymmetric e^+ (3.5 GeV) e^- (8 GeV) collider:
  - $\sqrt{s}$ = 10.58 GeV, $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\ \bar{B}$
  - $\sqrt{s}$ = 10.52 GeV, e+e-→ qqbar (u,d,s,c) 'continuum'
- ideal detector for high precision measurements:
  - tracking acceptance θ [17 °;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  - ~1.8 $*10^9$ events at 10.58 GeV,
  - ~220 $*10^6$ events at 10.52 GeV

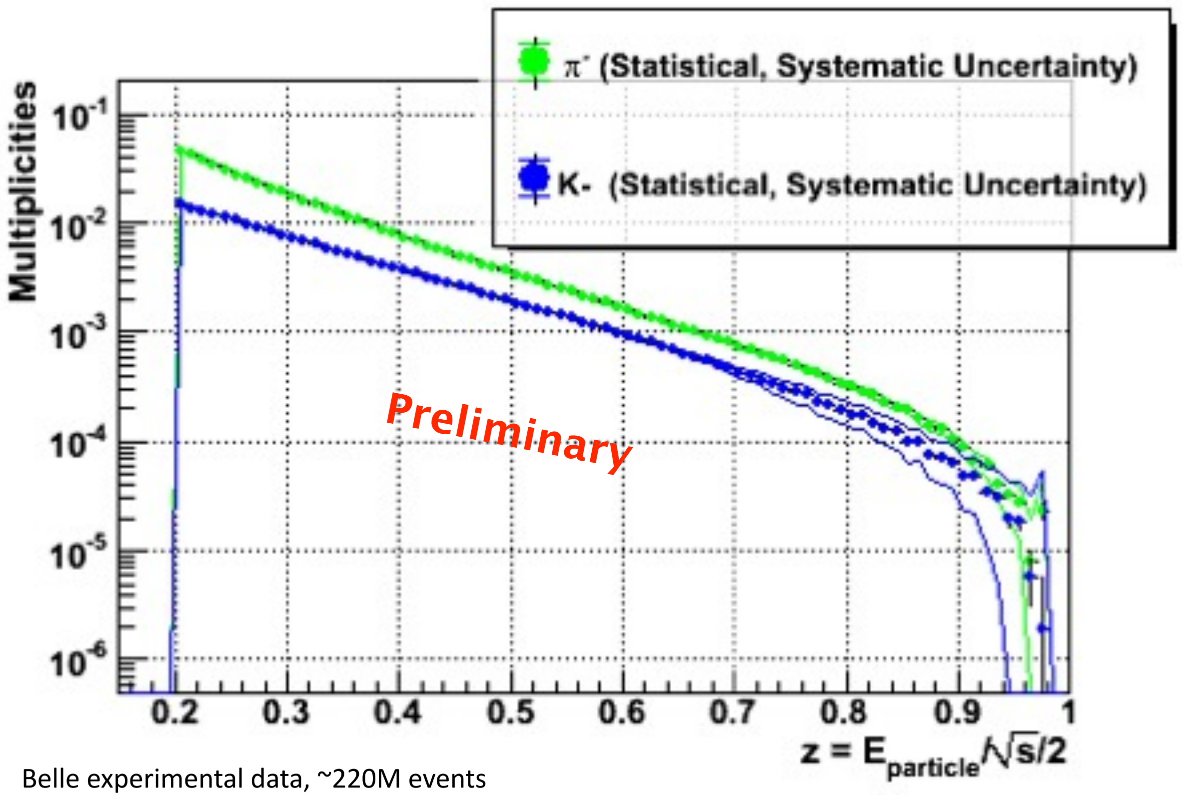




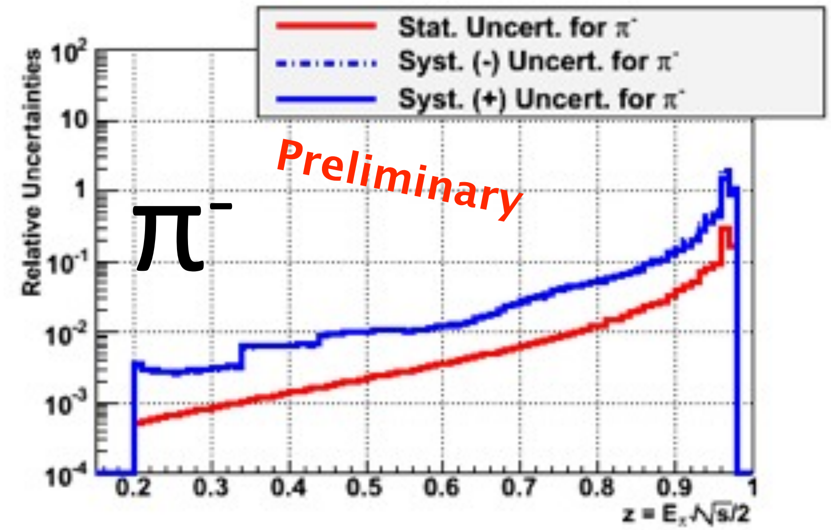
Pion and Kaon Multiplicities

Preliminary Results

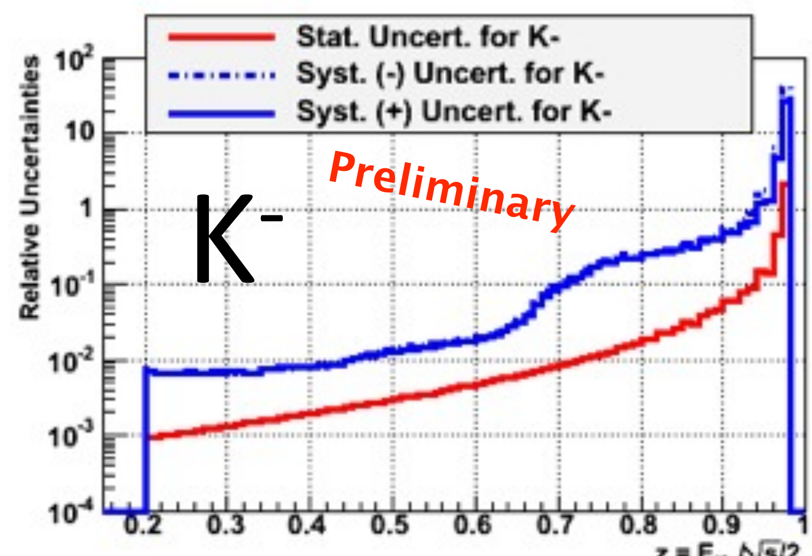
- Binning in z: width = 0.01; yields normalized to hadronic cross section
- Systematic uncertainties: z ~0.6: 1% (2%) for π (K);
  z ~0.9: 14% (50%) for π (K)



Belle experimental data, ~220M events



Additional normalization uncertainty of 1.4% not shown.



Anselm Vossen

Can we disentangle $\langle k^2_\perp \rangle$, $\langle p^2_\perp \rangle$?

- Global fit coming for new unpol **multiD-binned** xsecs from
  - SIDIS: HERMES, COMPASS, JLab
  - e+e–: BELLE (impossibly large statistics)
  - DY: COMPASS-II, SeaQuest
- Can relations like $\mathbf{p^h_T = k_\perp - z\, p_\perp}$ help? Too sloppy?
- $\langle k^2_\perp \rangle$ and $\langle p^2_\perp \rangle$ likely depend on **flavor, PDF/FF, scale** ...

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Is this Doable? At least for pions / light-quarks?

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Is this Doable? At least for pions / light-quarks?

work together,
bears

Conventions:

Trento II

Trans. mom. notations

Amsterdam	Torino	INT	Description
p	k	k	momentum of parton in distribution function
$\boldsymbol{p}_T$	$\boldsymbol{k}_\perp$	$\boldsymbol{k}_\perp$	parton transverse momentum in distribution function
k	p	p	momentum of fragmenting parton
$\boldsymbol{k}_T$		$\boldsymbol{p}_\perp$	trans. momentum of fragmenting parton w.r.t. final hadron
$\boldsymbol{K}_T$	$\boldsymbol{p}_\perp$	$\boldsymbol{P}_\perp$	trans. momentum of final hadron w.r.t. fragmenting parton
$\boldsymbol{P}_{h\perp}$	$\boldsymbol{P}_T$	$\boldsymbol{P}_{hT}$	transverse momentum of final hadron w.r.t. virtual photon
$\boldsymbol{q}_T$		$\boldsymbol{q}_T$	transverse momentum of final photon w.r.t. hadron-hadron axis

Ingredients of symbology

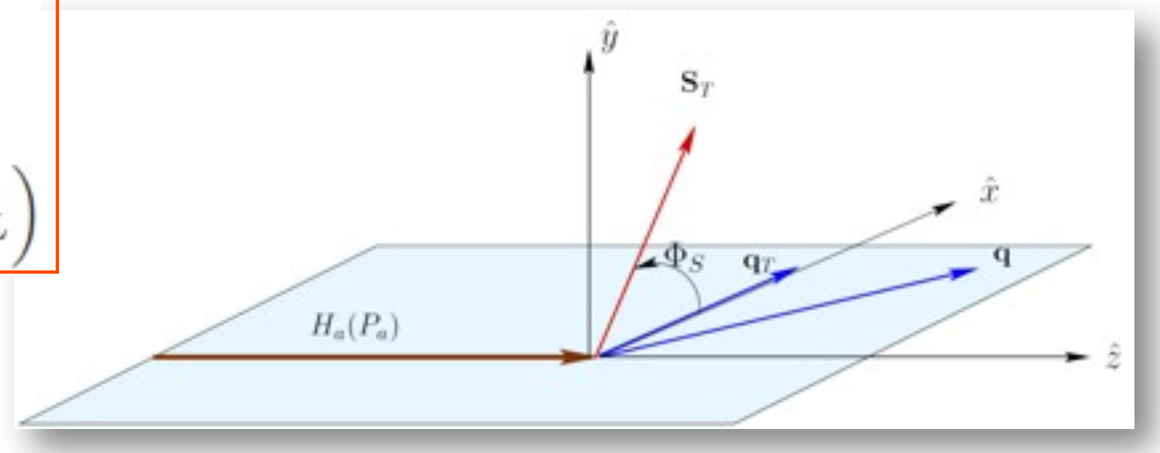
- k vs p — parton from distribution vs fragmentation function
- ⊥ vs T — internal vs measurable transverse component
- a vs A — quark vs hadron variable

Source: Alessandro Bacchetta, Marco Radici

Angular variables

figures: Aram Kotzinian

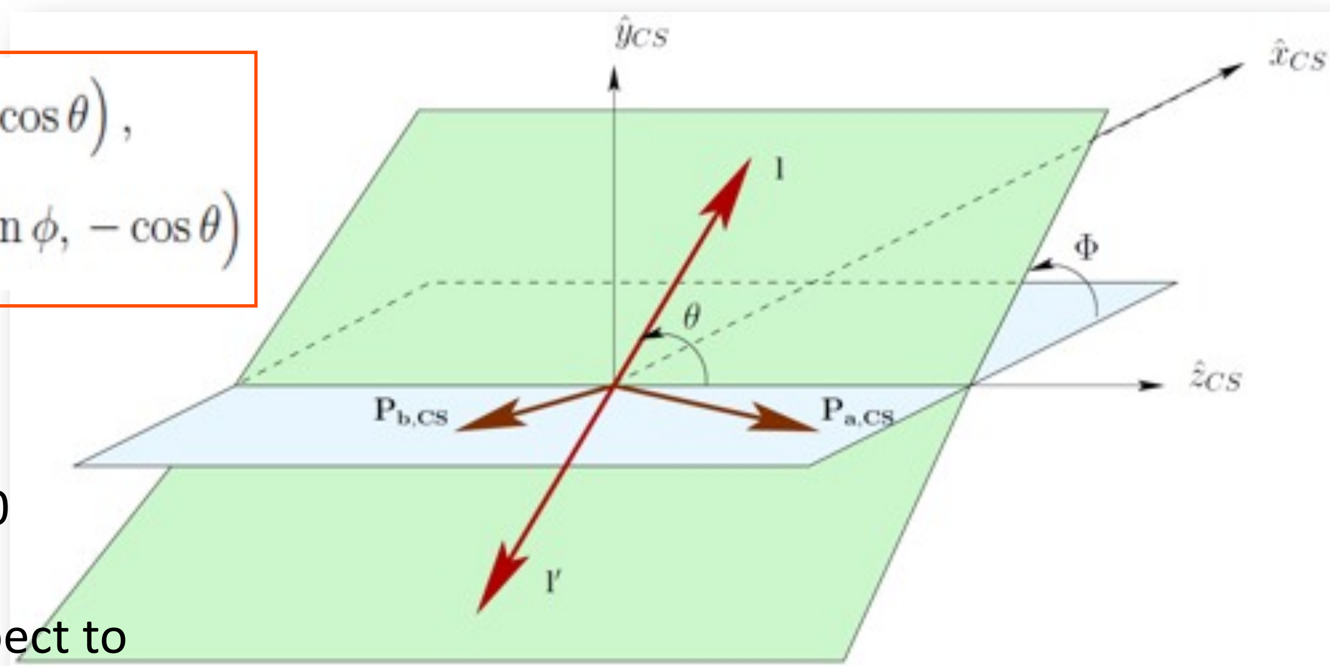
$$
\begin{aligned}
P^{\mu}_{a,TF} &= (E,\,0,\,0,\,P^{3}_{a,TF})\,,\\
P^{\mu}_{b,TF} &= (M_b,\,0,\,0,\,0)\,,\\
q^{\mu}_{TF} &= (q_{0,TF},\,q_T,\,0,\,q_{L,TF})\,,\\
S^{\mu}_{TF} &= \left(0,\,|\vec{S}_T|\cos\phi_S,\,|\vec{S}_T|\sin\phi_S,\,S_L\right)
\end{aligned}
$$



Target rest frame (TF)

1. Define ϕ_{spin} as shown

$$
\begin{aligned}
l^{\mu}_{CS} &= \frac{q}{2}\left(1,\,\sin\theta\cos\phi,\,\sin\theta\sin\phi,\,\cos\theta\right)\,,\\
l'^{\mu}_{CS} &= \frac{q}{2}\left(1,\,-\sin\theta\cos\phi,\,-\sin\theta\sin\phi,\,-\cos\theta\right)
\end{aligned}
$$



Collins-Soper frame (CS)

1. Boost along beam until $q_L = 0$
2. Boost along q until $q_T = 0$
3. lepton θ,ϕ defined with respect to lepton (μ^-,e^-) not anti-lepton