TMDs AND UNPOLARIZED SIDIS

Contalbrigo Marco
INFN Ferrara

Transversity 2014
June 9, 2014 Chia

quark polarisation (columns) / **nucleon polarisation** (rows)

N/q	U	L	T
U	f_1 *Number Density*		$h_1^{\perp}$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^{\perp}$ *Worm-gear*
T	$f_{1T}^{\perp}$ *Sivers*	$g_{1T}^{\perp}$ *Worm-gear*	h_1 *Transversity* $h_{1T}^{\perp}$ *Pretzelosity*

Number density:

Focusing here in transverse momentum dependence

Leading Twist TMDs

quark polarisation

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^{\perp}$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^{\perp}$ *Worm-gear*
T	$f_{1T}^{\perp}$ *Sivers*	$g_{1T}^{\perp}$ *Worm-gear*	h_1 *Transversity* $h_{1T}^{\perp}$ *Pretzelosity*

Number density:

Focusing here in transverse momentum dependence

Off-diagonal elements:

Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects

Testing QCD at the amplitude level

T-odd elements:

→ sign change between DY and SIDIS
- universality of TMDs

Leading Twist TMDs

quark polarisation (columns) / nucleon polarisation (rows)

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

$$D^{\perp,unf} \sim \tfrac{1}{2} D^{\perp,fav}$$

$$H^{\perp,unf} \sim -H^{\perp,fav}$$

$$fav: \quad u \rightarrow \pi^+$$

$$unf: \quad u \rightarrow \pi^-$$

Number density:

Focusing here in transverse momentum dependence

Off-diagonal elements:

Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects

Testing QCD at the amplitude level

T-odd elements:

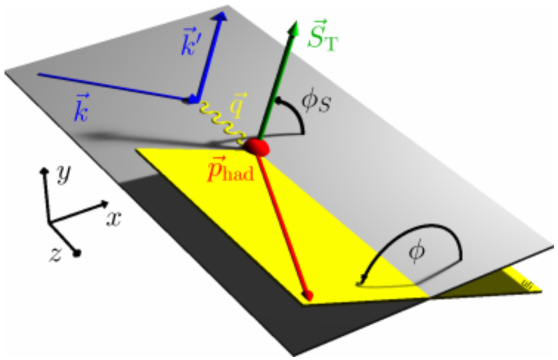
→ sign change between DY and SIDIS
- universality of TMDs

quark polarisation (columns) / nucleon polarisation (rows)

N/q	U	L	T
U	D_1 *Unpolarized*		$H_1^\perp$ *Collins*
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

The SIDIS case

SIDIS cross section (transversely pol. target):

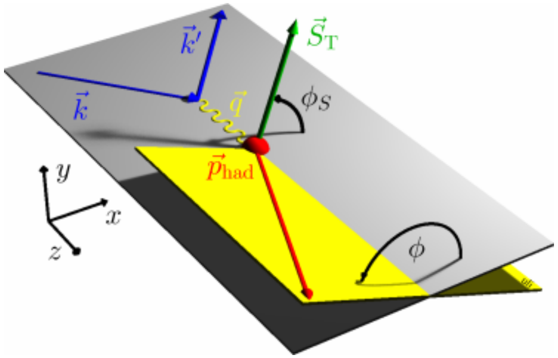


$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \overset{Leading}{\underset{Twist}{\propto}} S_T\left\{\sin(\phi-\phi_S)F_{UT,T}^{\sin(\phi-\phi_S)}\right\}$$

$$+S_T\left\{\varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)}+\varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right\}$$

$$+S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right\}+\ldots$$

SIDIS cross section (transversely pol. target):



$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \overset{Leading}{\underset{Twist}{\propto}} S_T\left\{\sin(\phi-\phi_S)F_{UT,T}^{\sin(\phi-\phi_S)}\right\}$$

$$+S_T\left\{\varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right\}$$

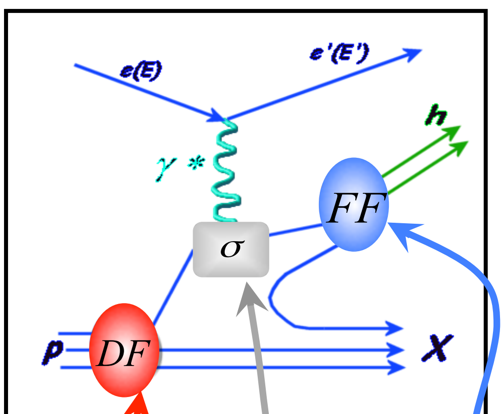
$$+S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right\}+\ldots$$

$h_1 \otimes H_1^\perp$

$f_{1T}^\perp \otimes D_1$

$h_{1T}^\perp \otimes H_1^\perp$

$g_{1T}^\perp \otimes D_1$



$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

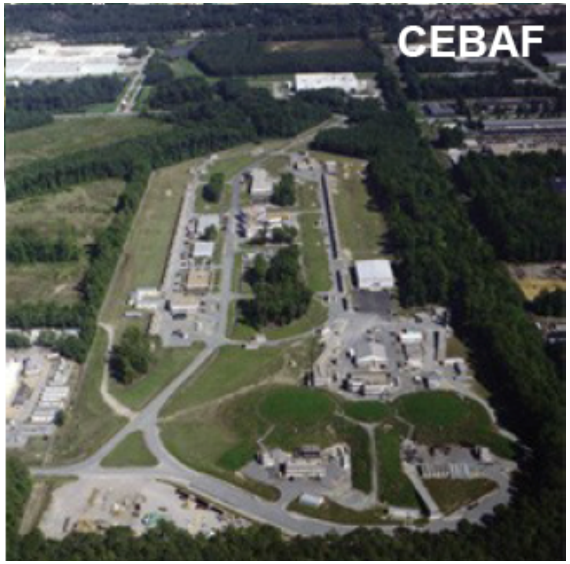
TMD factorization for P_T<<Q

$$f\otimes D = \int_q e_q^2 d^2p_T d^2k_T \ldots w(k_T,p_T) f^q(x,k_T^2) D^q(z,p_T^2)$$

Involved phenomenology due to the convolution over transverse momentum

The SIDIS Factories

HERMES:
Polarized 27 GeV e+/e-
Polarized pure gaseous H&D targets
Excellent Particle ID

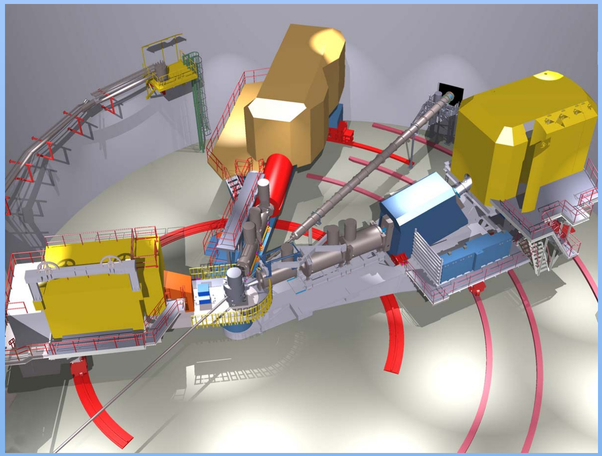


HALL-A, B , C:
Polarized 6 GeV e-
Polarized ^{3}He, NH_3 & HDice targets
High- Luminosity

COMPASS:
Polarized 160 GeV μ
Polarized ^{6}LiD & NH_3 targets
High-Energy

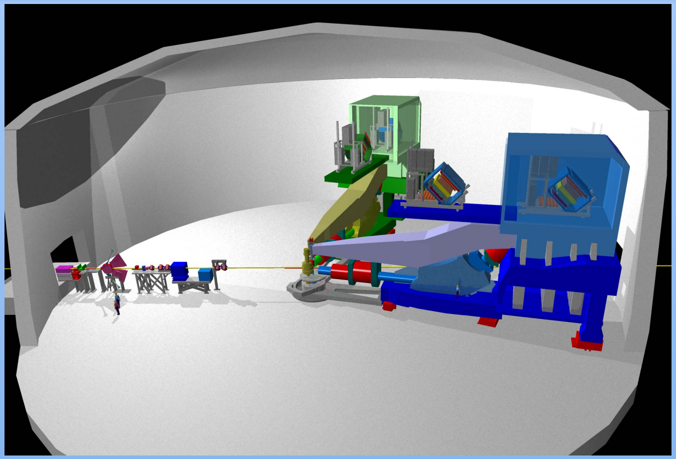
JLab12 Experimental Halls

Hall-C



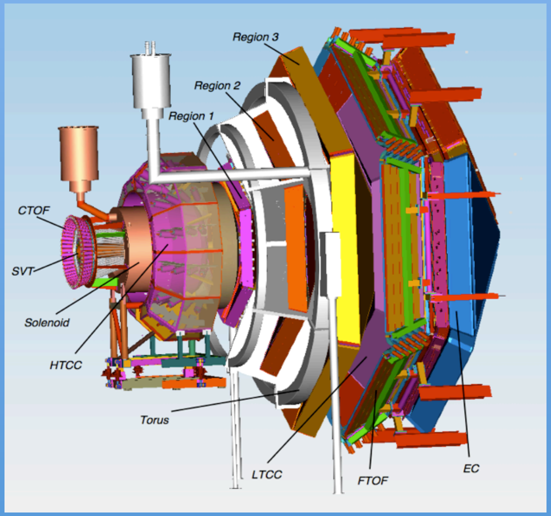
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A



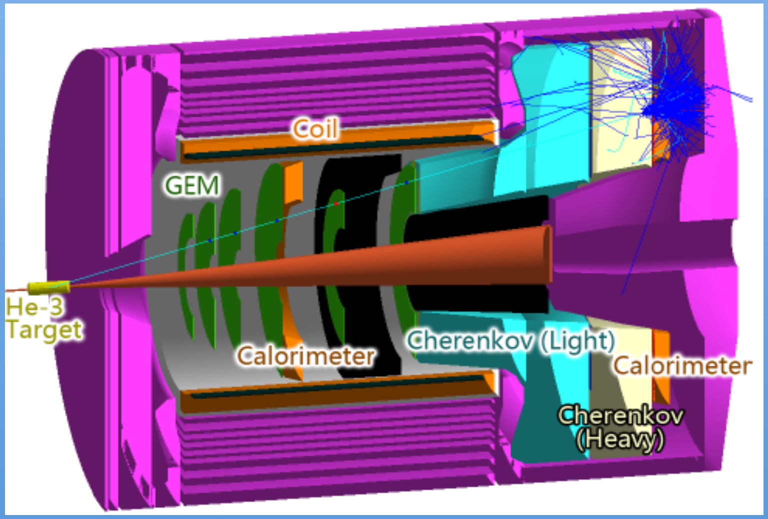
Spectrometer Pair, polarized ^{3}He target
up to to 10^{38} cm^{-2} s^{-1} hadron ID

Hall-B



CLAS12 H,D polarized targets up to 10^{35} cm^{-2} s^{-1}
“complete” acceptance, hadron ID

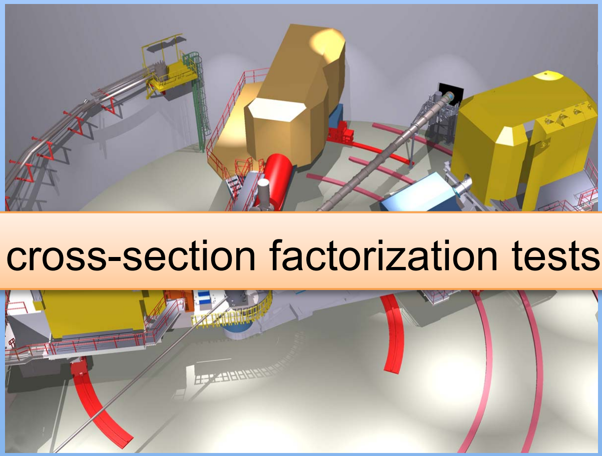
Hall-A



SOLID ^{3}He, NH_3 polarized targets
up to 10^{36} cm^{-2} s^{-1} large acceptance, pion ID

JLab12 Experimental Halls

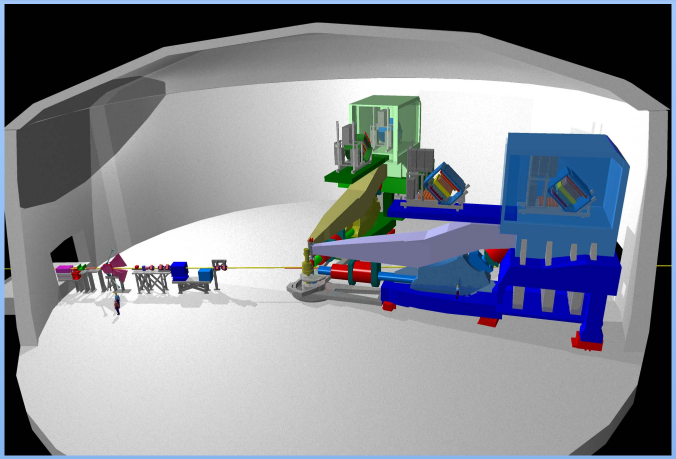
Hall-C



SIDIS cross-section factorization tests

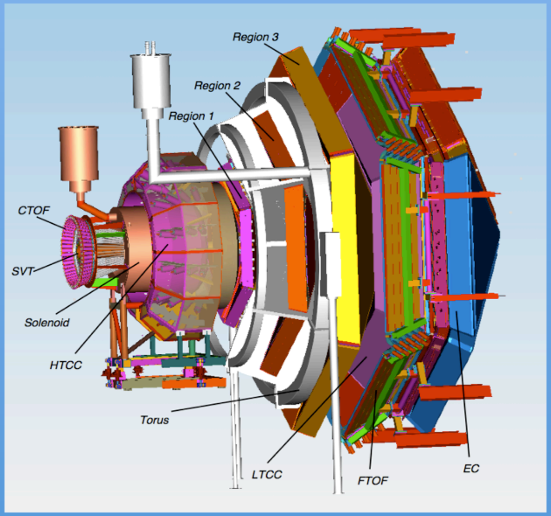
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A



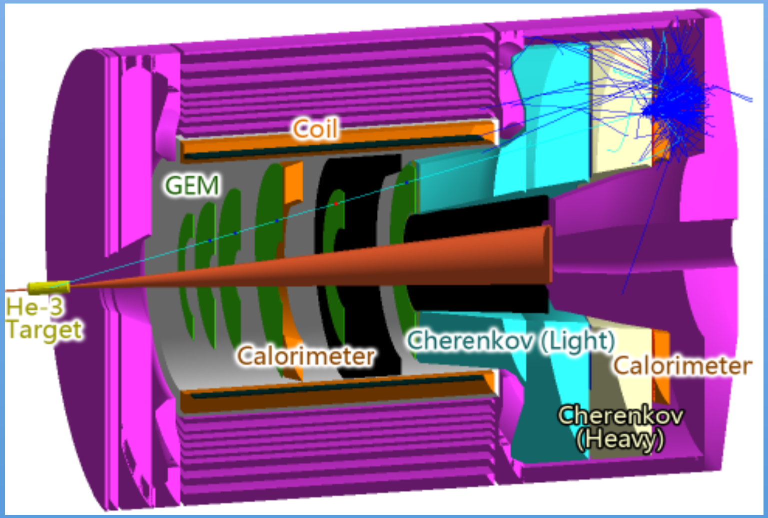
Spectrometer Pair, polarized ^{3}He target
up to to 10^{38} cm^{-2} s^{-1} hadron ID

Hall-B



CLAS12 H,D polarized targets up to 10^{35} cm^{-2} s^{-1}
“complete” acceptance, hadron ID

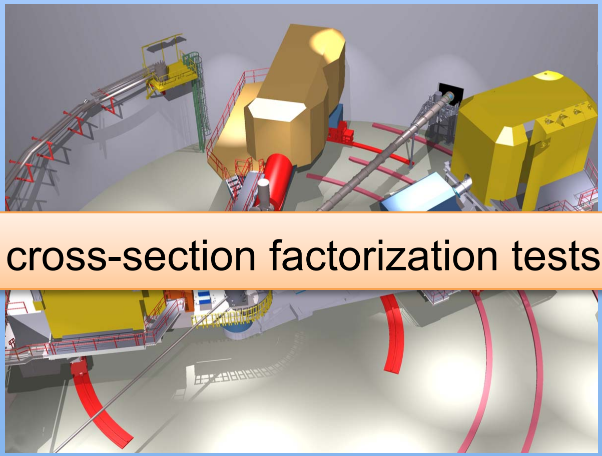
Hall-A



SOLID ^{3}He, NH_3 polarized targets
up to 10^{36} cm^{-2} s^{-1} large acceptance, pion ID

JLab12 Experimental Halls

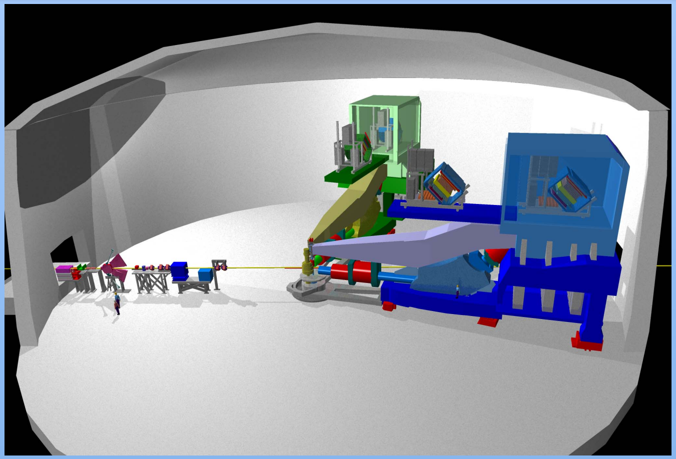
Hall-C



SIDIS cross-section factorization tests

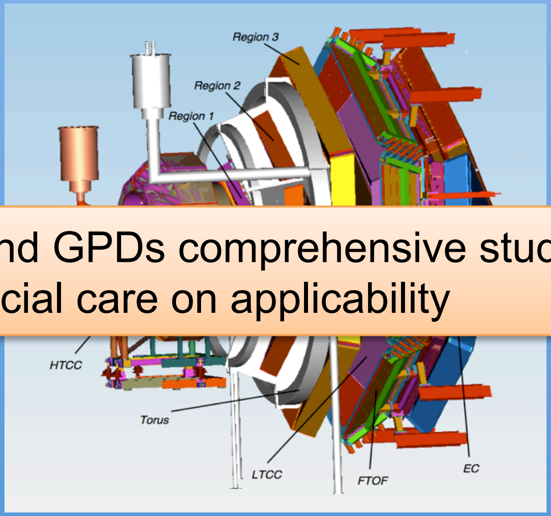
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A



Spectrometer Pair, polarized ^{3}He target
up to to 10^{38} cm^{-2} s^{-1} hadron ID

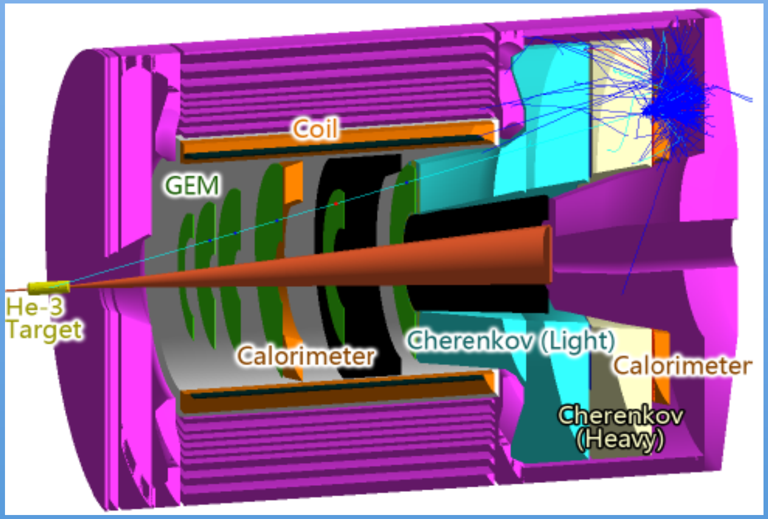
Hall-B



TMDs and GPDs comprehensive study,
with special care on applicability

CLAS12 H,D polarized targets up to 10^{35} cm^{-2} s^{-1}
"complete" acceptance, hadron ID

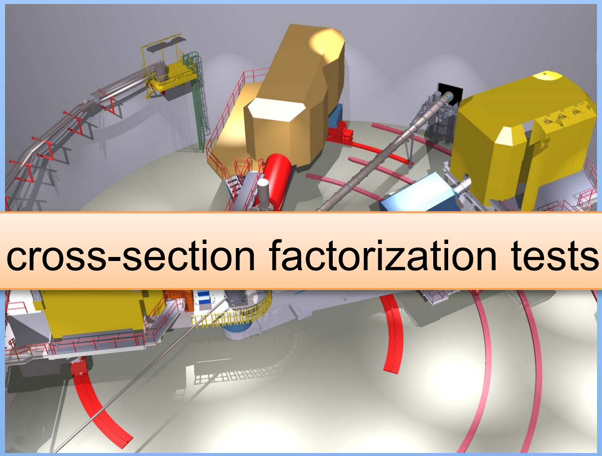
Hall-A



SOLID ^{3}He, NH_3 polarized targets
up to 10^{36} cm^{-2} s^{-1} large acceptance, pion ID

JLab12 Experimental Halls

Hall-C



SIDIS cross-section factorization tests

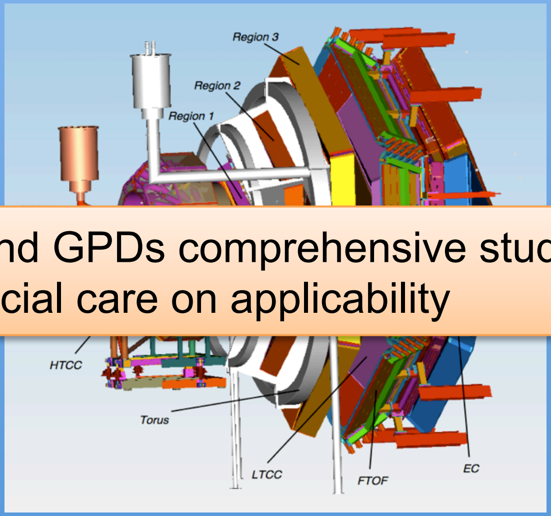
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A

Luminosity frontier
World leading ^{3}He target

Spectrometer Pair, polarized ^{3}He target
up to to 10^{38} cm^{-2} s^{-1} hadron ID

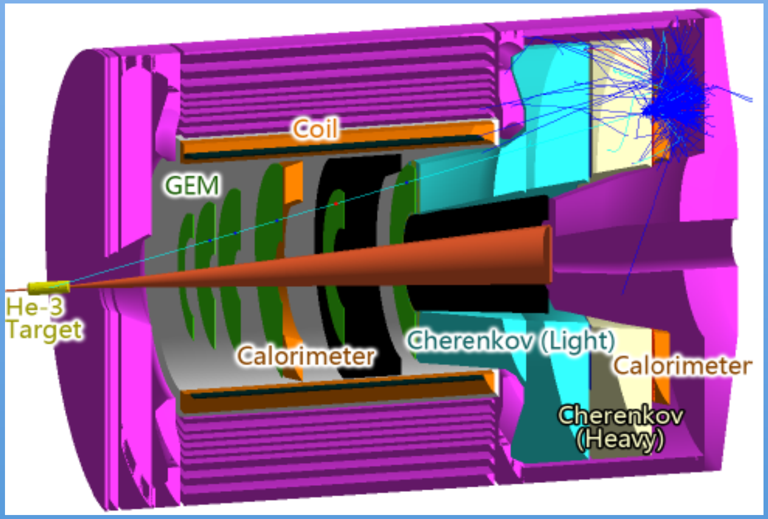
Hall-B



TMDs and GPDs comprehensive study,
with special care on applicability

CLAS12 H,D polarized targets up to 10^{35} cm^{-2} s^{-1}
"complete" acceptance, hadron ID

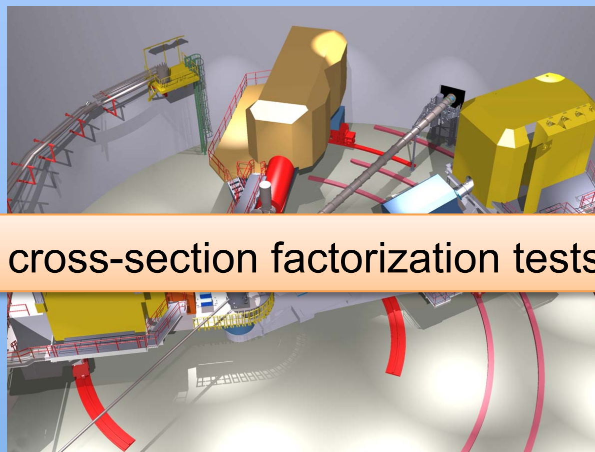
Hall-A



SOLID ^{3}He, NH_3 polarized targets
up to 10^{36} cm^{-2} s^{-1} large acceptance, pion ID

JLab12 Experimental Halls

Hall-C



SIDIS cross-section factorization tests

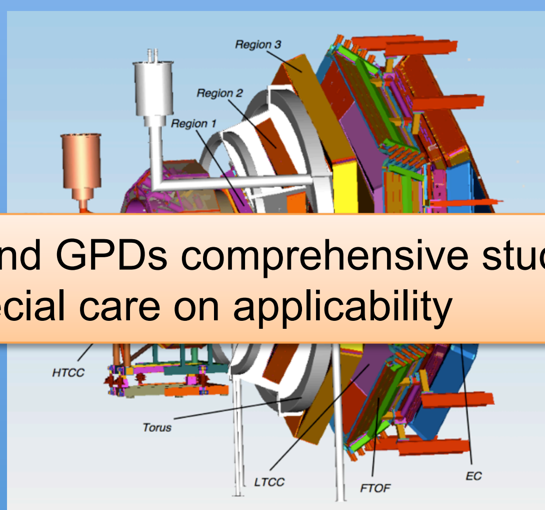
Super High Momentum Spectrometer (SHMS)
unpolarized SIDIS, hadron ID

Hall-A

Luminosity frontier
World leading ^{3}He target

Spectrometer Pair, polarized ^{3}He target
up to to 10^{38} cm^{-2} s^{-1} hadron ID

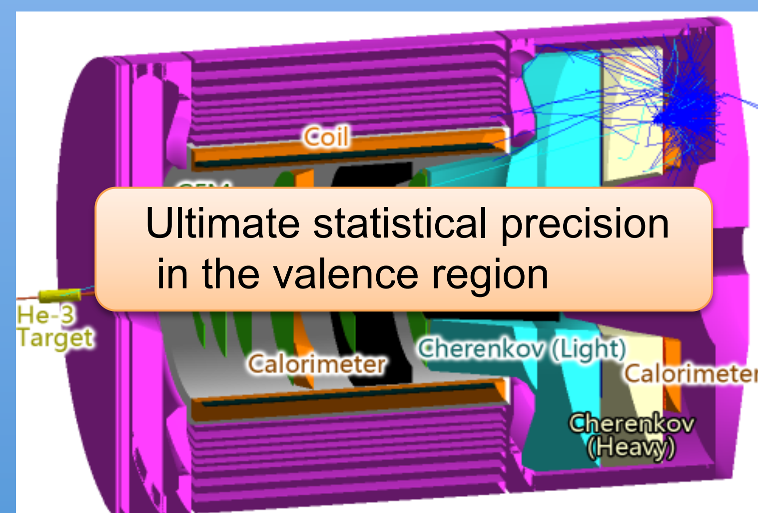
Hall-B



TMDs and GPDs comprehensive study,
with special care on applicability

CLAS12 H,D polarized targets up to 10^{35} cm^{-2} s^{-1}
"complete" acceptance, hadron ID

Hall-A

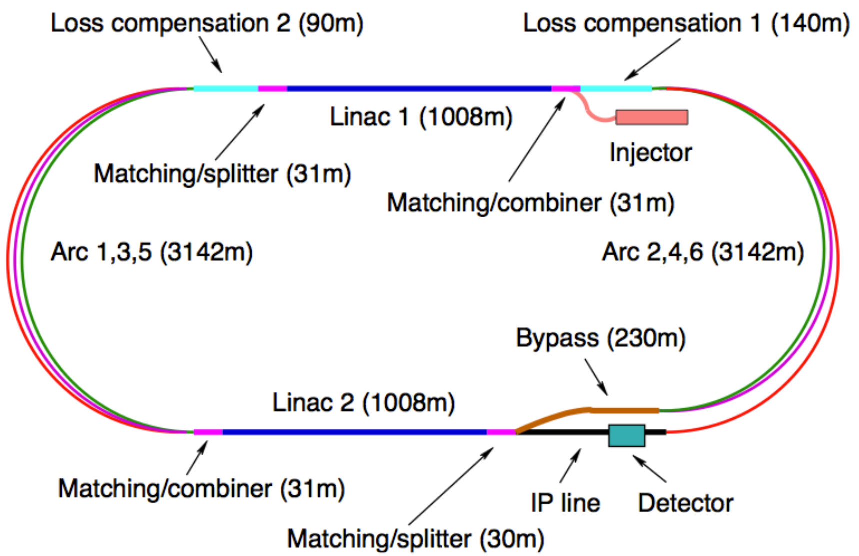


Ultimate statistical precision
in the valence region

SOLID ^{3}He, NH_3 polarized targets
up to 10^{36} cm^{-2} s^{-1} large acceptance, pion ID

The Future in Europe

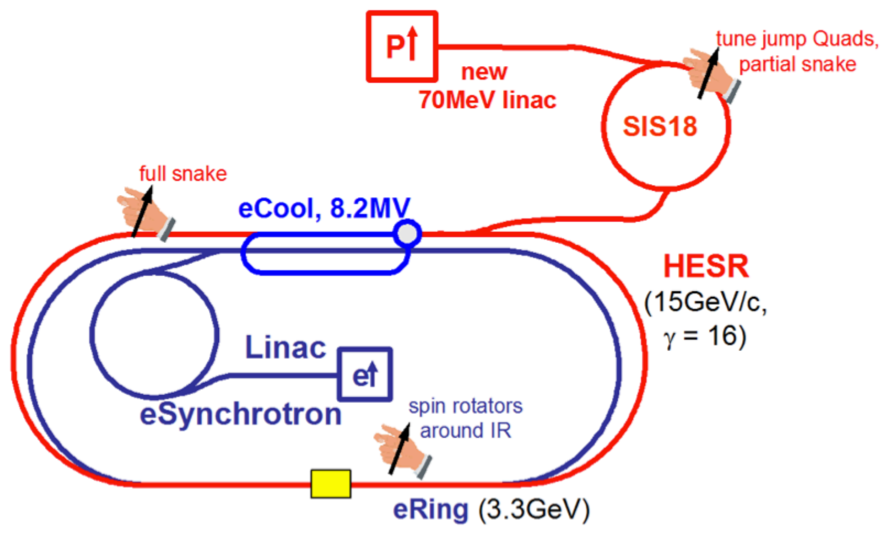
LeHC



Goals:

- ✓ High electron polarization
- ✓ $Q^2 > 1$ TeV^2
- ✓ Luminosity 10^{32} cm^{-2}s^{-1}

ENC

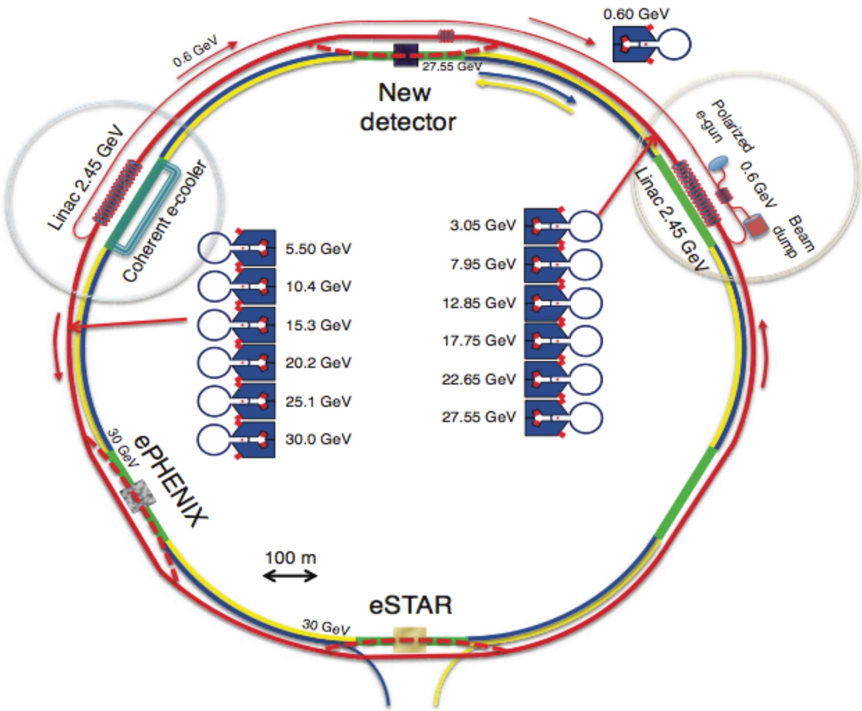


Goals:

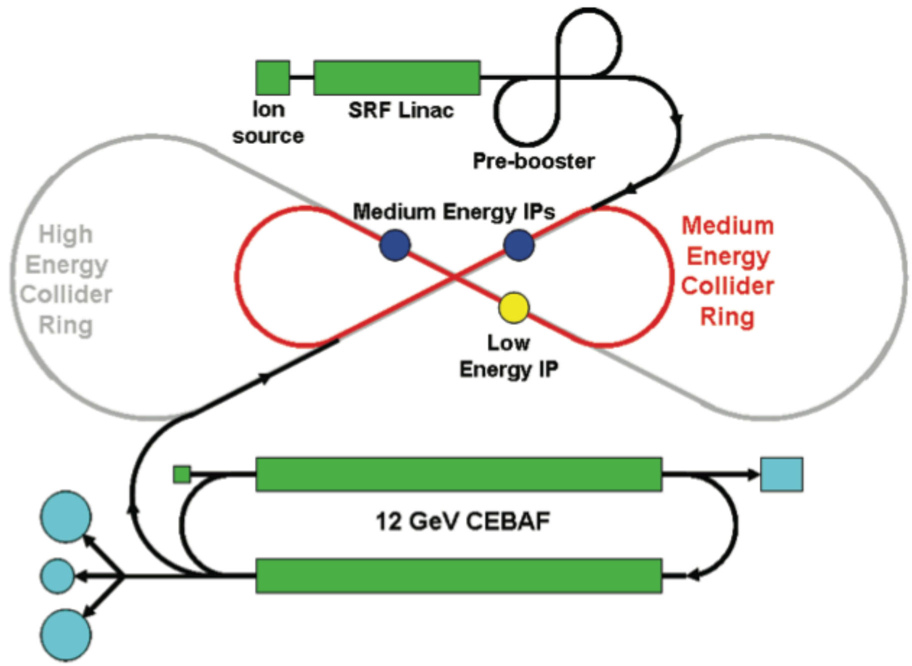
- ✓ Electron and p, d polarization
- ✓ Center of mass energy 14 GeV
- ✓ Luminosity 10^{32}-10^{33} cm^{-2}s^{-1}

The Future in the States

eRHIC



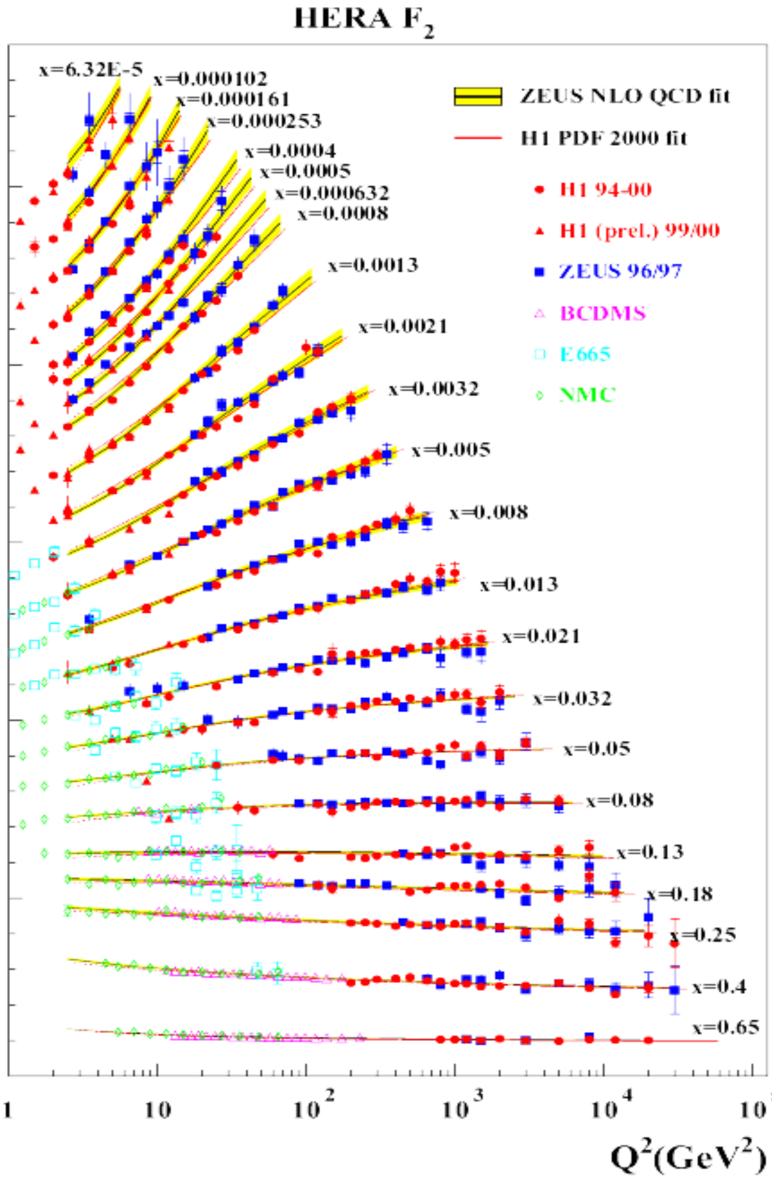
ELIC



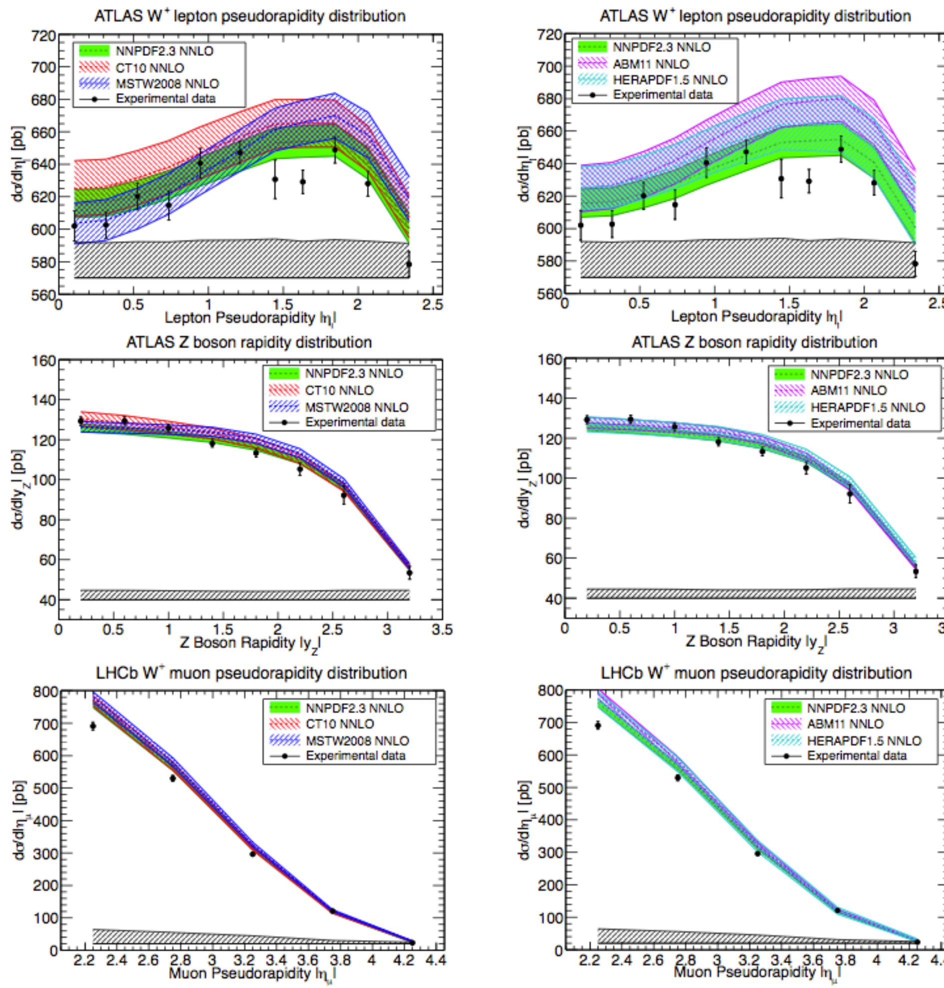
Goals:

- ✓ High polarized (~ 70%) electron and nucleon beams
- ✓ Ion beams from deuteron to lead
- ✓ Variable center-of-mass energy from 20 up to 100 GeV and beyond
- ✓ High collision luminosity 10^{33}-10^{34} cm^{-2}s^{-1}

Parton Number Density

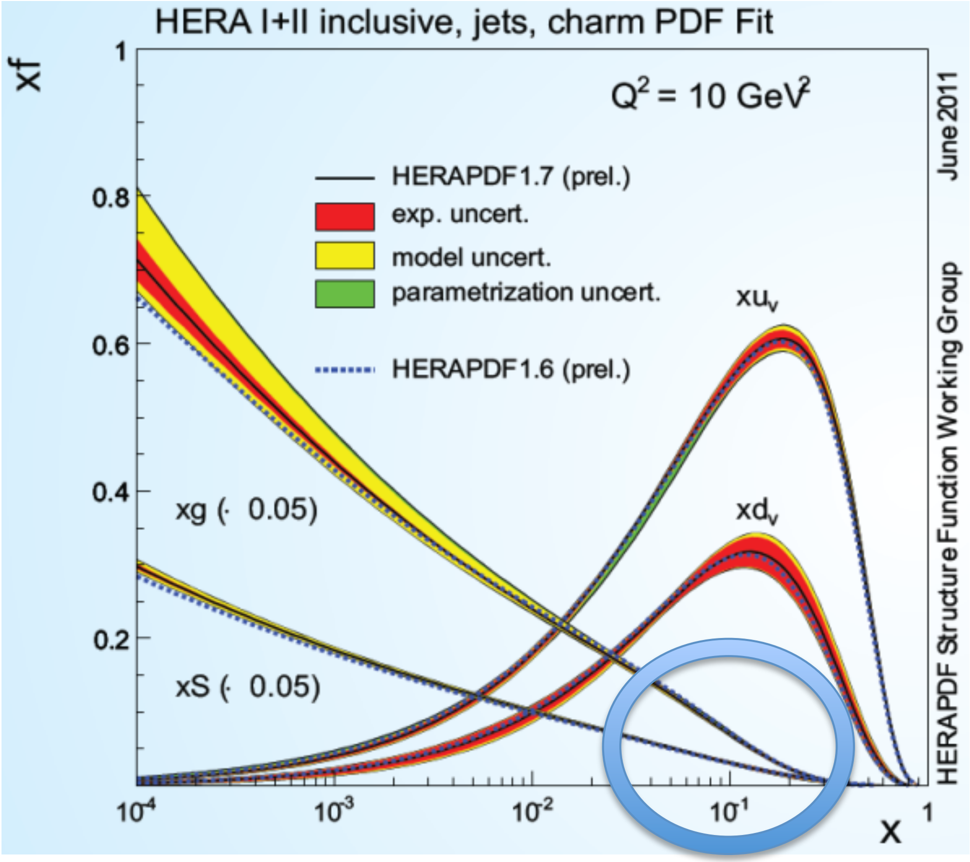


LHC gauge boson production



R.D. Ball ++ [arXiv:1211.5142]

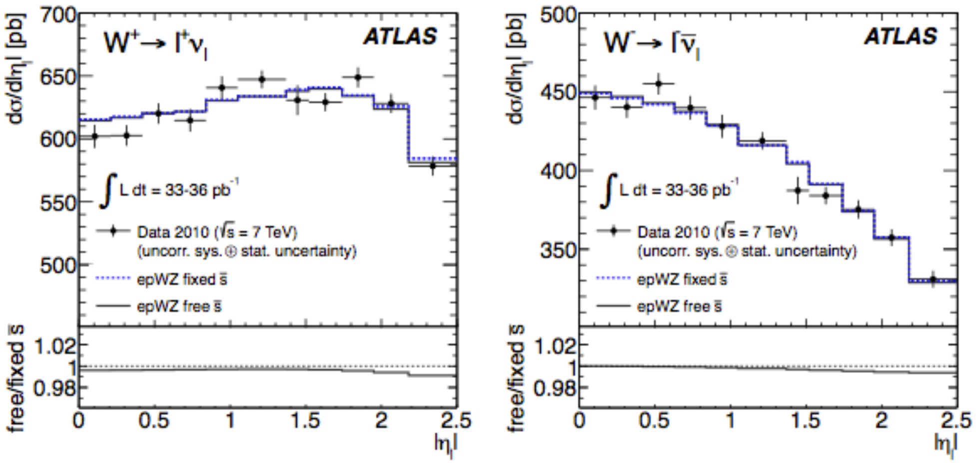
The Strange Quark Distribution

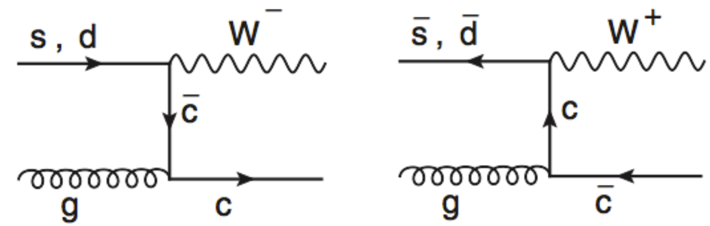


The Strange Quark Distribution

ATLAS: $pp \rightarrow W + X$

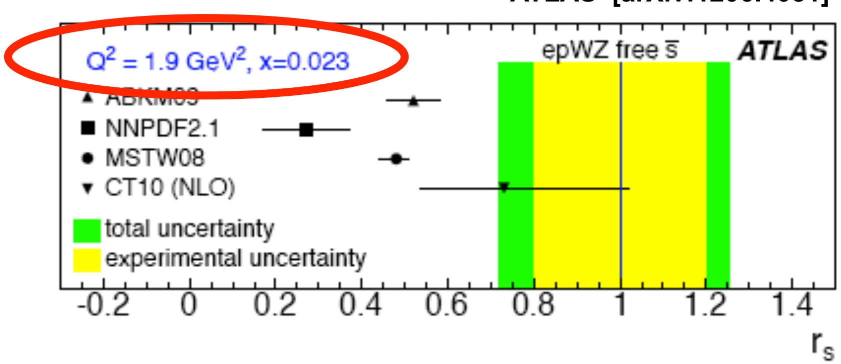
CMS: $pp \rightarrow W + c + X$



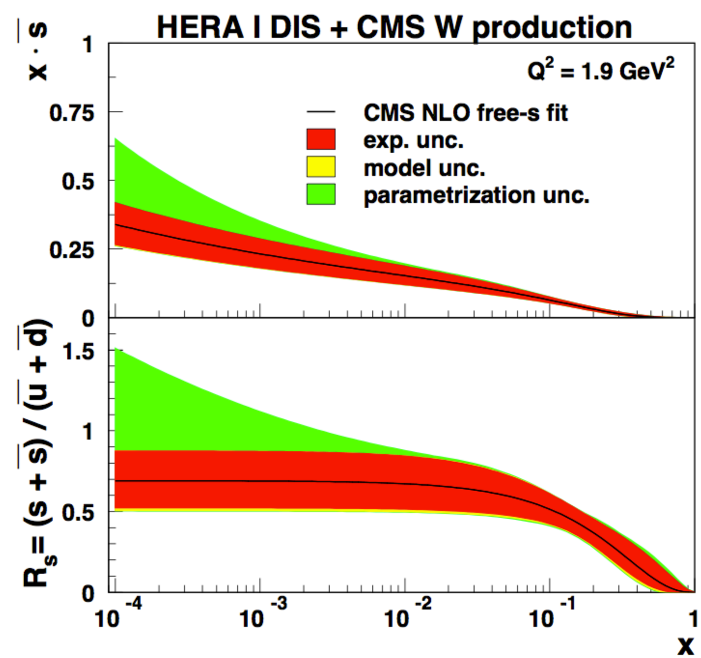


CMS [arXiv:1312.6283]

ATLAS [arXiv:1206.4051]



$$r_s = 0.5(s + \bar{s})/\bar{d}.$$

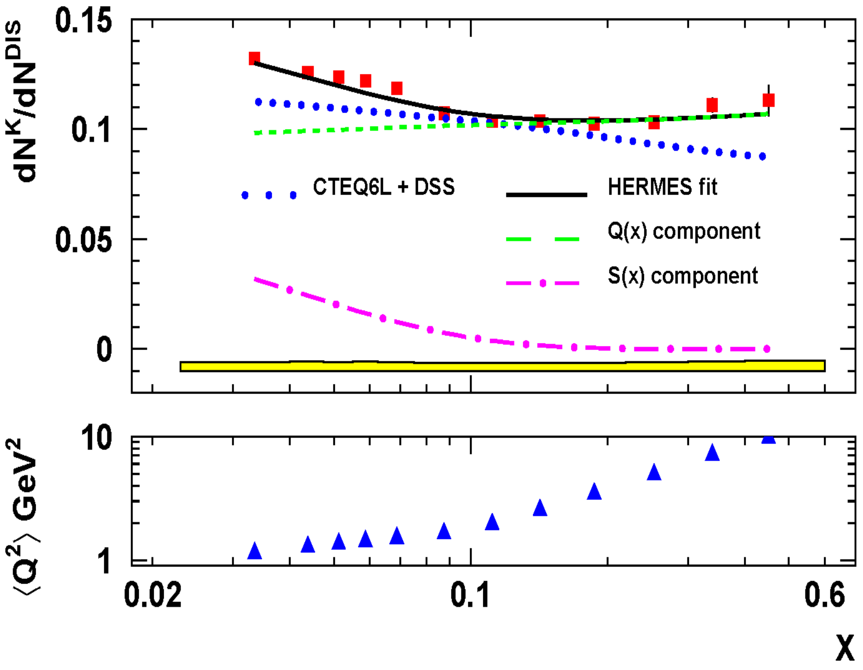


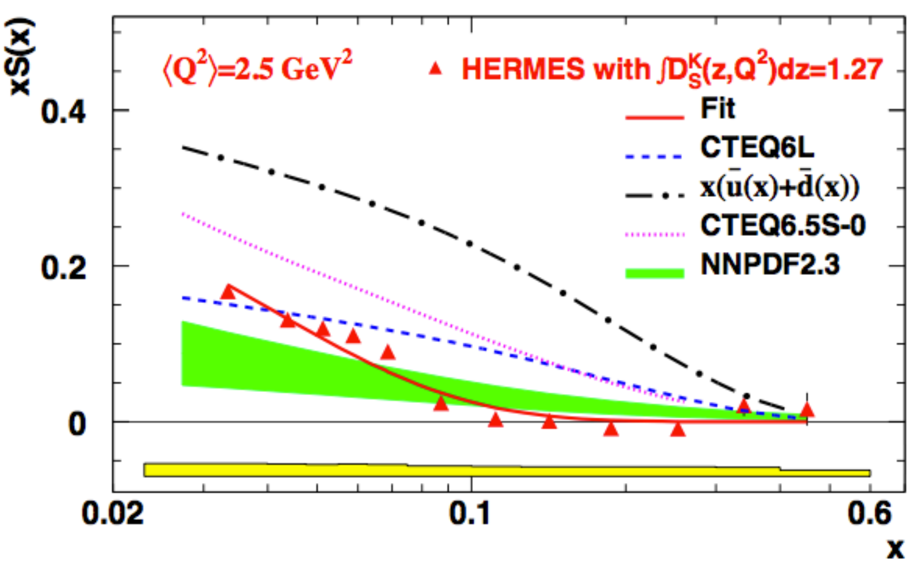
The Strange Quark Distribution

SIDIS extraction:

$$\int_{0.2}^{0.85} M^{K^{+}+K^{-}}(x,z)dz = \frac{Q(x)\int D_{Q}^{K}(z)dz + S(x)\int D_{S}^{K}(z)dz}{5Q(x)+2S(x)}$$

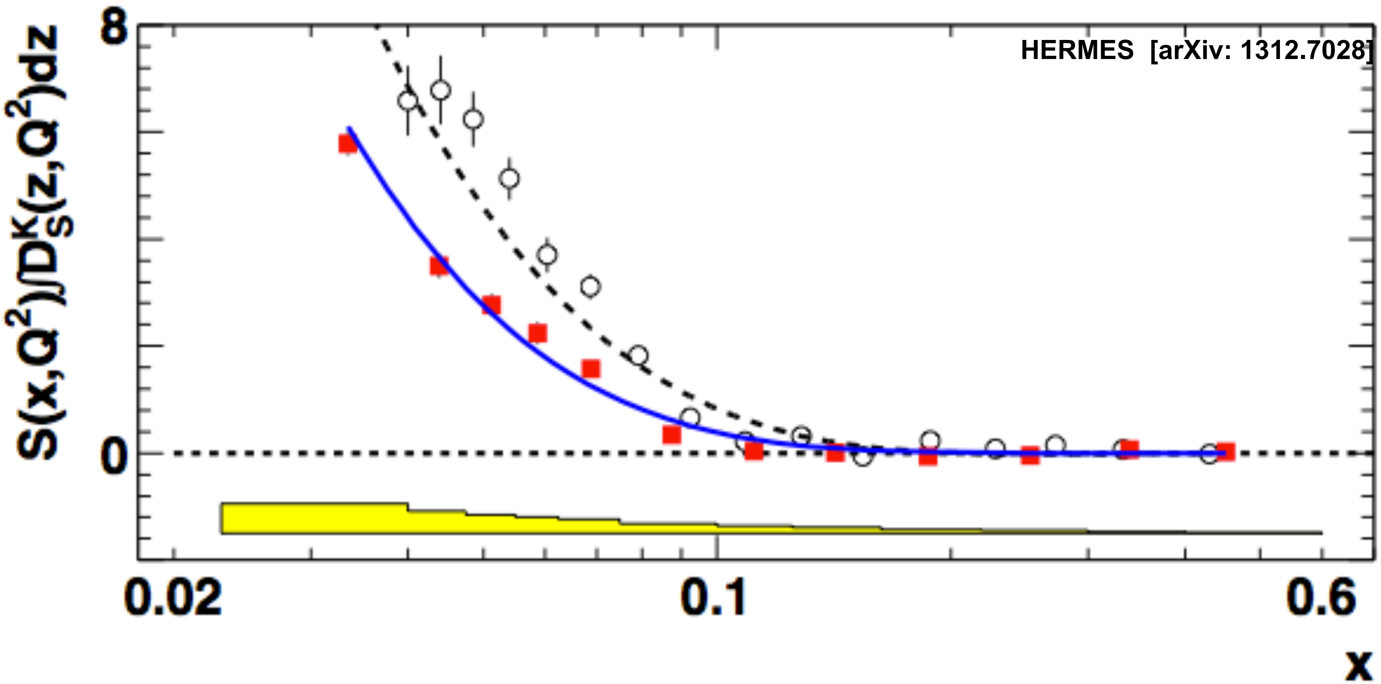
HERMES [arXiv: 1312.7028]





HERMES Re-evaluation

- ✓ Apply novel TMD paradigma: 3D unfolding in x,z and p_T
- ✓ Remove un-necessary 2 GeV momentum cut



Change in magnitude not in shape

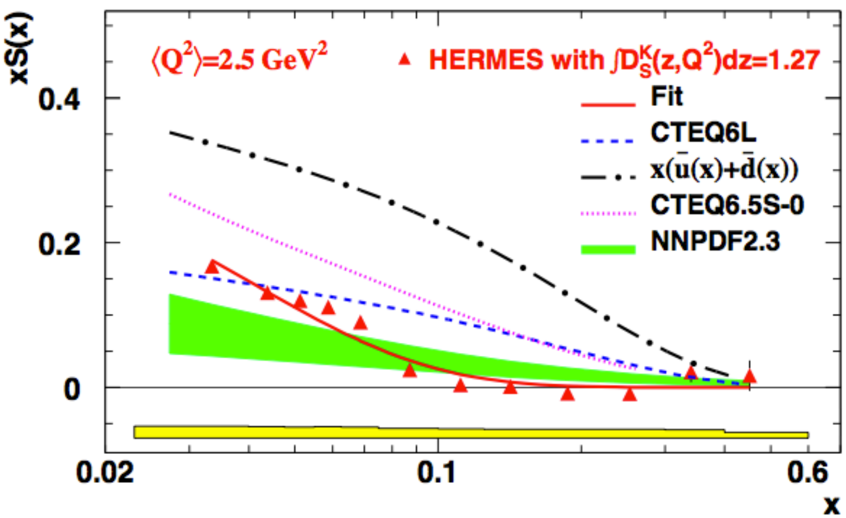
Real effect on strange distribution subject to updated FFs

The Strange Quark Distribution

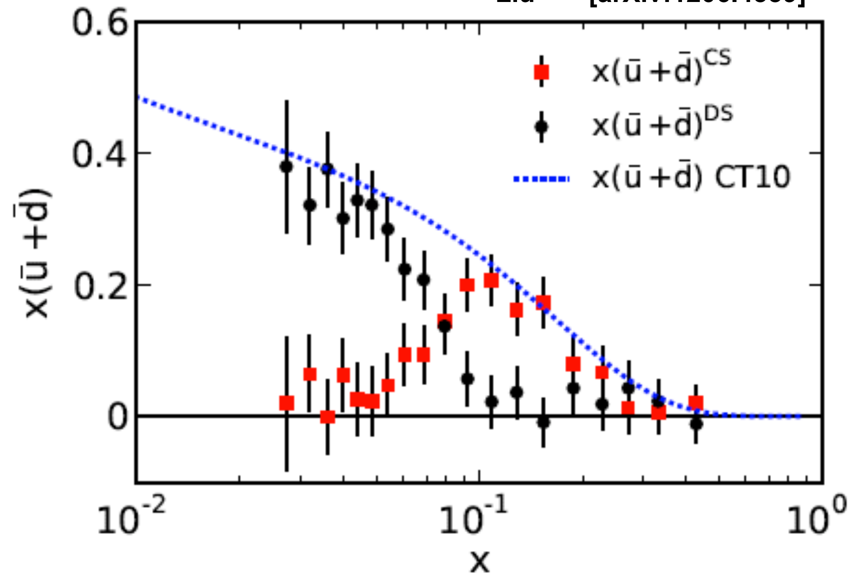
SIDIS extraction:

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x)+2S(x)}$$

HERMES [arXiv: 1312.7028]



Liu++ [arXiv:1206.4339]

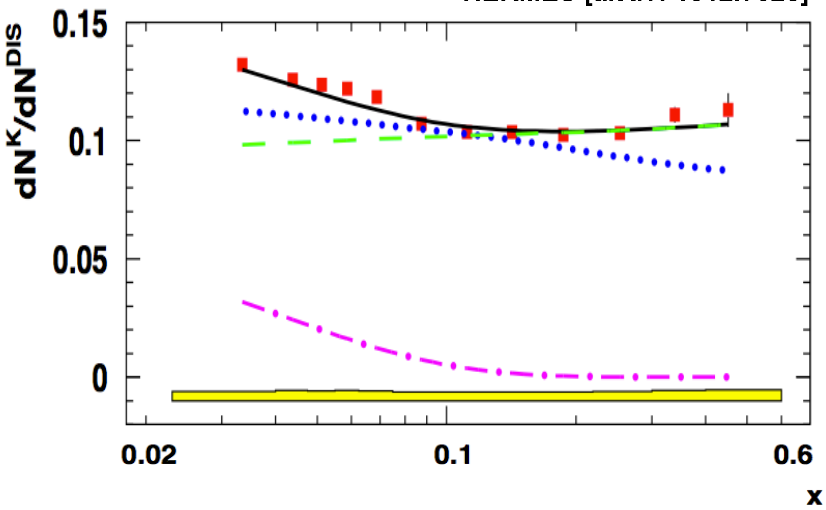


The Strange Quark Distribution

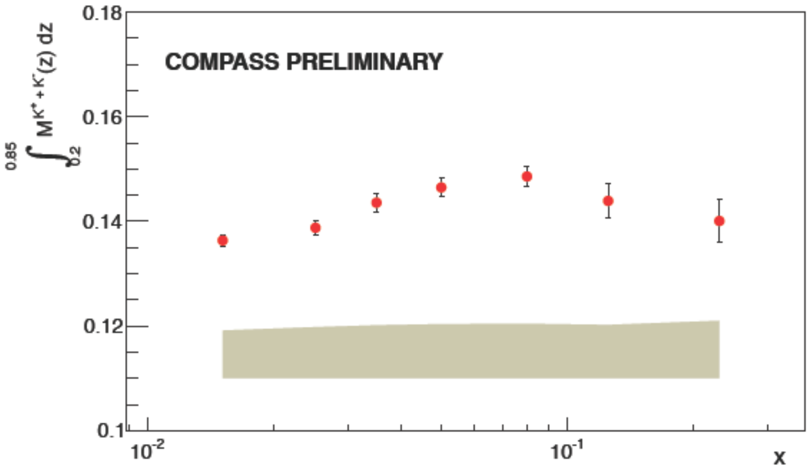
SIDIS extraction:

$$\int_{0.2}^{0.85} M^{K^{+}+K^{-}}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x)+2S(x)}$$

HERMES [arXiv: 1312.7028]



N. Makke [talk at DIS2013]

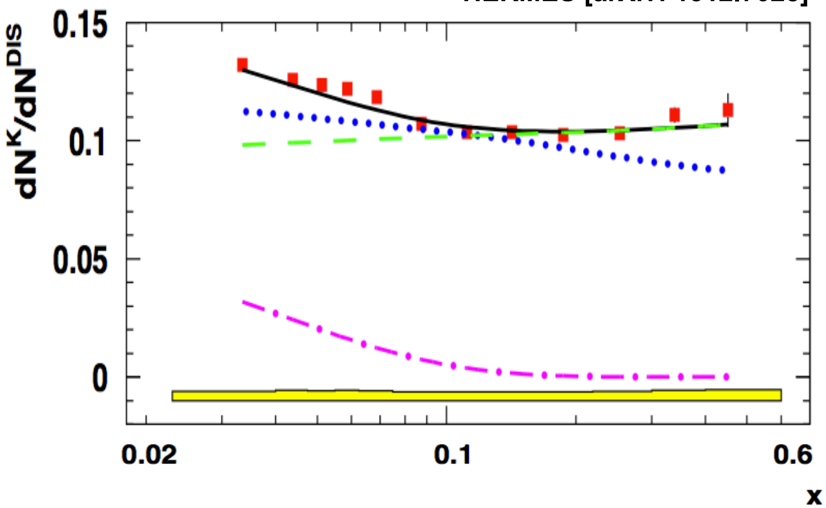


The Strange Quark Distribution

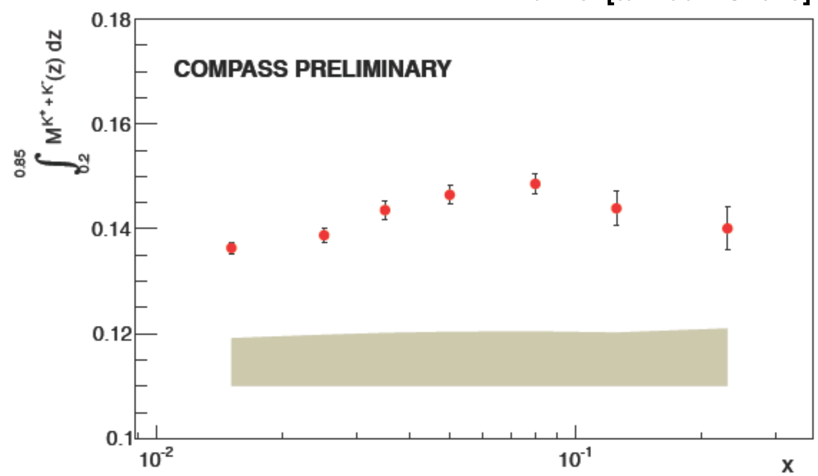
SIDIS extraction:

$$\int_{0.2}^{0.85} M^{K^+ + K^-}(x,z)dz = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5Q(x) + 2S(x)}$$

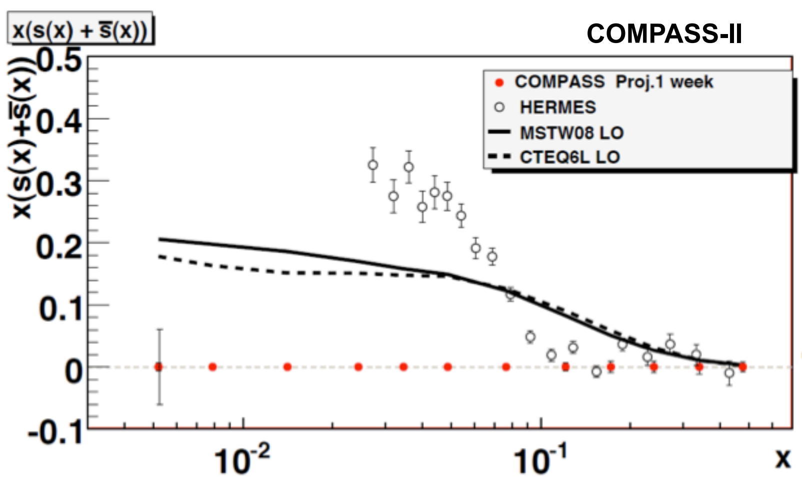
HERMES [arXiv: 1312.7028]



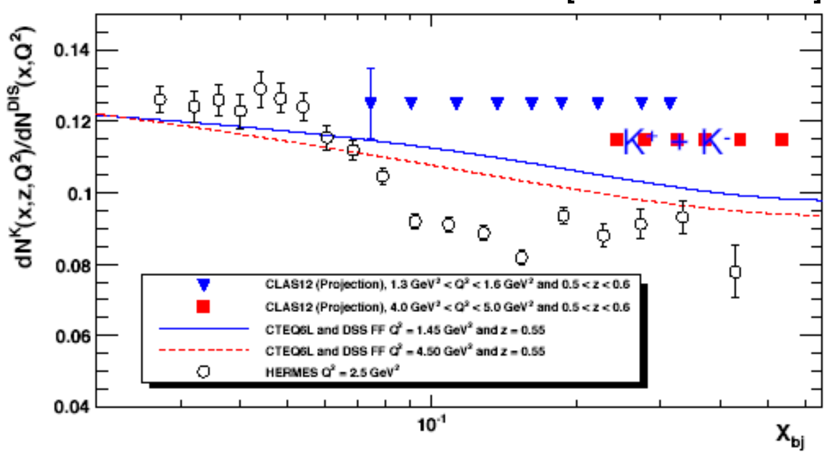
N. Makke [talk at DIS2013]



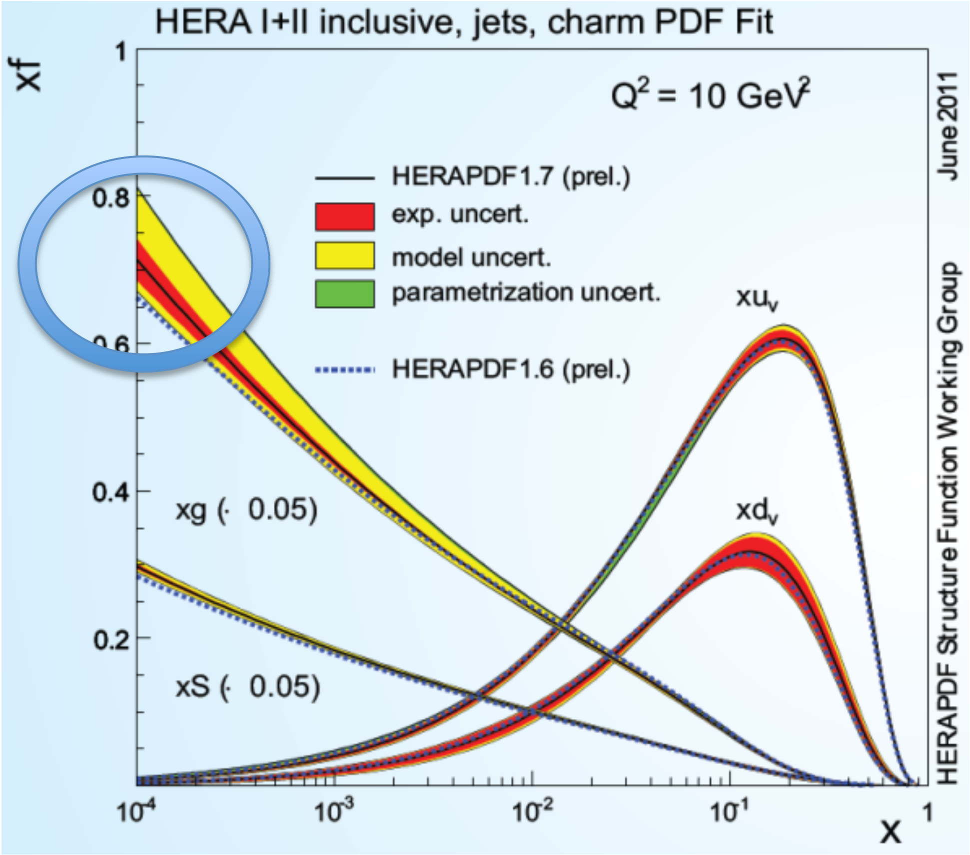
COMPASS-II



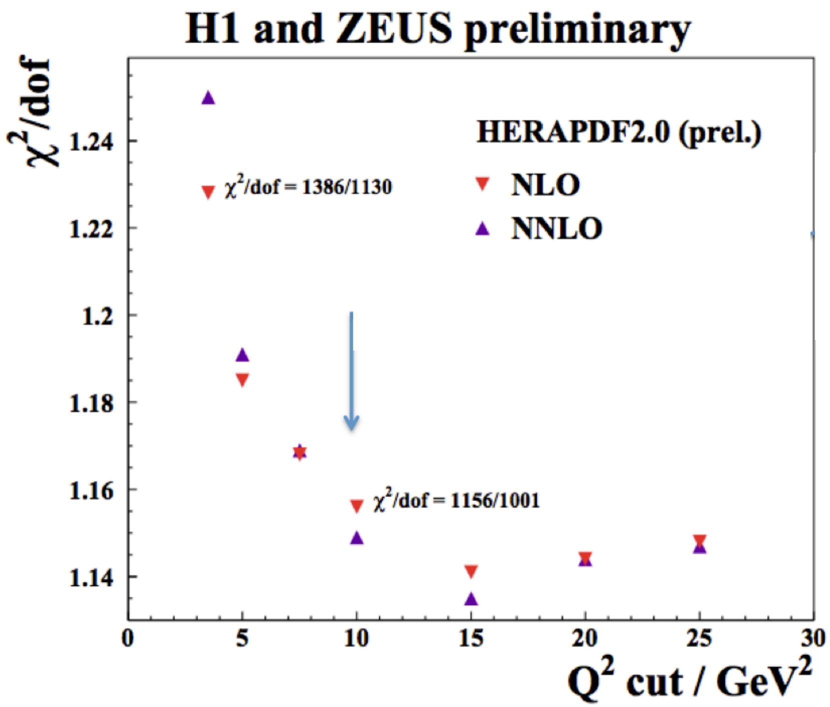
JLab12 [E12-07-104 Hall-B]

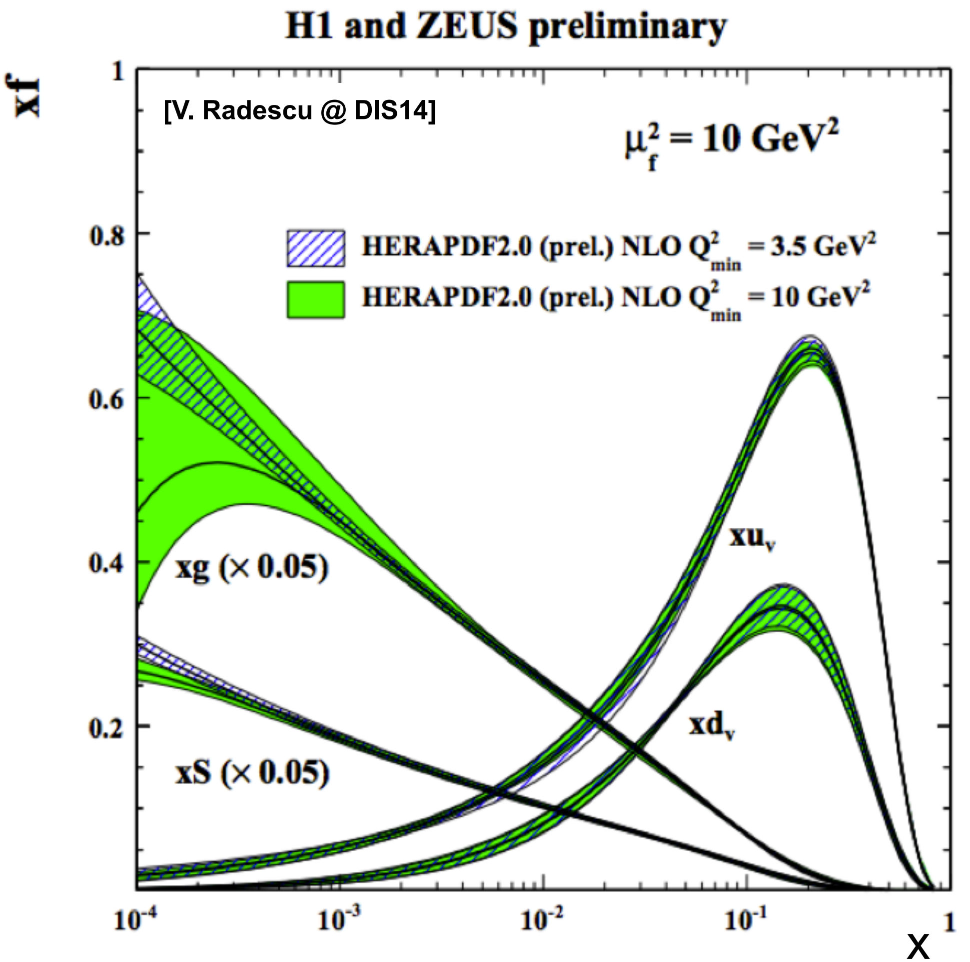


Low-x Physics



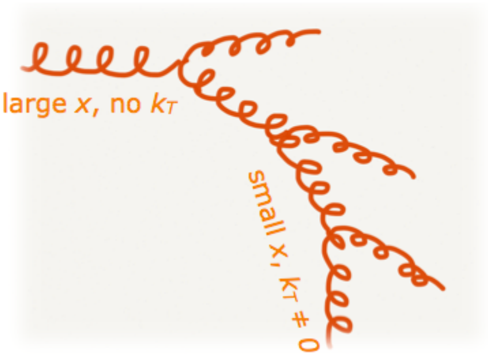
Low-x Physics





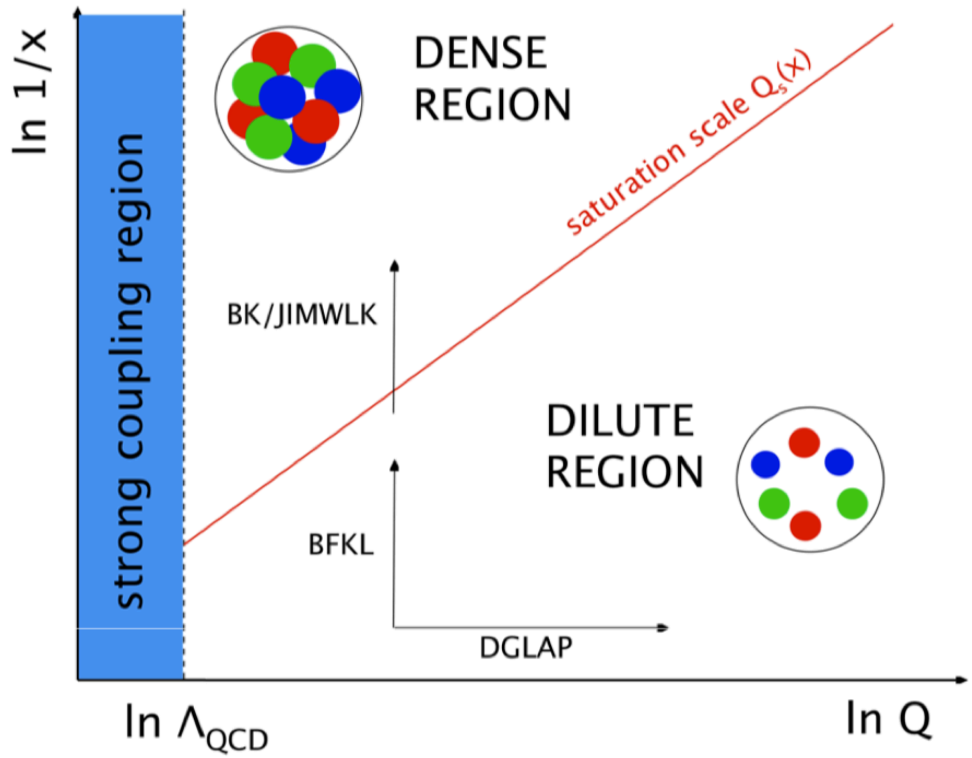
Interplay of the data cut at low Q^2 and impact on gluon at low x

QCD Phase Diagram



***x* low, Q^2 not too high:**

- **partonic k_T** may become important!
  - are (perturbative) parton showers enough to describe this?
  - or does one need something more? k_T-dependent parton densities?



BFKL must be the correct theory of low-x QCD

It naturally incorporates k_T-unintegrated PDFs

Mechelen at DIS2014: no clear evidence of BFKL in experimental data

Gluon TMDs

F. Hautmann and H. Jung [arXiv 1312.7875]

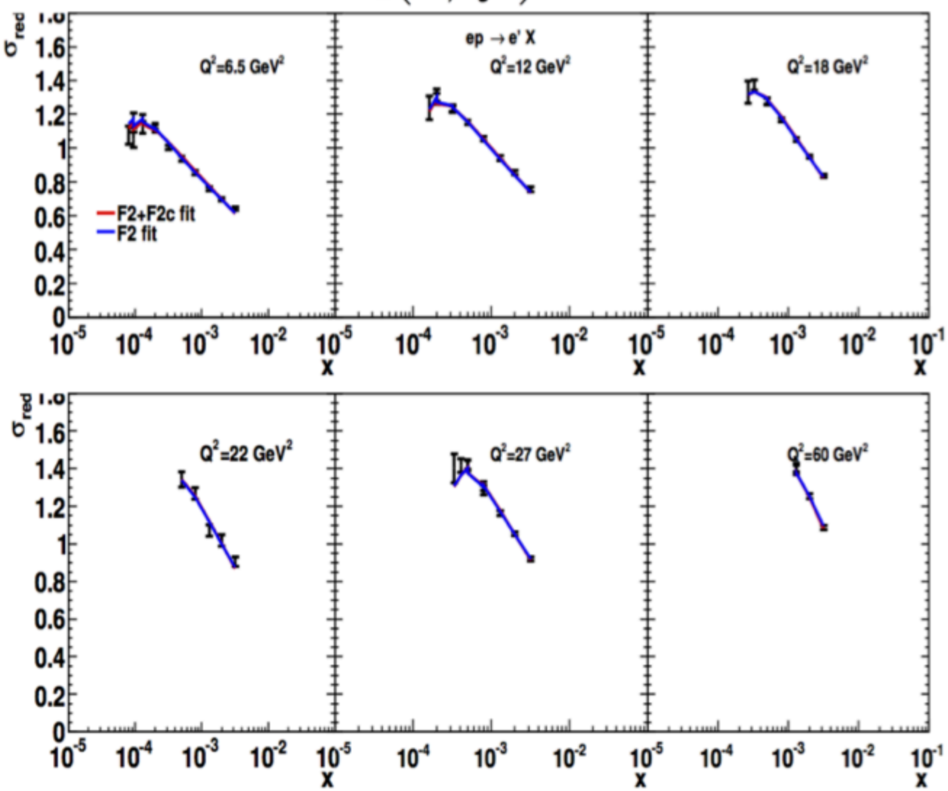
Starting distribution for gluons at q_0

$$x\mathcal{A}_0(x,k_\perp) \quad = \quad N x^{-B} \cdot (1-x)^C \left(1 - Dx + E\sqrt{x}\right) \exp[-k_t^2/\sigma^2]$$

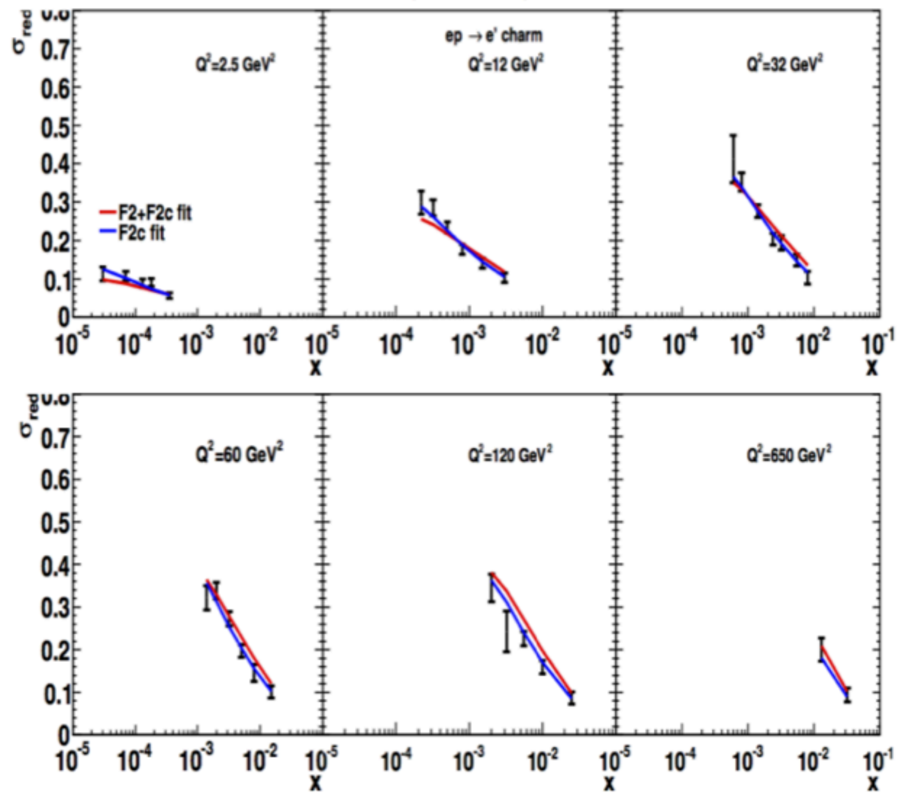
$\sigma^2 = q_0^2 / 2$

CCFM (BFKL like) evolution + herafitter package

$F_2(x,Q^2)$

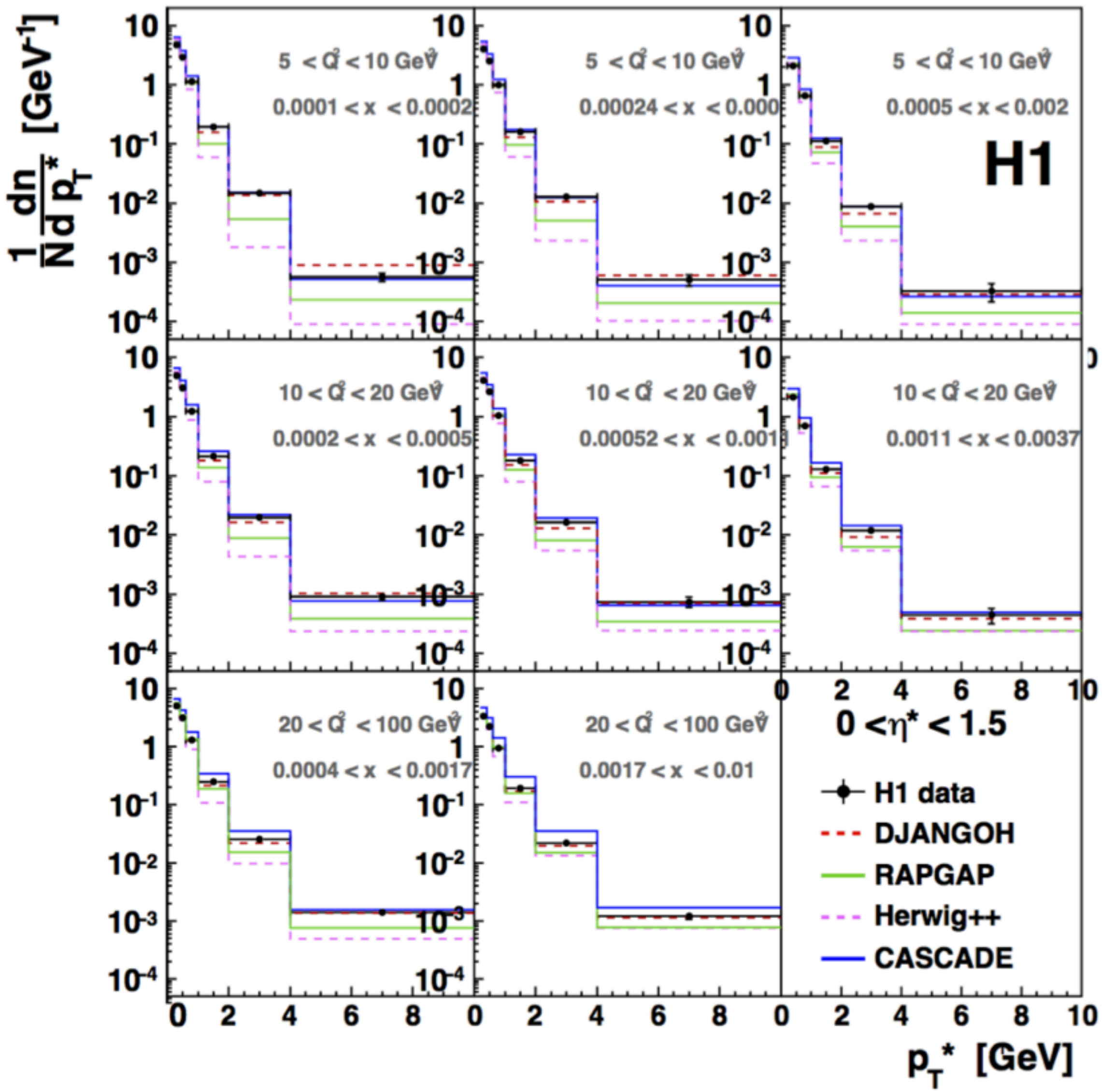


$F_2^c(x,Q^2)$



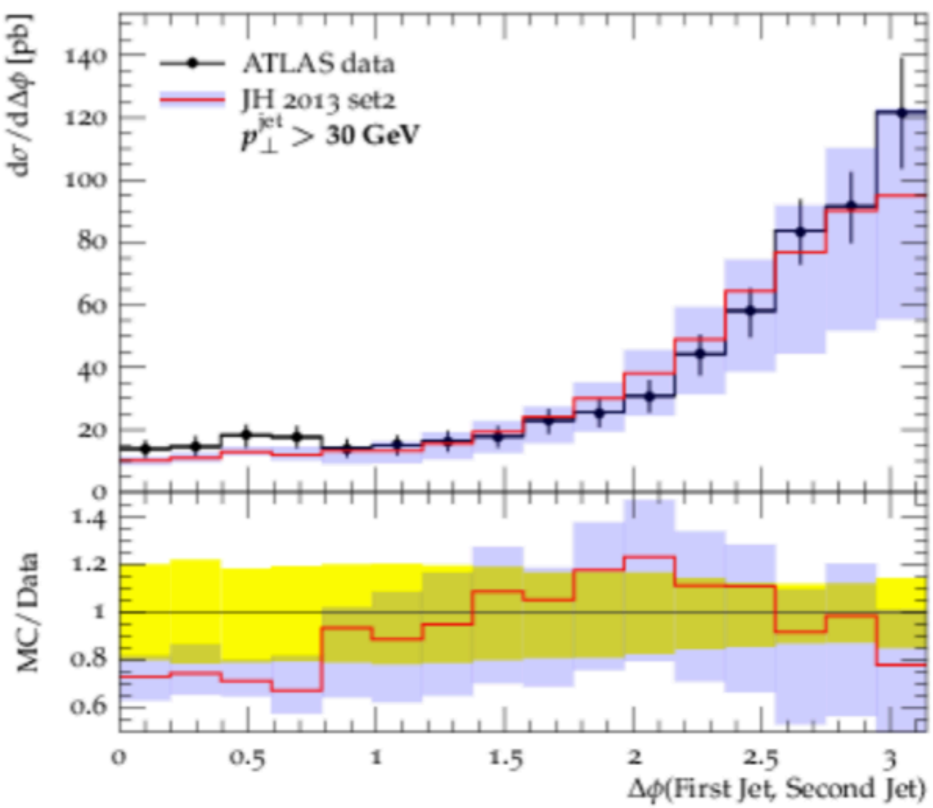
Charge Particle Spectra at HERA

[H1 EPJC 73 (2013) 2406]

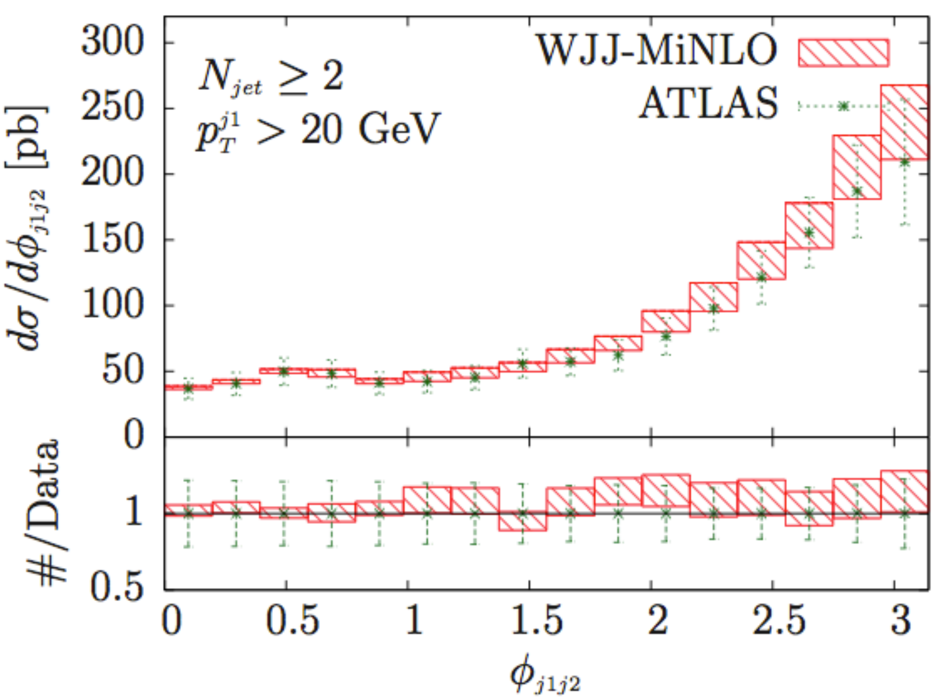


Azimuthal Distance of Leading Jets

F. Hautmann [talk at DIS2014]



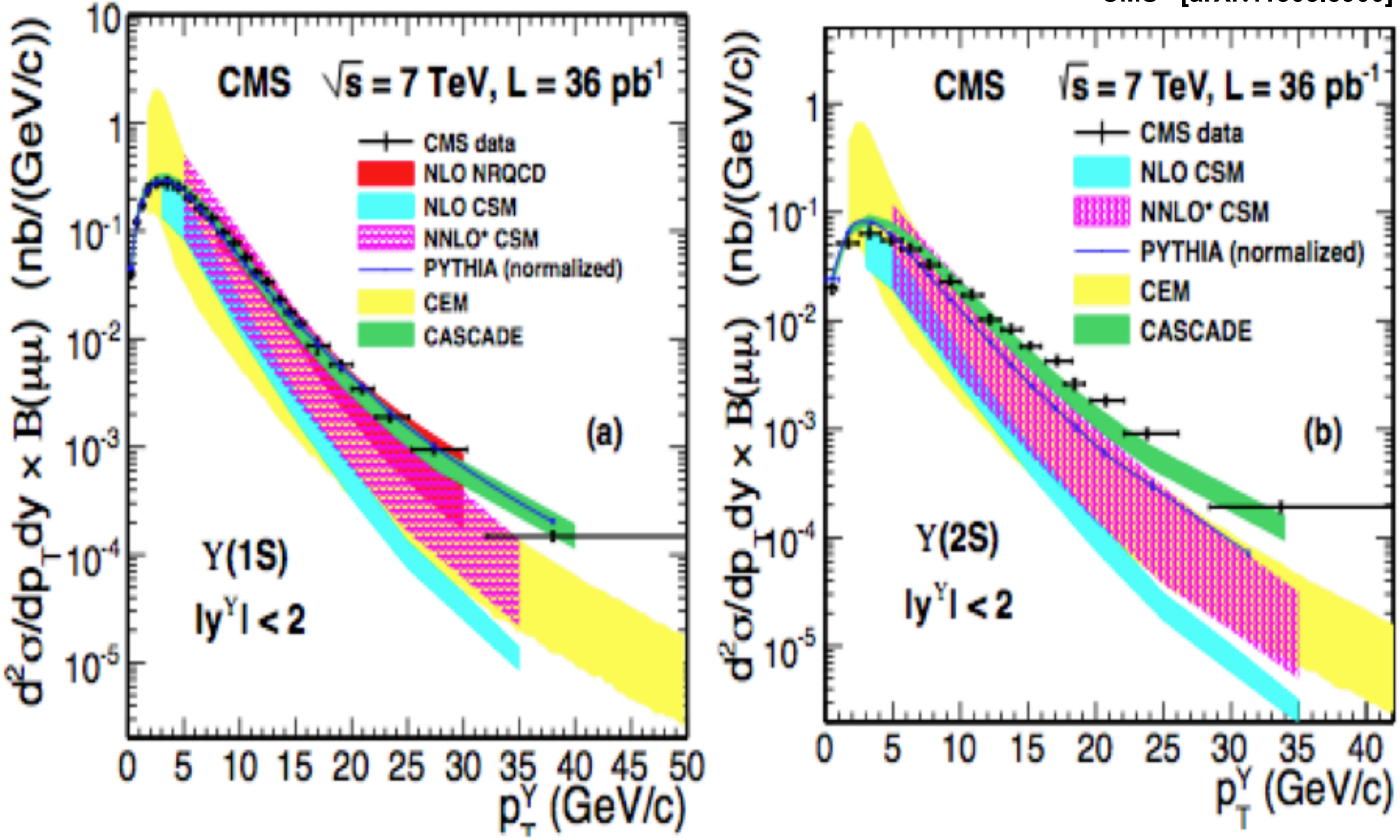
J. M. Campbell ++ [arXiv 1303.5447]



Upsilon Production

$$g^*g^* \to \Upsilon g,\ g^*g^* \to \chi_b \to \Upsilon + X$$

CMS [arXiv:1303.5900]



The Hadron Multiplicities

$$f_1 \cdot D_1$$

$$\frac{d^5\sigma^{ep\to e'hX}}{dx\, dy\, dz\, d\phi\, dP_{h\perp}^2} \propto \{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \varepsilon\, \mathrm{s}\cos(2\phi) F_{UU}^{\cos(2\phi)}\}$$

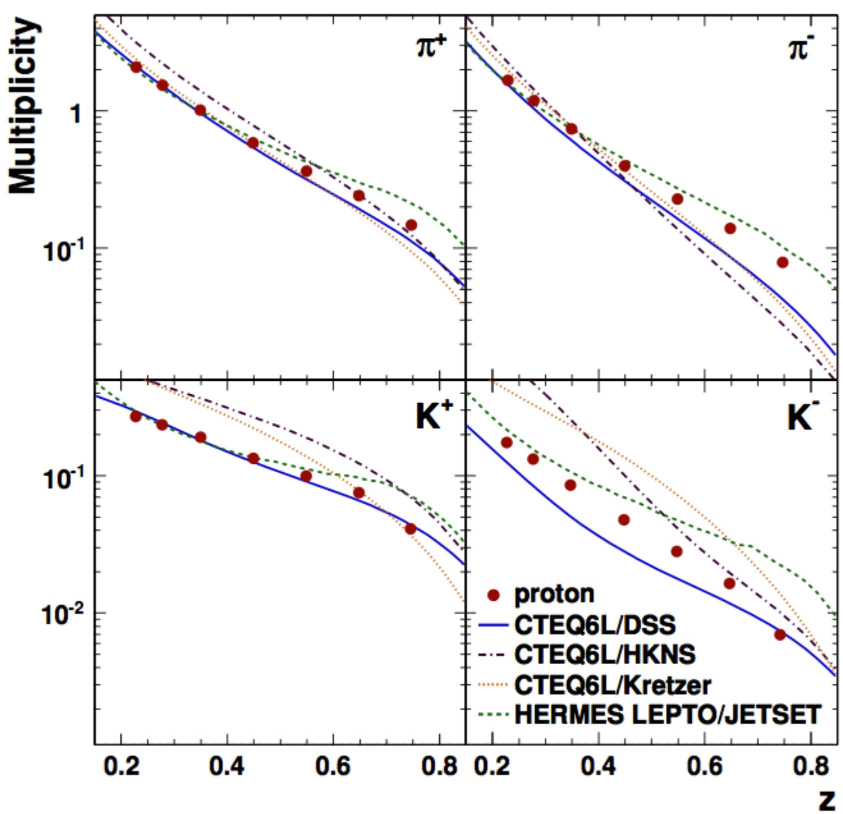
The Hadron Multiplicities

$f_1 \cdot D_1$

$$\frac{d^5\sigma^{ep\to e'hX}}{dx\,dy\,dz\,d\phi\,dP_{h\perp}^2} \propto \{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon\,\mathrm{s}\cos(2\phi)F_{UU}^{\cos(2\phi)}\}$$

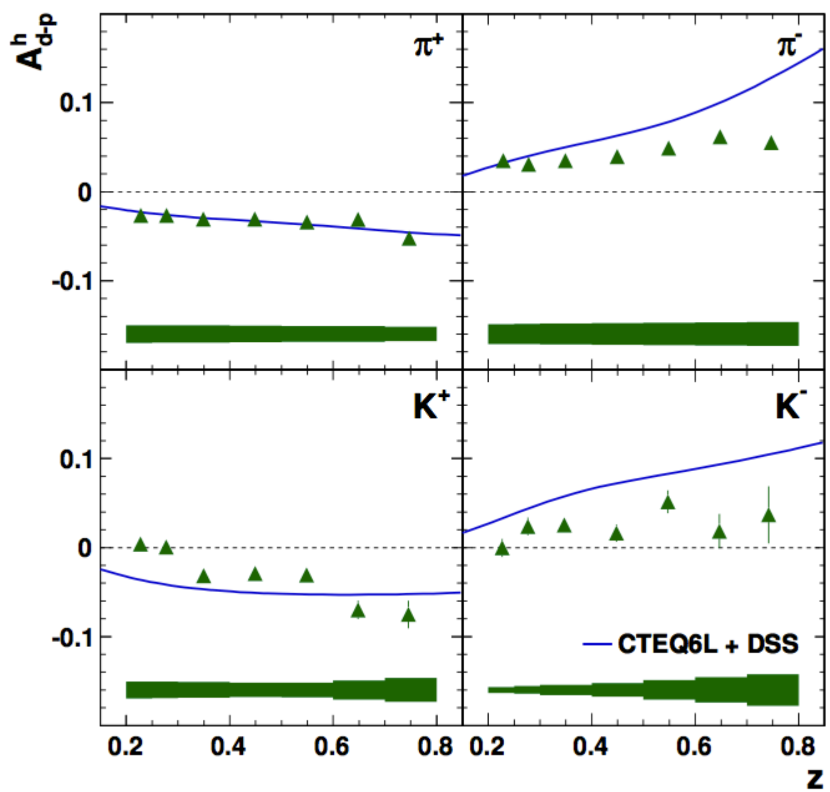
$f_1 \otimes D_1$

SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity



Proton-deuteron asymmetry:

Reflects different flavor content
Correlated systematics cancels



The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$

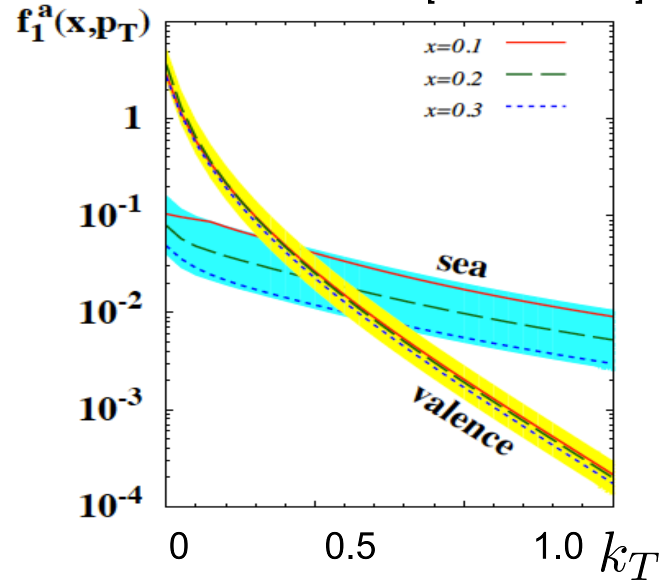
$$M_N^h(z) = \frac{1}{N_N^{DIS}(Q^2)} \frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\ f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\ f_{1q}(x,Q^2)}$$

Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation p_T,

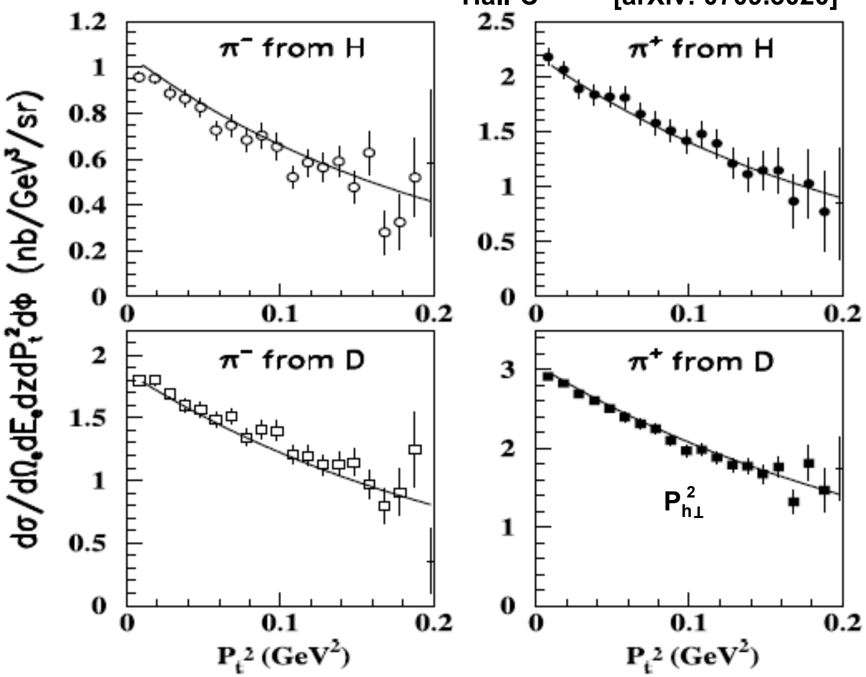
i.e. from gaussian anstaz:

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$

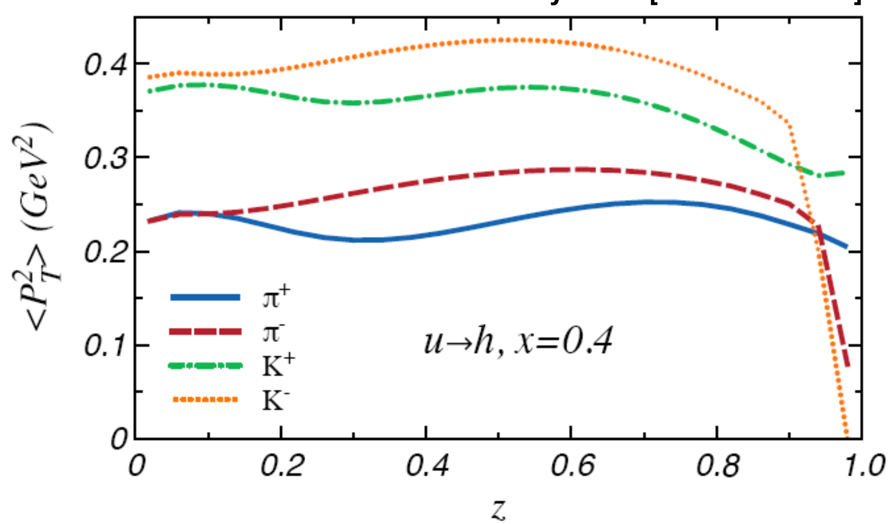
P. Schweitzer++ [arXiv:1210.1267]



Hall-C [arXiv: 0709.3020]



Matevosyan++ [arXiv:1111.1740]



The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$

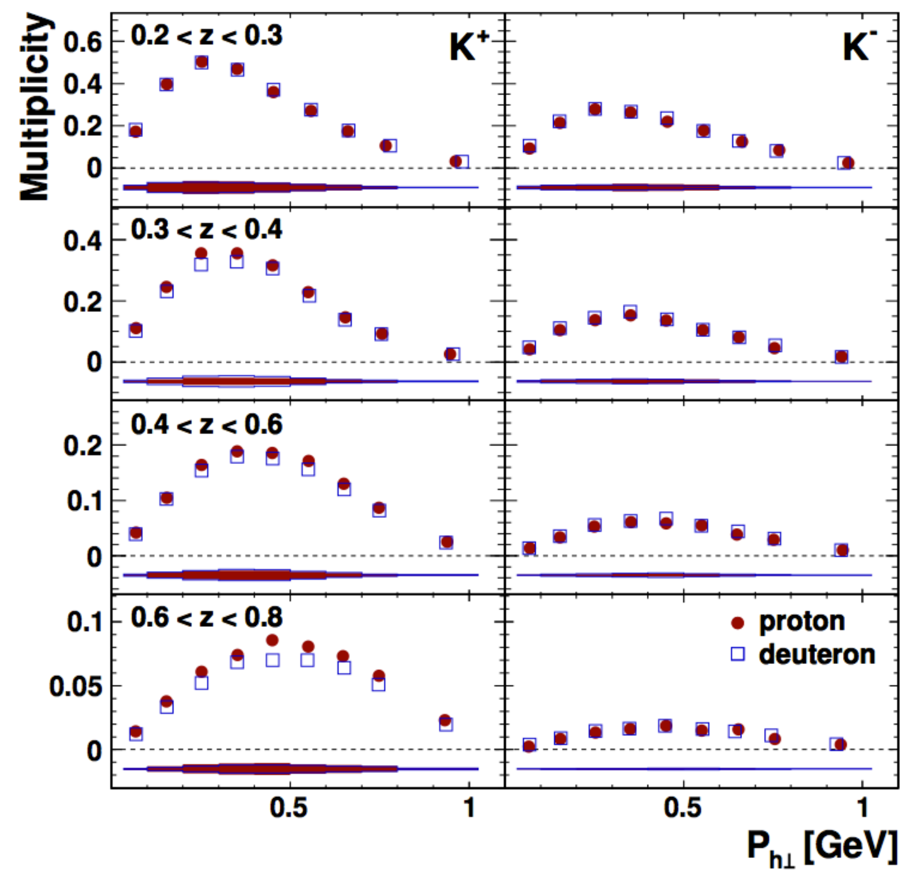
$$M_N^h(z) = \frac{1}{N_N^{DIS}(Q^2)} \frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\ f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\ f_{1q}(x,Q^2)}$$

Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation $p_{T,}$

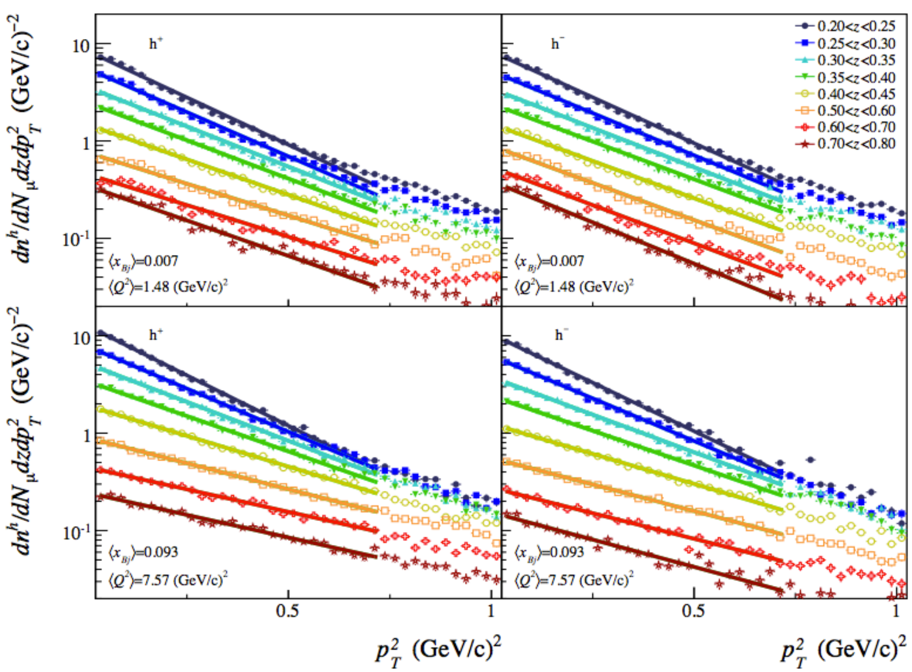
i.e. from gaussian anstaz:

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$

HERMES **[arXiv: 1212.5407]**



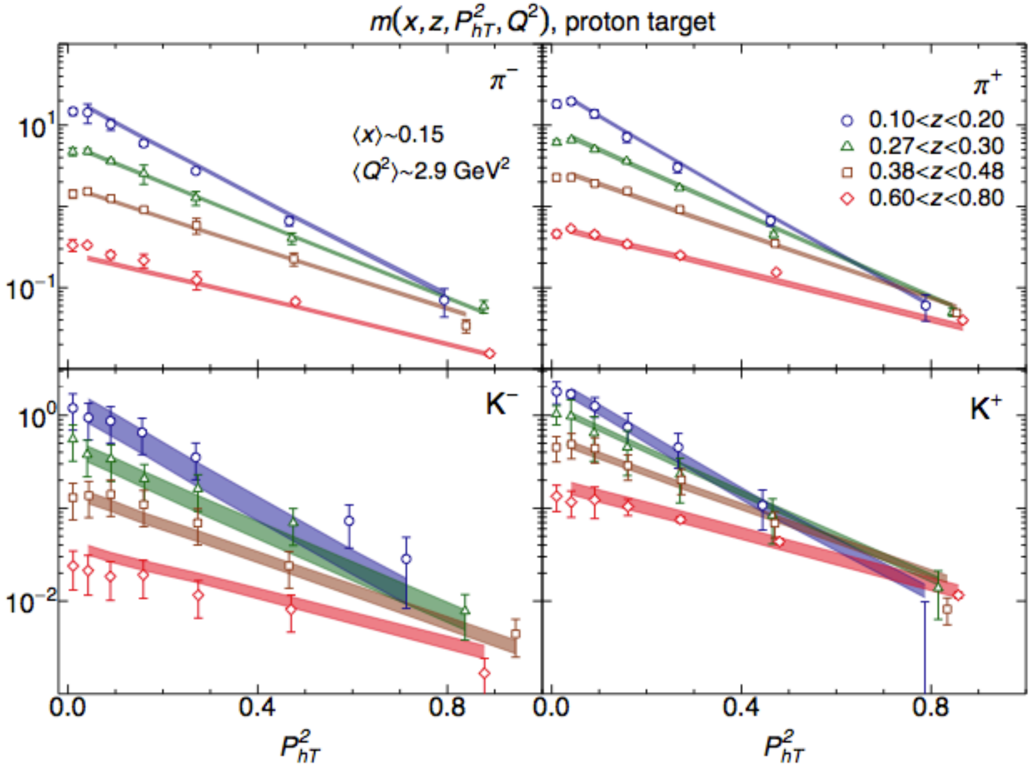
COMPASS **[arXiv: 1305.7317]**

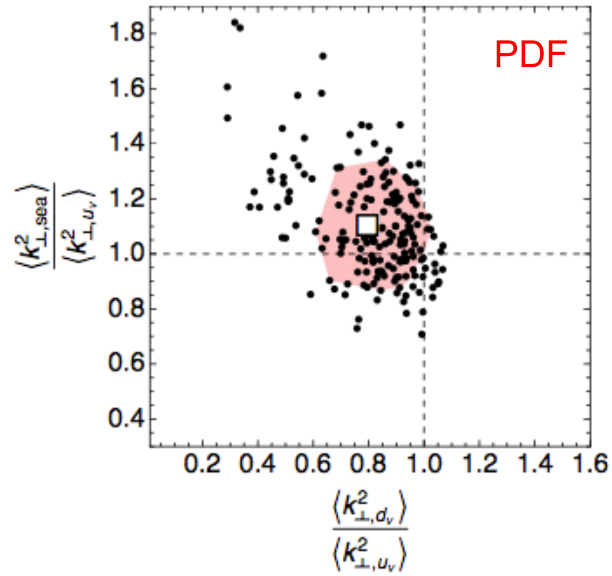


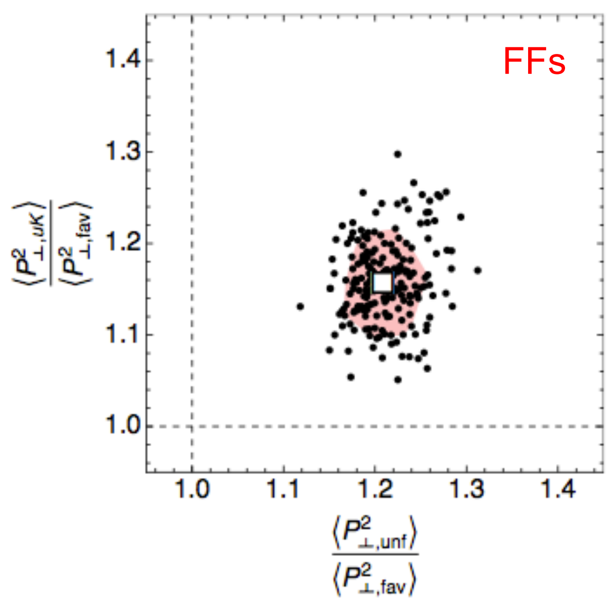
G. Karyan, N. Makke

The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$

A. Signori++ [arXiv:1309.3507]

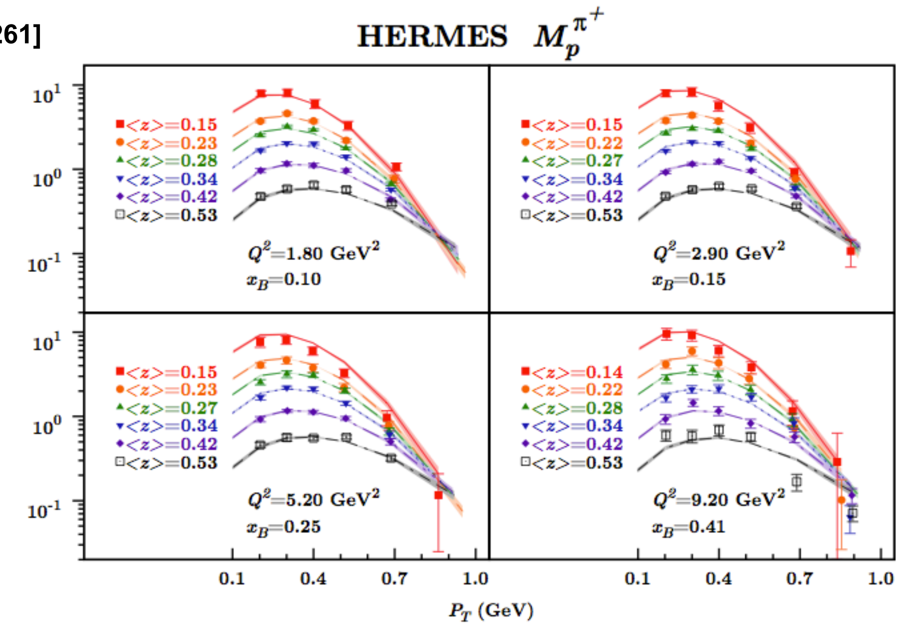




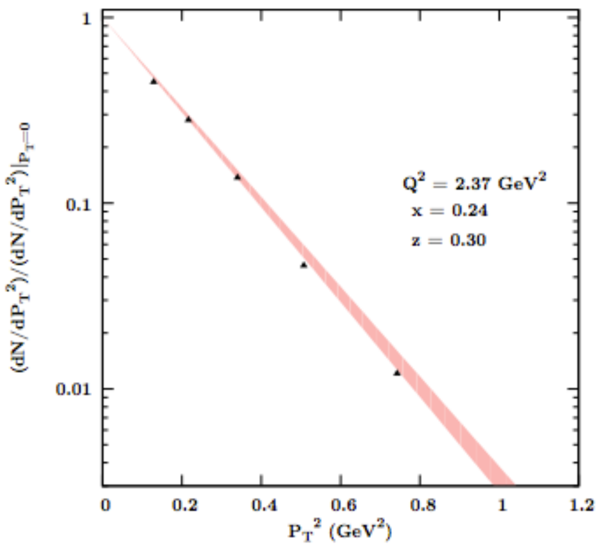


A. Signori

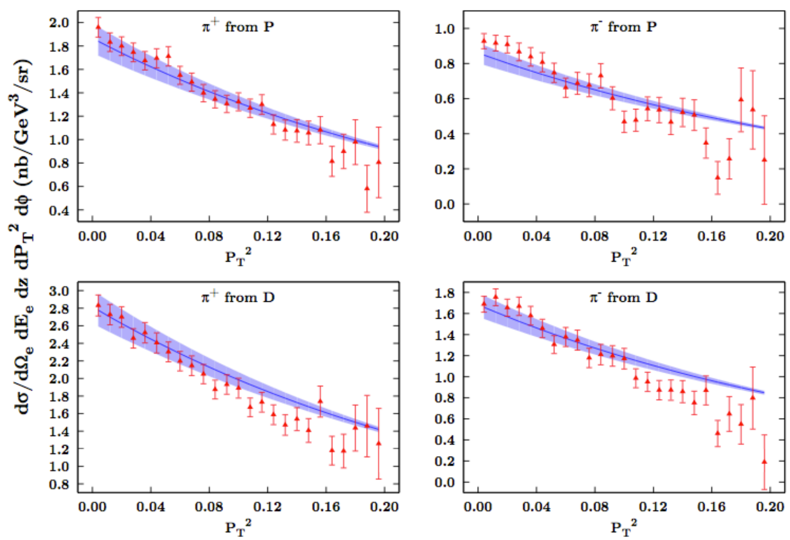
M. Anselmino++ [arXiv:1312.6261]



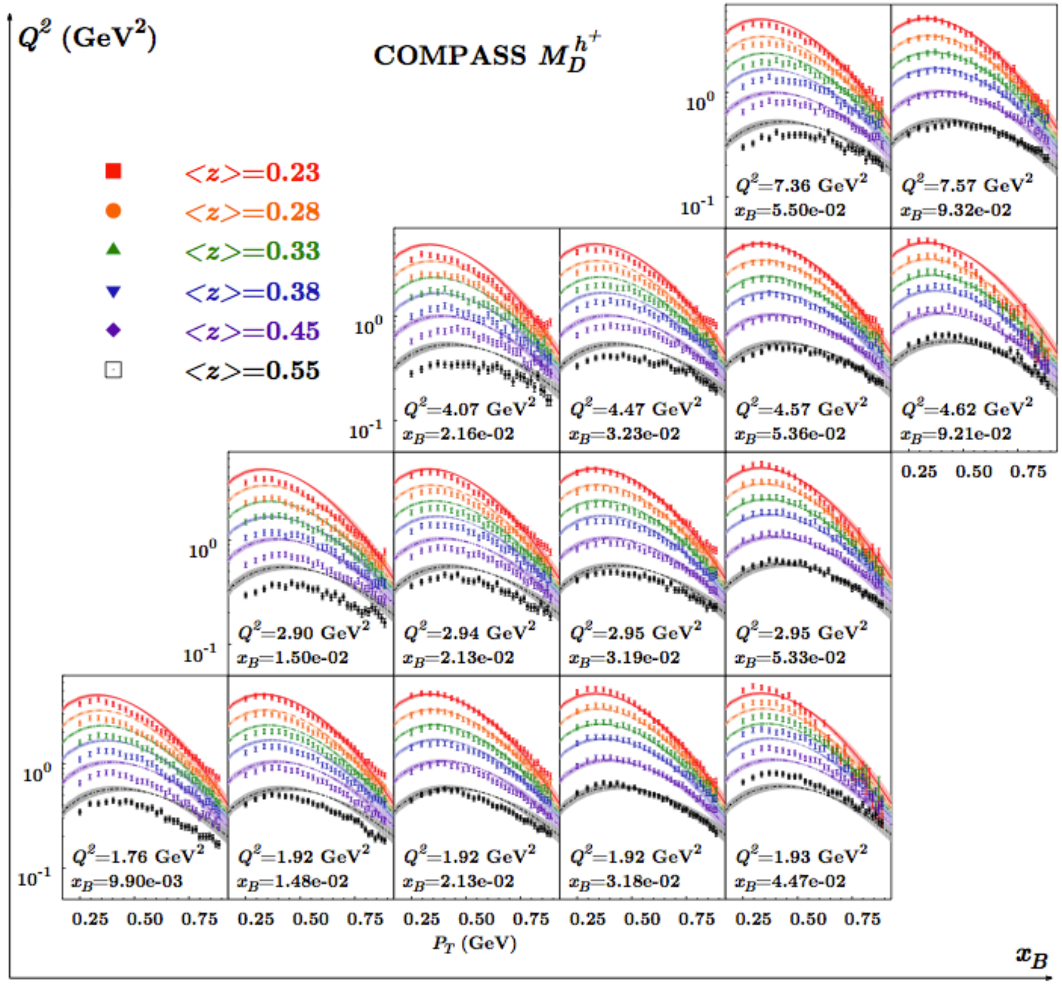
CLAS [arXiv: 0809.1153]



Hall-C [arXiv: 0709.3020]



The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$



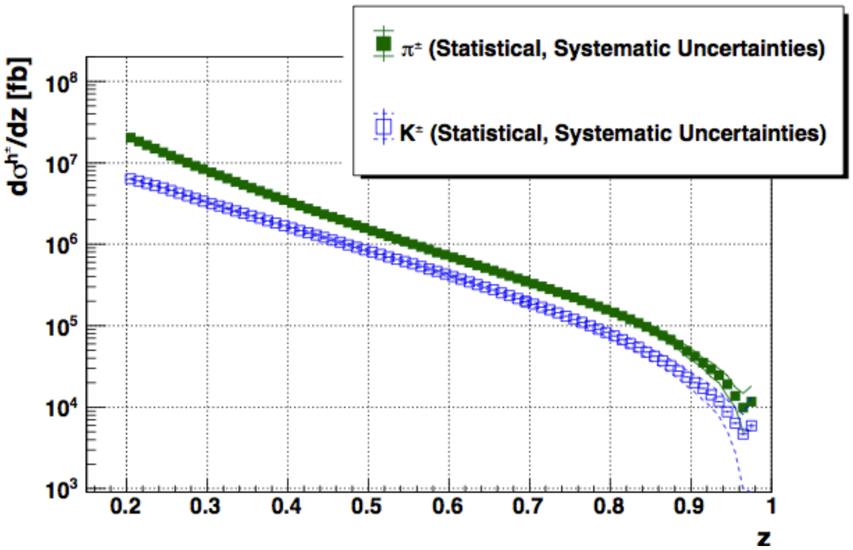
J.O. Gonzales

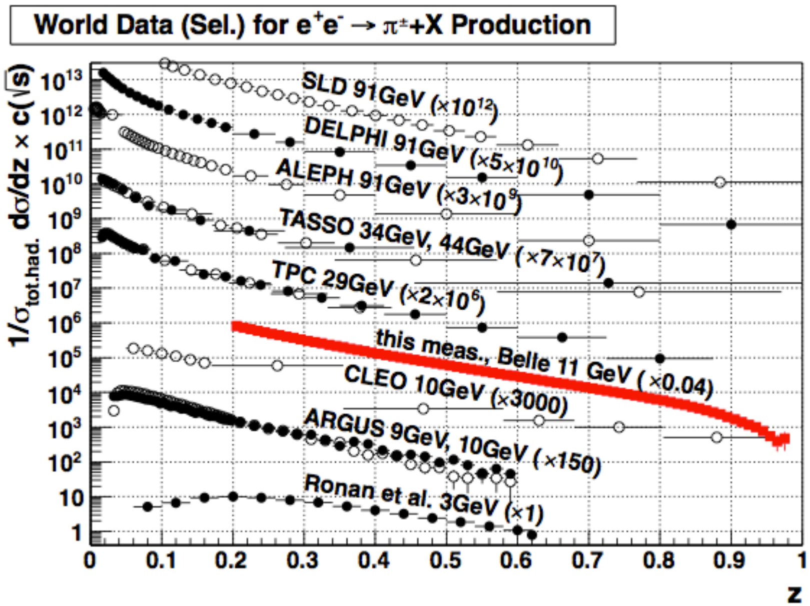
Normalization, range validity and evolution still under study

Despite the high precision data no clear sensitivity on k_T, p_T flavor dependence

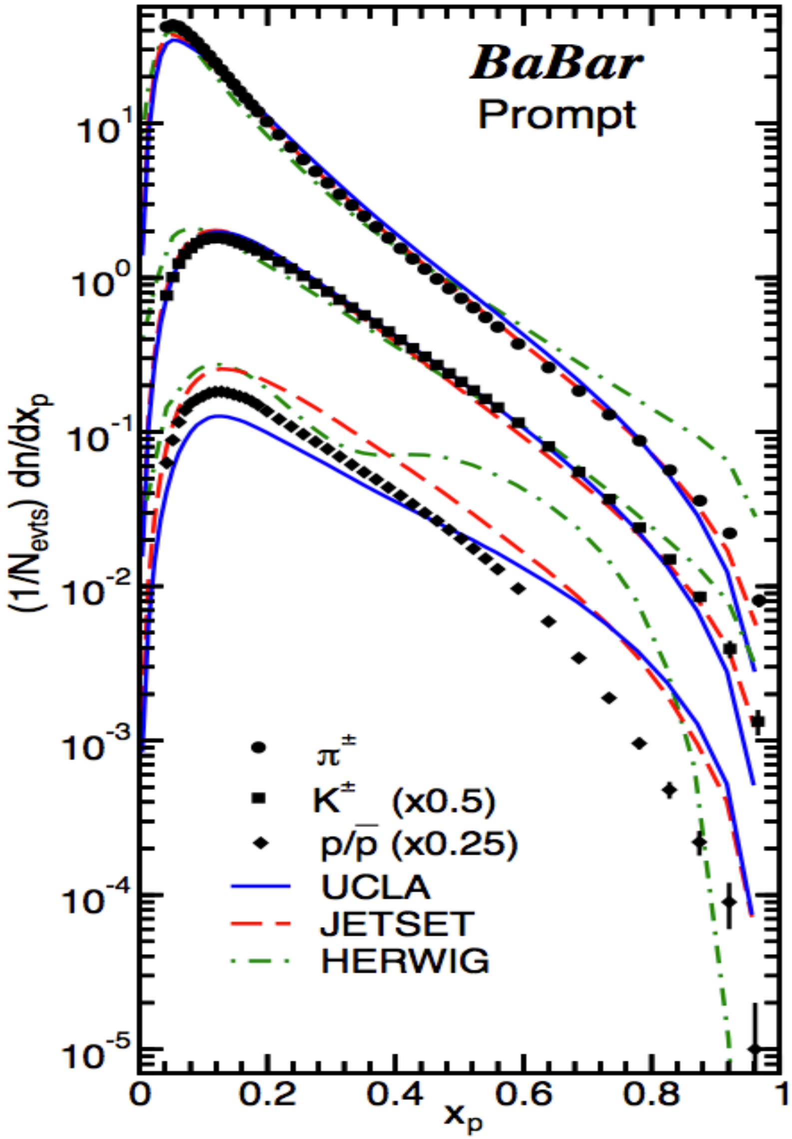
Fragmentation Functions @ B-factories

Belle [arXiv 1301.6183]





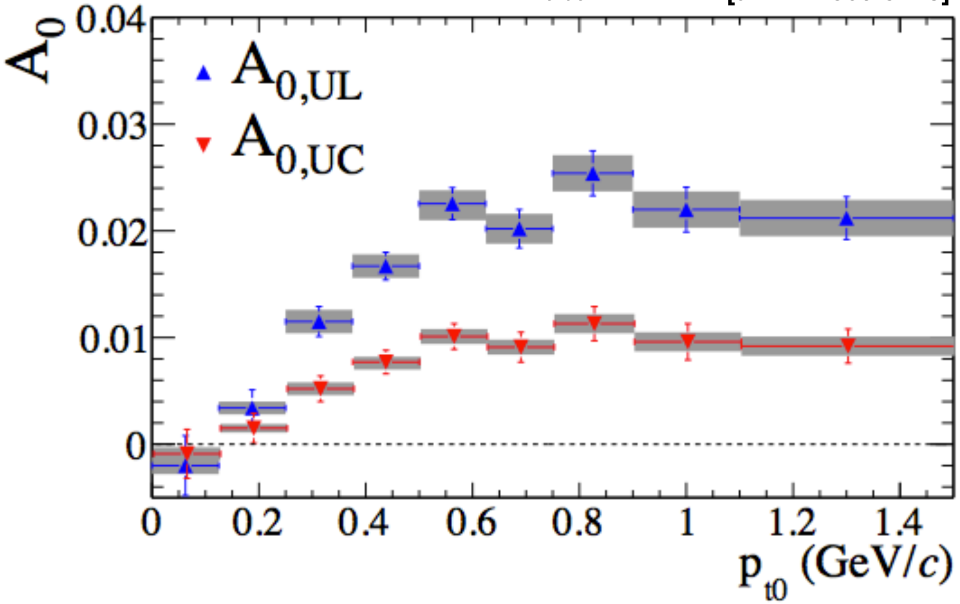
Babar [arXiv 1306.2895]



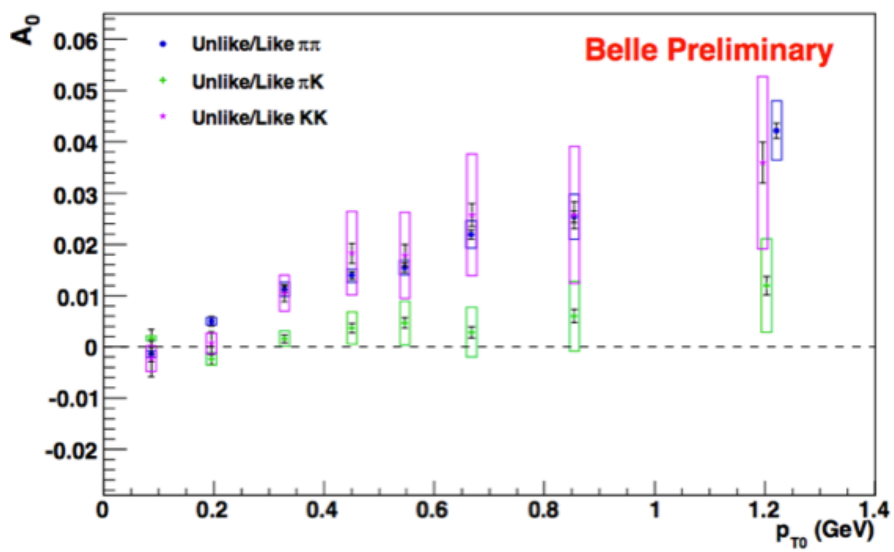
Fragmentation Functions @ B-factories

Crucial to seek unintegrated FFs

Babar [arXiv 1309.5278]

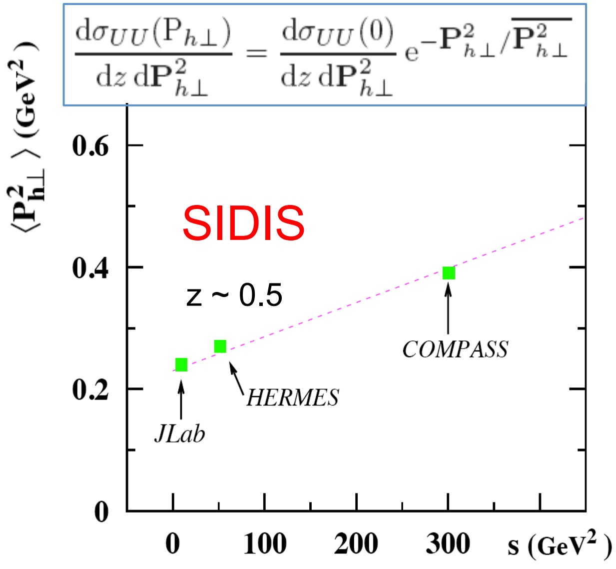


F. Giordano [talk at DIS2014]

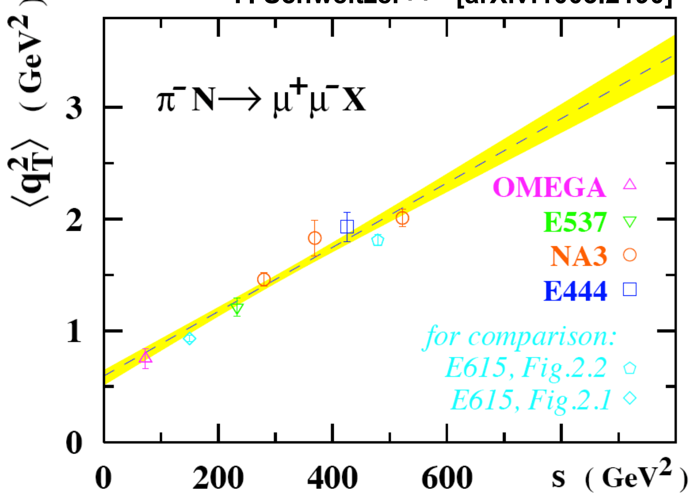


I. Garzia, F. Giordano Talks

$f_1 \otimes D_1$



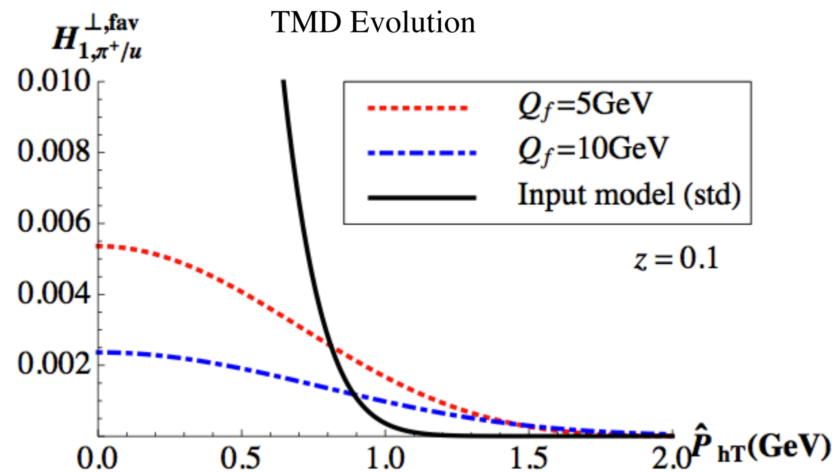
P. Schweitzer++ [arXiv:1003.2190]

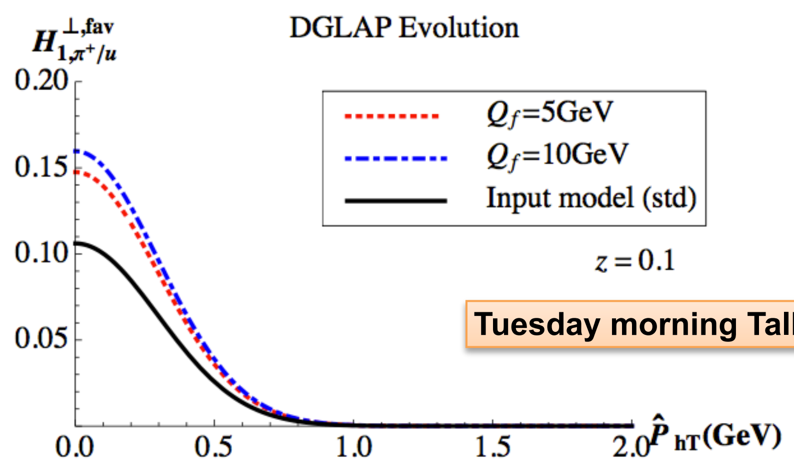


Indication of a k_T and p_T broadening with c.m. energy:

TMD Q^2 evolution ≠ DGLAP

M.G. Echevarria++ [arXiv:1402.0869]



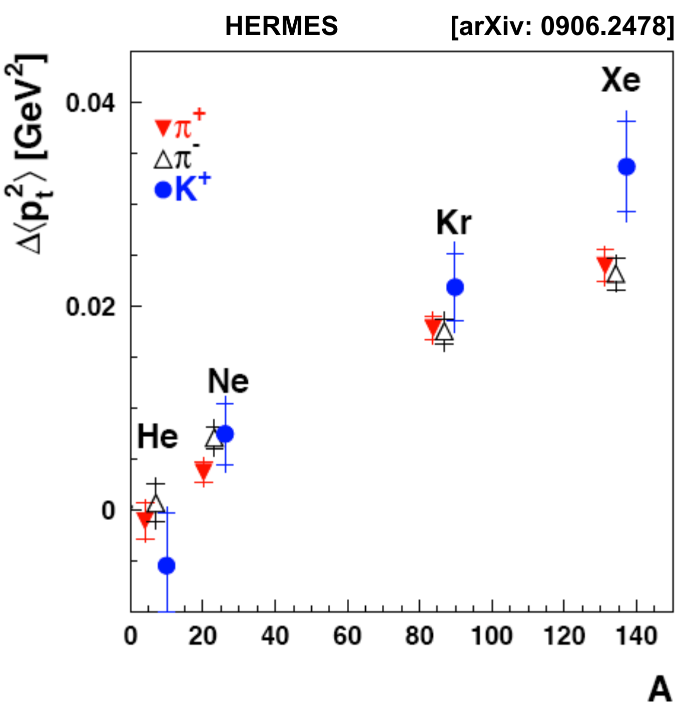


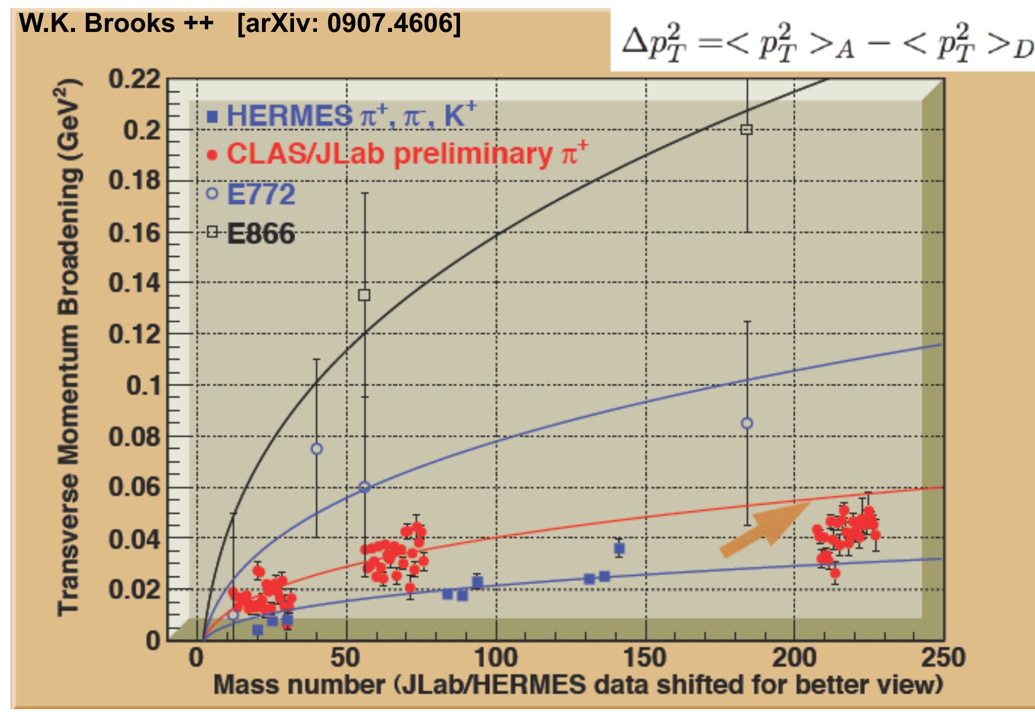
Tuesday morning Talks

Medium modification

In terms of the QCD, there are several contributions to P_T distribution of hadrons produced in SIDIS:

- primordial transverse momentum,
- gluon radiation of the struck quark,
- the formation and soft multiple interactions of the "pre-hadron"
- the interaction of the formed hadrons with the surrounding hadronic medium

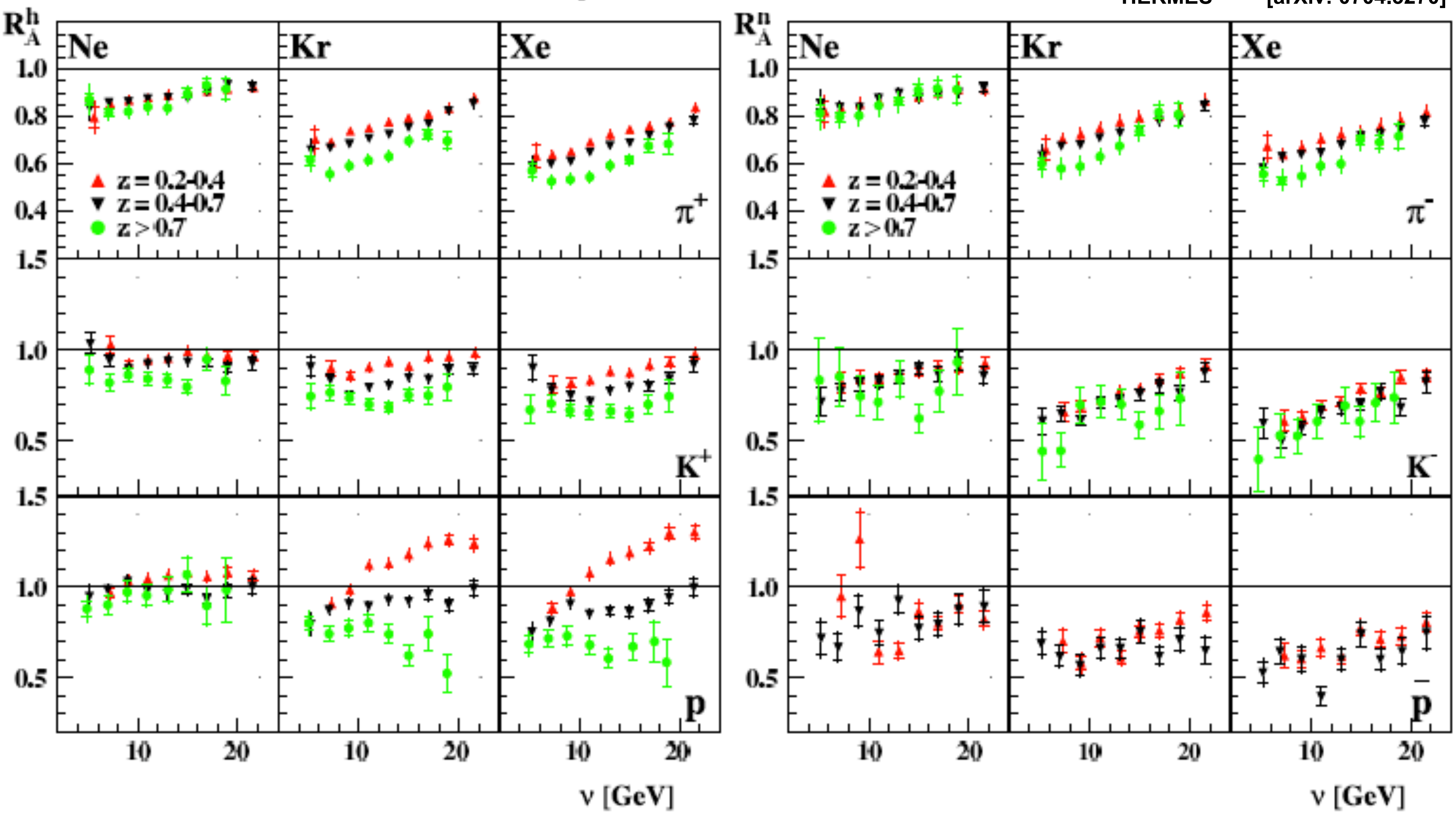




Medium modification

$$R_M(z,\nu,Q^2,p_t^2)=\frac{\left.\dfrac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}\right|_A}{\left.\dfrac{N_h(z,\nu,Q^2,p_t^2)}{N_{DIS}}\right|_D}\propto\frac{\left.\dfrac{\Sigma e_f^2 q_f(x,Q^2,p_T^2)D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}\right|_A}{\left.\dfrac{\Sigma e_f^2 q_f(x,Q^2,p_T^2)D_f^h(z,Q^2,k_T^2)}{\Sigma e_f^2 q_f(x,Q^2,p_T^2)}\right|_D}$$

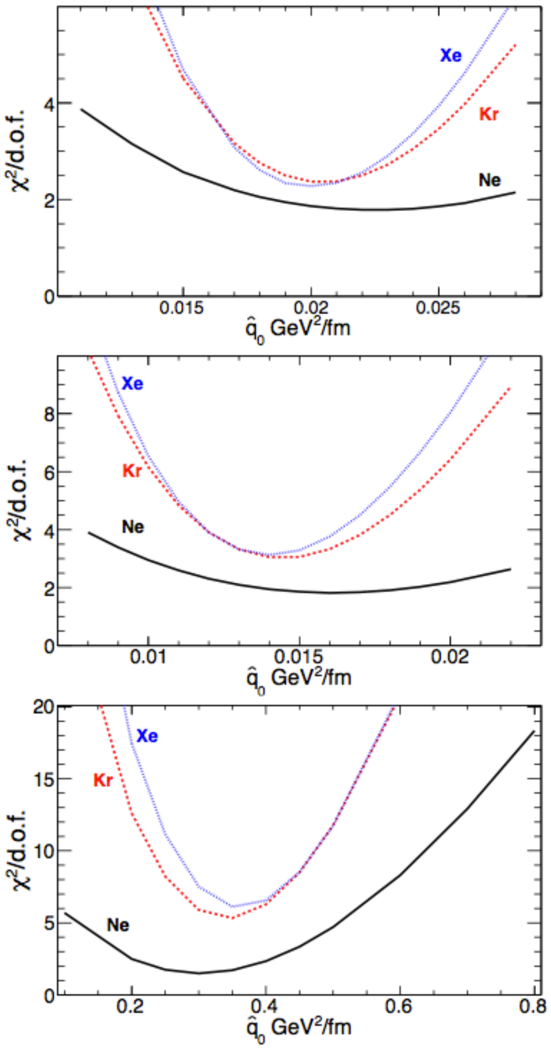
HERMES [arXiv: 0704.3270]

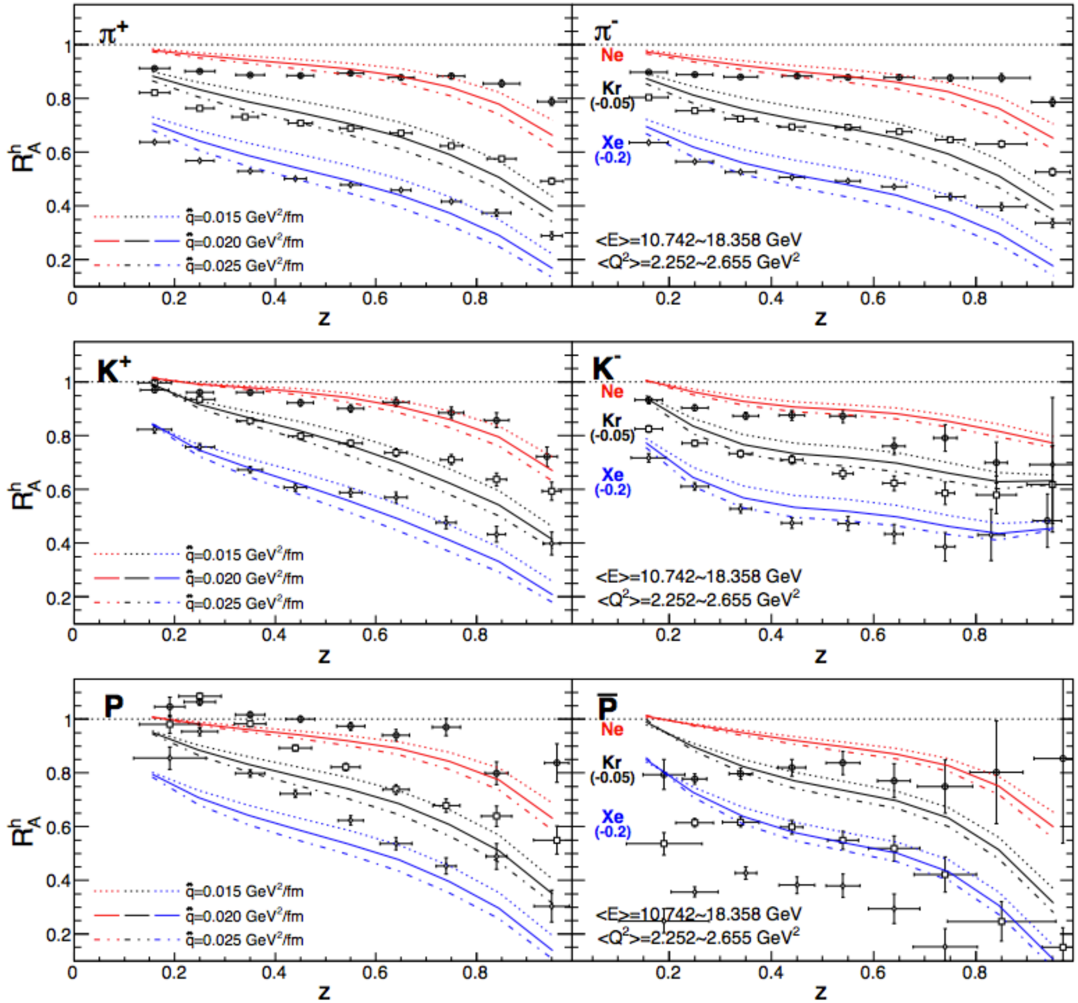


DIS

$$\hat{q}_0 \approx 0.020 \pm 0.005\ \mathrm{GeV}^2/\mathrm{fm}$$

N-B Chang ++ [arXiv:1401.5109]



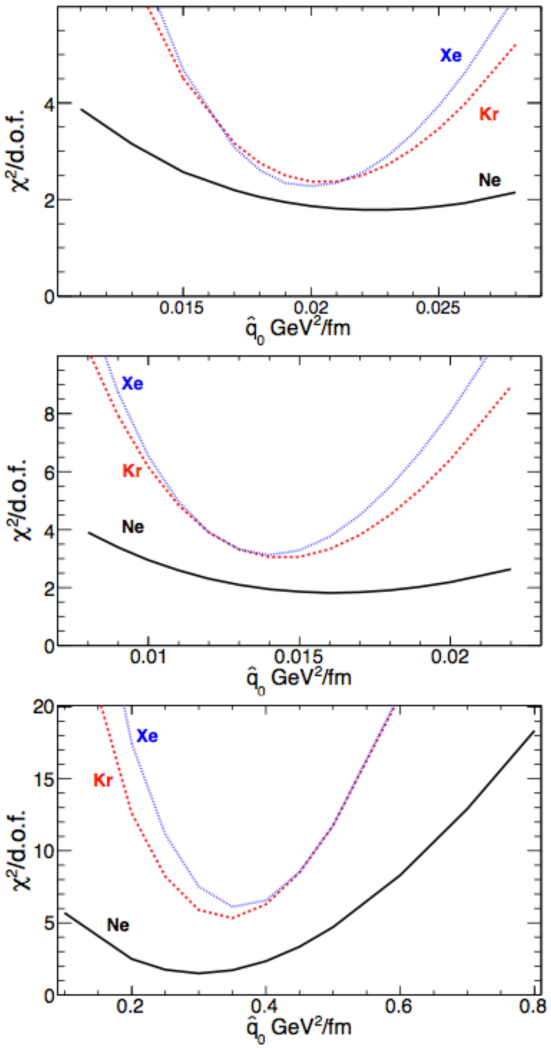


Quark Transport Parameter

DIS

$$\hat{q}_0 \approx 0.020 \pm 0.005\ \mathrm{GeV}^2/\mathrm{fm}$$

N-B Chang ++ [arXiv:1401.5109]

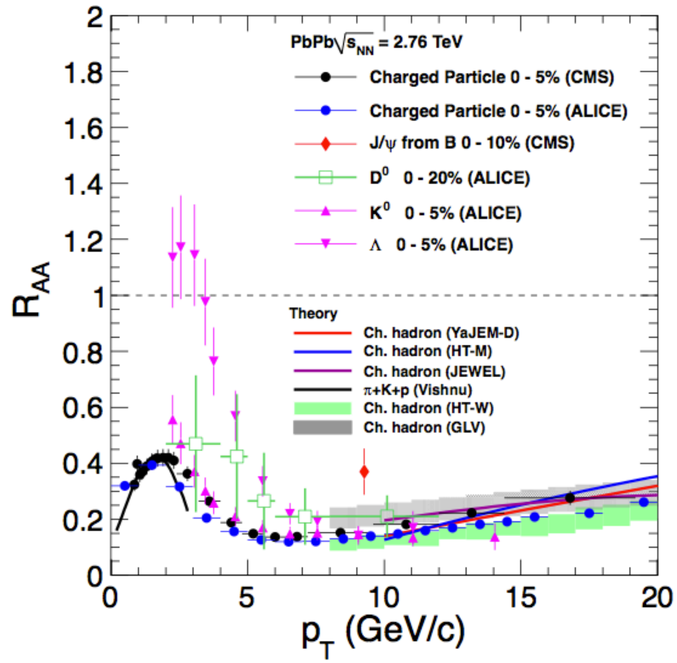


RHIC

$$\hat{q} \approx 1.2 \pm 0.3\ \mathrm{GeV}^2/\mathrm{fm}$$

Au+Au $\sqrt{s} = 200\ \mathrm{GeV/n}$

JET Coll. [arXiv:1312.5003]

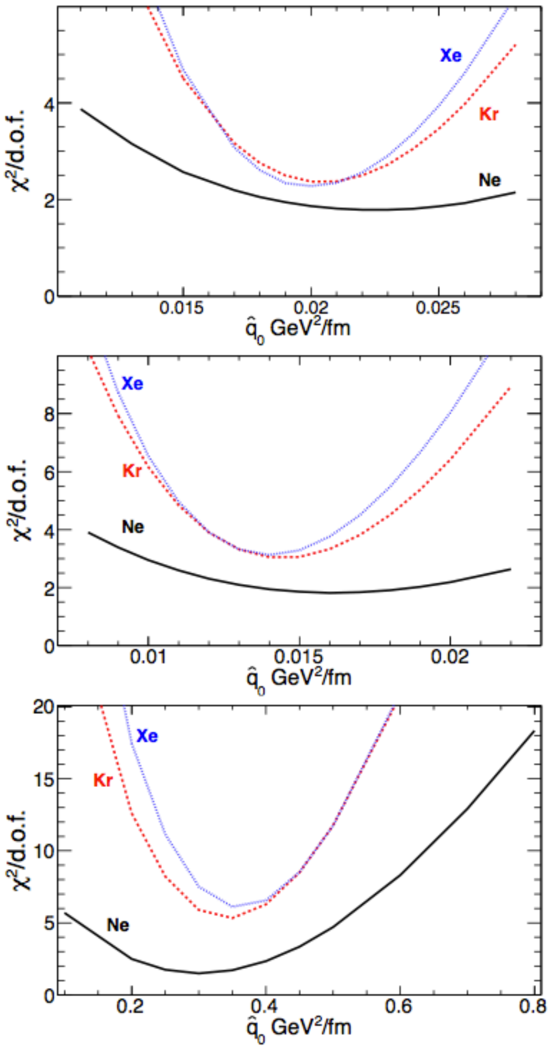


Medium modification

DIS

$$\hat{q}_0 \approx 0.020 \pm 0.005\ \mathrm{GeV}^2/\mathrm{fm}$$

N-B Chang ++ [arXiv:1401.5109]



RHIC

$$\hat{q} \approx 1.2 \pm 0.3\ \mathrm{GeV}^2/\mathrm{fm}$$

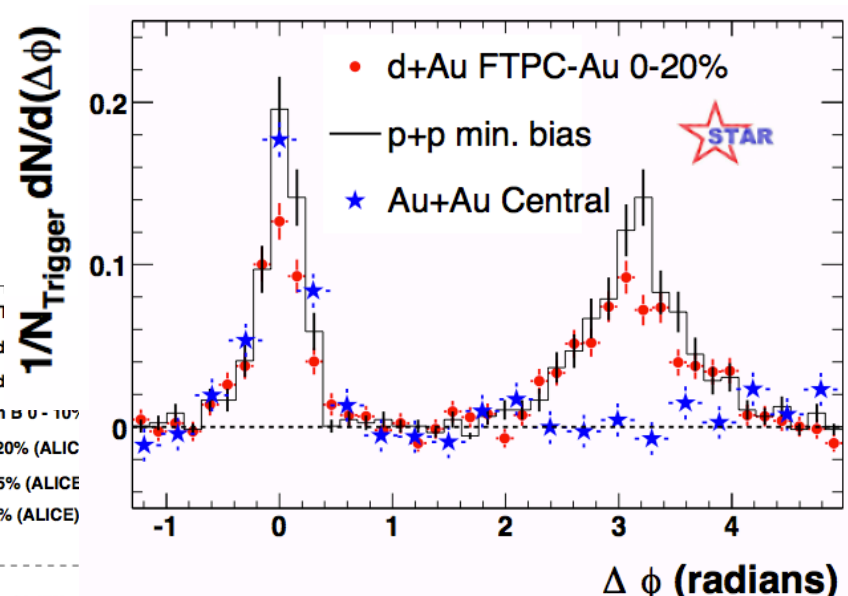
Au+Au $\sqrt{s} = 200\ \mathrm{GeV/n}$

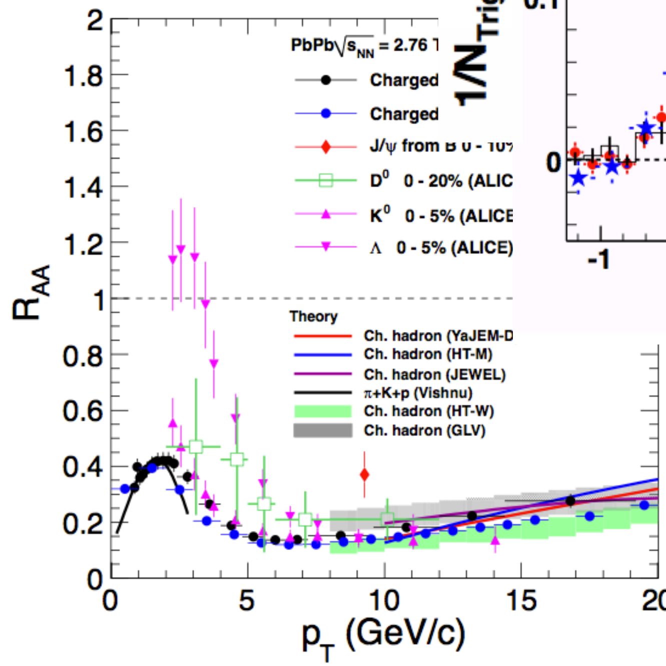
LHC

$$\hat{q} \approx 1.9 \pm 0.7\ \mathrm{GeV}^2/\mathrm{fm}$$

Pb+Pb $\sqrt{s} = 2.76\ \mathrm{TeV/n}$

JET Coll. [arXiv:1312.5003]





Medium modification

$$f_1^N(x,\ell_\perp) = \frac{1}{\pi\alpha} f_1^N(x) e^{-\vec{\ell}_\perp^2/\alpha}$$

$$f_1^A(x,k_\perp) \approx \frac{A}{\pi\alpha_A} f_1^N(x) e^{-\vec{k}_\perp^2/\alpha_A}$$

$\alpha + \Delta_{2F}$

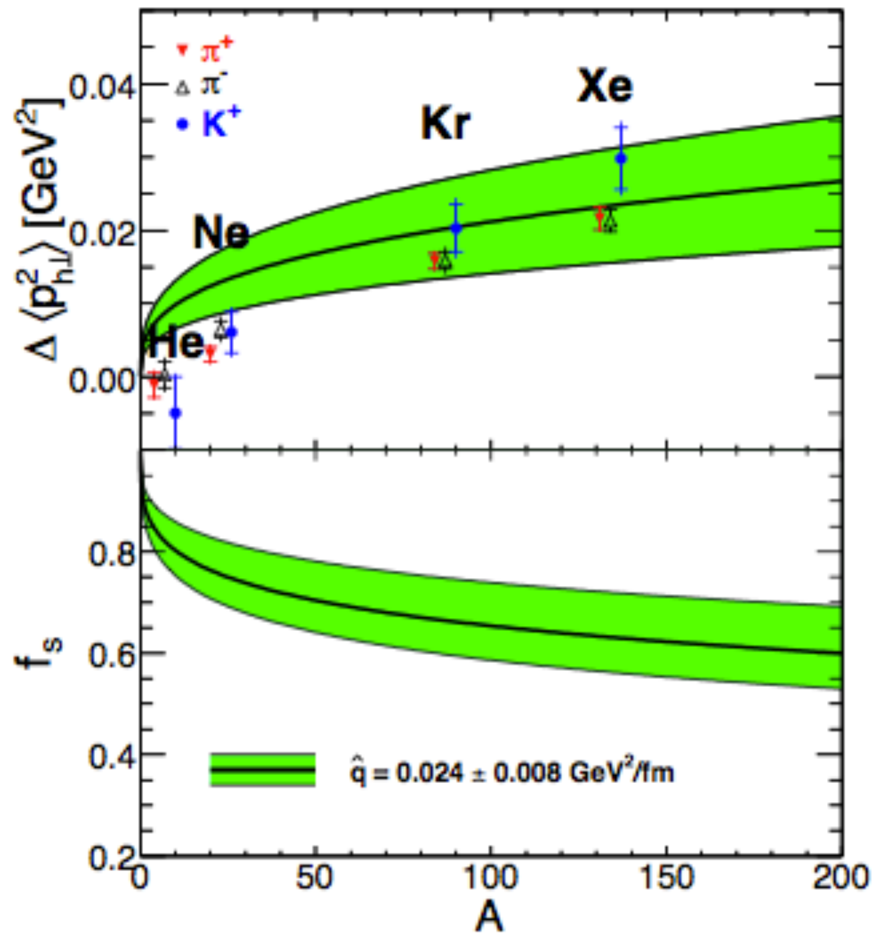
N-B Chang ++ [arXiv:1402.3042]

$$\Delta_{2F} = 3\sqrt{2}\hat{q}_0 r_0 A^{1/3}/4$$

$$\frac{\langle\cos\phi\rangle_{UU}^{eA}}{\langle\cos\phi\rangle_{UU}^{eN}} \approx \frac{\langle\sin\phi\rangle_{LU}^{eA}}{\langle\sin\phi\rangle_{LU}^{eN}} \approx \frac{\alpha}{\alpha+\Delta_{2F}} = f_s$$

$$\frac{\langle\sin(\phi-\phi_s)\rangle_{UT}^{eA}}{\langle\sin(\phi-\phi_s)\rangle_{UT}^{eN}} = \frac{\langle\cos(\phi-\phi_s)\rangle_{UT}^{eA}}{\langle\cos(\phi-\phi_s)\rangle_{UT}^{eN}} = \frac{\langle\sin\phi\rangle_{UL}^{eA}}{\langle\sin\phi\rangle_{UL}^{eN}} \approx \frac{2J_A}{A}\frac{\alpha}{\alpha+\Delta_{2F}}$$

HERMES [arXiv: 0906.2478]

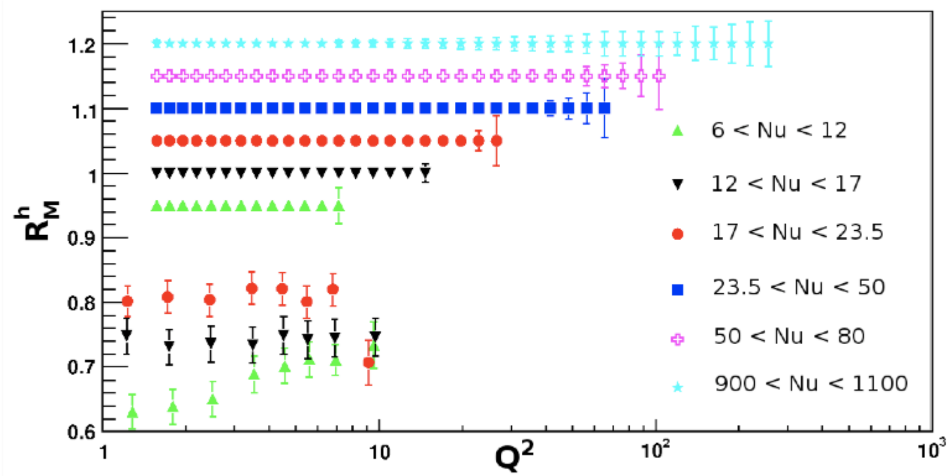


Medium modification @ JLab12

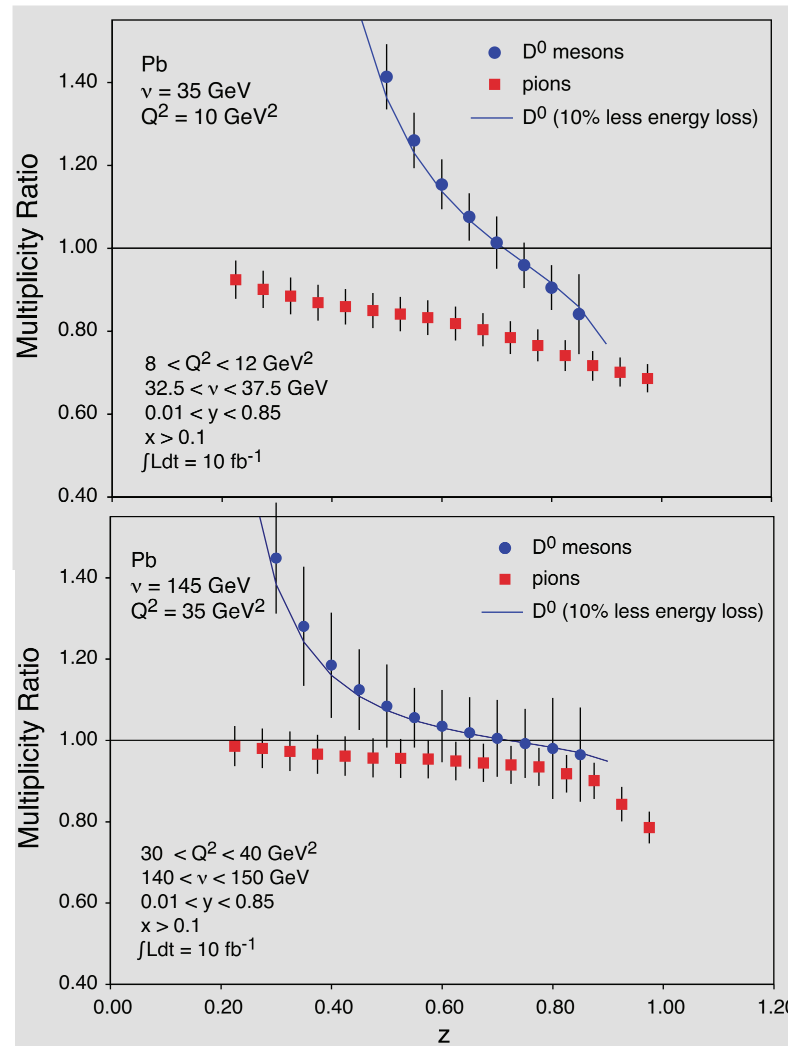
JLab12 [E12-06-117 Hall-B]

Medium modification @ EIC

Unprecedent precision and Q^2, ν range



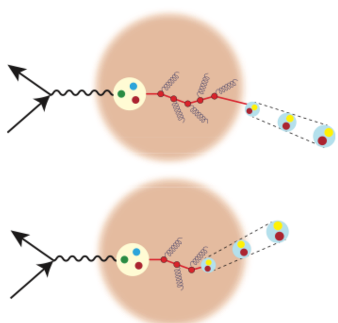
A. Accardi et al. [arXiv 1212.1701]

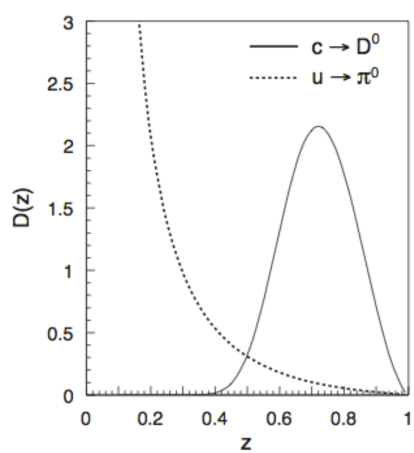


Light vs heavy quarks

D^0 enhancement:

- due to the different FFs
- slope sensitive to the transport parameter
- shape sensitive to ν





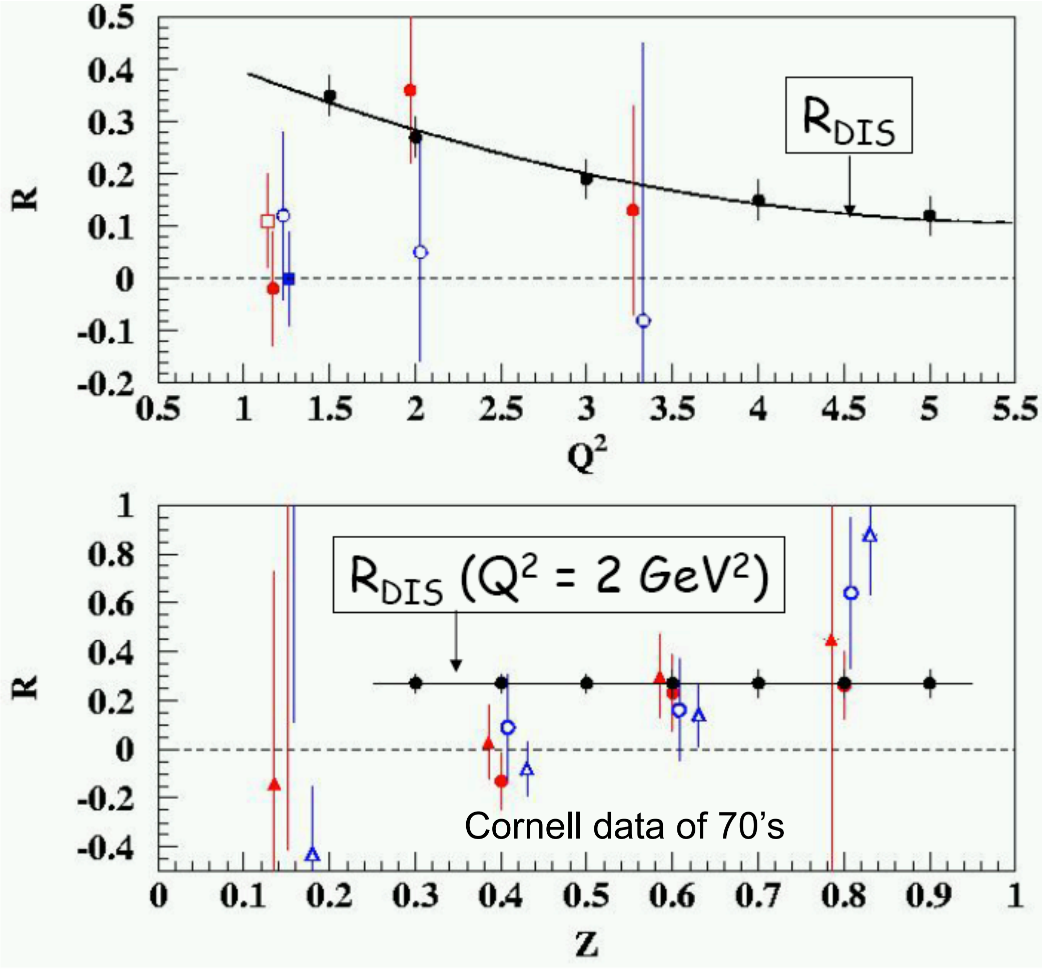
Longitudinal Cross-section

$$\frac{d^5\sigma^{ep\to e'hX}}{dx\,dy\,dz\,d\phi\,dP_{h\perp}^2} \propto \{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon\, s\cos(2\phi)F_{UU}^{\cos(2\phi)}\}$$

Knowledge on $R = \sigma_L/\sigma_T$ in SIDIS is non-existing!

To be accounted in any TMD asymmetry interpretation

JLab12 [E12-06-104 Hall-C]



- $R_{DIS} \to 0$ at $Q^2 \to \infty$ due to scattering off spin-½ quarks
- R_{DIS} sensitive to gluon and higher-twist effects
- $R_{SIDIS}(z,pT)$ = un-integrated R_{DIS}

The Azimuthal Modulation

$h_1^\perp \otimes H_1^\perp$

$$\frac{d^5\sigma^{ep\to e'hX}}{dx\,dy\,dz\,d\phi\,dP_{h\perp}^2} \propto \{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon\,s\cos(2\phi)F_{UU}^{\cos(2\phi)}\}$$

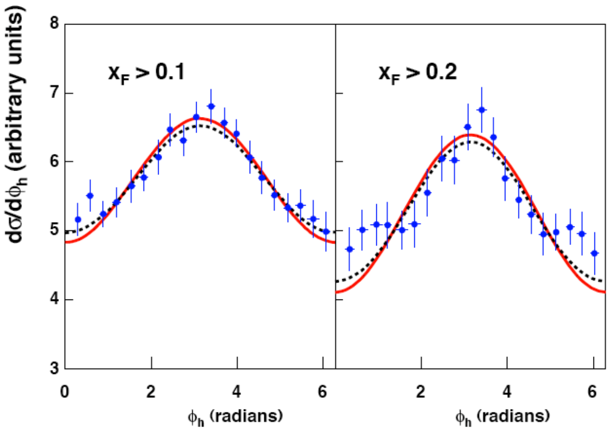
Cahn PLB 78 (1978)

Boer & Mulders PRD 57 (1998)

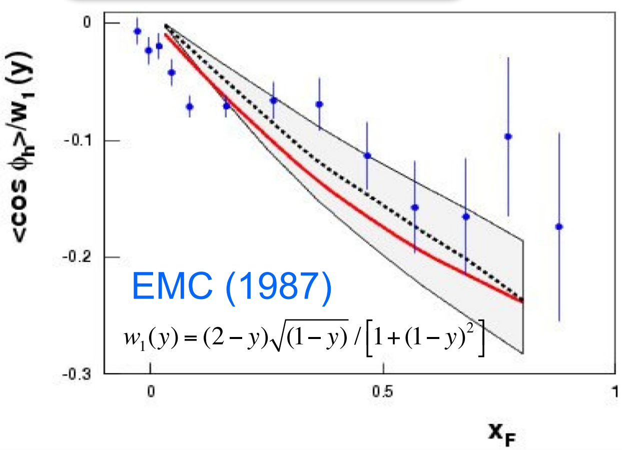
Kinematical effect predicted since 1978 by Cahn due to non-zero intrinsic k_T

Leading-twist contribution introduced by Boer & Mulders in 1998

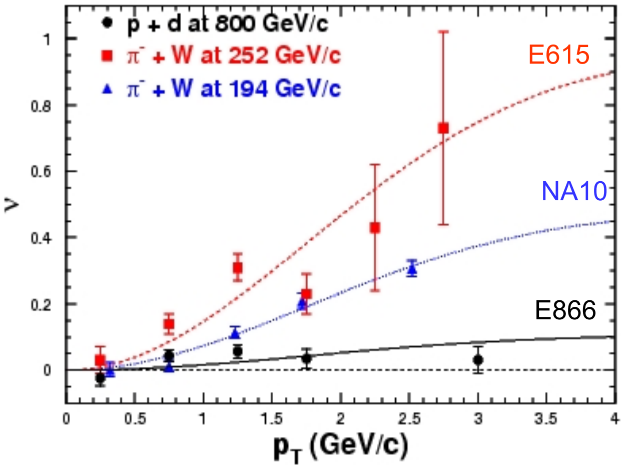
SIDIS: qualitative agreement with Cahn expectations till 2008



- No hadron identification
- No charge separation
- Poor statistics for cos2φ



DY: violation of Lam-Tung relation



The SIDIS cos2ϕ Amplitude

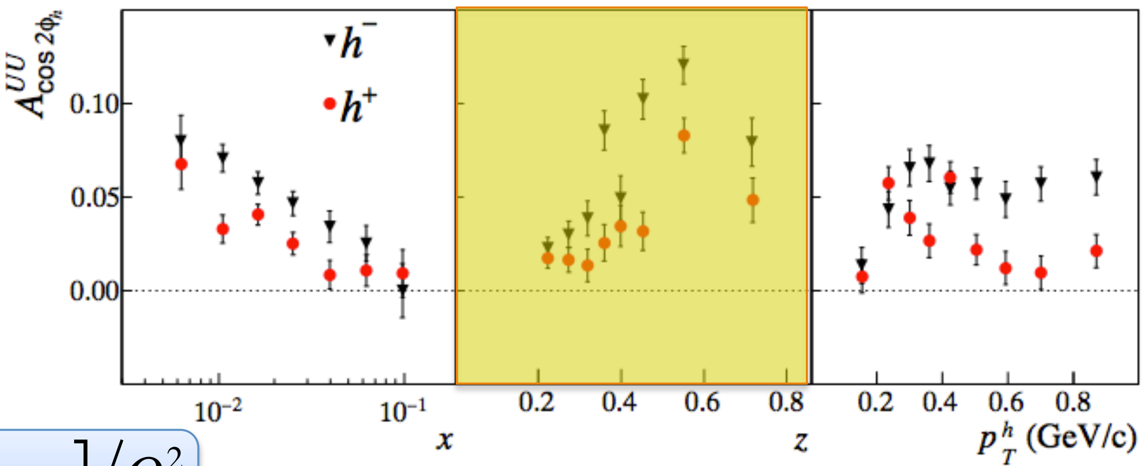
cos2ϕ non-zero !

Difference in hadron charge !

Smaller magnitude for π+

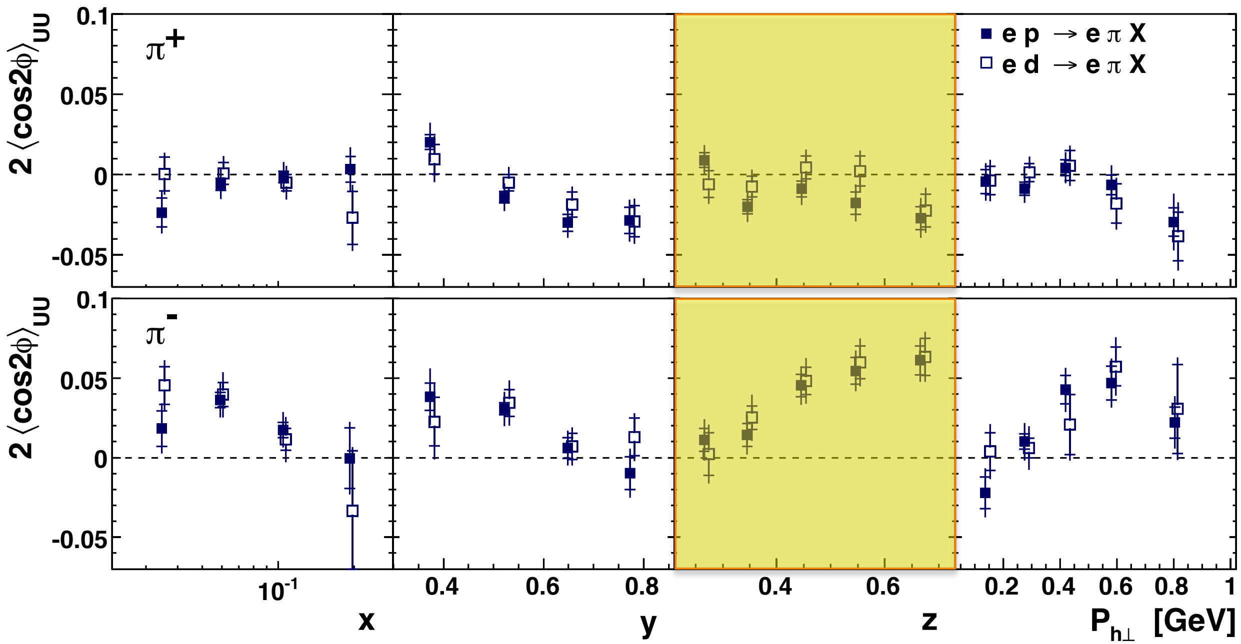
Inconsistency in experiments for h+ ?

COMPASS [arXiv:1401.6284]



$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

HERMES [arXiv:1204.4161]



Quark d vs u contribution ?
DATA support Boer-Mulders of same sign for u and d

cosϕ large and negative !

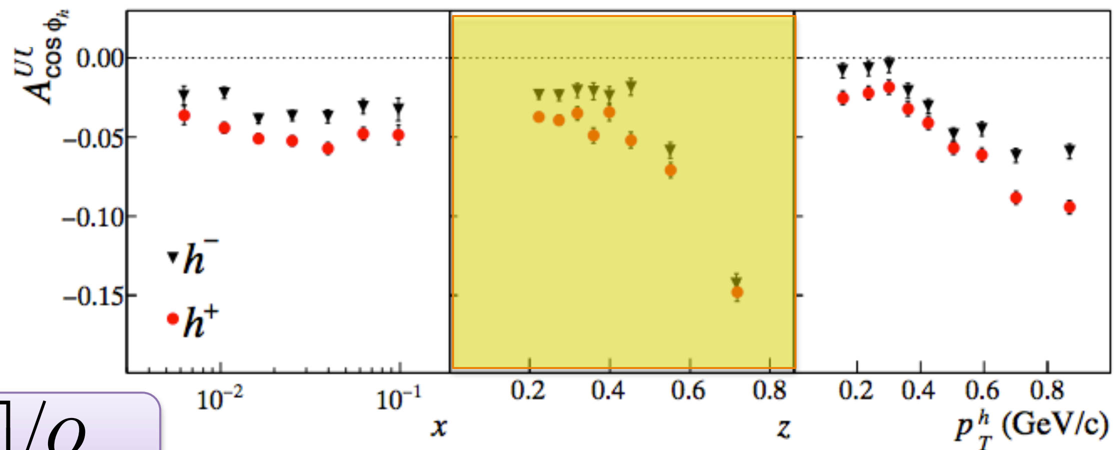
Increasing with z and P_h

Large difference in hadron charge !

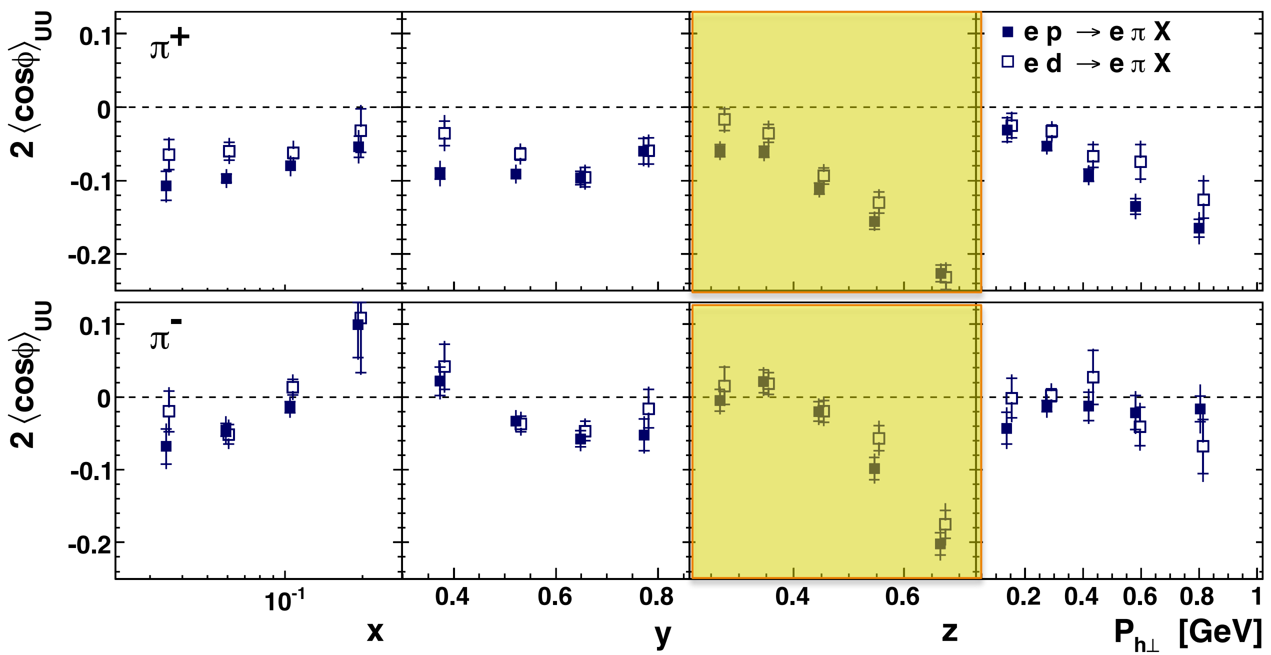
Larger in magnitude for π+

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

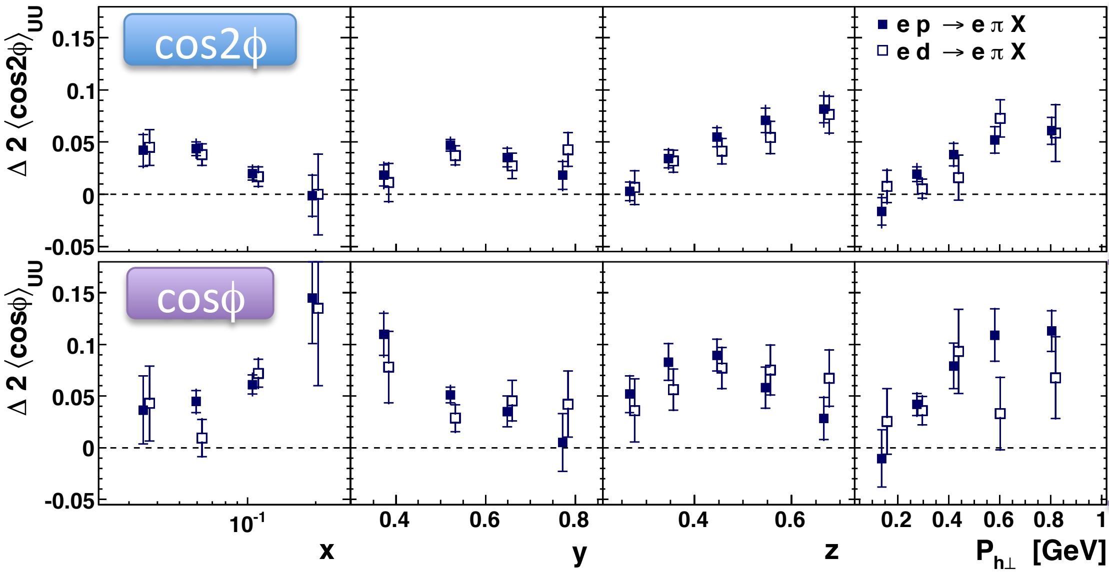
COMPASS [arXiv:1401.6284]



HERMES [arXiv:1204.4161]



Difference in pion charge



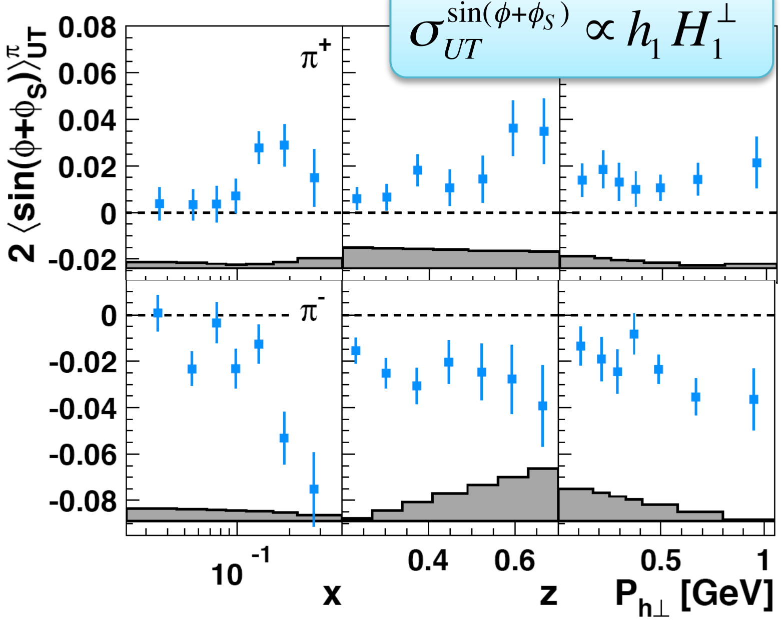
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 D_1 + \dots \right] / Q^2$$

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 D_1 + h_1^\perp \otimes H_1^\perp + \dots \right] / Q$$

Mild flavor dependence of k_T expected

From A_{UT}: Collins favored ($u \rightarrow \pi+$) and unfavored ($u \rightarrow \pi-$) fragmentation opposite in sign

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^\perp$$



With u-dominance
Collins makes the difference !
Hint of non-zero Boer-Mulders

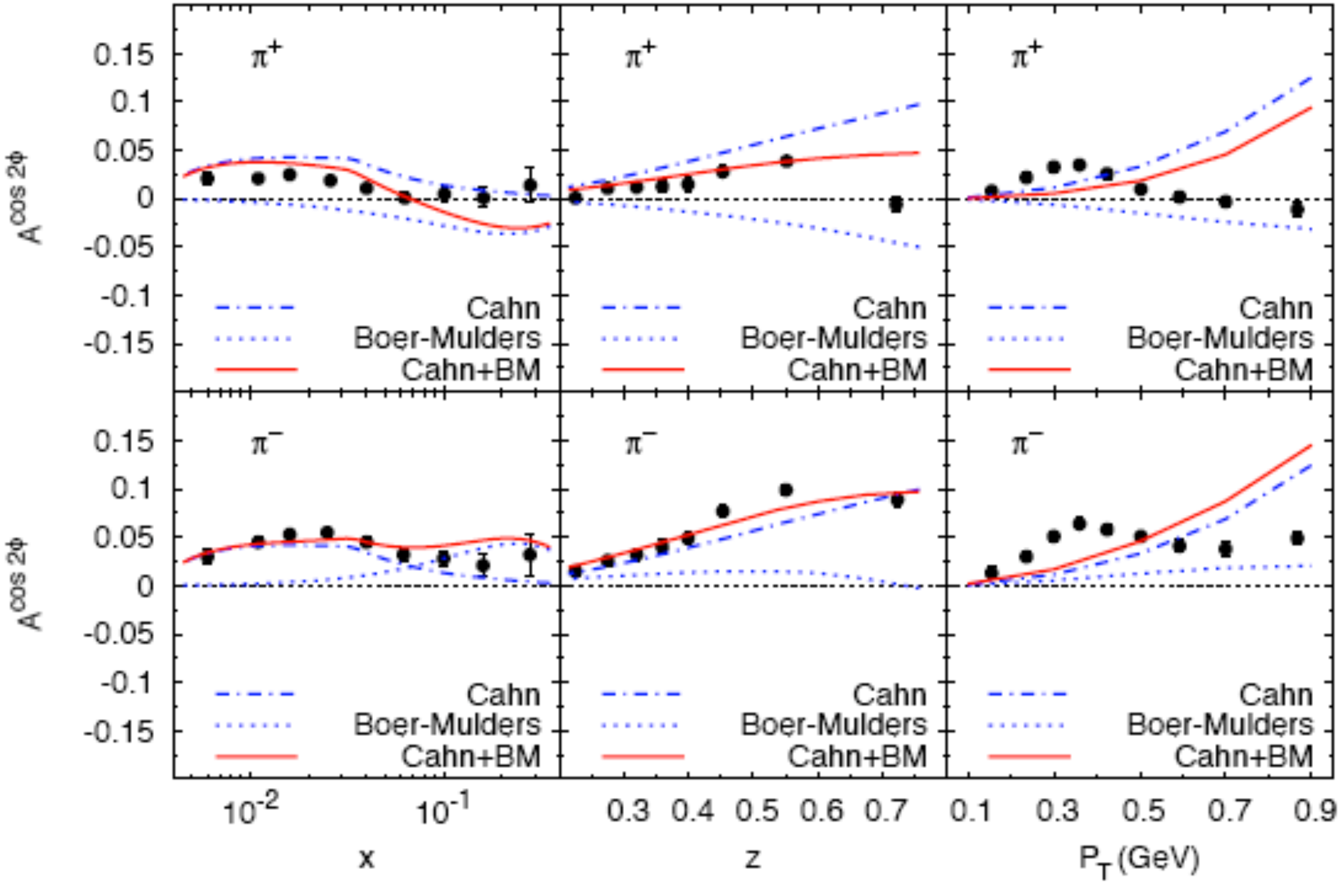
The SIDIS cos2ϕ Amplitude

$h_1^\perp \otimes H_1^\perp$

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

Can be explained by large uncertainty on Cahn and neglected HT effects ?

V. Barone ++ [arXiv: 0912.5194]

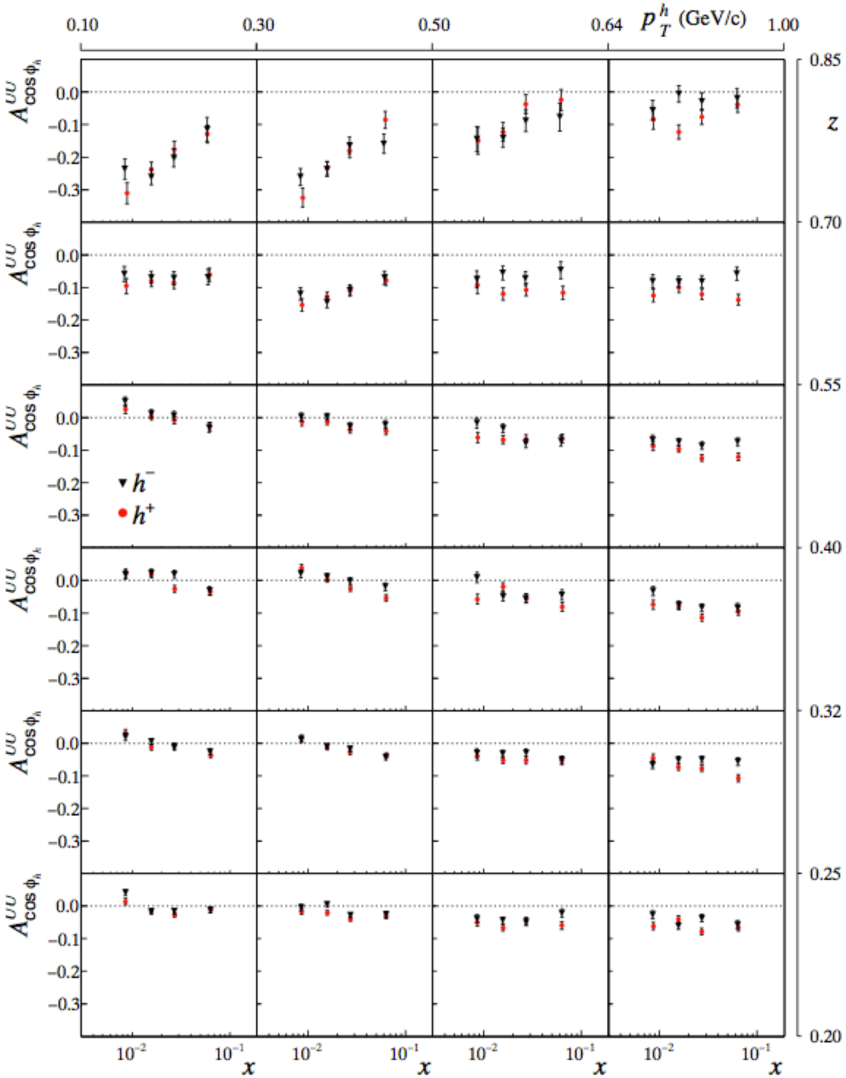


Kinematic dependence

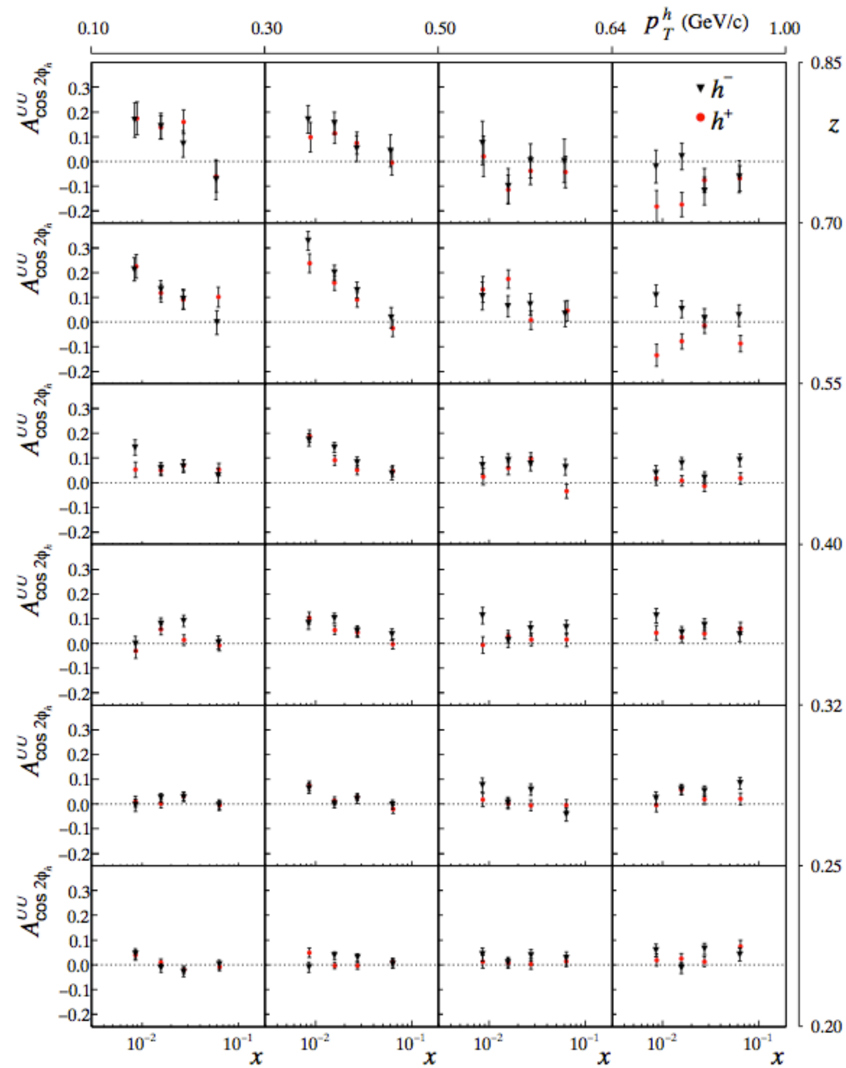
$h_1^\perp \otimes H_1^\perp$

COMPASS [arXiv:1401.6284]

cosϕ

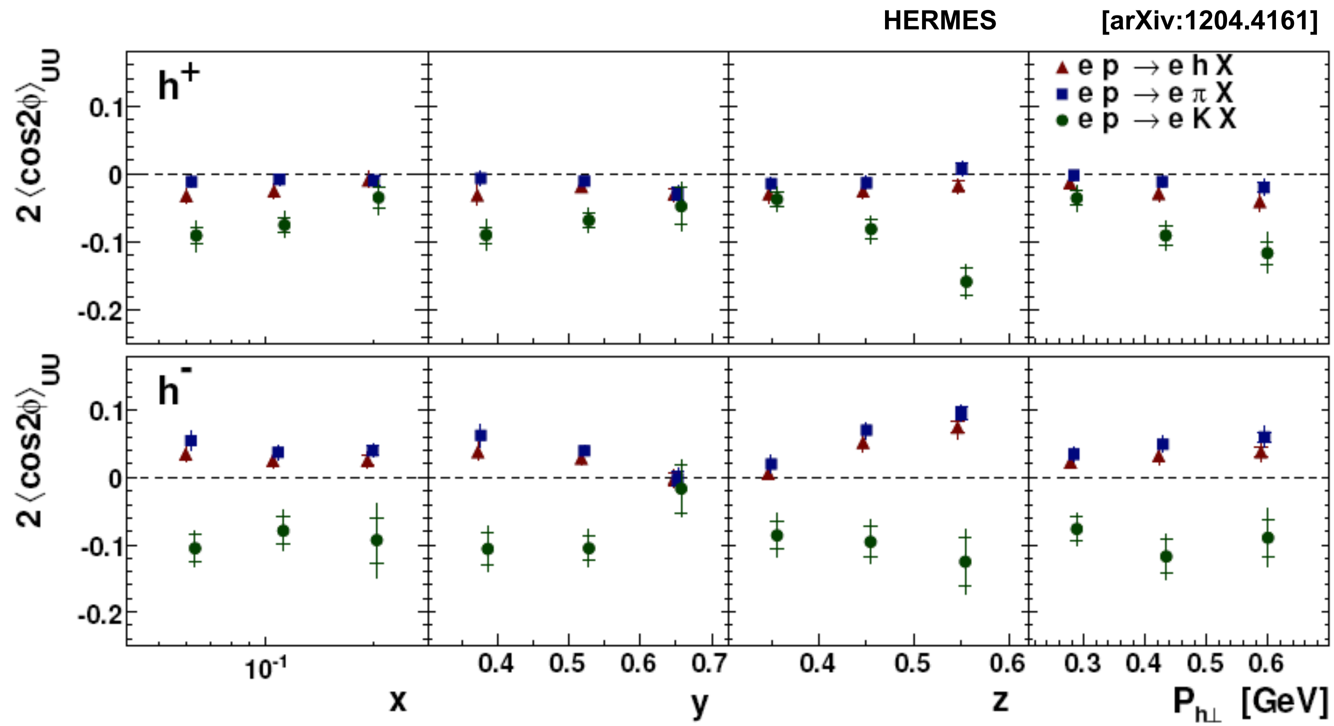


cos2ϕ

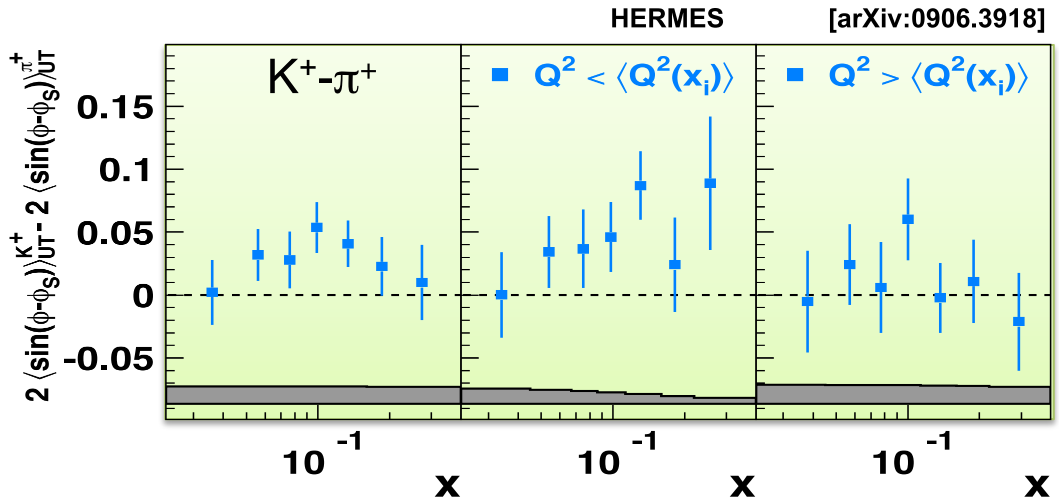


Multidimensional analysis is mandatory: x trend changes from small z to large z values

Role of Higher Twists



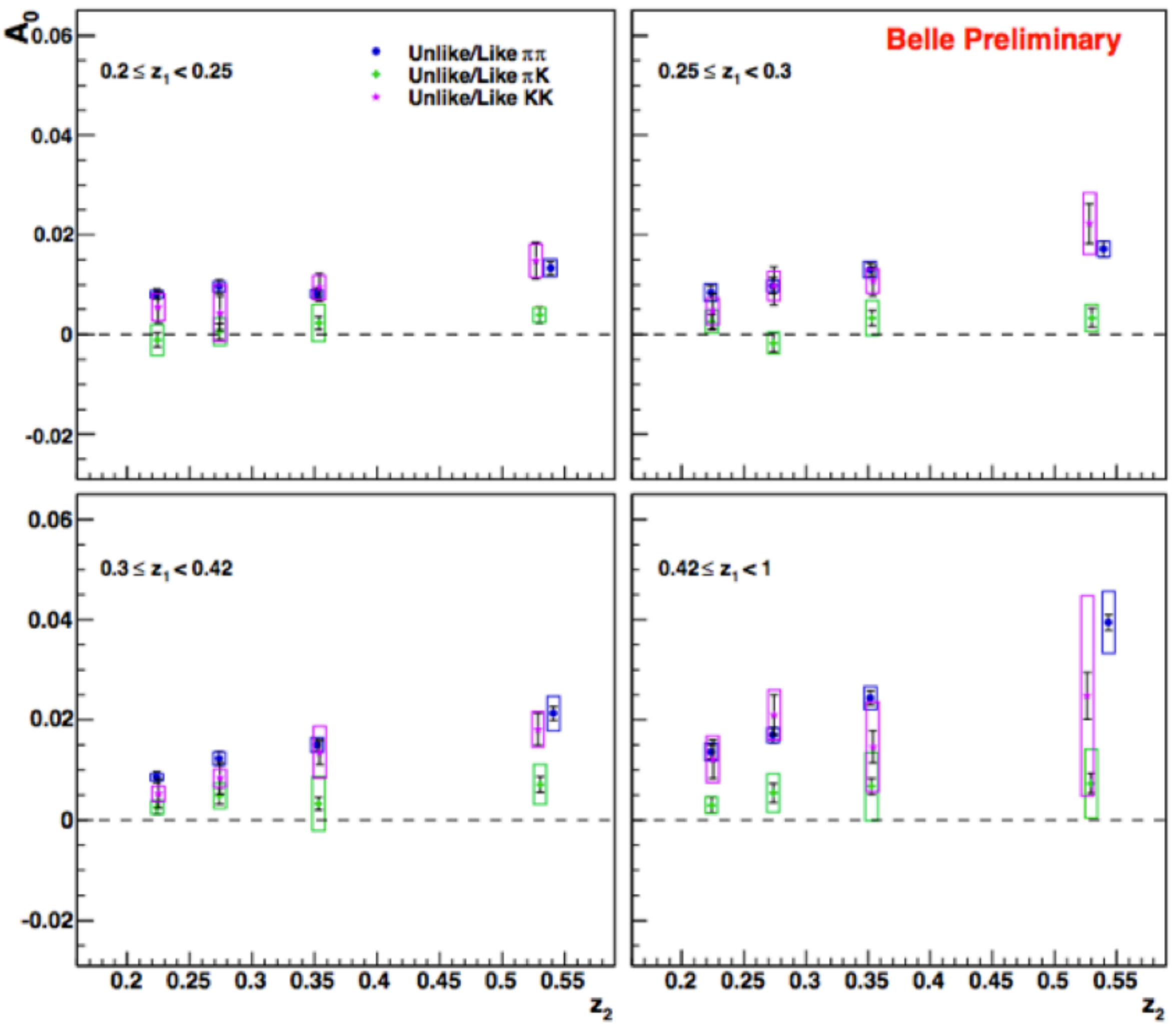
Cosϕ: striking difference among hadron types



Sivers: large kaon amplitude concentrates at low-Q^2

The Kaon Collins $H_1^{\perp} \otimes H_1^{\perp}$

F. Giordano [talk at DIS14]



$\pi\pi$ => non-zero asymmetries, increase with z_1, z_2

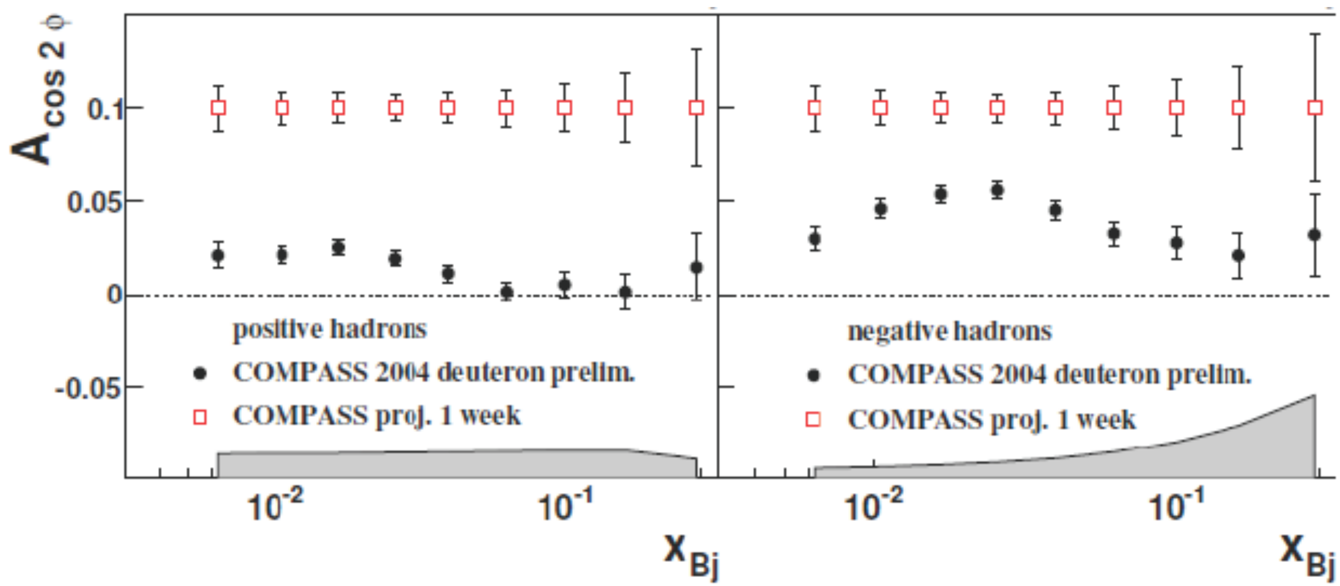
πK => asymmetries compatible with zero

KK => non-zero asymmetries, increase with z_1,z_2 similar size of pion-pion

SIDIS News in 2014+

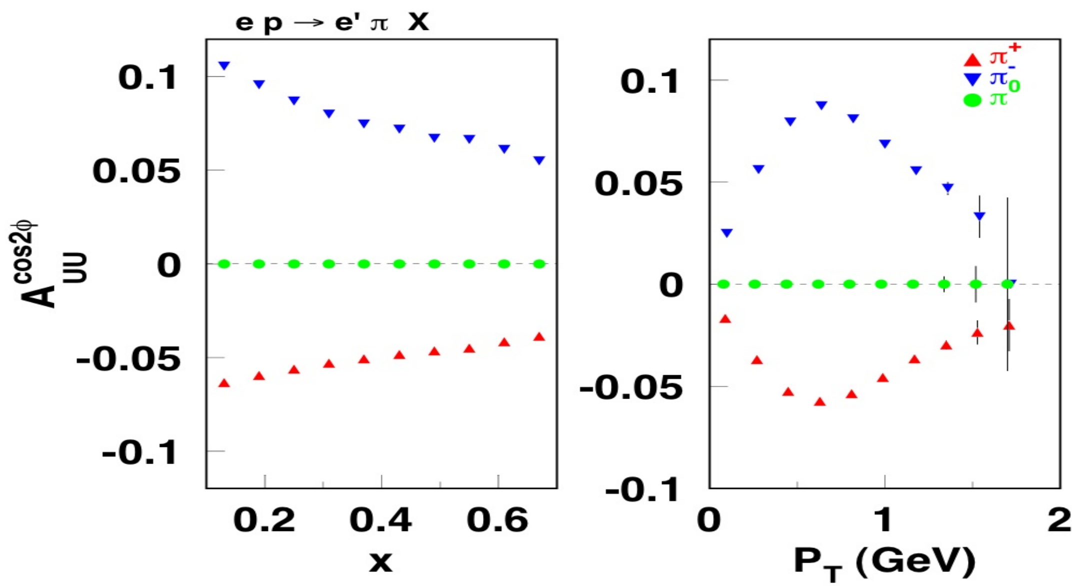
COMPASS-II:

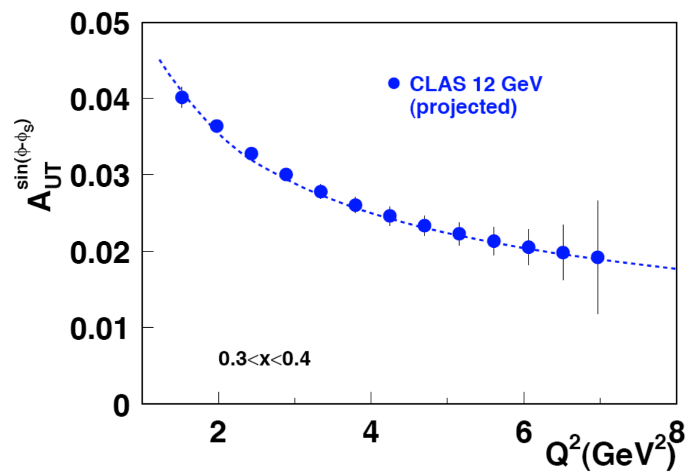
LH_2 target
160 GeV/c muons



CLAS12:

LH2 target
12 GeV/c electrons
L~10^{35} $cm^{-2}s^{-1}$





Conclusions

✓ SIDIS offers a rich playground for TMDs investigation

- access to PDF and FFs
- flavor separation from various hadron types and targets
- separation of ISI/FSI
- control of parton kinematics in medium via scattered lepton

✓ A lot of data have been recently released and new experiments are coming soon

✓ A big effort is ongoing to make an EIC facility a reality

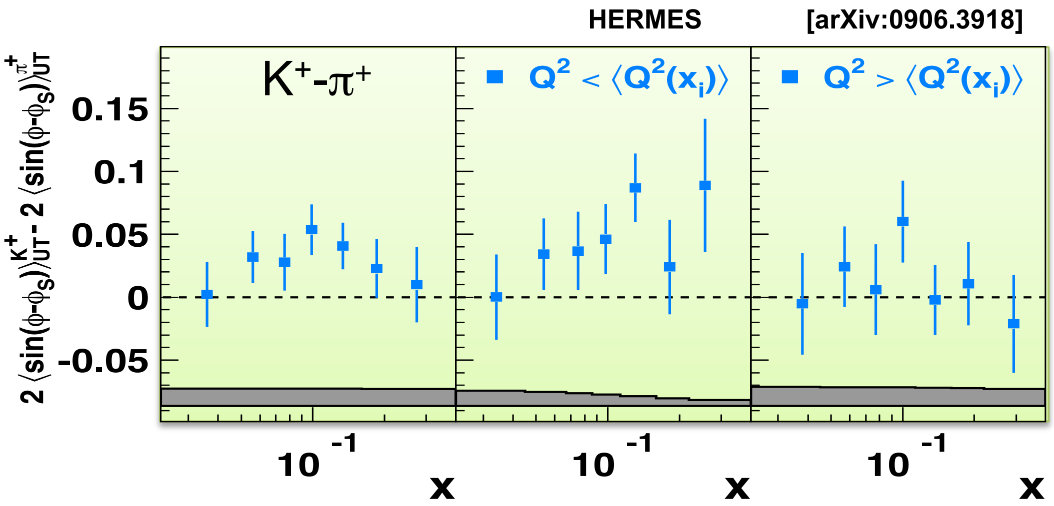
✓ Important to complete the theoretical assessment grounds (i.e. evolution) to exploit the full potentiality in TMD mechanisms

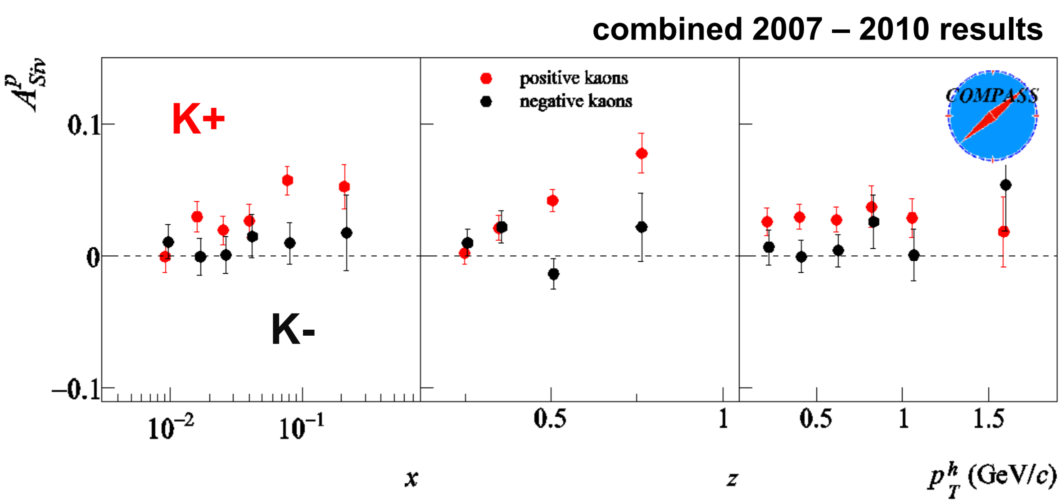
Unpolarized reactions are the basic tool linking many different fields of investigation

Even non-TMD observables could get contributions from TMD phenomena

$f_{1T}^{\perp} \otimes D_1$

K+ amplitudes larger than π+:





The SIDIS Landscape

DIS Experiments *(TMD disentanglement)*

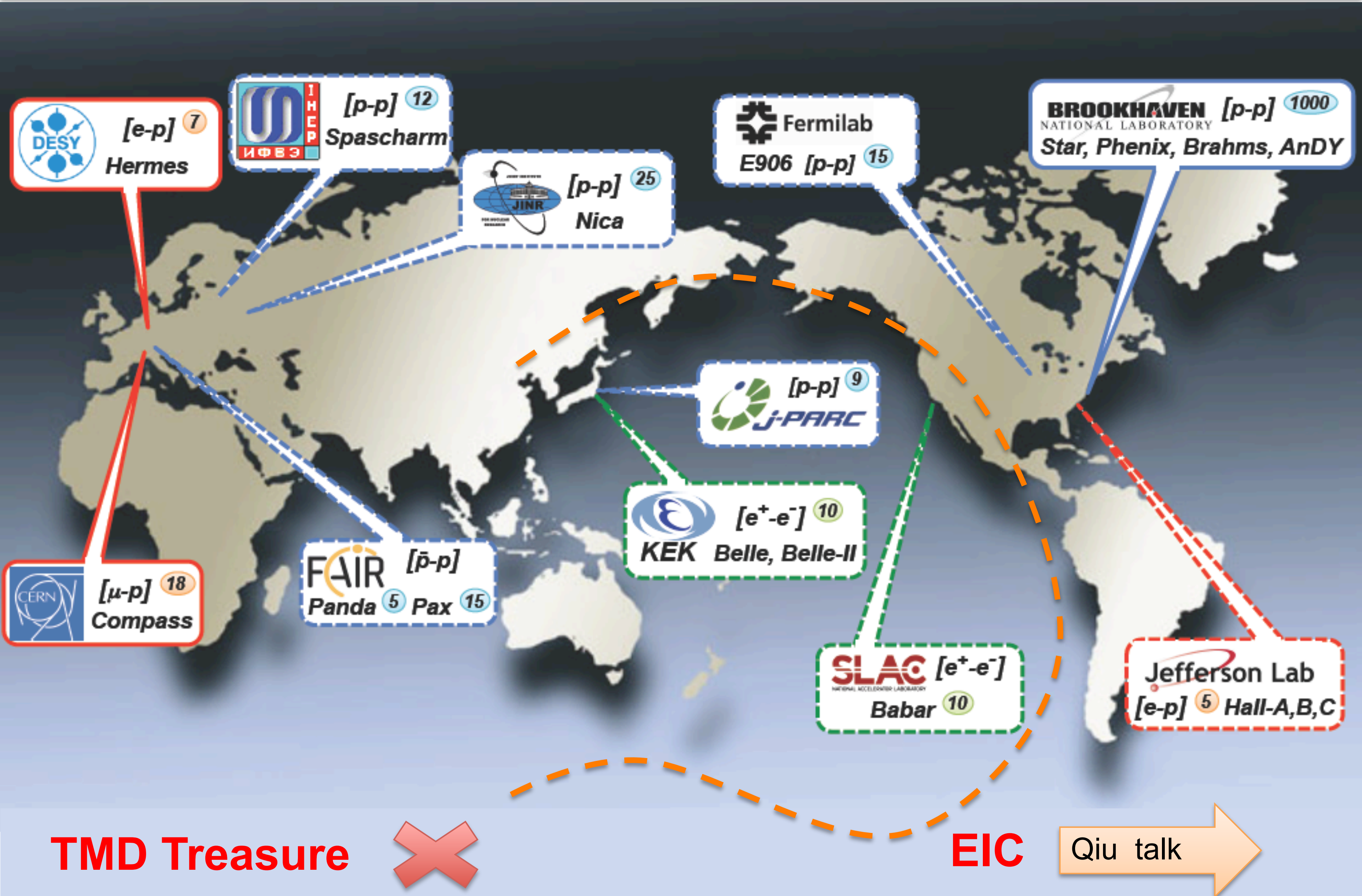
Multidimensional analysis

Flavor separation: various hadron types and different targets

TMD formalism: di-hadron vs single-hadron h_1 extraction, inclusive SSA measurements

Scale dependence & Higher twists

A World-wide Challenge



Higgs Parity in γγ Channel

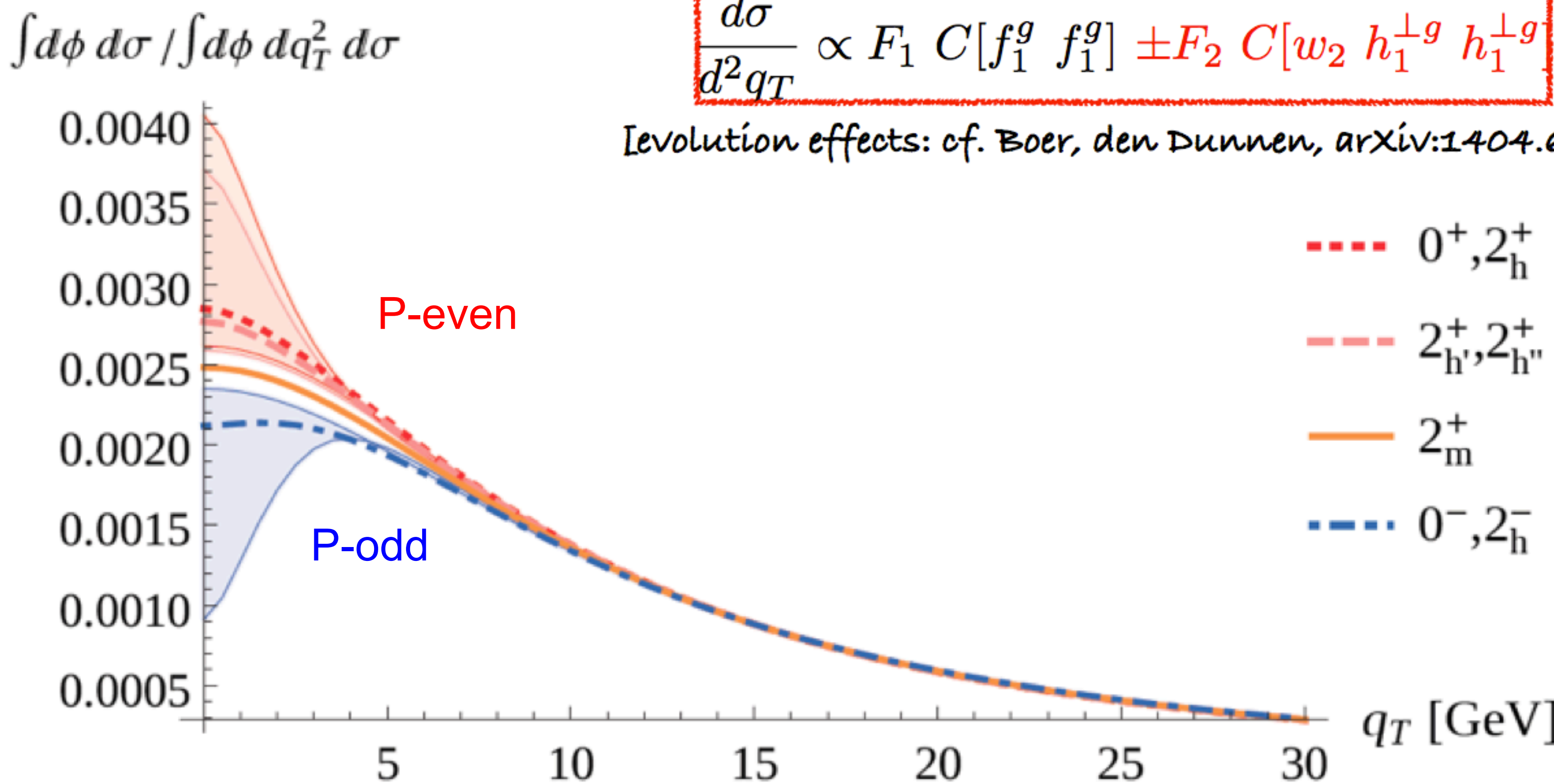
f_1^g → TMD distribution of unpolarized gluons

$h_1^{\perp g}$ → TMD distribution of linearly polarized gluons

[M. Schlegel at DIS2014]

$$\frac{d\sigma}{d^2 q_T} \propto F_1\, C[f_1^g\ f_1^g] \pm F_2\, C[w_2\, h_1^{\perp g}\ h_1^{\perp g}]$$

[evolution effects: cf. Boer, den Dunnen, arXiv:1404.675



Number Density

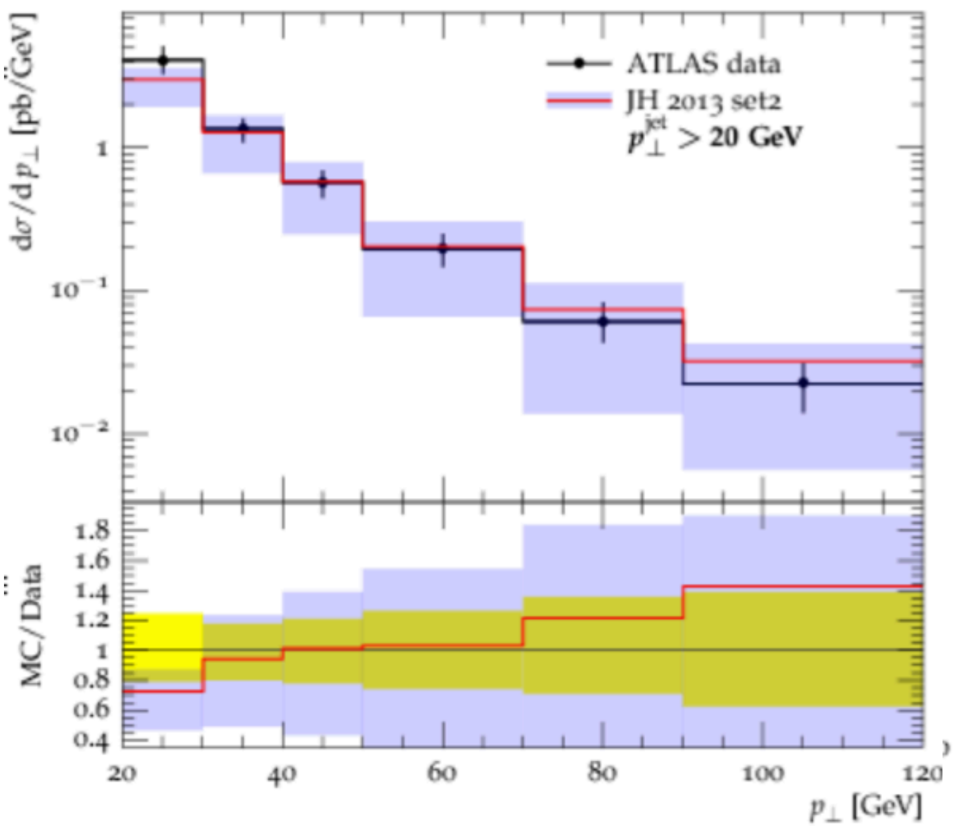
nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ Boer-Mulders
L		g_1 Helicity	$h_{1L}^\perp$ Worm-gear
T	$f_{1T}^\perp$ Sivers	$g_{1T}^\perp$ Worm-gear	h_1 Transversity $h_{1T}^\perp$ Pretzelosity

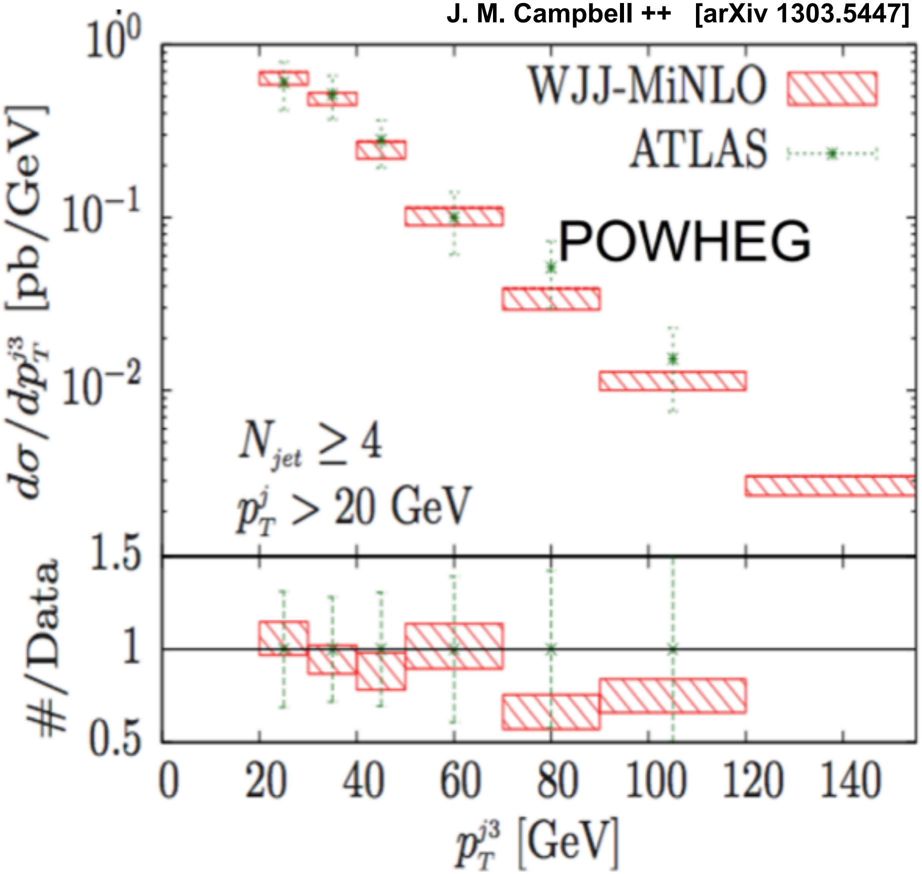
(The Baseline)

Transverse Momentum of Leading Jets

F. Hautmann [talk at DIS2014]



J. M. Campbell ++ [arXiv 1303.5447]



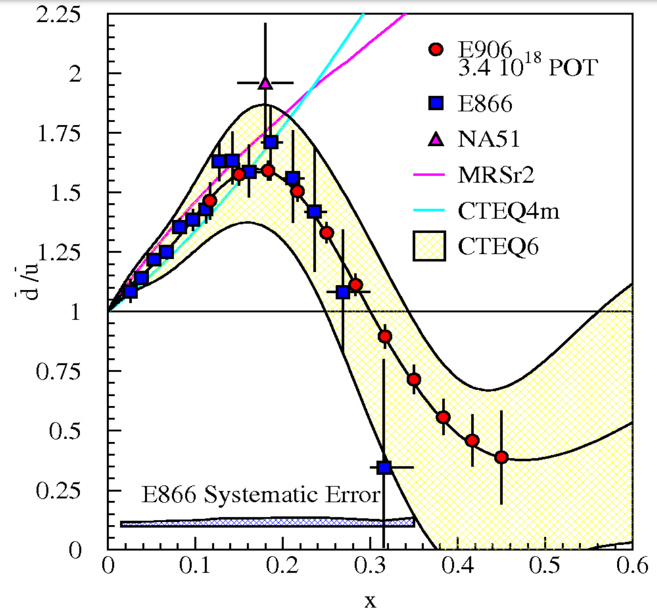
The Drell-Yan Landscape 2014+

Proton beam @ Fermilab

$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_b \gg x_t} \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right]$$

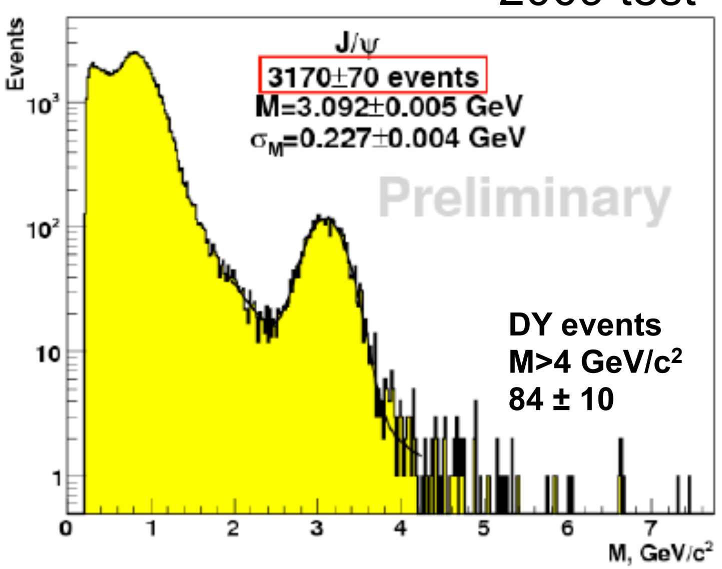
E906: test run this year

Extends E866 measurements at 120 GeV
xsec scales as 1/s
background scales as s.



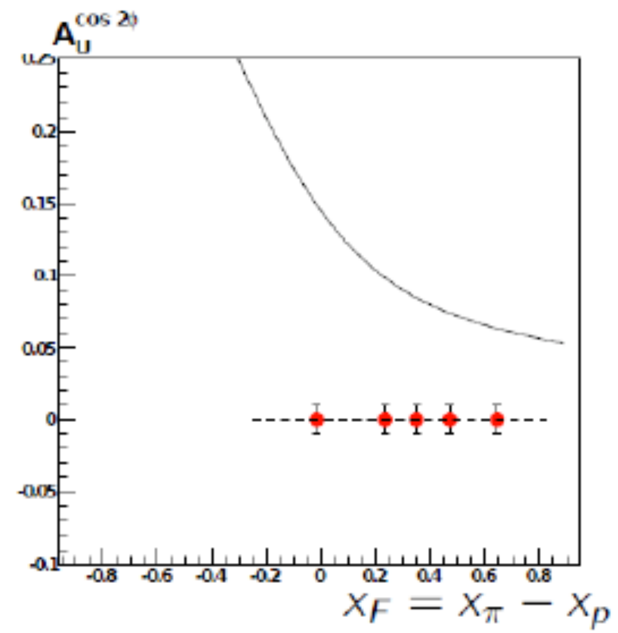
Pion beam @ CERN

2009 test



Boer-Mulders
⊗
Boer-Mulders

2 years
4 < M < 9 GeV/c²

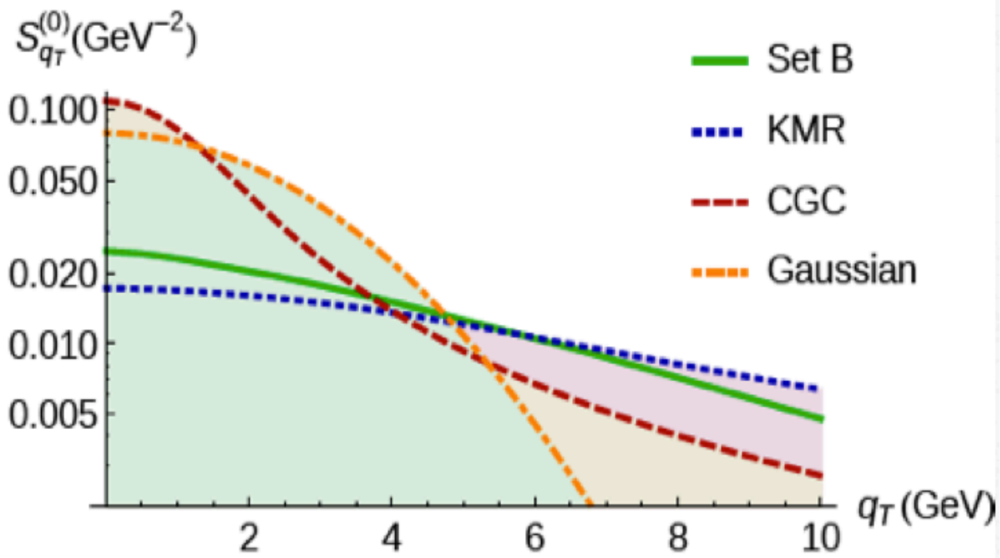


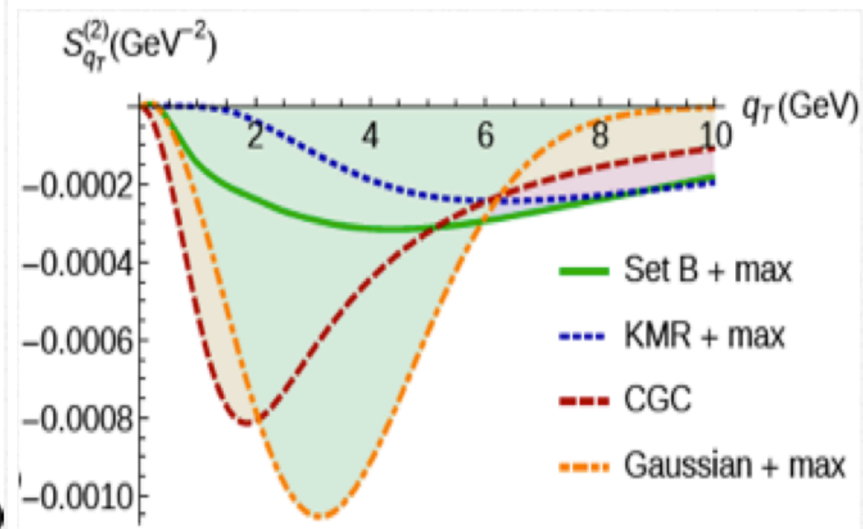
Upsilon + γ Production

W.J. den Dunnen ++ [arXiv:1401.7611]

$$S^{(0)}_{q_T} = \frac{C[f_1^g f_1^g]}{\int \mathrm{d}\boldsymbol{q}_T^2\, C[f_1^g f_1^g]}$$

$$S^{(2)}_{q_T} = \frac{F_3\, C[w_3 f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2]}{2F_1 \int \mathrm{d}\boldsymbol{q}_T^2\, C[f_1^g f_1^g]}$$

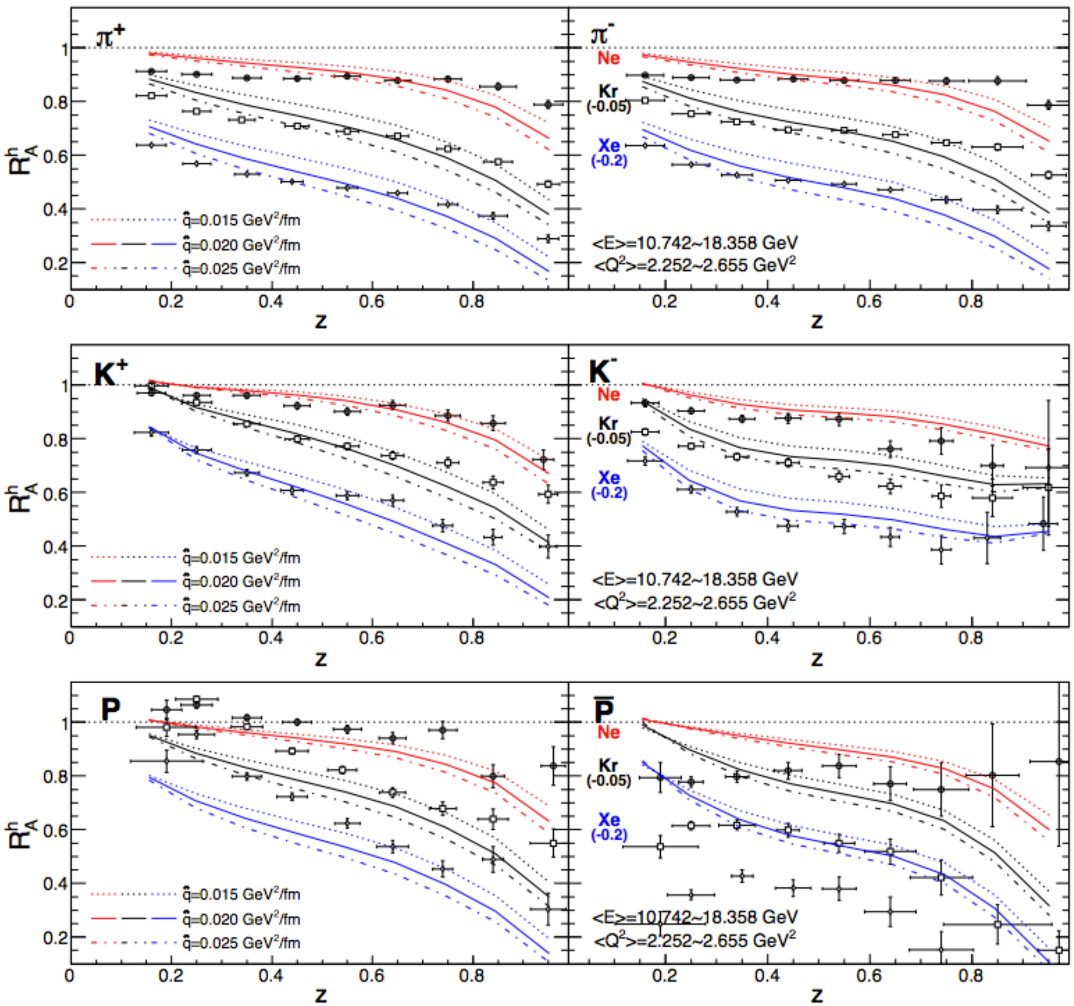




"q_T - integrated" $\cos(2\phi) \sim -(2\% - 3\%)$

Medium modification

$$R_A^h(z,\nu) = \left(\frac{N^h(z,\nu)}{N^e(\nu)}|_A\right) / \left(\frac{N^h(z,\nu)}{N^e(\nu)}|_D\right) = \left(\frac{\Sigma e_q^2 q(x)\widetilde{D}_q^h(z)}{\Sigma e_q^2 q(x)}|_A\right) / \left(\frac{\Sigma e_q^2 q(x) D_q^h(z)}{\Sigma e_q^2 q(x)}|_D\right)$$



Medium modified DGLAP to account for multiple gluon emission.
Issue: unknown modified distribution at the initial scale Q_0 (due to parton energy loss below scale Q_0)

Main parameter: quark transport q_0
Effective transverse momentum broadening squared per unit distance

$q_0 \propto$ nucleon density x gluon distr.

N-B Chang ++ [arXiv:1401.5109]

HERMES [arXiv: 0704.3270]

Cahn & Boer-Mulders

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

Naïve-T-odd
Chirally-odd
Spin effect in unpolarized reactions

(The Neglected Effects)