SIDIS Analysis: Understanding the Physics Backgrounds

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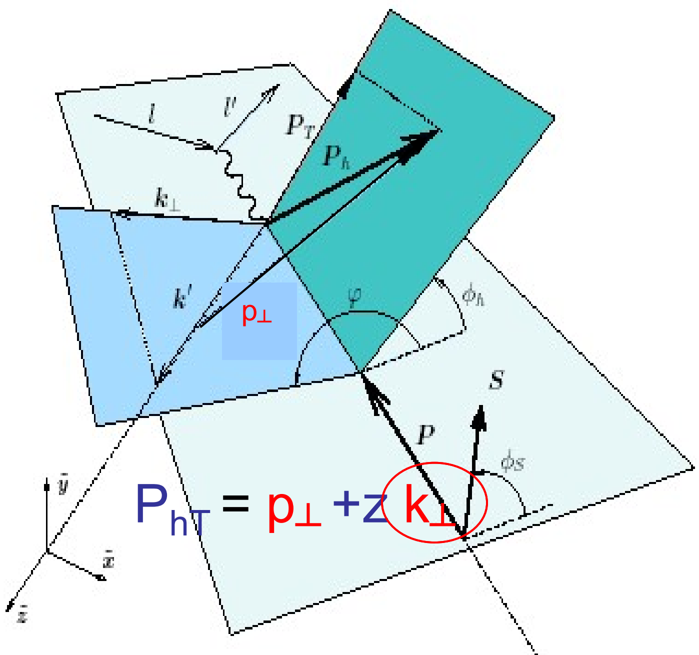
CLAS Collaboration Meeting, Nov 10, 2023

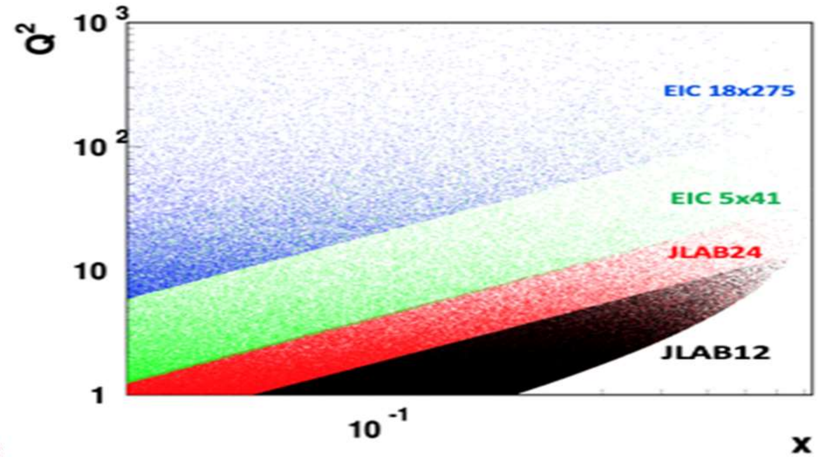
- SIDIS analysis framework
- Dispelling myths in SIDIS (independent fragmentation, suppressed HT at high Q^2,….)
- Reforming SIDIS: what we need to apply the TMD theory?
  - –phase space corrections
  - –understanding contributions from exclusive processes (mainly rho)
  - –separating/evaluating the longitudinal photon contributions
  - –separating the kinematics of current and target fragmentation
  - –understanding the role of hadron correlations in SIDIS
- A new CAA for RGC
- Summary

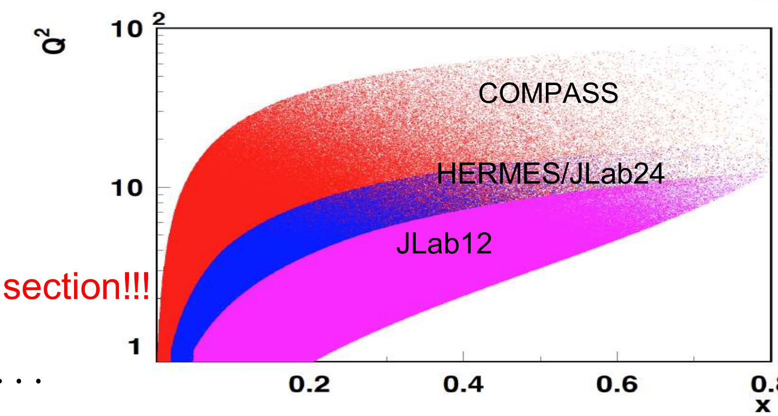
*)In collaboration with Timothy Hayward (UCONN)

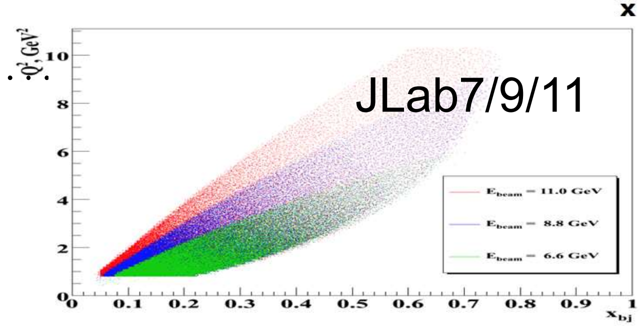
SIDIS kinematical coverage and observables



EIC







Experiments measure the full azimuthal dependence of the cross section!!!

$$\sigma \propto F_{UU} + P_b\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi}\sin\phi + P_t\epsilon F_{UL}^{\sin 2\phi}\sin 2\phi + \ldots$$

$$+\epsilon F_{UU,L} + |S_\perp|[F_{UT}^{\sin\phi-\phi_S}\sin(\phi-\phi_S) + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S] + \ldots$$

- Studies of azimuthal modulations give access to underlying 3D partonic distributions
- QCD predicts only the Q^2-dependence of 3D PDFs

TMDs in SIDIS in Leading Order

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_q \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\,\delta(z\boldsymbol{k}_\perp-\boldsymbol{P}_{hT}+\boldsymbol{P}_\perp) + Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2)+\mathcal{O}(M^2/Q^2)$$

Major advance in theory in last years

$$\hat{f}_1^a(x,b_T^2;\mu_f,\zeta_f) = \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2} e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} f_1^q(x,k_\perp^2;\mu_f,\zeta_f)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x,b_T^2;\mu_f,\zeta_f) = [C\otimes f_1](x,\mu_{b_*})\, e^{\int_{\mu_{b_*}}^{\mu_f}\frac{d\mu}{\mu}\left(\gamma_F-\gamma_K\ln\frac{\sqrt{\zeta_f}}{\mu}\right)}\left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\rm resum}+g_K} f_{1\,NP}(x,b_T^2;\zeta_f,Q_0)$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

nonperturbative part of TMD

$$g_K(b_T^2) = -g_2^2\frac{b_T^2}{4}$$

CS-kernel→independent on any other variables

CS kernel discribes the interaction of out-going parton with the confining potential
Provides nonperturbative part of evolution for TMDs

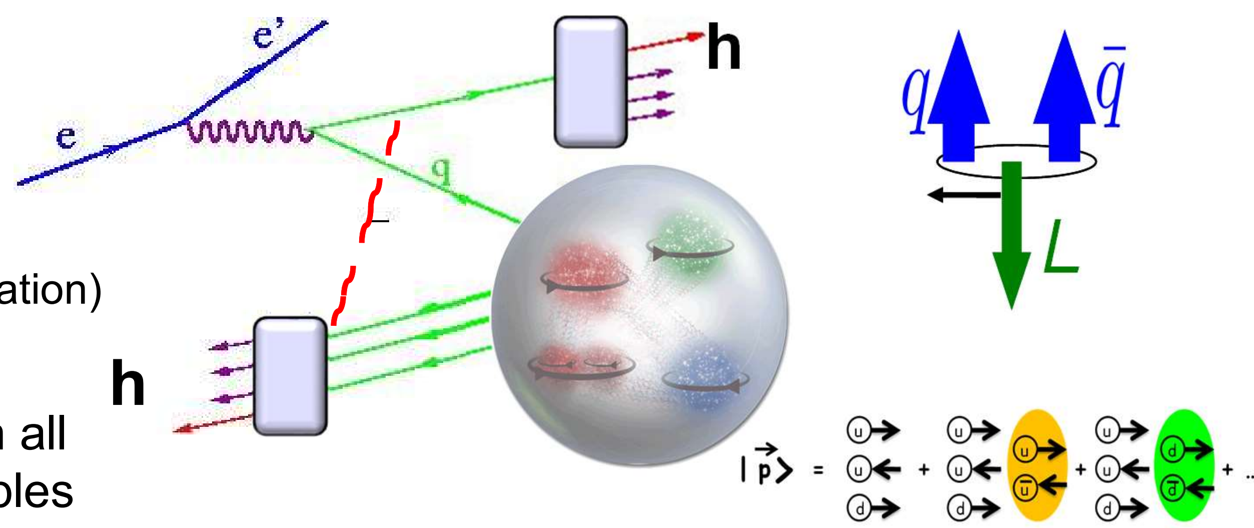
Hadron production in hard scattering in SIDIS

Study of QCD dynamics through correlations of spins and momenta

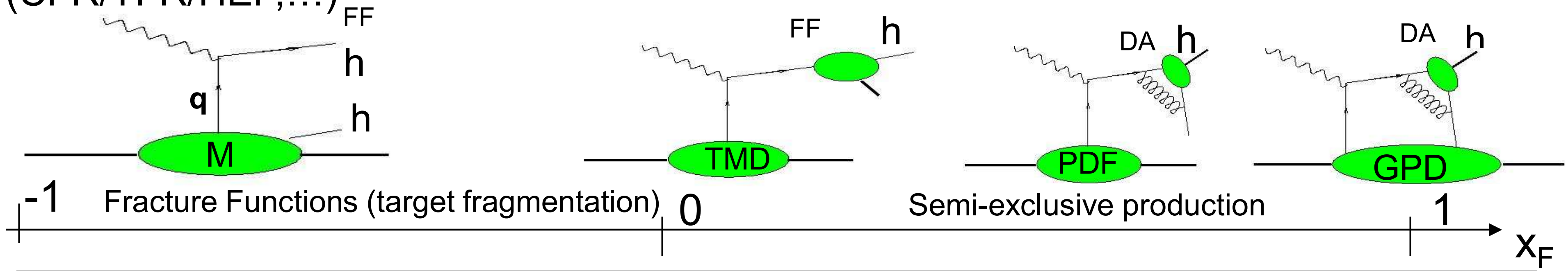
x_F – fractional momentum in the CM frame

x_F>0 (current fragmentation)

x_F<0 (target fragmentation)



Polarized partons will appear in all polarized distributions/observables (CFR/TFR/HEP,…)



Different non-perturbative objects may be involved in description, depending on kinematical conditions, introducing different dependence on Q^2

SIDIS cross section: separating $F_{UU,L}$

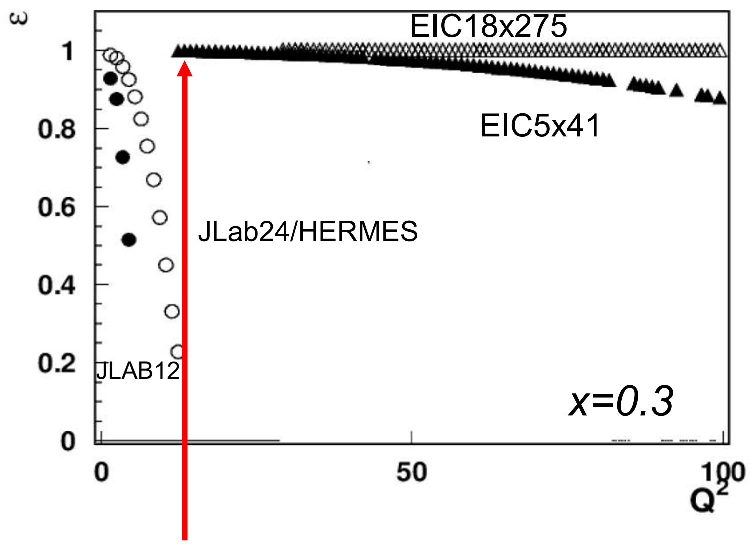
Semi-Inclusive:

ratio of longitudinal and transverse photon flux

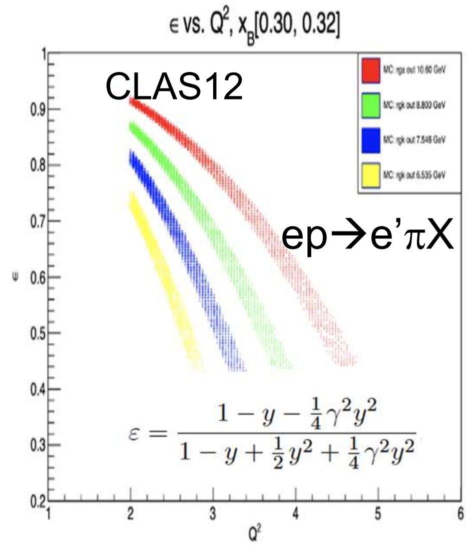
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{ F_{UU,T} + \varepsilon F_{UU,L} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+ S_{\|}\left[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] + S_{\|}\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL}\Big\}$$

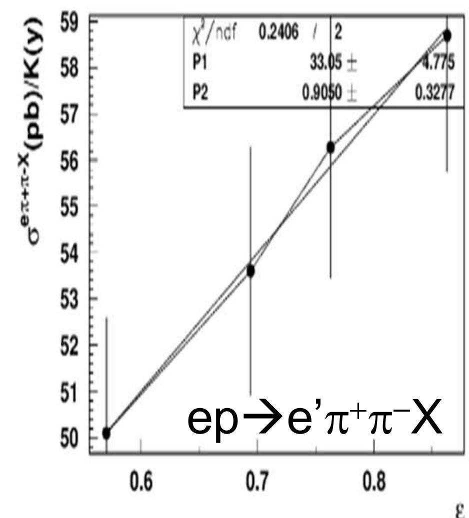
Hall-C E12-06-104
E12-23-014
Hall-B E12-16-010C

Separation of contributions from longitudinal and transverse photons critical for interpretation



Wide ε-coverage needed!!!



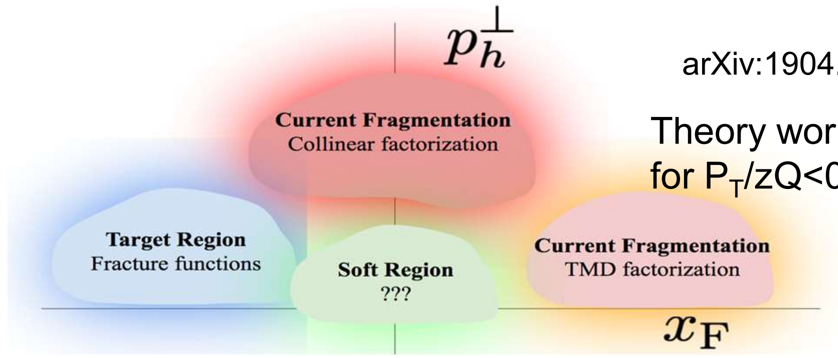


- At higher energies longitudinal photon contributions kinematically enhanced (at EIC 5 times bigger at Q^2~10)
- JLab studies critical for EIC data interpretation

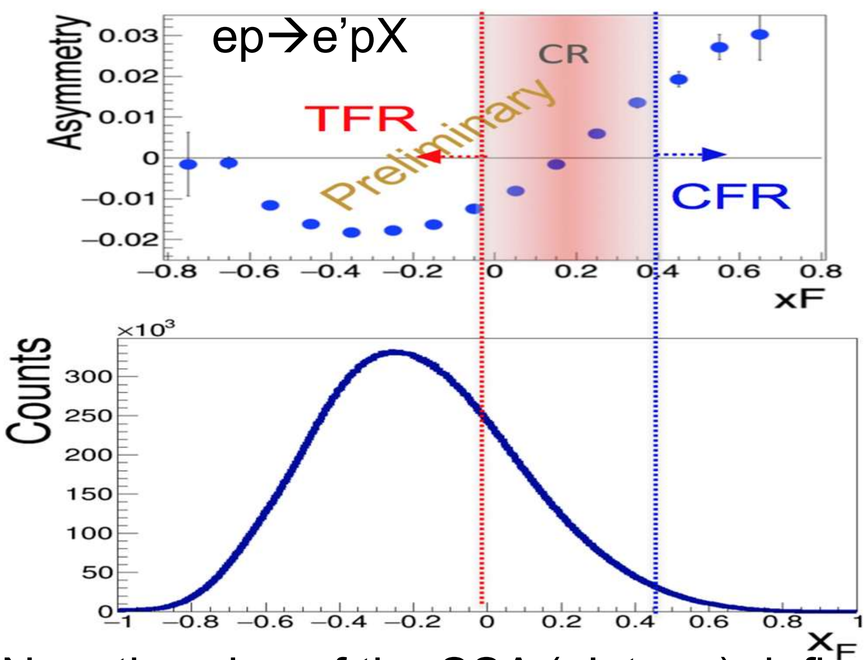
$R=F_{UU,L}/F_{UU,T}$ depend on the process, need for all relevant ones, in all kinnematics!

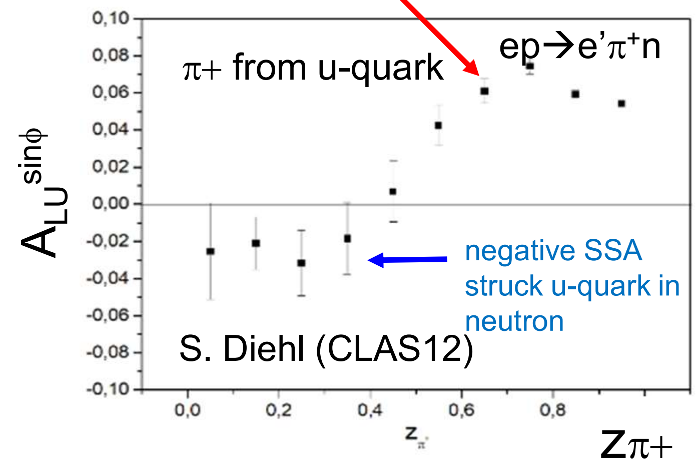
Beam SSAs: Separating kinematic regions

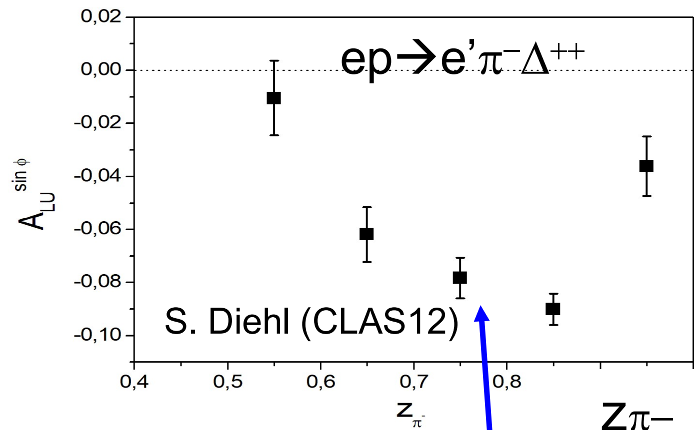
arXiv:1904.12882



Theory works well for $P_T/zQ<0.25$







Negative sign of the SSA (plateau) defines the TFR dominance (use to separate!!!)

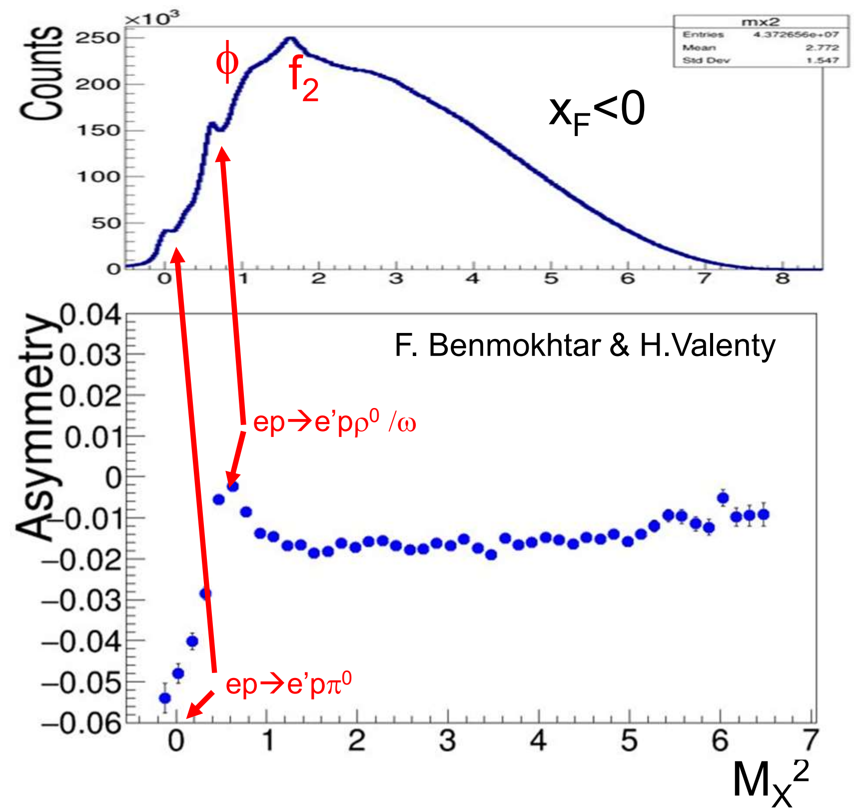
Polarized d-quark, is hard to locate, and one obvious process where we can guarantee it was hit, is the production of Δ++ (negative SSA)

Dissecting the beam SSA (A_{LU}) in ep→e'pX

- SIDIS is a sum over multiple exclusive states, but has to keep an eye to make sure it is not dominated by some dominant channel (extraction of Q2-dependence critical)
- The cut on the missing mass of the proton eliminates obvious exclusive channels, which tend to have higher positive or negative SSAs(ex. ep→e'pπ^0 or e'pρ^0)
- M_X>1.5 no structures and SSA goes to plato (no single channel dominates it) decreasing as the correlations get suppressed with multiple hadron production

Significant beam spin SSAs observed for exclusive ep→e'pπ^0 (~8%) and ep→e'pρ^0 (~10-15%)

What is SIDIS?

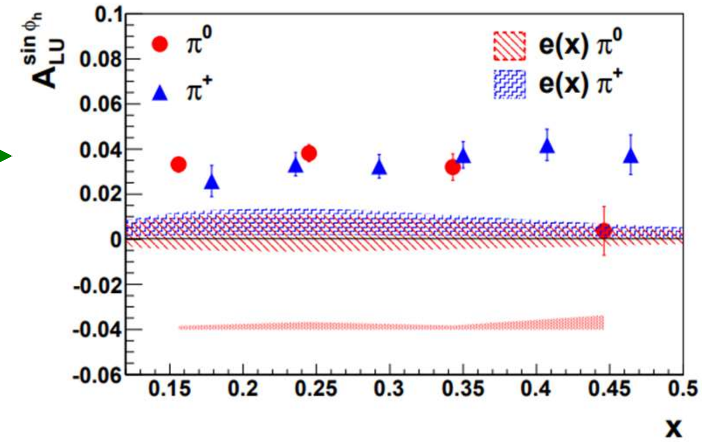


Quark-gluon correlations: flavor dependence

Higher Twist PDFs

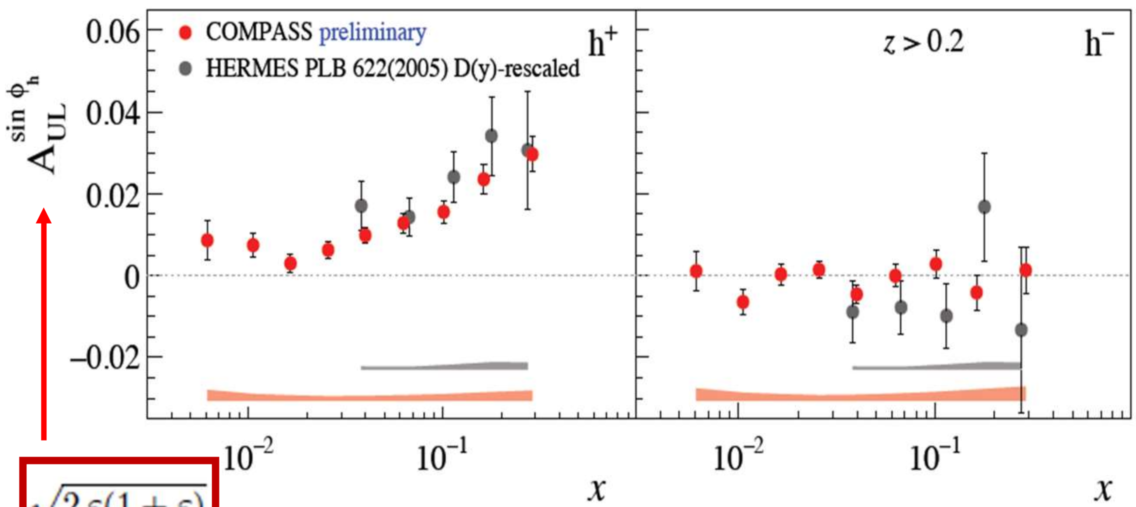
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

$\sqrt{2\varepsilon(1-\varepsilon)}$

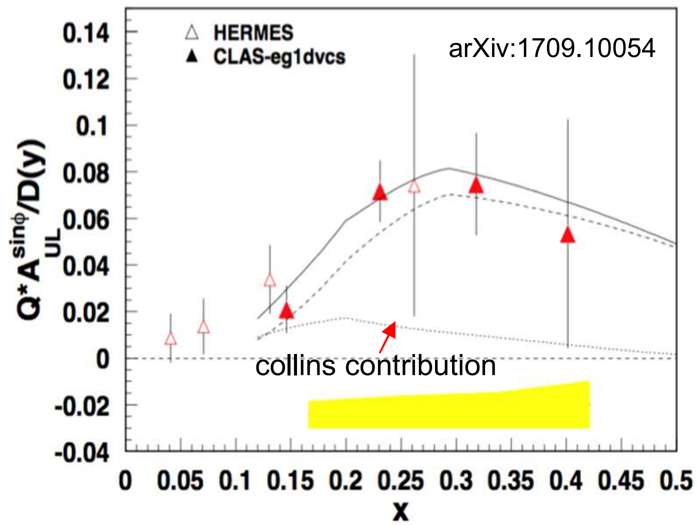


1) roughly equal π^+/π^0 SSA
2) π^- SSA much smaller, consistent with 0 or<0

CLAS/HERMES

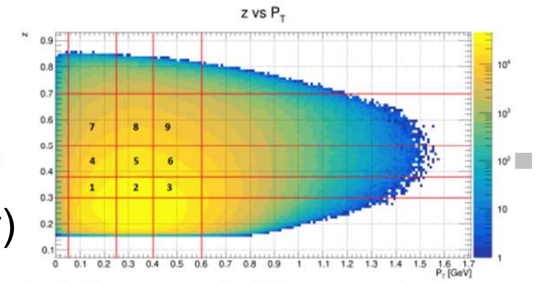


$\sqrt{2\varepsilon(1+\varepsilon)}$



- Significant longitudinal beam and target SSA measured at HERMES, JLab and COMPASS
- $\sin\phi$ modulations for π^+/π^0 consistent with dominance of Sivers like mechanism (initial state effects)
- Subleading asymmetries comparable with leading ones large at large x (1/Q terms should be accounted)

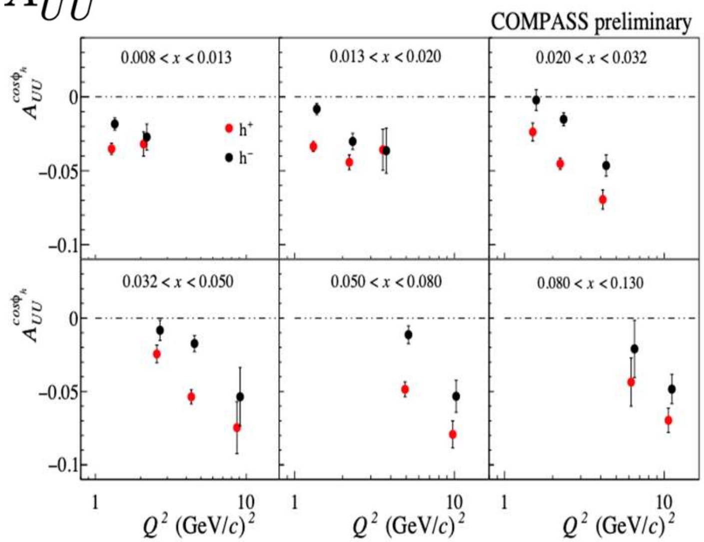
Attempts to understand Q^2-dependence of HT



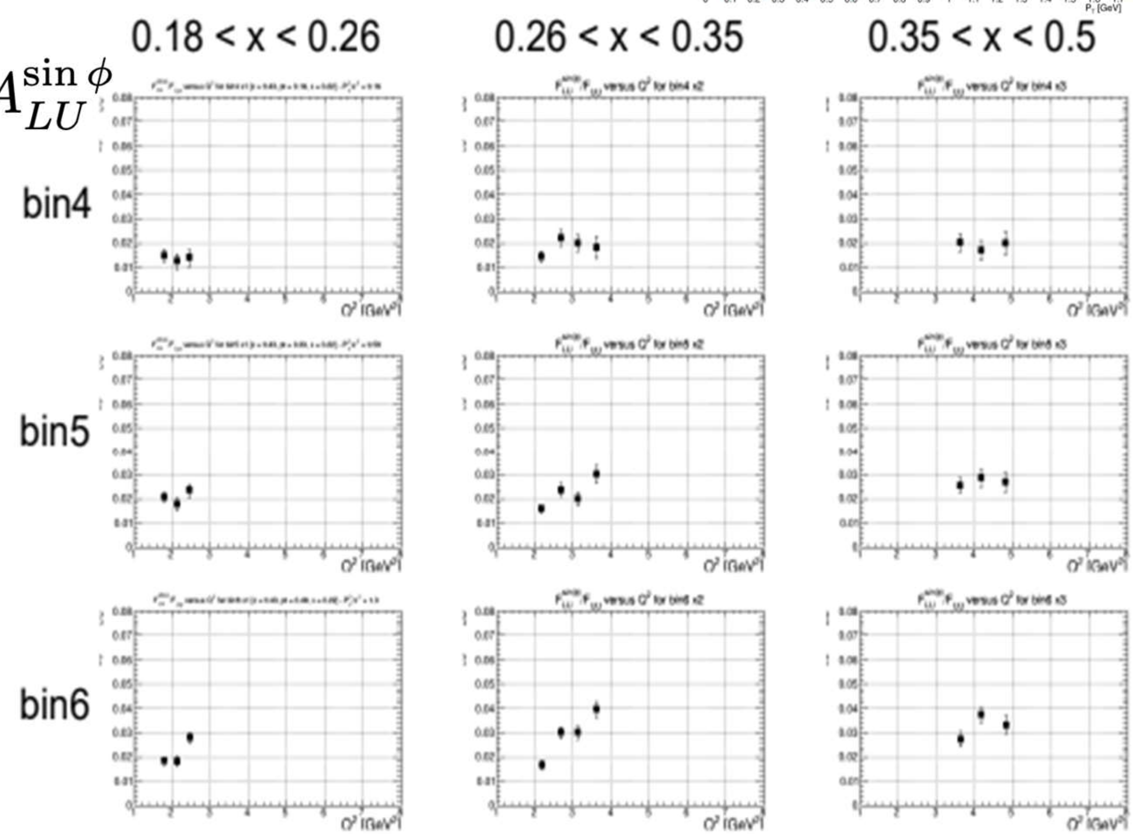
$\sqrt{2\,\varepsilon(1+\varepsilon)}$ $\sqrt{2\,\varepsilon(1-\varepsilon)}$

CLAS12(preliminary)

$A_{UU}^{\cos\phi}$ COMPASS



$A_{LU}^{\sin\phi}$



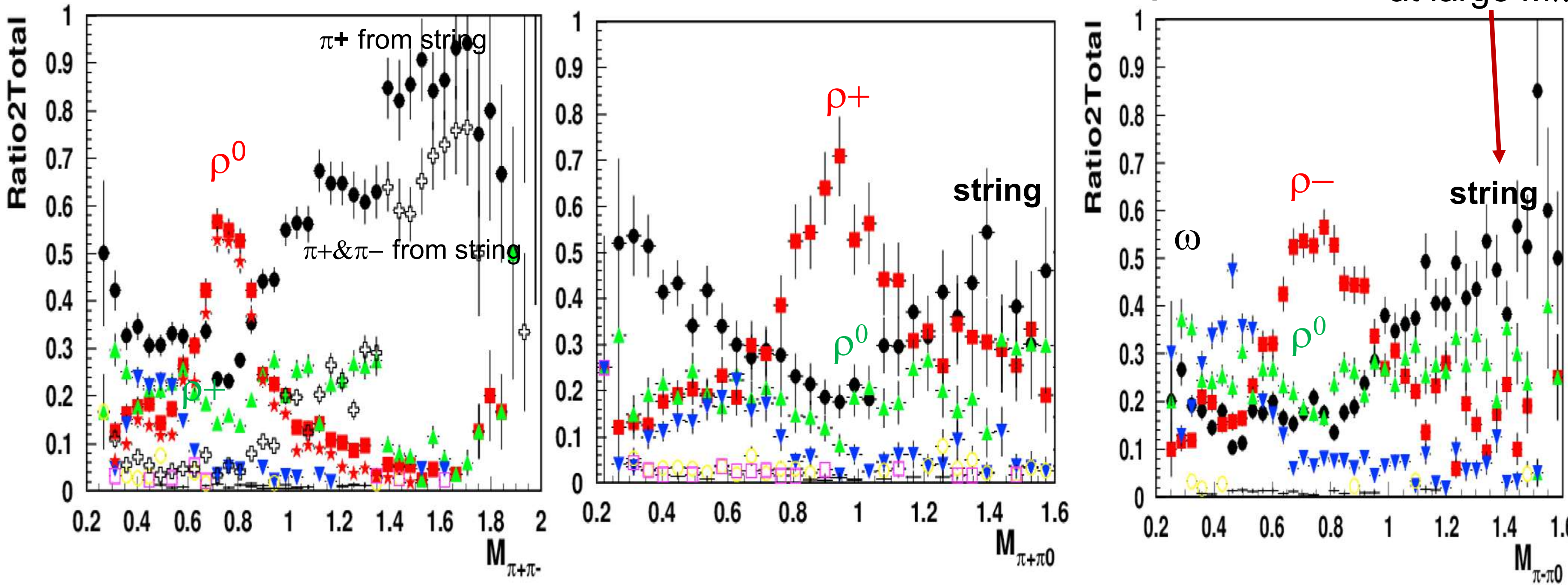
- We always measure ratio to $F_{UU,T} + \varepsilon\, F_{UU,L}$

- The moments defined as a ratio to ϕ-independent x-section(to $F_{UU,T}$), are not decreasing with Q!!!
- The HT observables, don't look much like HT observables, something missing in understanding
- **Understanding of these behavior can be a key to understanding of other inconsistencies**
- Checking the Q^2 and P_T-dependences of the $F_{UU,L}$ may provide crucial input for validation

Sources of inclusive pions: CLAS12 MC

Detection of π^0s allows also studies of $\rho^{\pm}$

High P_T pions at large $M\pi\pi$



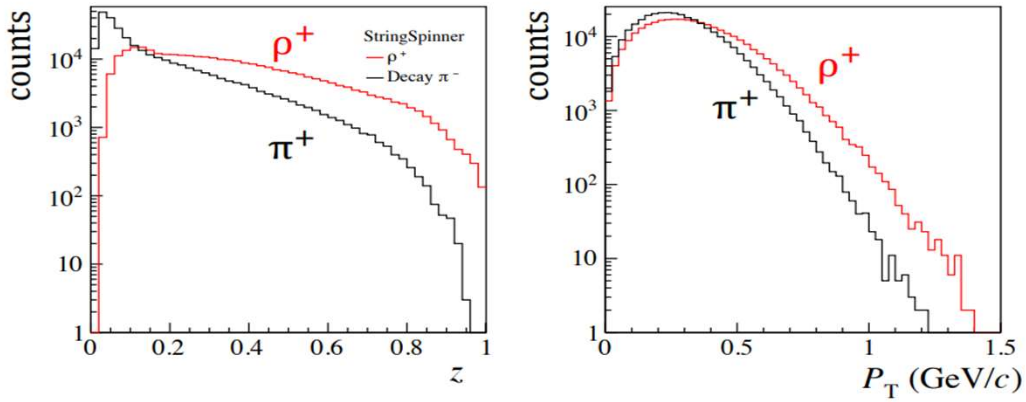
Dominant fraction of 2 pion combinations come from VM decays

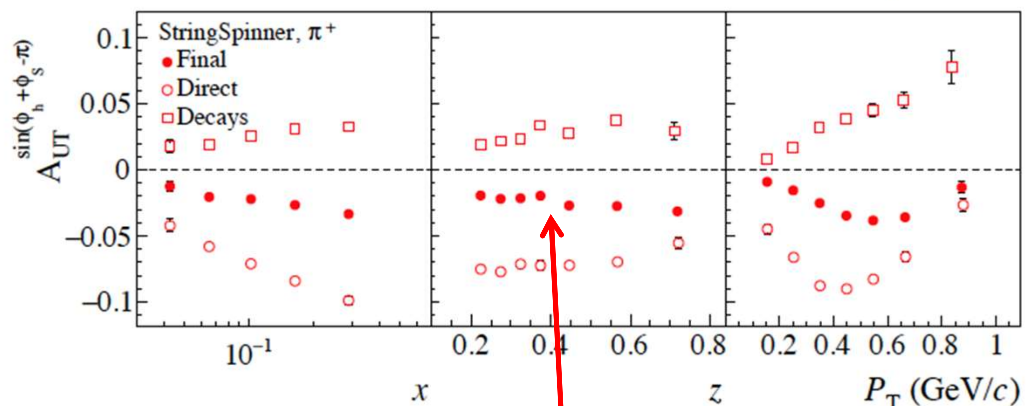
- ρ
- string
- ω

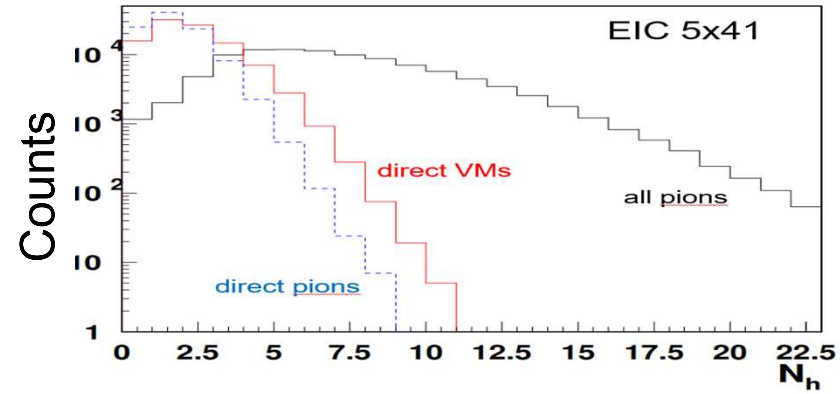
All measured 2 pion combinations are dominated by VM decays, indicate that all inclusive pions are dominated by VM decays at small P_Ts, and in particular at lower z!!!

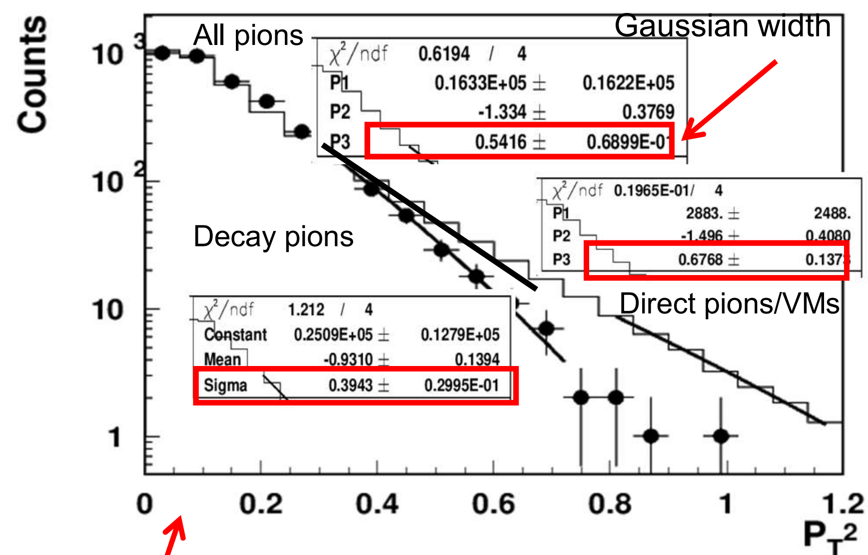
VM contributions

A. Kerbizi (Trieste U.)





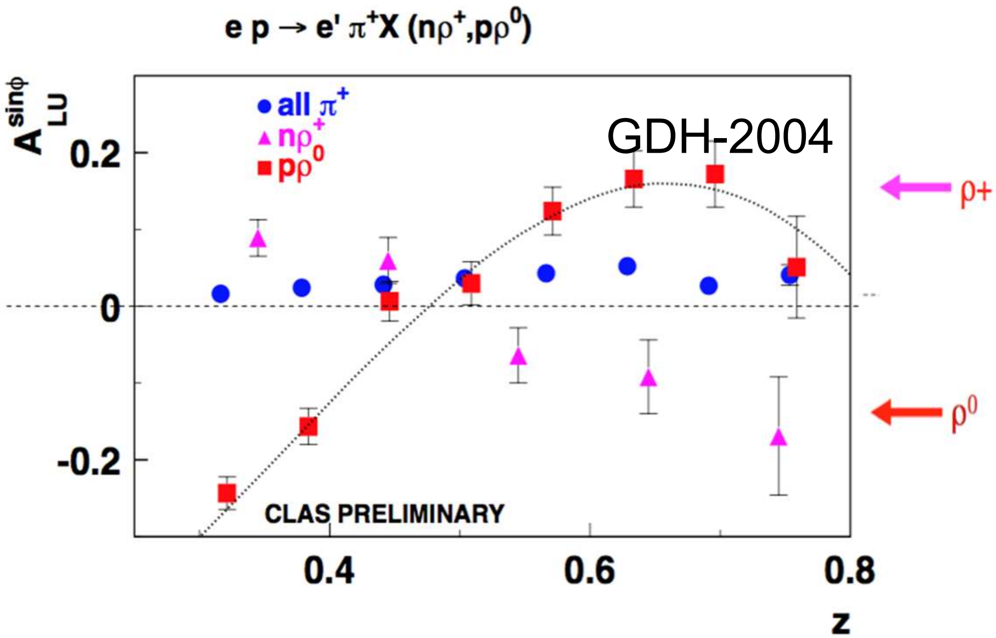


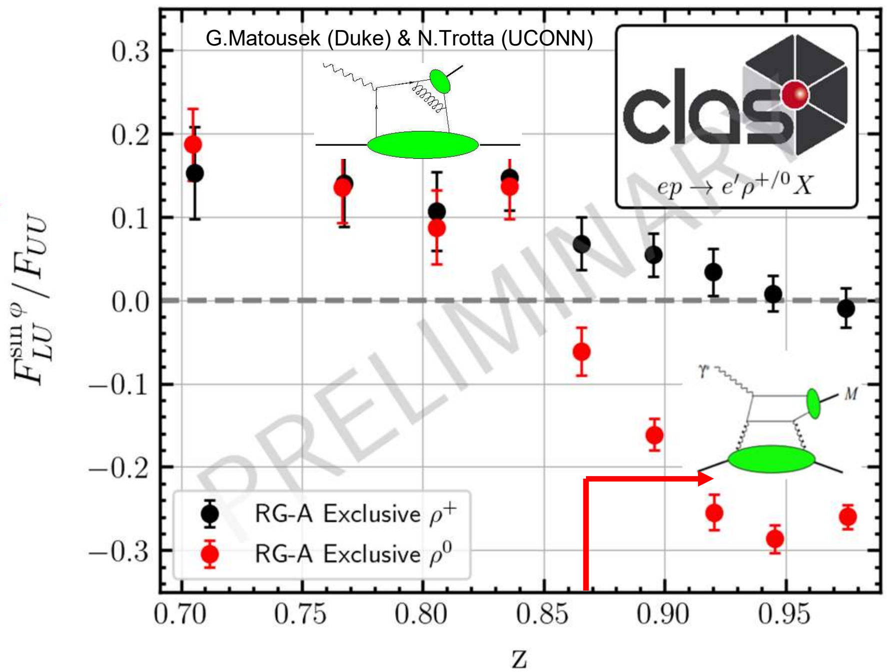


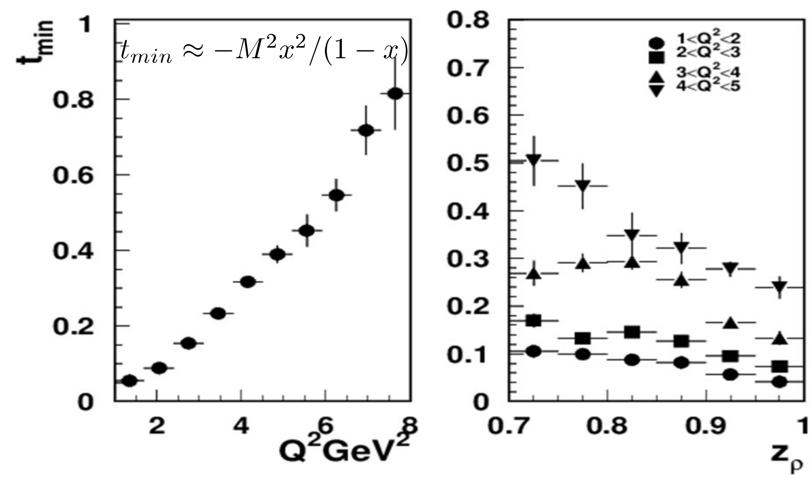
- Strong dilution of SSAs(3-5 for pions 2-3 for Kaons) due to VM decays
- Significant differences in pions vs Kaons from VMs(JLab can measure also K*, and their SSAs)

Understanding VMs is critical for interpretation even for unpolarized data

Quark-gluon correlations: impact of VMs







- Understanding of SSAs of VMs is critical in interpretation of the pion SIDIS
- A_{LU} sign change can define the dominating process!!!
- At large x the diffractive processes are suppressed by the minimum t

P. Kroll & S. Goloskokov

Exclusive production of VMs

helicity amplitudes σ_T σ_L

$$A_{LU}^{\sin(\phi)}(V)\sigma_o^V = -\sqrt{\varepsilon(1-\varepsilon)}\,\mathrm{Im}\left[2\mathcal{M}^{V*}_{0+,++}\mathcal{M}^{V}_{0+,0+} + \mathcal{M}^{V*}_{0-,++}\mathcal{M}^{V}_{0-,0+}\right]$$
$$A_{UL}^{\sin(\phi)}(V)\sigma_o^V = -\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Im}\left[\mathcal{M}^{V*}_{0-,++}\mathcal{M}^{V}_{0-,0+}\right],$$
$$A_{LL}^{\cos(0\phi)}(V)\sigma_0^V = \sqrt{1-\varepsilon^2}\left\{2\mathrm{Re}\left[\mathcal{M}^{VN*}_{++,++}\mathcal{M}^{VU}_{++,++}\right] + \frac{1}{2}|\mathcal{M}^{V}_{0-,++}|^2\right\},$$
$$A_{LL}^{\cos(\phi)}(V)\sigma_0^V = -\sqrt{\varepsilon(1-\varepsilon)}\,\mathrm{Re}\left[\mathcal{M}^{V*}_{0-,++}\mathcal{M}^{V}_{0-,0+}\right].$$

the same with helicity flip of proton

L→L: $\mathcal{H}^V_{0\lambda,0\lambda} \propto 1,$

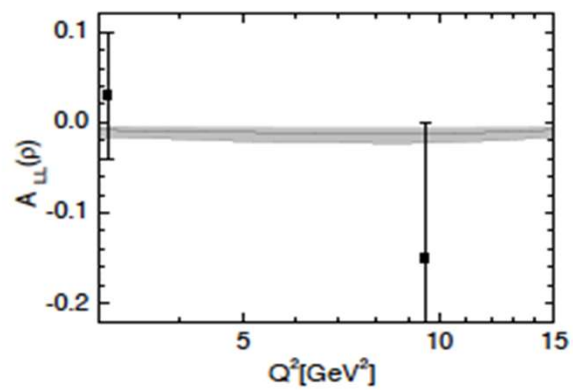
T→L: $\mathcal{H}^V_{0\lambda,+\lambda} \propto \frac{\sqrt{-t}}{Q},$

T→T: $\mathcal{H}^V_{+\lambda,+\lambda} \propto \frac{\langle k_\perp^2\rangle^{1/2}}{Q},$

L→T: $\mathcal{H}^V_{+\lambda,0\lambda} \propto \frac{\sqrt{-t}}{Q}\frac{\langle k_\perp^2\rangle^{1/2}}{Q},$

T→-T: $\mathcal{H}^V_{-\lambda,+\lambda} \propto \frac{-t}{Q^2}\frac{\langle k_\perp^2\rangle^{1/2}}{Q}.$

H^V_{μ′λ′,μλ} for γ∗g → V g (μ and μ′ denote the helicities of γ∗ and V, λ and λ' initial and final state proton helicities)



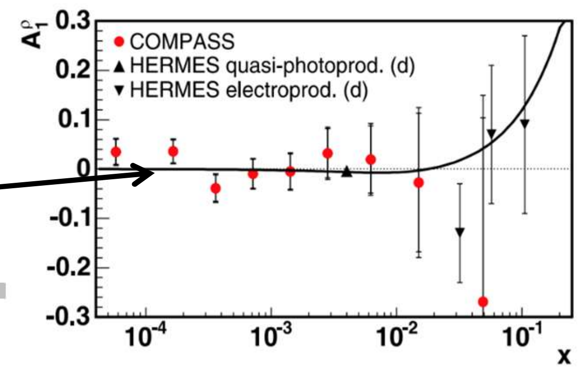
leading-twist contribution to the L → L amplitude

$$\mathcal{M}^{\rm coll}_{0+,0+} = e\,\frac{8\pi\alpha_s f_{VL}}{N_c Q}\,\langle 1/\tau\rangle_{VL}\,\mathcal{C}_V\int_0^1 d\bar{x}\,\frac{H^g(\bar{x},\xi)}{(\bar{x}+\xi)(\bar{x}-\xi+i\hat{\varepsilon})}$$

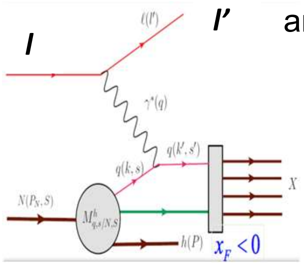
A_{LL} is an interference between the H^g and the $\widetilde{H}^g$

$$A_{LL}[ep\to epV] = 2\sqrt{1-\varepsilon^2}\,\frac{\mathrm{Re}\left[\mathcal{M}^{H}_{++,++}\mathcal{M}^{\widetilde{H}*}_{++,++}\right]}{\varepsilon|\mathcal{M}^{H}_{0+,0+}|^2+|\mathcal{M}^{H}_{++,++}|^2} \sim \langle k_\perp^2\rangle/Q^2\ \langle\widetilde{H}^g\rangle/\langle H^g\rangle$$

At small x expected to be small (data SMC) $A_1^\rho = \frac{2A_1}{1+(A_1)^2}$



Hadron production in TFR



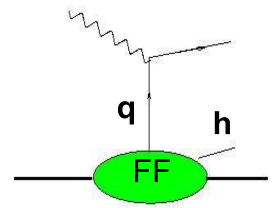
arXiv:2308.11251

$$F_{UL}^{\sin\phi_h} = -\frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 u_L^h$$

unpolarized quarks in the longitudinally polarized proton

$$F_{LU}^{\sin\phi_h} = \frac{2|\vec{P}_{h\perp}|}{Q} x_B^2 l^h$$

longitudinally polarized quarks in the unpolarized proton

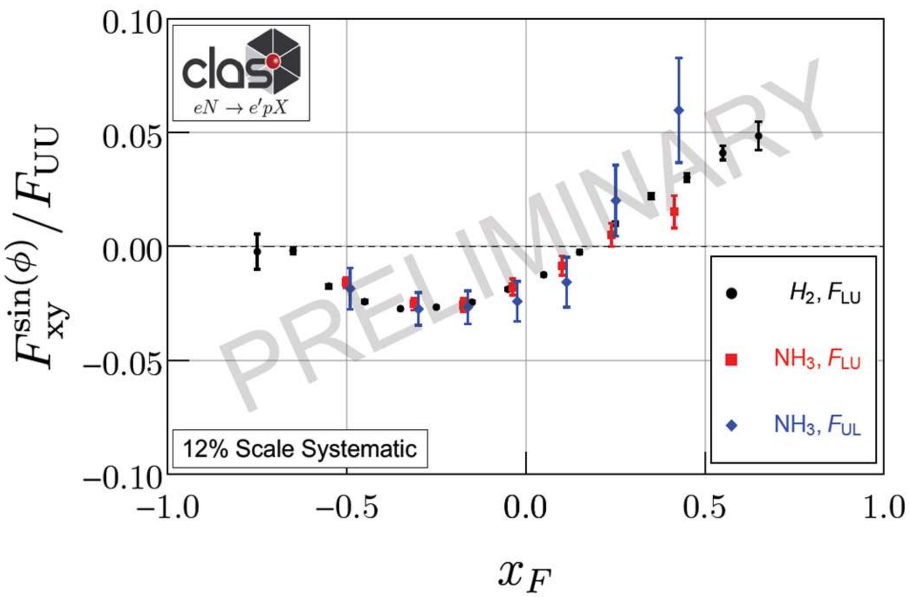


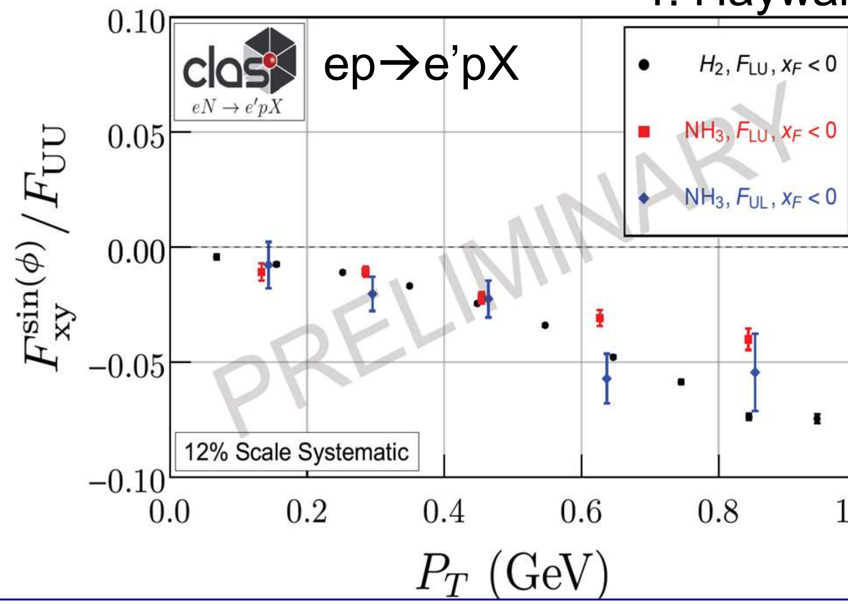
Conditional probability to produce a hadron ***h***, when kicking out quark ***q***

The Twist-3 Fracture Functions responsible for SSAs A_{LU} and A_{UL}

ep→e'pX

T. Hayward



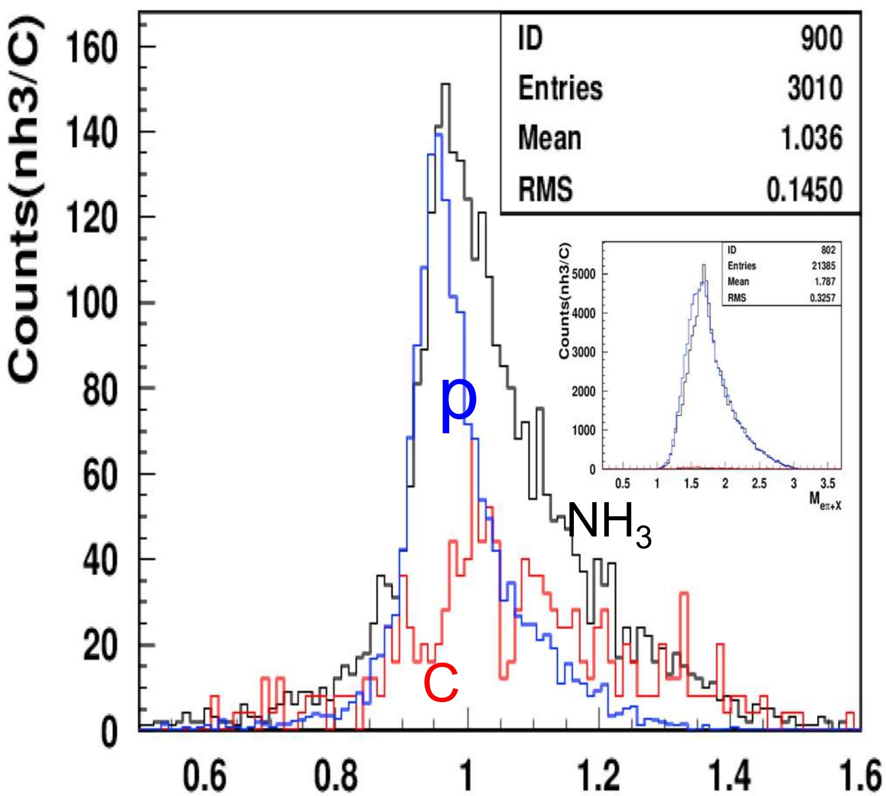


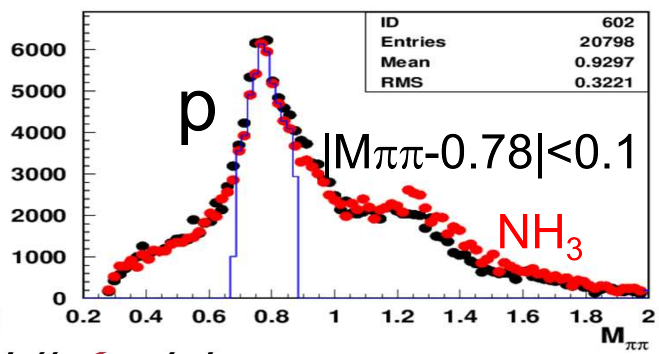
Asymmetries in epX generated by unpolarized quarks in the longitudinally polarized target (RGC) F_{UL} or longitudinally polarized quarks in the unpolarized target (RGA) F_{LU} (consistent with each other)

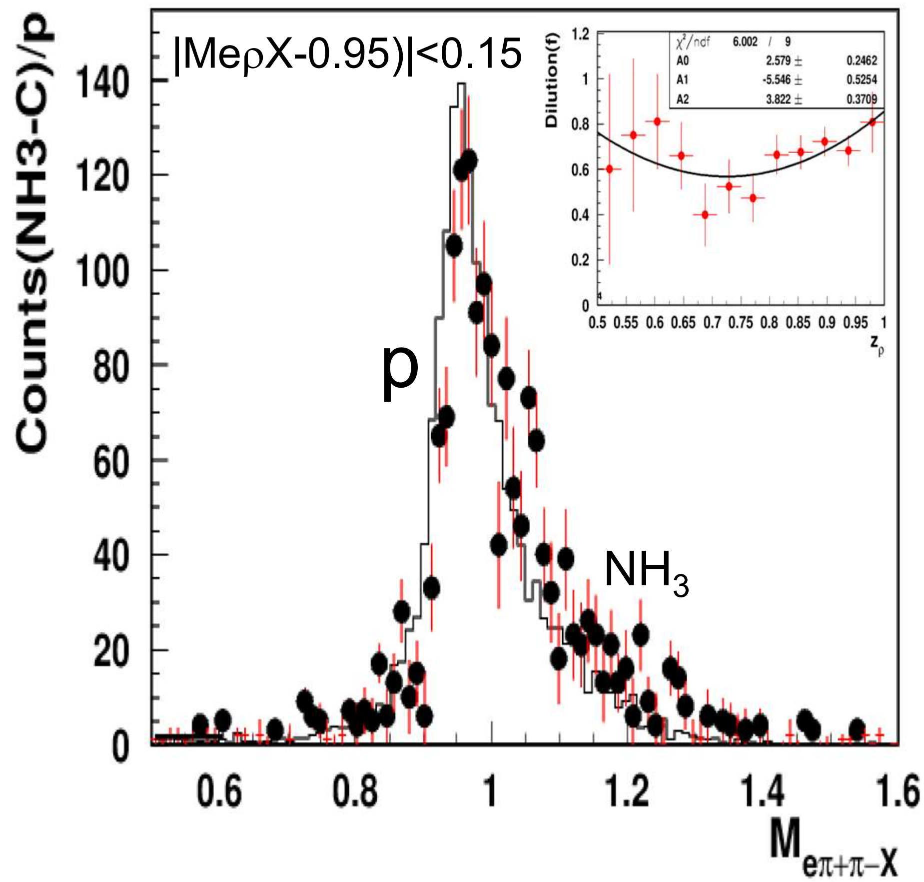
Note: F_{LU} for Nitrogen practically the same as for proton → no medium modification

check other observables

Separating the exclusive rhos: RGA vs RGC

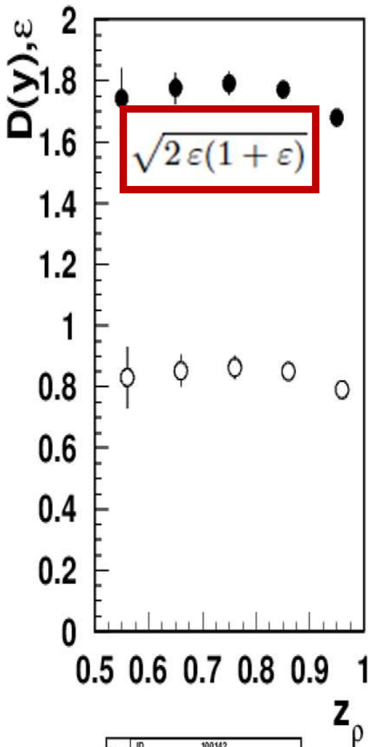






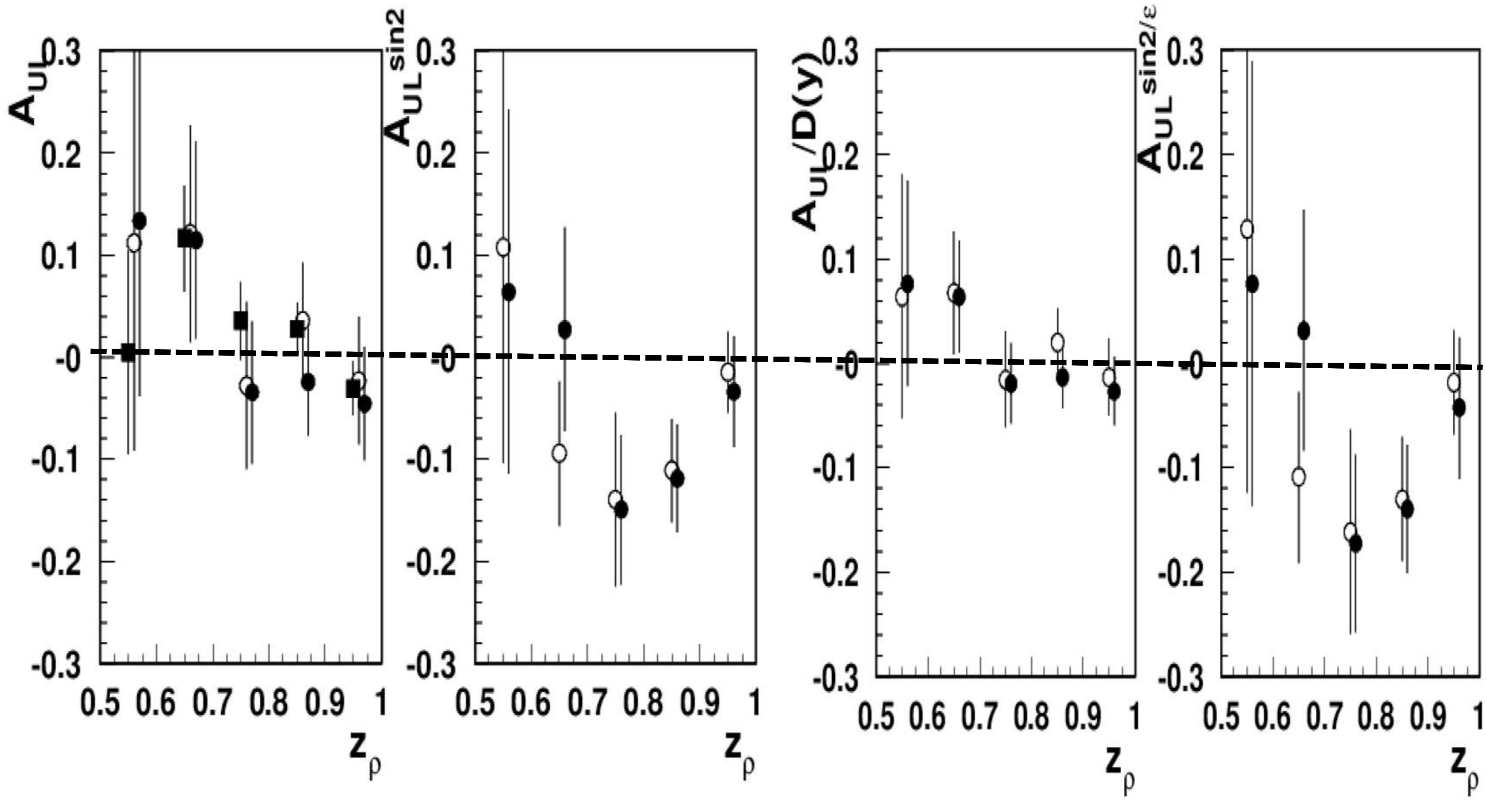
Resolutions reasonable in the RGC set (~5% of RGC).

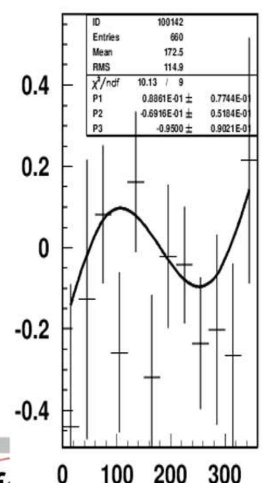
Exclusive rho: Target SSA from RGC



(N⁺-N⁻)/(N⁺+N⁻)

(N⁺-N⁻)/(N⁺+N⁻)/Depolarization

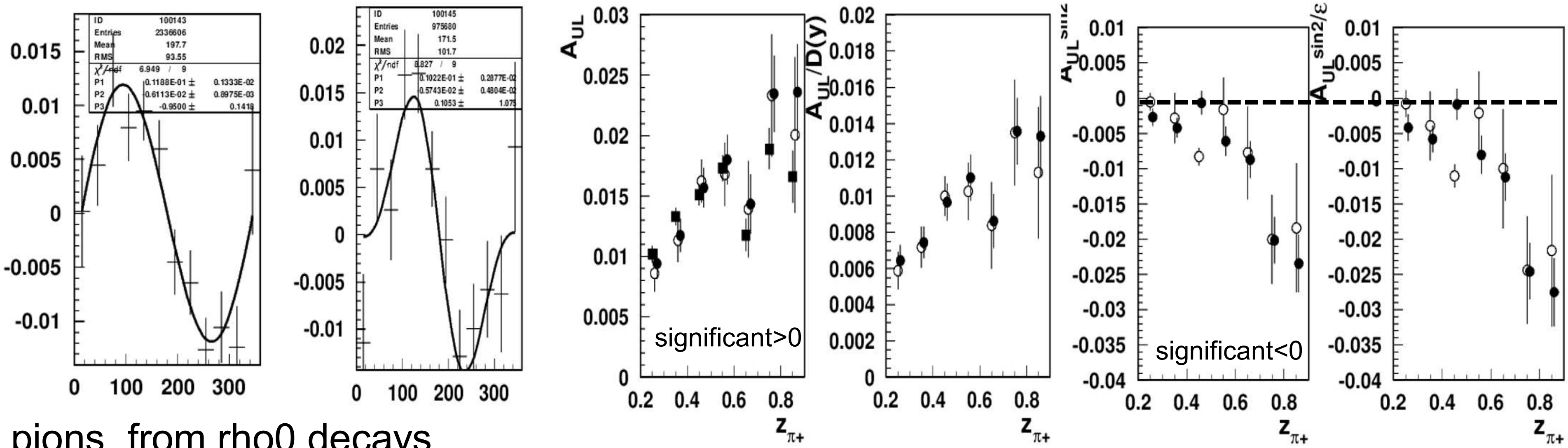




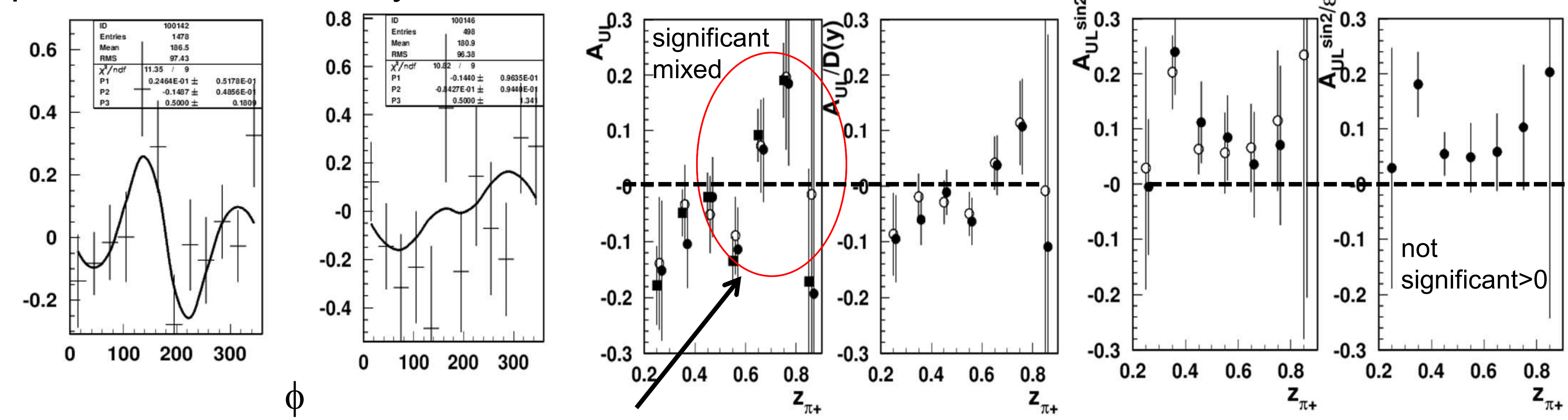
$A_{UL}^{\sin 2\phi}$ SSA , may be negative, need more statistics

Exclusive rho: impact on π+ A_{UL} SSAs

All pions

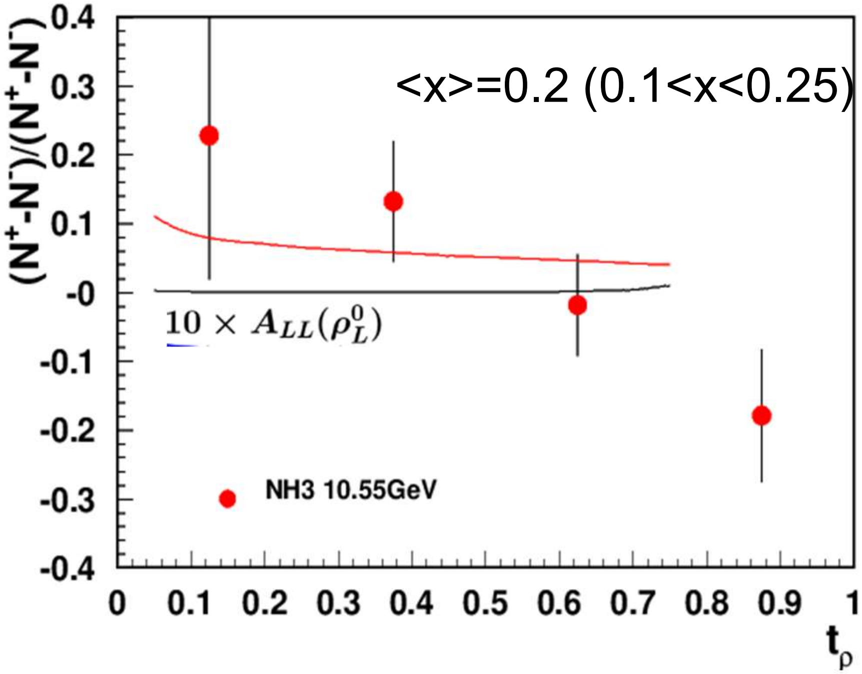


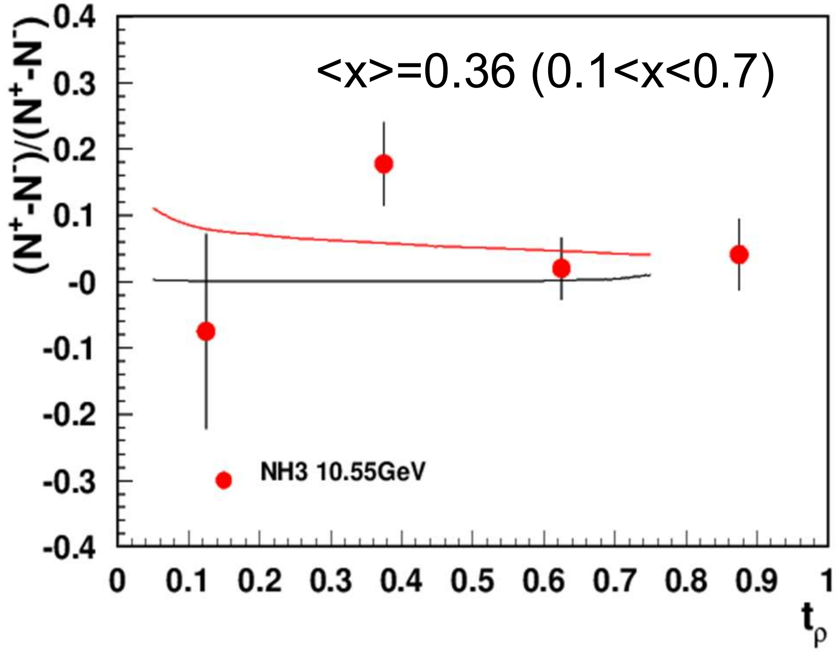
pions from rho0 decays



At large z the impact of rho may be significant, even if rho itself may not have significant SSA

What is the gluon polarization at large x?



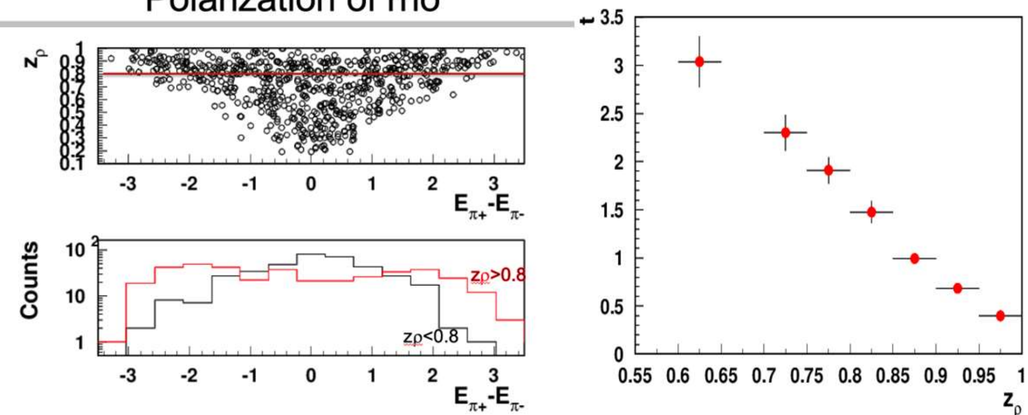


Curves calculated by Kroll&Goloskokov (x=0.12)

The full sample would allow fine binning in x

and separation of longitudinal/transverse ρ

Polarization of rho

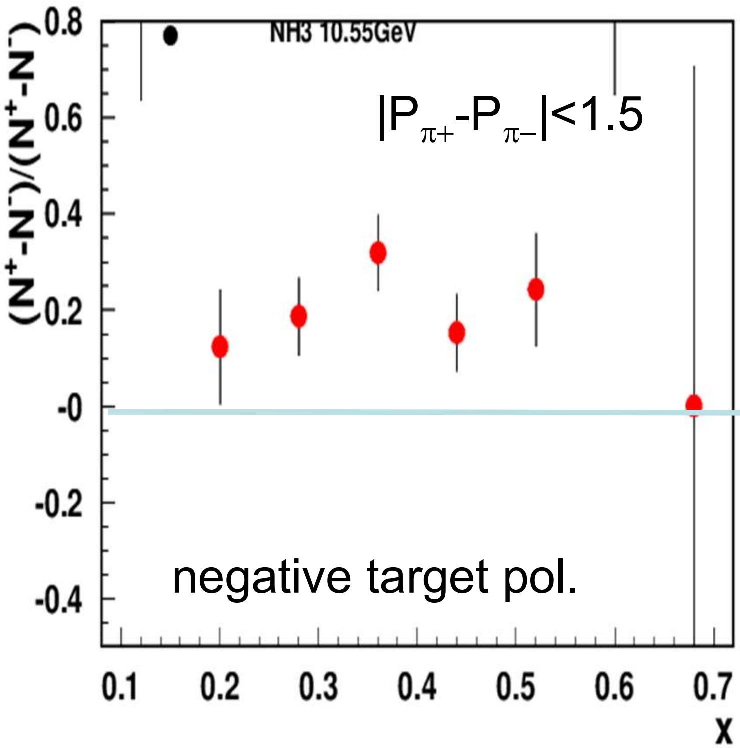


A_{LL} for exclusive rho from RGC

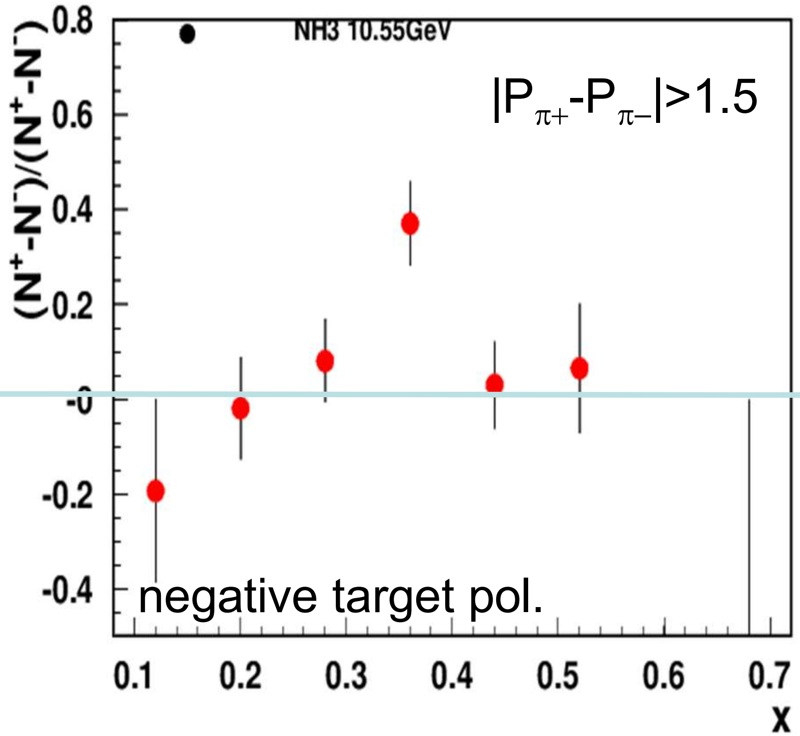
Polarization of final rho matters?

$|MepX-0.83|<0.1$
$z_\rho>0.8$

transverse/symmetric



longitudinal/asymmetric



A_{LL} seem to be lower for asymmetric decays

What we learned: missing parts of the mosaic

- SIDIS, with hadrons detected in the final state, from experimental point of view, is a measurement of observables in 5D space (x,Q^2,z,P_T,ϕ), 6D for transverse target, $+\phi_S$
  Collinear SIDIS, is just the proper integration, over P_T,ϕ,ϕ_S
- SIDIS observations relevant for interpretations of experimental results:
  1. Understanding the kinematic domain where non-perturbative effects of interest are significant (ex. x,P_T-range)
  2. Understanding of P_T-dependences of observables in the full range of P_T dominated by non-perturbative physics is important
  3. Understanding of phase space effects is important (additional correlations)
  4. Understanding the role of vector mesons is important
  5. Understanding of evolution properties and longitudinal photon contributions
  6. Understanding of radiative effects may be important for interpretation
  7. Overlap of modulations (acceptance, RC,…) is important in separation of SFs
  8. Multidimensional measurements with high statistics, critical for separation of different ingredients

- QCD calculations may be more applicable at lower energies when 1)-7) clarified

SUMMARY

- Studies of QCD dynamics with controlled systematics involving Semi-Inclusive DIS, requires multidimensional measurements of cross sections/multiplicities/asymmetries as a function of all involved kinematical variables (including P_T and ϕ)
- For interpretation of the SIDIS data it is critical to separate contributions from different structure functions, as well as separation of different production mechanisms in a given structure function (JLab is the unique place to do that)
- To evaluate the systematics of extracted 3D PDFs (TMDs and GPDs) , it is critical to validate the formalism (ex. evolution studies), and understand main contributions violating the factorized picture based on the dominance of the leading twist contributions
- Measurements and interpretation of azimuthal modulations of inclusive pions, and multiplicities of pion pairs require detailed studies of pions from decays of VMs (JLab is the unique place to do that!!!)
- Submit a CAA to study single and double spin asymmetries of exclusive rhos (rho0) from the longitudinally polarized target measurements (RGC data)

- support slides

Multiplicities of hadrons in SIDIS

Gaussian Ansatz for $F_{UU,T}$ $f_1^q \otimes D_1^{q\to h} = x f_1^q(x)\, D_1^{q\to h}(z) \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

TMDs universal, so what is the origin of the differences observed ?

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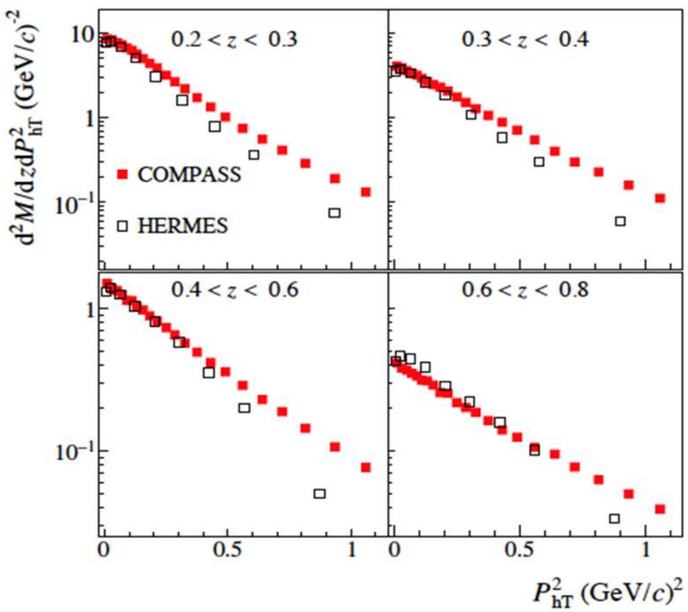
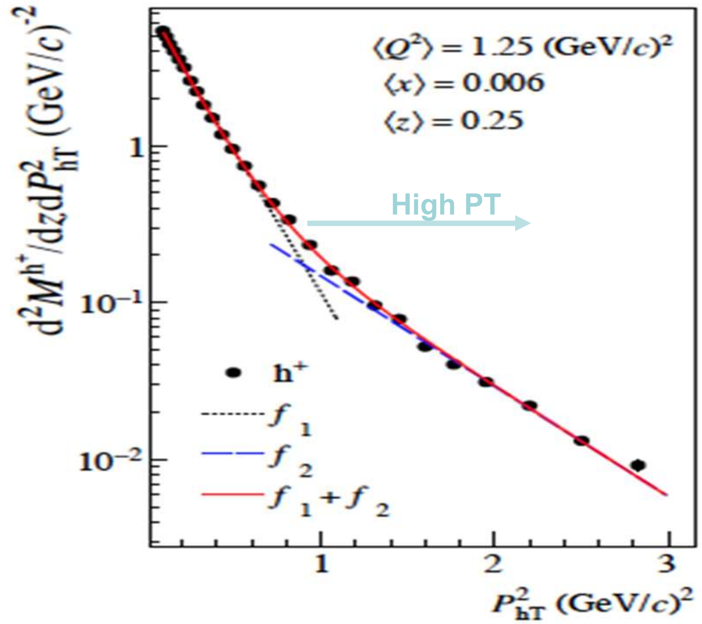
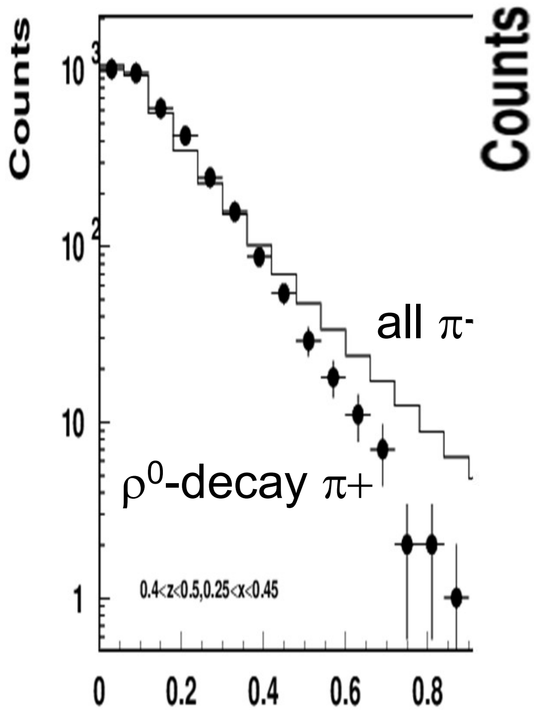


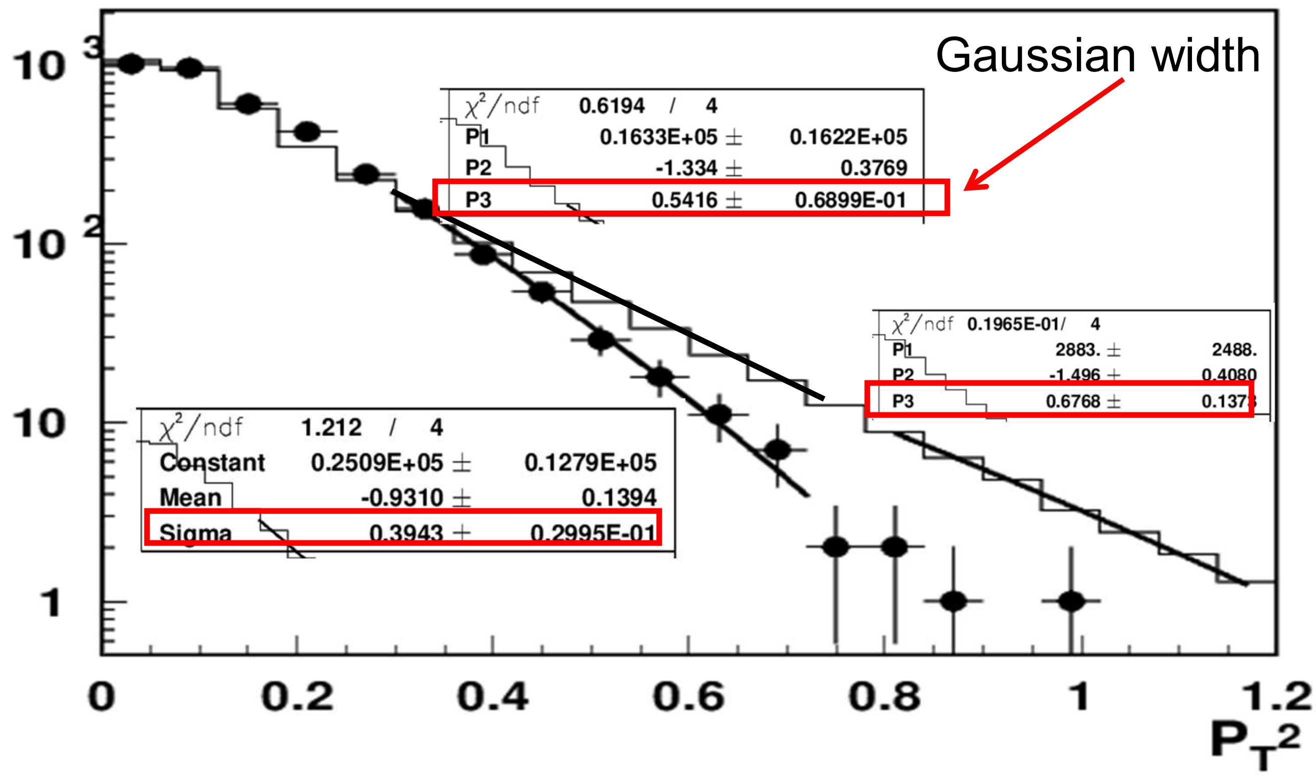


HERMES: not enough luminosity to access large P_T

- What is the origin of the "high" P_T (0.8-1.8) tail?
  1) Perturbative contributions?
  2) Non perturbative contributions?

VM contributions:2D space



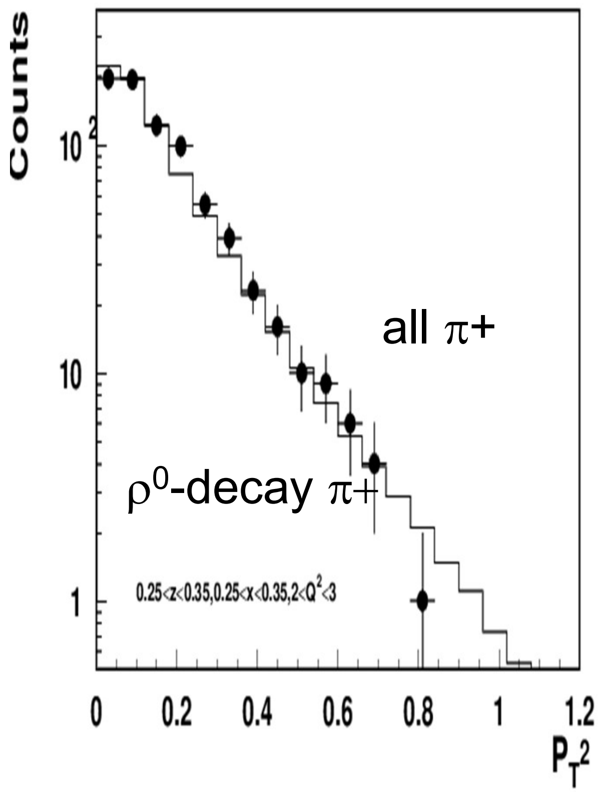


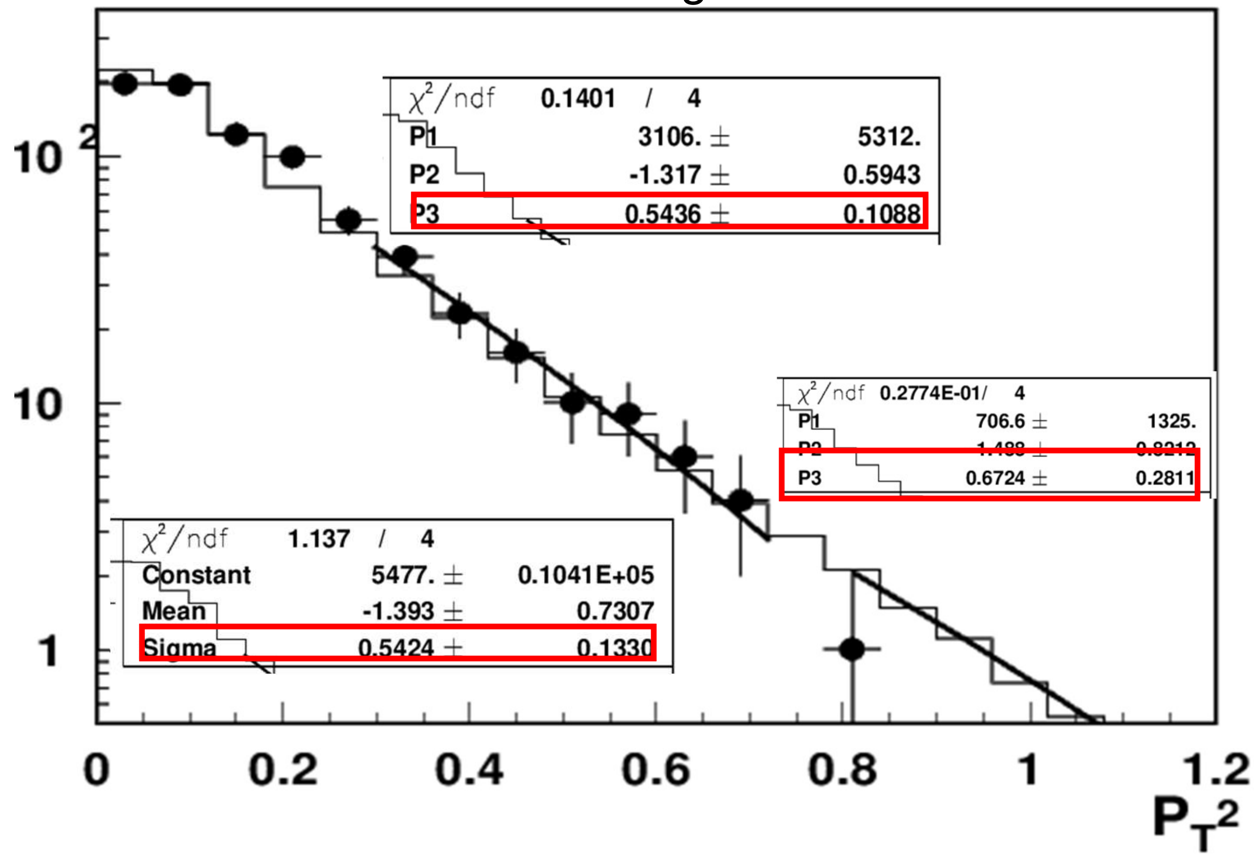
Understanding VMs is critical for interpretation, extraction of P_T-widths (lower for decays), following extraction of k_T-widths

Similar situation with Kaons and K*

VM contributions:3D space

Use a single Gaussian fit

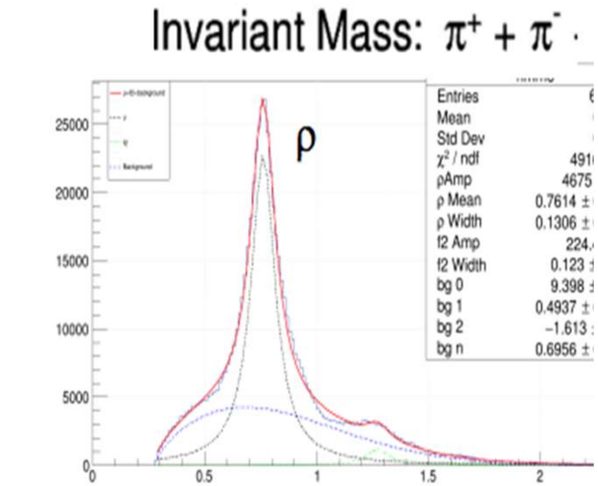


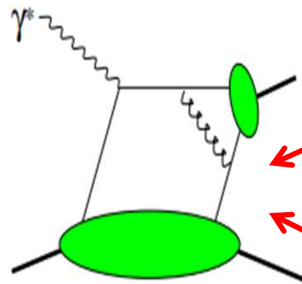


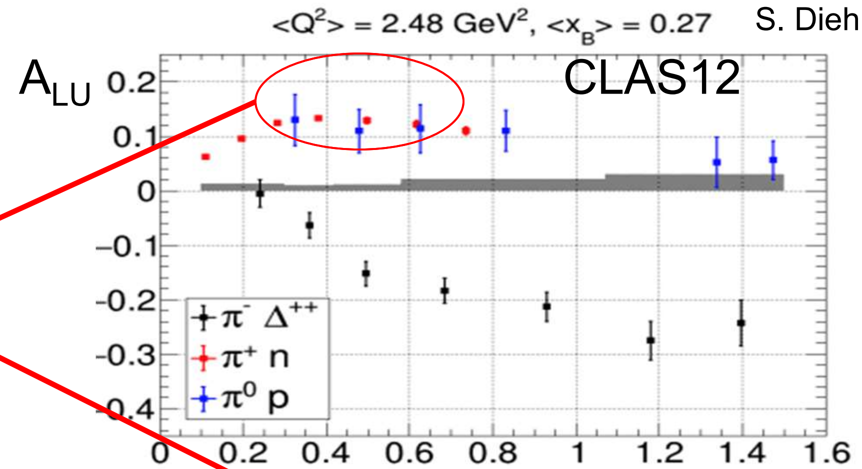
Understanding VMs is critical for interpretation, extraction of P_T-widths, following extraction of k_T-widths (tails stay the same)

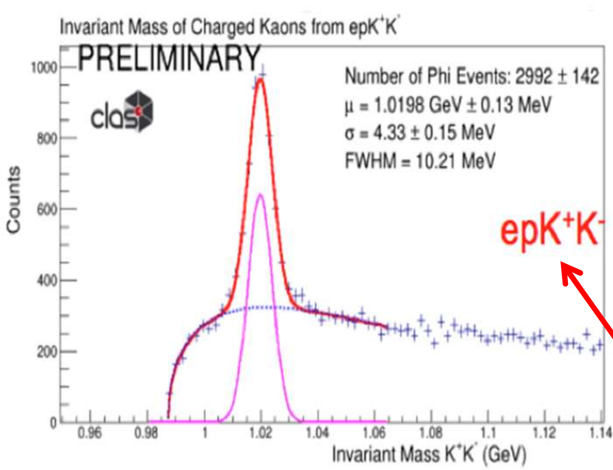
Similar situation with Kaons and K*

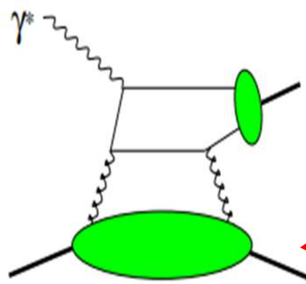
Current hadrons: exclusive limit

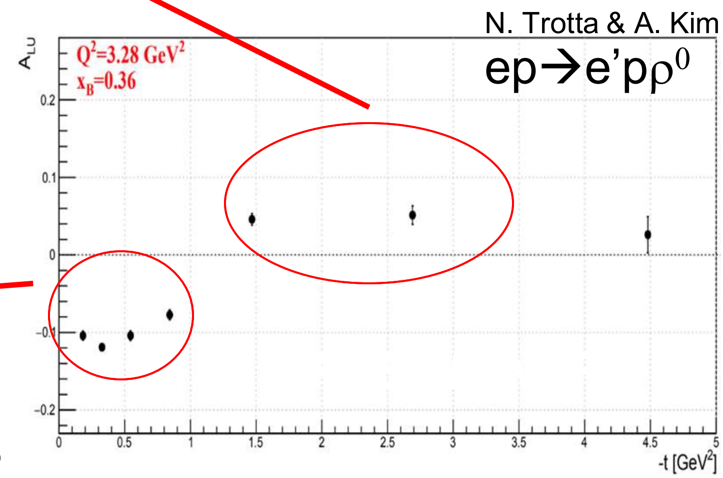












A_{LU}=-0.084+/-0.038

SSA negative→ΔG negative?

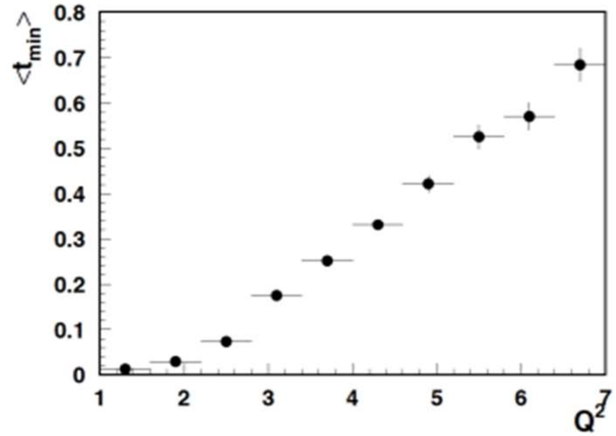
-t(GeV²)

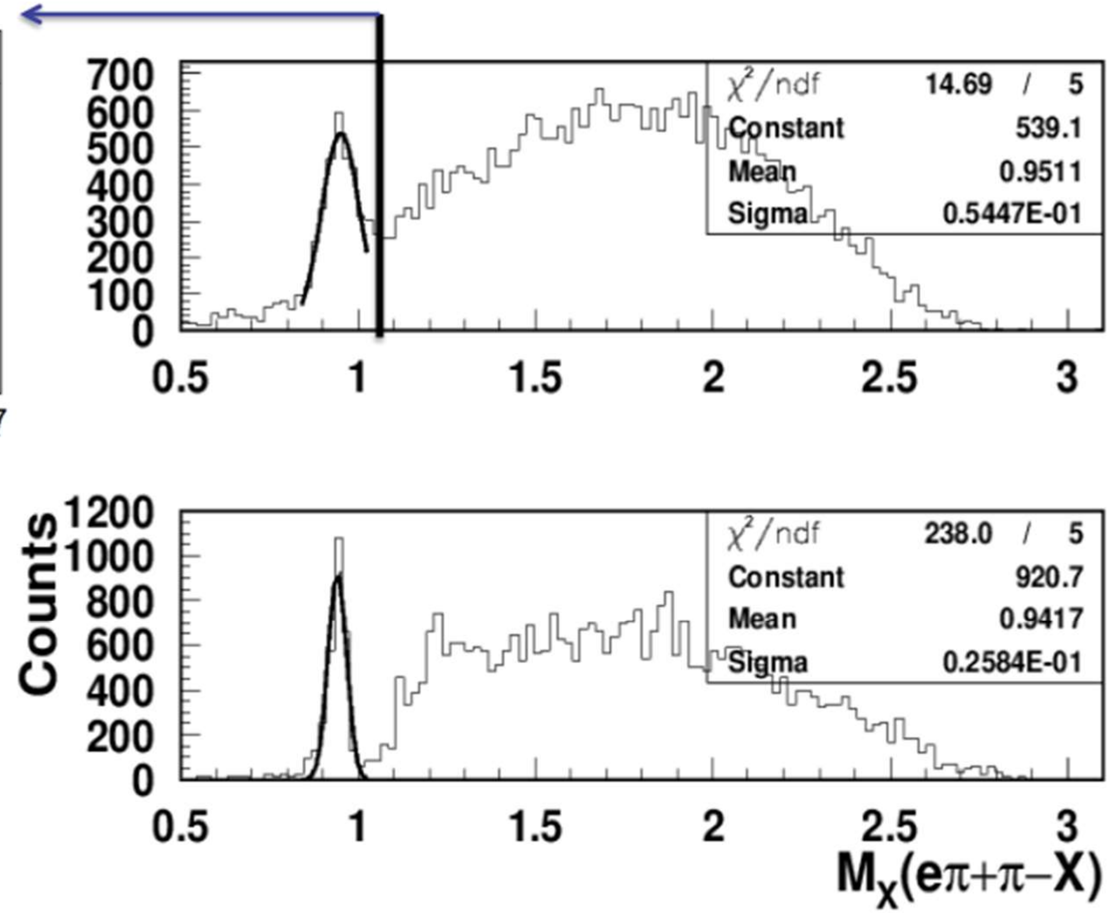
CLAS can measure all final states in exclusive production

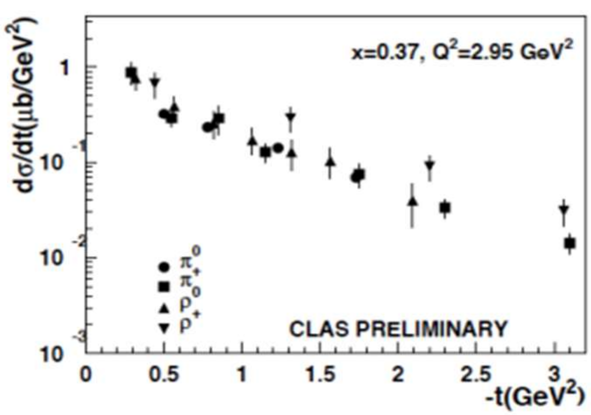
Hadrons produced from u-quark have positive SSA, d-quarks and gluons negative.

https://indico.jlab.org/event/320/contributions/5024/attachments/4103/4973/2019-June20-ccm-2hadrons.pdf

Comparing MC and data (6715) v.6b2.0







Possible sources of large P_T behaviour

1) Perturbative contributions and p_T-dependence of unpolarized FFs (so far unlikely...)

2) Significantly wider in k_T distributions of u-quarks with spin opposite to proton spin (possible sign flips in asymmetries related to polarization of partons)

3) Significantly wider in k_T distributions of d-quarks (possible sign flips in asymmetries related to polarization of partons)

4) Significantly wider in k_T sea quark distributions (study contributions dominated by sea, K-,..)

---

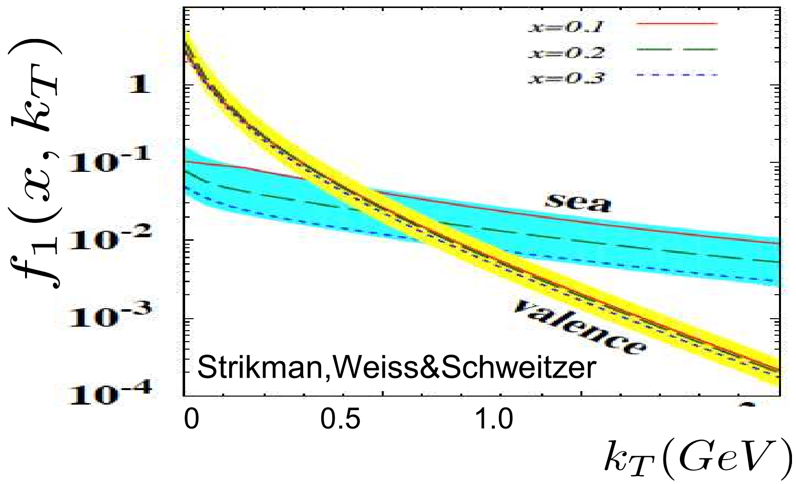
5) Increasing fraction of hadrons due to $F_{UU,L}$ (needed for proper interpretation
→ separation of $F_{UU,L}$ from total)

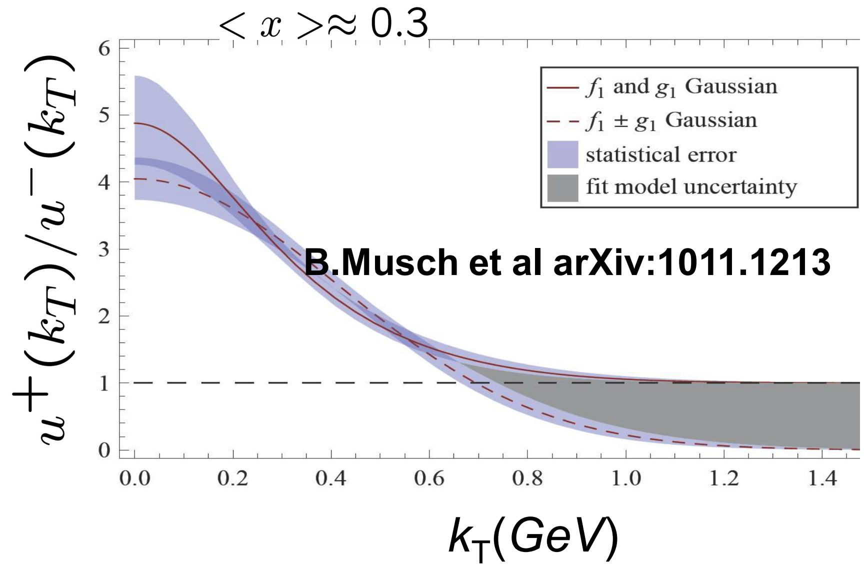
6) Significant contributions from VMs to low P_T pion multiplicities, with direct pions showing up at large P_T (needed for proper interpretation → much wider in k_T original parton distributions)

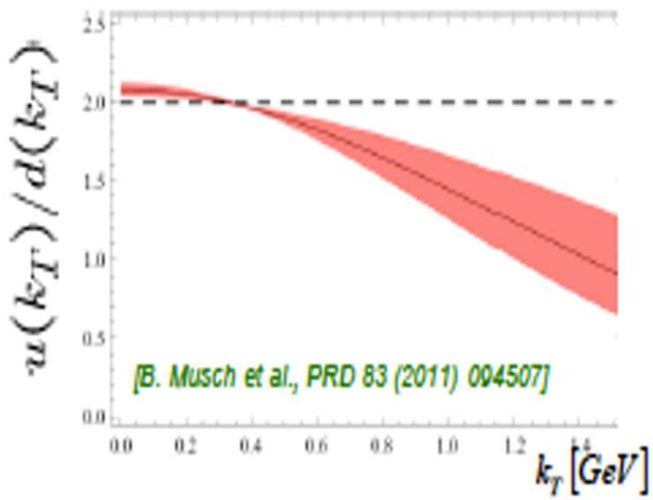
7) Radiative corrections (need the full x-section, typically applied to pions, while may be needed for underlying VMs,...)

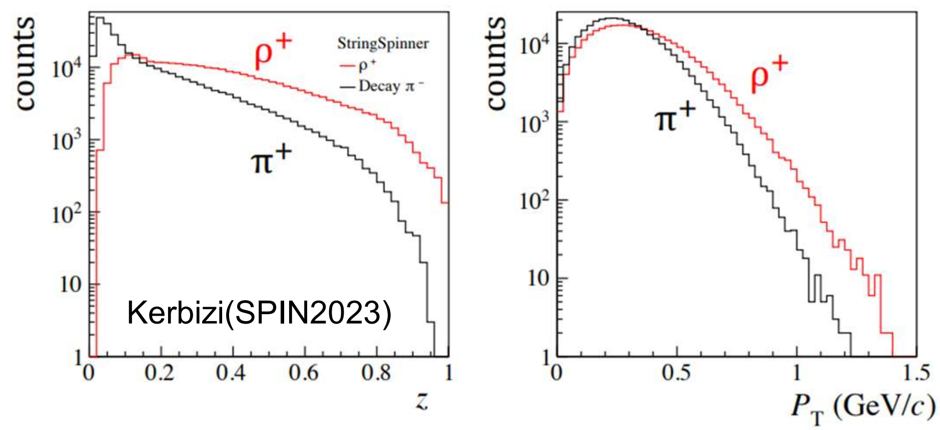
....

Hadron production in hard scattering



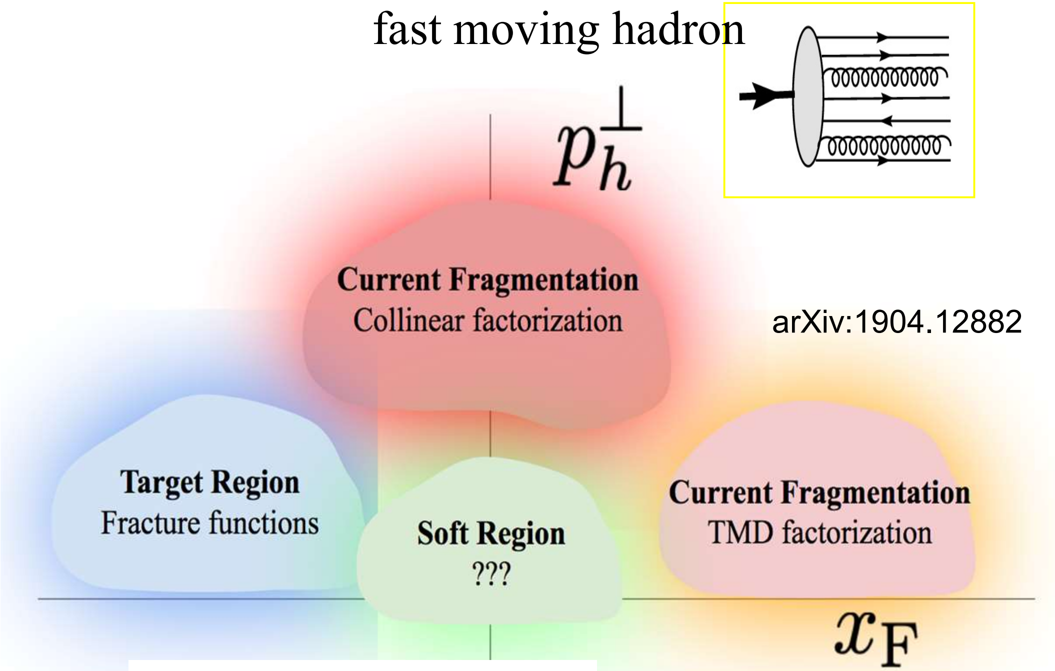




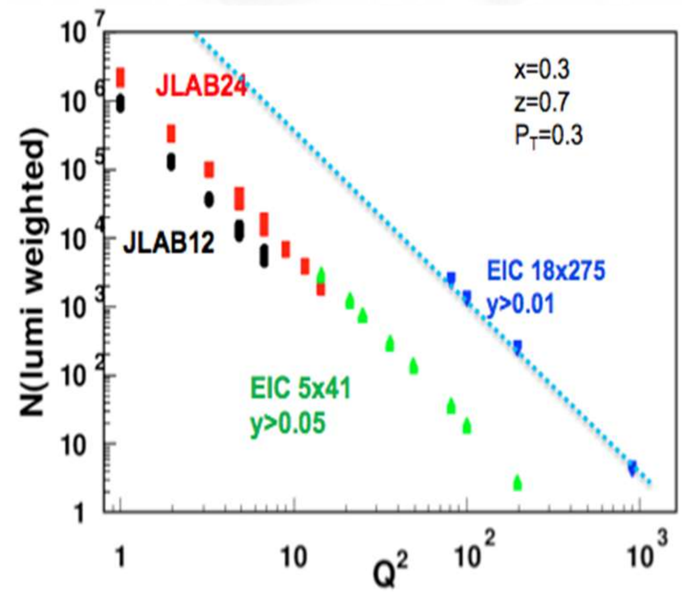


Understanding the k_T-structure may require detailed studies of P_T-dependences in a wide range, and separation of different contributions

Kinematical regions in SIDIS



x_F – fractional momentum in the CM frame



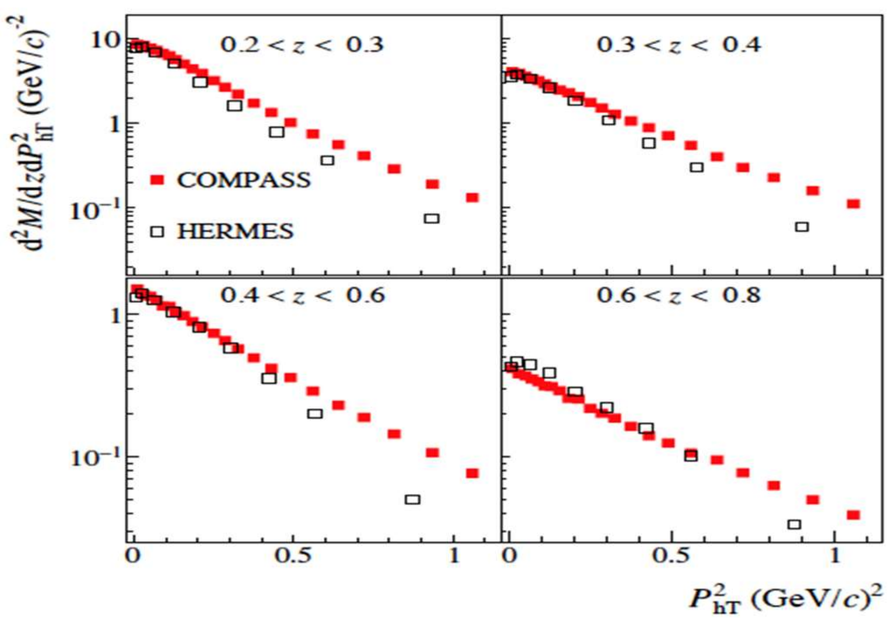
1) Kinematic regions not trivial to separate, in particular for polarized measurements
2) Theoretical separation of kinematic region requires some assumptions (no decays,…)
3) Multi-dimensional measurements critical, requiring high lumi

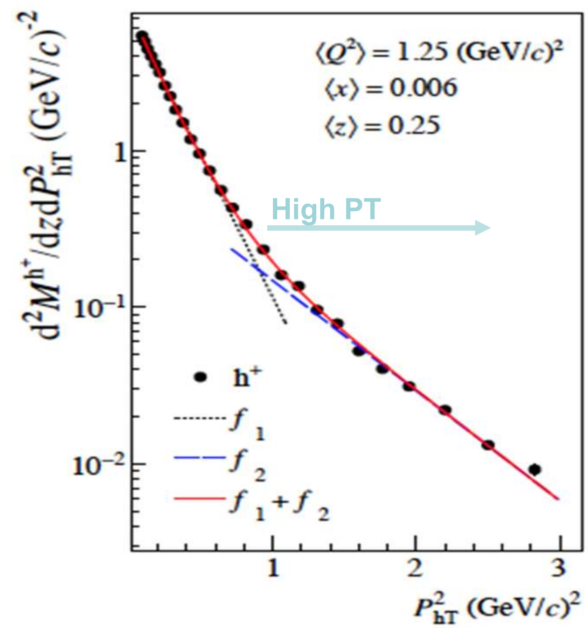
Multiplicities of hadrons in SIDIS

Gaussian Ansatz for $F_{UU,T}$ $$f_1^q \otimes D_1^{q\to h} = x f_1^q(x)\, D_1^{q\to h}(z)\, \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$$

TMDs universal, so what is the origin of the differences observed ?

COMPASS:1709.07374

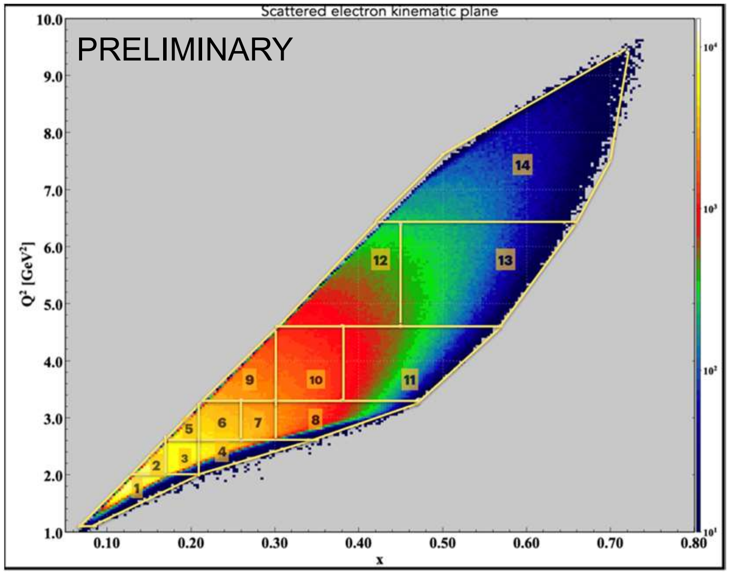


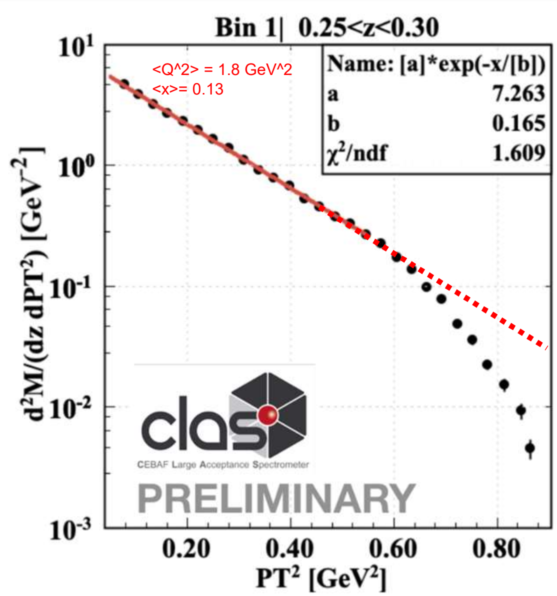


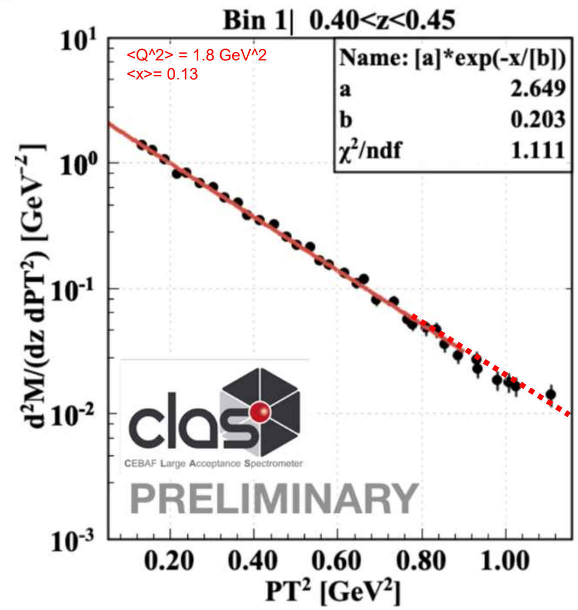
JLab: not enough energy to produce large P_T
HERMES: not enough luminosity to access large P_T

- What is the origin of the "high" P_T (0.8-1.8) tail?
  1) Perturbative contributions?
  2) Non perturbative contributions?

CLAS12 1h Multiplicities: high P_T & phase space

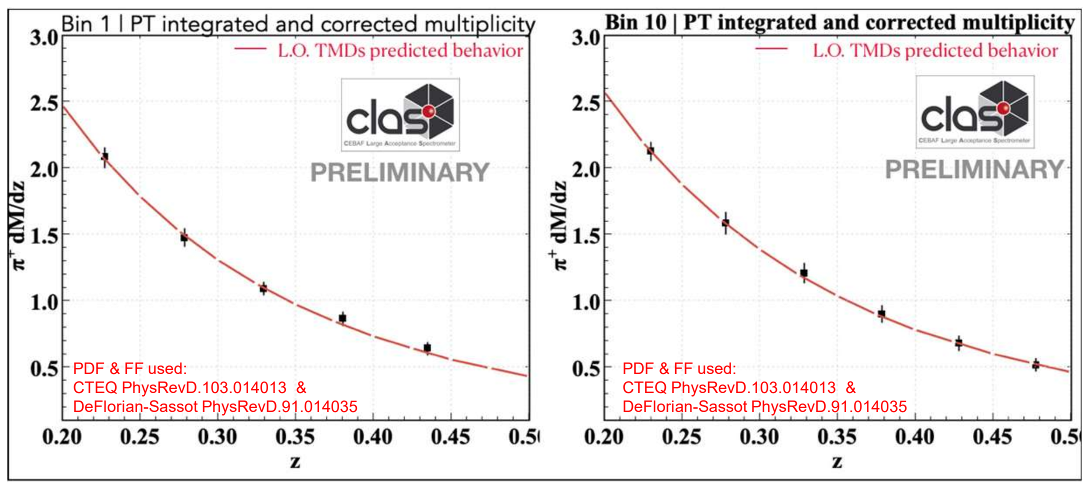






For some kinematic regions, at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).

If the effect is accounted, the CLAS data follows global fits.

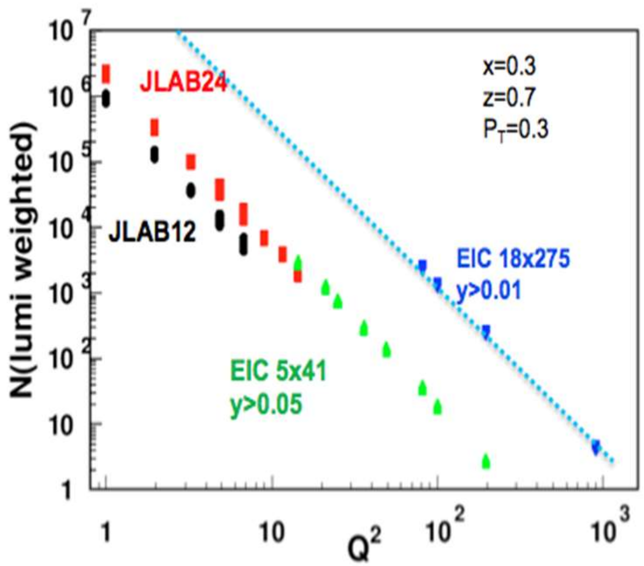


Structure functions and depolarization factors

- **At large x fixed target experiments are sensitive to ALL Structure Functions**
- **At higher energies (EIC), observables surviving the $\varepsilon \to 1$ limit (F_{UU}, F_{UL}, Transversely pol. F_{UT})**

x-section for eN→e'hX

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_L\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

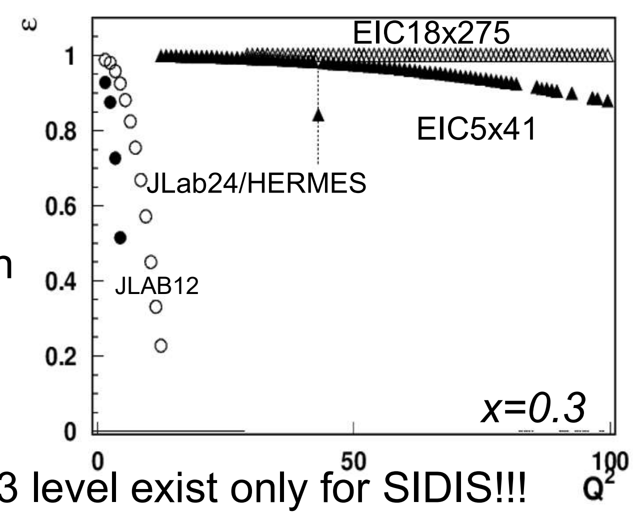


x-section from Bacchetta et al, 1703.10157

Combination of statistics and depolarization factors defines measurable SFs

1) Measurements of $F_{UU,T}$ and Sivers requires *separation*, evaluation of longitudinal photon (JLab)

2) Meaningful interpretation the Collins effects requires *separation* of VMs(JLab)



Full decomposition of SFs to underlying 3D PDFs up to twist 3 level exist only for SIDIS!!!

P. Kroll & S. Goloskokov

In terms of GPDs

$$A_{UT}^{\sin(\phi-\phi_s)} \sim \mathrm{Im}[< E >^* < H >].$$

$$A_{UT}^{\sin(\phi_s)} \sim \mathrm{Im}[< H_T >^* < H >].$$

$$\mathrm{L} \to \mathrm{L}: \quad \mathcal{H}^V_{0\lambda,0\lambda} \propto 1\,,$$

$$\mathrm{T} \to \mathrm{L}: \quad \mathcal{H}^V_{0\lambda,+\lambda} \propto \frac{\sqrt{-t}}{Q}\,,$$

$$\mathrm{T} \to \mathrm{T}: \quad \mathcal{H}^V_{+\lambda,+\lambda} \propto \frac{\langle k_\perp^2\rangle^{1/2}}{Q}\,,$$

$$\mathrm{L} \to \mathrm{T}: \quad \mathcal{H}^V_{+\lambda,0\lambda} \propto \frac{\sqrt{-t}}{Q}\frac{\langle k_\perp^2\rangle^{1/2}}{Q}\,,$$

$$\mathrm{T} \to -\mathrm{T}: \quad \mathcal{H}^V_{-\lambda,+\lambda} \propto \frac{-t}{Q^2}\frac{\langle k_\perp^2\rangle^{1/2}}{Q}\,.$$

ALL^cos(0phi) ~ 2 Re[<H_eff>_TT^*<Htilde_eff>_TT] + 2 Re[<E>^*_TT <Etilde>_TT]

+ 1/2 |<H_T>_LT|^2

ALL^cos(phi) ~ Re[<H_T>^*_LT <E>_LL]

ALU^sin(phi) ~ Im[<H_T>^*_LT <E>_LL]

$$t = \Delta^2 = -\frac{4\xi^2 m^2 + \Delta_\perp^2}{1-\xi^2}\,,$$

a minimal value is implied by the positivity of $\Delta_\perp^2$

$$-t_{\min} = 4m^2\frac{\xi^2}{1-\xi^2}\,.$$

$$\xi \simeq \frac{x_{\mathrm{Bj}}}{2-x_{\mathrm{Bj}}}\left[1 + m_V^2/Q^2\right].$$

<K>_AB means convolution of GPD K with a subprocess amplitude where the vector meson has helicity A and the photon helicity B. Thus, L stands for a longitudinal vector meson (or photon) and T for a transversal vector meson (or photon).

$$t_0 = -2\frac{(m^2+M^2)\xi^2 + (M^2-m^2)\xi}{1-\xi^2}$$

Items for discussion (REF2023)

Understanding of the impact of various assumptions and approximations

- Dominance of the transverse photon and applicability of TMD formalism
- Independent fragmentation and impact of correlations (ex. VMs, TFR-CFR)
- How do we do Radiative Corrections in SIDIS
- Impact of other structure functions, ex. FUT^\sin\phi_S, FUU^cos\phi contributions
- What is the role medium modification of TMDs in polarized target measurements (NH3,ND3,LiD,…)

Development of validation procedures

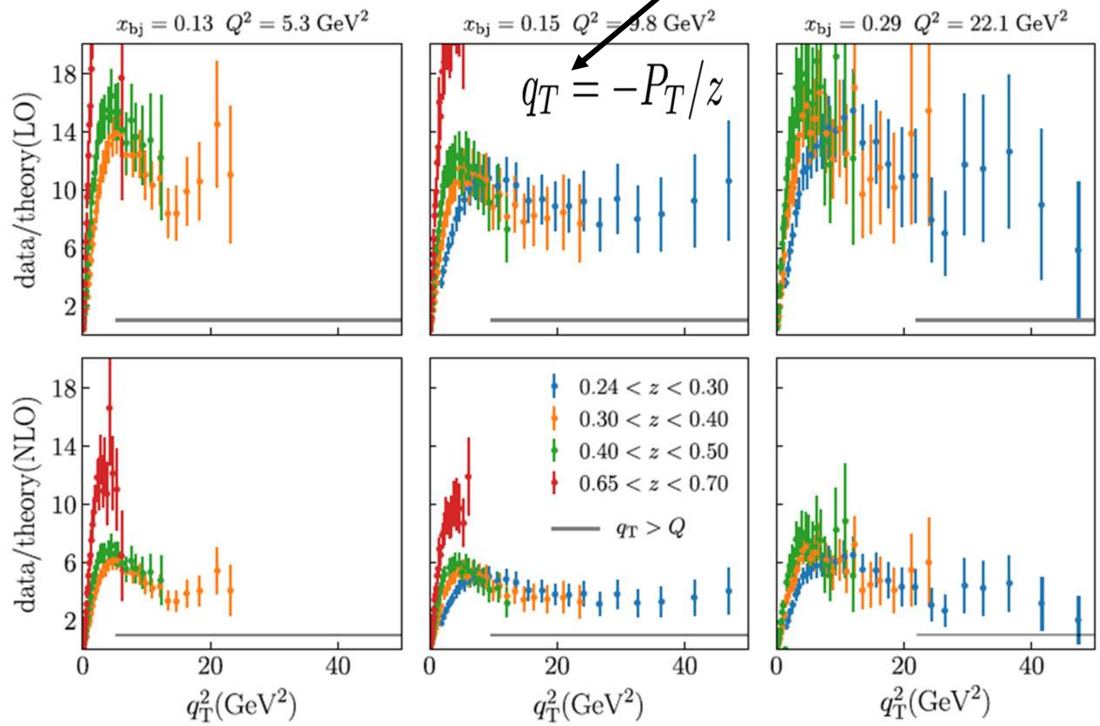
- The need of MC
- What the studies of observables vs Q2 can give (how to validate)

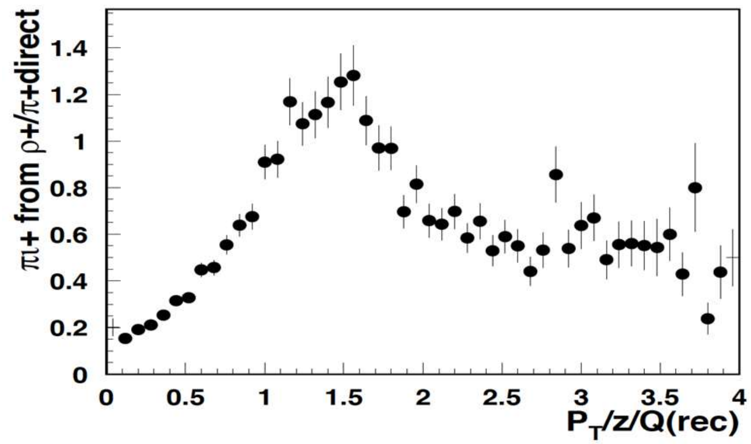
Does it matter if the pion comes from correlated pairs?

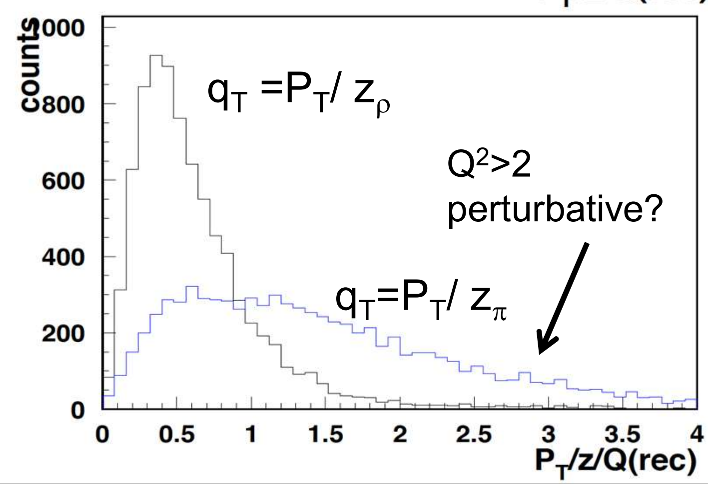
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

quark transverse momentum





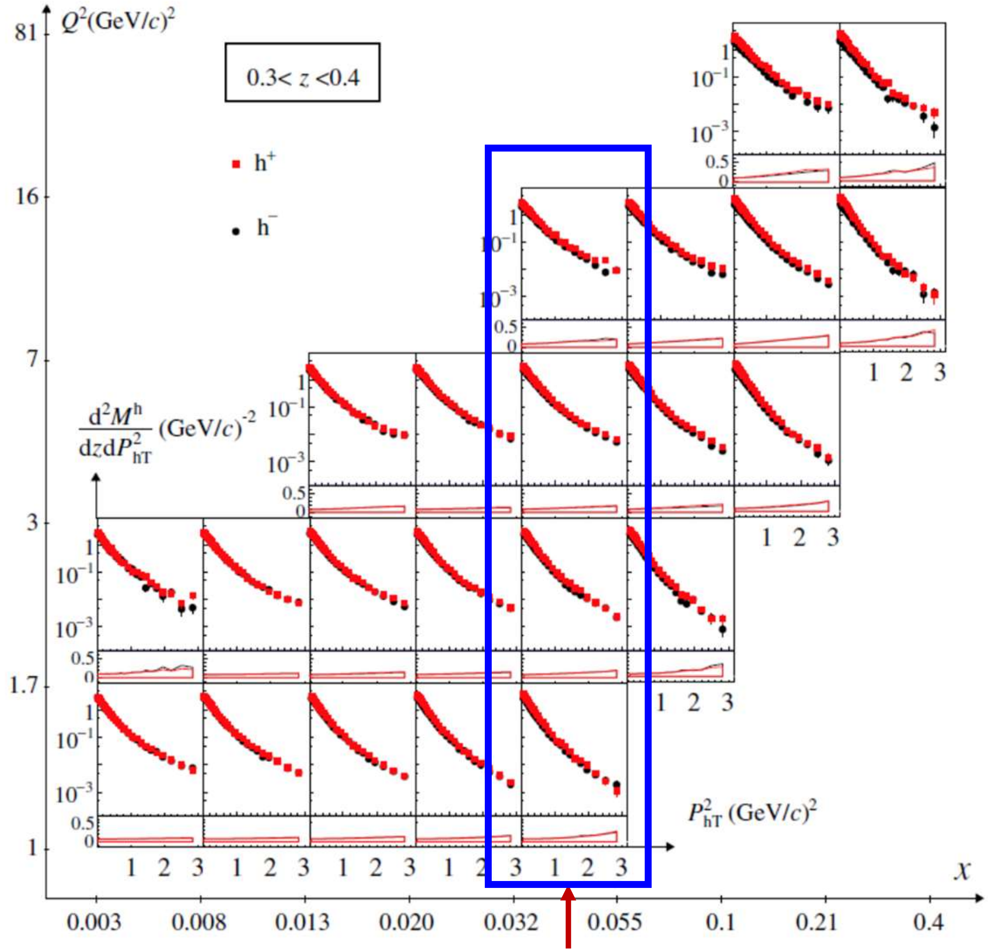


The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

Gonzalez-Hernandez et al, PRD 98, 114005 (2018)

understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

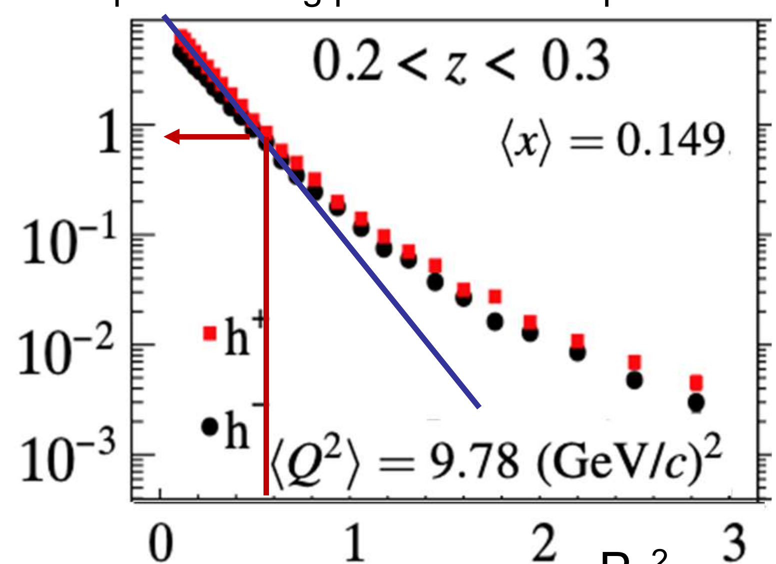
q_T-crisis or misinterpretation



The $q_T=P_T/z$ theory "trustworthy" cut:

1) Suppresses moderate Q^2 and large P_T (sensitive to k_T), where all kind of azimuthal modulations are most significant
2) Enhances large z region (ex. Exclusive Events) in TMD and low z in FO calculations
3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES COMPASS, and even EIC.

https://arxiv.org/pdf/1709.07374.pdf



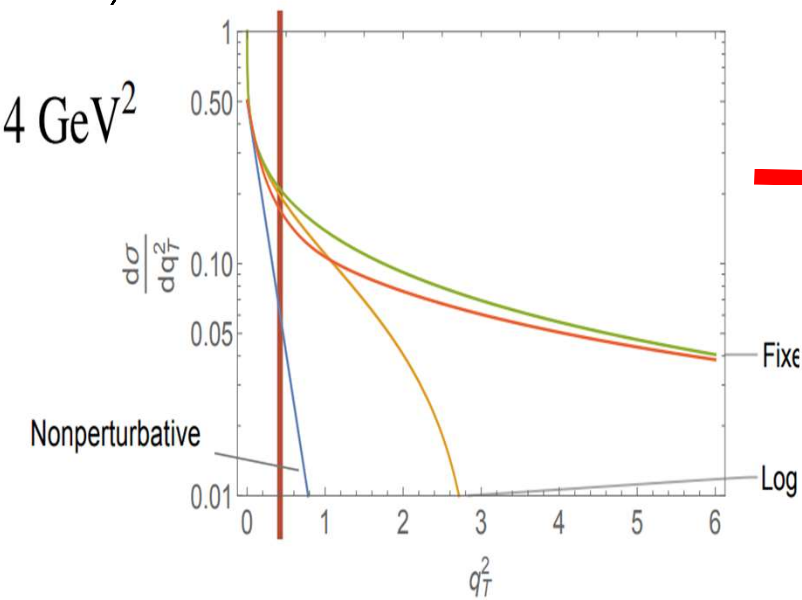
at higher Q^2 the slope in P_T changes, why?

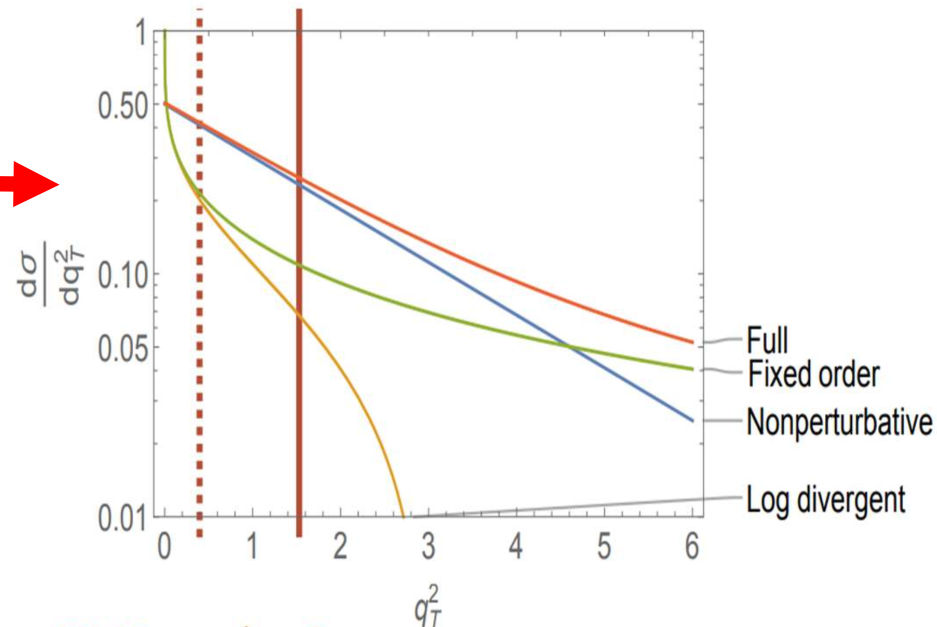
Theory unable to explain the correlation of P_T and Q

TMD theory problems

Perturbative approach: TMD region = where the log divergence of the fixed-order calculation dominates (resummation is required)

$\langle Q^2 \rangle = 4\ \mathrm{GeV}^2$





TMD region?

Nonperturbative approach: TMD region = where either the log divergence OR the nonperturbative contributions dominate

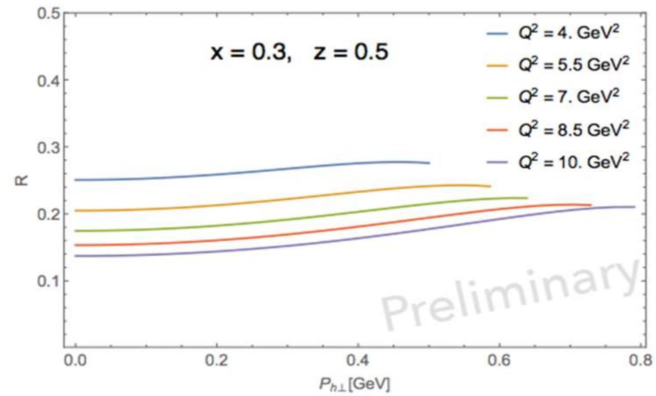
Longitudinal photon contributions in SIDIS

	observable	twist (low P_T)	twist (high P_T)
"SIDIS F_T"	$F_{UU,T}$	2	2
"SIDIS F_L"	$F_{UU,L}$	4	2
"Cahn" - $f^\perp$	$F_{UU}^{\cos\phi_h}$	3	2
"Boer-Mulders"	$F_{UU}^{\cos 2\phi_h}$	2	2
e, $g^\perp$ and friends	$F_{LU}^{\sin\phi_h}$	3	2
	$F_{UL}^{\sin\phi_h}$	3	2
"Kotzinian-Mulders"	$F_{UL}^{\sin 2\phi_h}$	2	
"SIDIS g_1"	F_{LL}	2	2
	$F_{LL}^{\cos\phi_h}$	3	2
"Sivers"	$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	2	3
	$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	4	3
"Collins"	$F_{UT}^{\sin(\phi_h+\phi_S)}$	2	3
"Pretzelosity"	$F_{UT}^{\sin(3\phi_h-\phi_S)}$	2	3
f_T and friends	$F_{UT}^{\sin\phi_S}$	3	3
	$F_{UT}^{\sin(2\phi_h-\phi_S)}$	3	3
"Worm gear"	$F_{LT}^{\cos(\phi_h-\phi_S)}$	2	3
"SIDIS g_2" - g_T	$F_{LT}^{\cos\phi_S}$	3	
	$F_{LT}^{\cos(2\phi_h-\phi_S)}$	3	

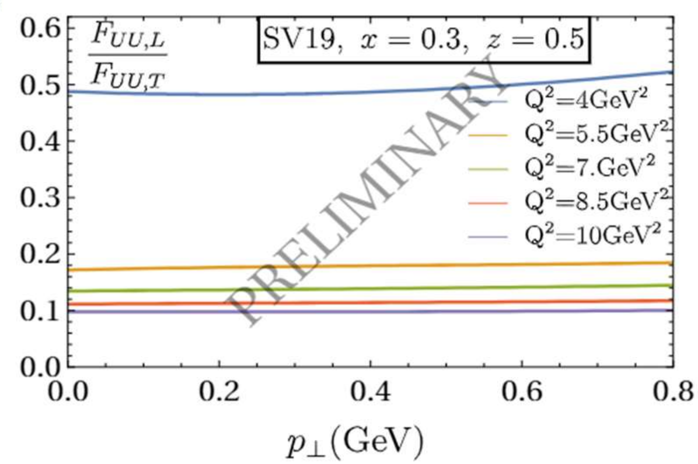
There are several possibilities:

- Twist 2 TMD matching twist 2 PDI
- Twist 3 TMD matching twist 2 PDI
- Twist 2 TMD matching twist 3 PDI
- Expected mismatch
- Twist 4 TMD matching twist 2 PDF?

A. Bacchetta



A. Vladimirov



$$R = \frac{F_{UU,L}}{F_{UU,T}}$$

→ Contributes everywhere,
→ we know nothing!!!

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2} = \frac{2\pi\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\left\{2\pi F_{UU,T}(x,z,P_{h\perp}^2,Q^2) + \varepsilon\,2\pi F_{UU,L}(x,z,P_{h\perp}^2,Q^2)\right\}$$

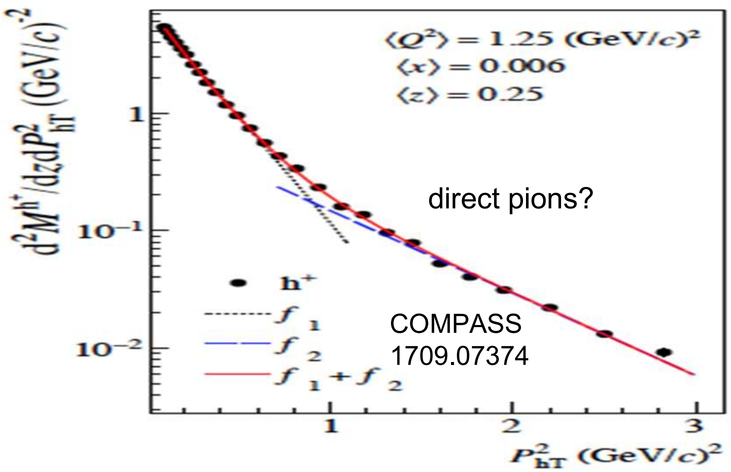
$$\frac{d\sigma}{dx\,dy\,dz} = \frac{4\pi\alpha^2}{x\,y\,Q^2}\frac{y^2}{2\,(1-\varepsilon)}\left\{F_{UU,T}(x,z,Q^2) + \varepsilon\,F_{UU,L}(x,z,Q^2)\right\}$$

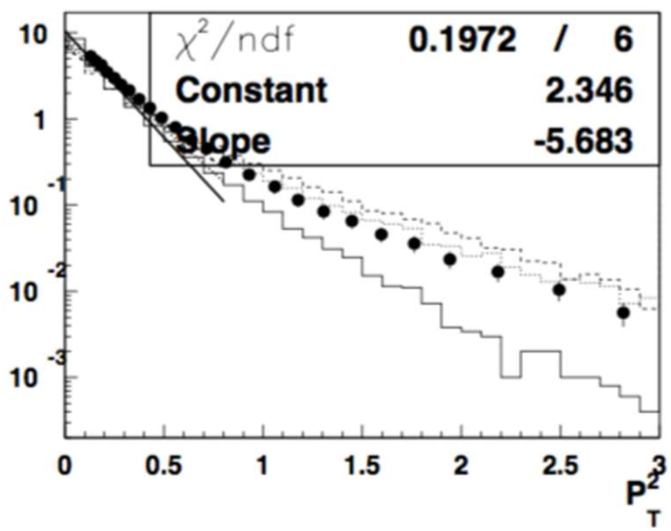
$F_{UU,L}$ tends to stay large even at Q^2>100GeV^2 !!!
$F_{UU,L}$ /$F_{UU,T}$ ~ 0.2 at P_T=0.4 → $F_{UU,L}$ /$F_{UU,T}$ >1 at P_T=1.0 GeV

What about
P_T-dependence ???

Dihadrons: key to hadronization?

Origin of non-Gaussian tails



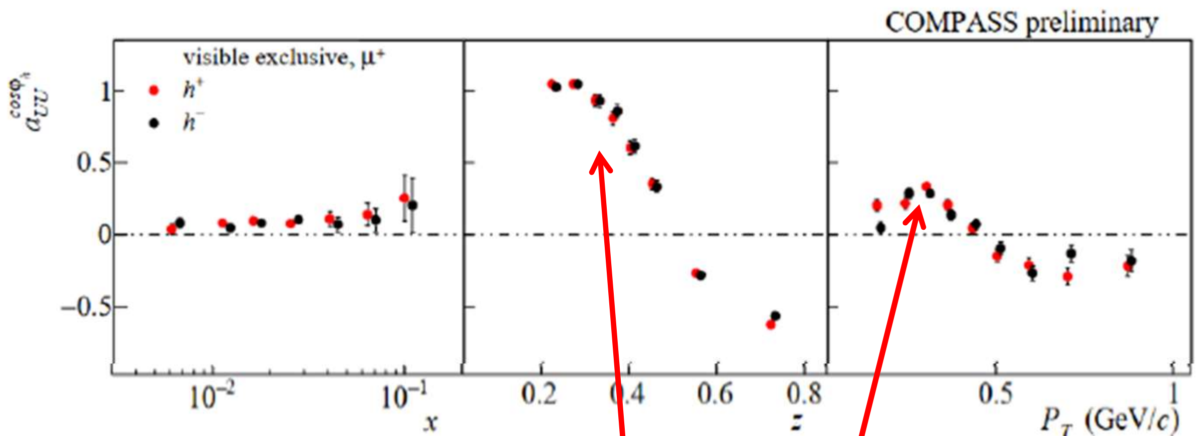


1) the "real" multiplicity may be lower with most hadrons produced from struck quark with large z, and low z fraction filled by VM decay pions
   - intrinsic k_T may be higher
   - the z-dependence enhanced at large z (may be tuned better to describe single and di-hadron distributions)
   - contributions to pions from target fragmentation may be less relevant

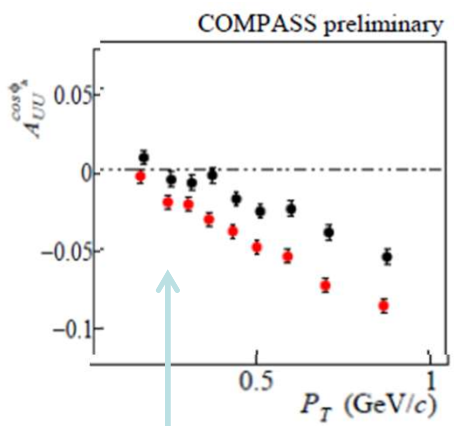
2) Combined increase of average transverse momentum and fraction of VMs allows description of non Gaussian tails at large P_T indicating most hadrons come from TMD region

COMAPASS multiplicities and cosine modulations

Moretti et al→ COMPASS

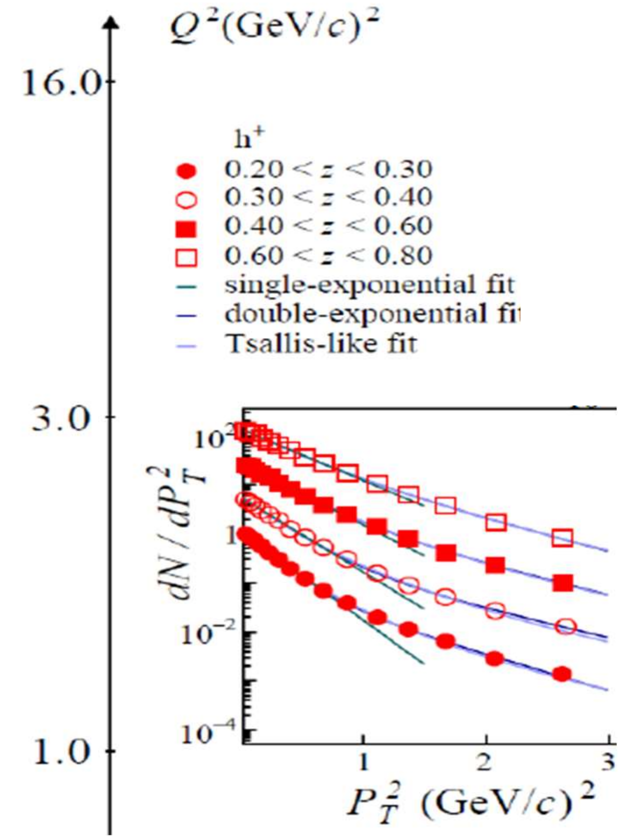


Negative cos of ρ^0 converts to positive for low P_T pions (sign flip ~z=0.5)



Indication of dominant VM contributions in the inclusive hadron samples, in particular at low P_T, critical for understanding of the QCD dynamics

ρ0–decay pions mess up linear dependence at low P_T



Theory is not able to explain the large P_T behavior of pion multiplicities !!!

Trnaverse & Longitudinal photons

Structure function	γ^* helicity	prefactor	low-P_{hT} twist	low-P_{hT} PDF	high-P_{hT} calculation twist	order	power	JLab	EIC
$F_{UU,T}$	TT	1	2	f_1	2	α_s	$1/P_{hT}^2$	+	+
$F_{UU,L}$	LL	ϵ	4		2	α_s	$1/Q^2$	+	=
$F_{UU}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$h,\ f^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	=
$F_{UU}^{\cos 2\phi_h}$	TT	ϵ	2	$h_1^\perp$	2	α_s	$1/Q^2$ [*]	+	+
$F_{LU}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$e,\ g^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	−
$F_{UL}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$h_L,\ f_L^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	=
$F_{UL}^{\sin 2\phi_h}$	TT	ϵ	2	$h_{1L}^\perp$	2	α_s^2	$1/Q^2$ [*]	+	=
F_{LL}	TT	$\sqrt{1-\epsilon^2}$	2	g_1	2	α_s	$1/P_{hT}^2$	+	=
$F_{LL}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$e_L,\ g_L^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	−
$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	TT	1	2	$f_{1T}^\perp$	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	LL	ϵ	4		3	α_s	$1/(Q^2P_{hT})$	+	−
$F_{UT}^{\sin(\phi_h+\phi_S)}$	TT	ϵ	2	h_1	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT}^{\sin(3\phi_h-\phi_S)}$	TT	ϵ	2	$h_{1T}^\perp$	3	α_s	$1/(Q^2P_{hT})$ [*]	=	−
$F_{UT}^{\sin\phi_S}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$f_T,\ h_T,\ h_T^\perp$+ tw. 2	3	α_s	$1/(QP_{hT}^2)$	+	=
$F_{UT}^{\sin(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$f_T^\perp,\ h_T,\ h_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(\phi_h-\phi_S)}$	TT	$\sqrt{1-\epsilon^2}$	2	g_{1T}	3	α_s	$1/P_{hT}^3$	+	=
$F_{LT}^{\cos\phi_S}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$g_T,\ e_T,\ e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$g_T^\perp,\ e_T,\ e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−

Very few pure transverse

Impact of Radiative corrections

Proper RC involves the full x-section

$$\sigma^{ehX}_{Rad}(x,y,z,P_T,\phi,\phi_S) \to \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

Simplest rad. correction

$$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$$

$$\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&+ \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&+ S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&+ \varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}$$

- L/T interference
- Not suppressed at high energies
- Measured to be huge in exclusive limit ~100%
- May couple to radiative cos\phi producing bck SSAs

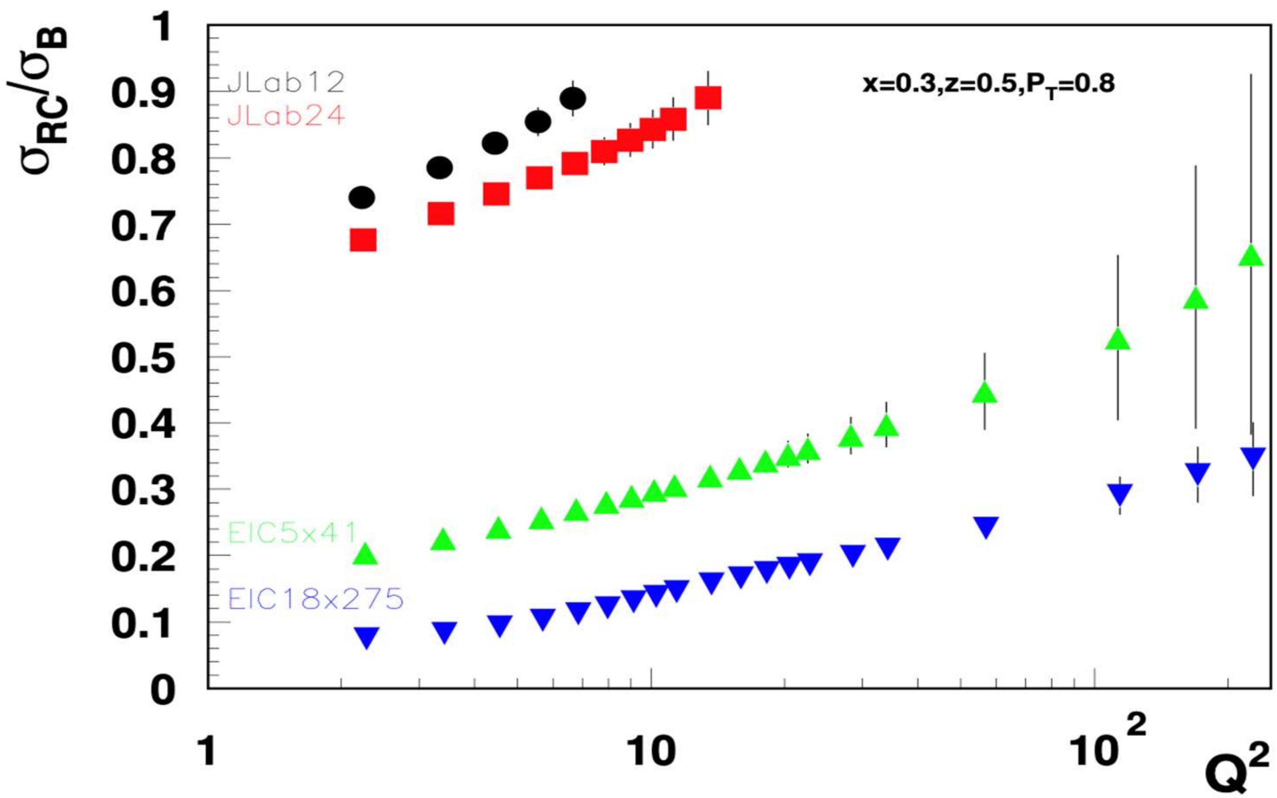
Ex. Correction to SSA

$$\sigma_0(1 + sS_T\sin\phi_S)R_0(1 + r\cos\phi_h) \to \sigma_0 R_0(1 + sr/2S_T\sin(\phi_h-\phi_S) + sr/2S_T\sin(\phi_h+\phi_S))$$

From JLab to EIC: complementarity

The ratio of radiative cross (σ_{RC}) section to Born (σ_B) in SIDIS

T. Liu et al
JHEP 11 (2021) 157
Gaussian F_{UU} (ϕ_h=0)



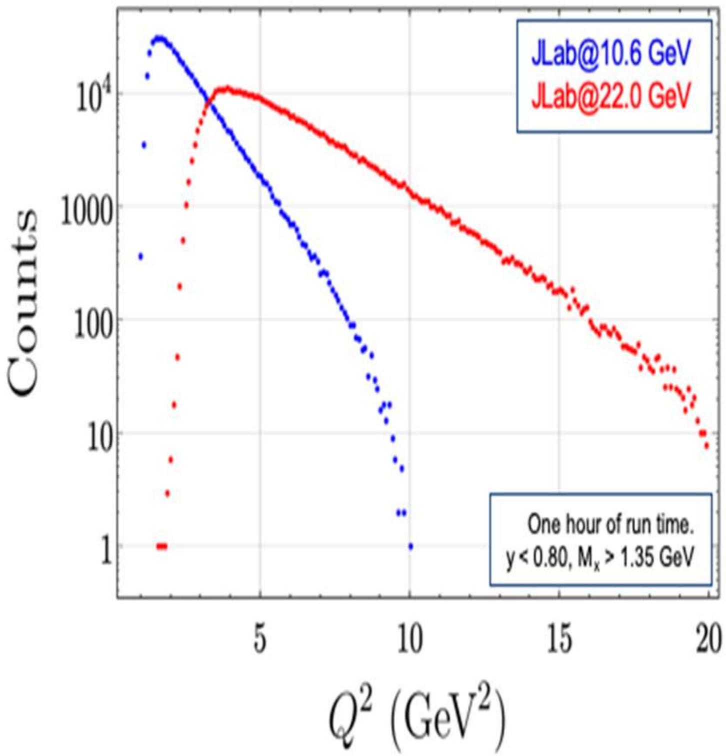
Cross section at low Q^2 suppressed at higher CM energies

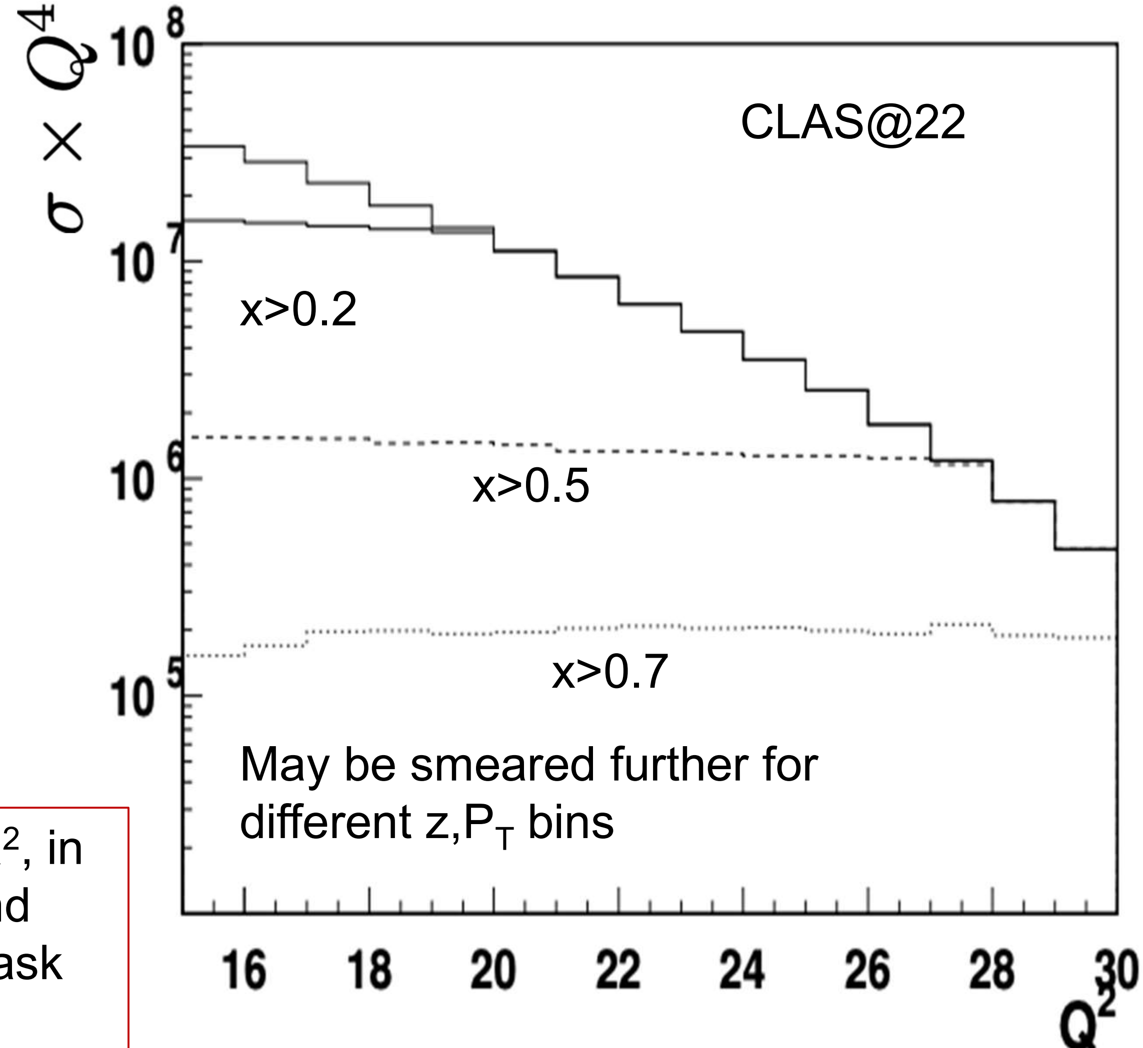
- The radiative effects in SIDIS may be very significant and measurements in multidimensional space at different facilities will be crucial for understanding the systematics in evolution studies.
- Most sensitive to RC will be all kind of azimuthal modulations sensitive to cosines

Validation of the phenomenology needed for credibility of theoretical predictions

Critical for making projections used to build new facilities

Finite energy: Kinematic limitations

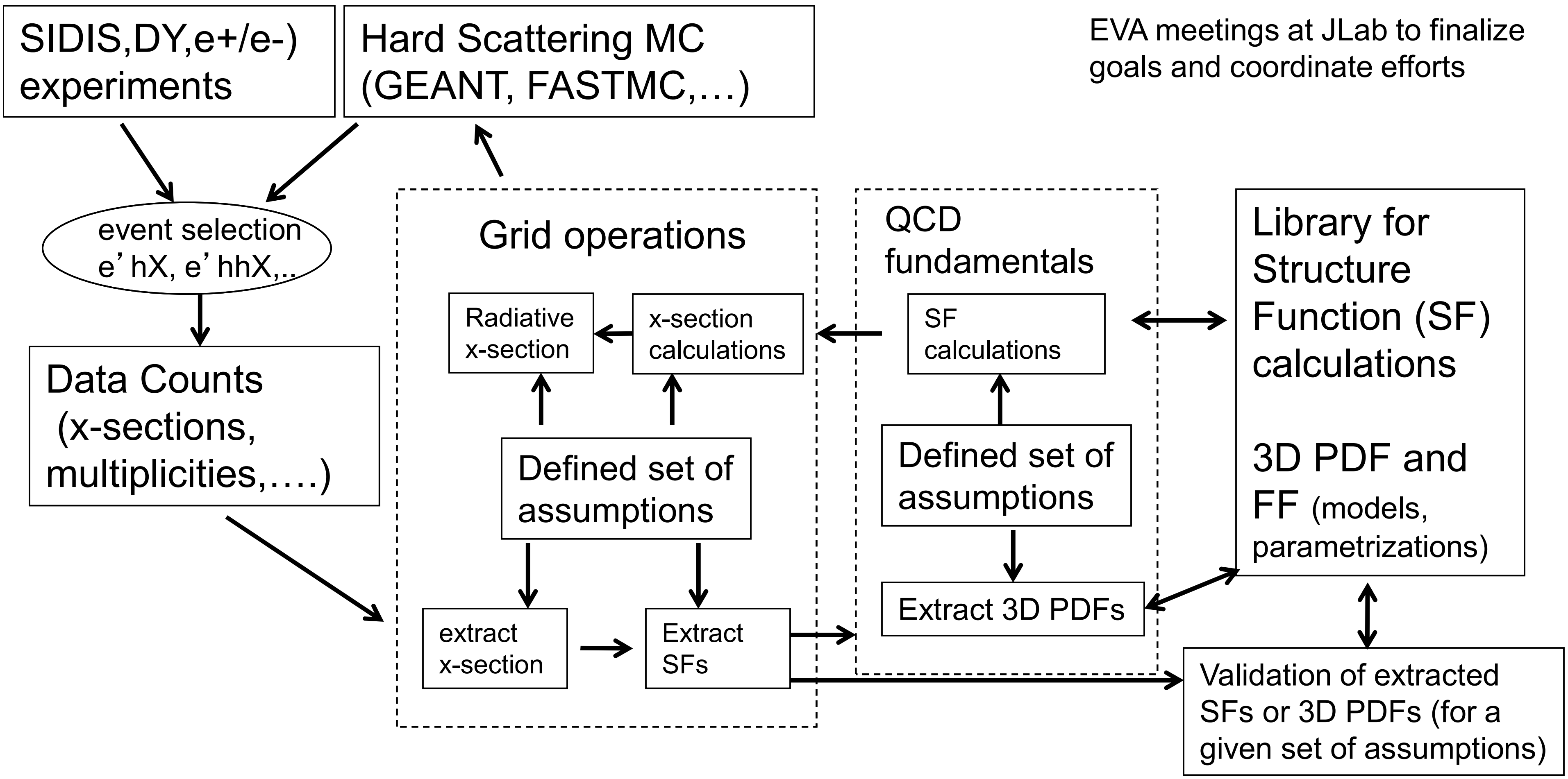




Kinematic correlations, (P_T and Q^2, in particular) due to trivial energy and momentum conservation, may mask the real dependences

- Can be easily accounted

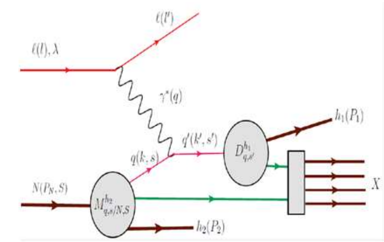
3D PDF Extraction and VAlidation (EVA) framework

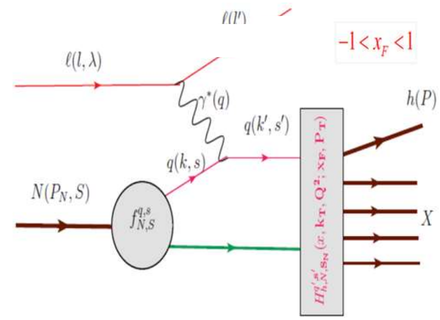


Development of a reliable techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

MC simulations: Why LUND works?

- A single-hadron MC with the SIDIS cross-section where widths of k_T-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.

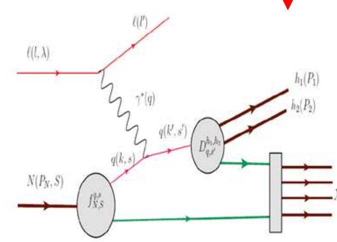


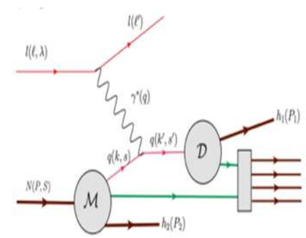


So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

•The hadronization into different hadrons, in particular Vector Mesons is accounted (full kinematics)
•Accessible phase space properly accounted
•The correlations between hadrons, as well a as target and current fragments accounted
•….

subsamples

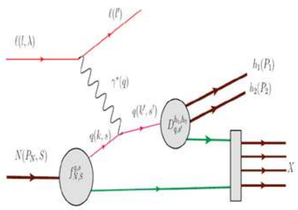




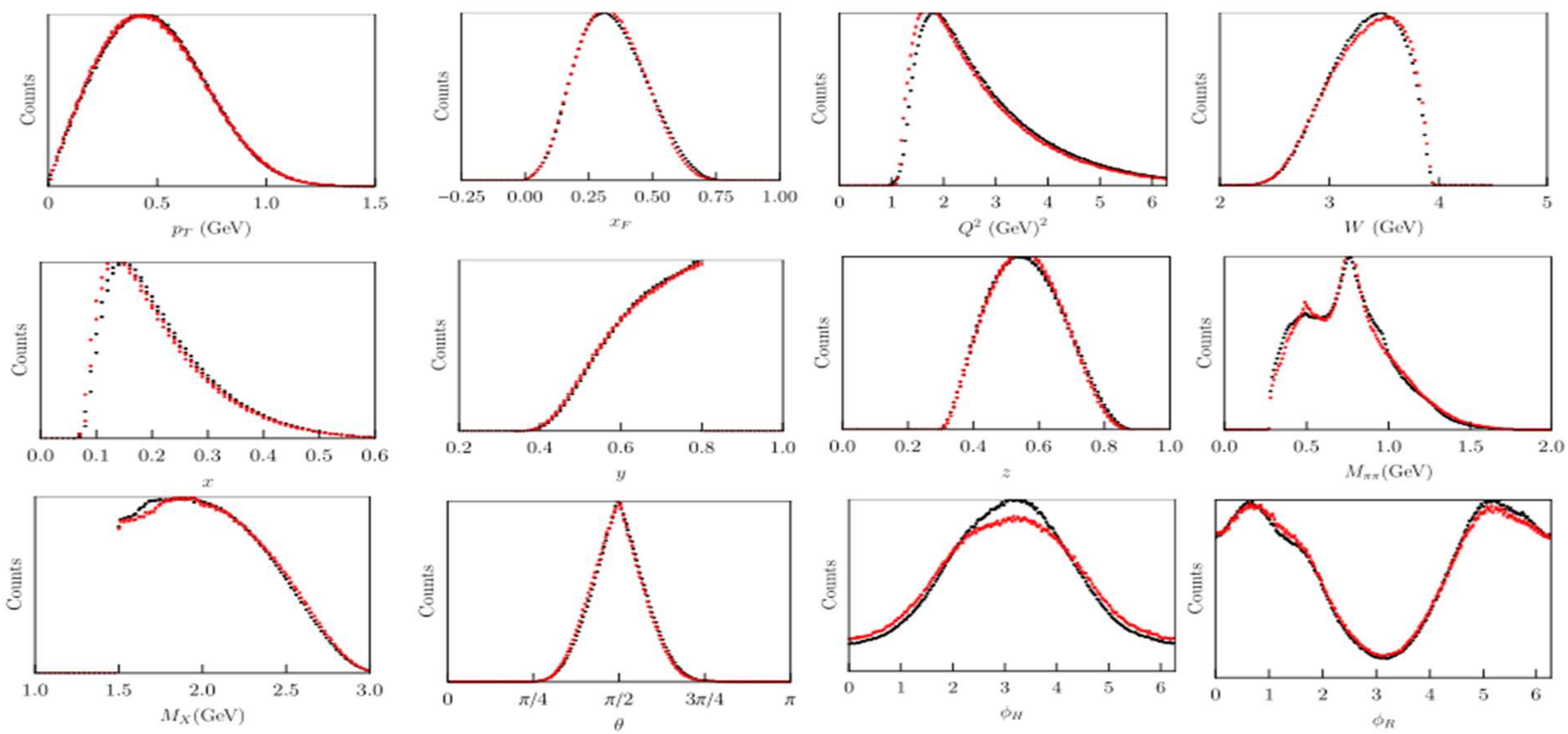
To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

SIDIS ehhX: CLAS12 data vs MC



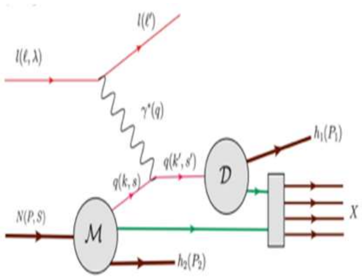
CLAS12 dihadron production ep→ehhX

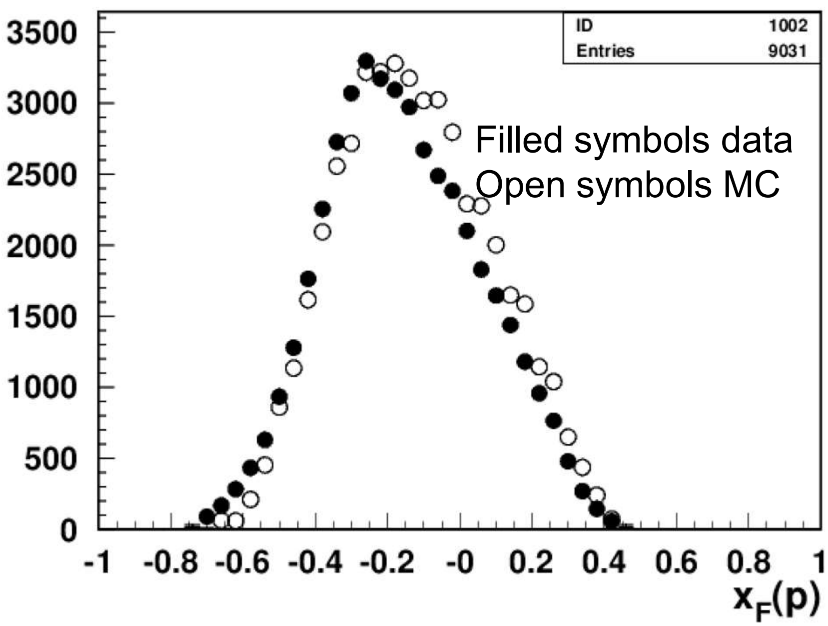


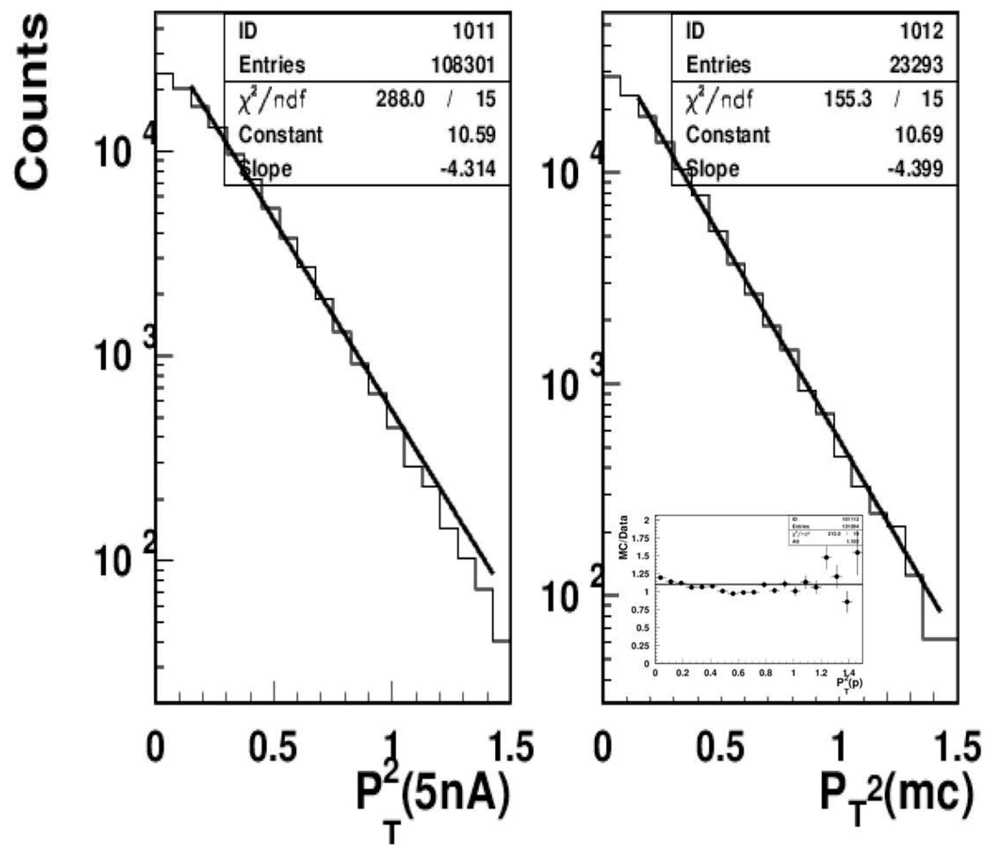
CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters ”default” is in a good agreement with CLAS12 measurements for all relevant distributions

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator



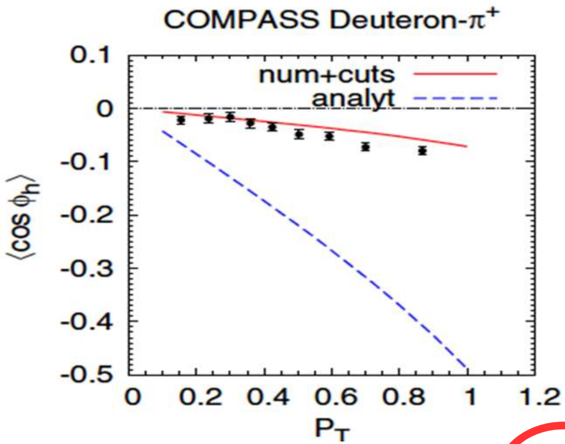


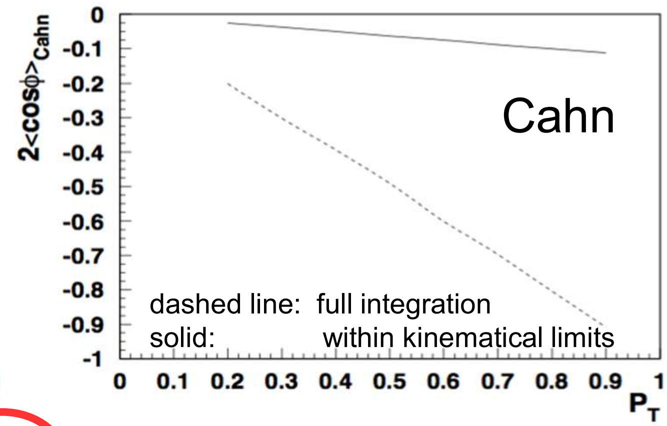


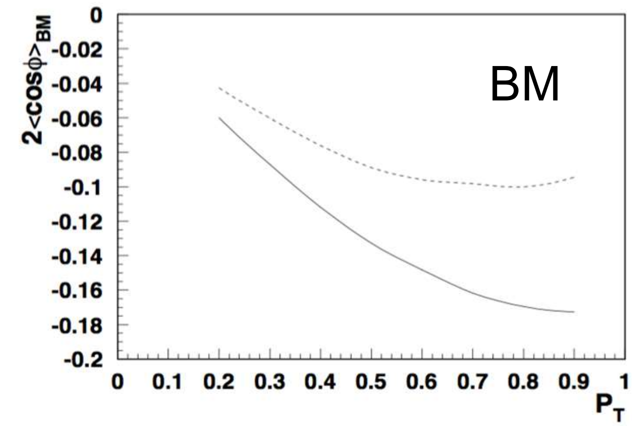
- Kinematic distributions, z,x_F,P_T-distributions of protons, and widths are in good agreement with LEPTO
- TFR may be a valuable source for studies of widths in hadronization
- Expect significantly better separation of TFR and CFR at JLab24

k_T-max effects on observables

M. Boglione, S. Melis & A. Prokudin **Phys. Rev. D 84, 034033 2011**





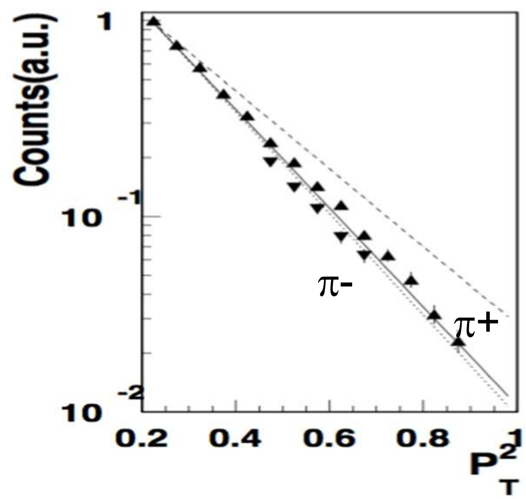


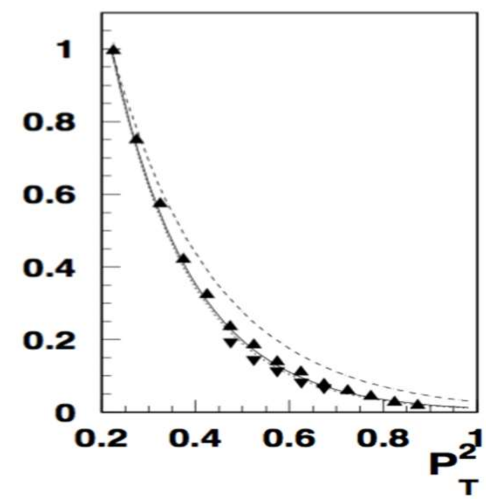
$$\mathcal{C}[w, fD] = x \sum_a e_a^2 \int_0^{k_{\perp max}} k_\perp dk_\perp \int_0^{2\pi} d\phi \, w(k_\perp, p_\perp(k_\perp)) f^a(x, k_\perp^2) \, D^a(z, (P_{h\perp} - z k_\perp)^2)$$

in WW approximation

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q} \mathcal{C}\left[\frac{\hat{h}\cdot p_\perp}{z M_h} \frac{k_\perp^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{h}\cdot k_\perp}{M} z f_1 D_1\right]$$

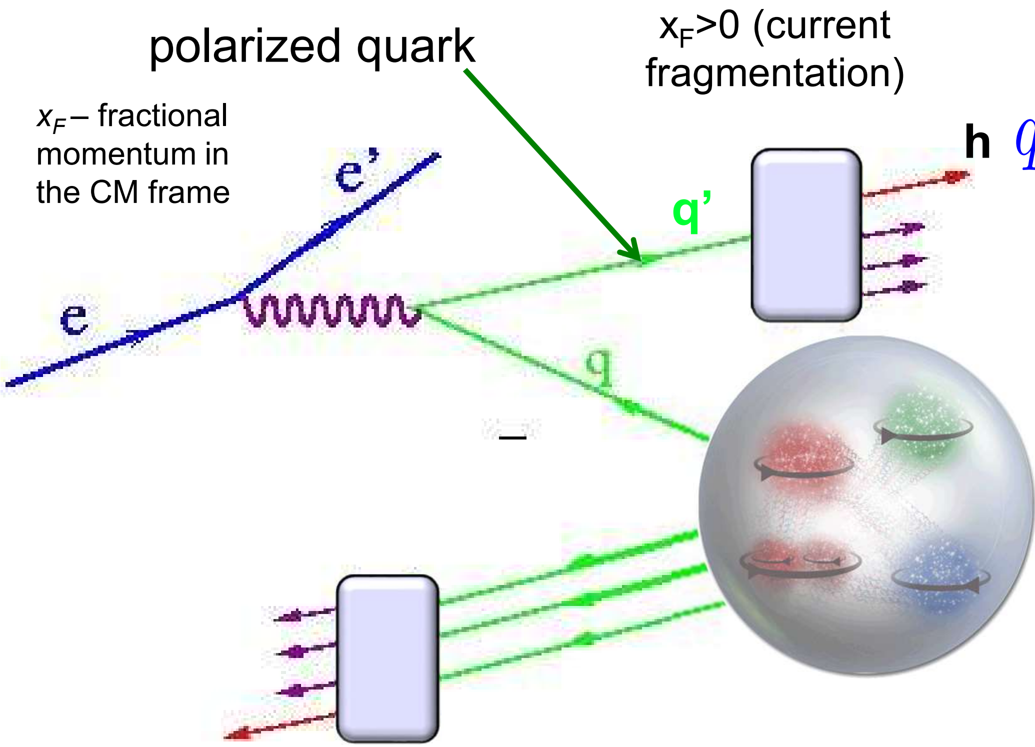
BM contribution seem to be less sensitive to phase space limitations

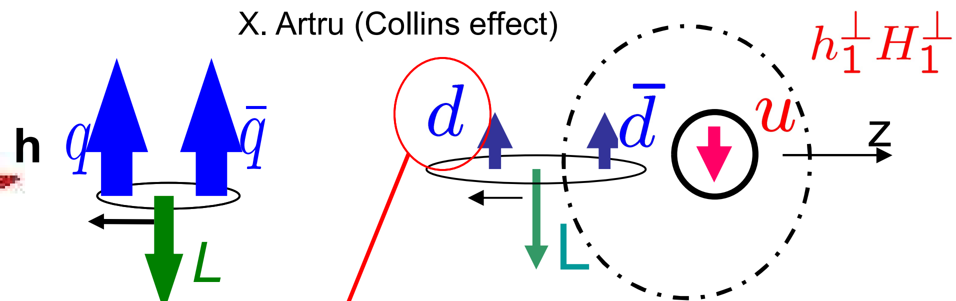


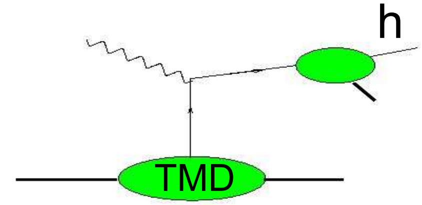


multiplicities are also sensitive to kinematic limitations (phase space)

Hadron production in hard scattering: SIDIS



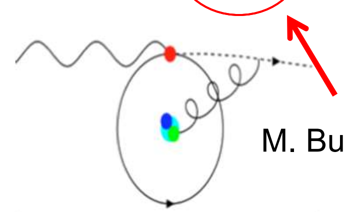




CFR/Current Fragmentation Region
→hadrons produced from struck quark

Transverse Momentum Distributions

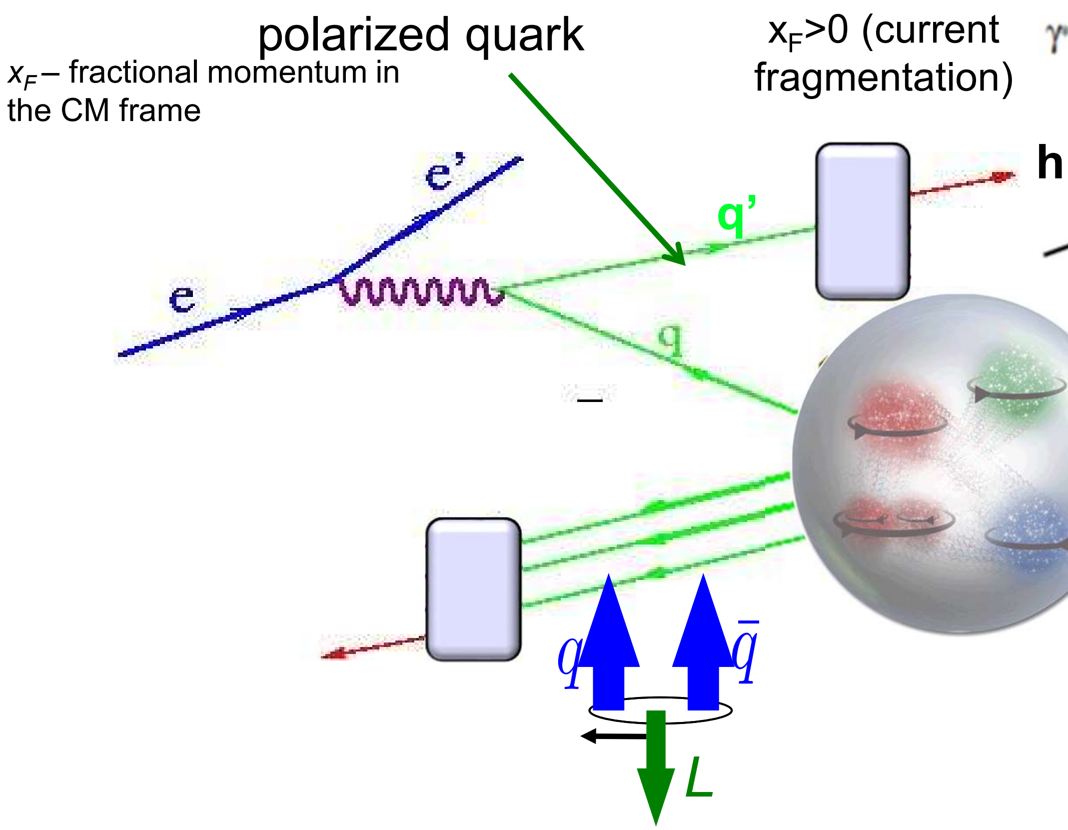
N/q	U	L	T
U	f_1	x	$h_1^\perp$
L	x	g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1\ h_{1T}^\perp$

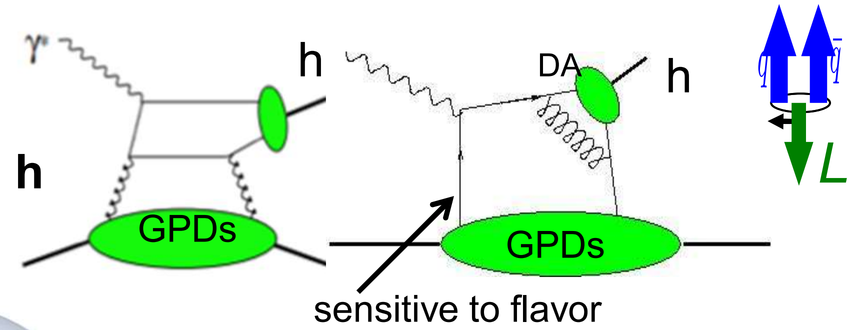


M. Burkardt (Sivers effect)

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles in SIDIS

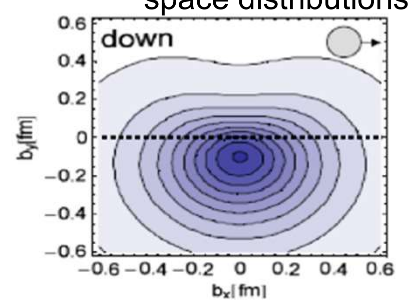
Exclusive hadron production in hard scattering





N/q	U	L	T
U	H	X	$\mathcal{E}_T$
L	X	$\widetilde{H}$	X
T	E	X	$H_T, \widetilde{H}_T$

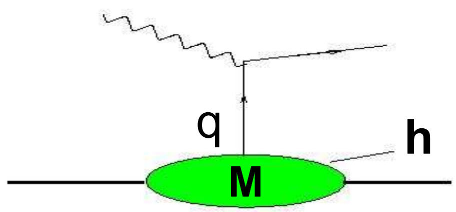
space distributions



Current Fragmentation Region
→ nucleon and transition GPDs, access to properties like "pressure",….

Correlations of the spin of the target or/and the momentum and the spin of quarks define the azimuthal distributions of produced particles in hard exclusive production of hadrons

Hadron production in hard scattering: SIDIS

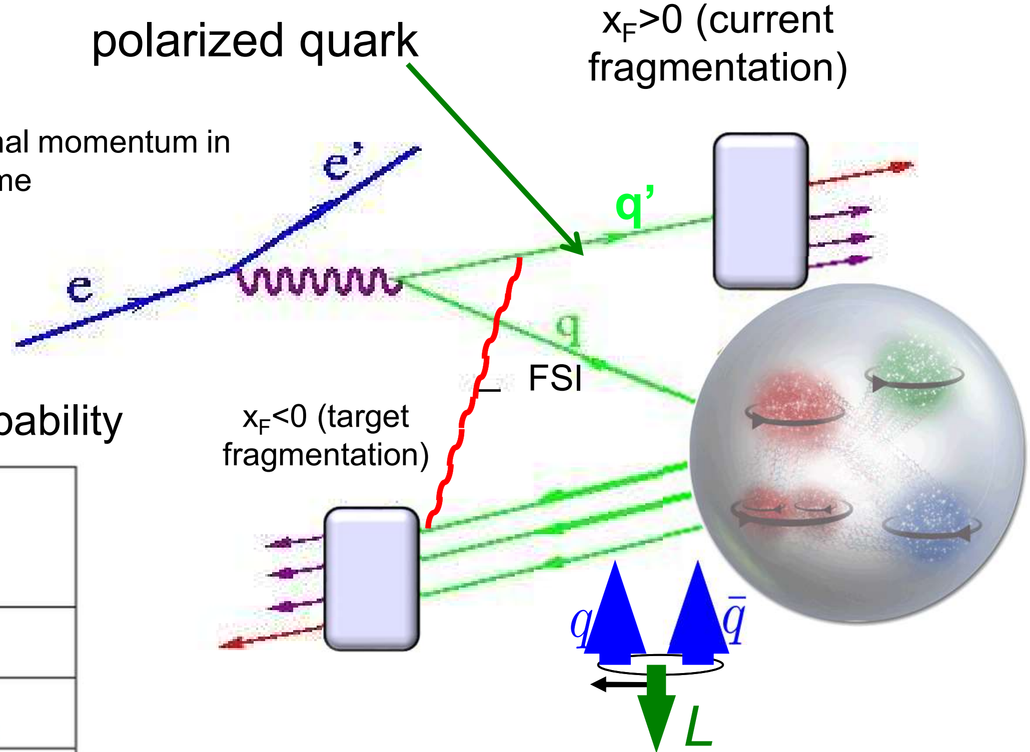


Fracture Function→ conditional probability

N \ q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

Anselmino, Barone, Kotzinian

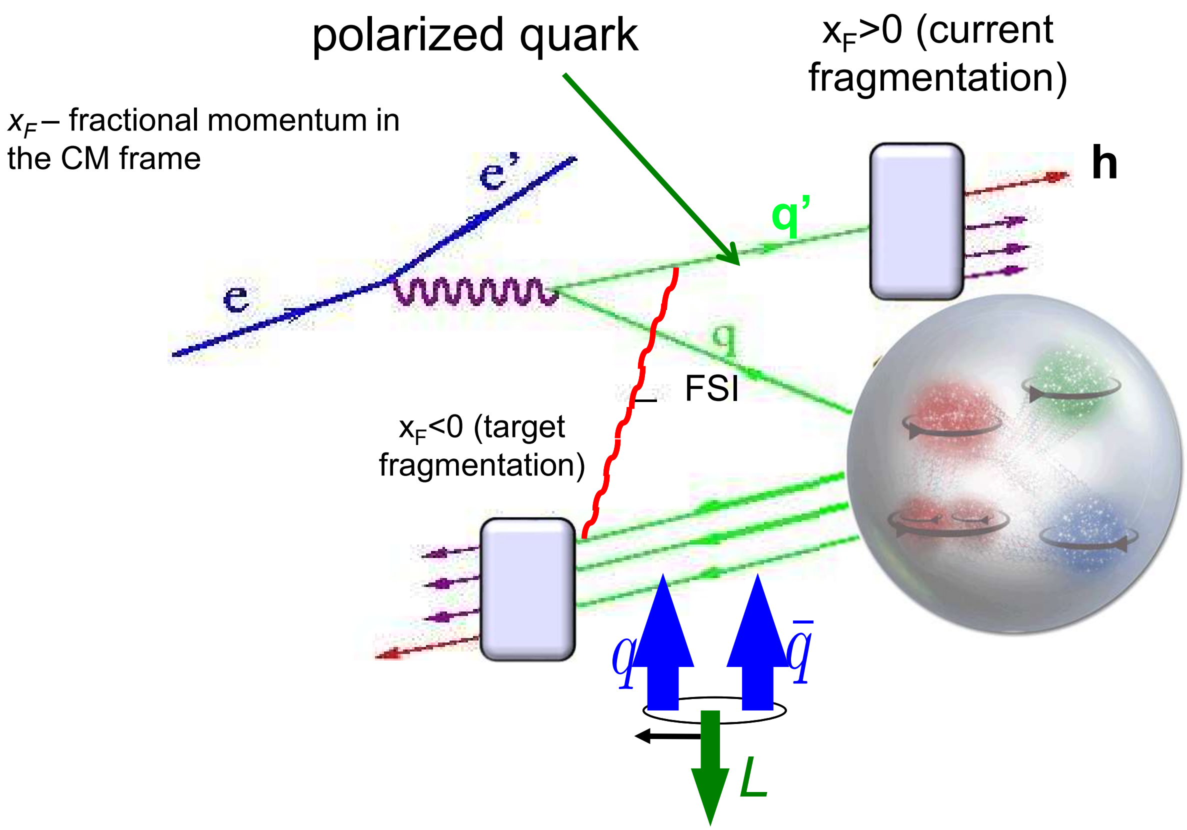
x_F – fractional momentum in the CM frame



TFR/Target Fragmentation Region
→hadrons produced from remnant, access to entanglement,…

Correlations of the struck quark and the target remnant combined with final state interactions define the azimuthal distributions of particles in the backward hemisphere (TFR), providing complementary information on nucleon structure

Exclusive hadron production in hard scattering



Quark qluon correlations described by higher twist 3D PDFs

Twist3 GPDs

N \ q	U	L	T
U	$\mathcal{E}_{2T}$	$\mathcal{E}'_{2T}$	$\mathcal{H}_2, \mathcal{H}'_2$
L	$\tilde{\mathcal{E}}_{2T}$	$\tilde{\mathcal{E}}'_{2T}$	$\tilde{\mathcal{H}}_2, \tilde{\mathcal{H}}'_2$
T	$\mathcal{H}_{2T}, \tilde{\mathcal{H}}_{2T}$	$\mathcal{H}'_{2T}, \tilde{\mathcal{H}}'_{2T}$	$\mathcal{E}_2, \tilde{\mathcal{E}}_2, \mathcal{E}'_2, \tilde{\mathcal{E}}'_2$

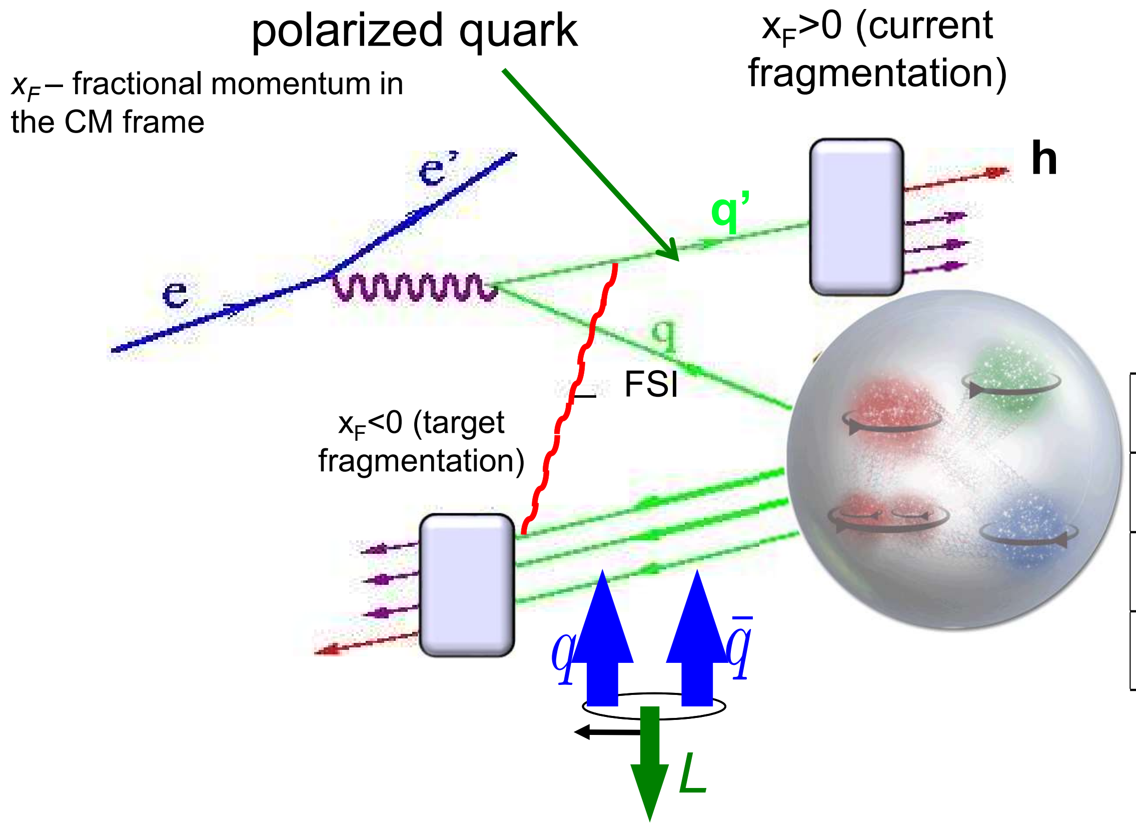
OAM

$$-\int dx\, x\, \tilde{E}_{2T}(x,0,0) = L_z^q + 2S_z^q$$

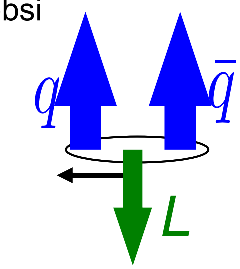
Lorce&Pasquini, arXiv:1208.3065

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles in exclusive limit

Hadron production in hard scattering: SIDIS



X. Artru & Z. Belghobsi



Higher Twist TMDs

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

Quark gluon correlations described by higher twist 3D TMD PDFs, access to details of the QCD dynamics "forces",….

Final state interactions and quark-gluon correlations give rise to detectable spin-azimuthal modulations of produced particles

CLAS12: Mass corrections to x_B and z_h

$$x_N = -\frac{q^+}{P^+} = \frac{2x_{Bj}}{1+\sqrt{1+\frac{4x_{Bj}^2 M^2}{Q^2}}}$$

$$z_N = \frac{Q^4 x_N z_h \left(1 \pm \sqrt{1 - \frac{4M^2 M_B^2 x_{Bj}^2 (Q^4 + x_N^2 M^2 \mathbf{q}_T^2)}{Q^8 z_h^2}}\right)}{2x_{Bj}(Q^4 + x_N^2 M^2 \mathbf{q}_T^2)}$$