U.S. DEPARTMENT OF ENERGY | Office of Science

TOWARDS TRANSVERSE MOMENTUM DEPENDENCE IN DISTRIBUTIONS AND FRAGMENTATION

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Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- Transverse Momentum Dependence: 3D Distributions

- Transverse Momentum Dependence: 3D Fragmentation

- The emergence of hadrons
    - Lessons from the 70's
    - To disembroil the Lund string

- Towards a QM description of the final state
    - Balancing the transverse momentum – candles of space-time
    - The Collins Function – candle of DχSB
    - Balancing the spin
    - Creating polarization from nothing

- Summary

TMDs and 3D FFs

Functions surviving on integration over Transverse Momentum

The **others** are sensitive to ***intrinsic k_T*** in the nucleon & in the fragmentation process

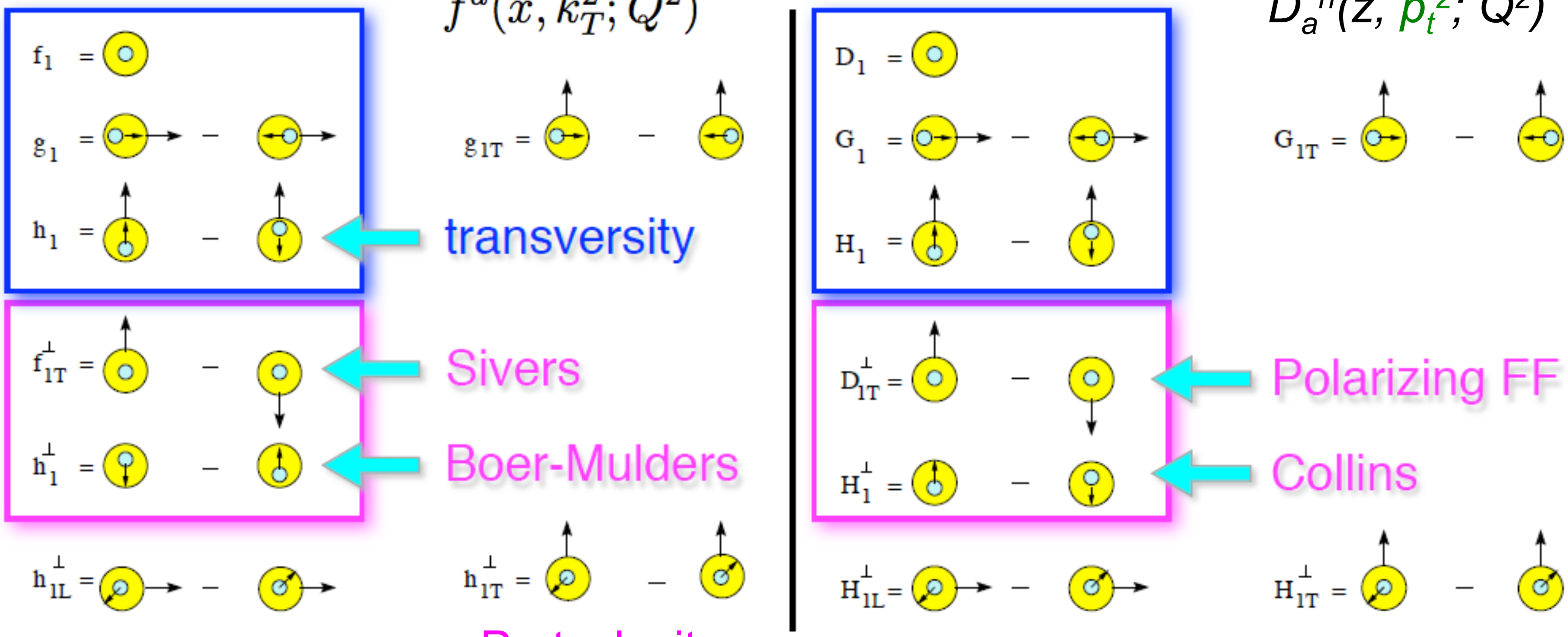
Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions

$f^a(x, k_T^2; Q^2)$

Fragmentation Functions

$D_a^h(z, p_t^2; Q^2)$



transversity

Sivers

Boer-Mulders

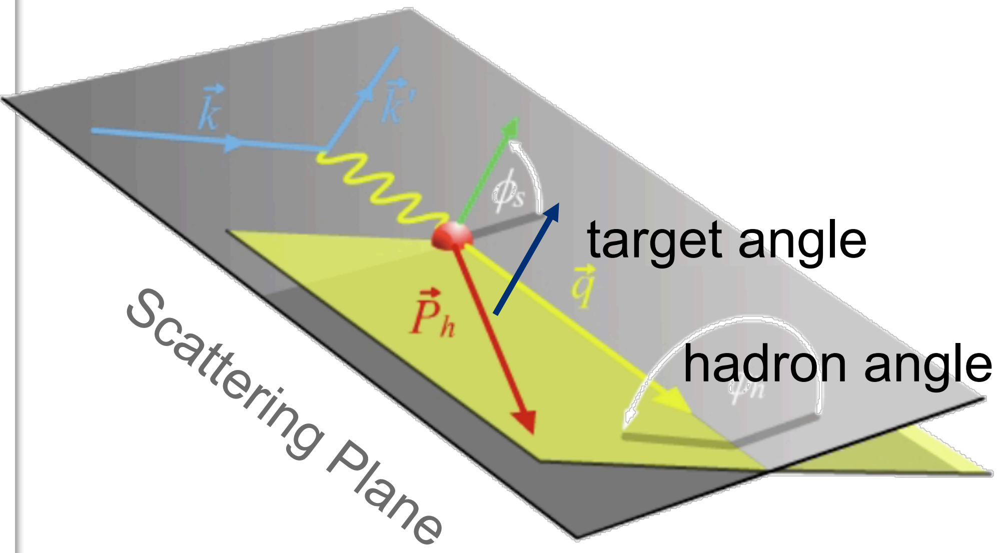
Polarizing FF

Collins

Pretzelosity

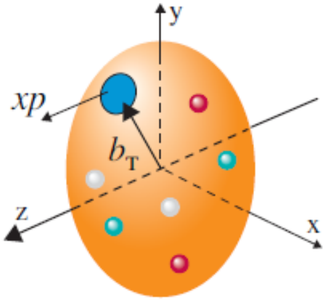
TMDs Accessible through Semi-Inclusive Physics

- Separate Sivers and Collins effects



Naturally, two scales:
- High Q: localized probe to "see" quarks and gluons
- Low P_T: sensitive to confining scale to "see" their confined motion

+ Theory input: TMD QCD factorization
TMD QCD evolution



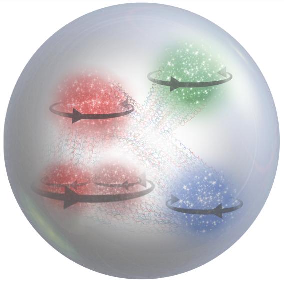
- **Sivers** angle, effect in distribution function: $(\phi_h - \phi_s)$

Or other combinations: Pretzelosity: $(3\phi_h - \phi_s)$

- **Collins** angle, effect in fragmentation function: $(\phi_h + \phi_s)$

Pay attention to this one!

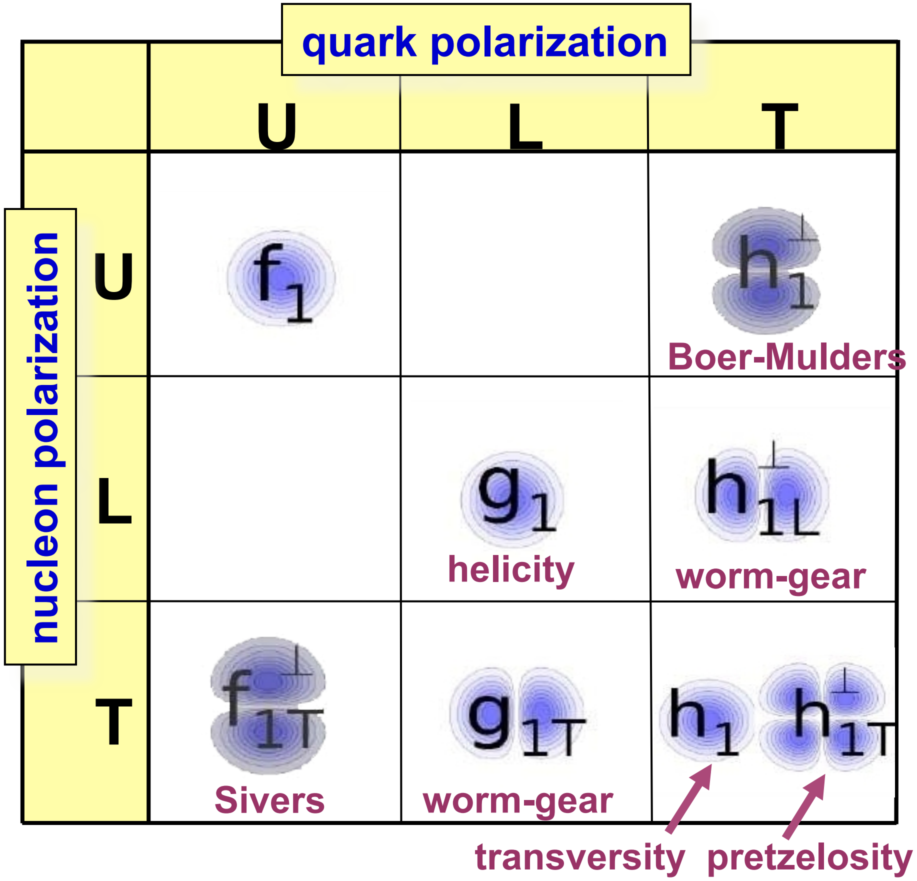
3D Distributions/TMDs



$$f^a(x, k_T^2; Q^2)$$

Ex. TMD PDF for a given combination of parton and nucleon spins

Understanding of the 3D structure of nucleon requires studies of spin and flavor dependence of quark transverse momentum and space distributions



quark polarization

nucleon polarization

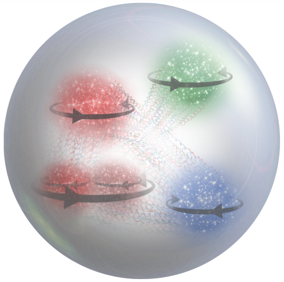
	U	L	T
U	f_1		$h_1^\perp$ **Boer-Mulders**
L		g_1 **helicity**	$h_{1L}^\perp$ **worm-gear**
T	$f_{1T}^\perp$ **Sivers**	g_{1T} **worm-gear**	h_1 $h_{1T}^\perp$

transversity **pretzelosity**

$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$

$$f^a(x, k_T^2; Q^2)$$

3D Distributions/TMDs



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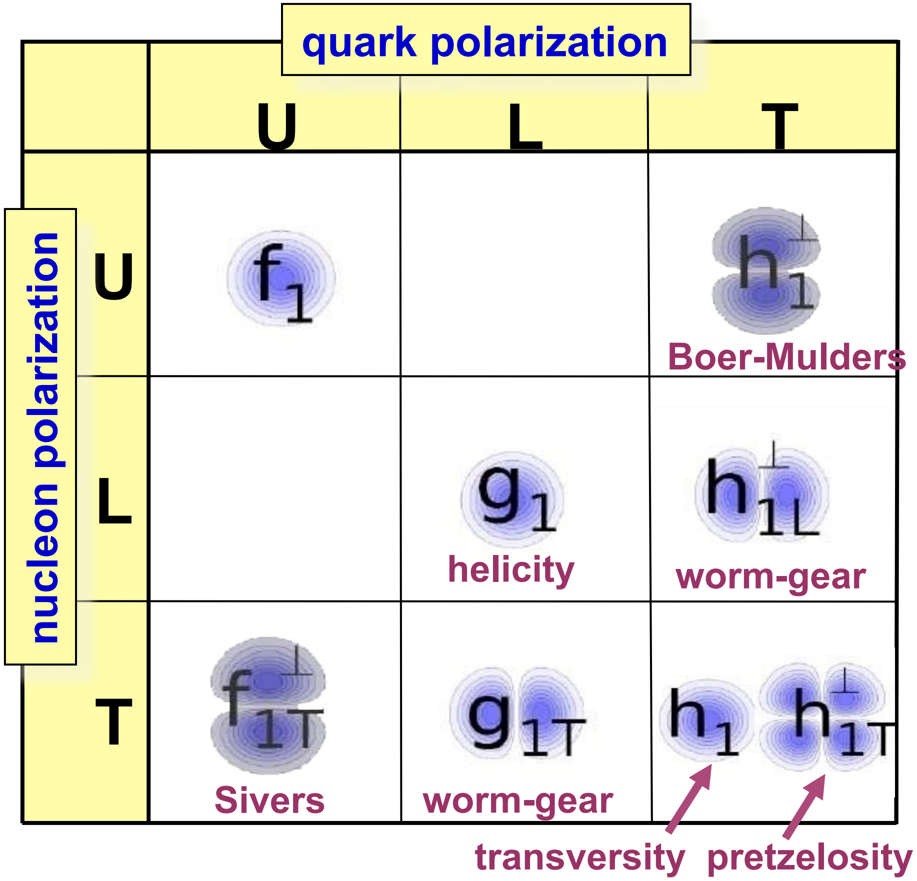


quark polarization

nucleon polarization

	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 $h_{1T}^\perp$

transversity pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

Hall C SIDIS Program – basic (e,e'π) cross sections

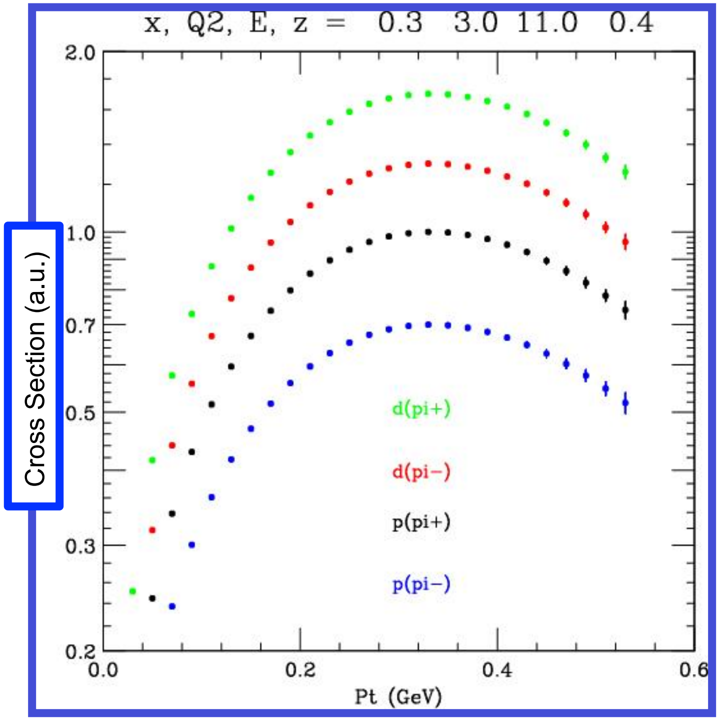
Goal: Measure the basic SIDIS cross sections of **π^+, π^-, π^0 (and K$^+$)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

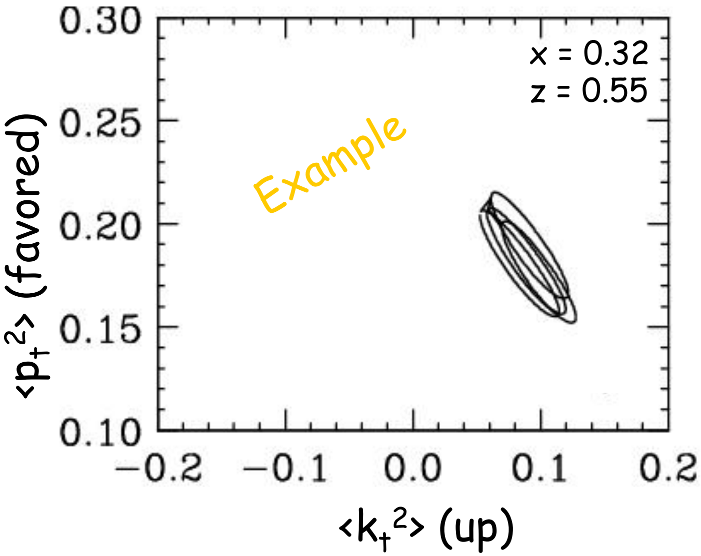
$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

$\pi^{+/-}$

(Kinematics II, z = 0.4 bin only)





Basic precision cross section measurements:

- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain Q^2 dependence & TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

π^0 with Neutral-Particle Spectrometer (NPS)

Hall C SIDIS Program (typ. x/Q^2 ~ constant)

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS; w. typical z range 0.3-0.65

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

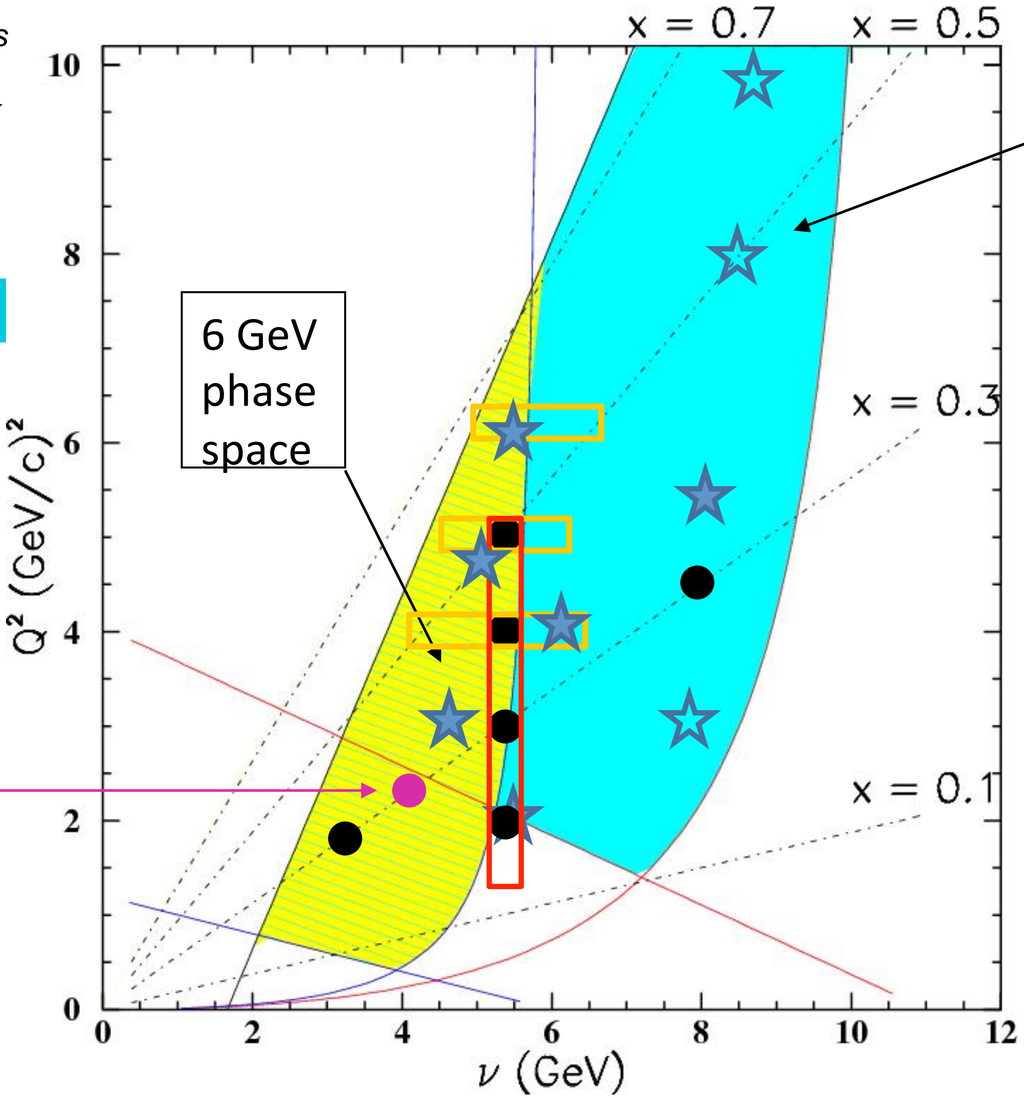
E12-13-007

★ Neutral pions:

Scan in (x,z,P_T)
Overlap with
E12-09-017 &
E12-09-002

☆ Parasitic with
E12-13-010

E00-108
(6 GeV)



6 GeV phase space

11 GeV phase space

Charged pions:

▯ E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

● E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2
at fixed x

▭ E12-09-002
+ scans in z

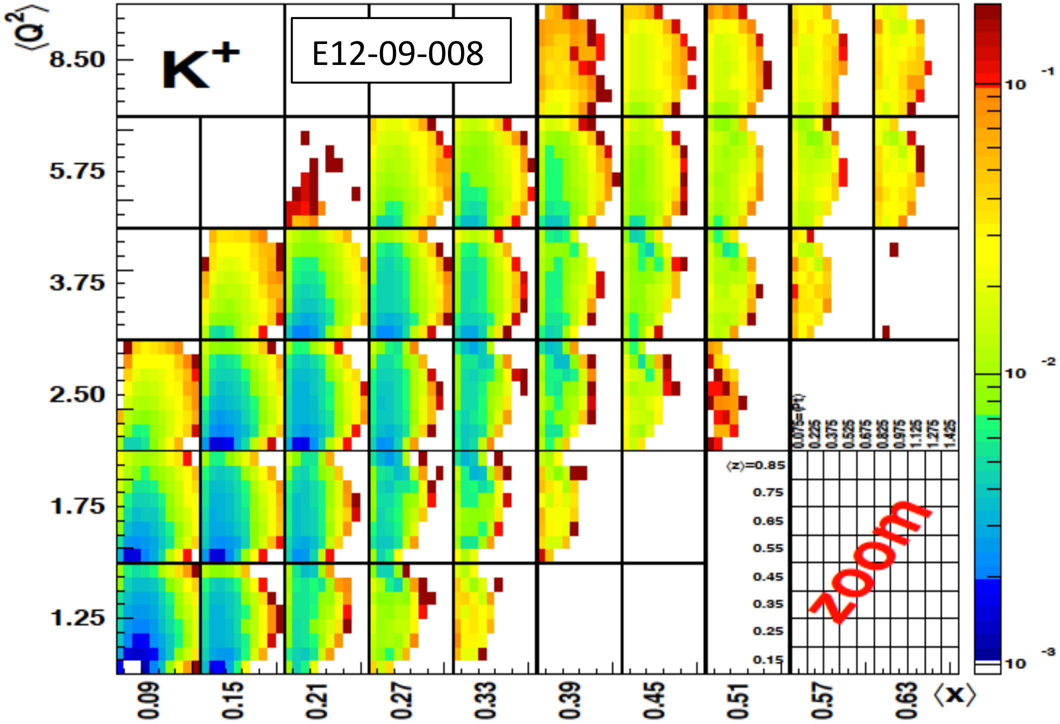
SIDIS π/K on unpolarized protons/deuterons

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

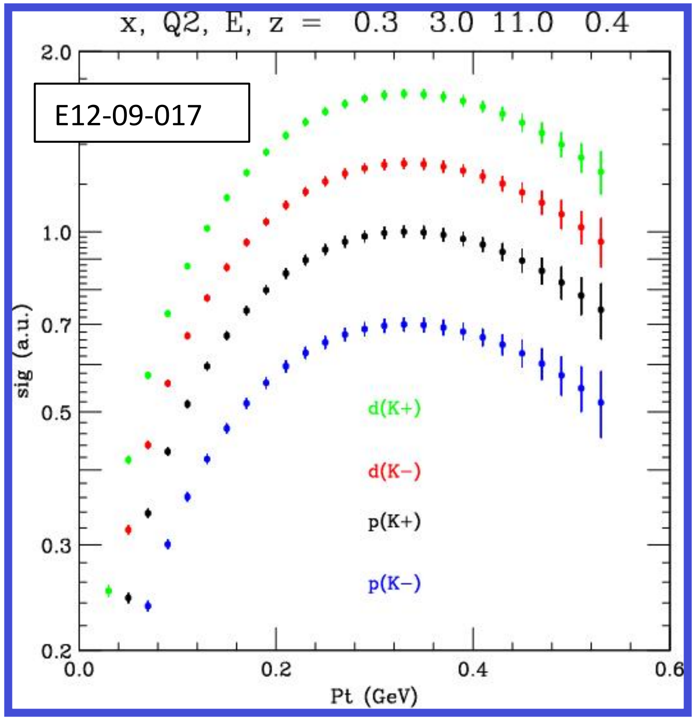
E12-06-112

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\Big\},$$

Kaons



(CLAS12)

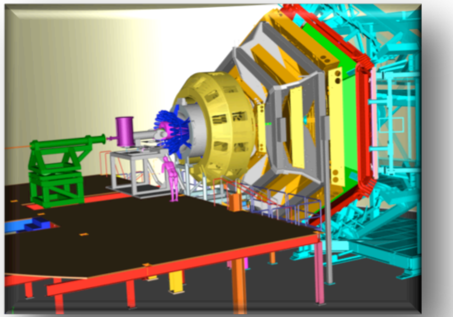


(Hall C, Kinematics II, z = 0.4 bin only)

Together stronger: SIDIS Studies with 12 GeV

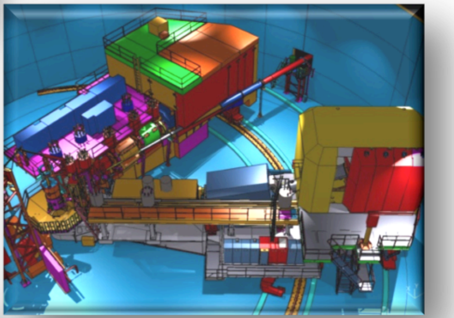
- **CLAS12 in Hall B**

  General survey, medium lumi



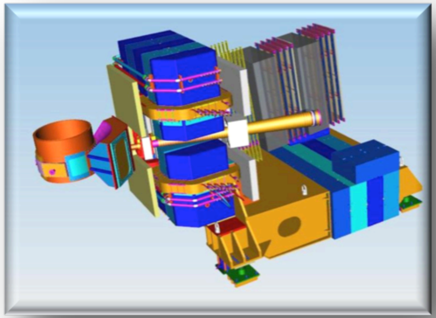
- **SHMS, HMS, NPS in Hall C**

  L-T studies, precise $\pi^+/\pi^-/\pi^0$ ratios



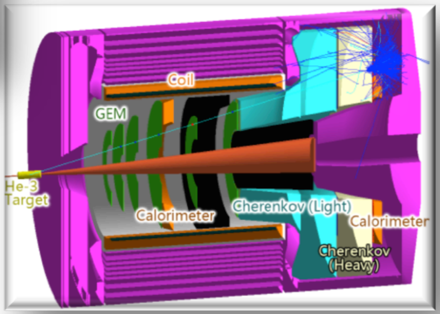
- **SBS in Hall A**

  High x, High Q^2, 2-3D



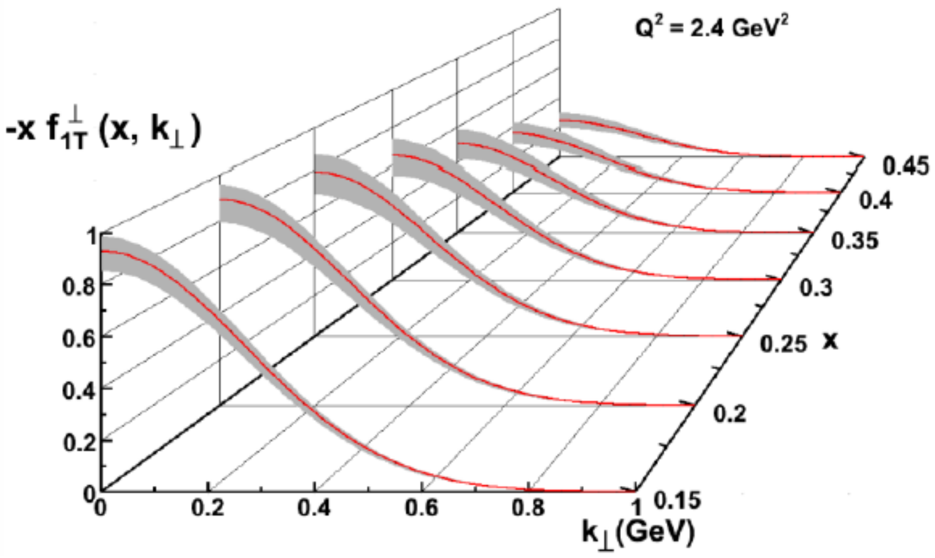
- **SOLID in Hall A**

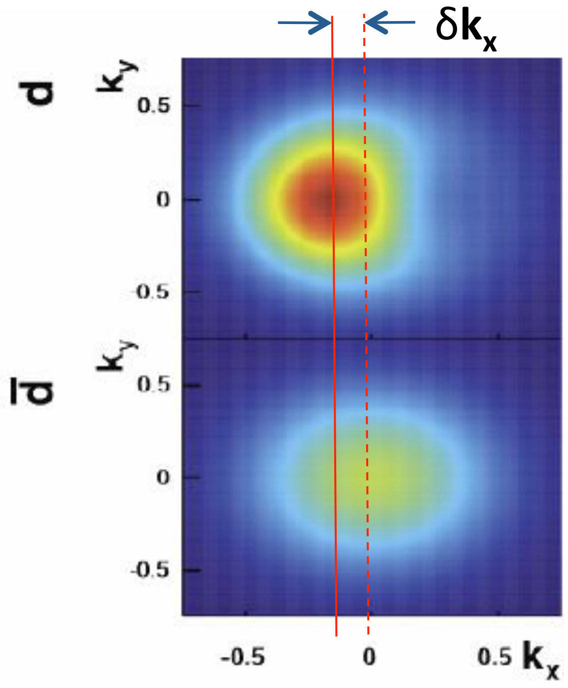
  High lumi and acceptance – 4D



Momentum Tomography with TMDs

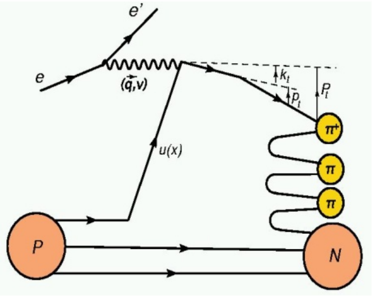
Sivers function for d-quarks extracted from model simulations with a transverse polarized ^{3}He target.





d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $\mathbf{k_x}$. A non-zero $\delta\mathbf{k_x}$ value requires a non-zero orbital angular momentum.

3D Fragmentation



$D_h^a(z, p_t^2; Q^2)$

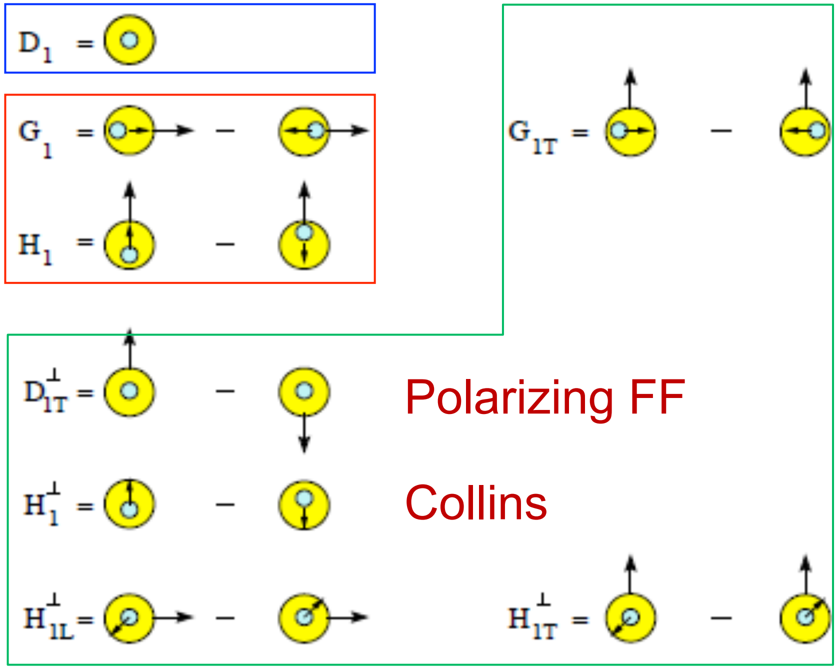
Ex. p_t-dependent FF for a given combination of parton and hadron species

Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.

Unpolarized

Spin-Spin Correlations

Spin-Momentum Correlations



Polarizing FF

Collins

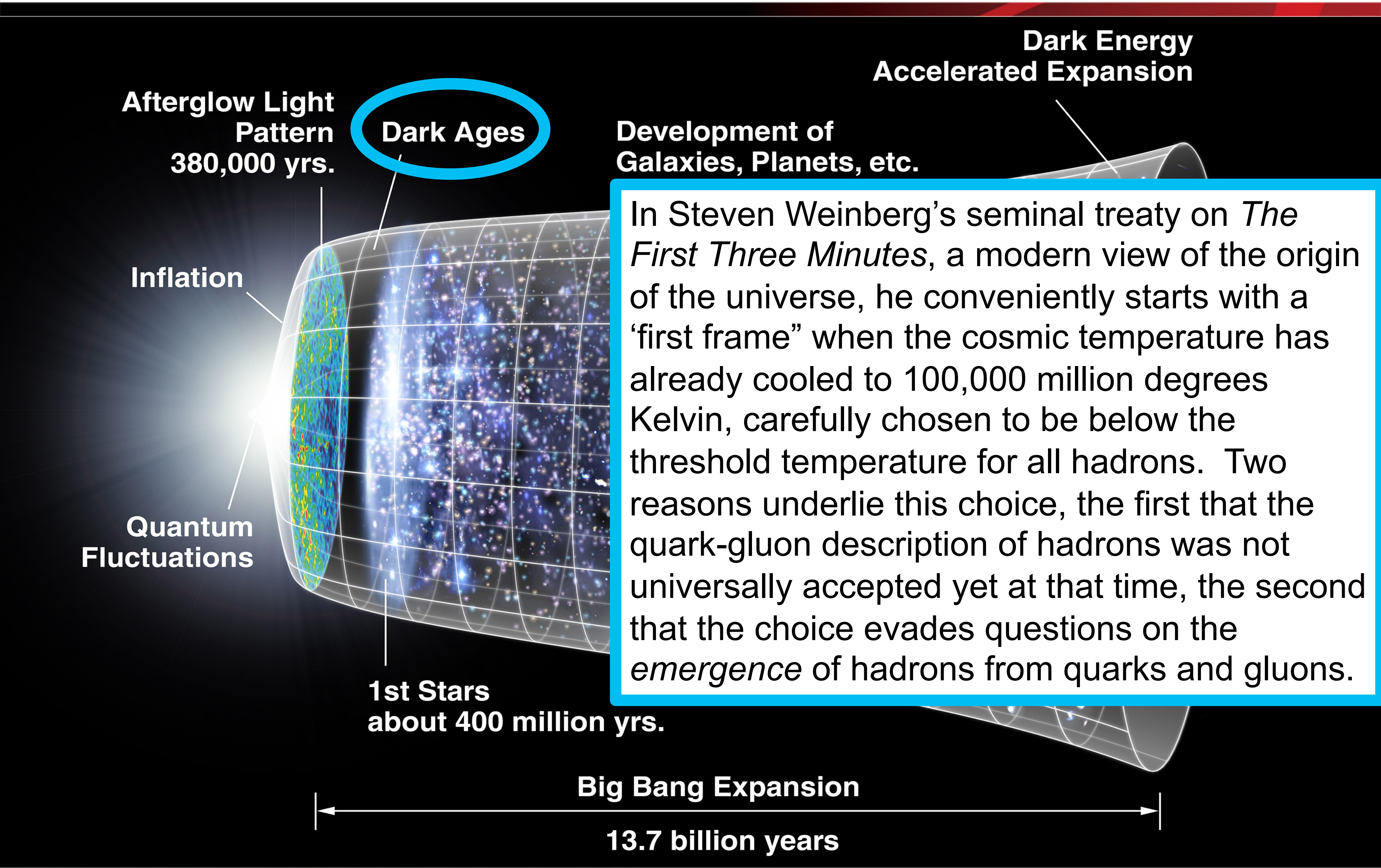
$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

$f^a(x, k_T^2; Q^2)$

$D_a^h(z, p_t^2; Q^2)$

Understanding of the 3D structure of fragmentation into a hadron requires studies of transverse momentum, spin and hadron species dependence

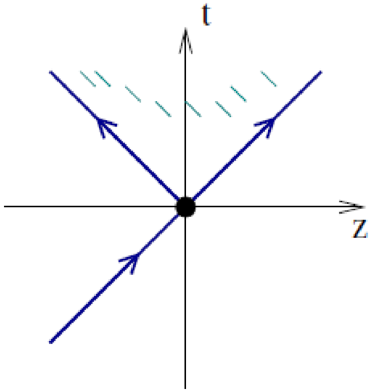
Timeline of the Universe



In Steven Weinberg's seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a 'first frame" when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. Two reasons underlie this choice, the first that the quark-gluon description of hadrons was not universally accepted yet at that time, the second that the choice evades questions on the *emergence* of hadrons from quarks and gluons.

Lessons from the 70s to Now

The emergence of hadrons – mass from massless gluons and nearly-massless quarks

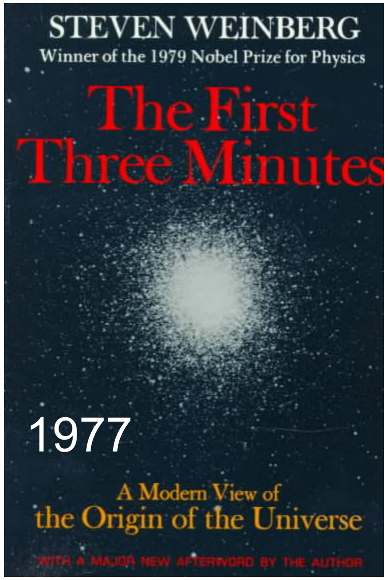


Space-time view of parton model idea of hadronization (in γ*p CM frame)

Basis on Parton Model Intuition:

- Localization in space-time & momentum
- Lorentz contraction, time dilation, causality
- Sharp separation of scales (…)
- Ideas about string-like hadronization

Issues: no direct connection with field theory
Sharp separation of scales?
Final state evolution in space-time??



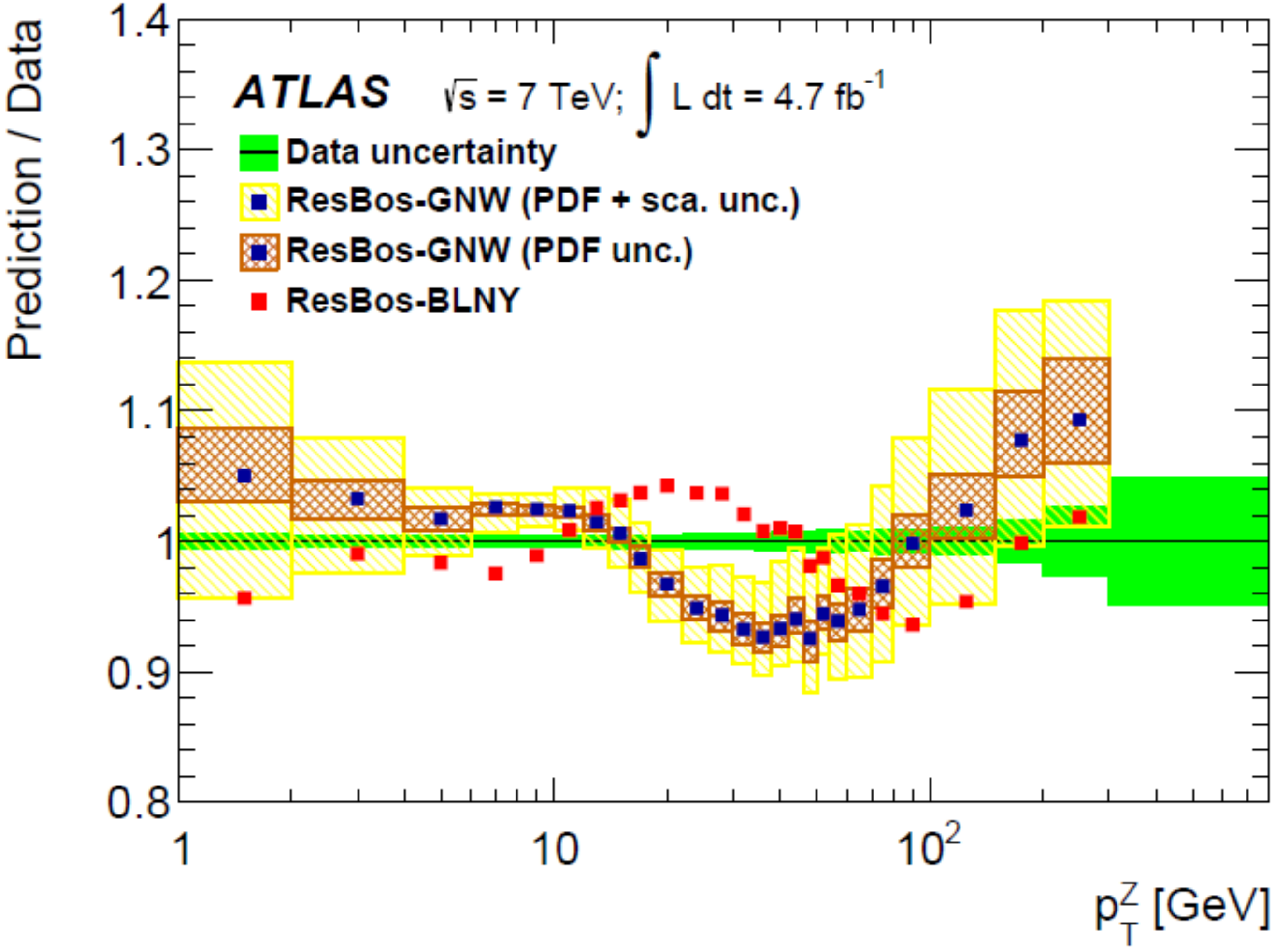
1977

History/timeline

- Late 60s/early 70s: Parton Model
- QCD ~ 1974
- Factorization ~ 1980
- ~2008 Transverse spin physics provokes new definition of pdfs (TMDs) - Back to need for separation of scales

Successful predictions at High E

Z production at the LHC



To Disembroil the Lund String

- Excellent description of high-energy transverse momentum spectra

  → Lund model must do something right…

- Started from best quantum mechanical insight of the time (Schwinger)

- Incorporates acquisition of mass and transverse momentum

$$\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$$

- The transverse momentum acquired in the LUND string model a la Schwinger is about what we see from the (early stage) TMD analyses.

- Is there reciprocity between TMDs and fragmentation?

What does the Lund Model know that we don't know?

Successful at High E, but …

There have been important conceptual advances (. . .) to recent times. One important area needing much further advance:

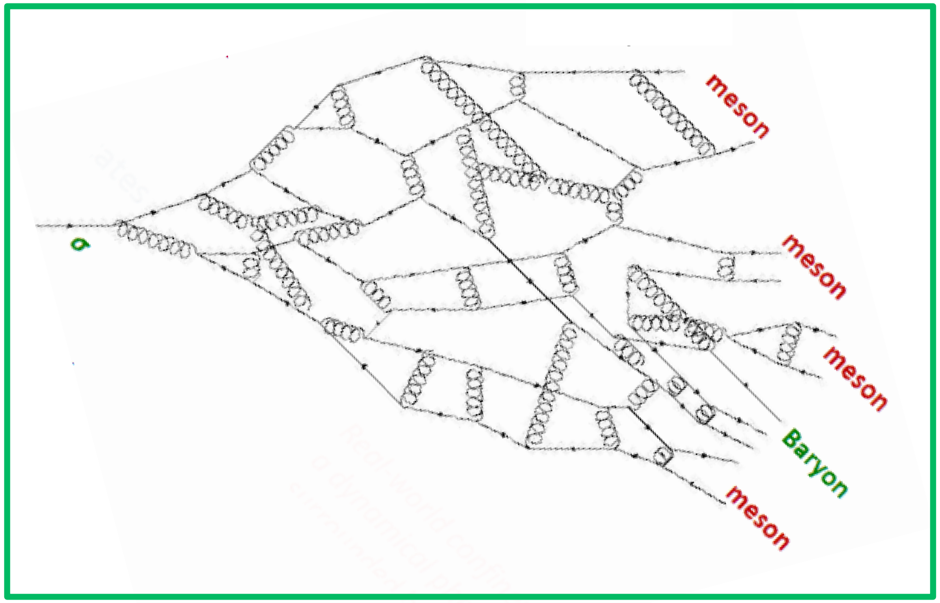
> How do we properly and accurately understand the space-time evolution from a state simply described in terms of a few partons of large relative rapidity to a measurable state of many hadrons?

→ Objects like correlation functions (fragmentation functions (TMD, collinear, dihadron, etc) need to be resolved and studied in terms of their underlying non-perturbative physics.

Fragmentation Process

- Colored object
- Nearly massless object
- Asymptotically free object

- Colorless objects
- Massive objects
- Confined objects



Color to colorless

→ loss of color? No, color of first parton always was balanced by another leg.

Characteristics of fragmentation process must be influenced by

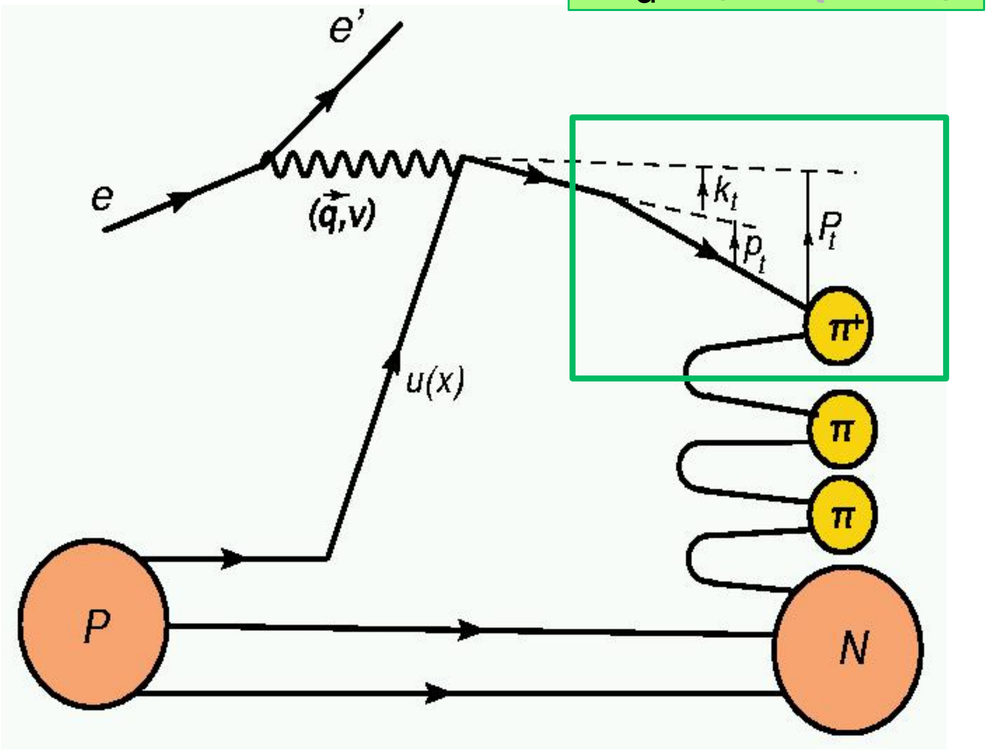
- Dynamical Chiral Symmetry Breaking
- Confinement

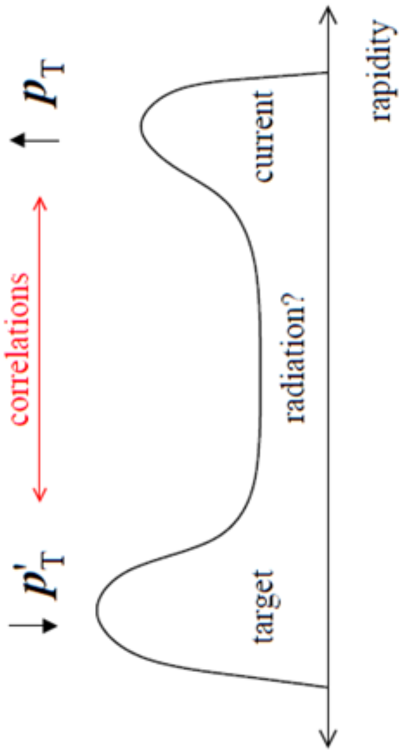
Color neutralization – it's a correlated 3D problem

Final transverse momentum of the detected pion **P_t** arises from convolution of the struck quark transverse momentum **k_t** *with the transverse momentum generated during the fragmentation* **p_t**.

Can we learn more on how hadrons emerge from color charge by correlating one hadron with the residual system, and *track where it's momentum and spin originate*?

$D_u^{\pi^+}(z,p_t^2,Q^2)$

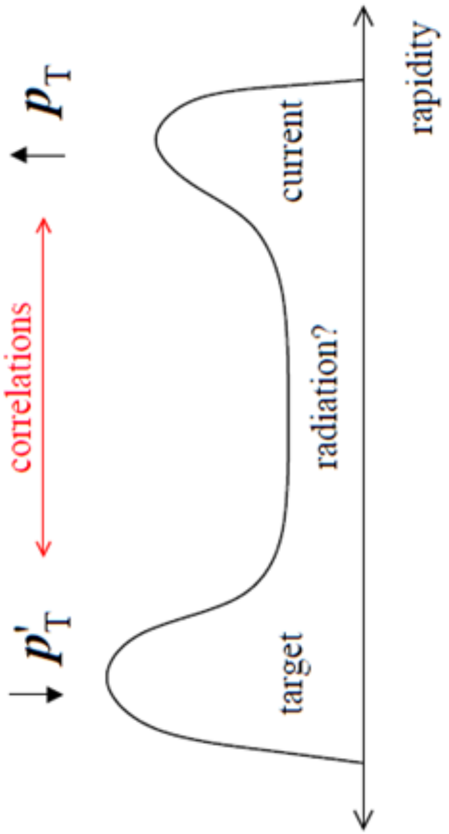


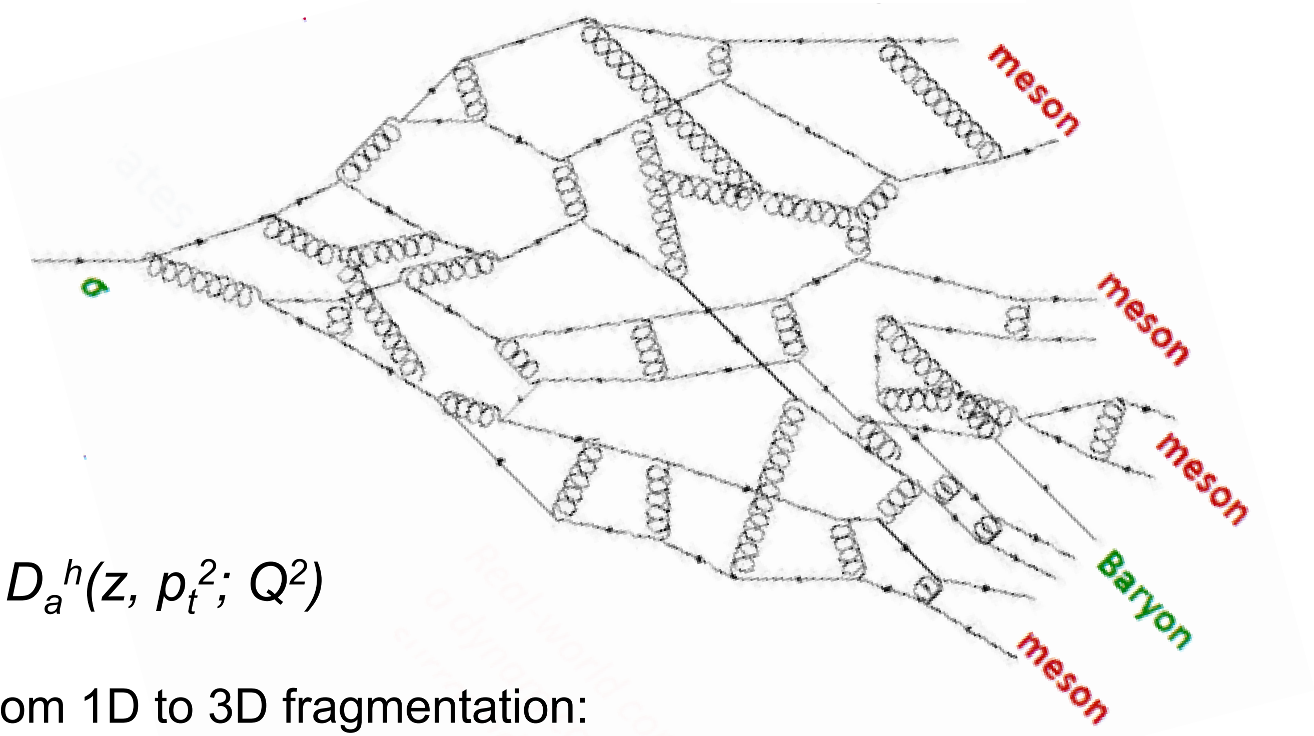


Mass of hadrons = E/c^2

Towards a QM Description of the Final State

Balancing the transverse momentum – candles of space-time





$D_a^h(z, p_t^2; Q^2)$

From 1D to 3D fragmentation:

- Many more variables,
  Many more angles
- Multi-dimensional data
- Fine binnings

First step is always unpolarized cross sections → JLab/12 GeV (but limited in kinematics)

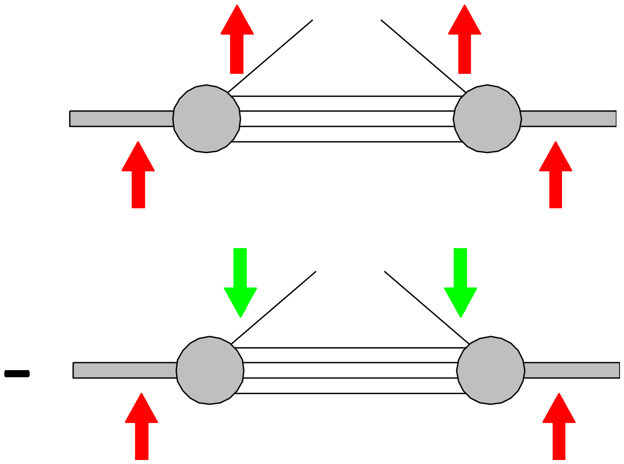
Towards a QM Description of the Final State

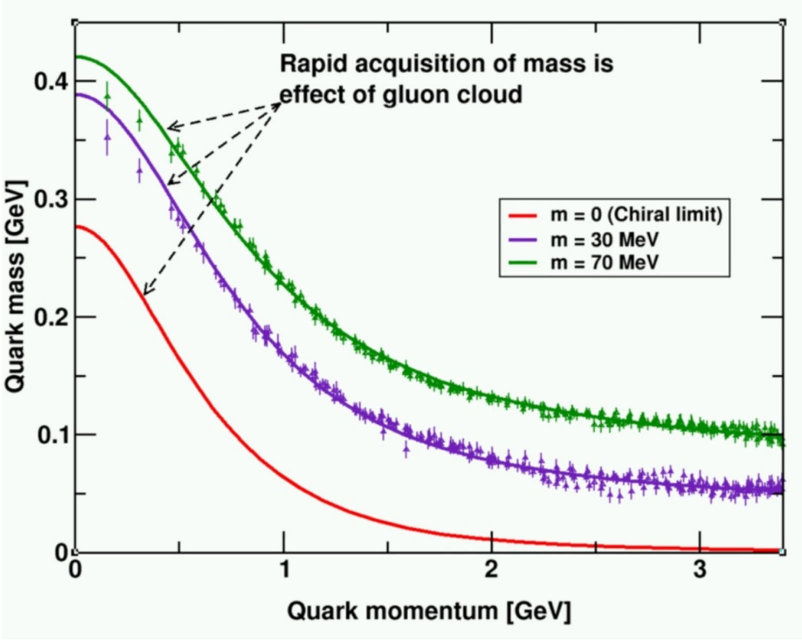
The Collins Function – candle of DχSB

Recall the origin of the Collins function as motivated by forward π spin asymmetry. Requirements for non-zero effect:

1) Interference – helicity must be heavily broken. Can't be by small current quark mass as ~ m_q/Q. Chiral symmetry breaking (in dynamical situation) can do it.
2) Transverse momentum correlations.

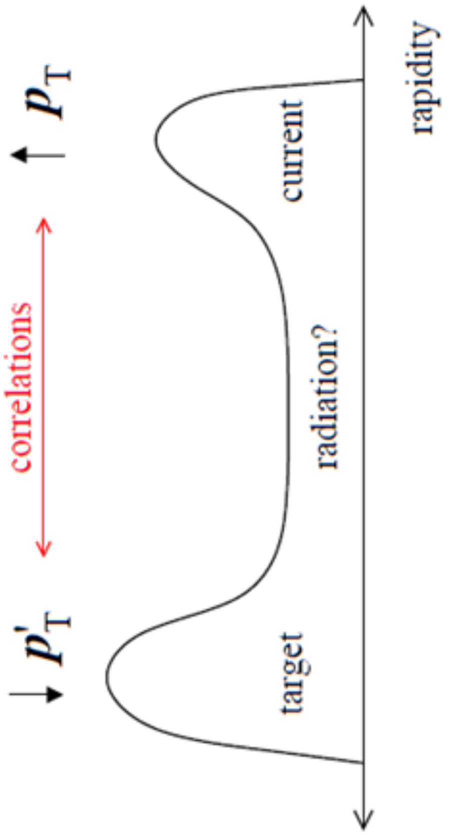
$\delta q(x) \sim$ (in transverse basis)

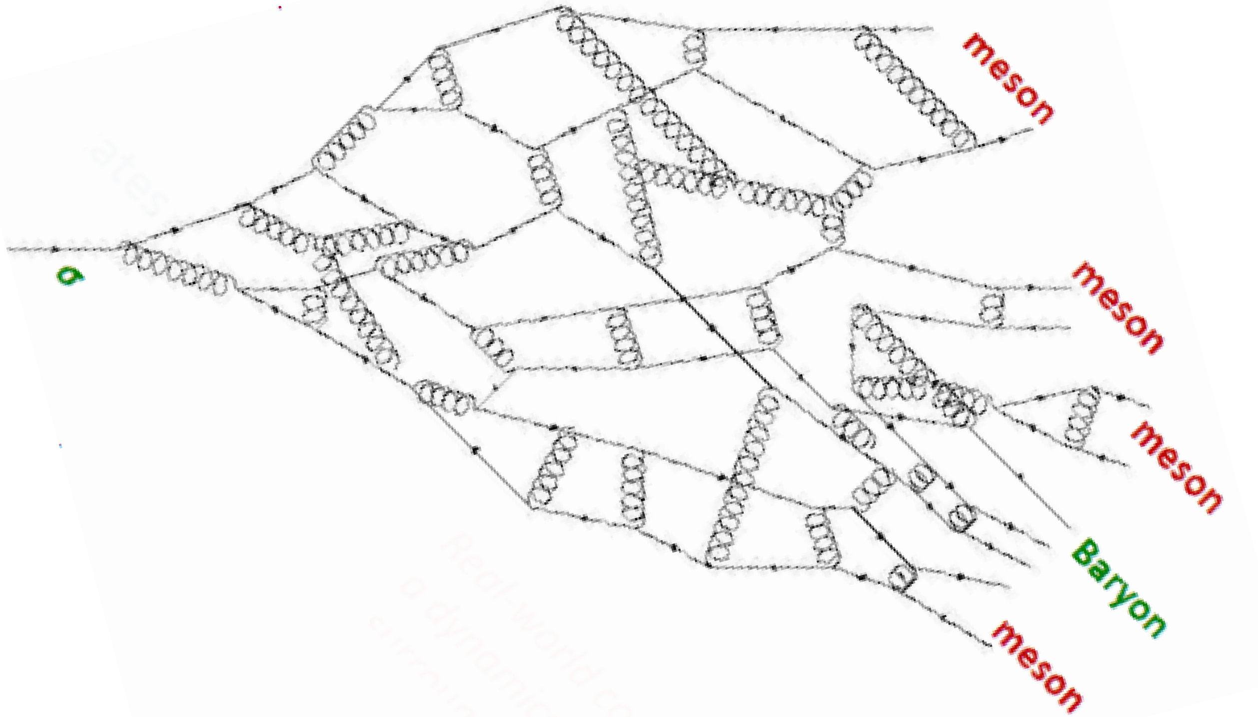




Towards a QM Description of the Final State

The Collins Function – candle of DχSB



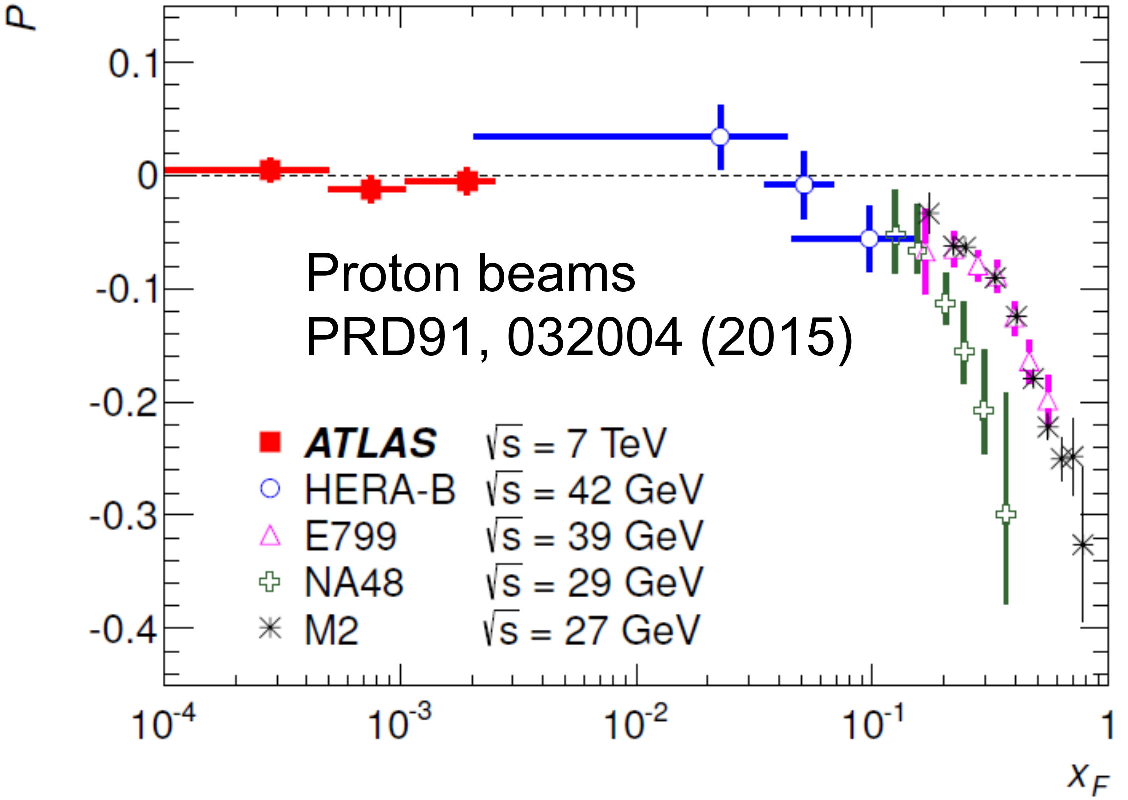


Map the Collins function
over the regions of rapidity?

Towards a QM Description of the Final State

Balancing the Spin

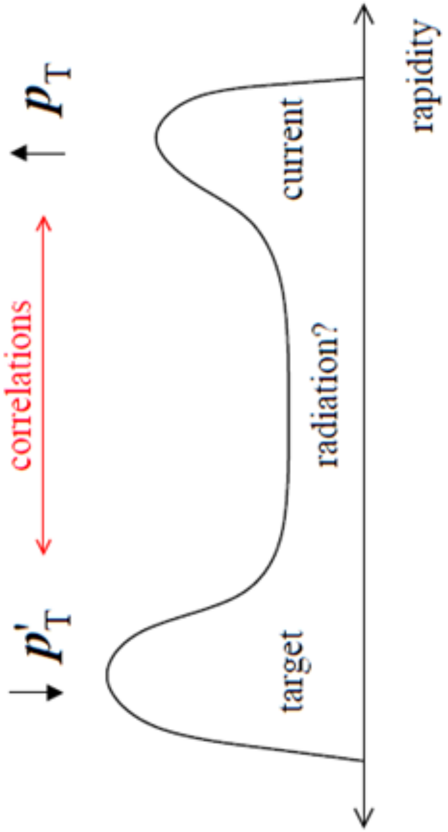
Feynman-x dependence of Λ Polarization
in hadronic collisions

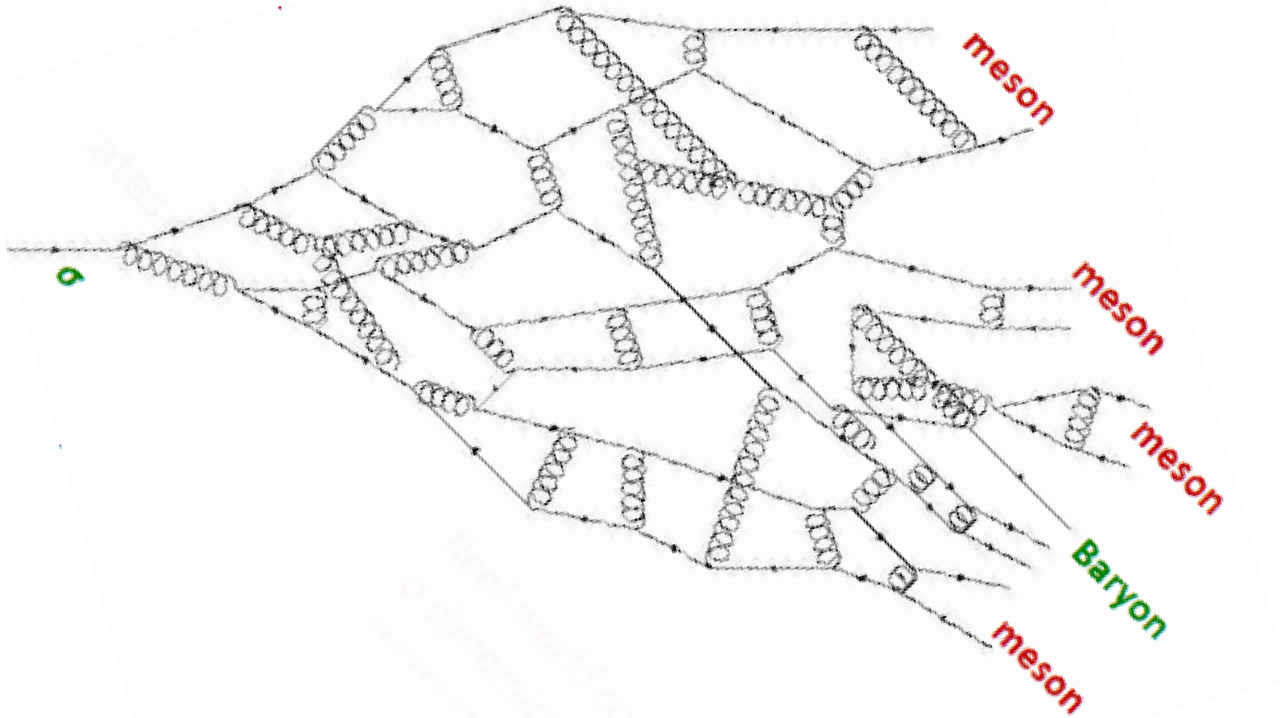


Proton beams
PRD91, 032004 (2015)

Towards a QM Description of the Final State

Balancing the Spin



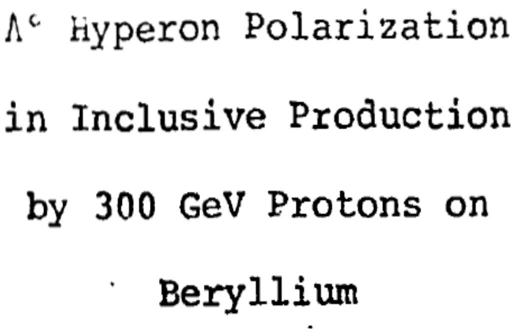


What happens with spin degrees of freedom over the regions of rapidity? Naively one would assume spin diffuses with a few quark-gluon scatterings.

See yesterday's talk by Hrayr Matevosyan

Towards a QM Description of the Final State

Creating Polarization from Nothing – the prototype example



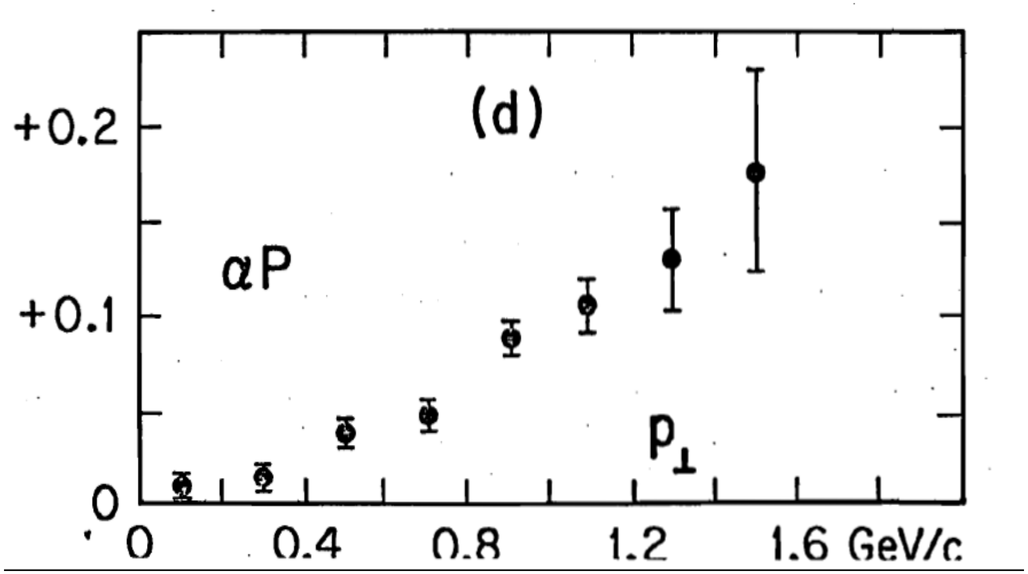
Λ^0 Hyperon Polarization

in Inclusive Production

by 300 GeV Protons on

Beryllium

PRL36, 1113 (1976)



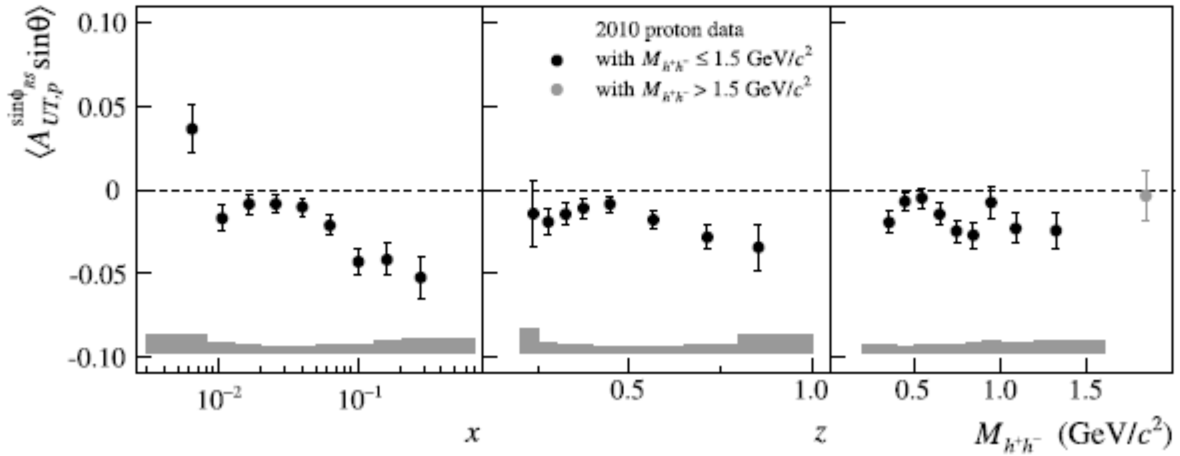
Towards a QM Description of the Final State

Creating Polarization from Nothing – a recent TMD example

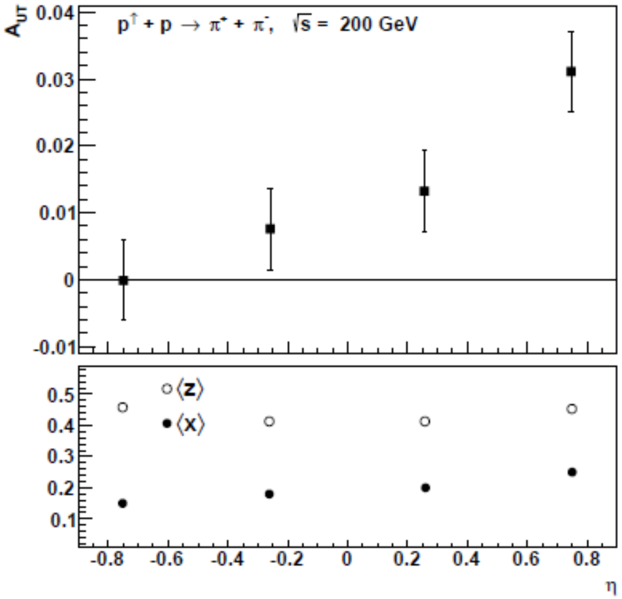
Di-hadron interference fragmentation function

Transverse single-spin asymmetry in dihadron production, 200 GeV p+p

STAR, arXiv:1504.00415



COMPASS, PLB736, 124 (2014)



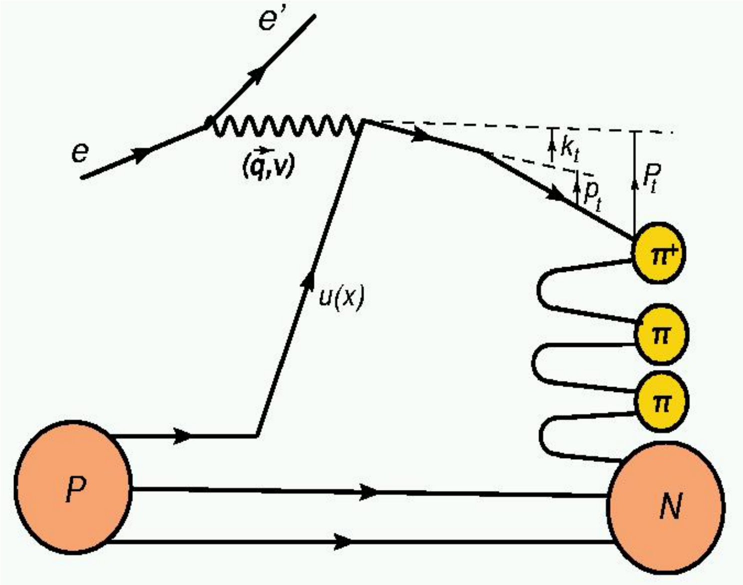
- Pion pair hadronizes from same quark
- correlation with quark transverse spin
- chiral-odd

- Clear nonzero asymmetry
- Pseudorapidity dependence
- Sensitive to transversity x IFF

Towards a QM Description of the Final State

Creating Polarization from Nothing

Boer-Mulders effect can create polarization due to spin-orbit correlations. Since spin in fragmentation process likely dilutes fast, maybe perhaps more a 12-GeV experiment.



Want only few pions produced

e + p → e’ + $\vec{p}$ + X (few mesons only…)

There could be measurable polarization of the proton in the final state in a fully unpolarized SIDIS process!
→ looking into possible JLab 12-GeV proposal.

Connecting the NP and HEP Descriptions

LDRD Scope: Map the non-perturbative description of hadronization in the Pythia MCEG to the correlation functions of TMD factorization.

(**Diefenthaler**, Collins, Joosten, Lönnblad, Melnitchouk, Prestel, Rogers, Sato, Sjöstrand)

Hadronization / fragmentation:

- How do partonic degrees of freedom transform into the experimentally observed hadrons?

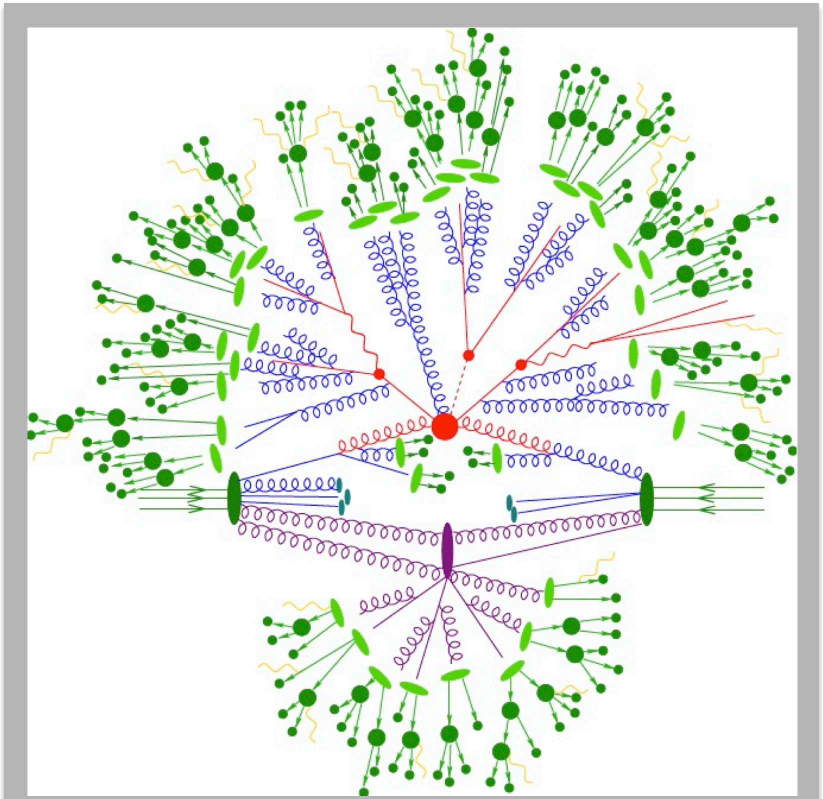
Pythia MCEG

- deal with the theory of final state hadronization in high-energy collisions.

QCD factorization theorems

- first principle QCD calculations of specific cross sections
- non-perturbative physics is contained in **universal** correlation functions

It is critical for the two to be combined if QCD studies of non-perturbative structure are to proceed.



Theoretical description of a collision process

Summary

- Overall goal of Jefferson Lab SIDIS Program (in x > 0.1 region):
  validate basic reaction mechanism of SIDIS at JLab energies
  and then
  spin and flavor dependence of quark transverse momentum distributions

- There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different k_T dependences of quark flavor distributions

- The final hadron following the SIDIS process accumulates a momentum transverse to the beam direction by a convolution of the transverse momentum of the struck quark and the transverse momentum of the additional antiquark. This turns the understanding of fragmentation into a correlated 3D problem.

- Objects like correlation functions (fragmentation functions (TMD, collinear, dihadron, etc) need to be resolved and studied in terms of their underlying non-perturbative physics.

- Characteristics of fragmentation process must be influenced by
  - Dynamical Chiral Symmetry Breaking
  - Confinement

  We should isolate experimental signatures that are most likely to give insight

Acknowledgements

Much gathered from a recent workshop
From 1D Fragmentation towards 3D Correlated Fragmentation
ECT* Trento, Italy
26-30 October 2015

Participants

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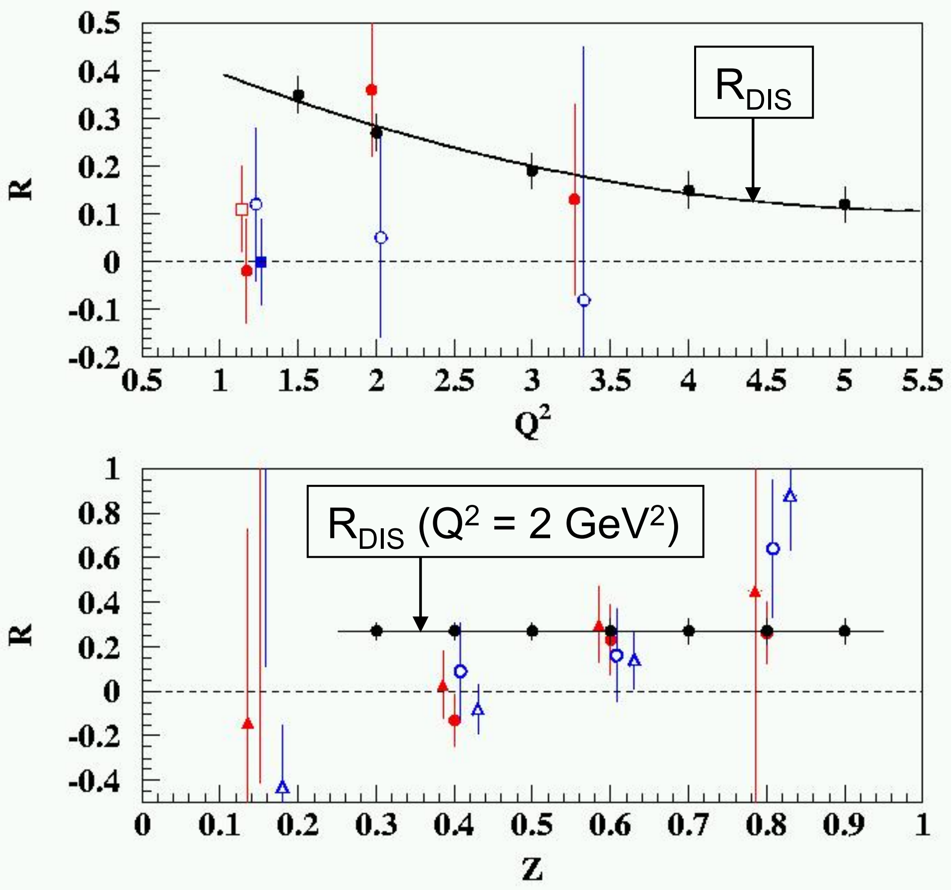
Marco Stratmann (U Tuebingen, Germany)
Anselm Vossen (Indiana U, USA)

Longitudinal Cross Section: $R = \sigma_L/\sigma_T$ in SIDIS

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum:
  $R = 4(M^2x^2 + \langle k_T^2\rangle)/(Q^2 + 2\langle k_T^2\rangle)$.
- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents

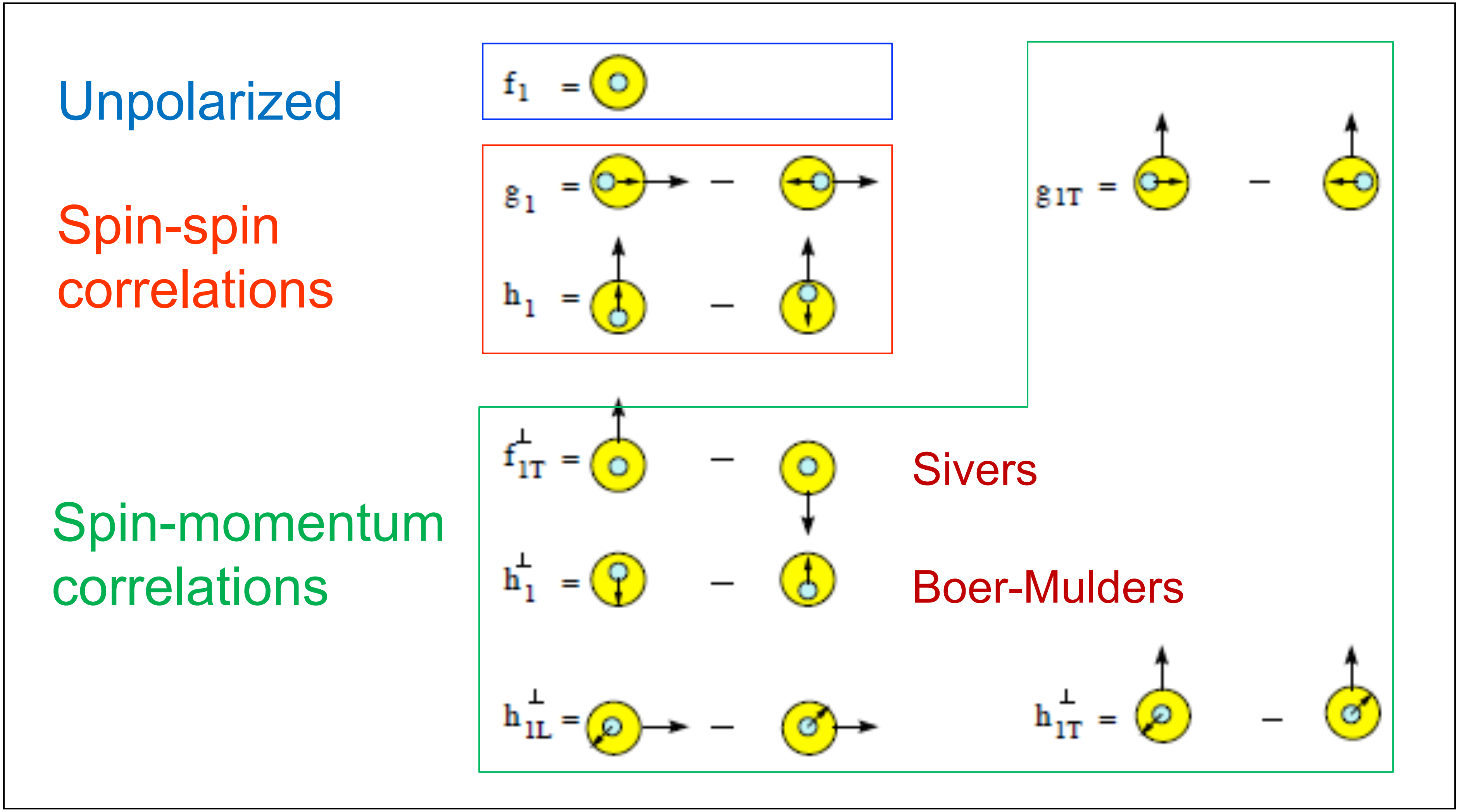


Only existing SIDIS data: Cornell 70's (H and D, π^+ and π^-)

- Knowledge on R_{SIDIS} is non-existing
- R_{SIDIS} may (will!) vary with z, and with p_T
  (JLab E12-06-104 will scan versus p_T too!)
- Knowledge on R_{SIDIS} needed for any TMD-related asymmetry
- Even if one can relate R_{SIDIS} to a flavor-dependent average transverse momentum in a naïve parton model (W. Melnitchouk *et al*, in progress), R_{SIDIS} can not easily be integrated in a global TMD analysis as it is sensitive to gluon and HT effects.

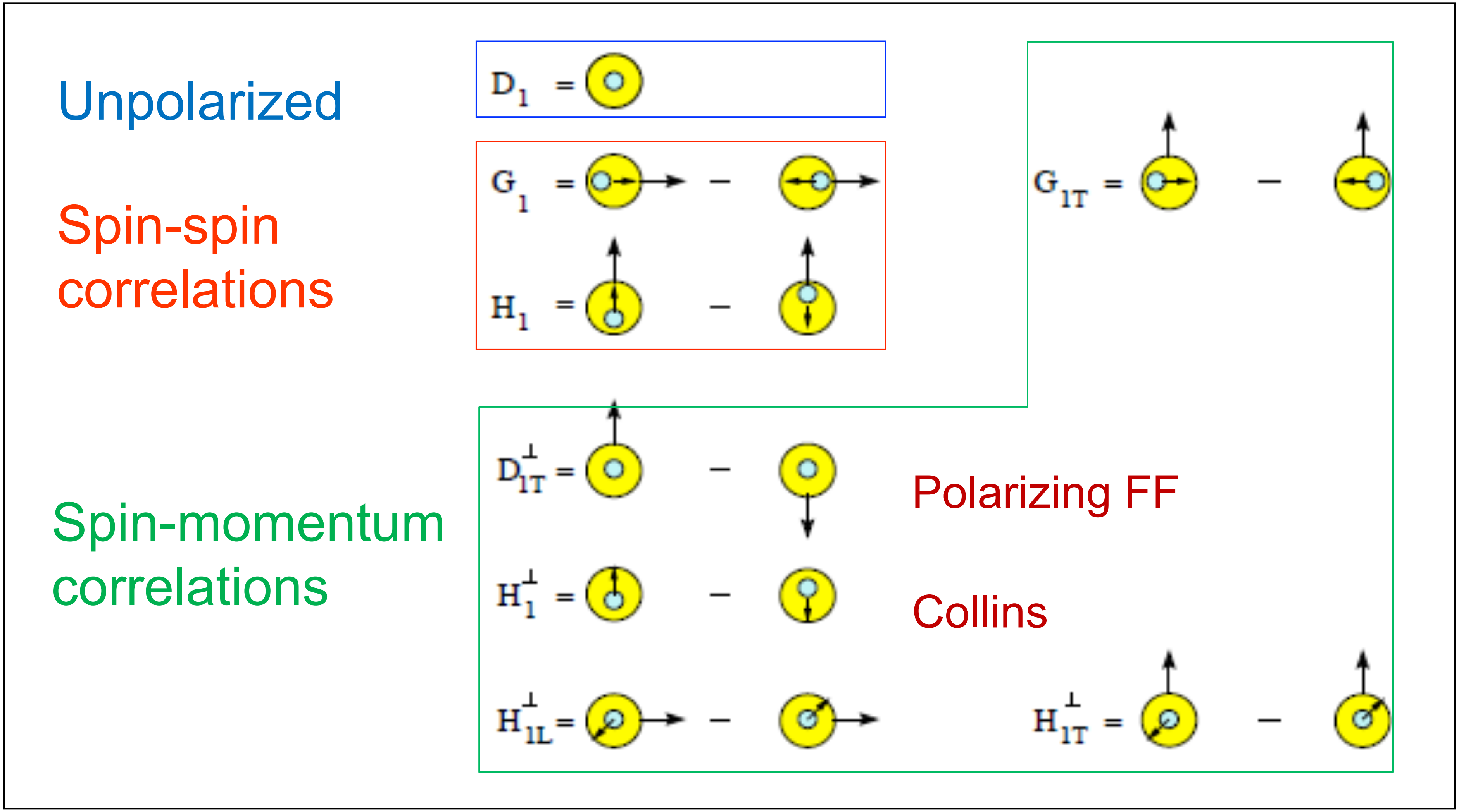
Twist-2 3D Distribution Functions

$f^a(x, k_T^2; Q^2)$



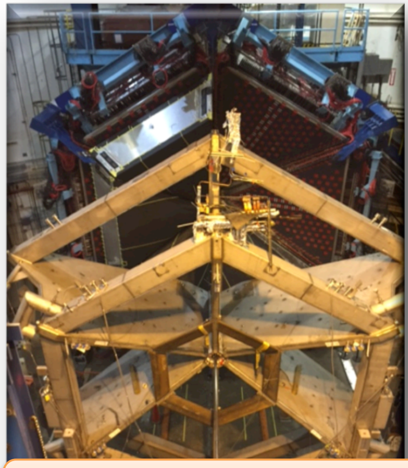
Twist-2 3D Fragmentation Functions

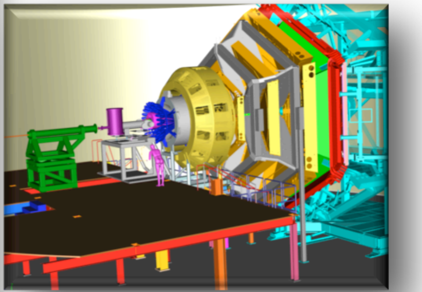
$D_a^h(z, p_t^2; Q^2)$



12 GeV (GPD/TMD) Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

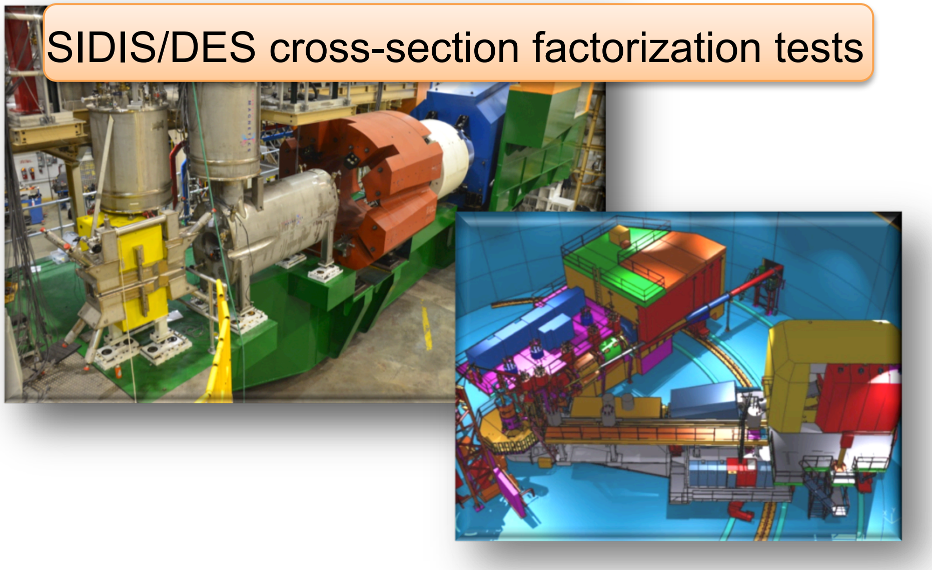




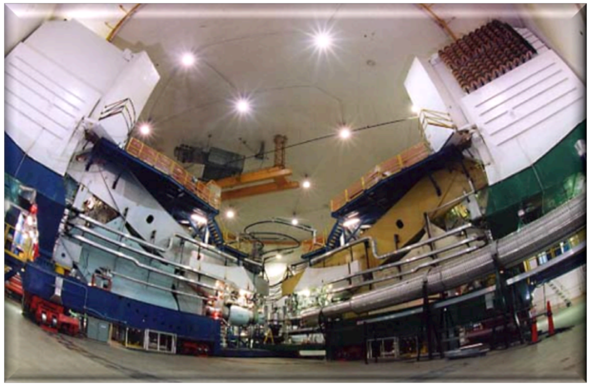
TMDs and GPDs comprehensive study

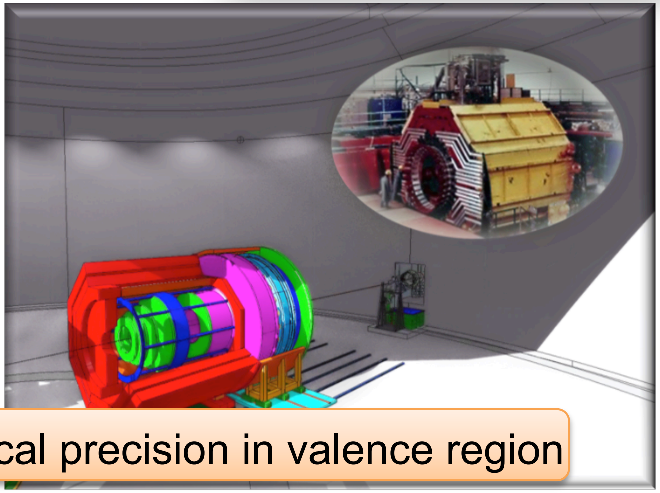
Hall C **– precision determination of valence quark properties in nucleons/nuclei**

SIDIS/DES cross-section factorization tests



Hall A **– polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)**





Ultimate TMD statistical precision in valence region

JLab Tentative Timeline

- Up to FY17: 12-GeV Upgrade Project ongoing
- FY16: ongoing program in
  - Hall A: Deeply-Virtual Compton Scattering &
    Proton Magnetic Form Factor
  - Hall B < 6 GeV science: Heavy Photon Search &
    Proton Radius Experiment
  - Hall C: Beam line/dump test
  - Hall D: GlueX engineering run
- FY17: completion of Halls C and B equipment upgrades
  official (DOE) start of 12 GeV science operations
  (typical lifetime of facility science program ~ 15 years)

After few years:

- Precision Spatial and Momentum Imaging of Hadrons ←
  (note: flexibility as 12 GeV operations compatible with EIC operations)
- Somewhere beyond 2025: EIC construction complete

Hall C SIDIS Program – basic (e,e'π) cross sections

Why need for (e,e'π) cross sections?

PAC37 Report: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate P_T and ϕ-dependence for small P_T."

$$\boxed{\sigma = \sum_q e_q^2 f(x) \otimes D(z)}$$

Basic precision cross section measurements:

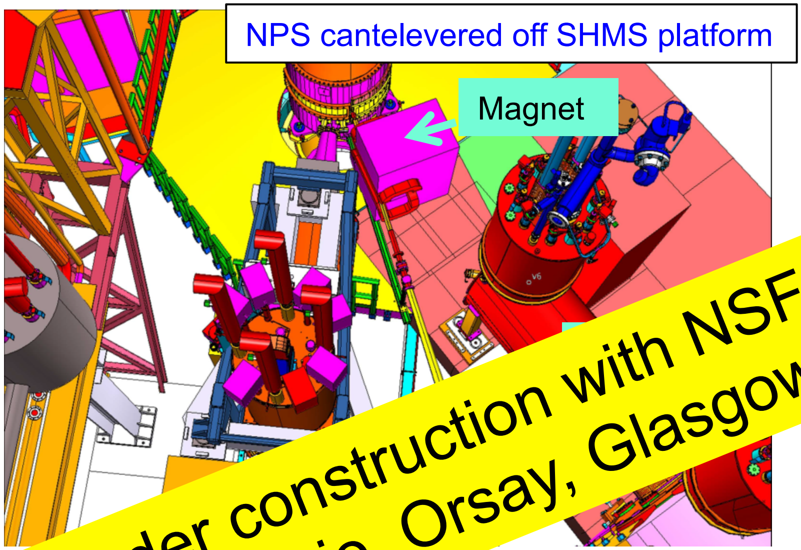
- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain Q^2 dependence & TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

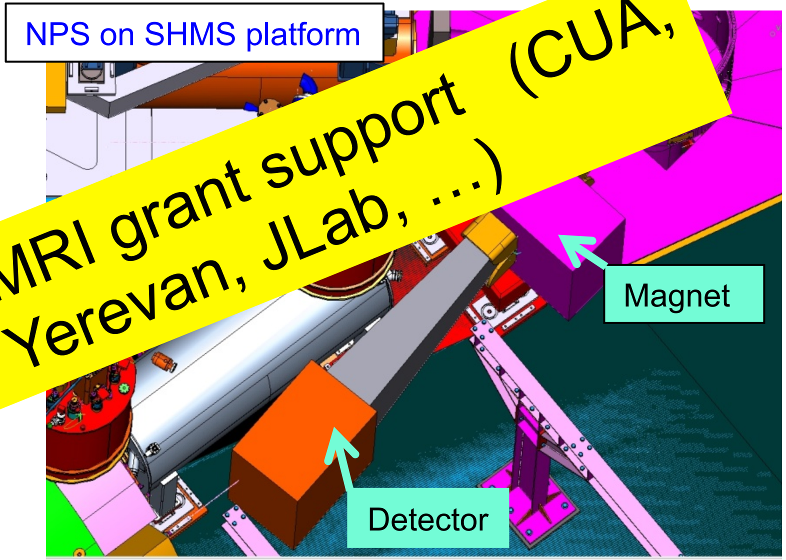
Goal: Measure the basic SIDIS cross sections of π^+, π^-, π^0 **(and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0). The NPS will be remotely rotatable off the SHMS platform.





Under construction with NSF/MRI grant support (CUA, ODU, Ohio, Orsay, Glasgow, Yerevan, JLab, …)

[illegible].5 – 30 degrees

NPS angle range: 25 – 60 degrees

The larg[illegible]st for such a device can be exemplified by the PAC-approved science program:
E12-13-0[illegible]7 – Measurement of Semi-inclusive π^0 production as Validation of Factorization
E12-13-010 – Exclusive Deeply Virtual Compton and
Neutral Pion Cross Section Measurements in Hall C
(E12-13-007 & E12-13-010 runs as one run group – first run group in Hall C)
E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons **(runs as run group with E12-14-003)**
E12-14-006 – Initial State Helicity Correlation in Wide-Angle Compton Scattering

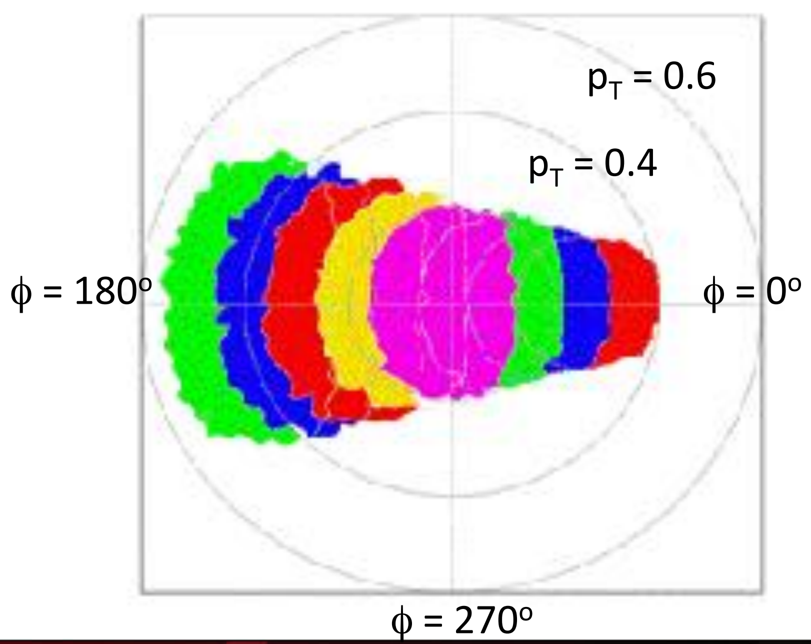
HMS + SHMS: P_T coverage

E12-09-017

Can do meaningful $\pi^{+/-}$ measurements at low p_T (down to 0.05 GeV) due to excellent momentum and angle resolutions!

- Excellent ϕ coverage
  up to P_T = 0.2 GeV
- Sufficient up to P_T = 0.4 GeV
  → coverage at $\phi = 0, \pi$
- Limited up to P_T = 0.5 GeV
  → use f(ϕ) from CLAS12

$\pi^{+/-}$



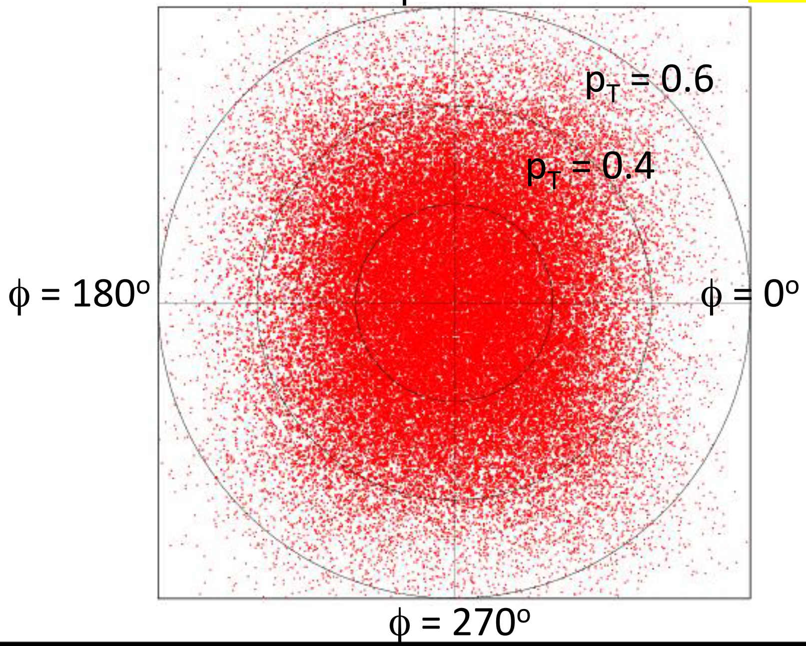
HMS + NPS: P_T coverage

E12-13-007

Basic π^0 SIDIS cross sections with excellent precision, and very good momentum and angle resolutions!

- Excellent ϕ coverage
  up to P_T = 0.3 GeV
- Good up to P_T = 0.4 GeV
- Limited up to P_T = 0.5 GeV
  → use f(ϕ) from CLAS12

π^0



The Emergence of Hadrons

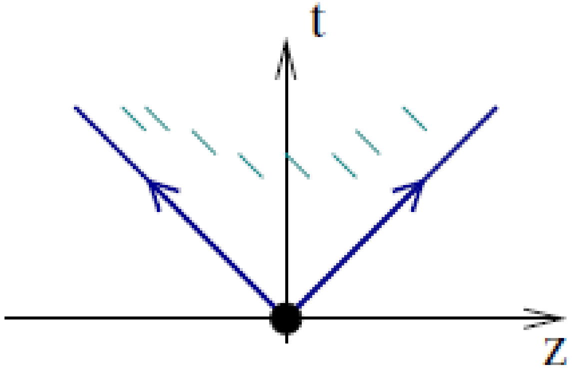
The emergence of hadrons – mass from massless gluons and nearly-massless quarks

> *Wikipedia – Emergence is a field of study, defined as:*
> *In philosophy, systems theory, science, and art, emergence is conceived as a process whereby larger entities, patterns, and regularities arise through interactions among smaller or simpler entities that themselves do not exhibit such properties.*

Sounds a bit like the larger baryons and mesons resulting through interactions from the smaller and simpler quarks and gluons, with different properties.

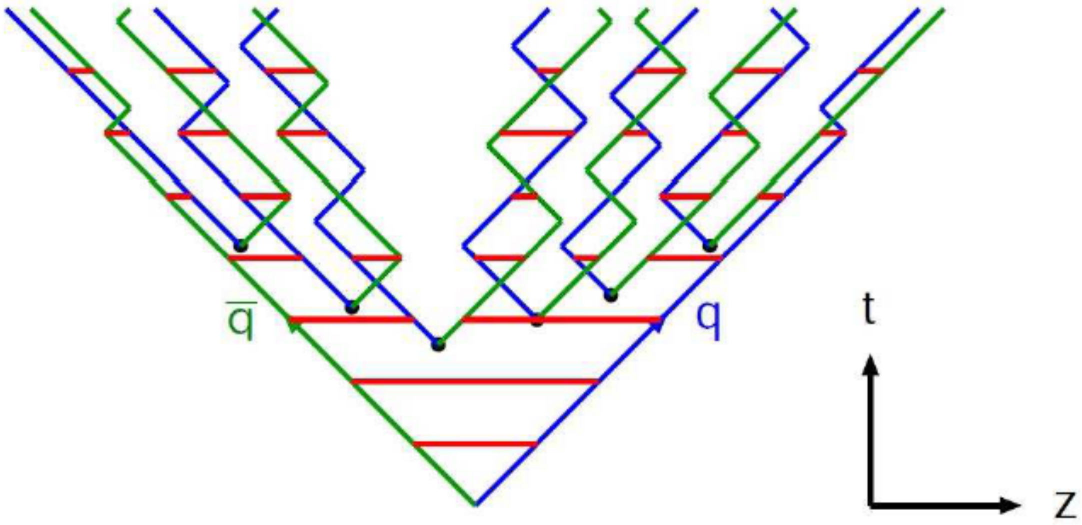
To Disembroil the Lund String

Born from intuition from the parton model era



- Semi-classical picture
- Uses localization in both space-time and momentum

To Disembroil the Lund String



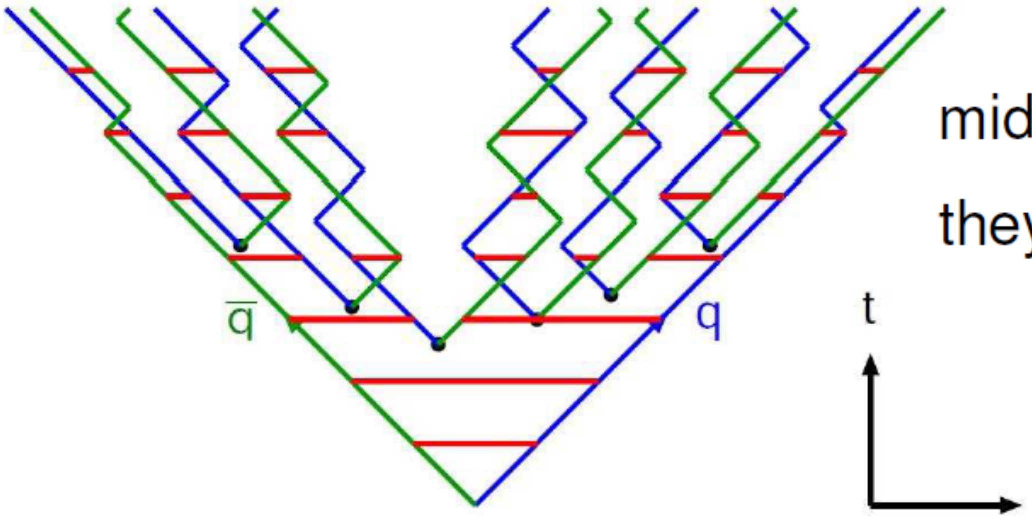
The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism (à la Schwinger)

$$\mathcal{P} \propto e^{-\frac{\pi m_{q\perp}^2}{\kappa}} = e^{-\frac{\pi m_q^2}{\kappa}} e^{-\frac{\pi p_\perp^2}{\kappa}}$$

Gives a natural supression of heavy quarks

$d\bar{d} : u\bar{u} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$

To Disembroil the Lund String



The break-ups starts in the middle and spreads outward, but they are causually disconnected.

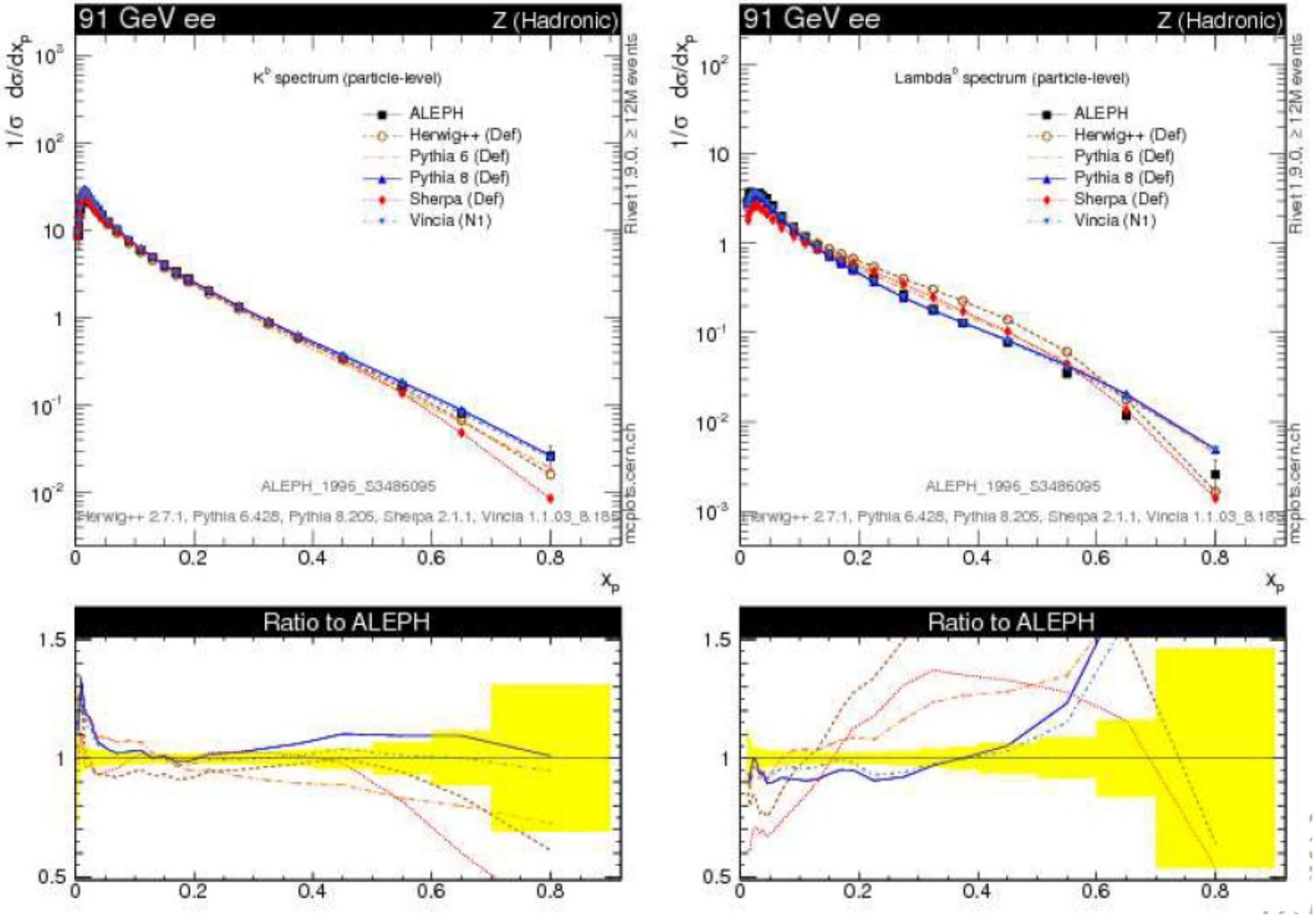
Requiring left-right symmetry we obtain a unique *fragmentation function* for a hadron taking a fraction *z* of the energy of a string end in a breakup

$$p(z) = N\frac{(1-z)^a}{z}e^{-bm_\perp^2/z}$$

The Lund symmetric fragmentation function.

As far as I can judge, some of the intuition that such forms are reasonable comes from early 70s pp → π^0 + X data

To Disembroil the Lund String

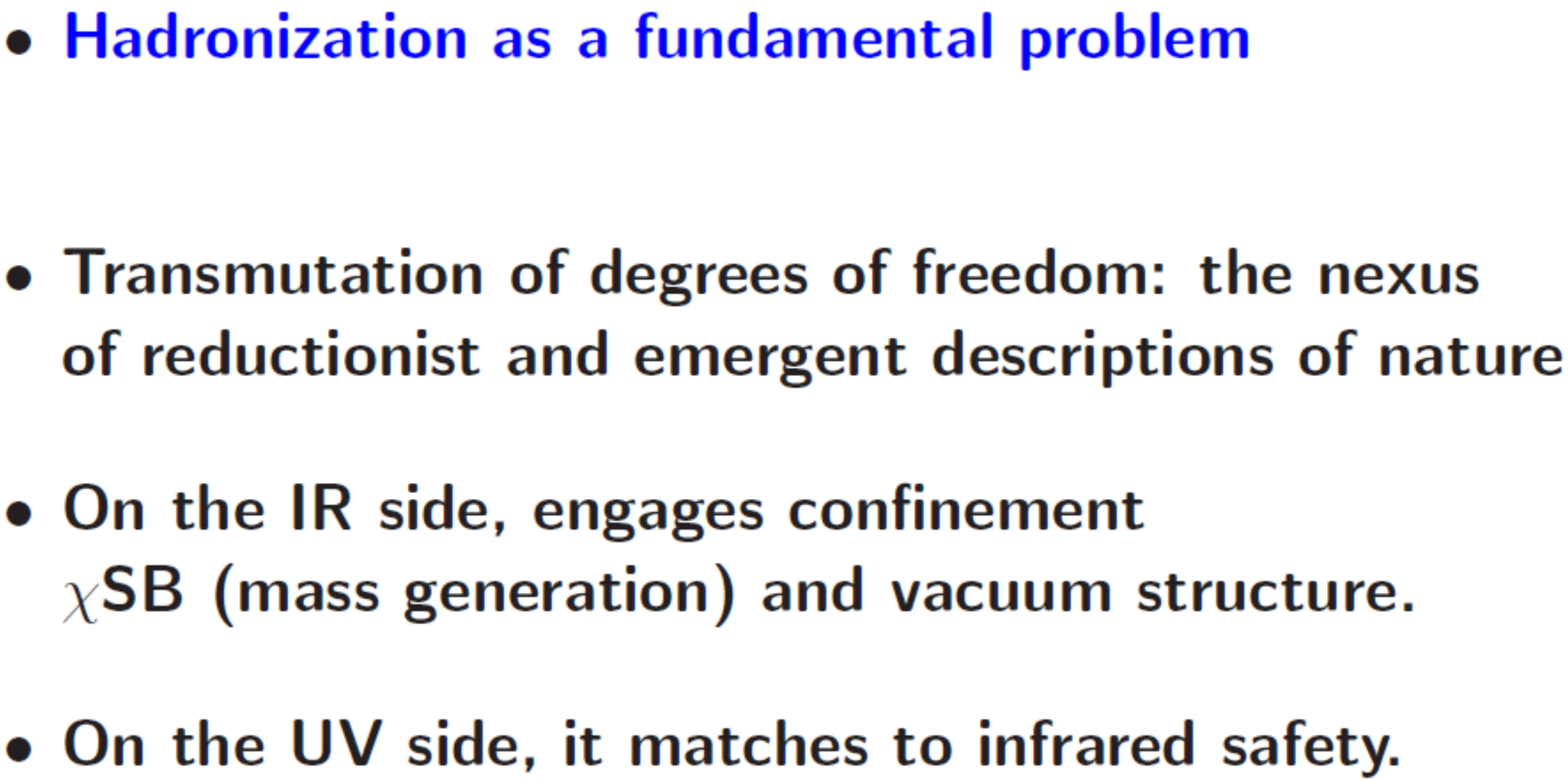


mcplots.cern.ch

Lund model must do something right…

Towards a QM Description of the Final State

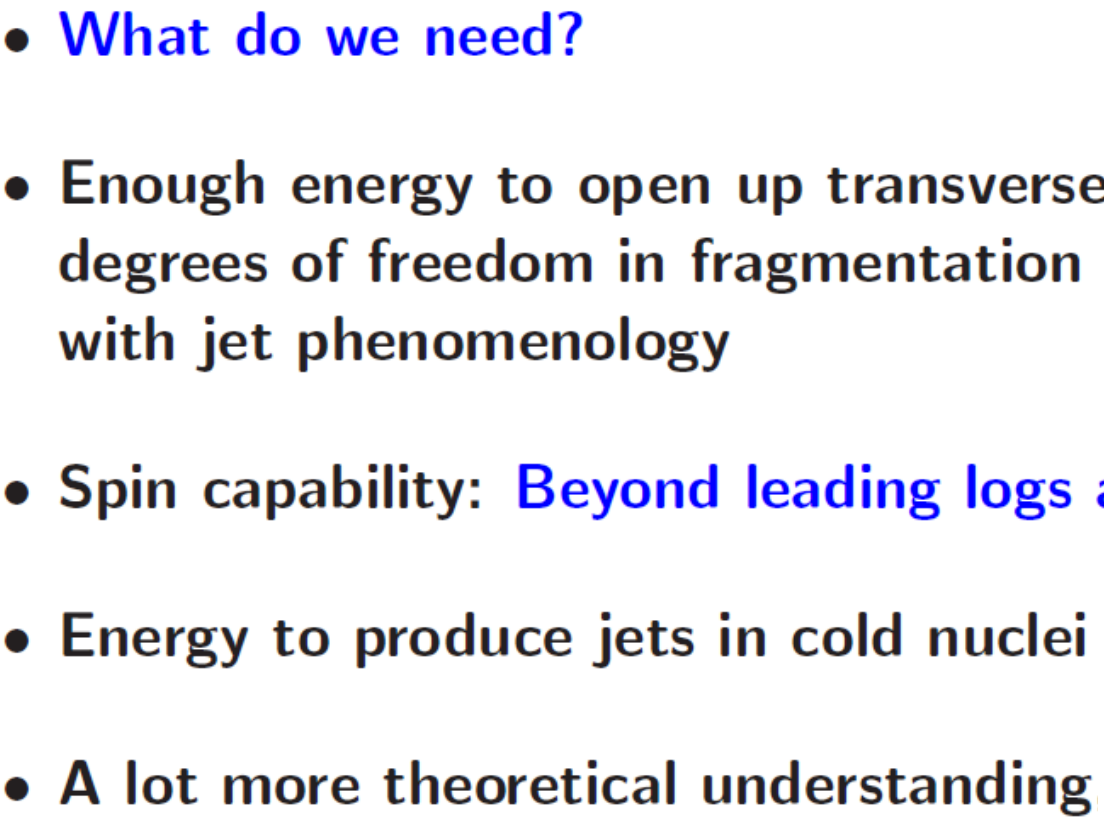
Workshop on QCD in preparation of 2007 Long-Range Plan, talk of George Sterman



- Hadronization as a fundamental problem
- Transmutation of degrees of freedom: the nexus of reductionist and emergent descriptions of nature
- On the IR side, engages confinement χSB (mass generation) and vacuum structure.
- On the UV side, it matches to infrared safety.

Towards a QM Description of the Final State

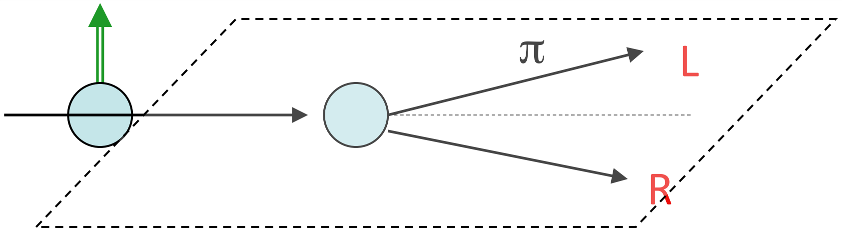
Workshop on QCD in preparation of 2007 Long-Range Plan, talk of George Sterman



- What do we need?
- Enough energy to open up transverse as well as longitudinal degrees of freedom in fragmentation and make contact with jet phenomenology
- Spin capability: Beyond leading logs and color flows?
- Energy to produce jets in cold nuclei and in nucleus
- A lot more theoretical understanding

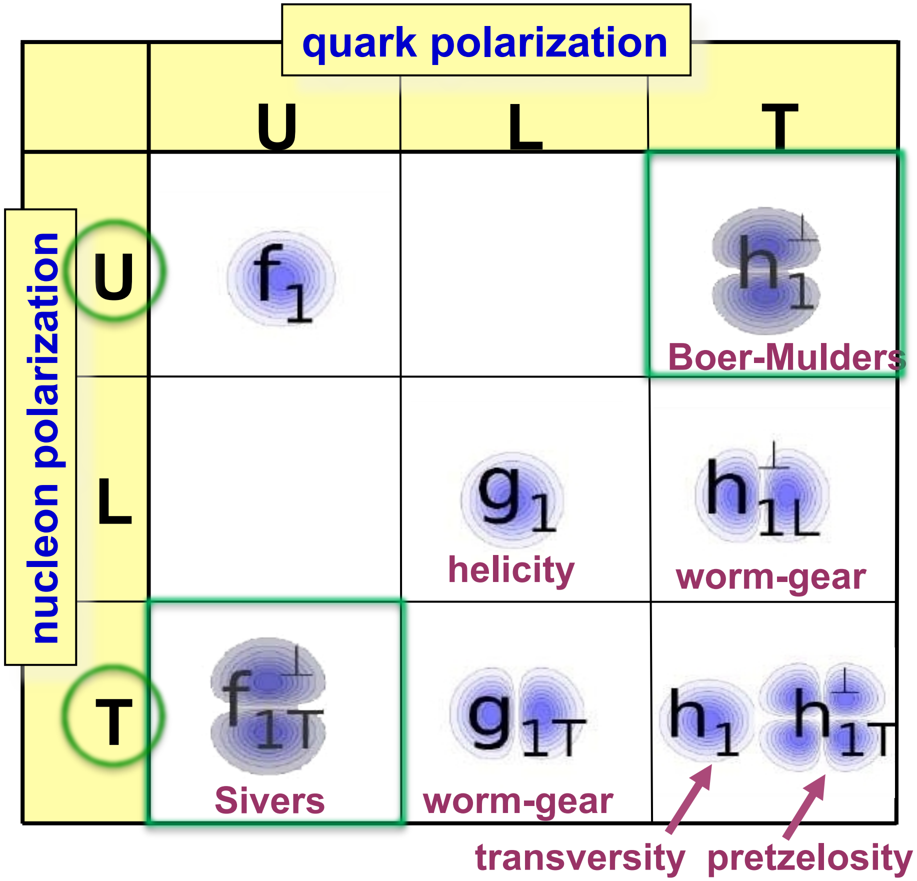
RE: Some 10 years later these seem wise words, looks like we are moving in this direction

Towards a QM Description of the Final State



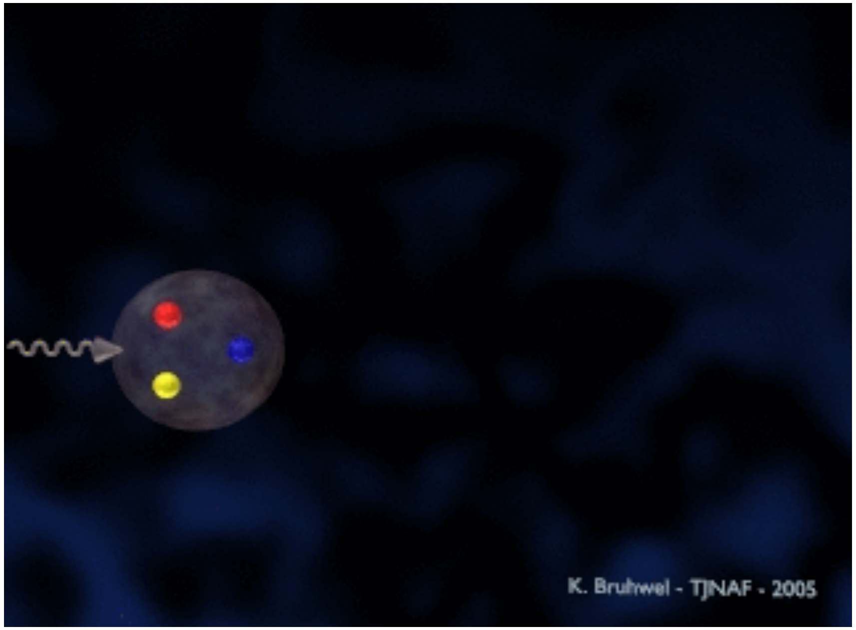
$$A_N = \frac{L - R}{L + R} \qquad \vec{\mathbf{S}}_\perp \cdot \left(\vec{\mathbf{P}} \times \vec{\mathbf{k}}_\perp^\pi\right)$$

Creating Polarization from Nothing



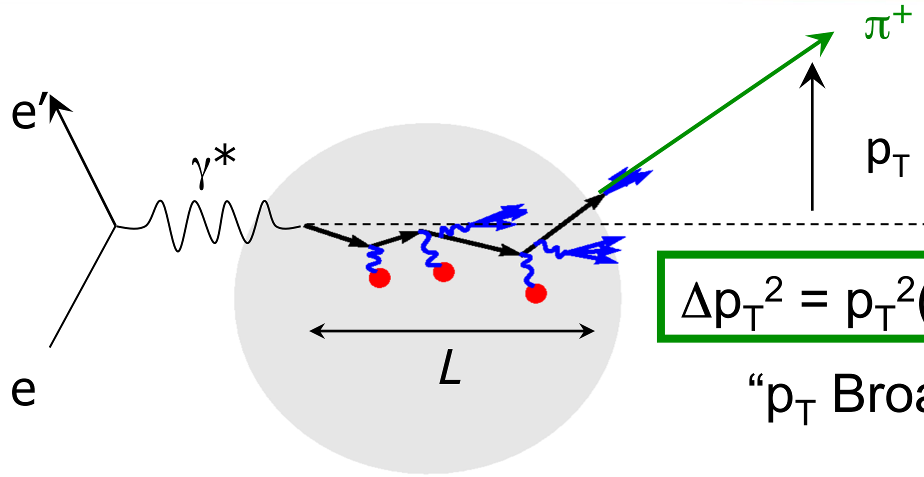
nucleon polarization	quark polarization		
	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 $h_{1T}^\perp$

transversity pretzelosity



Spin-Orbit Effects in Fragmentation

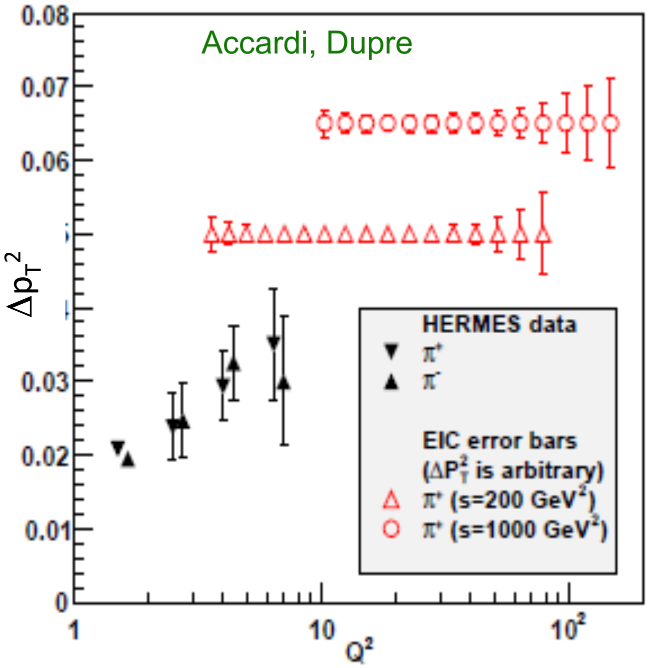
Hadronization – parton propagation in matter



Multiple gluon scattering making transverse momentum beyond the Lund string-breaking mechanism

$$\boxed{\Delta p_T^2 = p_T^2(A) - p_T^2(^2H)}$$

"p_T Broadening"



Comprehensive studies possible:

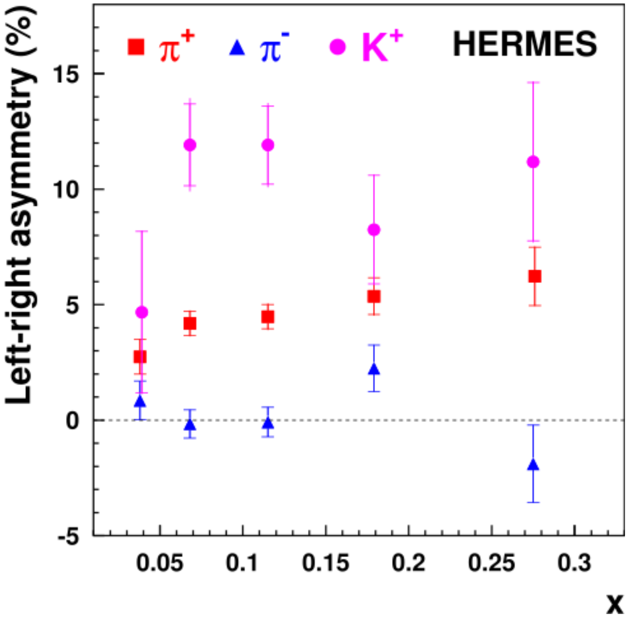
- wide range of energy ν = 10-1000 GeV
- wide range of Q^2: evolution
- Hadronization of charm, bottom
- High luminosity for 3D and correlations

EIC: Understand the conversion of color charge to hadrons through fragmentation and breakup

Towards a QM Description of the Final State

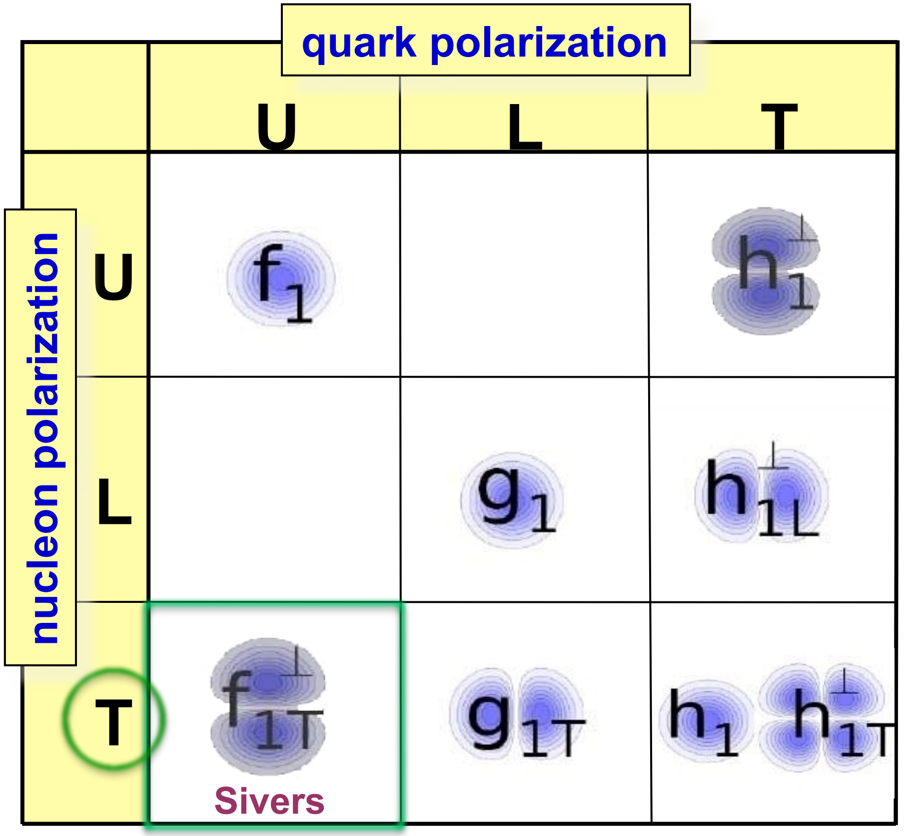
The Collins Function

A surprise of transverse-spin experiments



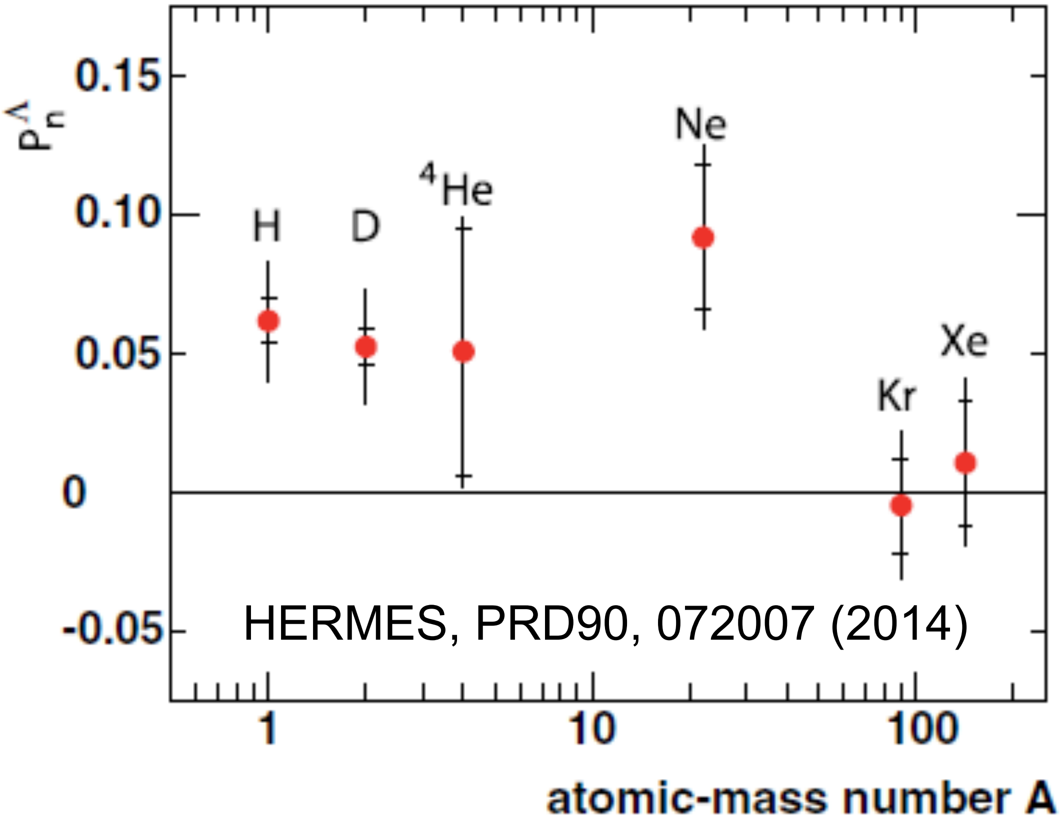
Observables: Azimuthal asymmetries due to correlations of spin q/n and transverse momentum of quarks

This surprise led to the introduction of the Sivers function – effect induced by effect in distribution function, and the Collins function – effect induced by effect in fragmentation function.



Towards a QM Description of the Final State

Creating Polarization from Nothing



HERMES, PRD90, 072007 (2014)

Lambda polarization maintained in the (light to medium-heavy) nuclear medium, as observed in semi-inclusive DIS