PT-Dependent Fragmentation in DIS on Protons and Nuclei

→

3D Fragmentation – Protons and Nuclei

Rolf Ent

Acknowledgements

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

Participants

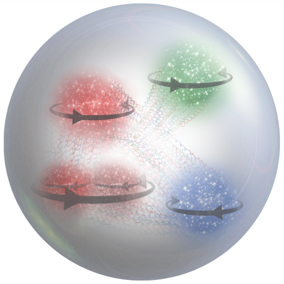
Christine Aidala (U Michigan, USA)
Vincenzo Barone (Piemonte Orientale U, INFN Torino, Italy)
Will Brooks (UTFSM, Chile)
Ian Cloet (Argonne National Lab, USA)
Rolf Ent (Jefferson Lab, USA)
Osvaldo Gonzalez (Torino U, Italy)
Tom Kaufmann (U Tuebingen, Germany)
Leif Lönnblad (Lund U, Sweden)
Hrayr Matevosyan (Adelaide U, Australia)
Piet Mulders (Vrije U Amsterdam/NIKHEF, Netherlands)
Marco Radici (INFN Pavia, Italy)
Ted Rogers (Old Dominion U and Jefferson Lab, USA)
Dennis Sivers (Portland Physics Institute/Michigan, USA)
Alexey Vladimirov (U Regensburg, Germany)

Daniele Anderle (U Tuebingen, Germany)
Mariaelena Boglione (Torino U, Italy)
Federico Ceccopieri (Liege University, Belgium)
John Collins (Penn State University, USA)
Carl Gagliardi (Texas A&M U, USA)
Marco Guzzi (U Manchester, UK)
Yuji Koike (Niigata U, Japan)
Nour Makke (INFN Trieste/Trieste U, Italy)
Stefano Melis (Turin U, Italia)
Duff Neil (MIT, USA)
German Rodrigo (U Valencia, Spain)
Andrea Signori (Vrije U Amsterdam/NIKHEF, NL)
Marco Stratmann (U Tuebingen, Germany)
Anselm Vossen (Indiana U, USA)

Outline

- 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
  - When does a jet become a jet

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

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

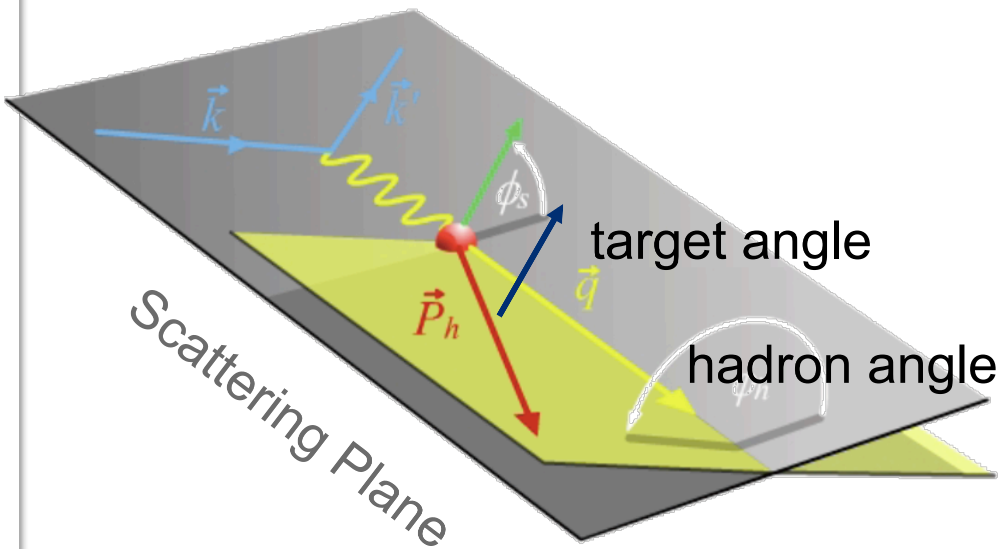
↓

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

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 (transversity), $h_{1T}^\perp$ (pretzelosity)

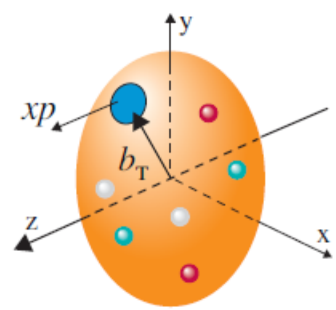
TMDs Accessible through Semi-Inclusive Physics

- 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



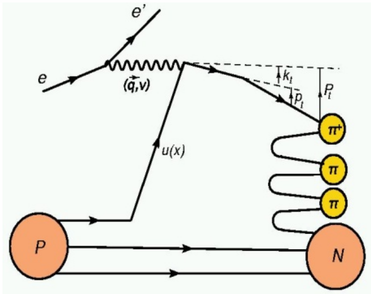
- **Sivers** angle, effect in distribution function: **(ϕ_h-ϕ_s)**

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

- **Collins** angle, effect in fragmentation function: **(ϕ_h+ϕ_s)**

  Pay attention to this one!

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 $\mathbf{p}_t$.

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 (transversity), $h_{1T}^\perp$ (pretzelosity)

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

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

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

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

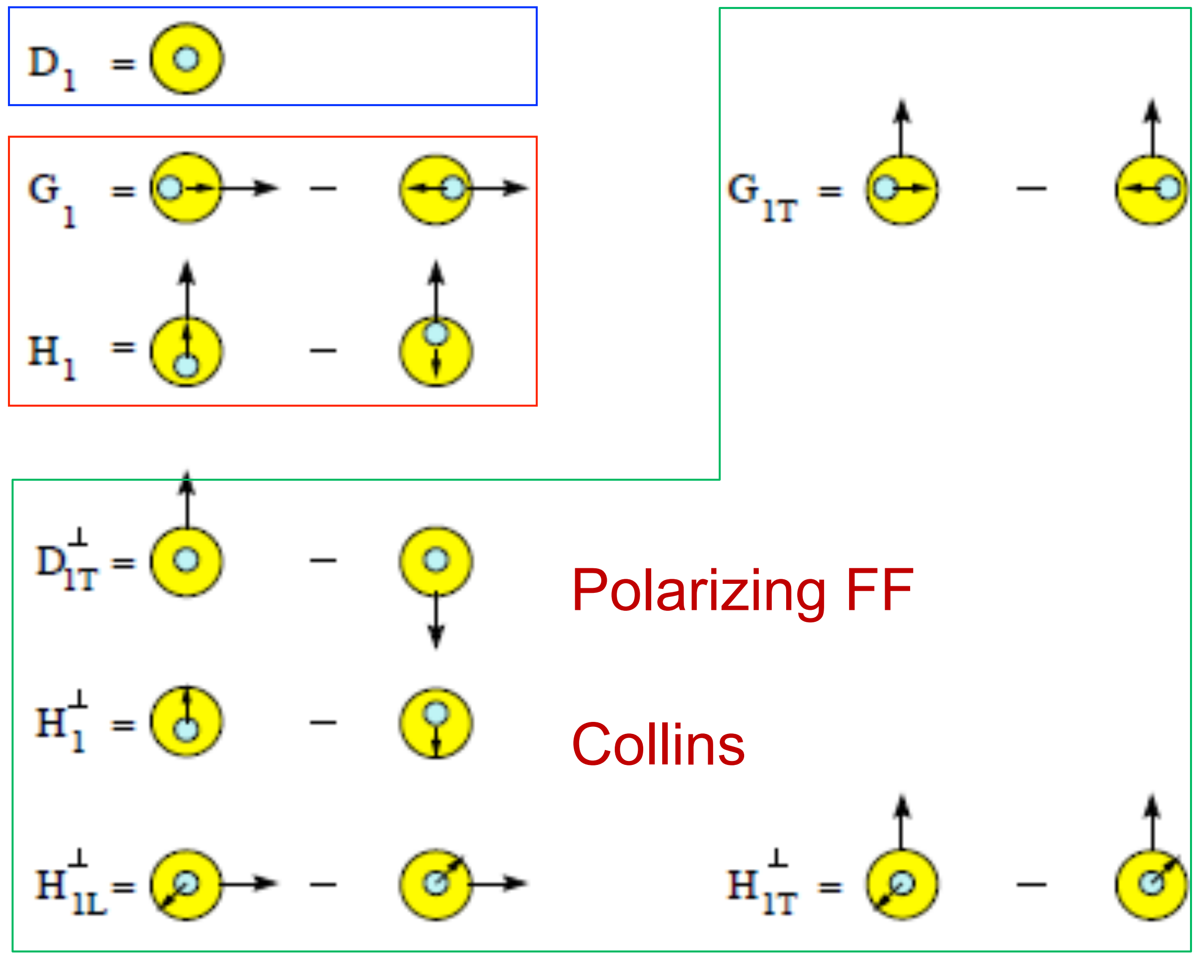
Twist-2 3D Fragmentation Functions

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

Unpolarized

Spin-spin correlations

Spin-momentum correlations



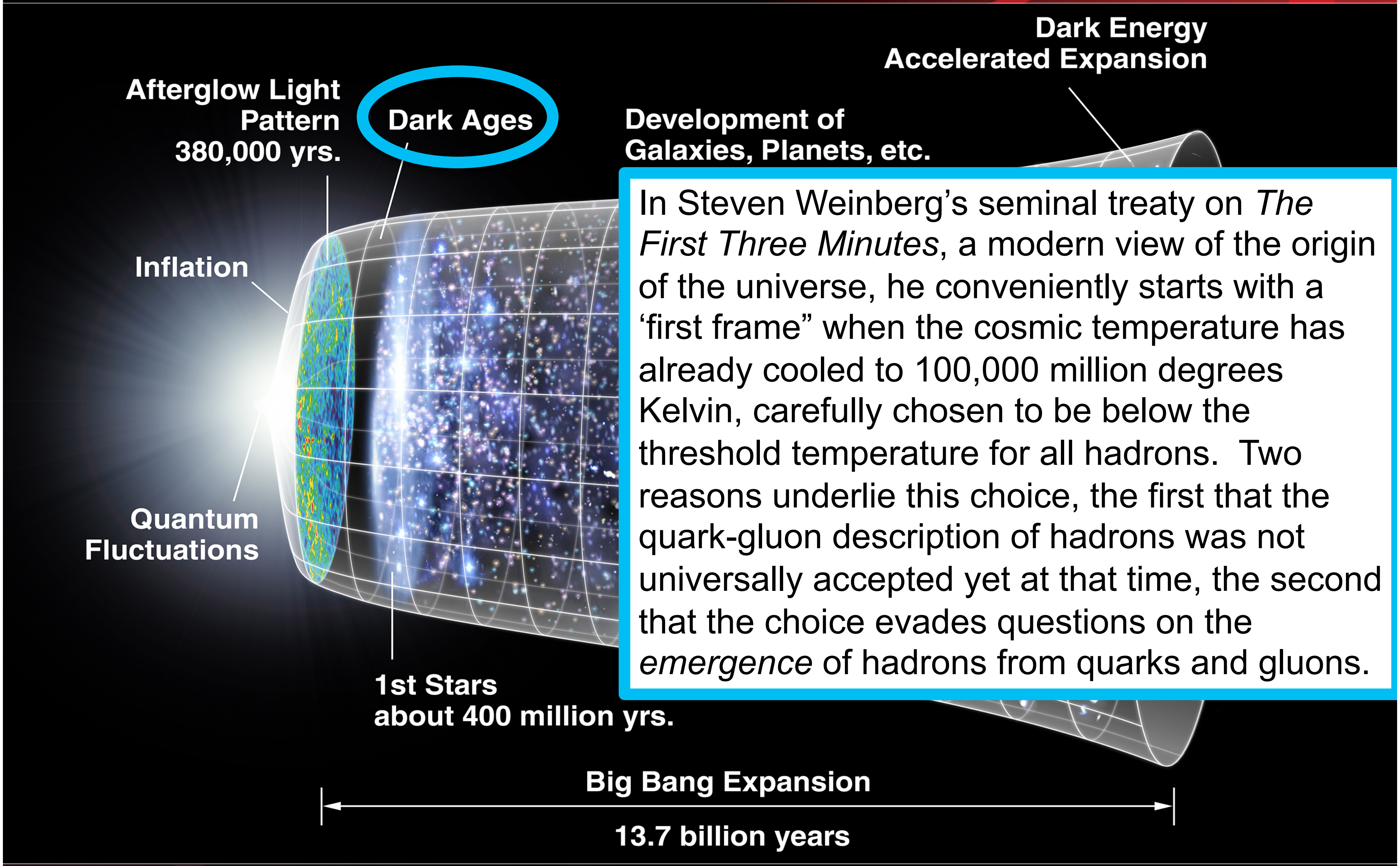
The Emergence of Hadrons

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.

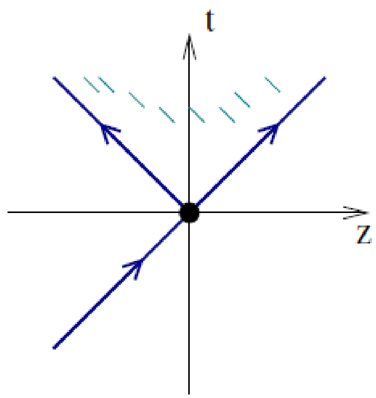
Timeline of the Universe



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

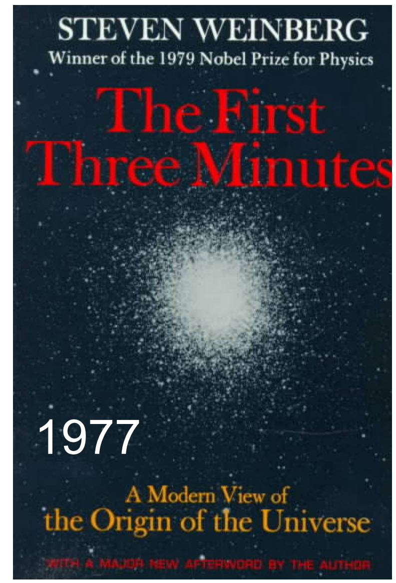


Space-time view of parton model idea of hadronization (in γ^*p CM frame)

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??

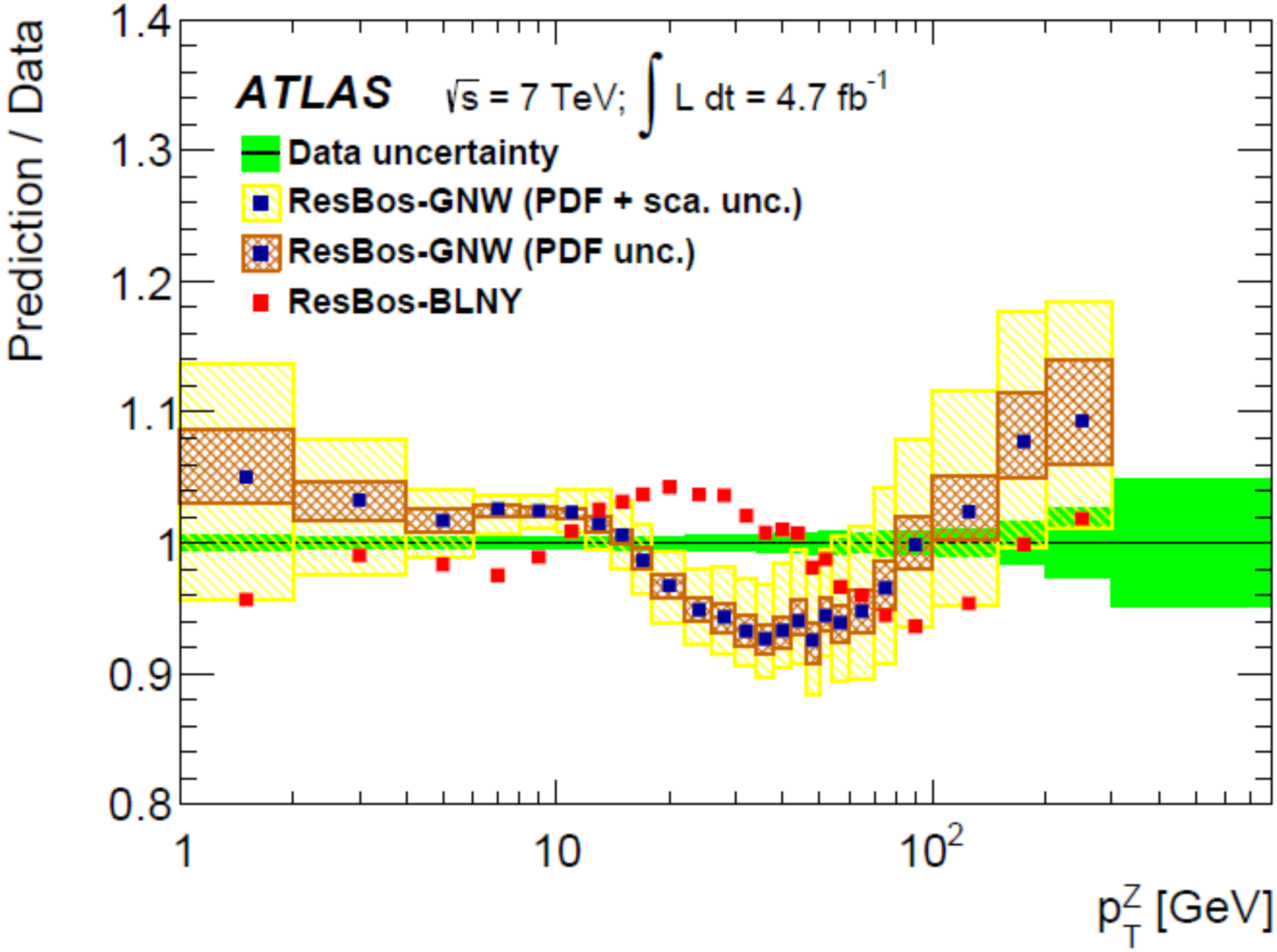


History/timeline

- 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

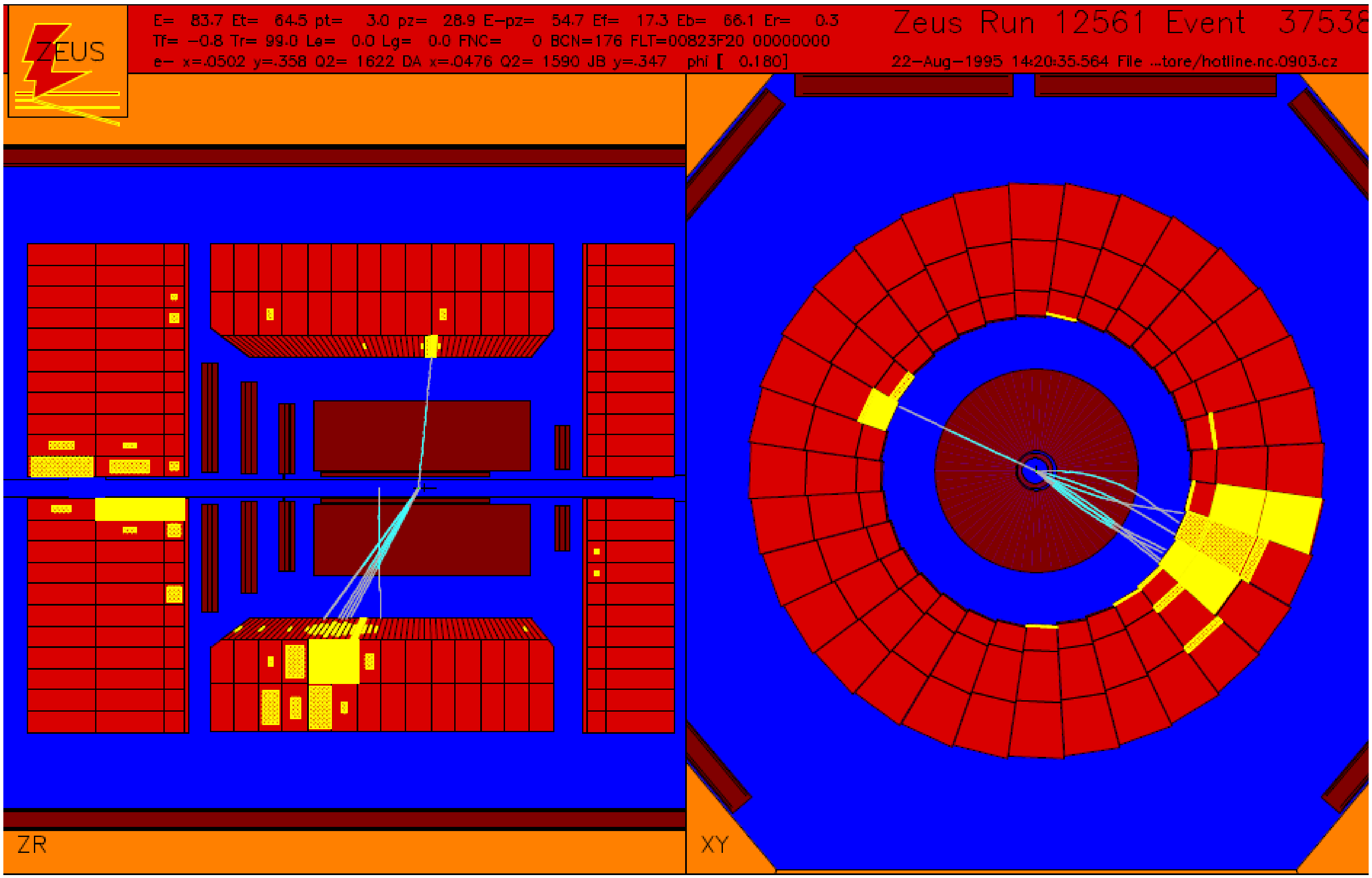
Successful predictions at High E

Z production at the LHC



High E: Jet Hadronization

Reality of jet hadronization of high energy parton



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

Confinement

Color to color neutral

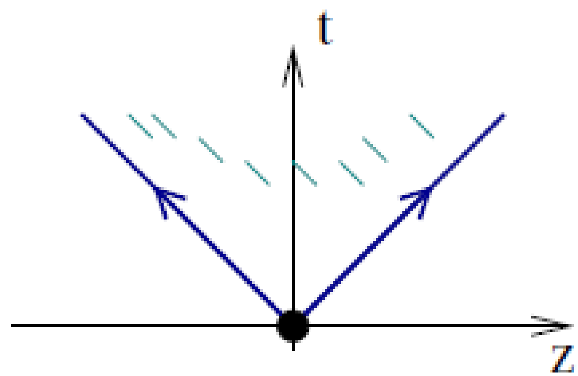
→ loss of color. But color of first thing always was balanced by another leg.

Characteristics of fragmentation process must be influenced by

- Dynamical Chiral Symmetry Breaking
- Confinement

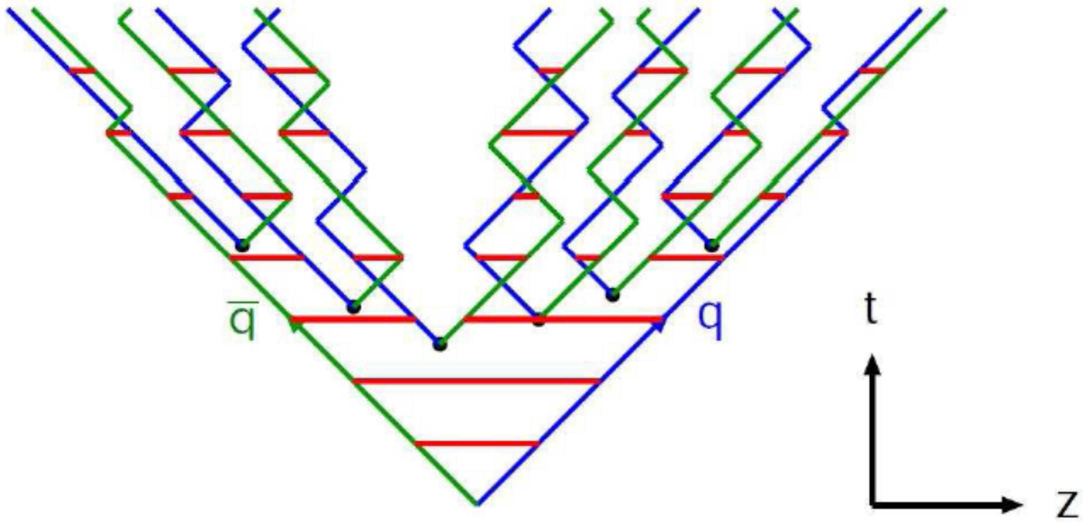
To Disembroil the Lund String

Born from intuition from the parton model era



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

To Disembroil the Lund String



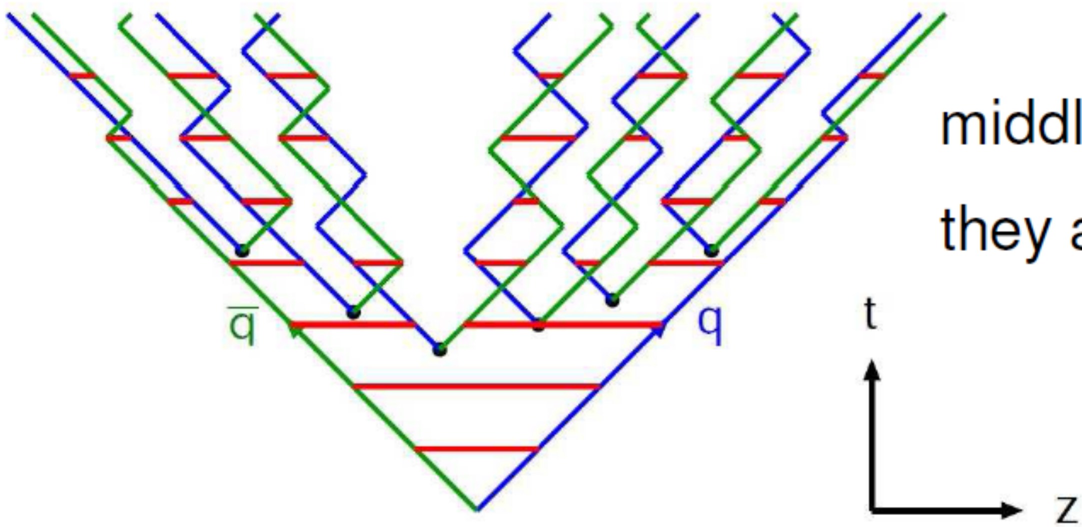
The quarks obtain a mass and a transverse momentum in the breakup through a tunneling mechanism (à la Schwinger)

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

Gives a natural supression of heavy quarks

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

To Disembroil the Lund String



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

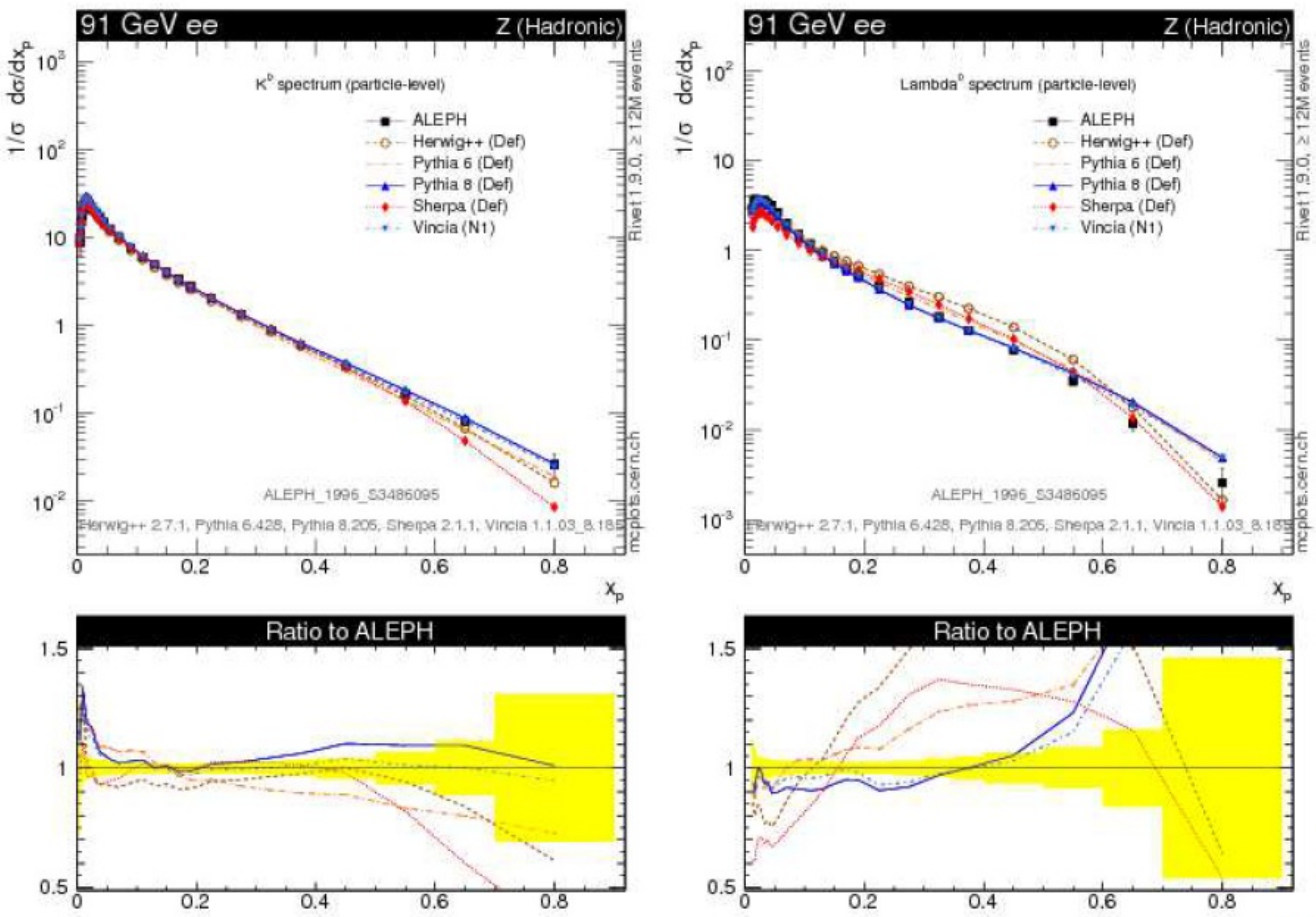
Requiring left-right symmetry we obtain a unique *fragmentation function* for a hadron taking a fraction *z* of the energy of a string end in a breakup

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

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…

To Disembroil the Lund String

- Excellent description of high-energy transverse momentum spectra
- Started from best quantum mechanical insight of the time (Schwinger)
- Incorporates acquisition of mass and transverse momentum

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

- Even more, parameters inducing transverse momentum close to what we empirically determine from TMDs – reciprocity at work?

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

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

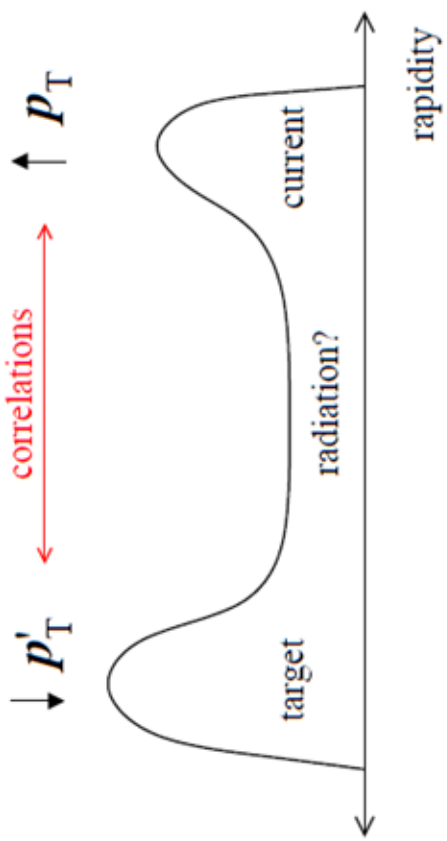
RE: Some 10 years later these seem wise words, looks like we are moving in this direction

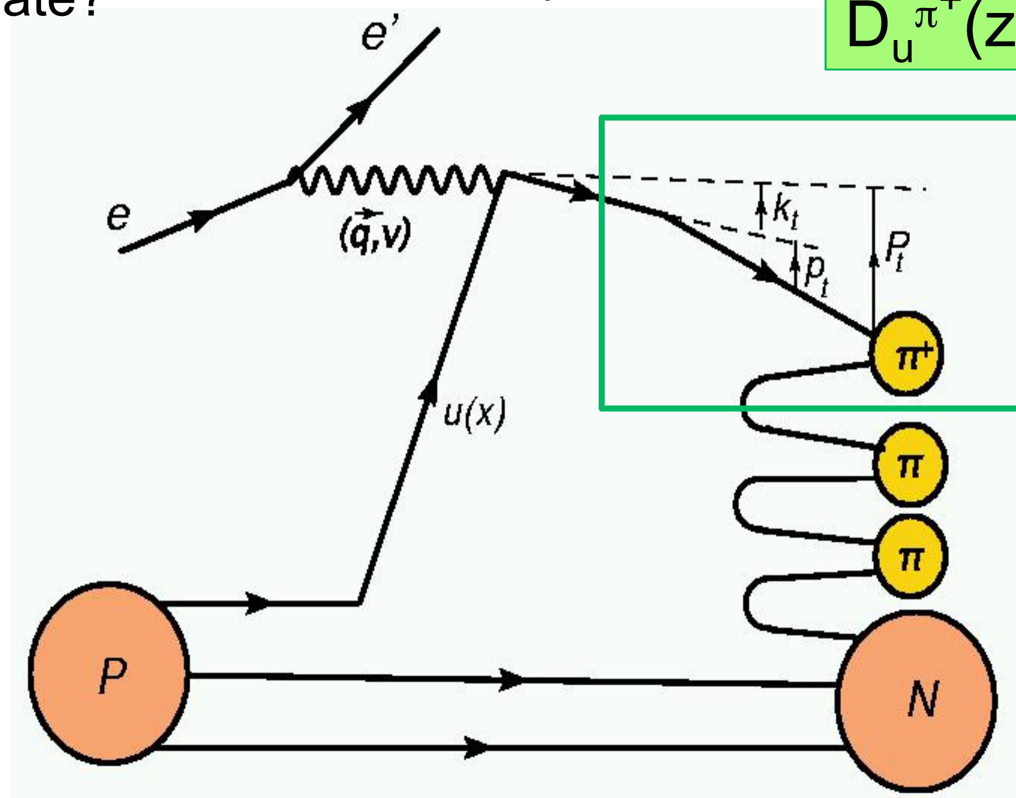
Color neutralization – it's a correlated 3D problem

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?

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* $\mathbf{p}_t$.

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

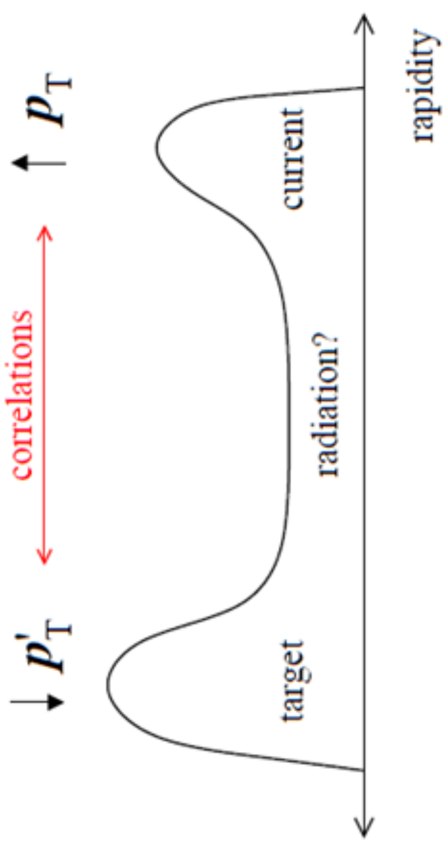


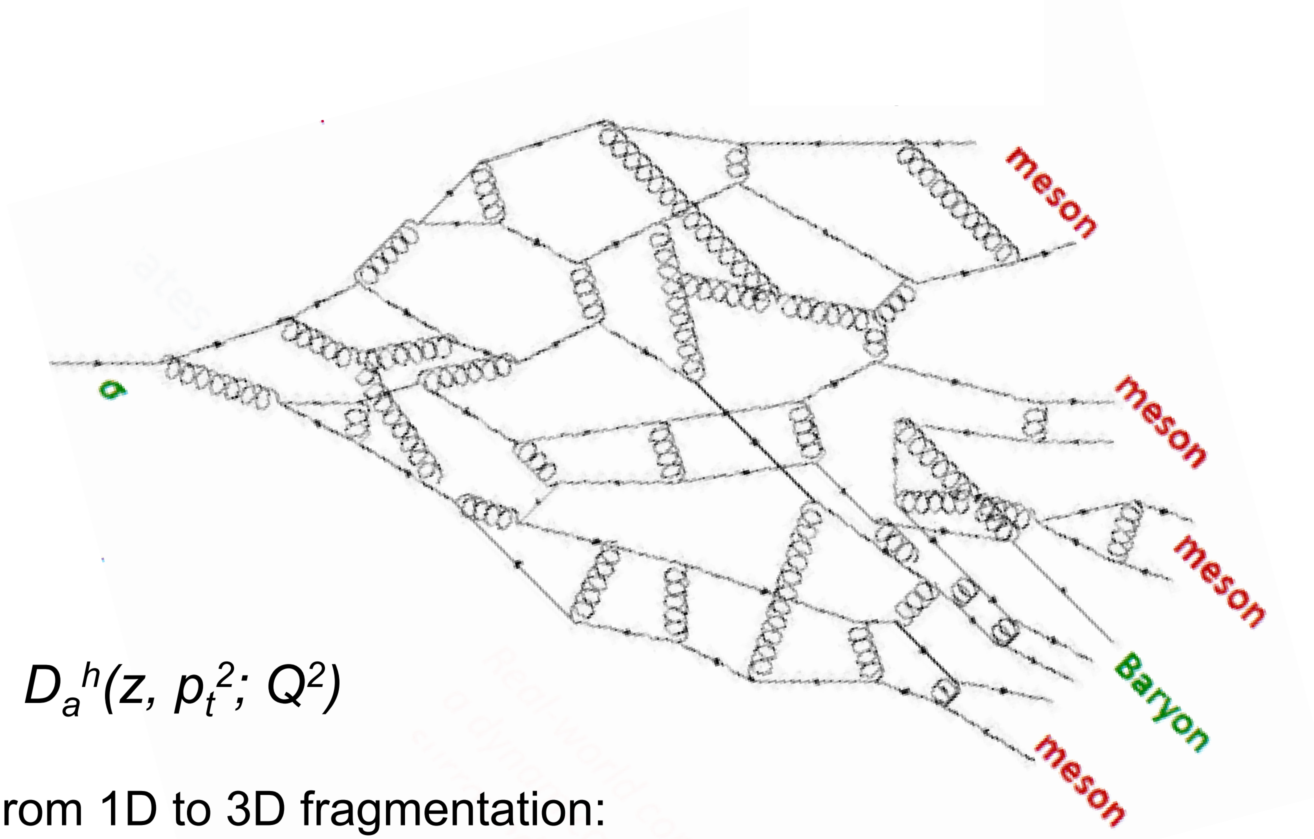


Mass of hadrons = E/c^2

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 will but limited in kinematics

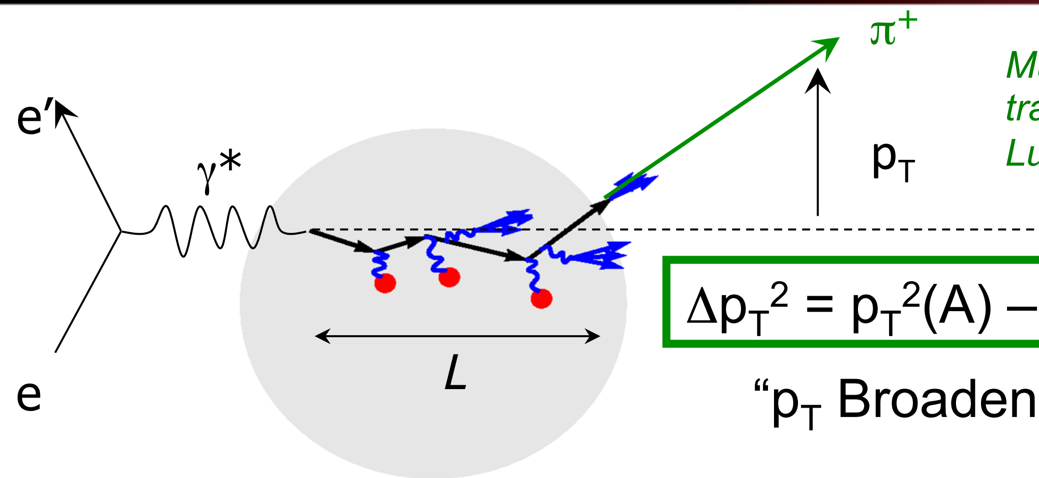
Towards a QM Description of the Final State

Balancing the transverse momentum – candles of space-time

Is there reciprocity between TMDs and fragmentation?

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

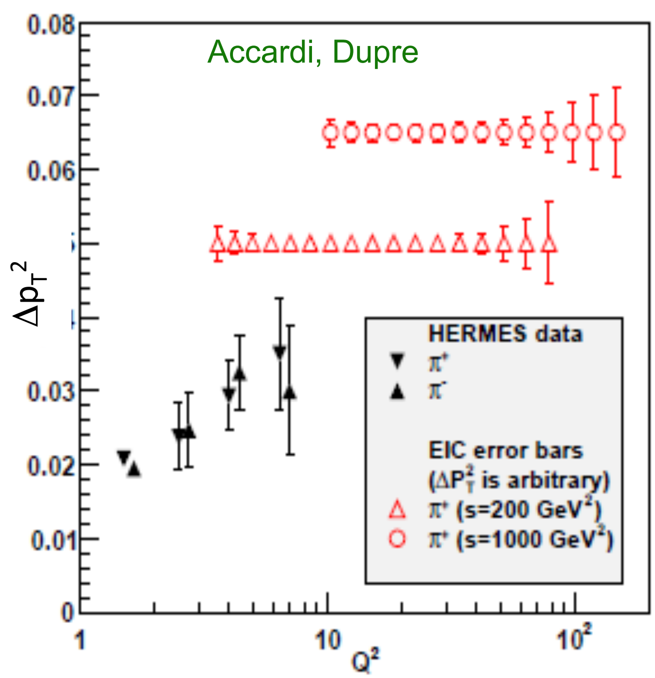
Hadronization – parton propagation in matter



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

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

"p_T Broadening"



Comprehensive studies possible:

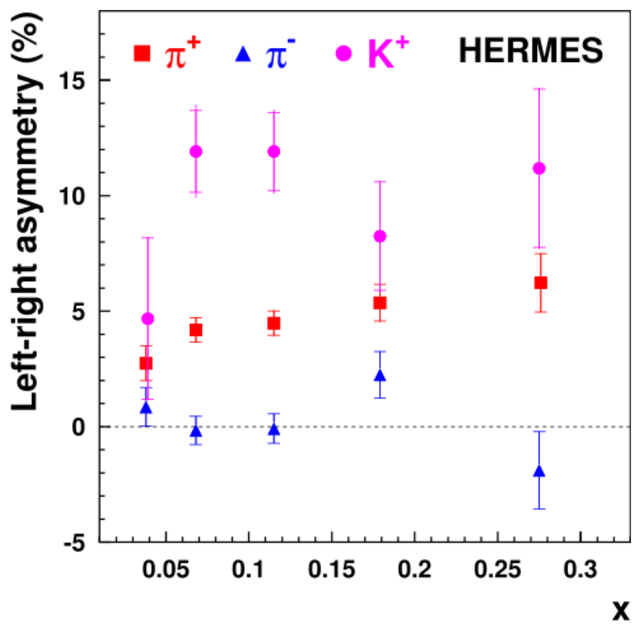
- wide range of energy ν = 10-1000 GeV
- wide range of Q^2: evolution
- Hadronization of charm, bottom
- High luminosity for 3D and correlations

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

Towards a QM Description of the Final State

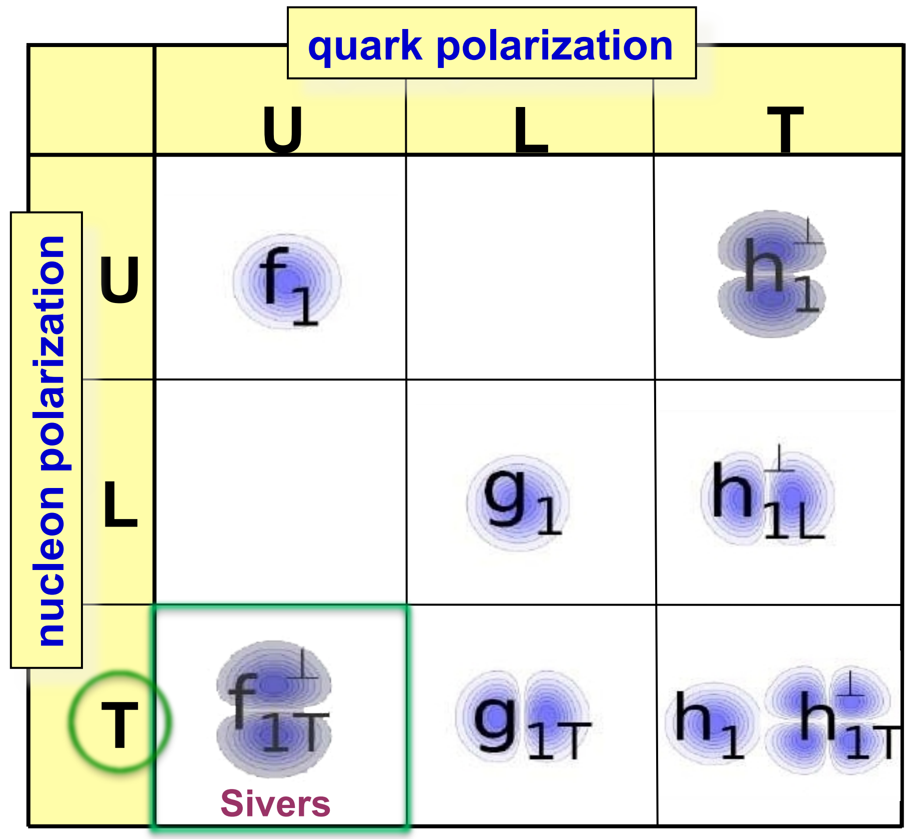
The Collins Function

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.



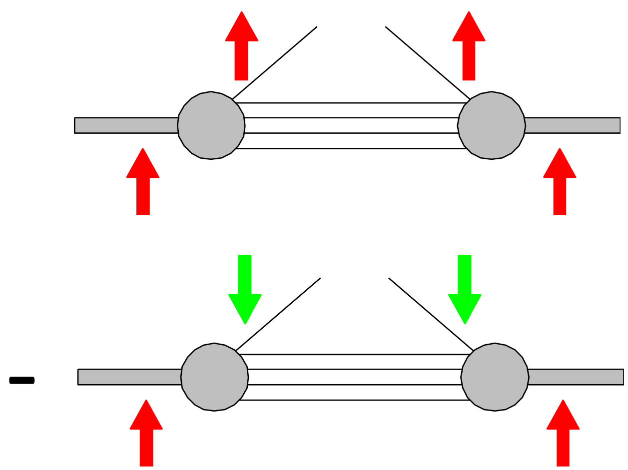
Towards a QM Description of the Final State

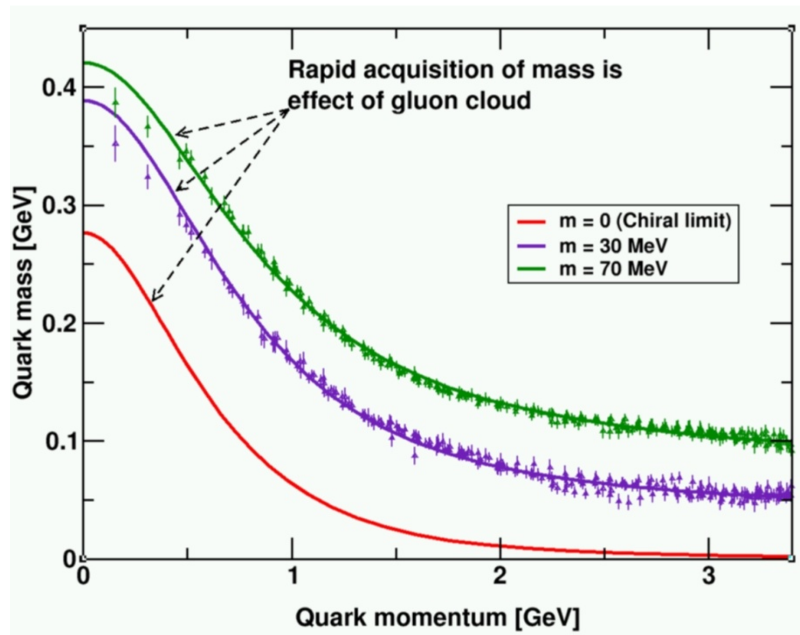
The Collins Function – candle of DχSB

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 due to small current quark mass as effects ~ m_q/Q. Chiral symmetry breaking (in dynamical situation) can do it.
2) Transverse momentum correlations.

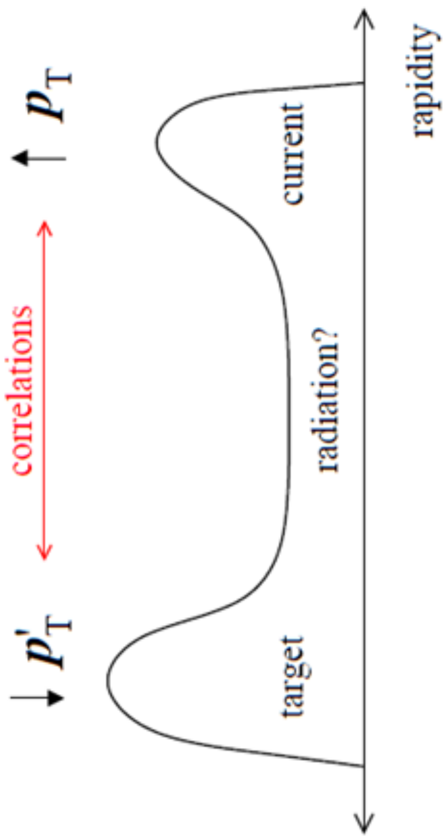
δq(x) ~ (in transverse basis)





Towards a QM Description of the Final State

The Collins Function – candle of DχSB

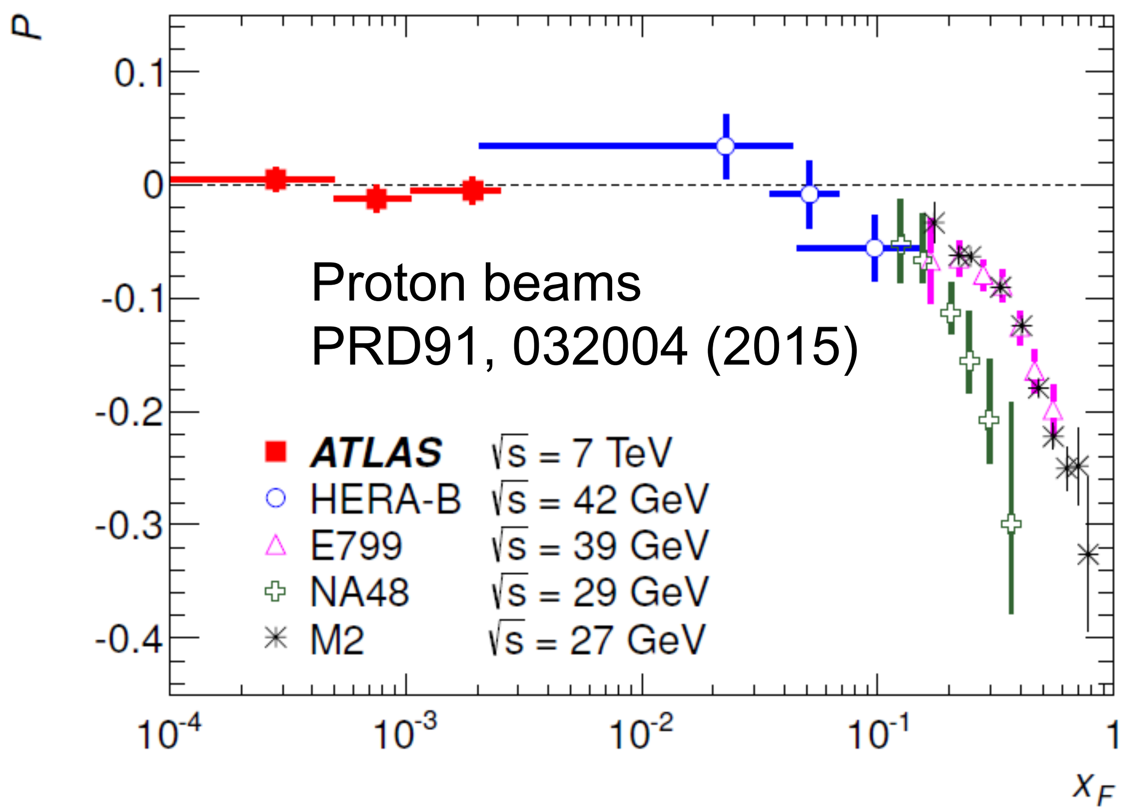


Map the Collins function
over the regions of rapidity?

Towards a QM Description of the Final State

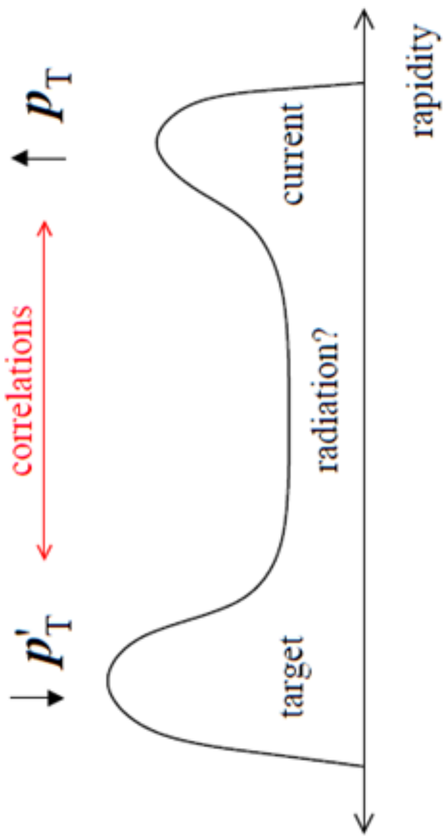
Balancing the Spin

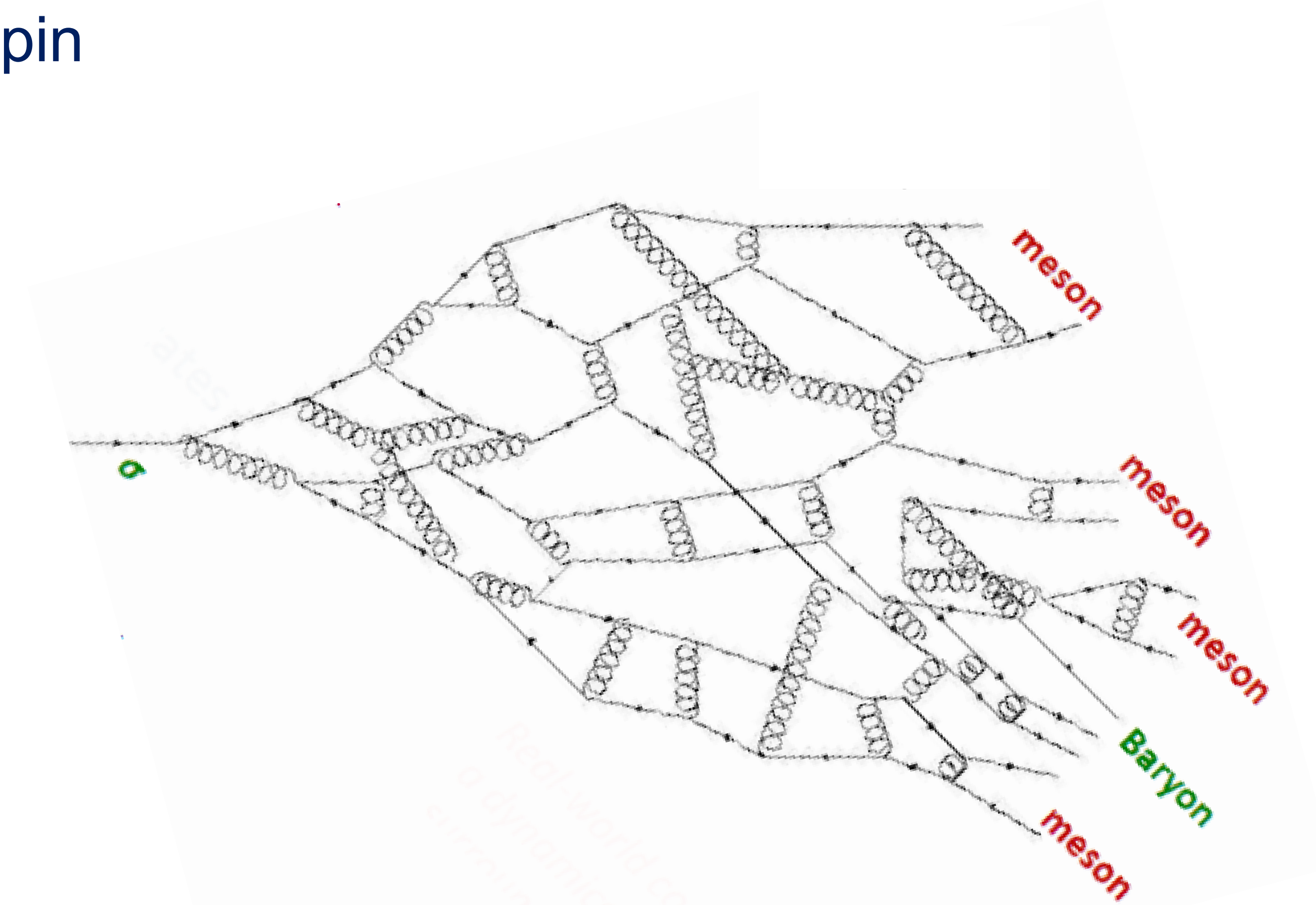
Feynman-x dependence of Λ Polarization in hadronic collisions



Towards a QM Description of the Final State

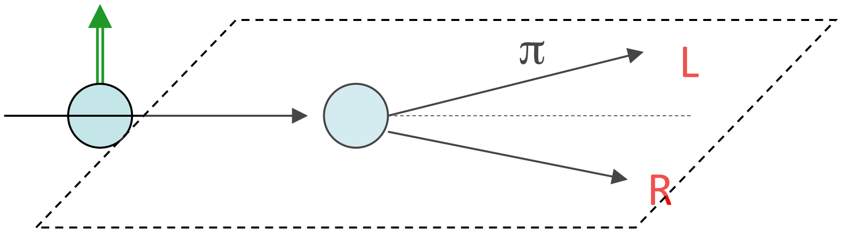
Balancing the Spin





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

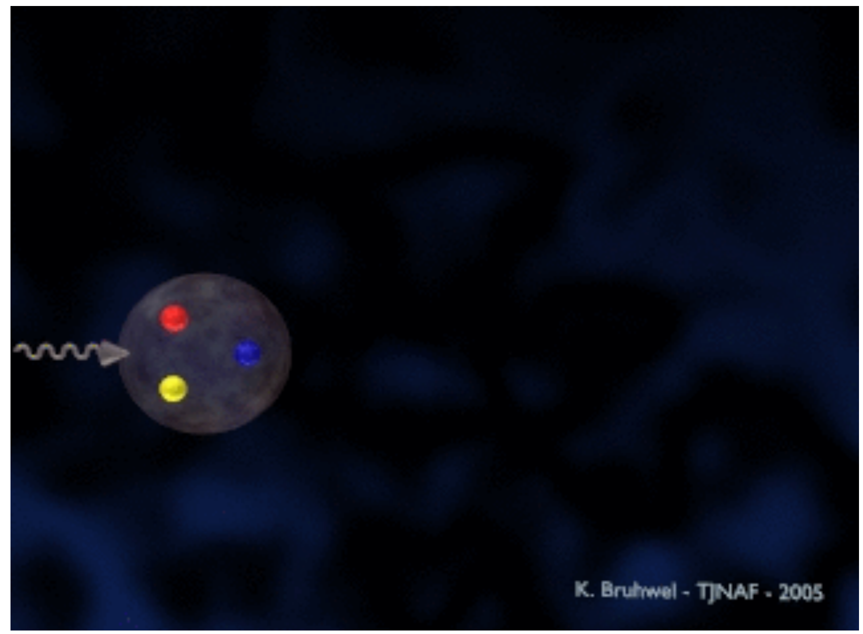
Towards a QM Description of the Final State



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

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 transversity, $h_{1T}^\perp$ pretzelosity



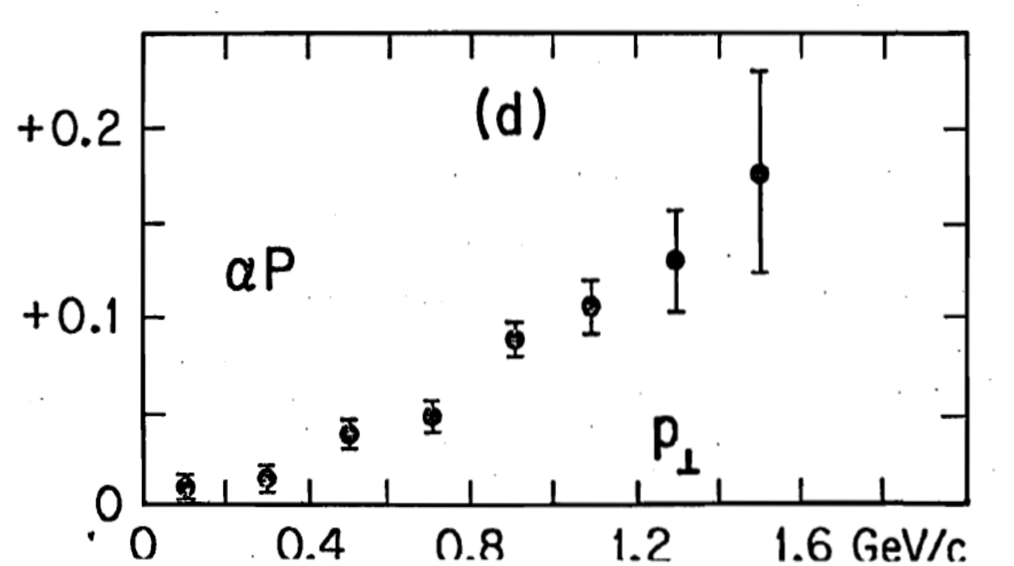
Spin-Orbit Effects in Fragmentation

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

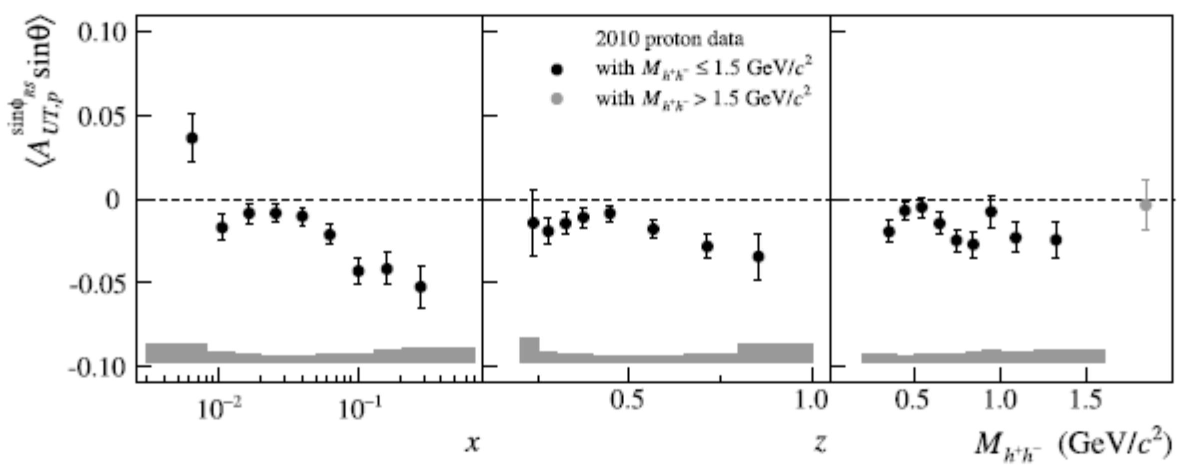
PRL36, 1113 (1976)



Towards a QM Description of the Final State

Creating Polarization from Nothing – a recent TMD example

Di-hadron interference fragmentation function

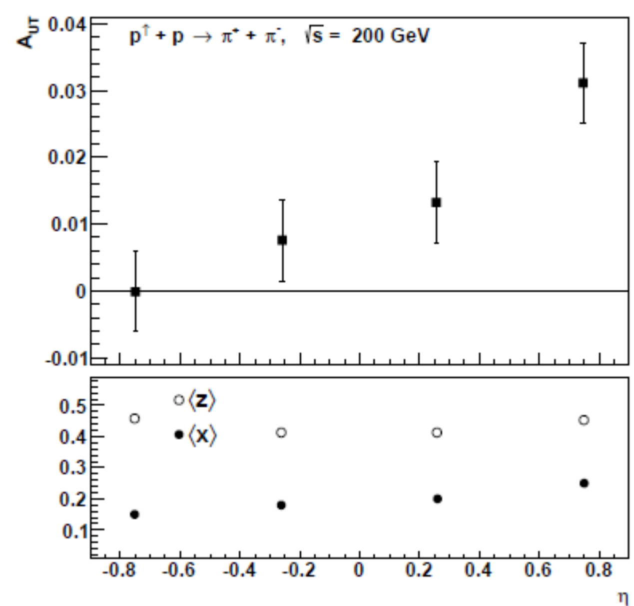


COMPASS, PLB736, 124 (2014)

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

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

STAR, arXiv:1504.00415

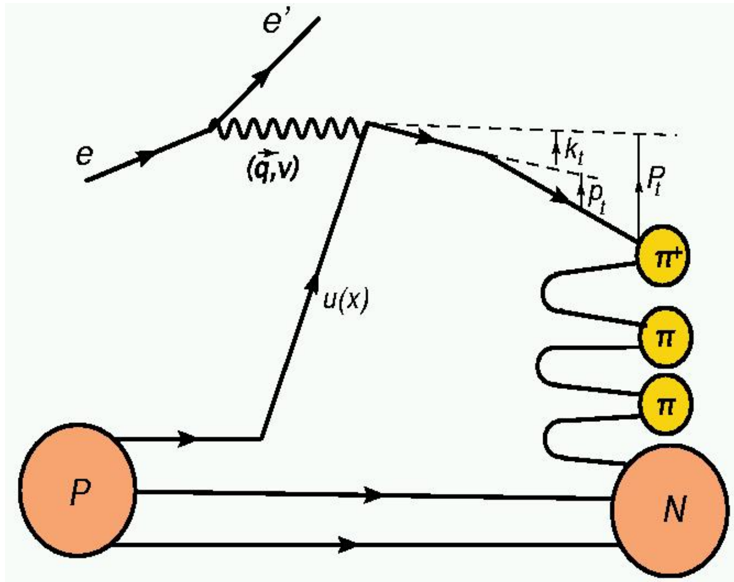


- Clear nonzero asymmetry
- Pseudorapidity dependence
- Sensitive to transversity x IFF

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 gets diluted fast, maybe perhaps more a 12-GeV experiment.



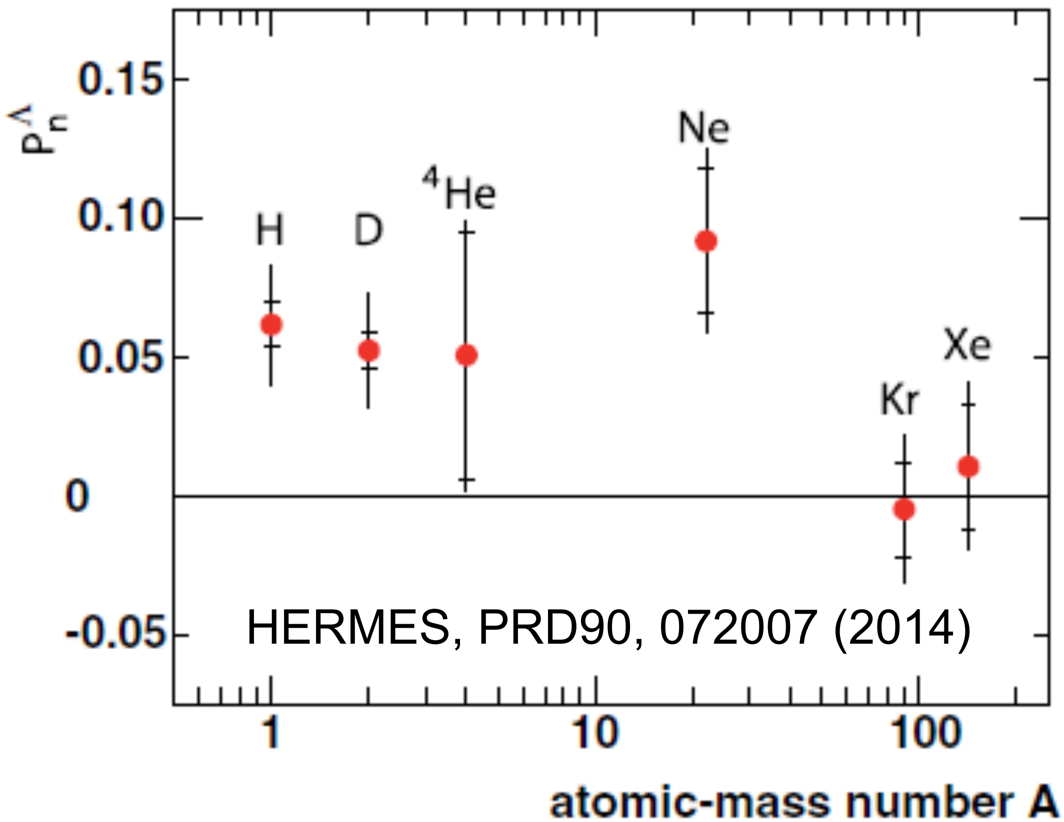
Want only few pions produced

$$e + p \rightarrow e' + \vec{p} + X \text{ (few mesons only...)}$$

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

Towards a QM Description of the Final State

Creating Polarization from Nothing

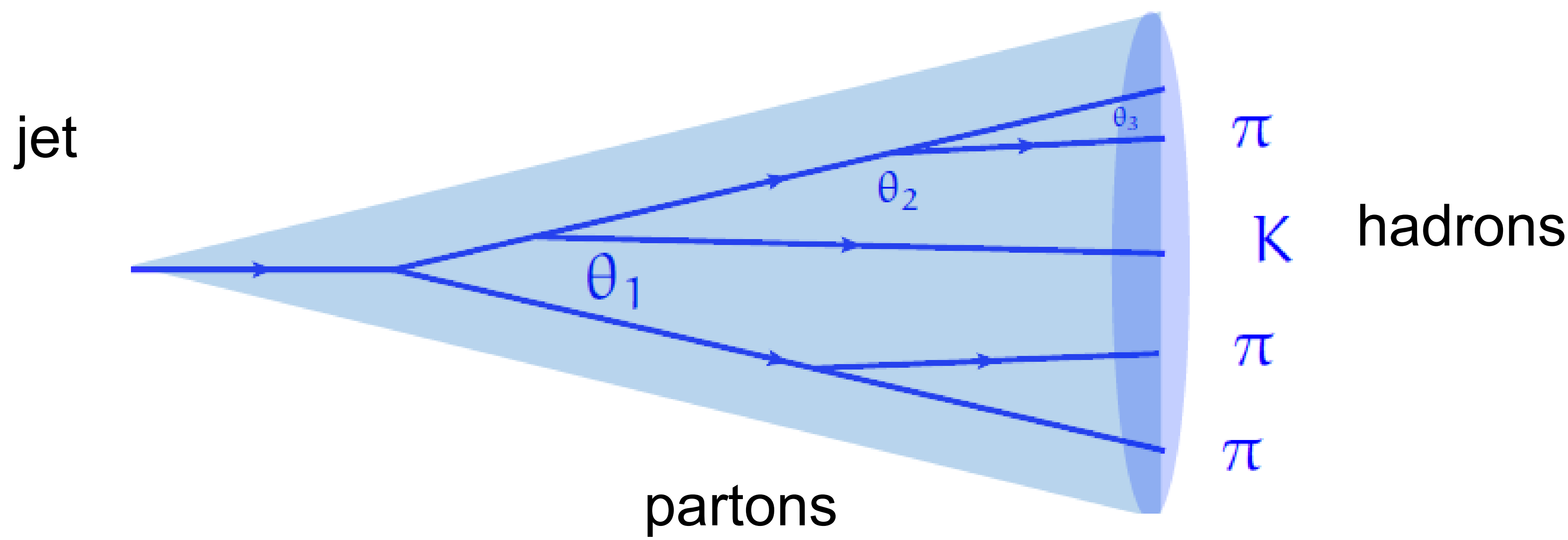


Lambda polarization maintained in the (light to medium-heavy) nuclear medium, as observed in semi-inclusive DIS

Towards a QM Description of the Final State

When Does a Jet Become a Jet – understand the cosmology of the jet

- At some point, if (nearly) all particles measured within reconstructed jet, could you potentially constrain sum of probabilities for each flavor parton to be (nearly) 1?
- Or, alternately, if all particles are measured, how many (or few) does one need to obtain jet characteristics? Is there a hadron-jet duality?
- Can we link this to jet substructure observables? → Ivan Vitev talk
- Note: the Lund String-Breaking Model does not care about jets or hadrons



Outlook

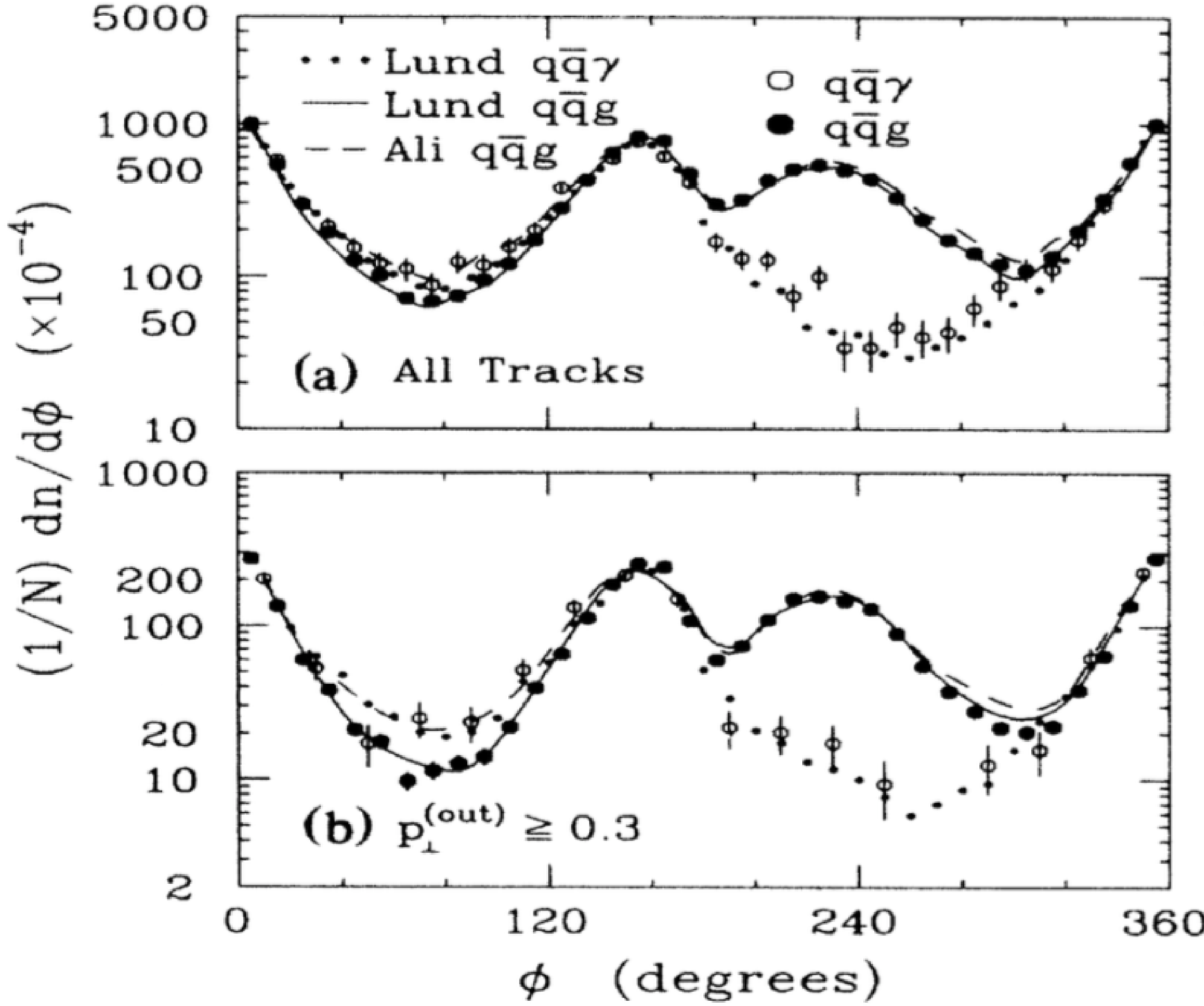
Objects like correlation functions (fragmentation functions (TMD, collinear, dihadron, etc) need to be resolved and studied in terms of their underlying non-perturbative physics.

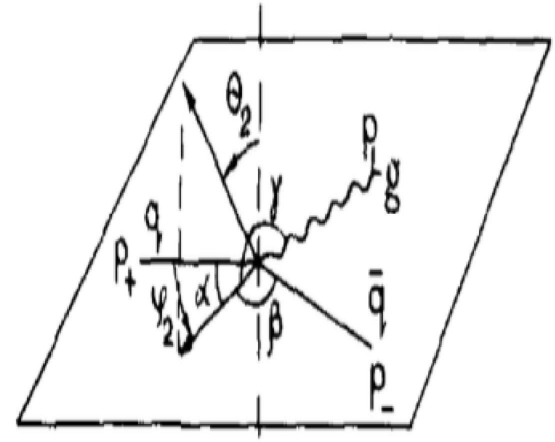
Characteristics of fragmentation process must be influenced by

- Dynamical Chiral Symmetry Breaking
- Confinement

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

Lund Model and Three-Jet Events





TMDs and 3D FFs

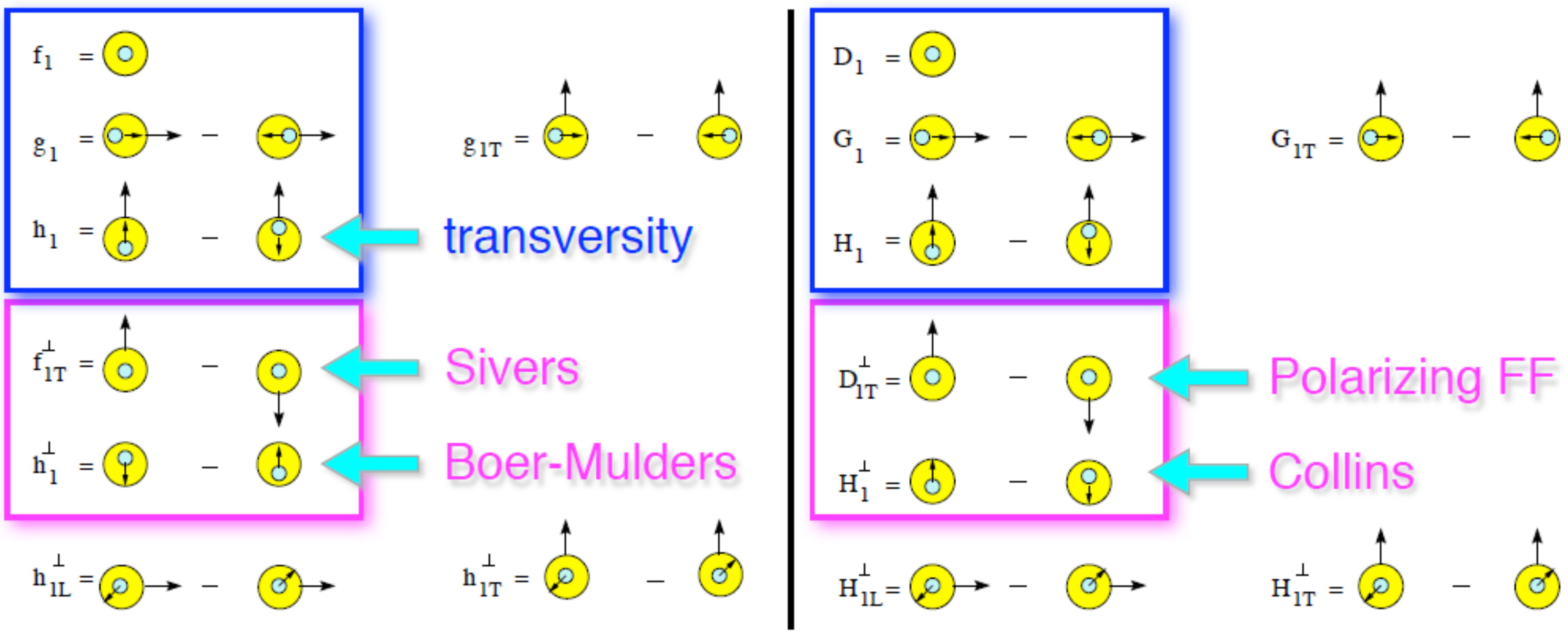
Functions surviving on integration over Transverse Momentum

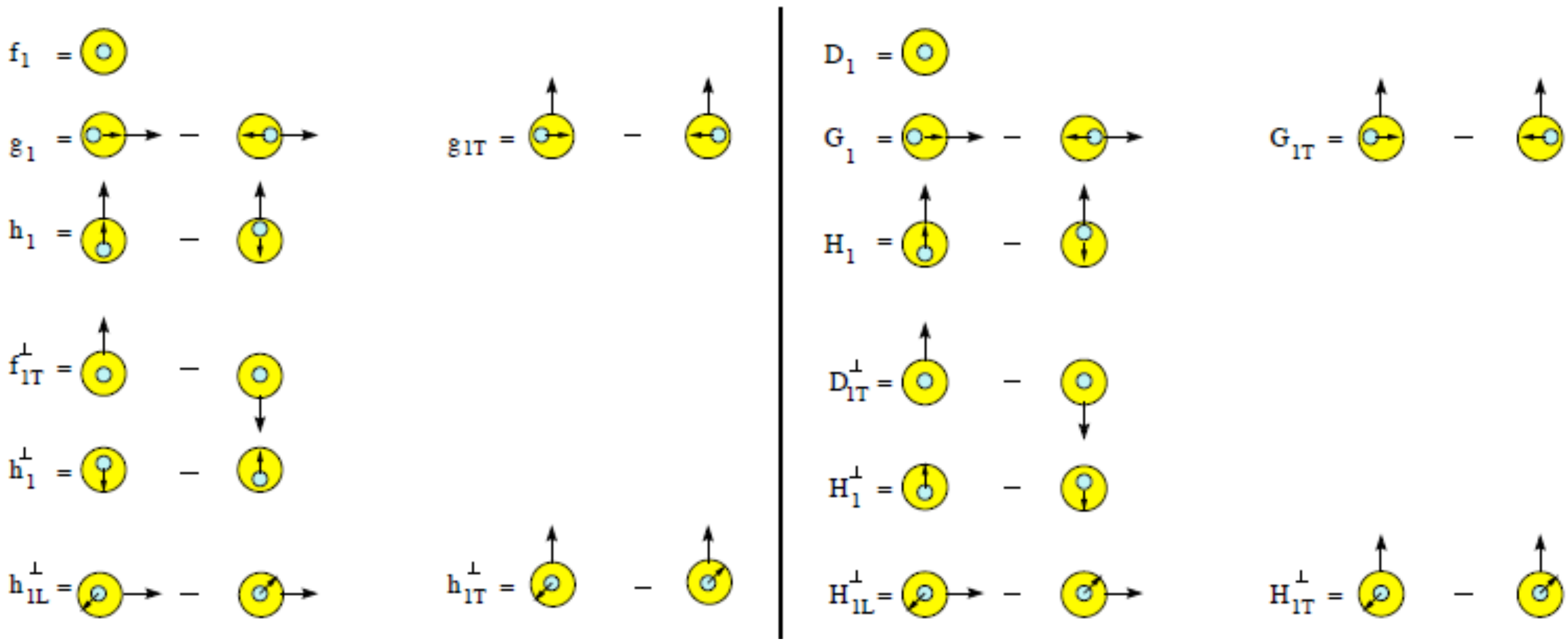
The **others** are sensitive to ***intrinsic k_T*** in the nucleon & in the fragmentation process

Mulders & Tangerman, NPB 461 (1996) 197

Distribution Functions

Fragmentation Functions




f_1 =
g_1 = −
g_{1T} = −
h_1 = −
$f_{1T}^{\perp}$ = −
$h_1^{\perp}$ = −
$h_{1L}^{\perp}$ = −
$h_{1T}^{\perp}$ = −
D_1 =
G_1 = −
G_{1T} = −
H_1 = −
$D_{1T}^{\perp}$ = −
$H_1^{\perp}$ = −
$H_{1L}^{\perp}$ = −
$H_{1T}^{\perp}$ = −