Uncovering the inner structure of matter: the 3D structure of nucleons

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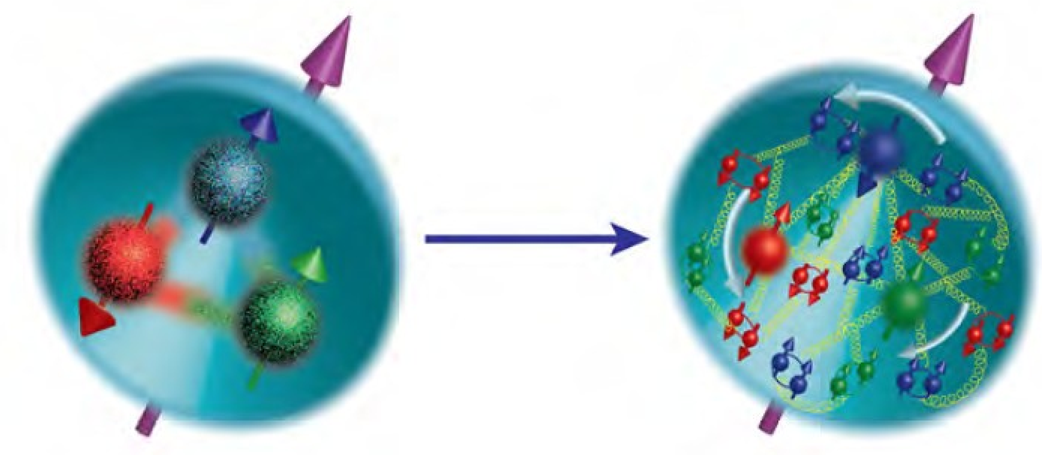
3D Nucleon Structure

- Several decades of experiments on deep inelastic scattering (DIS) of electron or muon beams off nucleons have taught us about how quarks and gluons share the momentum of a fast-moving nucleon.

- However, they have not resolved the question of how partons share the nucleon's spin and build up other nucleon intrinsic properties, such as its mass and magnetic moment. Earlier studies, in fact, were limited to providing a one-dimensional (longitudinal) view of nucleon structure.

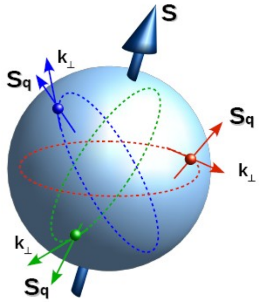
- Our goal is to achieve a much greater insight into the nucleon structure, and to build multi-dimensional maps of the distributions of partons in space, momentum (including momentum components transverse to the nucleon momentum), spin, and flavour.



The 3D Structure of the Nucleon

The exploration of the ***3-dimensional structure of the nucleon***, both in momentum and in configuration space, is one of the major issues in high energy hadron physics.

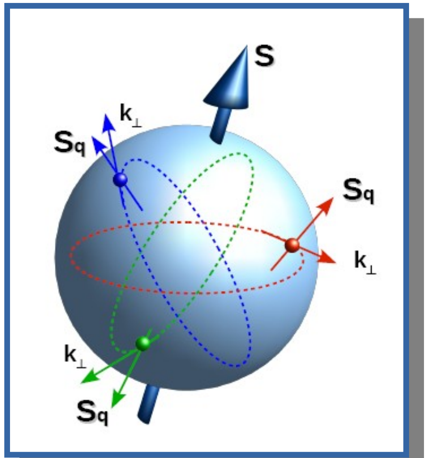
Information on the 3-dimensional structure of the nucleon is embedded in the ***Transverse Momentum Dependent*** distribution and fragmentation functions (***TMDs***).

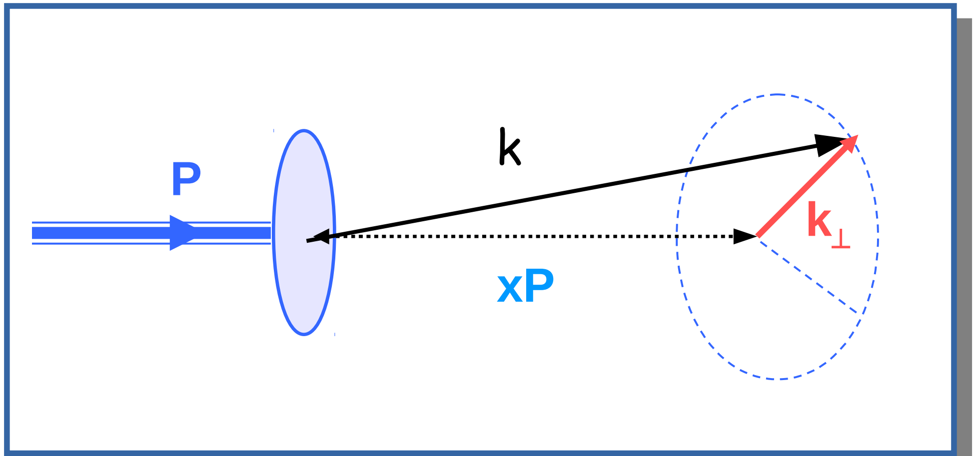


In a very simple **phenomenological** approach, hadronic cross sections and spin asymmetries are generated, within a ***QCD* factorization** framework, as convolutions of **distribution** and (or) **fragmentation** functions with **elementary cross sections**.

This simple approach can successfully describe a wide range of experimental data.

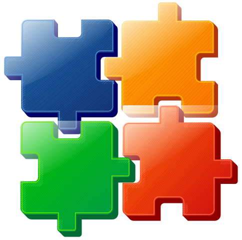
Intrinsic Transverse Momentum





We cannot learn about the spin structure of the nucleon without taking into account the **transverse motion** of the partons inside it

Transverse motion is usually integrated over, but there are important **spin-$k_\perp$** correlations which should not be neglected



Several theoretical and experimental evidences for transverse motion of partons within nucleons, and of hadrons within fragmentation jets.

Where can we learn about the 3D structure of matter ?

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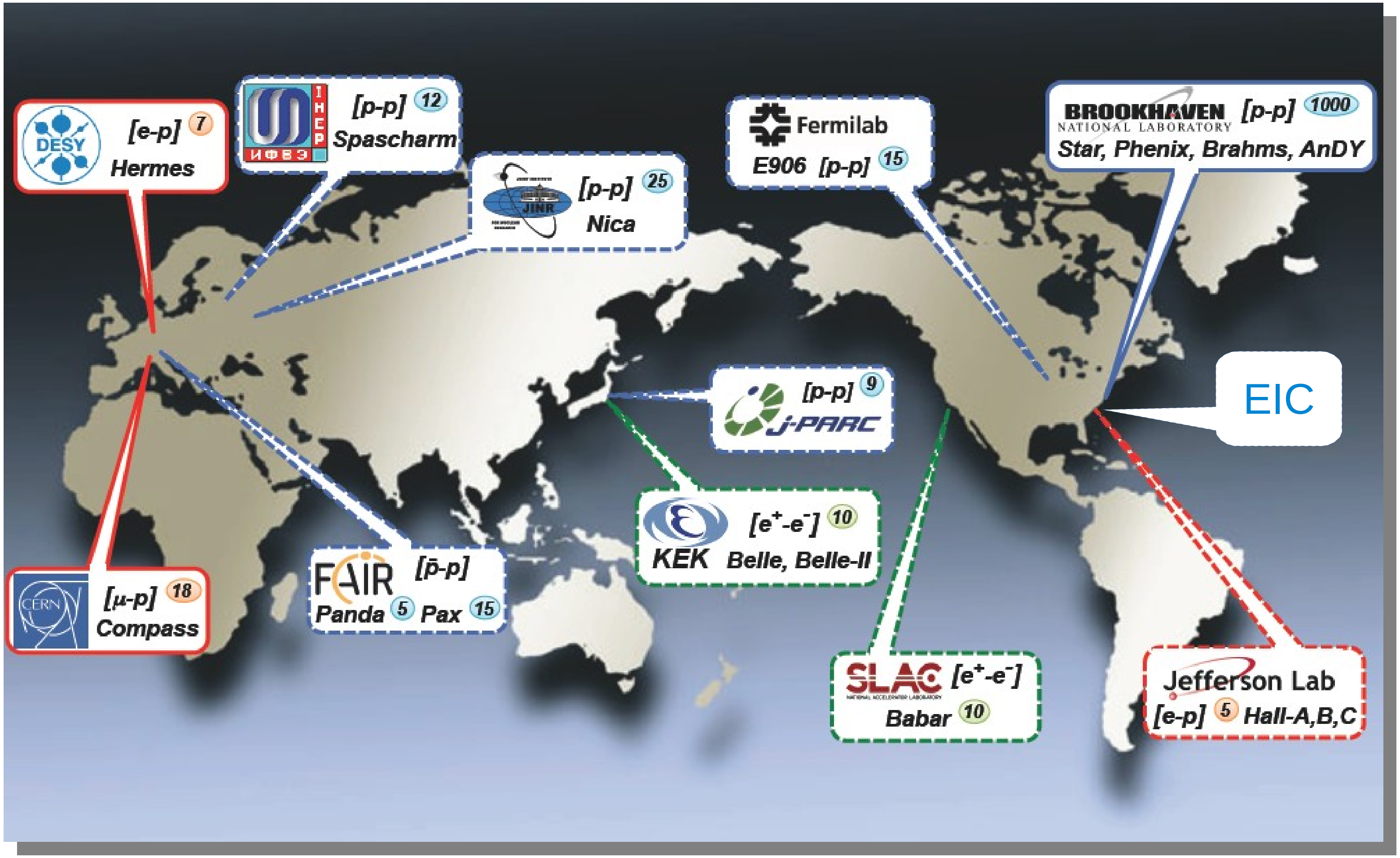
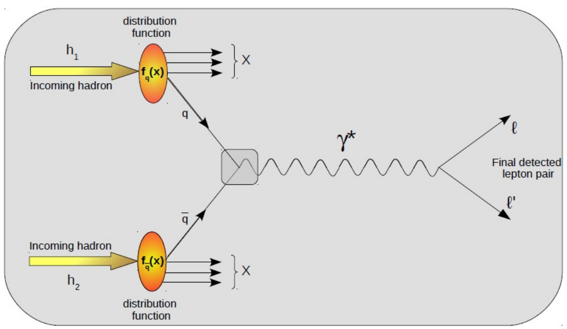


Experimental data for TMD studies

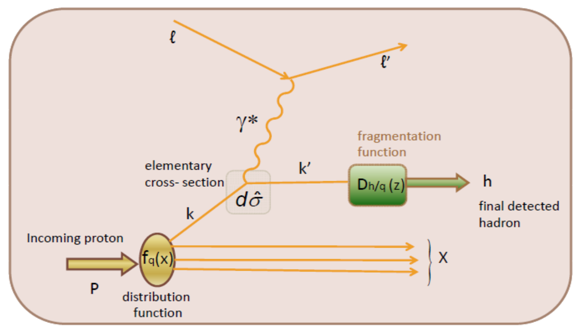
Unpolarized and Polarized Drell-Yan scattering



$$\sigma_{Drell-Yan} = f_q(x,k_\perp)\otimes f_{\bar q}(x,k_\perp)\otimes \hat\sigma^{q\bar q\to\ell\ell'}$$

Allows extraction of distribution functions

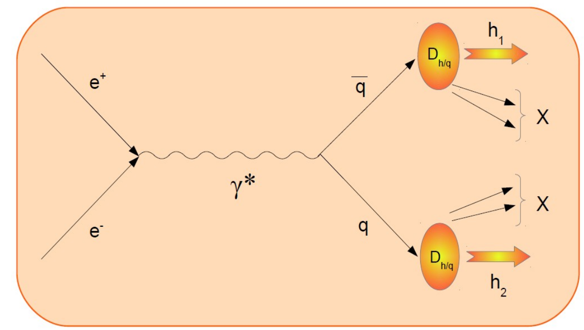
Unpolarized and Polarized SIDIS scattering



$$\sigma_{SIDIS} = f_q(x)\otimes\hat\sigma\otimes D_{h/q}(z)$$

Allows extraction of distribution and fragmentation functions

$e^+ e^- \to h_1\, h_2\, X$



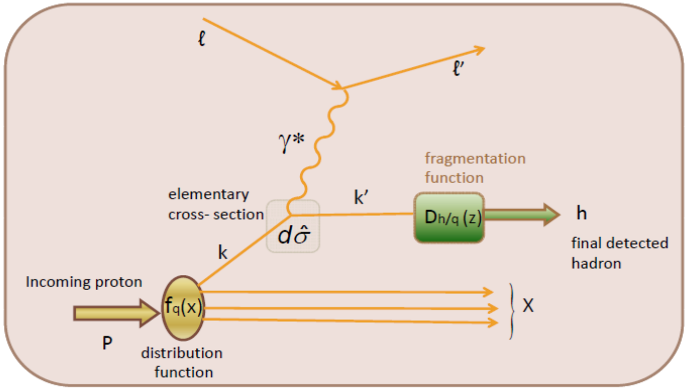
$$\sigma_{h1\,h2}\propto D(z_1)\otimes D(z_2)\otimes\hat\sigma$$

Allows extraction of fragmentation functions

Experimental data for TMD studies

In SIDIS reactions, the hadron, which results from the fragmentation of a scattered quark, “remembers” the original motion of the quark, including its transverse momentum.

Unpolarized and Polarized SIDIS scattering

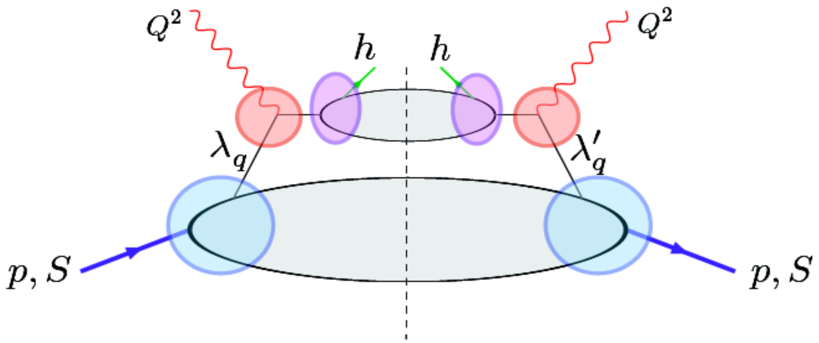


$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

Allows the extraction of TMD distribution and fragmentation functions

From the theory point of view ...

Perturbative QCD
Renormalization
Parton model
Factorization theorems
...



TMD factorization holds at large Q^2 and $P_T \approx k_\perp \approx \lambda_{QCD}$

Two scales: $P_T << Q^2$

(Collins, Soper, Ji, Ma, Yuan, Qiu, Vogelsang,Collins, Metz)

$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell'+h+X}}{dx_B\,dQ^2\,dz_h\,d^2\boldsymbol{P}_T\,d\phi_S} = \rho^{\ell,S_\ell}_{\lambda_\ell,\lambda'_\ell}\otimes\rho^{q/p,S}_{\lambda_q,\lambda'_q}\,\hat f_{q/p,S}(x,\boldsymbol{k}_\perp)\otimes \hat M_{\lambda_\ell,\lambda_q;\lambda_\ell,\lambda_q}\,\hat M^*_{\lambda'_\ell,\lambda'_q;\lambda'_\ell,\lambda'_q}\otimes\hat D^h_{\lambda_q,\lambda'_q}(z,\boldsymbol{p}_\perp)$$

TMD-PDF **hard scattering** **TMD-FF**

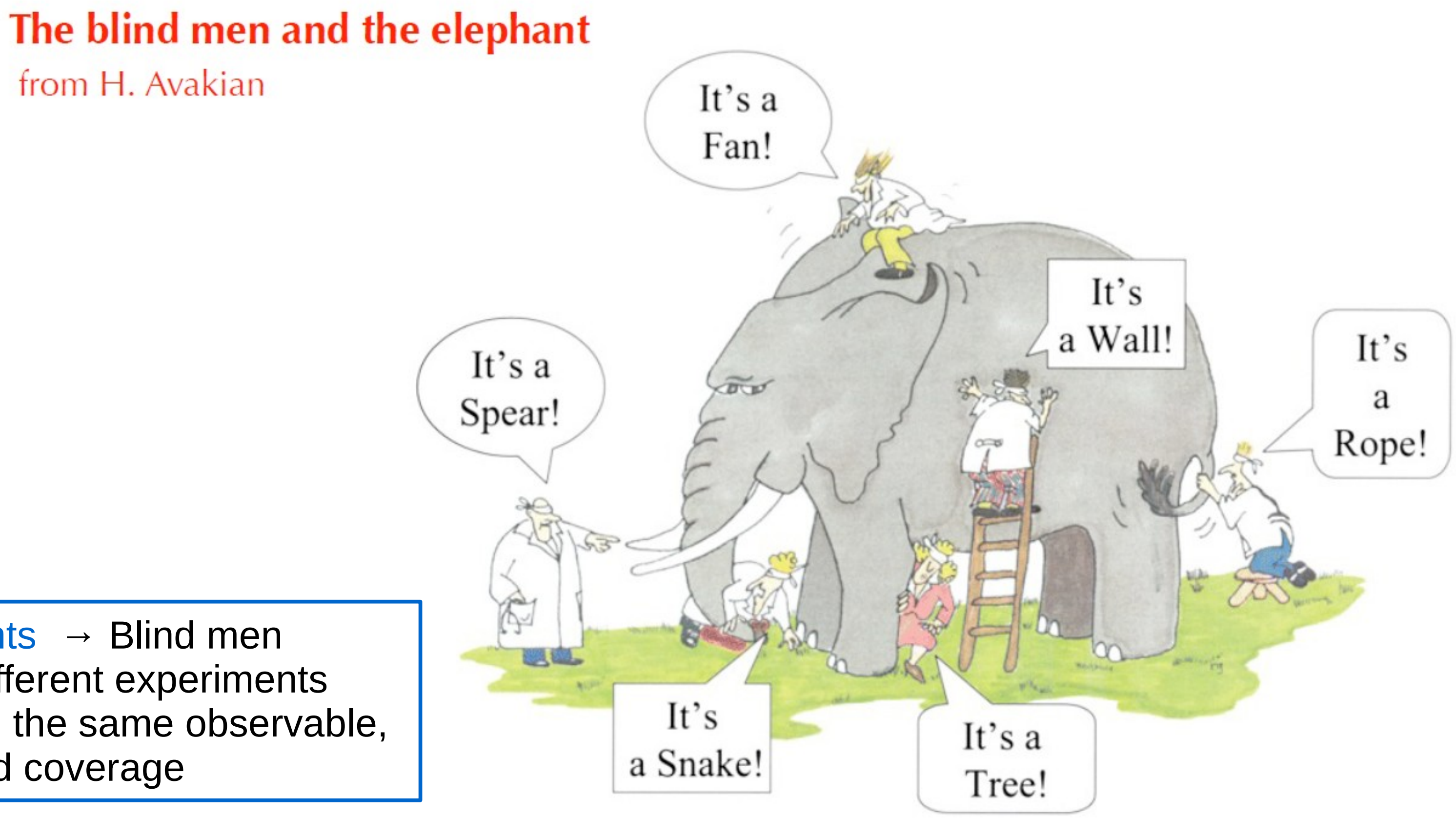
Phenomenology

THEORY
- Perturbative QCD
- Renormalization
- Factorization theorems
- Resummation
- ...

PHENOMENOLOGY
Mission: devise simple flexible and efficient models to link THEORY with EXPERIMENTS

EXPERIMENTS
- Drell-Yan scattering
- Di-hadron production from e+e- scattering
- DIS and SIDIS processes
- Inclusive single particle production from hadronic scattering

Phenomenology



Experiments → Blind men
Several different experiments measuring the same observable, with limited coverage

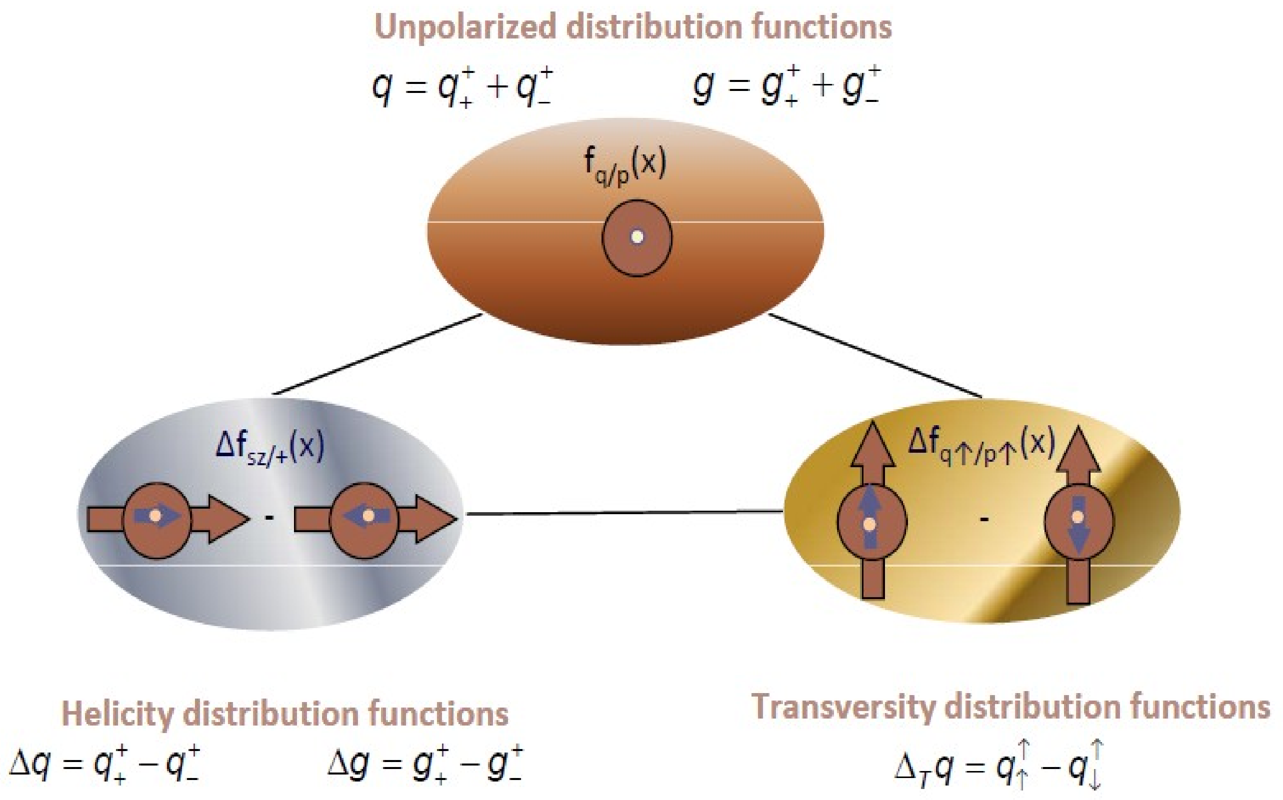
Phenomenology → "where everything comes together nicely"
Combine different sources of information to get the whole picture

How can we learn about the 3D structure of matter ?

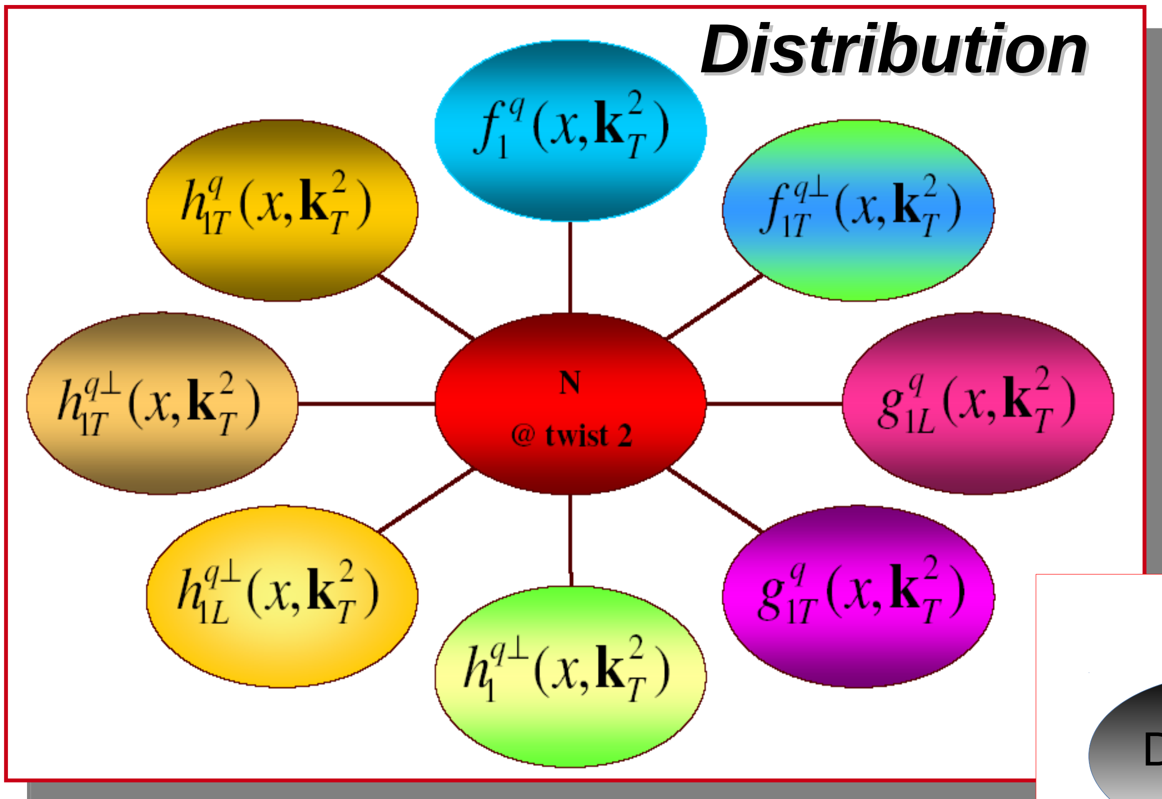
- *The mechanism which describes how quarks and gluons are bound into hadrons is embedded in the parton distribution and fragmentation functions (PDFs and FFs), the so-called “soft parts” of the hadronic scattering processes.*

- *These are non-perturbative objects which connect the ideal world of pointlike and massless particles (pQCD) to our much more complex real world, made of nucleons, nuclei and atoms.*

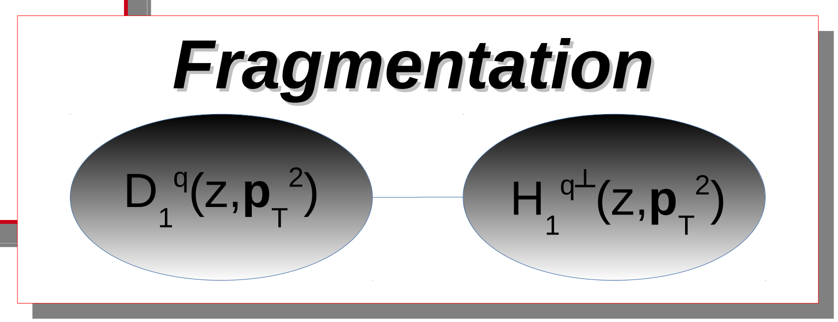
Collinear parton distribution functions



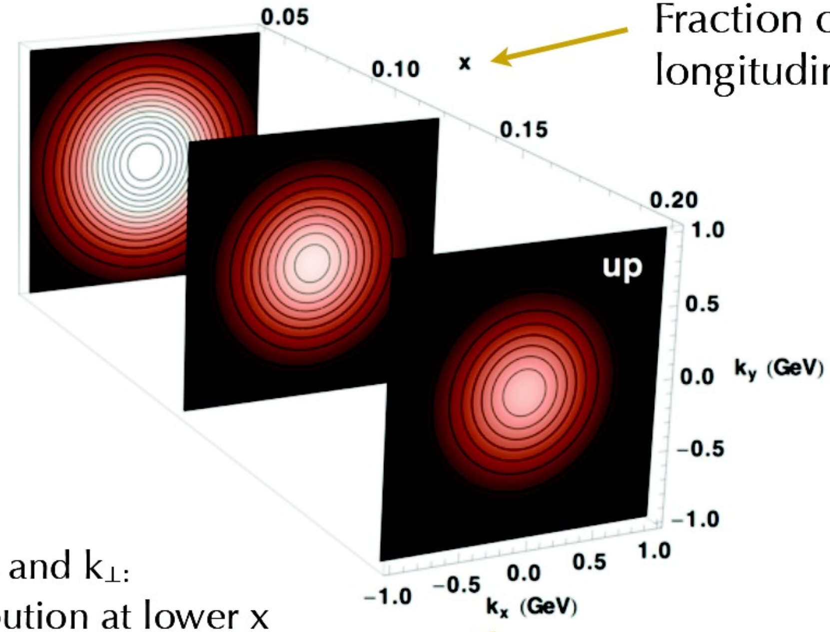
TMD distribution and fragmentation functions



Correlations between spin and transverse momentum



The unpolarized TMD



Fraction of longitudinal momentum

Transverse momentum

Correlation between x and $k_\perp$: widening of the distribution at lower x

We know the integrated PDF very well.
We know the TMD still poorly.

Transversity

- The **transversity distribution function** contains basic information on the spin structure of the nucleons.

- Being related to the expectation value of a chiral odd operator, it appears in physical processes which require a quark helicity flip; therefore it cannot be measured in usual DIS.

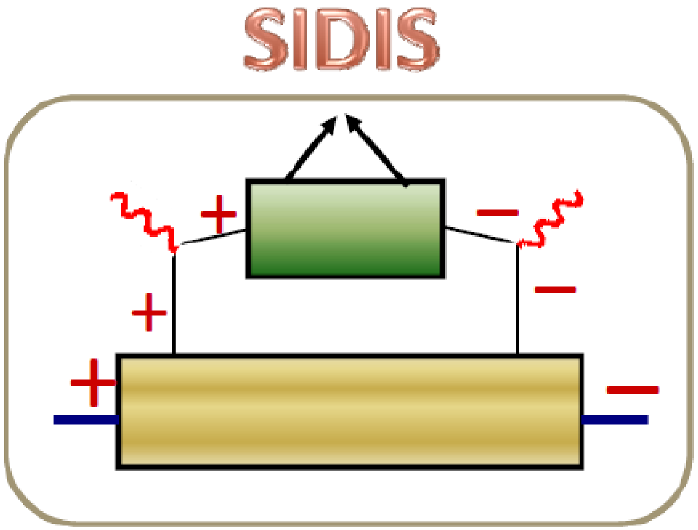
- Drell-Yan → planned experiments in polarized pp at PAX.

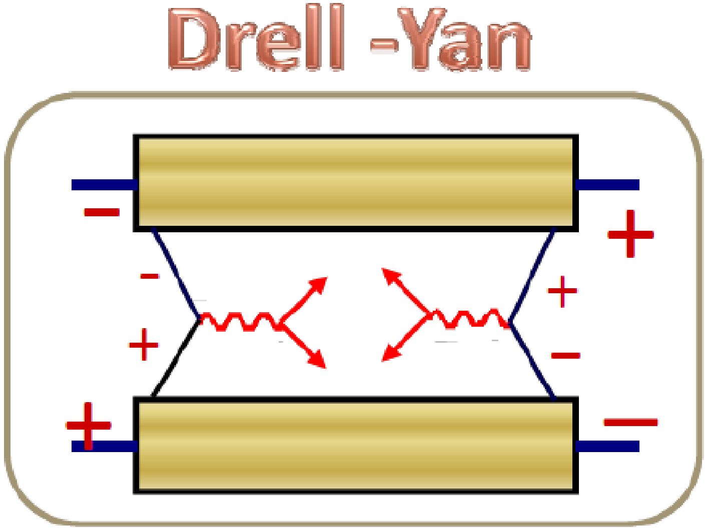
- At present, the only chance of gathering information on transversity is **SIDIS**, where it appears associated to the Collins fragmentation function.

- **DOUBLE PUZZLE**: we cannot determine the transversity parton distribution if we do not know the Collins fragmentation function.

Transversity

- There is no gluon transversity distribution function
- Transversity cannot be studied in deep inelastic scattering because it is chirally odd
- Transversity can only appear in a cross-section convoluted to another chirally odd function





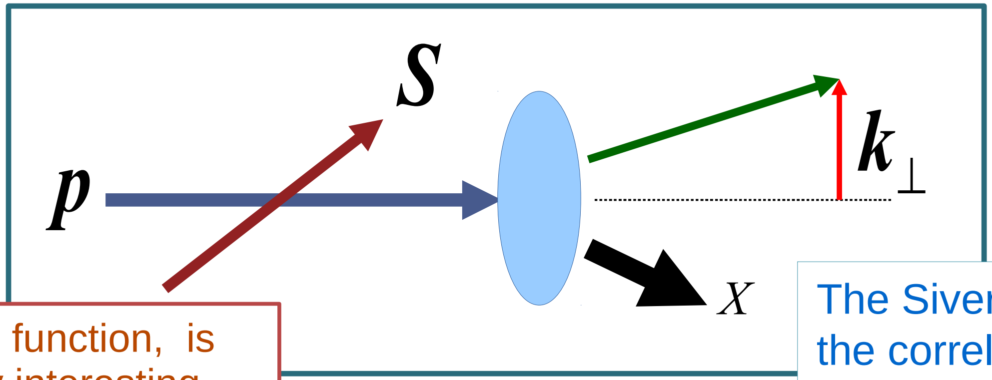
The Sivers function

$$f_{q/p,\boldsymbol{S}}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

The Sivers function is related to the probability of finding an unpolarized quark inside a transversely polarized proton

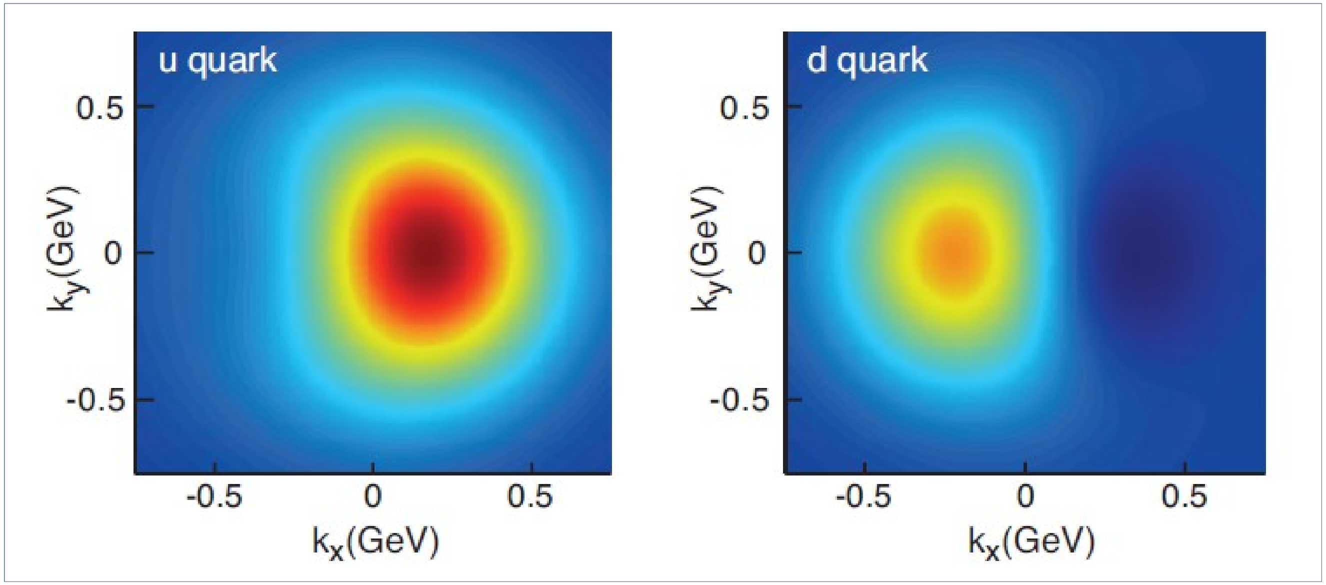
The Sivers function is T-odd



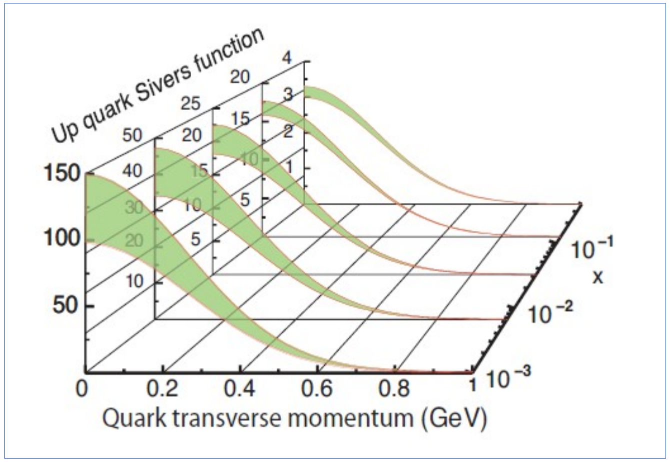
The Sivers function, is particularly interesting, as it provides information on the partonic orbital angular momentum

The Sivers function embeds the correlation between the proton spin and the quark transverse momentum

The Sivers function



The transverse momentum distribution of an up quark (left) and a down quark (right) with longitudinal momentum fraction x=0.1 in a transversely polarized proton moving in the z-direction, while being polarized in the y- direction. The color code indicates the probability of finding the up quarks.



The transverse momentum profile of the up quark Sivers function at five x values, with the corresponding statistical uncertainties.

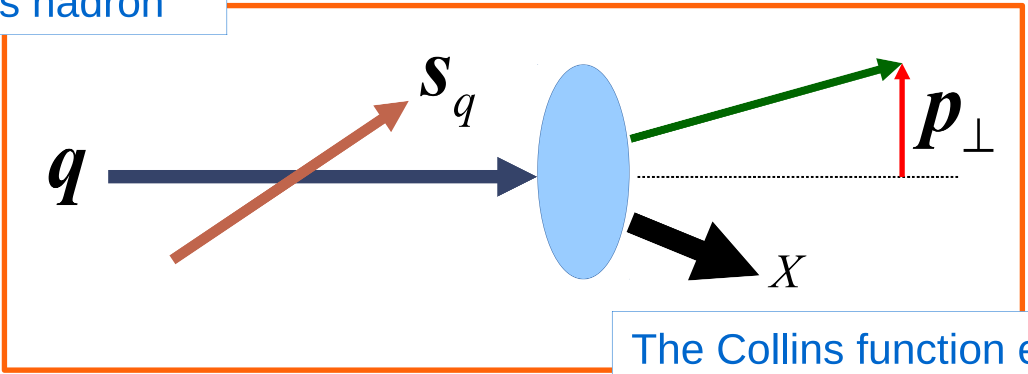
The Collins function

$$D_{h/q,\boldsymbol{s}_q}(z,\boldsymbol{p}_\perp) = D_{h/q}(z,p_\perp) + \frac{1}{2}\Delta^N D_{h/q^\uparrow}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

$$= D_{h/q}(z,p_\perp) + \frac{p_\perp}{z\,M_h} H_1^{\perp q}(z,p_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}_q\times\hat{\boldsymbol{p}}_\perp)$$

The Collins function is related to the probability that a transversely polarized struck quark will fragment into a spinless hadron

The Collins function is chirally odd



The Collins function embeds the correlation between the fragmenting quark spin and the transverse momentum of the produced hadron

- *Polarized TMDs are best studied in polarized processes, most commonly they are extracted from spin or azimuthal asymmetries.*

- *However, to compute these asymmetries in a reliable way, we must be able to reproduce the unpolarized cross sections in the best possible way, over the largest possible range in q_T.*

Unpolarized TMDs ...
... where it all begins

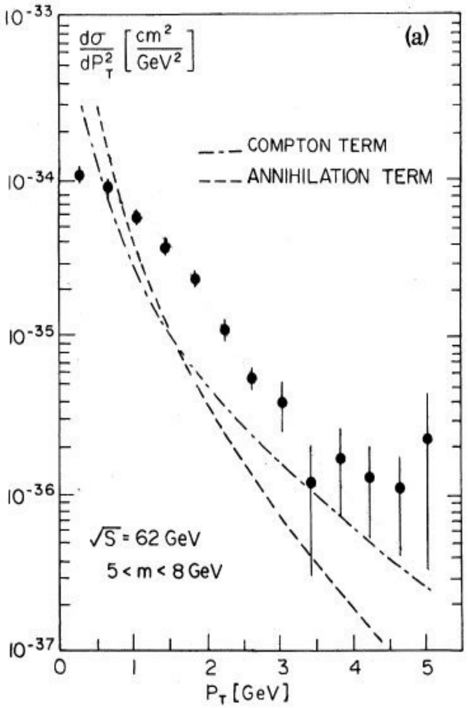
Naive TMD approach

- Calculating a cross section which describes a hadronic process over the whole q_T range is a highly non-trivial task

Let's consider Drell Yan processes (for historical reasons)

- Fixed order calculations cannot describe DY data at **small q_T**:

  At Born Level the cross section is vanishing
  At order α_s the cross section is divergent...



$$q_T \to 0$$

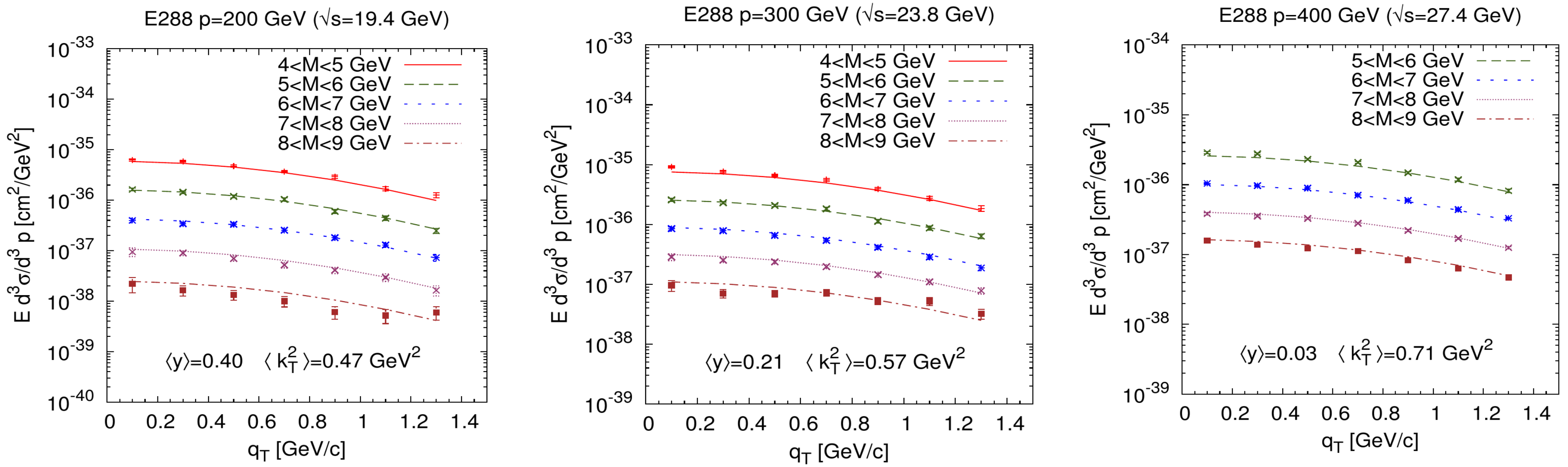
$$\frac{1}{\sigma_0}\frac{d\sigma}{dq_T^2} = \frac{2C_F}{2\pi q_T^2}\alpha_s \ln\left(\frac{M^2}{q_T^2} - \frac{3}{2}\right)$$

R. D. Field, Applications of Perturbative QCD, Vol. 77 (Addison-Wesley, Redwood City, California, 1989

Naive TMD approach

$$\frac{d\sigma}{dP_T^2} \propto \frac{\alpha_{em}}{M^2} \sum_q f_{q/h_1}(x_1) \bar{f}_{q/h_2}(x_2) \frac{\exp(-P_T^2/\langle P_T^2 \rangle)}{\pi \langle P_T^2 \rangle}$$

- Considering the same DY process at different energies:

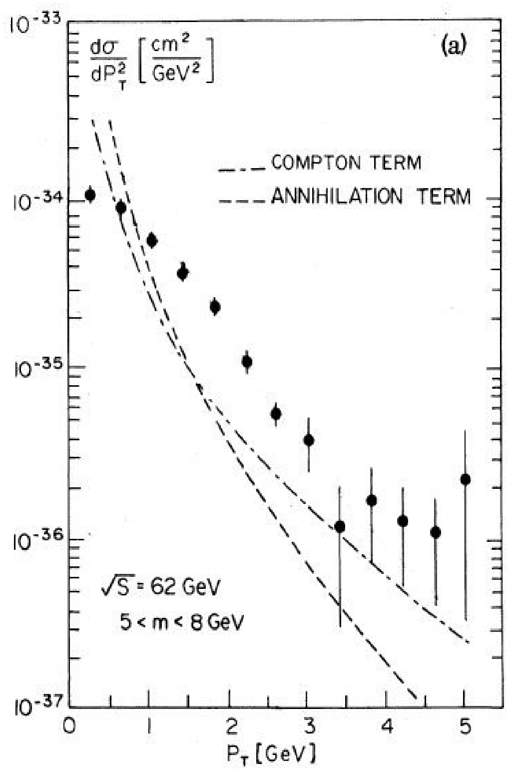


Plot credit: Stefano Melis

Each data set is Gaussian but with a different width

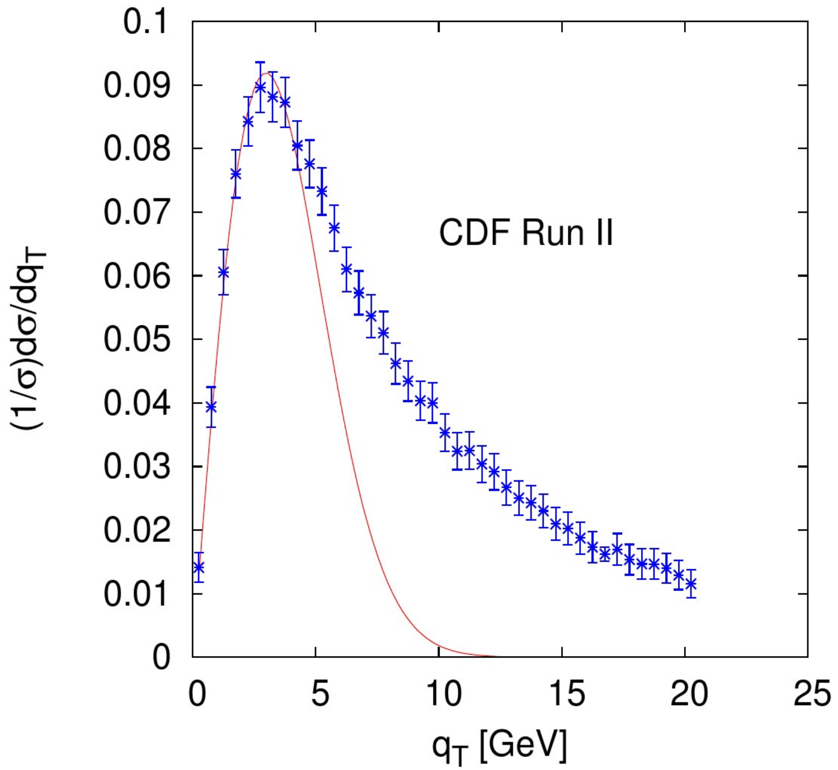
Drell-Yan phenomenology

Fixed order calculations cannot describe correctly DY cross sections at small q_T



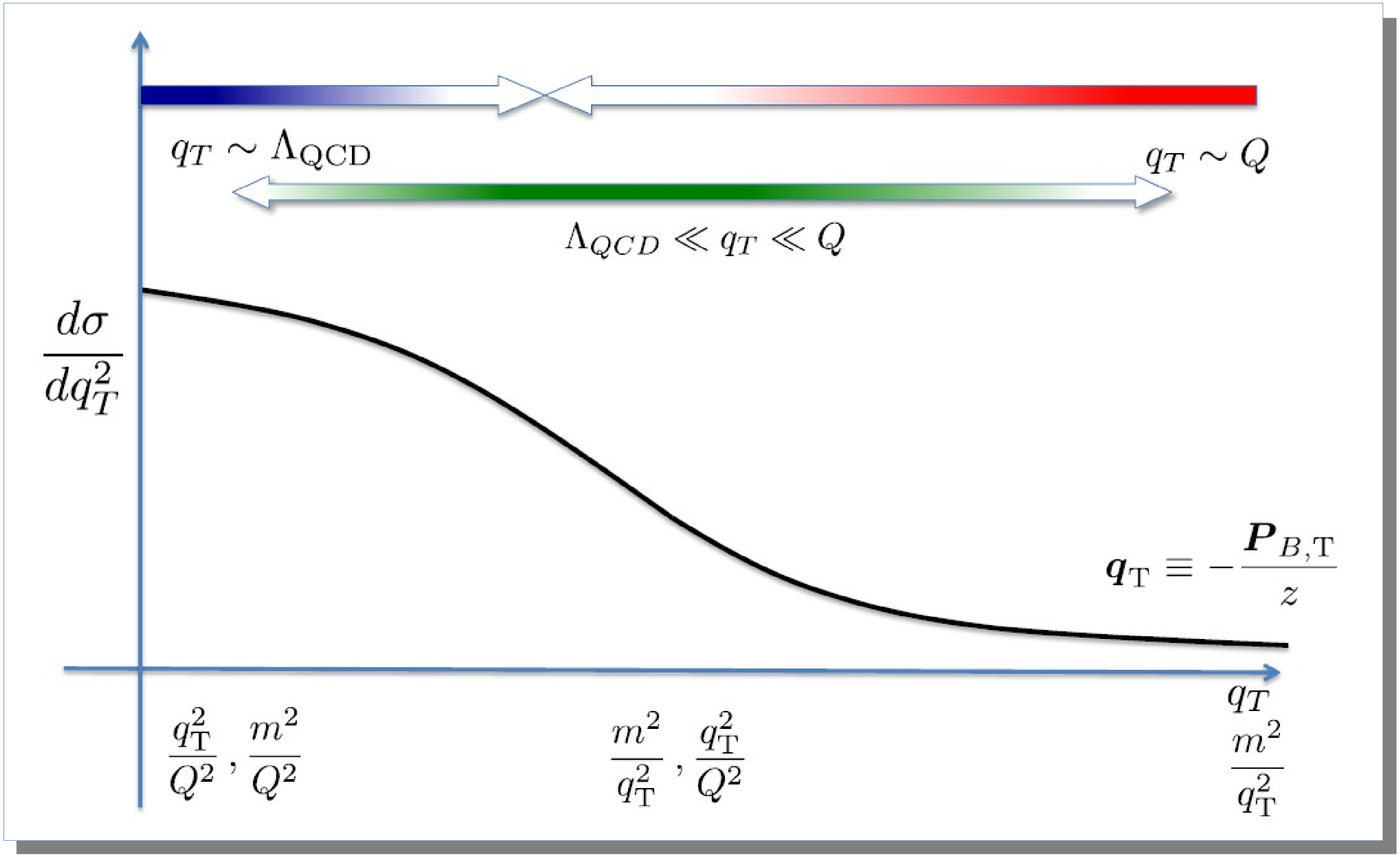
R. D. Field, Applications of Perturbative QCD, Vol. 77 (Addison-Wesley, Redwood City, California, 1989)

DY cross sections do not show a Gaussian behaviour at large q_T



Plot credit: Stefano Melis

Unpolarized cross section vs. transverse momentum



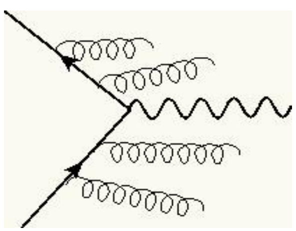
Plot credit: Ted Rogers

Resummation / TMD factorization

- Fixed order calculations cannot describe correctly DY/SIDIS data at small q_T

$$\frac{1}{\sigma_0}\frac{d\sigma}{dq_T^2} = \frac{2C_F}{2\pi q_T^2}\alpha_s \ln\left(\frac{M^2}{q_T^2} - \frac{3}{2}\right)$$

- These divergencies are taken care of by TMD evolution/resummation



The cross section is written in **b_T space**:

$$\frac{1}{\sigma_0}\frac{d\sigma}{dQ^2 dy dq_T^2} = \int \frac{d^2\boldsymbol{b}_T e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}}{(2\pi)^2}\sum_j \overbrace{e_j^2 W_j(x_1,x_2,b_T,Q)}^{\text{Resummed term}} + \overbrace{Y(x_1,x_2,q_T,Q)}^{\text{Finite term}}$$

Resummation / TMD factorization

$$\frac{1}{\sigma_0}\frac{d\sigma}{dQ^2dydq_T^2} = \int \frac{d^2\boldsymbol{b}_T e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}}{(2\pi)^2}\sum_j \overbrace{e_j^2 W_j(x_1,x_2,b_T,Q)}^{\text{Resummed term}} + \overbrace{Y(x_1,x_2,q_T,Q)}^{\text{Finite term}}$$

$Y = \sigma^{FO} - \sigma^{ASY}$

- The W term is designed to work well at low and moderate q_T, when $q_T << Q$. (Actually, W is devised to work down to $q_T \sim 0$, however collinear-factorization works up to $q_T > M$; therefore, TMD-factorization and collinear-factorization can be simultaneously applied only when $q_T >> M$).
- The W term becomes unphysical when $q_T \geq Q$, where it becomes negative (and large).
- The Y term corrects for the misbehaviour of W as q_T gets larger, providing a consistent (and positive) q_T differential cross section.
- The Y term should provide an effective smooth transition to large q_T, where fixed order perturbative calculations are expected to work.

Non perturbative region

- This is a perturbative scheme. All the scales must be frozen when reaching the non perturbative region:

$$b_T \longrightarrow b_* = \frac{b_T}{\sqrt{1 + b_T^2/b_{max}^2}} \qquad \mu = \frac{C_1}{b_T} \longrightarrow \mu_b = C_1/b_*$$

- Then we define a non perturbative function for large b_T:

$$\frac{W_j(x_1, x_2, b_T, Q)}{W_j(x_1, x_2, b_*, Q)} = F_{NP}(x_1, x_2, b_T, Q)$$

Perturbatively calculable, but process dependent

Non-perturbative, must be inferred from experiment, but universal

$$W_j(x_1, x_2, b_T, Q) = \sum_{i,k} \exp\left[S_j(b_*, Q)\right] \left[C_{ji} \otimes f_i\left(x_1, \mu_b\right)\right] \left[C_{\bar{j}k} \otimes f_k\left(x_2, \mu_b\right)\right] F_{NP}(x_1, x_2, b_T, Q)$$

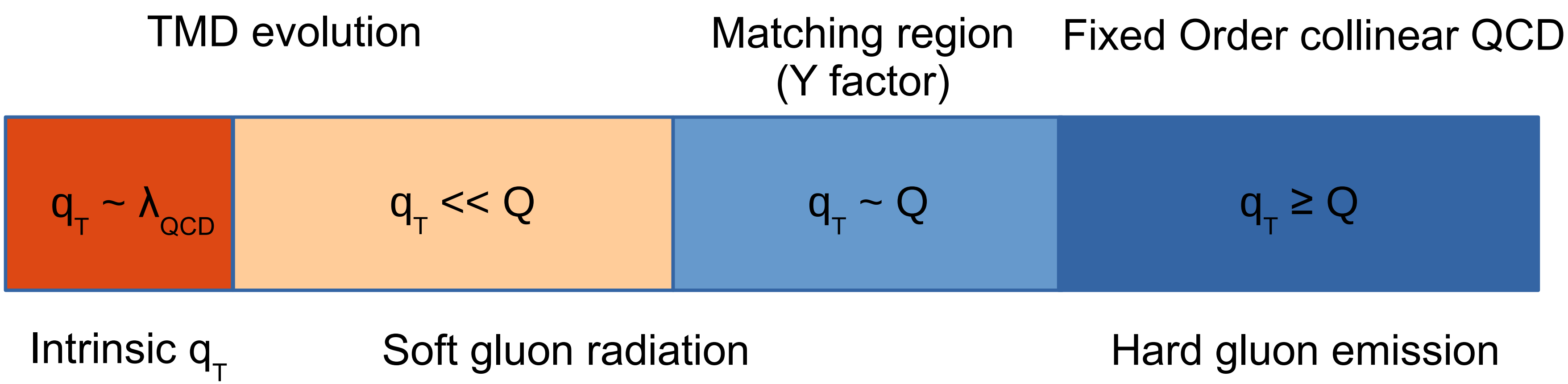
$$b_*,\ \mu_b \qquad b_T$$

$$C_1 = 2\exp(-\gamma_E)$$

Collins, Soper, Sterman, Nucl. Phys. B250, 199 (1985)

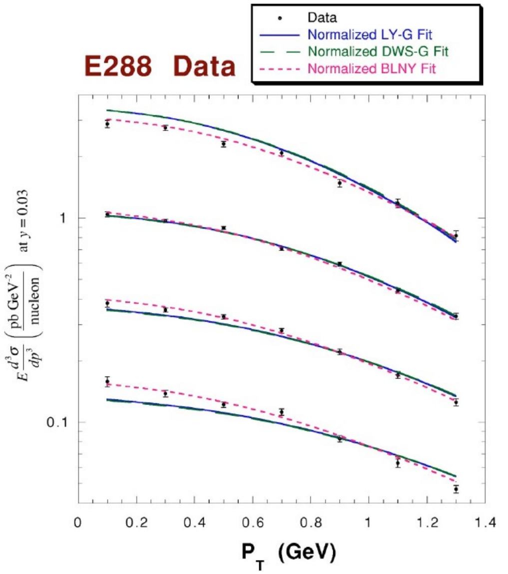
TMD regions

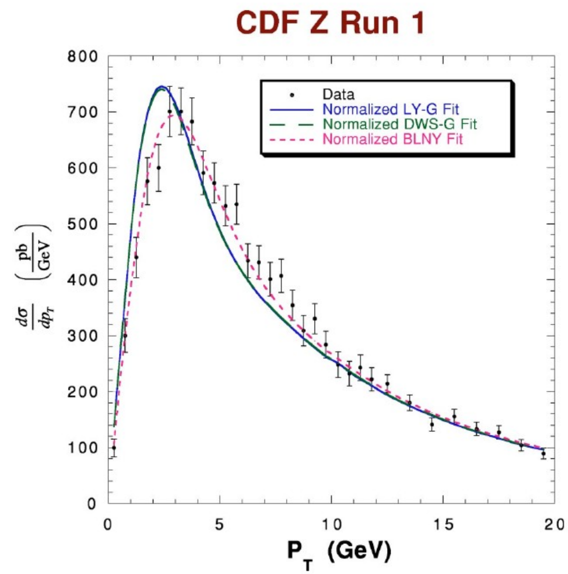
- For this scheme to work, 4 distinct kinematic regions have to be identified
- They should be large enough and well separated



CSS for DY processes

Nadolsky et al.* analyzed successfully low energy DY data and Z_0 production data using different parametrizations





Parameter	DWS-G fit	LY-G fit	BLNY fit
g_1	0.016	0.02	0.21
g_2	0.54	0.55	0.68
g_3	0.00	-1.50	-0.60
CDF Z Run-0 N_{fit}	1.00 (fixed)	1.00 (fixed)	1.00 (fixed)
R209 N_{fit}	1.02	1.01	0.86
E605 N_{fit}	1.15	1.07	1.00
E288 N_{fit}	1.23	1.28	1.19
DØ Z Run-1 N_{fit}	1.01	1.01	1.00
CDF Z Run-1 N_{fit}	0.89	0.90	0.89
χ^2	416	407	176
χ^2/DOF	3.47	3.42	1.48

$b_{max} = 0.5\ \mathrm{GeV}^{-1}$

**Nadolsky et al., Phys.Rev. D67,073016 (2003)*

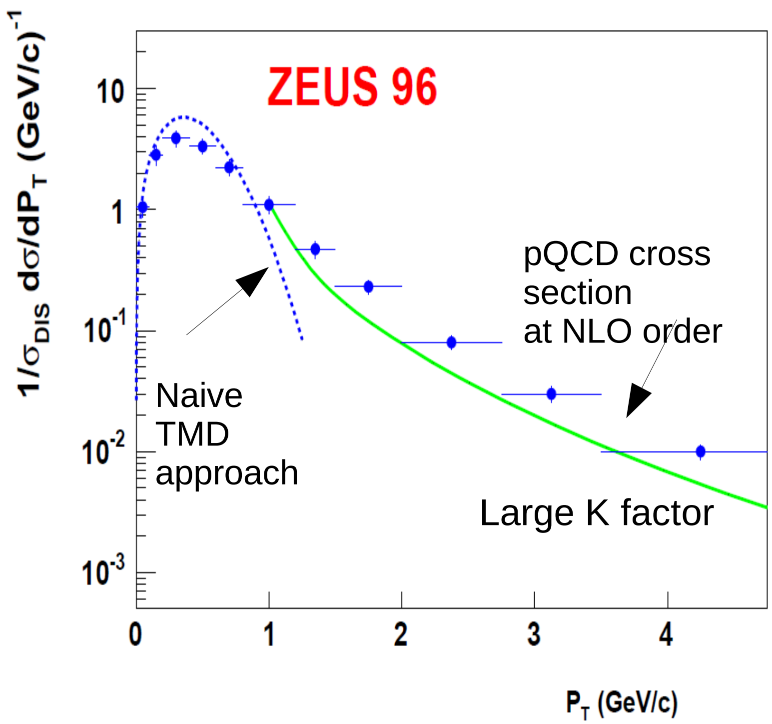
$$+$$

SIDIS processes

$$\ell + p \to \ell' + h + X$$

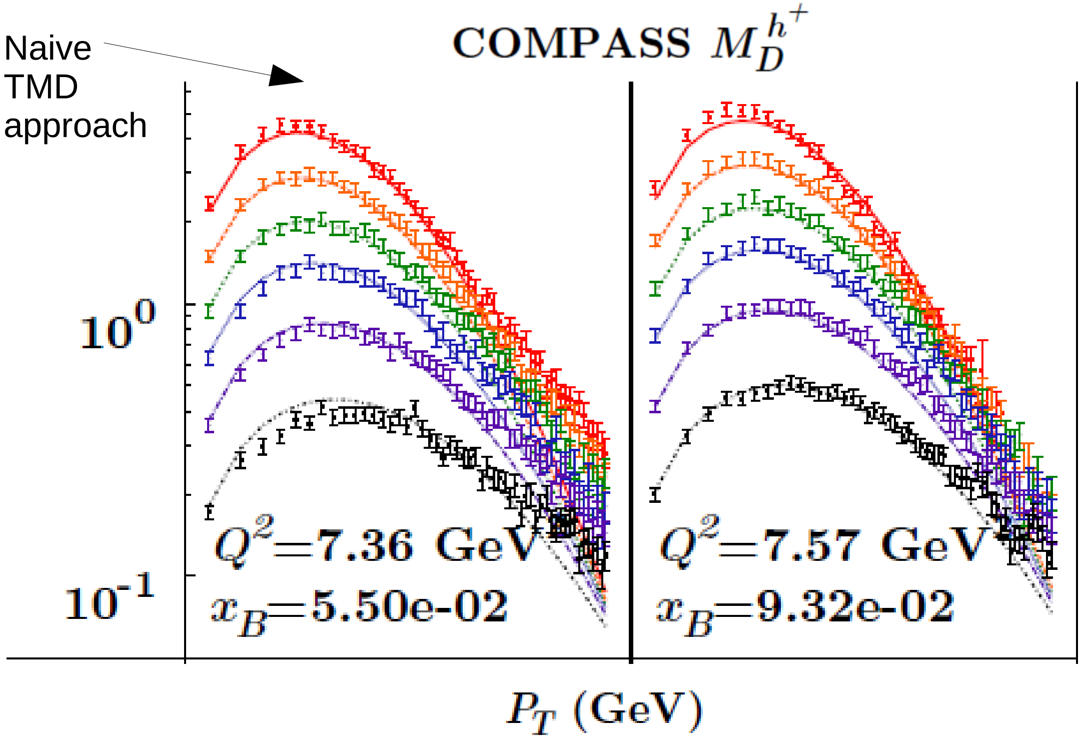
Factorization in SIDIS

- As mentioned above
  - fixed order pQCD calculation fail to describe the SIDIS cross sections at small $q_{T,}$
  - the cross section tail at large q_T is clearly non-Gaussian.



Anselmino, Boglione, Prokudin, Turk, Eur.Phys.J. A31 (2007) 373-381

ZEUS Collaboration (M. Derrick), Z. Phys. C 70, 1 (1996)



Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (2014) 005

COMPASS, Adolph et al., Eur. Phys. J. C 73 (2013) 2531

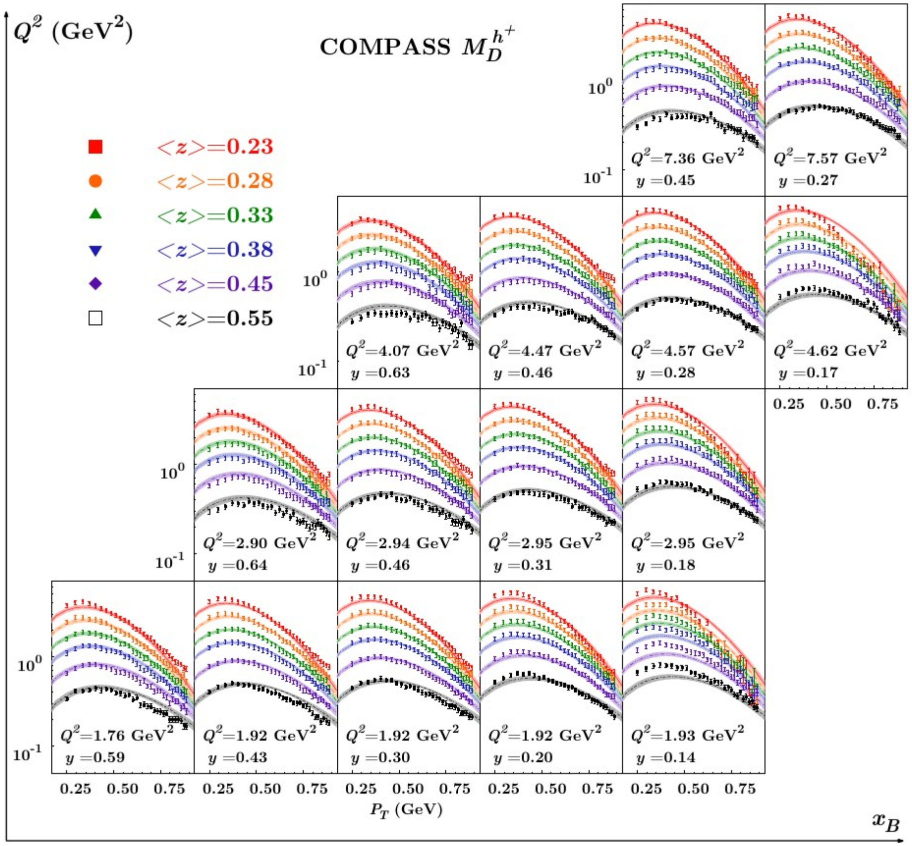
Need resummation of large logs and matching perturbative to non-perturbative contributions

Naive TMD approach

M. Anselmino, M. Boglione, O. Gonzalez, S. Melis, A. Prokudin, JHEP 1404 (2014) 005, ArXiv:1312.6261

$$F_{UU} = \sum_q e_q^2 \, f_{q/p}(x_B) \, D_{h/q}(z_h) \frac{e^{-P_T^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

$$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle$$



$$\langle k_\perp^2 \rangle = 0.60 \pm 0.14 \ \mathrm{GeV}^2$$

$$\langle p_\perp^2 \rangle = 0.20 \pm 0.02 \ \mathrm{GeV}^2$$

$$\chi^2_{\mathrm{dof}} = 3.42$$

Fit over 6000 data points with 2 free parameters

$$N_y = A + B\,y$$

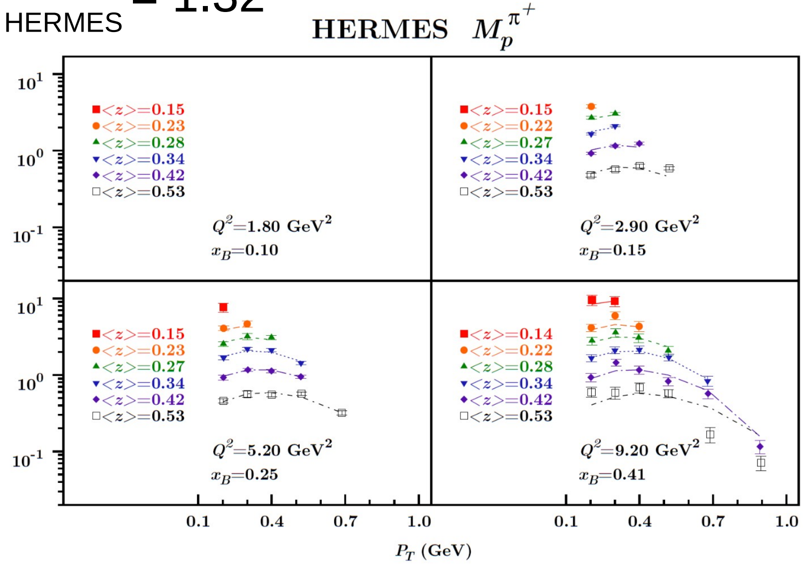
"The point-to-point systematic uncertainty in the measured multiplicities as a function of p_T^2 is estimated to be 5% of the measured value. The systematic uncertainty in the overall normalization of the p_T^2-integrated multiplicities depends on z and y and can be as large as 40%".

Erratum Eur.Phys.J. C75 (2015) 2, 94

Fit of HERMES and COMPASS data
Attempting "Resummation" in SIDIS ...

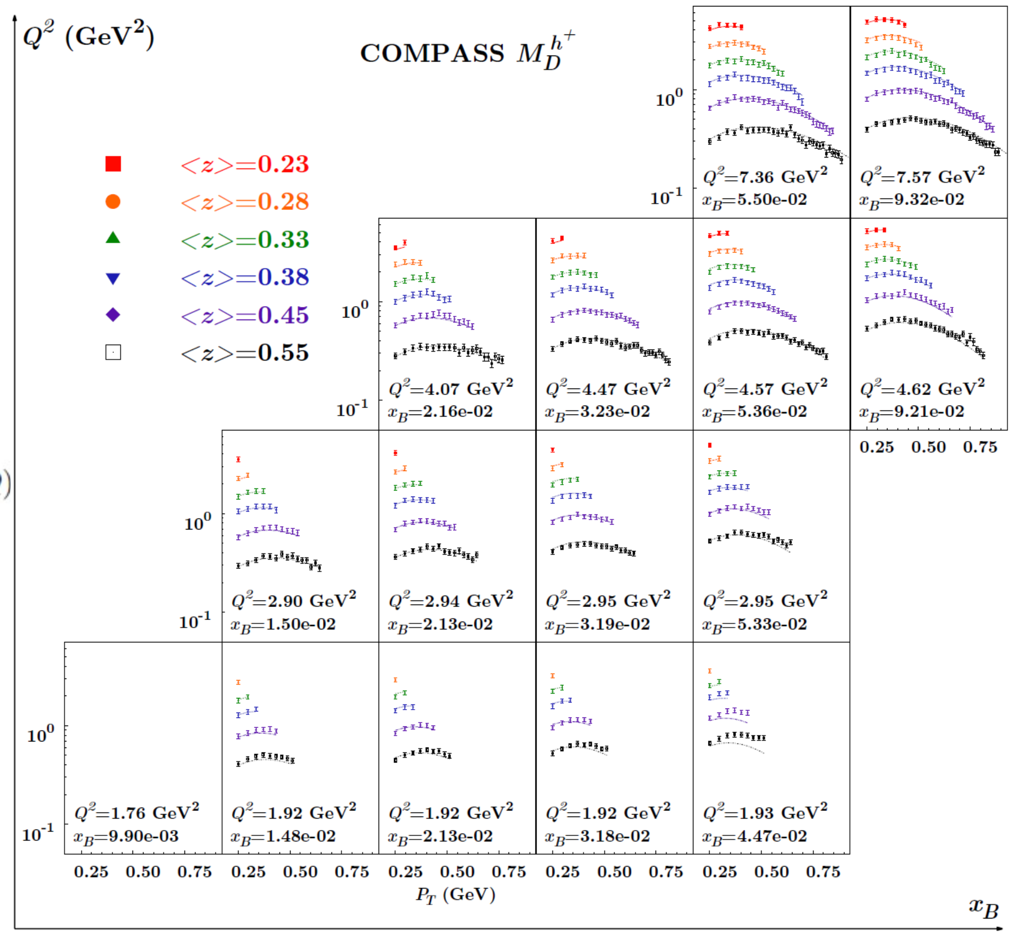
J. Osvaldo Gonzalez Hernandez, work in progress

$\chi^2_{\text{HERMES}} = 1.32$



$\chi^2_{\text{tot}} = 1.17$

$\chi^2_{\text{COMPASS}} = 1.12$



$$\frac{d\sigma}{dx\,dy\,dz\,dq_T^2} = \pi\sigma_0^{DIS}\left\{\int \frac{d^2\mathbf{b_T}e^{i\mathbf{q_T}\cdot\mathbf{b_T}}}{(2\pi)^2} W^{SIDIS}(x,z,b_*,Q,C_1,C_2,C_3) F_{NP}^{SIDIS}(x,z,b_T,Q) + Y^{SIDIS}(x,z,q_T,Q,C_4)\right\},$$

Y-term is neglected

$$F_{NP}^{SIDIS}(x,z,Q) = \exp\left\{\left[-\frac{g_1 + g_{1f}/z^2}{2} - g_2\ln(Q/(2Q_0)) - g_1 g_3 \ln(10x)\right] b_T^2\right\}$$

N ~ 2 (One overall normalization parameter is required)
g1 ~ 0.5 (too large compared to the value extracted from DY data)
g2 ~ 0.5
g3 ~ - 0.03

Global fits

A. Bacchetta, F. Delcarro, C. Pisano, M. Radici, A. Signori, JHEP06 (2017) 081

Extraction of partonic transverse momentum distributions from semi-inclusive deep-inelastic scattering, Drell-Yan and Z-boson production

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Abstract: We present an extraction of unpolarized partonic transverse momentum distributions (TMDs) from a simultaneous fit of available data measured in semi-inclusive deep-inelastic scattering, Drell-Yan and Z boson production. To connect data at different scales, we use TMD evolution at next-to-leading logarithmic accuracy. The analysis is restricted to the low-transverse-momentum region, with no matching to fixed-order calculations at high transverse momentum. We introduce specific choices to deal with TMD evolution at low scales, of the order of 1 GeV^2. This could be considered as a first attempt at a global fit of TMDs.

JHEP06(2017)081

Although the shape in transverse momentum space is well described, normalization is very problematic

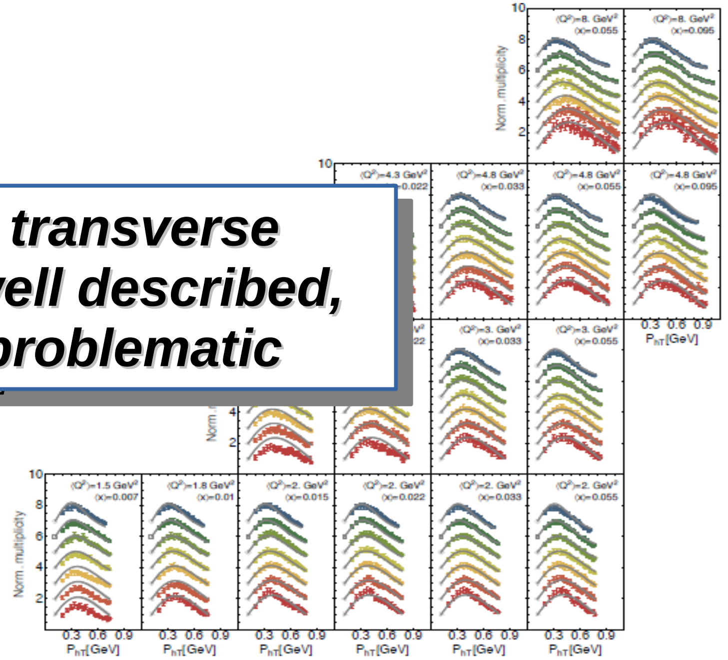

Figure 5. COMPASS multiplicities for production of negative hadrons (π^-) off a deuteron for different $\langle x \rangle$, $\langle z \rangle$, and $\langle Q^2 \rangle$ bins as a function of the transverse momentum of the detected hadron P_{hT}. Multiplicities are normalized to the first bin in P_{hT} for each $\langle z \rangle$ value (see (3.1)). For clarity, each $\langle z \rangle$ bin has been shifted by an offset indicated in the legend.

$$\chi^2_{tot} = 1.55$$

- Y-term is neglected
- Sum of two Gaussian k_T distributions is introduced

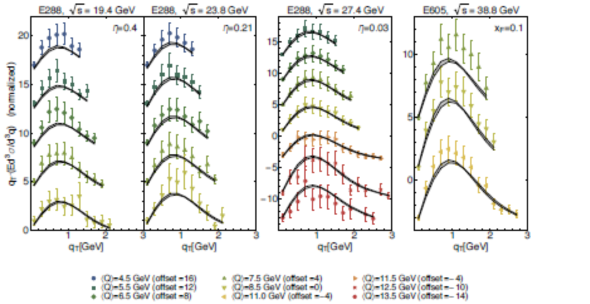

Figure 7. Drell-Yan differential cross section for different experiments and different values of $\sqrt{s}$ and for different $\langle Q \rangle$ bins. For clarity, each $\langle Q \rangle$ bin has been normalized (the first data point has been set always equal to 1) and then shifted by an offset indicated in the legend.

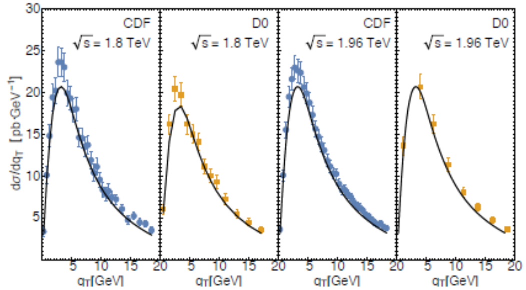

Figure 8. Cross section differential with respect to the transverse momentum q_T of a Z boson produced from $p\bar{p}$ collisions at Tevatron. The four panels refer to different experiments (CDF and D0) with two different values for the center-of-mass energy ($\sqrt{s} = 1.8$ TeV and $\sqrt{s} = 1.96$ TeV). In this case the band is narrow due to the narrow range for the best-fit values of g_2.

Large transverse momentum behaviour in SIDIS

J.O. Gonzalez-Hernandez, T.C. Rogers, N. Sato, B. Wang, Phys. Rev. D98 (2018) n. 11, 114005

Challenges with Large Transverse Momentum in Semi-Inclusive Deeply Inelastic Scattering

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[2]Dipartimento di Fisica, Università di Torino, Via P. Giuria 1, 10125 Torino, Italy
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[4]Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606, USA
[5]Zhejiang Institute of Modern Physics, Department of Physics, Zhejiang University, Hangzhou 310027, China
(Dated: 13 August 2018)

We survey the current phenomenological status of semi-inclusive deep inelastic scattering at moderate hard scales and in the limit of very large transverse momentum. As the transverse momentum becomes comparable to or larger than the overall hard scale, the differential cross sections should be calculable with fixed order pQCD methods, while small transverse momentum (TMD factorization) approximations should eventually break down. We find large disagreement between HERMES and COMPASS data and fixed order calculations done with modern parton densities, even in regions of kinematics where such calculations should be expected to be very accurate. Possible interpretations are suggested.

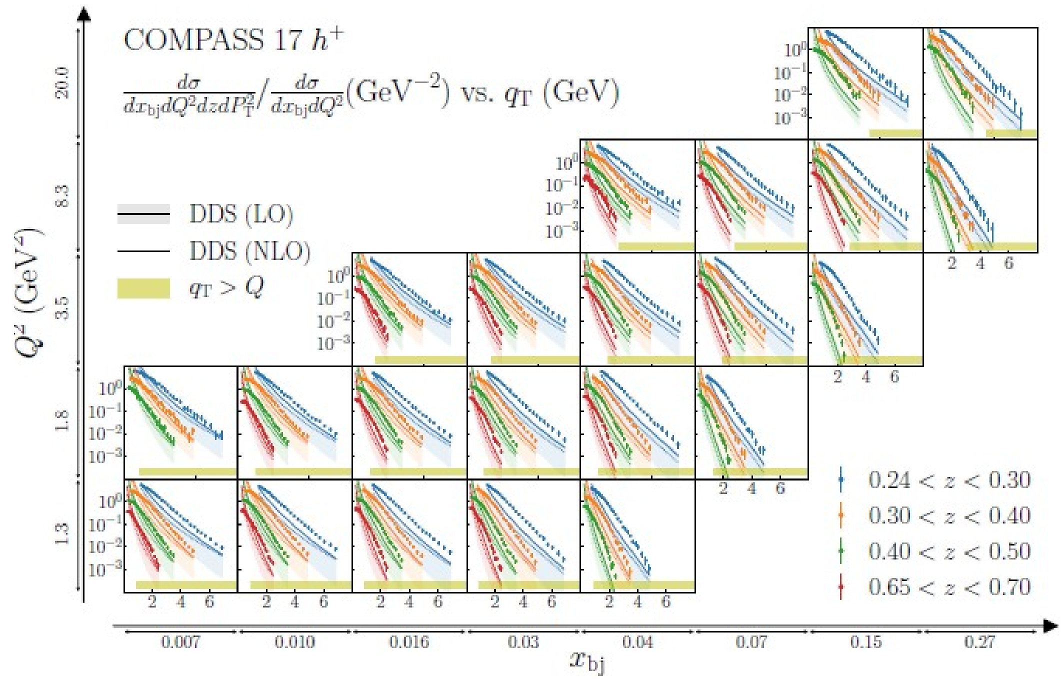


FIG. 4. Calculation of $O(\alpha_s)$ and $O(\alpha_s^2)$ transversely differential multiplicity using code from [22], shown as the curves labeled DDS. The bar at the bottom marks the region where $q_T > Q$. The PDF set used is CJNLO [25] and the FFs are from [26]. Scale dependence is estimated using $\mu = ((\zeta_Q Q)^2 + (\zeta_{q_T} q_T)^2)^{1/2}$ where the band is constructed point-by-point in q_T by taking the min and max of the cross section evaluated across the grid $\zeta_Q \times \zeta_{q_T} = [1/2, 1, 3/2, 2] \times [0, 1/2, 1, 3/2, 2]$ except $\zeta_Q = \zeta_{q_T} = 0$. The red band is generated with $\zeta_Q = 1$ and $\zeta_{q_T} = 0$. A lower bound of 1 GeV is place on μ when $Q/2$ would be less than 1 GeV.

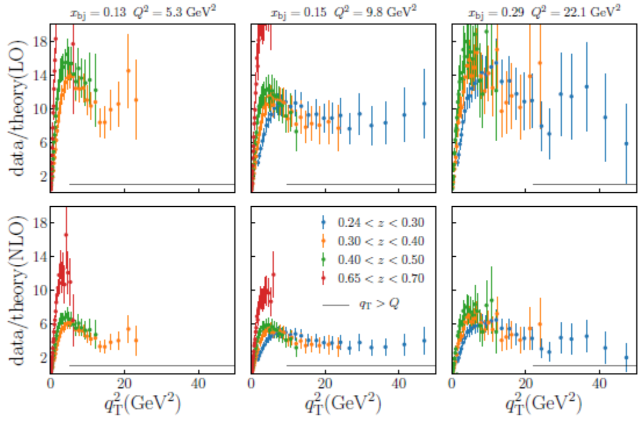


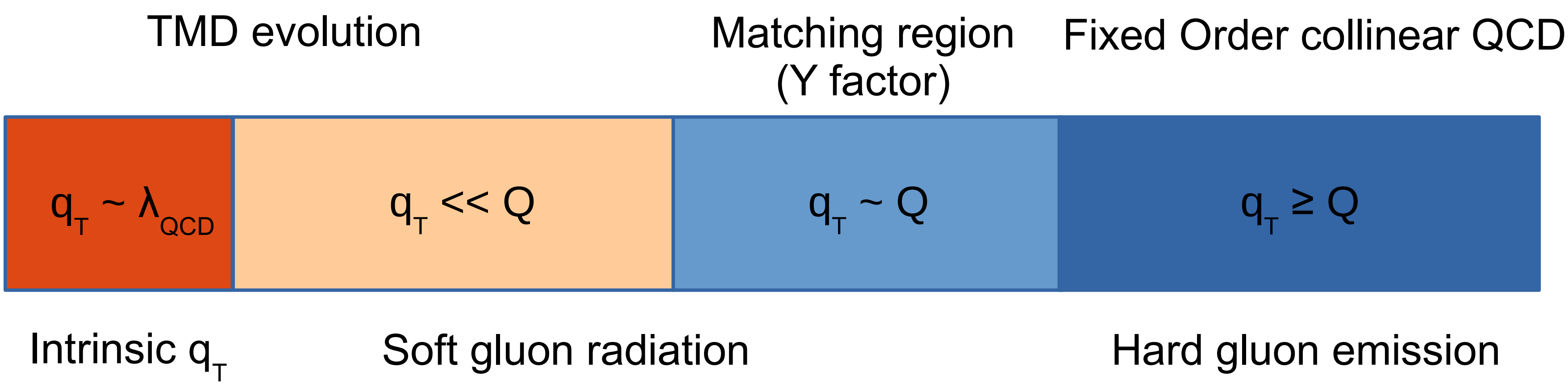
FIG. 5. Ratio of data to theory for several near-valence region panels in Fig. 4. The grey bar at the bottom is at 1 on the vertical axis and marks the region where $q_T > Q$.

There are large discrepancies between data and fixed order calculations. They seem to be generated by collinear PDFs and FFs

What's going on ???

TMD regions

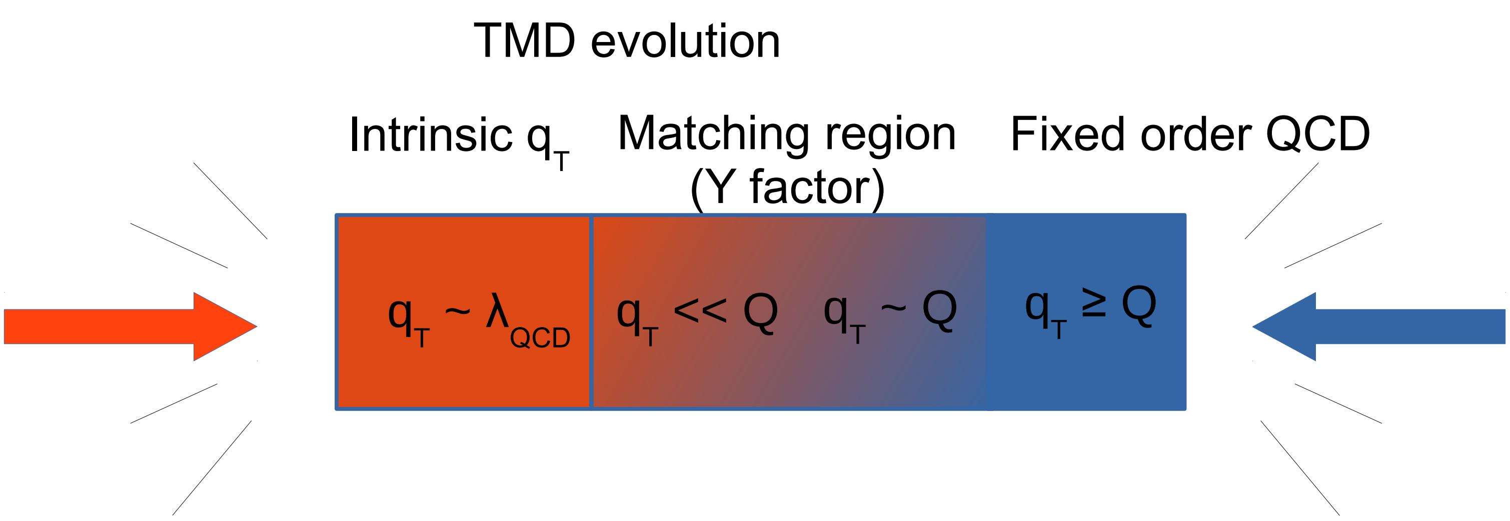
- For this scheme to work, 4 distinct kinematic regions have to be identified
- They should be large enough and well separated



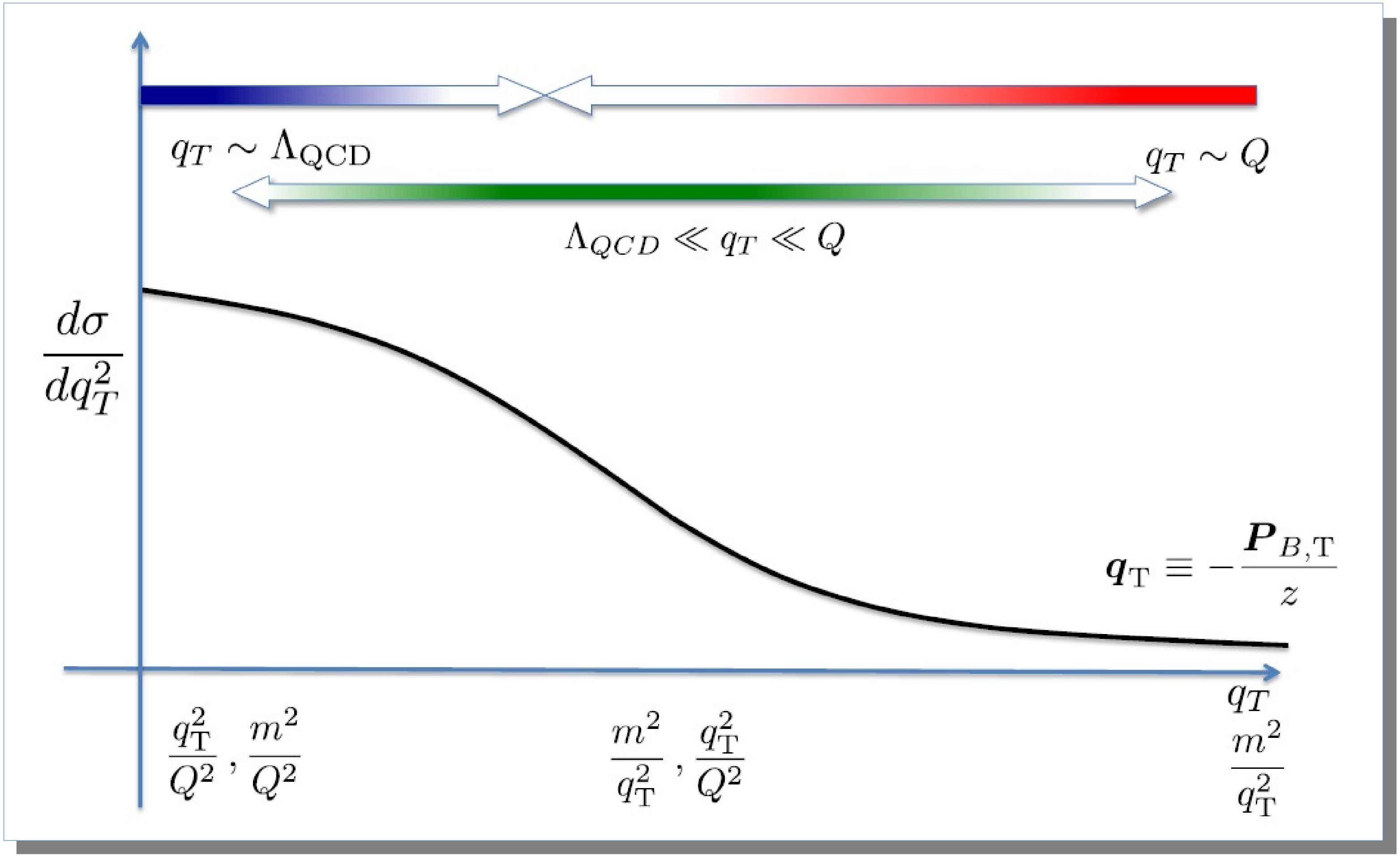
TMD regions

- For this scheme to work, 4 distinct ki … have to be identified
- They should be large … separated

Does not work in SIDIS !



Unpolarized cross section vs. transverse momentum



Plot credit: Ted Rogers

Mapping the kinematical regimes of SIDIS

M. Boglione, A. Dotson, L. Gamberg, S. Gordon, J. O. Gonzalez-Hernandez, A. Prokudin, T. C. Rogers, N. Sato, ArXiv:1904.12882
Accepted for publication in JHEP

- If all energies and hard scales are extremely large, we are in the asymptotic freedom regime and pictures of partonic interactions rooted in perturbation theory can usually be applied confidently and with very high accuracy and precision. Wever here we ar little sensitive to the inner hadronic structure.

- Instead, it is in the moderate-to-low Q range that we can reasonably expect some sensitivity to intrinsic properties of hadron structure and other non-perturbative effects.

- Sophisticated theoretical frameworks (like perturbation theory and QCD factorization) have long existed for describing specific underlying physical mechanisms in terms of partonic degrees of freedom.

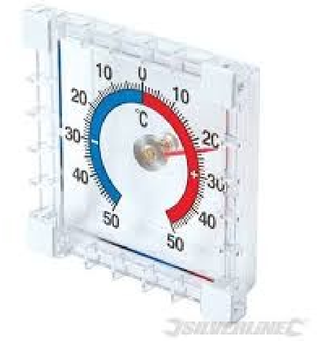
- However, they always assume specific kinematic limiting cases, e.g. very large or very small transverse momentum, or very large or very small rapidity.

- The interface between different physical regimes remains unclear in practice, especially when the hard scales involved are not particularly large.

- Estimating the kinematic boundaries of any specific QCD approach or approximation beyond very rough orders of magnitude is difficult and subtle. It requires at least some model assumptions, e.g. about the role of parton virtuality and/or the onset of various non-perturbative or hadronic mechanisms generally.

- Need to organize an interpretation strategy, applicable with any model of underlying non-perturbative dynamics, independent of assumptions about factorization.

- Probe the proximity of any given kinematic configuration to a conventional partonic region of SIDIS, and probe the sensitivity to the various model assumptions needed to make such an assessment.



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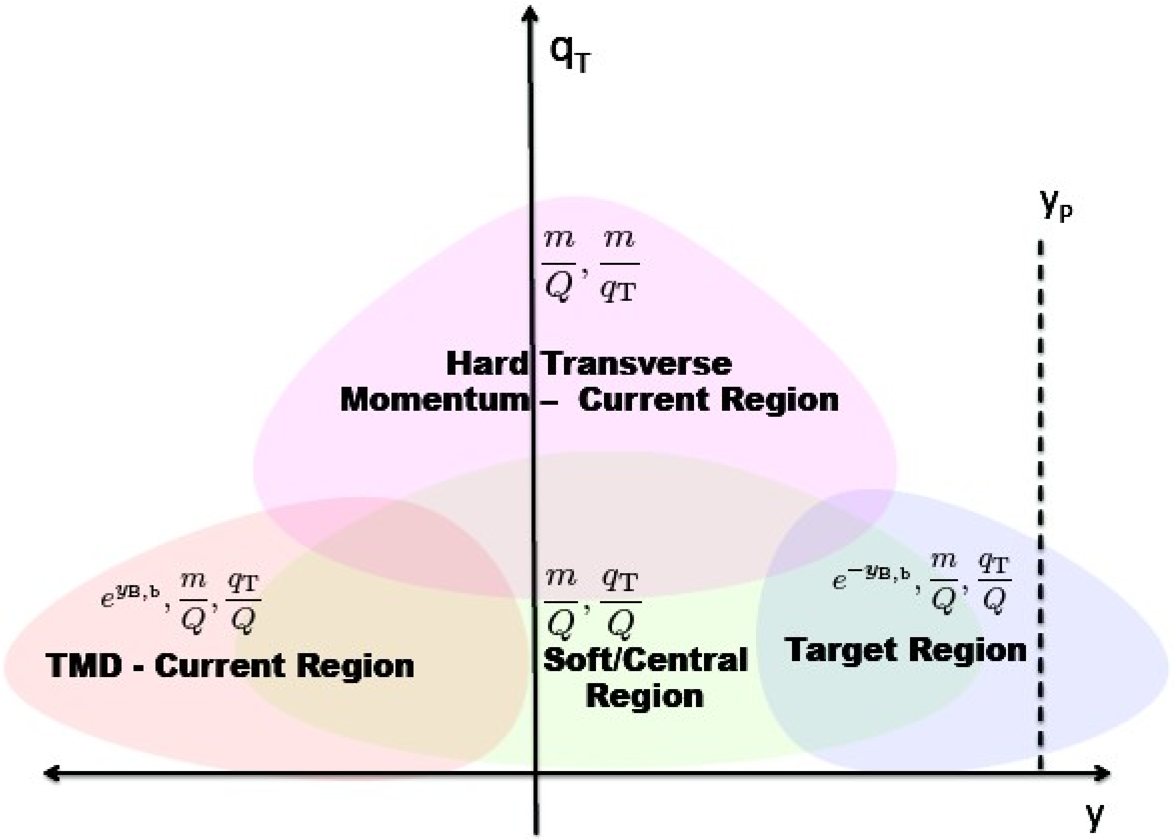

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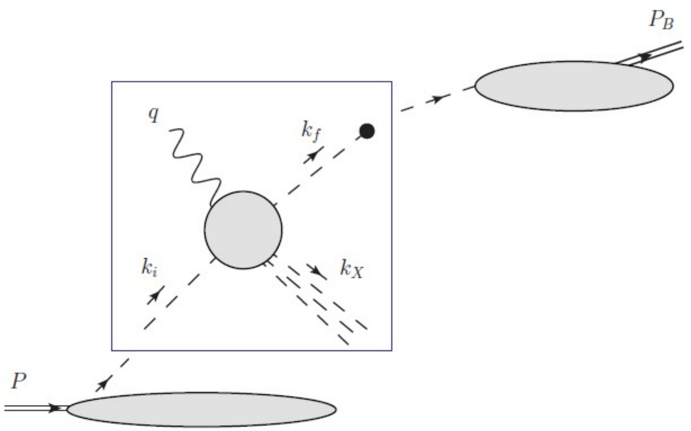
$$\text{General Hardness Ratio} = R_0 \equiv \max\left(\left|\frac{k_\text{i}^2}{Q^2}\right|, \left|\frac{k_\text{f}^2}{Q^2}\right|, \left|\frac{\delta k_\text{T}^2}{Q^2}\right| \right)$$

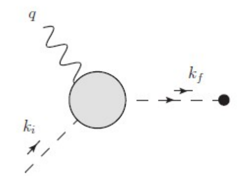
$$\text{Collinearity} = R_1 \equiv \frac{P_\text{B} \cdot k_\text{f}}{P_\text{B} \cdot k_\text{i}}$$

$$\text{Transverse Hardness Ratio} = R_2 \equiv \frac{|k^2|}{Q^2}$$

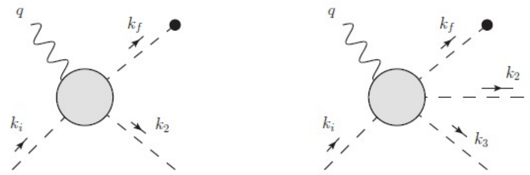
$$\text{Spectator Virtuality Ratio} = R_3 \equiv \frac{|k_\text{X}^2|}{Q^2}$$



	R_0	R_1	R_2	R_3	R_1'
TMD Current region	small	small	small	X	large
Hard region	small	small	large	small (low order pQCD)	large
	small	small	large	large (high order pQCD)	large
Target region	small	large	X	X	small
Soft region	small	large	small	X	large



(a)



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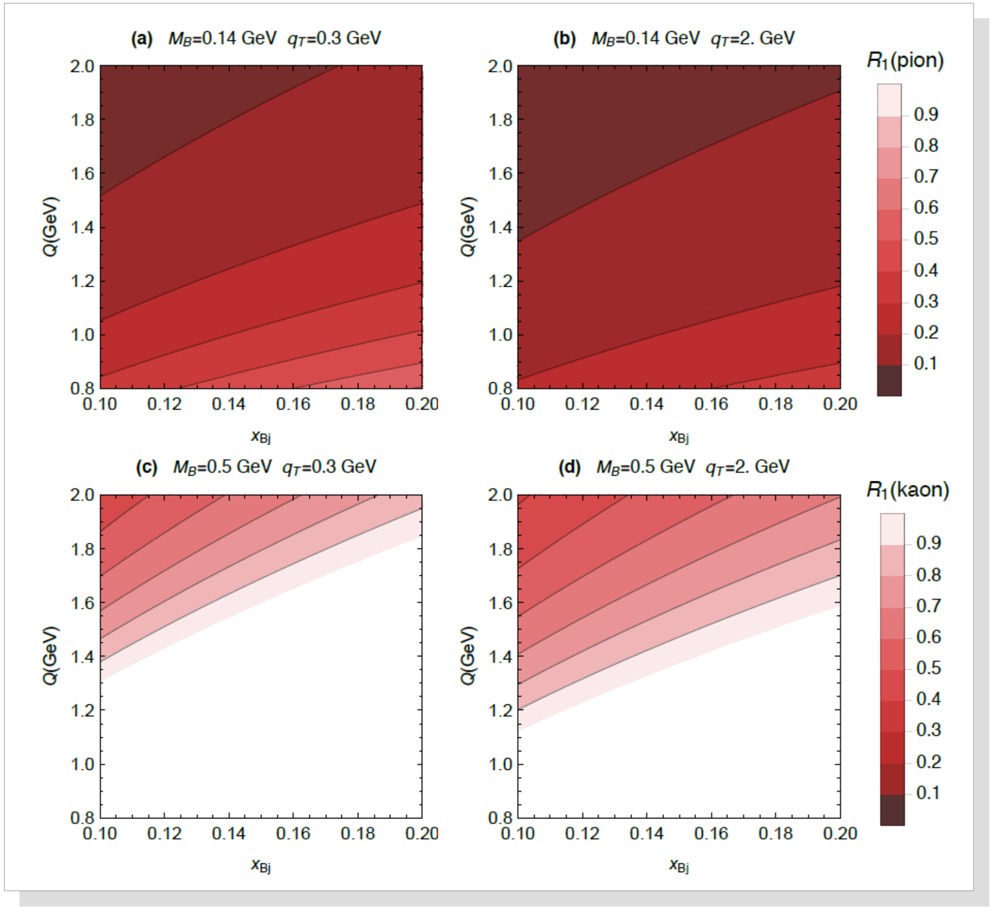
Collinearity

- At large Q and not-too-large xBj, R1 remains small for all transverse momenta, while corrections might be necessary at smaller Q and larger xBj.
- Notice the rather strong flavour dependence.



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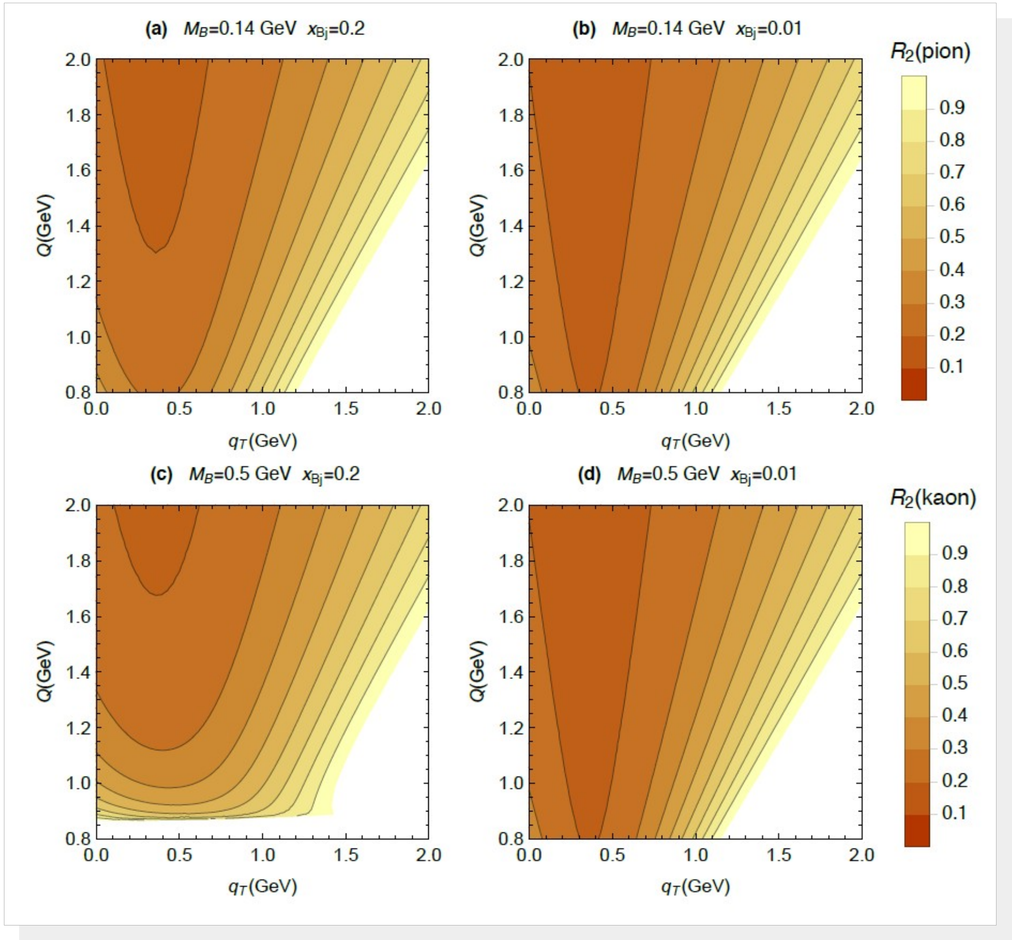
Transverse hardness ratio

- R2 maps out the applicability of large and small transverse momentum approximations.
- "large-qT" grows with Q
- While the hadron is in the current region for most qT, the small transverse momentum region is much more restrictive.
- There is a broad intermediate region where the situation is not clear.
- The flavour of the final state hadron is decisive in determining the relevant factorization region.
- The flavour of the final state hadron has little effect on the transverse momentum hardness



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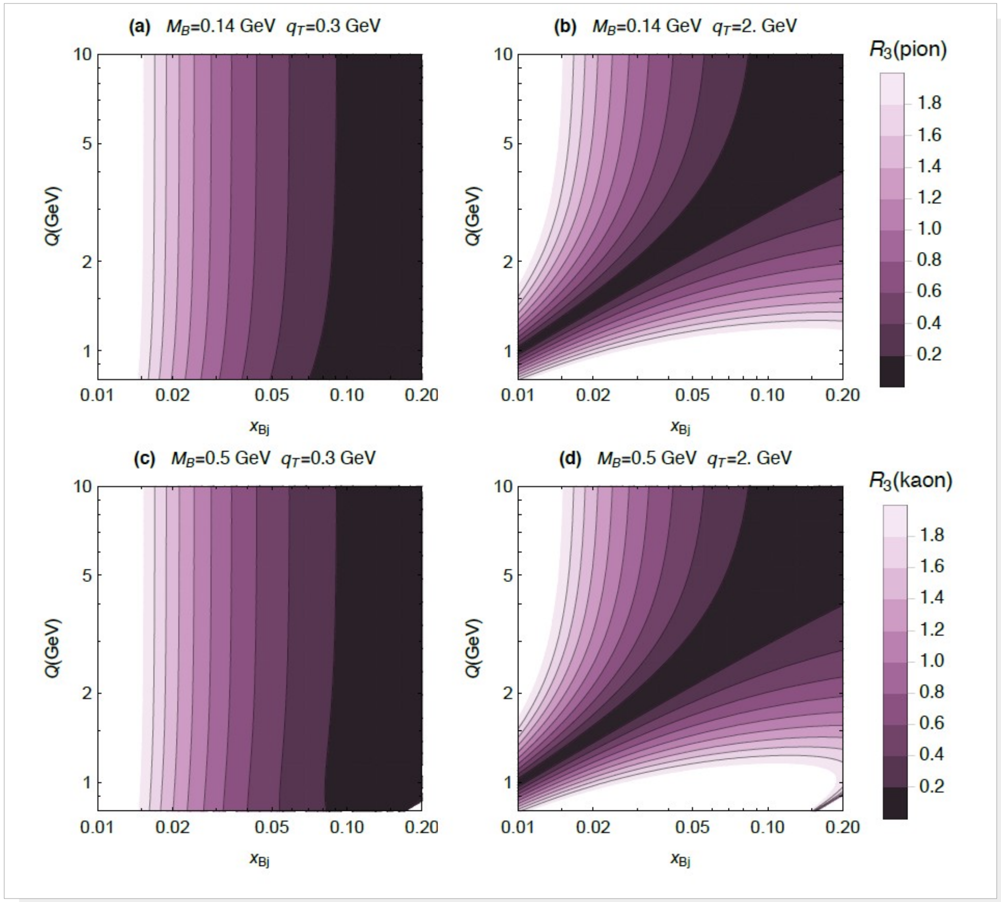
Spectator Virtuality ratio

- R_3 helps us deciding whether a LO calculation is enough or whether higher order perturbative corrections are necessary.
- Large R_3 coupled with large R_2 signal a large q_T region, where higher order pQCD corrections are relevant
- Small R_3 together with small R_2 indicate a TMD current region, which requires a TMD factorization scheme.
- At large transverse momentum there is a linear region in the Q versus x_{Bj} plane where the 2→2 process is the optimal description (R_3 is small) and low order QCD computations are applicable.



Summary

- Naive TMD Models can describe HERMES and COMPASS data at low transverse momentum

- Similarly to DY, the Q^2 dependence is not clearly visible in the shape of the spectrum

- The phenomenological implementation of the TMD factorization scheme is difficult
  - no information on unpolarized TMD fragmentation functions
  - global fitting is affected by normalization issues
  - matching schemes are affected by strong problems - Y-term is difficult to include
  - the non-perturbative behaviour seems to be dominant
  - difficult to work in b_T space where we loose phenomenological intuition

- Fixed order calculation fail to reproduce the correct behaviour of the cross section at large transverse momentum (even at $O(\alpha_s)$!)

- Need an extra effort to devise theories/models/prescriptions which simultaneously explain experimental data from different experiments, over a wide range of transverse momentum values

- Need new, high-precision experimental data to be able to perform solid and realistic phenomenological analyses of TMD physics (**EIC** !)