Extraction of TMD distributions from data

Nobuo Sato

Workshop on “TMD studies: from JLab to EIC”
JLab May 3 2021

Outline

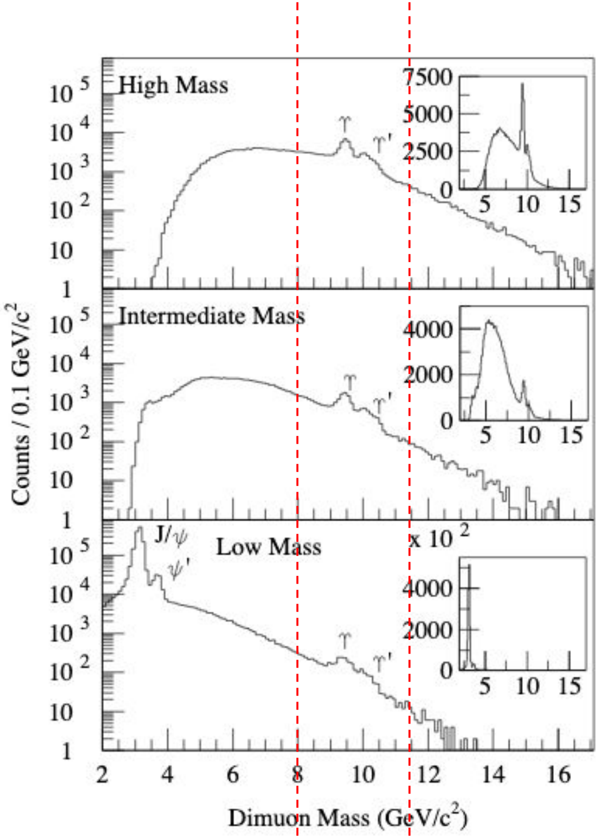
- What is SIDIS?
- SIDIS regions
- Successes and challenges

What is DY?

Improved Measurement of the $\bar{d}/\bar{u}$ Asymmetry in the Nucleon Sea

(FNAL E866/NuSea Collaboration)

$$P_A + P_B \rightarrow l + \bar{l} + \boxed{X}$$



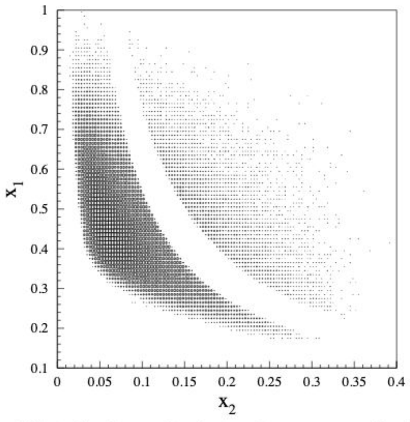
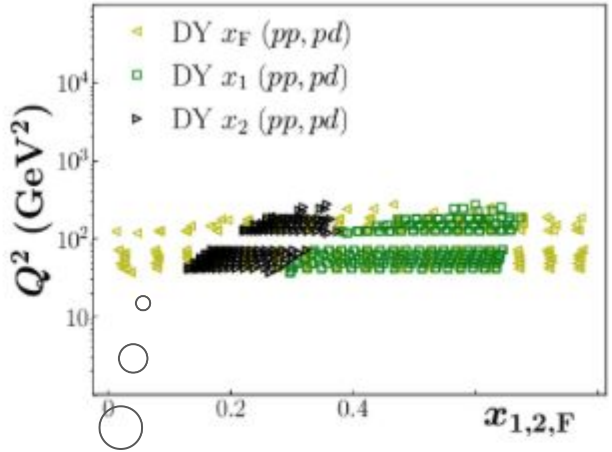
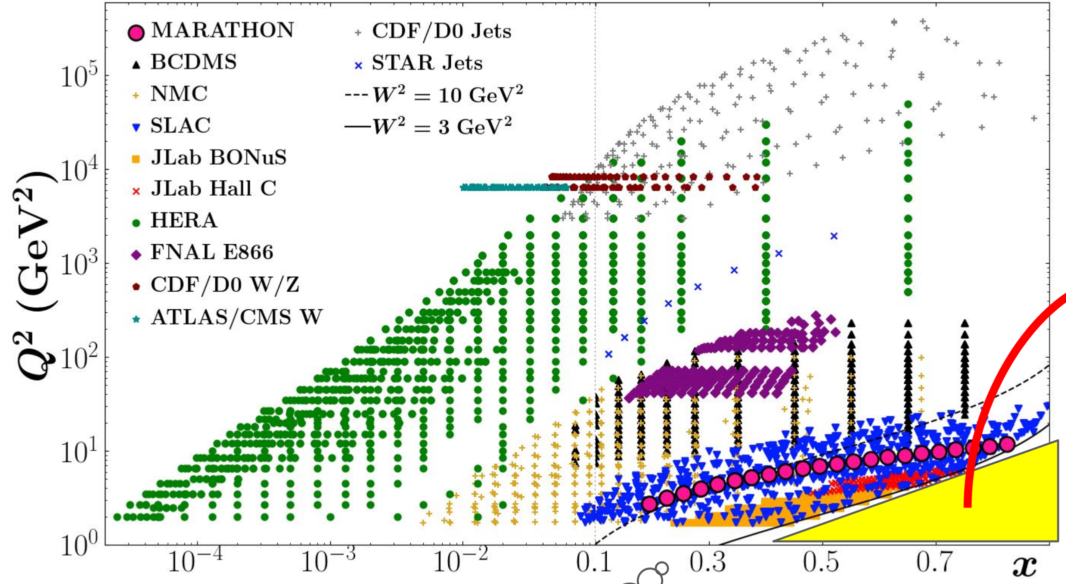


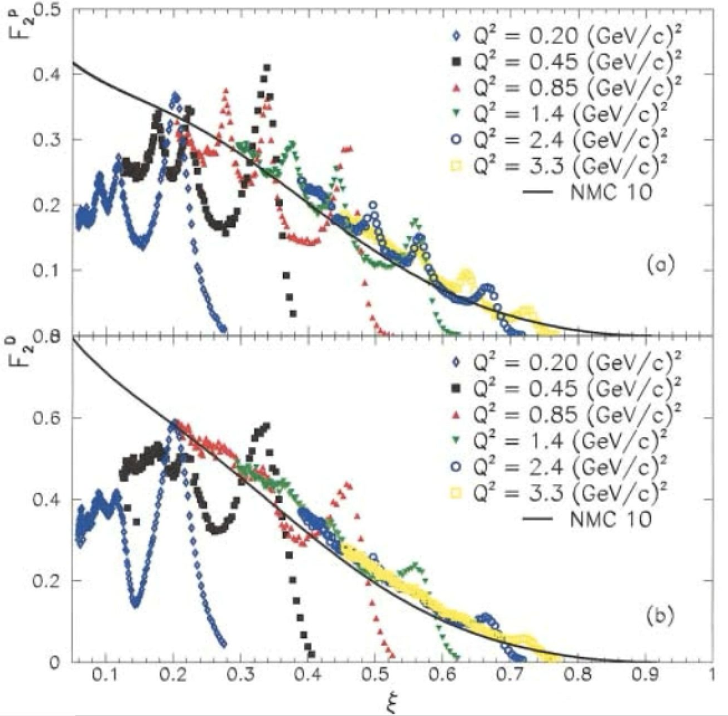
FIG. 3. The dimuon distributions for x_1 versus x_2 for the high mass setting.



E866 provided the data by removing the upsilon without compromising the non-resonant region - “only modest modeling of upsilon” involved

What is DIS?

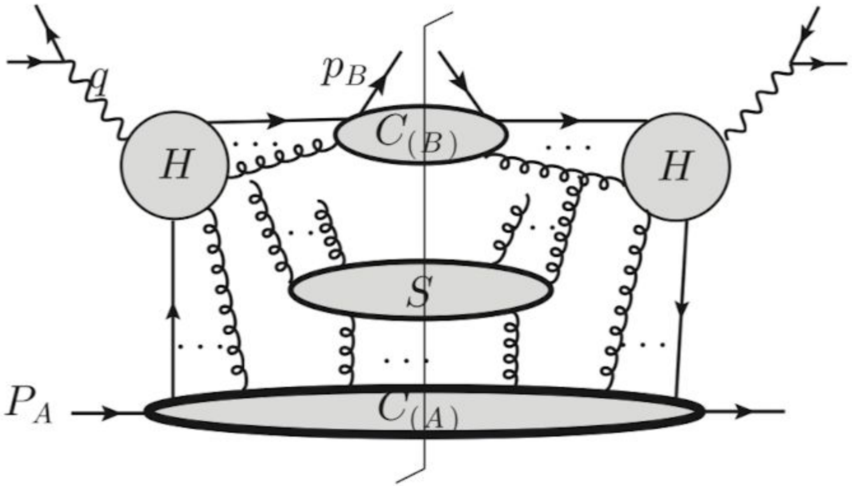




Cuts on W2, Q2 are needed to stay in the continuum DIS region

$$l + P_A \to l' + \boxed{X}$$

What is SIDIS?



$$l + P_A \to l' + P_B + \boxed{X}$$

Sum over all final states

$$W^{\mu\nu}_{\mathrm{SIDIS}}(P, q, P_{\mathrm{B}}) \equiv \sum_X \delta^{(4)}(P + q - P_{\mathrm{B}} - P_X)\, \langle P, S | j^\mu(0) \boxed{| P_{\mathrm{B}}, X\rangle\langle P_{\mathrm{B}}, X |} j^\nu(0) | P, S\rangle\,.$$

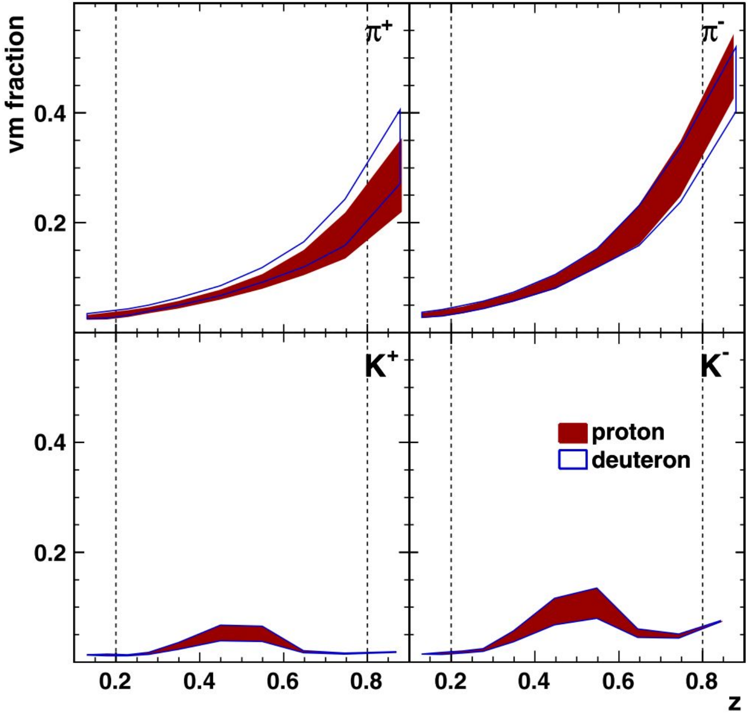
PHYSICAL REVIEW D **87,** 074029 (2013)

Multiplicities of charged pions and kaons from semi-inclusive deep-inelastic scattering by the proton and the deuteron

(HERMES Collaboration)

4. Exclusive vector-meson contribution

The exclusive production of vector-mesons (ρ^0, ω, or ϕ) can be described in the vector-meson dominance (VMD) model as the fluctuation of the virtual photon into a $q\bar{q}$ pair before its interaction with the target nucleon. These vector mesons subsequently decay into lighter hadrons that are then found in the final hadronic state. The cross sections for the exclusive production show a $1/Q^6$ dependence and can be considered as higher-twist effects. They do not involve the fragmentation of quarks originating from the target nucleon. If fragmentation functions were to be extracted from multiplicities that include such an exclusive production, they would be process dependent. For this reason the data presented in this paper have been corrected for hadrons stemming from these processes, but the final tabulation includes data with and without this correction.



Multiplicities of charged pions and unidentified charged hadrons from deep-inelastic scattering of muons off an isoscalar target

The COMPASS Collaboration

3.4 Vector meson correction

A fraction of the mesons measured in SIDIS originates from diffractive production of vector mesons, which subsequently decay into lighter hadrons. This fraction can be considered as a higher-twist contribution to the SIDIS cross section [8]. It cannot be described by the QCD parton model with the independent-fragmentation mechanism, which is encoded in the FFs. Moreover, fragmentation functions extracted from data including this fraction would be biased, which violates in particular the universality principle of the model. Therefore, the fraction of final-state hadrons originating from diffractive ρ^0 decay is estimated. Our evaluation is based on two MC simulations, one using the LEPTO event generator simulating SIDIS free of diffractive contributions (see Section 3.3), and the other one using the HEPGEN [19] generator simulating diffractive ρ^0 production. Further channels, which are characterised

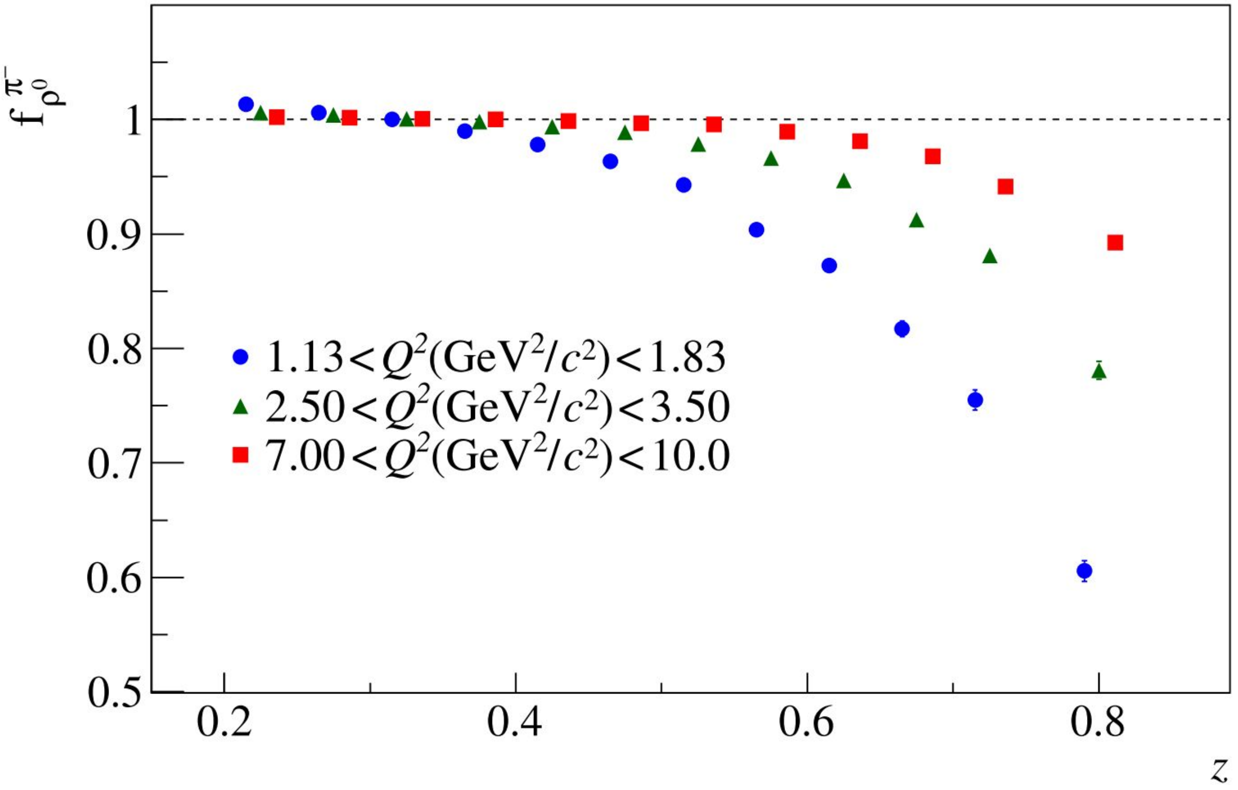


Figure 2: Correction due to diffractive ρ^0 contamination, shown for negative-pion multiplicities as a function of z for three Q^2 bins

Transverse-momentum-dependent Multiplicities of Charged Hadrons in Muon-Deuteron Deep Inelastic Scattering

The COMPASS Collaboration

3.4 Diffractive vector meson contribution

The final-state hadron(s) selected as described above may also originate from diffractive production of vector mesons (ρ^0, ϕ, ω) that decay into lighter hadrons (π, K, p) [4, 26, 27]. This process, which can be described by the fluctuation of the virtual photon into a vector meson that subsequently interacts diffractively with the nucleon through multiple gluon exchange, is different from the interaction of the virtual photon with a single quark in the DIS process. The fraction of selected final-state hadrons originating from diffractive vector-meson decays and their contribution to the SIDIS yields are estimated in each kinematic bin using two Monte Carlo simulations. The first one uses the LEPTO generator to simulate SIDIS events, and the other one uses the HEPGEN generator [28] to simulate diffractively produced ρ^0

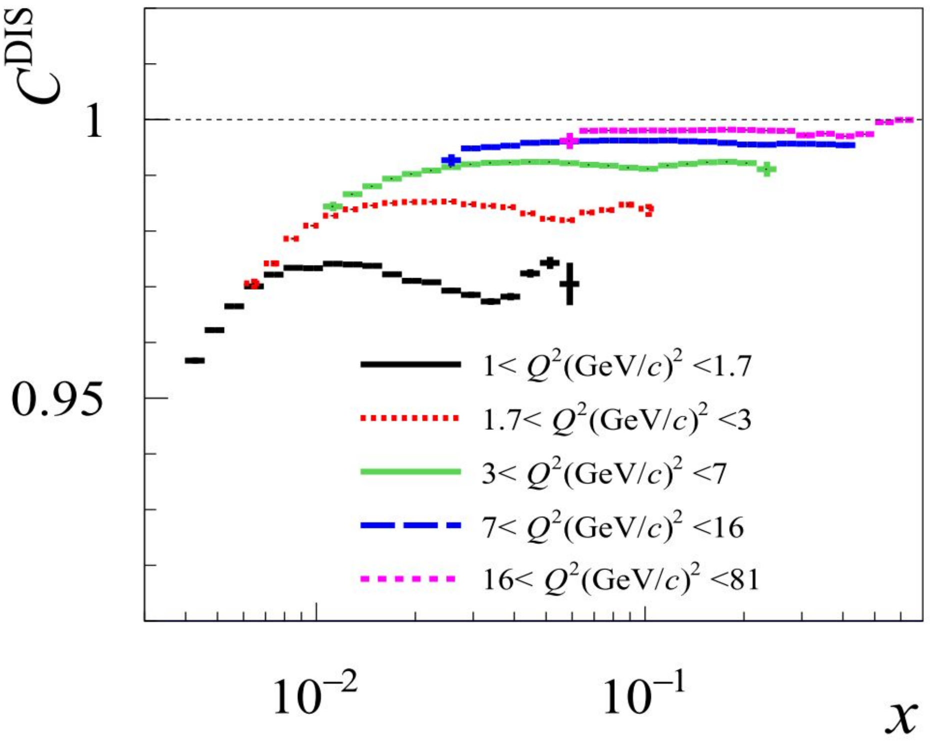
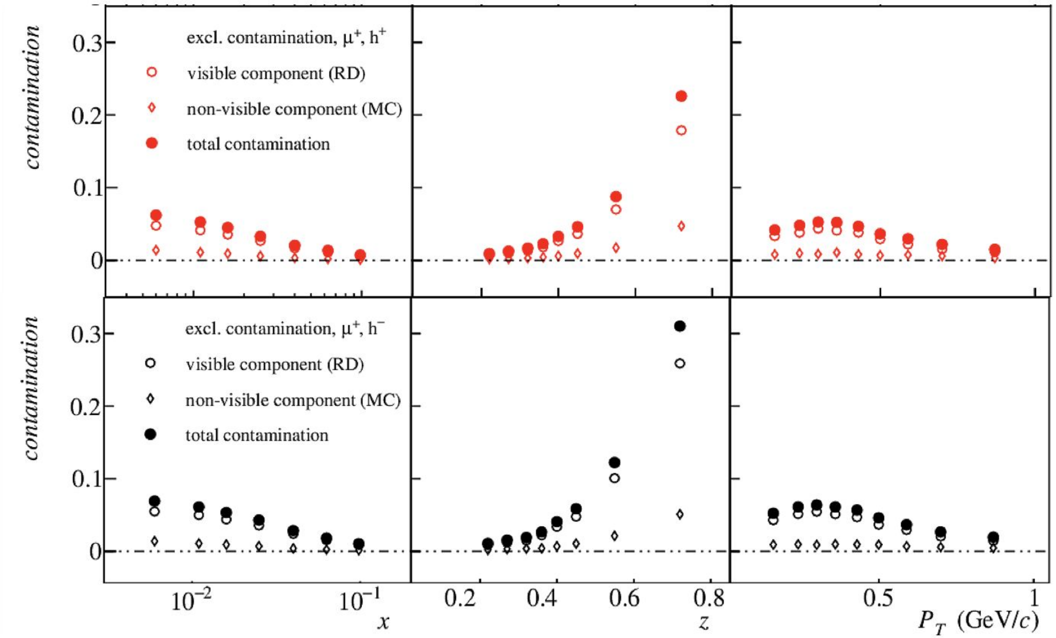


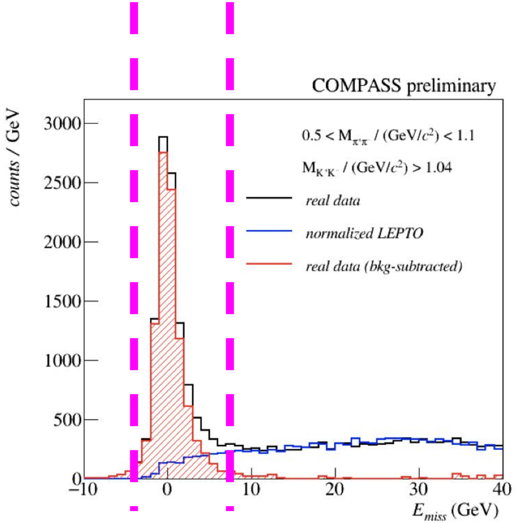
Fig. 3: Correction factor to the DIS yield due to diffractive ρ^0 production as a function of x in the five Q^2 bins.

Talk by A. Moretti (DIS21)



Estimated exclusive hadrons contaminations

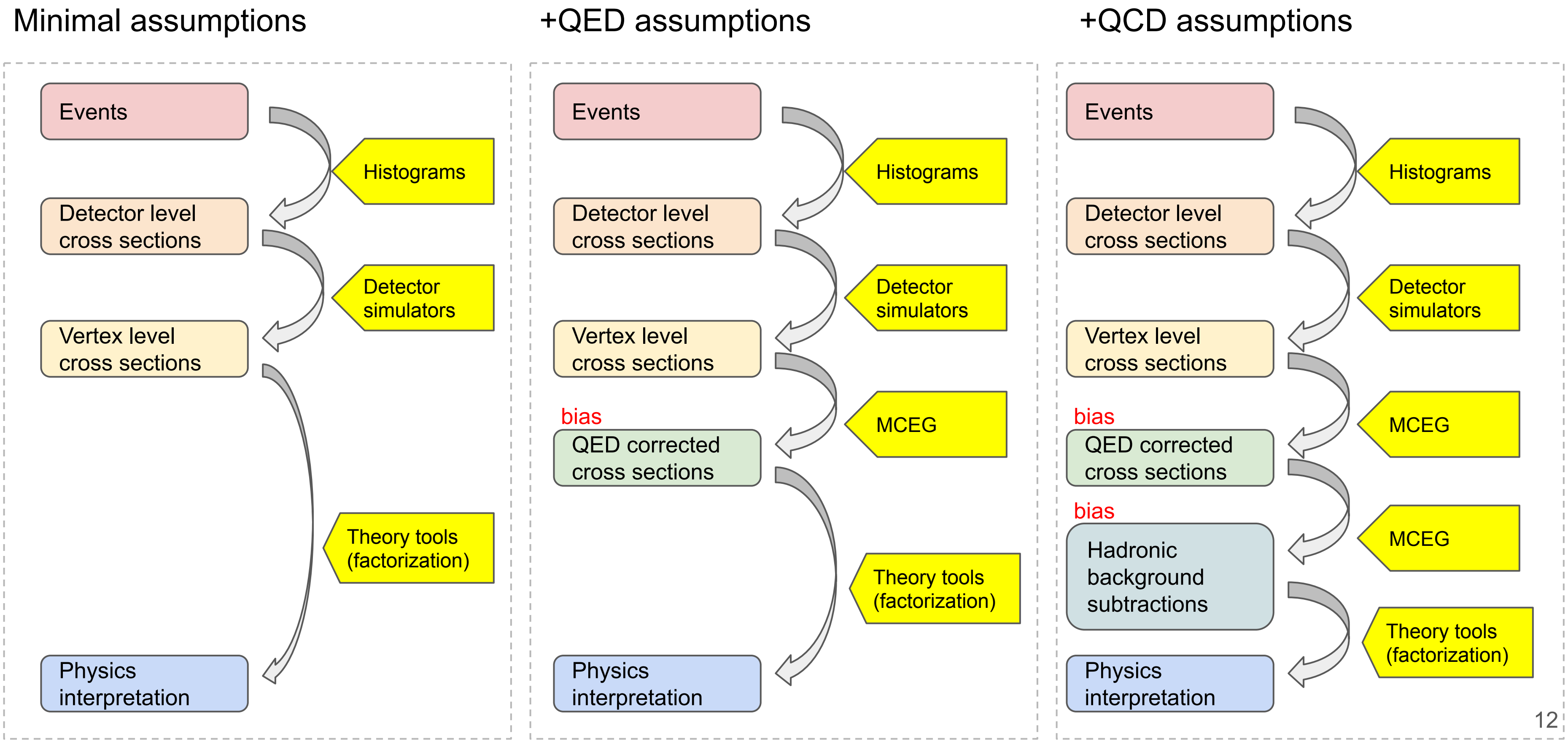
Add vertical lines to mimic DY



The exclusive peak as observed in the data

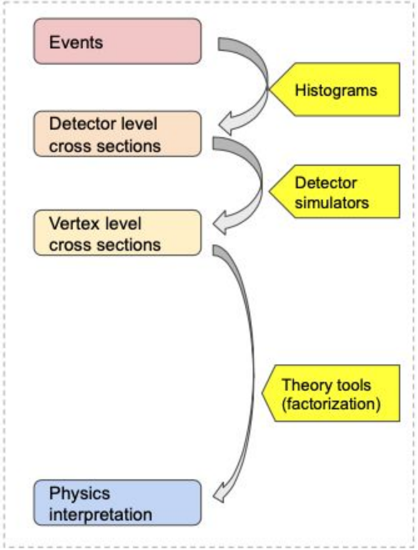
SIDIS data are
modified with models

So what is SIDIS?



Level 1

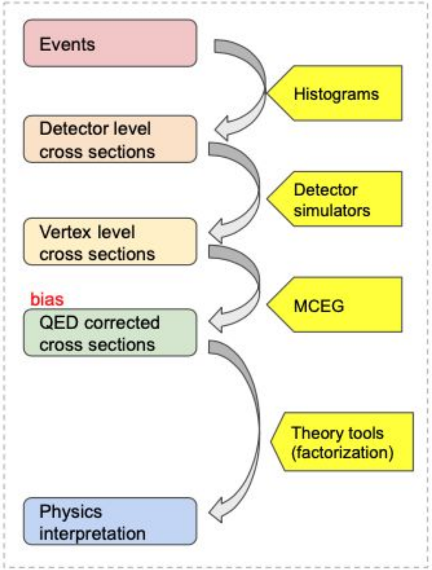
Minimal assumptions



Pros: no theory assumptions, clean constraints on TMDs
Cons: not that easy for QCD pheno but not impossible, less kinematic bins

Level 2

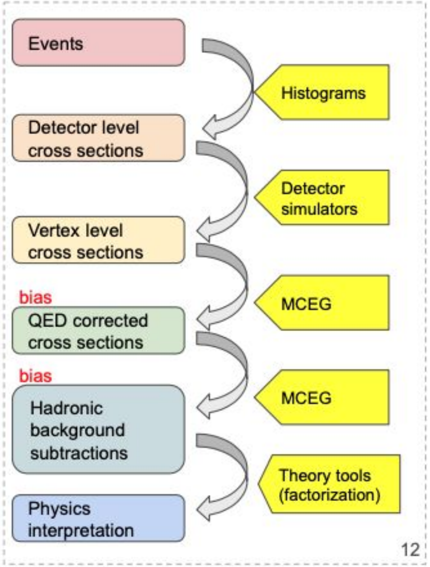
+QED assumptions



Pros: easy for QCD pheno groups
Cons: issues with QED deconvolution

Level 3

+QCD assumptions



Pros: wider kinematic coverage for “TMD physics”
Cons: model dependent, increase risk of confirmation bias

So what should we aim for?

- **Provide** data with different levels of assumptions 1,2,3,...
- **Quantify** the degree of bias/assumptions across all levels

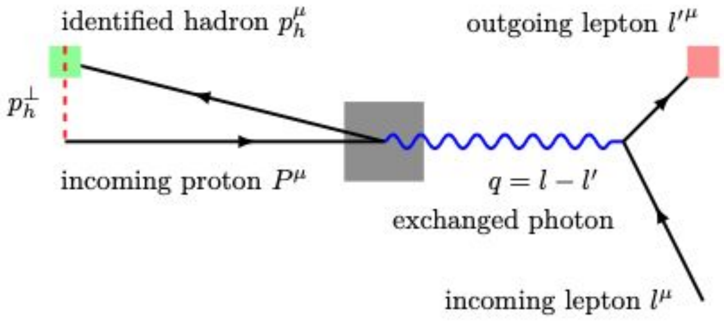
Outline

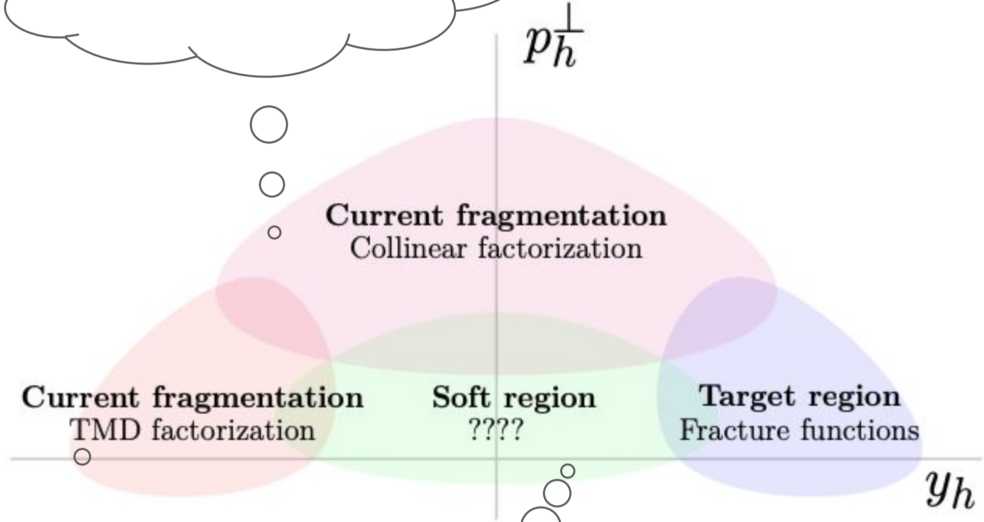
- What is SIDIS
- SIDIS regions
- Successes and challenges

SIDIS regions

Is this region described well?

Breit frame





How confident can we interpret the data as current fragmentation

Existing theory framework is incomplete

arXiv:1904.12882 (hep-ph)

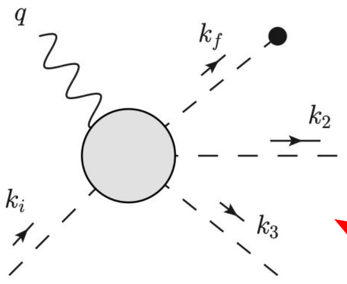
[Submitted on 29 Apr 2019]

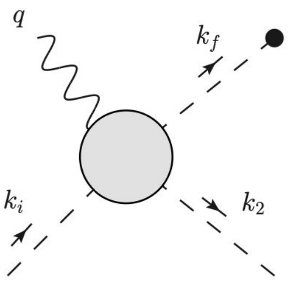
Mapping the Kinematical Regimes of Semi-Inclusive Deep Inelastic Scattering

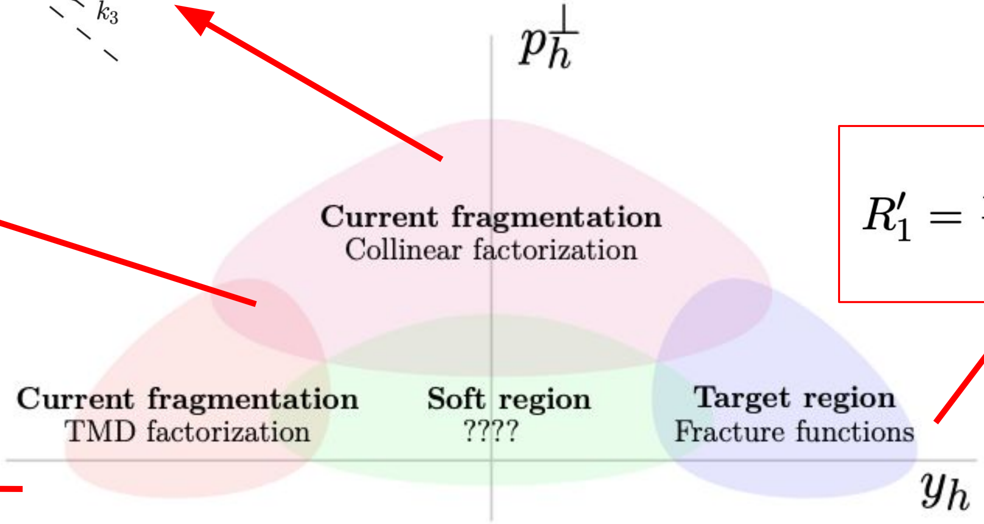
M. Boglione, A. Dotson, L. Gamberg, S. Gordon, J. O. Gonzalez-Hernandez, A. Prokudin, T. C. Rogers, N. Sato

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

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

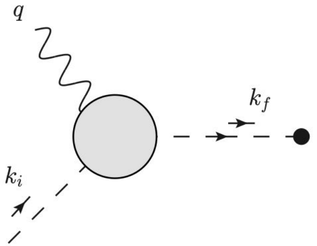






$$R_1' = \frac{P_B \cdot P}{Q^2}$$

$$\text{Collinearity} = R_1 \equiv \frac{P_B \cdot k_f}{P_B \cdot k_i}$$



TMD affinity map based on R_i

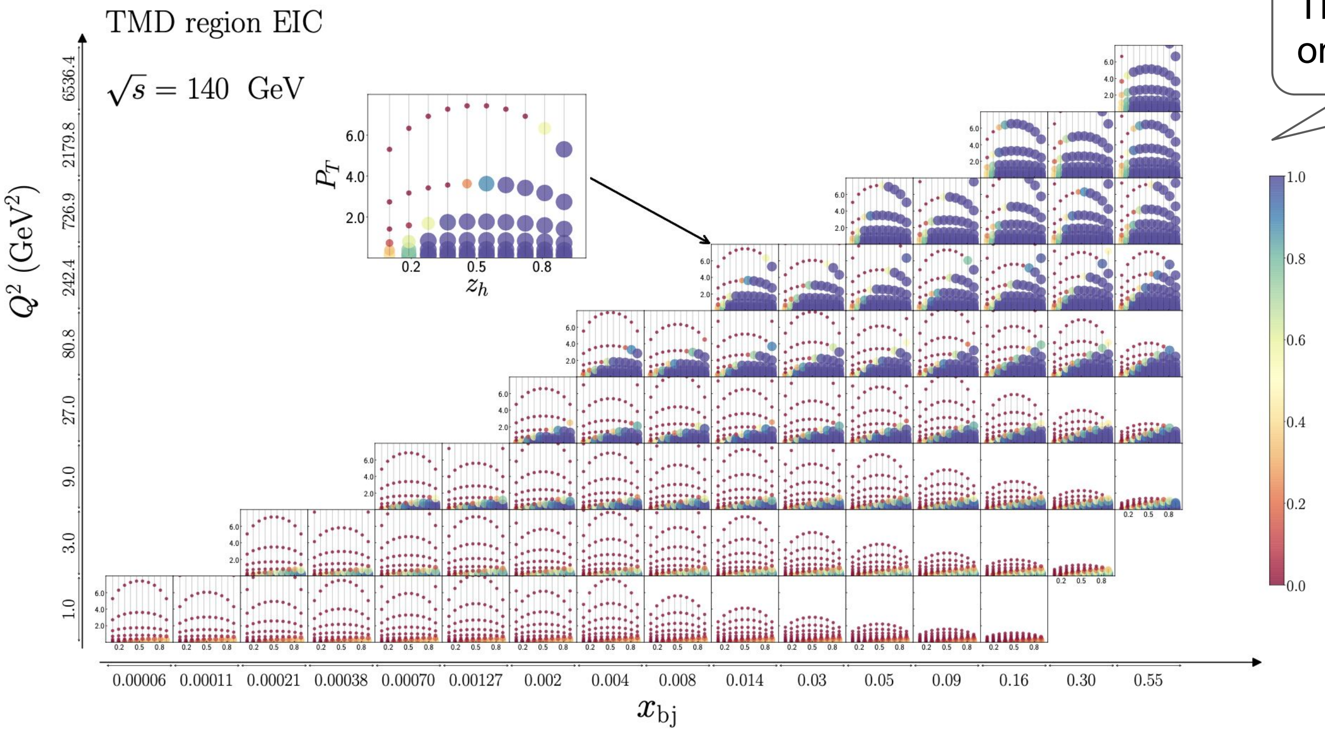
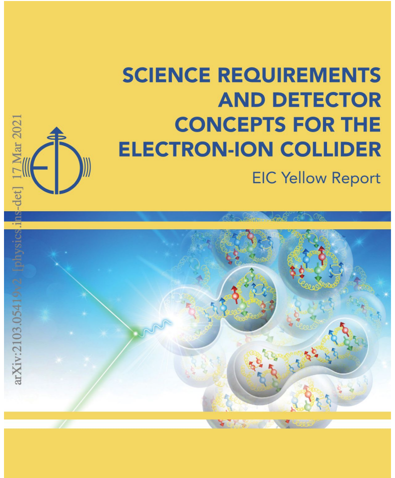


Figure 7.50: The $x - Q^2$ plane with future EIC measurements at $\sqrt{s} = 140$ GeV. Each panel displays $z_h \approx z$ vs. P_T ranges of measurements (shown by gray lines). The colored symbols represent the estimated affinity of the measurement to TMD factorization region. The color code is proportional to the affinity. (See text for more details.)



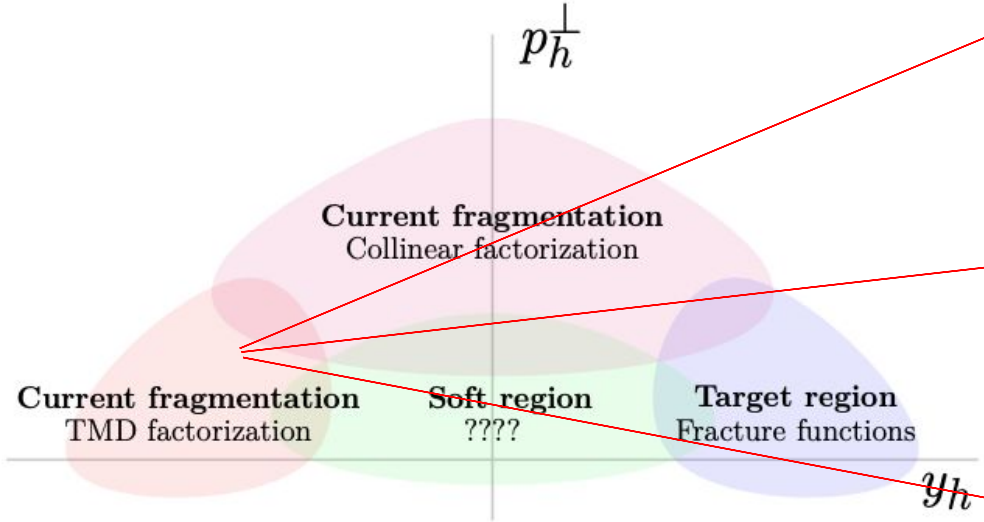
The Quark Structure of the Nucleon from the CERN Muon Experiments

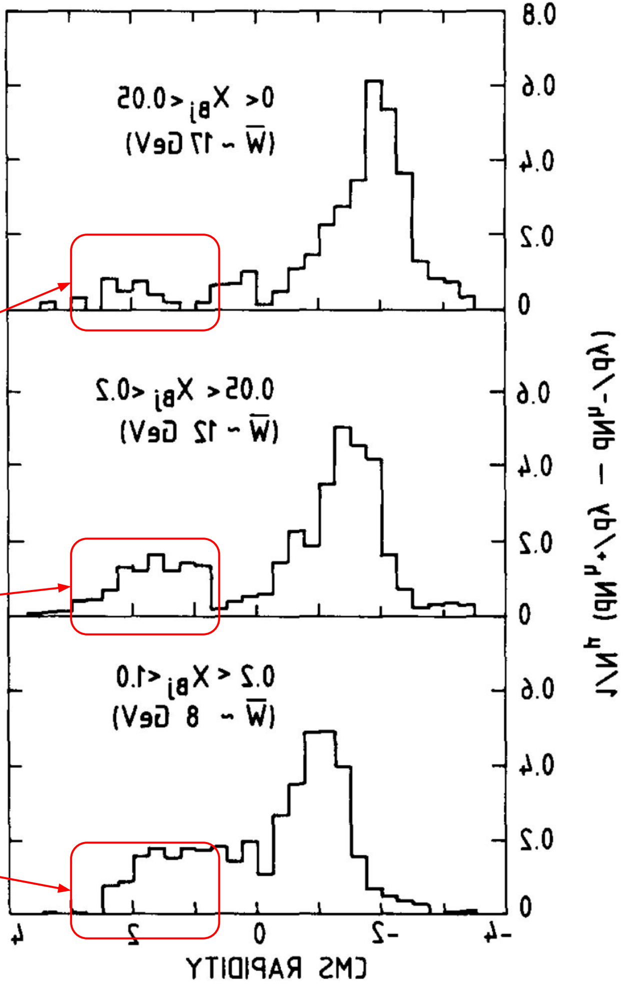
T. Sloan (Lancaster U. and CERN and Munich U.), R. Voss (Lancaster U. and CERN and Munich U.), G. Smadja (Saclay)

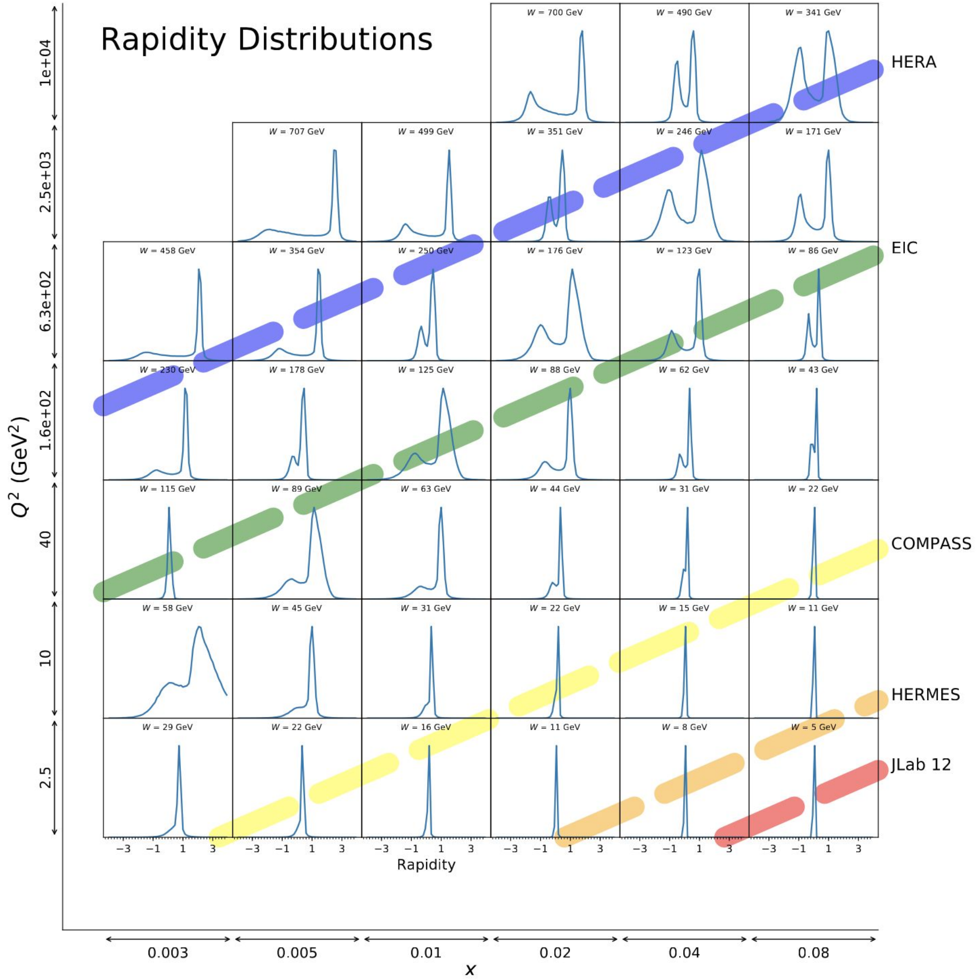
1988

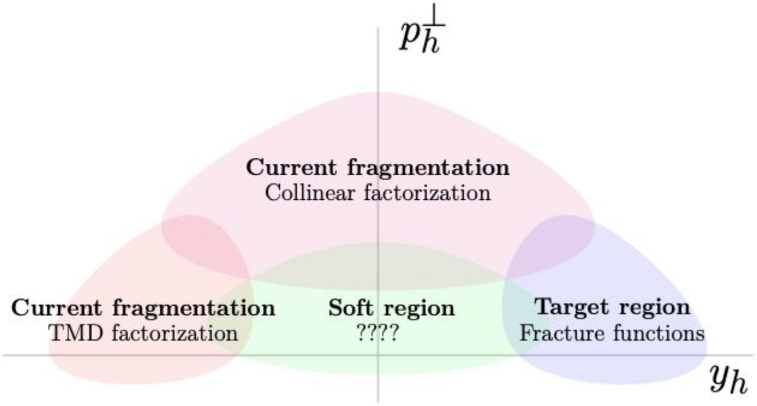
123 pages

Published in: *Phys.Rept.* 162 (1988) 45-167









Estimated using Pythia8
(unpublished)

So what should we aim for?

- **Provide** rapidity distributions @ Lab frame, Breit frame

- Use metrics like affinity/R to estimate TMD like phase space

Outline

- What is SIDIS
- SIDIS regions
- Successes and challenges

Need for a global analysis

Give F2p and F2n across x, can we say with confidence that the extract *u* & *d* are intrinsic property of hadrons?

$$\tilde{F}_2^p(x) = \frac{4}{9}u(x) + \frac{1}{9}d(x)$$

$$\tilde{F}_2^n(x) = \frac{4}{9}d(x) + \frac{1}{9}u(x)$$

No: fitting *u* & *d* is just data parametrization

One needs to have an **over constrained** system of equations with overlapping kinematics

[Submitted on 19 Feb 2020 (v1), last revised 2 Sep 2020 (this version, v2)]

Origin of single transverse-spin asymmetries in high-energy collisions

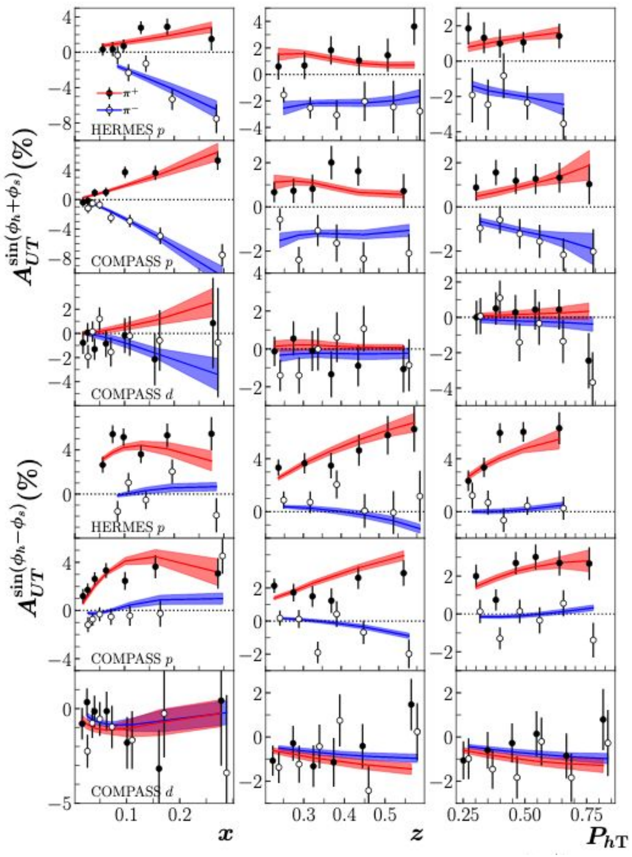
Justin Cammarota, Leonard Gamberg, Zhong-Bo Kang, Joshua A. Miller, Daniel Pitonyak, Alexei Prokudin, Ted C. Rogers, Nobuo Sato

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\text{pts.}}$	Refs.
$A_{\text{SIDIS}}^{\text{Siv}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$150.0/126 = 1.19$	[65, 66, 68]
$A_{\text{SIDIS}}^{\text{Col}}$	$e+(p,d)^{\uparrow} \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^{\perp}(z,z^2p_{\perp}^2)$	$111.3/126 = 0.88$	[66, 68, 71]
$A_{\text{SIA}}^{\text{Col}}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^{\perp}(z,z^2p_{\perp}^2)$	$154.5/176 = 0.88$	[74–77]
$A_{\text{DY}}^{\text{Siv}}$	$\pi^- + p^{\uparrow} \to \mu^+\mu^- + X$	$f_{1T}^{\perp}(x,k_T^2)$	$5.96/12 = 0.50$	[73]
$A_{\text{DY}}^{\text{Siv}}$	$p^{\uparrow} + p \to (W^+,W^-,Z)+X$	$f_{1T}^{\perp}(x,k_T^2)$	$31.8/17 = 1.87$	[72]
A_N^h	$p^{\uparrow} + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x) = \frac{1}{\pi} f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60 = 1.11$	[7, 9, 10, 13]

TABLE I. Summary of the SSAs analyzed in our global fit. There are a total of 18 different reactions. (UC and UL stand for "unlike-charged" and "unlike-like" pion combinations.) There are also a total of 6 non-perturbative functions when one takes into account flavor separation.

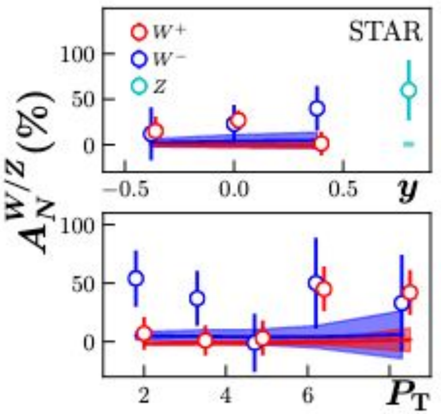
There are a total of 18 different reactions.

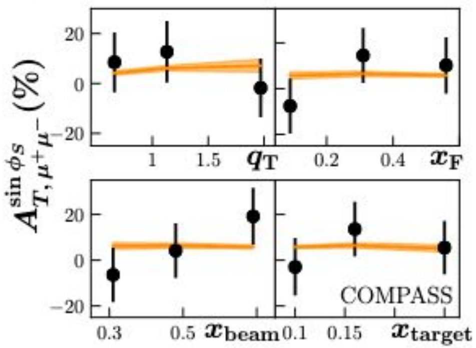
There are also a total of 6 non-perturbative functions



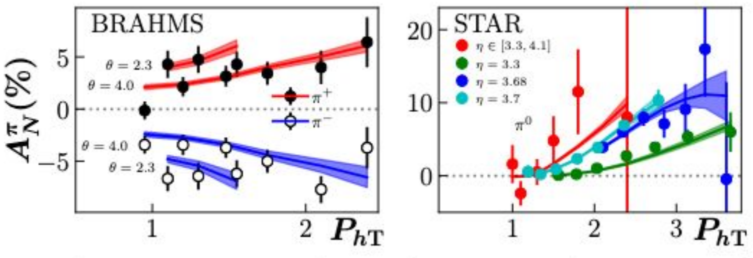
$$e + (p,d)^{\uparrow} \to e + (\pi^+, \pi^-, \pi^0) + X$$
$$e + (p,d)^{\uparrow} \to e + (\pi^+, \pi^-, \pi^0) + X$$

$$p^{\uparrow} + p \to (W^+, W^-, Z) + X$$

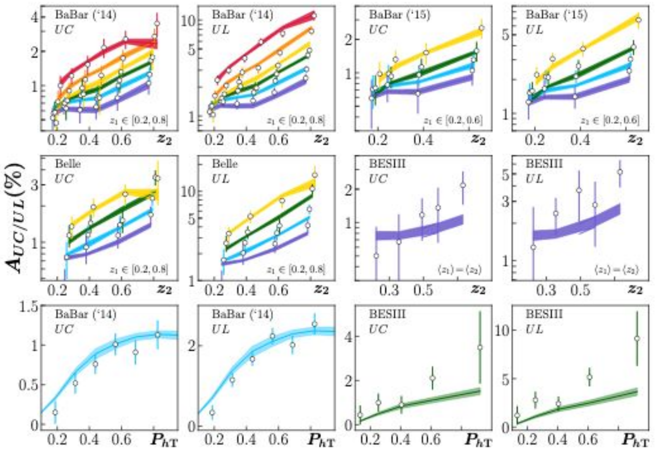




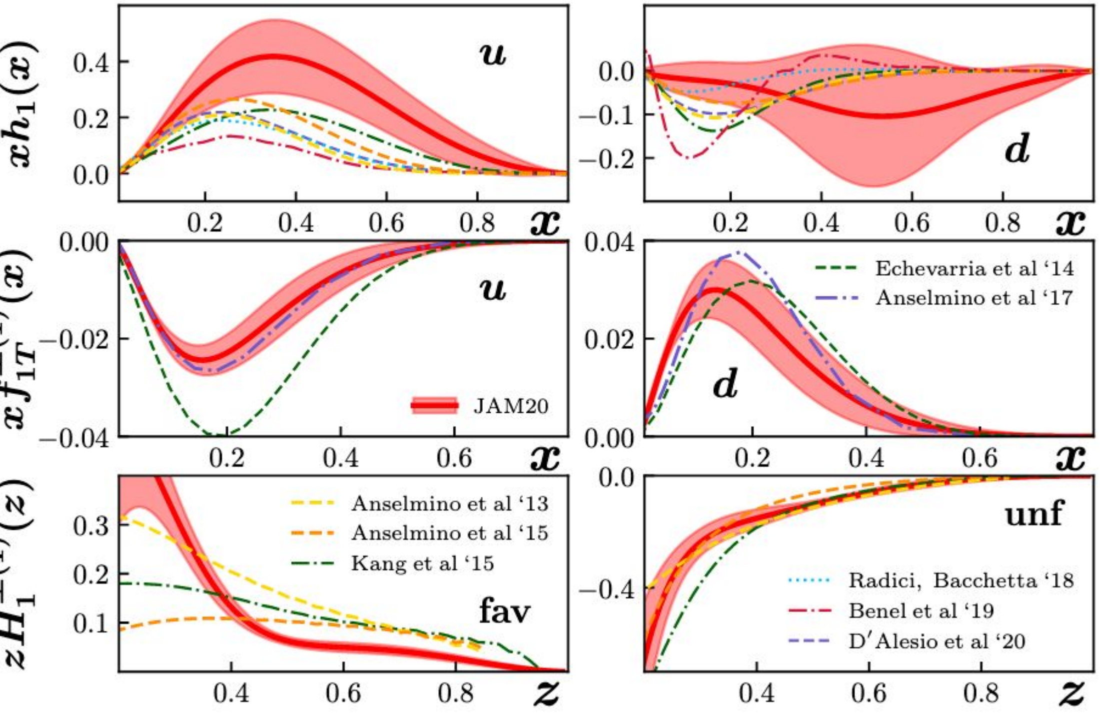
$$\pi^- + p^{\uparrow} \to \mu^+\mu^- + X$$

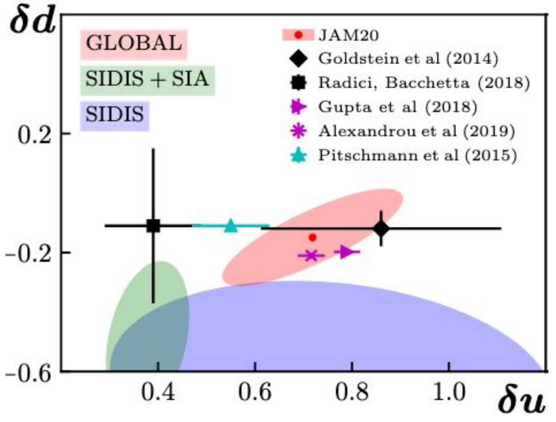


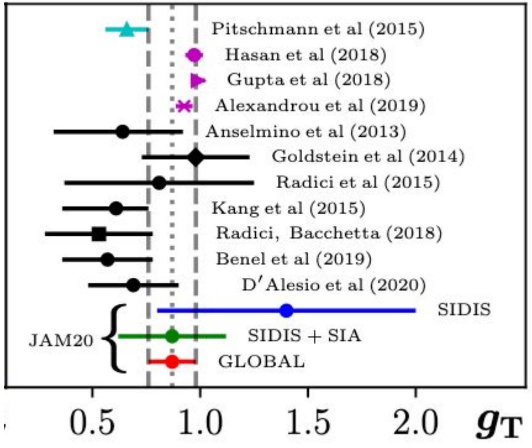
$$p^{\uparrow} + p \to (\pi^+, \pi^-, \pi^0) + X$$



$$e^+ + e^- \to \pi^+\pi^-(UC, UL) + X$$

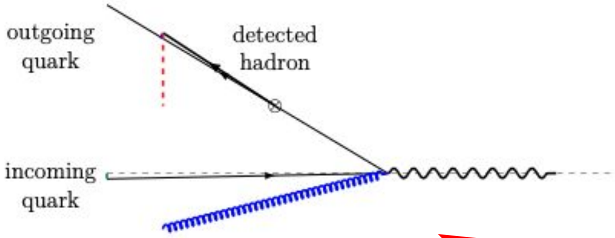




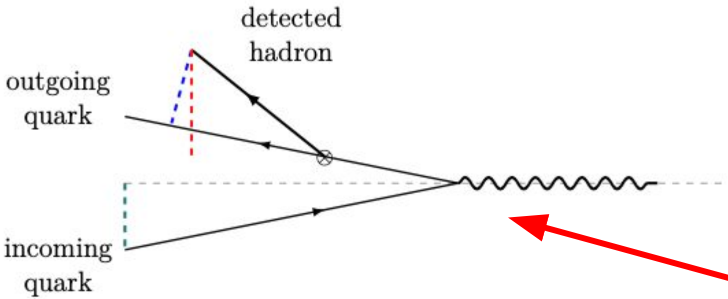


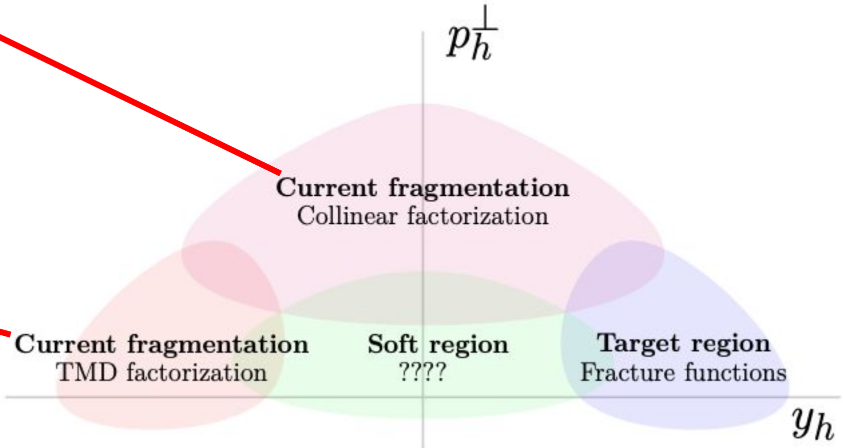
- An indication for a possible origin of SAA
- Need to study/include proper QCD evolution

Large transverse momentum



$$
\begin{aligned}
\frac{d\sigma}{dx\,dQ^2\,dz\,dp_h^{\perp}} &= \mathrm{W} + \mathrm{FO} - \mathrm{ASY} + \mathcal{O}(m^2/Q^2) \\
&\sim \mathrm{W} \quad \text{for } q_{\mathrm{T}} \ll Q \\
&\sim \mathrm{FO} \quad \text{for } q_{\mathrm{T}} \sim Q
\end{aligned}
$$

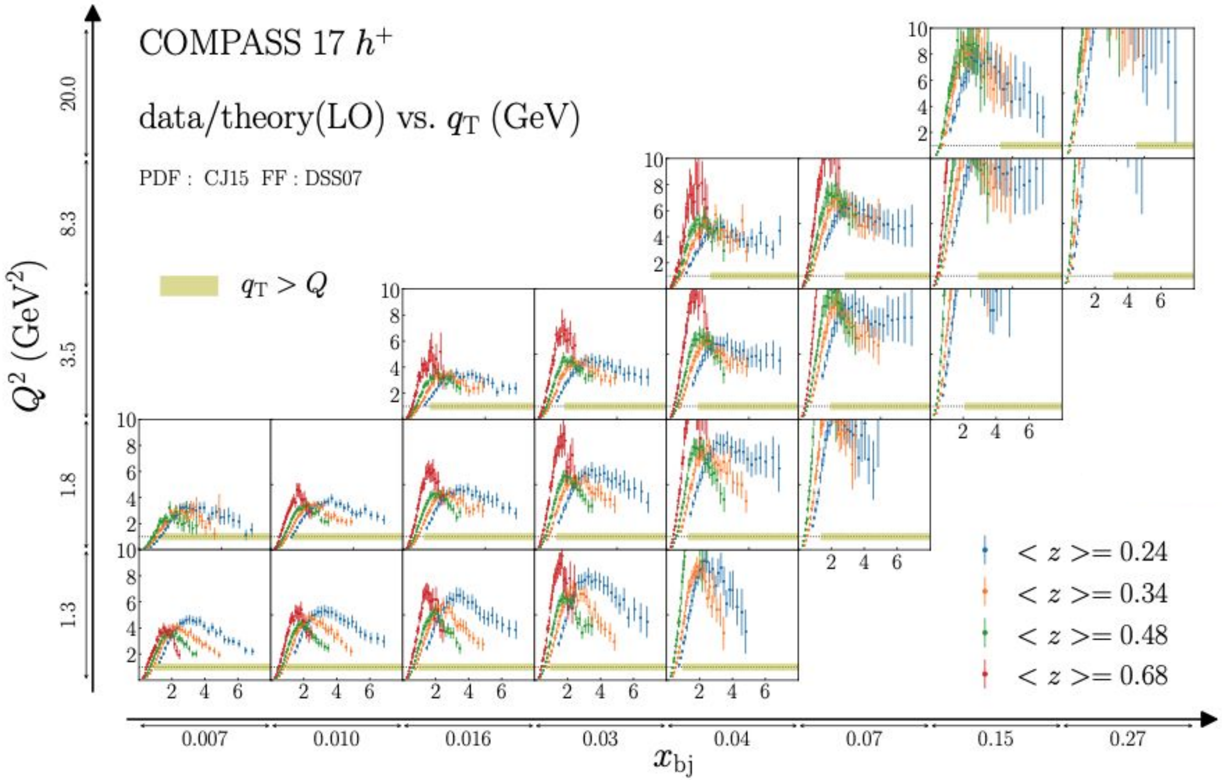


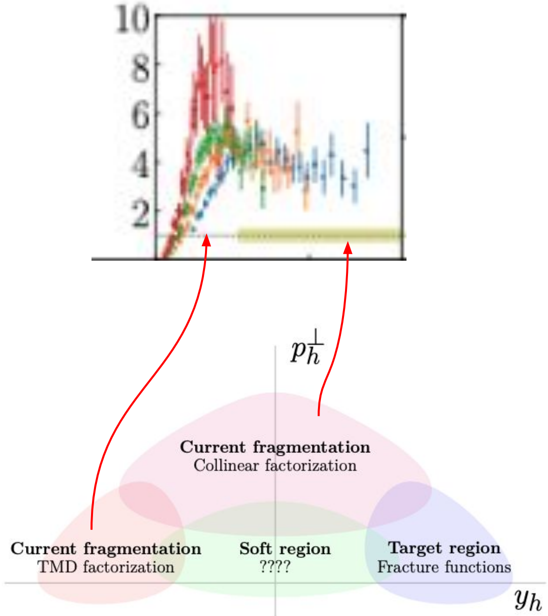


[Submitted on 13 Aug 2018 (v1), last revised 12 Dec 2018 (this version, v2)]

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

J. O. Gonzalez-Hernandez, T. C. Rogers, N. Sato, B. Wang





Large qT region not well described

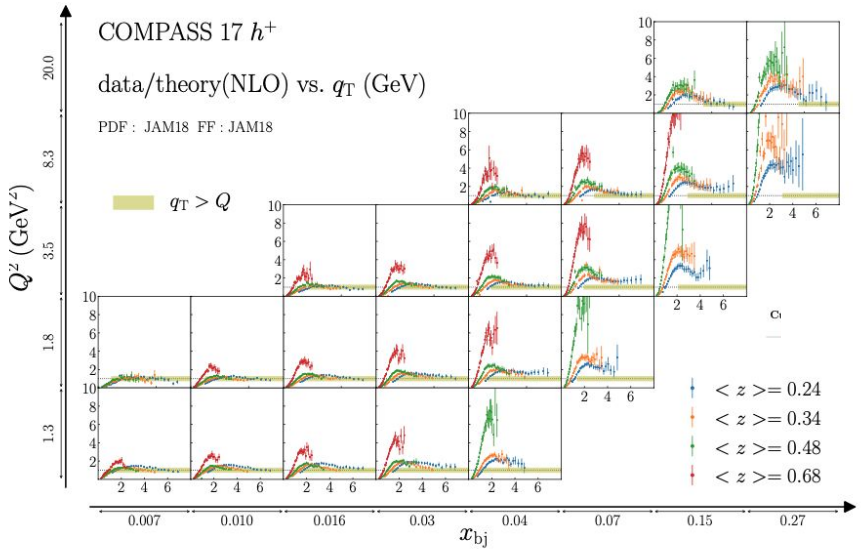
Status

[Submitted on 4 Mar 2019]

Large Transverse Momentum in Semi-Inclusive Deeply Inelastic Scattering Beyond Lowest Order

B. Wang, J. O. Gonzalez-Hernandez, T. C. Rogers, N. Sato

- NLO corrections does not seems to solve the problem
- NLO + refitting PDFs and FFs seems to help (unpublished)
- Other physical mechanism has been proposed

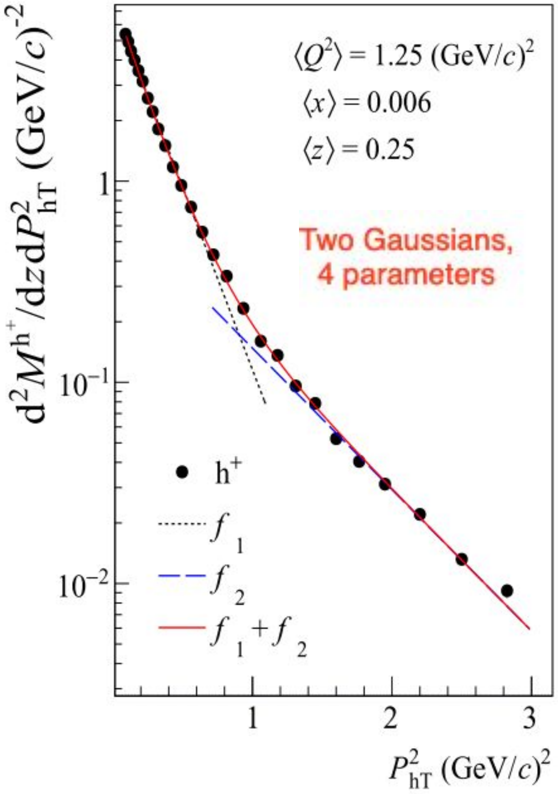


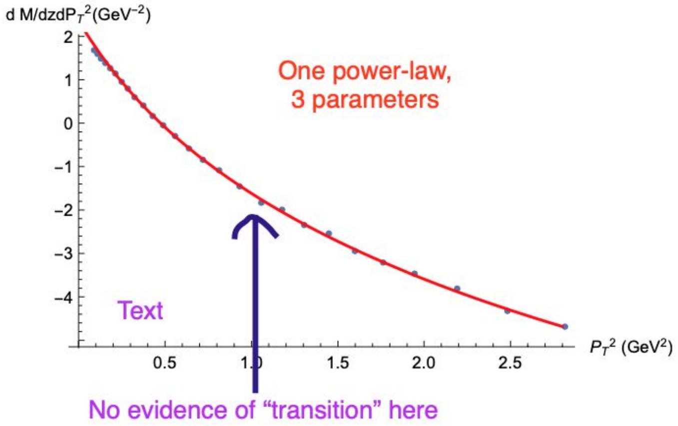
[Submitted on 13 Jul 2019 (v1), last revised 14 Jan 2020 (this version, v2)]

Power corrections in semi-inclusive deep inelastic scatterings at fixed target energies

Tianbo Liu, Jian-Wei Qiu

Evidence for large pT region?





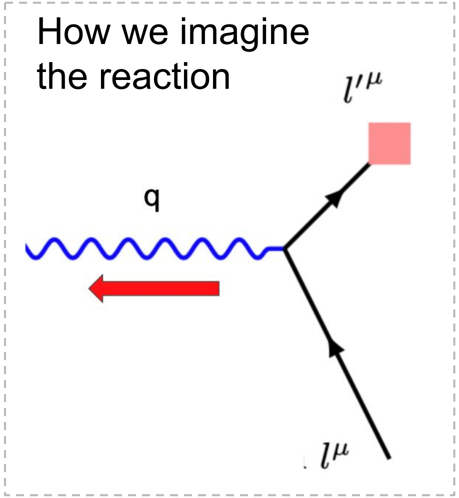
What is the physical origin of the large pT tail?

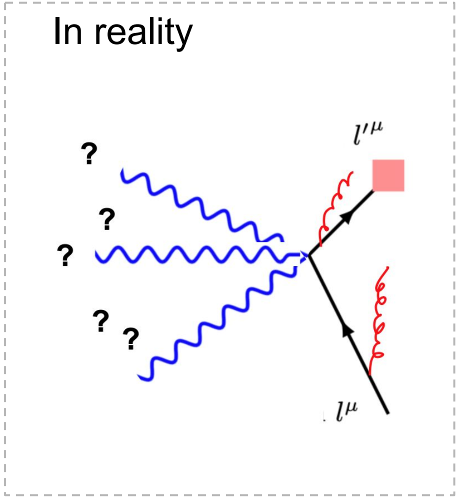
- hard gluon radiation
- power corrections
- …?

Is an open question

Role of QED effects

[Submitted on 6 Aug 2020 (v1), last revised 17 Mar 2021 (this version, v3)]
Factorized approach to radiative corrections for inelastic lepton-hadron collisions
Tianbo Liu, W. Melnitchouk, Jian-Wei Qiu, N. Sato



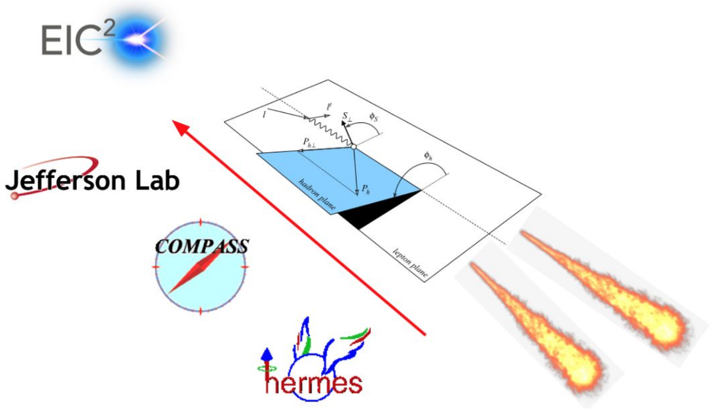


- In the presence of QED radiation, **the q direction is not fixed**
- The experimental Breit Frame **does not need to coincide with the actual Breit-frame** needed in QCD factorization

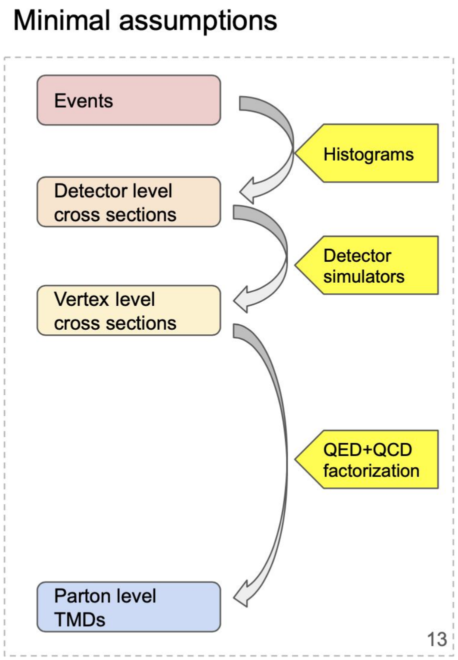
See talk by Tianbo Liu

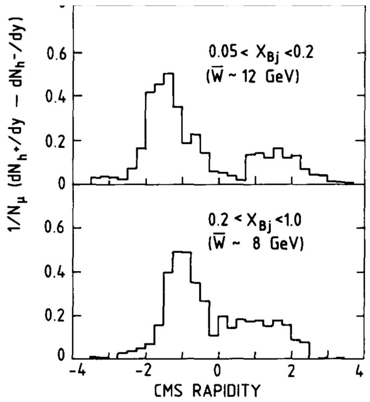
So what should we aim for?

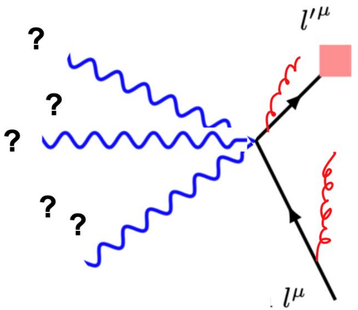
- Systematically include/test all the effects:
  - NLO,
  - pdf/ff refitting,
  - power corrections,
  - QED
  - ....

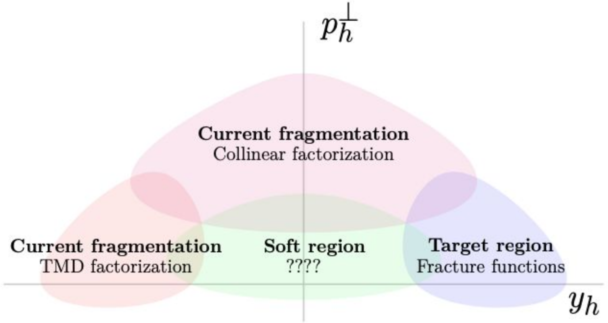


Summary & outlook









- What is SIDIS
- SIDIS regions
- Successes and challenges

Backup

At this workshop we will discuss the existing theoretical approaches, future measurements worldwide and data analyses, focusing on different issues in theoretical interpretations and possible limitations from experimental capabilities. The workshop aims to help define a clear path for realistic evaluation of possible interpretations of data and planning for future measurements. We plan to focus on the kinematic region with large enough x (x>0.02), where spin-orbit correlations are significant enough to be measured.

1) The status of the theory, different factorizations for SIDIS process and their applicability in different kinematic regions, and validation/test by data.

2) Projections for any kind of future measurements, with clear systematics due to unknown behavior in the kinematics, where the parameterizations are not constrained by data.

3) Experimental limitations, in particular phase space limitations.

4) Understanding of the impact of unknown fragmentation functions and the associated systematics in the extraction of TMDs, in particular their P_T-dependence, and the role of vector mesons produced in hadronization of quarks.

5) Development of a framework for evaluation of systematics of different extraction procedures, due to experimental uncertainties, limited phase space coverage, various assumptions and approximations used in phenomenology for extraction of TMDs from the existing and future data sets, in particular in kinematic regions not covered by data.

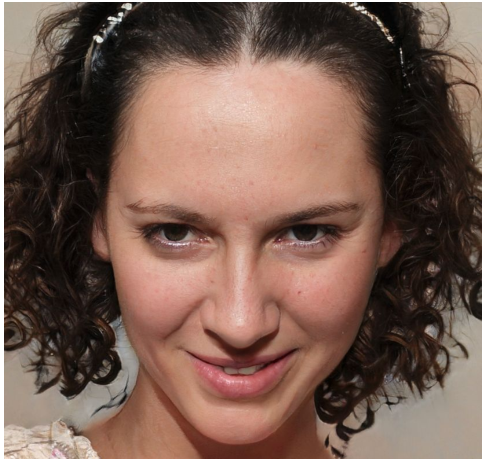
6) Development of realistic and versatile generators allowing for the implementation of different frameworks and phenomenology, which will be crucial for simulations of realistic "pseudo-data", and can be used in validation of various extraction frameworks. Such generators should also allow for the study of model dependence in extracting TMDs.

7) The EIC measurements at large *x*, including coverage, resolutions, large Q_2 behavior of SSAs, complementarity with JLab

8) Lattice calculations: input in phenomenology and MC simulations

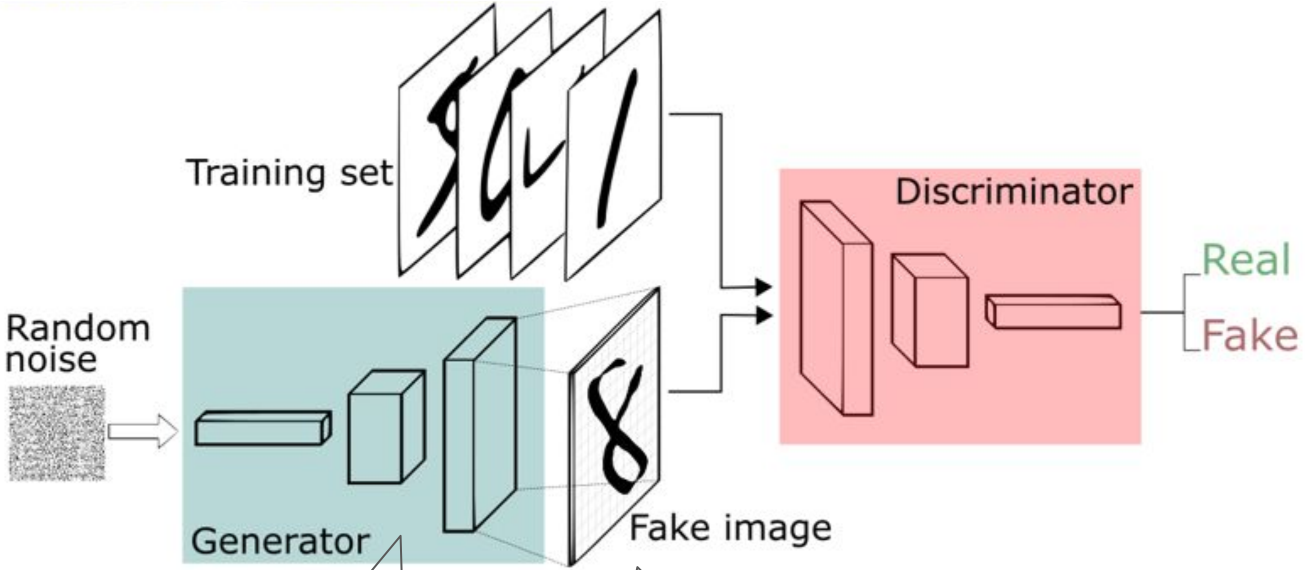






Fake people

https://thispersondoesnotexist.com



Underlying law of human faces

A random sample from underlying law

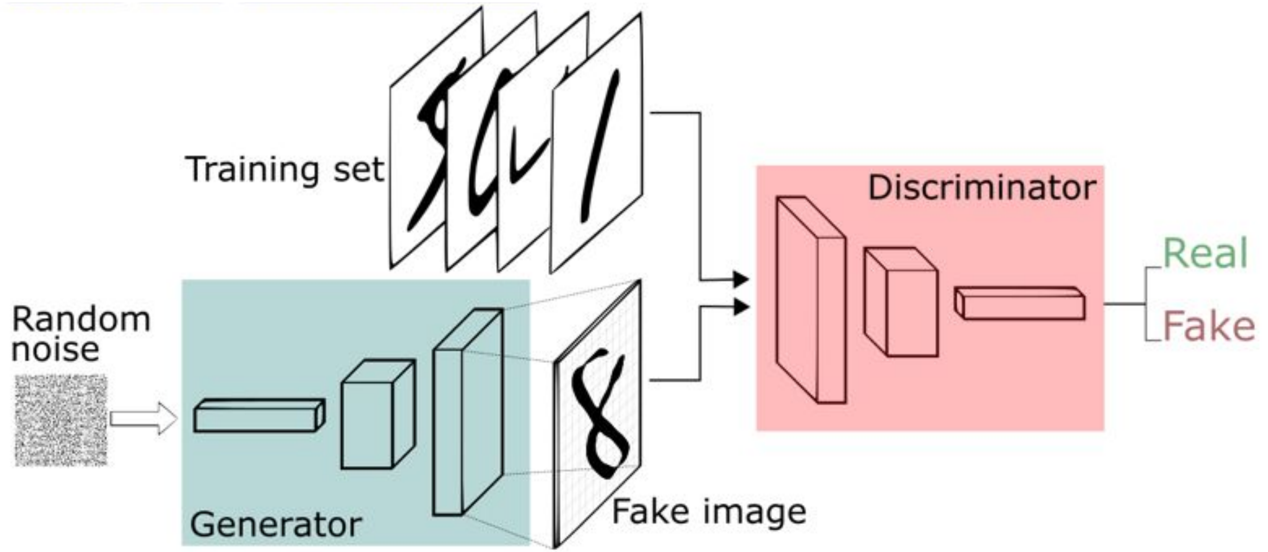
Each image is an event

Statistics > Machine Learning

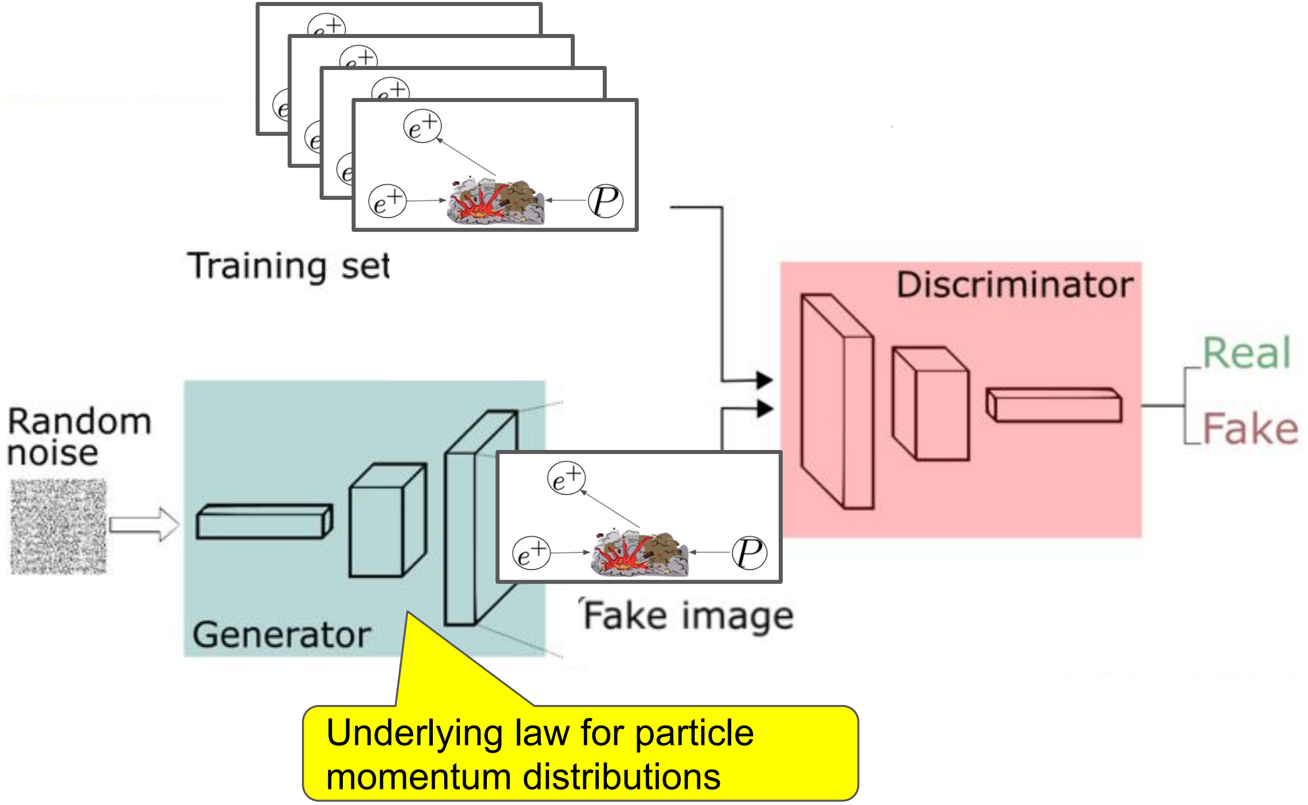
[Submitted on 10 Jun 2014]

Generative Adversarial Networks

Ian J. Goodfellow, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron Courville, Yoshua Bengio



Can we apply GAN for particle reactions?

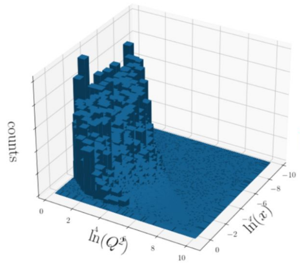


Traditional approach

Events

event	E'	theta'	phi'
1	E'_1	theta'_1	phi'_1
2	E'_2	theta'_2	phi'_2
3	E'_3	theta'_2	phi'_3
⋮	...	...	...

Histogram



Discretized representation of the underlying law

x	Q2	$\frac{d\sigma}{d\Omega}$	uncer.
x_1	Q2_1	rho_1	unc_1
x_2	Q2_2	rho_2	unc_2
x_3	Q2_3	rho_3	unc_3
x_4	Q2_4	rho_4	unc_4
⋮	...	...	...

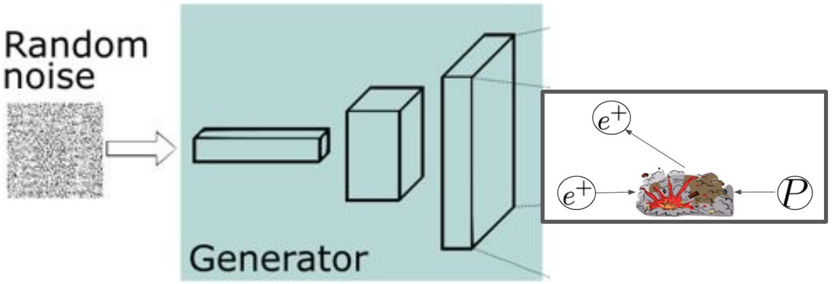
Supervised directly at the event level

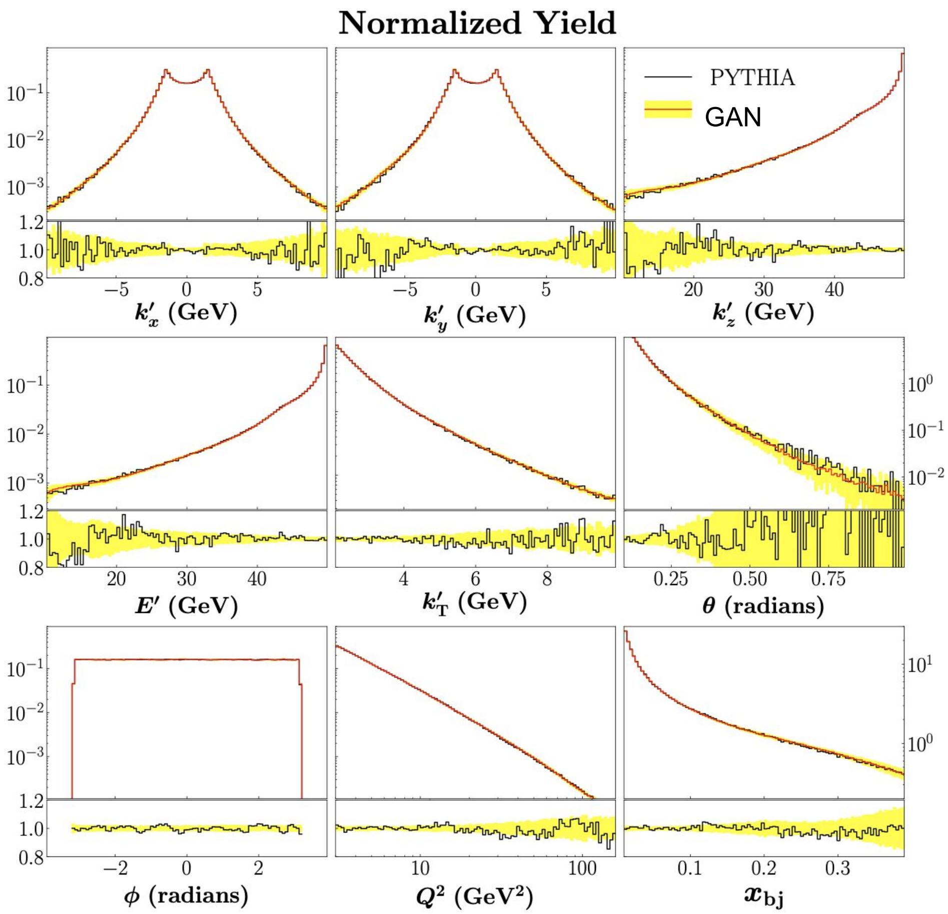
GAN approach

Events

event	E'	theta'	phi'
1	E'_1	theta'_1	phi'_1
2	E'_2	theta'_2	phi'_2
3	E'_3	theta'_2	phi'_3
⋮	...	...	...

ML data representation



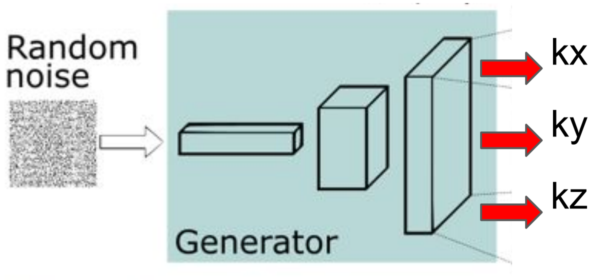


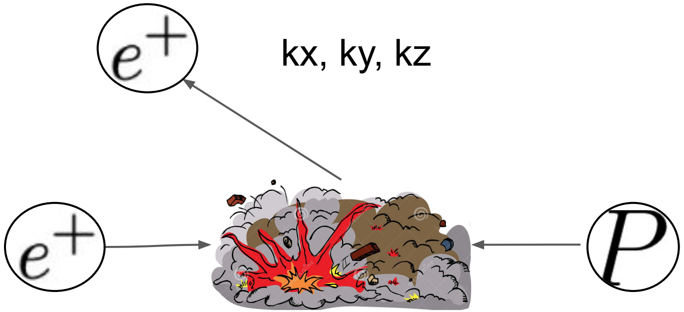
High Energy Physics - Phenomenology

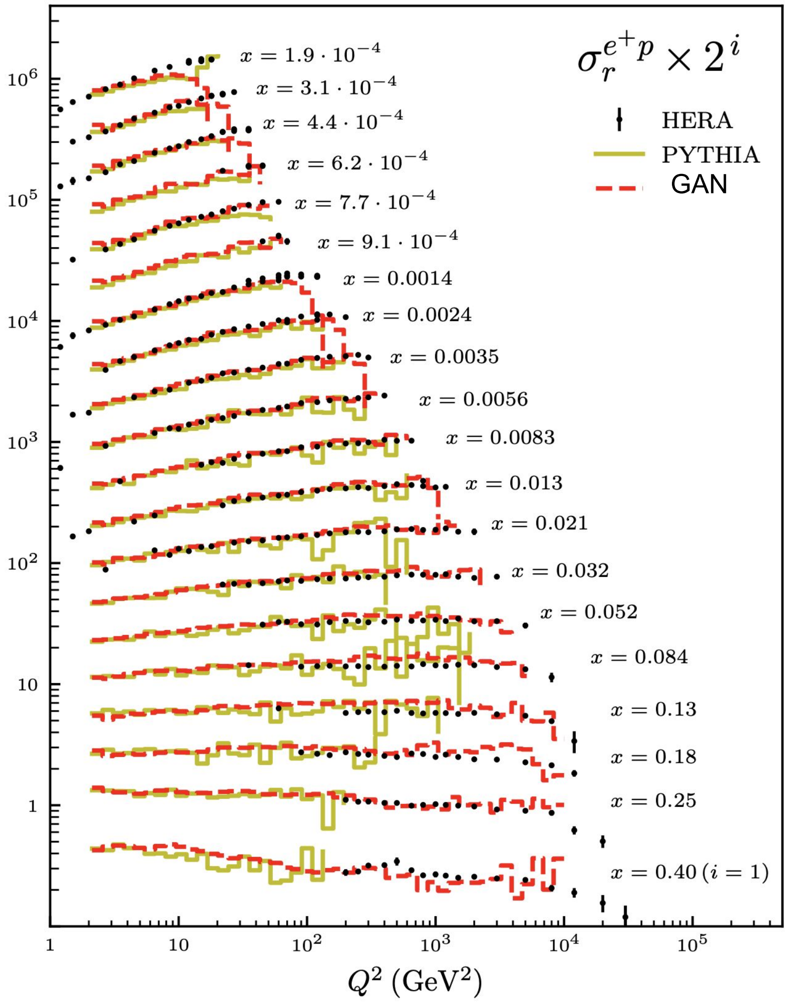
[Submitted on 6 Aug 2020]

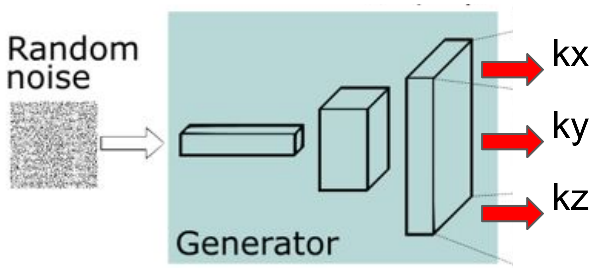
AI-based Monte Carlo event generator for electron-proton scattering

Y. Alanazi, P. Ambrozewicz, M.P. Kuchera, Y. Li, T. Liu, R.E. McClellan, W. Melnitchouk, E. Pritchard, M. Robertson, N. Sato, R. Strauss, L. Velasco





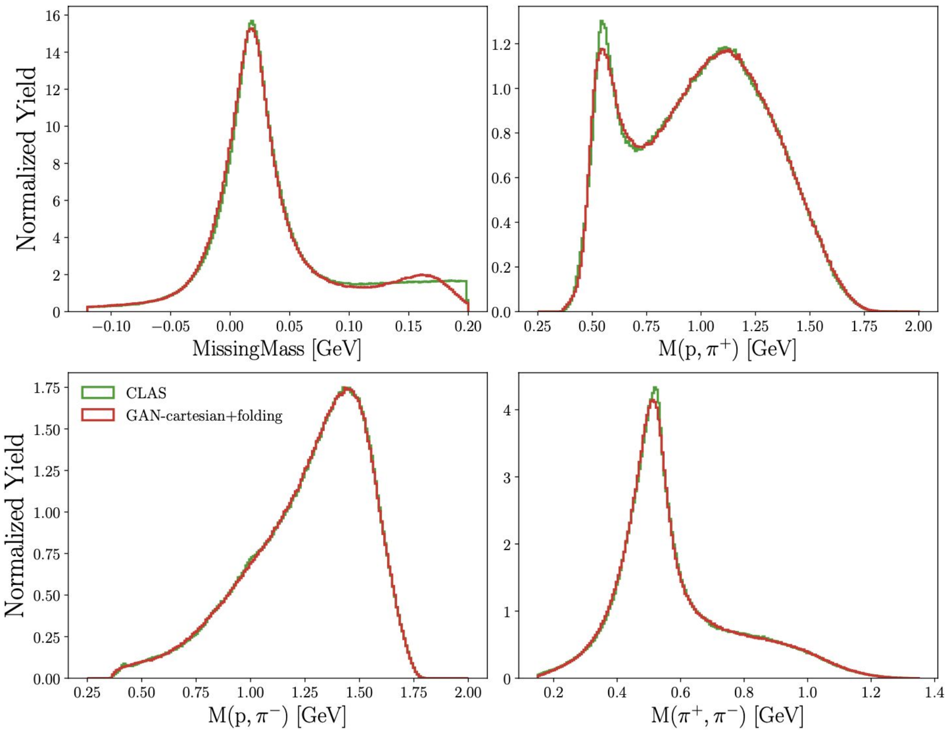


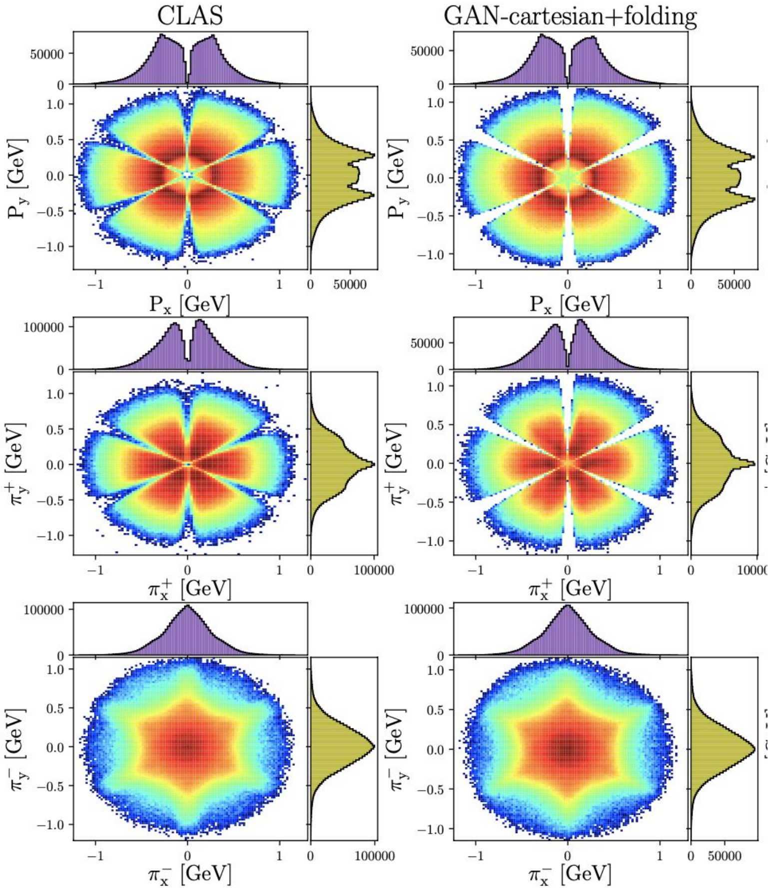


- PYTHIA has 1M events
- GAN was trained with 1M events
- GAN predictions from 100M events
- GAN has learned accurately the underlying low with lower statistics

Case study: CLAS 6 GeV data

$$\gamma + p \rightarrow p' + \pi^{+} + \pi^{-}$$

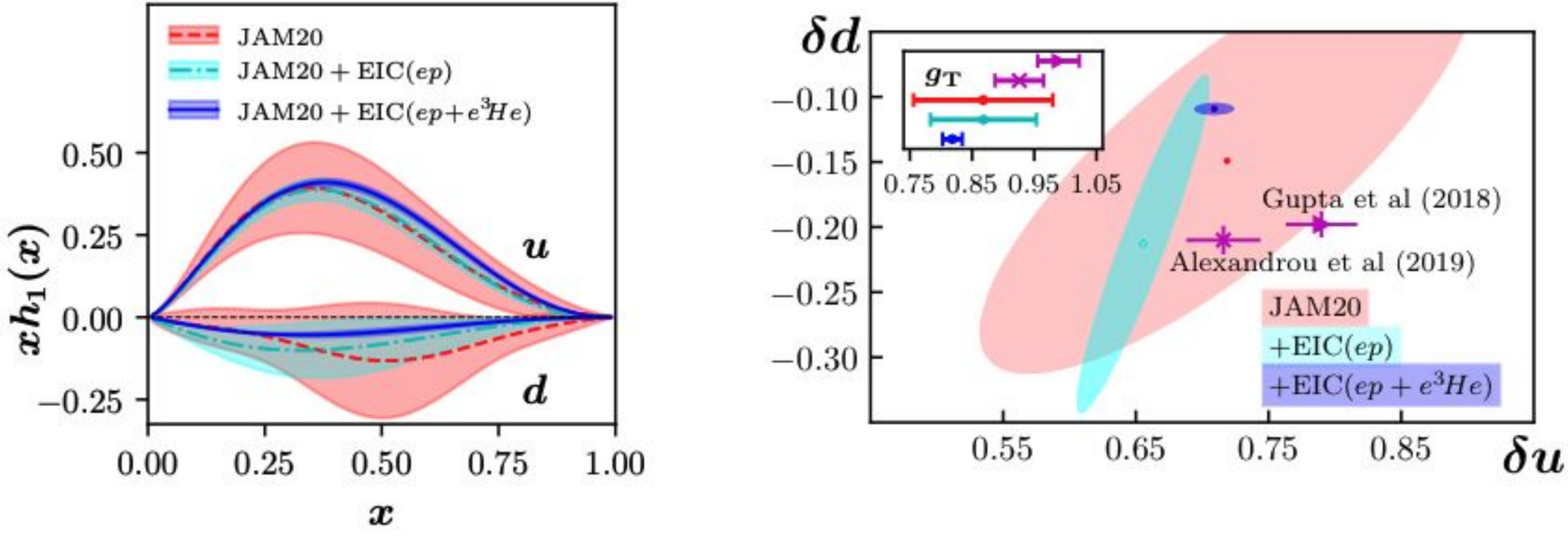




[Submitted on 15 Jan 2021 (v1), last revised 31 Mar 2021 (this version, v3)]

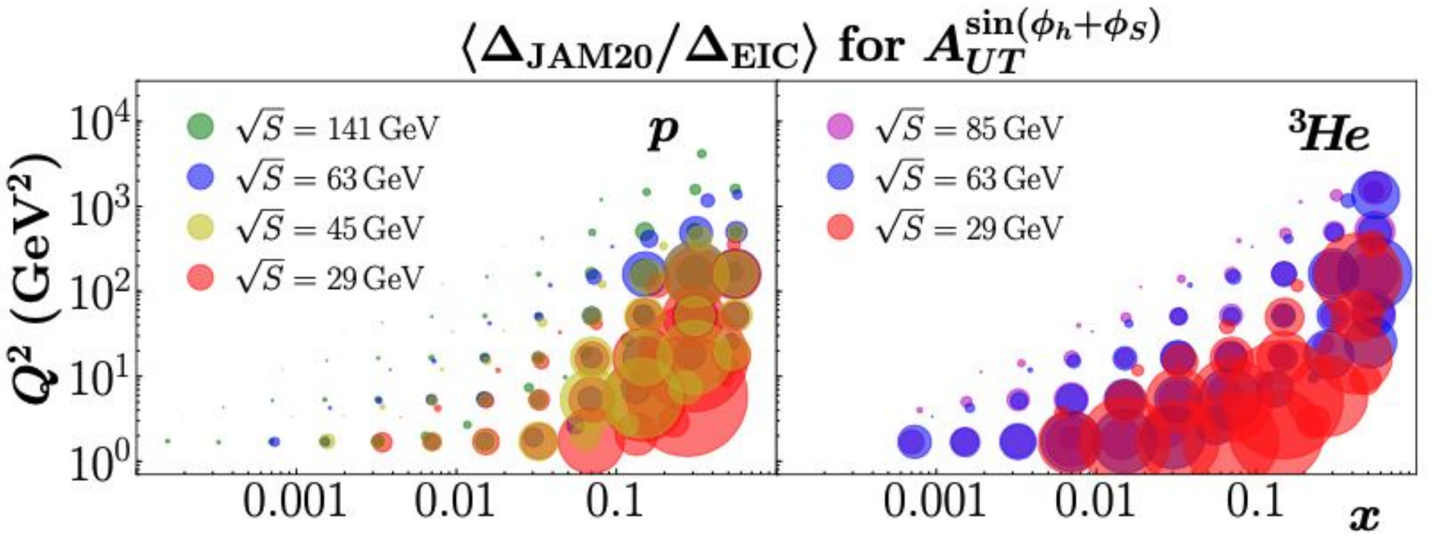
Electron-Ion Collider impact study on the tensor charge of the nucleon

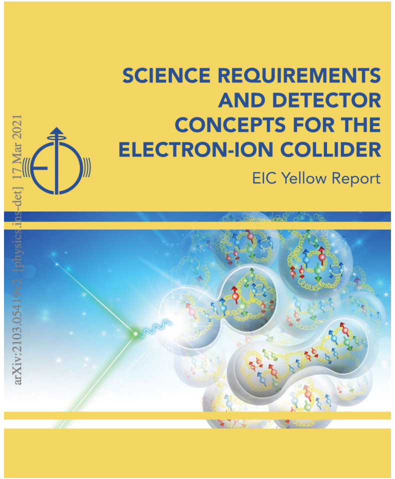
Leonard Gamberg, Zhong-Bo Kang, Daniel Pitonyak, Alexei Prokudin, Nobuo Sato, Ralf Seidl



3He data are crucial for **flavor separation**

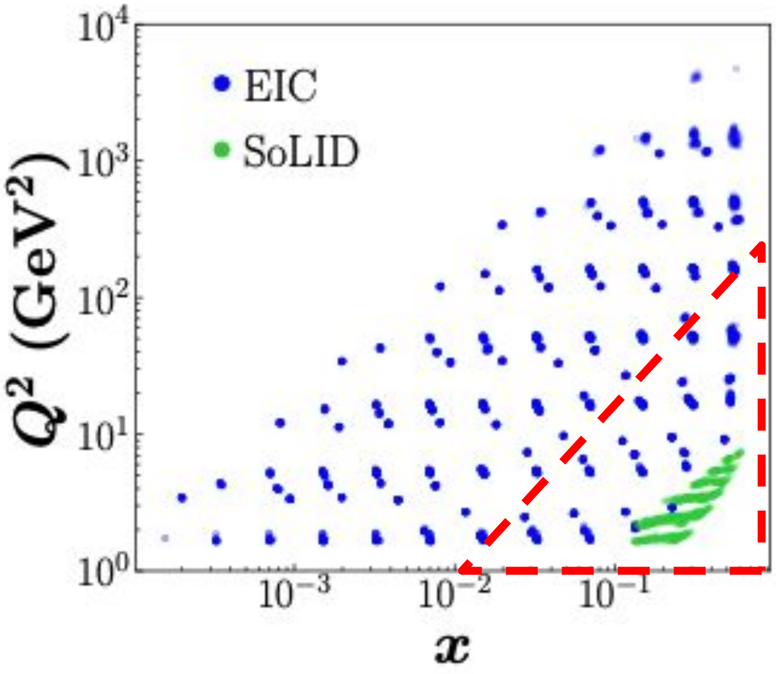
Impact of EIC (from YR)



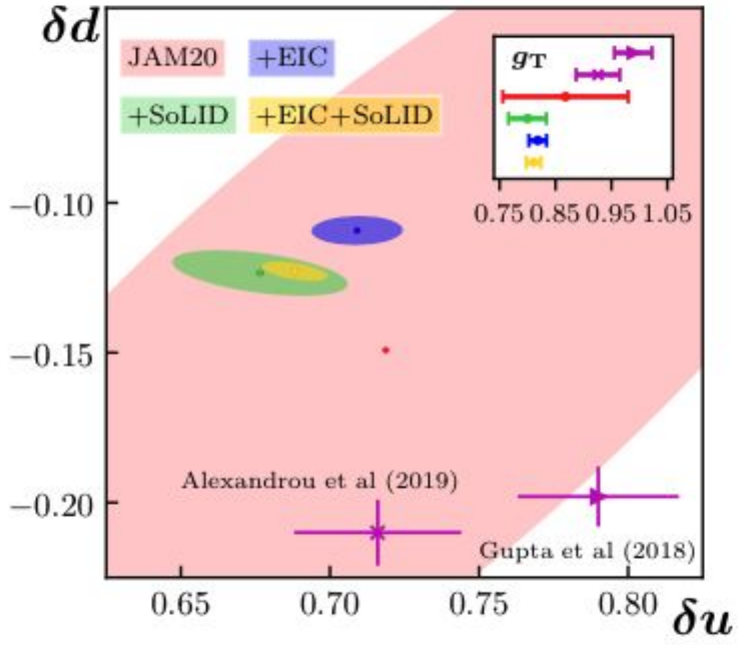


High-x region provides significant constraints

Impact of low Q (from SoLID study)



High-x region provides significant constraints



Accuracy vs. Precision