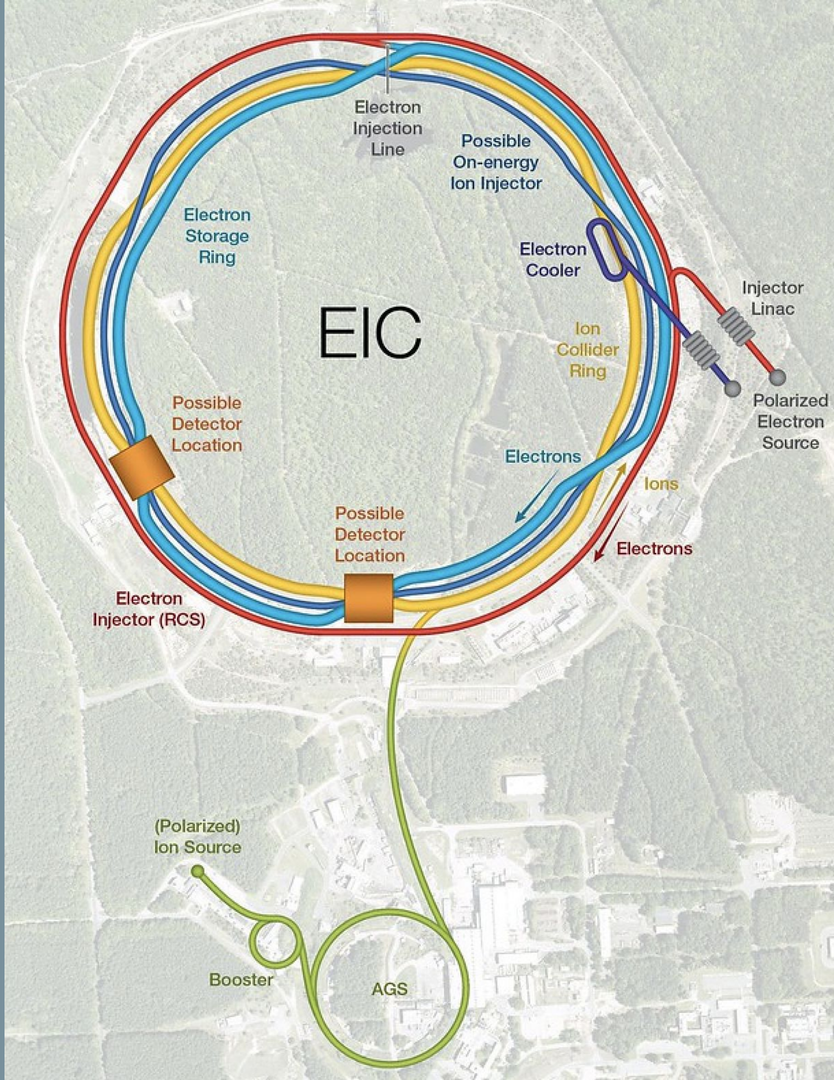
Femtoscale Imaging of Nuclei using ML and Exascale Platforms

Nobuo Sato

Oct 20 2022, SciDAC collaboration

Outline

1. Motivations
2. Complexity of SIDIS
3. Integrated THY/EXP analysis
4. Summary

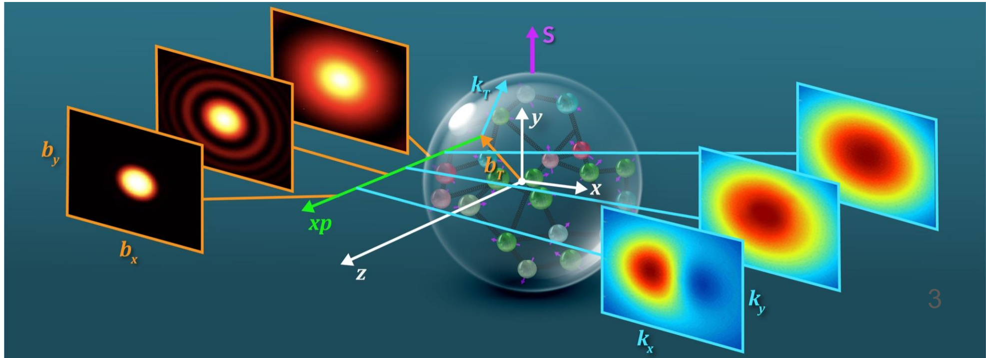


Motivations

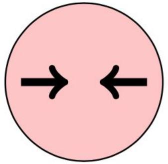
- **WHAT?: Synthesis of 3D tomography/nuclear imaging -** quantum correlation functions (QCFs)
  - hadron structure (PDFs, TMDs, GPDs, ...)
  - hadronization (FFs, TMDFFs)

- **HOW?: Data (EXP), Factorization (THY/LQCD), Inference (CS)**
  - test of universality & theory predictive power
  - significant computing and data analysis
  - systematic improvements (resummation, evolution, HO calculations)
  - synergy with lattice QCD (Bayesian priors)

- **WHY?: Opportunities**
  - origin of proton spin
  - quark and gluon tomography
  - structure of proton sea (strangeness, antimatter asymmetry)
  - origin of nuclear EMC effect
  - small-*x* phenomena
  - precision EW physics (Weinberg angle)
  - …



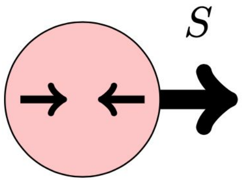
Collinear Spin structures



$$f = f_{\rightarrow} + f_{\leftarrow}$$

Parton distribution functions

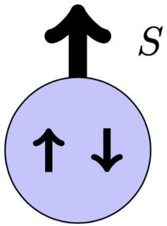
$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\psi_i(0)|N\rangle$$



$$\Delta f = f_{\rightarrow} - f_{\leftarrow}$$

Helicity distribution

$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\gamma_5\psi_i(0)|N\rangle$$



$$\delta_\mathrm{T} f = f_{\uparrow} - f_{\downarrow}$$

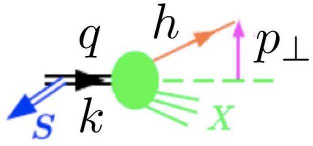
Transversity

$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\gamma_\perp\gamma_5\psi_i(0)|N\rangle$$

TMD Spin structures

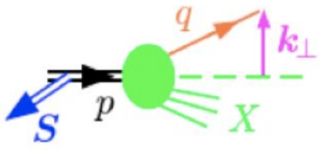
Sivers `89

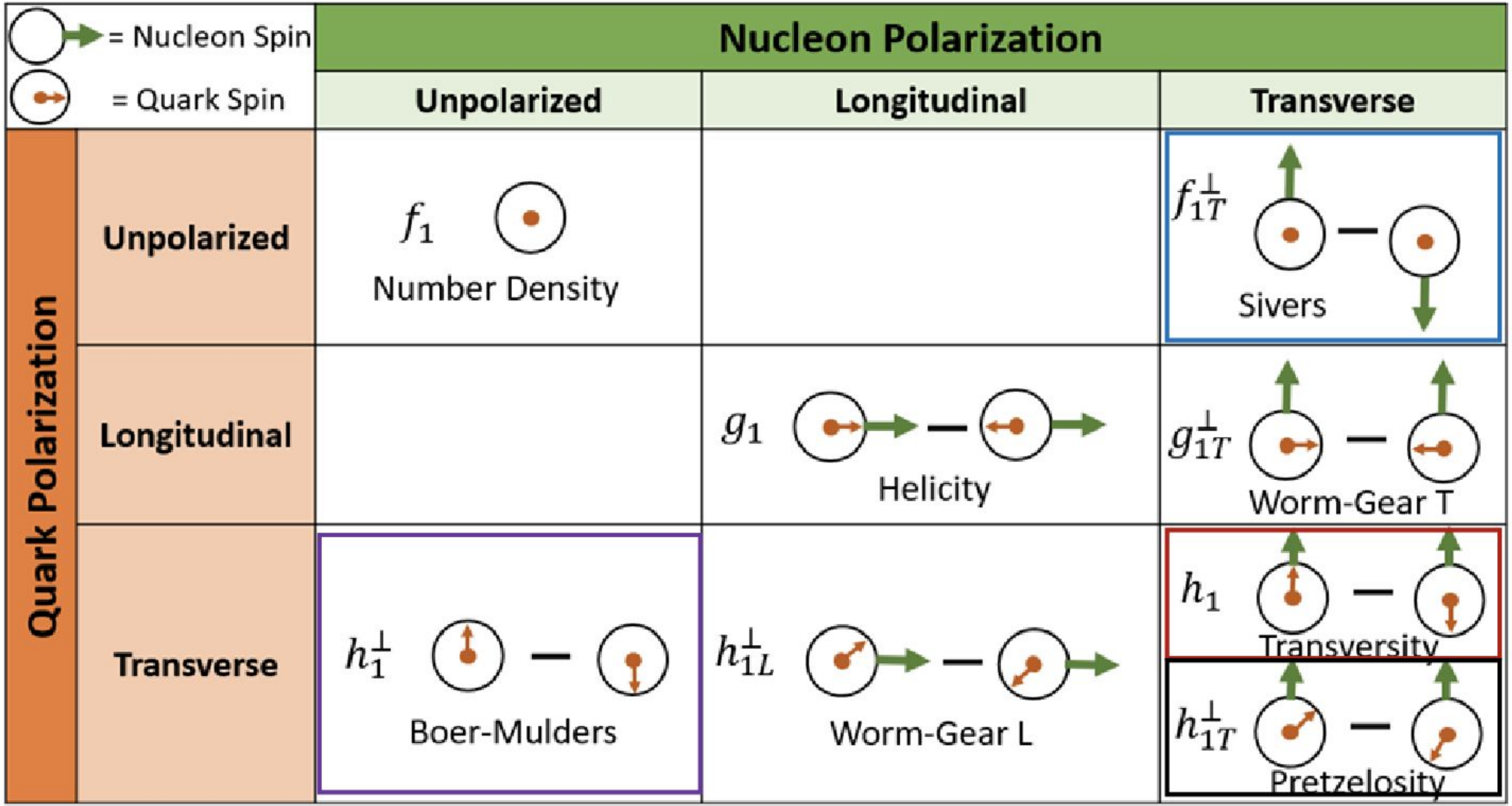
$$f_{q/h^\uparrow}(x,\vec{k}_\perp,\vec{S}) = f_{q/h}(x,k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp^2)\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$$



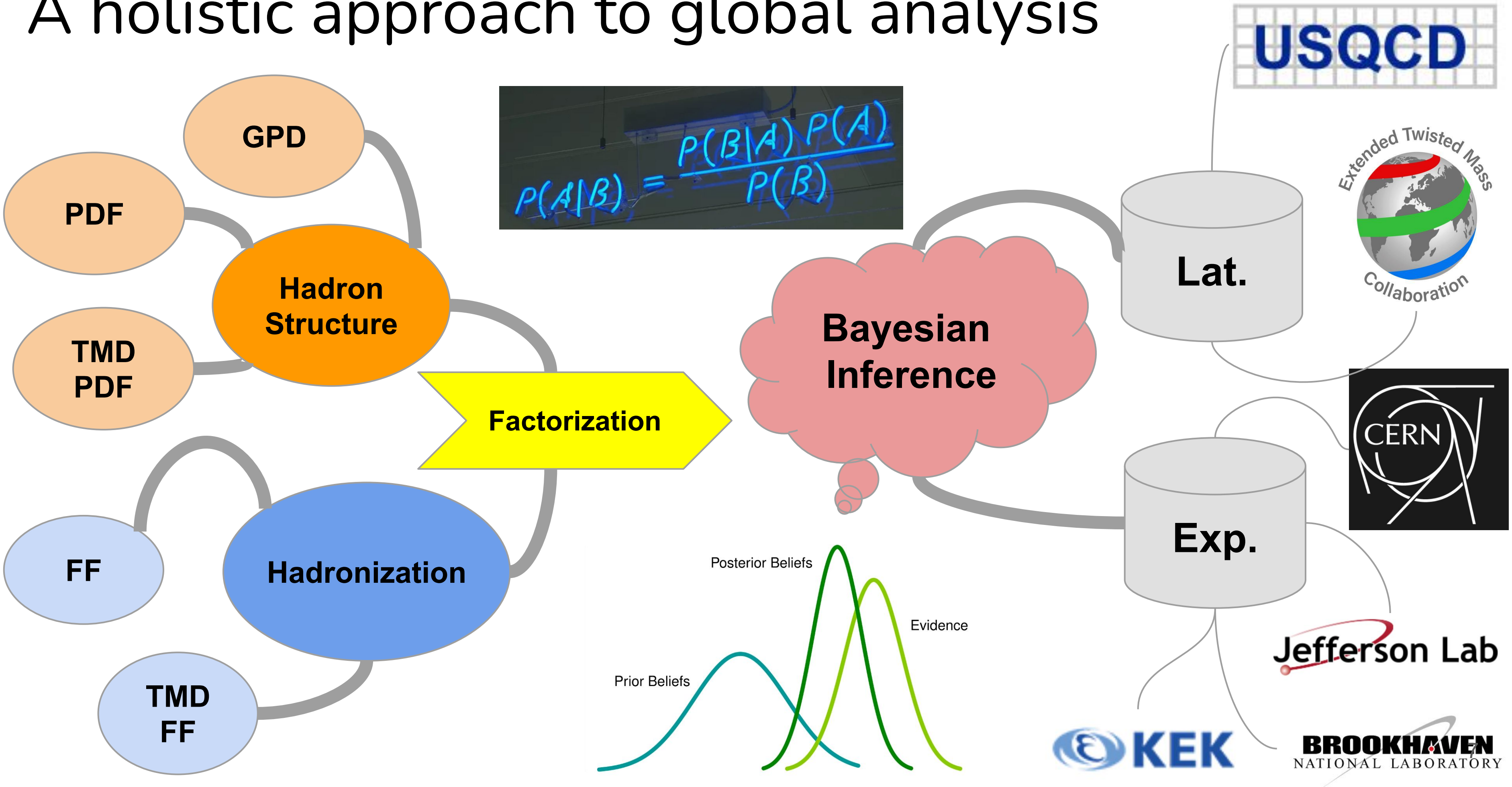
Collins `92

$$D_{q/h}(z,\vec{p}_\perp,\vec{s}_q) = D_{q/h}(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\vec{s}_q\cdot(\hat{k}\times\vec{p}_\perp)$$



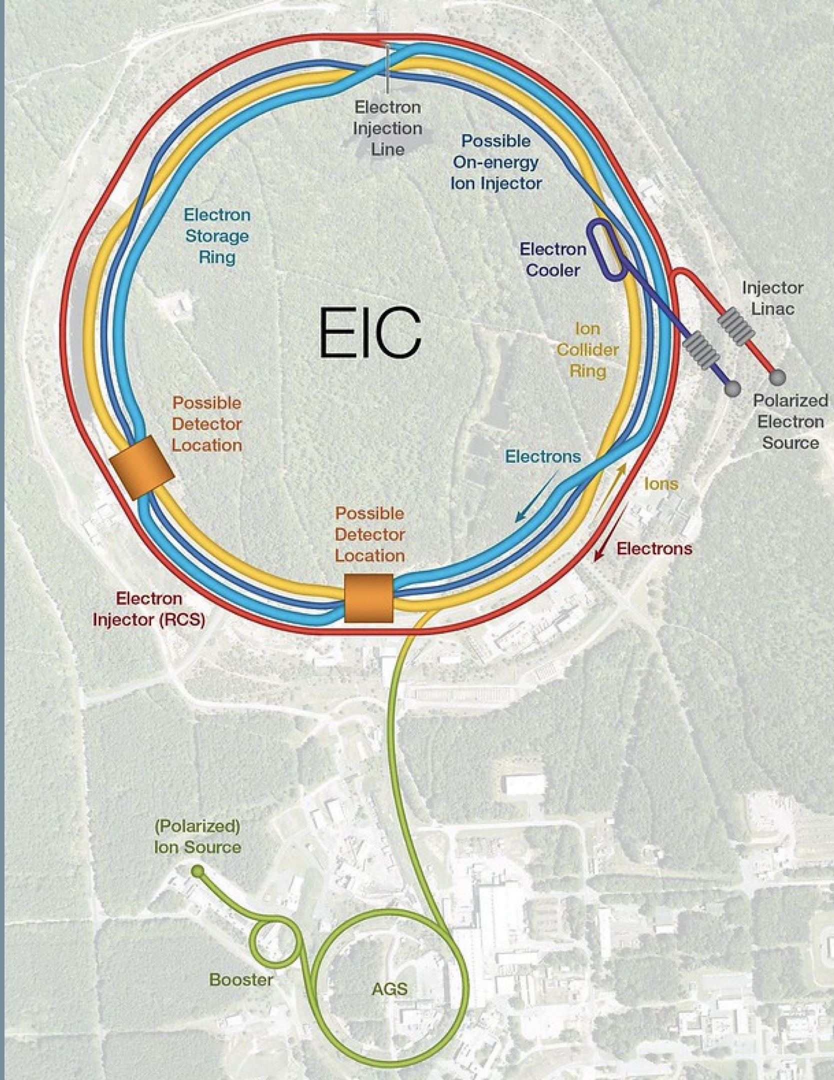

= Nucleon Spin
= Quark Spin
Nucleon Polarization
Unpolarized
Longitudinal
Transverse
Quark Polarization
Unpolarized
Longitudinal
Transverse
f_1
Number Density
$f_{1T}^{\perp}$
Sivers
g_1
Helicity
$g_{1T}^{\perp}$
Worm-Gear T
$h_1^{\perp}$
Boer-Mulders
$h_{1L}^{\perp}$
Worm-Gear L
h_1
Transversity
$h_{1T}^{\perp}$
Pretzelosity

A holistic approach to global analysis

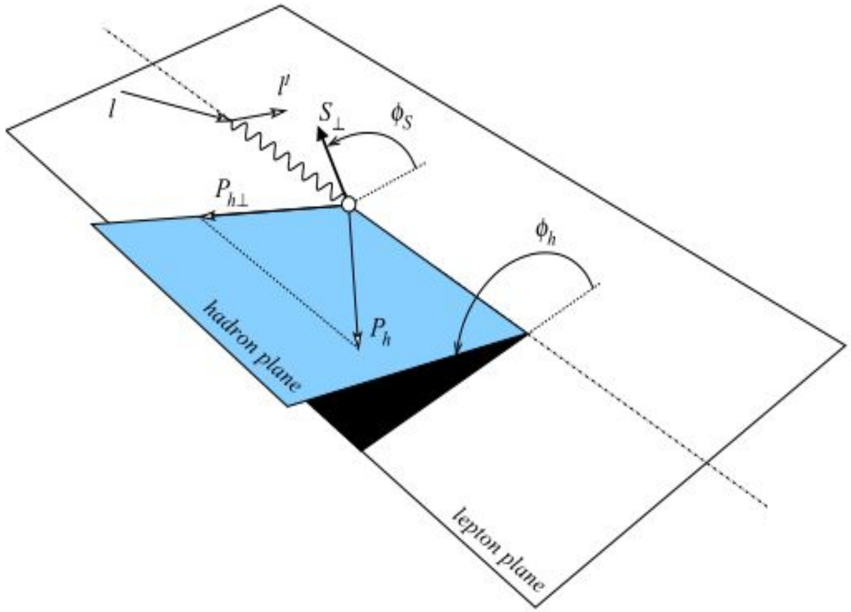


Outline

1. Motivations
2. Complexity of SIDIS
3. Integrated THY/EXP analysis
4. Summary



3D hadron structure using SIDIS



A prime experiment in existing and future facilities

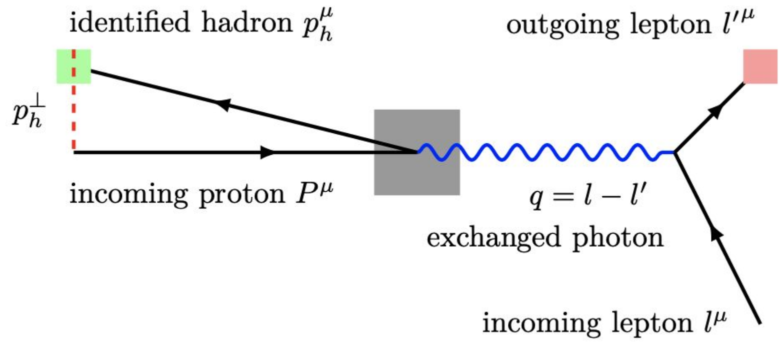
hermes
COMPASS
Jefferson Lab
EIC[2]

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
&\quad + S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&\quad + S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad + |\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
&\qquad + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
&\quad + |\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},
\end{aligned}
$$

Physics goals

Name	Symbol	meaning
upol. PDF	f_1^q	U. pol. quarks in U. pol. nucleon
pol. PDF	g_1^q	L. pol. quarks in L. pol. nucleon
Transversity	h_1^q	T. pol. quarks in T. pol. nucleon
Sivers	$f_{1T}^{\perp(1)q}$	U. pol. quarks in T. pol. nucleon
Boer-Mulders	$h_1^{\perp(1)q}$	T. pol. quarks in U. pol. nucleon
Boer-Mulders	$h_1^{\perp(1)q}$	T. pol. quarks in U. pol. nucleon
⋮	⋮	⋮
FF	D_1^q	U. pol. quarks to U. pol. hadron
Collins	$H_1^{\perp(1)q}$	T. pol. quarks to U. pol. hadron
⋮	⋮	⋮

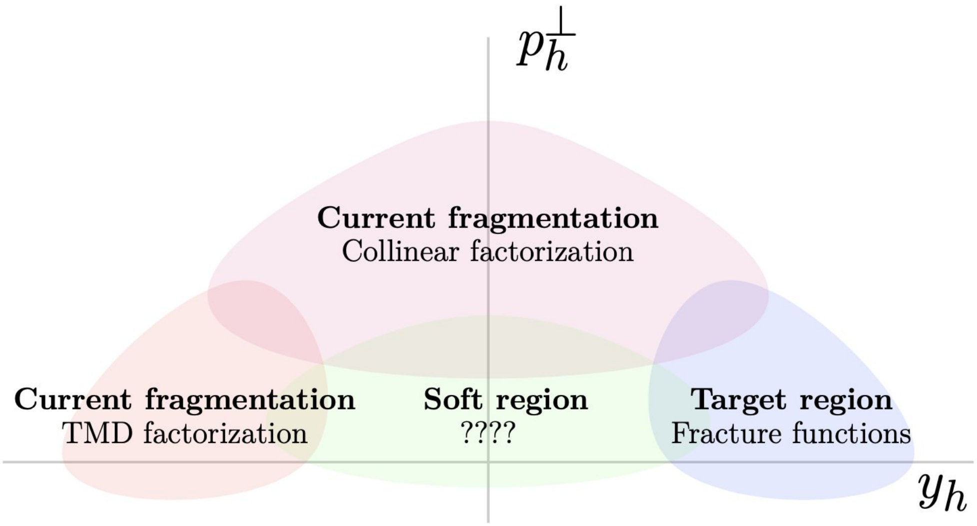
Breit frame

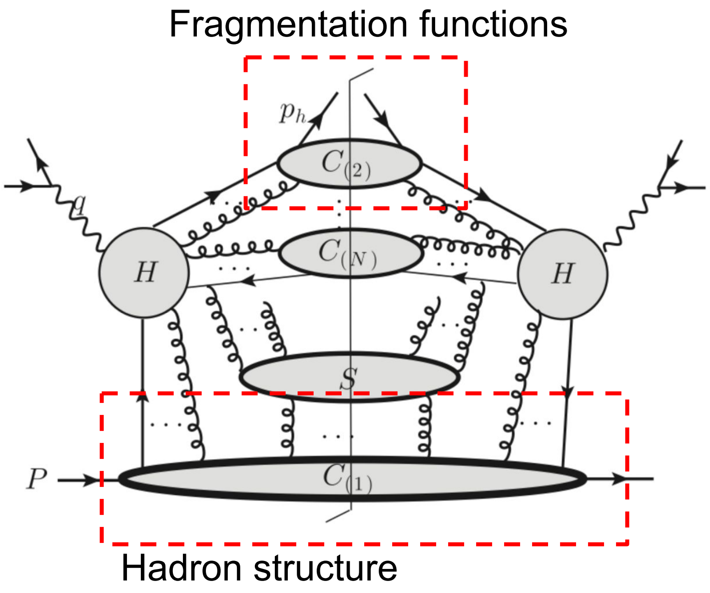


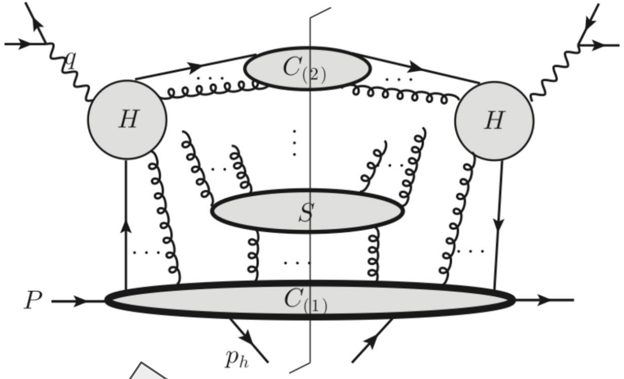
Large vs small pT

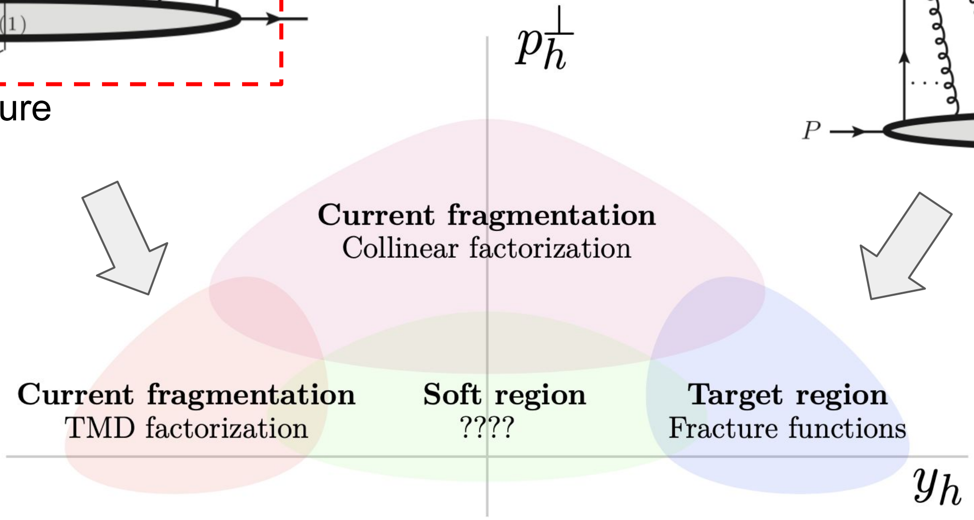
$$q_T = p_h^\perp / z$$

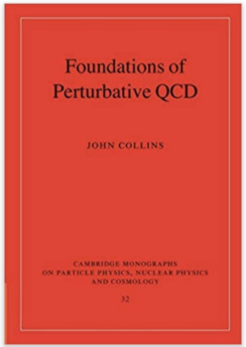
q_T / Q ⇨ The scale separation




Fragmentation functions
p_h
$C_{(2)}$
q
H
$C_{(N)}$
S
P
$C_{(1)}$
Hadron structure


q
$C_{(2)}$
H
S
P
$C_{(1)}$
p_h


$p_h^\perp$
Current fragmentation
Collinear factorization
Current fragmentation
TMD factorization
Soft region
????
Target region
Fracture functions
y_h


Foundations of Perturbative QCD
JOHN COLLINS
CAMBRIDGE MONOGRAPHS ON PARTICLE PHYSICS, NUCLEAR PHYSICS AND COSMOLOGY

$$W = \sum_f H_f(Q,\mu) \int \frac{d^2 \boldsymbol{b}_T}{(2\pi)^2} e^{-i \boldsymbol{q}_T \cdot \boldsymbol{b}_T}$$

$$\times\, e^{-g_{f/N}(x, b_T, b_{\max})} \int_x^1 \frac{d\hat{x}}{\hat{x}} \boldsymbol{f}_{f/N}(\hat{x}, \mu_{b_*}) \tilde{C}_{f/p}(x/\hat{x}, b_*, \mu_{b_*}^2, \alpha_S(\mu_{b_*}))$$

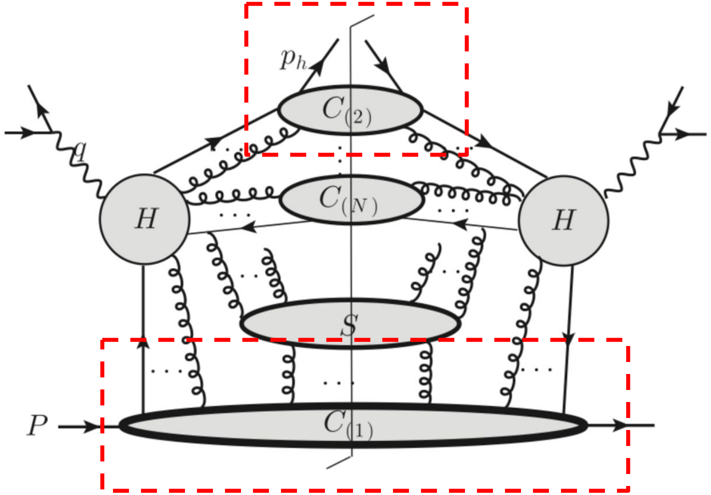
$$\times\, e^{-g_{h/f}(z, b_T, b_{\max})} \int_z^1 \frac{d\hat{z}}{\hat{z}^3} \boldsymbol{d}_{h/f}(\hat{z}, \mu_{b_*}) \tilde{C}_{h/f}(z/\hat{z}, b_*, \mu_{b_*}^2, \alpha_S(\mu_{b_*}))$$

$$\times \left(\frac{Q^2}{Q_0^2}\right)^{-g_K(b_T, b_{\max})} \left(\frac{Q^2}{\mu_{b_*}^2}\right)^{\tilde{K}(b_*, \mu_{b_*})}$$

$$\times \exp\left[\int_{\mu_{b_*}}^{\mu_Q} \frac{d\mu'}{\mu'} \left[2\gamma(\alpha_S(\mu'), 1) - \ln\frac{Q^2}{(\mu')^2} \gamma_K(\alpha_S(\mu'))\right]\right]$$

Aybat, Rogers '11

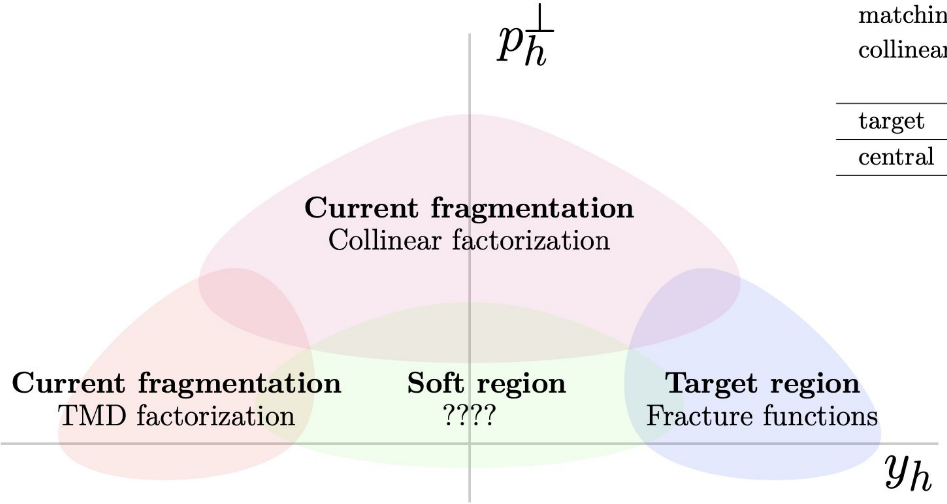
Fragmentation functions



Hadron structure

Linking external kinematics with regions

Boglione et al ‘22

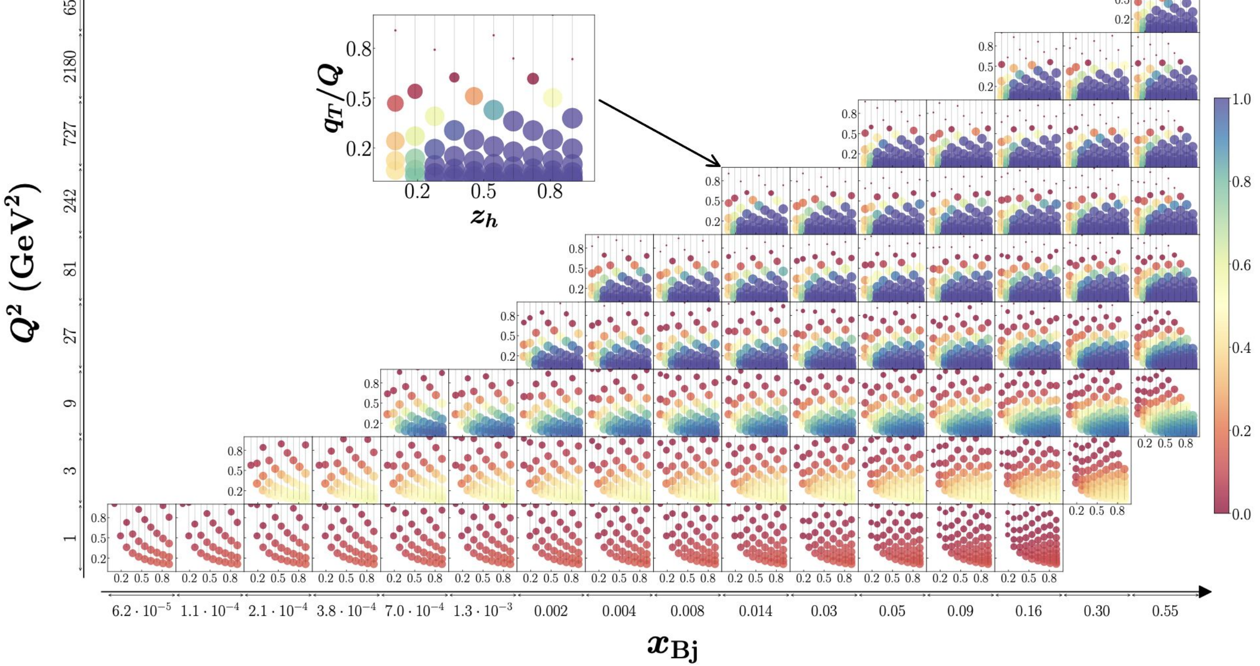


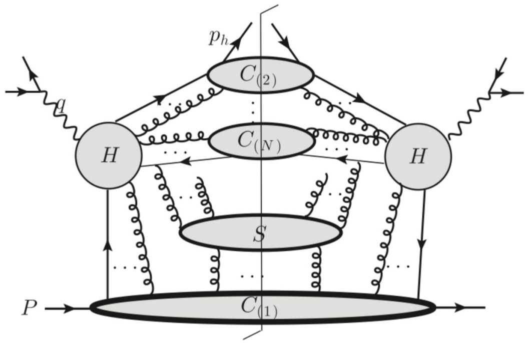
Region	R_0	R_1	R_1'	R_2	R_3	R_4
TMD	small	small	×	small	×	×
matching	small	small	×	small	×	×
collinear	small	small	×	large	small (LO pQCD) large (HO pQCD)	small
target	small	large	small	×	×	×
central	small	not small	not small	small	×	×

Ratio		Definition
R_0	general hardness	$\max\left(\left\|\frac{k_i^2}{Q^2}\right\|, \left\|\frac{k_f^2}{Q^2}\right\|, \left\|\frac{\delta k_T^2}{Q^2}\right\|\right)$
R_1	collinearity	$\frac{P_h \cdot k_f}{P_h \cdot k_i}$
R_1'	target proximity	$\frac{P_h \cdot P}{Q^2}$
R_2	transverse hardness	$\frac{\|k^2\|}{Q^2}$
R_3	spectator virtuality	$\frac{\|k_X^2\|}{Q^2}$
R_4	large transverse momentum	$\max\left(\left\|\frac{k_i^2}{k^2}\right\|, \left\|\frac{k_f^2}{k^2}\right\|, \left\|\frac{\delta k_T^2}{k^2}\right\|, \left\|\frac{k_{iT}^2}{k^2}\right\|\right)$

$$\mathcal{A}(x_{\rm Bj}, Q^2, z_h, P_{hT} | \text{region}) = \int \mathrm{d}\{R_i\} \;\; \Theta(\{R_i\} | \text{ region}) \times \int \mathrm{d}^4 k_i \, \mathrm{d}^4 k_f \, \mathrm{d}^4 \delta k_{\rm T} \; \mathcal{P}(\{R_i\} | x_{\rm Bj}, Q^2, z_h, P_{hT}; k_i, k_f, \delta k_T) \; \pi(k_i, k_f, \delta k_T),$$

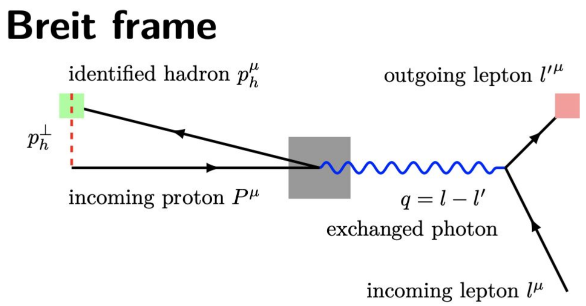
TMD region EIC

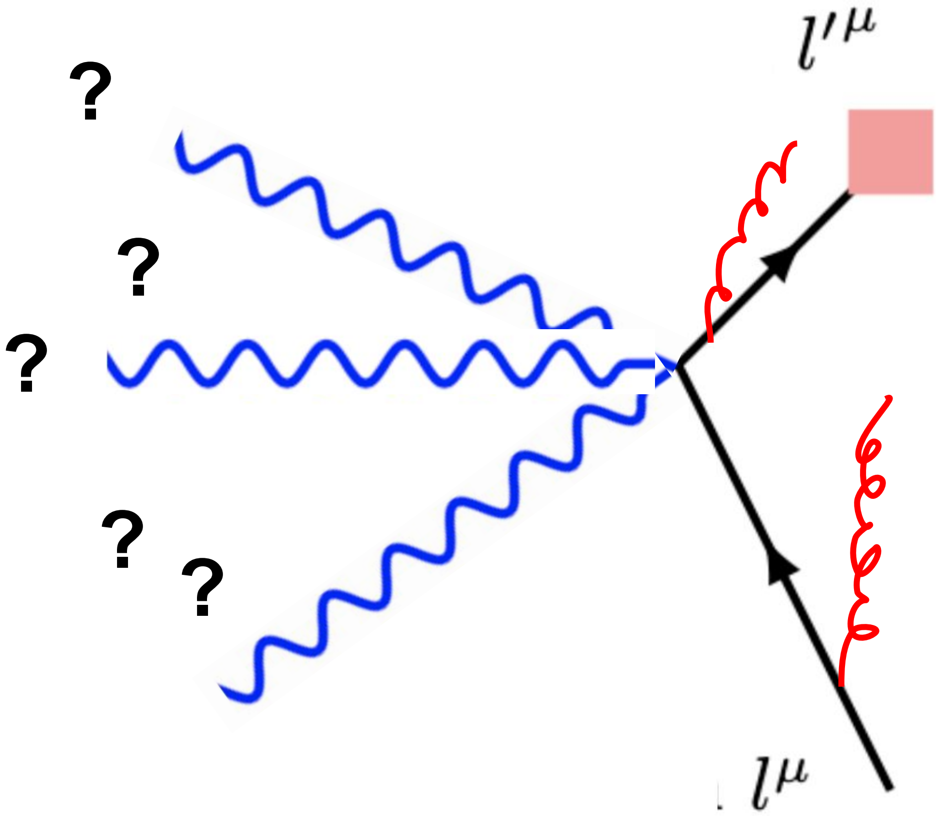




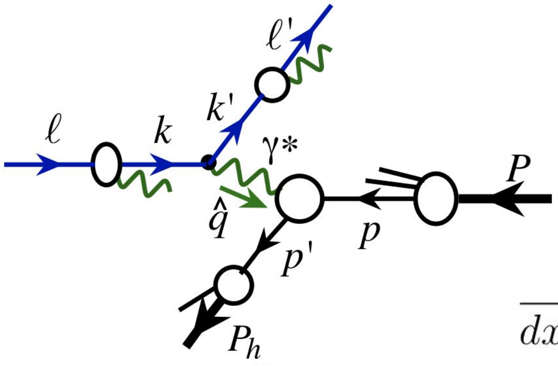
Role of QED effects

- 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





Hybrid QED+QCD factorization approach

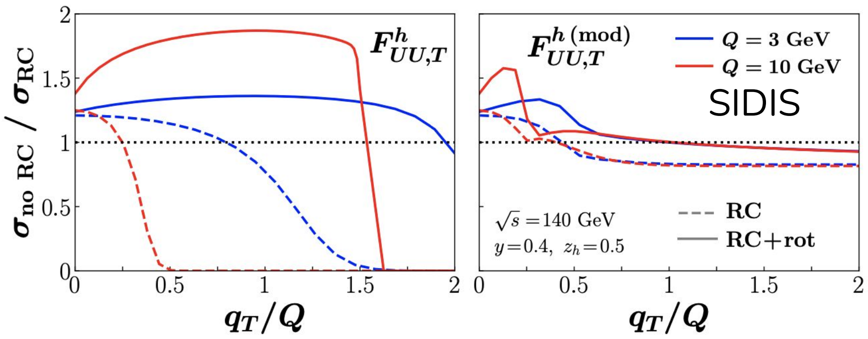


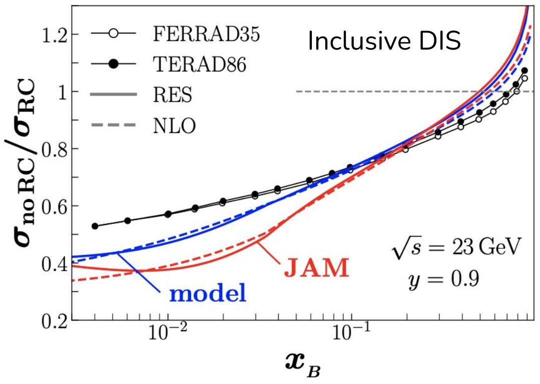
Liu, Melnitchouk, Qiu, Sato '21

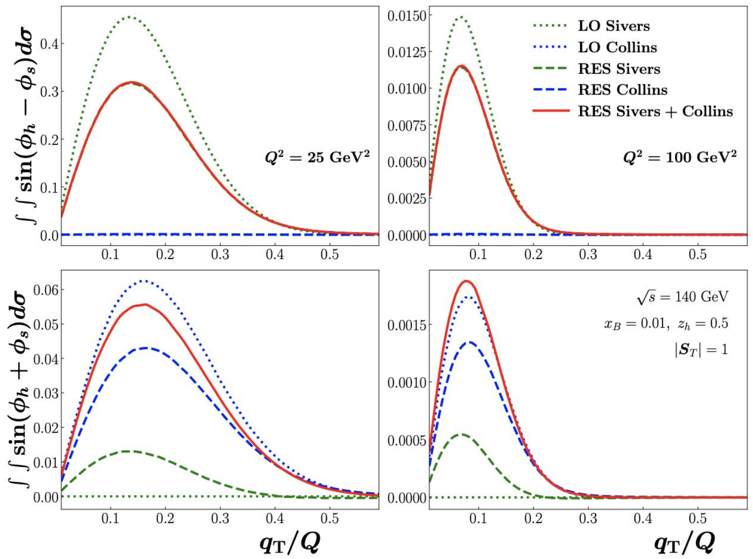
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sum_i w_i F_i(x, Q^2, z, \mathbf{P}_{h\perp})$$

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \int_{\zeta_{\min}}^{1} d\zeta \int_{\xi_{\min}(\zeta)}^{1} d\xi\, f_{k/l}(\xi)\, d_{k'/l'}(\zeta) \times \frac{\hat{x}}{x\xi\zeta}\left[\frac{\alpha^2}{\hat{x}\hat{y}\widehat{Q}^2}\frac{\hat{y}}{2(1-\hat{\varepsilon})}\left(1+\frac{\hat{\gamma}^2}{2\hat{x}}\right)\sum_i \hat{w}_i F_i(\hat{x}, \widehat{Q}^2, \hat{z}, \hat{\mathbf{P}}_{h\perp})\right]$$

QED effects in eP reactions





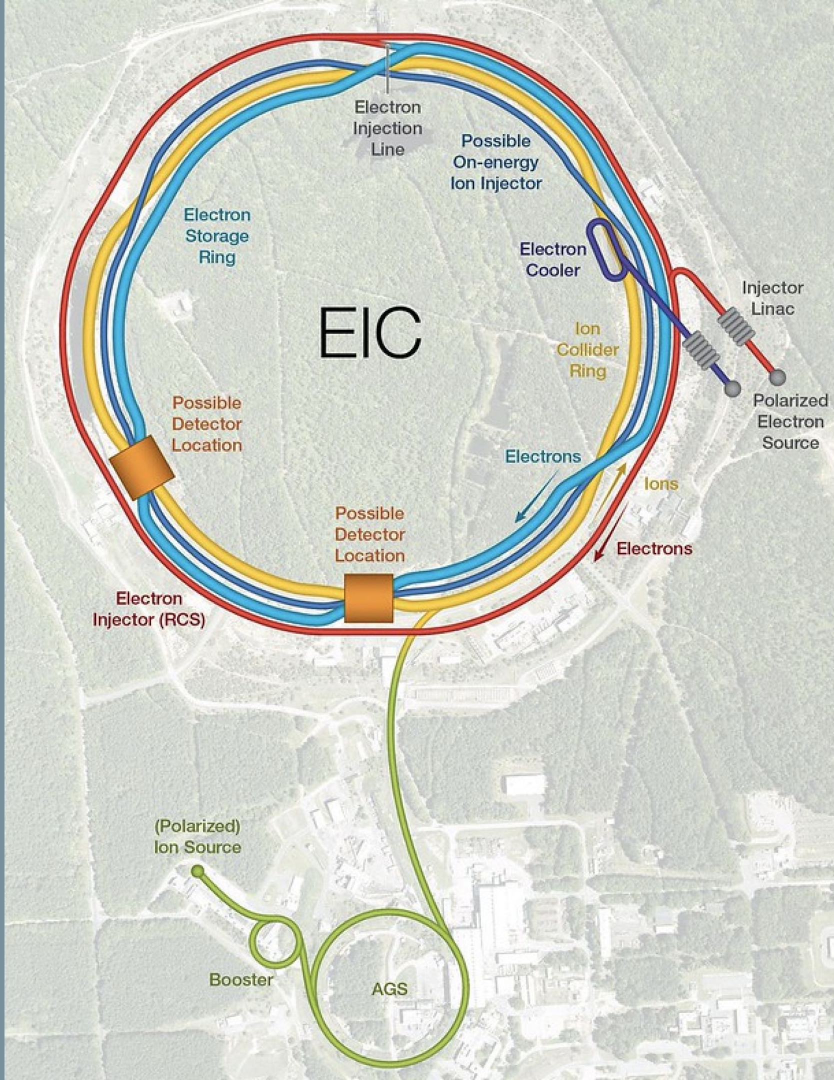


- Non-uniqueness of QED RC corrections
- Need for a combined analysis including QED and QCD effects

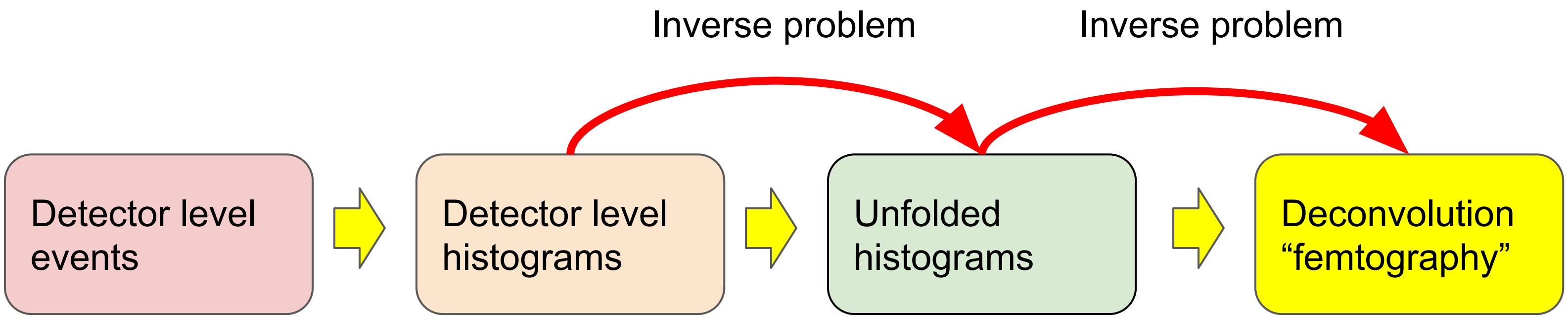
- Hybrid QED+QCD framework to study SSAs in SIDIS within global analysis
- *Crucial to control QED backgrounds in transverse spin asymmetries*

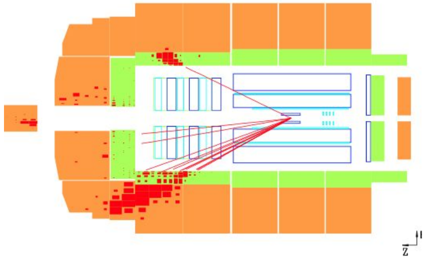
Outline

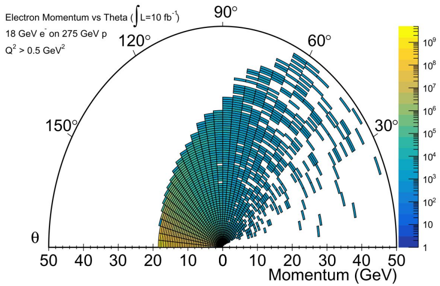
1. Motivations
2. Complexity of SIDIS
3. Integrated THY/EXP analysis
4. Summary

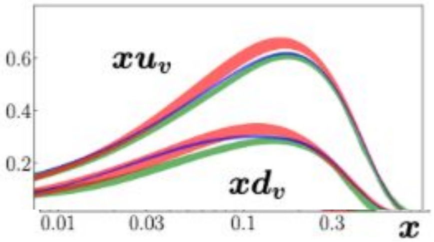


Existing paradigm -> histogram approach



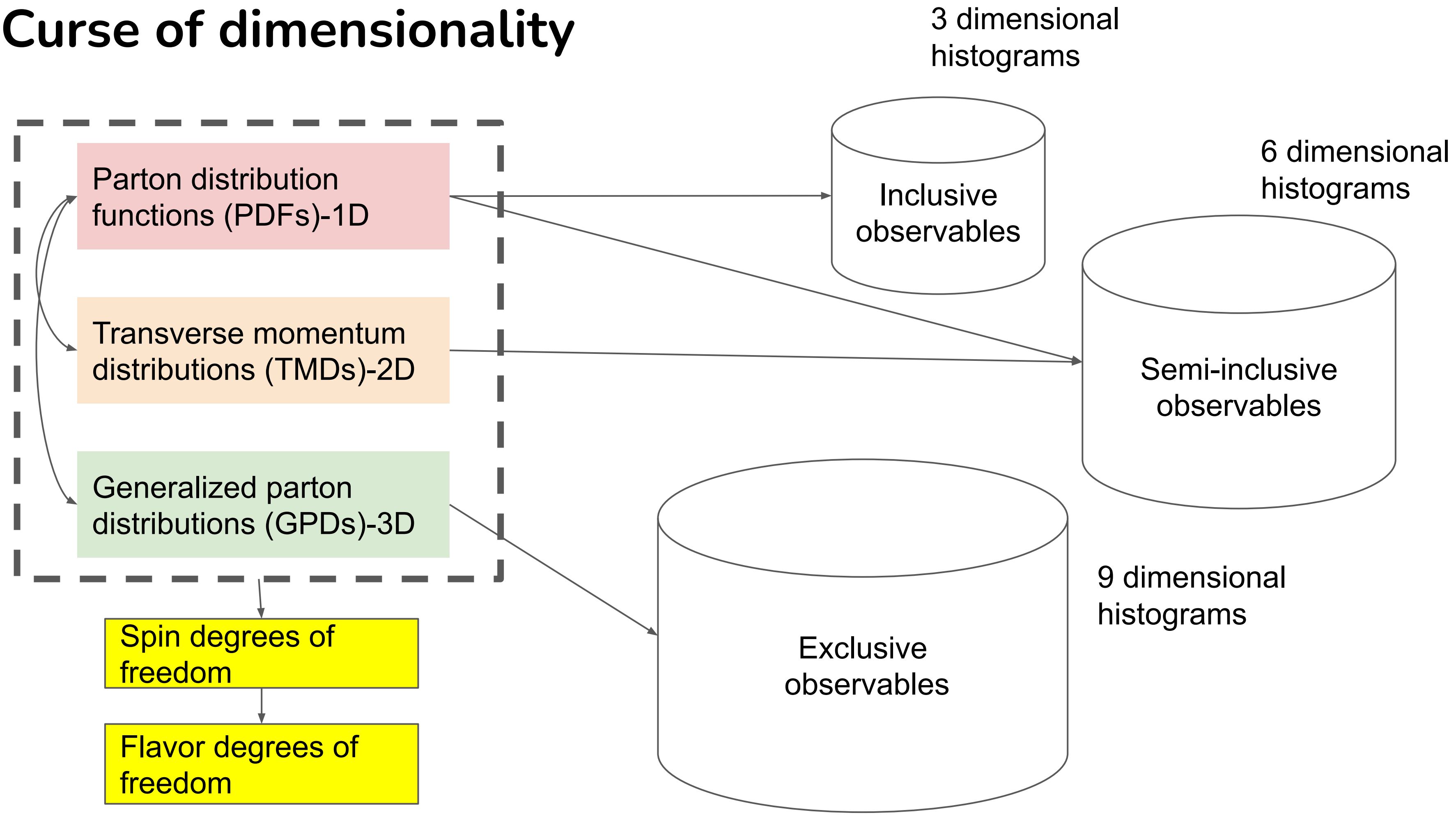






1D QCFs

Curse of dimensionality

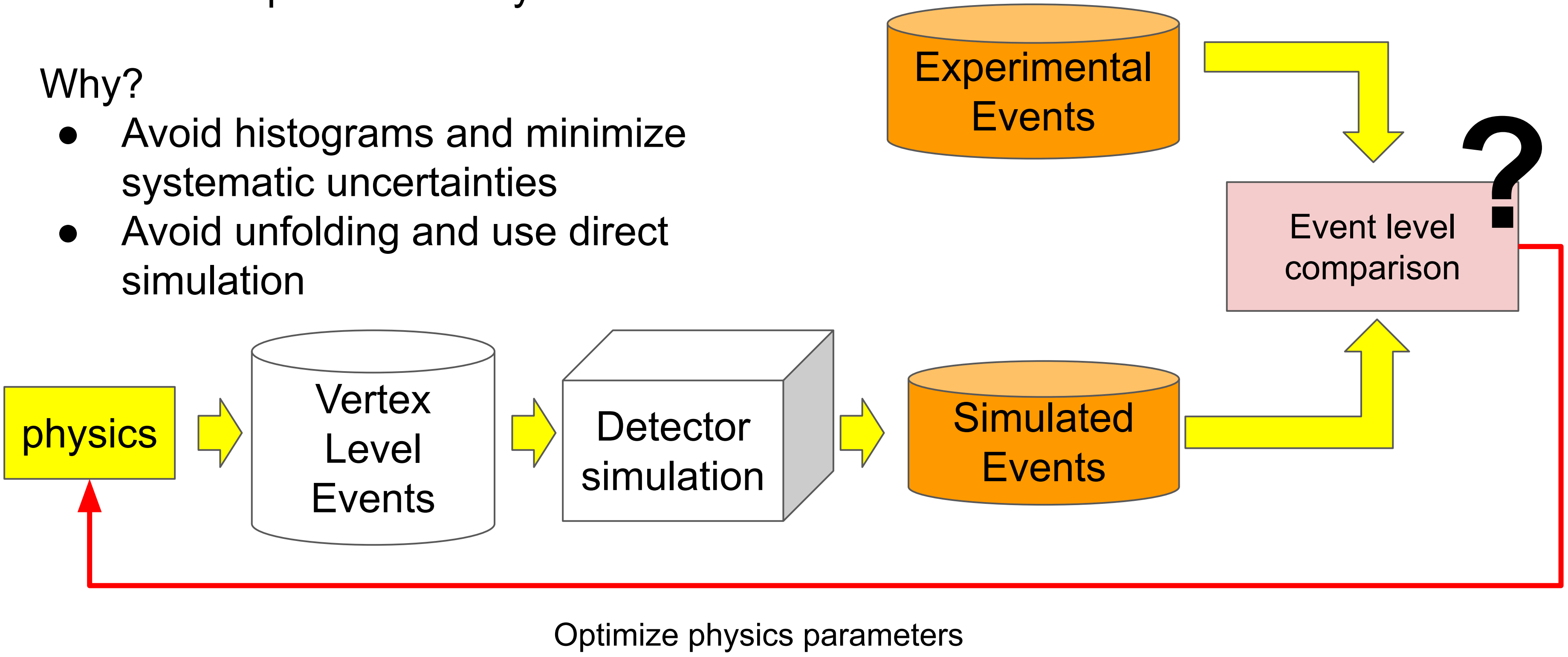


Event-based analysis?

Can we compare real vs synthetic events?

Why?

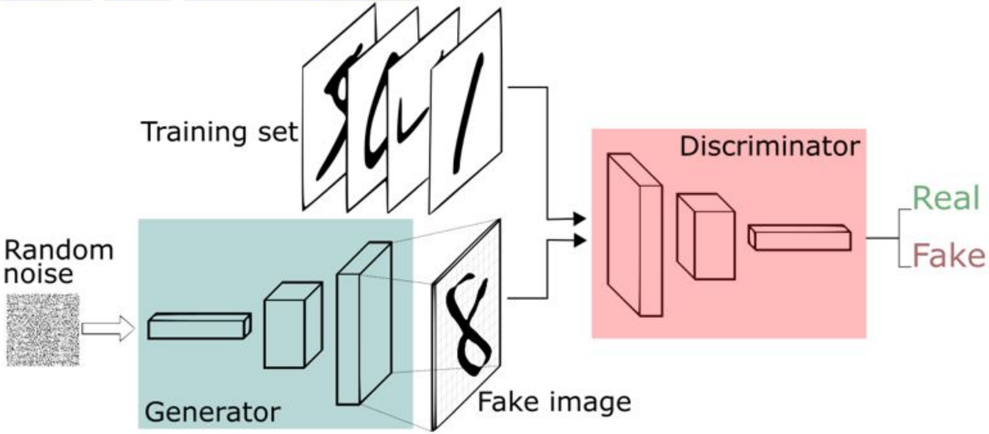
- Avoid histograms and minimize systematic uncertainties
- Avoid unfolding and use direct simulation



So, how do we compare events?

A Short Introduction to Generative Adversarial Networks

[machine-learning deep-learning representation-learning tensorflow python gans generative-models]

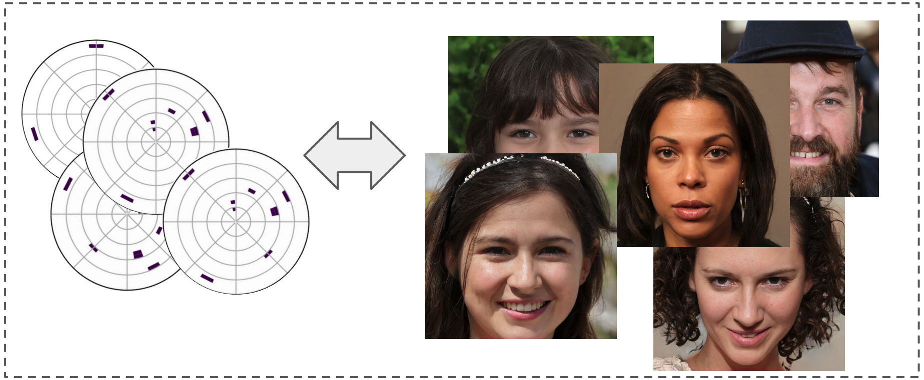


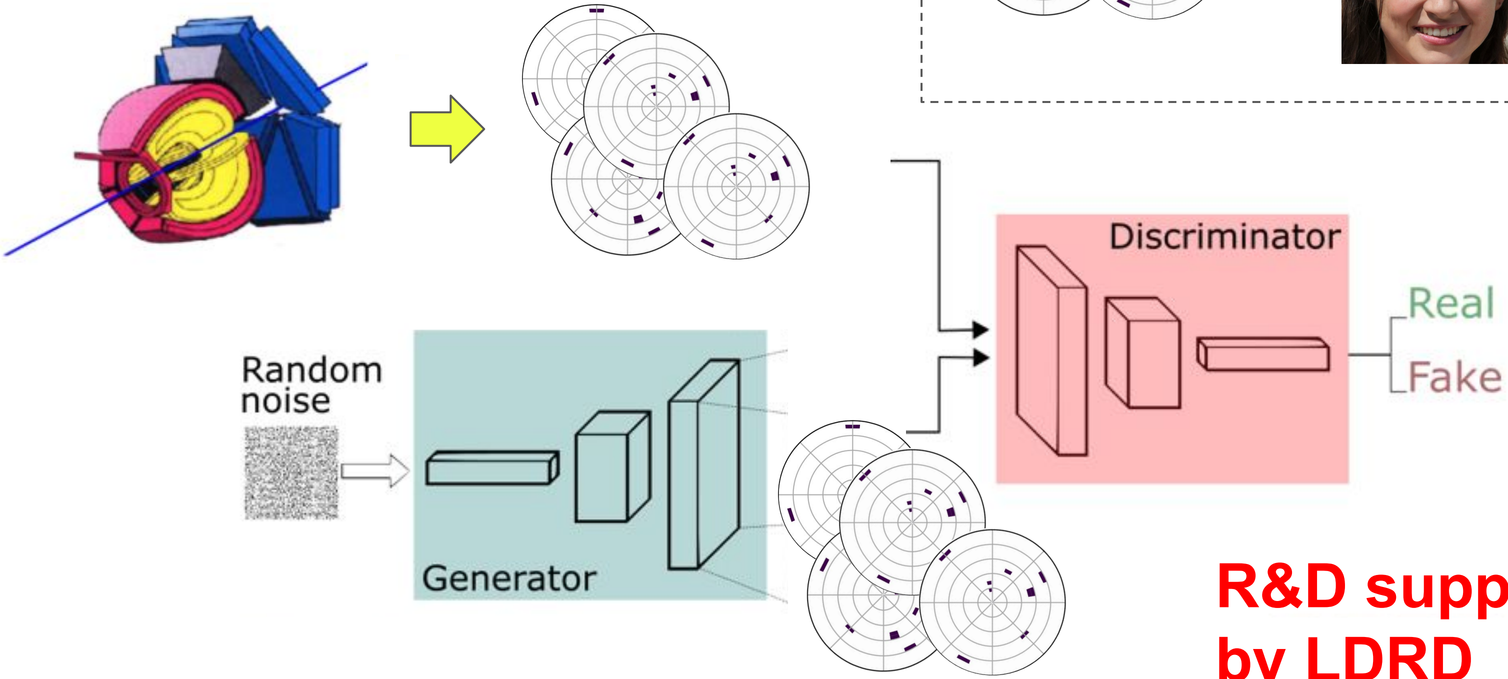
Jun 7, 2017

Fake people

https://thispersondoesnotexist.com

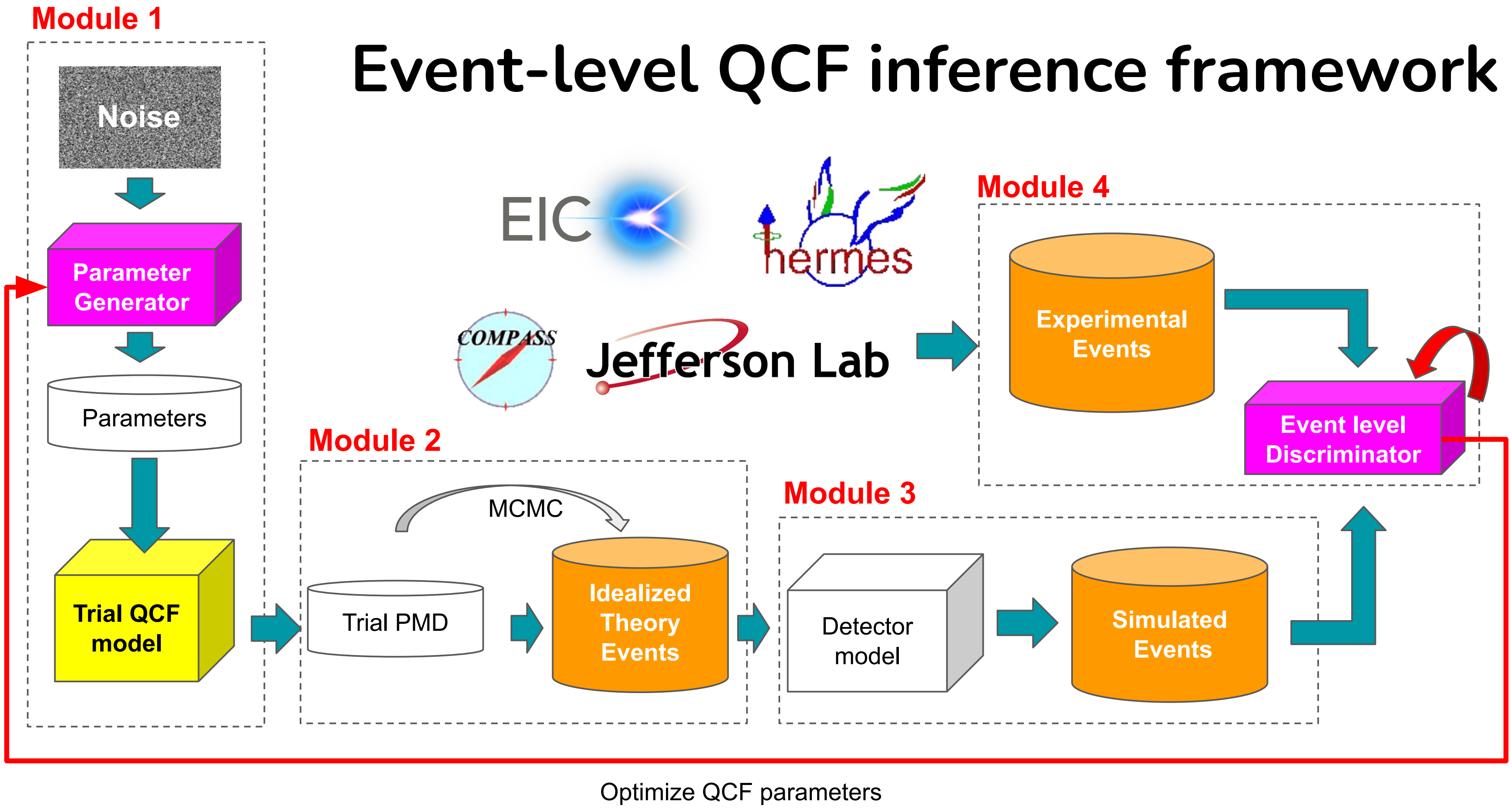
Events as faces





R&D supported by LDRD

Event-level QCF inference framework

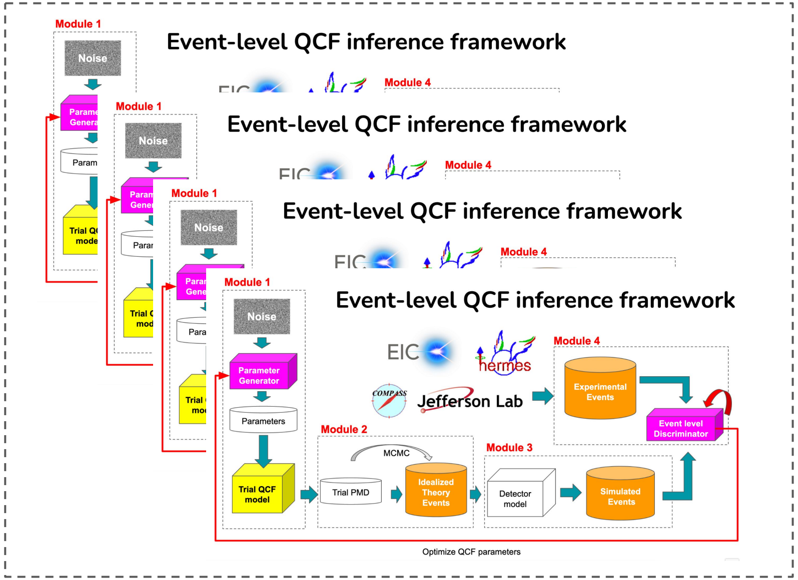


Opportunities

- Unified Theory+Exp analysis framework for hadron structure -> paradigm shift
- Near real time analysis and expedite scientific discovery

Challenges

- Big event level data processing from JLab/EIC requires large scale computing -> exascale computing
- Dedicated distributed ML workflow needs to be developed



QuantOm Collaboration

Argonne NATIONAL LABORATORY

Jefferson Lab

VT

Supported by DOE SciDAC funds

OLD DOMINION UNIVERSITY

Summary

- New era of global analysis of hadron structure *unified theory & experiment* analysis

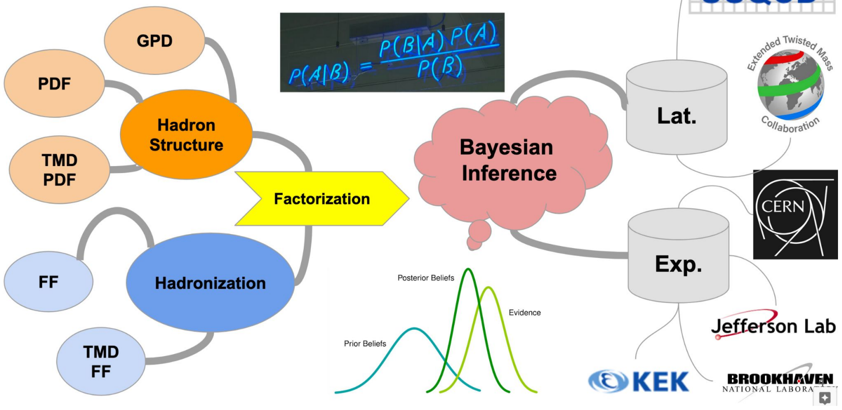
- AI/ML provides new tools/tricks to map QCFs from events and boost the discovery potential of current and future experimental facilities

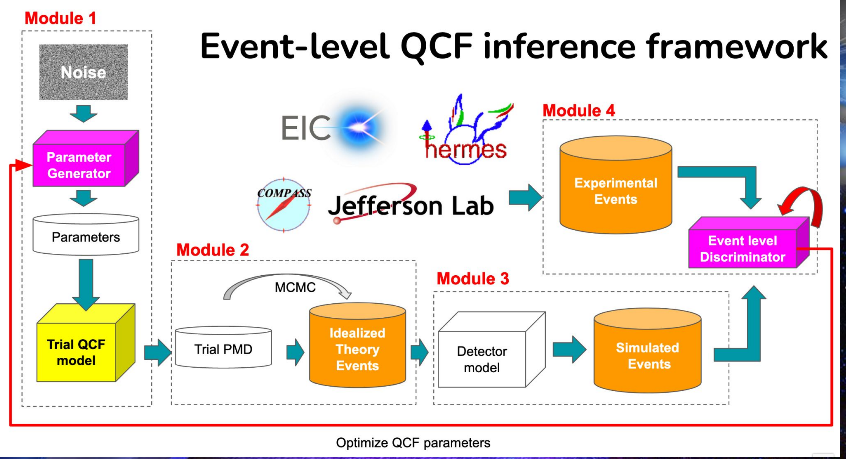
- Large scale computing is needed -> opportunity to use ECP

QuantOm Collaboration

$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (i\gamma_\mu D^\mu - m_q)\psi_q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

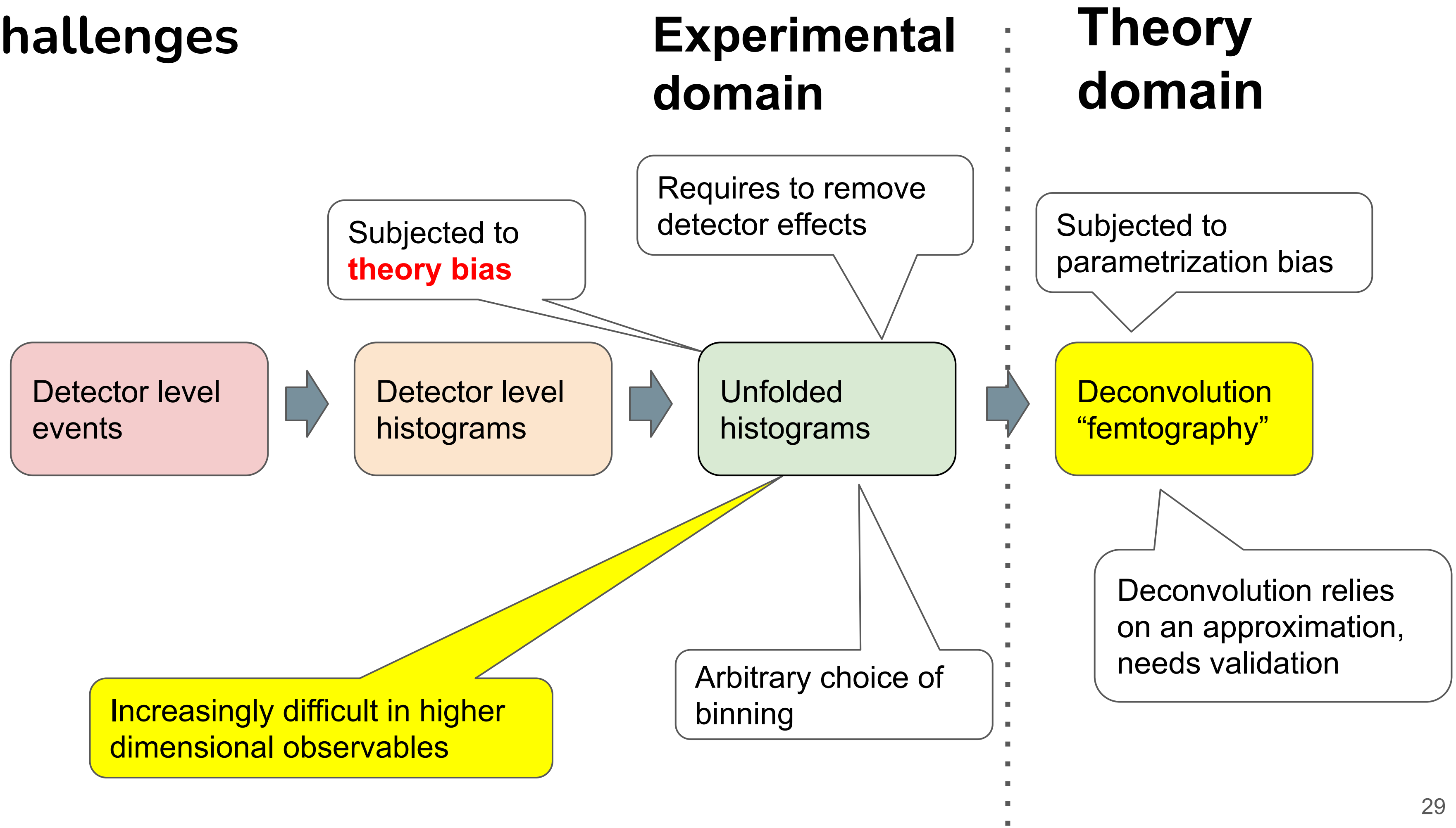
A holistic approach to global analysis





Backup

Challenges



Experimental domain
Theory domain
Subjected to **theory bias**
Requires to remove detector effects
Subjected to parametrization bias
Detector level events
Detector level histograms
Unfolded histograms
Deconvolution "femtography"
Increasingly difficult in higher dimensional observables
Arbitrary choice of binning
Deconvolution relies on an approximation, needs validation