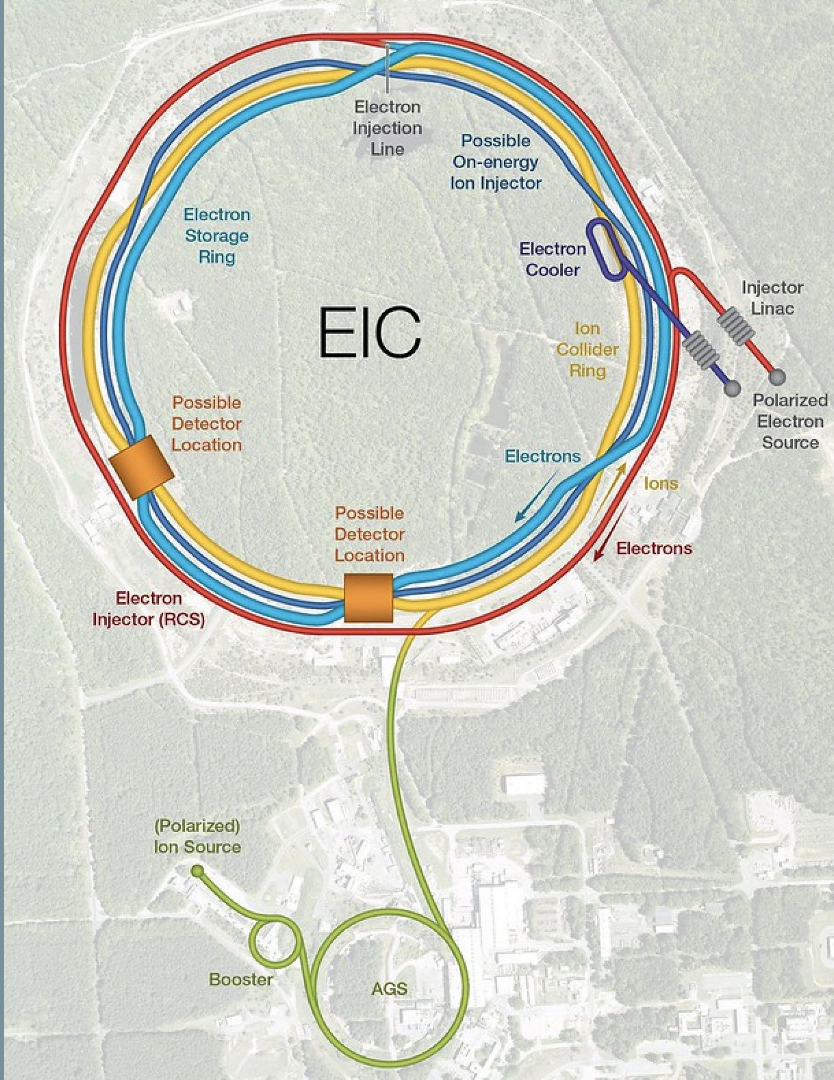
Femtoscale Imaging of Nuclei using ML and Exascale Platforms

Nobuo Sato

Oct 11 2022, William & Mary

Outline

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

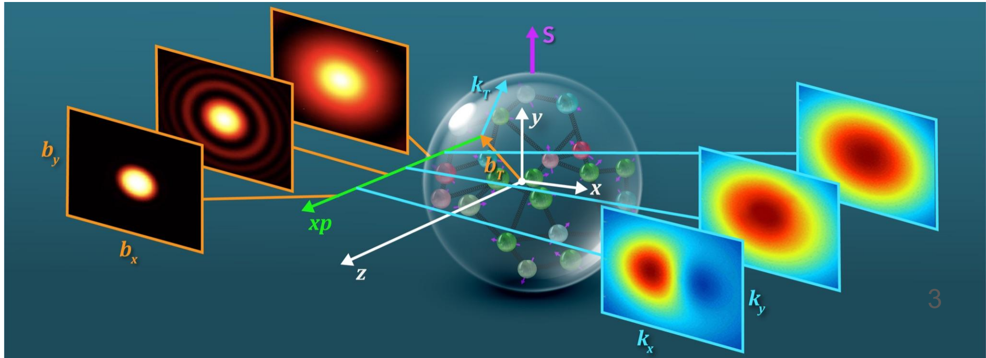


Motivations

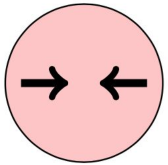
- **WHAT?: Synthesis of 3D tomography/nuclear imaging -** quantum correlation functions (QCFs)
  - hadron structure (PDFs, TMDs, GPDs, ...)
  - hadronization (FFs, TMDFFs)

- **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)
  - …



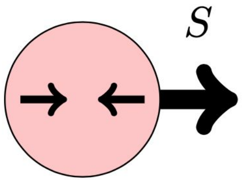
Collinear Spin structures



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

Parton distribution functions

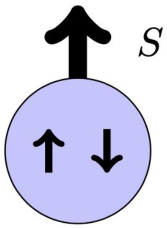
$$\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\psi_i(0)|N\rangle$$



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

Helicity distribution

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



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

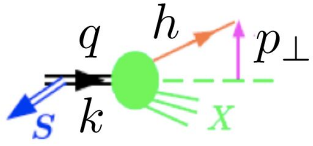
Transversity

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

TMD Spin structures

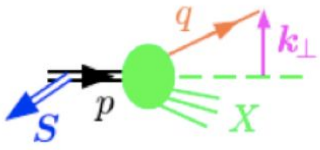
Sivers `89

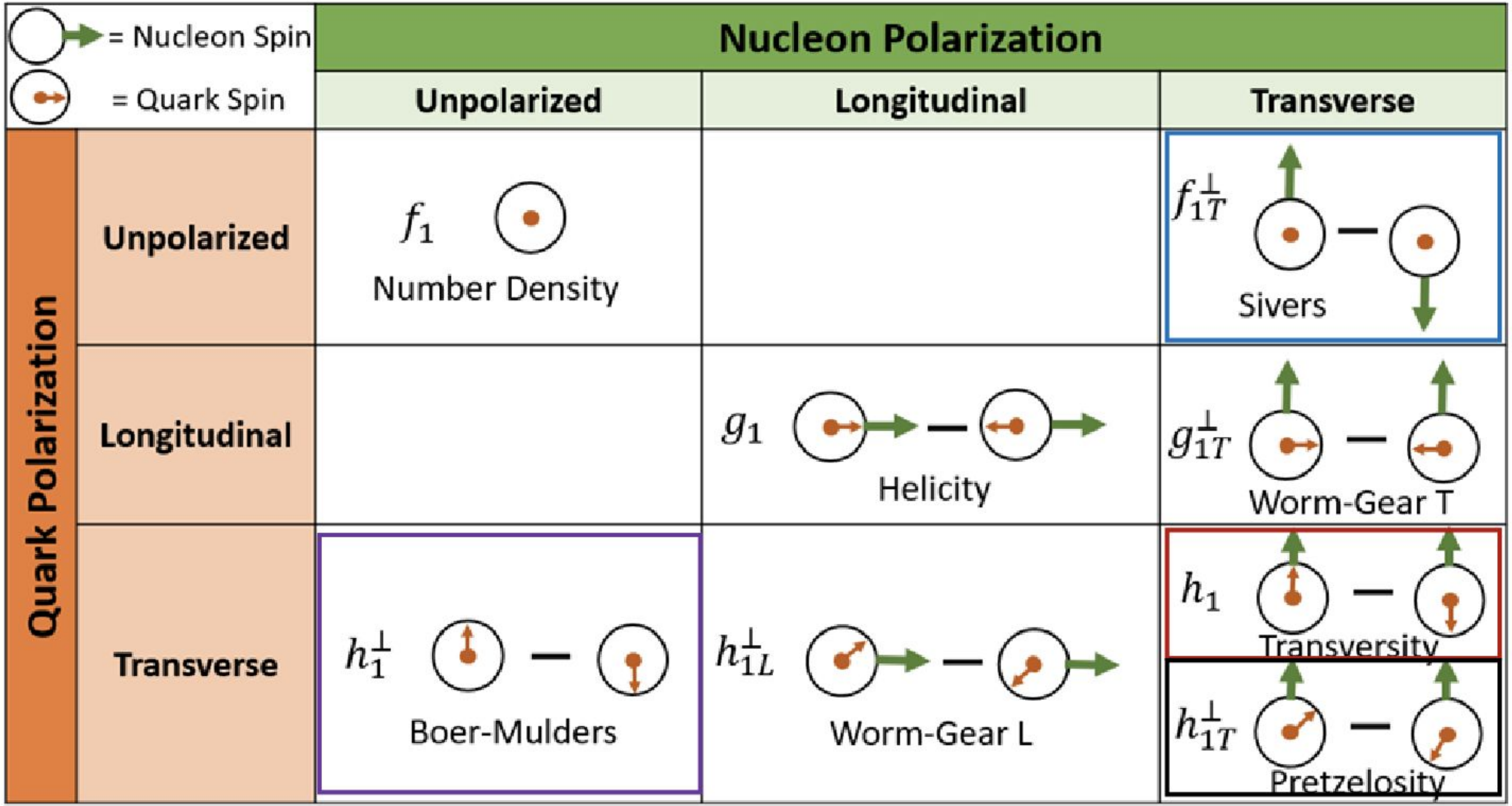
$$f_{q/h^\uparrow}(x,\vec{k}_\perp,\vec{S}) = f_{q/h}(x,k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp^2)\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$$



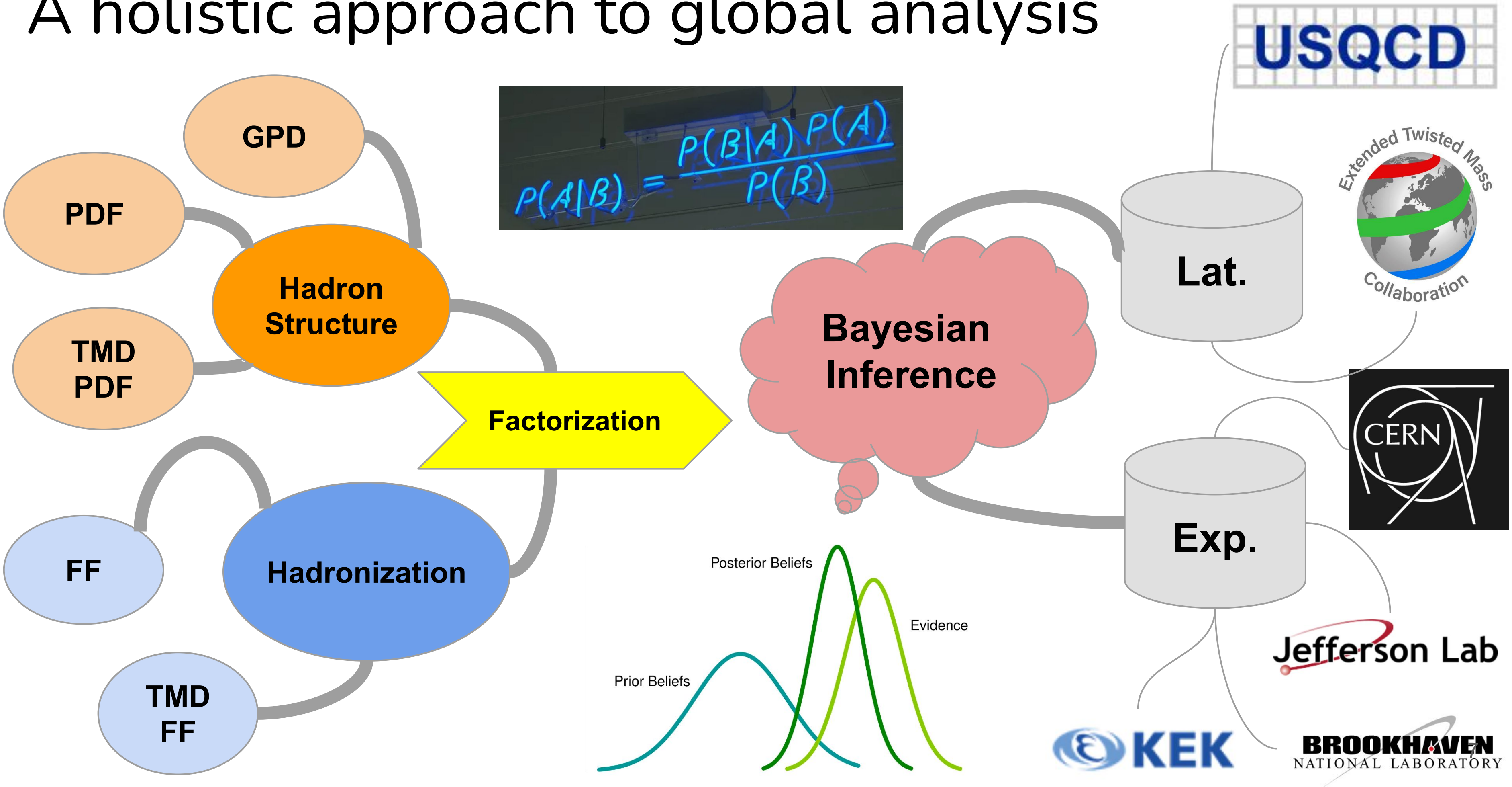
Collins `92

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




= 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



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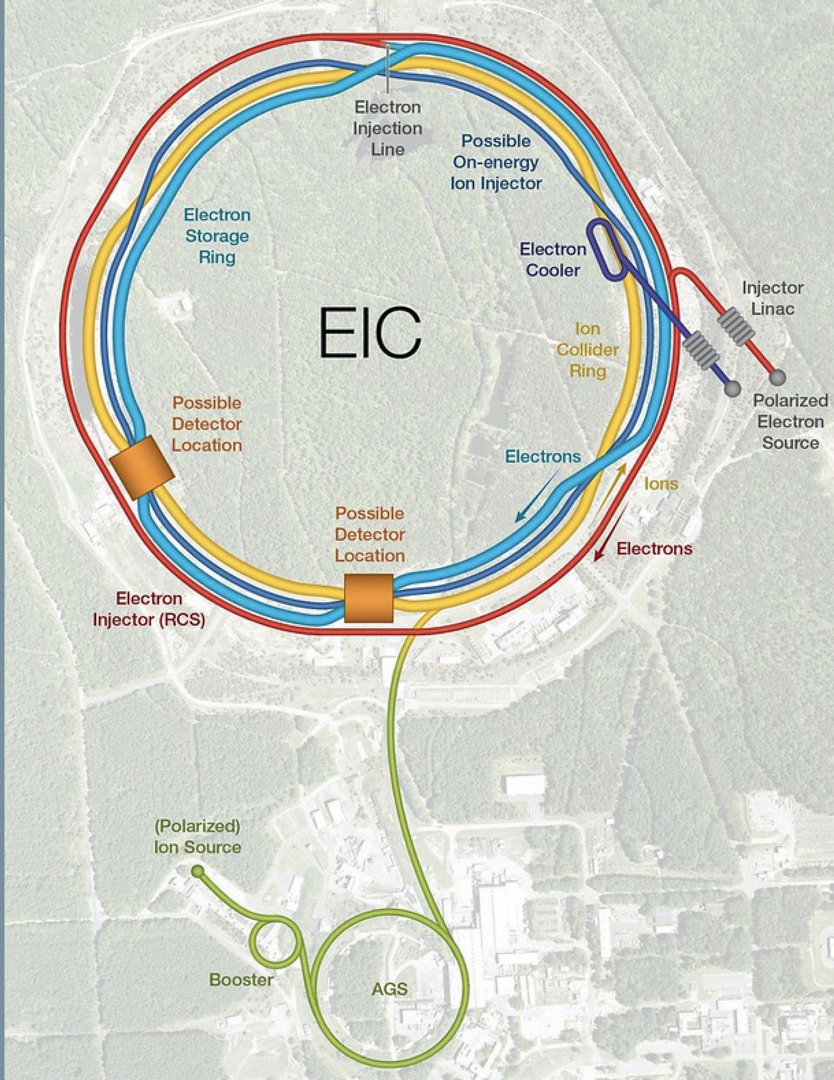
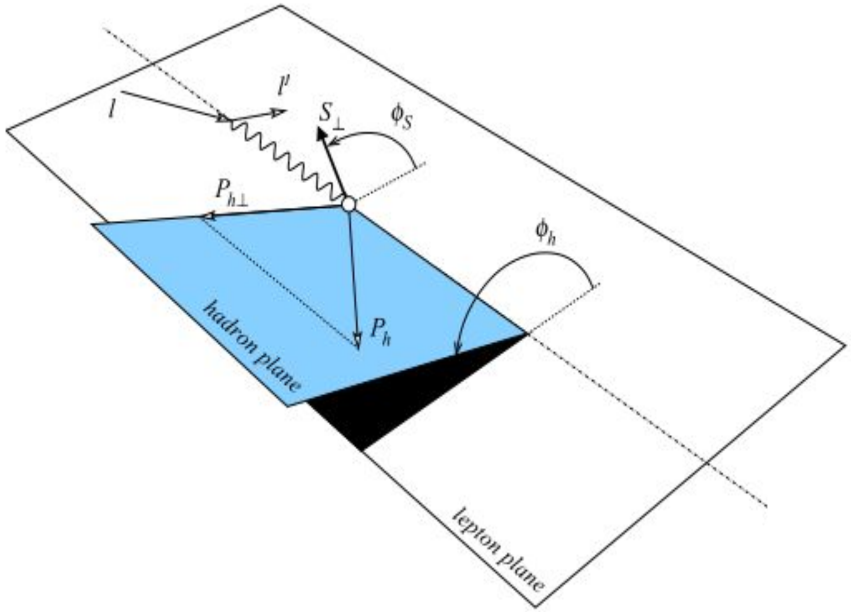


3D hadron structure using SIDIS



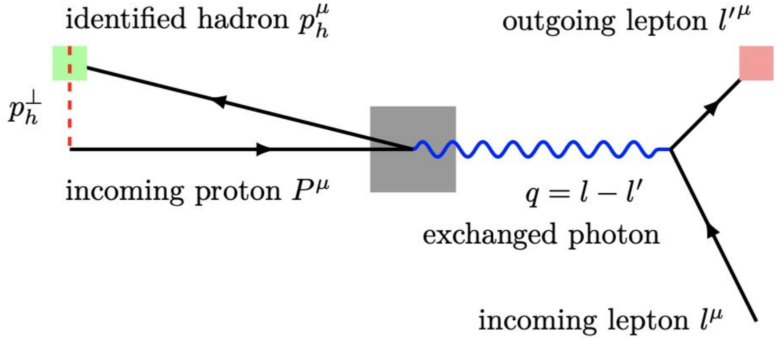
A prime experiment in existing and future facilities

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

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
⋮	⋮	⋮

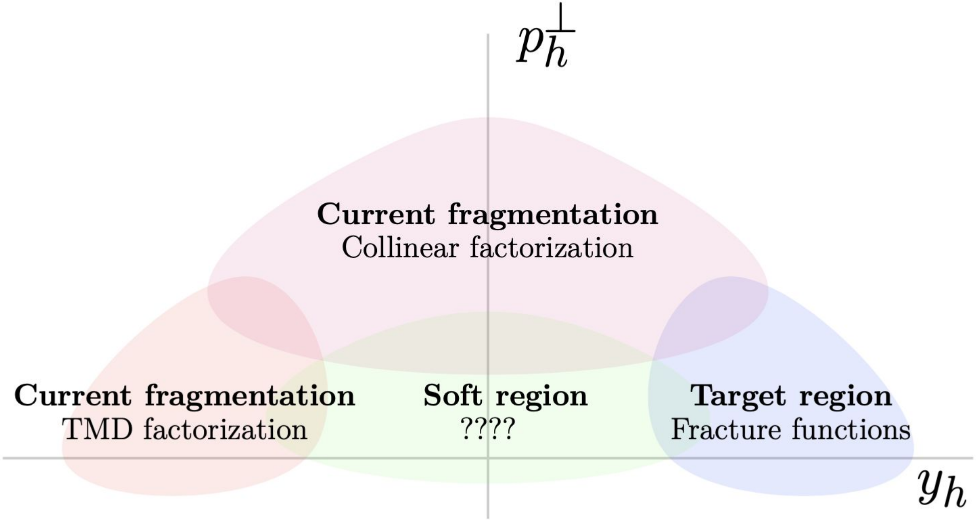
Breit frame

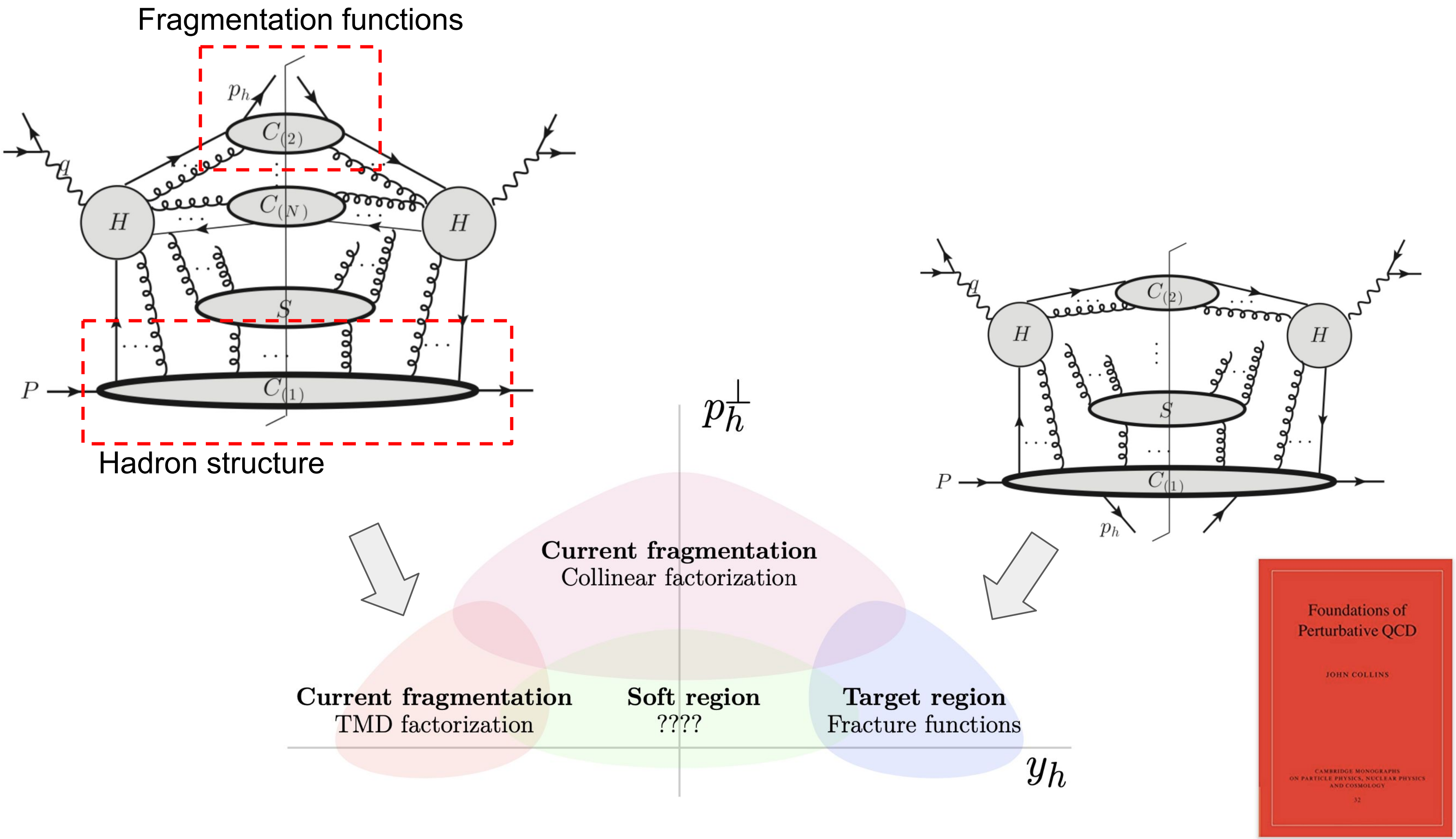


Large vs small pT

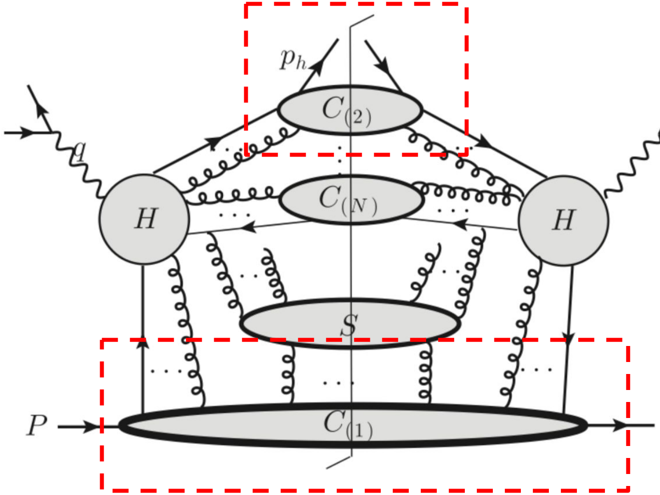
$$q_{\rm T} = p_h^\perp / z$$

$q_{\rm T}/Q$ ⇨ The scale separation




Fragmentation functions
Hadron structure
p_h
q
$C_{(2)}$
$C_{(N)}$
H
S
$C_{(1)}$
P
$p_h^\perp$
y_h
Current fragmentation
Collinear factorization
Current fragmentation
TMD factorization
Soft region
????
Target region
Fracture functions
Foundations of Perturbative QCD
JOHN COLLINS

Fragmentation functions



Hadron structure

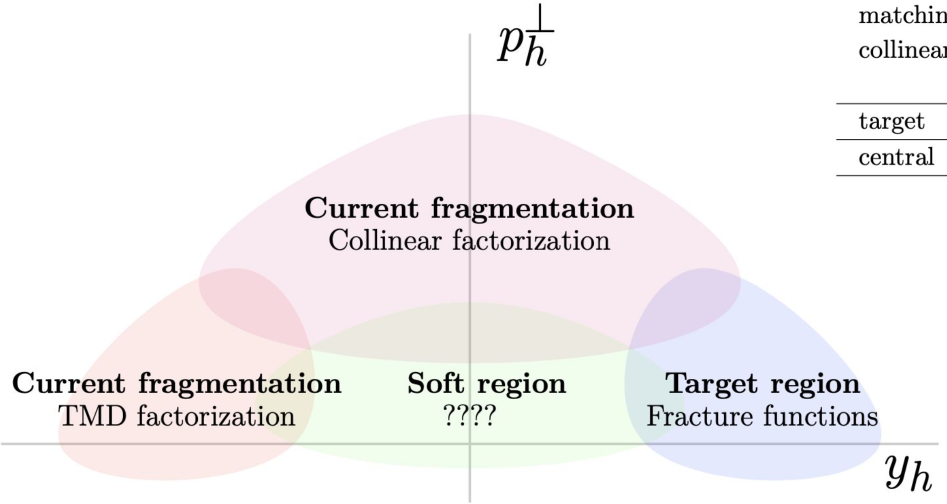
$$
\begin{aligned}
W = &\sum_f H_f(Q,\mu) \int \frac{d^2\boldsymbol{b}_\mathrm{T}}{(2\pi)^2} e^{-i\boldsymbol{q}_\mathrm{T}\cdot\boldsymbol{b}_\mathrm{T}} \\
&\times e^{-g_{f/N}(x,b_\mathrm{T},b_\mathrm{max})} \int_x^1 \frac{d\hat{x}}{\hat{x}} \boldsymbol{f}_{f/N}(\hat{x},\mu_{b_*}) \tilde{C}_{f/p}(x/\hat{x}, b_*, \mu_{b_*}^2, \alpha_S(\mu_{b_*})) \\
&\times e^{-g_{h/f}(z,b_\mathrm{T},b_\mathrm{max})} \int_z^1 \frac{d\hat{z}}{\hat{z}^3} \boldsymbol{d}_{h/f}(\hat{z},\mu_{b_*}) \tilde{C}_{h/f}(z/\hat{z}, b_*, \mu_{b_*}^2, \alpha_S(\mu_{b_*})) \\
&\times \left(\frac{Q^2}{Q_0^2}\right)^{-g_K(b_\mathrm{T},b_\mathrm{max})} \left(\frac{Q^2}{\mu_{b_*}^2}\right)^{\tilde{K}(b_*,\mu_{b_*})} \\
&\times \exp\left[\int_{\mu_{b_*}}^{\mu_Q} \frac{d\mu'}{\mu'} \left[2\gamma(\alpha_S(\mu'),1) - \ln\frac{Q^2}{(\mu')^2}\gamma_K(\alpha_S(\mu'))\right]\right]
\end{aligned}
$$

Aybat, Rogers ‘11

Linking external kinematics with regions

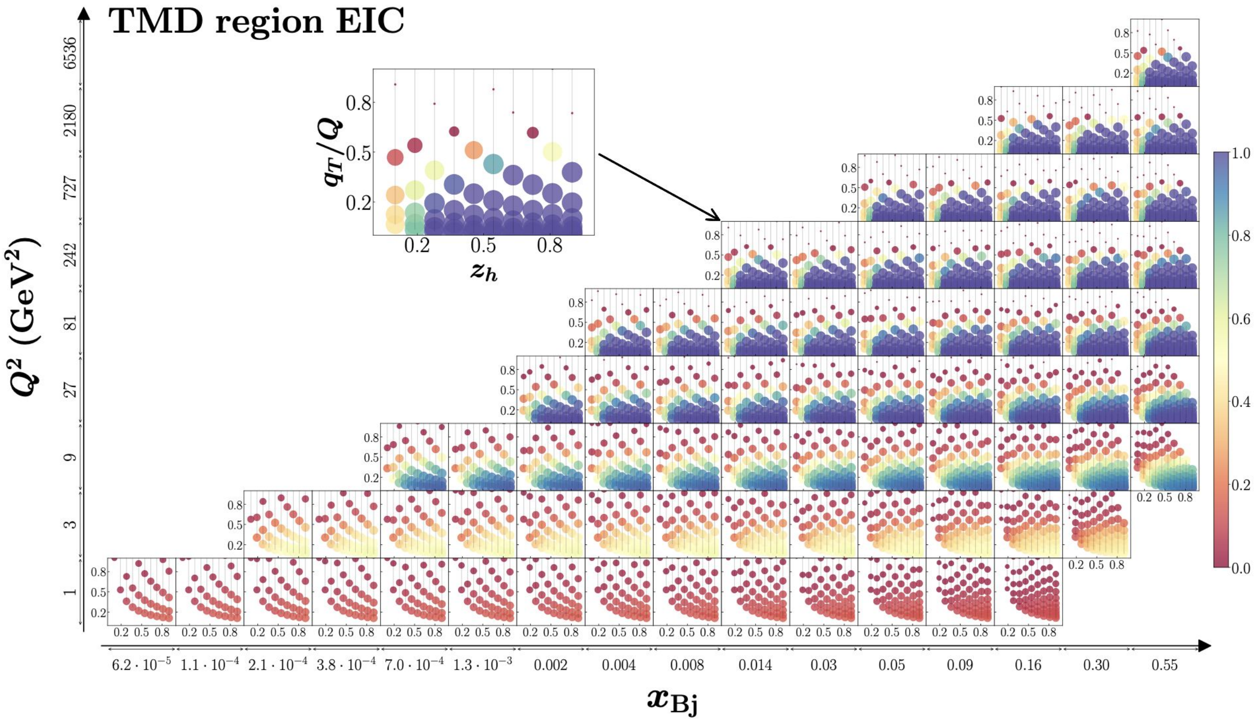
Boglione et al ‘22

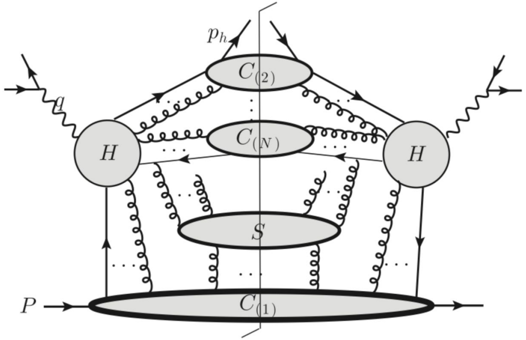
Region	R_0	R_1	R_1'	R_2	R_3	R_4
TMD	small	small	×	small	×	×
matching	small	small	×	small	×	×
collinear	small	small	×	large	small (LO pQCD) large (HO pQCD)	small
target	small	large	small	×	×	×
central	small	not small	not small	small	×	×



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	$\max\left(\left\|\frac{k_i^2}{k^2}\right\|,\left\|\frac{k_f^2}{k^2}\right\|,\left\|\frac{\delta k_T^2}{k^2}\right\|,\left\|\frac{k_{iT}^2}{k^2}\right\|\right)$

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

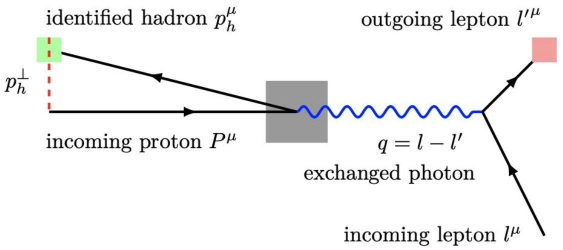

TMD region EIC
Q^2 (GeV^2)
6536
2180
727
242
81
27
9
3
1
q_T/Q
z_h
$x_{\rm Bj}$
$6.2 \cdot 10^{-5}$
$1.1 \cdot 10^{-4}$
$2.1 \cdot 10^{-4}$
$3.8 \cdot 10^{-4}$
$7.0 \cdot 10^{-4}$
$1.3 \cdot 10^{-3}$
0.002
0.004
0.008
0.014
0.03
0.05
0.09
0.16
0.30
0.55
0.0
0.2
0.4
0.6
0.8
1.0

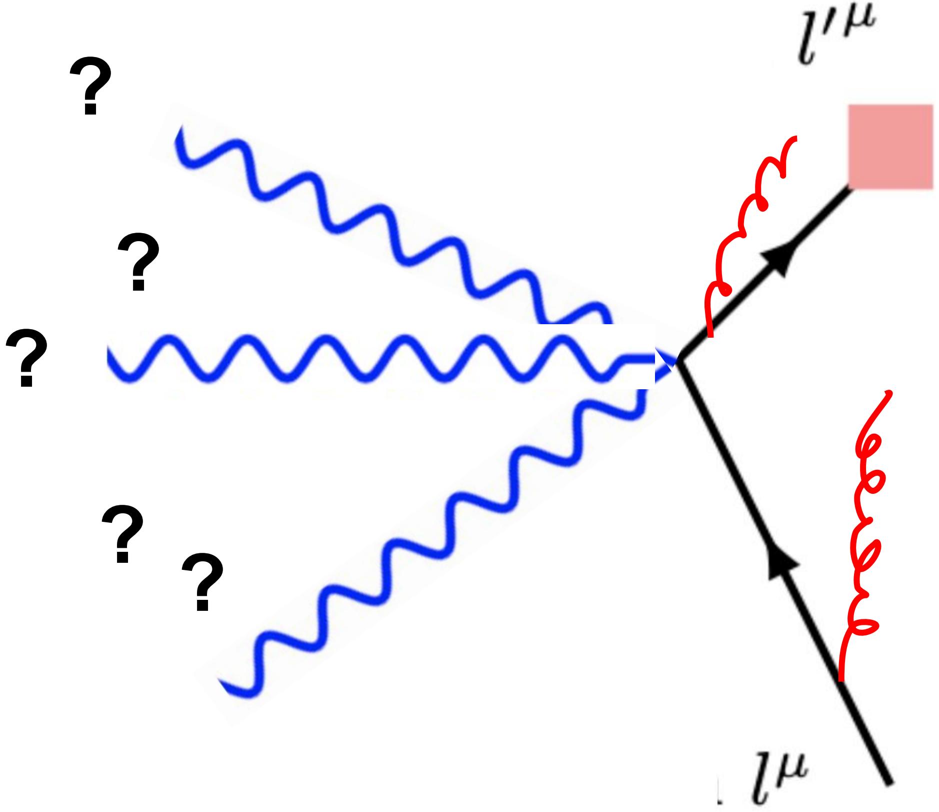

p_h
q
$C_{(2)}$
$C_{(N)}$
H
H
S
P
$C_{(1)}$

Role of QED effects

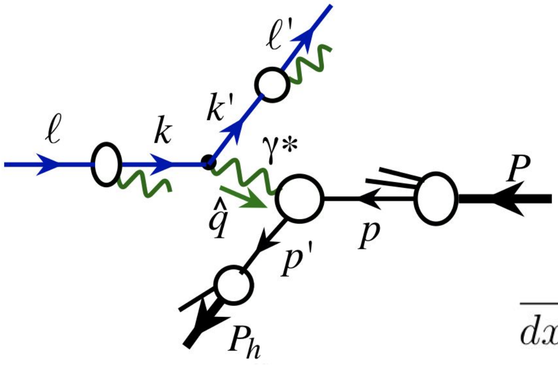
- In the presence of QED radiation, **the q direction is not fixed**
- The experimental Breit Frame **does not need to coincide with the actual Breit-frame** needed in QCD factorization

Breit frame





Hybrid QED+QCD factorization approach



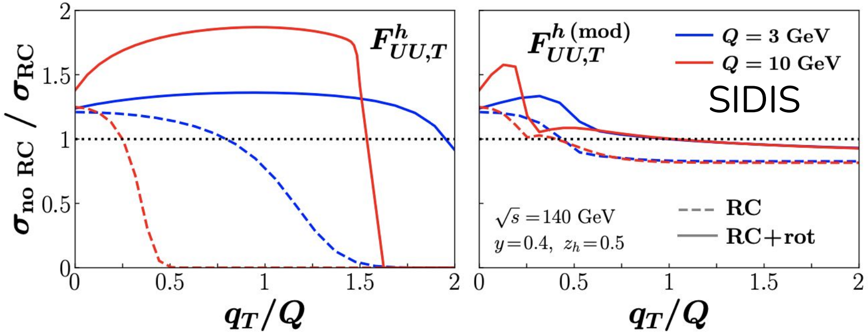
Liu, Melnitchouk, Qiu, Sato '21

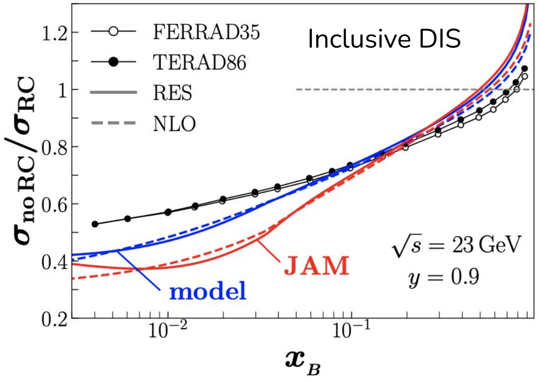
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\sum_i w_i F_i(x, Q^2, z, \mathbf{P}_{h\perp})$$

⬇

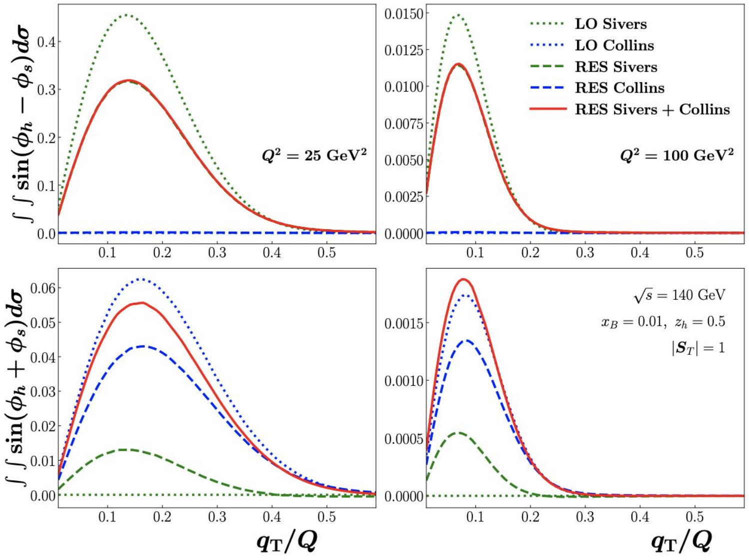
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \int_{\zeta_{\min}}^{1} d\zeta \int_{\xi_{\min}(\zeta)}^{1} d\xi\, f_{k/l}(\xi)\, d_{k'/l'}(\zeta) \times \frac{\hat{x}}{x\xi\zeta}\left[\frac{\alpha^2}{\hat{x}\hat{y}\widehat{Q}^2}\frac{\hat{y}}{2(1-\hat{\varepsilon})}\left(1+\frac{\hat{\gamma}^2}{2\hat{x}}\right)\sum_i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

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*

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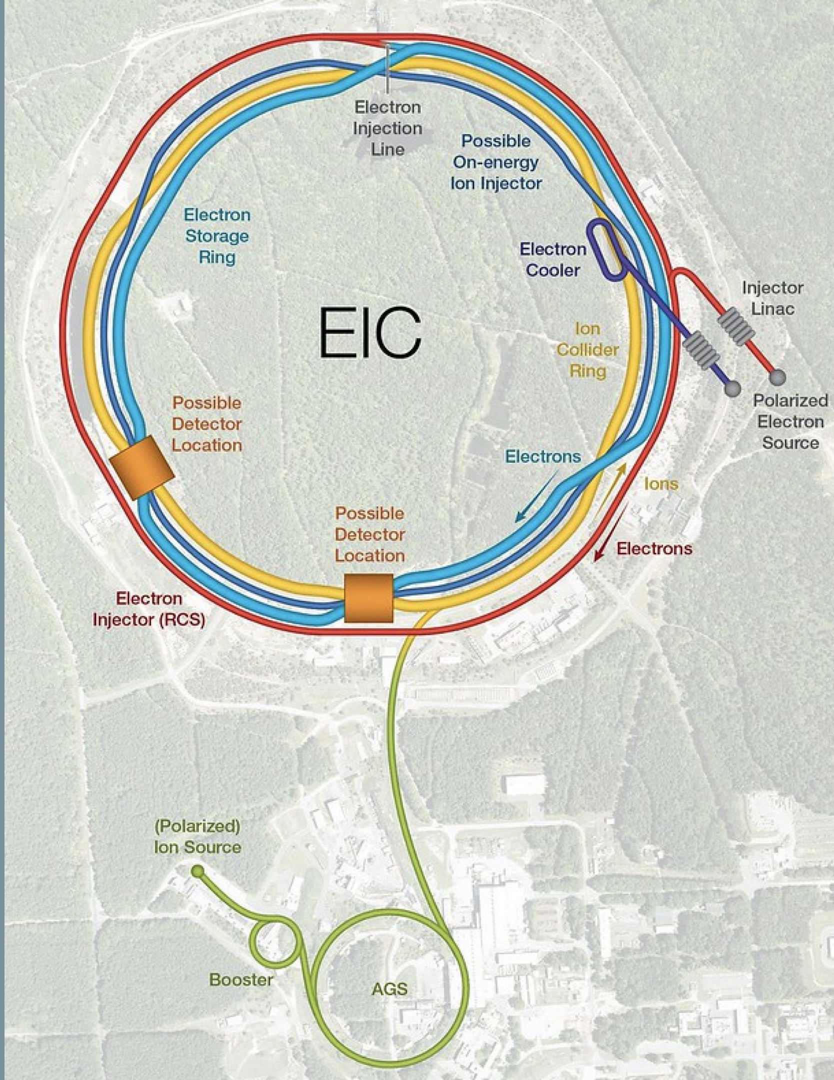
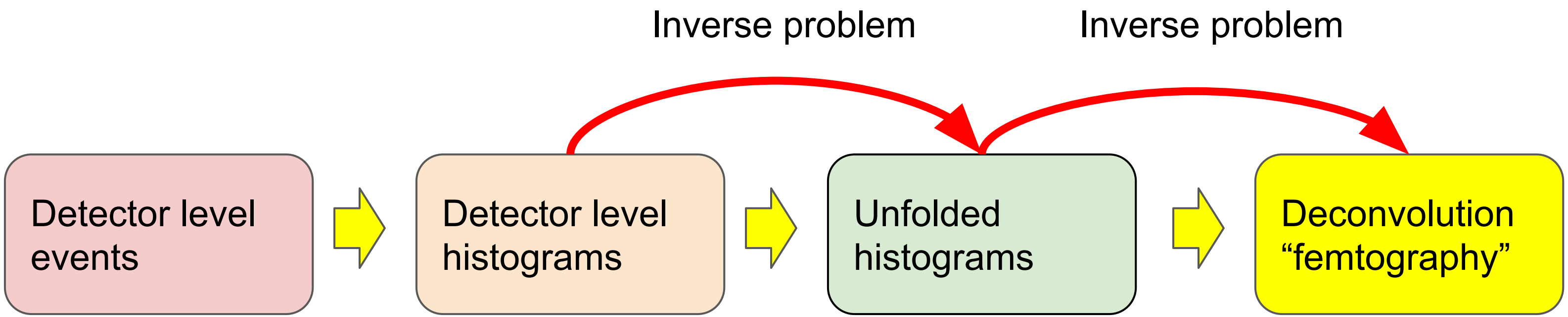
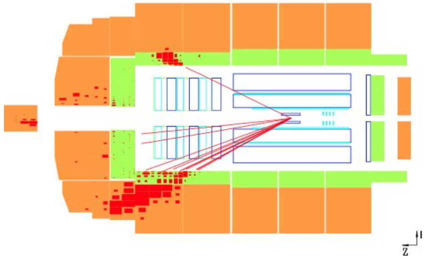
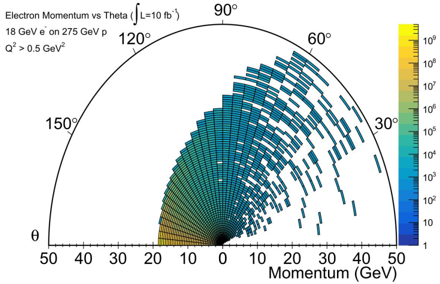
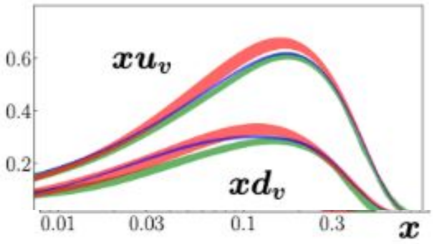


Existing paradigm -> histogram approach



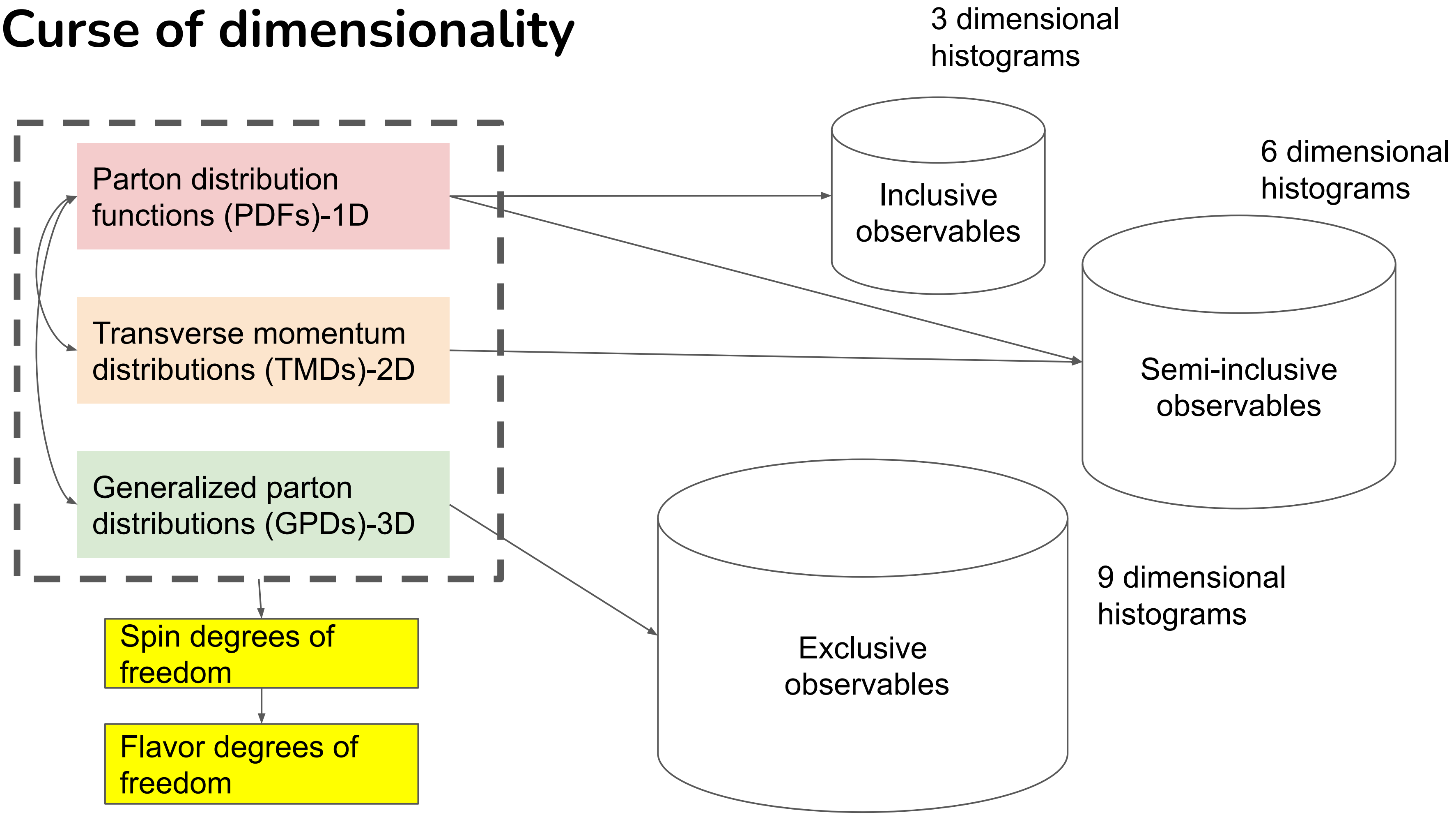






1D QCFs

Curse of dimensionality

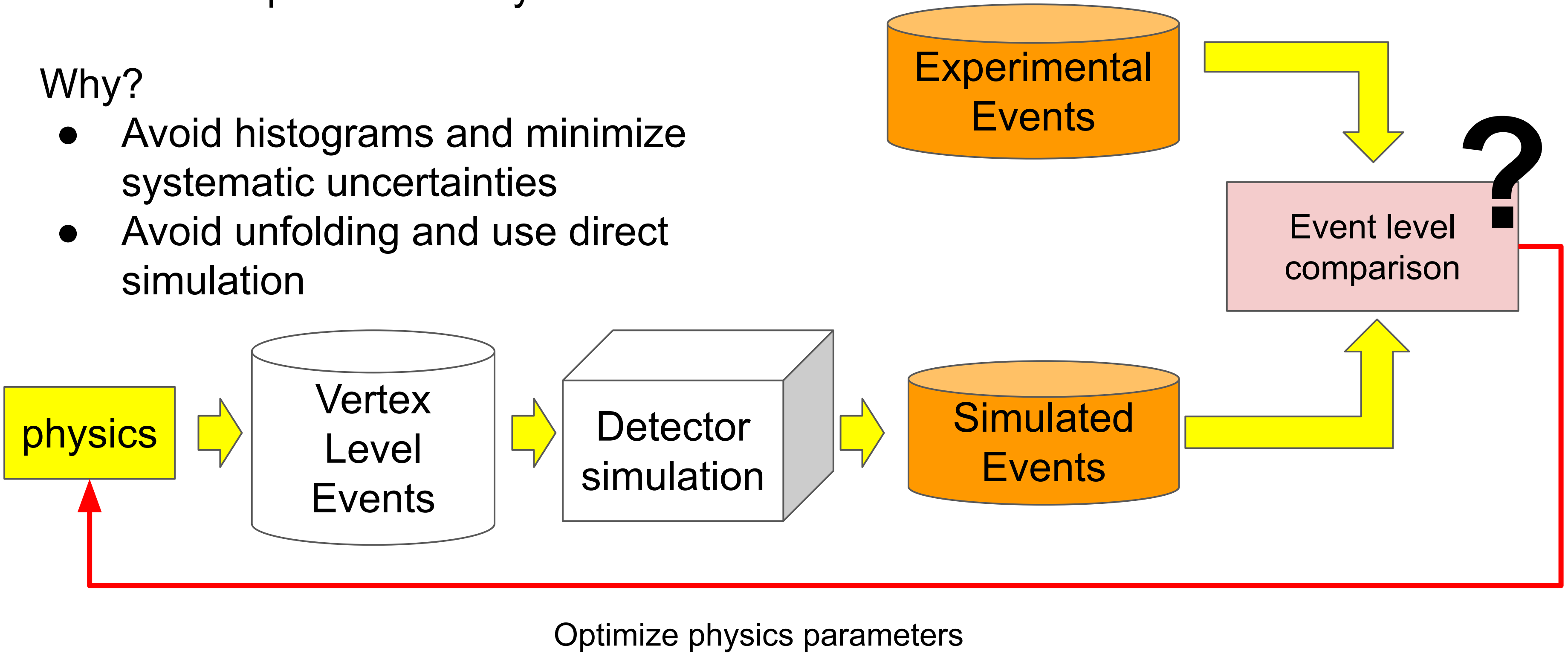


Event-based analysis?

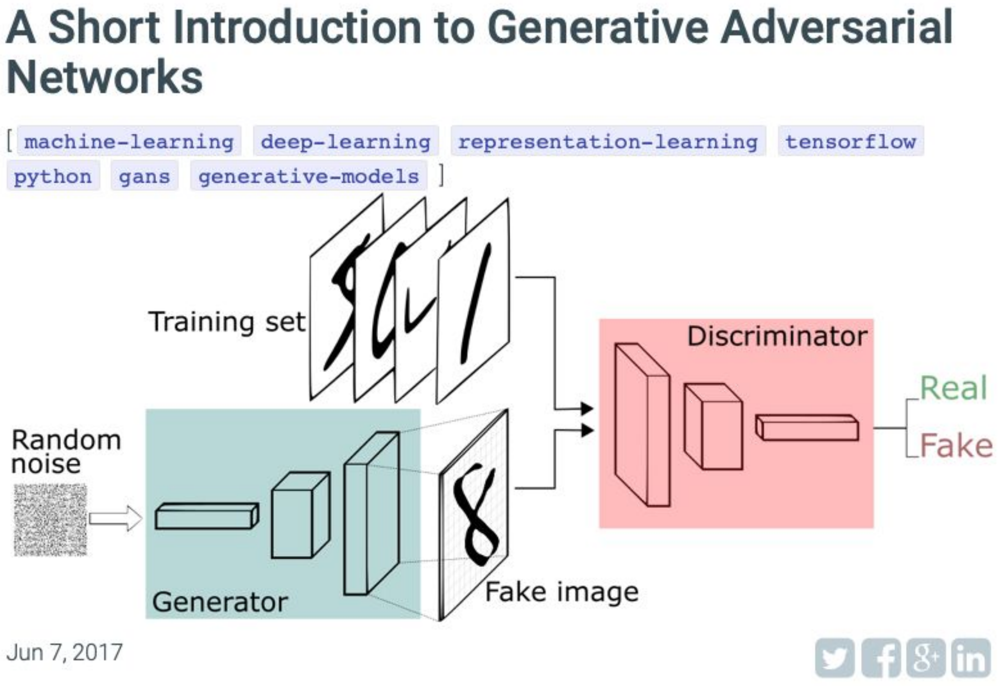
Can we compare real vs synthetic events?

Why?

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



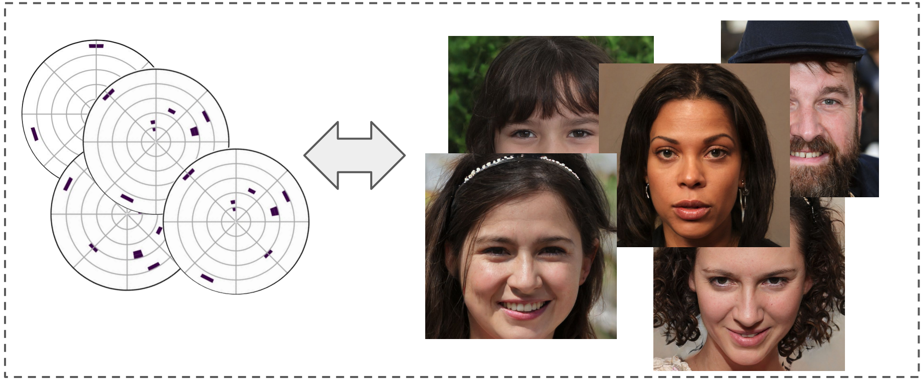
So, how do we compare events?

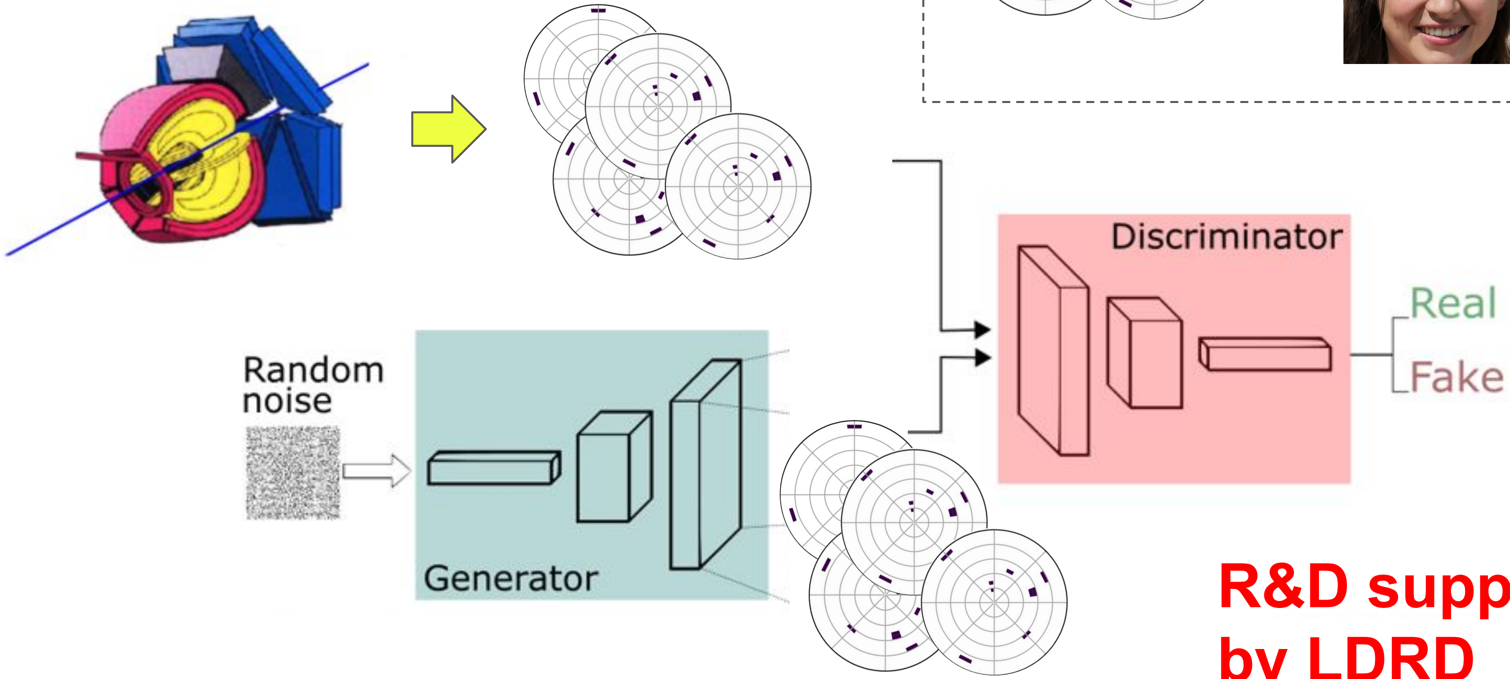


Fake people

https://thispersondoesnotexist.com

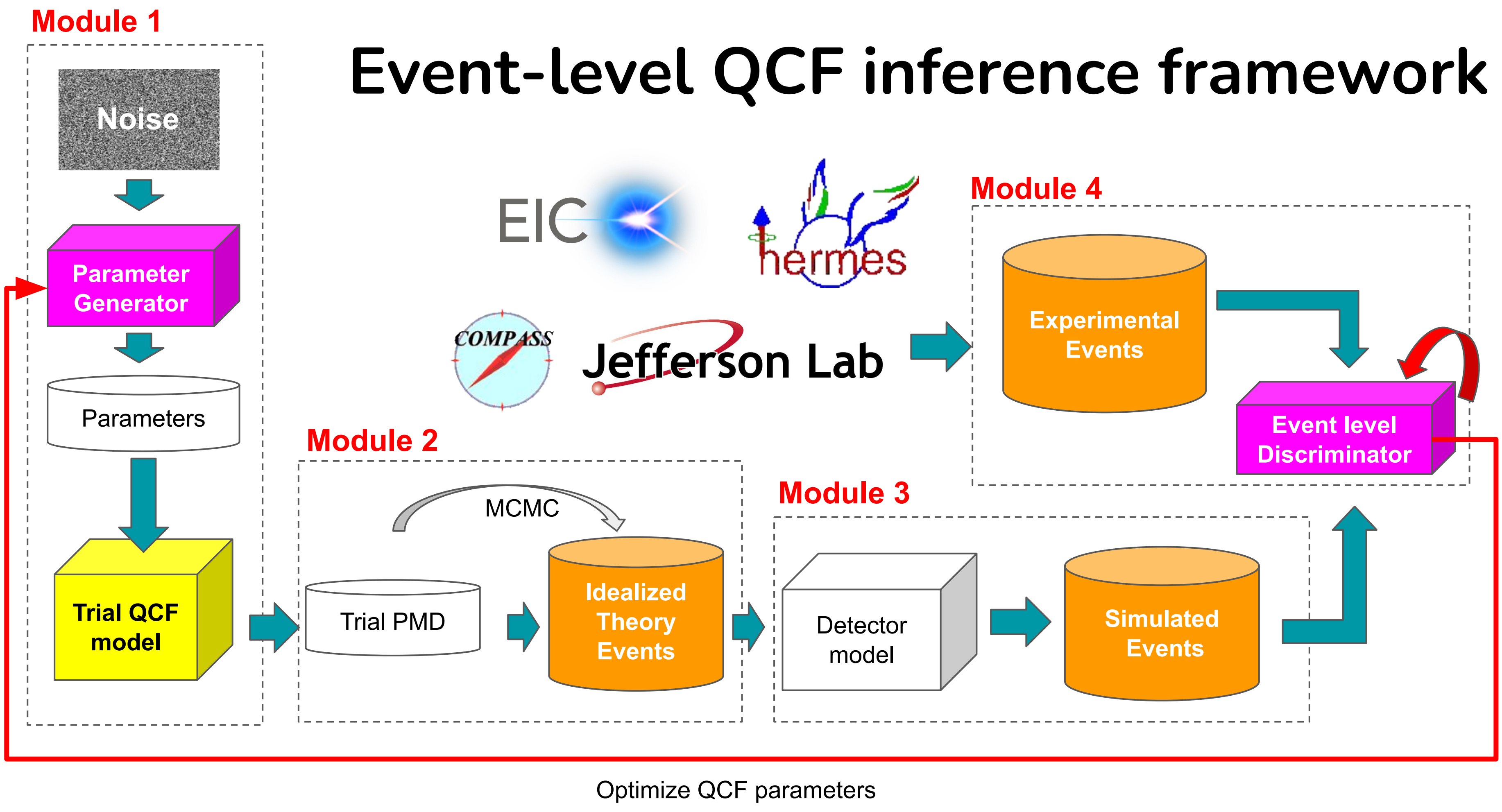
Events as faces





R&D supported by LDRD

Event-level QCF inference framework

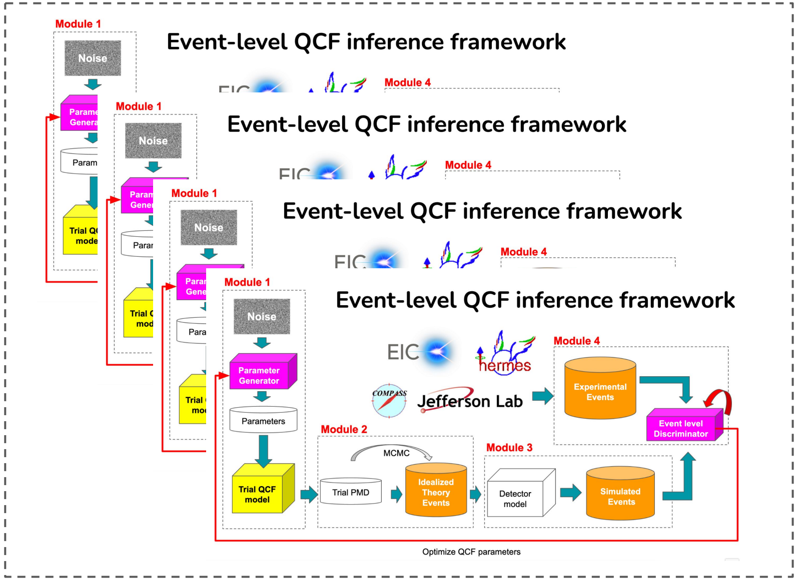


Opportunities

- 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 | OLD DOMINION UNIVERSITY

Supported by DOE SciDAC funds

Summary

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

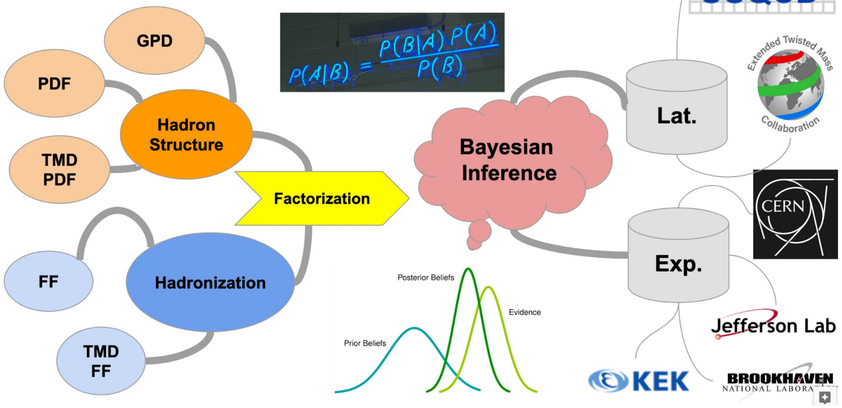
- AI/ML provides new tools/tricks to map QCFs from events and boost the discovery potential of current and future experimental facilities

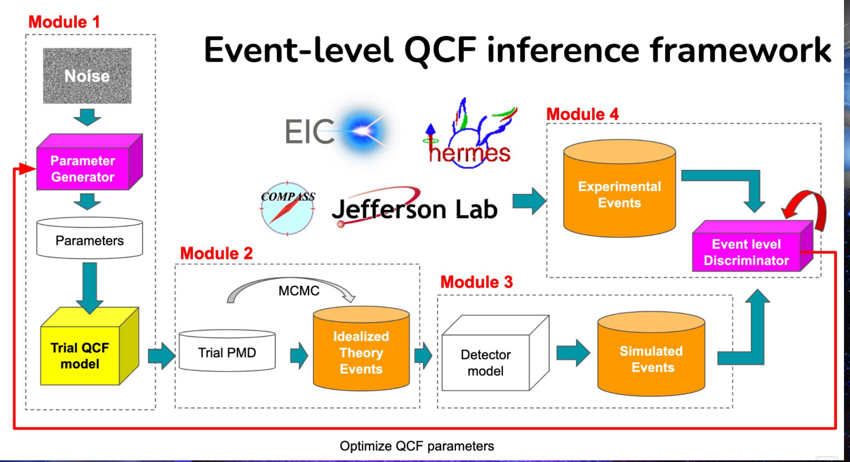
- Large scale computing is needed -> opportunity to use ECP

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