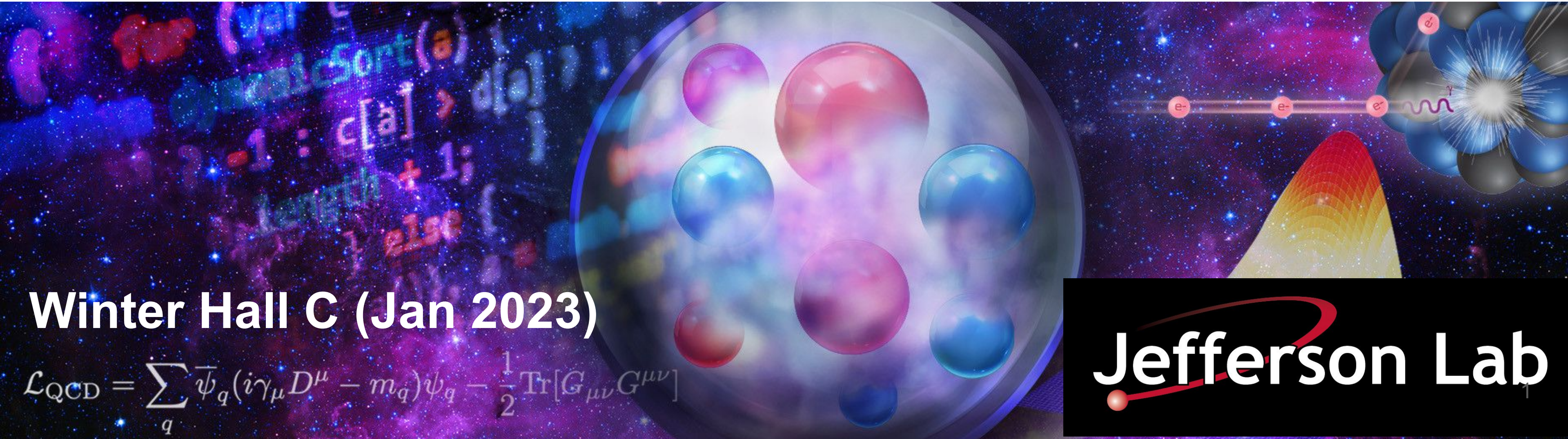
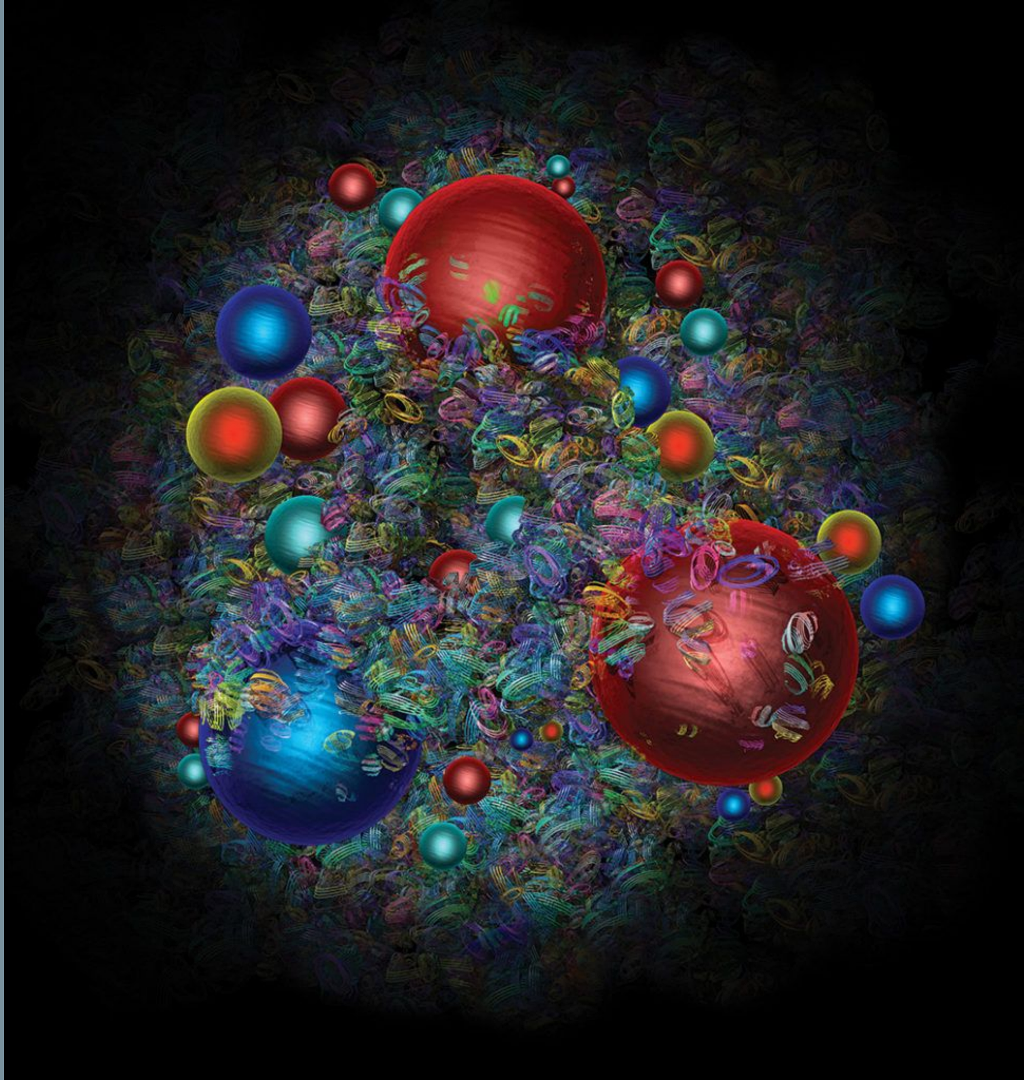
Correlation functions and uncertainty quantification

Nobuo Sato

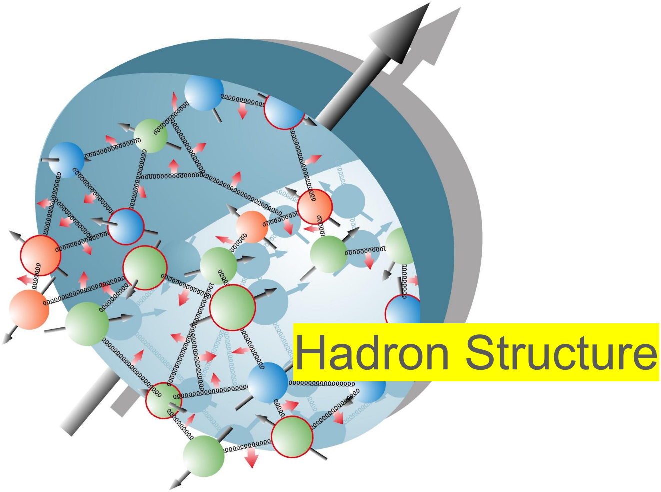


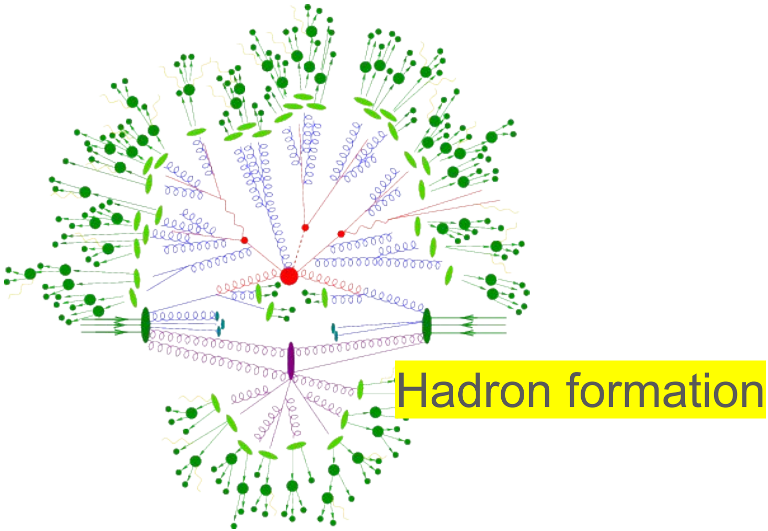
Outline

1. Brief overview of QCFs
2. Recent highlights
3. Integrating THY/EXP/CS
4. Summary



Quantum correlation functions (QCFs) in Nuclear femtography



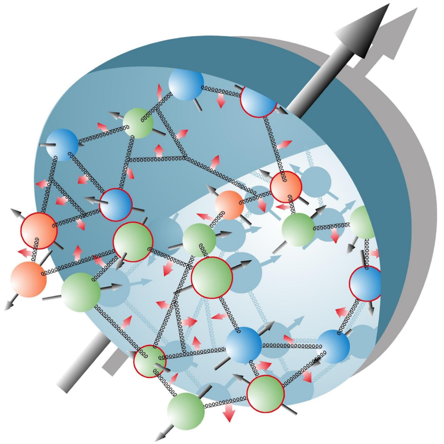


Parton distribution functions (PDFs)

Transverse momentum distributions (TMDs)

Generalized parton distributions (GPDs)

What do we mean by "hadron structure" ?



$$\xi = \frac{k^+}{P^+}$$

Parton momentum fraction relative to **parent hadron**

$$f_i(\xi) = \int \frac{\mathrm{d}w^-}{4\pi} e^{-i\xi p^+ w^-} \boxed{\langle N|\bar{\psi}_i(0, w^-, \mathbf{0}_\mathrm{T})\gamma^+\psi_i(0)|N\rangle}$$

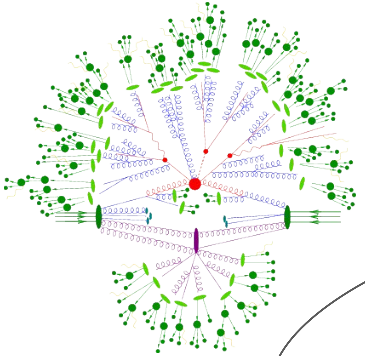
parton distribution function (PDF)

in non-interacting QCD

$$\psi_i(x) = \sum_{k,\alpha} b_{k,\alpha}(x^+) u_{k,\alpha} e^{-ik^+x^- + ik_\mathrm{T}\cdot x_\mathrm{T}} + d^\dagger_{k,\alpha}(x^+) u_{k,-\alpha} e^{ik^+x^- - ik_\mathrm{T}\cdot x_\mathrm{T}}$$

$$f_i(\xi) \sim \sum_\alpha \int \mathrm{d}^2k_\mathrm{T} \, \langle N| \underbrace{b^\dagger_{k,\alpha} b_{k,\alpha}(\xi p^+, k_\mathrm{T}, \alpha)}_{\text{number operator}} |N\rangle$$

What do we mean by “hadronization” ?



$$\zeta = \frac{p_h^+}{k^+}$$

hadron momentum fraction relative to parent parton

$$d_{h/j}(\zeta) = \frac{\mathrm{Tr}_{\mathrm{color,Dirac}}}{4N_{c,j}} \sum_X \zeta \int \frac{dw^+}{2\pi} e^{i(p_h^-/\zeta)w^+}$$
$$\times\, \gamma^- \boxed{\langle 0 | \bar{\psi}_j(0, w^+, \mathbf{0}_\mathrm{T})\ | p_h, X \rangle \langle p_h, X |\ \psi_j(0) | 0 \rangle}$$

Fragmentation functions (FFs)

X = all states except detected hadron ***h***

Extensions to 3D

$$f(\xi, b_\mathrm{T})$$

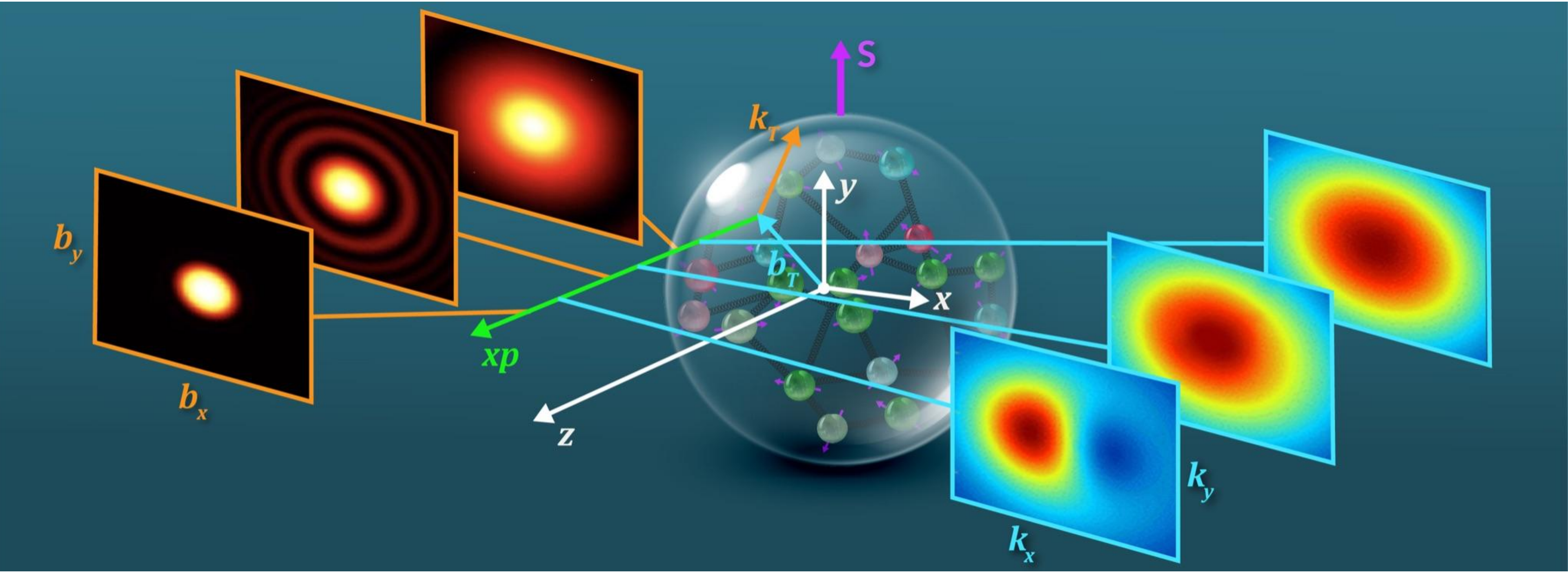
Impact parameter distribution -> **GPDs**

$$f(\xi)$$

PDFs

$$f(\xi, k_\mathrm{T})$$

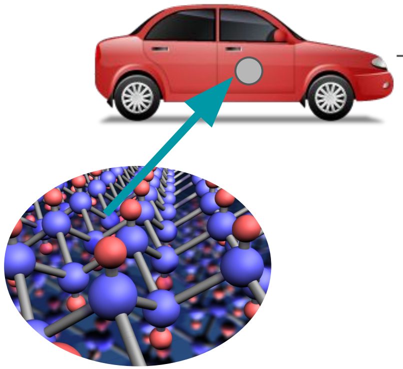
Transverse momentum distribution -> **TMDs**



So how do we get hadron structure from experimental data?

Want to see
internal structure

What part of this is
the "**internal
structure**"?

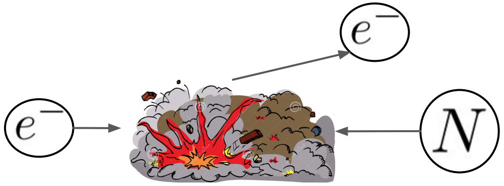


But we only see **debris**

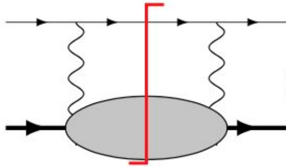
The inverse problem

Factorization

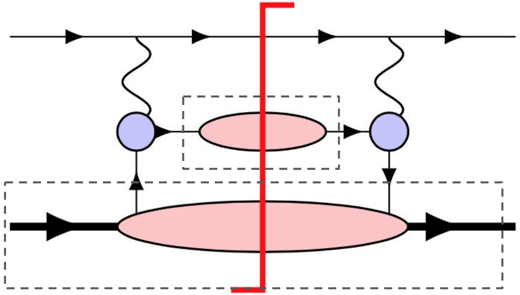
Factorization in deep-inelastic scattering

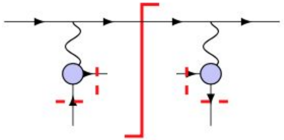


$$E' \frac{\mathrm{d}\sigma}{\mathrm{d}^3 l'}$$

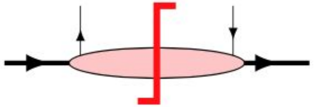


Approximations





Collision dependent factor



Internal structure

$$E' \frac{\mathrm{d}\sigma}{\mathrm{d}^3 l'} = \sum_i \int_x^1 \frac{\mathrm{d}\xi}{\xi} H_i(\xi) \, f_i\left(\frac{x}{\xi}\right) + \mathcal{O}\left(\frac{m^2}{Q^2}\right)$$

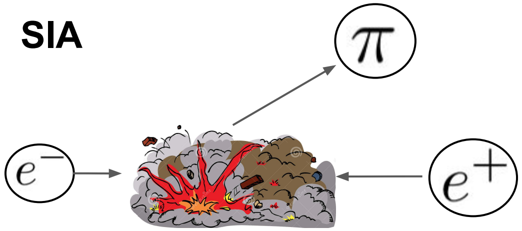
Error of approximations

$$E' \frac{d\sigma}{d^3 l'} = \sum_i \int_x^1 \frac{d\xi}{\xi} H_i(\xi) \boxed{f_i\left(\frac{x}{\xi}\right)}$$

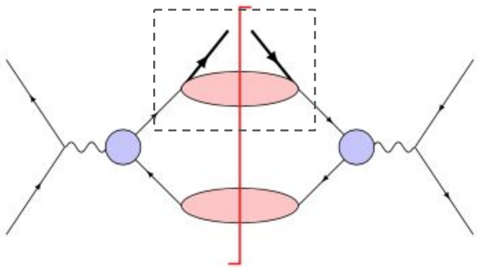
- There is no formal way to invert analytically this expression for the pdfs
- Is not possible to say that the measured x corresponds to parton momentum fraction
- PDFs are technically not measurable point by point -> inverse problem

Factorization in other reactions

SIA

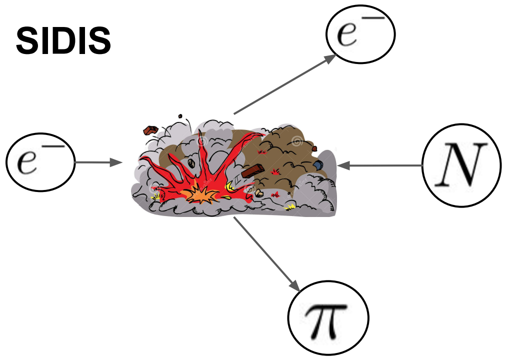


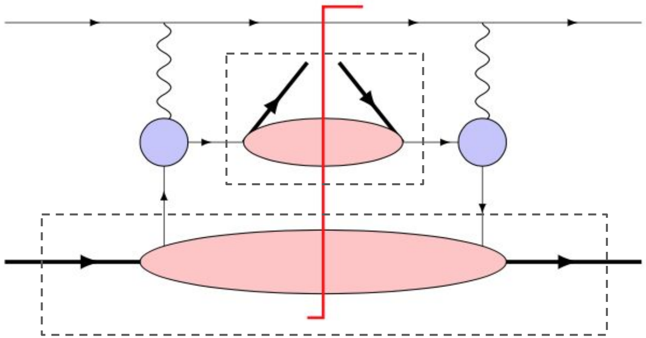
hadronization



$$d\sigma = \sum_i H_i^{\mathrm{SIA}} \otimes d_i$$

SIDIS



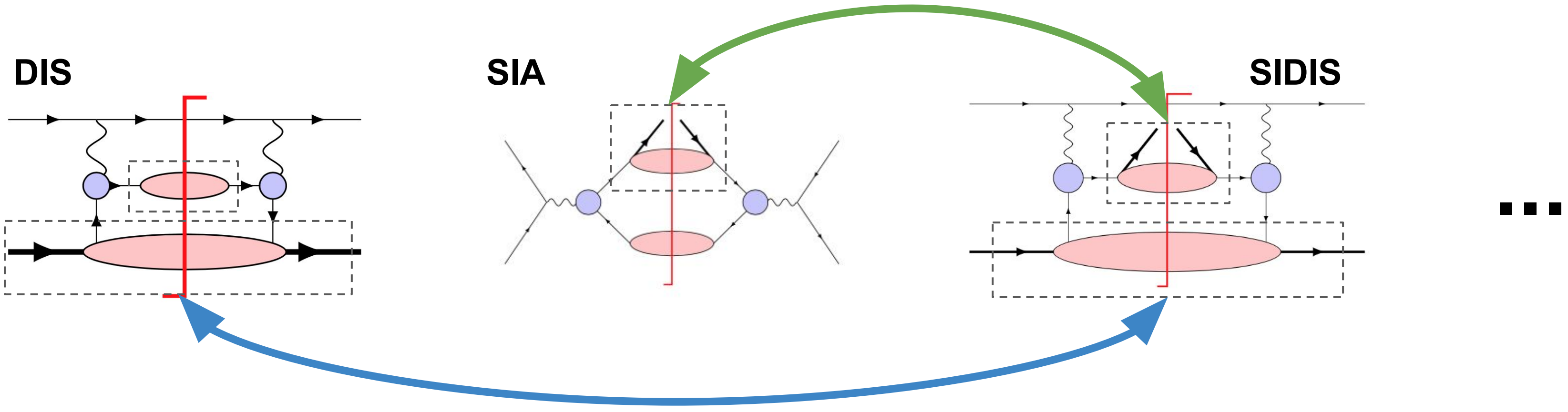


$$d\sigma = \sum_{ij} H_{ij}^{\mathrm{SIDIS}} \otimes f_i \otimes d_j$$

structure + hadronization

..and many more

Universality



cross sections described by **universal non-perturbative** functions, e.g. PDFs, FFs

We cannot measure QCFs,
….we can only make infer them

Priors:

- Models for the QCFs
- Precision of the perturbative calculation
- LQCD

The Bayesian inference

Experiments = theory + errors

$$d\sigma_{\rm DIS} = \sum_i H_i^{\rm DIS} \otimes f_i$$

$$d\sigma_{\rm DY} = \sum_{ij} H_{ij}^{\rm DY} \otimes f_i \otimes f_j$$

$$d\sigma_{\rm SIA} = \sum_i H_i^{\rm SIA} \otimes d_i$$

$$d\sigma_{\rm SIDIS} = \sum_{ij} H_{ij}^{\rm SIDIS} \otimes f_i \otimes d_j$$

RGE boundary conditions (QCF modeling)

$$f_i(\xi, \mu_0^2) = N_i \xi^{a_i} (1-\xi)^{b_i} (1+\ldots)$$

$$d_i(\zeta, \mu_0^2) = N_i \zeta^{a_i} (1-\zeta)^{b_i} (1+\ldots)$$

$$\mathbf{a} = (N_i, a_i, b_i, \ldots)$$

$$\rho(\mathbf{a}|\text{data}) \sim \mathcal{L}(\mathbf{a}, \text{data})\pi(\mathbf{a})$$

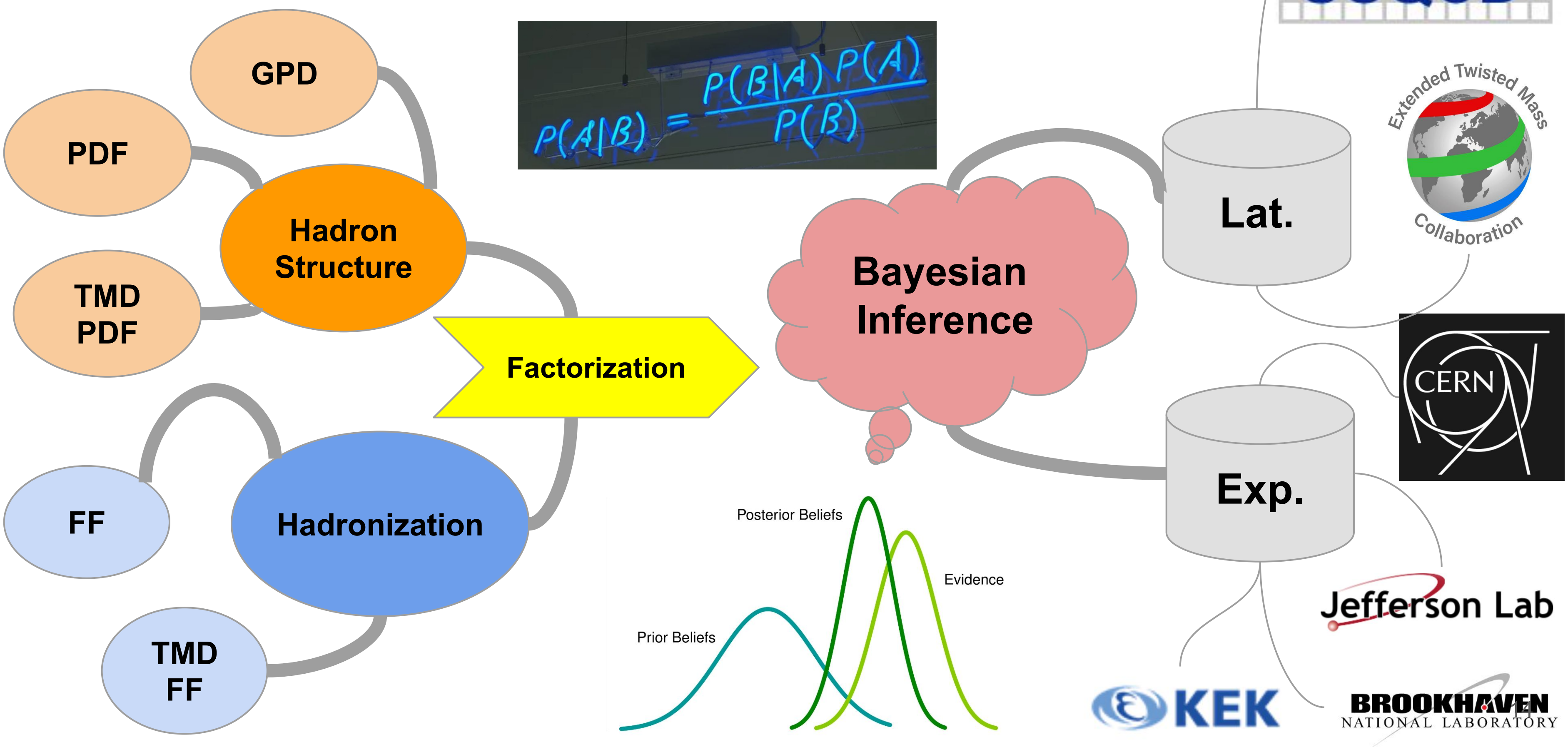
$$\mathcal{L}(\boldsymbol{a}, \text{data}) = \exp\left[-\frac{1}{2}\chi^2(\boldsymbol{a}, \text{data})\right]$$

$$\chi^2(\boldsymbol{a}) = \sum_{i,e} \left(\frac{d_{i,e} - \sum_k r_e^k \beta_{i,e}^k - T_{i,e}(\boldsymbol{a})/N_e}{\alpha_{i,e}} \right)^2$$

$$\mathrm{E}[f_i(\xi,\mu^2)] = \int d^n\mathbf{a}\, \rho(\mathbf{a}|\text{data}) f_i(\xi,\mu^2;\mathbf{a})$$

$$\mathrm{V}[f_i(\xi,\mu^2)] = \int d^n\mathbf{a}\, \rho(\mathbf{a}|\text{data}) \left[f_i(\xi,\mu^2;\mathbf{a}) - \mathrm{E}[f_i(\xi,\mu^2)]\right]^2$$

A holistic approach for global analysis



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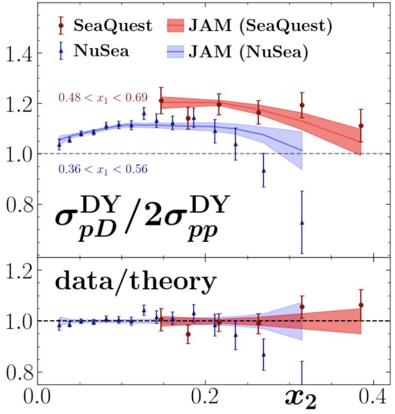
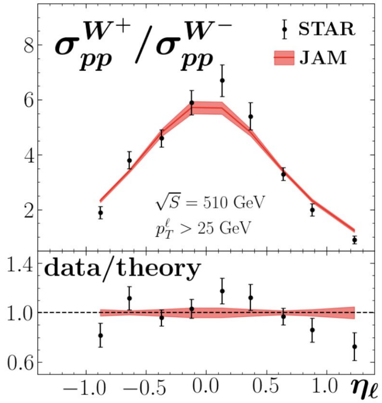
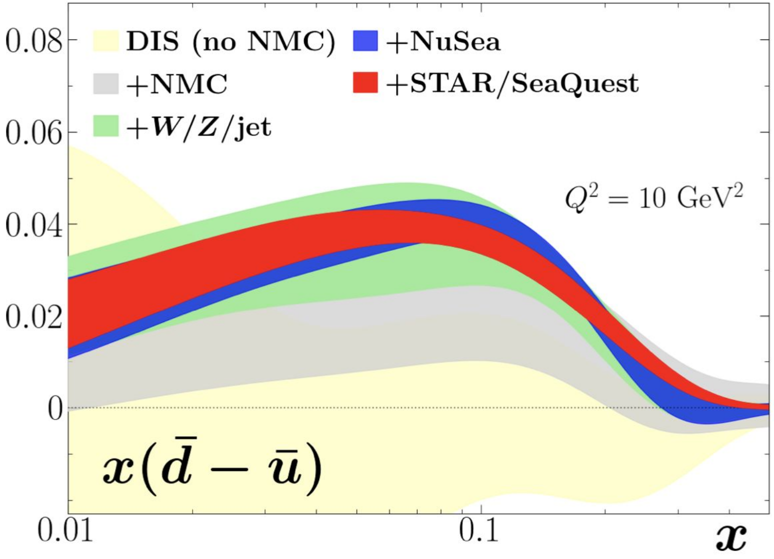
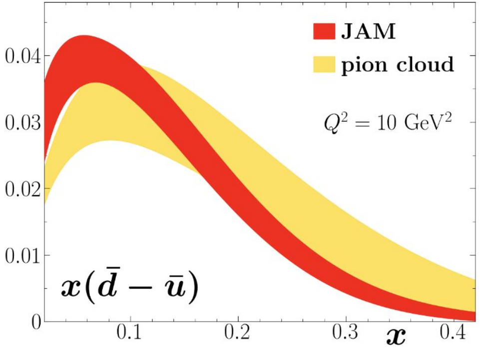
Antimatter asymmetry

Cocuzza, Melnitchouk, Metz, Sato (PRD)









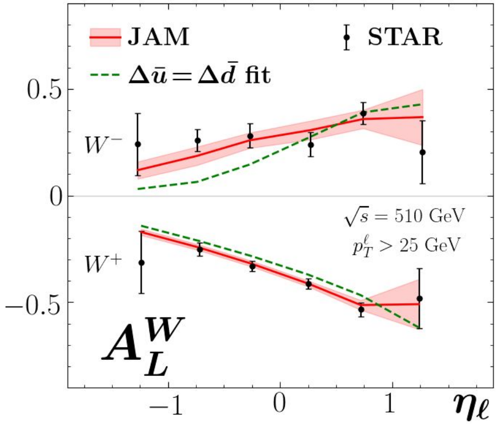
$$(\bar{d} - \bar{u})(x) = \left[\left(f_{n\pi^+} + f_{\Delta^0\pi^+} - f_{\Delta^{++}\pi^-}\right) \otimes \bar{q}_v^\pi\right](x),$$

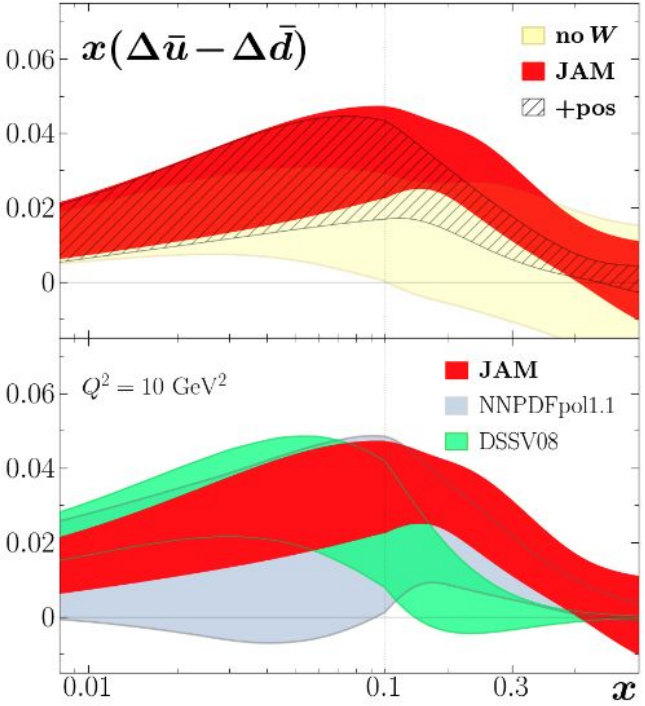
- First global analysis to include latest SeaQuest and STAR data
- Most precise phenomenological extraction of *dbar-ubar* asymmetry to date
- Quantitative test of the pion-cloud model

Polarized antimatter asymmetry

Cocuzza, Melnitchouk, Metz, Sato (PRD)

process	N_{dat}	χ^2/N_{dat}
polarized		
inclusive DIS	365	0.93
inclusive jets	83	0.81
SIDIS (π^+, π^-)	64	0.93
SIDIS (K^+, K^-)	57	0.36
STAR $W^\pm$	12	0.53
PHENIX $W^\pm/Z$	6	0.63
total	**587**	**0.85**
unpolarized		
inclusive DIS	3908	1.11
inclusive jets	198	1.11
Drell-Yan	205	1.19
W/Z production	153	0.99
total	**4464**	**1.11**
SIA $(\pi^\pm)$	231	0.85
SIA $(K^\pm)$	213	0.49
total	**5495**	**1.05**





- First simultaneous extraction of unpolarized and helicity PDFs and FFs in global analysis with inclusion of RHIC spin *W*+/- data

- Most precise phenomenological extraction of polarized *dbar-ubar* asymmetry to date

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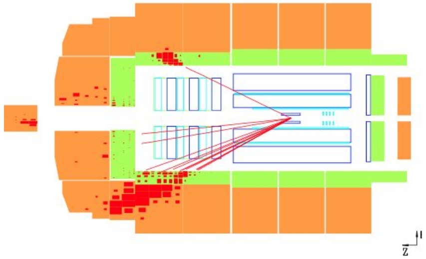
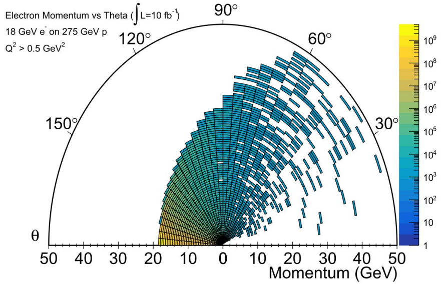
Existing paradigm -> histogram approach

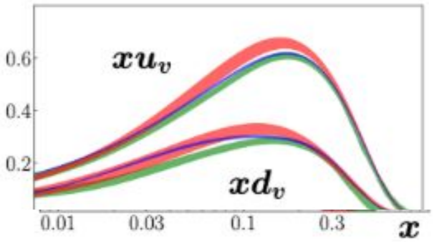
Inverse problem

Inverse problem

Detector level events → Detector level histograms → Unfolded histograms → Deconvolution “femtography”

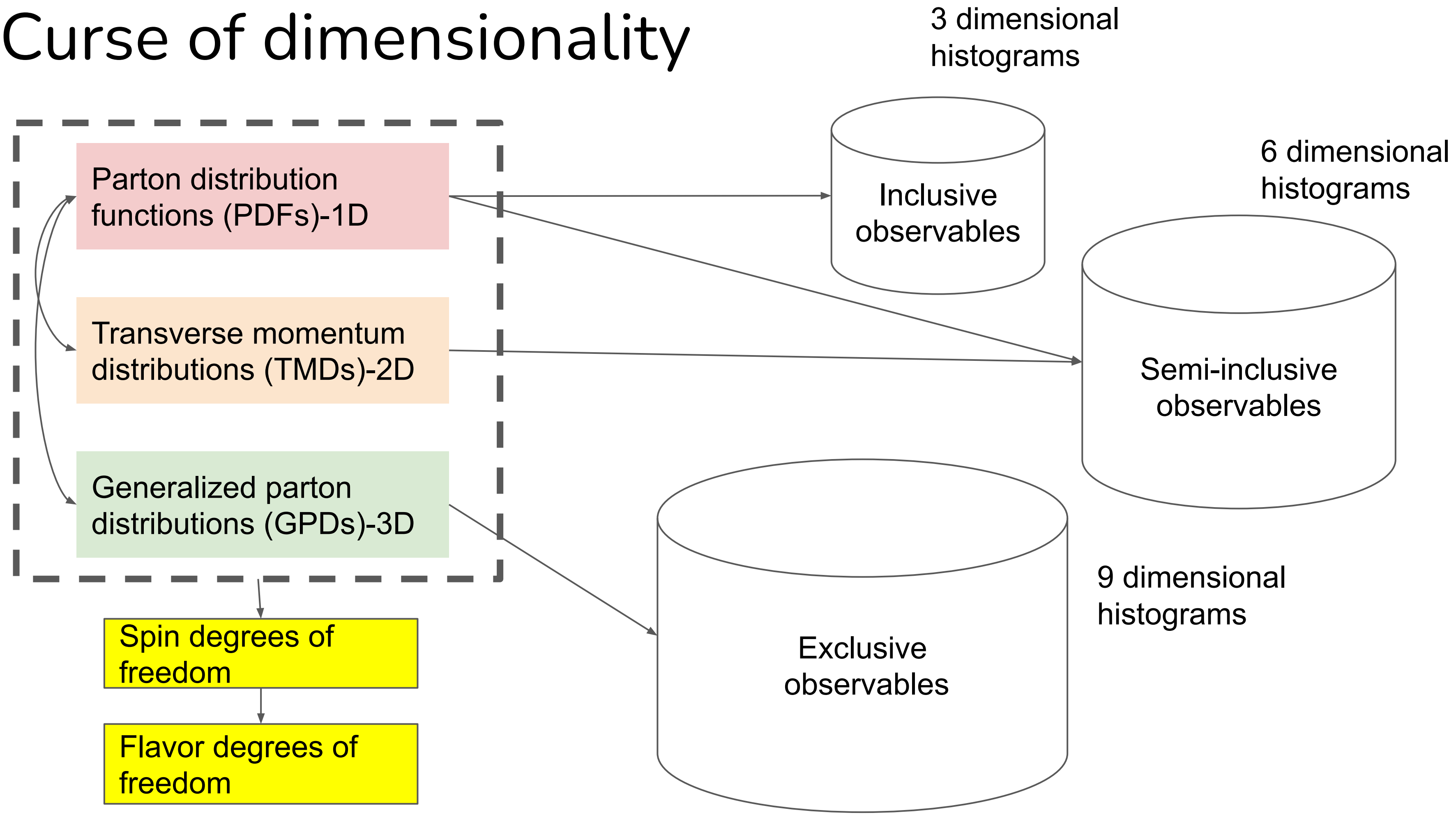






1D QCFs

Curse of dimensionality

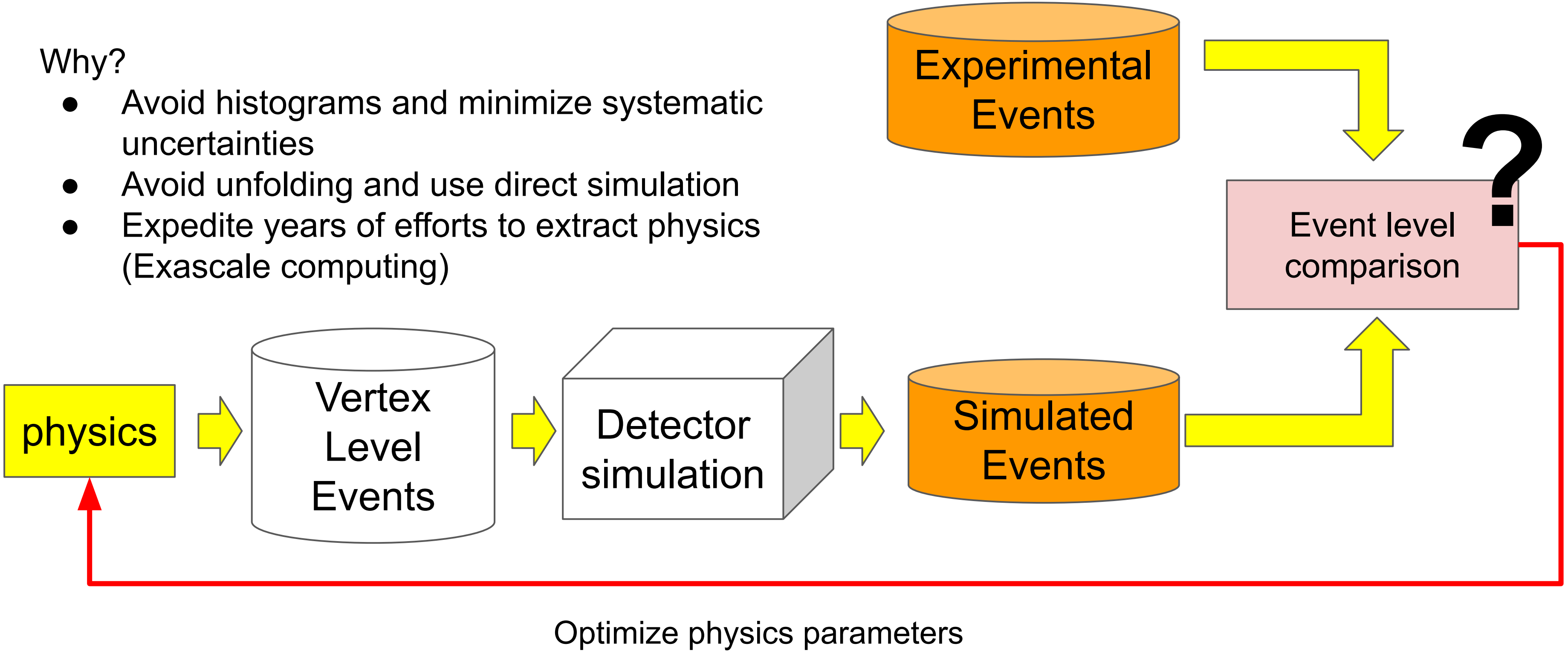


Event-based analysis for global analysis?

Can we compare real vs synthetic events?

Why?

- Avoid histograms and minimize systematic uncertainties
- Avoid unfolding and use direct simulation
- Expedite years of efforts to extract physics (Exascale computing)



QuantOm Collaboration

Jefferson Lab

Argonne NATIONAL LABORATORY

OLD DOMINION UNIVERSITY

Theory

- Jianwei Qiu (PI)
- NS
- Adam Freez (postdoc)

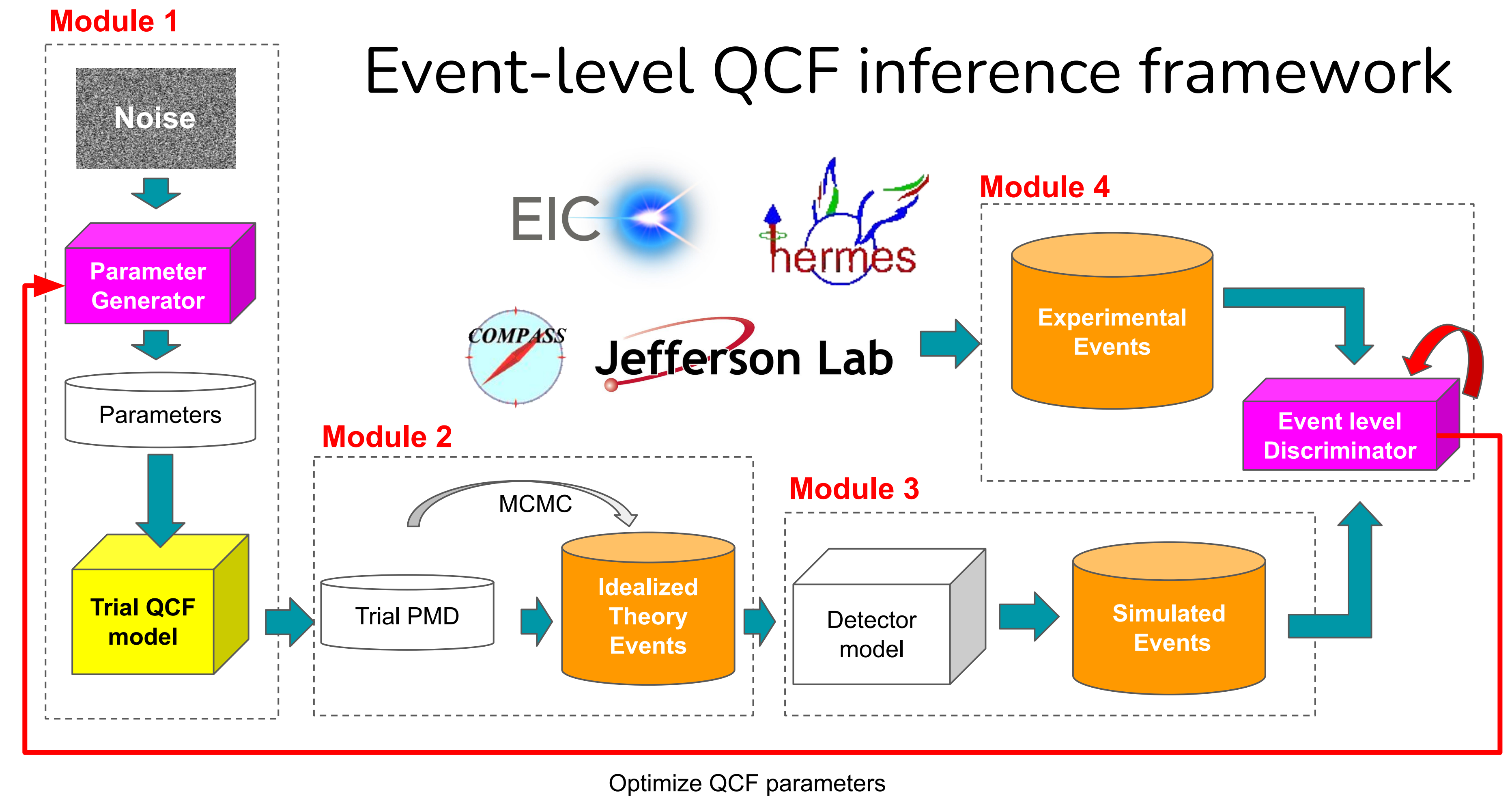
Experiment

- Markus Diefenthaler
- Daniel Lersch

CS

- Malachi Schram
- Kishan Rajput
- Daniel Lersch
- Yasir Alanazi (postdoc)

Supported by DOE SciDAC

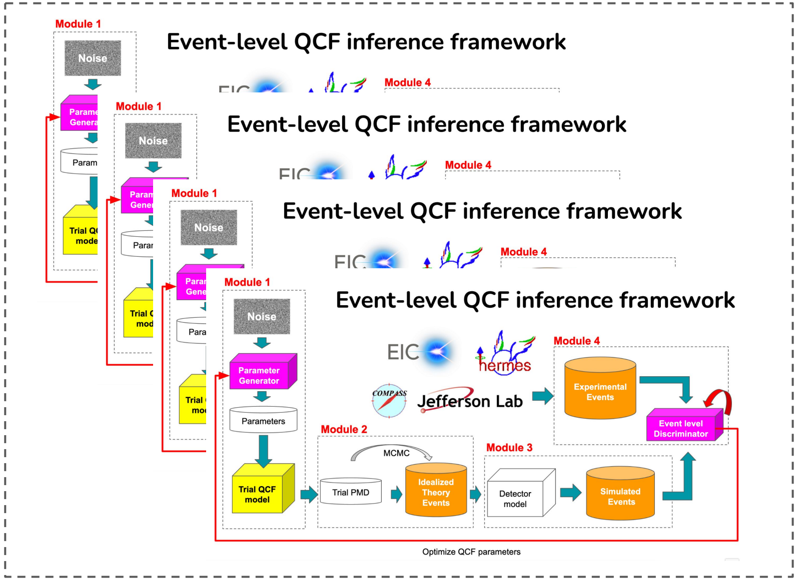

Event-level QCF inference framework
Module 1
Noise
Parameter Generator
Parameters
Trial QCF model
Module 2
MCMC
Trial PMD
Idealized Theory Events
Module 3
Detector model
Simulated Events
Module 4
Experimental Events
Event level Discriminator
EIC
hermes
COMPASS
Jefferson Lab
Optimize QCF parameters

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



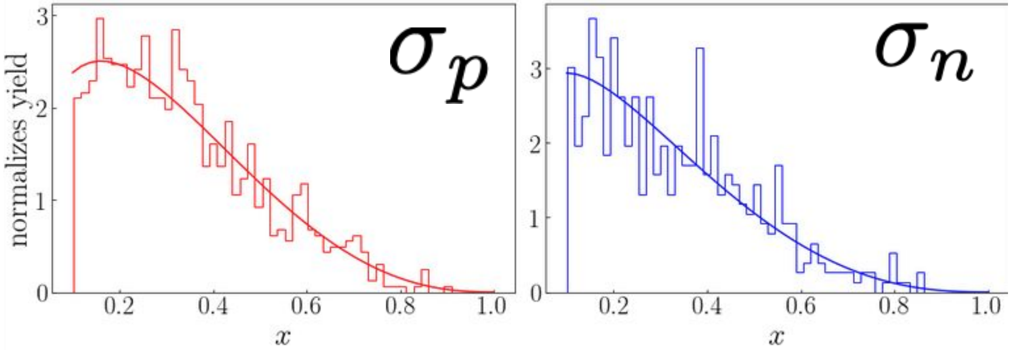
An example with a proxi theory

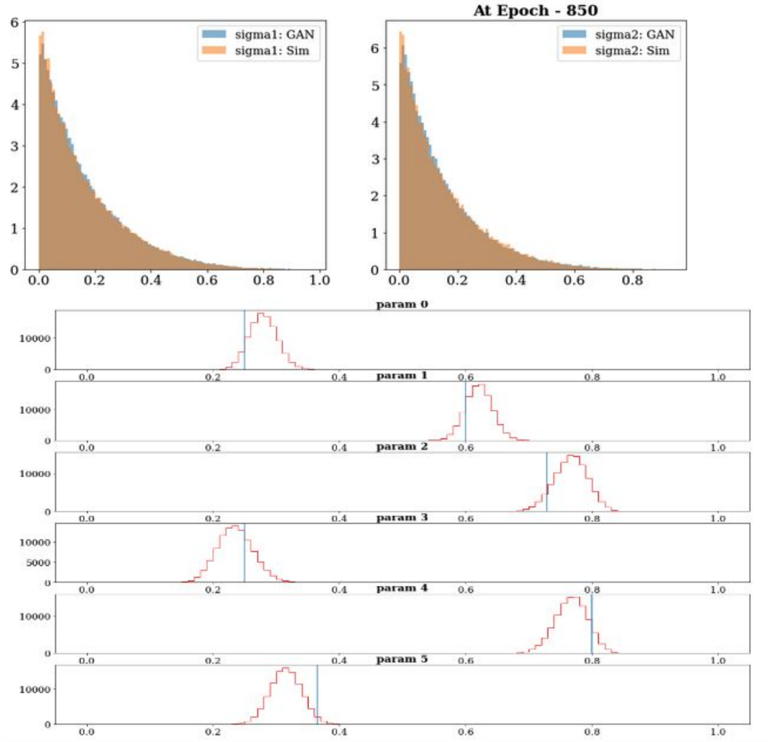
$$u(x) = N_u x^{a_u}(1-x)^{b_u}$$
$$d(x) = N_d x^{a_d}(1-x)^{b_d}$$

6 parameter QCFs model

$$\sigma_p(x) = 4\,u(x) + d(x),$$
$$\sigma_n(x) = 4\,d(x) + u(x).$$

Proxi cross sections





Workflow can produce parameter samples close to the truth

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