Exploring the inner structure of the nucleon using QCD factorization theorems

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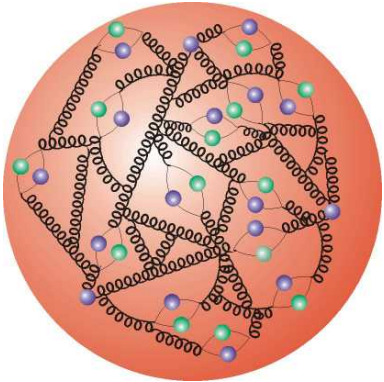
ODU/JLab

Seminar at TNT
Raleigh, 2018

How can we probe the inner structure of nucleons?



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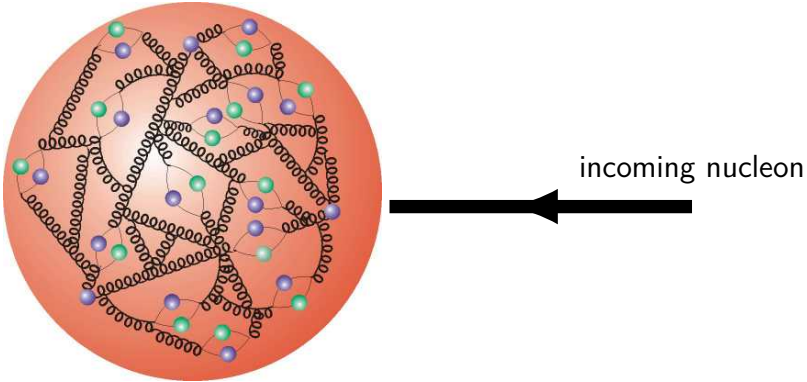

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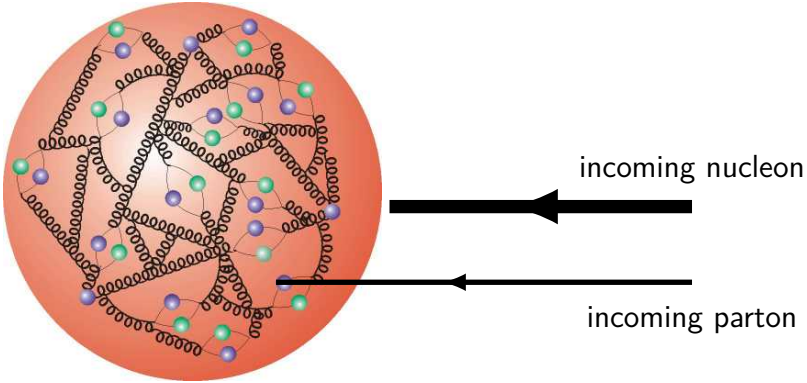

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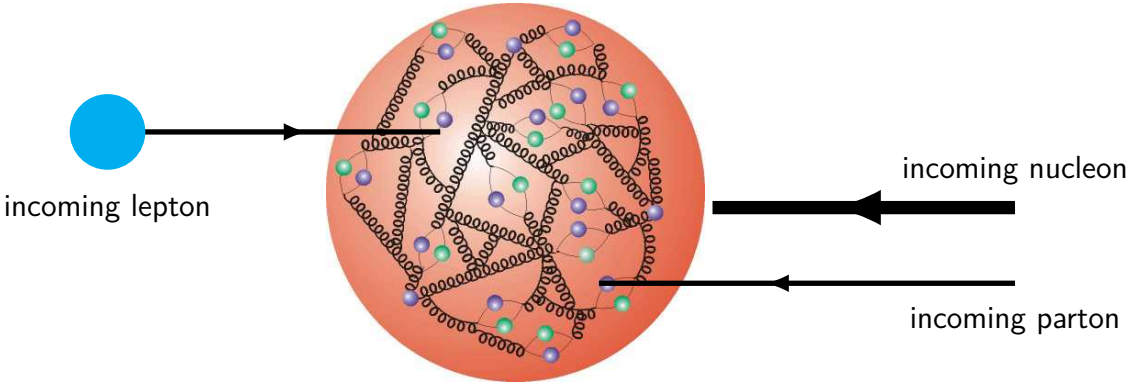

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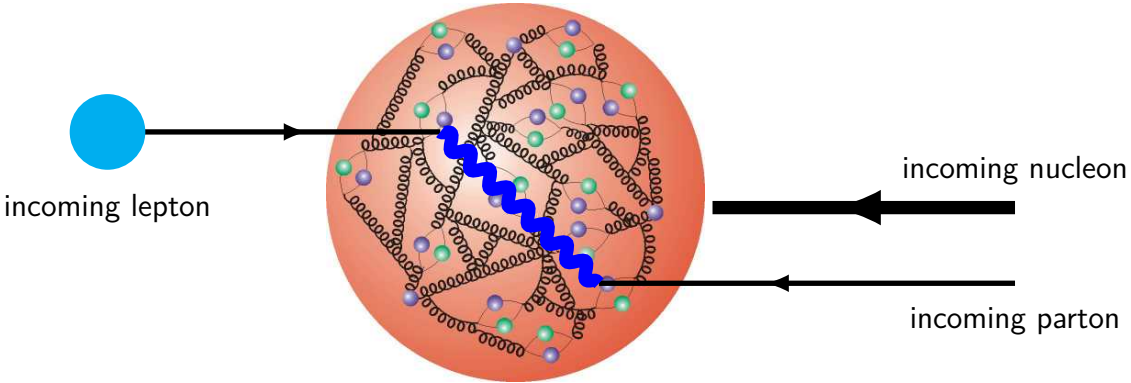

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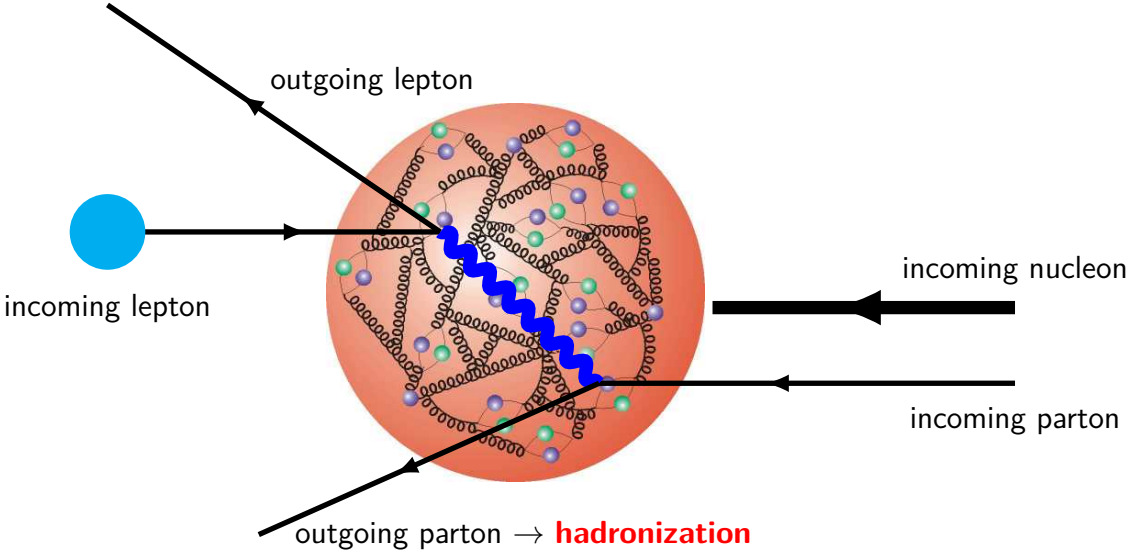
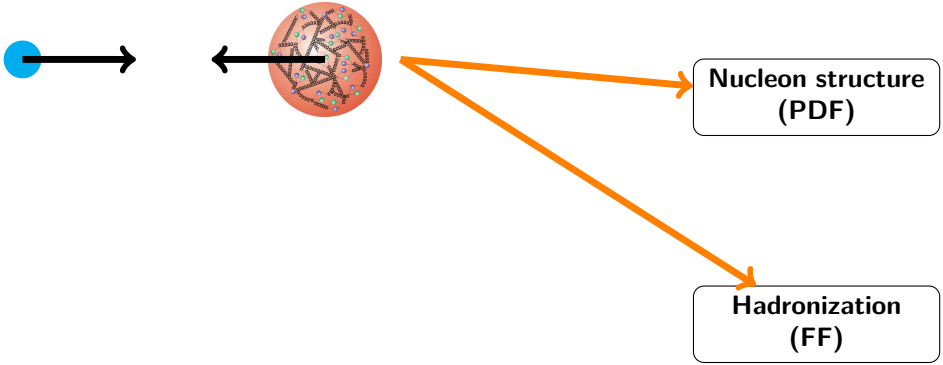


Nucleon structure and hadronization



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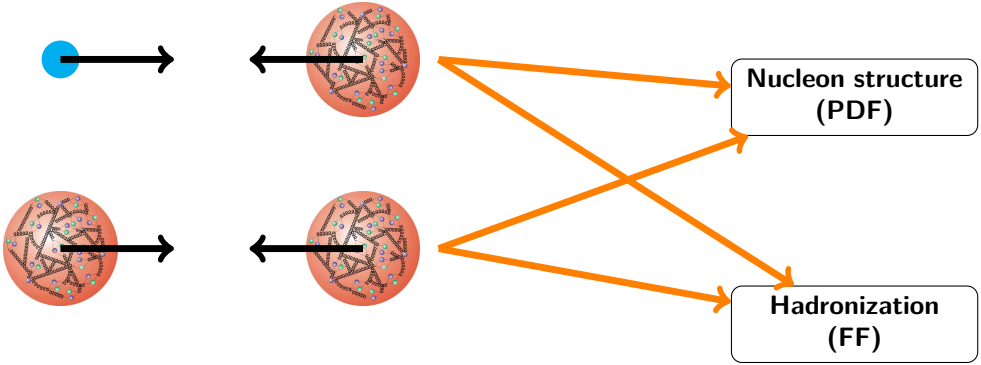

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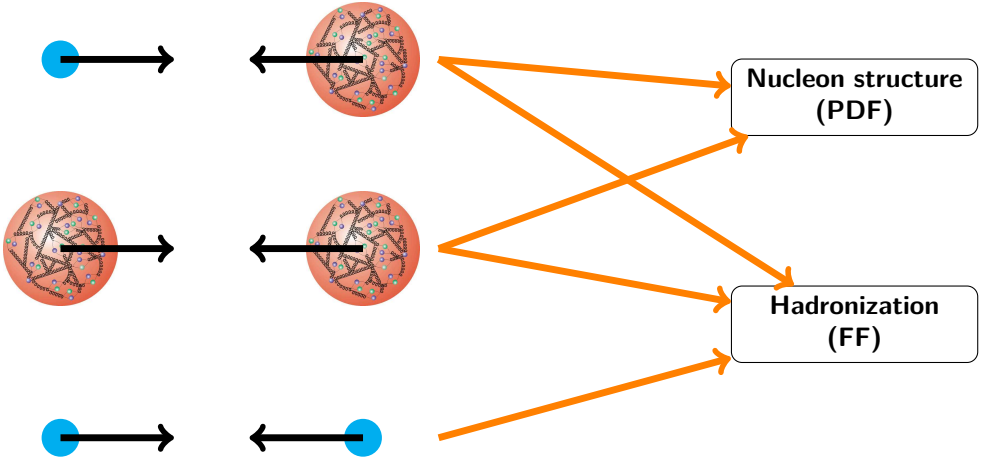

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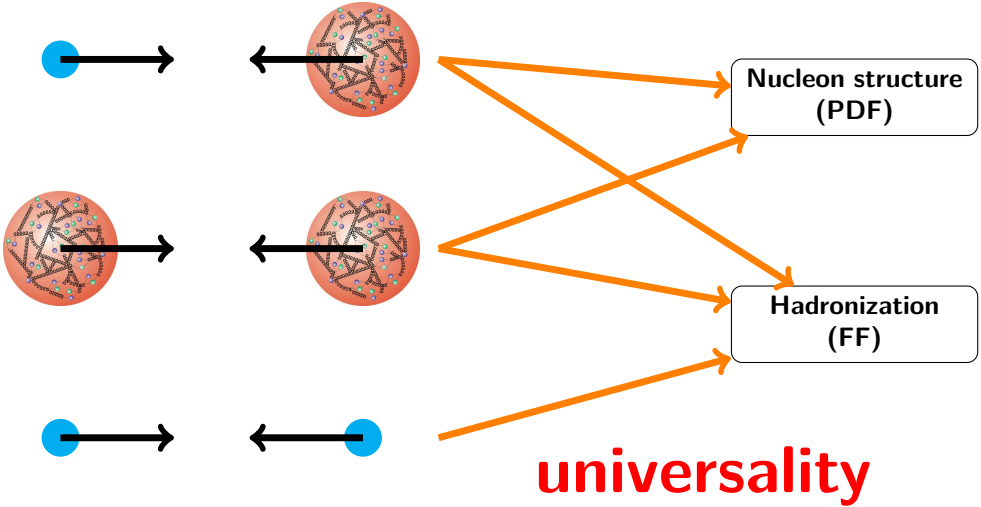

Link between experiment and theory frameworks

Experiment

$$\boxed{\mathcal{L}^{-1}\ \frac{dN}{d\Omega} = \frac{d\sigma}{d\Omega}}$$

Link between experiment and theory frameworks

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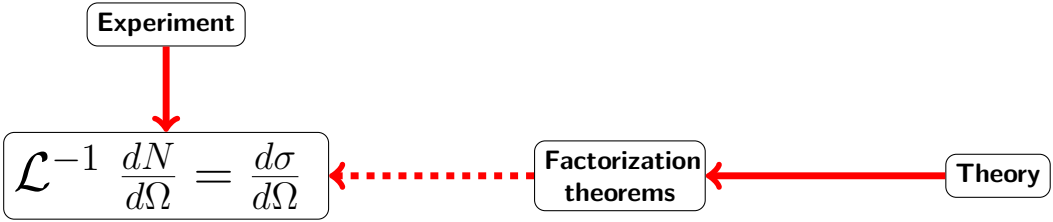
$$\mathcal{L}^{-1}\,\frac{dN}{d\Omega} = \frac{d\sigma}{d\Omega}$$

Theory

Link between experiment and theory frameworks



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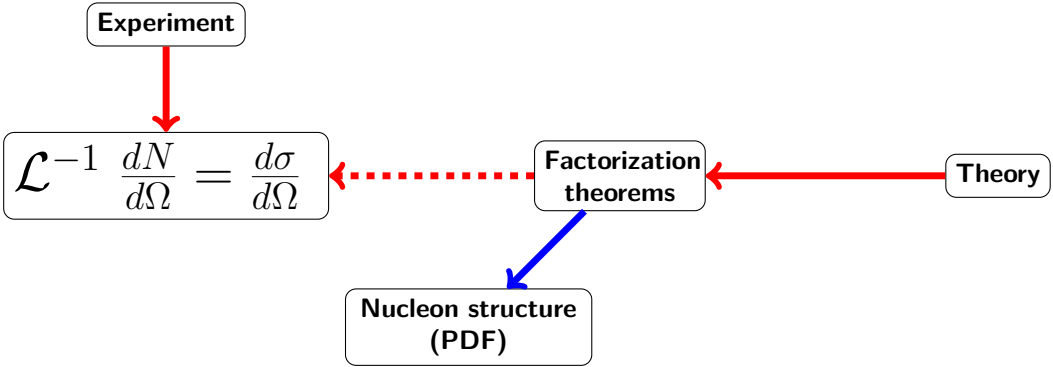

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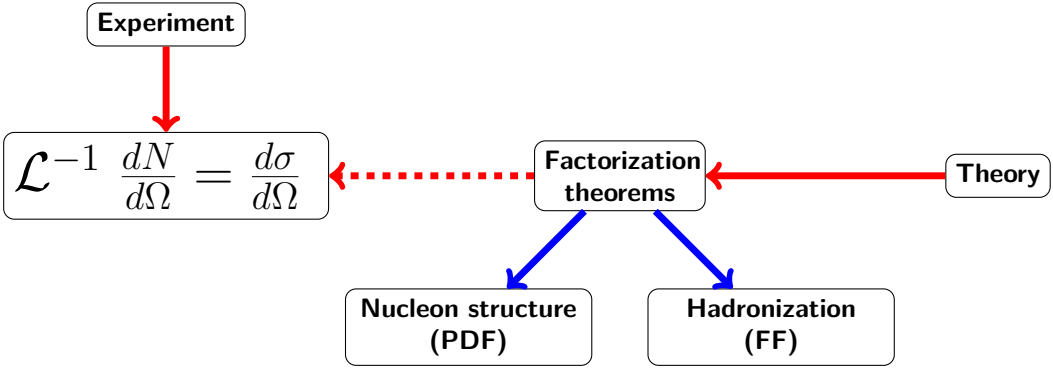

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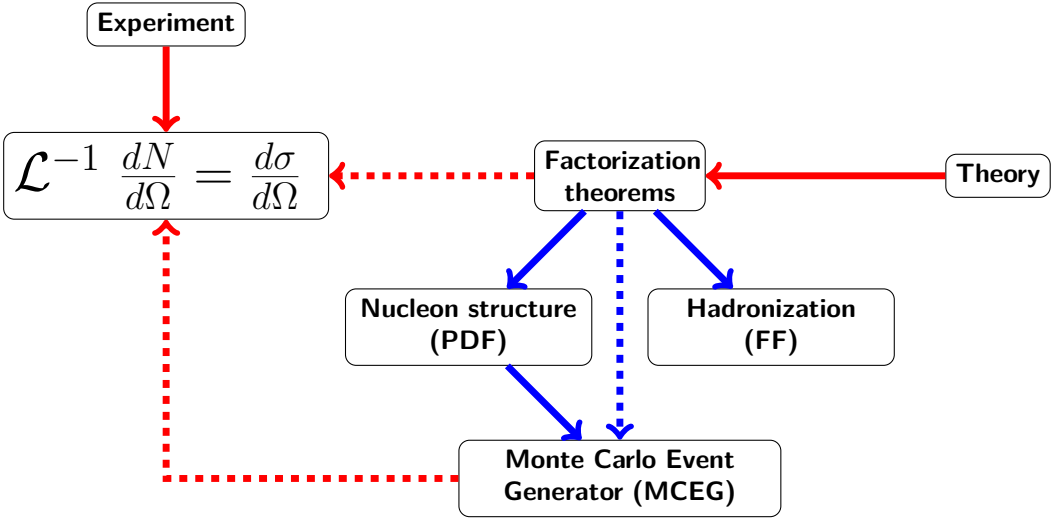

Building up theoretical cross section for lN reaction

$$d\sigma = \frac{1}{\text{flux}} \mid \Psi \mid^2 d\Omega$$

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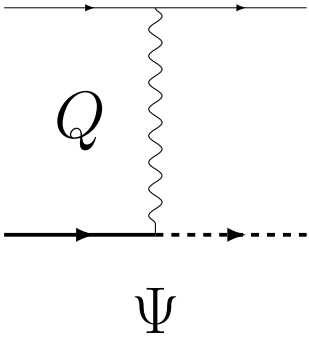
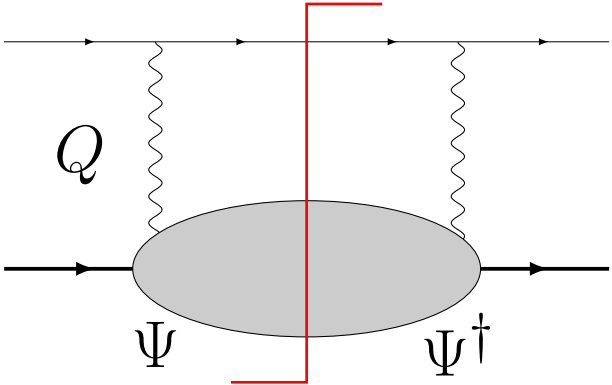


Building up theoretical cross section for lN reaction

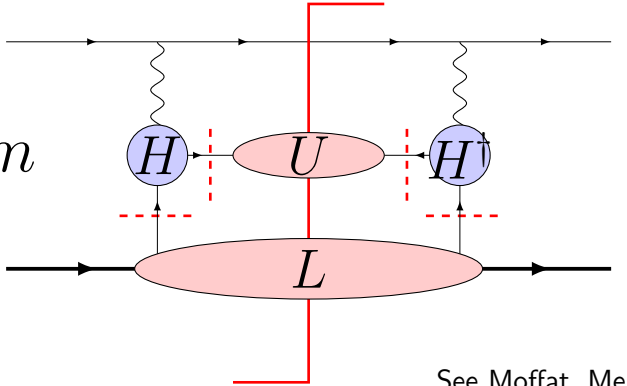
$$d\sigma = \frac{1}{\text{flux}} \mid \Psi \mid^2 d\Omega$$



Factorization in inclusive DIS

$$d\sigma \sim \underbrace{|\,H\,|^2}_{\text{Hard}} \underbrace{\int dk^- dk^\perp L(xP^+, k^-, k^\perp)}_{\text{Parton densities}} \underbrace{\int dl^+ U(l^+)}_{\text{Jet function}} d\Omega + O(m^2/Q^2)$$

$$Q \gg m$$

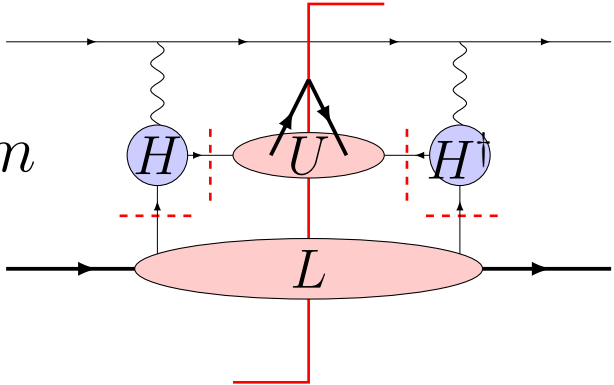


See Moffat, Melnitchouk, Rogers and NS

Factorization in semi-inclusive DIS

$$d\sigma \sim \underbrace{|\,H\,|^2}_{\text{Hard}} \underbrace{\int dk^- dk^\perp L(xP^+, k^-, k^\perp)}_{\text{Parton densities}} \underbrace{\int dk_h^+ dk_h^\perp U(k_h^+, zP_h^-, k_h^\perp)}_{\text{Fragmentation function}} d\Omega + O(m^2/Q^2)$$

$$Q \gg m$$



Extend the formalism to hadron-hadron reactions

$$d\sigma \sim \underbrace{|\ H\ |^2}_{\text{Hard}} \underbrace{\int dk^- dk^\perp L(x_a P_A^+, k^-, k^\perp)}_{\text{Parton densities}} \underbrace{\int dl^- dl^\perp U(x_b P_B^+, l^-, l^\perp)}_{\text{Parton densities}} d\Omega + O(m^2/Q^2)$$

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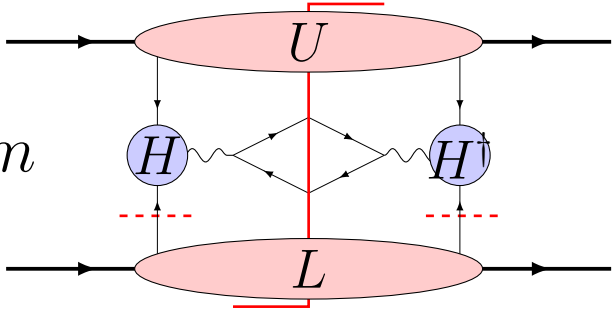
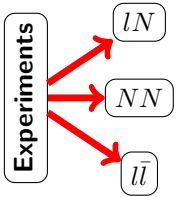


Examples of nucleon distributions

- **Colliner densities**
  - ξ : Light-cone momentum fraction
  - $f_q(\xi) = \overrightarrow{q}(\xi) + \overleftarrow{q}(\xi)$
  - $\Delta f_q(\xi) = \overrightarrow{q}(\xi) - \overleftarrow{q}(\xi)$
  - $h_{1q}(\xi) = q^{\uparrow}(\xi) - q^{\downarrow}(\xi)$
- **Transverse momentum distributions**
  - ξ : Light-cone momentum fraction
  - $k_\perp$: intrinsic transverse momentum
  - $f_q(\xi, k_\perp) = \overrightarrow{q}(\xi, k_\perp) + \overleftarrow{q}(\xi, k_\perp)$
  - $\Delta f_q(\xi, k_\perp) = \overrightarrow{q}(\xi, k_\perp) - \overleftarrow{q}(\xi, k_\perp)$
  - $h_{1q}(\xi, k_\perp) = q^{\uparrow}(\xi, k_\perp) - q^{\downarrow}(\xi, k_\perp)$
- **Myths in QCD**
  - $f_q(\xi) = \int d^2k_\perp f_q(\xi, k_\perp)$ ✗
  - μ dependence in $f_q(\xi, \mu) \rightarrow$ renormalization of collinear singularities ✗

Global analysis in a nutshell



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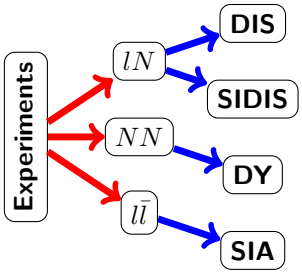

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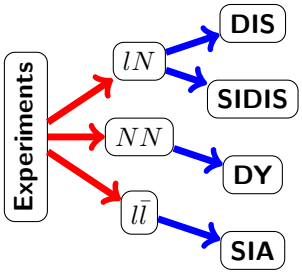

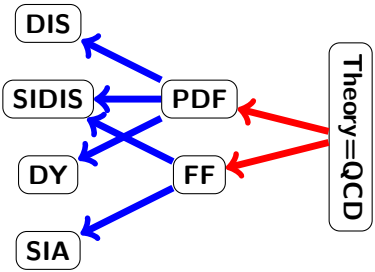

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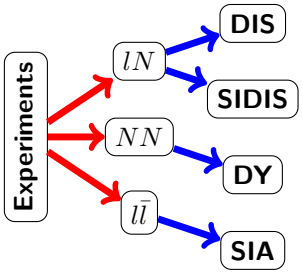

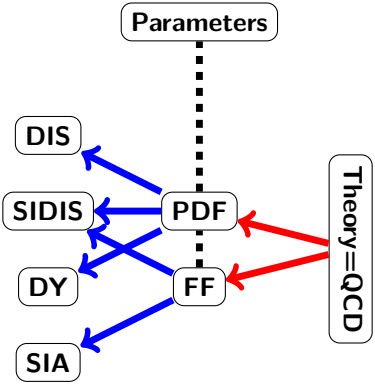

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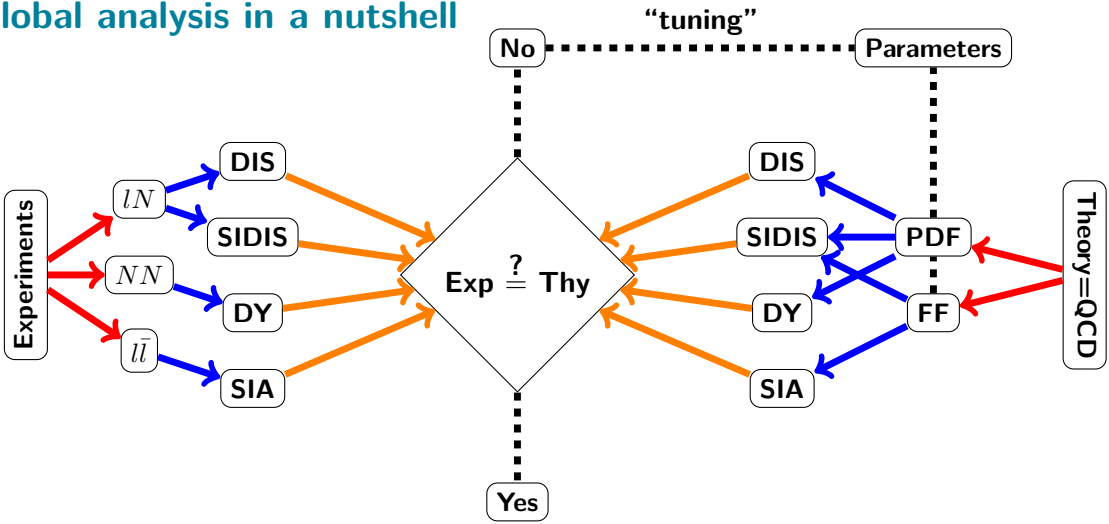

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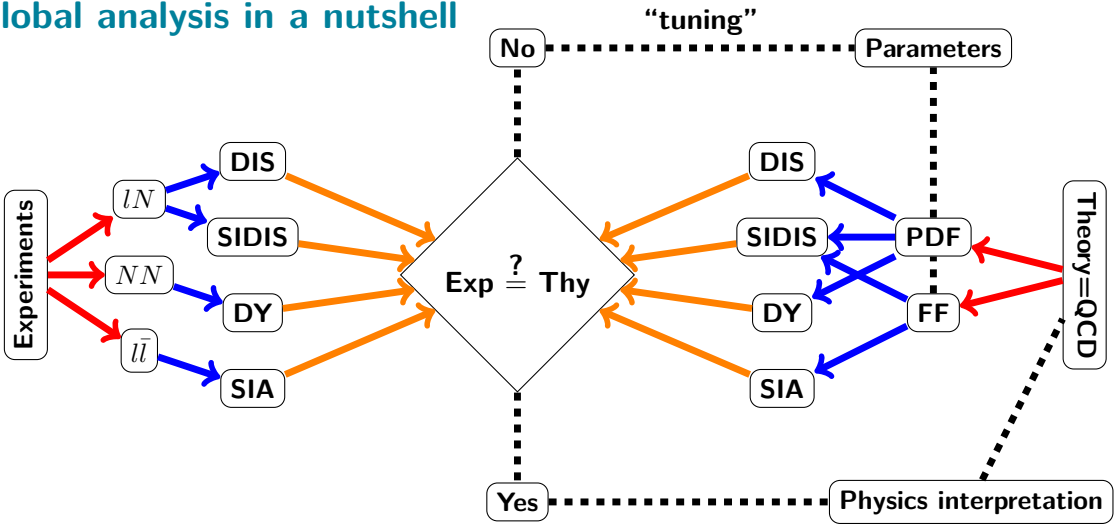

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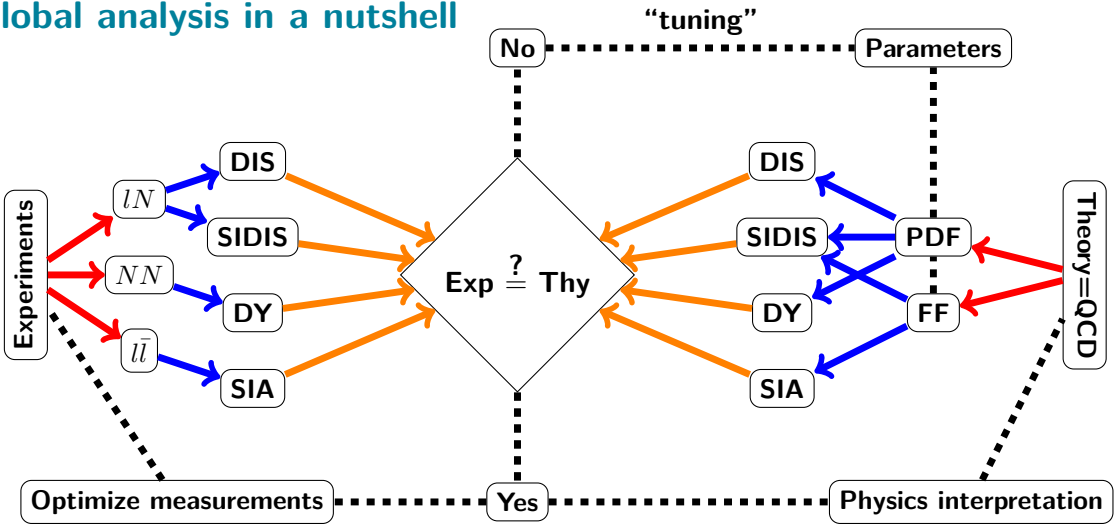
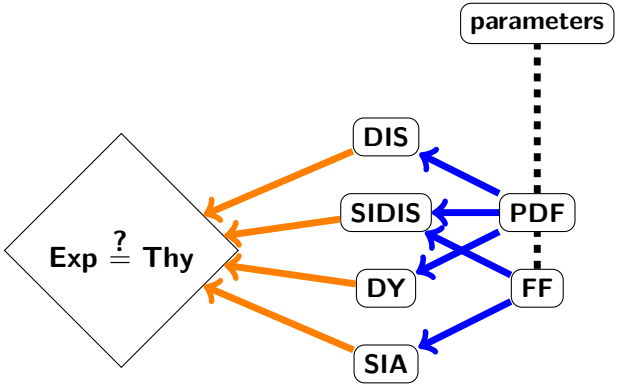
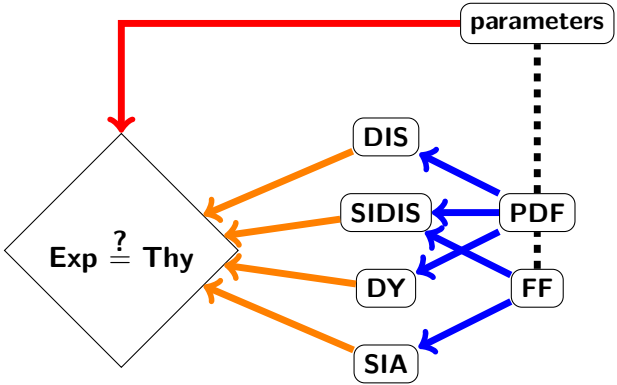


Metrics (Collinear PDFs and FFs)



Metrics (Collinear PDFs and FFs)

~ 40 **CPU secs**



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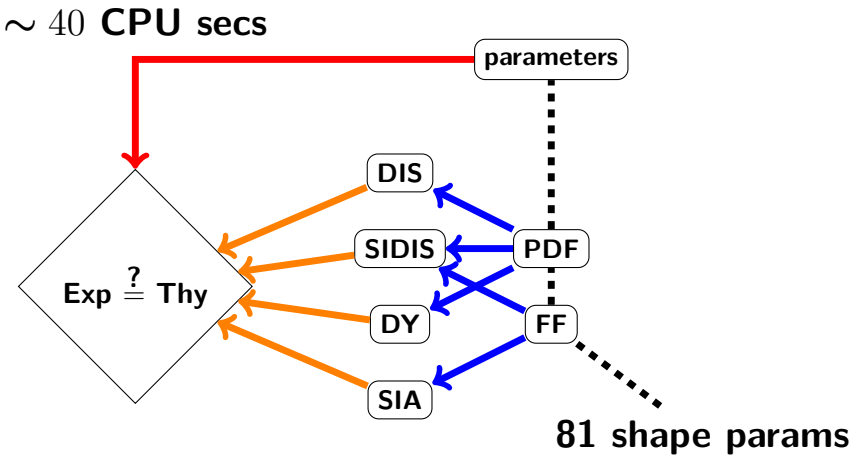

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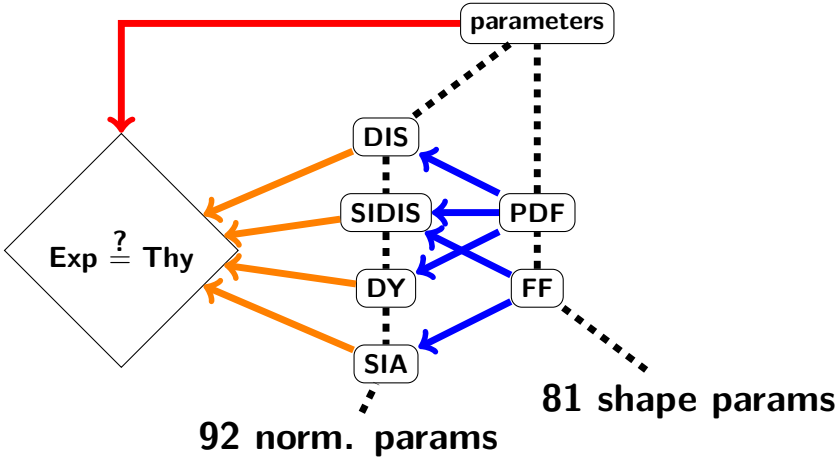

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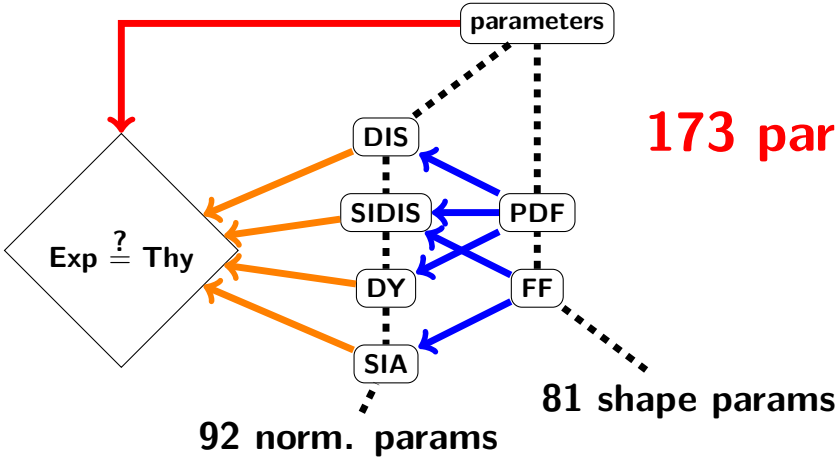
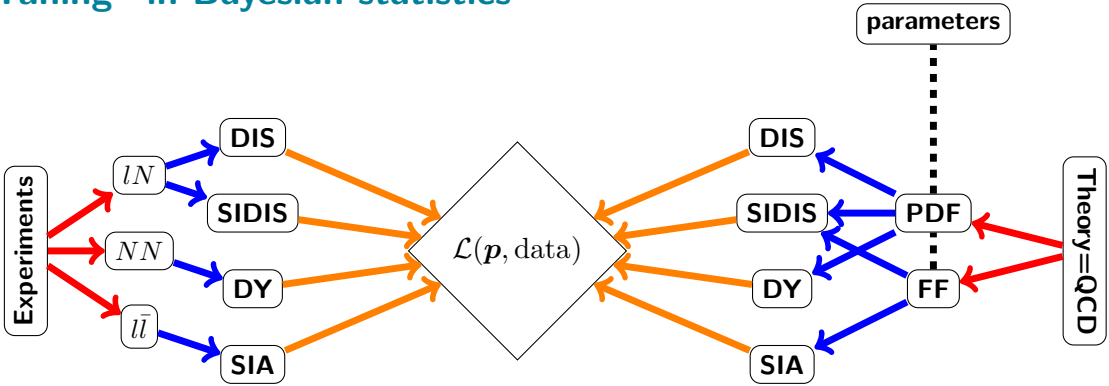


173 parameters

“Tuning” in Bayesian statistics



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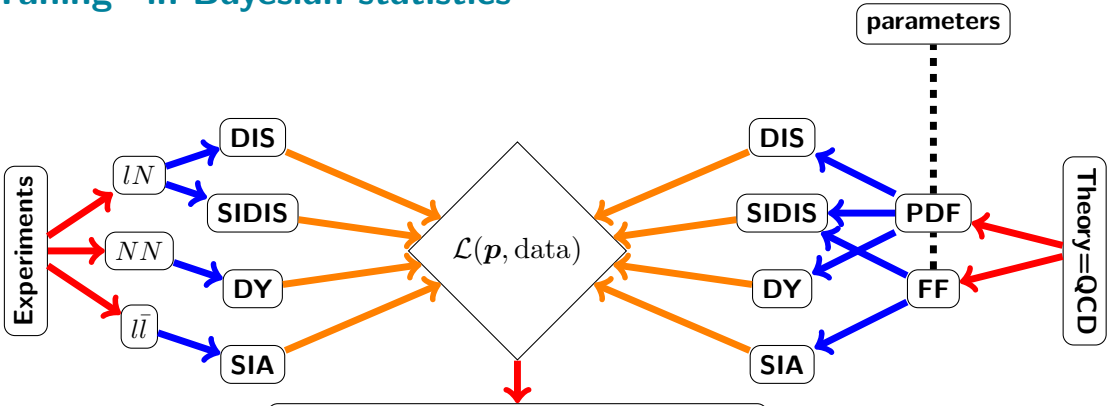

$$\mathcal{P}(\boldsymbol{p} \mid \text{data}) = \mathcal{L}(\boldsymbol{p}, \text{data})\pi(\boldsymbol{p})$$

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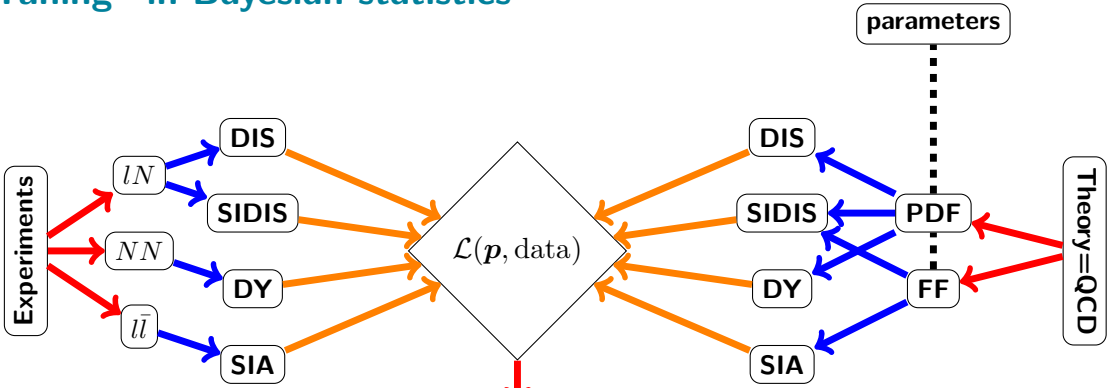


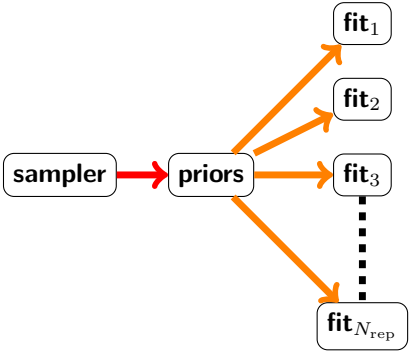
$$\mathcal{P}(\boldsymbol{p} \mid \text{data}) = \mathcal{L}(\boldsymbol{p}, \text{data})\pi(\boldsymbol{p})$$

$\{\boldsymbol{p}\}$: MC samples

Iterative Monte Carlo approach

sampler → **priors**

Iterative Monte Carlo approach



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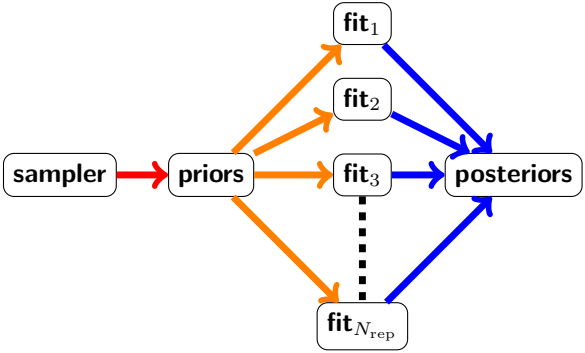

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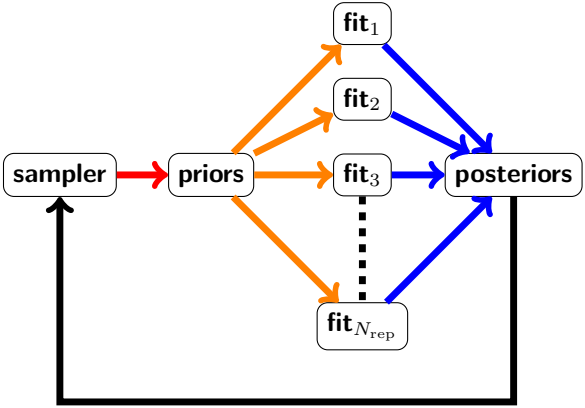
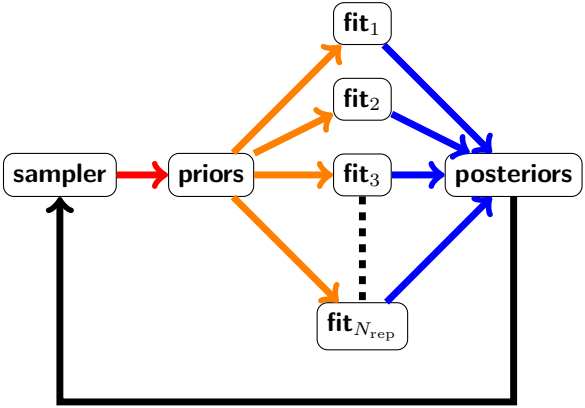


repeat $N_{\rm iter}$ until convergence

Iterative Monte Carlo approach

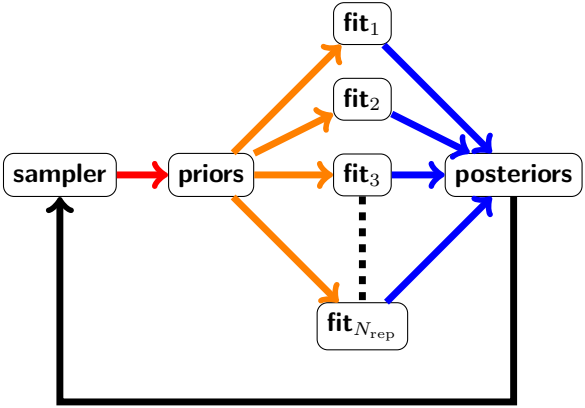


repeat $N_{\rm iter}$ until convergence

Collinear PDF and FFs

- $N_{\rm params} = 173 \rightarrow N_{\rm steps} = 30k$
- $\tau_{\rm cpu/step} \sim 40$ secs
- $N_{\rm samples} = N_{\rm steps} \times N_{\rm rep} \times N_{\rm iter}$
  $= 30k \times 1k \times 20$
- $\tau_{\rm total} \sim 7,000,000$ hours/trial

Iterative Monte Carlo approach



repeat $N_{\rm iter}$ until convergence

TMD PDF and FFs

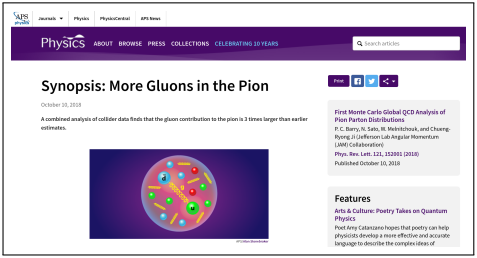
- $N_{\rm params} = 173 \rightarrow N_{\rm steps} = 30k$
- $\tau_{\rm cpu/step} \sim 10$ mins
- $N_{\rm samples} = N_{\rm steps} \times N_{\rm rep} \times N_{\rm iter}$
  $= 30k \times 1k \times 20$
- $\tau_{\rm total} \sim 100,000,000$ hours/trial

JAM highlights

- Barry, NS, Melnitchouk, Ji
  Phys. Rev. Lett. **121**, 1525001 (2018)

- Lin, Melnitchouk, Prokudin, NS, Shows
  Phys. Rev. Lett. **120**, 152502 (2018)

- Ethier, NS and Melnitchouk
  Phys. Rev. Lett. **119**, 132001 (2017)



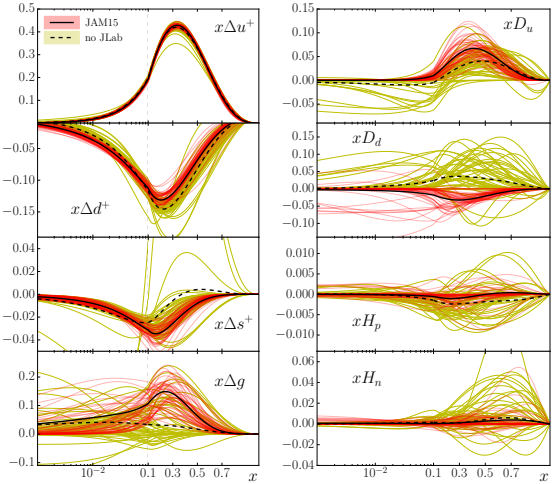
featured in APS

- NS, Ethier, Hirai, Kumano, Melnitchouk, Accardi
  Phys. Rev. D **94**, 114004 (2016)

- NS, Melnitchouk, Kuhn, Ethier, Accardi
  Phys. Rev. D **93**, 074005 (2016)

JAM15: ΔPDFs

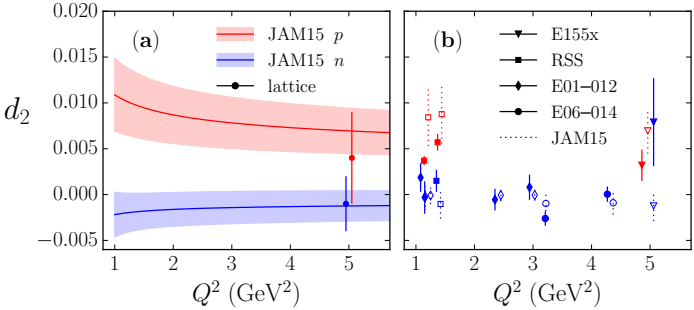
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



- Inclusion of all JLab 6 GeV data $\rightarrow$ $0.1 < x < 0.7$
- Non vanishing twist 3 quark distributions
- Residual twist 4 contributions consistent with zero

JAM15: d_2 matrix element

NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)

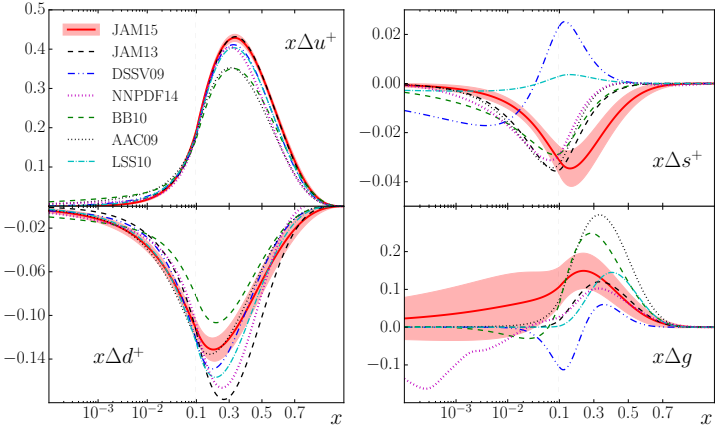


- Existing measurements of d_2 are in the resonance region $\rightarrow$ **quark-hadron duality**

$$d_2(Q^2) \equiv \int_0^1 dx x^2 \left[2g_1^{\tau 3}(x,Q^2) + 3g_2^{\tau 3}(x,Q^2)\right]$$

JAM15: ΔPDFs

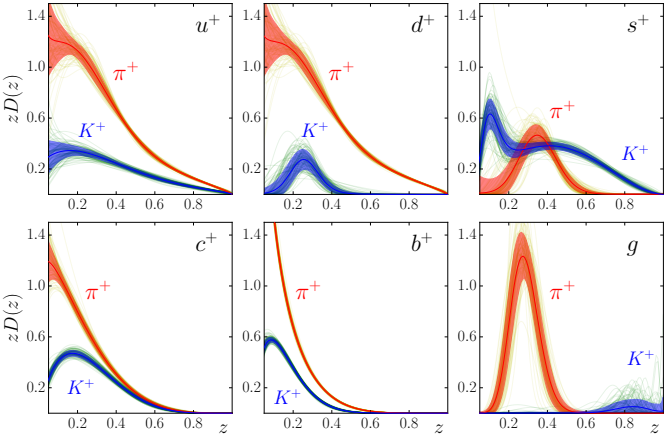
NS, Melnitchouk, Kuhn, Ethier, Accardi (PRD)



- SU2, SU3 constraints imposed
- **What determines the sign of Δs^+?**

JAM16: FFs

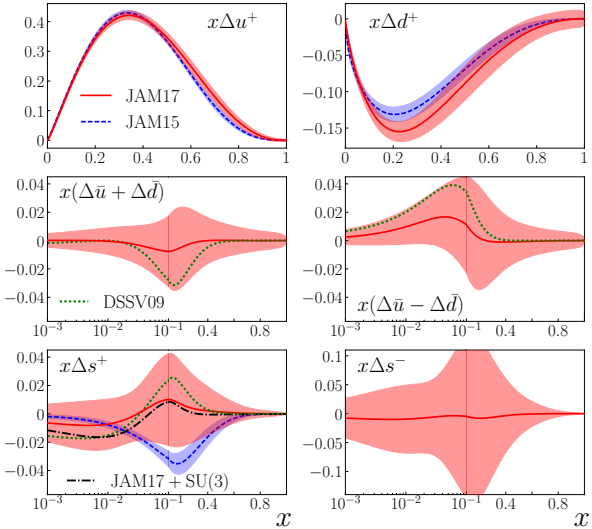
NS, Ethier, Melnitchouk, Hirai, Kumano, Accardi (PRD)



- π and K Belle, BaBar up to LEP energies
- JAM and DSS $D_{s^+}^K$ **consistent**

JAM17: ΔPDF +FF

Ethier, NS, Melnitchouk (PRL)

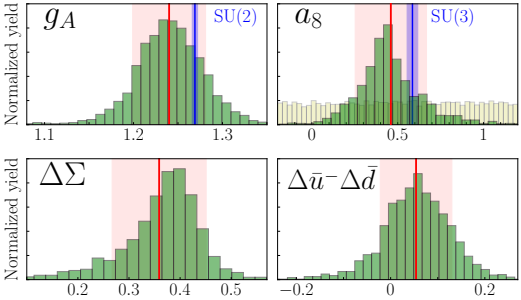


- No SU(3) constraints
- Sea polarization consistent with zero
- Precision of ΔSIDIS is not sufficient to determine sea polarization

JAM17: ΔPDF +FF

Ethier, NS, Melnitchouk (PRL)

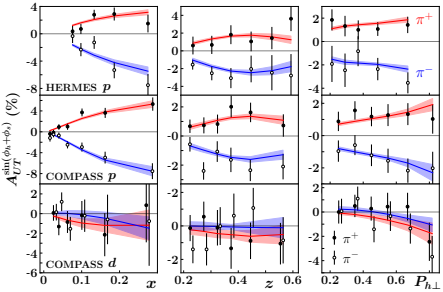
- **Flat priors** that gives flat a_8 in order to have an unbias extraction of a_8
- Data prefers smaller values for $a_8 \to 25\%$ larger total spin carried by quarks.
- a_3 which is in a good agreement with values from β decays **within** 2%.

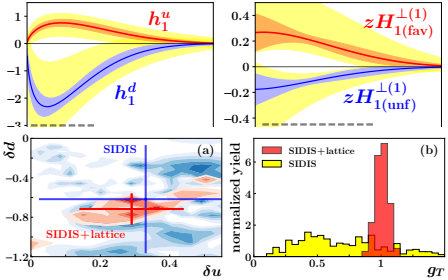


obs.	JAM15	JAM17
g_A	$1.269(3)$	$1.24(4)$
g_8	$0.586(31)$	$0.46(21)$
$\Delta\Sigma$	$0.28(4)$	$0.36(9)$
$\Delta\bar{u}-\Delta\bar{d}$	0	0.05(8)

SIDIS+Lattice analysis of nucleon tensor charge

Lin, Melnitchouk, Prokudin, NS, Shows (PRL)

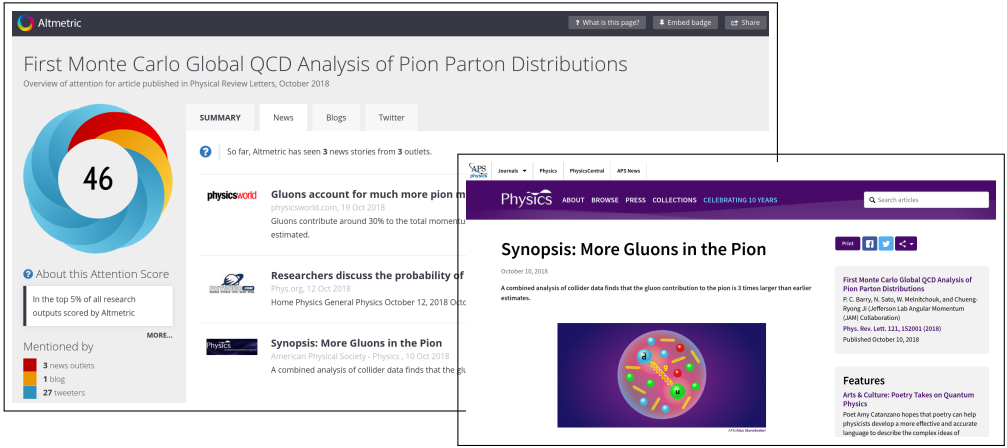




- Extraction of transversity and Collins FFs from SIDIS A_{UT}+Lattice g_T
- In the absence of Lattice, SIDIS has no significant constraints on g_T

First global Monte Carlo analysis of pion PDFs

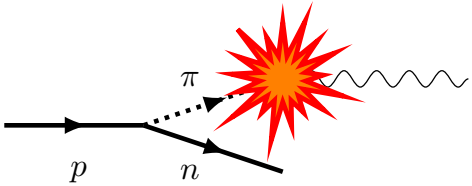
Barry, NS, Melnitchouk, Ji (PRL)



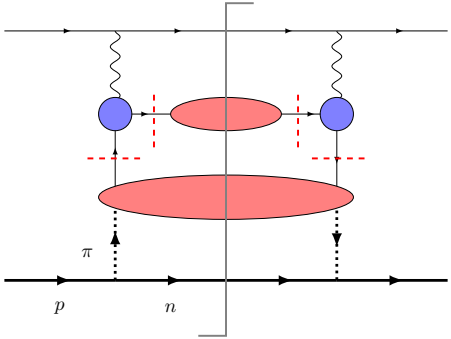
First global Monte Carlo analysis of pion PDFs

Barry, NS, Melnitchouk, Ji (PRL)

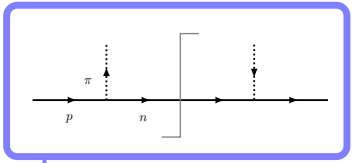
- **How to probe pion structure**
  - $+$ $\pi + A \to l\bar{l} + X$ **(Drell-Yan)**
  - $+$ $\pi + A \to \gamma + X$ (prompt photons)
  - $+$ $e + p \to e' + n + X$ **(SIDIS)** $\to$ small x_π gluon PDF



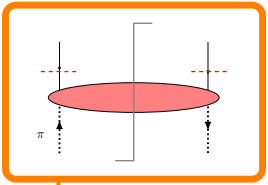
First global Monte Carlo analysis of pion PDFs



χEFT

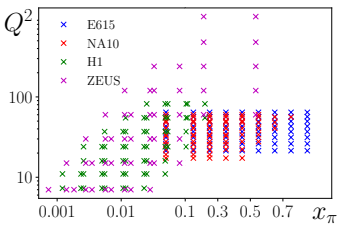


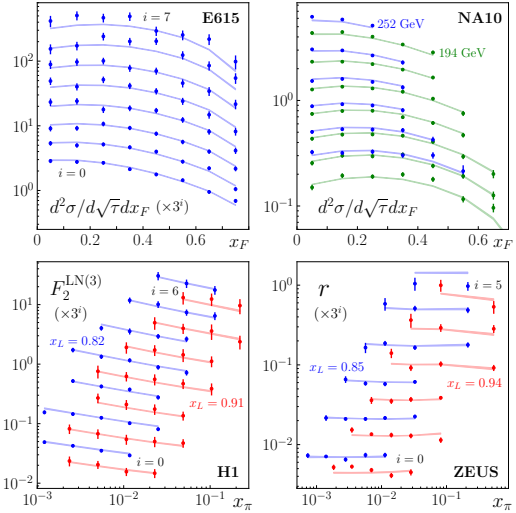
pQCD



$$\frac{d\sigma}{dx dQ^2 dy} \sim f_{p\to\pi+n}(y) \times \sum_q \int_{x/y}^{1} \frac{d\xi}{\xi} C(\xi)\, q\left(\frac{x/y}{\xi}, Q^2\right)$$

First global Monte Carlo analysis of pion PDFs



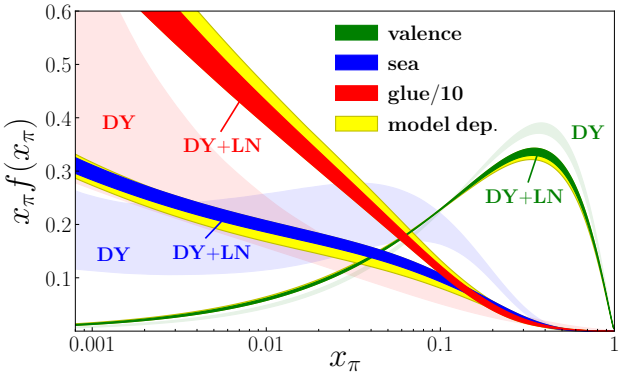


- Our new analysis extends previous pion PDF analysis down to $x \sim 0.001$
- The OPE+pQCD can describe the HERA data **simultaneously** with the DY data

$$F_2^{LN(3)}(x, Q^2, y) = 2 f_{p\to\pi+n}(y) F_2^{\pi}(x_\pi, Q^2)$$

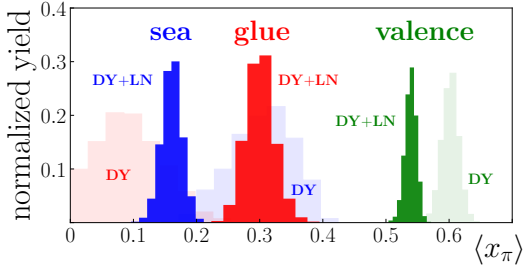
$$r(x, Q^2, y) = \frac{d^3\sigma^{LN}/dxdQ^2dy}{d^2\sigma^{inc}/dxdQ^2}\Delta y$$

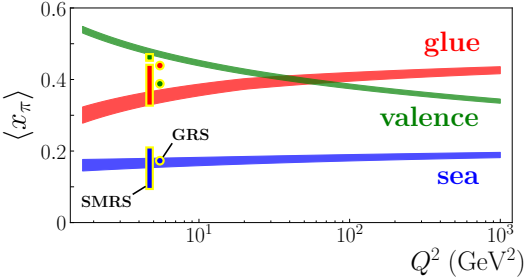
First global Monte Carlo analysis of pion PDFs



- Significant reduction of the uncertainties
- Non-overlapping uncertainties $\rightarrow$ tensions among the data
- Accuracy will be improved with future TDIS (JLab12/EIC)

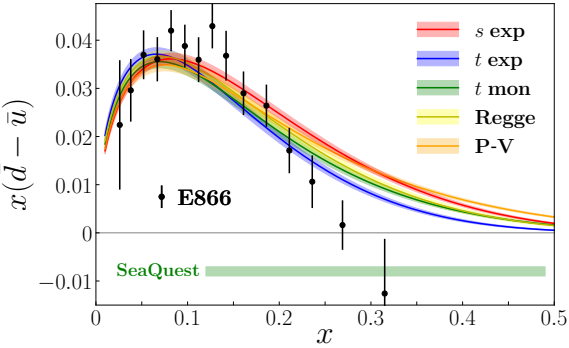
First global Monte Carlo analysis of pion PDFs





- Constraints from HERA significantly increase $\langle x_\pi^g \rangle$.
  The role of the glue is more important than suggested by DY alone
- In contrast, the strength of the sea is reduced
- Due to momentum sum rule $\langle x_\pi^{\text{valence}} \rangle$ decreases

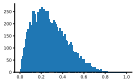
First global Monte Carlo analysis of pion PDFs



- We performed an additional analysis of LN+DY+E866
  $\rightarrow$ good description of E866 data except for large x

Future

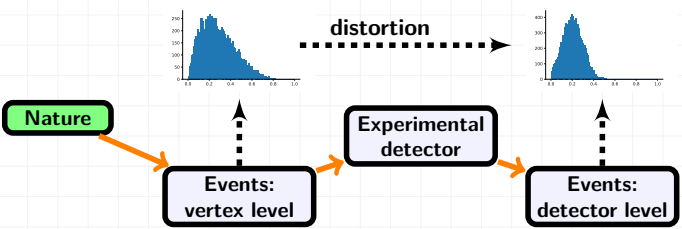
Machine learning applications?



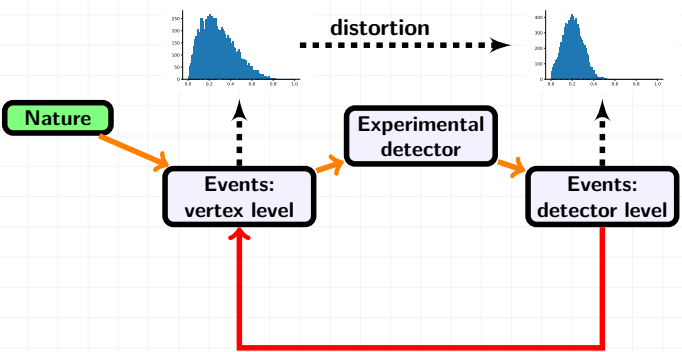
Nature

Events: vertex level

Machine learning applications?



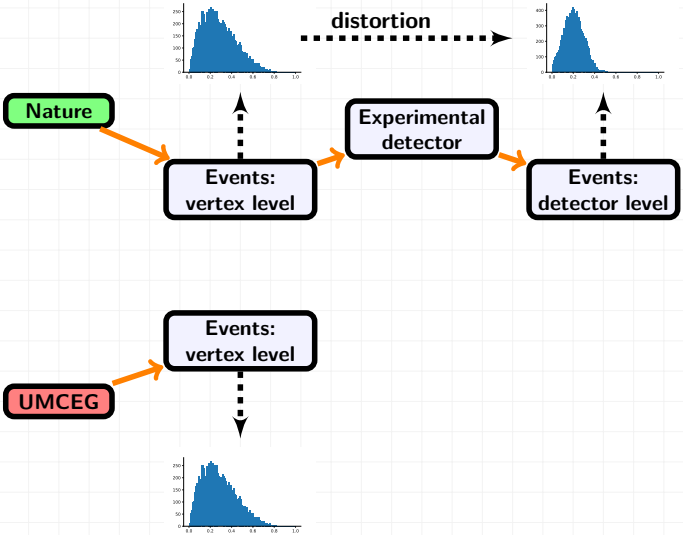
Machine learning applications?



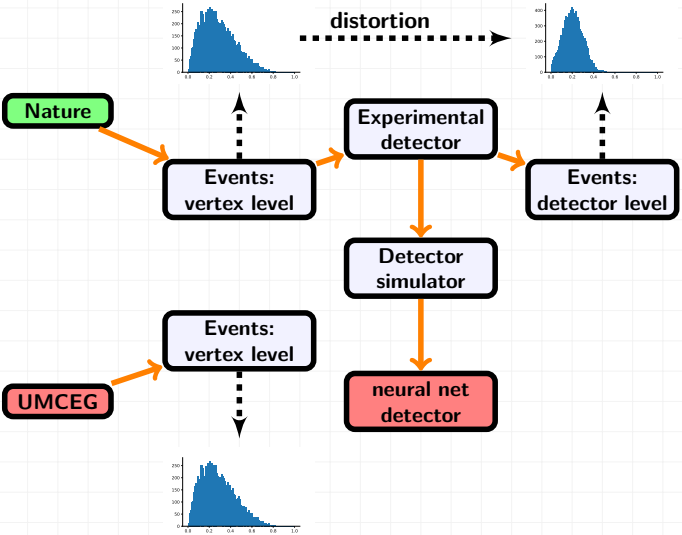
Inverse problem → solutions are not unique

→ Model dependent

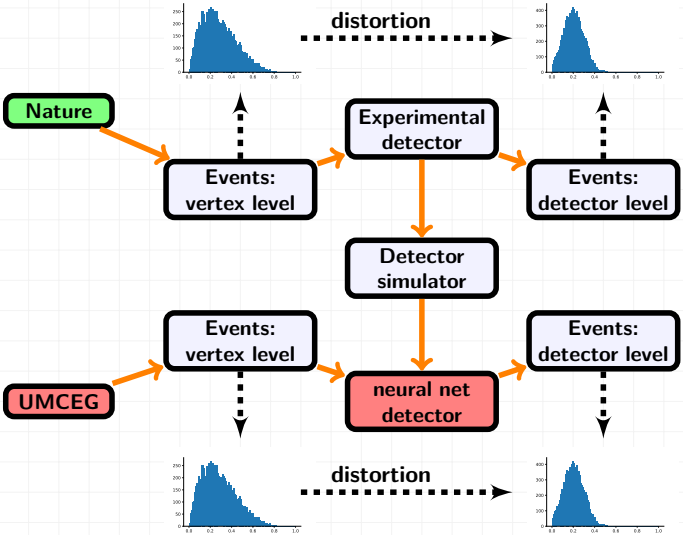
Machine learning applications?



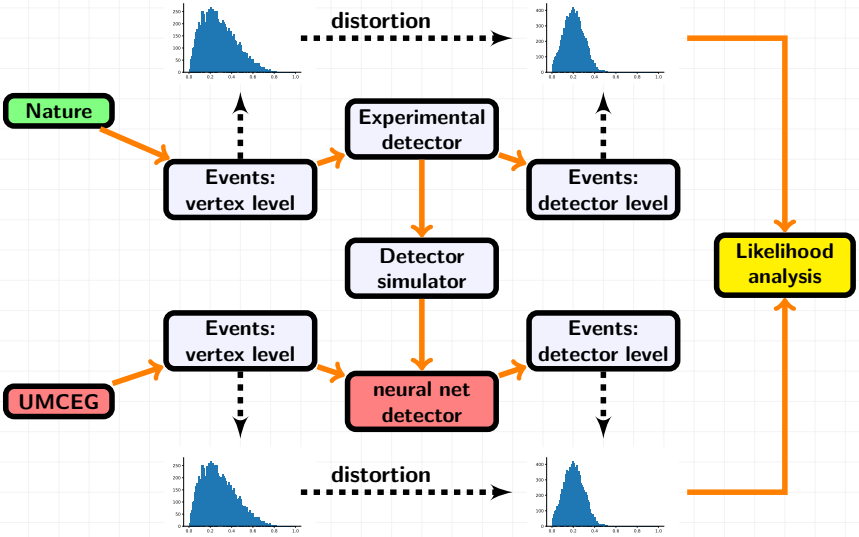
Machine learning applications?



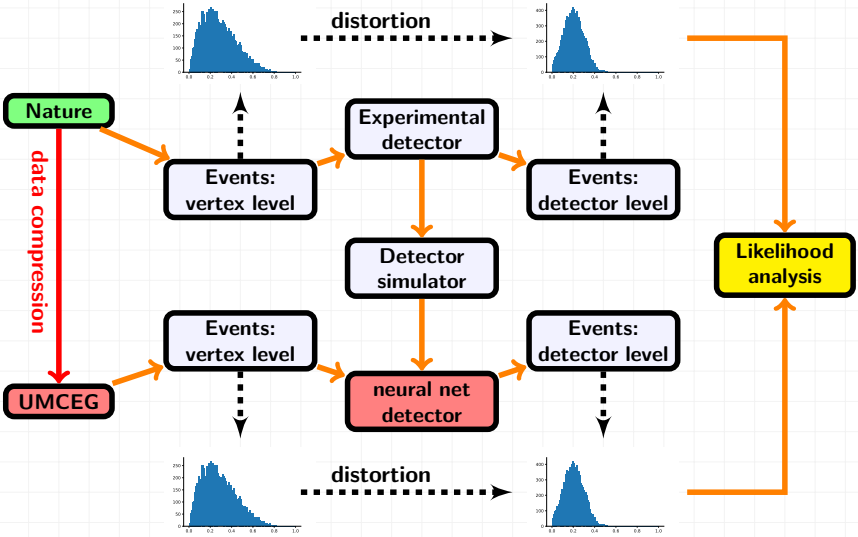
Machine learning applications?



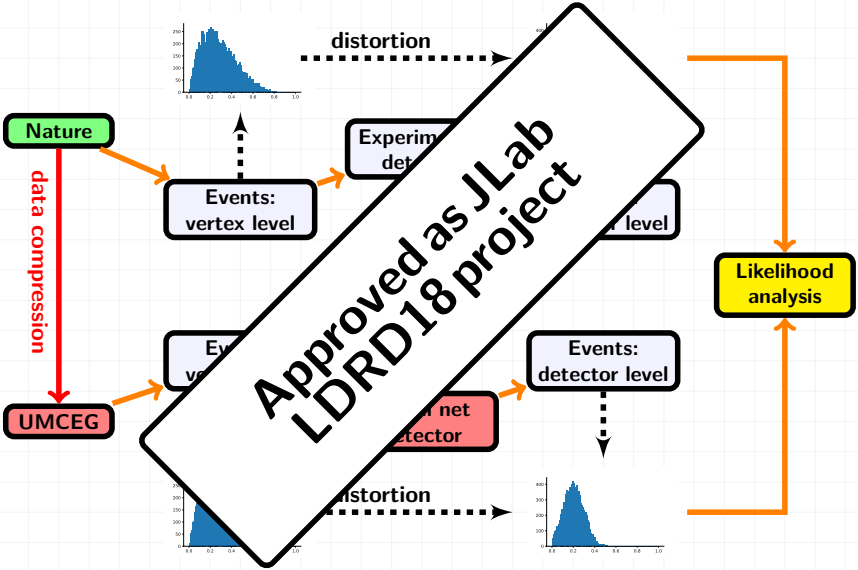
Machine learning applications?



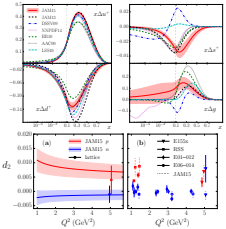
Machine learning applications?

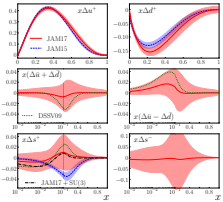


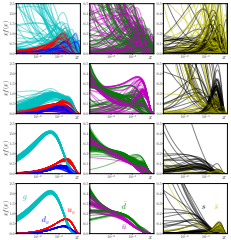
Machine learning applications?



Summary and outlook







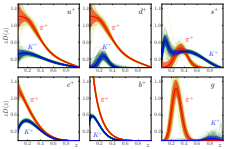
webfitter

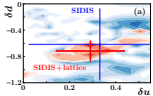
RHIC data

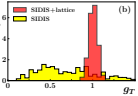
TMDs

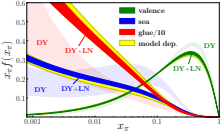
2015 2016 2017 2018 2019 2020

EIC









Jefferson Lab Angular Momentum Collaboration