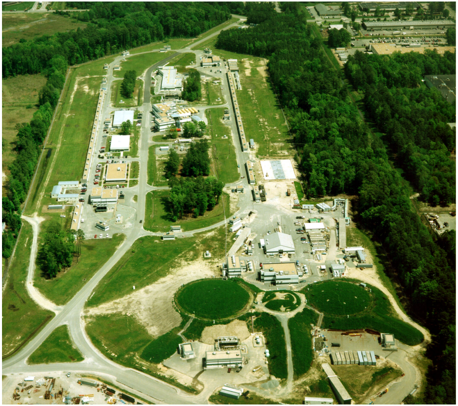
The quest to unveil partonic degrees of freedom in hadrons using high energy reactions

Nobuo Sato
University of Connecticut/JLab
JLab seminar, Mar 1 2017

Physics questions for JLab12

- How does QCD work at energy scales of a few GeV?



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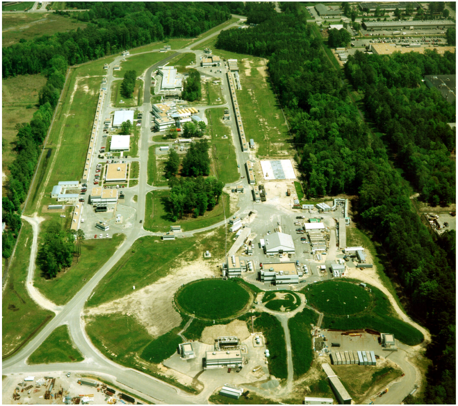

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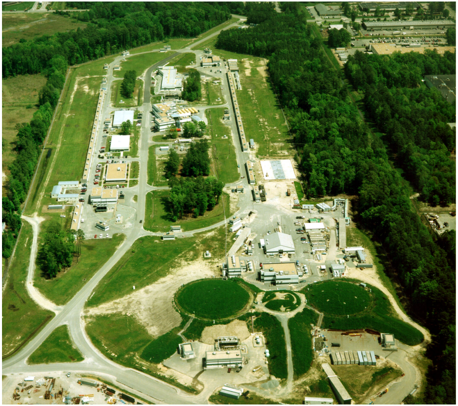

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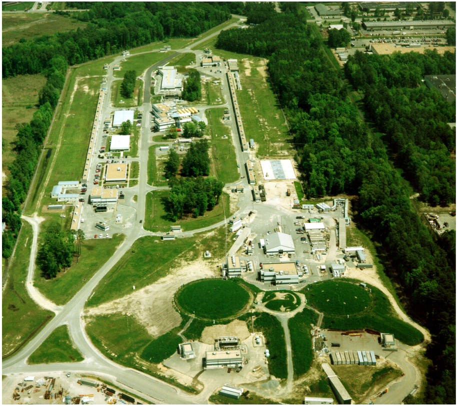

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- How does QCD work at energy scales of a few GeV?
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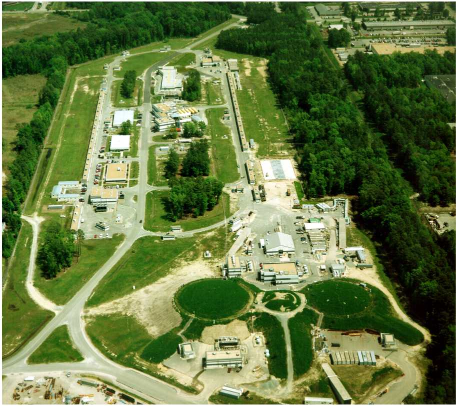
- How do final state partons combine to form hadrons?



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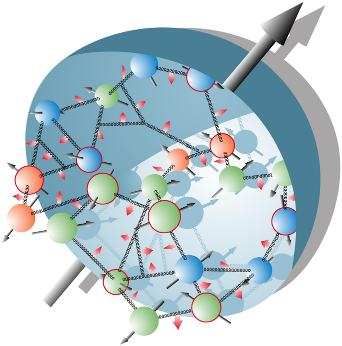

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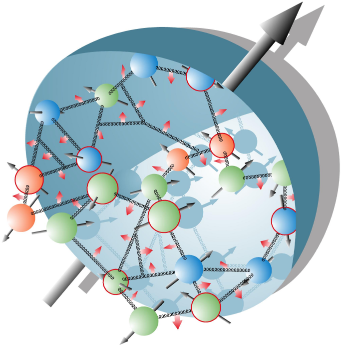

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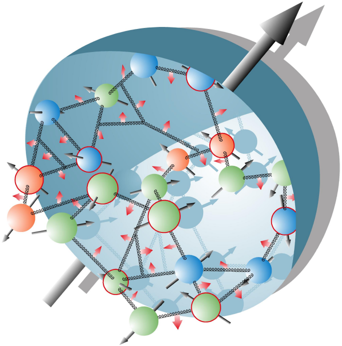

Physics questions for JLab12

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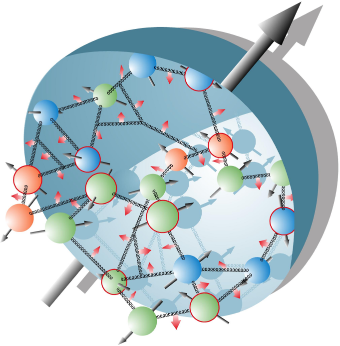
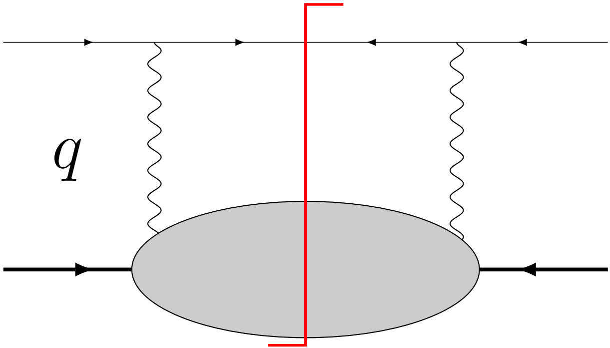
- What is the detailed partonic structure of the nucleons?
- How does confinement work?
- Can we interpret single spin asymmetries?



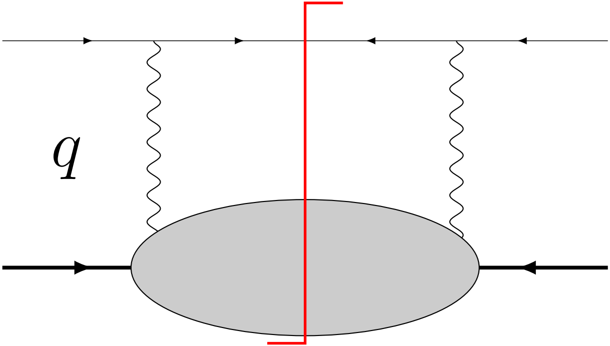
Quick review of QCD framework in DIS

DIS theoretical framework



- The upper part of the diagram can be calculated using QED
- The lower part is more complicated → **Factorization**

Factorization in inclusive DIS



- The lower blob represents a collection of Feynman diagrams

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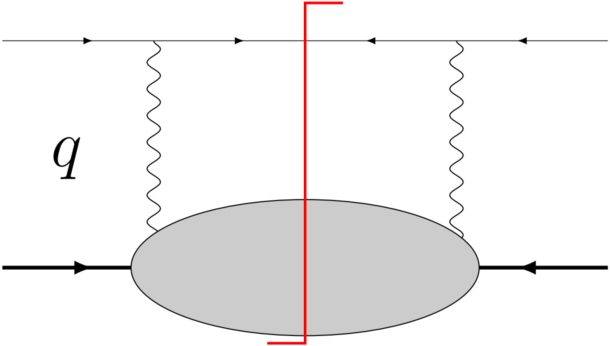

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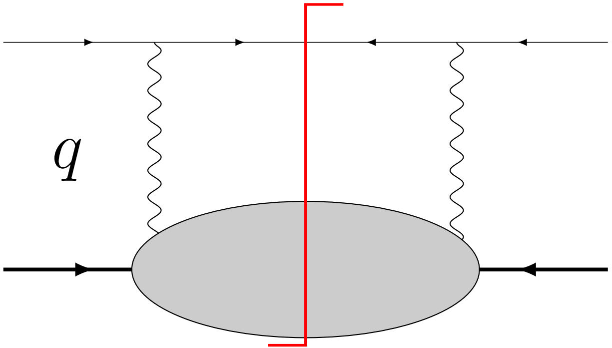

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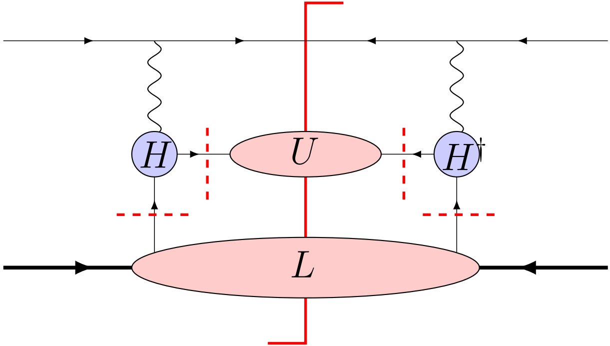

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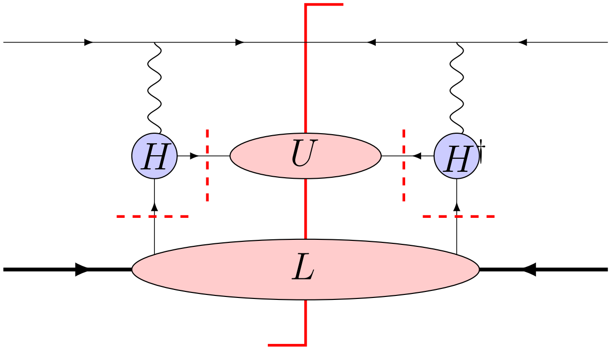
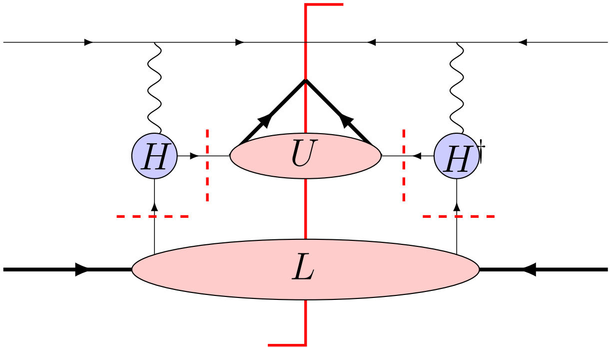


Schematically

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

Factorization in SIDIS



- Additional information about the lower blob can be accessed by measuring hadrons in the final state (i.e., flavor separation, intrinsic transverse momentum)

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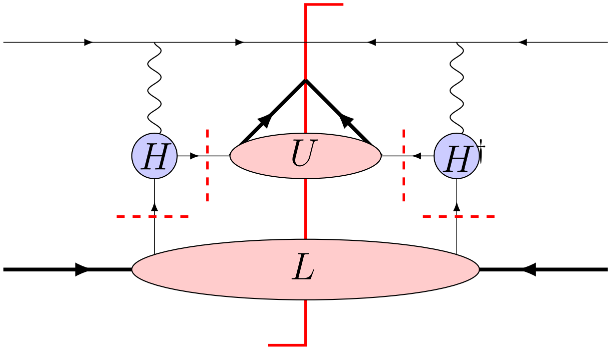

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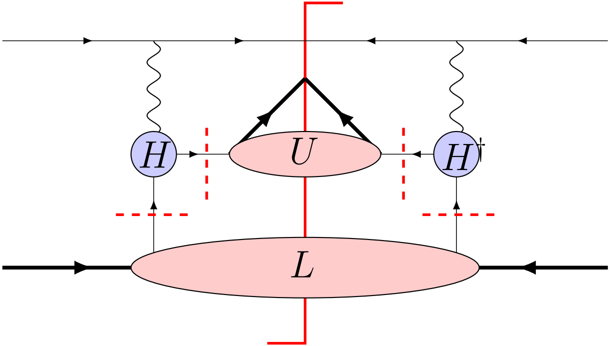

- Additional information about the lower blob can be accessed by measuring hadrons in the final state (i.e., flavor separation, intrinsic transverse momentum)
- The upper blob along with tagged hadrons characterizes formation of hadrons from partons
- Factorization of these regions assumes large $Q^2 = -q^2$

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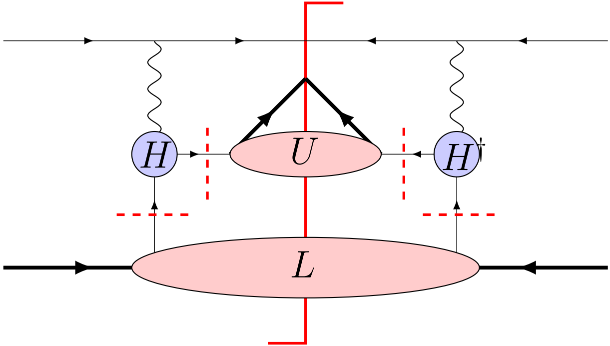

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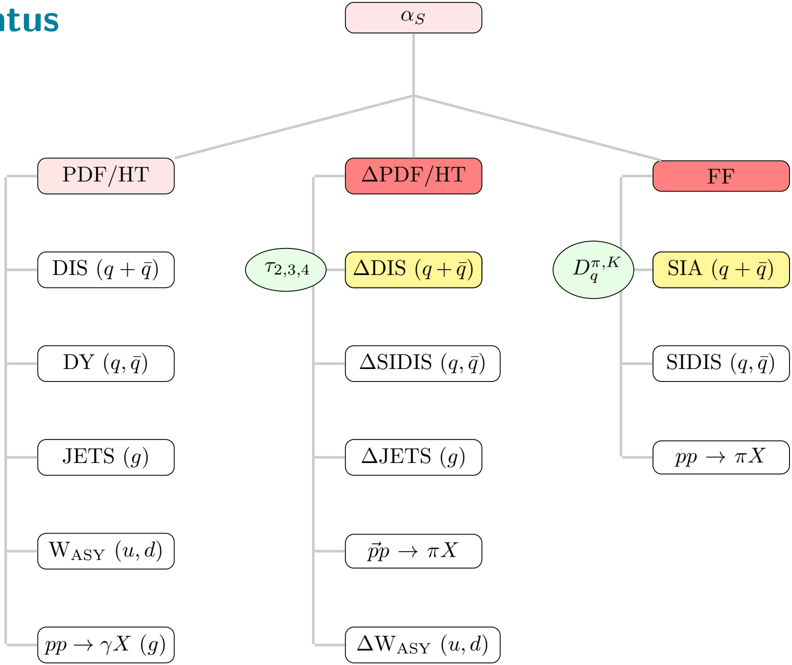
Longitudinal distributions

The collinear master plan

- Extract reliable collinear polarized and unpolarized parton distribution functions (PDFs) and fragmentation functions (FFs)
- Improvements in fitting methodology:
  Iterative Monte Carlo
- Reliable description of q_T integrated SIDIS data.

Status


α_S
PDF/HT
ΔPDF/HT
FF
DIS $(q+\bar{q})$
$\tau_{2,3,4}$
ΔDIS $(q+\bar{q})$
$D_q^{\pi,K}$
SIA $(q+\bar{q})$
DY $(q,\bar{q})$
ΔSIDIS $(q,\bar{q})$
SIDIS $(q,\bar{q})$
JETS (g)
ΔJETS (g)
$pp \to \pi X$
W$_{\text{ASY}}$ (u,d)
$\vec{p}p \to \pi X$
$pp \to \gamma X$ (g)
ΔW$_{\text{ASY}}$ (u,d)

Milestones

- Global analysis of all inclusive polarized DIS data

Iterative Monte Carlo analysis of spin-dependent parton distributions

Nobuo Sato,[1] W. Melnitchouk,[1] S. E. Kuhn,[2] J. J. Ethier,[3] and A. Accardi[4,1]
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PHYSICAL REVIEW D **94,** 114004 (2016)

First Monte Carlo analysis of fragmentation functions from single-inclusive e^+e^- annihilation

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- Invited talk in FCCee workshop

Parton Radiation and Fragmentation from LHC to FCC-ee

Workshop Proceedings, CERN, Geneva, Nov. 22nd–23th, 2016

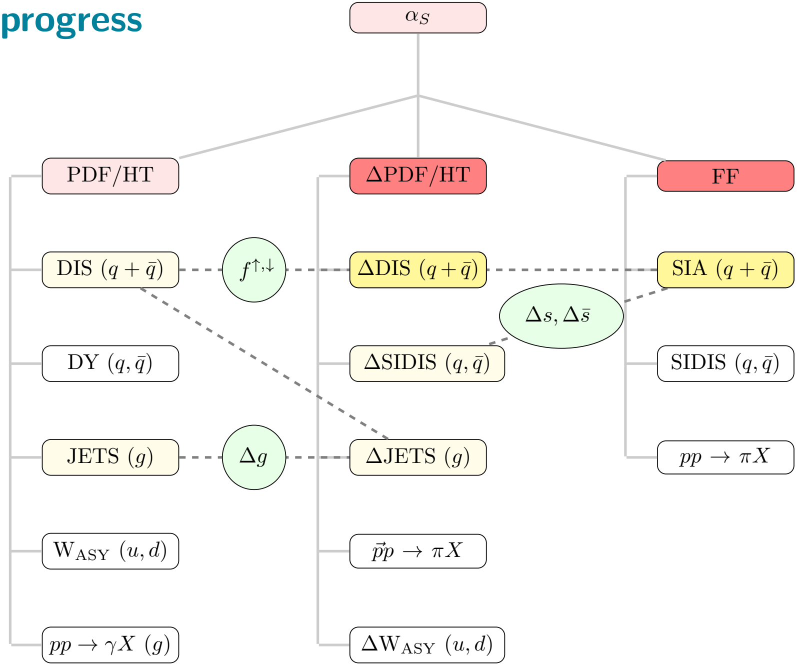
Editors

David d'Enterria (CERN), Peter Z. Skands (Monash)

Authors

D. Anderle (U. Manchester), F. Anulli (INFN Roma), J. Aparisi (IFIC València), G. Bell (U. Siegen), V. Bertone (NIKHEF, VU Amsterdam), C. Bierlich (Lund Univ.), S. Carrazza (CERN), G. Corcella (INFN-LNF Frascati), D. d'Enterria (CERN), M. Dasgupta (U. Manchester), I. García (IFIC València), T. Gehrmann (U. Zürich), O. Gituliar (U. Hamburg), K. Hamacher (B.U. Wuppertal), A.H. Hoang (U. Wien), N.P. Hartland (NIKHEF, VU Amsterdam), A. Hornig (LANL Los Alamos), S. Jadach (IFJ-PAN Krakow), T. Kaufmann (U. Tübingen), S. Kluth (T.U. München),

In progress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Innovations in fitting methodology

Theory of fitting

The goal is to estimate:

$$\mathrm{E}[\mathcal{O}] = \int d^n a \;\; \mathcal{P}(\boldsymbol{a}|data) \;\; \mathcal{O}(\boldsymbol{a})$$

$$\mathrm{V}[\mathcal{O}] = \int d^n a \;\; \mathcal{P}(\boldsymbol{a}|data) \;\; [\mathcal{O}(\boldsymbol{a}) - \mathrm{E}[\mathcal{O}]]^2$$

Monte Carlo methods

- $\mathcal{P}(\boldsymbol{a}|data) \rightarrow \{\boldsymbol{a}_k\}$
- $\mathrm{E}[\mathcal{O}] \approx \frac{1}{N} \sum_k \mathcal{O}(\boldsymbol{a}_k)$
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Maximum Likelihood

- Maximize $\mathcal{P}(\boldsymbol{a}|data) \rightarrow \boldsymbol{a}_0$
- $\mathrm{E}[\mathcal{O}] \approx \mathcal{O}(\boldsymbol{a}_0)$
- $\mathrm{V}[\mathcal{O}] \approx$ hessian, $\Delta\chi^2$ envelope,...

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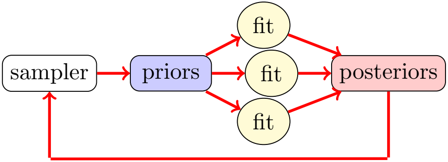
Iterative Monte Carlo analysis (IMC)



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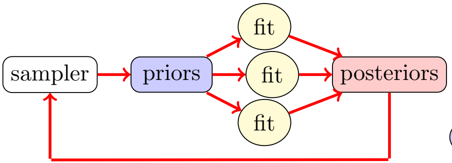

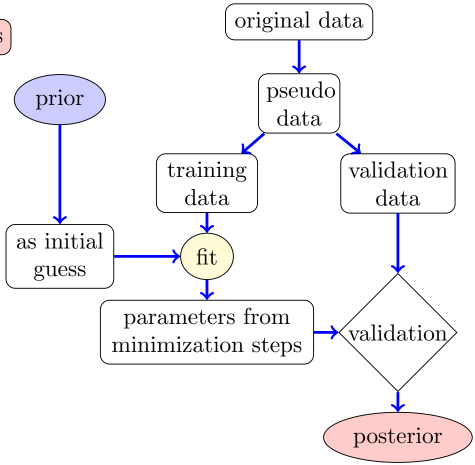

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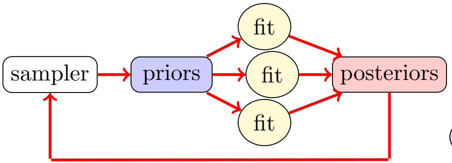
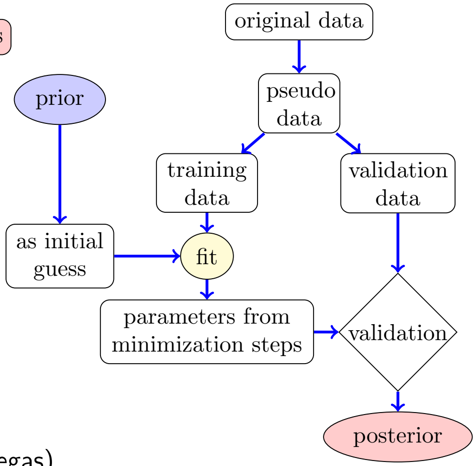
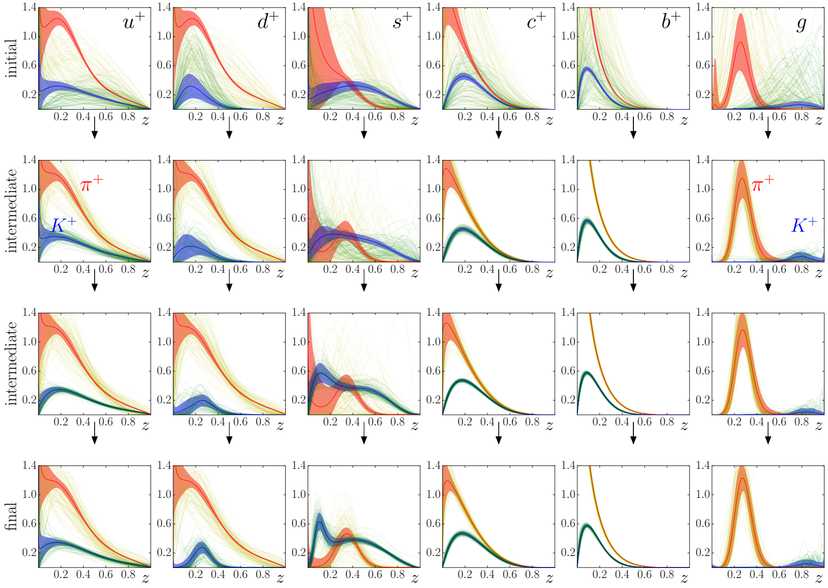


- Use traditional ansatz
  $xf(x) = {\color{red}N} x^{\color{red}a}(1-x)^{\color{red}b}(1+{\color{red}c}\sqrt{x}+{\color{red}d}x)$
- Keep all the parameters free.
  No assumptions on the exponents
- Avoid over-fitting by Cross-Validation
- **Iterative procedure**
  $\rightarrow$ Adaptive MC integration (like in Vegas)
- Robust estimation of uncertainties

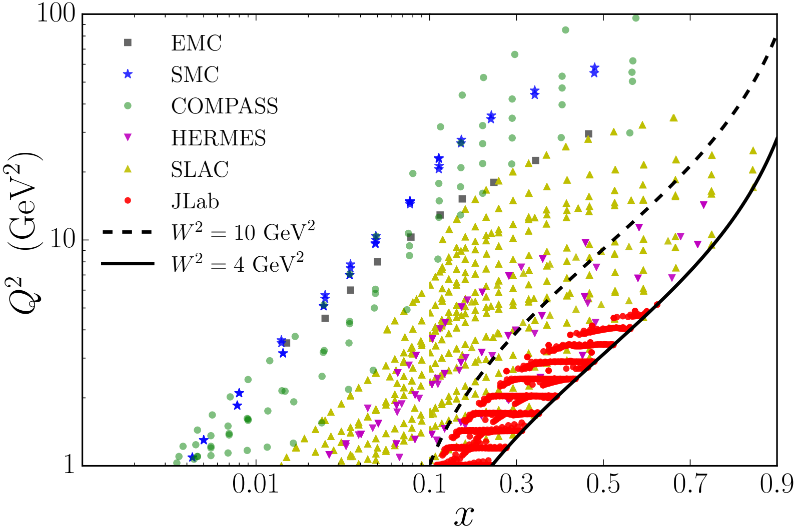


IMC in action (e.g., FFs analysis)

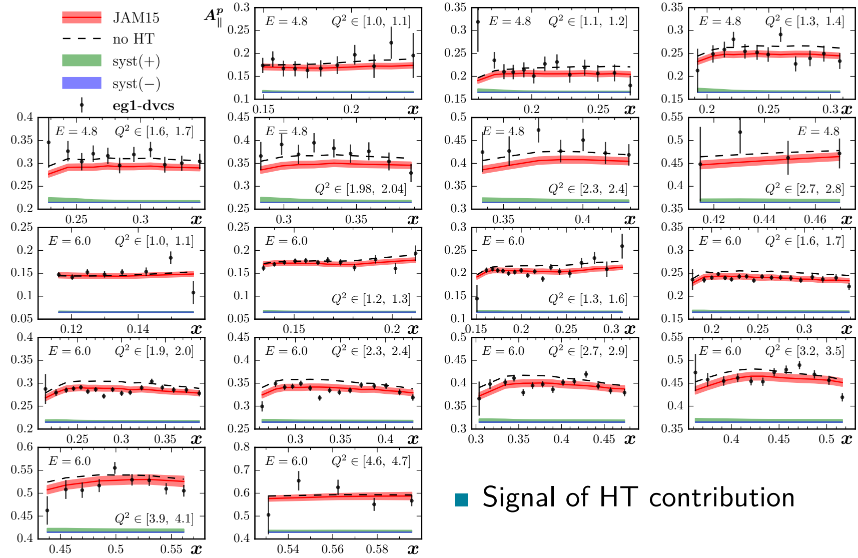


Spin PDFs from polarized DIS

Global polarized DIS data

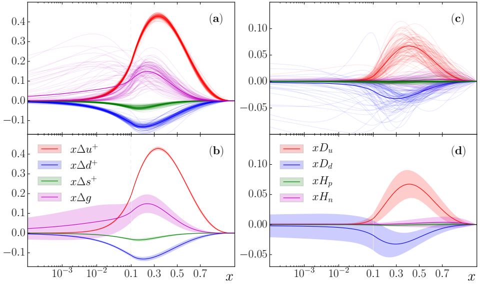


Data vs theory: proton JLab eg1-dvcs

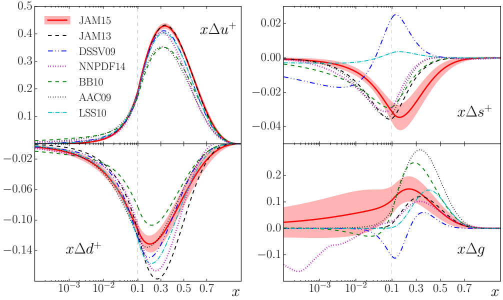


- Signal of HT contribution

Results



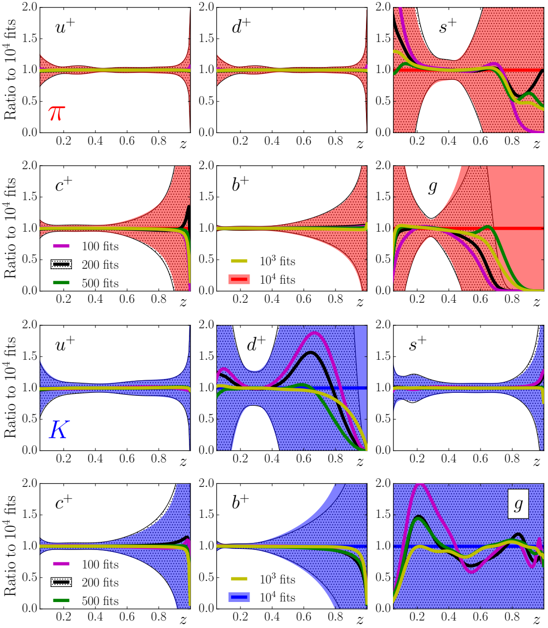
moment	truncated	full
Δu^+	0.82 ± 0.01	0.83 ± 0.01
Δd^+	-0.42 ± 0.01	-0.44 ± 0.01
Δs^+	-0.10 ± 0.01	-0.10 ± 0.01
$\Delta \Sigma$	0.31 ± 0.03	0.28 ± 0.04
ΔG	0.5 ± 0.4	1 ± 15
d_2^p	0.011 ± 0.004	0.011 ± 0.004
d_2^n	-0.002 ± 0.002	-0.002 ± 0.002
h_p	-0.000 ± 0.001	0.000 ± 0.001
h_n	0.001 ± 0.002	0.001 ± 0.003



- $\chi^2/N_{npts} = 1.07$
- Sign of τ_3 distributions is the same as τ_2
- **Negative** Δs^+
- Δg compatible with the most recent DSSV fits
- Moment of Δg not constrained

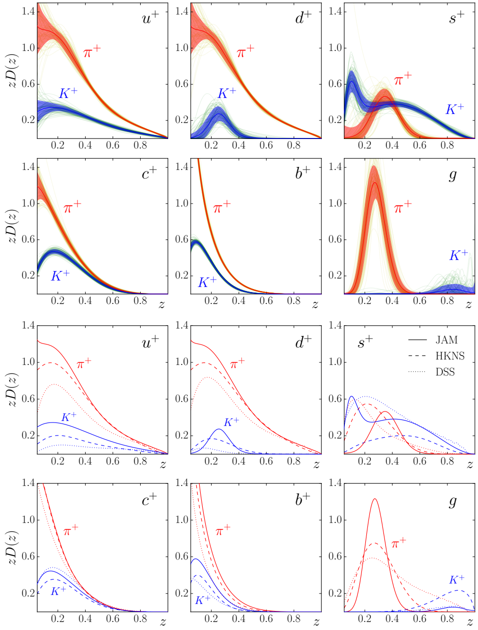
Fragmentation Functions from SIA data

Fragmentation functions



- Stronger constraints on favored FFs than unfavored FFs
- More sensitivity on D_g^π than D_g^K
- D_g^K is unknown
- Convergence attained with ~ 200 posteriors

Fragmentation functions

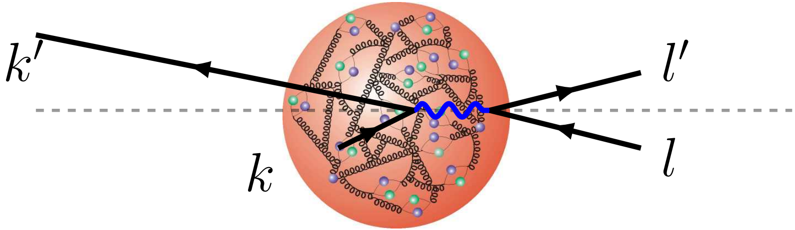


- D_g^π and D_g^K behave differently
- HQ distributions becomes comparable in size with favored distributions
- JAM $D_{s^+}^K$ is compatible with DSS. **Will it change the sign of Δs^+?**

TMD physics

Intuitive picture

The Breit frame: $q = (0, 0, 0, -Q)$ and $P = (P^0, 0, 0, P_z)$



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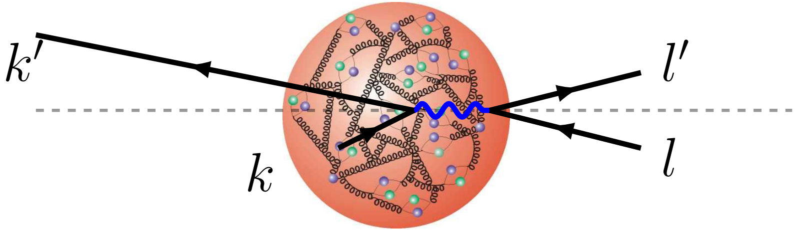
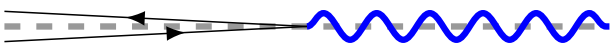
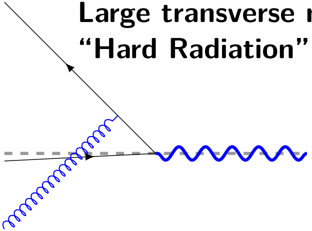


Small transverse mom.
"Intrinsic"



Large transverse mom.
"Hard Radiation"



Formal developments

- Factorization in TMD observables

$$\Gamma = d\sigma/dq_T$$
$$q_T = p^h/z$$

$$
\begin{aligned}
\Gamma &= \Gamma \\
&= \mathbf{T}_{\mathrm{TMD}}\Gamma + [\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma] \\
&= \underbrace{\mathbf{T}_{\mathrm{TMD}}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\mathrm{coll}}\left[\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma\right]}_{\mathbf{Y}} + \mathcal{O}(m^2/Q^2)\Gamma
\end{aligned}
$$

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- Region of $q_T \ll Q$

  - TMD approx. dominates $\rightarrow$ $\Gamma \approx \mathbf{T}_{\text{TMD}}\Gamma$
  - $\mathbf{Y}$ term small

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- Region of $q_T \ll Q$
  - TMD approx. dominates $\rightarrow$ $\Gamma \approx \mathbf{T}_{\mathrm{TMD}}\Gamma$
  - $\mathbf{Y}$ term small

- Region of $q_T \gtrsim Q$
  - Collinear approx. dominates $\rightarrow$ $\Gamma \approx \mathbf{T}_{\mathrm{coll}}\Gamma$
  - At large Q, $\mathbf{T}_{\mathrm{TMD}}\Gamma$ is mostly perturbative

Formal developments

- Factorization in TMD observables

$$\Gamma = d\sigma/dq_T$$
$$q_T = p^h/z$$

$$\begin{aligned}\Gamma &= \Gamma \\ &= \mathbf{T}_{\mathrm{TMD}}\Gamma + [\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma] \\ &= \underbrace{\mathbf{T}_{\mathrm{TMD}}\Gamma}_{\mathbf{W}} + \underbrace{\mathbf{T}_{\mathrm{coll}}\left[\Gamma - \mathbf{T}_{\mathrm{TMD}}\Gamma\right]}_{\mathbf{Y}} + \mathcal{O}(m^2/Q^2)\Gamma\end{aligned}$$

- Region of $q_T \ll Q$
  - TMD approx. dominates $\rightarrow$ $\Gamma \approx \mathbf{T}_{\mathrm{TMD}}\Gamma$
  - $\mathbf{Y}$ term small

$$\boxed{\begin{aligned}\mathbf{W} &= \mathbf{T}_{\mathrm{TMD}}\Gamma \\ \mathbf{FO} &= \mathbf{T}_{\mathrm{coll}}\Gamma \\ \mathbf{ASY} &= \mathbf{T}_{\mathrm{coll}}\mathbf{T}_{\mathrm{TMD}}\Gamma \\ \mathbf{Y} &= \mathbf{FO} - \mathbf{ASY}\end{aligned}}$$

- Region of $q_T \gtrsim Q$
  - Collinear approx. dominates $\rightarrow$ $\Gamma \approx \mathbf{T}_{\mathrm{coll}}\Gamma$
  - At large Q, $\mathbf{T}_{\mathrm{TMD}}\Gamma$ is mostly perturbative

SIDIS (One of the main programs of JLab12)

- **Cross section and structure functions**

$$\frac{d^5\sigma(S_\perp)}{dx_B dQ^2 dz_h d^2P_{h\perp}} = \sigma_0\Big[F_{UU} + \sin(\phi_h - \phi_s)\ F_{UT}^{\sin(\phi_h-\phi_s)} + \sin(\phi_h + \phi_s)\,\frac{2(1-y)}{1+(1-y)^2}\,F_{UT}^{\sin(\phi_h+\phi_s)} + \ldots\Big]$$

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- **CSS formalism**

$$F_{UU} = H_{\rm SIDIS}\frac{1}{z_h^2}\int_0^\infty \frac{db\,b}{(2\pi)} J_0(q_{h\perp}b)\,\widetilde{W}_{UU}(b_*) + Y_{UU}$$

$$F_{UT}^{\sin(\phi_h-\phi_s)} = -H_{\rm SIDIS}\frac{M_P}{z_h^2}\int_0^\infty \frac{db\,b^2}{(2\pi)} J_1\left(q_{h\perp}b\right)\,\widetilde{W}_{UT}^{\sin(\phi_h-\phi_s)}(b_*) + Y_{UT}^{\sin(\phi_h-\phi_s)}$$

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SIDIS: small transverse momentum

- **W term formulation in b_T space**

$$\widetilde{W}_{UU}(b_*) \equiv e^{-S_{pert}(Q,b_*)-S_{\mathrm{NP}}^{\mathrm{f_1}}(Q,b)-S_{\mathrm{NP}}^{\mathrm{D_1}}(Q,b)}\, \widetilde{F}_{UU}(b_*)$$

$$\widetilde{W}_{UT}^{\sin(\phi_h-\phi_s)}(b_*) \equiv e^{-S_{pert}(Q,b_*)-S_{\mathrm{NP}}^{\mathrm{f_{1T}^{\perp}}}(Q,b)-S_{\mathrm{NP}}^{\mathrm{D_1}}(Q,b)}\, \widetilde{F}_{UT}^{\sin(\phi_h-\phi_s)}(b_*)$$

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- **Small b_T contribution**

$$\widetilde{F}_{UU}(b_*) = \sum_q e_q^2 \left(C_{q\leftarrow i}^{\mathrm{f}_1} \otimes f_1^i(x_B,\mu_b)\right)\left(\hat{C}_{j\leftarrow q}^{\mathrm{D}_1} \otimes D_{h/j}(z_h,\mu_b)\right)$$

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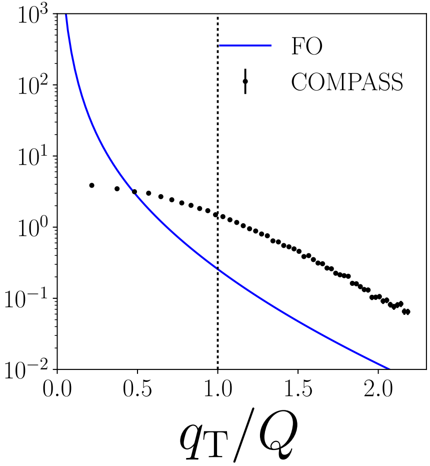
- **Collinear distribution are important in TMDs**

Does it work?

$$\frac{\frac{d\sigma}{dx\,dz\,dQ^2\,dp_T^2}}{\frac{d\sigma}{dx\,dQ^2}}$$



- Kinematics

  $Q^2 = 1.92\ \mathrm{GeV}^2$

  $x = 0.0318$

  $z = 0.375$

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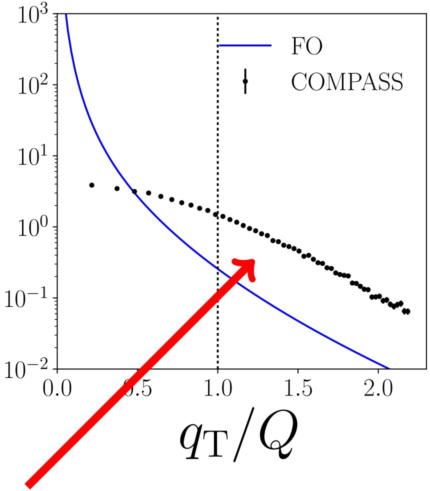

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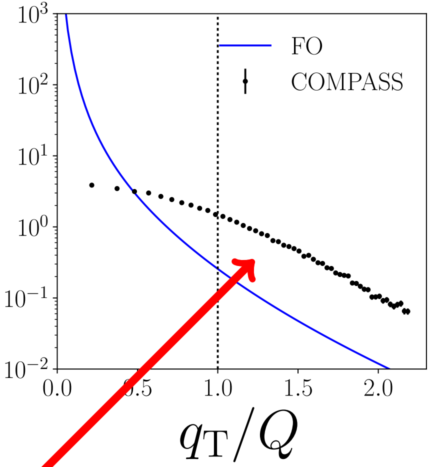

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The unpolarized SIDIS cross sections needs to be ready to interpret upcoming TMD data from JLab 12

Progress

- Improve the matching → extensions to $W + Y$

PHYSICAL REVIEW D **94,** 034014 (2016)

Relating transverse-momentum-dependent and collinear factorization theorems in a generalized formalism

J. Collins,[1,*] L. Gamberg,[2,†] A. Prokudin,[2,3,‡] T. C. Rogers,[4,3,§] N. Sato,[3,∥] and B. Wang[4,3,¶]

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- SIDIS Kinematics analysis

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Kinematics of current region fragmentation in semi-inclusive deeply inelastic scattering

CrossMark

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- Applicability of collinear factorization at low energies

What are the moderate-Q and large-x limits of collinear QCD factorization theorems?

E. Moffat,[1,*] W. Melnitchouk,[2,†] T. C. Rogers,[1,2,‡] and N. Sato[2,§]

SIDIS kinematics analysis

- **Can we apply factorization theorems in SIDIS measurements?**

SIDIS kinematics analysis

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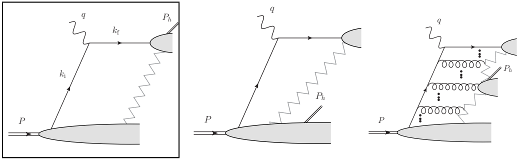
- Factorization demands that



$$p_h \cdot k_f = \mathcal{O}(m^2)$$
$$p_h \cdot k_i = \mathcal{O}(Q^2)$$

- Define a *collinearity* parameter

$$R = \frac{(p_h \cdot k_f)}{(p_h \cdot k_i)} = \mathcal{O}(m^2/Q^2)$$

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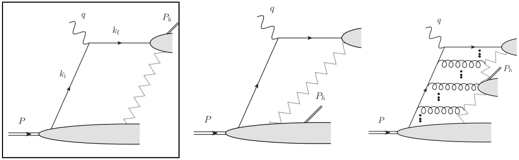

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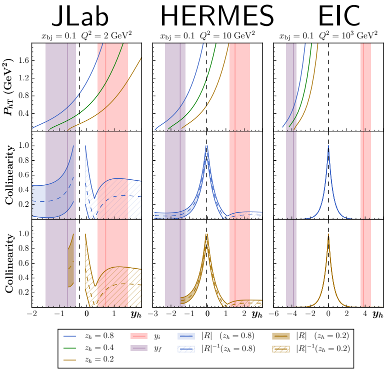

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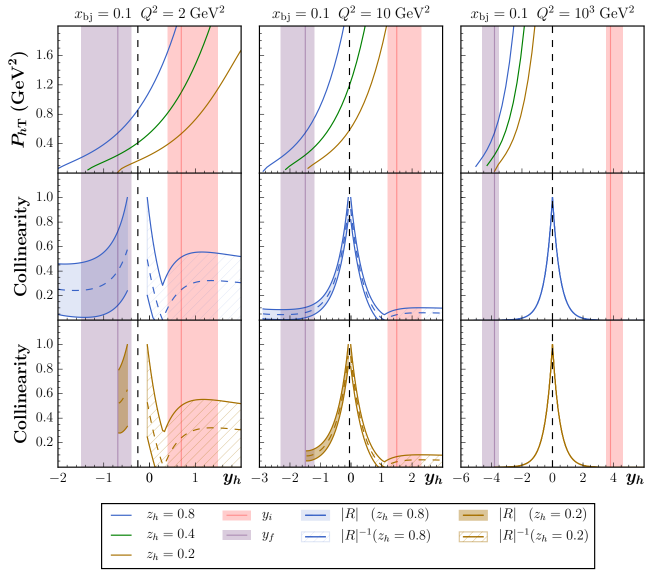

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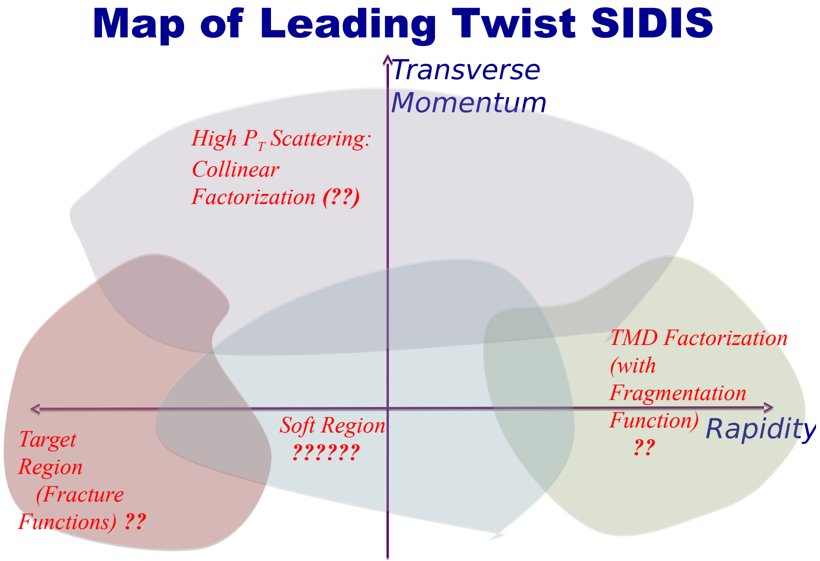

$\mathcal{O}(\alpha_S^2)$ corrections for the Y term

- NLO QCD correction to q_T dependent SIDIS

- The steps:

    1. Computation of the Born contribution $d\sigma_\mathrm{Born}$

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  4. Computation of the counter cross section (CCS)

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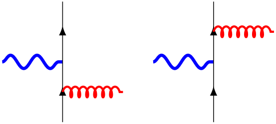
  1. Computation of the Born contribution $d\sigma_{\mathrm{Born}}$
  2. Computation of the virtual contribution $d\sigma_{\mathrm{Virtual}}$
     (with counter terms to remove UV divergences)
  3. Computation of the real contribution $d\sigma_{\mathrm{Real}}$
  4. Computation of the counter cross section (CCS)
  5. $d\sigma = d\sigma_{\mathrm{Born}} + d\sigma_{\mathrm{Virtual}} + d\sigma_{\mathrm{Real}} + d\sigma_{\mathrm{CCS}} \rightarrow$ IR finite

$\mathcal{O}(\alpha_S^2)$ **corrections to** $\gamma^* + q \to q + g$

Born contribution



$\mathcal{O}(\alpha_S^2)$ corrections to $\gamma^* + q \to q + g$

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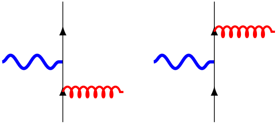
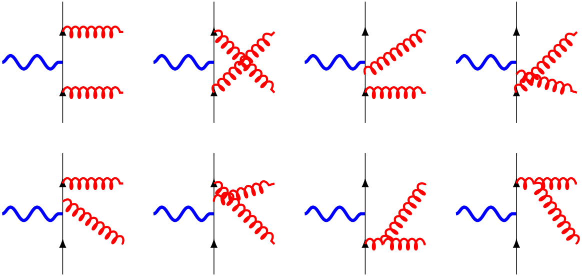


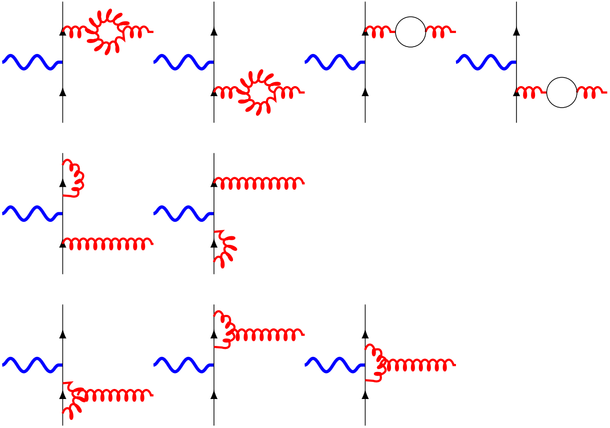
Real contribution



- integration of the extra gluon emission is the most non trivial part

$\mathcal{O}(\alpha_S^2)$ corrections to $\gamma^* + q \to q + g$

Virtual contribution

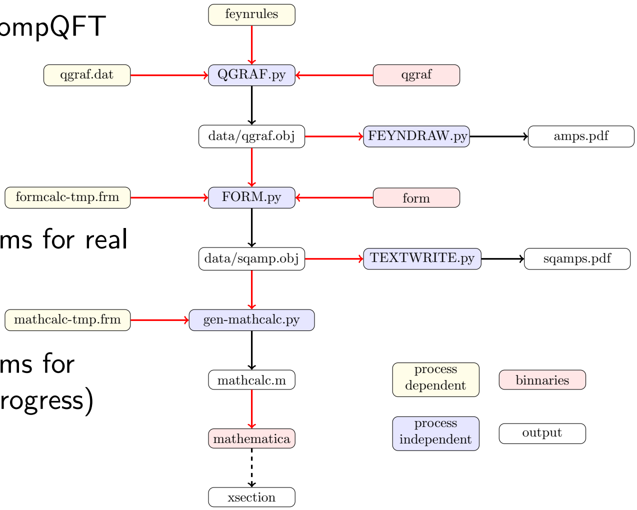


Framework for automatic Feynman amps calculation

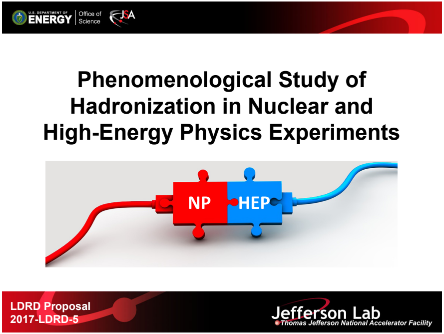
- We perform the calculation using the package CompQFT
- CompQFT is still in development

✓ Real emission diagrams for real photons

- Real emission diagrams for virtual photons (in progress)
- Virtual contributions (in progress)



MCEG for TMDs studies



- MCEG for SIDIS with spin
- Understanding hadronization process: comparison between Lund string models and CSS
- Extension of CSS to describe hadronization from the soft region

Summary and outlook

- **The collinear master plan:** Baseline PDFs and FFs for the TMD analysis
  - ✓ New MC fitting methodology
  - ✓ New IMC analysis for polarized PDFs and FFs
  - Combine polarized PDFs and FF analysis (in progress)
  - Universal analysis for all collinear distributions (ultimate goal)

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- **MCEG for SIDIS:** Language dictionary
  - Pythia8 validation of Hermes multiplicities (in progress)
  - Extraction of FFs from Pythia 8: test of DGLAP and Pythia8's parton shower