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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- Can we use small coupling techniques?
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- Are the factorization theorems valid at such scales?
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- Can we use small coupling techniques?
- Are the factorization theorems valid at such scales?
- How can we model the transition from nonperturbative physics to perturbative physics?
- How do final state partons combine to form hadrons?
How do the quarks and gluons carry the spin of the proton?
Physics questions for JLab12

- How do the quarks and gluons carry the spin of the proton?
- What is the detailed partonic structure of the nucleons?
How do the quarks and gluons carry the spin of the proton?

What is the detailed partonic structure of the nucleons?

How does confinement work?
Physics questions for JLab12

- How do the quarks and gluons carry the spin of the proton?

- 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
The upper part of the diagram can be calculated using QED
The lower part is more complicated $\rightarrow$ Factorization
Factorization in inclusive DIS

The lower blob represents a collection of Feynman diagrams

$q$

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Factorization in inclusive DIS

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- It is possible to identify the most relevant contributions to the blob classifying them into different regions (Libby-Sterman).
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Using kinematic approximations one can disentangle the various regions assuming $Q^2 = -q^2$ is large.
The lower blob represents a collection of Feynman diagrams. It is possible to identify the most relevant contributions to the blob classifying them into different regions (Libby-Sterman). Using kinematic approximations one can disentangle the various regions assuming $Q^2 = -q^2$ is large.
Factorization in inclusive DIS

\[ d\sigma \sim |H|^2 \int dk^- dk^\perp L(xP^+, k^-, k^\perp) \int dl^+ U(l^+) \, d\Omega \]

Schematically

\[ \text{Hard} \quad \text{Parton densities} \quad \text{Jet function} \]
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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The upper blob along with tagged hadrons characterizes formation of hadrons from partons.
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 $Q^2 = -q^2$
Factorization in SIDIS

Schematically

\[ d\sigma \sim |H|^2 \int dk_- dk_\perp L(xP^+, k^-, k_\perp) \int dk_+^h dk_\perp^h U(k_+^h, k_\perp^h) \, d\Omega \]

- Hard
- Parton densities
- Fragmentation function
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.
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. Accardi4,1

(Jefferson Lab Angular Momentum Collaboration)
Milestones

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- Global analysis of all SIA data
  - 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**
  
  
  **Editors**
  David d’Enterria (CERN), Peter Z. Skands (Monash)
  
  **Authors**
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  N.P. Hartland (NIKHEF, VU Amsterdam), A. Hornig (LANL Los Alamos),
In progress

PDF/HT

DIS \( (q + \bar{q}) \)

DY \( (q, \bar{q}) \)

JETS \( (g) \)

\( \alpha_S \)

PP \( \rightarrow \gamma X \ (g) \)

\( f^{\uparrow, \downarrow} \)

PDF/HT

\( \Delta PDF/HT \)

\( \Delta DIS \ (q + \bar{q}) \)

\( \Delta SIDIS \ (q, \bar{q}) \)

\( \rho pp \rightarrow \pi X \)

\( \Delta W_{ASY} \ (u, d) \)

\( \Delta W_{ASY} \ (u, d) \)

\( \Delta SIA \ (q + \bar{q}) \)

\( \Delta JETS \ (g) \)

\( \Delta g \)

\( \Delta s, \Delta \bar{s} \)

FF

SIA \( (q + \bar{q}) \)

SIDIS \( (q, \bar{q}) \)

\( pp \rightarrow \pi X \)
Innovations in fitting methodology
Theory of fitting

The goal is to estimate:

\[ E[O] = \int d^n a \ P(a|data) \ O(a) \]

\[ V[O] = \int d^n a \ P(a|data) \ [O(a) - E[O]]^2 \]

Monte Carlo methods

- \( P(a|data) \rightarrow \{a_k\} \)
- \( E[O] \approx \frac{1}{N} \sum_k O(a_k) \)
- \( V[O] \approx \frac{1}{N} \sum_k [O(a_k) - E[O]]^2 \)

Maximum Likelihood

- Maximize \( P(a|data) \rightarrow a_0 \)
- \( E[O] \approx O(a_0) \)
- \( V[O] \approx \text{hessian, } \Delta \chi^2 \text{ envelope,...} \)
Theory of fitting

The goal is to estimate:

\[
\begin{align*}
E[\mathcal{O}] &= \int d^m a \ P(a|\text{data}) \ \mathcal{O}(a) \\
V[\mathcal{O}] &= \int d^m a \ P(a|\text{data}) \ [\mathcal{O}(a) - E[\mathcal{O}]]^2
\end{align*}
\]

Monte Carlo methods

- \( P(a|\text{data}) \rightarrow \{a_k\} \)
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Maximum Likelihood

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- \( V[\mathcal{O}] \approx \text{hessian}, \ \Delta \chi^2 \text{ envelope,}... \)
Iterative Monte Carlo analysis (IMC)
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Iterative Monte Carlo analysis (IMC)

- Use traditional ansatz
  \[ x f(x) = N x^a (1 - x)^b (1 + c \sqrt{x} + d x) \]
- 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

- JAM15
- no HT
- syst(+)
- syst(−)

eg1-dvcs

Signal of HT contribution
Results

<table>
<thead>
<tr>
<th>moment</th>
<th>truncated</th>
<th>full</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta u^+$</td>
<td>0.82 ± 0.01</td>
<td>0.83 ± 0.01</td>
</tr>
<tr>
<td>$\Delta d^+$</td>
<td>$-0.42 ± 0.01$</td>
<td>$-0.44 ± 0.01$</td>
</tr>
<tr>
<td>$\Delta s^+$</td>
<td>$-0.10 ± 0.01$</td>
<td>$-0.10 ± 0.01$</td>
</tr>
<tr>
<td>$\Delta \Sigma$</td>
<td>0.31 ± 0.03</td>
<td>0.28 ± 0.04</td>
</tr>
<tr>
<td>$\Delta G$</td>
<td>0.5 ± 0.4</td>
<td>1 ± 15</td>
</tr>
</tbody>
</table>

- $\chi^2/N_{npts} = 1.07$
- Sign of $\tau_3$ distributions is the same as $\tau_2$
- **Negative $\Delta s^+$**
- $\Delta g$ compatible with the most recent DSSV fits
- Moment of $\Delta g$ not constrained
Fragmentation Functions from SIA data
Fragmentation functions

- Stronger constraints on favored FFs than unfavored FFs
- More sensitivity on $D_\pi^g$ than $D^K_g$
- $D^K_g$ is unknown
- Convergence attained with $\sim 200$ posteriors
**Fragmentation functions**

- $D_g^\pi$ and $D_g^K$ behave differently
- HQ distributions becomes comparable in size with favored distributions
- JAM $D^K_{s^+}$ is compatible with DSS. **Will it change the sign of $\Delta s^+$?**
TMD physics
The Breit frame: \( q = (0, 0, 0, -Q) \) and \( P = (P^0, 0, 0, P_z) \)
Intuitive picture

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

Small transverse mom.  "Intrinsic"

Large transverse mom.  "Hard Radiation"
Formal developments

- Factorization in TMD observables

\[ \Gamma = \frac{d\sigma}{dq_T} \]
\[ q_T = \frac{p^h}{z} \]

\[ \Gamma = \Gamma \]
\[ = T_{TMD}\Gamma + [\Gamma - T_{TMD}\Gamma] \]
\[ = T_{TMD}\Gamma + T_{coll}[\Gamma - T_{TMD}\Gamma] + \mathcal{O}(m^2/Q^2)\Gamma \]

Region of \( q_T \ll Q \) - TMD approx. dominates
\[ \Gamma \approx T_{TMD}\Gamma \]
\[ \text{FO} \]
\[ \text{ASY} \]
\[ W \]

Region of \( q_T \gg Q \) - Collinear approx. dominates
\[ \Gamma \approx T_{coll}\Gamma \]
\[ \text{At large } Q, T_{TMD}\Gamma \text{ is mostly perturbative} \]
Formal developments

- Factorization in TMD observables

\[ \Gamma = \Gamma = T_{\text{TMD}} \Gamma + \left[ \Gamma - T_{\text{TMD}} \Gamma \right] = T_{\text{TMD}} \Gamma + T_{\text{coll}} \left[ \Gamma - T_{\text{TMD}} \Gamma \right] + \mathcal{O} \left( \frac{m^2}{Q^2} \right) \Gamma \]

- Region of \( q_T \ll Q \)
  - TMD approx. dominates \( \rightarrow \) \( \Gamma \approx T_{\text{TMD}} \Gamma \)
  - \( Y \) term small
Formal developments

- Factorization in TMD observables

\[ \Gamma = \frac{d\sigma}{dq_T} \]
\[ q_T = \frac{p^h}{z} \]

\[ \Gamma = \Gamma = T_{TMD}\Gamma + [\Gamma - T_{TMD}\Gamma] \]
\[ = T_{TMD}\Gamma + T_{coll}[\Gamma - T_{TMD}\Gamma] + O\left(\frac{m^2}{Q^2}\right)\Gamma \]

- Region of \( q_T \ll Q \)
  - TMD approx. dominates \( \rightarrow \) \( \Gamma \approx T_{TMD}\Gamma \)
  - \( Y \) term small

- Region of \( q_T \gtrsim Q \)
  - Collinear approx. dominates \( \rightarrow \) \( \Gamma \approx T_{coll}\Gamma \)
  - At large \( Q \), \( T_{TMD}\Gamma \) is mostly perturbative
Formal developments

- Factorization in TMD observables

\[ \Gamma = \Gamma \]
\[ = T_{TMD} \Gamma + \left[ \Gamma - T_{TMD} \Gamma \right] \]
\[ = \underbrace{T_{TMD} \Gamma} + \underbrace{T_{\text{coll}} \left[ \Gamma - T_{TMD} \Gamma \right]} + \mathcal{O}(m^2/Q^2) \Gamma \]

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  - At large \( Q \), \( T_{TMD} \Gamma \) is mostly perturbative

\[ \Gamma = d\sigma/dq_T \]
\[ q_T = p^h/z \]
SIDIS (One of the main programs of JLab12)

- Cross section and structure functions

\[
\frac{d^5 \sigma(S_{\perp})}{dx_B dQ^2 dz_h d^2 P_{h\perp}} = \sigma_0 \left[ F_{UU} + \sin(\phi_h - \phi_s) F_{UT}^{\sin(\phi_h-\phi_s)} + \sin(\phi_h + \phi_s) \frac{2(1-y)}{1 + (1-y)^2} F_{UT}^{\sin(\phi_h+\phi_s)} + \ldots \right]
\]
SIDIS (One of the main programs of JLab12)

■ Cross section and structure functions

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+ \sin(\phi_h + \phi_s) \frac{2(1-y)}{1 + (1-y)^2} F_{UT}^{\sin(\phi_h + \phi_s)} + \ldots \right]
\]

■ CSS formalism

\[
F_{UU} = H_{SIDIS} \frac{1}{z_h^2} \int_0^\infty \frac{db}{(2\pi)} J_0(q_{h\perp} b) \tilde{W}_{UU}(b^*) + Y_{UU}
\]

\[
F_{UT}^{\sin(\phi_h - \phi_s)} = -H_{SIDIS} \frac{M_P}{z_h^2} \int_0^\infty \frac{db}{(2\pi)} J_1(q_{h\perp} b) \tilde{W}_{UT}^{\sin(\phi_h - \phi_s)}(b^*) + Y_{UT}^{\sin(\phi_h - \phi_s)}
\]

\[
F_{UT}^{\sin(\phi_h + \phi_s)} = H_{SIDIS} \frac{M_h}{z_h^2} \int_0^\infty \frac{db}{(2\pi)} J_1(q_{h\perp} b) \tilde{W}_{UT}^{\sin(\phi_h + \phi_s)}(b^*) + Y_{UT}^{\sin(\phi_h + \phi_s)}
\]
SIDIS: small transverse momentum

- **W term formulation in** $b_T$ **space**

\[
\widetilde{W}_{UU}(b_*) \equiv e^{-S_{pert}(Q,b_*)} - S^f_{NP}(Q,b) - S^{D_1}_{NP}(Q,b) \widetilde{F}_{UU}(b_*)
\]

\[
\widetilde{W}_{UT}^{\sin(\phi_h-\phi_s)}(b_*) \equiv e^{-S_{pert}(Q,b_*)} - S^f_{NP}^{\perp}(Q,b) - S^{D_1}_{NP}(Q,b) \widetilde{F}_{UT}^{\sin(\phi_h-\phi_s)}(b_*)
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\[
\widetilde{W}_{UT}^{\sin(\phi_h+\phi_s)}(b_*) \equiv e^{-S_{pert}(Q,b_*)} - S^{h_1}_{NP}(Q,b) - S^{H_{1\perp}}_{NP}(Q,b) \widetilde{F}_{UT}^{\sin(\phi_h+\phi_s)}(b_*)
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Collinear distribution are important in TMDs.
SIDIS: small transverse momentum

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\]

- Small $b_T$ contribution

\[
\tilde{F}_{UU}(b_*) = \sum_q e_q^2 \left( C_{q\leftarrow i}^{f_1} \otimes f_1^i(x_B, \mu_b) \right) \left( \hat{C}_{j\leftarrow q}^{D_1} \otimes D_{h/j}(z_h, \mu_b) \right)
\]

\[
\tilde{F}_{UT}^{\sin(\phi_h-\phi_s)}(b_*) = \sum_q e_q^2 \left( C_{q\leftarrow i}^{f_{1T}} \otimes f_{1T}^{(1)i}(x_B, \mu_b) \right) \left( \hat{C}_{j\leftarrow q}^{D_1} \otimes D_{h/j}(z_h, \mu_b) \right)
\]

\[
\tilde{F}_{UT}^{\sin(\phi_h+\phi_s)}(b_*) = \sum_q e_q^2 \left( \delta C_{q\leftarrow i}^{h_1} \otimes h_1^i(x_B, \mu_b) \right) \left( \delta \hat{C}_{j\leftarrow q}^{H_1} \otimes \hat{H}_{1(1)j}^{(1)}(z_h, \mu_b) \right)
\]

Collinear distribution are important in TMDs
**SIDIS: small transverse momentum**

- **W term formulation in $b_T$ space**

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  $$

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  $$
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  $$

- **Collinear distribution are important in TMDs**
Does it work?

\[
\frac{d\sigma}{dx dz dQ^2 dp_T^2} = \frac{d\sigma}{dx dQ^2}
\]

Kinematics

\[Q^2 = 1.92 \text{ GeV}^2\]
\[x = 0.0318\]
\[z = 0.375\]
Does it work?

\[ \frac{d\sigma}{dx dz dQ^2 dp_T^2} \frac{d\sigma}{dx dQ^2} \]

**Kinematics**
- \( Q^2 = 1.92 \ \text{GeV}^2 \)
- \( x = 0.0318 \)
- \( z = 0.375 \)

- Need order \( \alpha_s^2 \) or beyond?
- Soft gluon resummation?
- Subleading power corrections?
Does it work?

\[ \frac{d\sigma}{dx dz dQ^2 dp_T^2} \]

\[ \frac{d\sigma}{dx dQ^2} \]

```
Kinematics
Q^2 = 1.92 \text{ GeV}^2
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```

- Need order $\alpha_S^2$ or beyond?
- Soft gluon resummation?
- Subleading power corrections?

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

- Improve the matching $\rightarrow$ extensions to $W + Y$

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

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

J. Collins,¹,² L. Gamberg,²,³ A. Prokudin,²,³,⁴ T. C. Rogers,²,³,⁴ N. Sato,³,⁴ and B. Wang²,³,⁴
Progress

- Improve the matching $\rightarrow$ extensions to $W + Y$

- SIDIS Kinematics analysis
Progress

- Improve the matching $\rightarrow$ extensions to $W + Y$

---

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


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SIDIS Kinematics analysis

---

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


---

Applicability of collinear factorization at low energies

---

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

E. Moffat, W. Melnitchouk, T. C. Rogers, and N. Sato
SIDIS kinematics analysis

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

Factorization demands that

\[ p_h \cdot k_f = O(m^2) \]
\[ p_h \cdot k_i = O(Q^2) \]

Define a *collinearity* parameter

\[ R = \frac{(p_h \cdot k_f)}{(p_h \cdot k_i)} = O(m^2/Q^2) \]
Can we apply factorization theorems in SIDIS measurements?

Factorization demands that

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

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Define a collinearity parameter
\[ R = \frac{p_h \cdot k_f}{p_h \cdot k_i} = O(m^2/Q^2) \]

- $P_{hT} (GeV^2)$
- $x_{bj} = 0.1$ $Q^2 = 2 GeV^2$
- $x_{bj} = 0.1$ $Q^2 = 10 GeV^2$
- $x_{bj} = 0.1$ $Q^2 = 10^3 GeV^2$
SIDIS kinematics analysis

Map of Leading Twist SIDIS

Transverse Momentum

High $P_T$ Scattering:
Collinear Factorization (??)

Target Region
(Fracture Functions) ??

Soft Region ?????

TMD Factorization (with Fragmentation Function) ??

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

- NLO QCD correction to \( q_T \) dependent SIDIS

- The steps:
  
  1. Computation of the Born contribution \( d\sigma_{\text{Born}} \)
$\mathcal{O}(\alpha_s^2)$ corrections for the $Y$ term

- NLO QCD correction to $q_T$ dependent SIDIS

- The steps:

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

2. Computation of the virtual contribution $d\sigma_{\text{Virtual}}$
   (with counter terms to remove UV divergences)
\( \mathcal{O}(\alpha_s^2) \) corrections for the \( Y \) term

- NLO QCD correction to \( q_T \) dependent SIDIS

- The steps:

1. Computation of the Born contribution \( d\sigma_{\text{Born}} \)

2. Computation of the virtual contribution \( d\sigma_{\text{Virtual}} \)
   (with counter terms to remove UV divergences)

3. Computation of the real contribution \( d\sigma_{\text{Real}} \)
\( \mathcal{O}(\alpha_s^2) \) corrections for the \( Y \) term

- NLO QCD correction to \( q_T \) dependent SIDIS

- The steps:
  1. Computation of the Born contribution \( d\sigma_{\text{Born}} \)
  2. Computation of the virtual contribution \( d\sigma_{\text{Virtual}} \)
     (with counter terms to remove UV divergences)
  3. Computation of the real contribution \( d\sigma_{\text{Real}} \)
  4. Computation of the counter cross section (CCS)
\( \mathcal{O}(\alpha_s^2) \) corrections for the \( Y \) term

- NLO QCD correction to \( q_T \) dependent SIDIS

- The steps:
  1. Computation of the Born contribution \( d\sigma_{\text{Born}} \)
  2. Computation of the virtual contribution \( d\sigma_{\text{Virtual}} \)
     (with counter terms to remove UV divergences)
  3. Computation of the real contribution \( d\sigma_{\text{Real}} \)
  4. Computation of the counter cross section (CCS)
  5. \( d\sigma = d\sigma_{\text{Born}} + d\sigma_{\text{Virtual}} + d\sigma_{\text{Real}} + d\sigma_{\text{CCS}} \to \text{IR finite} \)
$\mathcal{O}(\alpha_s^2)$ corrections to $\gamma^* + q \rightarrow q + g$

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

Born contribution

Real contribution

- Integration of the extra gluon emission is the most non trivial part
$\mathcal{O}(\alpha_s^2)$ corrections to $\gamma^* + q \rightarrow q + g$

Virtual contribution
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)
Summary and outlook

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    - $\mathcal{O}(\alpha_S^2)$ corrections to unpolarized SIDIS (in progress)
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    - New framework for TMD analysis (in development)
Summary and outlook

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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