Towards universal QCD global analysis for nucleon structure distributions

Nobuo Sato
University of Connecticut
Workshop on QCD Structure of Nucleons in the Modern Era,
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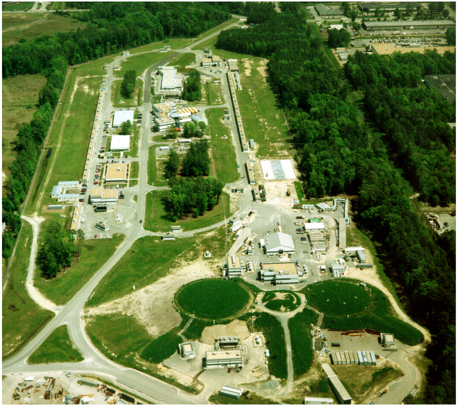
Physics questions for JLab12

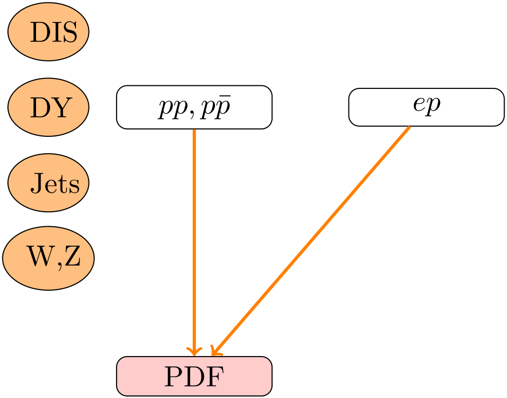
- How does QCD work at energy scales of a few GeV?
- Can we use small coupling techniques?
- Are the factorization theorems valid at such scales?
- How can we model the transition from nonperturbative physics to perturbative physics?



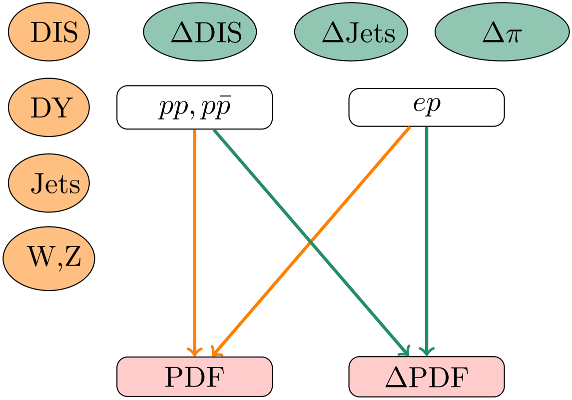
To address these questions we need:

- A solid theoretical framework
- Precise experimental measurements
- Robust data analysis framework

Towards an universal fit



Towards an universal fit



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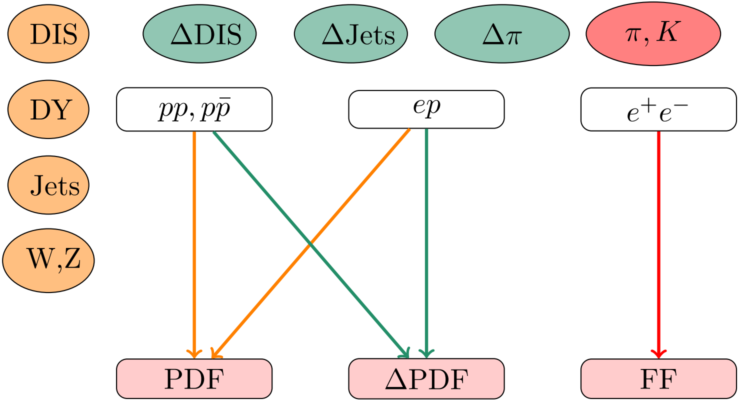

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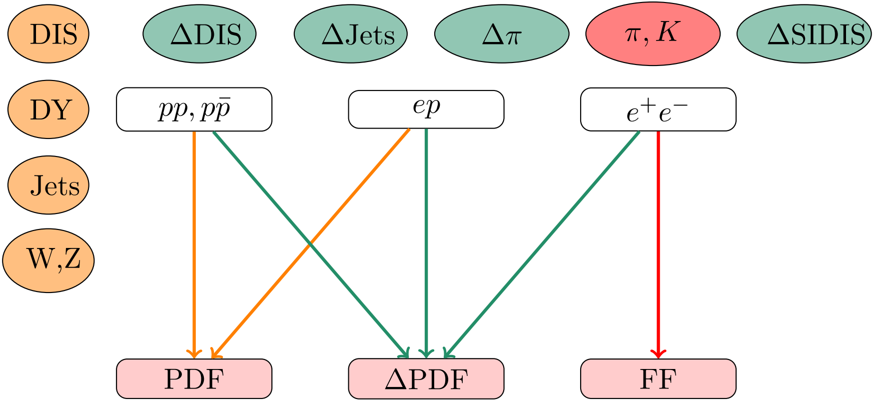

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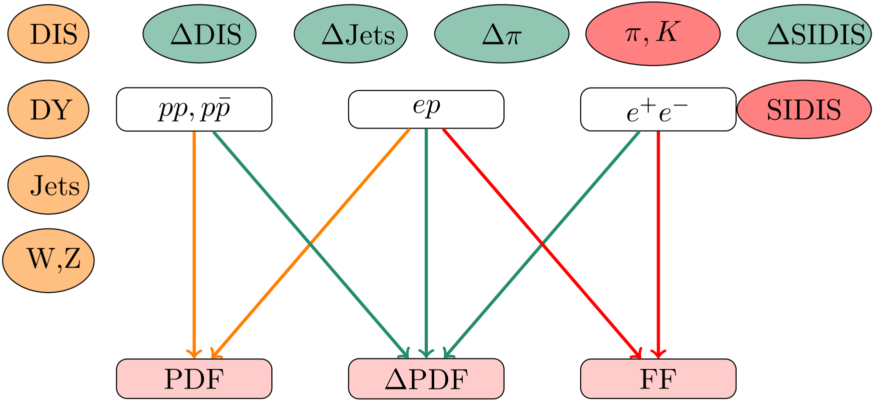

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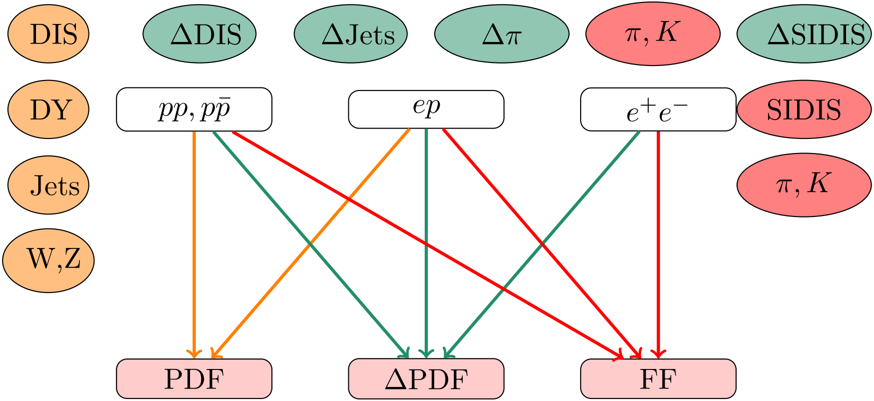

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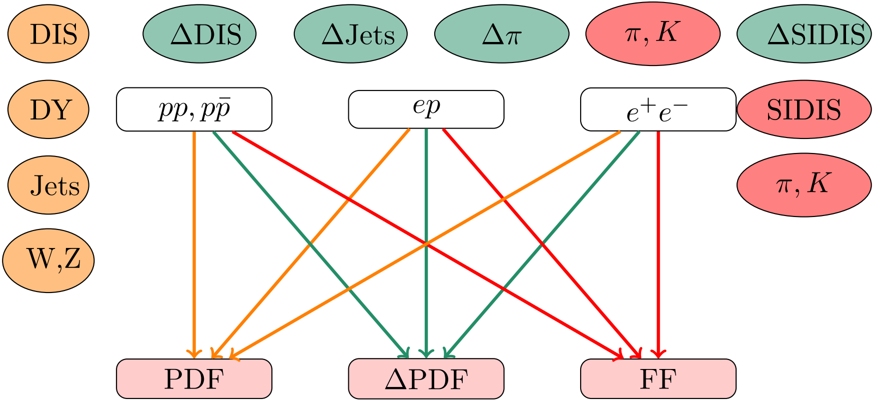

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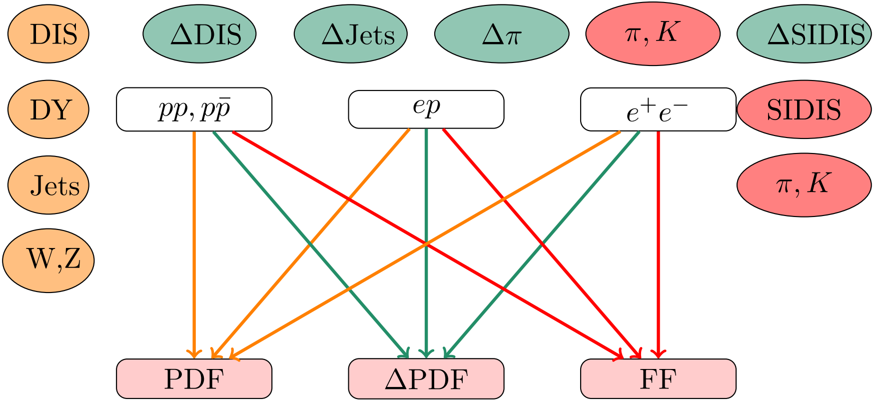


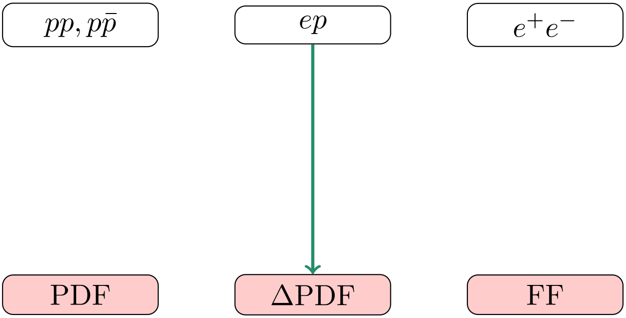
- Test of universality of collinear framework
- Robust data analysis framework is needed
- Collinear distributions are part of the TMD framework

So far...

$pp, p\bar{p}$ | ep | e^+e^-

PDF | ΔPDF | FF

So far...



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]
(Jefferson Lab Angular Momentum Collaboration)

So far...

PHYSICAL REVIEW D **94,** 114004 (2016)

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

Nobuo Sato,[1] J. J. Ethier,[2] W. Melnitchouk,[1] M. Hirai,[3] S. Kumano,[4,5] and A. Accardi[1,6]
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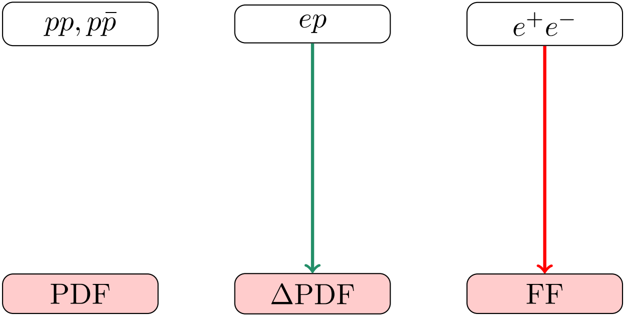

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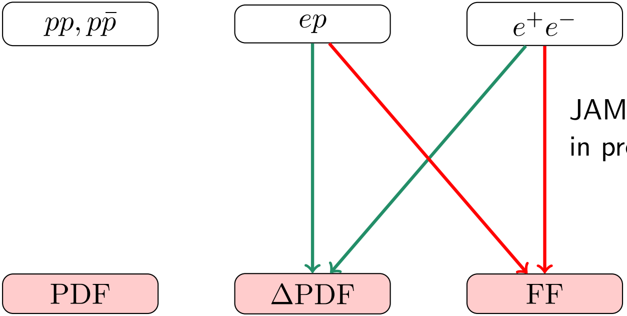

JAM17:
in preparation

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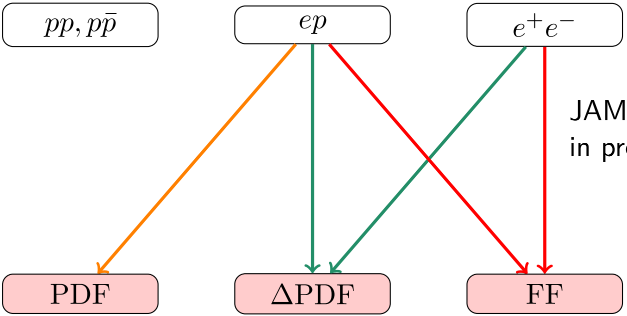
JAM17+:
in progress



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Data analysis framework:

The goal is to estimate:

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

- $\boldsymbol{a} = (N, a, b, c, d, ...)$ is a vector of parameters
  ¡1¿i.e. $f(x, Q_0^2) = N x^a (1-x)^b P(x)$
- $\mathcal{O}(\boldsymbol{a})$ is an observable: i.e. PDFs, ΔPDFs, FF, cross sections
- Each flavor increases the number of parameters typically by ~ 5
- The combined PDF,ΔPDF and FF amount to analyzing $30 + 30 + 20 \times 2 \sim 100$ shape parameters

Data analysis framework:

The goal is to estimate:

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Maximum Likelihood

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

Data analysis framework:

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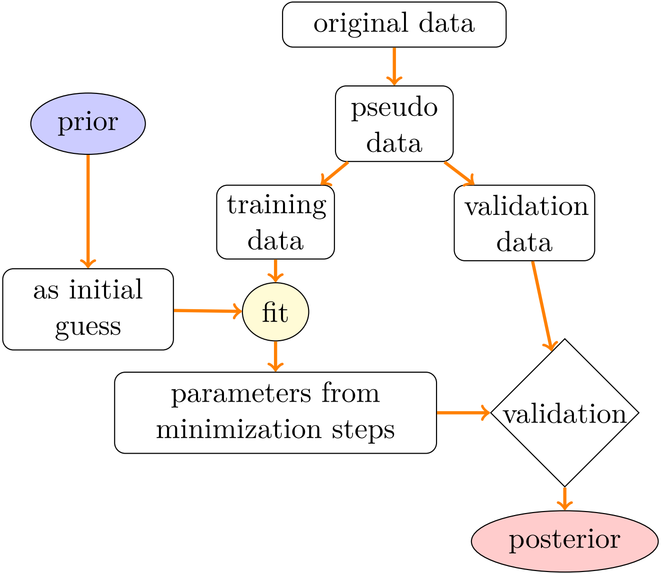
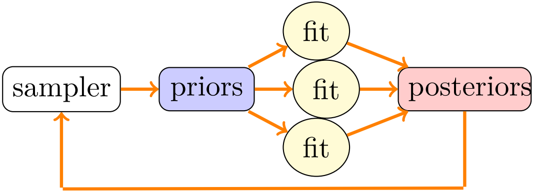
Monte Carlo methods

- $\mathcal{P}(\boldsymbol{a}|data) \rightarrow \{\boldsymbol{a}_k\}$
- $\mathrm{E}[\mathcal{O}] \approx \frac{1}{N}\sum_k \mathcal{O}(\boldsymbol{a}_k)$
- $\mathrm{V}[\mathcal{O}] \approx \frac{1}{N}\sum_k [\mathcal{O}(\boldsymbol{a}_k) - \mathrm{E}[\mathcal{O}]]^2$

Methodology



Iterative Monte Carlo analysis (IMC)



- Multiple iterations until convergence of posterior distribution
- 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

Fragmentation Functions from SIA data

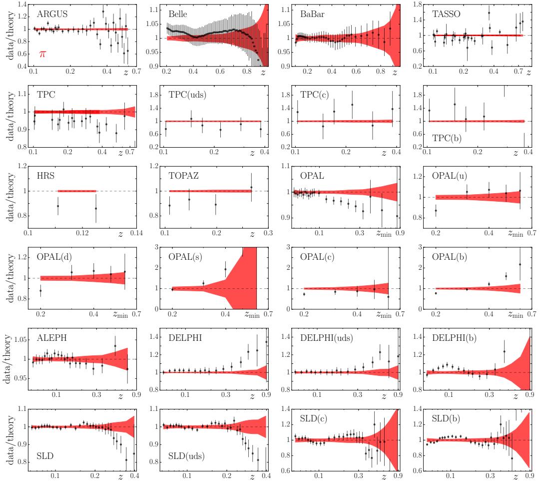
Technical details

- Use all available e^+e^- data from $Q = 10$ GeV $\rightarrow 91.2$ GeV that includes light and HQ separated samples
- Include recent measurements from Belle and BaBar
- Fit π and K FFs using pQCD @ NLO

$$\frac{1}{\sigma_{\rm TOT}}\frac{d\sigma^{h^\pm}}{dz}(z,Q^2) = \frac{2}{\sigma_{\rm TOT}}\left[\sum_q C_q \otimes D_{q^+}(z,Q^2) + C_g \otimes D_g(z,Q^2)\right]$$

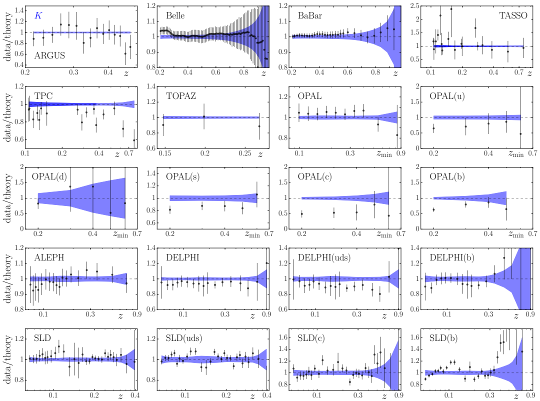
- ZMVS with input $Q_0^{u,d,s} = 1$ GeV and $Q_0^{c,b} = m_{c,b}$
- $z > 0.05$ for high energy data and $z > 0.1$ for low energy data
- Traditional ansatz
  - $D^{\rm favor}(z) = T_1(z) + T_2(z)$
  - $D^{\rm unfavor}(z) = T_1(x)$
  - $T_i(z) = \frac{M_i}{B(1+a_i,1+b_i)} z^{a_i}(1-z)^{b_i}$
- 24 kaon parameters and 18 pion parameters

π analysis $(\chi^2/N_{\text{pts}} = 1.31)$



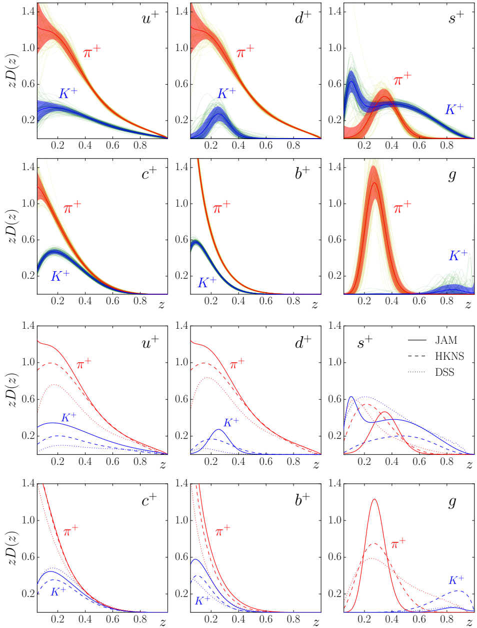
- We use BaBar prompt data set
- Belle data set needs 10% normalization
- Good agreement at low z for inclusive data sets
- Data inconsistencies at large z for $Q^2 = M_z^2$

K analysis $(\chi^2/N_{\rm pts} = 1.01)$



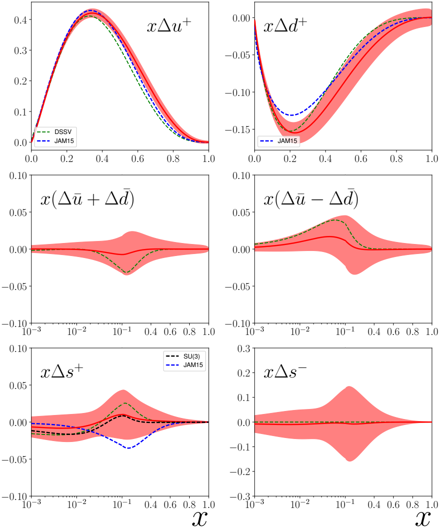
- $z_{\rm cut} > 0.2$ for low energies to avoid hadron mass corrections
- $z_{\rm cut} > 0.05$ for high energies
- Smaller χ^2 than π due to larger errors
- Consistent shapes across all z
- Inconsistencies mostly due to normalizations

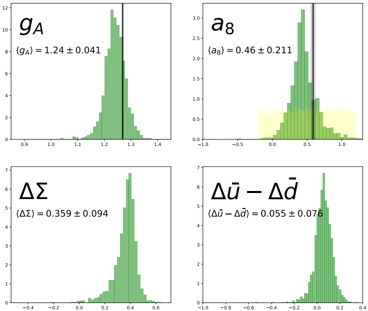
Fragmentation functions

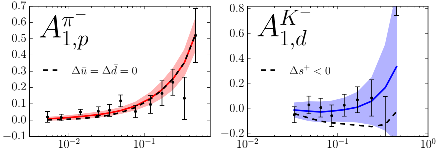


- Similar behavior of unfavored $D^{\pi}_{s^+}$ and $D^{K}_{d^+}$
- In contrast the D^{π}_{g} and D^{K}_{g} behave differently
- The charm and bottom FFs become compatible at large z
- Favored $D^{\pi}_{u^+}$ and $D^{K}_{s^+}$ have similar shape at large z
- JAM $D^{K}_{s^+}$ is more similar to DSS. **Will it change the sign of Δs^+?**

New combined analysis of ΔDIS+ΔSIDS+SIA





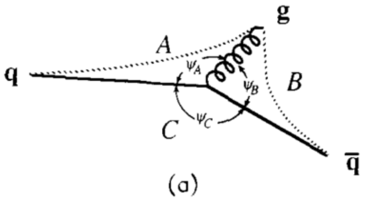


- The sign change of Δs^+ is given by Hermes K^-

Ethier et al. (2017)

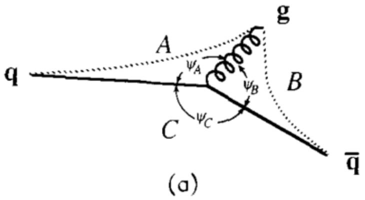
Study of FFs in pythia8+DIRE

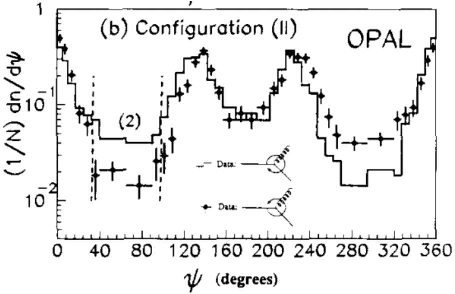
String effects: PLB261 (1991) (OPAL Collaboration)



- 3 Jets events: $Q\bar{Q}$ and gluon jets. Jets are projected into a plane
- ψ: angle of a given particle relative to the quark jet with the highest energy
- ψ_A: angle between highest energetic jet and gluon jet
- ψ_C: angle between quark jets
- Only events with $\psi_A = \psi_C$ are kept

String effects: PLB261 (1991) (OPAL Collaboration)





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- Only events with $\psi_A = \psi_C$ are kept
- **Particle flow asymmetry is observed → evidence of string effects**

Technical details

- Simulate e^+e^- at $Q = 30, 91.2, 1000$ GeV flavor by flavor

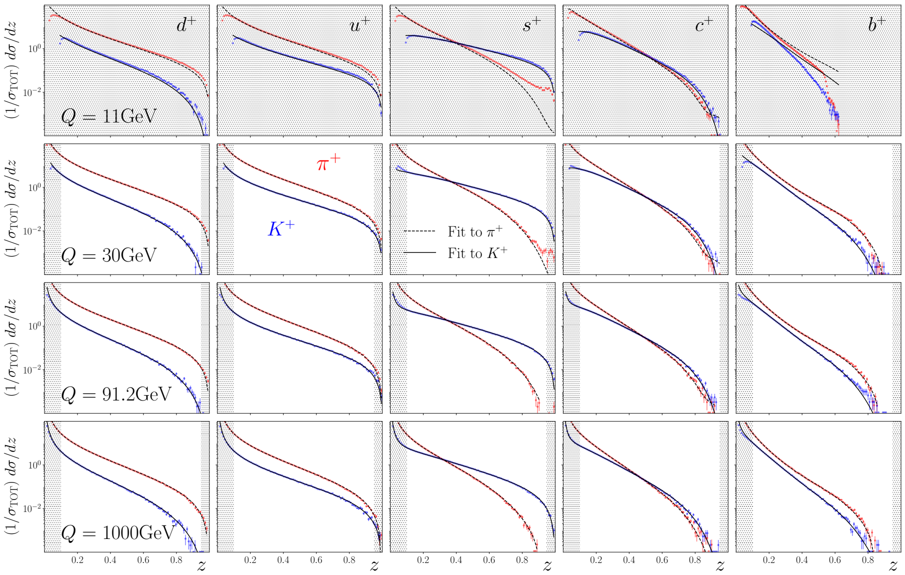
- Fit π and K FFs using pQCD @ NLO

$$\frac{1}{\sigma_{\rm TOT}}\frac{d\sigma_q^{h^\pm}}{dz}(z,Q^2) = \frac{2}{\sigma_{\rm TOT}}\left[C_q \otimes D_{q^+}(z,Q^2) + C_g \otimes D_g(z,Q^2)\right]$$

- ZMVS with input $Q_0 = 11\mathrm{GeV}$

- Parametrization: $D_{q^+}(z) = N z^\alpha (1-z)^\beta (1 + c_1 z + c_2 z^2 + ...)$

Pythia8 vs. collinear factorization (preliminary)



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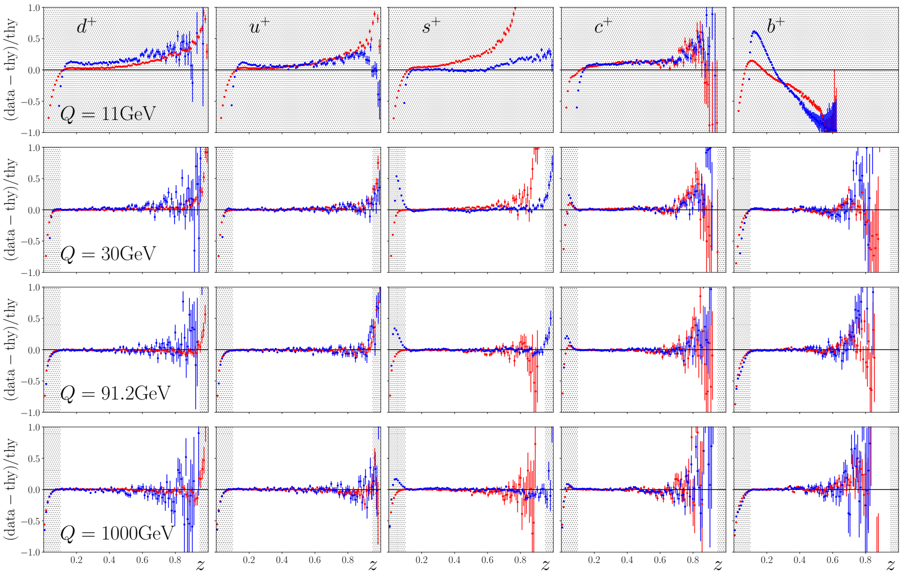

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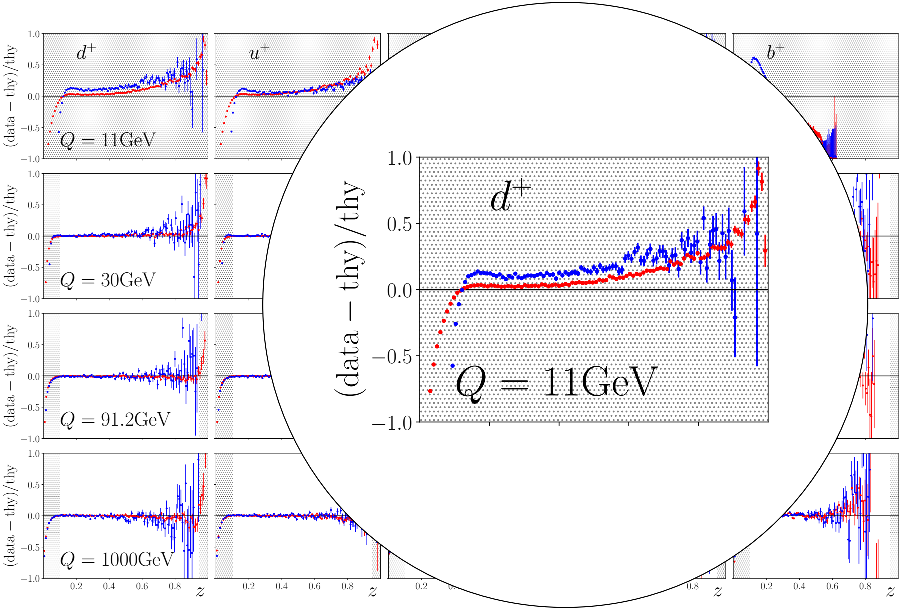
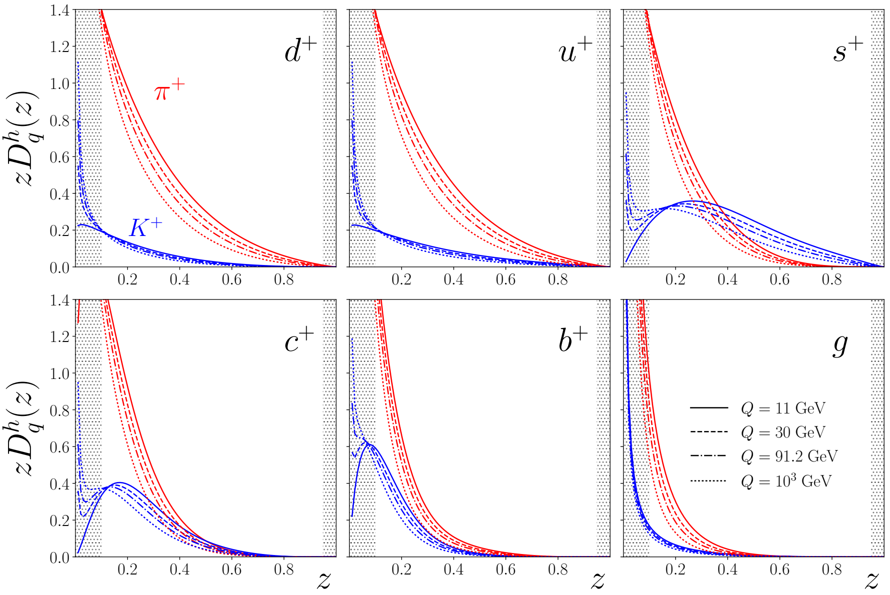


Pythia8+DIRE FFs (preliminary)



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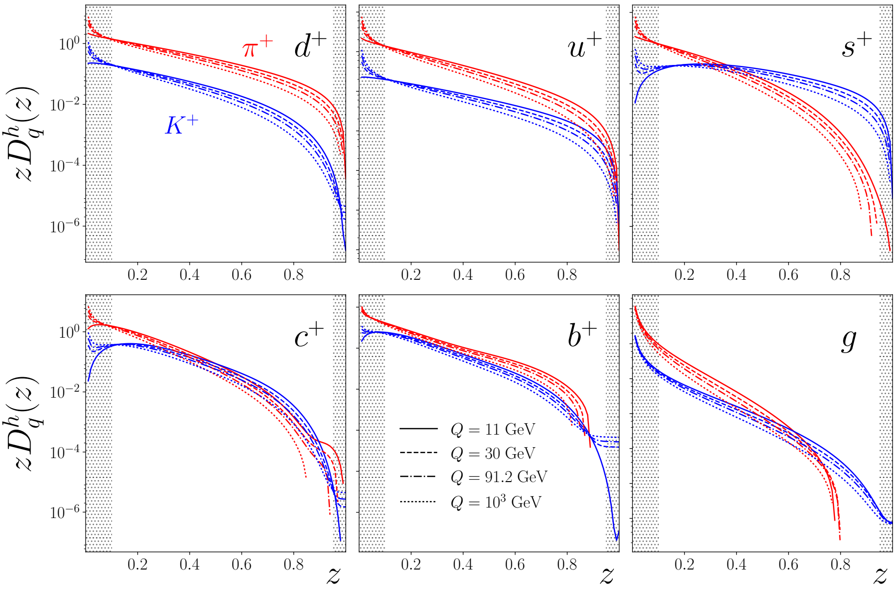
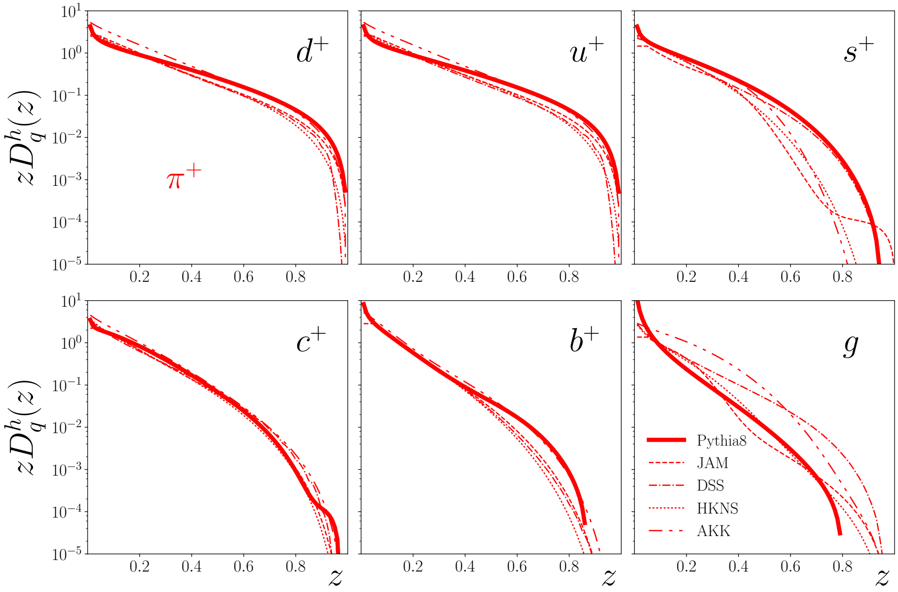
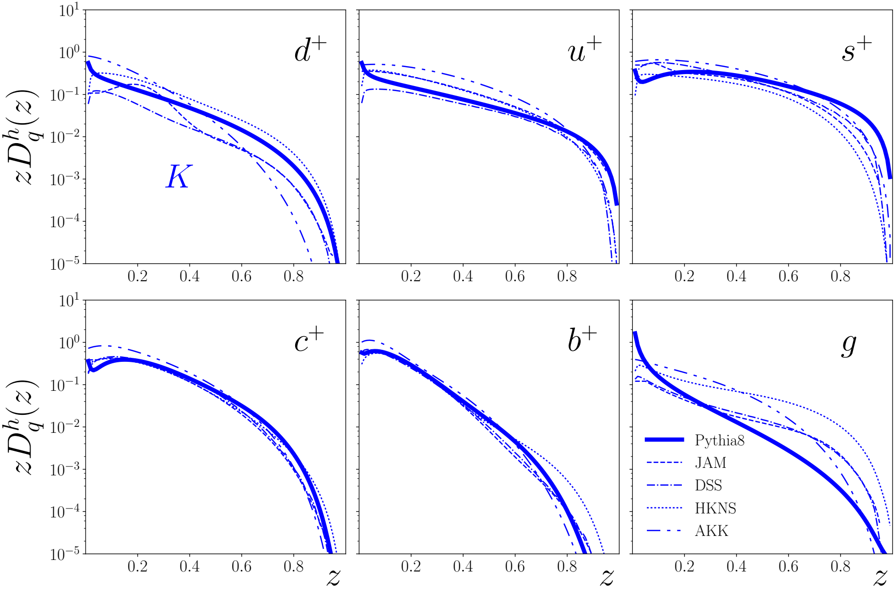


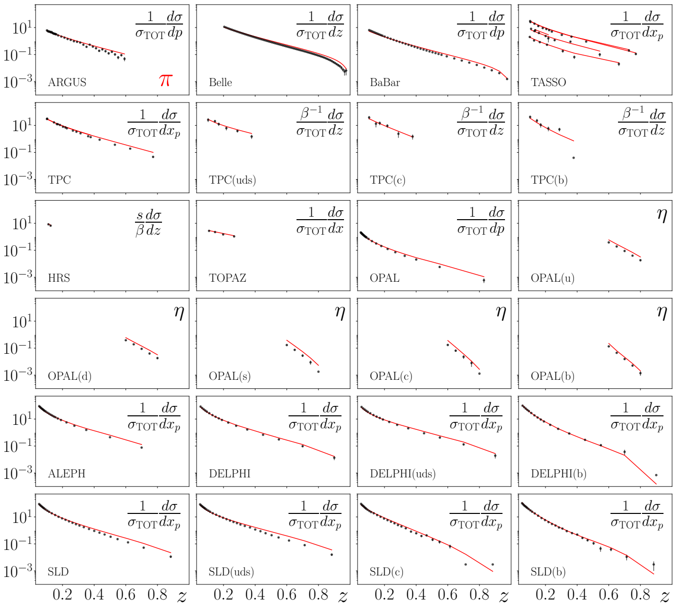
Pythia8+DIRE π FFs and other global analyses



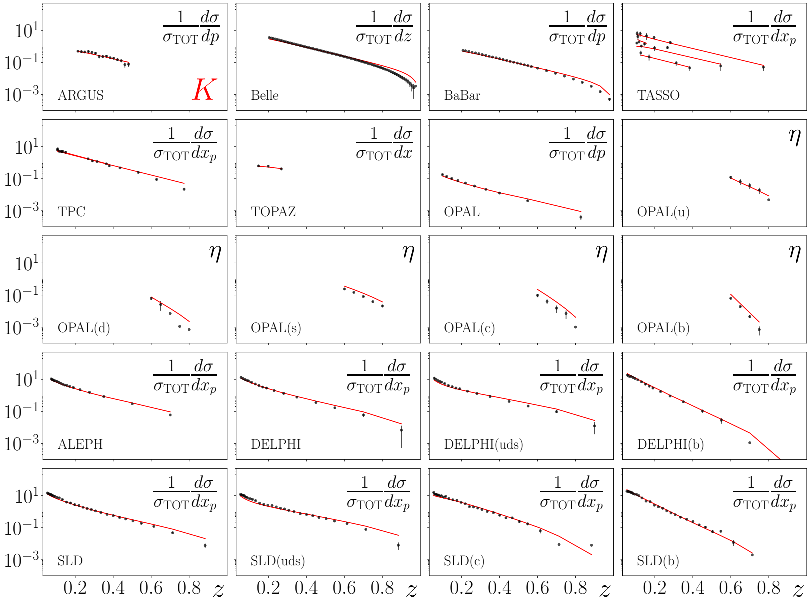
Pythia8+DIRE K FFs and other global analyses



Pythia8+DIRE vs global $e^+e^- \to \pi + X$



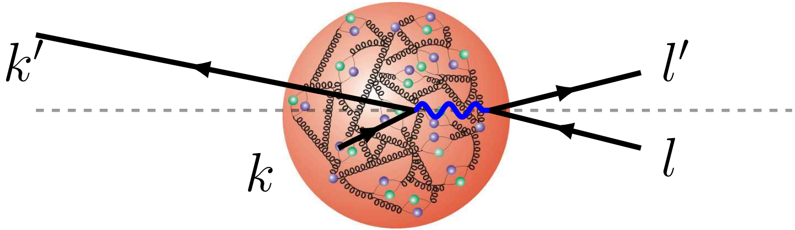
Pythia8+DIRE vs global $e^+e^- \to K + X$



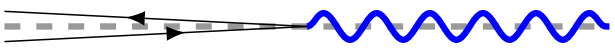
Beyond 1D distributions...

Intuitive picture

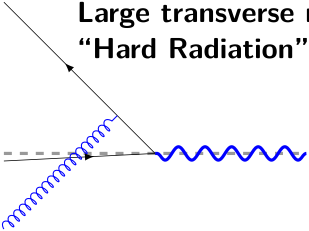
The Breit frame: $q = (0,0,0,-Q)$ and $P = (P^0, 0, 0, P_z)$



Small transverse mom.
“Intrinsic”



Large transverse mom.
“Hard Radiation”



Setup of the calculation

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

- Factorization in TMD observables

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

- 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**

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

- **CSS formalism**

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

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

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

SIDIS: small transverse momentum

- **W term formulation in b_T space**

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

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

$$\widetilde{W}_{UT}^{\sin(\phi_h+\phi_s)}(b_*) \equiv e^{-S_{pert}(Q,b_*)-S_{\mathrm{NP}}^{\mathrm{h_1}}(Q,b)-S_{\mathrm{NP}}^{\mathrm{H_1^{\perp}}}(Q,b)}\,\widetilde{F}_{UT}^{\sin(\phi_h+\phi_s)}(b_*)$$

- **Small b_T contribution**

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

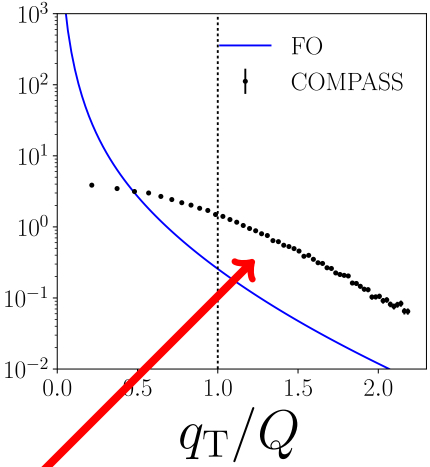
$$\widetilde{F}_{UT}^{\sin(\phi_h-\phi_s)}(b_*) = \sum_q e_q^2 \left(C_{q\leftarrow i}^{f_{1T}^{\perp}} \otimes f_{1T}^{\perp(1)i}(x_B,\mu_b)\right)\left(\hat{C}_{j\leftarrow q}^{\mathrm{D_1}} \otimes D_{h/j}(z_h,\mu_b)\right)$$

$$\widetilde{F}_{UT}^{\sin(\phi_h+\phi_s)}(b_*) = \sum_q e_q^2 \left(\delta C_{q\leftarrow i}^{h_1} \otimes h_1^i(x_B,\mu_b)\right)\left(\delta\hat{C}_{j\leftarrow q}^{\mathrm{H_1^{\perp}}} \otimes \hat{H}_1^{\perp(1)j}(z_h,\mu_b)\right)$$

- **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

  $Q^2 = 1.92$ GeV^2

  $x = 0.0318$

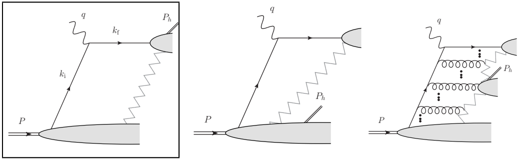
  $z = 0.375$

- Need order α_S^2 or beyond?
- Threshold resummation?
- Subleading power corrections?

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

SIDIS kinematics analysis Boglione et al (PLB.2017.01.02)

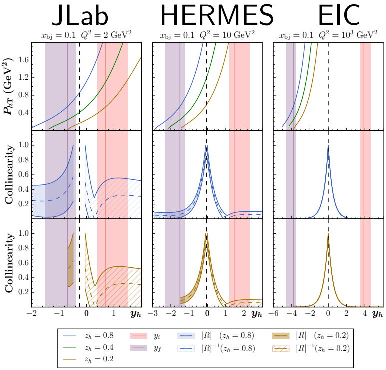
- **Can we apply factorization theorems in SIDIS measurements?**
- Factorization demands that



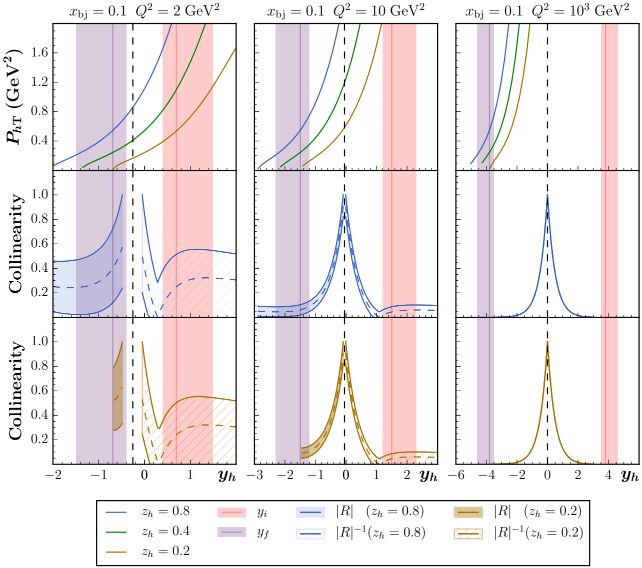
$$p_h \cdot k_f = \mathcal{O}(m^2)$$
$$p_h \cdot k_i = \mathcal{O}(Q^2)$$

- Define a *collinearity* parameter

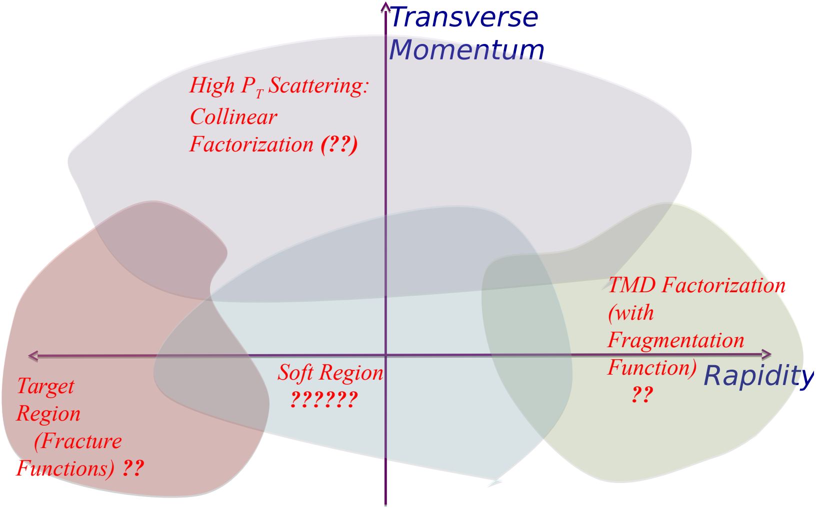
$$R = \frac{(p_h \cdot k_f)}{(p_h \cdot k_i)} = \mathcal{O}(m^2/Q^2)$$



SIDIS kinematics analysis



Map of Leading Twist SIDIS



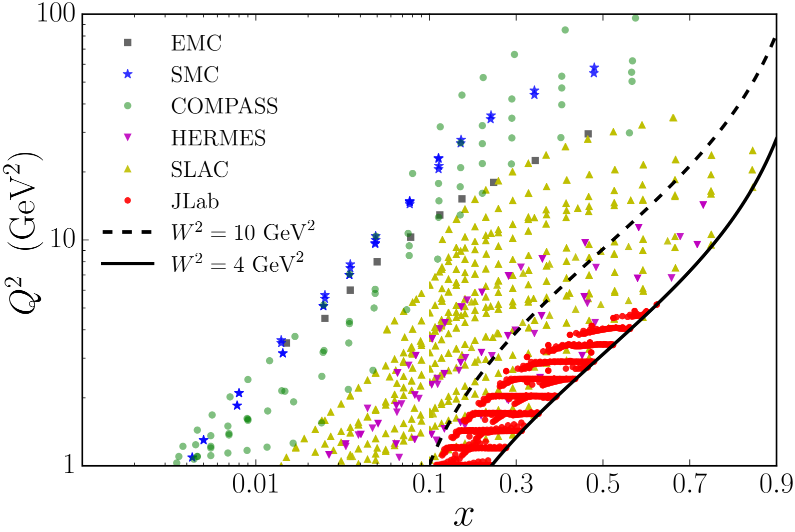
Summary and outlook

- **The collinear master plan:**
  - New MC fitting methodology
  - Combine polarized PDFs and FF analysis $\rightarrow$ sign of ΔS puzzle
  - The baseline PDFs, FFs for TMD studies
- **Open questions:**
  - Do we understand the shapes of FFs? Especially the gluon FF?
  - What governs the low–z FFs?
  - Can we trust in the collinear framework for SIDIS at low energies?
  - Are the SIDIS measurements in the current region?
- **MCEG for SIDIS:(new directions)**
  - Pythia8 validation of Hermes multiplicities
  - Extraction of FFs from Pythia8: test of DGLAP and Pythia8's parton shower

Backup

Spin PDFs from polarized DIS

Global polarized DIS data



Polarized DIS

Asymmetries

$$A_{||} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\downarrow\Downarrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\downarrow\Downarrow}} = D(A_1 + \eta A_2)$$

$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}} = d(A_2 - \xi A_1)$$

$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \qquad A_2 = \gamma \frac{(g_1 + g_2)}{F_1} \qquad \gamma^2 = \frac{4M^2x^2}{Q^2}$$

Polarized structure functions

$$g_1(x, Q^2) = g_1^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, \ldots) + g_1^{\mathrm{T3+TMC}}(D_u, D_d) + g_1^{\mathrm{T4}}(H_{p,n})$$

$$g_2(x, Q^2) = g_2^{\mathrm{LT+TMC}}(\Delta u^+, \Delta d^+, \Delta g, \ldots) + g_2^{\mathrm{T3+TMC}}(D_u, D_d)$$

Polarized DIS

$\rightarrow \xi = \frac{2x}{1+(1+4\mu^2x^2)^{1/2}}$
$\rightarrow \mu^2 = M^2/Q^2$

Leading twist structure functions:

$$g_1^{\mathrm{LT+TMC}}(x,Q^2) = \frac{x}{\xi}\frac{g_1^{\mathrm{LT}}(\xi)}{(1+4\mu^2x^2)^{3/2}} + 4\mu^2x^2\frac{x+\xi}{\xi(1+4\mu^2x^2)^2}\int_\xi^1 \frac{dz}{z} g_1^{\mathrm{LT}}(z) - 4\mu^2x^2\frac{2-4\mu^2x^2}{2(1+4\mu^2x^2)^{5/2}}\int_\xi^1\frac{dz}{z}\int_{z'}^1\frac{dz'}{z'}g_1^{\mathrm{LT}}(z')$$

$$g_2^{\mathrm{LT+TMC}}(x,Q^2) = -\frac{x}{\xi}\frac{g_1^{\mathrm{LT}}(\xi)}{(1+4\mu^2x^2)^{3/2}} + \frac{x}{\xi}\frac{(1-4\mu^2x\xi)}{(1+4\mu^2x^2)^2}\int_\xi^1\frac{dz}{z}g_1^{\mathrm{LT}}(z) + \frac{3}{2}\frac{4\mu^2x^2}{(1+4\mu^2x^2)^{5/2}}\int_\xi^1\frac{dz}{z}\int_{z'}^1\frac{dz'}{z'}g_1^{\mathrm{LT}}(z')$$

Leading twist quark distributions:

$$g_1^{\mathrm{LT}}(x) = \frac{1}{2}\sum_q e_q^2\left[\Delta C_{qq}\otimes\Delta q(x) + \Delta C_{qg}\otimes\Delta g(x)\right]$$

Polarized DIS

Twist-3 structure functions:

$$g_1^{\mathrm{T3+TMC}}(x,Q^2) = 4\mu^2x^2 \frac{D(\xi)}{(1+4\mu^2x^2)^{3/2}} - 4\mu^2x^2 \frac{3}{(1+4\mu^2x^2)^2} \int_\xi^1 \frac{dz}{z} D(z) + 4\mu^2x^2 \frac{2-4\mu^2x^2}{(1+4\mu^2x^2)^{5/2}} \int_\xi^1 \frac{dz}{z} \int_{z'}^1 \frac{dz'}{z'} D(z')$$

$$g_2^{\mathrm{T3+TMC}}(x,Q^2) = \frac{D(\xi)}{(1+4\mu^2x^2)^{3/2}} - \frac{1-8\mu^2x^2}{(1+4\mu^2x^2)^2} \int_\xi^1 \frac{dz}{z} D(z) - \frac{12\mu^2x^2}{(1+4\mu^2x^2)^{5/2}} \int_\xi^1 \frac{dz}{z} \int_{z'}^1 \frac{dz'}{z'} D(z')$$

Twist-3 quark distributions:

$$D(x,Q^2) = \frac{4}{9} D_u(x,Q^2) + \frac{1}{9} D_d(x,Q^2)$$

Polarized DIS

Twist-4 structure function (Nucleon d.o.f.):

$$g_1^{\mathrm{T4}(p,n)}(x, Q^2) = H^{(p,n)}(x)/Q^2$$

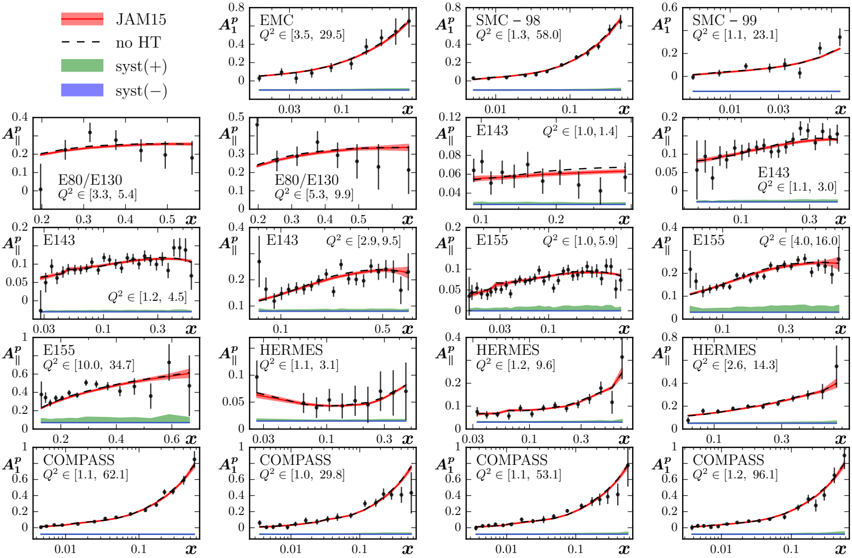
Nuclear corrections: $\rightarrow$ nuclear smearing functions

$$g_i^A(x, Q^2) = \sum_N \int \frac{dy}{y} f_{ij}^N(y, \gamma) g_j^N(x/y, Q^2)$$

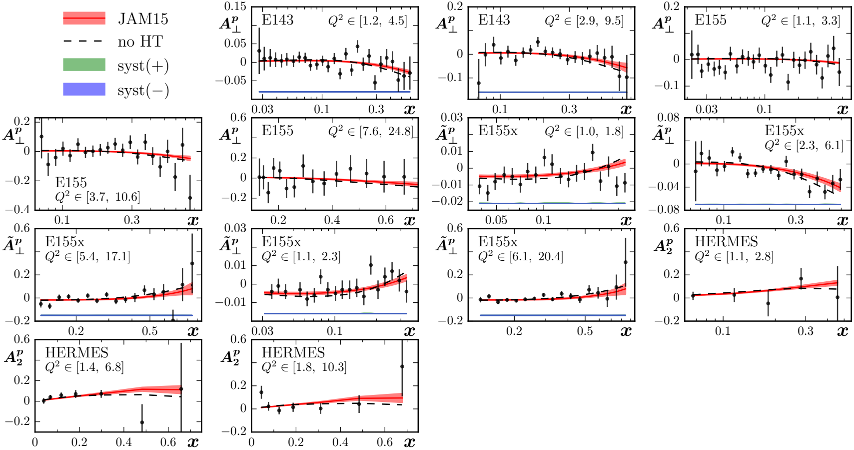
Addition constraints: $\rightarrow$ weak neutron and hyperon decay constants

- $\Delta u^{+(1)} - \Delta d^{+(1)} = F + D = 1.269(3)$
- $\Delta u^{+(1)} + \Delta d^{+(1)} - 2\Delta s^{+(1)} = 3F - D = 0.586(31)$

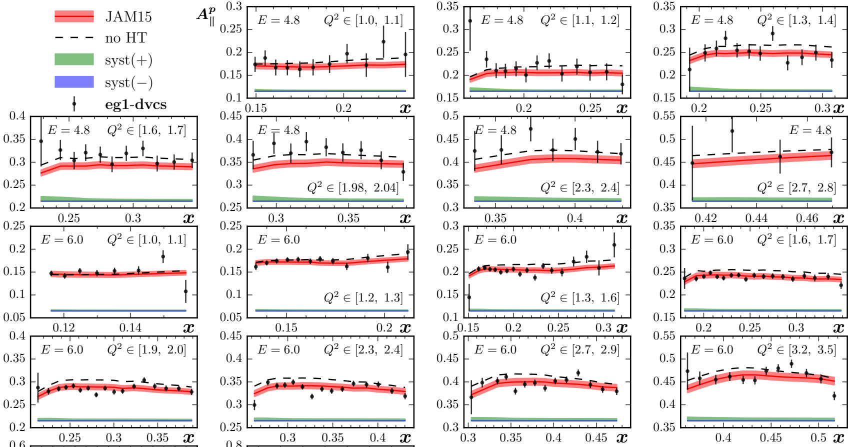
Data vs theory: proton

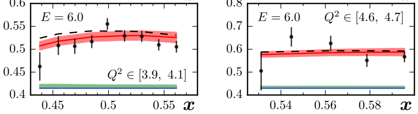


Data vs theory: proton



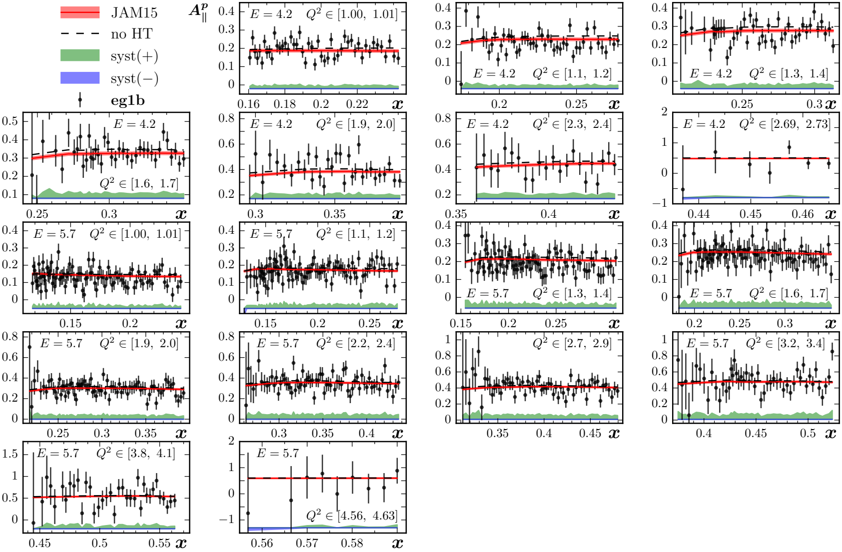
Data vs theory: proton JLab eg1-dvcs



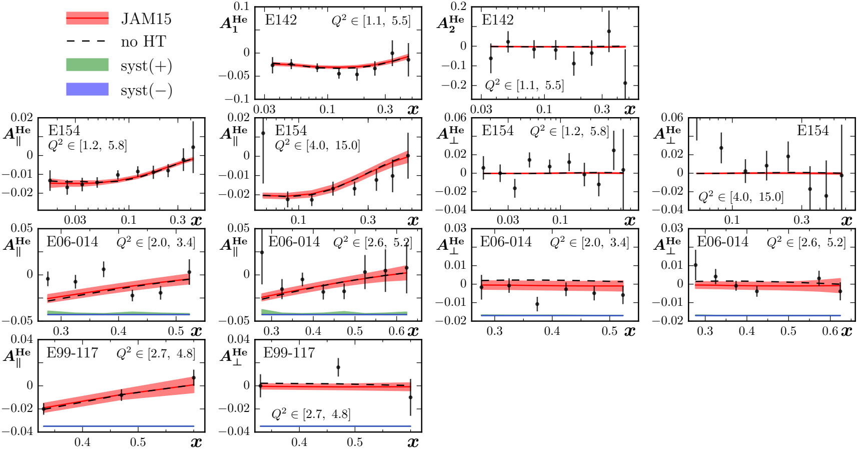


- Signal of HT contribution

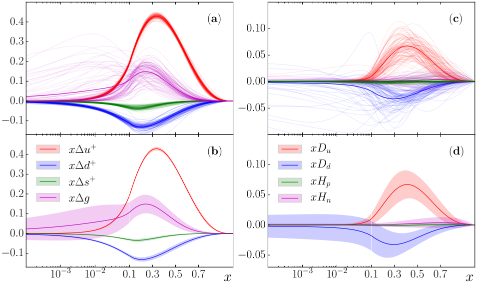
Data vs theory: proton JLab eg1b



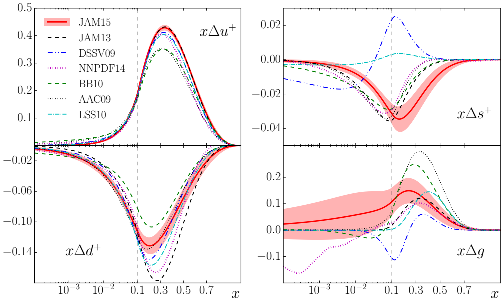
Data vs theory: ^{3}He



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	0.022 ± 0.008	0.022 ± 0.008
d_2^n	-0.004 ± 0.004	-0.004 ± 0.004
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