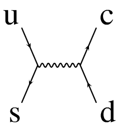
Correlations in Double Parton Scattering

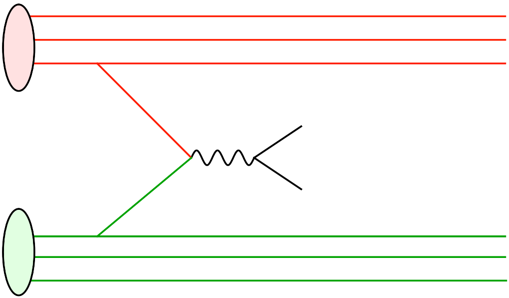
Wouter Waalewijn
UCSD



Pheno 2012

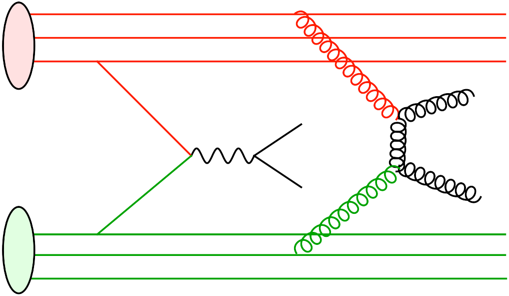
In collaboration with Aneesh Manohar
arXiv: 1202.3794,1202.5034

What is Double Parton Scattering?



- Single parton scattering (SPS): one partonic collision for colliding protons

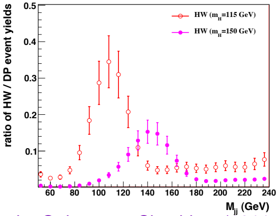
What is Double Parton Scattering?



- Single parton scattering (SPS): one partonic collision for colliding protons
- Double parton scattering (DPS): two partonic collisions (not pile-up!)
- DPS is $\Lambda^2_{\mathrm{QCD}}/Q^2$ suppressed, only important when signal is small

Examples

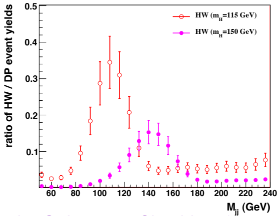
- Light Higgs searches, $pp \to WH \to \ell\nu b\bar{b}$: DPS background important
  [Del Fabbro, Treleani; Hussein; Berger, Jackson, Shaughnessy; Bandurin, Golovanov, Skachkov]



[Bandurin, Golovanov, Skachkov (1011.2186)]

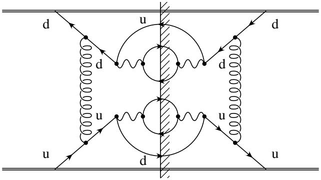
Examples

- Light Higgs searches, $pp \to WH \to \ell\nu b\bar{b}$: DPS background important
  [Del Fabbro, Treleani; Hussein; Berger, Jackson, Shaughnessy; Bandurin, Golovanov, Skachkov]



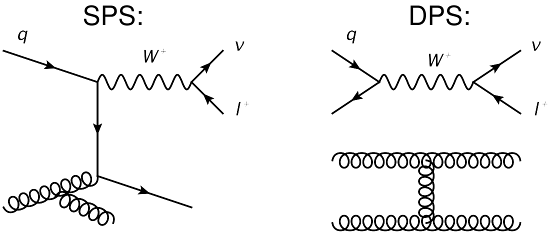
[Bandurin, Golovanov, Skachkov (1011.2186)]

- Same-sign leptons, $pp \to W^+W^+$: SPS requires additional jets
  [Kulesza, Stirling, Gaunt, Kom; Cattaruzza, Del Fabbro, Treleani; Meina]

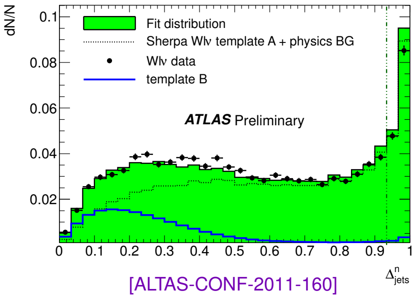


Examples

- $pp \to W + 2$ jets: DPS jets are back-to-back in transverse plane



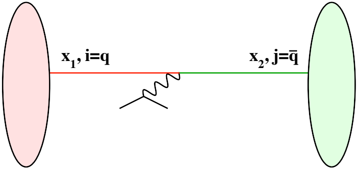
Double Parton Scattering at the LHC



[ALTAS-CONF-2011-160]

- $pp \to W + 2$ jets with $p_T^{\text{jet}} > 20$ GeV
- Use $\Delta^n_{\text{jets}} = |\vec{p}_T^{\text{ jet},1} + \vec{p}_T^{\text{ jet},2}| / (|\vec{p}_T^{\text{ jet},1}| + |\vec{p}_T^{\text{ jet},2}|)$
- DPS observed in $33\,\text{pb}^{-1}$ of data (no pile-up)
- Fit to shape of SPS/DPS from Monte Carlo
  $\to$ extract fraction of DPS events $f_{\text{DPS}} = 16\%$

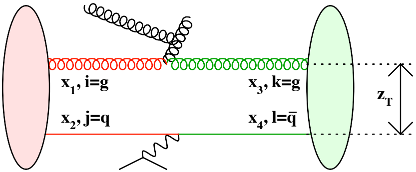
Calculating Cross Sections (Until Recently)



SPS: $$\mathrm{d}\sigma = \sum_{i,j} f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1 x_2 s)$$

- PDF $f_i(x)$ is probability in x for finding parton of type $i = g, u, \bar{u}, d, \ldots$
- $\hat{\sigma}_{ij}$ is partonic cross section for $ij \rightarrow$ final state

Calculating Cross Sections (Until Recently)



SPS:

$$\mathrm{d}\sigma = \sum_{i,j} f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}(x_1 x_2 s)$$

- PDF $f_i(x)$ is probability in x for finding parton of type $i = g, u, \bar{u}, d, \ldots$
- $\hat{\sigma}_{ij}$ is partonic cross section for $ij \to$ final state

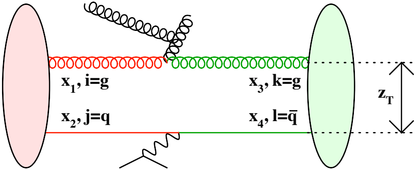
DPS:

$$\mathrm{d}\sigma = \int \mathrm{d}^2 z_T \sum_{i,j,k,l} F_{ij}(x_1, x_2, z_T) F_{kl}(x_3, x_4, z_T) \hat{\sigma}_{ik}(x_1 x_3 s) \hat{\sigma}_{jl}(x_2 x_4 s)$$

[Paver, Treleani]

- Double PDF $F_{ij}(x_1, x_2, z_T)$ depends on transverse separation z_T

Effective Cross Section

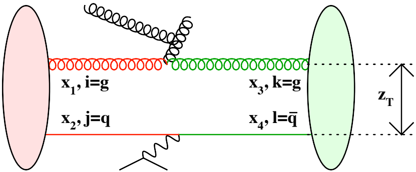


$$\mathrm{d}\sigma = \int \mathrm{d}^2 z_T \sum_{i,j,k,l} F_{ij}(x_1, x_2, z_T) F_{kl}(x_3, x_4, z_T) \hat{\sigma}_{ik}(x_1 x_3 s) \hat{\sigma}_{jl}(x_2 x_4 s)$$

Commonly-used assumptions:

- No correlation between x_i and z_T: $F_i(x_1, x_2, z_T) = F_i(x_1, x_2) F(z_T)$
- Uncorrelated partons: $F_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2)$
  Not valid at large x, since $x_1 + x_2 \leq 1$

Effective Cross Section



$$\mathrm{d}\sigma = \int \mathrm{d}^2 z_T \sum_{i,j,k,l} F_{ij}(x_1, x_2, z_T) F_{kl}(x_3, x_4, z_T) \hat{\sigma}_{ik}(x_1 x_3 s) \hat{\sigma}_{jl}(x_2 x_4 s)$$

Commonly-used assumptions:

- No correlation between x_i and z_T: $F_i(x_1, x_2, z_T) = F_i(x_1, x_2) F(z_T)$
- Uncorrelated partons: $F_{ij}(x_1, x_2) = f_i(x_1) f_j(x_2)$
  Not valid at large x, since $x_1 + x_2 \leq 1$

Effective cross section:

$$\sigma \sim \sigma_1 \sigma_2 \int \mathrm{d}^2 z_T \, F(z_T)^2 = \frac{\sigma_1 \sigma_2}{\sigma_{\text{eff}}}$$

- $\sigma_{\text{eff}} \sim 1/\Lambda^2_{\text{QCD}} \sim$ mB.
- Experimentally: $\sigma_{\text{eff}} \sim 5 - 15$ mB

Full QCD analysis

Our work:

- QCD factorization of the cross section (without assumptions)
- Field-theoretic definition of double PDFs $\rightarrow$ derive RGE and properties
- Addresses obstacles:
  - Rapidity divergences complicate factorization
  - Overlap between single and double PDFs

Full QCD analysis

Our work:

- QCD factorization of the cross section (without assumptions)
- Field-theoretic definition of double PDFs → derive RGE and properties
- Addresses obstacles:
  - Rapidity divergences complicate factorization
  - Overlap between single and double PDFs

Factorization for double Drell-Yan [Manohar, WW]

$$\frac{d\sigma^{\text{DPS}}}{dq_1^2\, dY_1\, dq_2^2\, dY_2} = \left(\frac{4\pi\alpha^2 Q_q^2}{3N_c\, s}\right)^2 \frac{1}{q_1^2 q_2^2} \int d^2 z_T \Big\{ \Big[F^1_{qq}F^1_{\bar q\bar q} + F^1_{q\bar q}F^1_{\bar q q} + F^1_{\Delta q\Delta q}F^1_{\Delta\bar q\Delta\bar q} + F^1_{\Delta q\Delta\bar q}F^1_{\Delta\bar q\Delta q}\Big]$$
$$+ \frac{2N_c}{C_F}\Big[(F^T_{qq}F^T_{\bar q\bar q} + F^T_{\Delta q\Delta q}F^T_{\Delta\bar q\Delta\bar q}) + (F^T_{q\bar q}F^T_{\bar q q} + F^T_{\Delta q\Delta\bar q}F^T_{\Delta\bar q\Delta q})\Big] S^{TT}$$
$$+ \frac{1}{2}\Big[(I^1_{\bar q q} + I^1_{\Delta\bar q\Delta q})(I^1_{q\bar q} + I^1_{\Delta q\Delta\bar q}) + I^1_{\delta\bar q\delta q}I^1_{\delta q\delta\bar q}\Big] S_I^{11}$$
$$+ \frac{N_c}{2}\Big[(I^T_{\bar q q} + I^T_{\Delta\bar q\Delta q})(I^1_{q\bar q} + I^1_{\Delta q\Delta\bar q}) + I^T_{\delta\bar q\delta q}I^1_{\delta q\delta\bar q} + (1\leftrightarrow T)\Big] S_I^{T1}$$
$$+ \frac{N_c}{C_F}\Big[(I^T_{\bar q q} + I^T_{\Delta\bar q\Delta q})(I^T_{q\bar q} + I^T_{\Delta q\Delta\bar q}) + I^T_{\delta\bar q\delta q}I^T_{\delta q\delta\bar q}\Big] S_I^{TT} + (q\leftrightarrow\bar q)\Big\}$$

- New effects: spin correlations, color correlations, interference in fermion number, soft radiation

Full QCD analysis

Our work:

- QCD factorization of the cross section (without assumptions)
- Field-theoretic definition of double PDFs → derive RGE and properties
- Addresses obstacles:
  - Rapidity divergences complicate factorization
  - Overlap between single and double PDFs

Factorization for double Drell-Yan [Manohar, WW]

$$\frac{d\sigma^{\text{DPS}}}{dq_1^2\, dY_1\, dq_2^2\, dY_2} = \left(\frac{4\pi\alpha^2 Q_q^2}{3N_c\, s}\right)^2 \frac{1}{q_1^2 q_2^2} \int d^2 z_T \Big\{ \Big[F^1_{qq} F^1_{\bar{q}\bar{q}} + F^1_{q\bar{q}} F^1_{\bar{q}q} + F^1_{\Delta q \Delta q} F^1_{\Delta\bar{q}\Delta\bar{q}} + F^1_{\Delta q\Delta\bar{q}} F^1_{\Delta\bar{q}\Delta q} \Big]$$

$$+ \frac{2N_c}{C_F} \Big[(F^T_{qq} F^T_{\bar{q}\bar{q}} + F^T_{\Delta q\Delta q} F^T_{\Delta\bar{q}\Delta\bar{q}}) + (F^T_{q\bar{q}} F^T_{\bar{q}q} + F^T_{\Delta q\Delta\bar{q}} F^T_{\Delta\bar{q}\Delta q}) \Big] S^{TT}$$

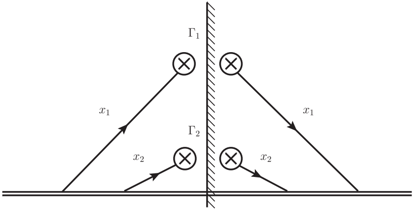
$$+ \frac{1}{2} \Big[(I^1_{\bar{q}q} + I^1_{\Delta\bar{q}\Delta q})(I^1_{q\bar{q}} + I^1_{\Delta q\Delta\bar{q}}) + I^1_{\delta\bar{q}\delta q} I^1_{\delta q\delta\bar{q}} \Big] S_I^{11}$$

$$+ \frac{N_c}{2} \Big[(I^T_{\bar{q}q} + I^T_{\Delta\bar{q}\Delta q})(I^1_{q\bar{q}} + I^1_{\Delta q\Delta\bar{q}}) + I^T_{\delta\bar{q}\delta q} I^1_{\delta q\delta\bar{q}} + (1 \leftrightarrow T) \Big] S_I^{T1}$$

$$+ \frac{N_c}{C_F} \Big[(I^T_{\bar{q}q} + I^T_{\Delta\bar{q}\Delta q})(I^T_{q\bar{q}} + I^T_{\Delta q\Delta\bar{q}}) + I^T_{\delta\bar{q}\delta q} I^T_{\delta q\delta\bar{q}} \Big] S_I^{TT} + (q \leftrightarrow \bar{q}) \Big\}$$

- New effects: spin correlations, color correlations, interference in fermion number, soft radiation
- We find: color correlations and interferences are Sudakov suppressed!

Double PDF Definition

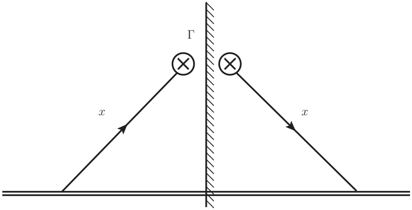


$$F^1_{qq}\left(\frac{q_1^-}{p_1^-}, \frac{q_2^-}{p_1^-}, z_T\right) = -4\pi\, p_1^- \int \frac{dz_1^+}{4\pi}\frac{dz_2^+}{4\pi}\frac{dz_3^+}{4\pi} e^{-iq_1^- z_1^+/2} e^{-iq_2^- z_2^+/2} e^{iq_1^- z_3^+/2}$$
$$\times \langle p_1 | \overline{T}\left\{\left[\overline{\psi}(z_1^+, 0, z_T)\frac{\not{\bar{n}}}{2}\right]_a \left[\overline{\psi}(z_2^+, 0, 0_T)\frac{\not{\bar{n}}}{2}\right]_b\right\}$$
$$T\left\{\psi_a(z_3^+, 0, z_T)\psi_b(0)\right\} |p_1\rangle$$

- Like a PDF at z_T and 0_T
- Wilson lines ensure gauge invariance (not shown)

Spin Correlations for Single PDF

[Mekhfi; Diehl, Ostermeier, Schäfer; Manohar, WW]



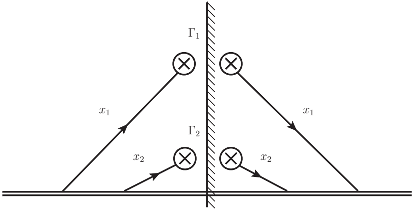
$$f_q(x) \sim \langle p | \bar{q} \Gamma q | p \rangle$$

- Single PDF spin structures:

$\Gamma = \frac{1}{2}\bar{n}\!\!\!/$	$q(x)$	unpolarized
$\Gamma = \frac{1}{2}\bar{n}\!\!\!/\gamma_5$	$\Delta q(x)$	longitudinally polarized
$\Gamma = \frac{i}{2}\bar{n}_\nu\sigma^{\mu\nu}\gamma_5$	$\delta q(x)$	transversely polarized

Spin Correlations for Double PDF

[Mekhfi; Diehl, Ostermeier, Schäfer; Manohar, WW]



$$F_{qq}(x_1, x_2, z_T) \sim \langle p | \bar{q}_1 \Gamma_1 q_1 \, \bar{q}_2 \Gamma_2 q_2 | p \rangle$$

- Single PDF spin structures:

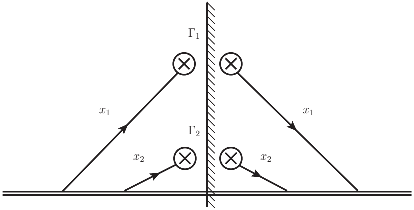
$\Gamma = \frac{1}{2}\bar{n}\!\!\!/$	$q(x)$	unpolarized
$\Gamma = \frac{1}{2}\bar{n}\!\!\!/\gamma_5$	$\Delta q(x)$	longitudinally polarized
$\Gamma = \frac{i}{2}\bar{n}_\nu \sigma^{\mu\nu}\gamma_5$	$\delta q(x)$	transversely polarized

- Unpolarized double PDF has spin correlations:

$$\Gamma_1 \otimes \Gamma_2 = \frac{1}{2}\bar{n}\!\!\!/ \otimes \frac{1}{2}\bar{n}\!\!\!/, \quad \frac{1}{2}\bar{n}\!\!\!/\gamma_5 \otimes \frac{1}{2}\bar{n}\!\!\!/\gamma_5, \quad \frac{1}{2}\bar{n}\!\!\!/ \otimes \frac{i}{2}\bar{n}^\mu \sigma_{\mu\rho}\gamma_5 \, z_T^\rho, \ \ldots$$

Spin Correlations for Double PDF

[Mekhfi; Diehl, Ostermeier, Schäfer; Manohar, WW]



$$F_{qq}(x_1, x_2, z_T) \sim \langle p|\bar{q}_1 \Gamma_1 q_1\, \bar{q}_2 \Gamma_2 q_2|p\rangle$$

- Single PDF spin structures:

$\Gamma = \frac{1}{2}\bar{n}\!\!\!/$	$q(x)$	unpolarized
$\Gamma = \frac{1}{2}\bar{n}\!\!\!/\gamma_5$	$\Delta q(x)$	longitudinally polarized
$\Gamma = \frac{i}{2}\bar{n}_\nu \sigma^{\mu\nu}\gamma_5$	$\delta q(x)$	transversely polarized

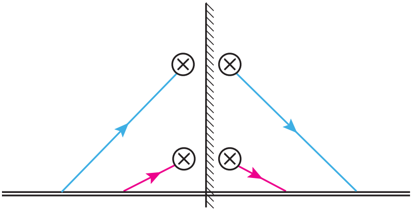
- Unpolarized double PDF has spin correlations:

$$\Gamma_1 \otimes \Gamma_2 = \frac{1}{2}\bar{n}\!\!\!/ \otimes \frac{1}{2}\bar{n}\!\!\!/, \quad \frac{1}{2}\bar{n}\!\!\!/\gamma_5 \otimes \frac{1}{2}\bar{n}\!\!\!/\gamma_5, \quad \frac{1}{2}\bar{n}\!\!\!/ \otimes \frac{i}{2}\bar{n}^\mu \sigma_{\mu\rho}\gamma_5\, z_T^\rho, \;\ldots$$

- Interpretation:

$$F_{\Delta q \Delta q} \sim \langle p|(a^\dagger_{1R} a_{1R} - a^\dagger_{1L} a_{1L})(a^\dagger_{2R} a_{2R} - a^\dagger_{2L} a_{2L})|p\rangle$$

Color Correlations

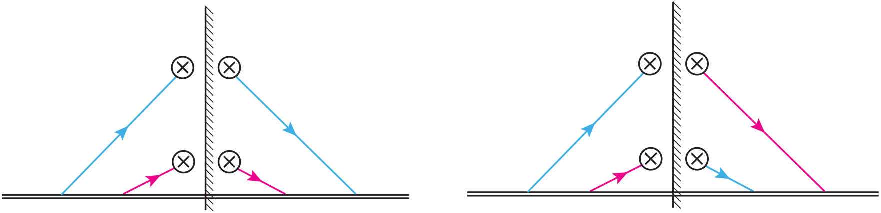


$$F_{q\bar{q}}(x_1, x_2, z_T) \sim \langle p|\bar{q}_1\Gamma_1 q_1\ \bar{q}_2\Gamma_2 q_2|p\rangle$$

- Double PDF color structures:

$$\Gamma_1 \otimes \Gamma_2 = \mathbf{1} \otimes \mathbf{1}, \quad T^A \otimes T^A$$

Color Correlations

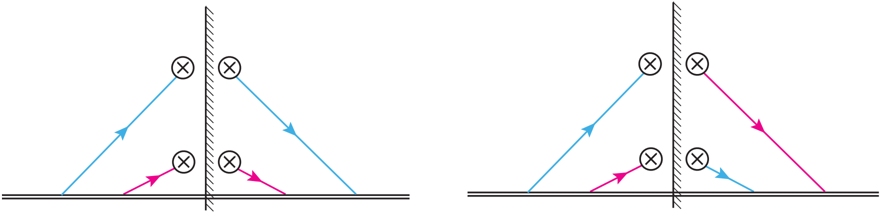


$$F_{q\bar{q}}(x_1, x_2, z_T) \sim \langle p|\bar{q}_1\Gamma_1 q_1\ \bar{q}_2\Gamma_2 q_2|p\rangle$$

- Double PDF color structures:

$$\Gamma_1 \otimes \Gamma_2 = 1 \otimes 1, \quad T^A \otimes T^A$$

Color Correlations



$$F_{q\bar{q}}(x_1, x_2, z_T) \sim \langle p|\bar{q}_1\Gamma_1 q_1\ \bar{q}_2\Gamma_2 q_2|p\rangle$$

- Double PDF color structures:

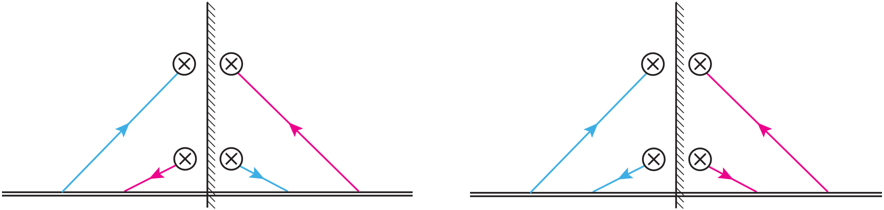
$$\Gamma_1 \otimes \Gamma_2 = 1 \otimes 1, \quad T^A \otimes T^A$$

- $T^A \otimes T^A$ measures color correlation

$$F^{(1)}_{q\bar{q}} = F^1_{q\bar{q}} + \frac{N^2-1}{2N} F^T_{q\bar{q}}, \quad F^{(8)}_{q\bar{q}} = F^1_{q\bar{q}} - \frac{1}{2N} F^T_{q\bar{q}}$$

$$F^{(6)}_{qq} = F^1_{qq} + \frac{N-1}{2N} F^T_{qq}, \quad F^{(\bar{3})}_{qq} = F^1_{qq} - \frac{N+1}{2N} F^T_{qq}$$

Interference Effects

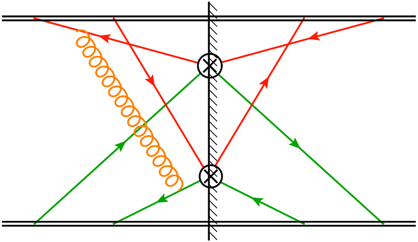


- Interference in fermion number is possible

$$I_{q\bar{q}}(x_1, x_2, z_T) \sim \langle p|\bar{q}_2\Gamma_1 q_1 \; \bar{q}_2\Gamma_2 q_1|p\rangle$$

- The interference double PDF does not have to be real: $I^*_{q\bar{q}} = I_{\bar{q}q}$

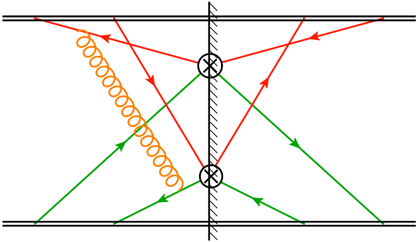
Soft Gluon Emissions



$$\sigma \sim \hat{\sigma}\hat{\sigma} \int d^2 z_T \, [F^1_{qq}(x_1, x_2, z_T) F^1_{\bar{q}\bar{q}}(x_3, x_4, z_T) S^{11}(z_T) + F^T_{qq}(x_1, x_2, z_T) F^T_{\bar{q}\bar{q}}(x_3, x_4, z_T) S^{TT}(z_T) + \ldots]$$

- Soft radiation resolves large $z_T \sim 1/\Lambda_{\mathrm{QCD}}$ separation

Soft Gluon Emissions



$$\sigma \sim \hat{\sigma}\hat{\sigma} \int d^2 z_T \, [F^1_{qq}(x_1, x_2, z_T) F^1_{\bar{q}\bar{q}}(x_3, x_4, z_T) S^{11}(z_T) + F^T_{qq}(x_1, x_2, z_T) F^T_{\bar{q}\bar{q}}(x_3, x_4, z_T) S^{TT}(z_T) + \ldots]$$

- Soft radiation resolves large $z_T \sim 1/\Lambda_{\rm QCD}$ separation
- Soft gluon emissions summed in eikonal Wilson lines S_n and $S_{\bar{n}}$

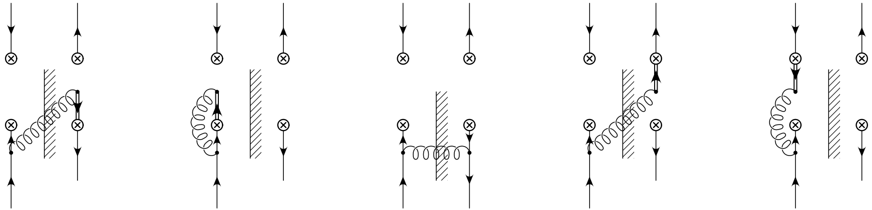
$$S^{11}(z_T) = \langle 0 | \mathrm{tr}[S^\dagger_{\bar{n}} S_n S^\dagger_n S_{\bar{n}}](0)\, \mathrm{tr}[S^\dagger_{\bar{n}} S_n S^\dagger_n S_{\bar{n}}](z_T) | 0 \rangle = \mathrm{tr}[1]^2 = N_c^2$$

$$S^{TT}(z_T) = \langle 0 | \mathrm{tr}[T^A S^\dagger_{\bar{n}} S_n T^B S^\dagger_n S_{\bar{n}}](0)\, \mathrm{tr}[T^A S^\dagger_{\bar{n}} S_n T^B S^\dagger_n S_{\bar{n}}](z_T) | 0 \rangle$$

[Manohar, WW]

Double PDF Evolution

[Manohar, WW]

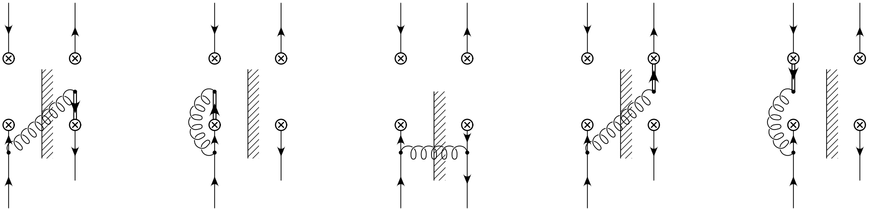


$$\gamma_\mu^{F^1} = \frac{\alpha_s C_F}{\pi} P_{qq}(x_1)\delta(1-x_2)$$

- $+ (x_1 \leftrightarrow x_2)$ and mixing contributions not included
- F^1_{qq} has the usual splitting function evolution

Double PDF Evolution

[Manohar, WW]

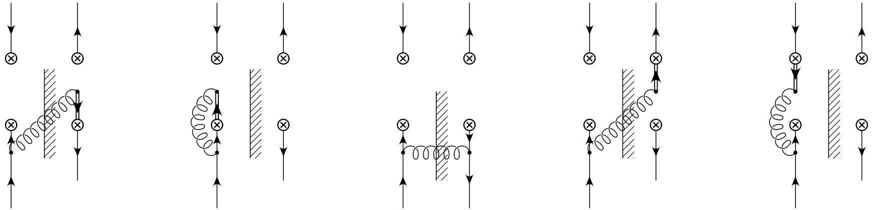


$$\gamma_\mu^{F^T} + \frac{1}{2}\gamma_\mu^{S^T} = \frac{\alpha_s}{\pi}\left[\left(C_F - \frac{1}{2}C_A\right)P_{qq}(x_1) + C_A\left(\frac{3}{4} - \ln\frac{p_1^-}{\mu}\right)\delta(1-x_1)\right]\delta(1-x_2)$$

- $+ (x_1 \leftrightarrow x_2)$ and mixing contributions not included
- Rapidity divergences require extra regulator, use [Chiu, Jain, Neill, Rothstein]
- F_{qq}^T has color factor $C_F - \frac{1}{2}C_A = -1/6 \to$ "reverse" evolution

Double PDF Evolution

[Manohar, WW]



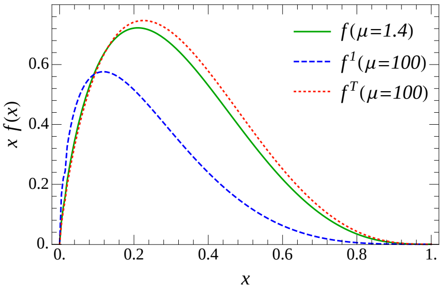
$$\gamma_\mu^{F^T} + \frac{1}{2}\gamma_\mu^{S^T} = \frac{\alpha_s}{\pi}\left[\left(C_F - \frac{1}{2}C_A\right)P_{qq}(x_1) + C_A\left(\frac{3}{4} - \ln\frac{p_1^-}{\mu}\right)\delta(1-x_1)\right]\delta(1-x_2)$$

- $+ (x_1 \leftrightarrow x_2)$ and mixing contributions not included
- Rapidity divergences require extra regulator, use [Chiu, Jain, Neill, Rothstein]
- F_{qq}^T has color factor $C_F - \frac{1}{2}C_A = -1/6 \to$ "reverse" evolution
- Remaining terms affect overall normalization $\to$ Sudakov suppression:

$$U_\mu(\Lambda, Q) = \exp\left[-\frac{\alpha_s C_A}{\pi}\left(\frac{1}{2}\ln^2\frac{Q^2}{\Lambda^2} - \frac{3}{2}\ln\frac{Q^2}{\Lambda^2}\right)\right]$$

[Agrees with Mekhfi, Artru]

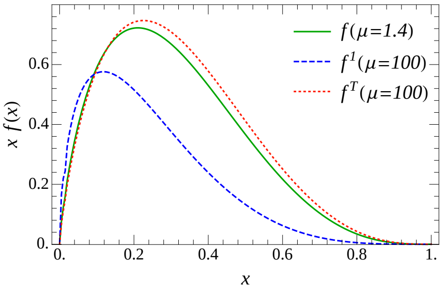
Numerical Results for Color Correlations

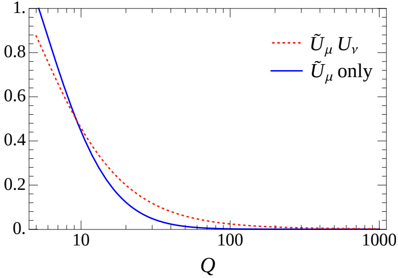


[Using HOPPET (Salam, Rojo)]

- The reverse evolution in x is shown for a sample PDF

Numerical Results for Color Correlations

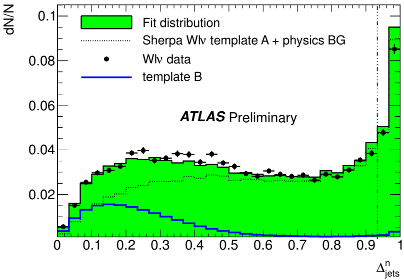


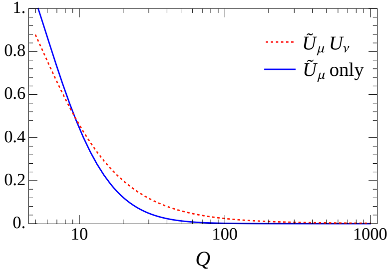


[Using HOPPET (Salam, Rojo)]

- The reverse evolution in x is shown for a sample PDF
- Sudakov double logarithmic suppression $\tilde{U}_\mu$ and Rapidity single logarithmic enhancement U_ν
- Mixing with single PDFs generates color correlations and is not included

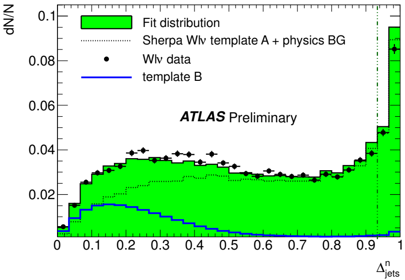
Conclusions

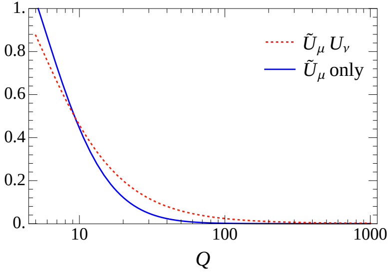




- Double parton scattering has been observed
- Higher twist but important for e.g. light Higgs
- Approximate description $\sigma \sim \sigma_1 \sigma_2 / \sigma_{\text{eff}}$
- Our QCD analysis:
  - Full factorization analysis of cross section
  - Field-theoretic definition of double PDF $\rightarrow$ derive evolution
  - Color correlations and interferences are Sudakov suppressed

Conclusions





- Double parton scattering has been observed
- Higher twist but important for e.g. light Higgs
- Approximate description $\sigma \sim \sigma_1\sigma_2/\sigma_{\text{eff}}$
- Our QCD analysis:
  - Full factorization analysis of cross section
  - Field-theoretic definition of double PDF $\rightarrow$ derive evolution
  - Color correlations and interferences are Sudakov suppressed

Thank You!