Direct Photon Production in Hadron-Hadron Collisions

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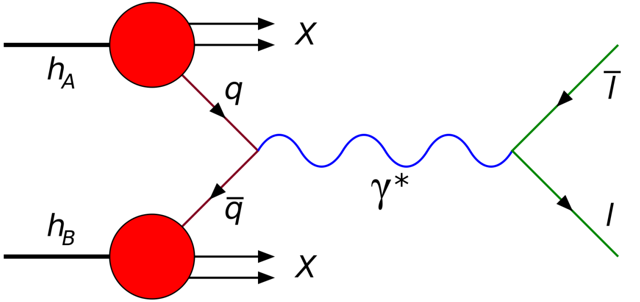
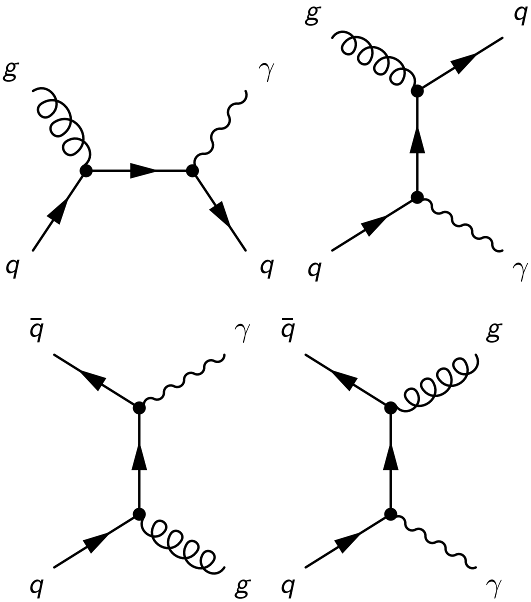
Factorization Theorems in QCD and Parton Model

Direct (prompt) photon is a photon with high p_T.

- Quantum Field Theory, QED+QCD
  - Perturbative QCD allowed by Factorization theorems:
    - high energies
    - large momentum tranfer



LO Diagrams

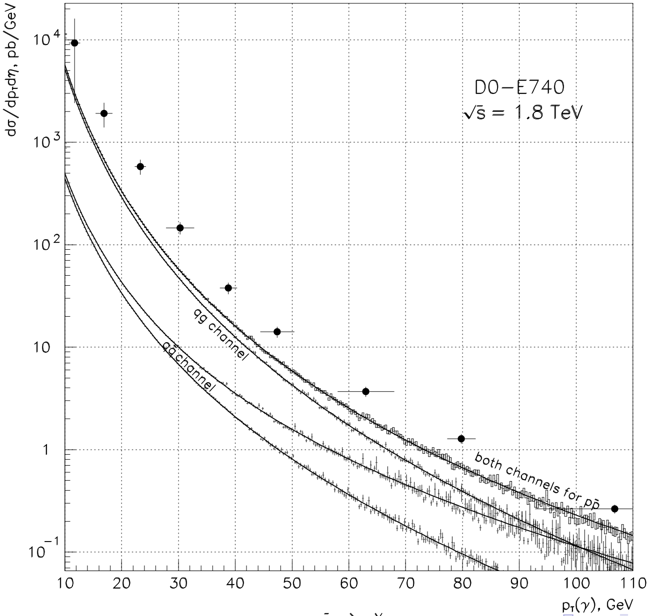


Master 2 → 2 Formula

$$E_\gamma \frac{d^3\sigma}{d^3 p_\gamma}(AB \to \gamma d) = \sum_{a,b} \int_{x_{amin}}^{1} dx_a D_{a/A}(x_a) D_{b/B}\left(\frac{x_a x_T e^{-\eta}}{2x_a - x_T e^{\eta}}\right)$$
$$\cdot \frac{2}{\pi} \frac{1}{2x_a - x_T e^{\eta}} \frac{d\sigma}{d\hat{t}}(ab \to \gamma d), \tag{1}$$

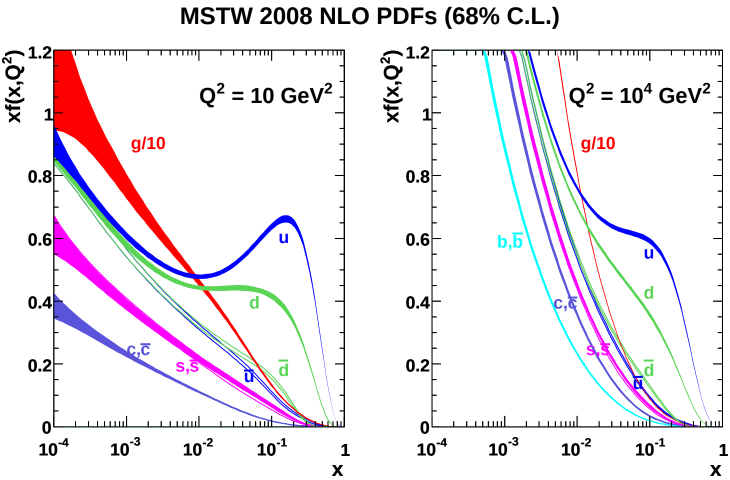
$$x_{amin} = \frac{x_T e^{\eta}}{2 - x_T e^{-\eta}}$$

LO Channels and Comparison with CalcHEP

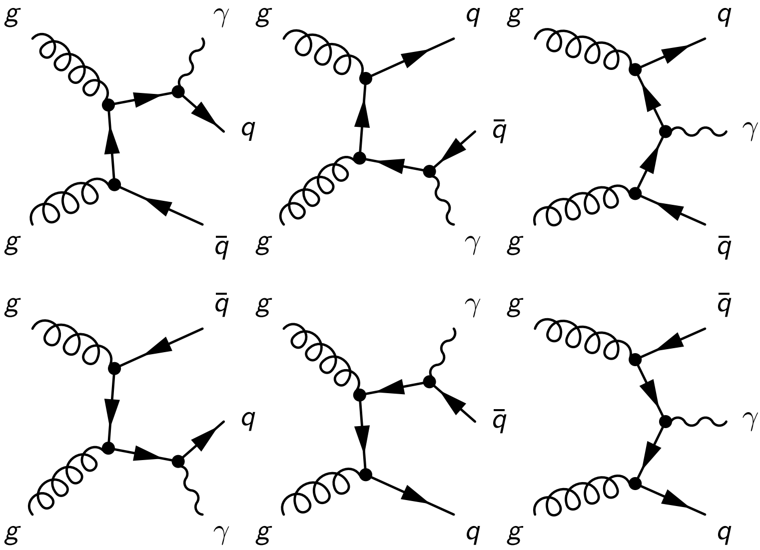


$p\bar{p} \rightarrow \gamma X$

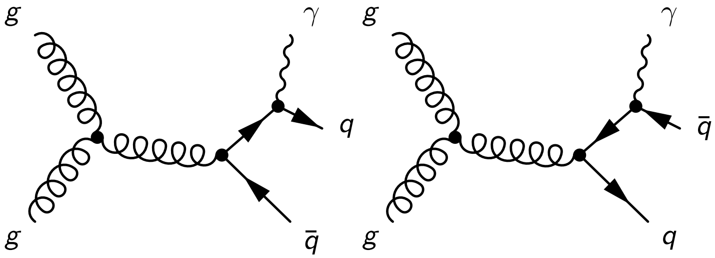
Parton Distribution Functions



2 → 3 NLO QED-like Gluon-Gluon Diagrams



$2 \to 3$ NLO Gluon-Gluon Diagrams with 3-Gluon Vertex



- 8 amplitude diagrams
- 36 unique cross section diagrams
  - 528 terms produced by CalcHEP (uses ghosts in initial and final states as a calculational trick)
  - 1500 terms in a specific axial gauge ($n = p4$, $\eta = 0$)
  - 25000 terms in the general axial gauge (unspecified n and η)

Gauge Invariance Check

Axial gauge:

$$\Delta^{ab}_{\mu\nu}(k) = \frac{i\delta^{ab}}{k^2 + i\epsilon}\left[-g_{\mu\nu} + \frac{k_\mu n_\nu + n_\mu k_\nu}{kn} - \frac{(n^2 + \eta k^2)k_\mu k_\nu}{(kn)^2}\right] \quad (2)$$

$$\sum_{polarizations} \epsilon_\mu(k)\epsilon^*_\nu(k) = -g_{\mu\nu} + \frac{k_\mu n_\nu + n_\mu k_\nu}{kn} - \frac{n^2 k_\mu k_\nu}{(kn)^2} \quad (3)$$

- symbolic calculations in FORM show that the cross section is independent of the axial gauge parameters n and η

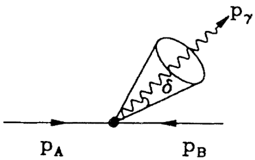
Master 2 → 3 Formula

$$E_\gamma \frac{d^3\sigma}{d^3p_\gamma}(AB \to \gamma de) = \sum_{a,b} \int \frac{x_d dx_d d\cos\theta_d d\varphi_d}{(2\pi)^5 2^3} \cdot \int_{x_{amin}}^1 \frac{dx_a}{x_a x_b} D_{a/A}(x_a) D_{b/B}(x_b) \cdot \frac{\theta\left(x_a + x_b - x_T ch\eta - x_d\right)}{2x_a - x_T e^\eta - x_d(1+\cos\theta_d)} \cdot \frac{1}{2\hat{s}} \sum |M(ab \to \gamma de)|^2 , \quad (4)$$

$$x_b = \frac{x_a\left(x_T e^{-\eta} - x_d(1+\cos\theta_d)\right) - x_d x_T\left(ch\eta - sh\eta\cos\theta_d - \cos\varphi_d \sin\theta\right.}{2x_a - x_T e^\eta - x_d(1+\cos\theta_d)}$$

$$x_{amin} = \frac{x_T e^\eta + x_d(1+\cos\theta_d) - x_d x_T\left(ch\eta - sh\eta\cos\theta_d - \cos\varphi_d\sin\theta_d\right)}{2 - x_T e^{-\eta} - x_d(1-\cos\theta_d)}$$

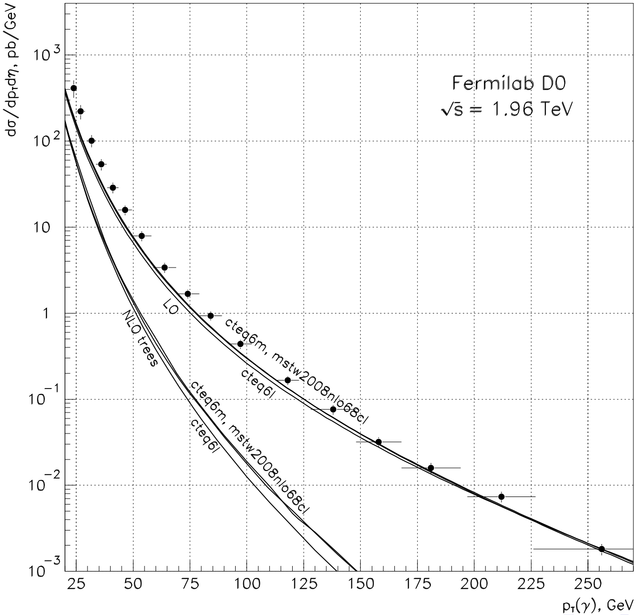
Photon Isolation Criteria



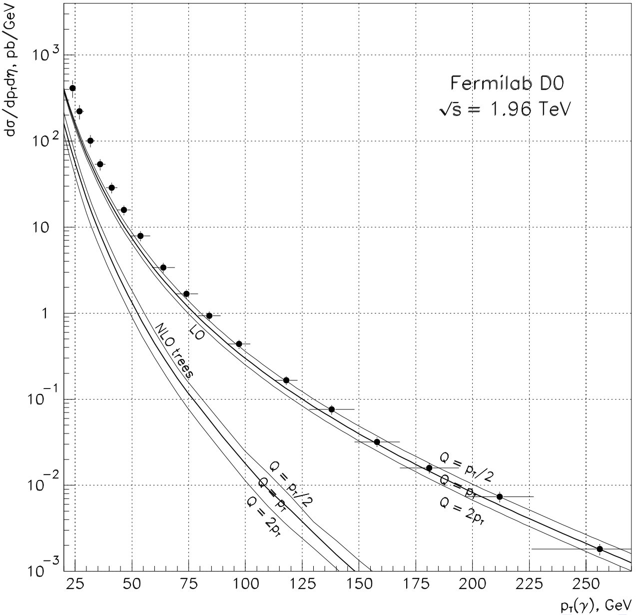
$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

$$\eta \approx y \approx 0 \Rightarrow \delta \approx R$$

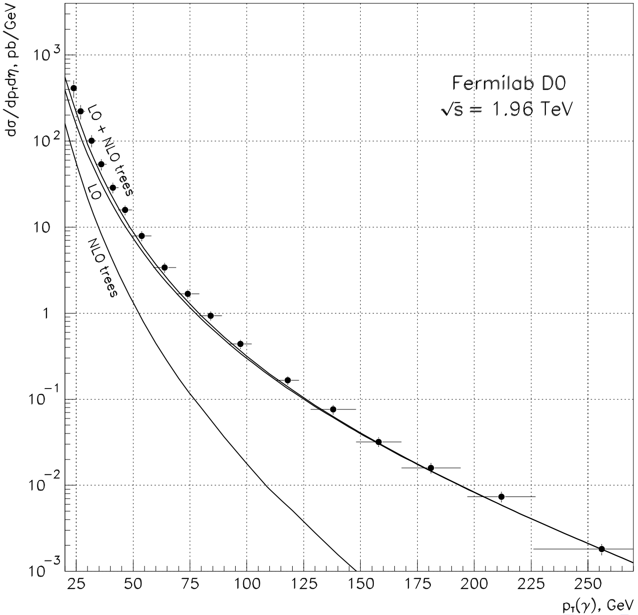
Comparison of different PDFs



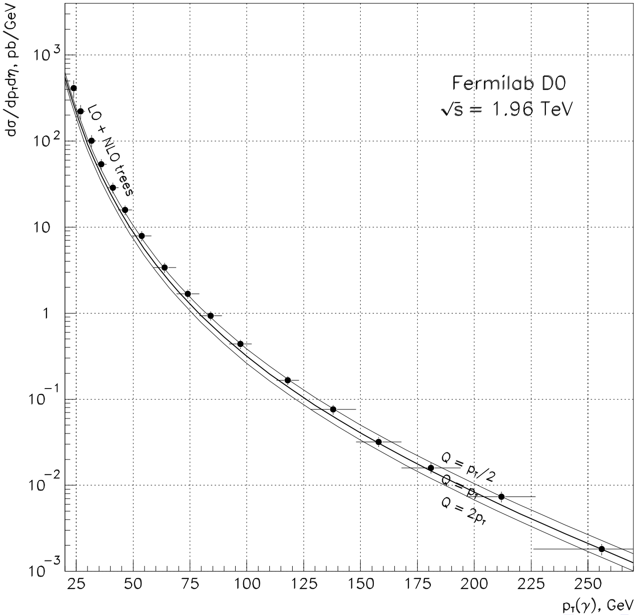
LO and NLO tree-level with theoretical errors (cteq6m)



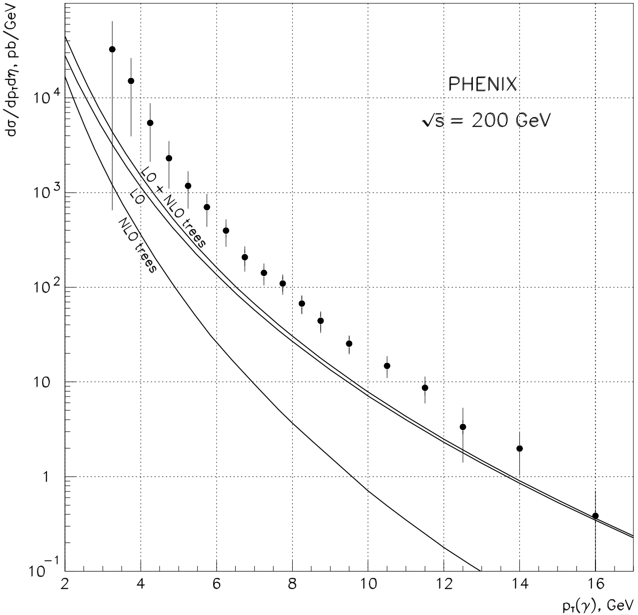
Tree-level LO+NLO (cteq6m)



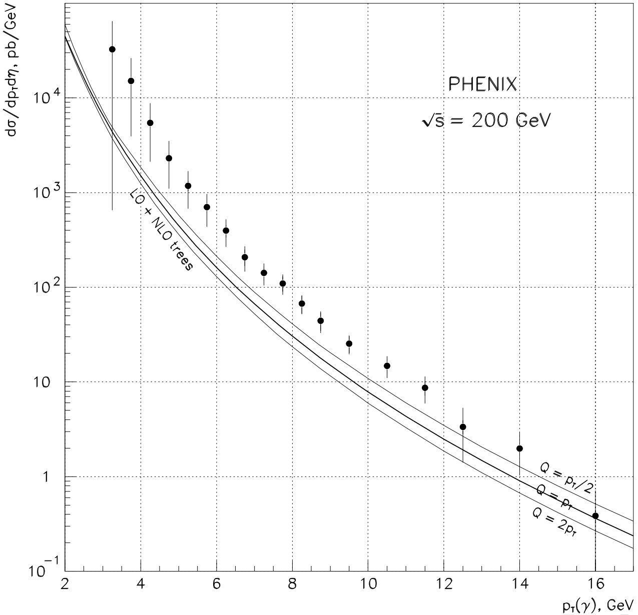
Tree-level LO+NLO with theoretical errors (cteq6m)



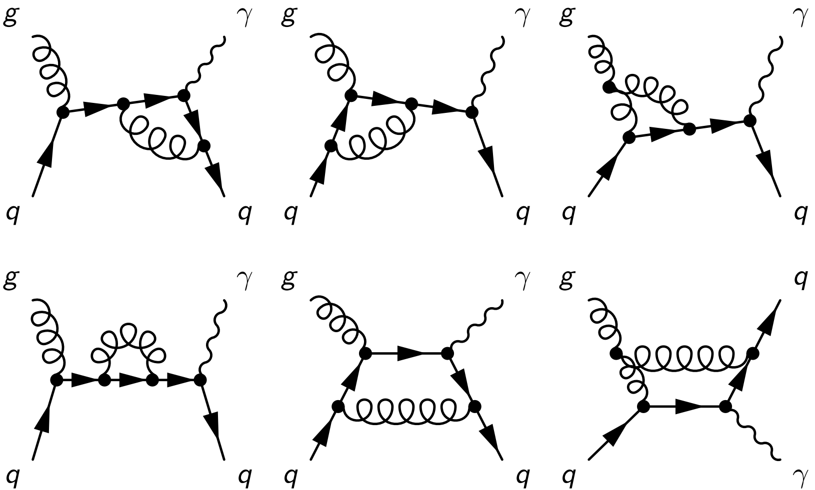
Tree-level LO+NLO (cteq6m)



Tree-level LO+NLO with theoretical errors (cteq6m)



Loop corrections for Compton subprocess



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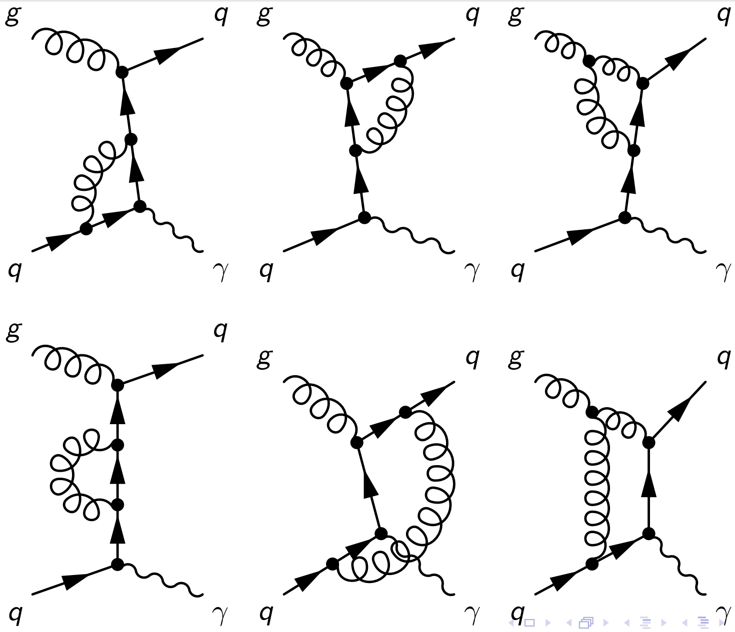
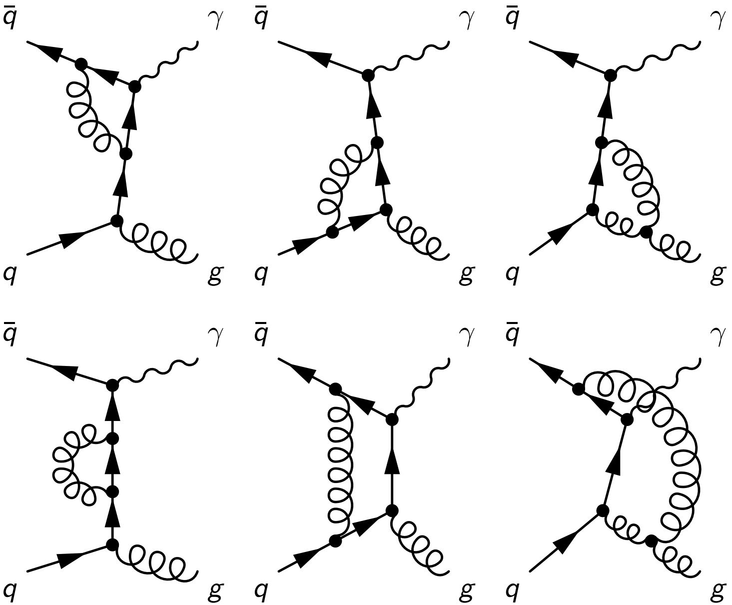
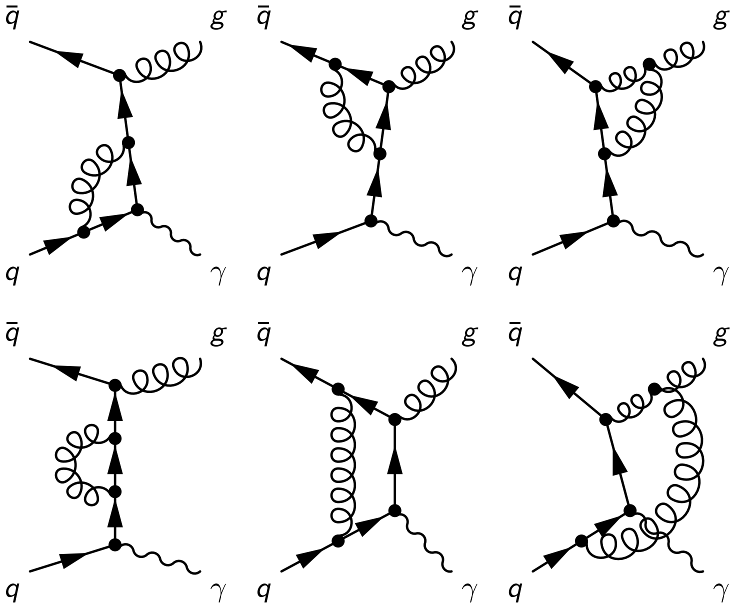


Loop corrections for annihilation subprocess



Loop corrections for annihilation subprocess



Conclusion

- tree-level LO+NLO calculations presented
- proven that the tree-level cross section calculated in the generalized axial gauge is independent of the axial gauge parameters n and η
- loop NLO work in progress

References

1. J. F. Owens, Rev.Mod.Phys.59, 465-503, 1987
2. E. L. Berger, J. Qiu, Phys.Rev.D44: 2002-2024, 1991
3. D0 Collaboration, Phys.Rev.Lett. 84: 2786-2791, 2000, arXiv:hep-ex/9912017
4. D0 Collaboration, Phys.Lett.B639: 151-158, 2006, arXiv:hep-ex/0511054
5. A. Pukhov et al, Preprint INP MSU 98-41/542, arXiv:hep-ph/9908288
6. http://hepforge.cedar.ac.uk/lhapdf/ arXiv:hep-ph/0508110
7. T. Horaguchi, Prompt photon production in proton-proton collisions at $\sqrt{s} = 200$ GeV, Tokyo Inst. Tech., Feb 2006

Auxiliary Formulae

$$\frac{d^2\sigma}{dp_T d\eta} = 2\pi p_T \cdot E\frac{d^3\sigma}{d^3p}$$

$$\frac{d^2\sigma}{dx_T d\eta} = \frac{2\pi s}{4} x_T \cdot E\frac{d^3\sigma}{d^3p}$$

$$p_T = \frac{x_T\sqrt{s}}{2}$$

$$E_a = \frac{x_a\sqrt{s}}{2}$$

$$E_b = \frac{x_b\sqrt{s}}{2}$$

$$E_d = \frac{x_d\sqrt{s}}{2}$$

$$E_e = \frac{x_e\sqrt{s}}{2}$$

$2 \to 2$ Formulae

$$d\sigma(AB \to \gamma d) = \frac{1}{2\hat{s}} \sum_{a,b} \frac{dx_a}{x_a} \frac{dx_b}{x_b} D_{a/A}(x_a) D_{b/B}(x_b)$$

$$\cdot (2\pi)^4 \delta^{(4)}(p_a + p_b - p_\gamma - p_d) \frac{d^3 p_\gamma}{(2\pi)^3 2E_\gamma} \frac{d^3 p_d}{(2\pi)^3 2E_d}$$

$$\cdot \sum |M(ab \to \gamma d)|^2$$

$$E_\gamma \frac{d^3\sigma}{d^3 p_\gamma}(AB \to \gamma d) = \sum_{a,b} \int \frac{dx_a}{x_a} \frac{dx_b}{x_b} D_{a/A}(x_a) D_{b/B}(x_b)$$

$$\cdot \frac{\hat{s}}{\pi} \frac{d\sigma}{d\hat{t}}(ab \to \gamma d) \delta_+ \left(\hat{s} + \hat{t} + \hat{u}\right)$$

$2 \longrightarrow 3$ Formulae

$$d\sigma(AB \to \gamma de) = \frac{1}{2\hat{s}} \sum_{a,b} \frac{dx_a}{x_a} \frac{dx_b}{x_b} D_{a/A}(x_a) D_{b/B}(x_b)$$
$$\cdot (2\pi)^4 \delta^{(4)}(p_a + p_b - p_\gamma - p_d - p_e)$$
$$\cdot \frac{d^3 p_\gamma}{(2\pi)^3 2E_\gamma} \frac{d^3 p_d}{(2\pi)^3 2E_d} \frac{d^3 p_e}{(2\pi)^3 2E_e}$$
$$\cdot \sum |M(ab \to \gamma de)|^2$$

$$E_\gamma \frac{d^3\sigma}{d^3 p_\gamma}(AB \to \gamma de) = \frac{1}{2\hat{s}} \sum_{a,b} \int \frac{dx_a}{x_a} \frac{dx_b}{x_b} D_{a/A}(x_a) D_{b/B}(x_b)$$
$$\cdot \frac{1}{(2\pi)^5 2^2} \frac{d^3 p_d}{E_d} \delta_+ \left((p_a + p_b - p_\gamma - p_d)^2\right)$$
$$\cdot \sum |M(ab \to \gamma de)|^2$$

Master 2 $\longrightarrow$ 3 Formula

$$
\begin{aligned}
E_\gamma \frac{d^3\sigma}{d^3 p_\gamma}(AB \to \gamma d e) = \sum_{a,b} \int \frac{dx_a}{x_a} \frac{dx_b}{x_b} \frac{1}{2\hat{s}} D_{a/A}(x_a) D_{b/B}(x_b) \\
\cdot \frac{x_d^2}{2x_a x_b - x_a x_T e^{-\eta} - x_b x_T e^{\eta}} \\
\cdot \frac{d\cos\theta_d \, d\varphi_d}{(2\pi)^5 2^3} \theta(x_d)\theta(x_e) \\
\cdot \sum |M(ab \to \gamma d e)|^2 ,
\end{aligned}
\tag{5}
$$

$$
x_d = \frac{2x_a x_b - x_a x_T e^{-\eta} - x_b x_T e^{\eta}}{x_a + x_b - (x_a - x_b)\cos\theta_d - x_T\left(ch\eta - sh\eta\cos\theta_d - \cos\varphi_d \sin\theta_d\right)}
$$

$$
x_e = x_a + x_b - x_T \cosh\eta - x_d
$$