Direct Photon Production in Association with a Heavy Quark

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Introduction

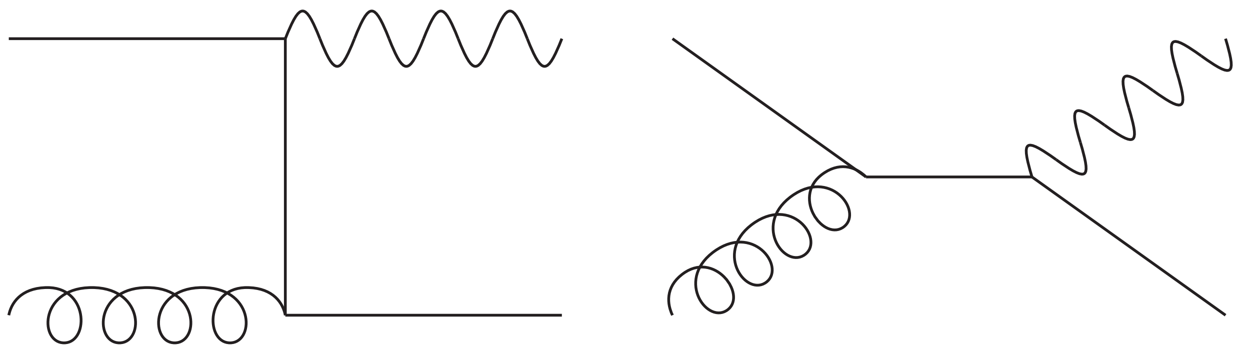
- Calculation of inclusive cross section for $p\bar{p}/pp \longrightarrow Q\gamma X$ (Q=c or b) up to Next to Leading Order, including NLO fragmentation effects, in the massless approximation $\longrightarrow$ comparison with D0 preliminary measurements
- Photon acts as a probe of the hard scattering
- Charge coupling allows for a distinction between charm and bottom
- Possibility to better constrain Parton Distribution Functions of heavy quarks

Direct Photon and Heavy Quarks

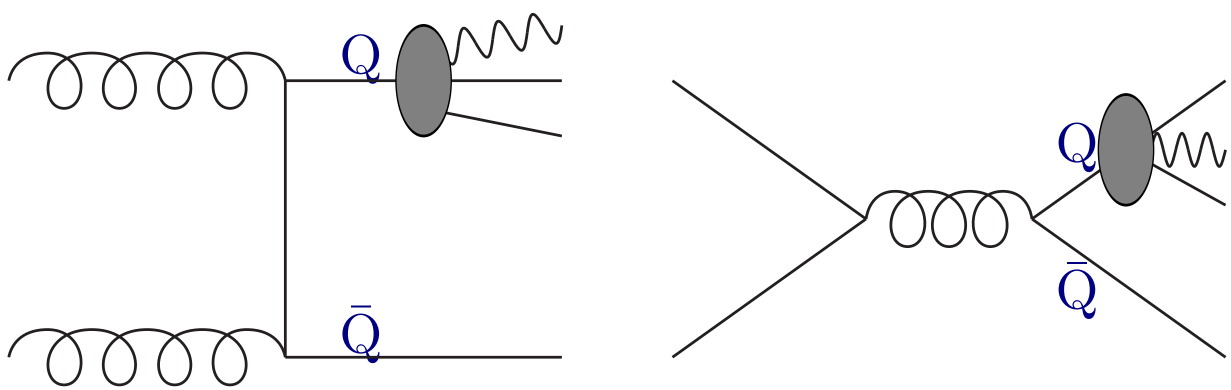
how are they produced?

To Leading Order - $O(\alpha\alpha_s)$

- Compton Subprocess $g + Q \rightarrow Q + \gamma$



- Fragmentation Effects: final state collinear singularities absorbed in Photon Fragmentation Function $D_{\gamma/q,g}(z, \mu_d)$ which is of order $O(\alpha/\alpha_s)$, need to include all $2 \rightarrow 2$ subprocesses $\sim O(\alpha_s^2)$, since $O(\alpha_s^2) \otimes D_{\gamma/q,g} \sim \alpha_s^2\alpha/\alpha_s = \alpha\alpha_s$



Direct Photon and Heavy Quarks

how are they produced?

To Next to Leading Order - $O(\alpha \alpha_s^2)$

- $2 \rightarrow 3$ body scattering subprocesses

$$Q + Q \rightarrow Q + Q + \gamma$$

$$Q + q \rightarrow q + Q + \gamma$$

$$q + \bar{q} \rightarrow Q + \bar{Q} + \gamma$$

$$g + Q \rightarrow g + Q + \gamma$$

$$g + g \rightarrow Q + \bar{Q} + \gamma$$

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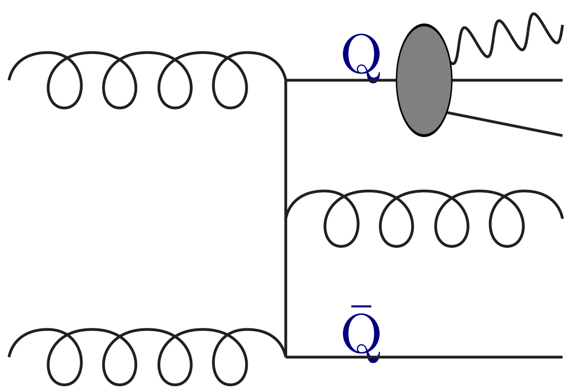
- Fragmentation Effects: need to include all $2 \rightarrow 3 \sim O(\alpha_s^3)$, since $O(\alpha_s^3) \otimes D_{\gamma/q,g} \sim \alpha_s^3 \alpha / \alpha_s = \alpha \alpha_s^2$

e.g.



Calculation

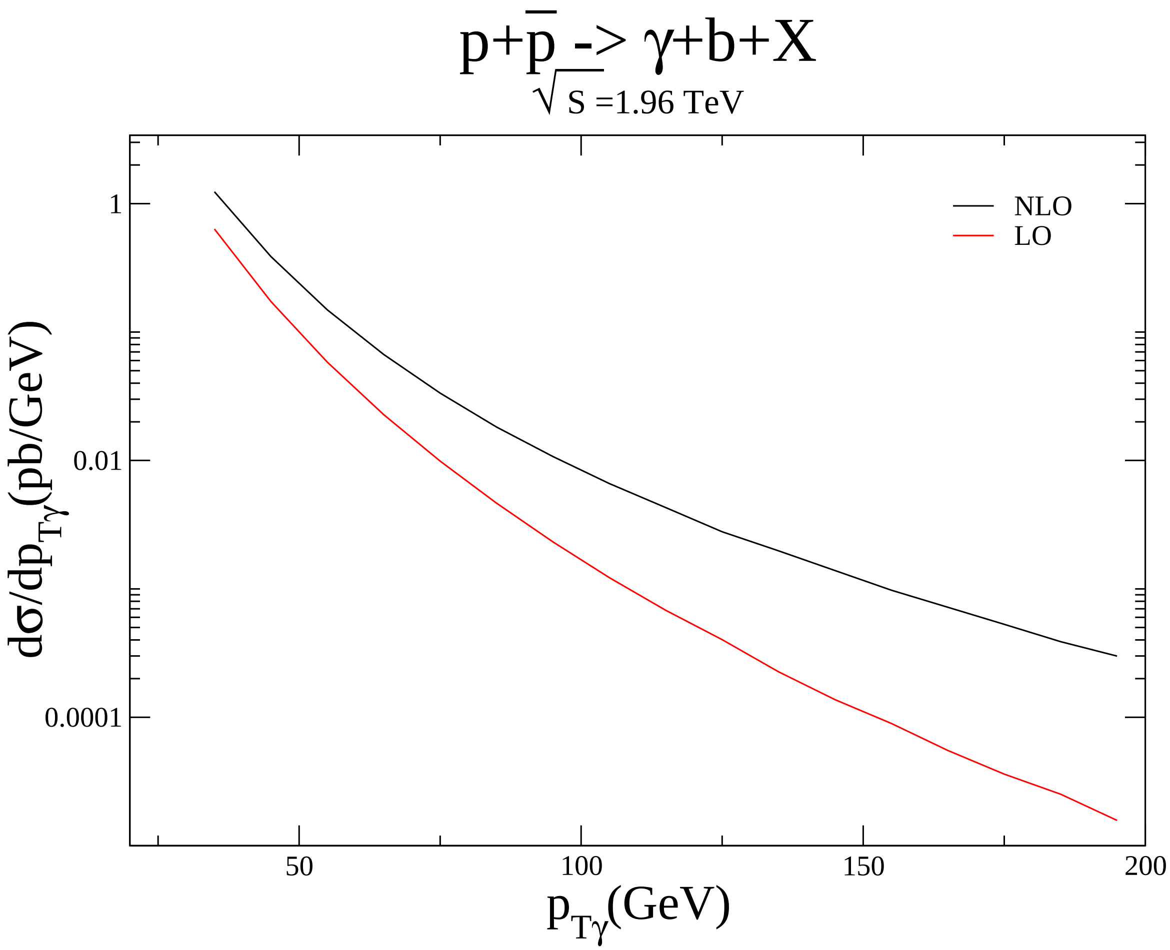
phase space slicing method

- divide phase space into $2 \to 2$ body and $2 \to 3$ body contributions
- divide $2 \to 3$ body phase space into
  - hard region - no singularities present
  - soft region - soft singularities gluon's energy $\to 0$
  - collinear region - 2 of the outgoing particles emitted collinearly
- use cutoffs - δ_s and δ_c
- soft region - $E_g < \delta_s \sqrt{\hat{s}}/2$
- collinear region - $s_{ij} < \delta_c \hat{s}$
- integrate in d dimensions, add $2 \to 2$, soft and collinear contributions
- singularities cancel, or have to be absorbed in PDFs and FFs
- integrate in 4 dimensions over finite region using Monte Carlo
- add $2 \to 2$ and $2 \to 3$ contributions, cutoff dependence cancels

Previous Work

- Analytic calculation of a prompt photon plus associated heavy flavor at next-to-leading order in QCD, E.L. Berger, L.E. Gordon, Phys.Rev. **D54**:2279, 1996
- Production of a Prompt Photon in Association with a Charm Quark at Next-to-Leading Order in QCD, B. Bailey, E.L. Berger and L.E. Gordon, Phys.Rev. **D54**:1896-1907, 1996
- Prompt photon plus charm quark production at $p\bar{p}$ colliders, M. Stratmann, W. Vogelsang, Phys.Rev. **D52**:1535, 1995

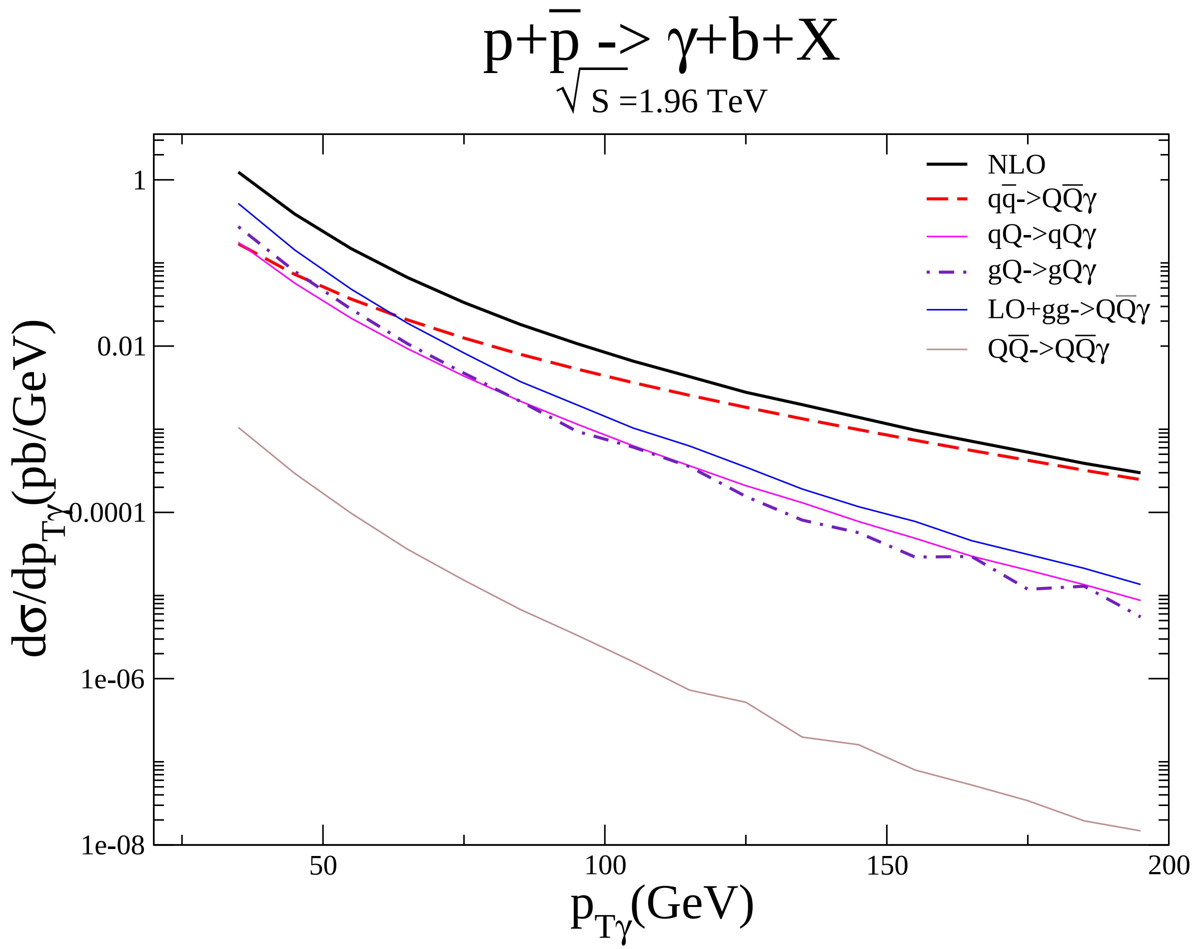
Tevatron Predictions



D0 cuts: $p_{T\gamma} > 30GeV, p_{Tb} > 15GeV, |y_\gamma| < 1, |y_b| < 0.8$

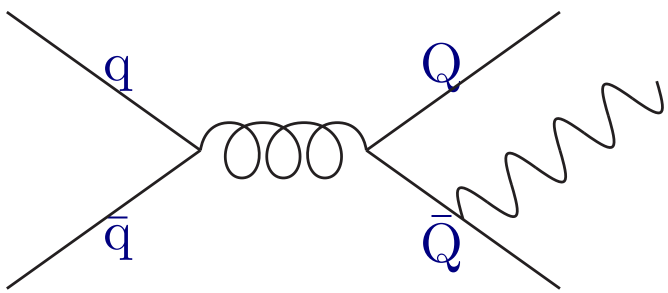
- as $p_{T\gamma}$ increases the difference between LO and NLO grows

Subprocess Contributions

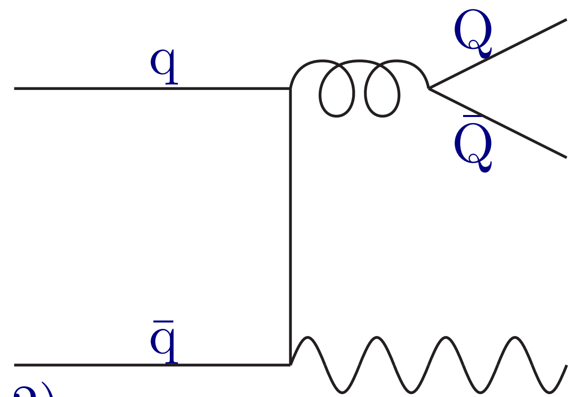


at $p_{T\gamma} \sim 70$ GeV $q\bar{q} \rightarrow Q\bar{Q}\gamma$ starts to dominate

What does $q\bar{q} \to Q\bar{Q}\gamma$ look like?



1)

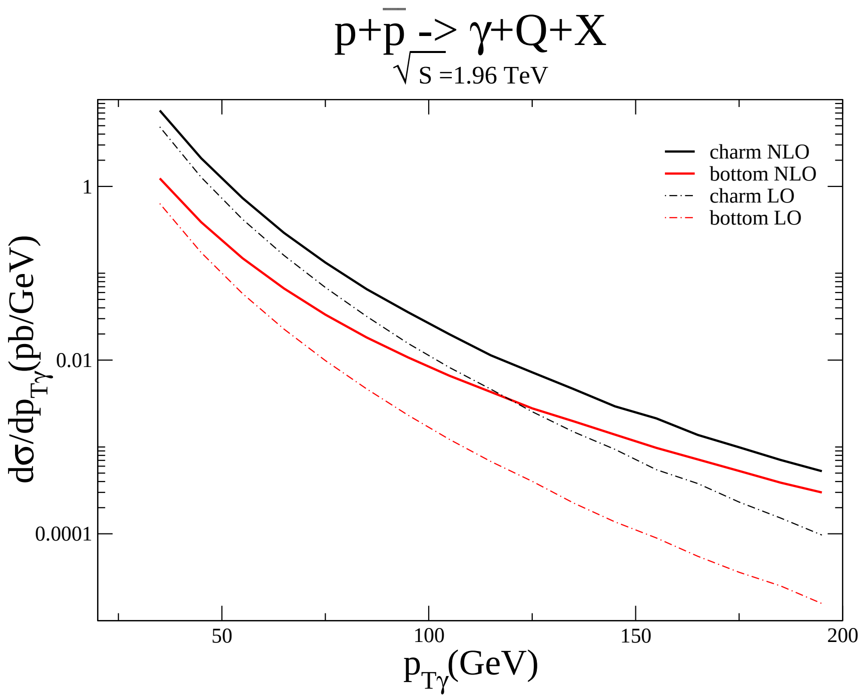


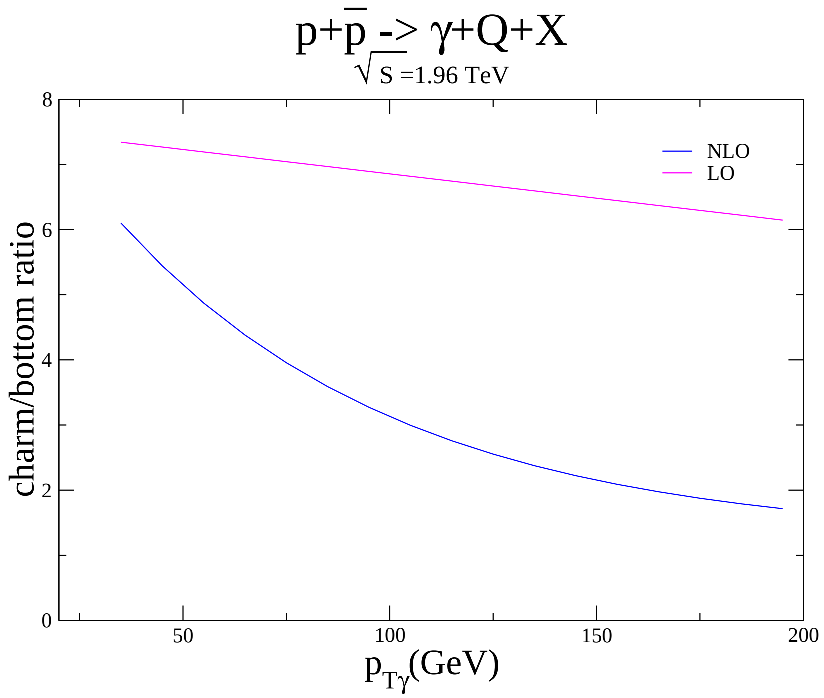
2)

- diagram 1)$\sim e_Q^2$ - photon couples to heavy quark
- diagram 2)$\sim e_q^2$ - photon couples to initial quarks

diagram 2) is the dominant one $\longrightarrow$ the difference between the c and b cross section should decrease at large p_T

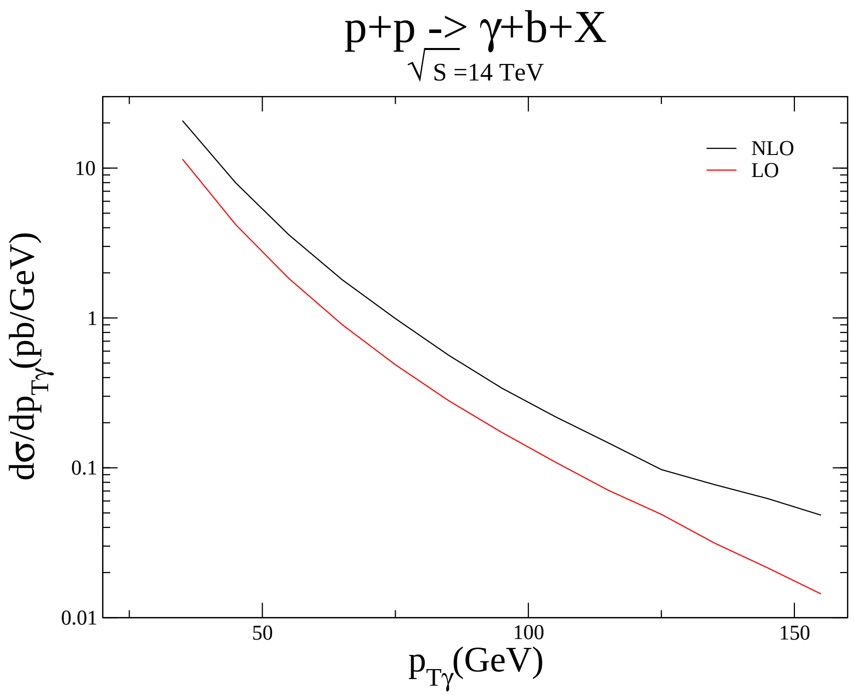
Comparison between charm and bottom

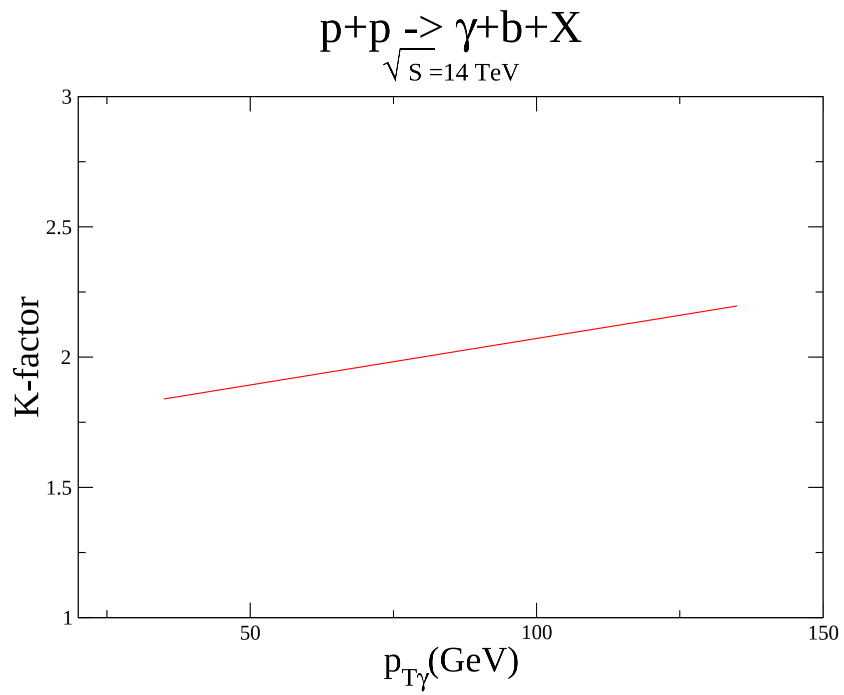




- difference between b and c: quark charge $e_c^2 = 4/9, e_b^2 = 1/9$ and c PDF larger than b PDF
- at higher $p_{T\gamma}, q\bar{q}$ dominates and difference is reduced

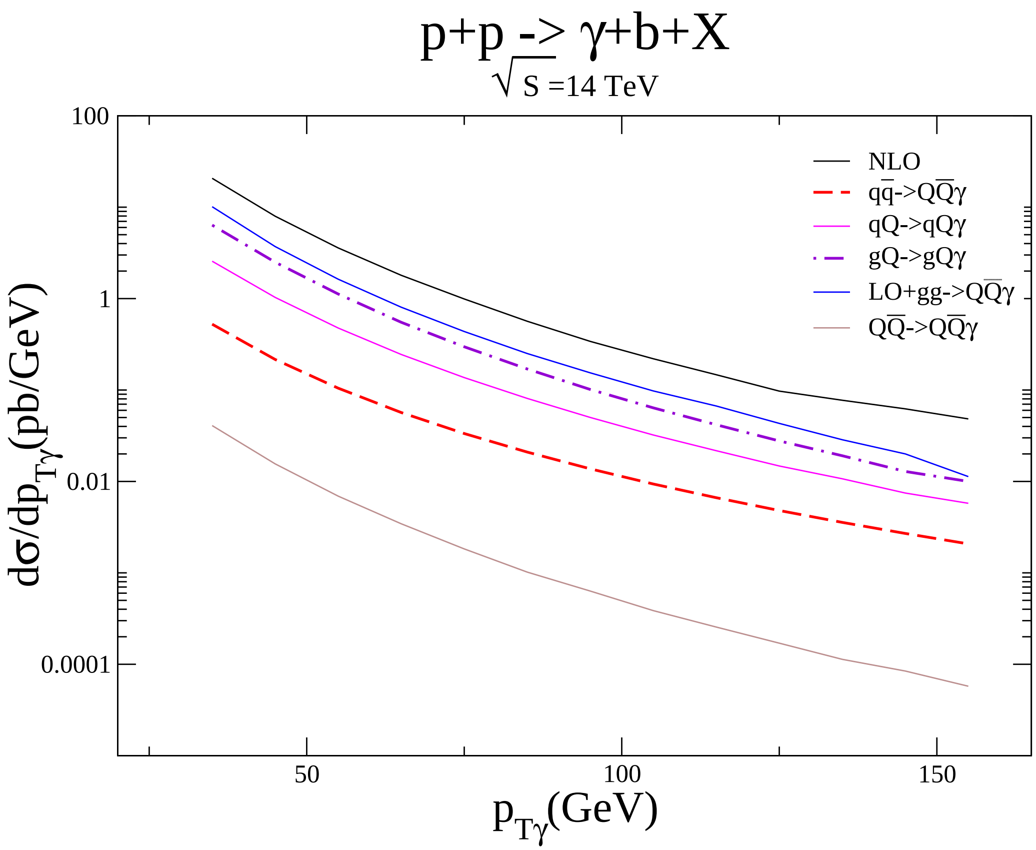
LHC Predictions





the difference between NLO and LO no longer grows at large $p_{T\gamma}$

Subprocess Contributions

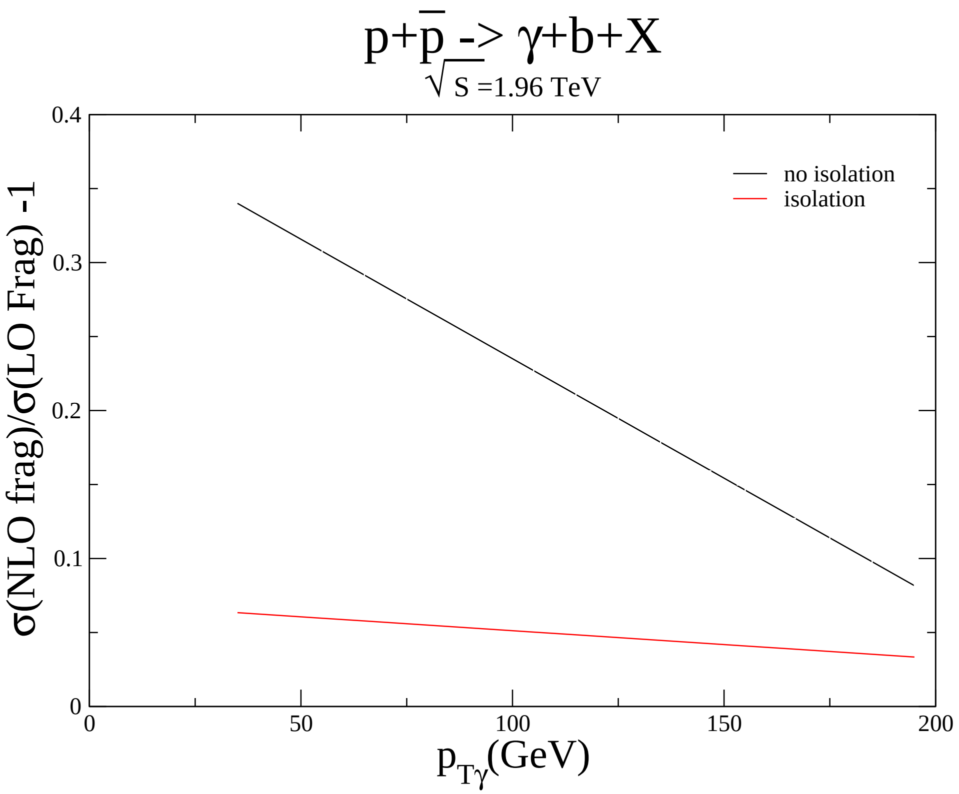


- $q\bar{q}$ no longer dominates
- LO and subprocesses with initial g dominate $\rightarrow$

\- no valence $\bar{q}$

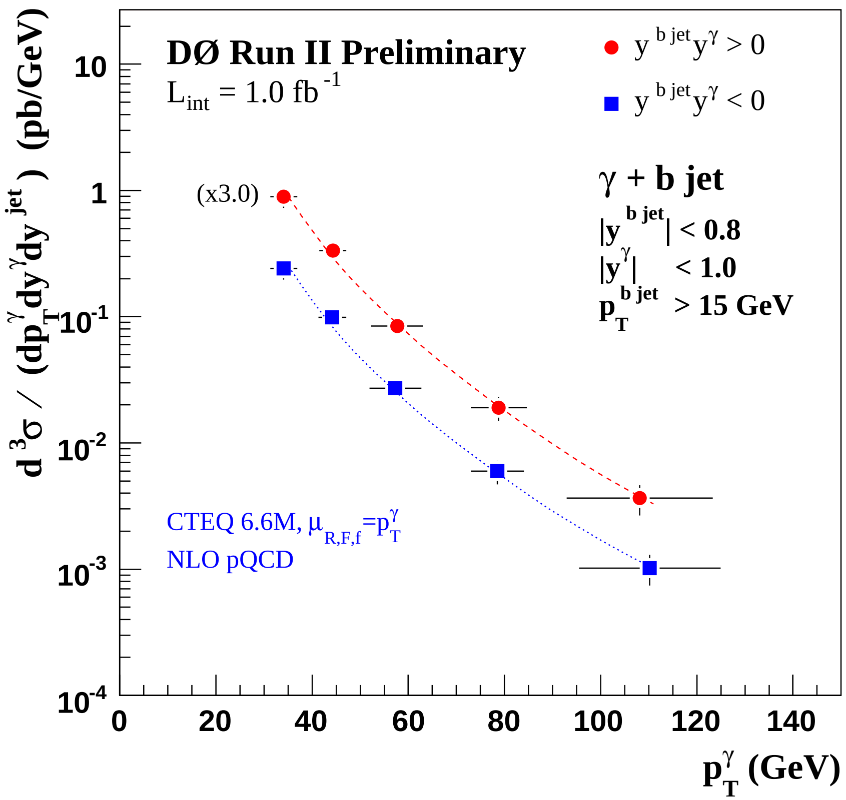
\- larger center of mass energy probes lower values of x in this region gluon PDFs dominate

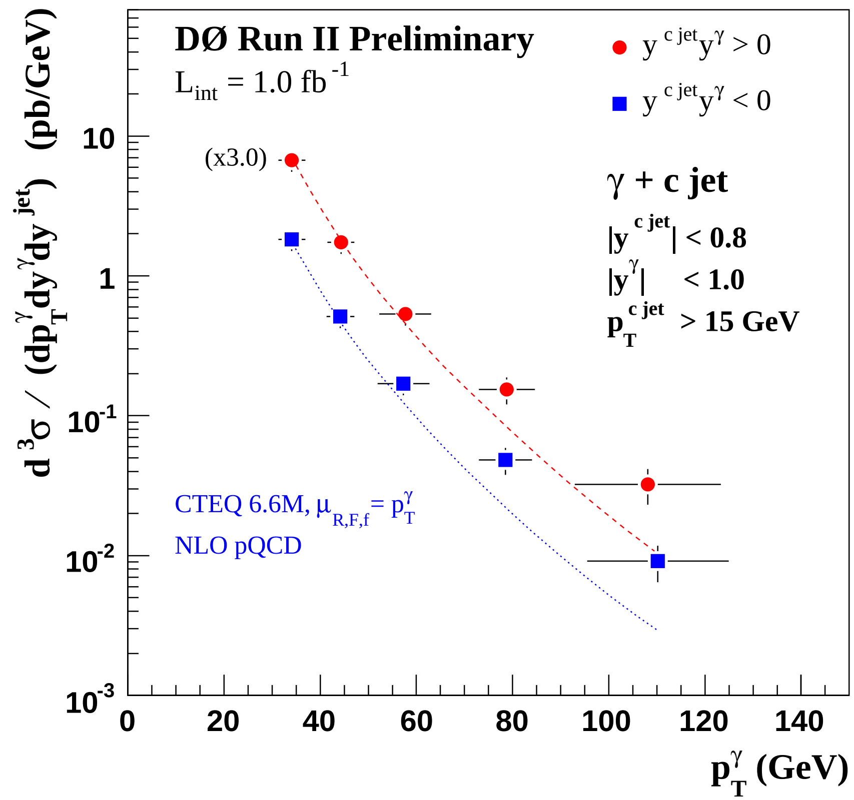
NLO Fragmentation



- Isolation: hadronic energy less than $E_h = \epsilon E_\gamma$ in $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$
- Isolation requirements: $R_1 < 0.2$, $\epsilon_1 < 0.04$ and $R_2 < 0.4$, $\epsilon_2 < 0.07$
- No isolation - NLO fragmentation increases the cross section up to $\sim 30\%$
- Isolation requirement decreases the NLO fragmentation contribution to a few %

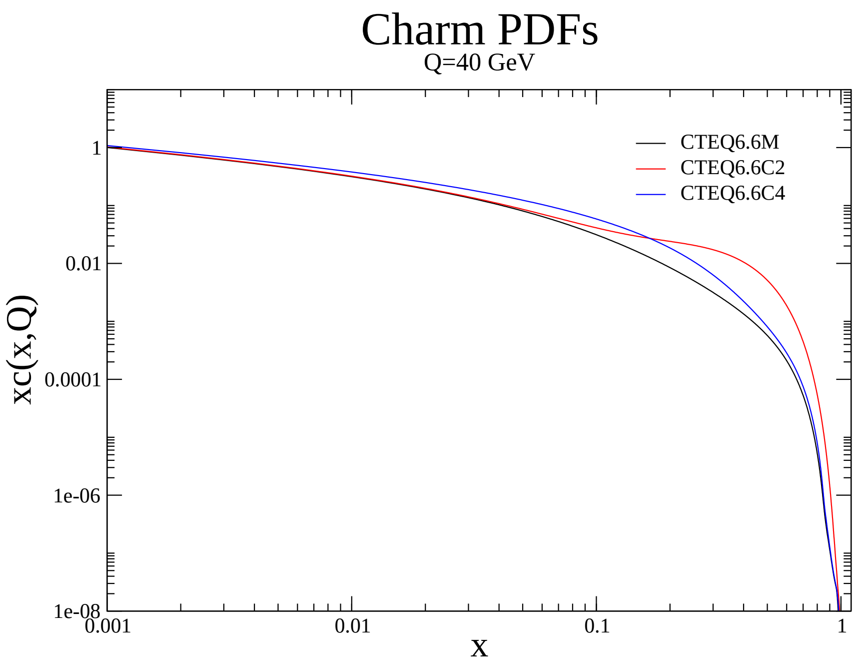
Comparison between theory and data

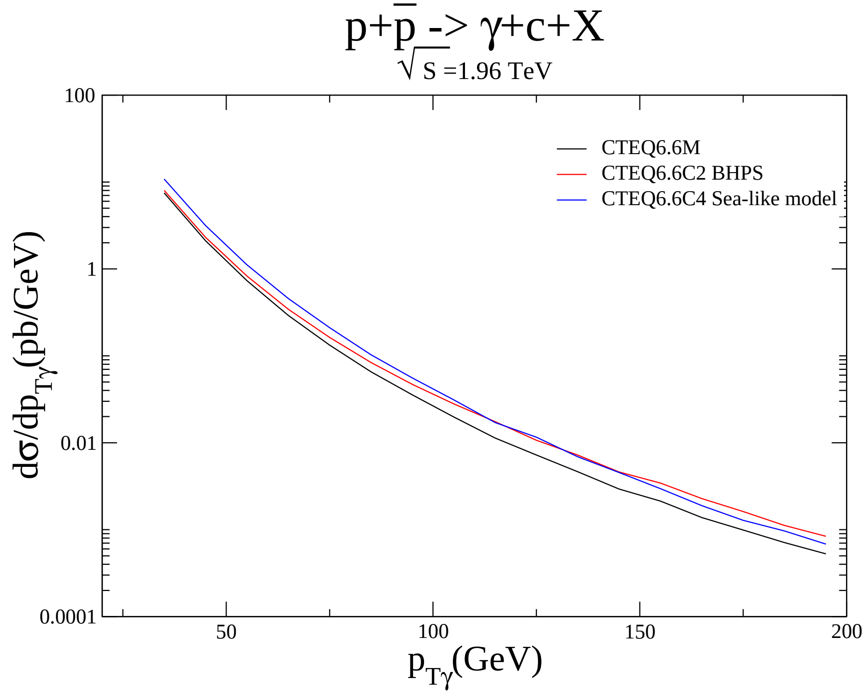




- there is really good agreement between data and theory for the bottom cross section
- for charm the data points at large $p_{T\gamma}$ lie above the theory curve $\rightarrow$ possible explanation - existence of intrinsic charm

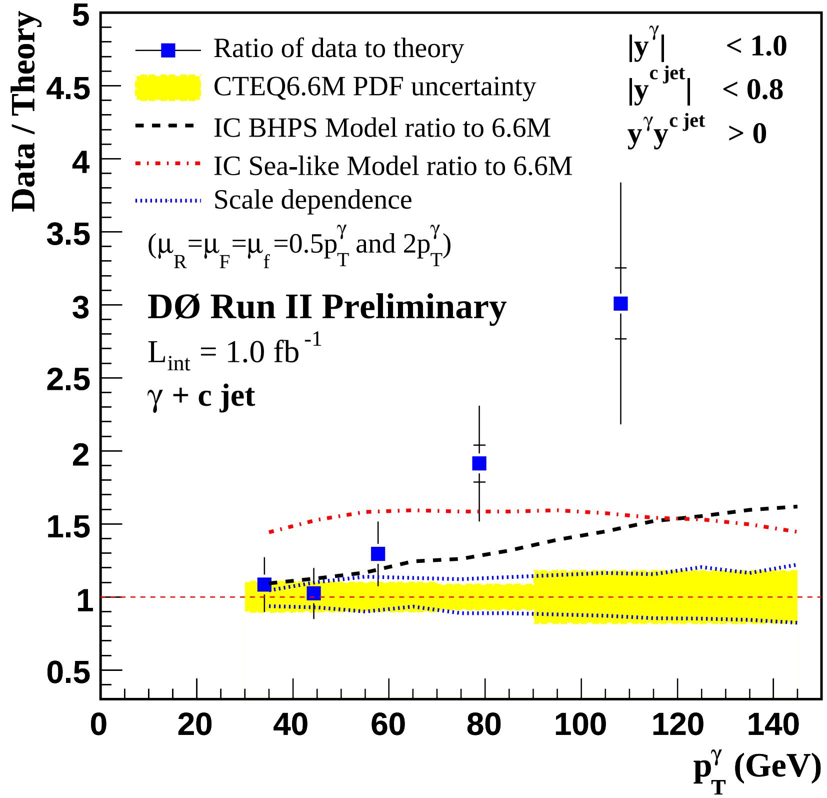
Intrinsic Charm

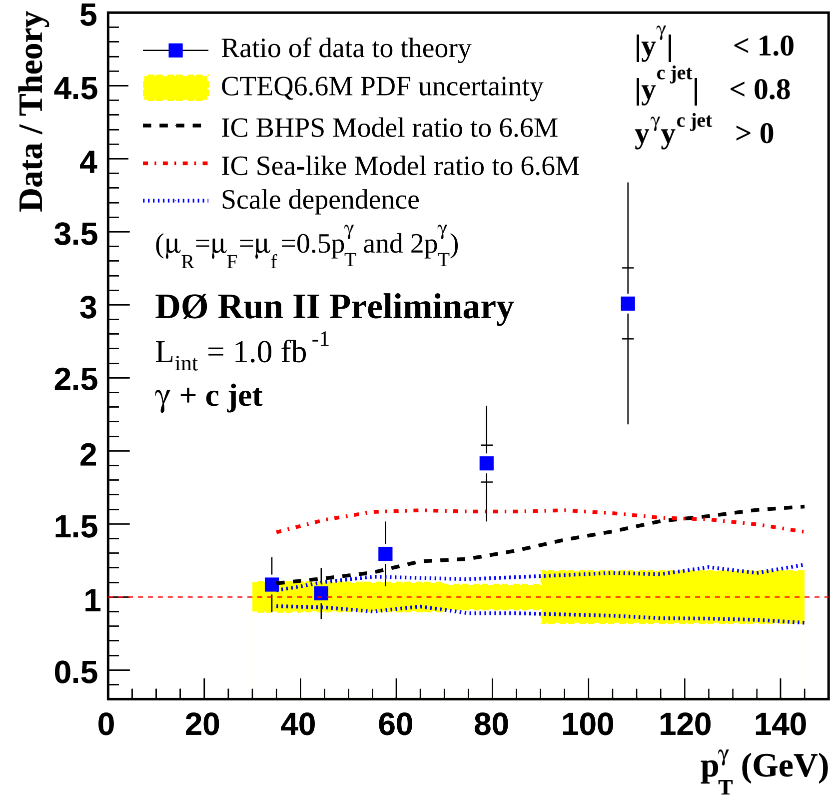




- CTEQ6.6M - radiatively generated charm - or no charm content of the nucleon at scales $\mu < m_c$
- CTEQ6.6C2 and CTEQ6.6C4 - PDFs that take into account the possibility of there being an intrinsic charm content of the nucleon

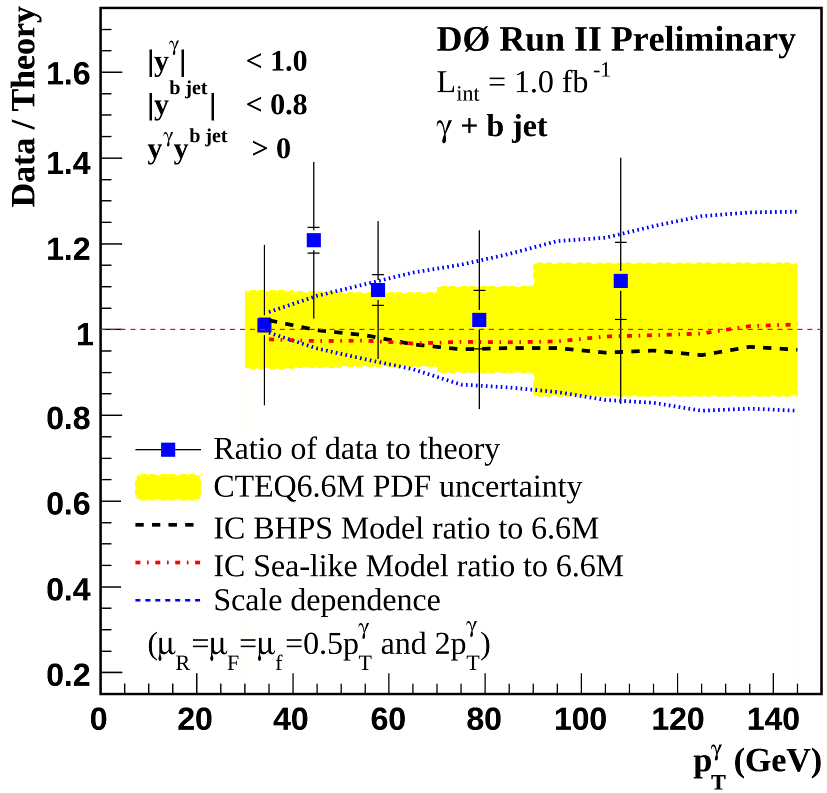
Data to Theory Ratio - Charm

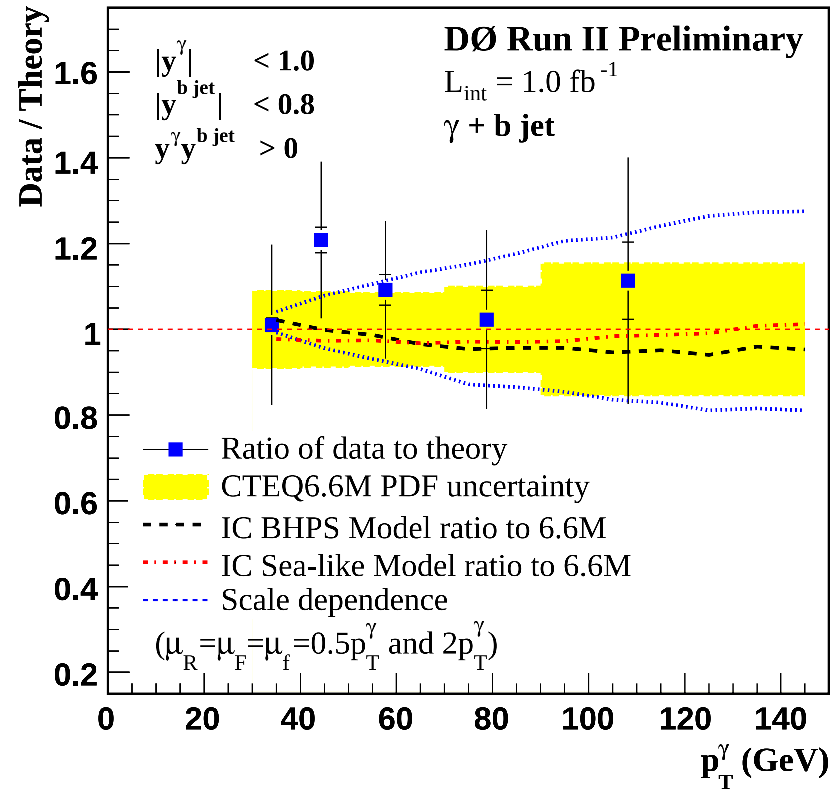




with the use of the BHPS PDFs the cross section grows at large $p_{T\gamma}$, but is still below the data

Data to Theory Ratio - Bottom





a closer look at the agreement between data and theory

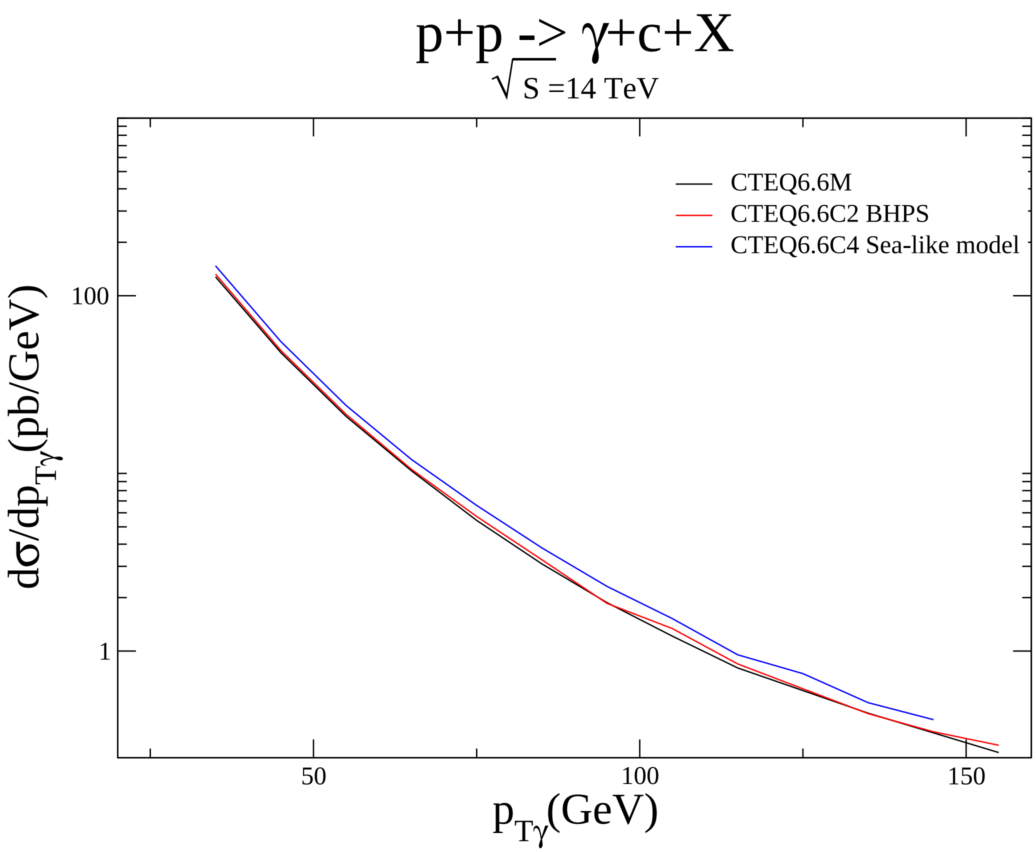
Conclusions

- At Tevatron energies $q\bar{q}$ starts to dominate the cross section at large $p_{T\gamma}$, difference between bottom and charm diminishes
- At the LHC processes with initial gluons and heavy quarks dominate
- NLO fragmentation has a noticeable effect on the cross section, but this effect decreases with the requirement of isolation
- Comparison with D0 measurements shows good agreement for the γ + b cross section, for the γ+c cross section there is agreement below $p_{T\gamma} \sim 60 GeV$

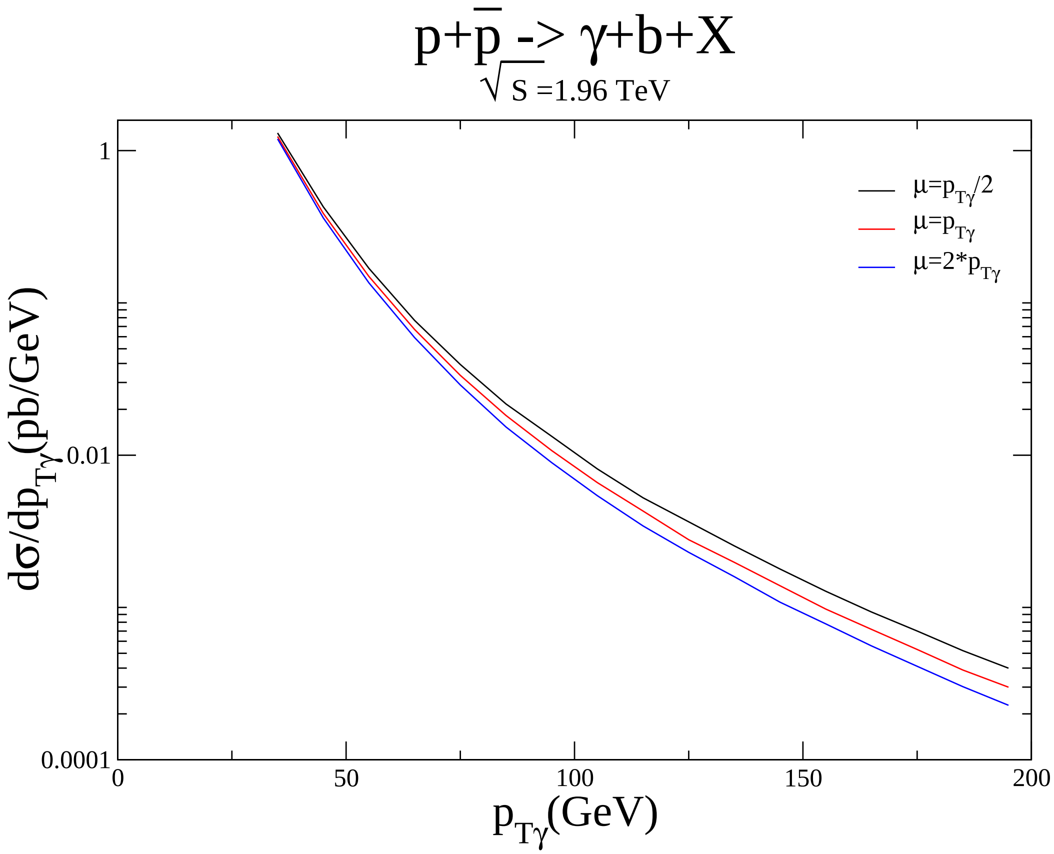
Backup Slides

- Intrinsic Charm at the LHC
- Scale Dependence 1
- Scale Dependence 2
- Subprocess Contributions for charm
- Comparison between charm and bottom at the LHC
- γ Fragmentation Function

Intrinsic Charm LHC

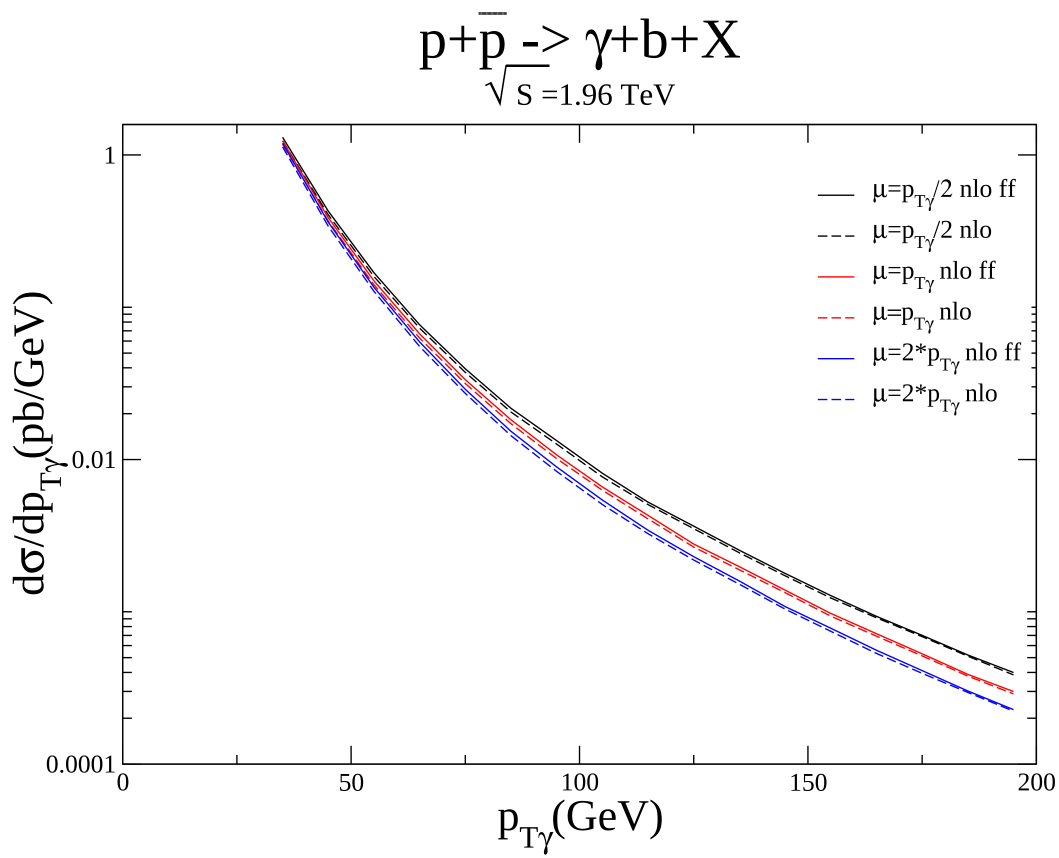


Scale Dependence

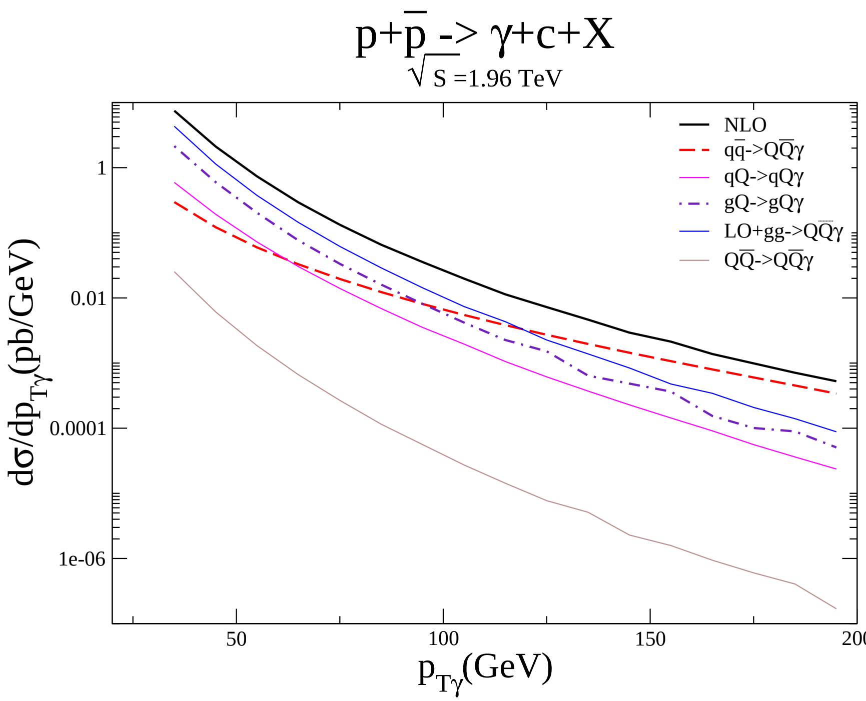


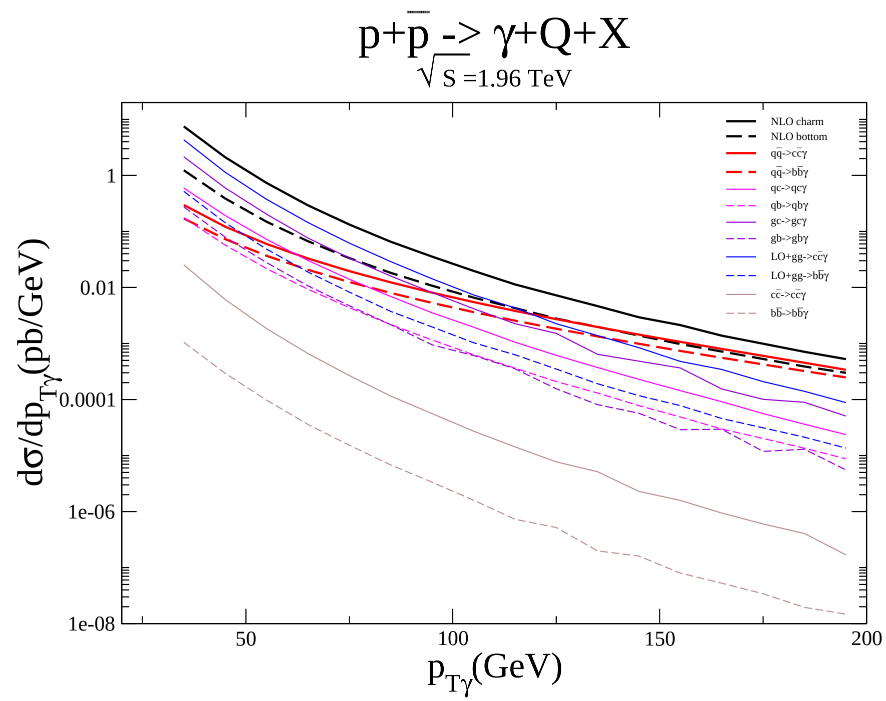
- scale dependence increases with $p_{T\gamma}$
- $q\bar{q} \to Q\bar{Q}\gamma$ dominates at large $p_{T\gamma}$, it should really be considered as a LO subprocess

Scale Dependence nloff nlo

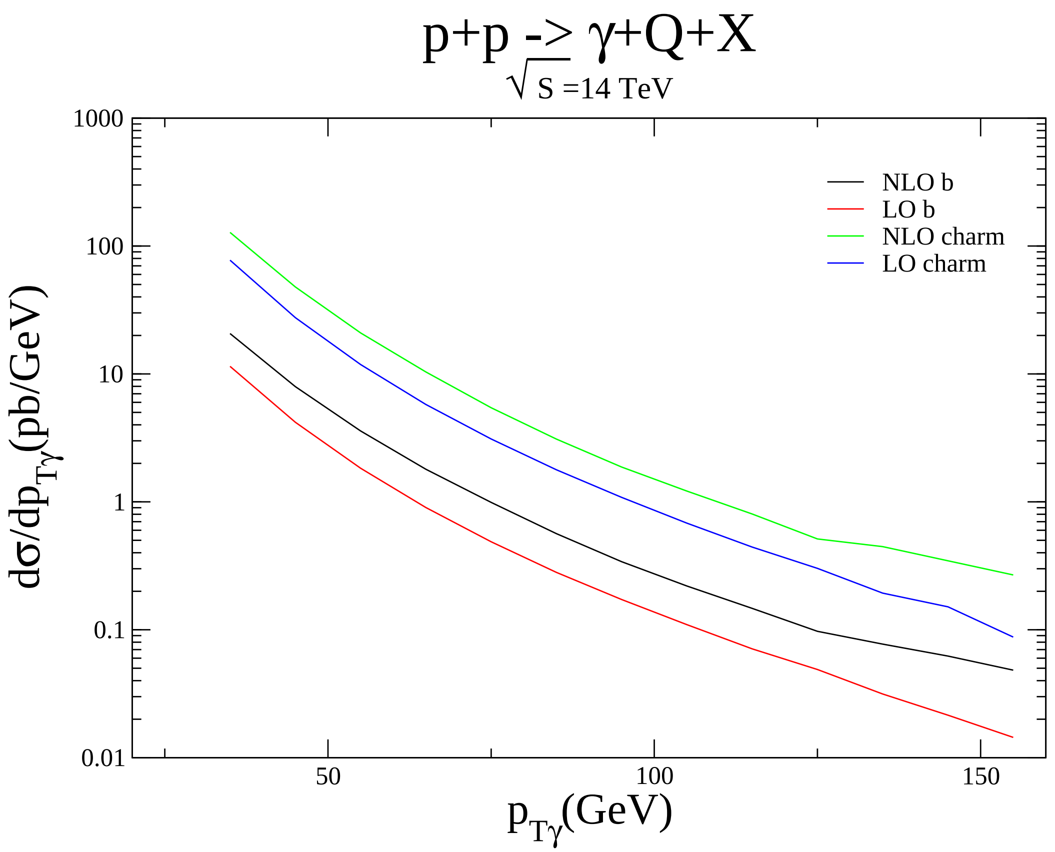


Subprocess Contributions charm, charm+bottom





LHC Predictions



Photon Fragmentation Function

$$\frac{dD_{\gamma/Q}(z)}{dt} = \frac{\alpha}{2\pi} P_{\gamma \leftarrow Q}(z) + \frac{\alpha_s}{2\pi} \int \frac{dy}{y} [D_{\gamma/Q}(z/y) P_{Q \leftarrow Q}(y) + D_{\gamma/g}(z/y) P_{g \leftarrow Q}(y)]$$

$$\frac{dD_{\gamma/g}(z)}{dt} = \frac{\alpha_s}{2\pi} \int \frac{dy}{y} [D_{\gamma/Q}(z/y) P_{Q \leftarrow g}(y) + D_{\gamma/g}(z/y) P_{g \leftarrow g}(y)]$$