Direct Photons at the Tevatron and LHC

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Outline

- Introduction
- Two Issues

  - Scale dependence
  - Isolation

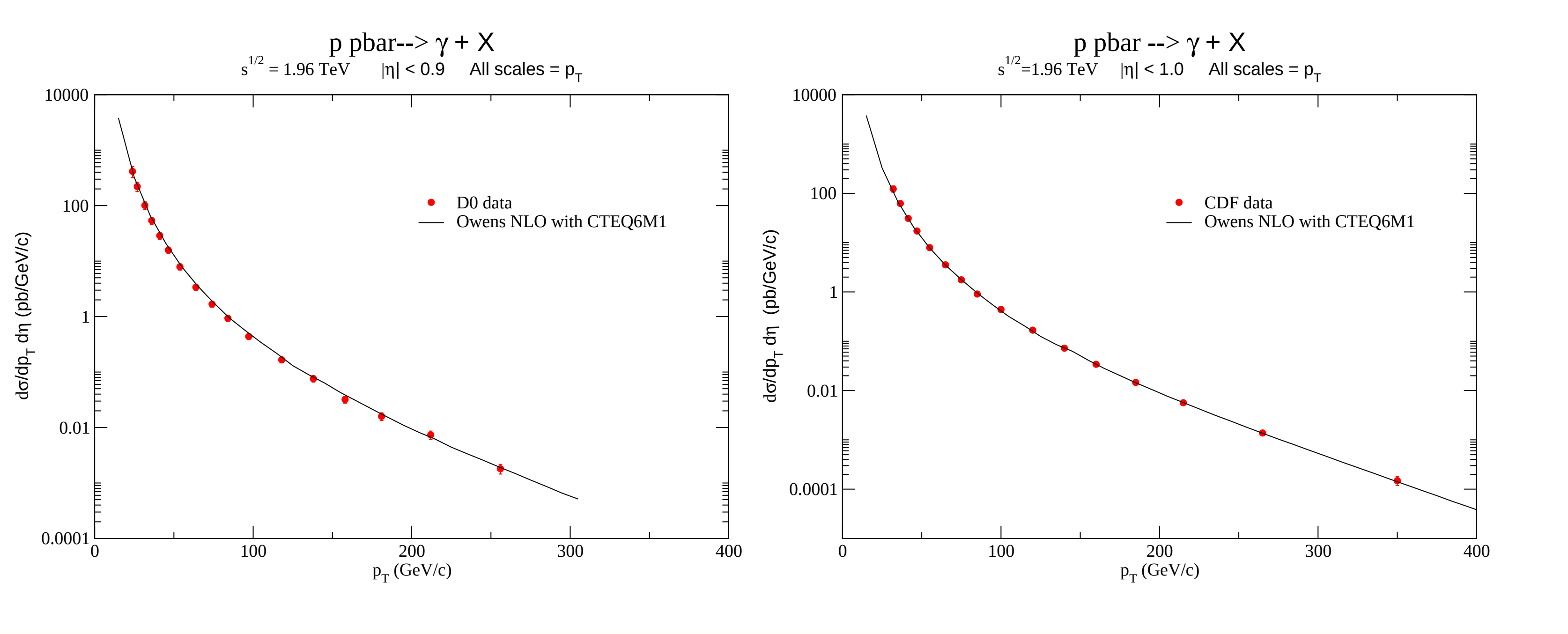
- Conclusion and Outlook

Introduction

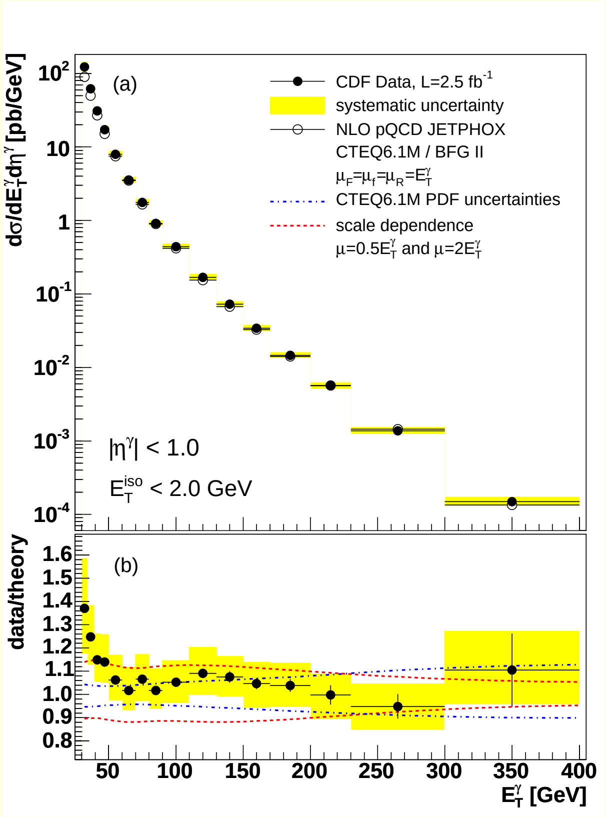
Why photons?

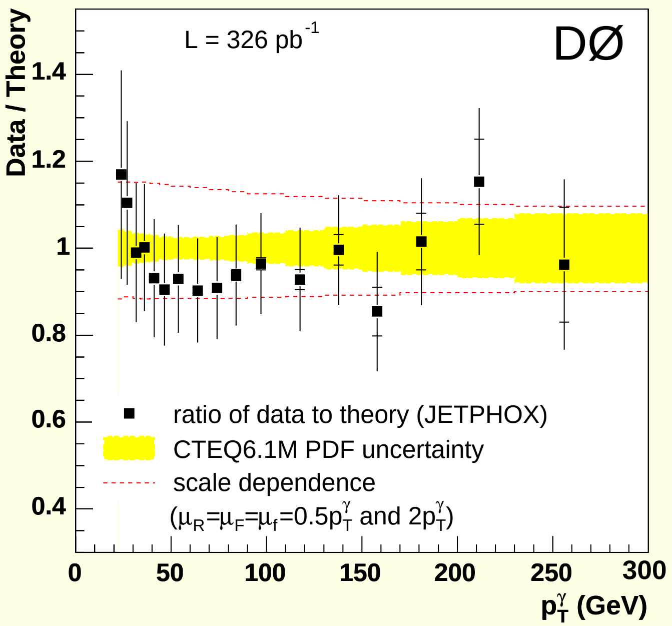
- Use a known electromagnetic probe to study the hard scattering
- Study properties of QCD
  - Angular distribution predicted to be different than for jets
  - Perturbative component of fragmentation
  - Interesting applications of resummation
- Constraints on PDFs(?)
- Necessary to understand as a background to "new physics" searches

At the Tevatron, NLO calculations do a credible job of describing the high quality data now available



Even on a linear scale, things look pretty good





Scale Dependence

- Generally, the LO predictions have a monotonic scale dependence
- In many cases the scale dependence is reduced at NLO
- Reduced scale dependence is often taken as a sign that the perturbative expansion is well controlled
- On the other hand, significant scale dependence can be a cause for concern and may indicate a reduced reliability for the predictions
- It is instructive to consider a simple example which shows the origin of the reduced scale dependence at NLO

Simple example - nonsinglet production of jets

- Consider jet production where only the quarks contribute, just to keep it simple
- In lowest order one has

$$E\frac{d^3\sigma}{dp^3} \equiv \sigma = a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M)$$

where $a(\mu) = \alpha_s(\mu)/2\pi$

- In next-to-leading-order the result is

$$\begin{aligned}
\sigma &= a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&+ 2a^3(\mu)\,b\ln(\mu/p_T)\hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&+ 2a^3(\mu)\,\ln(p_T/M)P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&+ a^3(\mu)\,K \otimes q(M) \otimes q(M).
\end{aligned}$$

Here

$$\mu \frac{\partial a(\mu)}{\partial \mu} = \beta(a(\mu))$$

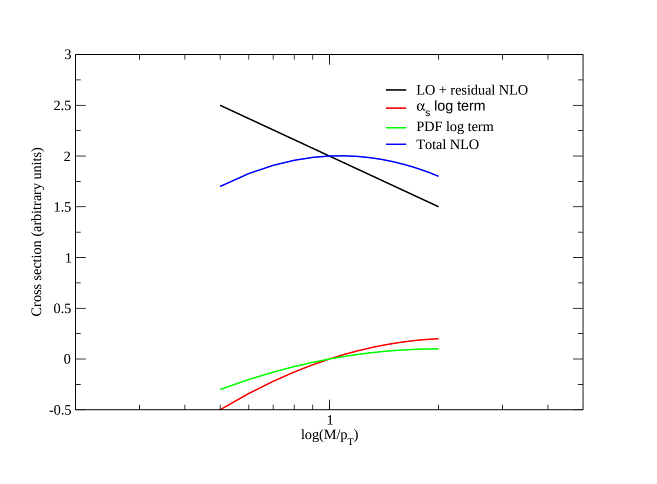
where $\beta = -ba^2(1 + ca)$ with $b = \frac{33-2f}{6}$ and $c = \frac{153-19f}{2(33-2f)}$

$$\begin{aligned} \sigma &= a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M) \\ &+ 2a^3(\mu)\,b\ln(\mu/p_T)\hat{\sigma}_B \otimes q(M) \otimes q(M) \\ &+ 2a^3(\mu)\,\ln(p_T/M)P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M) \\ &+ a^3(\mu)\,K \otimes q(M) \otimes q(M). \end{aligned}$$

- The first line is the LO expression
- The second has a log which partially cancels the effect of changing the scale of the running coupling
- The third has a log which partially cancels the effect of changing the factorization scale
- The fourth is the remainder of the $\mathcal{O}(\alpha_s^3)$ contribution
- The explicit logs cancel the scale variation up to $\mathcal{O}(\alpha_s^4)$

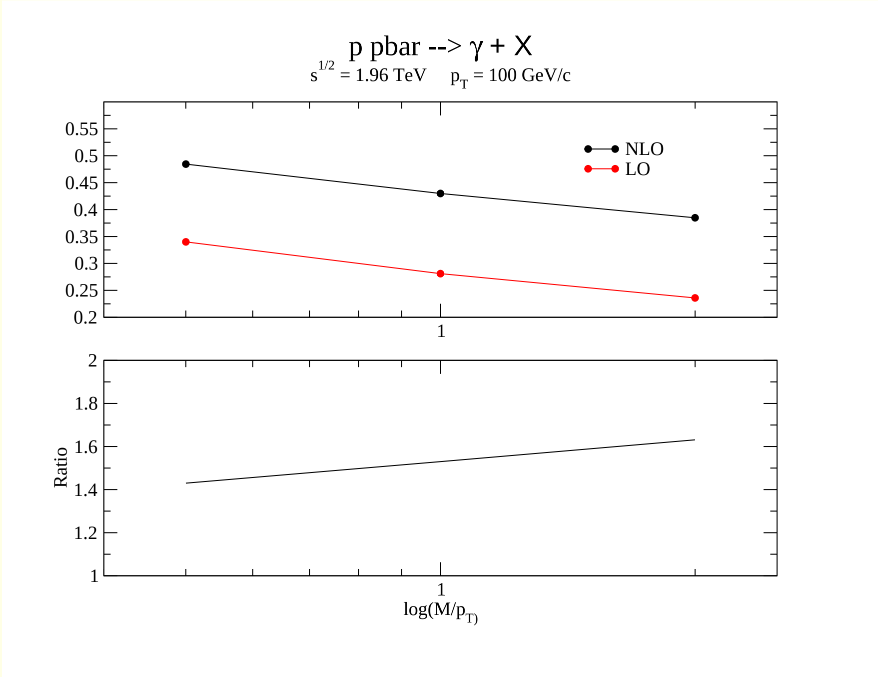
$$
\begin{aligned}
\sigma &= a^2(\mu)\,\hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&+ 2a^3(\mu)\,b\ln(\mu/p_T)\hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&+ 2a^3(\mu)\,\ln(p_T/M) P_{qq} \otimes \hat{\sigma}_B \otimes q(M) \otimes q(M) \\
&+ a^3(\mu)\,K \otimes q(M) \otimes q(M).
\end{aligned}
$$

- Lines 1 and 4 have a monotonically decreasing scale dependence
- Line 2 is negative for $\mu < p_T$ and rises with increasing scale
- Line 3 is negative for $M < p_T$ and rises with increasing scale, provided that x_T is larger than about .1 or so, so that the scaling violations have a negative slope



- Sketch of the various contribution to the scale dependence for jet production
- One sees that the stabilizing of the NLO scale dependence comes from the interplay of the LO terms and the α_s and PDF log terms from the NLO calculation
- As one goes to lower values of x_T, the slope of the PDF M^2 dependence changes signs - the PDFs rise with increasing M^2 at low x instead of falling
- This changes the slope of the green curve and it can become negative
- The result is that the peak of the blue curve moves to lower scales as x_T decreases

Now, what does the scale dependence for direct photons look like at the Tevatron?



- For the p_T value shown both the LO and NLO curves have a monotonically decreasing scale dependence
- The NLO/LO ratio is slightly rising with increasing scale over the range shown

Can one understand what is happening here?

How are jet production and direct photon production different?

- The NLO calculation for direct photon production has terms analogous to those in the previous example, but there is one less power of α_s
- It also has terms associated with the photon fragmentation functions (FFs)

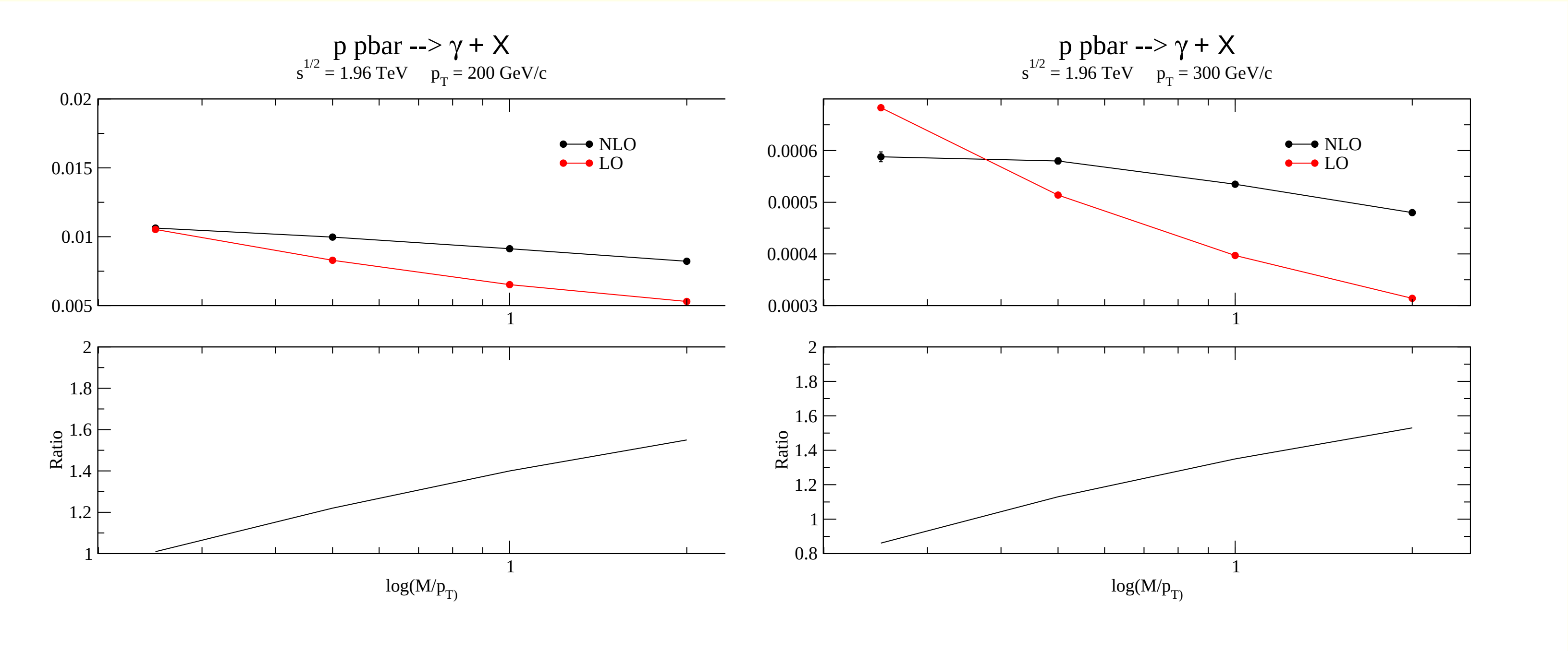
  - The results shown here are for the isolated cross section defined by requiring that the hadronic transverse energy in a cone of radius .4 be less than 2 GeV
  - This requires the fragmentation variable z to be limited to $z > 1/(1 + 2/p_{T\gamma})$
  - The fragmentation contribution is small and the dependence on the fragmentation scale is negligible

What else is different?

- There is one less power of α_s, so the relative weights of the different terms changes (factor of two in line two is replaced by one)
- There is a different mix of subprocesses than for jet production, so this can change the relative weight of the PDF log term since the M^2 scale violation slope will be different

Maybe nothing drastic has happened and we simply need to look at higher scale values

Go to higher p_T values: $x_T = .2$ and $.3$



- As x_T increases one starts to see the expected pattern
- The peak is starting to emerge from the low scale region
- So, the pattern of scale dependence seems typical of NLO calculations

Predictions for the LHC

- Switching to pp collisions instead of $p\bar{p}$ so the linear combination of subprocesses will change
- Energy is increased by a factor of 3.5
- Current data set includes data starting at $p_T \approx 20$ GeV/c
- This means that x_T will initially be much lower than at the Tevatron
- Fragmentation component, even with isolation, will be larger

Photon Fragmentation Functions

- In contrast to hadronic FFs, there are both perturbative and nonperturbative components for photon FFs.

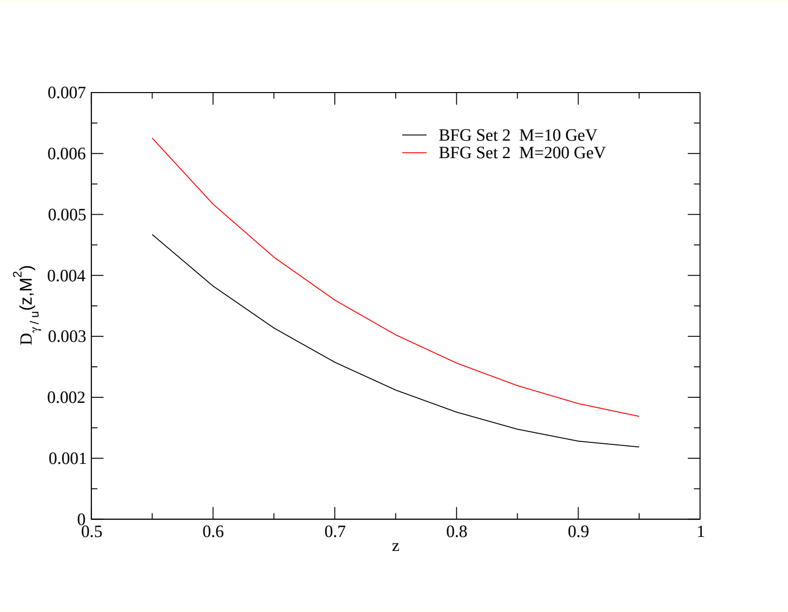
  Photon DGLAP Equations

$$\frac{dD_{\gamma/q}(z,M^2)}{d\ln M^2} = \frac{\alpha}{2\pi}P_{\gamma q}(z) + \frac{\alpha_s}{2\pi}\left(D_{\gamma/q}(y,M^2)\otimes P_{qq}(z/y) + D_{\gamma/g}(y,M^2)\otimes P_{gq}(z/y)\right)$$

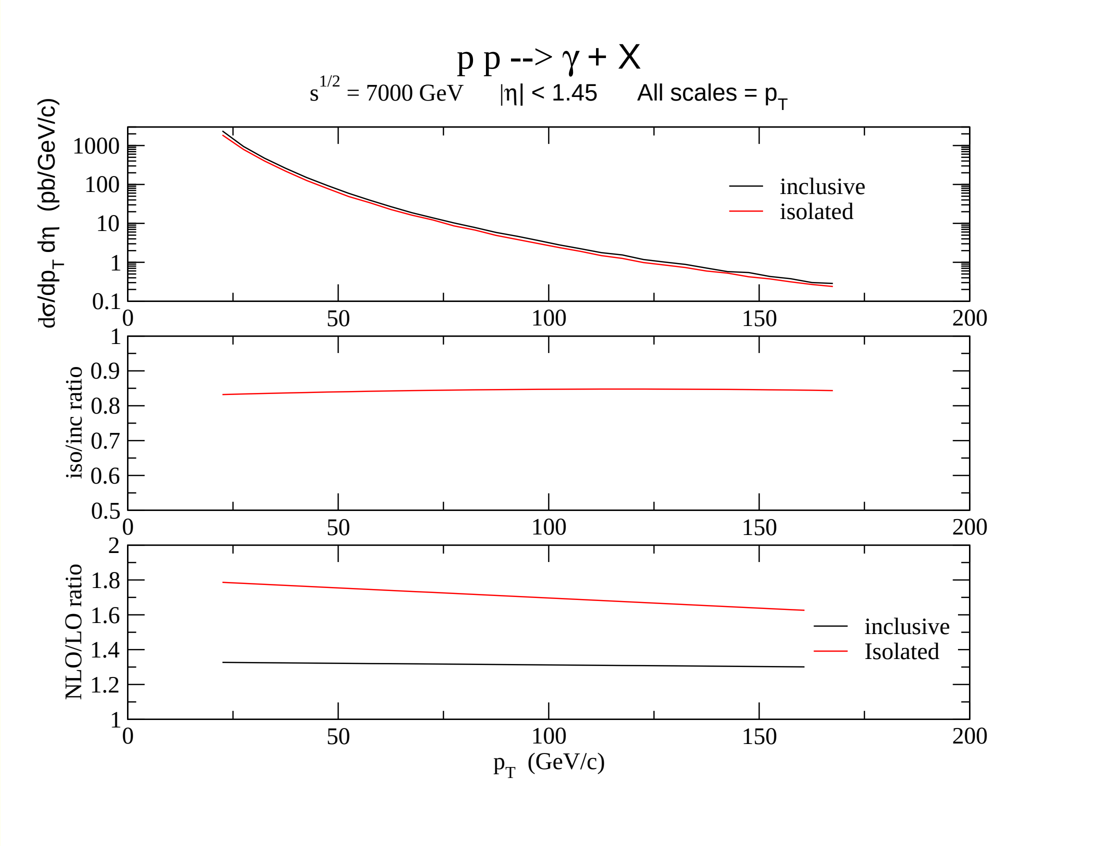
- Here $P_{\gamma q}(z) = e_i^2 \frac{1+(1-z)^2}{z}$
- The $P_{\gamma q}$ term leads to a lowest order perturbative photon FF of the form

$$D_{\gamma/q}(z,M^2) = \frac{\alpha}{2\pi}e_i^2\frac{1+(1-z)^2}{z}\ln\frac{M^2}{\Lambda^2}$$

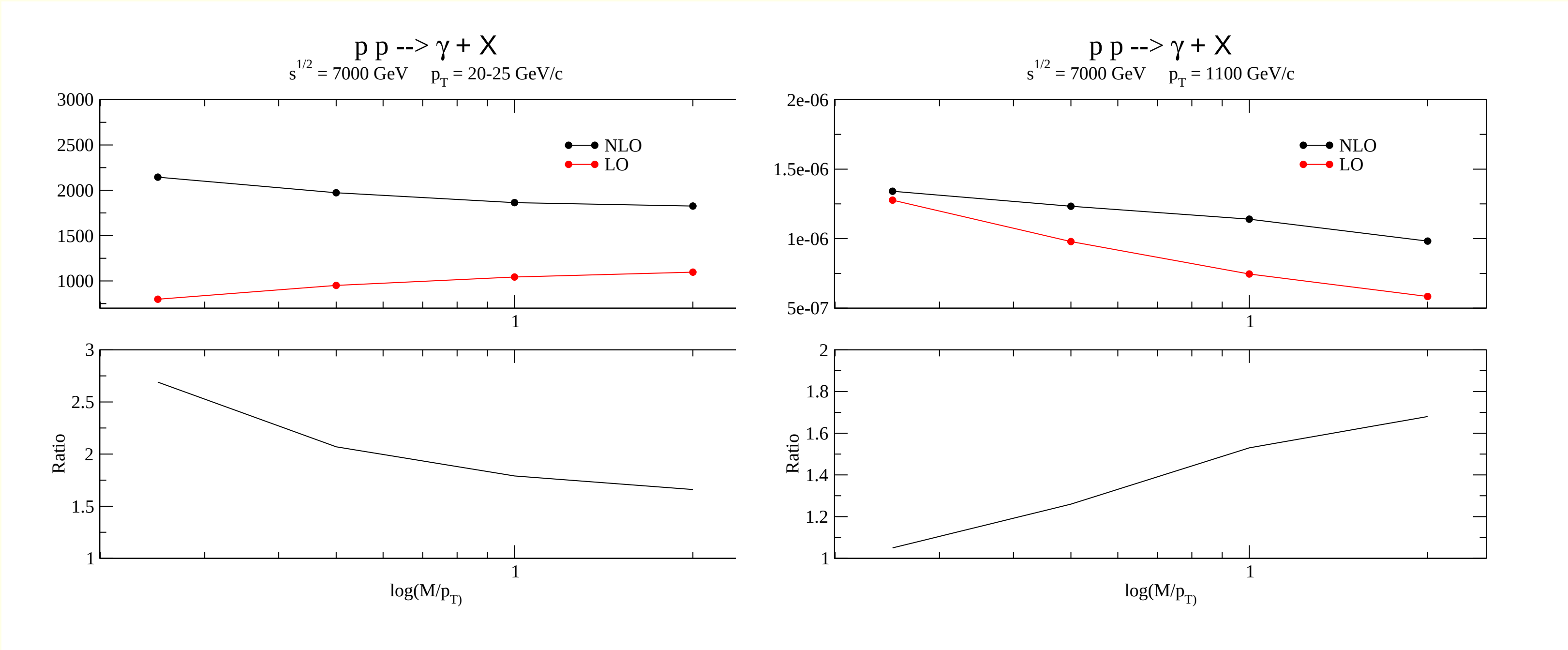
- This is augmented by a nonperturbative contribution at the starting scale used to solve the DGLAP equations
- The subtraction term which partially cancels the scale dependence has both a perturbative and a nonperturbative component
- At large values of z the perturbative component dominates because it does not vanish as $z \rightarrow 1$



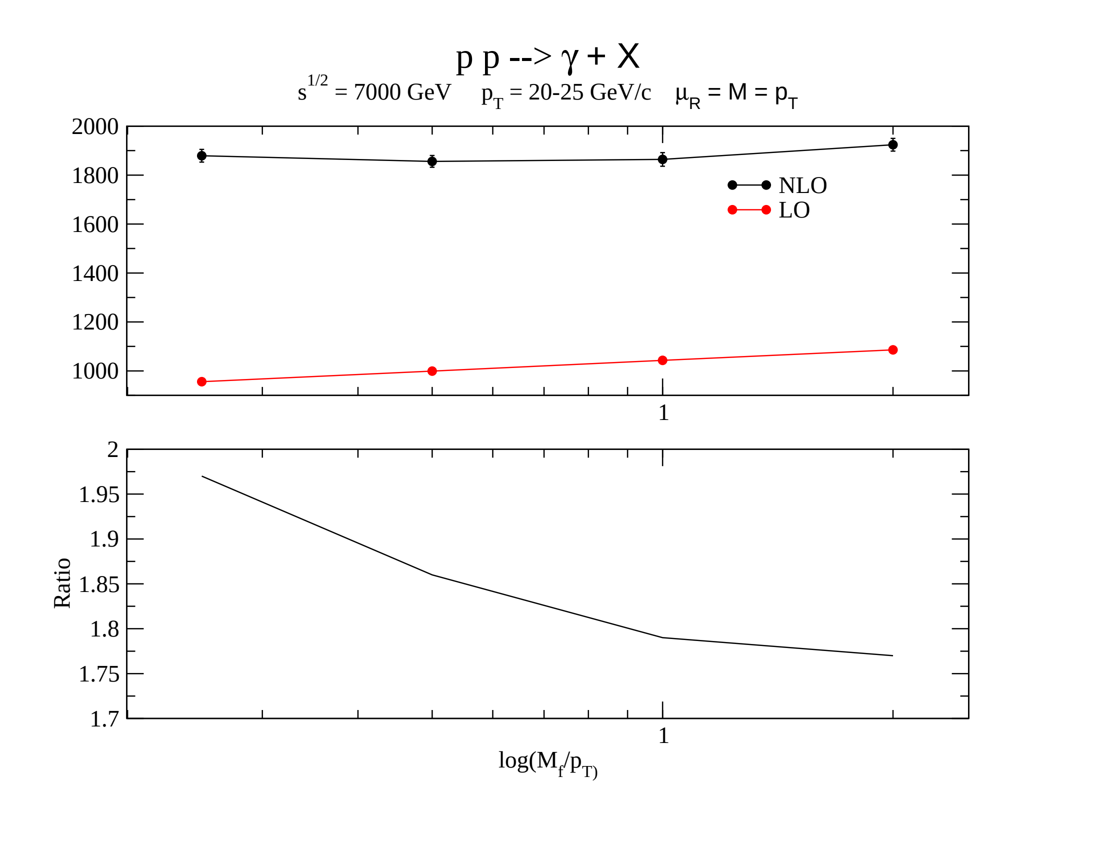
LHC Predictions



- The predictions seem well behaved - nothing stands out
- Isolation used is up to 5 GeV hadronic transverse energy in a cone of radius .4
- Let's look at the scale dependence



- See the same general pattern as at the Tevatron, although a few details are different
- The LO term at $p_T = 22.5$ GeV/c actually *rises* with increasing scale
- This is due to the very small values of x being probed, where the scaling violations rise rather than fall as the scale increases
- Pattern at $p_T = 1100$ GeV/c is more like one expects of a NLO calculation



- LO fragmentation scale dependence shows a slight rise with scale, as expected since the fragmentation function rises as $\log M_f^2$
- The NLO dependence is nearly flat
- The isolation cut forces z to be near one, where the perturbative contribution to the fragmentation function dominates
- The dependence on the fragmentation scale is under control

Comments

- Behavior of the LO calculation is easy to understand

  - Decrease of α_s with increasing scale
  - Slope of scaling violations at small x is positive, turning negative at larger values of x

- At $p_T \approx 40 - 45$ GeV/c the LO results are essentially scale independent over the range studied - this is an accidental cancellation and one would not use this to argue that perturbation theory is under control!
- As one goes to higher values of p_T one recovers the usual result that the NLO scale dependence is less than that of the LO calculation, as one would expect

What about the scale dependence?

- Resummation is known to reduce the scale dependence
- Resummation also increases the fragmentation component (important at fixed target energies - Vogelsang and de Florian)
- It would be interesting to study the γ + jet angular distribution

  - Direct component goes as $\frac{1}{1-\cos\theta}$
  - Fragmentation component goes as $\frac{1}{(1-\cos\theta)^2}$

- Could provide some insight as to the fragmentation fraction

Some Comments on Photon Isolation

Fragmentation functions are inclusive by nature

- Consider $e^+e^- \to \gamma + X$

$$\frac{1}{\sigma}\frac{d\sigma}{dz} = \sum_i e_i^2 \left(D_{\gamma/q_i}(z) + D_{\gamma/\overline{q}_i}(z)\right)$$

- All unobserved hadrons have been integrated over
- When higher order corrections are included, one integrates over the accompanying radiation
- The variable z gives the fraction of the parton's energy that is carried away by the photon
- Since the accompanying fragments from the jet and/or the accompanying radiation tend to go in the general directions of the photon, one makes the approximation that the photon is collinear with the parent parton. Note, this does *not* mean that all the associated particles are *exactly* collinear with the photon - after all , their angles have been integrated over. This is only a statement about the (approximate) direction of the photon.

Photon Isolation

- Isolation is often, though not always, required in order to define what is meant by a photon in high energy detectors
- Often phrased as a limit on the transverse hadronic energy in a cone about the photon
- If the cone is large enough, then one is essentially integrating over the accompanying fragments
- If the photon takes a fraction z of the parton's energy, then that of the associated hadrons is $(1 - z)$
- Limiting the transverse hadronic energy leads to a lower limit on the photon's z
- This restriction matches well with the inclusive nature of the photon's FF discussed above

Problems?

- A possible problem emerges if one wants to make restrictions on how the associated hadronic energy is distributed in the cone, e.g., perhaps in an annulus defined by two radii
- The fragmentation function contains no information on where the associated hadrons went, since this information has been integrated out
- The best one can do is to treat all the associated hadrons as being *exactly* collinear with the photon so that there is no cone size at all
- This extreme assumption can then be corrected order by order in perturbation theory
- But we have only gone one order, so far

- Frixione's isolation algorithm is designed to remove the fragmentation contribution altogether
- I would argue that the fragmentation is dominated by the large z region where the perturbative fragmentation contribution dominates
- Resummation techniques are available
- Removing the fragmentation contribution altogether may remove some interesting physics
- I advocate doing as little as possible to the data, since cuts designed to remove nonperturbative contributions may also remove perturbative pieces, as well
- May be difficult to replicate theoretically at the parton level

Summary and Conclusions

- Direct photon scale dependence at the Tevatron peaks at rather small scales for low values of x_T, but shows the usual NLO pattern at larger x_T
- This behavior is not related to the fragmentation component
- A similar pattern shows up for 7 TeV at the LHC
- Resummation is known to reduce the scale dependence in those cases where it has been applied - this is an active area of investigation
- Photon isolation cuts which use an inclusive cone definition, *i.e.*, those which do not place detailed restrictions on the angular dependence of the associated hadronic energy, are better matched to the inclusive nature of fragmentation functions
- If isolation algorithms with severe angular restrictions are adopted, then I advocate that an inclusive cone algorithm also be utilized as a cross check