Uncertainties in prompt photon production

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Outline

- Prompt Photon production in an hadronic environment
- Theoretical/Experimental issues with isolation
- Fragmentation functions
- Inclusive photon and Di-photon production @ the LHC
- Conclusions

Parton level Photon MC,

Shown below is the status of public NLO parton level MCs with experimental isolation.

Process	Jetphox	Diphox	Baur	MCFM
$pp \to \gamma j$	NLO in frag (BFG)	-	-	LO in Frag (BFG, GdRG)
$pp \to \gamma\gamma$	-	NLO in frag (BFG) LO in gg	-	NLO gg LO in frag
$pp \to V\gamma$	-	-	No FSR LO frag	LO frag $gg \to Z\gamma$.

In addition lots of results for smooth cone isolation available now too, a selection of recent results are,

$VV\gamma, V\gamma\gamma$ Bozzi, Campanario, Hankele, Rauch, Rzehak, Zeppenfeld (2009-2011) VBFNLO

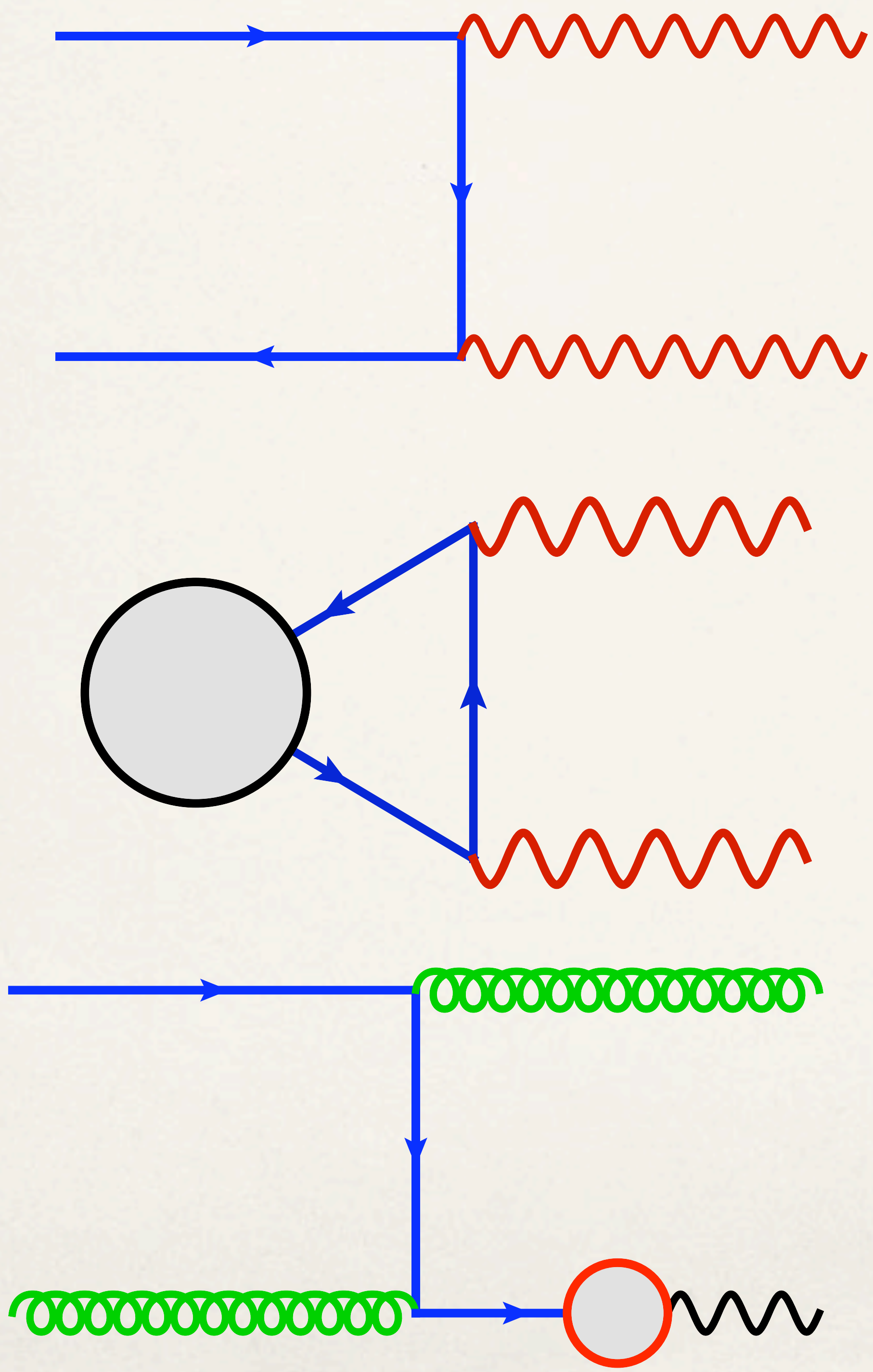
$V\gamma j$ Campanario, Englert, Spannowsky Zeppenfeld (2009,2010) VBFNLO

$t\bar{t}\gamma$ Melnikov, Scharf, Schulze (2011)

$\gamma j j$ Bern, Diana, Dixon, Febres Cordero, Hoeche, Ita, Kosower, Maitre, Ozeren (2011) Blackhat

Not to mention photons in Event generator MCs......

Photons in a hadronic environment



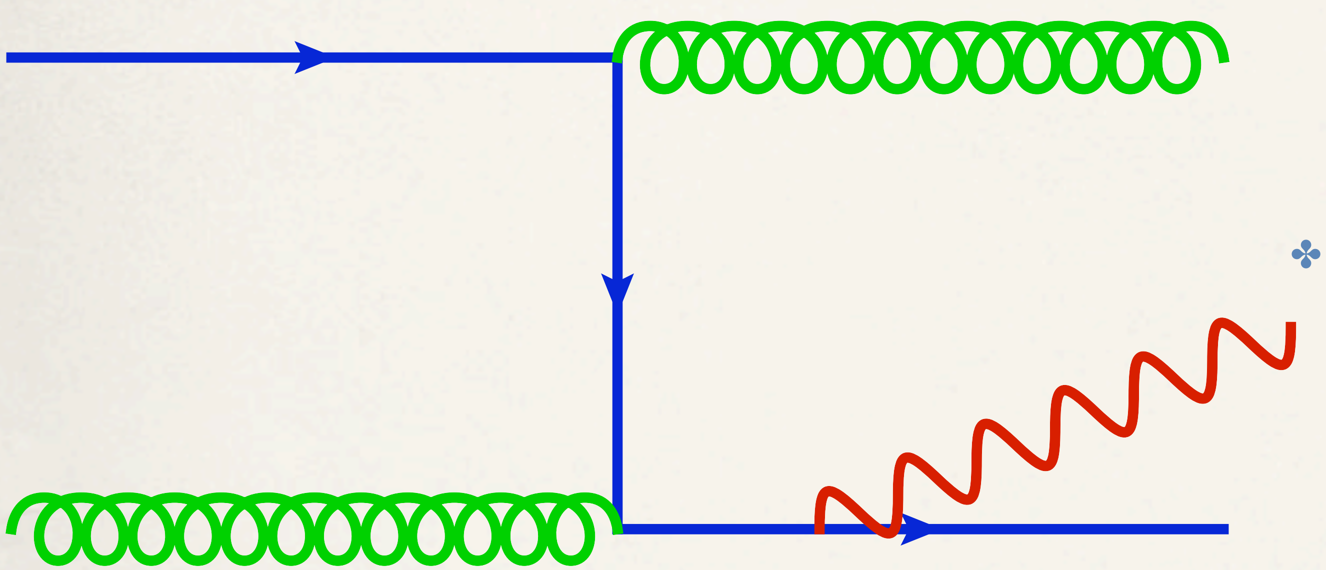
- Photons are readily produced from a variety of sources.
- Typically we are interested in those produced in hard scattering to study PDFs, anomalous couplings etc.
- Unfortunately secondary photons and those arising from fragmentation pollute this sample.
- This talk will discuss some of the theoretical issues regarding photon production at the LHC.

Experimental Procedures

- Have to reduce backgrounds from unwanted photons.
- Define isolated photons as those with requirements on the amount of hadronic energy deposited in a certain region in the detector.
- Typically require isolation of the form

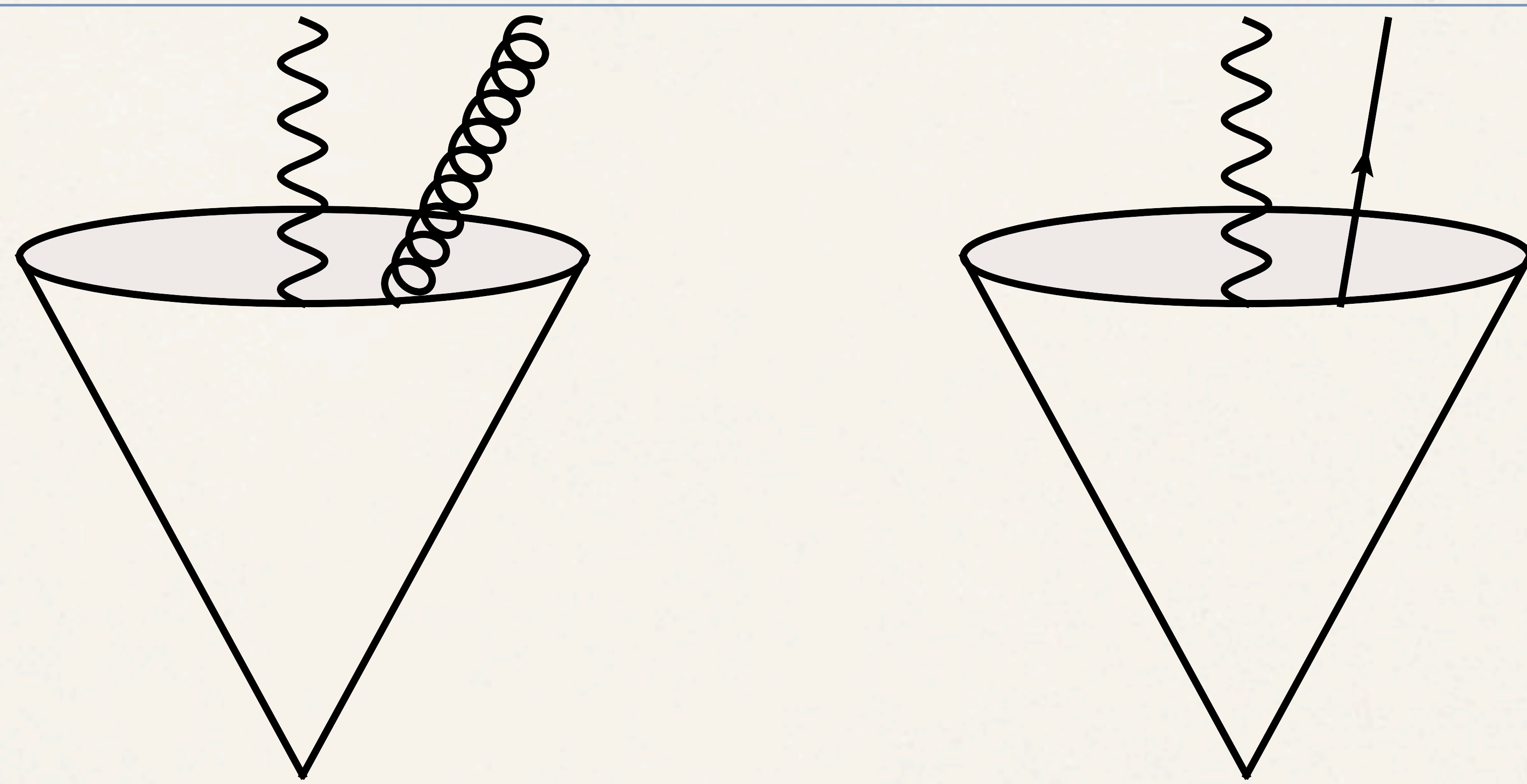
$$\sum_{\in R_0} E_T(\text{had}) < \epsilon_h \, p_T^{\gamma} \qquad \text{or} \qquad \sum_{\in R_0} E_T(\text{had}) < E_T^{\max}$$

Isolating photons - theoretical issues



- A given final state consisting of a photon + n jets is finite at LO.
- At NLO in QCD problems arise from collinear poles associated with a quark and a photon.
- Initial state poles are removed by demanding central photons, what about final state poles?

Isolating Photons theory



- IR singularity associated with quark - photon collinear pole
- Could ban all radiation in a cone around the photon (IR unsafe)
- Could use Frixione (98) isolation
- Could use Fragmentation functions

Frixione (smooth cone) isolation

- First proposed by Frixione (98), the idea is to remove the collinear pole by forbidding QCD radiation in the exact collinear limit whilst allowing arbitrarily soft radiation in the surrounding region, i.e.

$$\sum_{R_{j\gamma} \in R_0} E_T(\text{had}) < \epsilon_h p_T^\gamma \left(\frac{1 - \cos R_{j\gamma}}{1 - \cos R_0} \right).$$

- This is done pre-jet clustering, then one clusters and applies cuts only to the jets found outside of the cone.

- This approach preserves IR safety and does not require fragmentation contributions. If desired, one can change the power of the 1-cos terms.

Comparison with experiment?

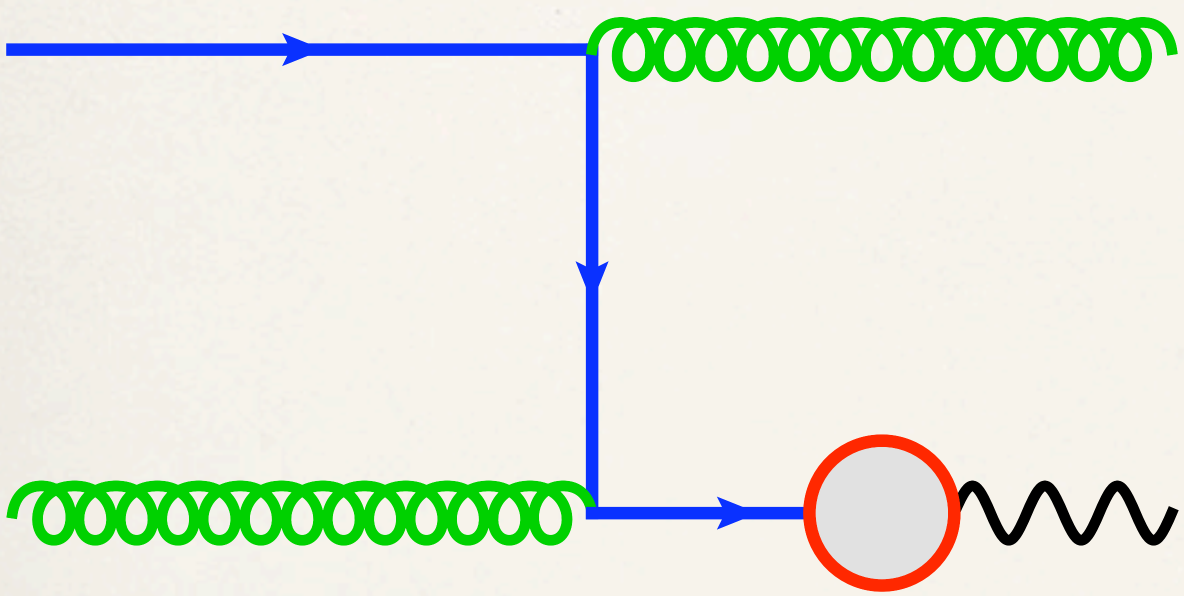
- Due to its theoretical ease Frixione isolation is routinely used by theorists in photon + X calculations.
- How to compare to data?
- I would suggest choosing Frixione parameters such that the total integrated energy in the cone is equal to E_{max} in the experimentalist set up. This results in controlled approximations on both sides.

Isolation radius	Direct contribution		Fragmentation contribution		Total
R	Born	NLO	Born	NLO	NLO
1.0	1764.6	3318.4	265.0	446.7	3765.1
0.7	1764.6	3603.0	265.0	495.0	4098.0
0.4	1764.6	3968.9	265.0	555.6	4524.5
0.1	1764.6	4758.2	265.0	678.9	5431.1
Without isolation	1764.6	3341.1	1724.3	1876.8	5217.9

Table 1. Isolated cross sections (the values are given in pb/GeV) corresponding to $\varepsilon_h = 0.13333$.

Taken from hep-ph/0204023 (Catani, Fontannaz, Guillet, Pilon)

Fragmentation of partons to photons



$$\sigma = \sigma^{\gamma}(M_F^2) + \int dz\, D^a(z)\sigma^a(z, M_F^2).$$

- Collinear singularity is of course not realised in reality
- As photon becomes collinear becomes indistinguishable from one produced by a QCD parton
- Fragmentation functions contain a pole which explicitly cancels collinear singularity.
- Only the combination is physical at NLO.

Fragmentation functions - theory

The evolution of fragmentation functions is given by the DGLAP equation,

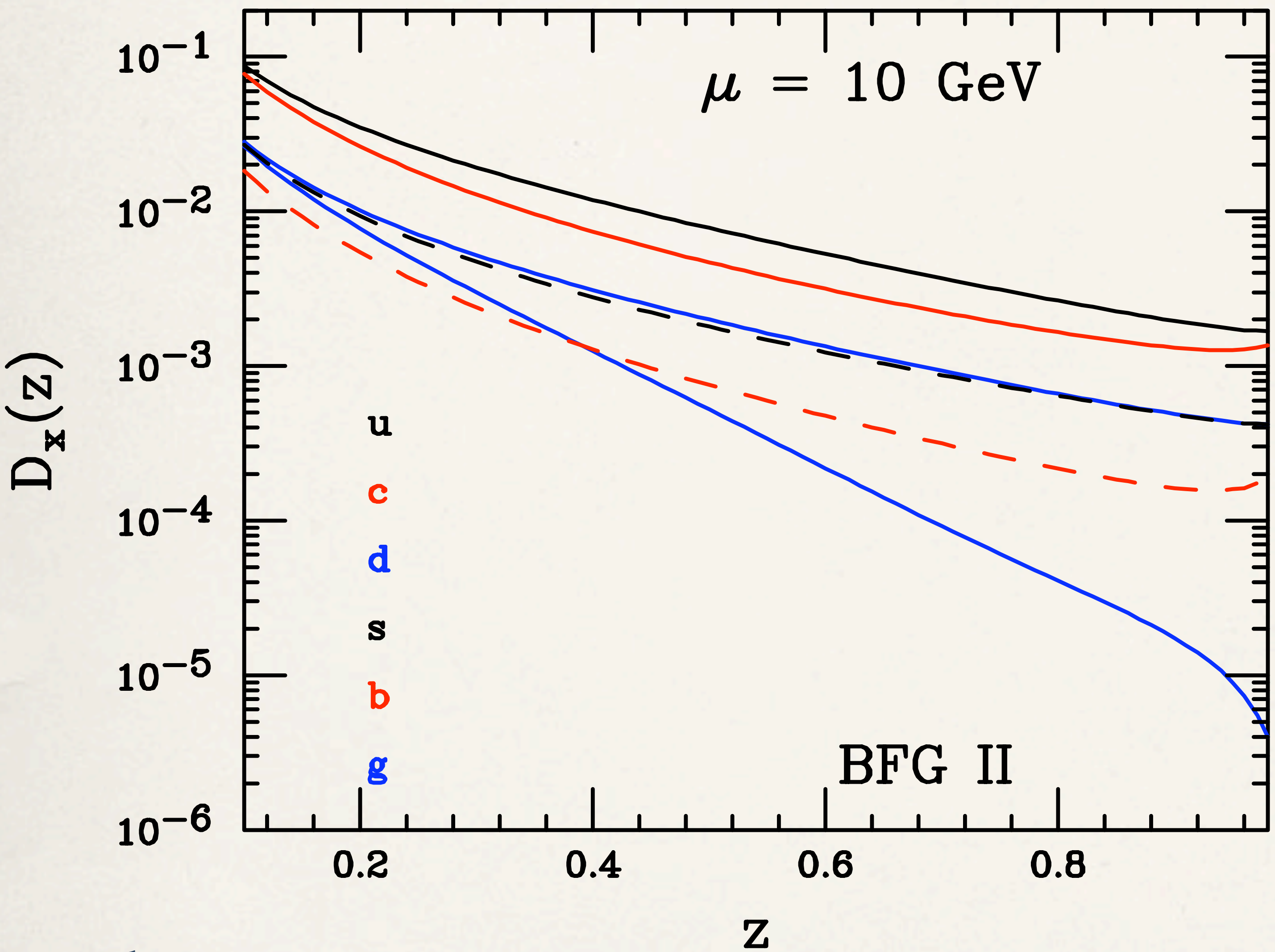
$$M^2 \frac{\partial D_q^\gamma}{\partial M^2} = C_s\ K_{\gamma q} + P_{qq} \otimes D_q^\gamma + P_{gq} \otimes D_g^\gamma$$

The solutions to this equation require non perturbative input for some given scale. $D^{np}_{q \to \gamma}(x, \mu_0)$

Commonly used Fragmentation functions are those of Bourhis, Fontannaz and Guillet (97) (BFG).

In addition, a different approach was proposed by Gehrmann-De Ridder and Glover (98).

Fragmentation functions BFG



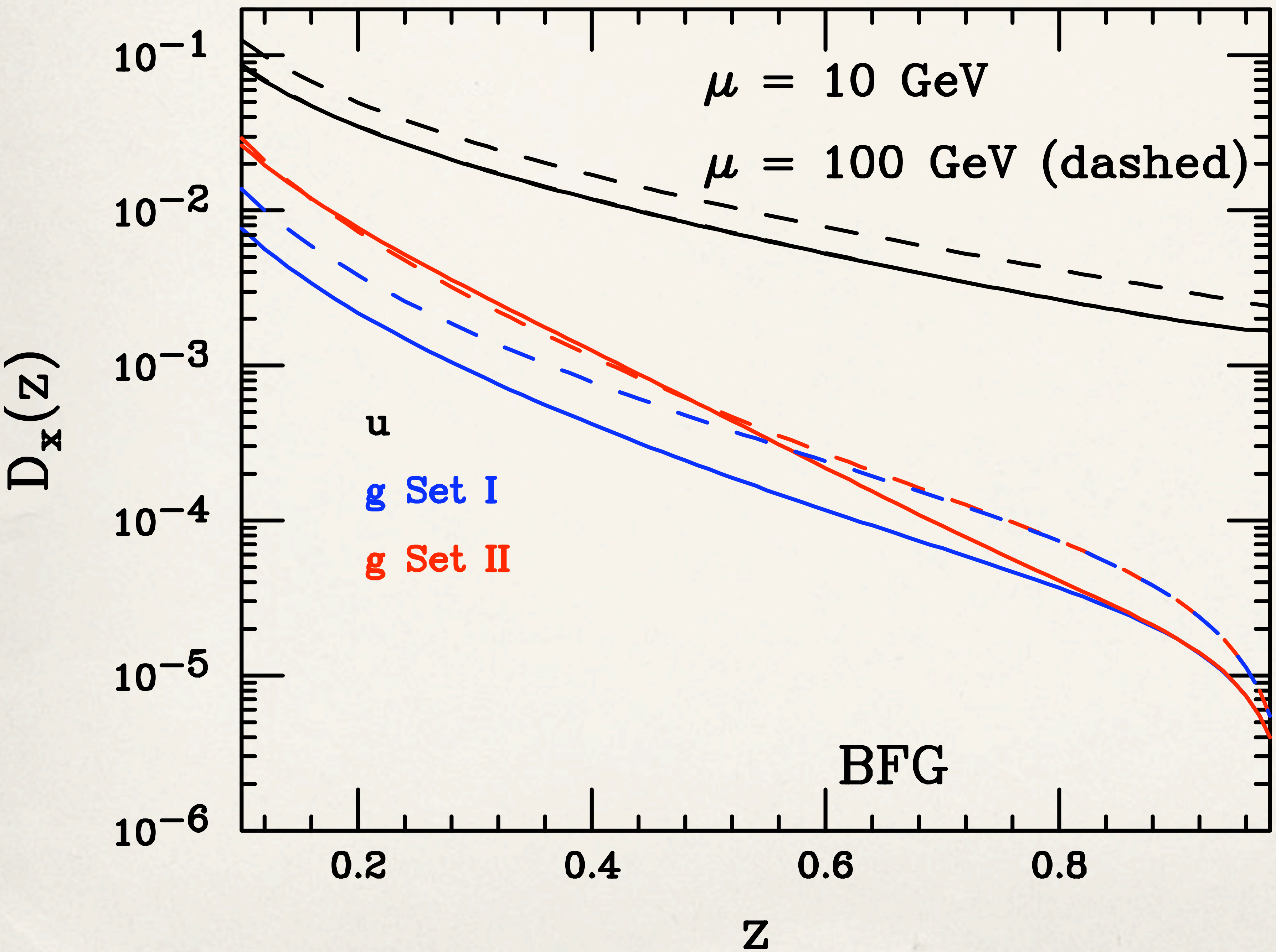
BFG use NLL solutions to the DGLAP equation in which logs of the form,

$$\ln\left(\frac{\mu_F^2}{\mu_0^2}\right)$$

Are summed to all orders.

The non perturbative input is taken from ALEPH and HRS data and assumes a Vector-dominance model (VDM) of the photon.

Fragmentation functions BFG-II



Gluon fragmentation is more sensitive to NP input, especially at lower scales.

Dependence on the fragmentation scale is small for up quarks. Gluon function changes shape more.

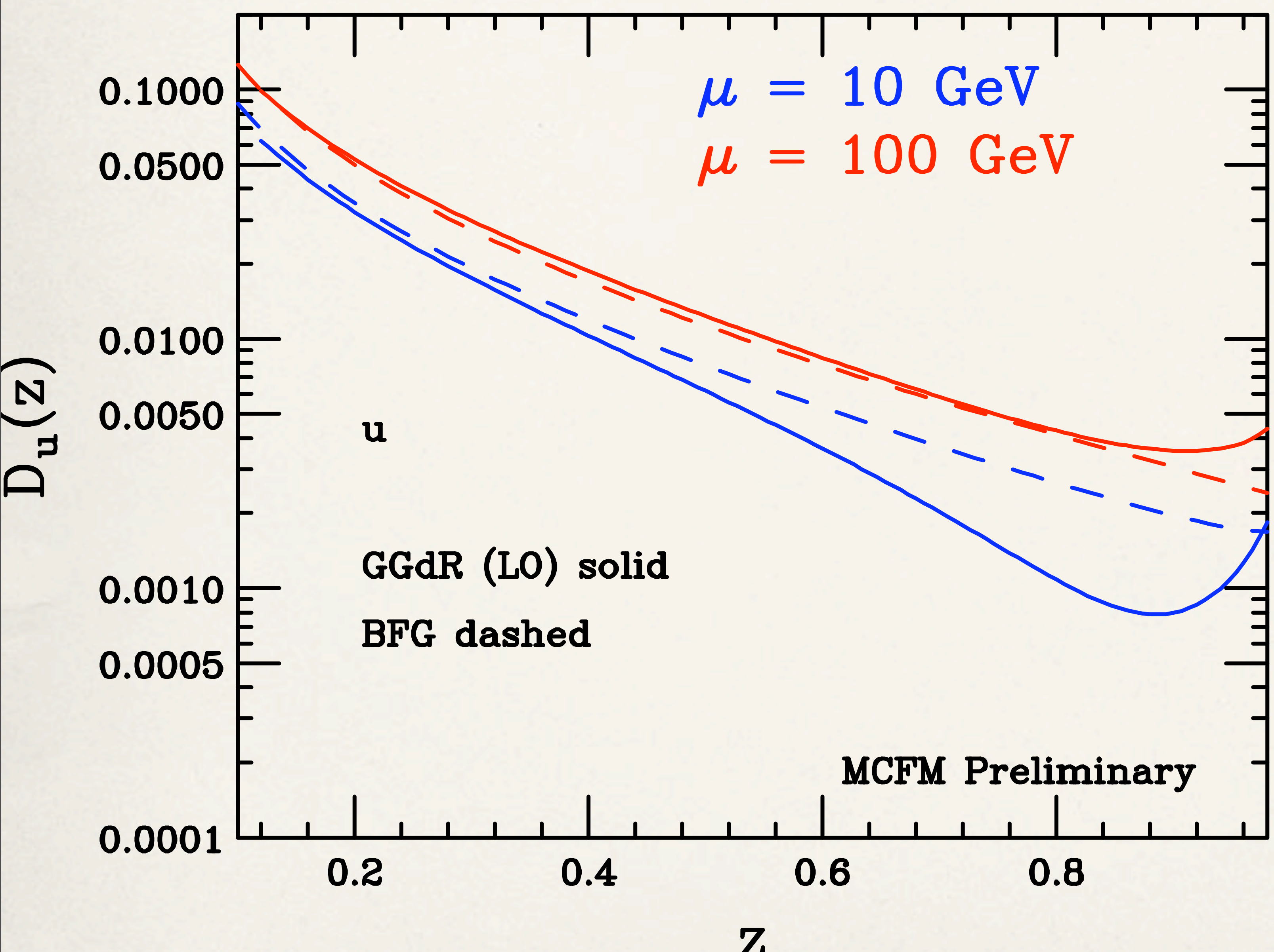
Fragmentation functions - GdRG

- Gehrmann-De Ridder and Glover (98) calculated the fragmentation functions using a fixed order expansion. The motivation being that logs of (1-z) can be compete with resumed logs for isolated photons.

- They found at NLO,

$$\begin{aligned} D^{(NLO)}_{q\to\gamma}(x,\mu_F) &= D^{np}_{q\to\gamma}(x,\mu_0) + \left(\frac{\alpha e_q^2}{2\pi}\right)\ln\left(\frac{\mu_F^2}{\mu_0^2}\right)P^{(0)}_{q\to\gamma}(x) \\ &+ \left(\frac{\alpha e_q^2}{2\pi}\right)\left(\frac{\alpha_s}{2\pi}\right)\ln\left(\frac{\mu_F^2}{\mu_0^2}\right)P^{(1)}_{q\to\gamma}(x) \\ &+ \frac{1}{2}\left(\frac{\alpha e_q^2}{2\pi}\right)\left(\frac{\alpha_s}{2\pi}\right)\ln^2\left(\frac{\mu_F^2}{\mu_0^2}\right)P^{(0)}_{q\to q}\otimes P^{(0)}_{q\to\gamma}(x) \\ &+ \left(\frac{\alpha_s}{2\pi}\right)\ln\left(\frac{\mu_F^2}{\mu_0^2}\right)P^{(0)}_{q\to q}\otimes D^{np}_{q\to\gamma}(x,\mu_0). \end{aligned}$$

GdRG II



- The NP pieces are fitted to ALEPH data at LO and at NLO.
- The plot shows the LO fragmentation functions, which are sufficient to remove the collinear singularity
- Biggest difference between BFG and GdRG is at large z

$$D^{np(LO)}_{q\to\gamma}(x,\mu_0) = \left(\frac{\alpha e_q^2}{2\pi}\right)\left(-P^{(0)}_{q\to\gamma}(x)\ln(1-x)^2 - 13.26\right),$$

Impact of isolation

$$\sum_{\in R_0} E_T(\text{had}) < \epsilon_h \, p_T^\gamma$$

- Upper limit on z is fixed

$$z_c = \frac{1}{1+\varepsilon_h}$$

- Typically z > 0.85

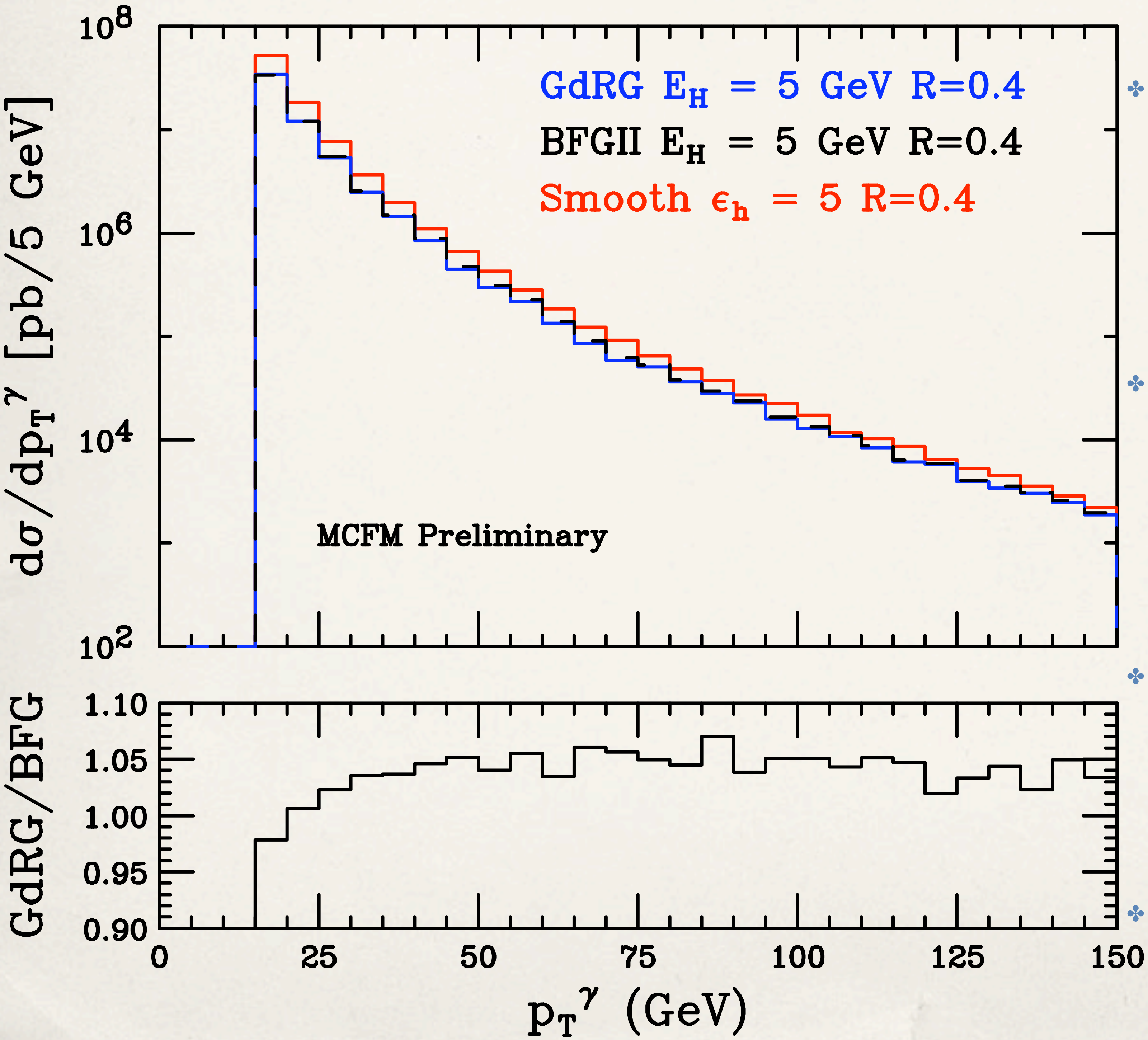
$$\sum_{\in R_0} E_T(\text{had}) < E_T^{\max} \, .$$

- Upper limit on z is now pT dependent

$$z_c = \frac{p_{T\,\gamma}}{E_{T\,max} + p_{T\,\gamma}}$$

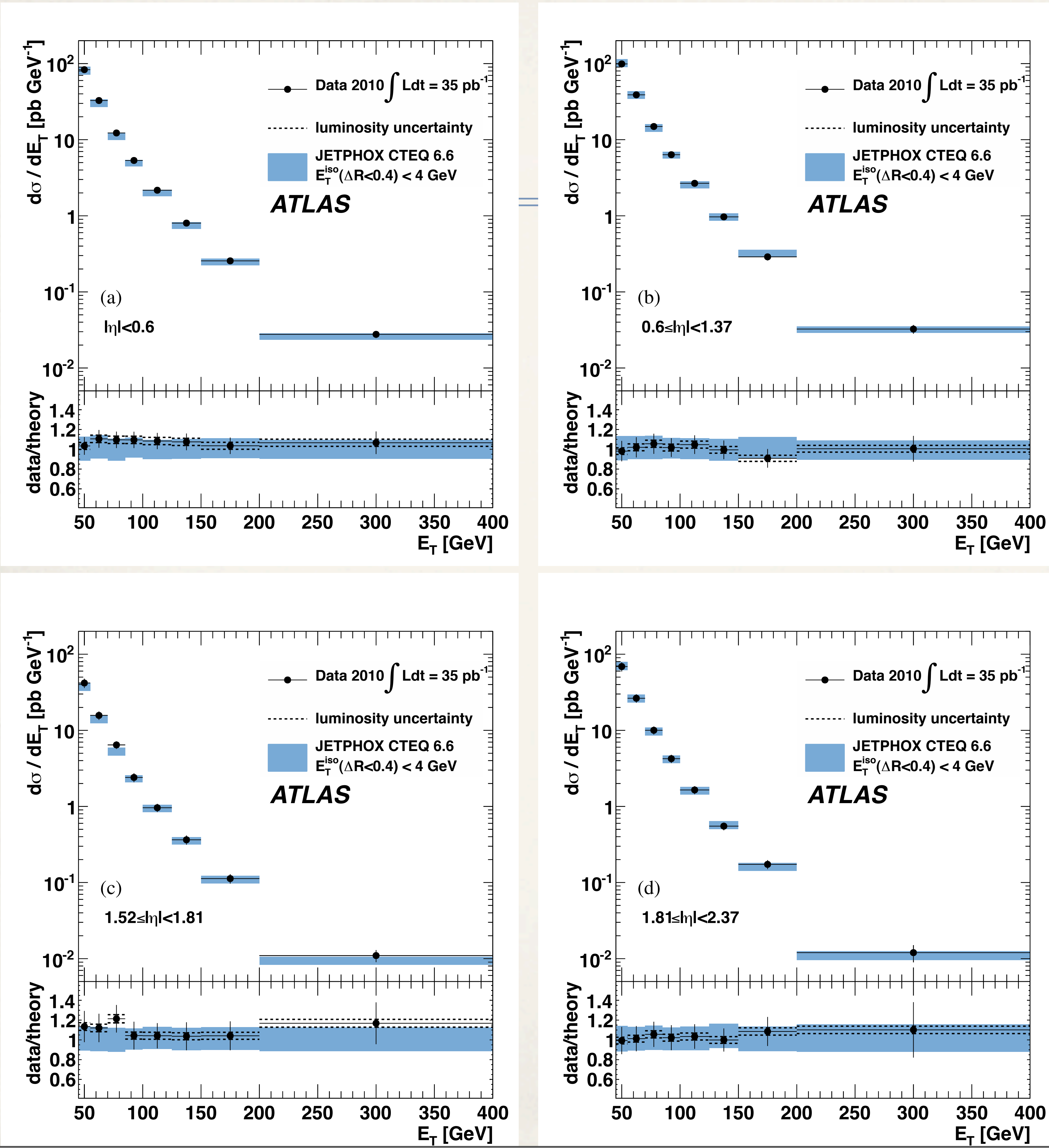
- Typically 20 GeV => z > 0.8 whereas 200 GeV => z > 0.98

Final impact on distributions



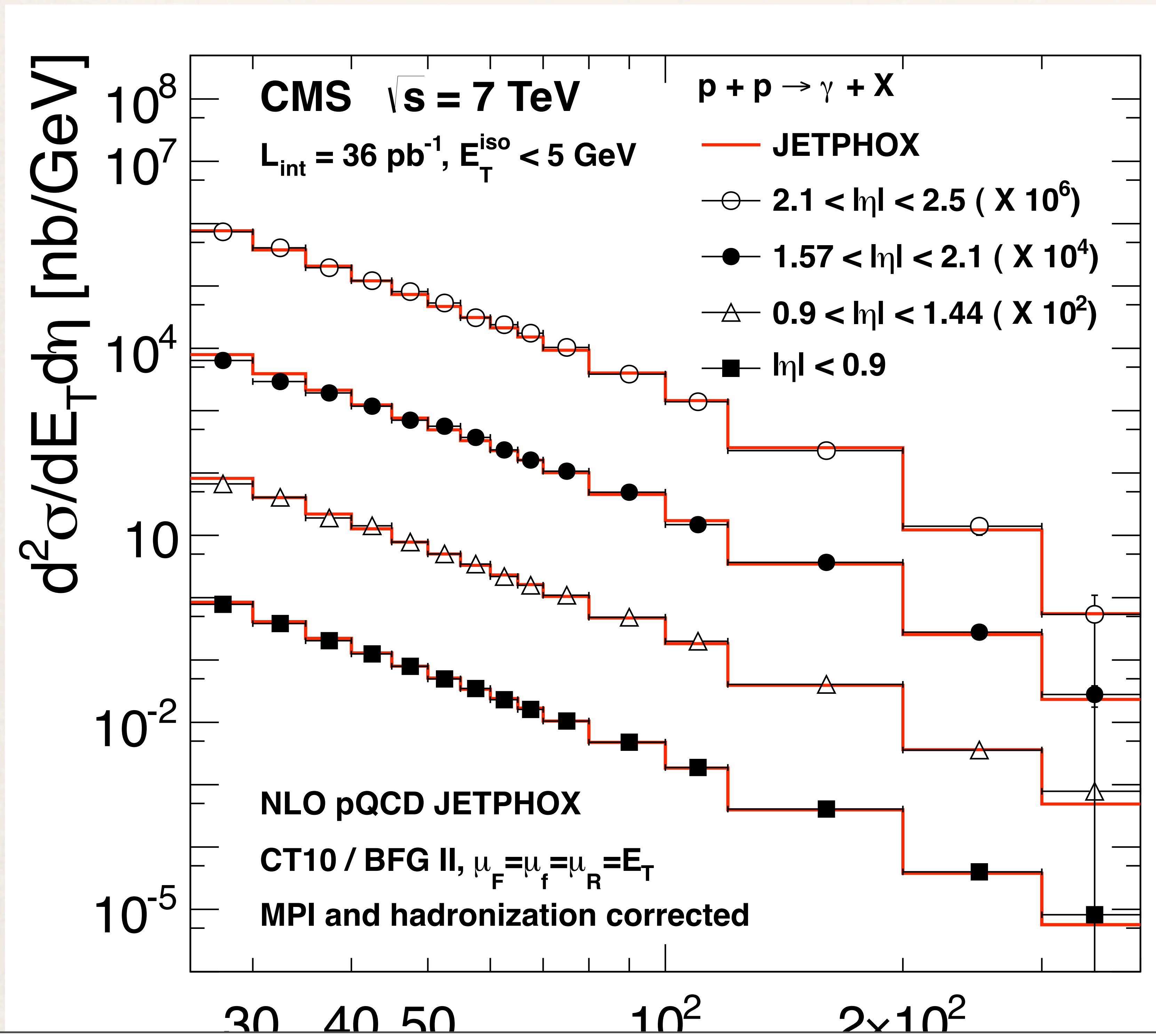
- Differences between fragmentation functions are at the level of 1 % on the scale of the total cross section.
- Changes the shape however, typically by around 5 %, certainly worth comparing both against data.
- Using Frixione isolation with naive parameters gives quite different results.
- MSTW2008 NLO pdfs used here.

Prompt photon production: data



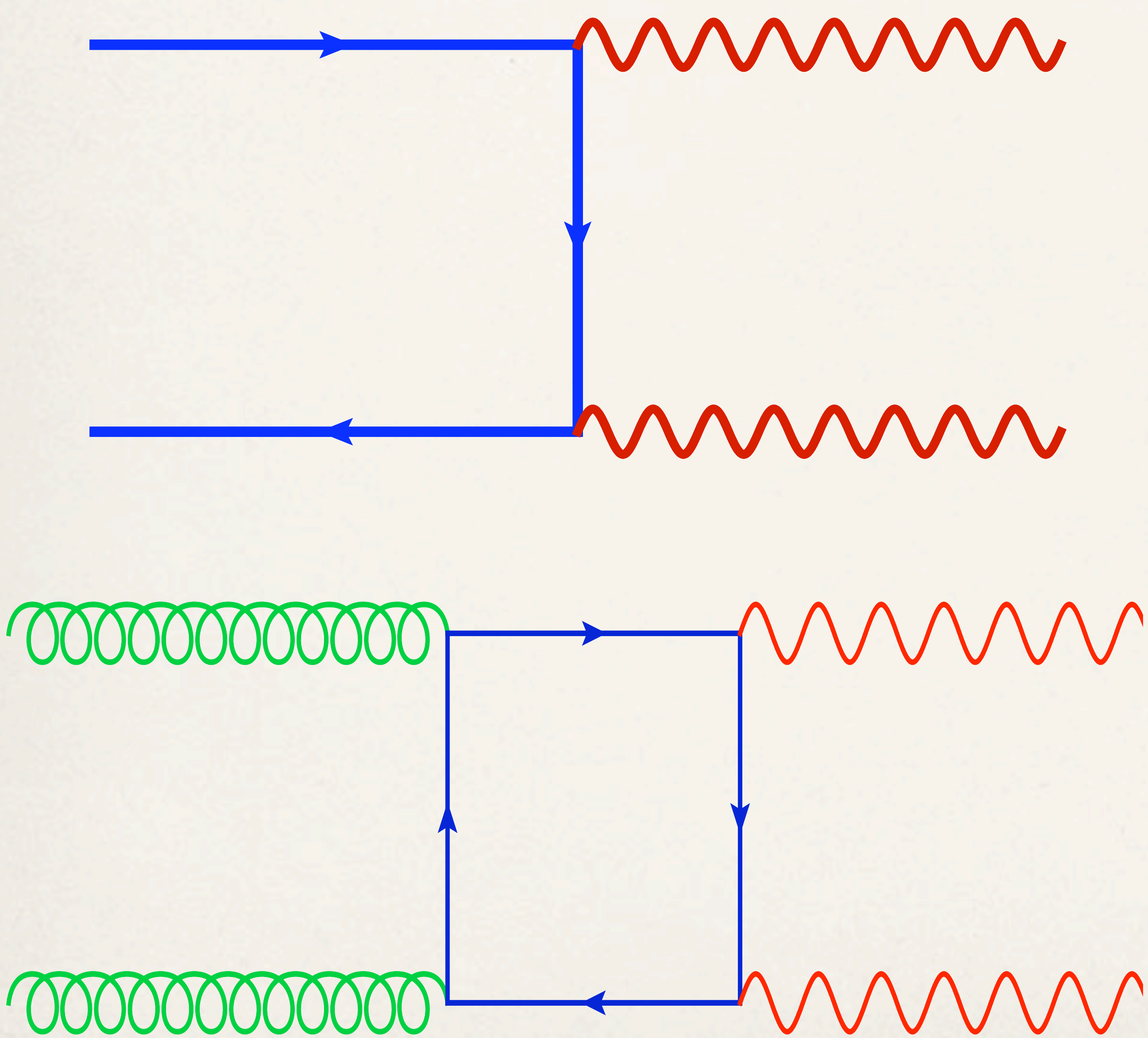
- ATLAS data from 1108.0253 shows good agreement between SM predictions and data.
- With isolation used z > 0.93 so fragmentation contribution is small.
- Typical 10 % uncertainty from NLO calculation

Prompt photon production : data



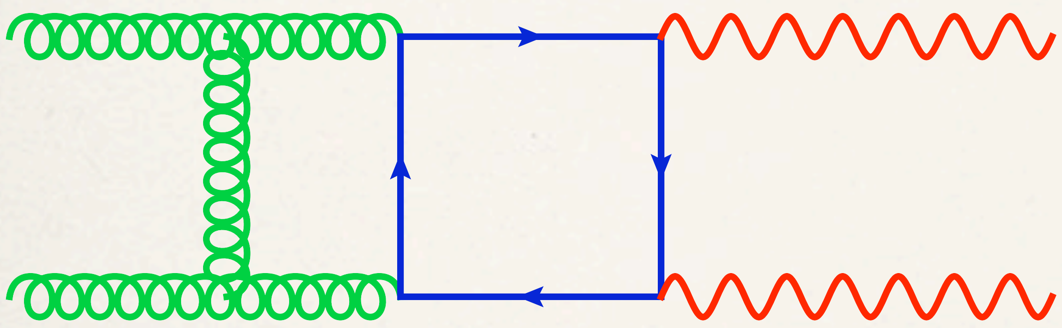
- CMS 1108.2044 also observe nice agreement with Jetphox over a wider pT range.
- Theory overshoots in some of the lowest pT bins at present.

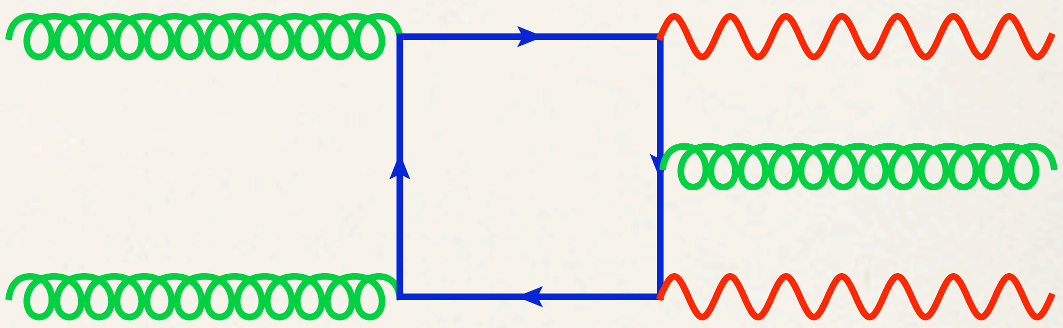
Di-photon Production at hadron colliders



- At LO two photons are produced by a quark pair
- At higher orders in perturbation theory one encounters gluon initiated pieces
- Separately gauge invariant, at higher operating energies can become a significant contribution.

Higher order pieces to gg pieces



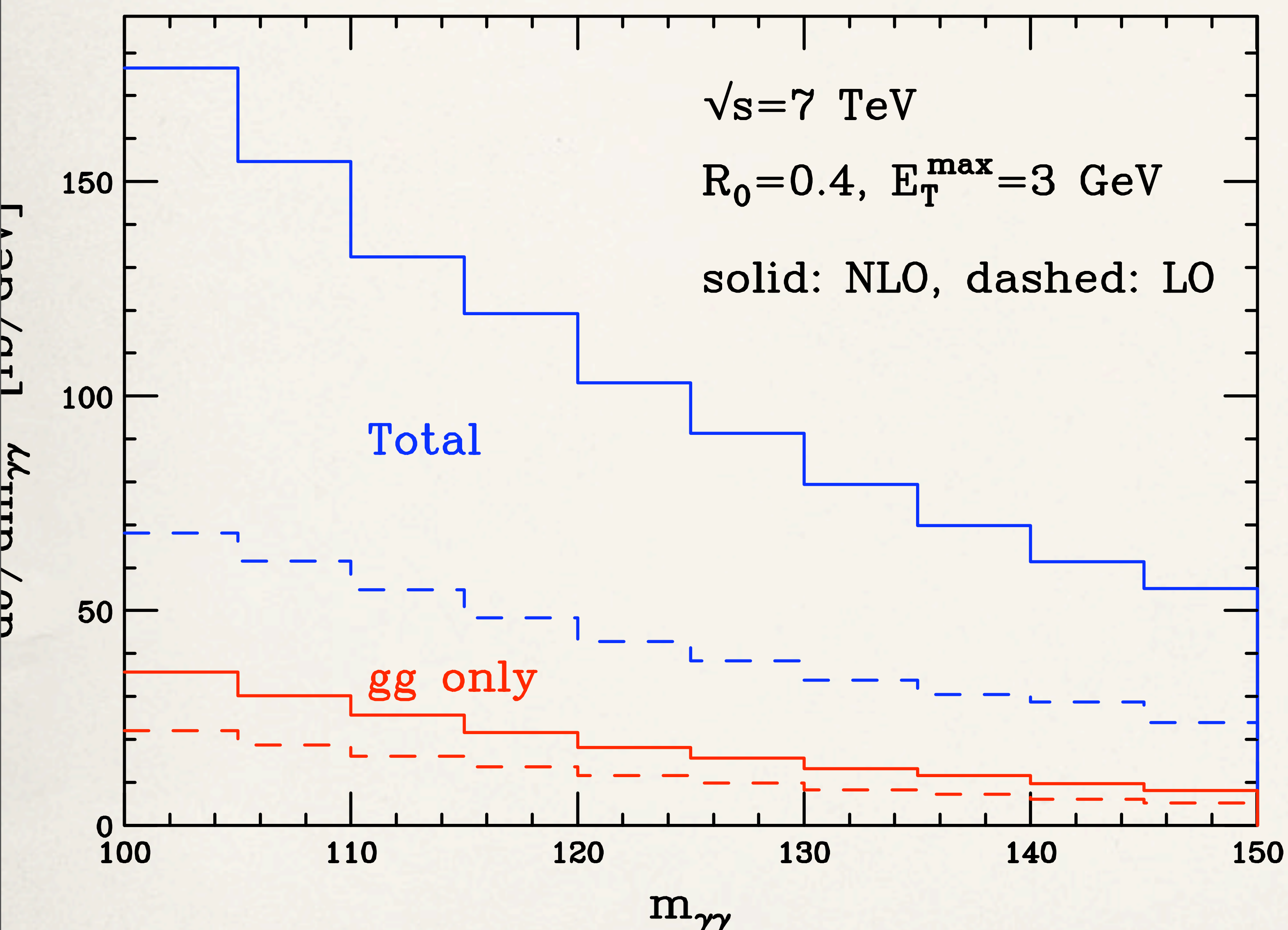


- In principle of order NNNLO, but large gluon flux means contribution is significant

- Due to finite nature of gg initiated pieces have same singularity structure as one-loop amplitudes

- Possible to implement in general NLO MC setting. We use the results of Bern, De Freitas and Dixon (2001).

Di-photon production

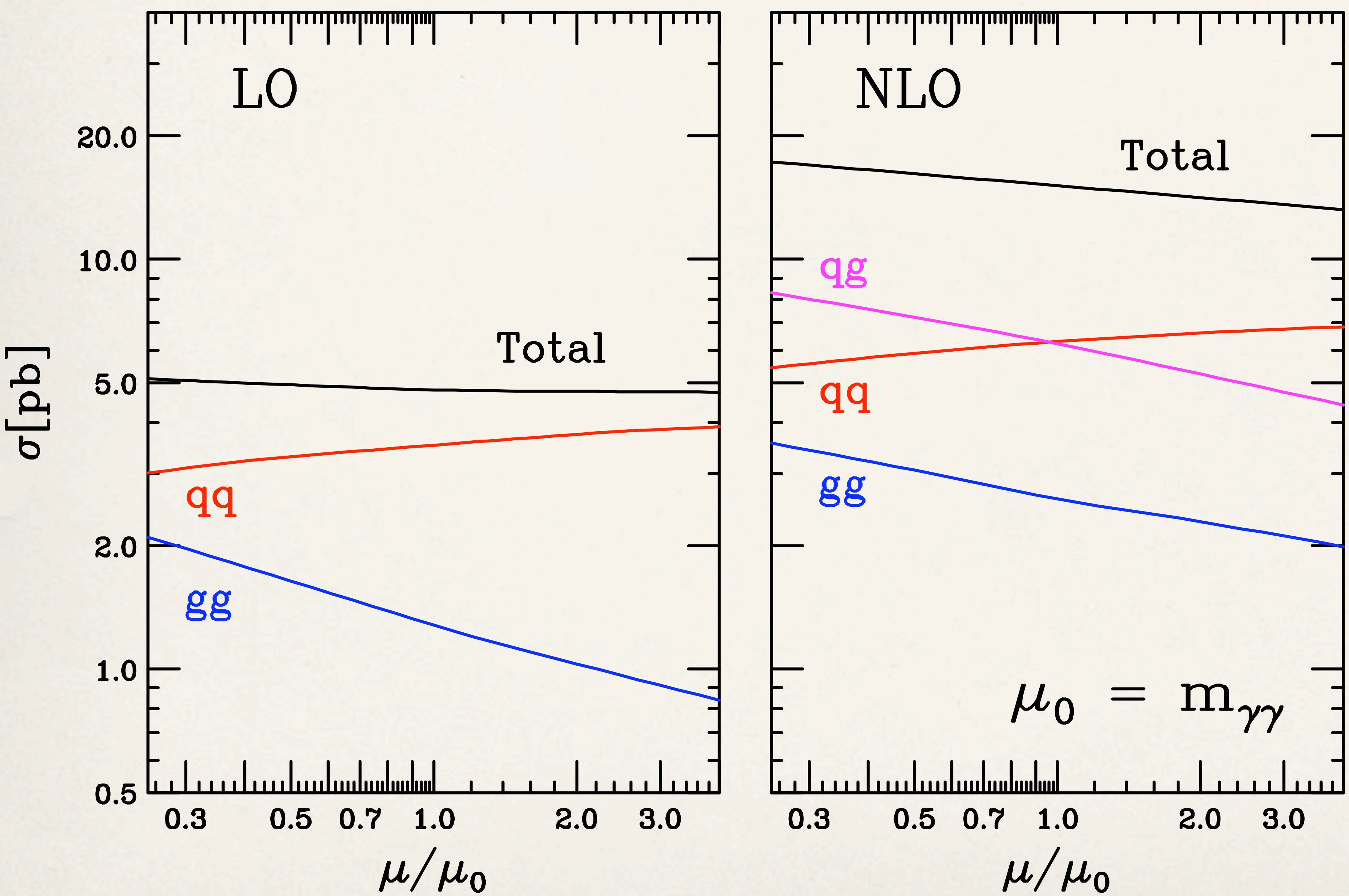


Shown is the invariant mass of the photon pair over the range of interest for Higgs searches. Clearly the gg pieces are important at both LO and NLO.

Somewhat surprising at first glance is the large K factor when going from LO to NLO.

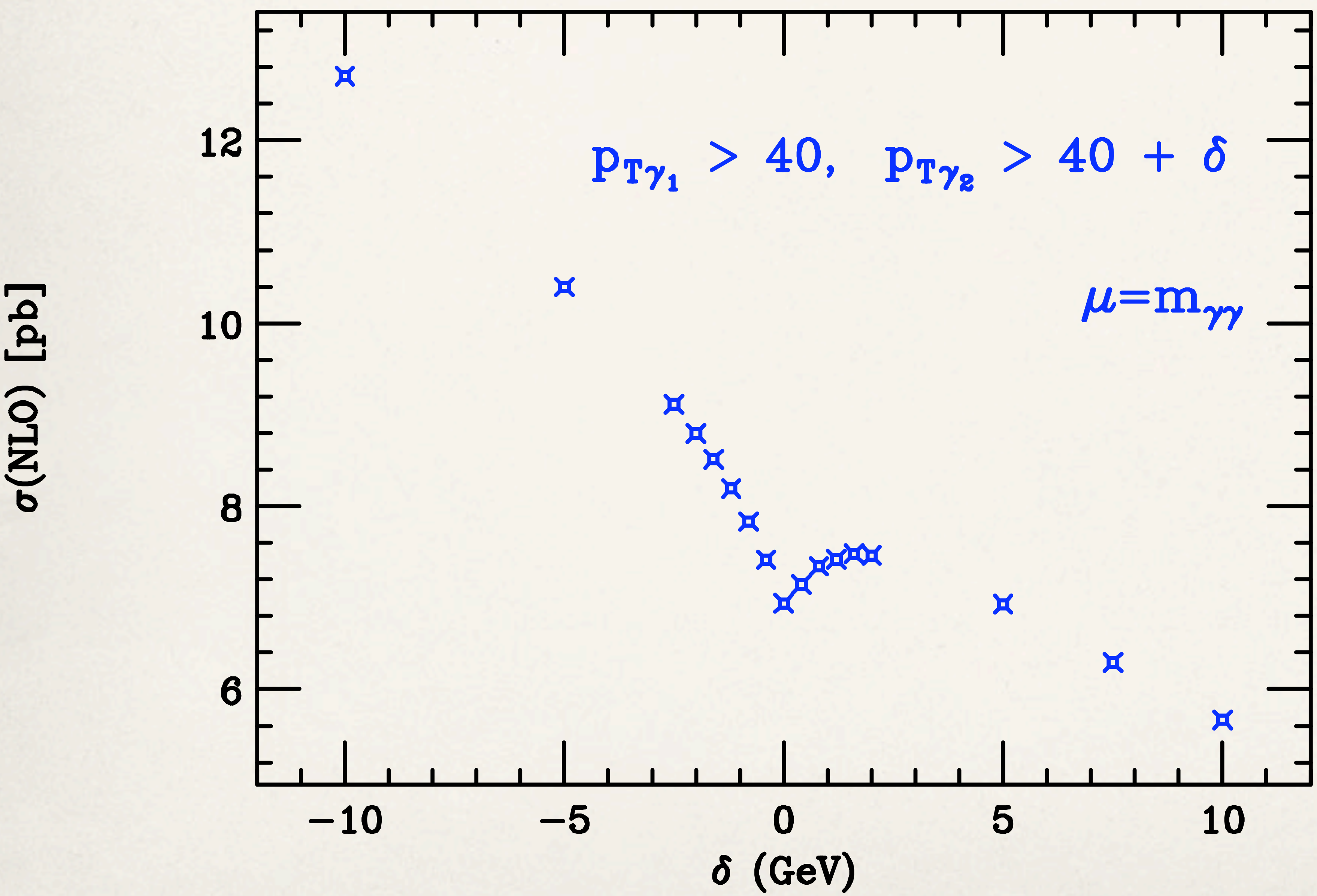
$$p_T^{\gamma_1} > 40 \text{ GeV} , \quad p_T^{\gamma_2} > 25 \text{ GeV} , \quad |\eta_{\gamma_i}| < 2.5 ,$$

Scale dependence of di photon production.



- Large K factor is a result of the staggered cuts applied to photons.
- Can be seen by dominance of the qg type pieces which are real only at NLO.

Staggering Photons



- Interesting feature for back to back photons.
- Arises from restricted phase space for real corrections. (Frixione, Ridolfi 97).
- Would be very interesting to see this plot made with LHC data!

Conclusions

- I have presented an overview of photon physics at the LHC, concentrating on the role of isolation, fragmentation and higher order corrections.
- Using current isolation conditions z is constrained to be close to 1 where the fragmentation functions are small. Different fragmentation functions yield similar results, but GdRG predicts harder photons than BFG.
- Frixione isolation can be used, probably some tuning required to obtain the best results. I personally am not sure that this is something experimentalists have to pursue.
- Data agrees well with theory within uncertainties, typically around the 10 % at NLO.
- Diphotons are also interesting, lots of stagger applied to photons can lead to large K factors. Although with no stagger NLO breaks down due to large logs of soft gluons.
- Higher orders in gg give a relatively large contribution, even tho they are NNNLO in perturbation theory.