NLO PREDICTIONS WITH MCFM

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OUTLINE

- Review of updated DiBoson processes in MCFM v6
- Applications to LHC Higgs searches

MCFM

MCFM is a publicly available NLO parton level Monte Carlo Computer program

First started in late 90's (Campbell, Ellis), now at version 6 (Campbell Ellis CW 1105.0200)

Can be downloaded from http://mcfm.fnal.gov

NLO MONTE CARLO

Born Level cross sections are simple(ish) to evaluate

$$\sigma_{LO} = \int_m d\sigma_{LO}$$

At NLO real and virtual terms are separately divergent

$$\sigma_{NLO} = \int_m d\sigma_{LO} + \int_m d\sigma_V + \int_{m+1} d\sigma_R$$

Use dipole subtraction (Catani, Seymour hep-ph/9605323) to regularise each piece individually

$$\sigma_{NLO} = \int_m d\sigma_{LO} + \int_m [d\sigma_V + \int_1 d\sigma_A]_{\epsilon=0} + \int_{m+1} [(d\sigma_R)_{\epsilon=0} - (d\sigma_A)_{\epsilon=0}]$$

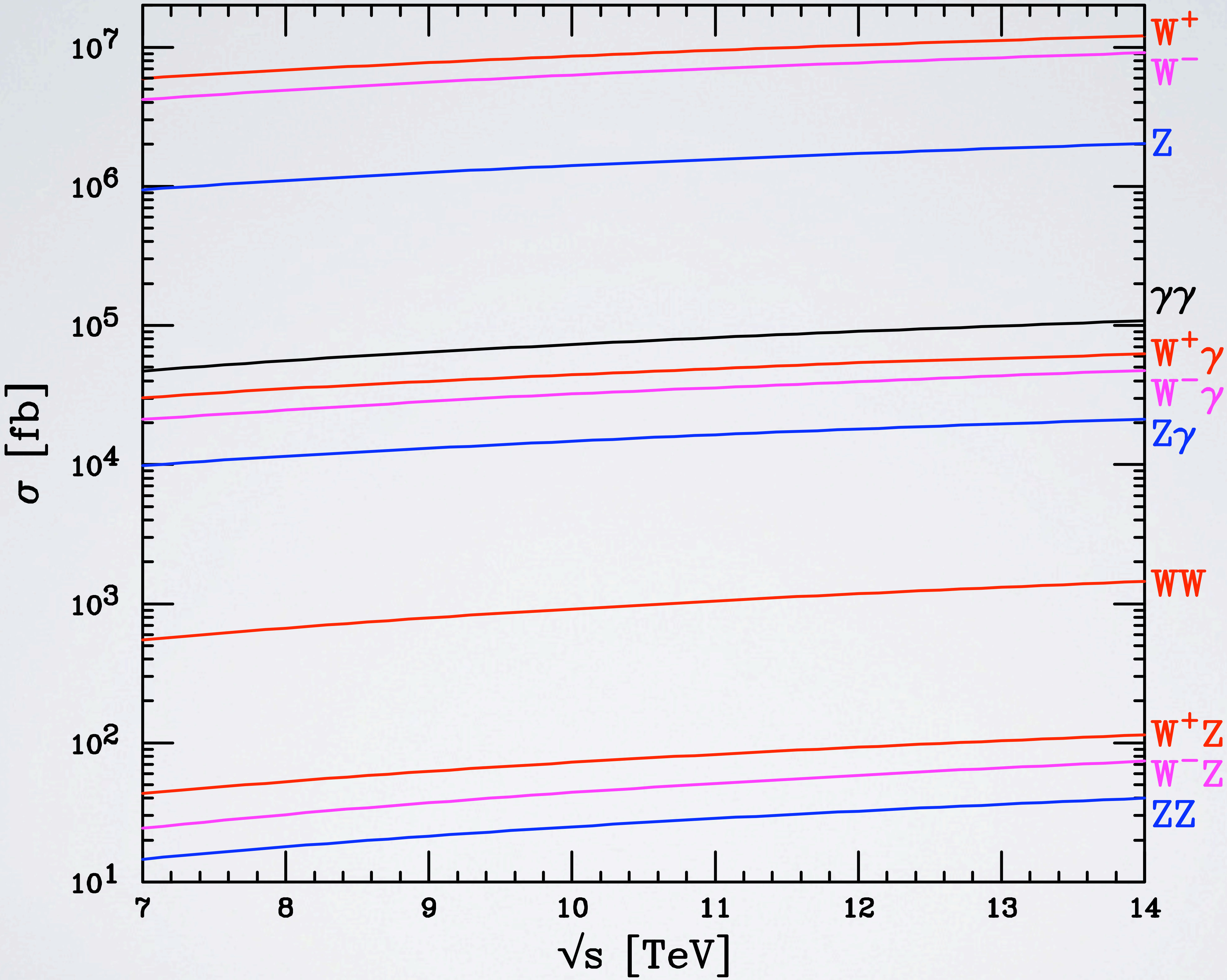
DiBoson Updates in MCFM v6

Improvements to all processes in this update

Process	MCFMv6.0
$pp \to \gamma\gamma$	New process in v6.0, flexible isolation, gg processes included
$pp \to V\gamma$	Flexible isolation procedure, gg for $Z\gamma$
$pp \to V_1V_2$	$gg \to V_1V_2$ included

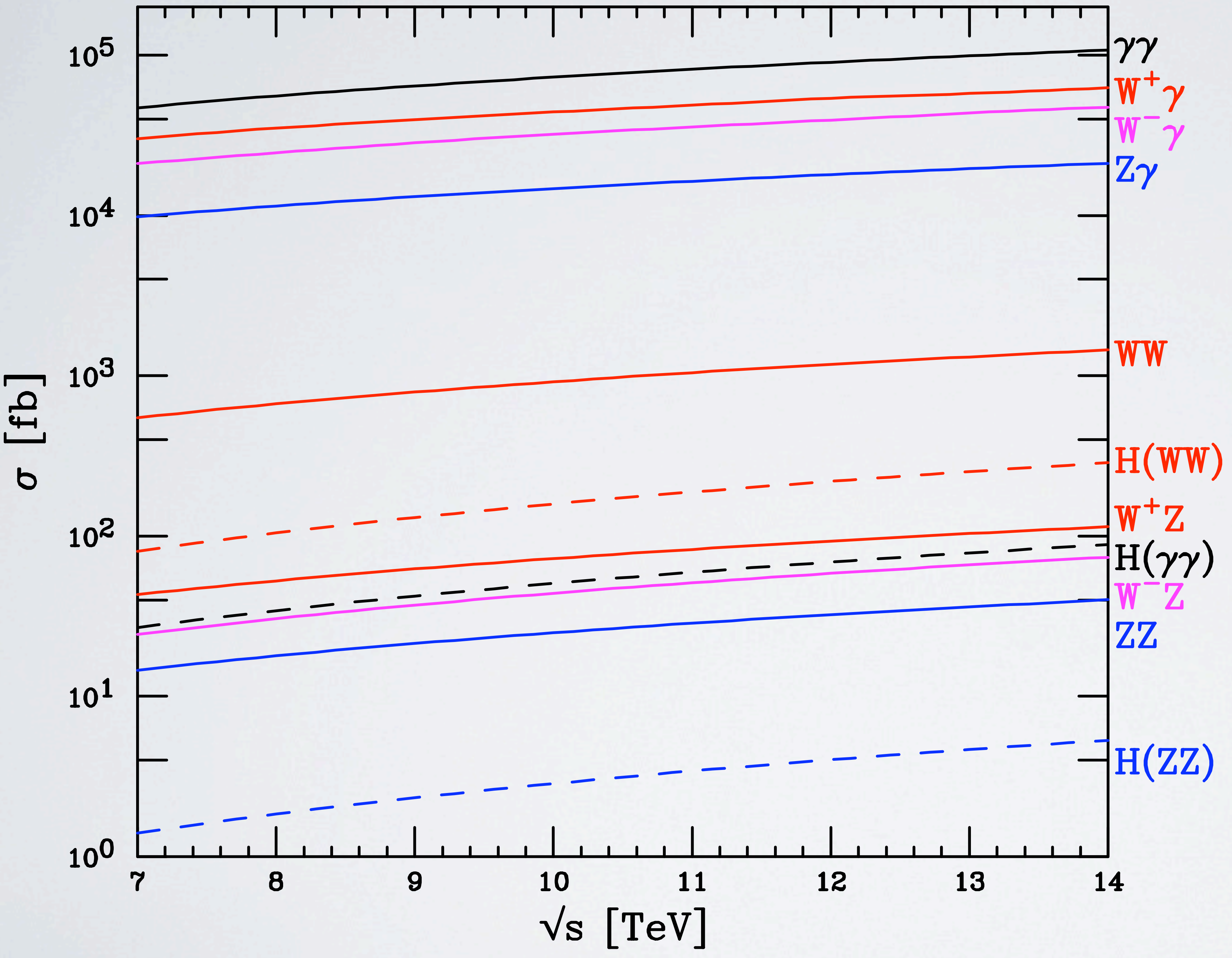
c.f. Ellis talk for more discussion of MCFM v6.

Vector Bosons @ the LHC



$$p_T^\gamma > 10\ (V\gamma), \quad > 25\ (\gamma\gamma)$$

Higgs in the picture?



Higgs mass (GeV)

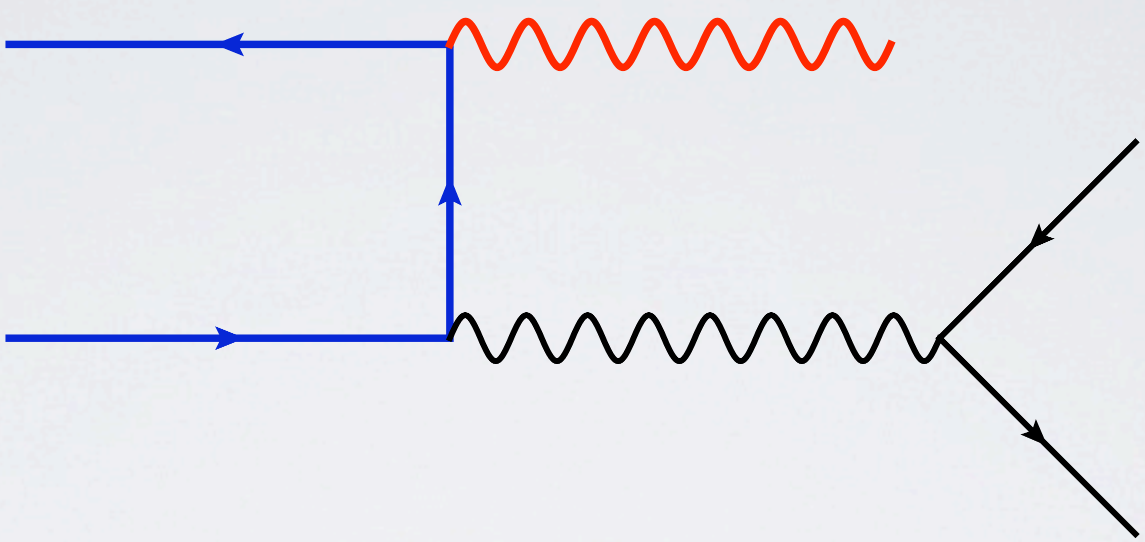
WW - 160

Diphoton - 120

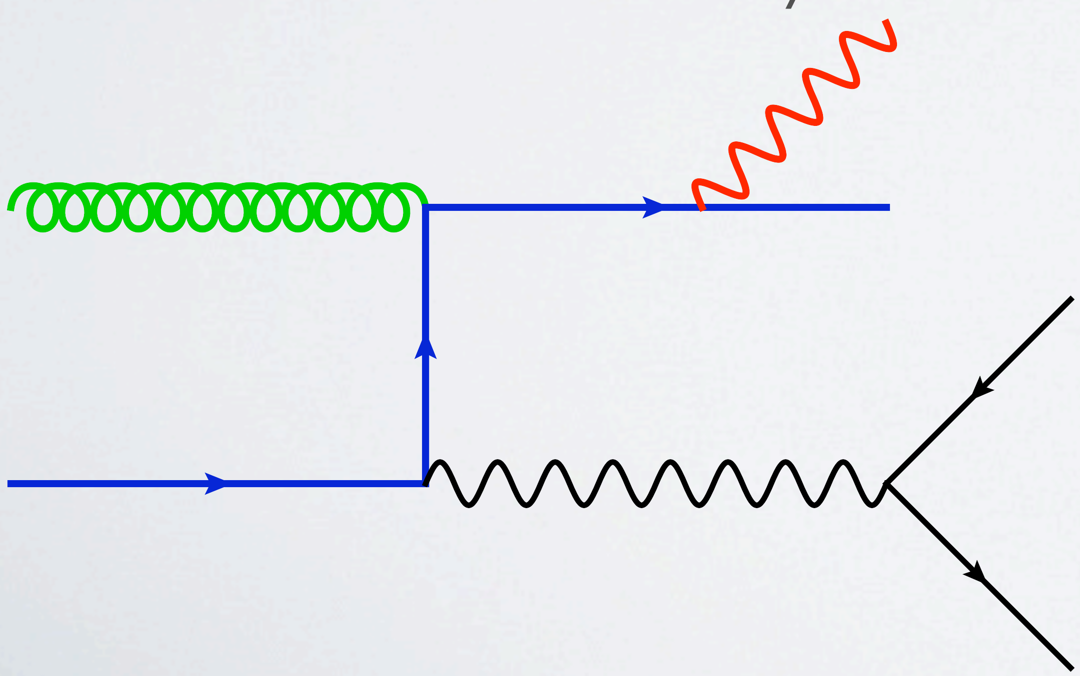
ZZ - 185

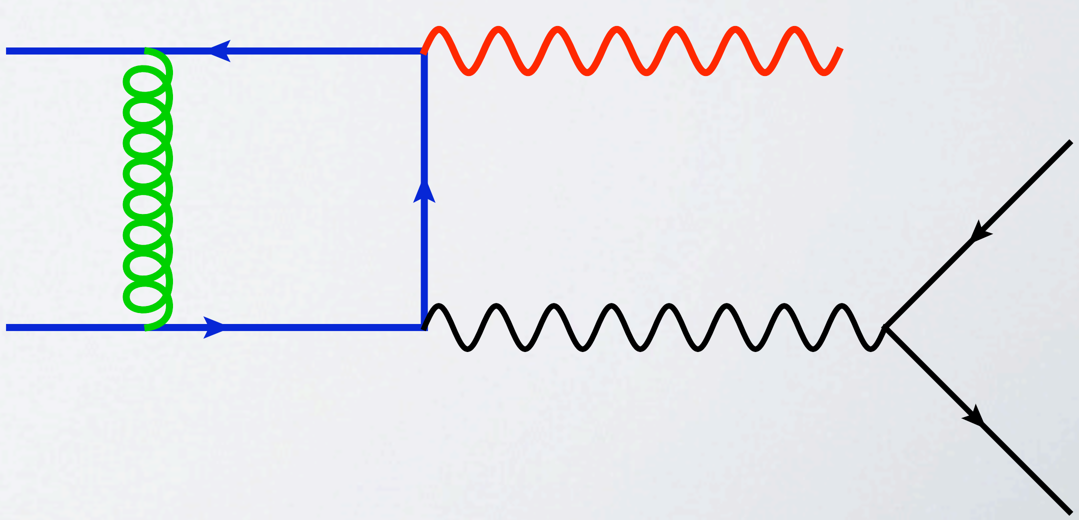
Isolating Photons in experiment and theory (c.f. Jaeger's talk)

At LO no issues, have n photons and m jets

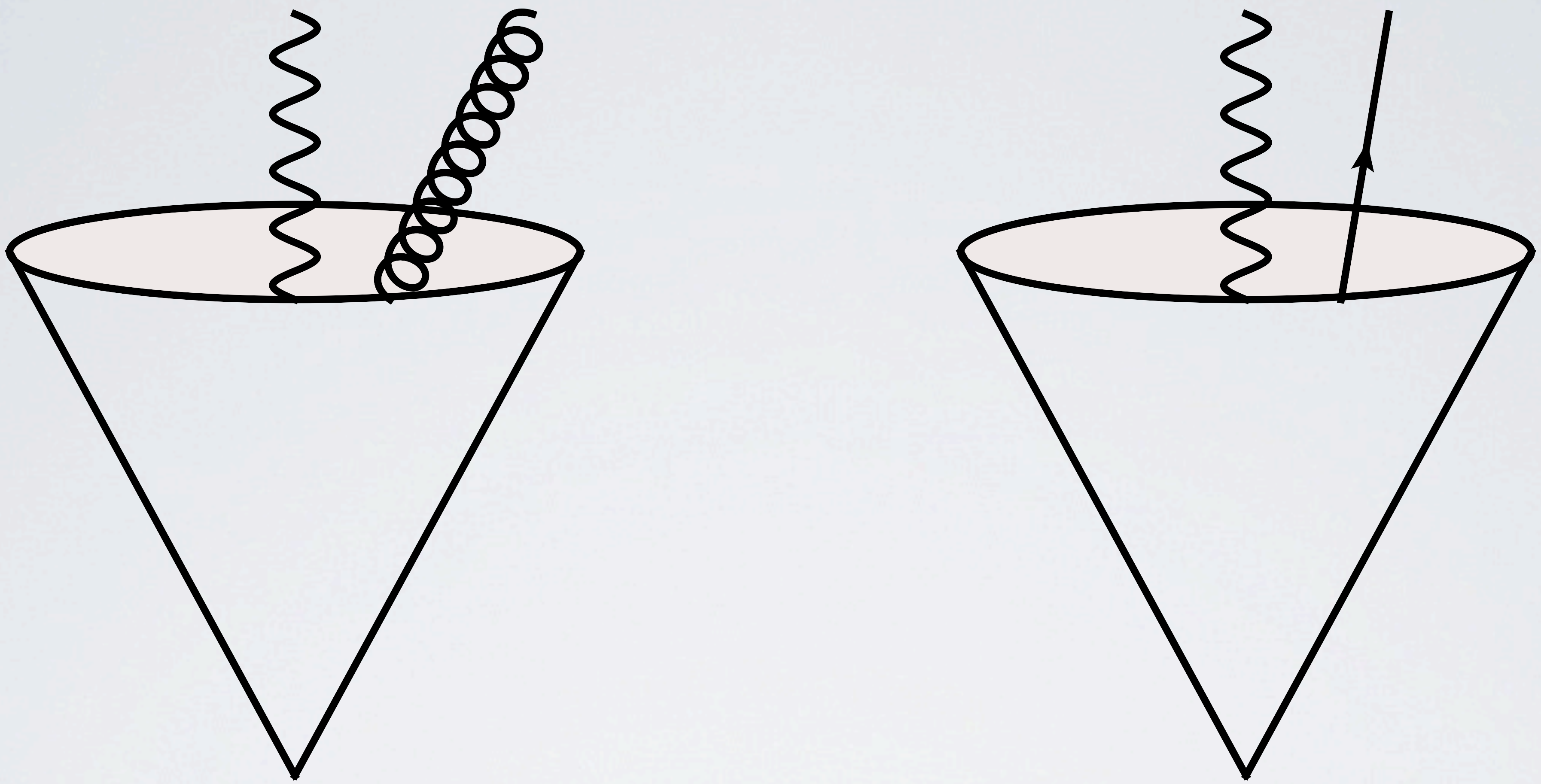


At NLO collinear quark - photon singularity is not removed by virtual diagrams





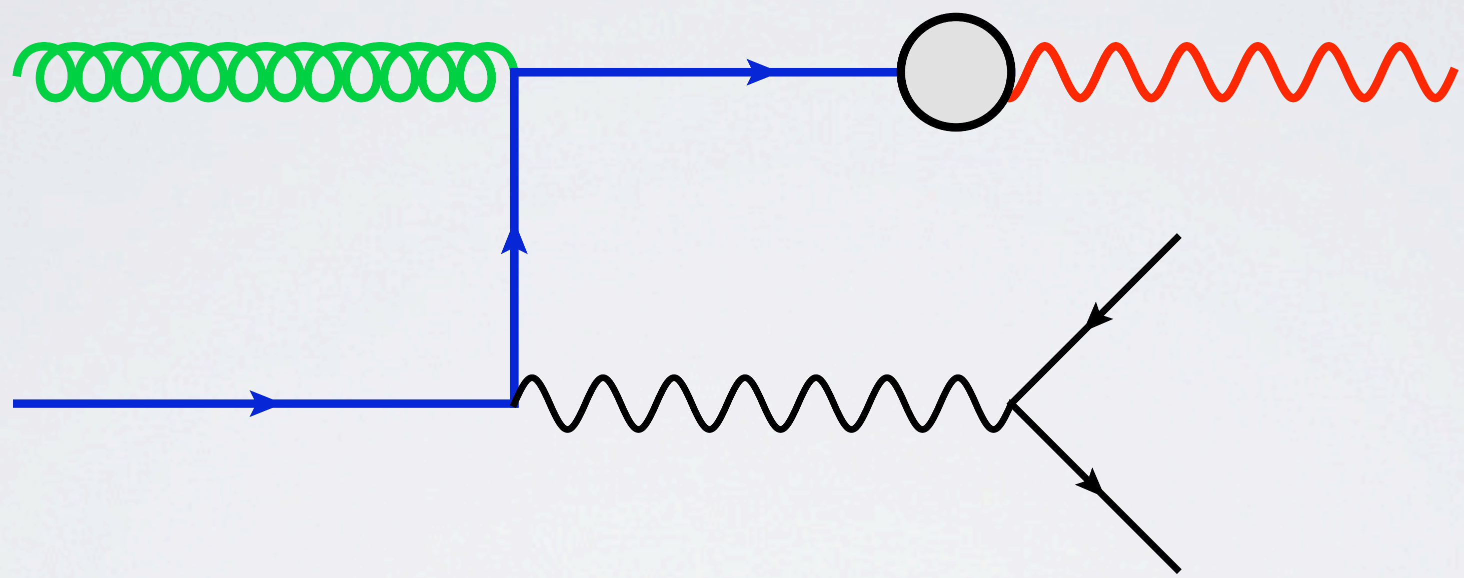
Dealing with the singularity



- Forbid all radiation in a cone around the photon (IR unsafe)
- Could allow only gluon radiation in the cone
- Implement angular dependent energy cuts (Frixione hep-ph/9801442)
- Or, could absorb singularity into Fragmentation functions

Fragmentation Functions

Second source of prompt photons arises from fragmentation of a hard parton into a photon + hadronic energy



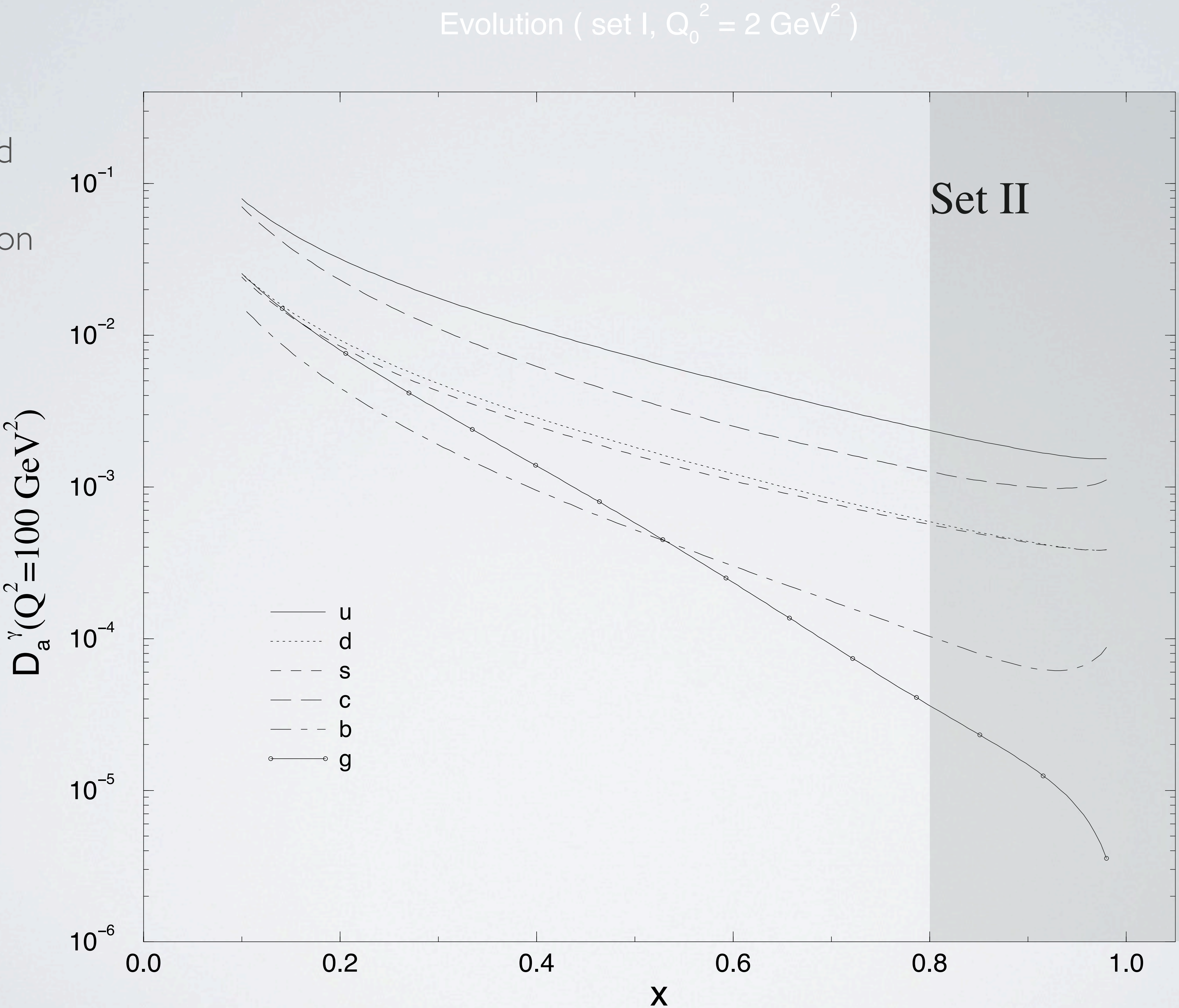
Resulting photon cross section is a combination of the two

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

$D^a(z)$ Is analogous to the PDFs, i.e. it has a perturbative running given by the DGLAP equations, with non-perturbative inputs required from data.

Fragmentation Functions and Isolation

For unisolated photons cross section is much larger



Isolating photon reduces allowed z range

Bourhis Fontannaz and Guillet(hep-ph/970447)

Experimental Isolation of photons

Want to limit impact of secondary photons/fragmentation

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

Including fragmentation allows us to use this isolation, since the singularity can be subtracted Catani, Fontannaz, Guillet and Pilon(hep-ph/0204023) Binoth, Guillet, Pilon and Werlen (hep-ph/9911340)

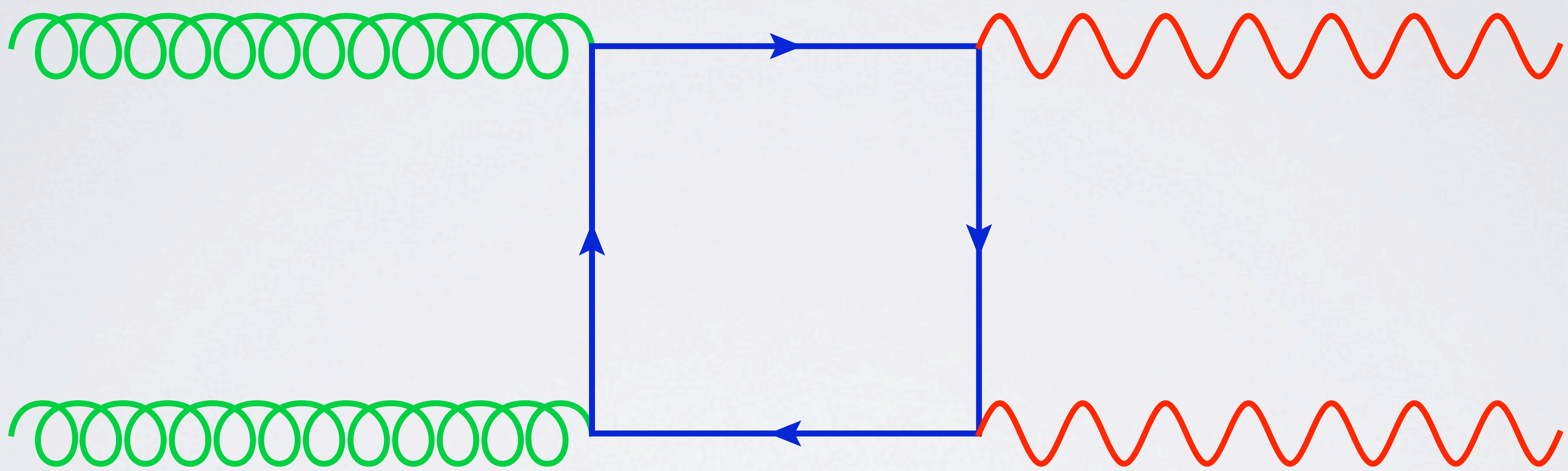
We treat the photon as an identified final state particle

Integrating the subtractions gives a pole piece of the form

$$D_q^\gamma = -\frac{1}{\epsilon}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu^2}{M_F^2}\right)\frac{\alpha}{2\pi}\, e_q^2 P_{\gamma q}(z) \; ,$$

Gluon initiated contributions

Formally of NNLO in perturbation theory



At LHC large flux of gluons from PDF can overcome this suppression

(Partial) History of gg pieces

$$g + g \to \gamma\gamma$$

"LO" : Ametller, Gava Paver and Treleani (1985)

Higgs background : Dicus and Willenbrock (1988)

"NLO" + pheno : Bern, De Freitas and Dixon hep-ph/0109078
Bern, Dixon and Schmidt hep-ph/0206194

Quark splittings : Nadolsky, Balazs, Berger and Yuan hep-ph/0702003

$$g + g \to Z\gamma$$

On-shell : van der Bij, Glover (1988)

Decays : Adamson, De Florian and Signer hep-ph/0211295

$$g + g \to W^+W^-$$

On shell (+ZZ) : Dicus, Kao and Repko (1987)
van der Bij and Glover (1989)

Full : Binoth, Ciccolini, Kauer and Kramer
hep-ph/0503094, hep-ph/0611170

$$g + g \to ZZ$$

Full : Binoth, Kauer and Mertsch 0807.0024

Other DiBoson Codes

- Diphox : Binoth, Guillet, Pilon and Werlen (hep-ph/9911340)
  Diphoton. Contains NLO direct + fragmentation gg @ LO

- AYLEN : De Florian and Signer (hep-ph/0002138)
  W,Z + photon. Contains Fragmentation, no FSR

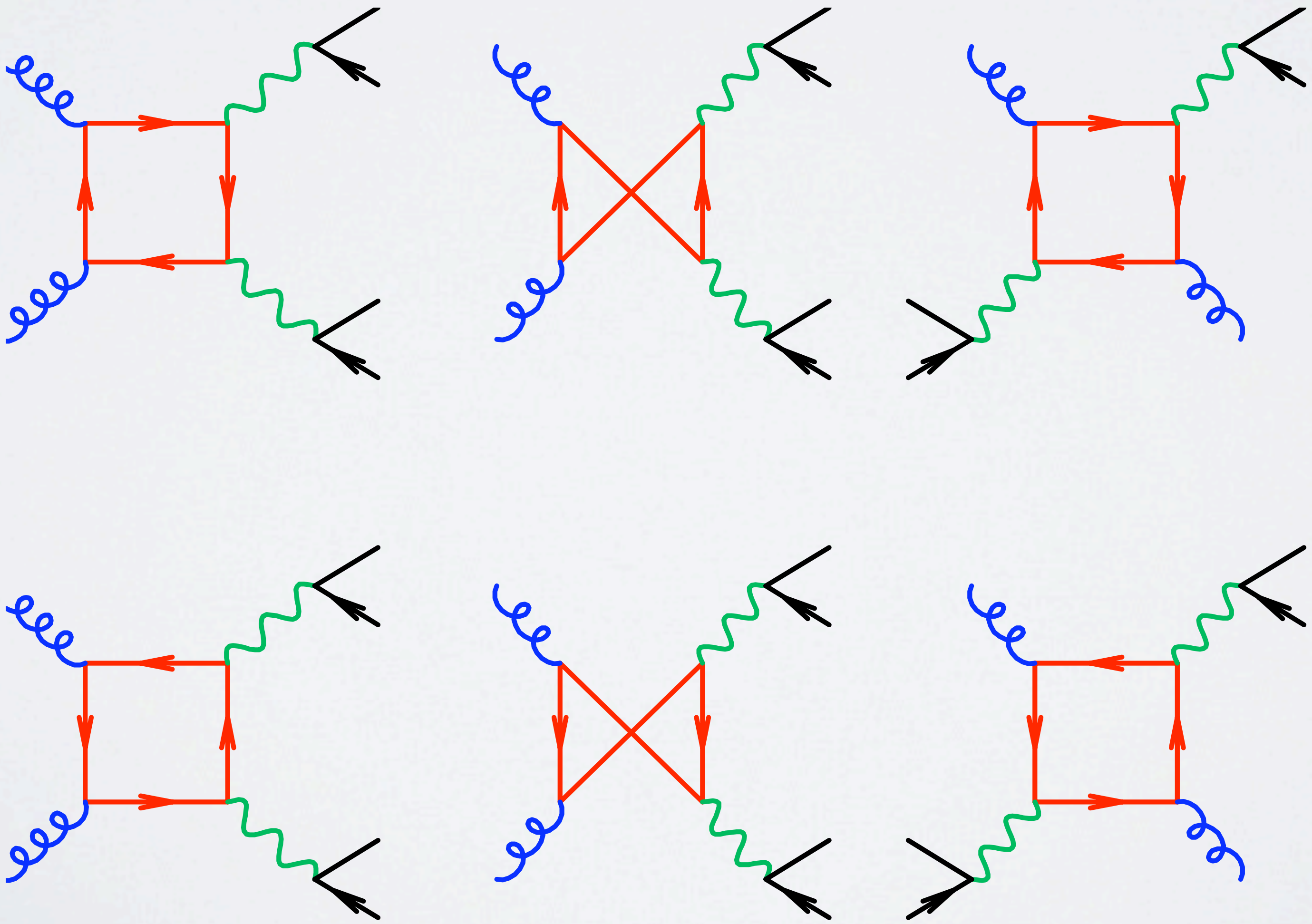
- BHO : Baur Han Ohnemus, (c.f. Han talk) VV pair production V decay to leptons NLO QCD corrections

- gg2WW (Binoth, Ciccolini, Kauer and Kramer hep-ph/0611170) and gg2ZZ (Binoth, Kauer and Mertsch 0807.0024) : gg pieces full top mass effects

Analytic Results for gg pieces

Apart from diphotons compact analytic expressions with spin correlations not written down before.

We found that they can be obtained simply from existing results for W+2jets (Bern Dixon Kosower hep-ph/9708238)



Example $Z\gamma$

Very simple formula

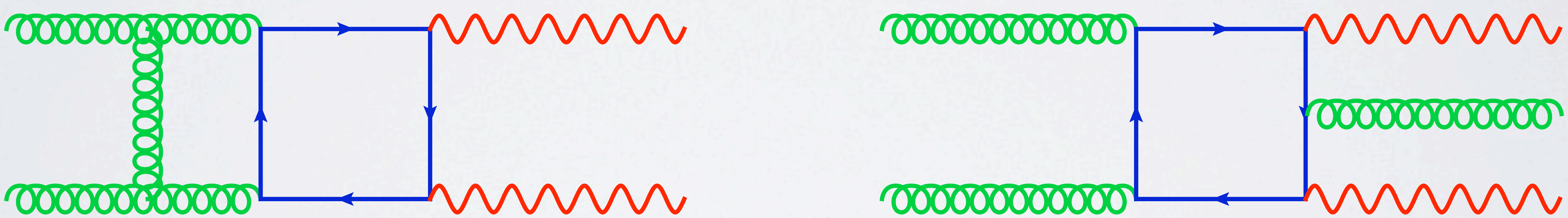
$$A_5^{(v)}(1_g^+, 2_g^+, 3_\gamma^-, 4_\ell^-, 5_{\bar\ell}^+) = +2\Bigg\{ \frac{\langle 1\,3\rangle^2 \langle 2\,4\rangle^2 + \langle 1\,4\rangle^2 \langle 2\,3\rangle^2}{\langle 1\,2\rangle^4 \langle 4\,5\rangle} \mathrm{Ls}_{-1}\left(\frac{-s_{13}}{-s_{123}}, \frac{-s_{23}}{-s_{123}}\right)$$
$$+ \left[2\frac{\langle 2\,3\rangle \langle 1\,4\rangle \langle 2\,4\rangle [2\,1]}{[3\,1] \langle 1\,2\rangle^3 \langle 4\,5\rangle} \mathrm{L}_0\left(\frac{-s_{123}}{-s_{13}}\right) - \frac{\langle 2\,4\rangle^2 [2\,1]^2}{[3\,1]^2 \langle 1\,2\rangle^2 \langle 4\,5\rangle} \mathrm{L}_1\left(\frac{-s_{123}}{-s_{13}}\right) \right.$$
$$\left. - \frac{\langle 1\,3\rangle \langle 2\,4\rangle [2\,1] [5\,1]}{[3\,1] \langle 1\,2\rangle^2 \langle 4\,5\rangle [5\,4]} \right] + \Big[1 \leftrightarrow 2 \Big] \Bigg\}$$

Taken from collinear limit of (Bern Dixon Kosower hep-ph/9708239)

DiPhotons in MCFM v6

- Fragmentation included with LO QCD matrix elements and NLL Fragmentation functions (Sets I and II of Bourhis Fontannaz and Guillet(hep-ph/970447)

- Gluon induced processes included @ NLO Bern, De Freitas and Dixon (hep-ph/0109078)



First "NNNLO" result in MCFM :-)

DiPhotons and Higgs Searches

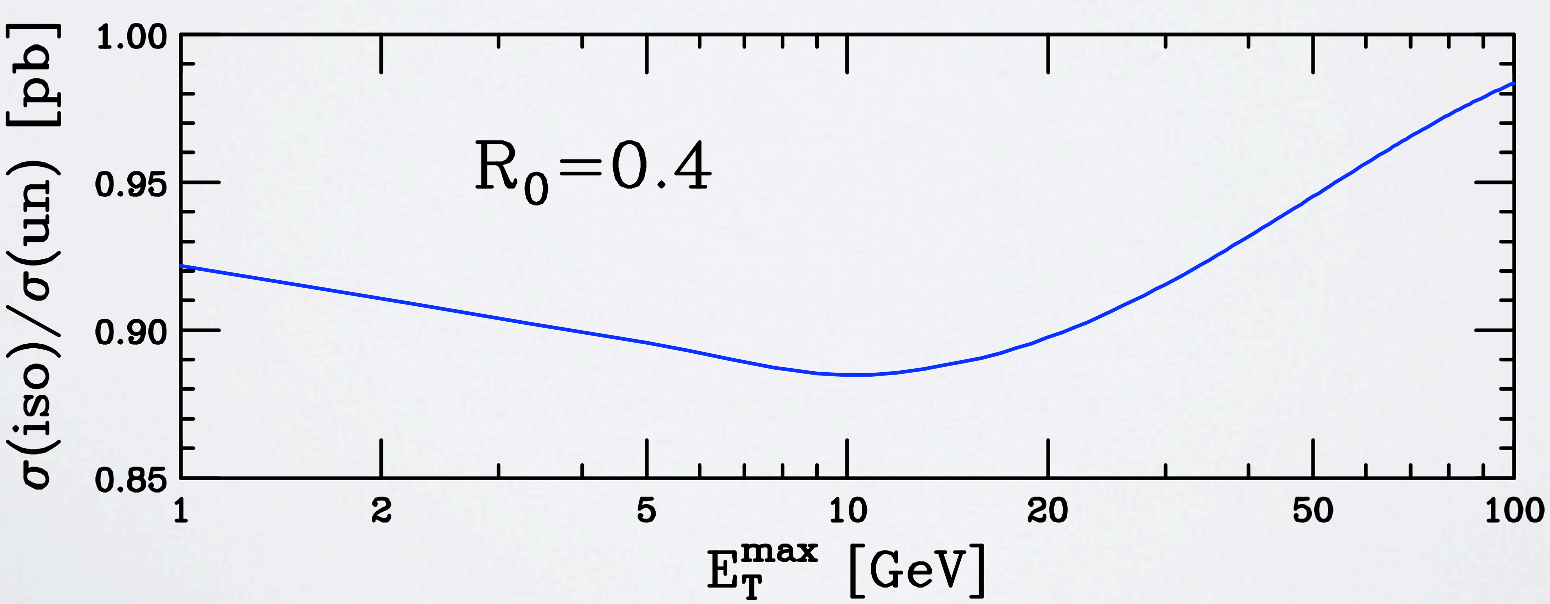
Currently the experiments at the LHC like to apply the following cuts

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

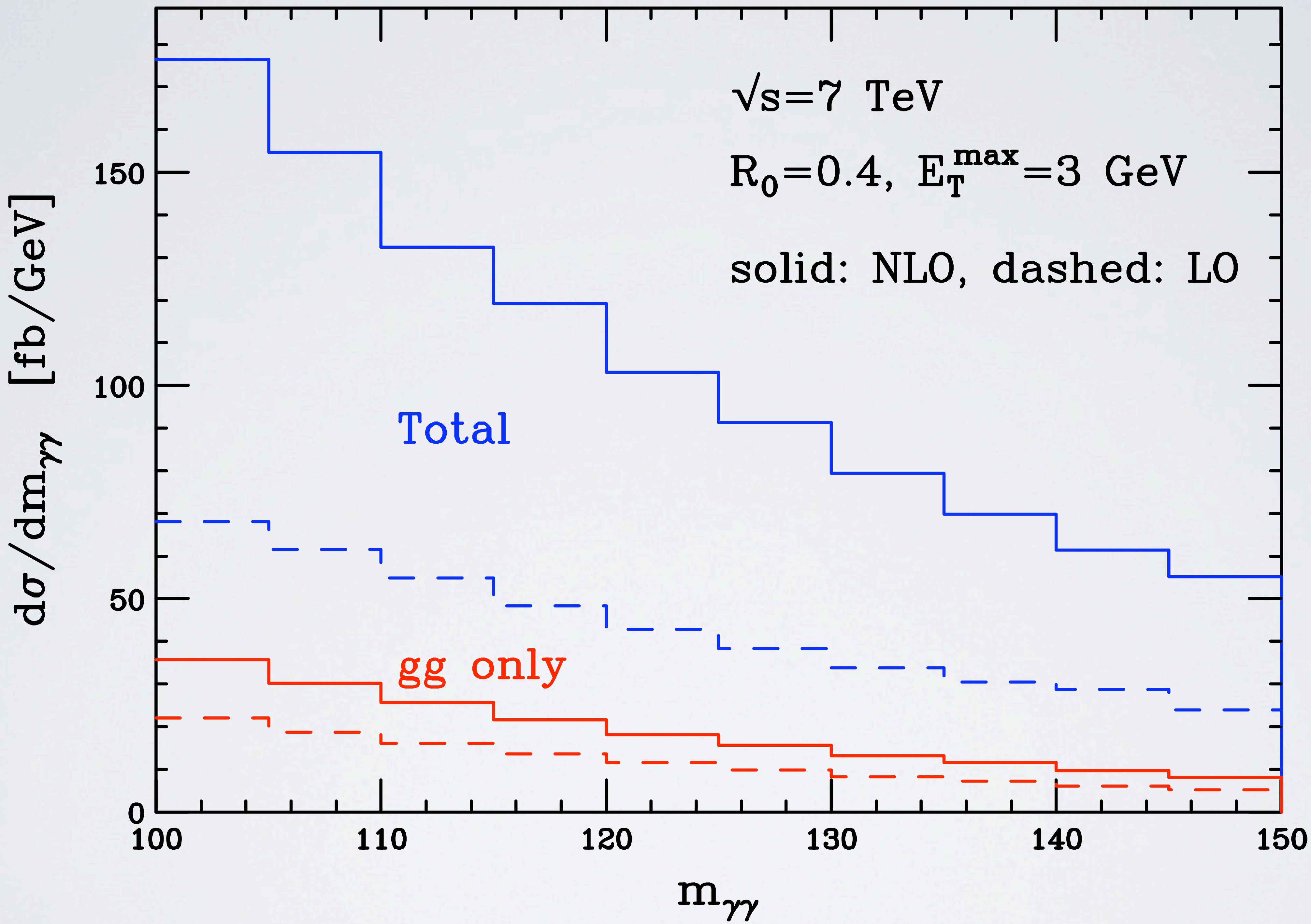
Photons are isolated using

$$R_0 = 0.4 \,, \quad E_T^{\max} = 3 \text{ GeV} \,.$$

How do these cuts affect the physics?

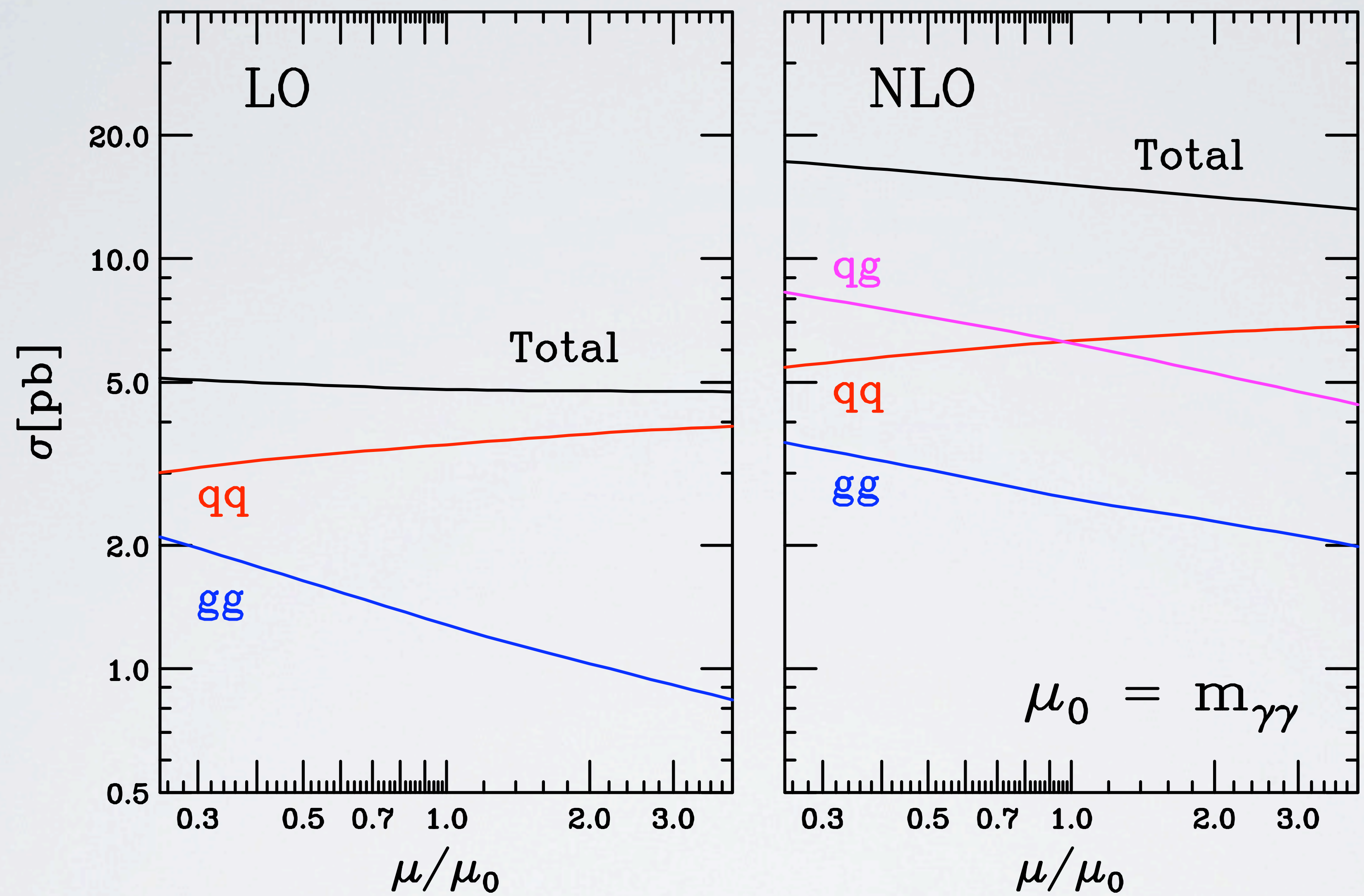


Invariant mass of DiPhotons



NLO corrections to gg clearly important

Scale Variation with Higgs search cuts



Huge K-factor (~3) seen in these plots, due to nature of cuts

Better Perturbative control if back to back cuts are used, with 25 GeV K~1.3

“Bumps” in invariant masses

NLO Higgs to photon cross section with search cuts is small

$$\sigma^{NLO}(pp \to H \to \gamma\gamma) = 18.7 \text{ fb}$$

Vector boson + photon is not

$$\sigma^{NLO}(pp \to V\gamma) \sim \mathcal{O}(10) \text{ pb}$$

Small (i.e. 0.1%) fake rate will easily produce cross sections of Higgs magnitude.

Situation made worse by turn on features around 110-120 GeV

SM Higgs cross section is an awful unit to use!

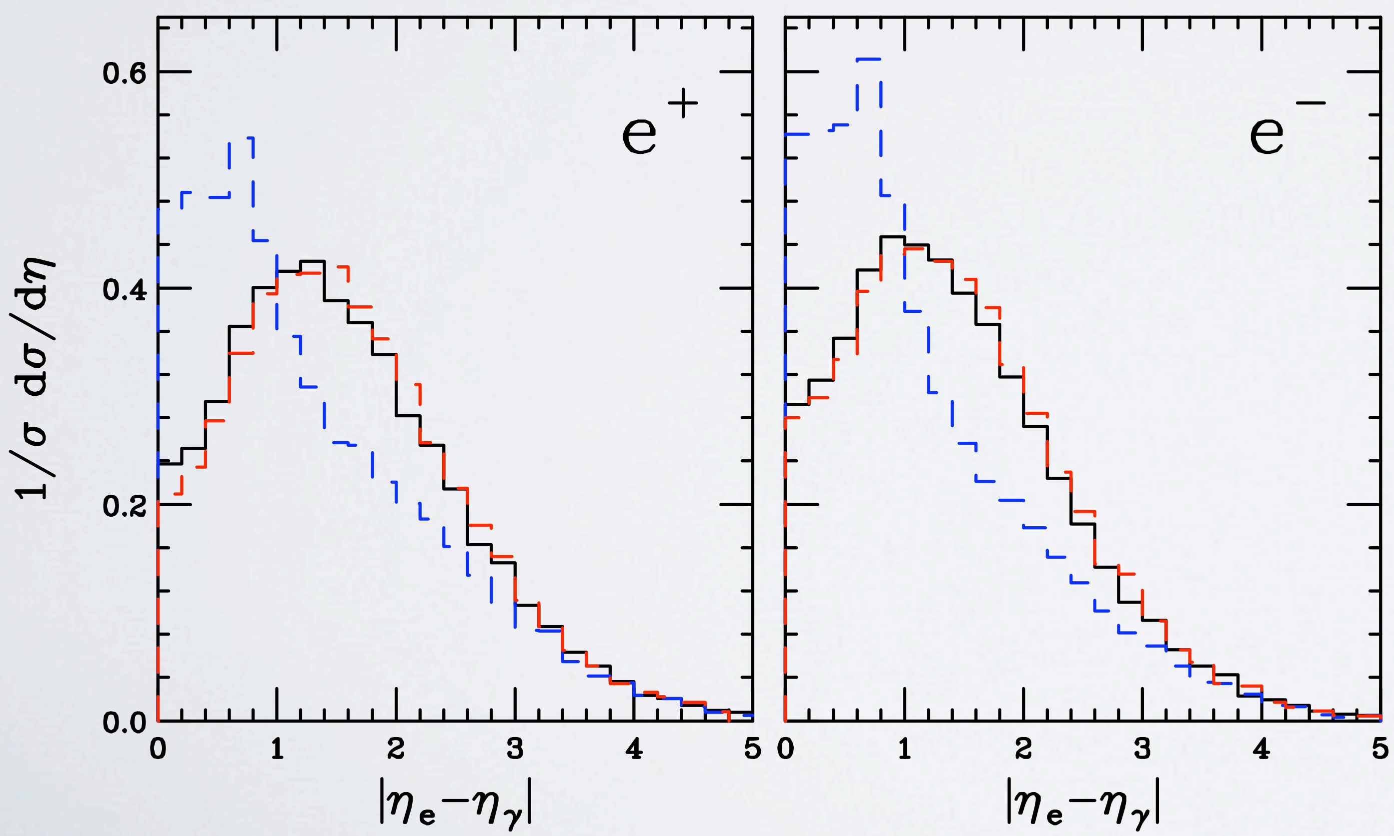
$W^{\pm}\gamma$

We can compare our NLO prediction (basic kinematic cuts) 10 GeV isolated photon

$$\sigma^{NLO}(pp \to W\gamma + X) \times BR(W \to \ell\nu) = 51.2^{+2.3}_{-3.5} \text{ pb}$$

with that reported by CMS

$$\sigma^{CMS}(pp \to W\gamma + X) \times BR(W \to \ell\nu) = 55.9 \pm 5.0 \text{ (stat)} \pm 5.0 \text{ (sys)} \pm 6.1 \text{ (lumi) pb}$$



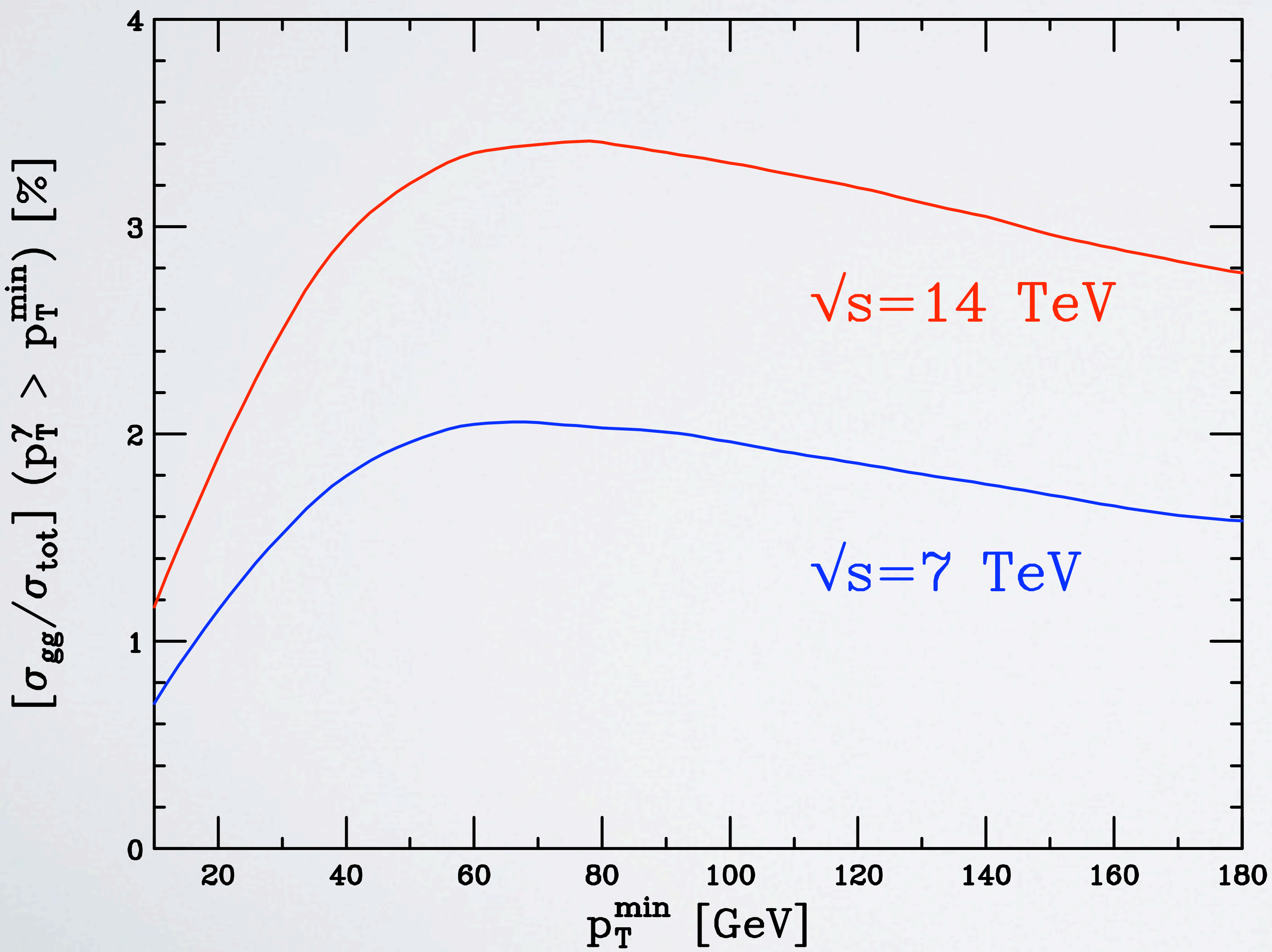
Need a cut on transverse mass of system to observe SM radiation zero (black curve)

$Z\gamma$

We can check our NLO prediction against CMS

$$\sigma^{NLO}(Z\gamma) \times BR(Z \to \ell^-\ell^+) = 9.83^{+0.35}_{-0.46} \text{ pb}$$

$$\sigma^{CMS}(Z\gamma) \times BR(Z \to \ell^-\ell^+) = 9.3 \pm 1.0 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 1.0 \text{ (lumi) pb}$$



The % effect of the gg piece is small but dependent on the pT.

VV in MCFMv6

- For WW we include 2 isodoublets of massless quarks (i.e. neglect (t,b)).
- Shown to be at most 12 % of the two-doublet result (Binoth, Ciccolini, Kauer and Kramer), since this is (at the most!) 30 % of the total cross section neglecting the (t,b) doublet gives us 4% deviation
- For ZZ we include 5 massless flavours.
- Top loops suppressed by four powers of top mass, at most 1 % of massless cross section (Binoth, Kauer and Mertsch)

WW

This cross section has recently been measured by both collaborations

$$\sigma^{ATLAS}(WW) = 41^{+20}_{-16}\,(\mathrm{stat}) \pm 5\ (\mathrm{syst})\ \pm 1\ (\mathrm{lumi})\ \mathrm{pb}\ ,$$
$$\sigma^{CMS}(WW) = 41.1 \pm 15.3\,(\mathrm{stat})\ \pm 5.8\,(\mathrm{syst}) \pm 4.5\ (\mathrm{lumi})\ \mathrm{pb}\ ,$$

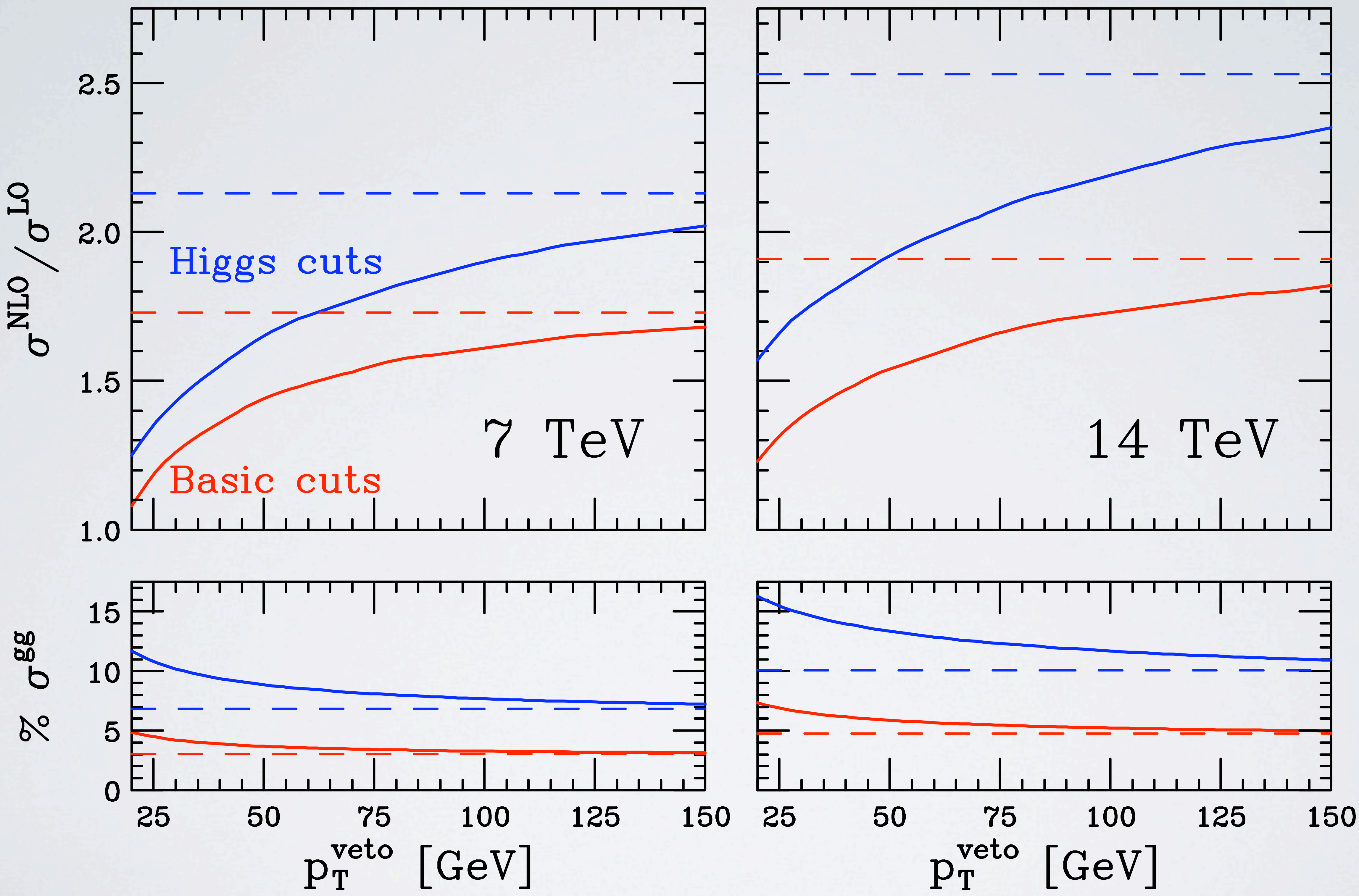
No conflict with the NLO prediction

$$\sigma^{NLO} = 47.0\,^{+2.1}_{-1.4}\ \mathrm{pb}$$

WW is an important Higgs search channel, investigate role of experimental cuts on the cross section

$$\text{Basic } WW \ :\ p_T^{\ell} > 20\ \mathrm{GeV},\ |\eta^{\ell}| < 2.5,\ E_T^{miss} > 20\ \mathrm{GeV}\ ,$$
$$\text{Higgs}\ :\ \text{Basic } WW + m_{\ell\ell} < 50\ \mathrm{GeV},\ \Delta\phi_{\ell\ell} < 60^{\circ},$$
$$p_T^{\ell,max} > 30\ p_T^{\ell,min} > 25\ \mathrm{GeV}\ .$$

Cross section as function of the veto



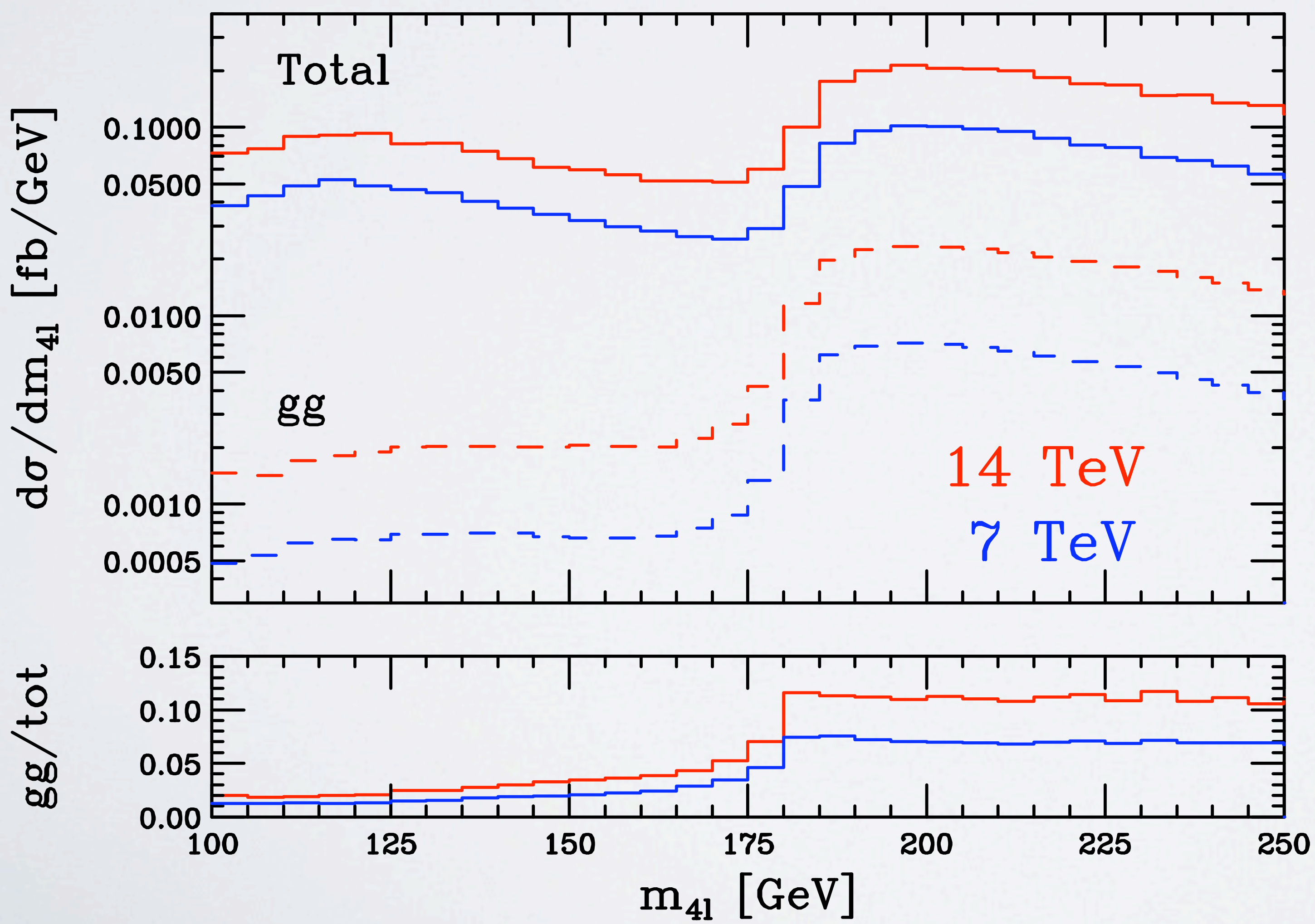
ZZ

No results *yet!* from LHC, NLO prediction is

$$\sigma^{NLO}(pp \to ZZ) = 6.46 \text{ pb}$$

Very promising Higgs search channel look at invariant mass with

$$p_T^{\ell_1,\ell_2} > 20 \text{ GeV},\ p_T^{\ell_3,\ell_4} > 5 \text{ GeV},\ |\eta_\ell| < 2.5,\ \ m_{\ell\ell}, m_{\ell'\ell'} > 5 \text{ GeV}$$



Gluon effects are strongly dependent on invariant mass can be neglected below 180

Conclusions

- Diboson production is an important background to nearly all searches at the LHC

- Fragmentation of partons into photons now included in MCFM allowing experimental isolation of photons

- Analytic results for gluon initiated pieces for all relevant diboson processes included, some "New" results for VV and Z photon.