Diphoton Theory

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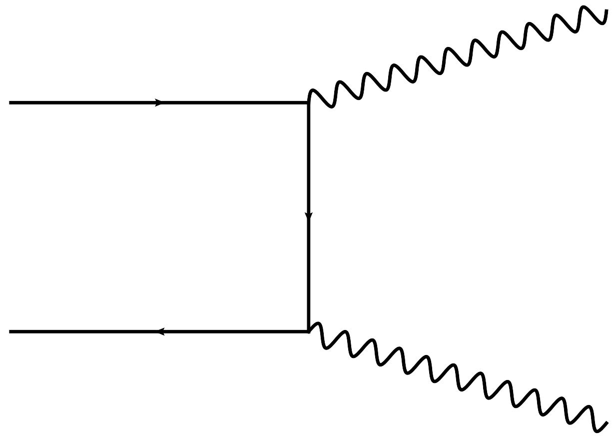
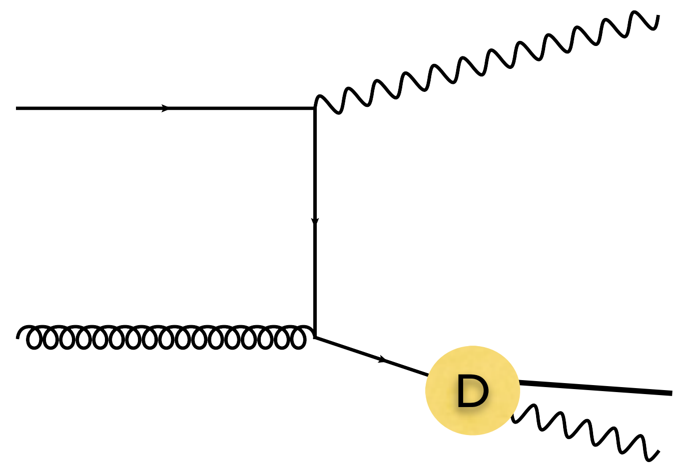
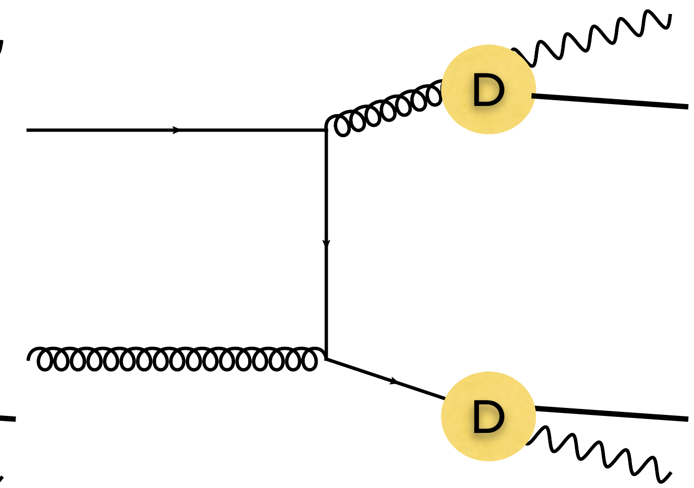
Two mechanisms for photon production



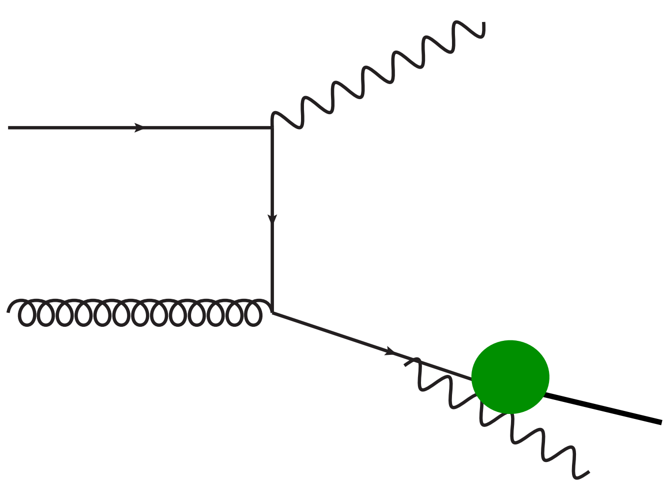




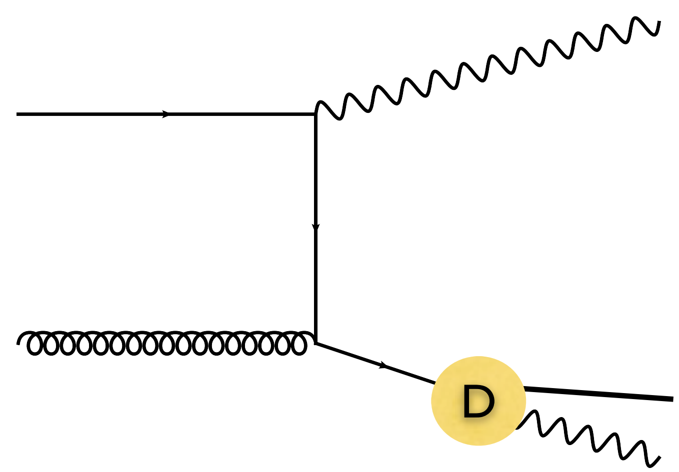
Direct (point-like)

Single and double resolved (collinear fragmentation)

Separation between them NOT physical in general (beyond LO)



collinear divergence



Cancelled by fragmentation

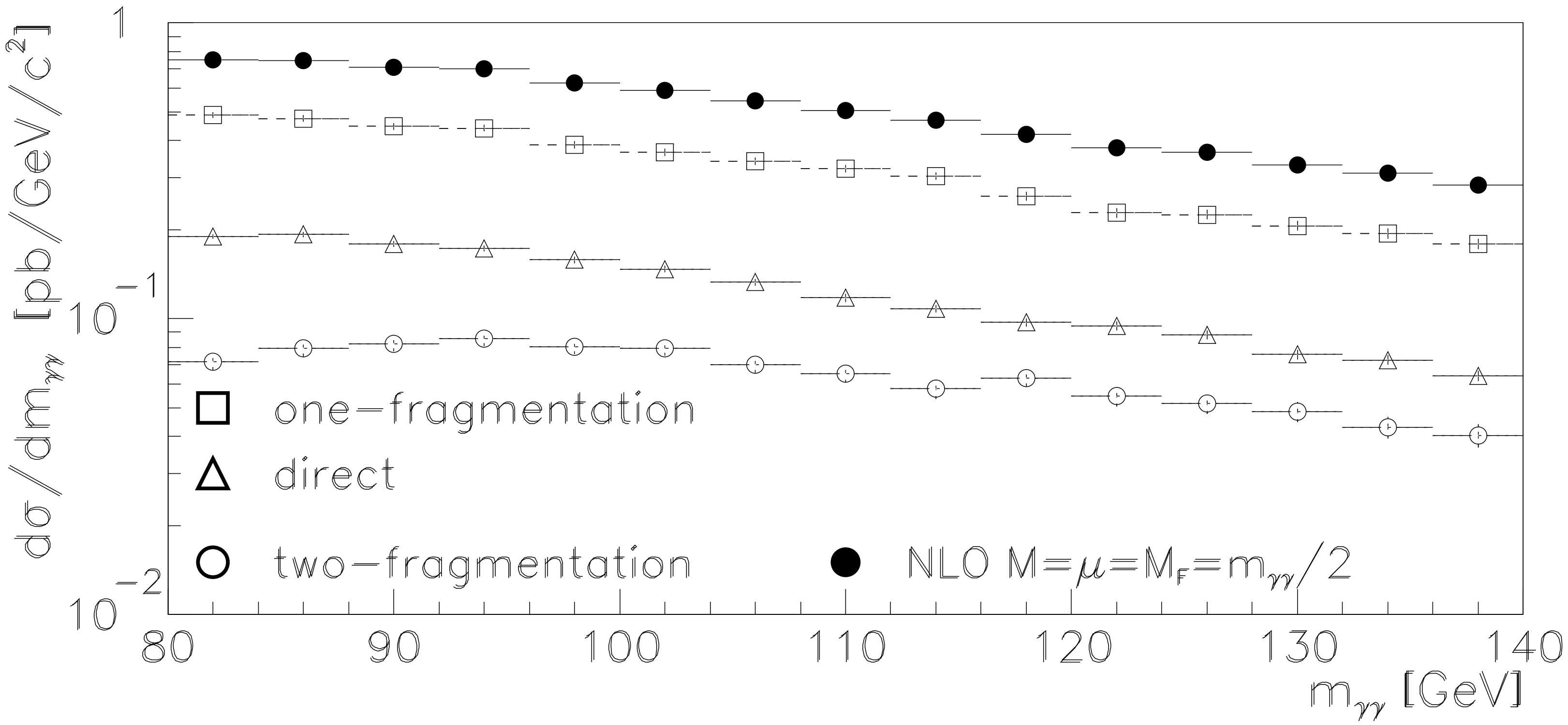
Still talk about direct and resolved at NLO and beyond:
$\overline{\text{MS}}$ factorization scheme (convention)

+ frag. fact. scale
dependence of each term

Direct + resolved

◉ Full NLO calculation available → Large Corrections

DIPHOX: T.Binoth, J.P.Guillet, E.Pilon, M.Werlen



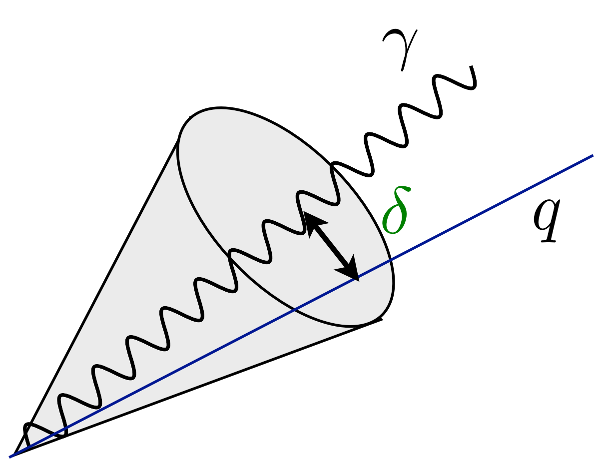
$$\sqrt{S} = 14\,\mathrm{TeV}$$

$$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$$

$$p_T^{\gamma\,soft} \geq 25\,\mathrm{GeV}$$

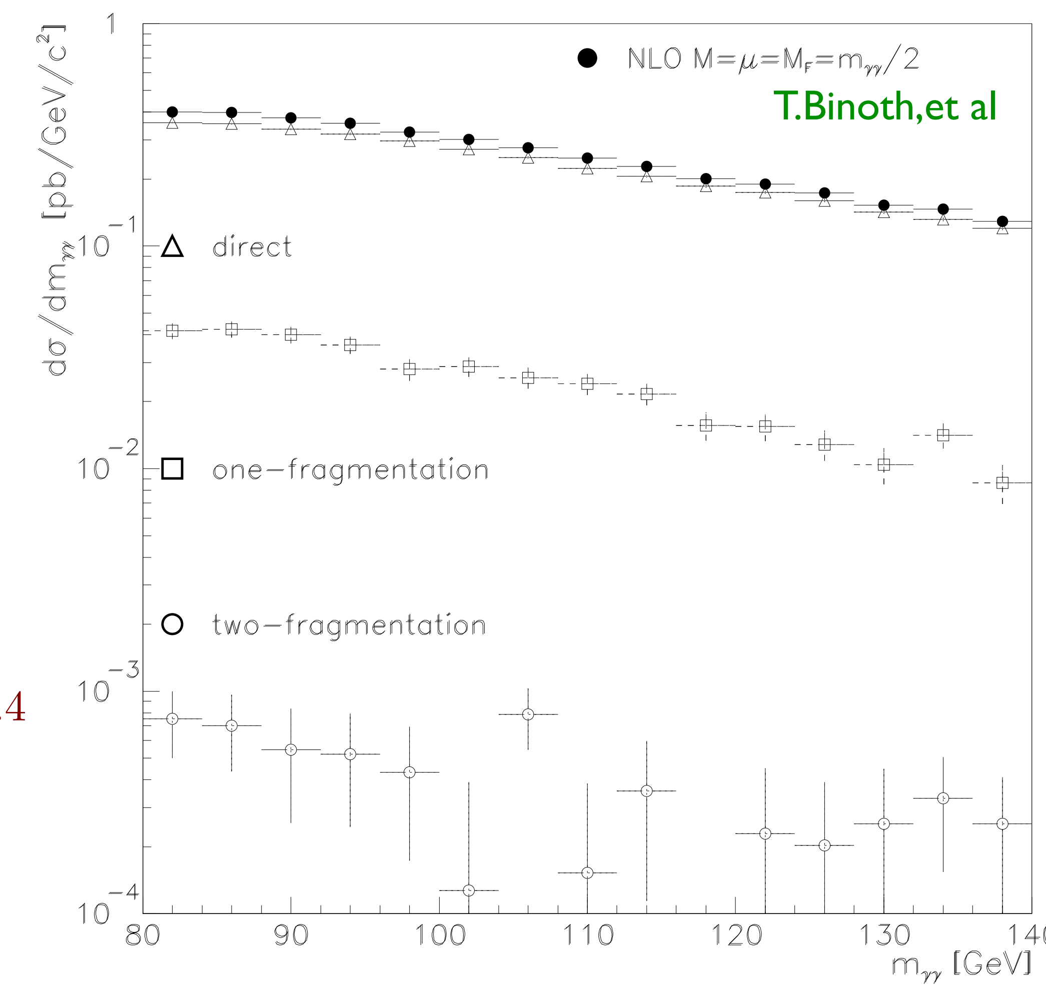
$$|\eta^{\gamma}| \leq 2.5$$

Experimental Photon Isolation reduces fragmentation component



$$E_T^{had}(\delta) \leq \epsilon\, E_T^{\gamma}$$

$E_T^{had}(\delta) \leq 5\,\mathrm{GeV}$, $\delta = 0.4$



- DIPHOX — NLO for direct and resolved + Box contribution (one piece of NNLO) — Binoth, Guillet, Pilon, Werlen

- MCFM — NLO for direct but only LO for resolved + Box contribution (one piece of NNLO) — Campbell, Ellis, Williams

- Resbos — NLL q_T resummation for direct (with regulator for collinear singularities) No fragmentation contribution — Balazs, Berger, Nadolsky, Yuan

- Gamma2MC — NLO direct contribution +correction to Box contribution partial N^3LO term added in other calculations as well — Bern, Dixon, Schmidt

$2\gamma\mathrm{NNLO}$ — NNLO for direct with smooth cone isolation — S.Catani, L.Cieri, DdeF, G.Ferrera, M.Grazzini

+ MC generators : Herwig, Pythia, SHERPA

Joey's request: Assume that the people in the room are experts. Where does the theory work? Where doesn't it work?

TH problems if...

- Isolation R<<1 → $(\alpha_s \log R)^n$

- Infrared sensitive observables
  - Non-smooth distributions

Invariant mass of diphotons close to LO threshold

$$\Delta\phi = \pi$$

back-to-back photons : perturbative instabilities → Integrable logarithmic singularities

Catani, Webber

Requires dedicated Sudakov resummation
or higher orders with "large" bins

Attempt to mitigate the effect of soft-gluon emission by reducing the contribution from back-to-back photons configuration : Asymmetric cuts

- Two scales very different : very low transverse momentum of diphoton pair

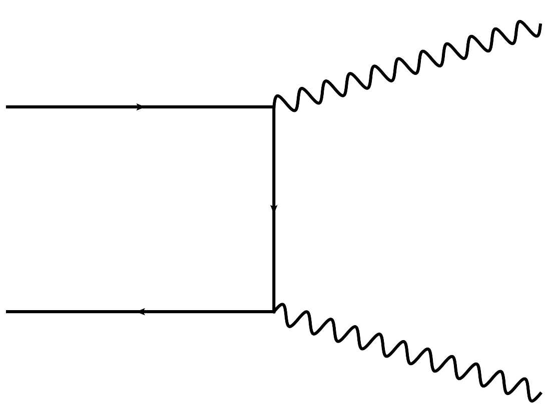
→ $\log \frac{q_T^{\gamma\gamma}}{M_{\gamma\gamma}}$ Requires transverse momentum resummation

- Observables that "start" at NLO and opening of phase space

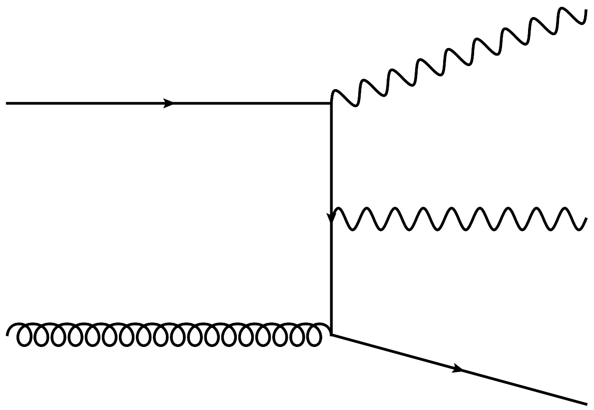
  - Invariant Mass below threshold
  - Small azimuthal angle between photons
  - Q_T of diphotons around Guillet-shoulder (phase space)

Require NNLO for cross-section (NLO +jet)
very asymmetric cuts can enhance the effect

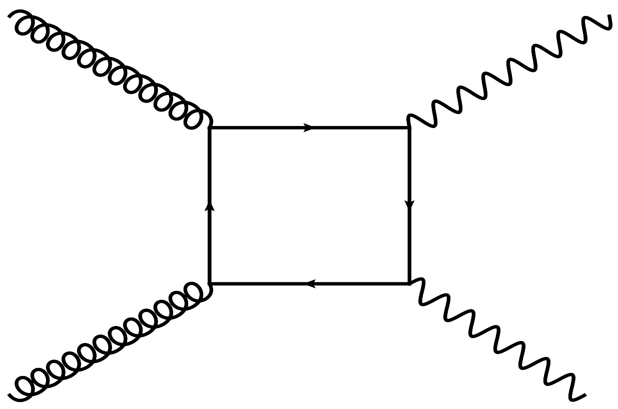
- Very general problem: opening of new channels at each order



$\mathcal{O}(\alpha_s^0)$ but $q\bar{q}$ Luminosity



$\mathcal{O}(\alpha_s)$ but qg Luminosity



$\mathcal{O}(\alpha_s^2)$ but gg Luminosity

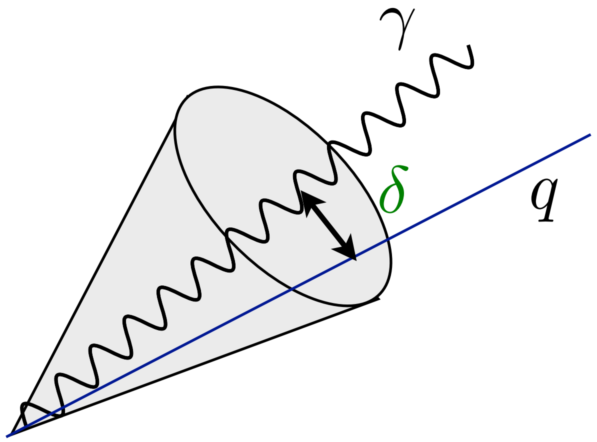
"NNLO" corrections to *qg* very important

Can not achieve enough precision without full NNLO...

Resolved at NNLO not possible right now

What about the dominant direct contribution?

Smooth Photon Isolation



Standard Photon Isolation

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}$$

Smooth Photon Isolation

S.Frixione

$$E_T^{had}(\delta) \leq E_{T\,max}^{had}\;\chi(\delta)$$

$$\chi(\delta) = \left(\frac{1-\cos(\delta)}{1-\cos(R_0)}\right)^n$$

≤ 1

only soft emission allowed if collinear to photon

- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined

More restrictive than usual cone : lower limit on cross section (close for small R)

In real (TH)life... how much different? NLO comparison $R_0 = 0.4 \quad n = 1$

CMS Higgs cuts at 7 TeV

Standard: direct+fragmentation (Diphox)

$E_{T\,max}^{had}$	standard/smooth
2 GeV	< 1%
3 GeV	< 1%
4 GeV	1%
5 GeV	3%
0.05 p_T	< 1%
0.5 p_T	11%

if isolation tight enough, hardly any difference between standard and smooth cone

Direct Contribution

2γNNLO

First exclusive NNLO in pp collisions with two final state particles

S.Catani, L.Cieri, DdeF, G.Ferrera, M.Grazzini

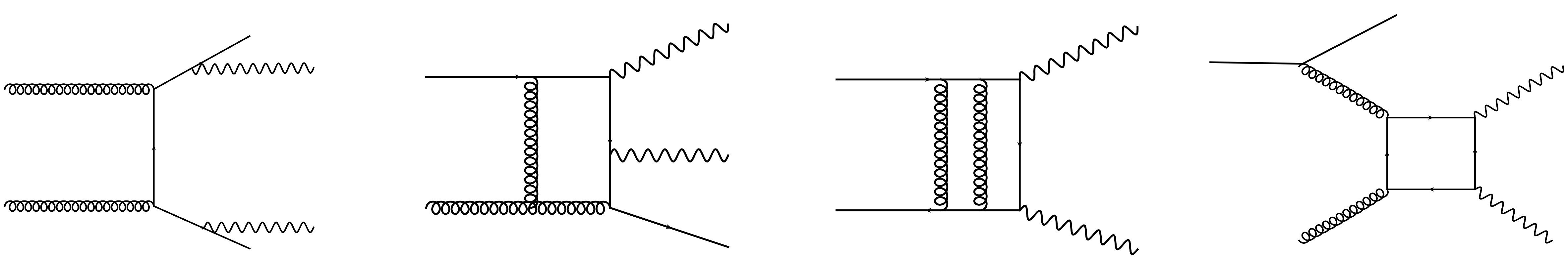
NNLO using q_T-Subtraction S.Catani, M.Grazzini

Generalized to any process with final state colorless system ***F*** S.Catani, L.Cieri, DdeF, G.Ferrera, M.Grazzini

Two-loop amplitudes available C.Anastasiou, E.W.N.Glover, M.E.Tejeda-Yeomans

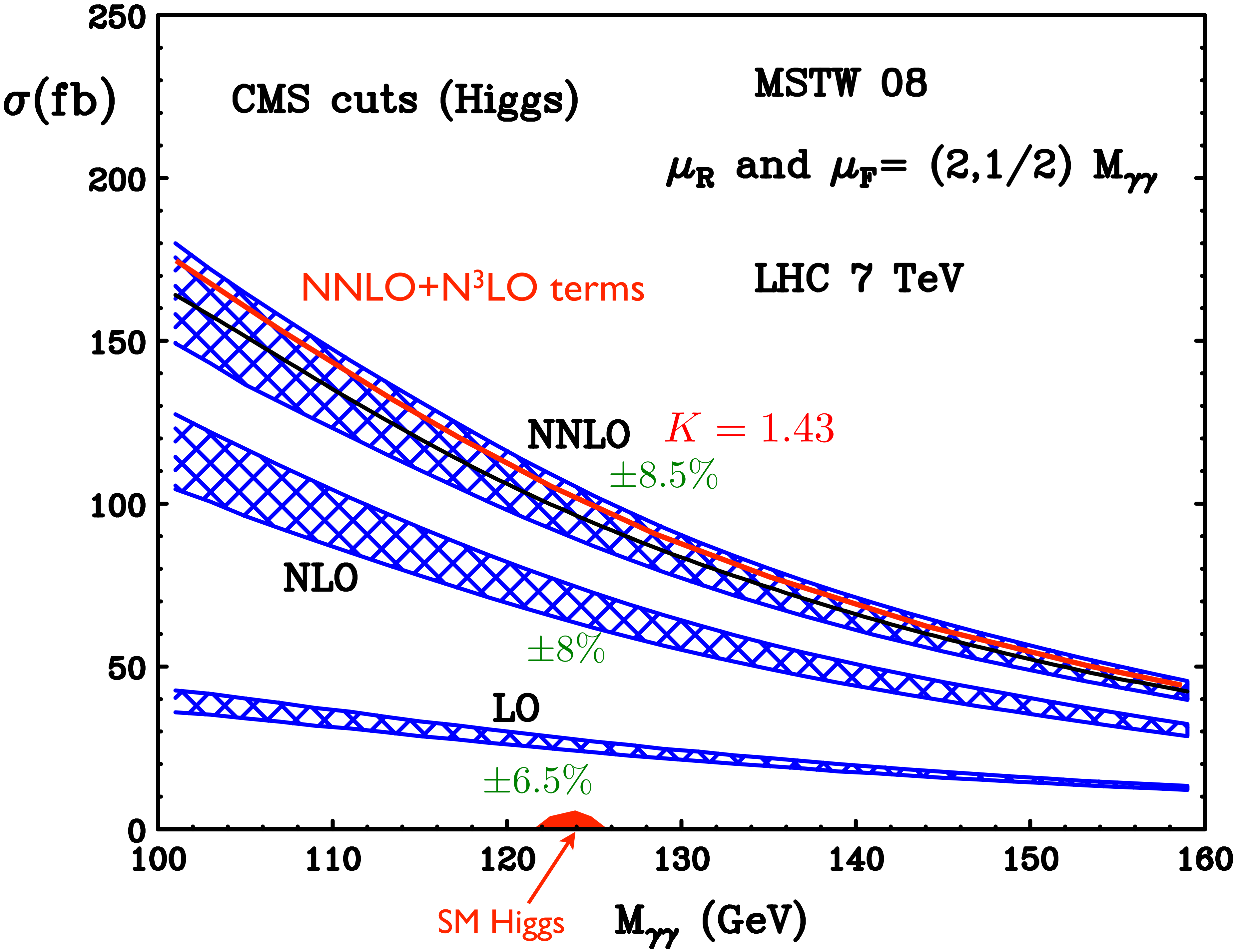
Diphoton + jet at NLO V.Del Duca, F.Maltoni, Z.Nagy, Z.Trocsanyi

Full NNLO control of Diphoton production



+ ....

Higgs search at 7 TeV : scale dependence



$p_T^{\gamma\, hard} \geq 40\,\text{GeV}$

$p_T^{\gamma\, soft} \geq 30\,\text{GeV}$

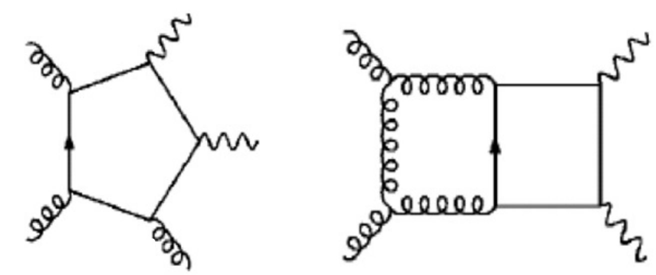
$100\,\text{GeV} \leq M_{\gamma\gamma} \leq 160\,\text{GeV}$

$|\eta^\gamma| \leq 2.5$

excluding $1.4442 \leq |\eta^\gamma| \leq 1.566$

$\epsilon = 0.05$

α_s^3 Bern, Dixon, Schmidt (2002)



Some N³LO terms known to contribute ~5%

- Scale does not represent TH uncertainties at LO and NLO → new channels
- All channels open at NNLO → estimate of TH uncertainties

DiPhoton production at NNLO

- **at 14 TeV** 2γNNLO

$\sqrt{S} = 14\,\mathrm{TeV}$

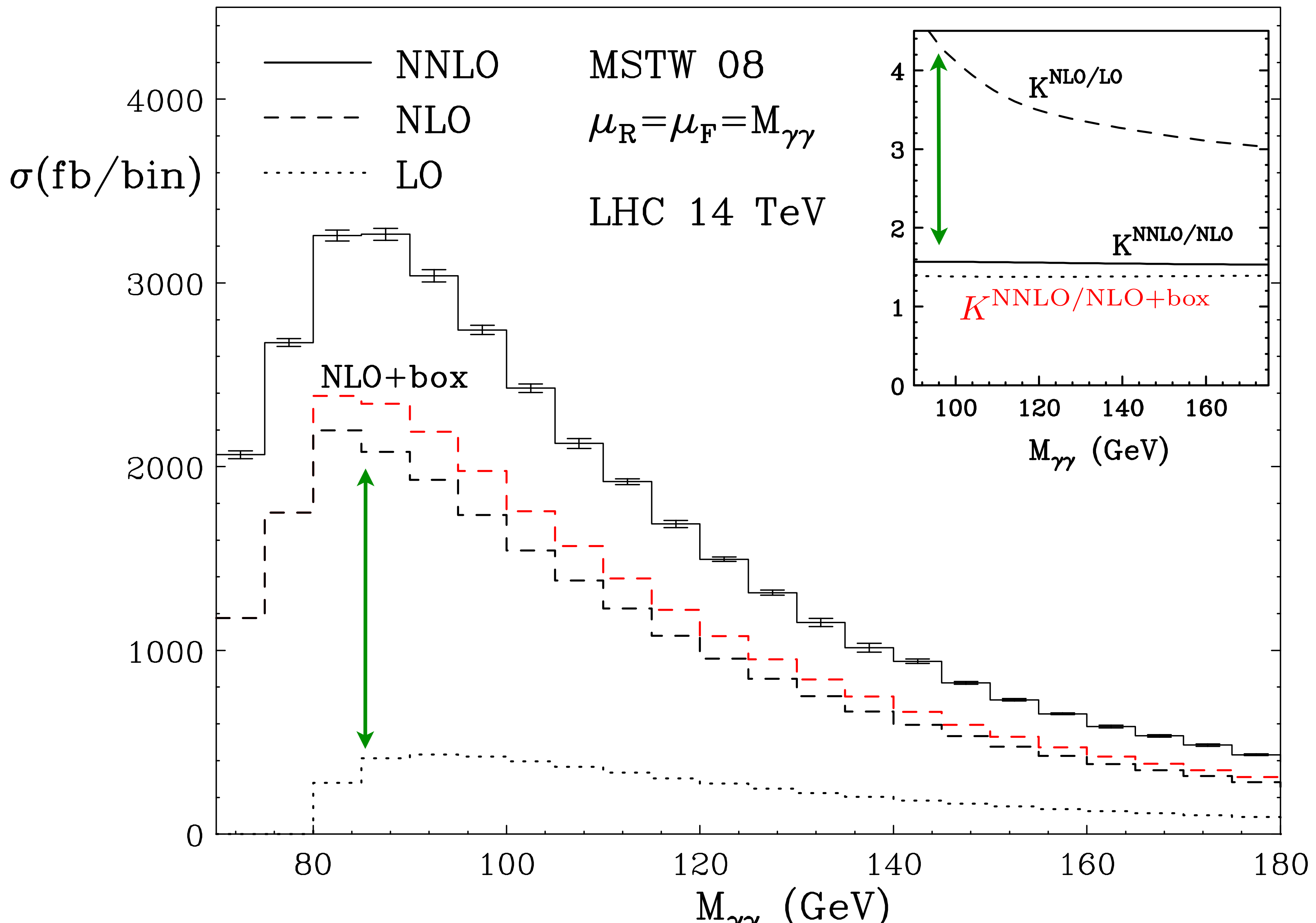
$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$

$p_T^{\gamma\, soft} \geq 25\,\mathrm{GeV}$

$|\eta^\gamma| \leq 2.5$

$20\,\mathrm{GeV} \leq M_{\gamma\gamma} \leq 250\,\mathrm{GeV}$

$\mu_R = \mu_F = M_{\gamma\gamma}$

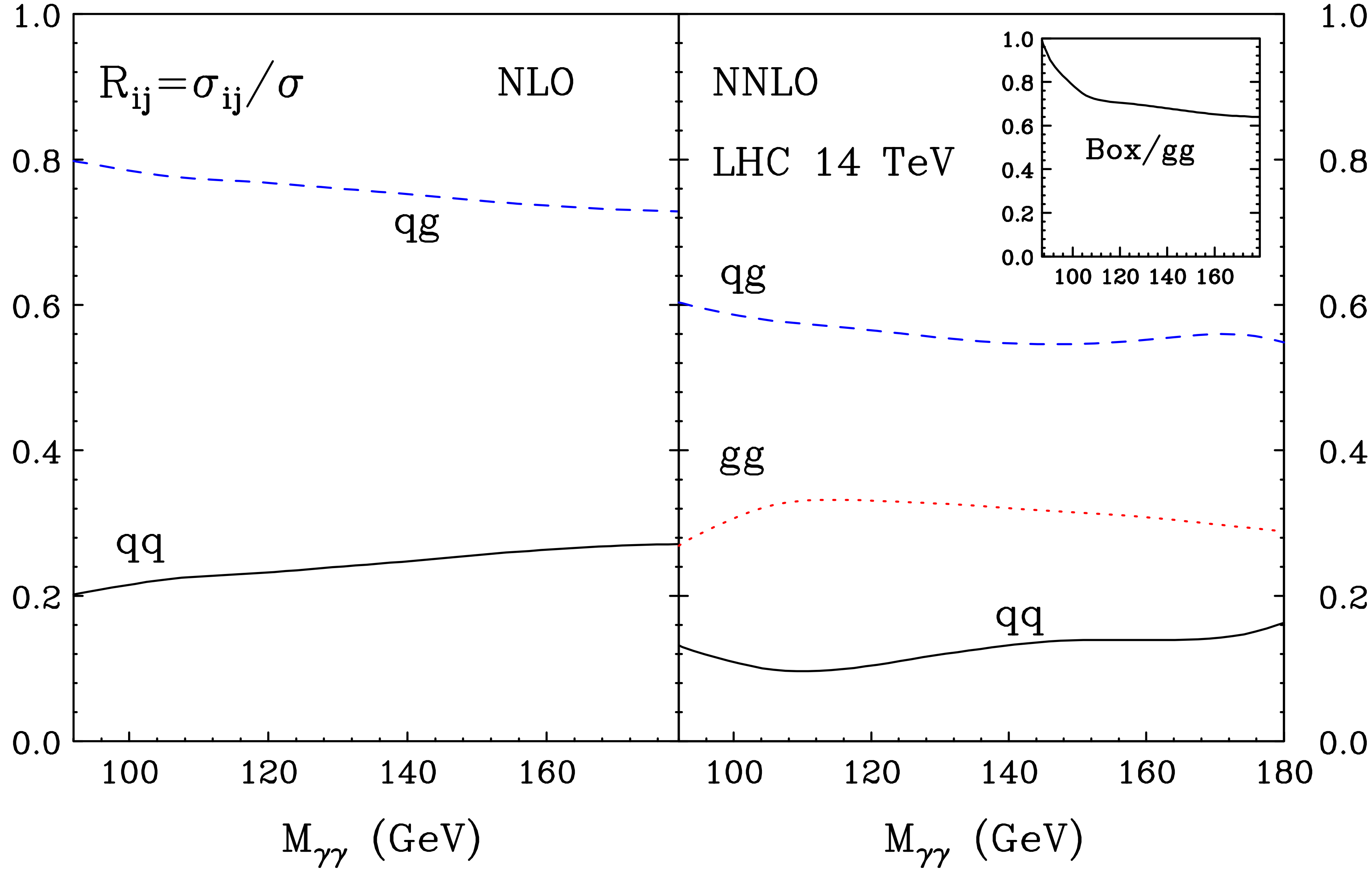


$$\frac{\sigma^{NNLO}}{\sigma^{NLO+Box}} \sim 1.35$$

$$\frac{\sigma^{NNLO}}{\sigma^{NLO}} \sim 1.55$$

Huge corrections 1 : new channels

Channels @ 14 TeV



Box only ~22% of NNLO correction

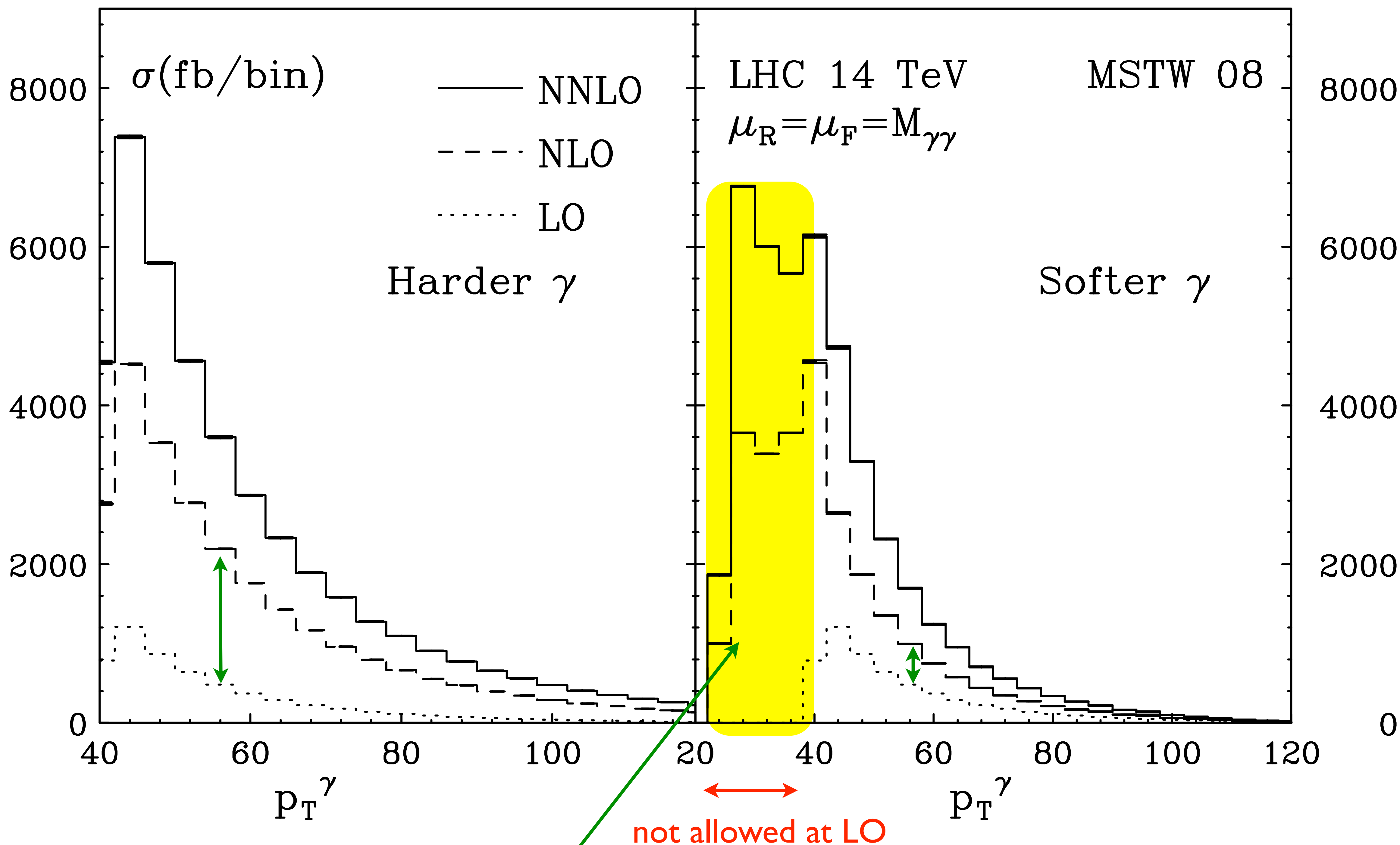
Main contribution from qg channel
(corrections to NLO dominant channel)

Huge corrections 2 : asymmetric cuts

$$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$$
$$p_T^{\gamma\, soft} \geq 25\,\mathrm{GeV}$$

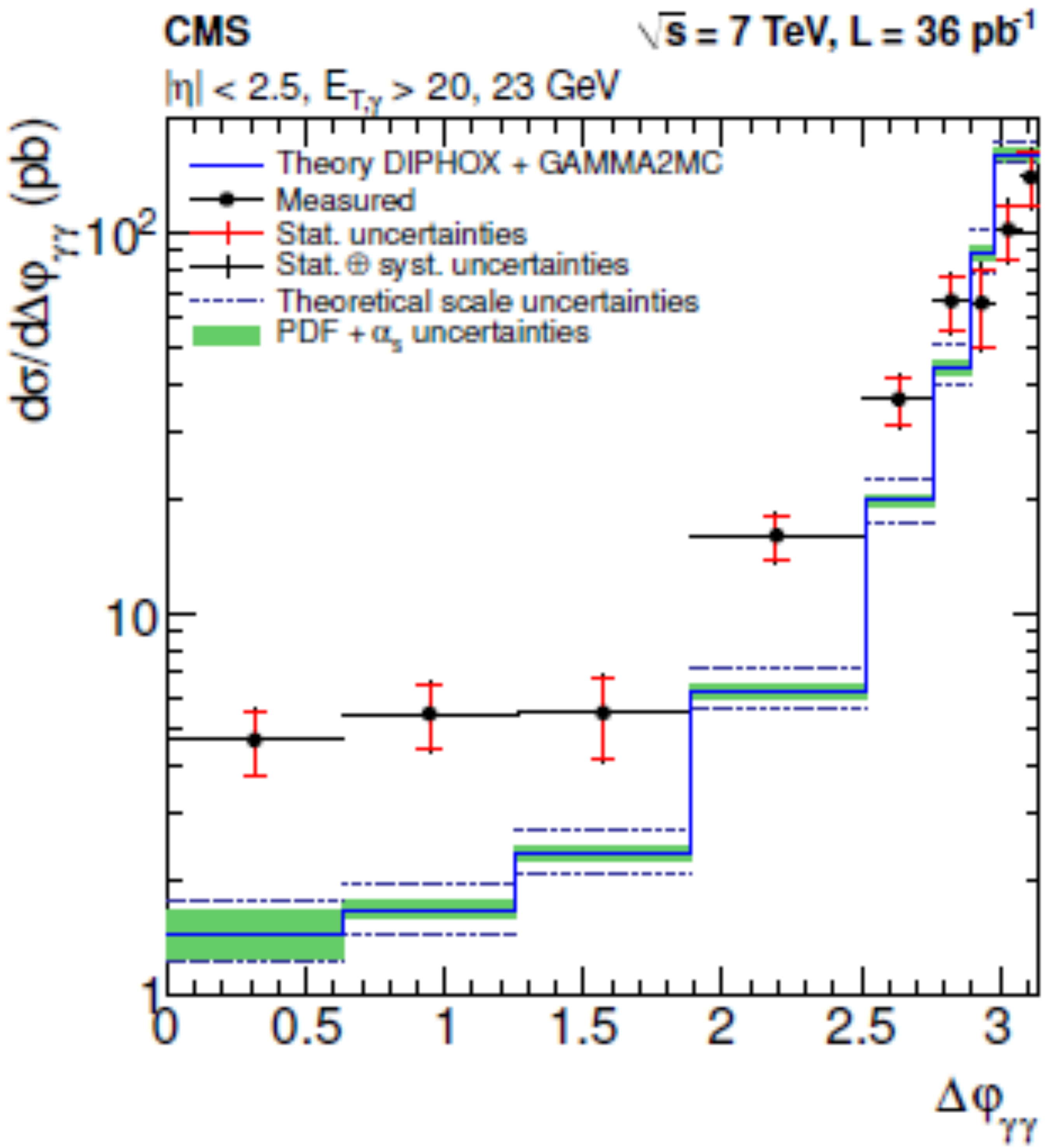
More exclusive distribution

p_T of harder and softer photon



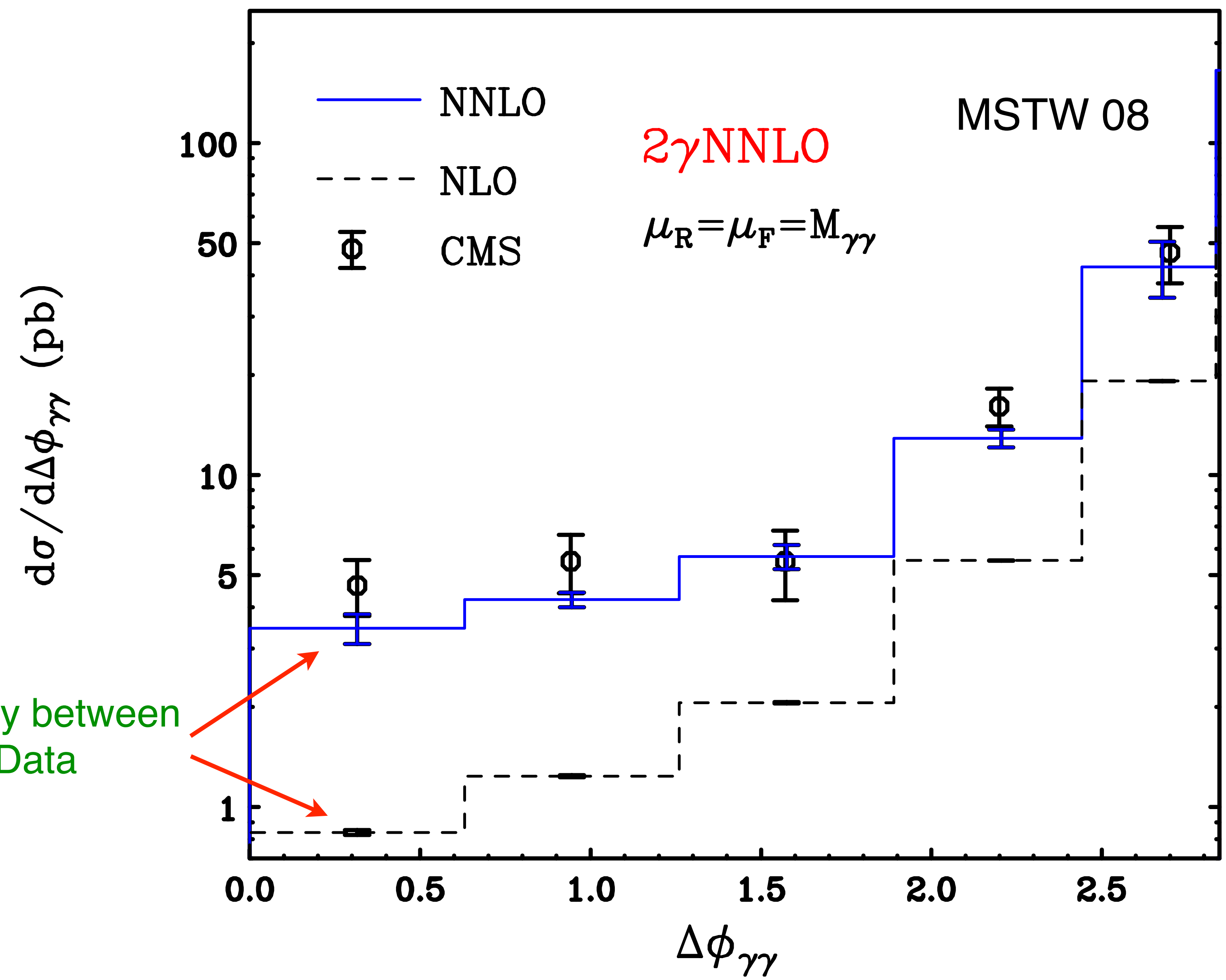
Large contribution to cross-section

Discrepancy found between NLO and Experimental data at low $\Delta\phi_{\gamma\gamma}$



NNLO Corrections much larger in some kinematical regions → "away from back-to-back configuration"

NLO effectively lowest order



large discrepancy between NLO and Data

$\sqrt{S} = 7\,\mathrm{TeV}$

CMS diphoton cuts

$p_T^{\gamma\,hard} \geq 23\,\mathrm{GeV}$

$p_T^{\gamma\,soft} \geq 20\,\mathrm{GeV}$

$|\eta^{\gamma}| \leq 2.5$

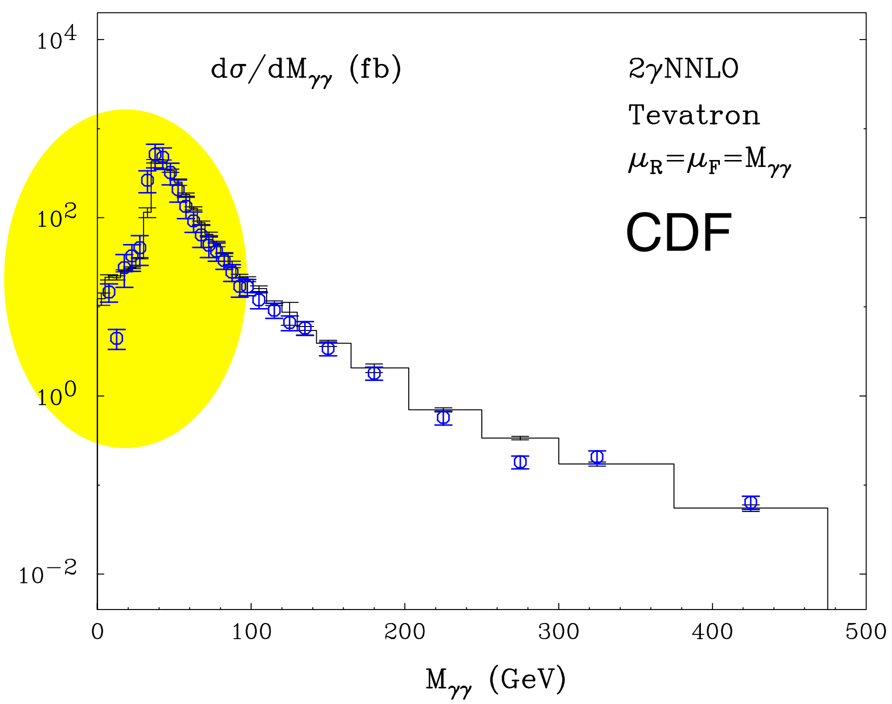
$R_{\gamma\gamma} > 0.45$

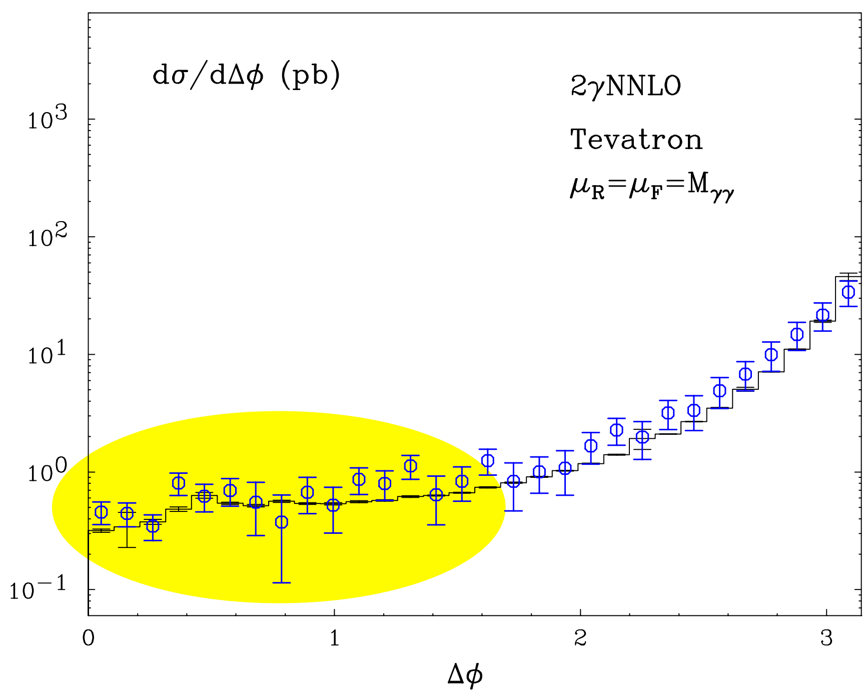
smooth cone isolation

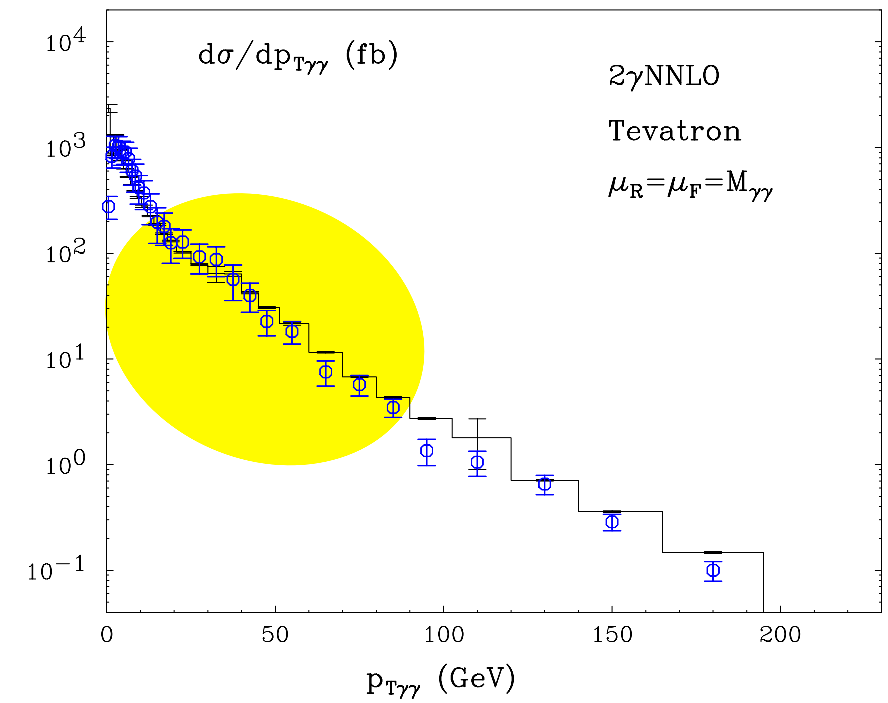
NNLO corrections essential to understand the data

In general, extra radiation at NNLO accuracy

- Sizable corrections where effectively NNLO (40-55 %)
- Fills in the gaps where NLO is effectively Born (huge K factor)
- Extends kinematical range coverage
- First order with all channels included
- First estimate of TH uncertainties







Conclusions

- TH mature and ready for comparison with experiments

- All measurements interesting
  - QCD "safe" observables
  - QCD "challenging" observables

- Still some work needed (TH and EXP) to understand isolation issues better

  - TH can not match exact EXP conditions : find a compromise

    Feasible for experiments
    Reproducible by TH (minimize non-perturbative corrections)

    - Study/measure with different isolation prescriptions
    - Dependence of cross section on isolation parameters
    - Match hadronic (EXP) and partonic (TH) kinematics

See in the following talks a more detailed comparison of TH tools to data

Backup Slides

Attempt to mitigate the effect of soft-gluon emission by reducing the contribution from back-to-back photons configuration

Asymmetric cuts

$$p_T^{\gamma\, harder} \geq (20 + \Delta)\,\text{GeV}$$
$$p_T^{\gamma\, softer} \geq 20\,\text{GeV}$$

for jets: Frixione, Ridolfi (1997)

Fixed order calculation not reliable at small Δ

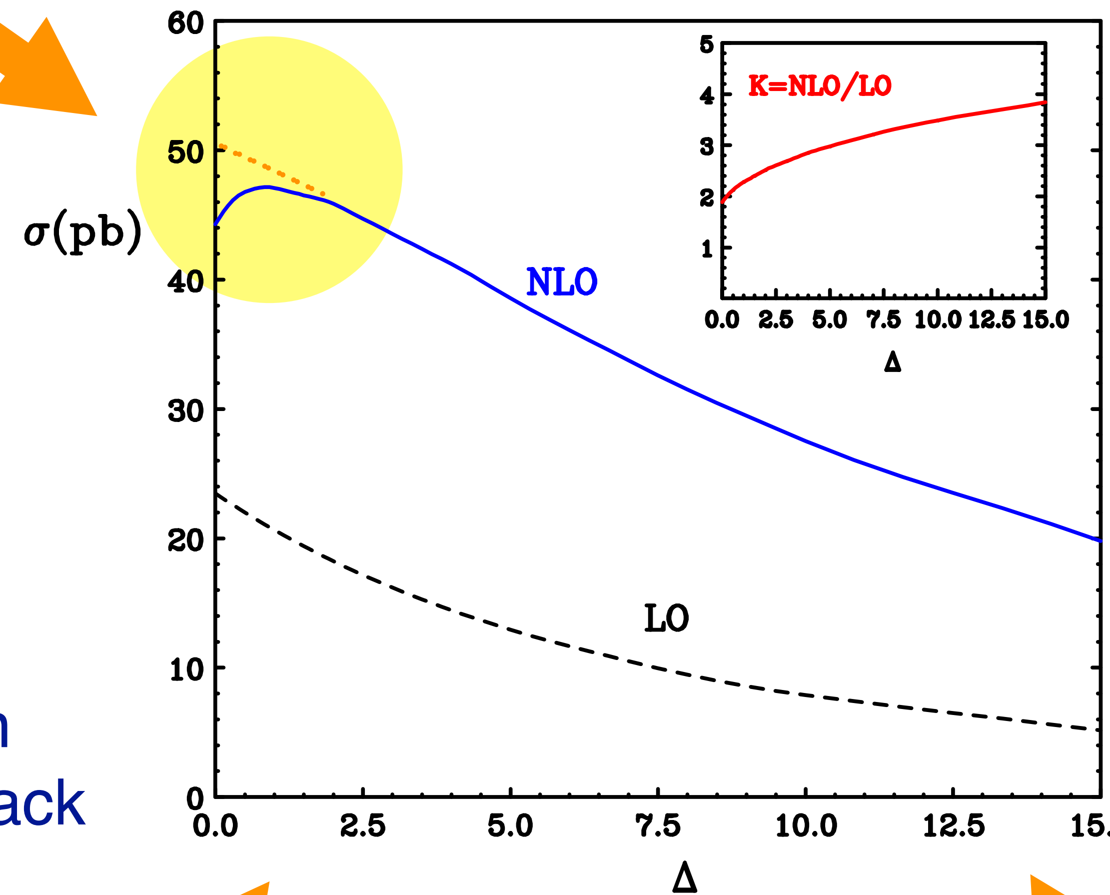
$\sqrt{S} = 7\,\text{TeV}$

$|\eta^\gamma| \leq 2.5$

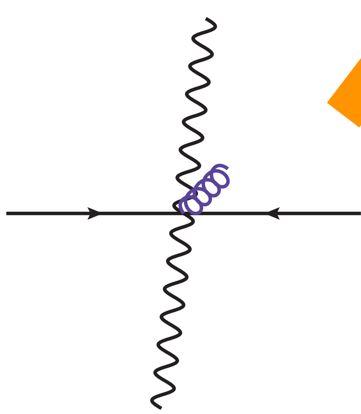
$R_{\gamma\gamma} > 0.45$

$\mu_R = \mu_F = M_{\gamma\gamma}$

CTEQ6 NLO pdfs

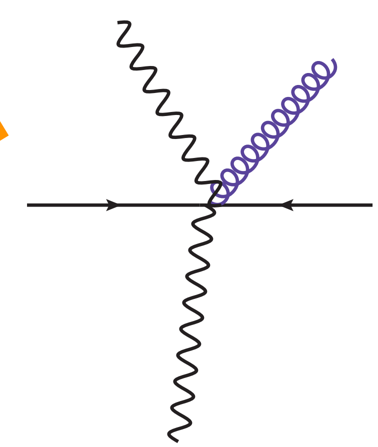


Sensitive to soft gluon emission (dominant in back to back configuration)



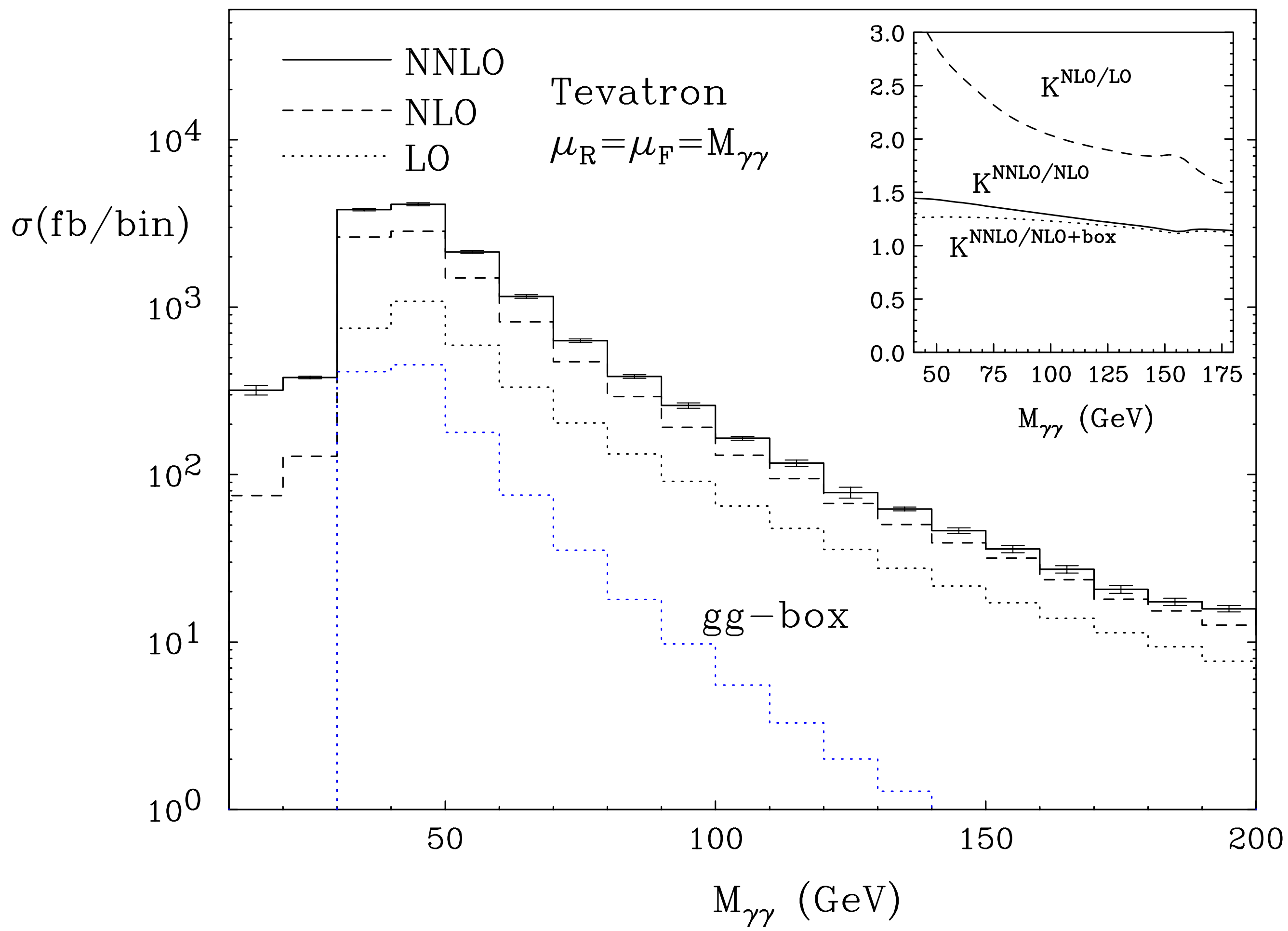
HIGGS Search

"Affected" by opening of phase space for "hard" radiation (not allowed at LO)



effectively LO away from back to back

damned if you do, damned if you don't



Tevatron

$$|\eta^\gamma| \le 1$$

$$p_T^{\gamma\,harder} \ge 17\,\mathrm{GeV}$$

$$p_T^{\gamma\,softer} \ge 15\,\mathrm{GeV}$$

$$\frac{\sigma^{NNLO}}{\sigma^{NLO+Box}} \sim 1.3$$