$H \to \gamma\gamma$

Signal and Background

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Universidad de Buenos Aires - Argentina
ITP, University of Zürich

The Zurich phenomenology workshop
Zurich, January 10 2012

New TH tools for signal and background

✓ Signal

HRes

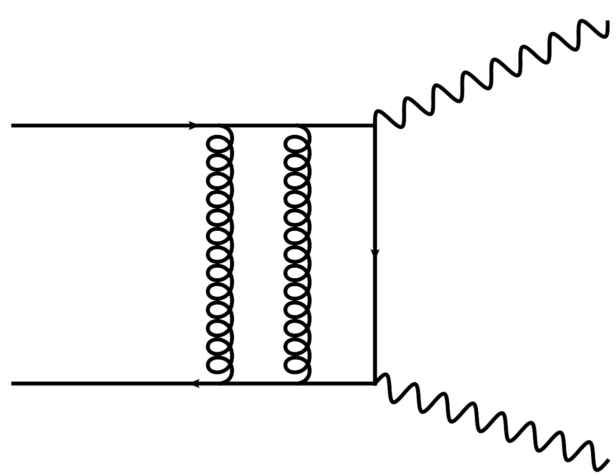
- More exclusive distributions: transverse momentum resummation with product decay

✓ Background

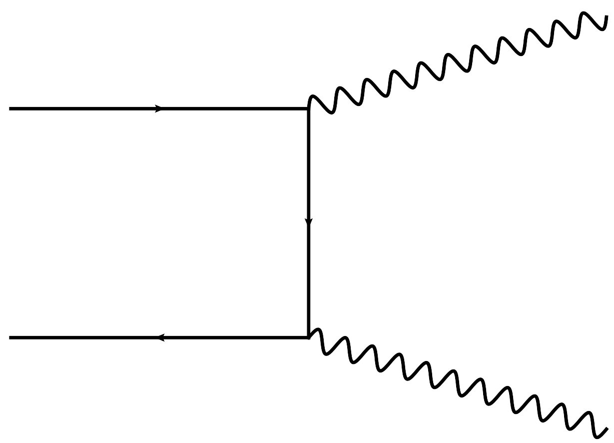
2γNNLO

- Diphoton production at NNLO

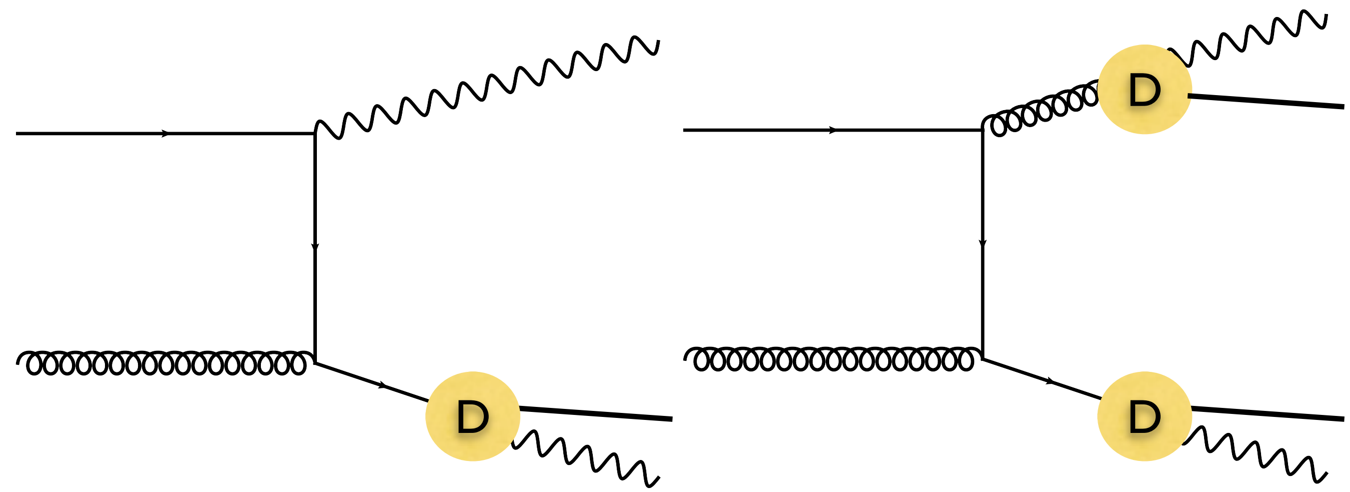
1. Diphoton Background



Two mechanisms for photon production

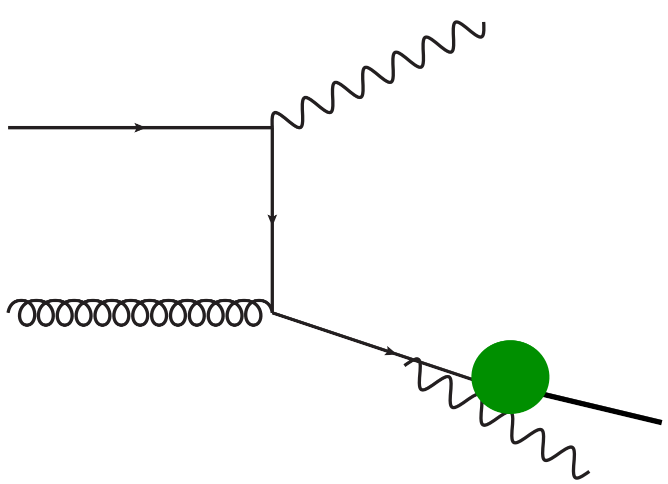


Direct (point-like)

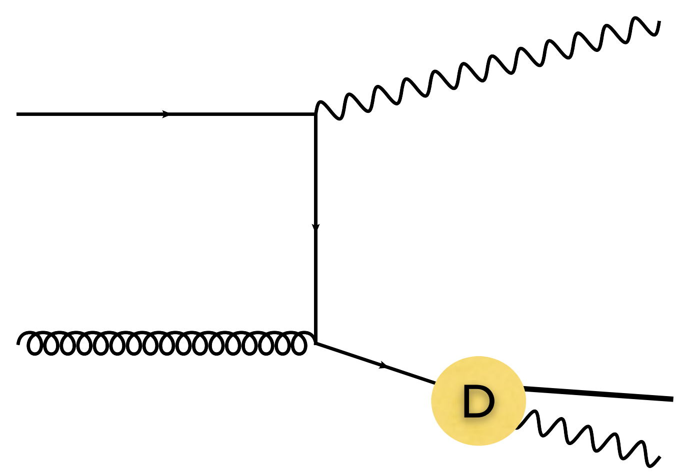


Single and double resolved (collinear fragmentation)

Separation between them NO 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

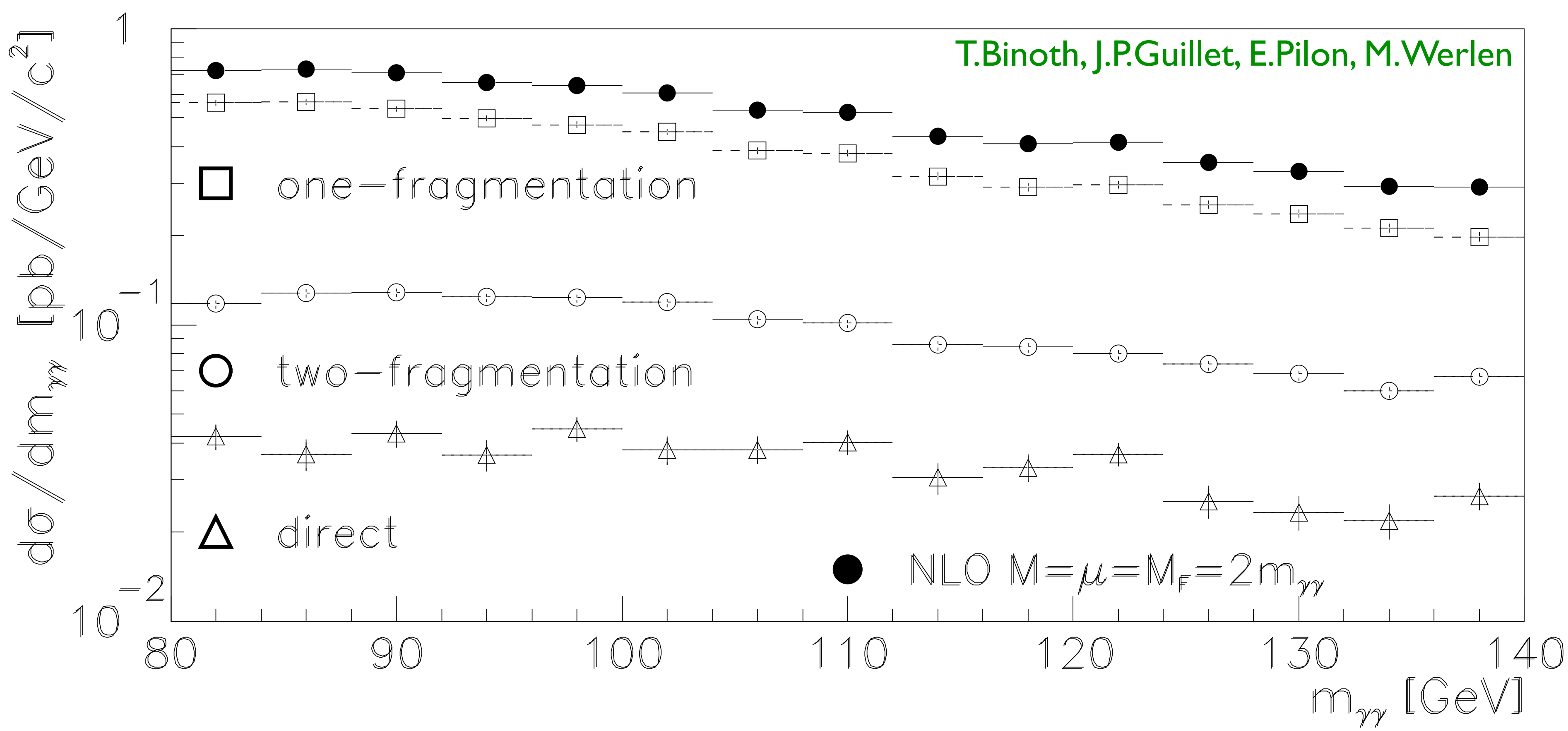
◉ Full NLO calculation available → Large Corrections

Aurenche, Baier Douiri, Fontannaz, Schiff

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

Resolved contributions dominate

• Complicates QCD calculations



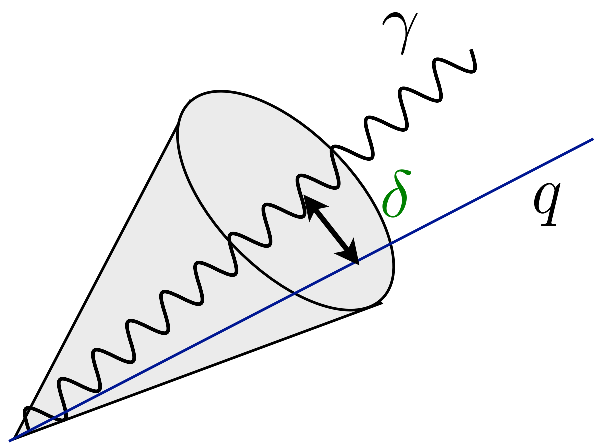
$\sqrt{S} = 14\,\mathrm{TeV}$

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

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

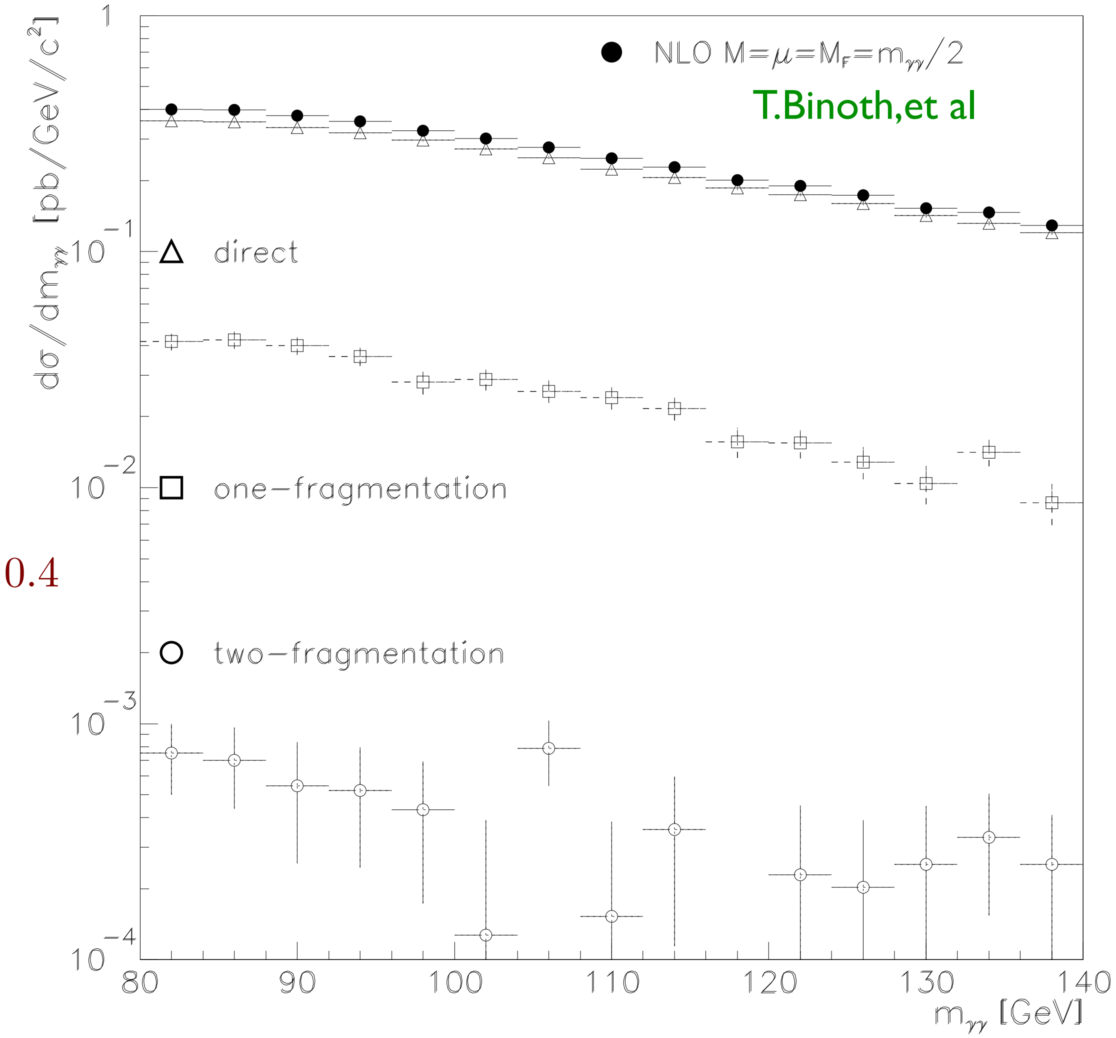
$|\eta^\gamma| \leq 2.5$

Experimental Photon Isolation reduces fragmentation component



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

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



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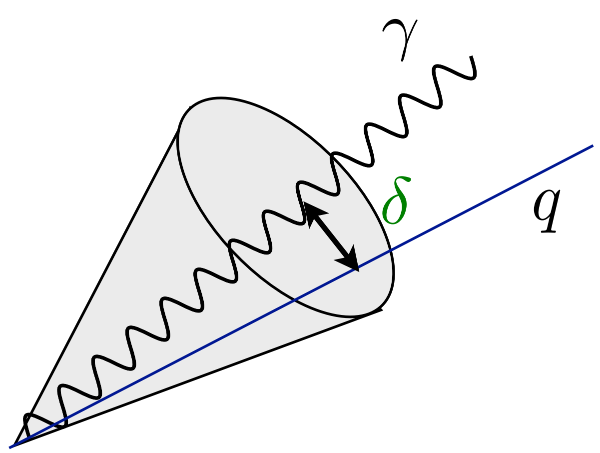

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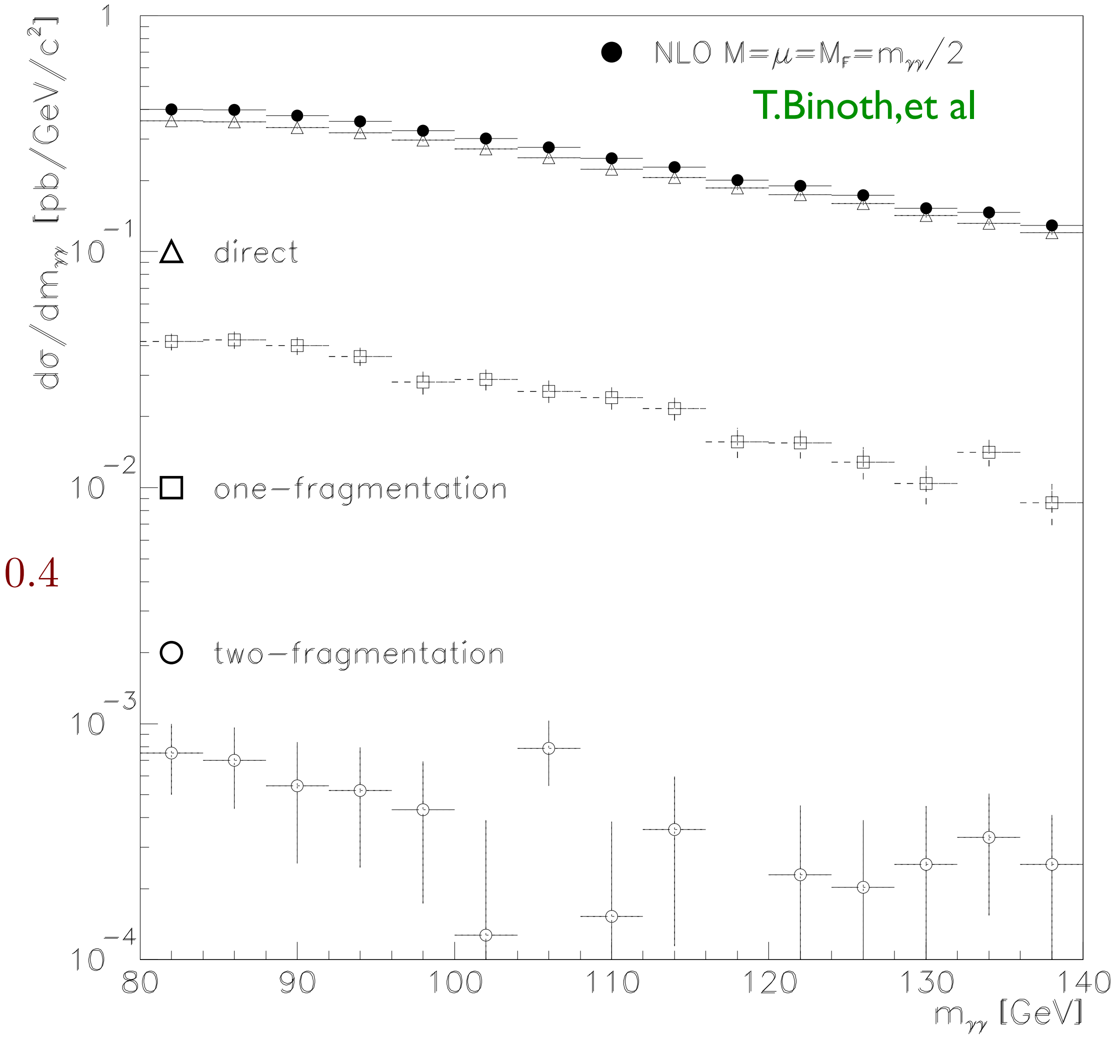


Smooth Photon Isolation S.Frixione

$$E_T^{had}(\delta) \le \chi(\delta) \text{ such that } \lim_{\delta \to 0} \chi(\delta) = 0$$

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

$n = 1$
$\epsilon_\gamma = 0.5$
$R_0 = 0.4$

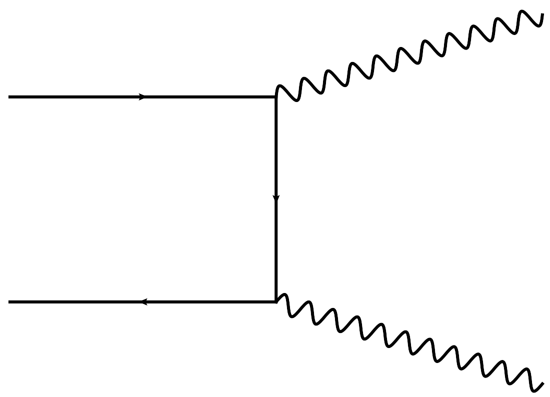
only soft emission allowed if collinear to photon

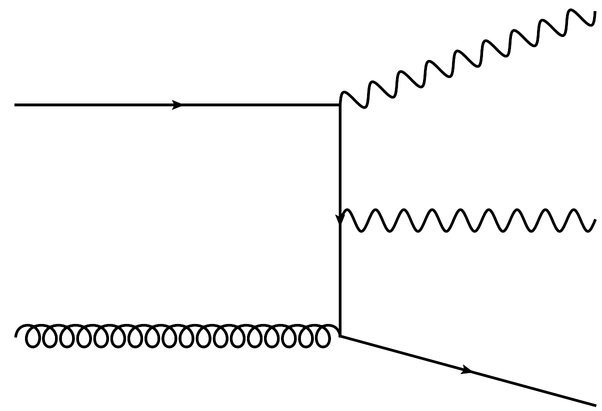
- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct contribution well defined

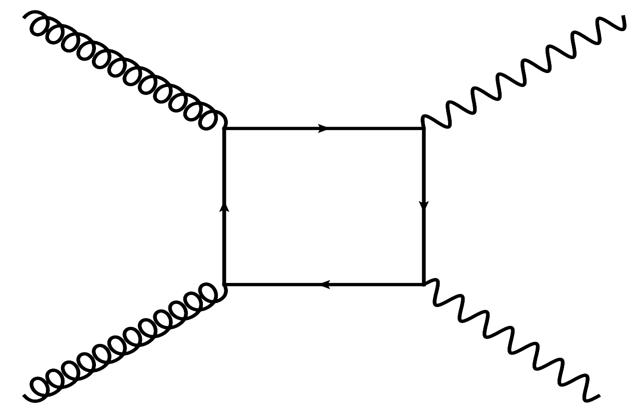
- Work on the discretized version $\epsilon_\gamma = 0.05$ practically eliminates frag. component

◉ Direct Contribution

Do we need higher order corrections for this observable?







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

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

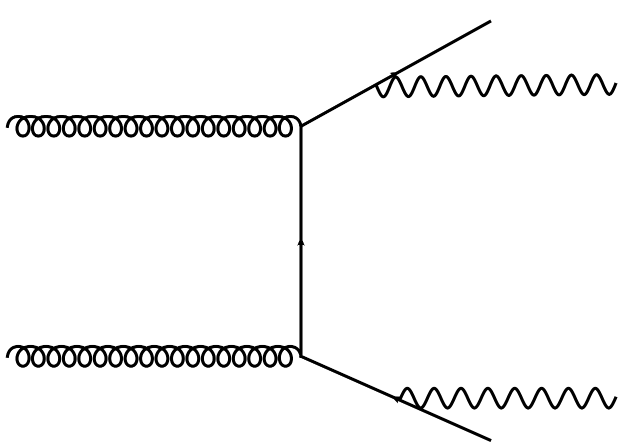
$\mathcal{O}(\alpha_s^2)$ but gg Luminosity

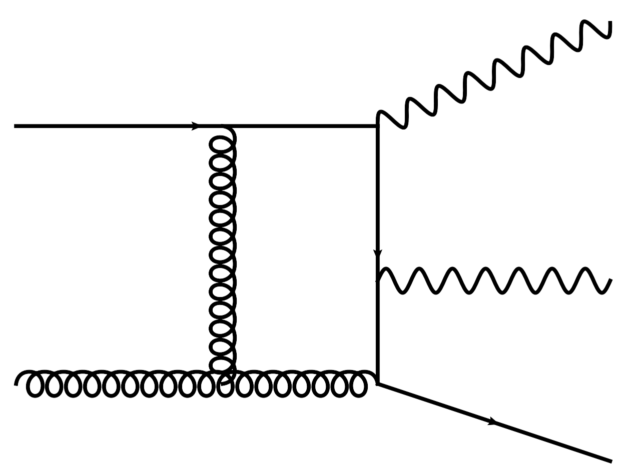
included in all calculations

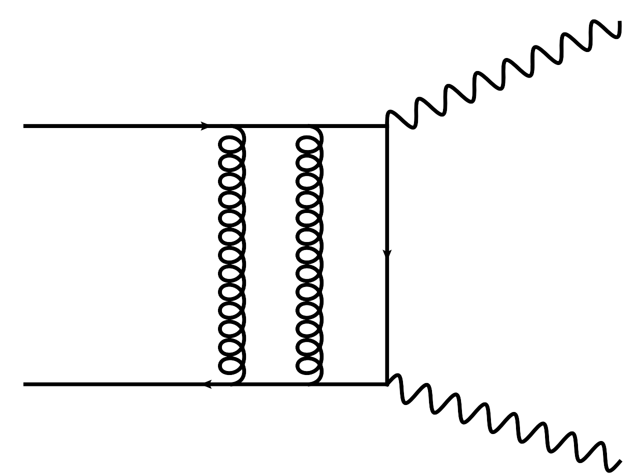
$\gamma\gamma$ production ➡ Box (subset of NNLO) known to be as large as Born!

Dicus, Willenbrock

◉ Full NNLO control of Diphoton production is desirable







+ ....

NNLO using q_T-Subtraction

S.Catani, M.Grazzini

- Originally used for Higgs and Drell-Yan
- Generalized to any process with final state colorless system ***F***

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

Fully exclusive NNLO code for $pp \to F$

2γNNLO

First exclusive NNLO in pp collisions with two final state particles

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

DiPhoton production at NNLO

- ***First*** results using $2\gamma\mathrm{NNLO}$ S.Catani, L.Cieri, DdeF, G.Ferrera, M.Grazzini

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

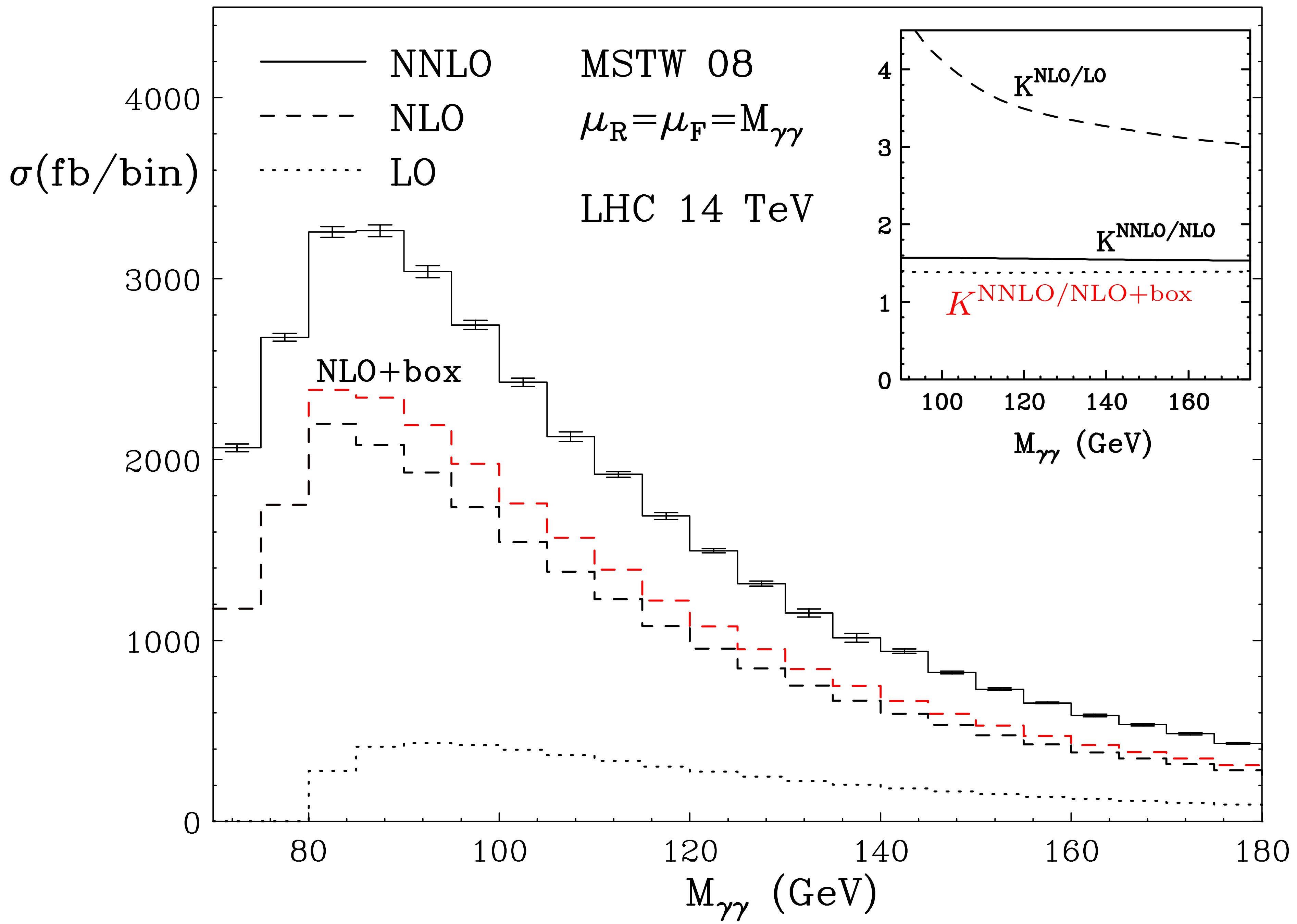
$p_T^{\gamma\,hard} \geq 40\,\mathrm{GeV}$

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

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

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

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



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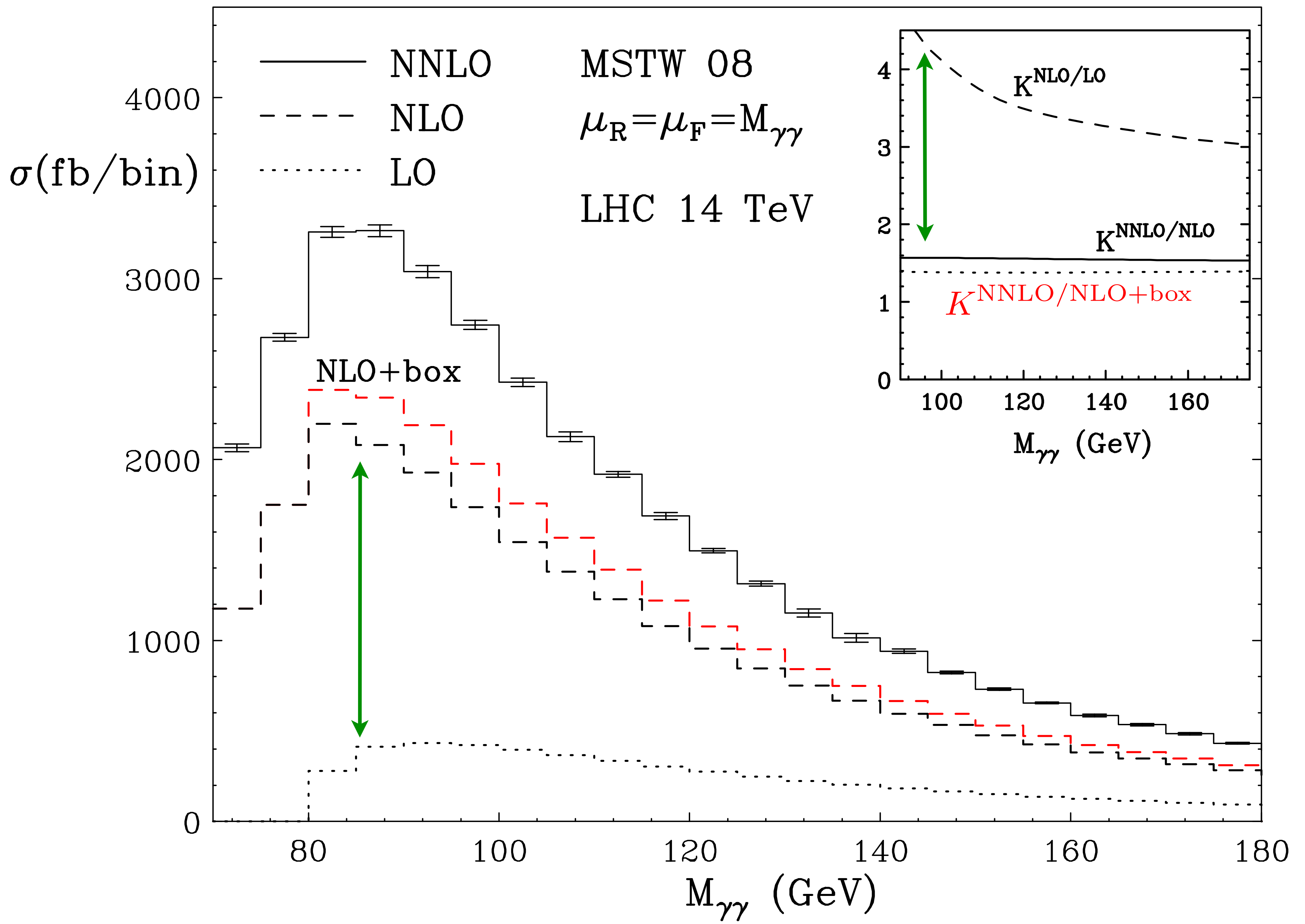

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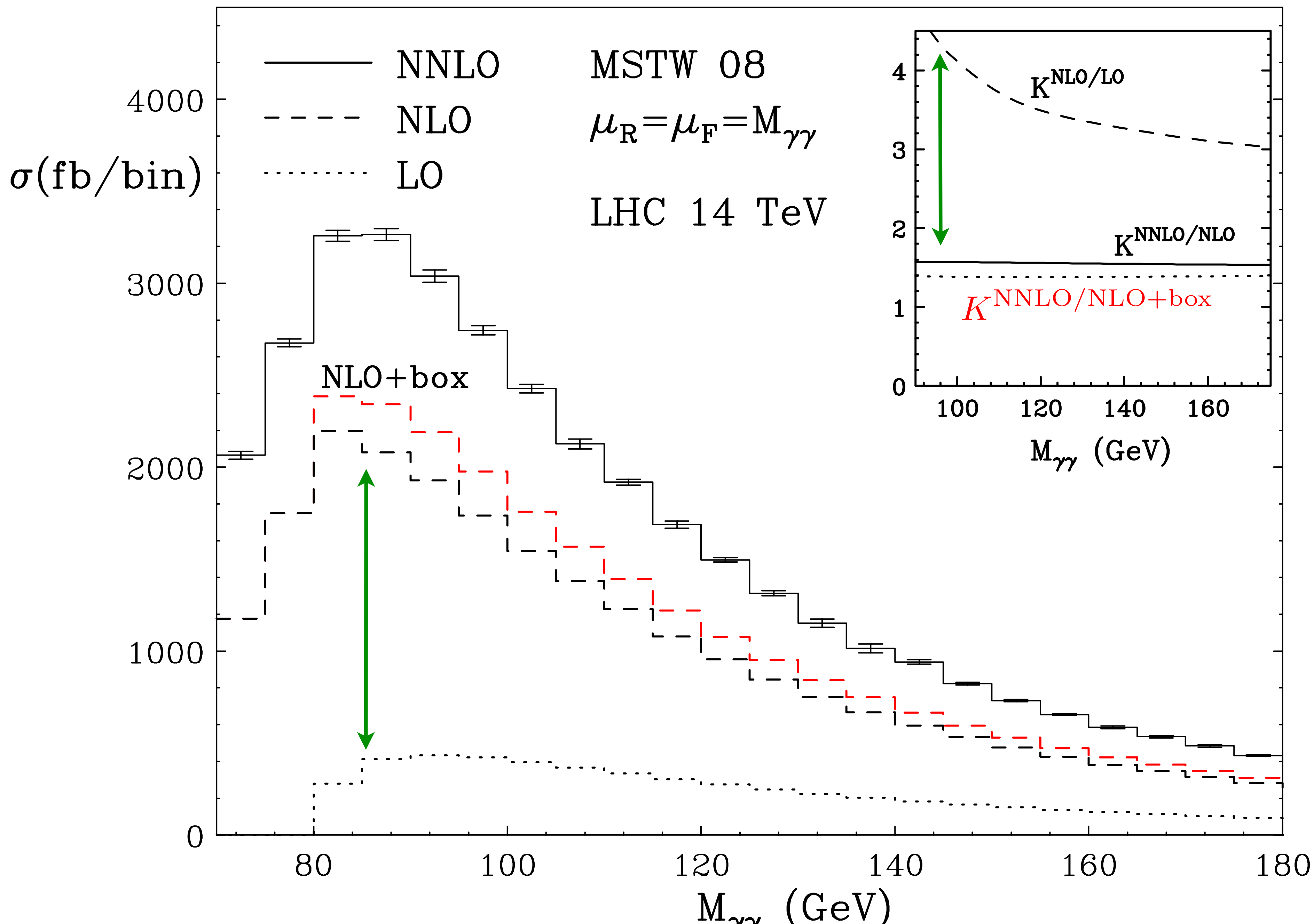
$$\frac{\sigma^{NNLO}}{\sigma^{NLO+Box}} \sim 1.35$$

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



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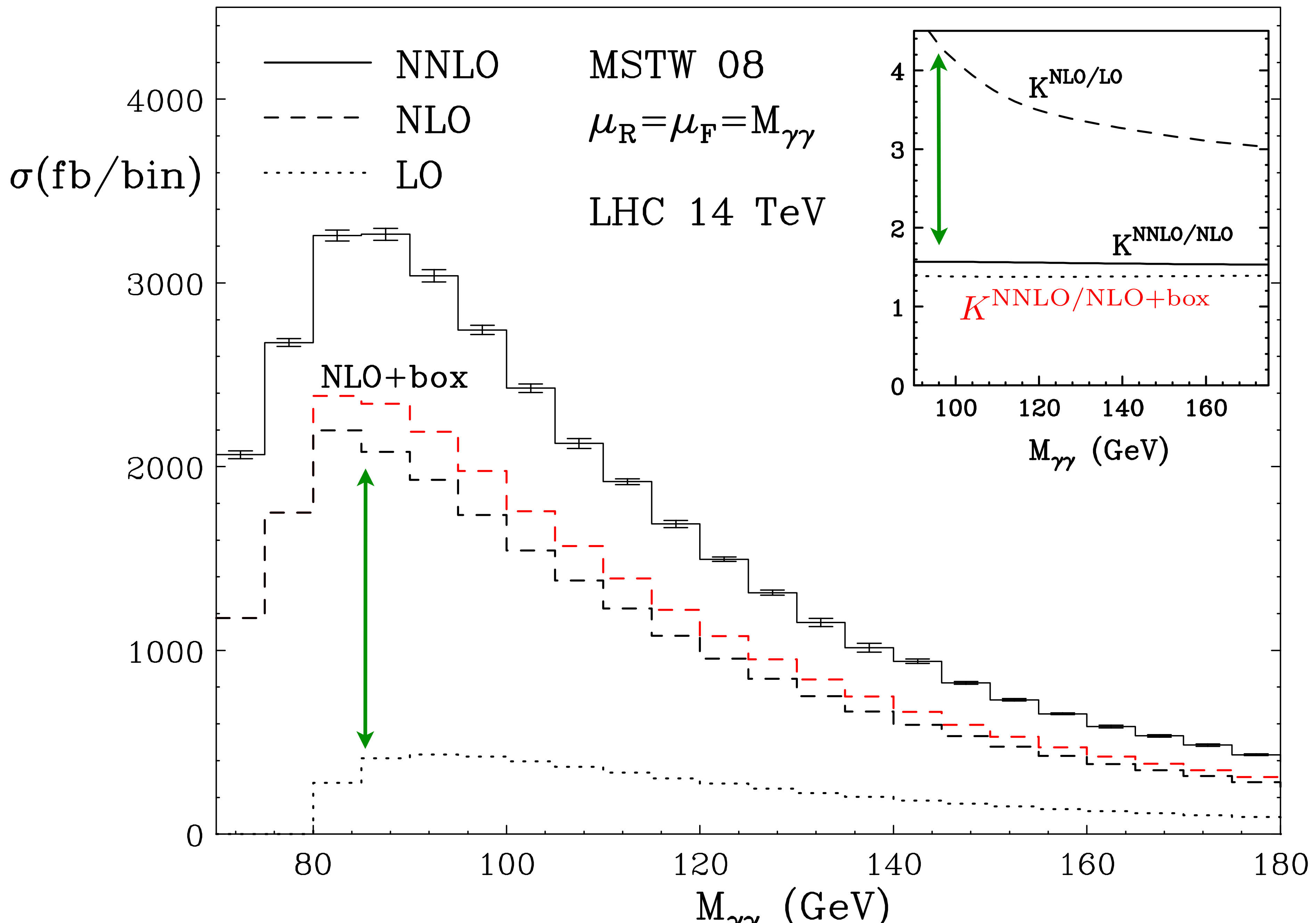

$$\frac{\sigma^{NNLO}}{\sigma^{NLO+Box}} \sim 1.35$$

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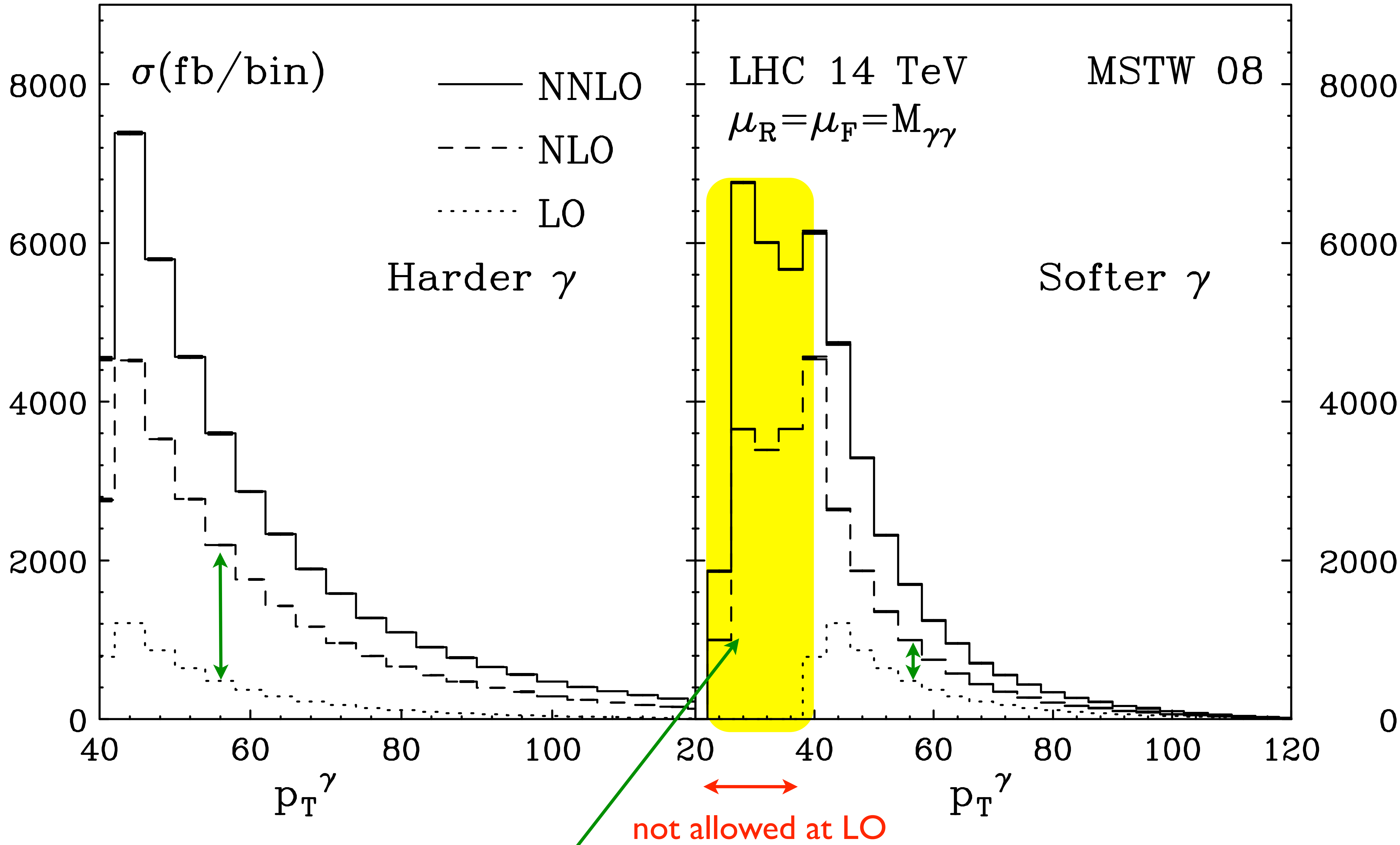
Box only ~22% of NNLO correction

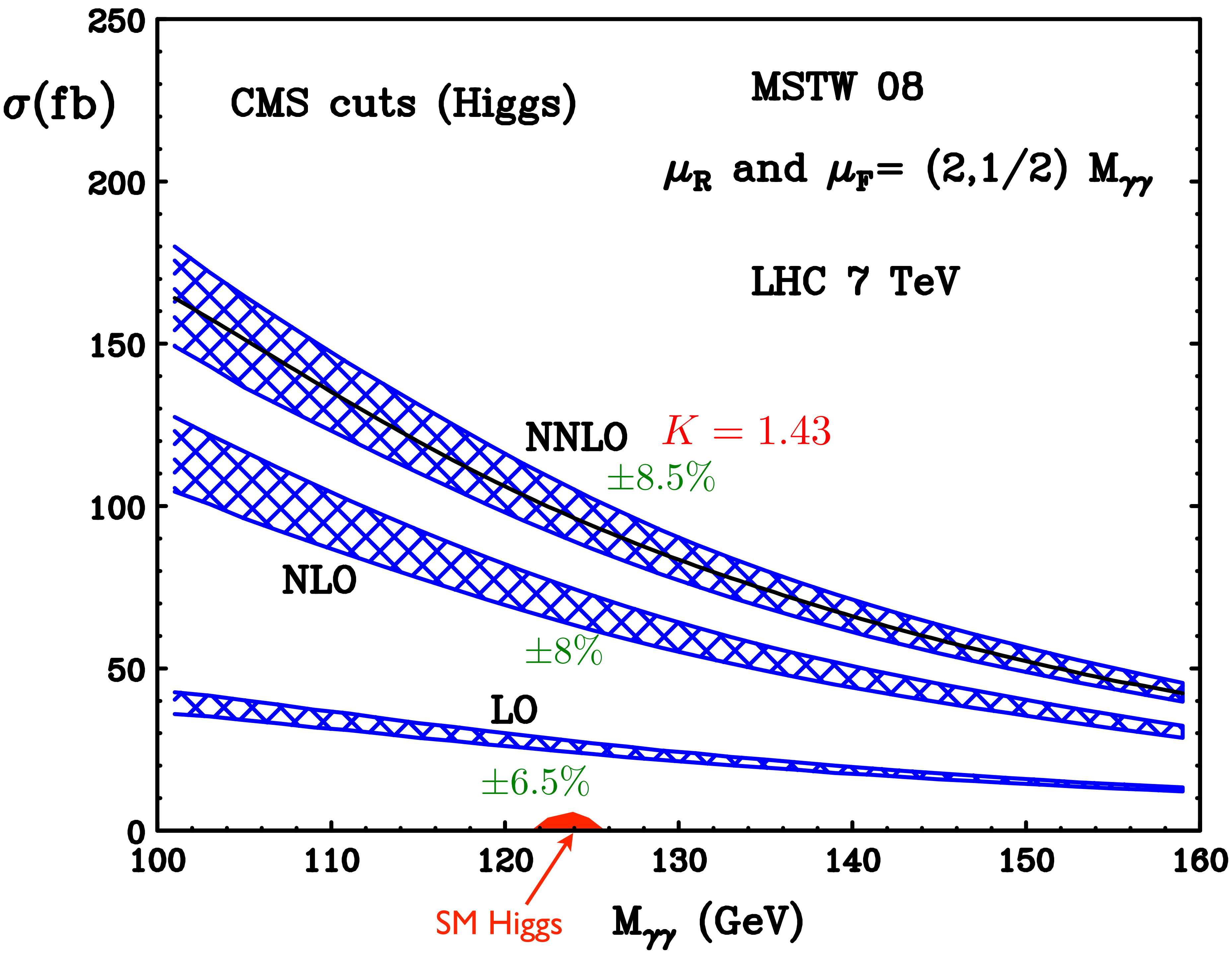
More exclusive distribution

p_T of harder and softer photon



Large contribution to cross-section

Higgs search at 7 TeV : scale dependence



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

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

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

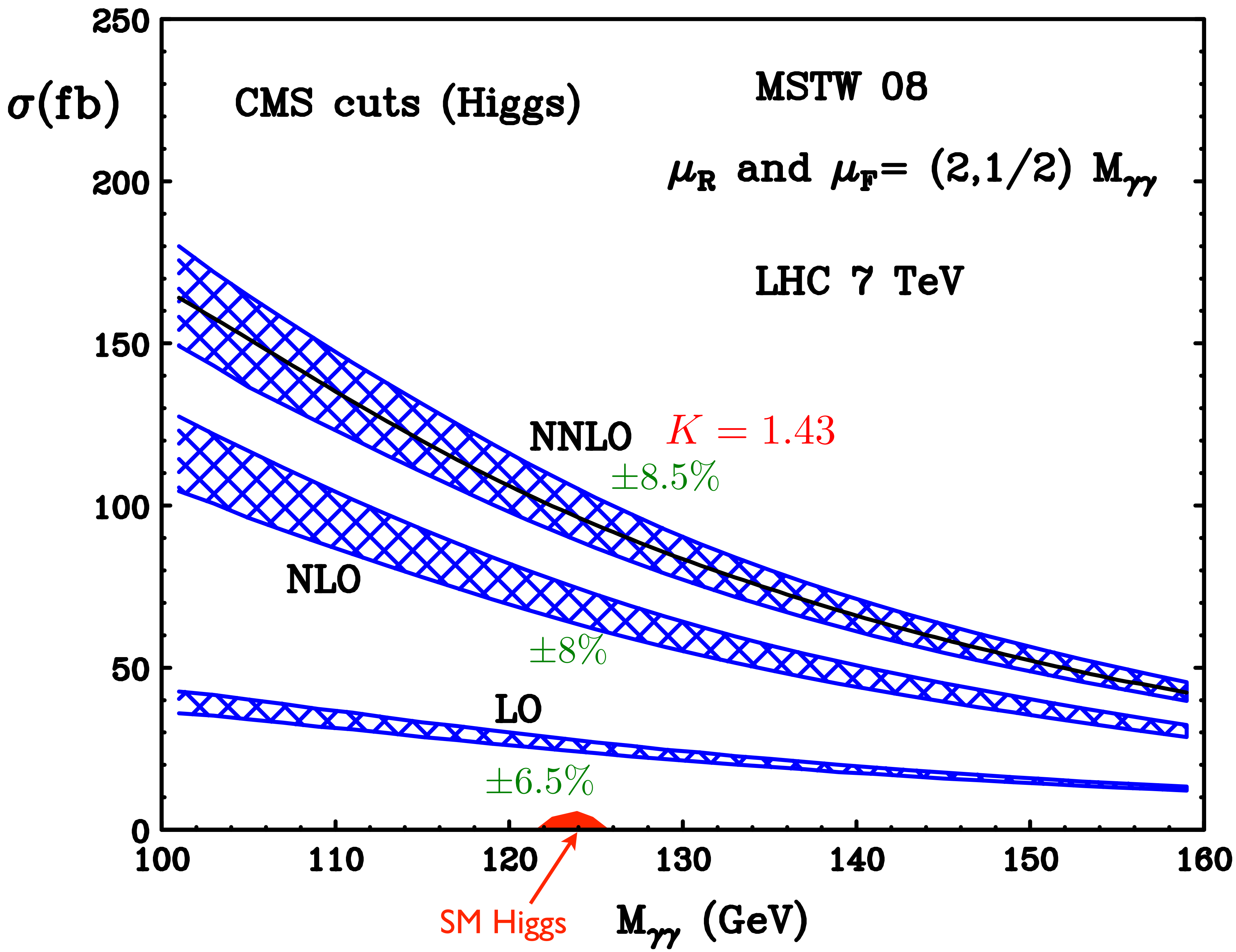
$|\eta^\gamma| \leq 2.5$

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

$\epsilon = 0.05$

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

Higgs search at 7 TeV : scale dependence



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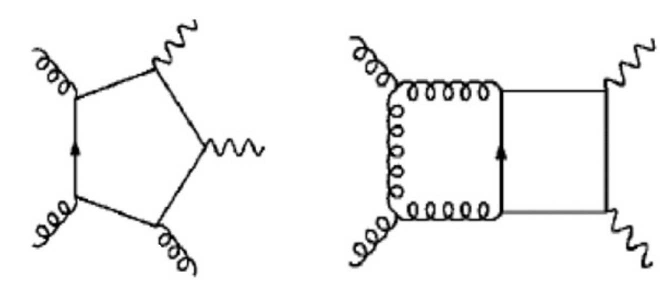
α_s^3 Bern, Dixon, Schmidt (2002)



Some N^3LO terms known to contribute ~5%

- Scale does not represent TH uncertainties at LO and NLO → new channels
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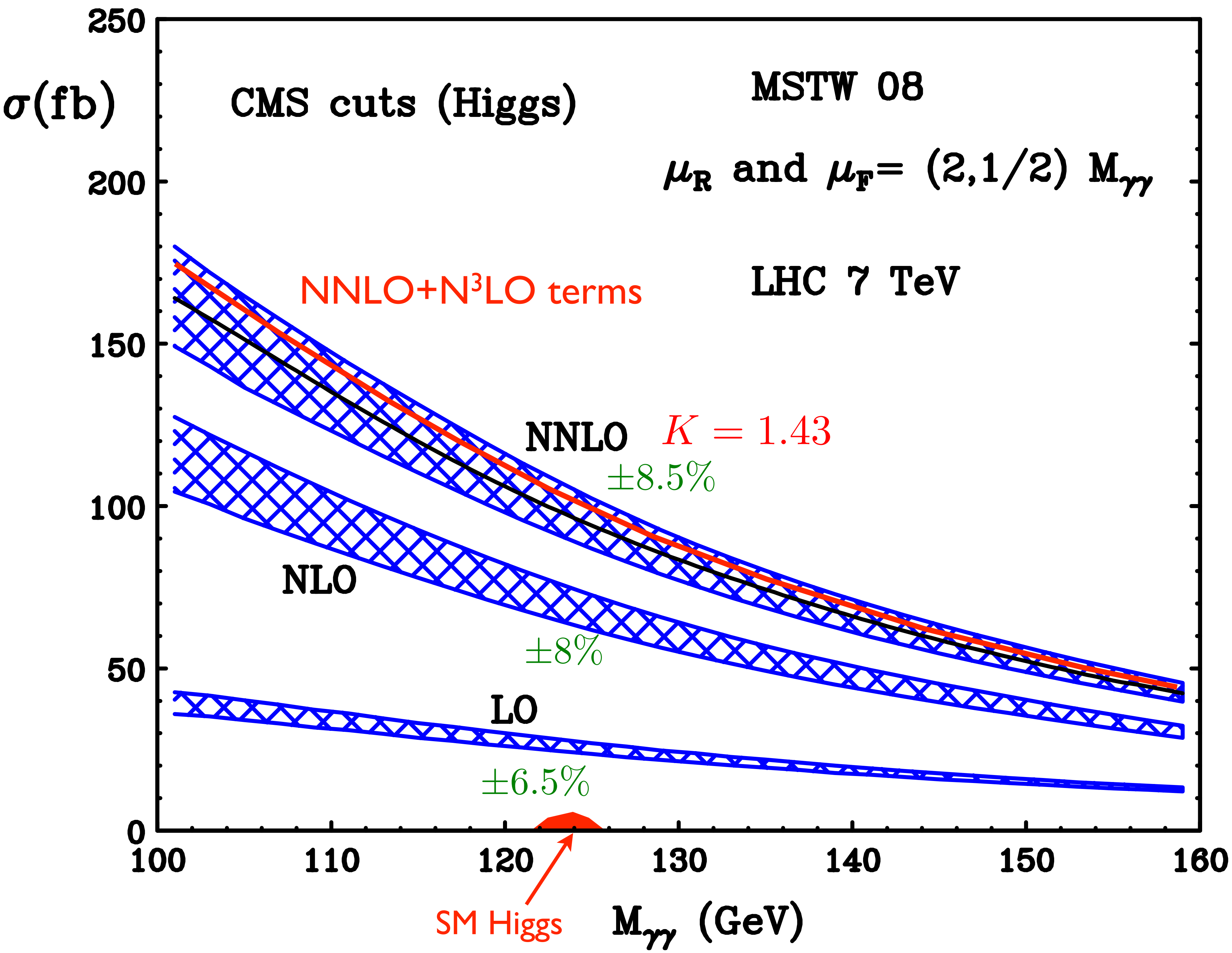

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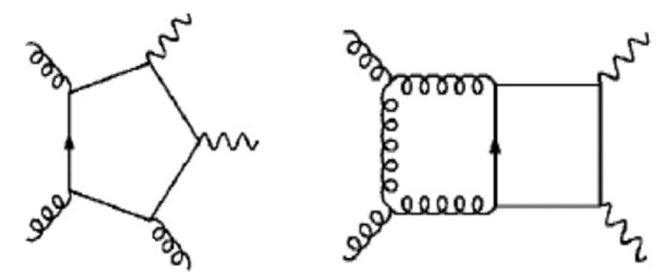

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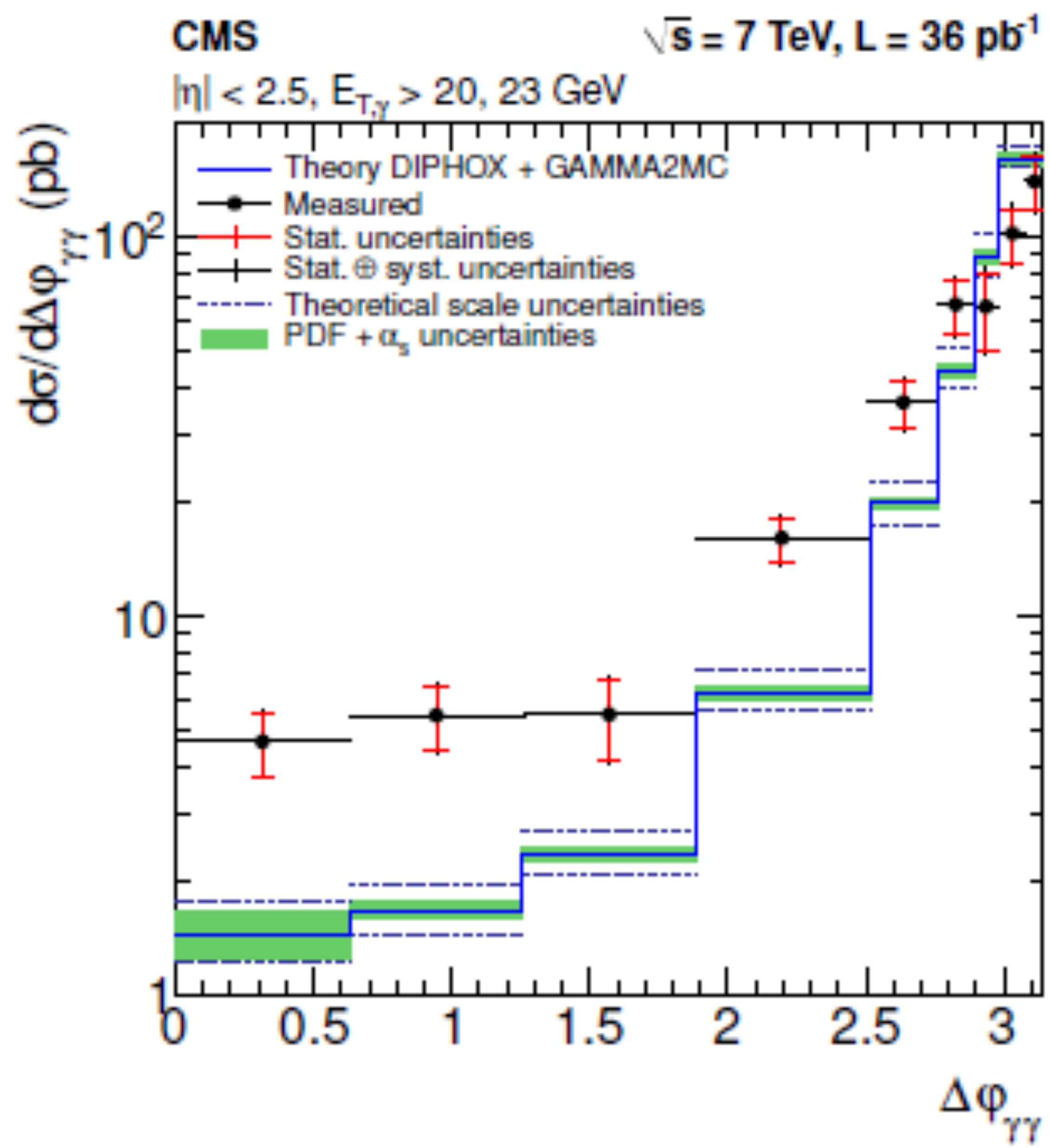
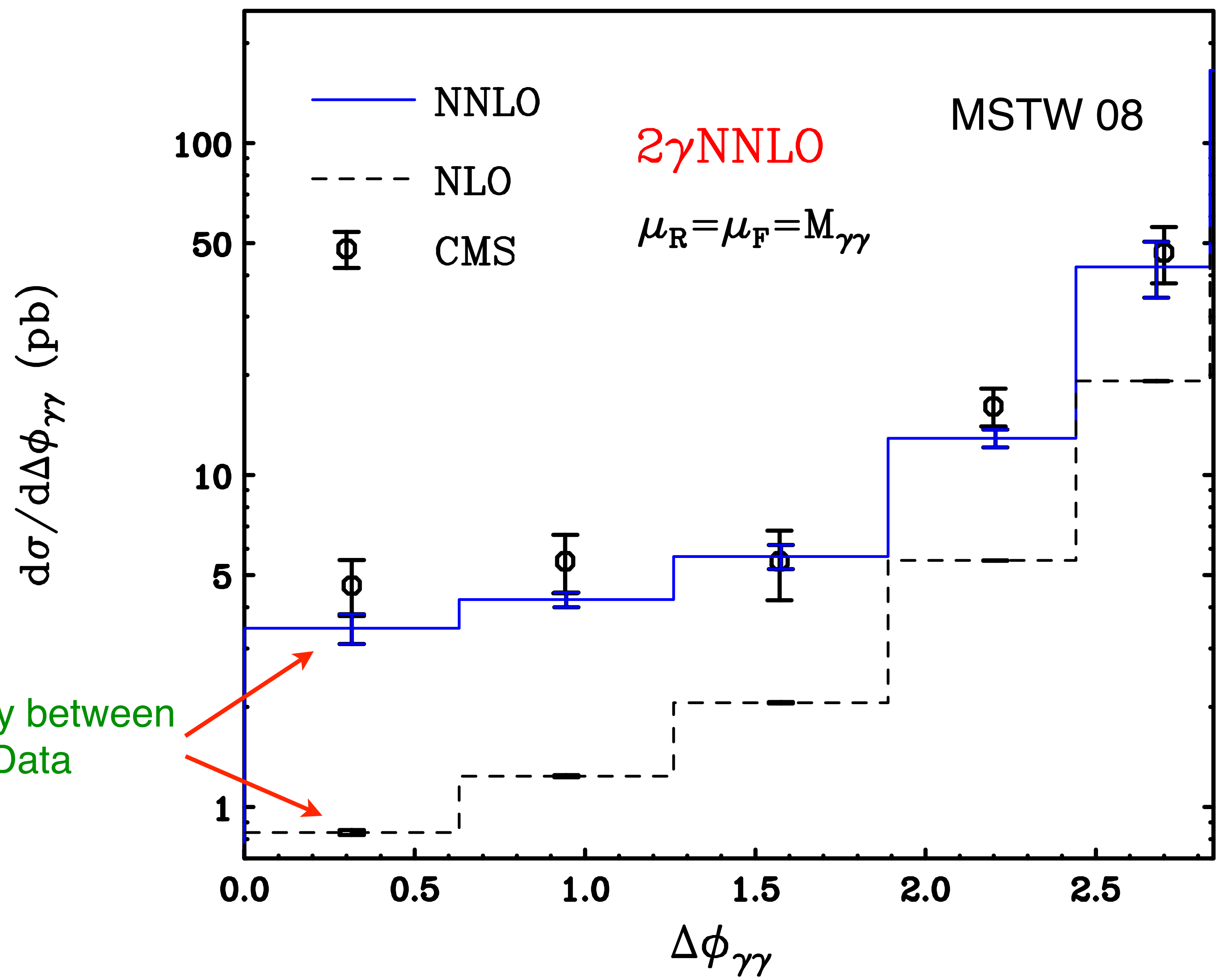
- Scale does not represent TH uncertainties at LO and NLO → new channels
- All channels open at NNLO → estimate of TH uncertainties

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

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

CMS diphoton cuts

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

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

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

$R_{\gamma\gamma} > 0.45$

smooth cone isolation

NNLO corrections essential to understand the background

Conclusions Background

✓ NNLO corrections sizable in invariant mass distribution relevant for Higgs → 40-55% effect over NLO

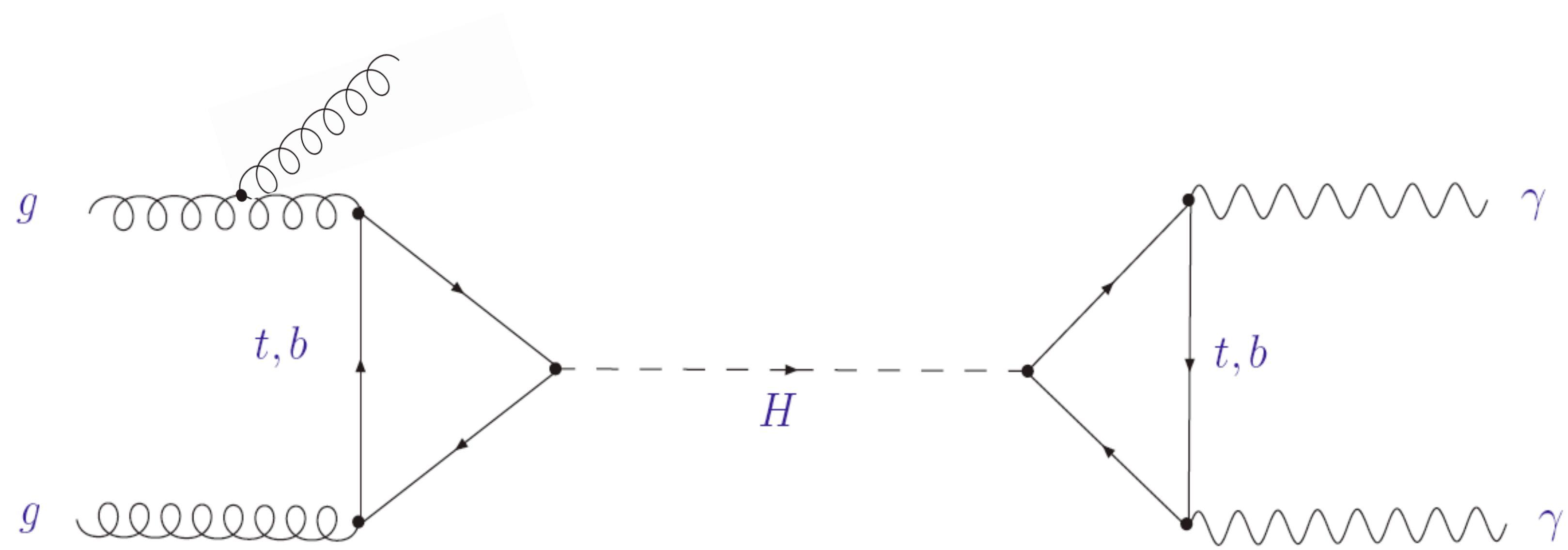
✓ NNLO very large away from back-to-back configuration (effectively NLO) → needed to understand LHC data

✓ at NNLO start to be able to quantify TH uncertainties

✓ User-friendly code will be available → beyond smooth cone isolation

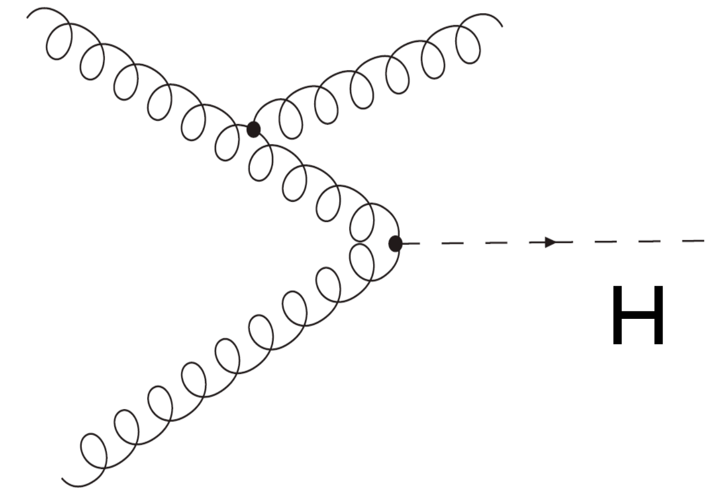
$2\gamma\mathrm{NNLO}$

2. Diphoton Signal



Higgs Transverse momentum distribution

Two scales problem M_H^2, q_T^2



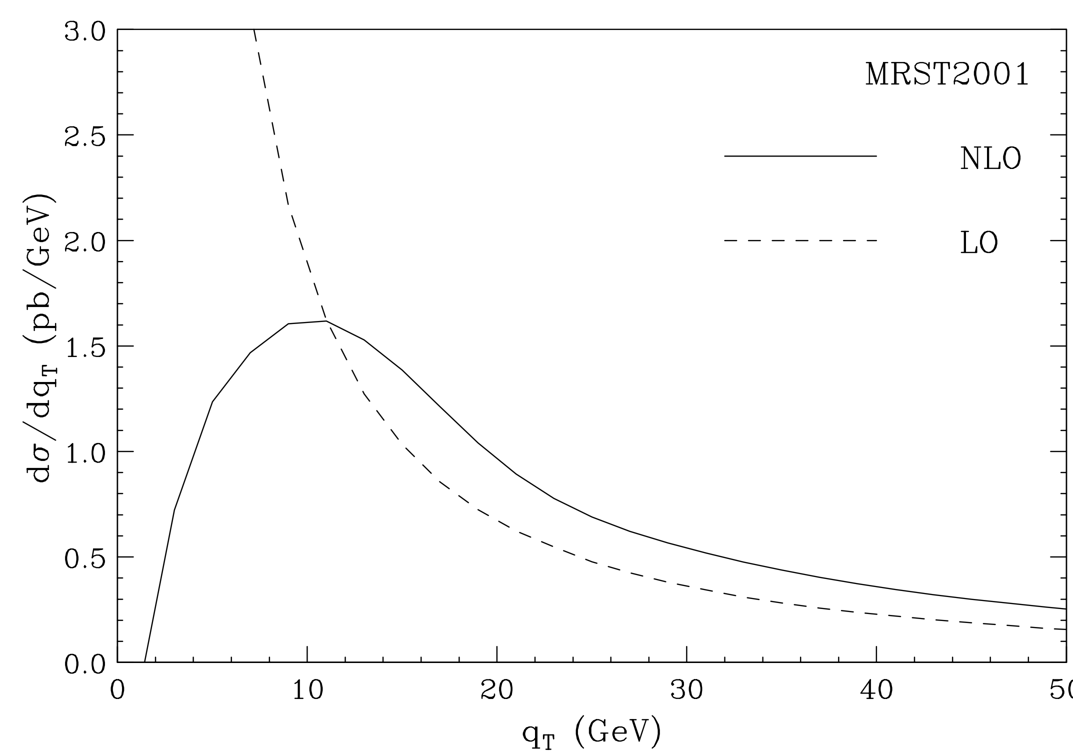
◉ QCD based on convergence of perturbative expansion

$$\frac{d\sigma}{dq_T^2} = \alpha_s^2(\alpha_s \mathcal{C}_1 + \alpha_s^2 \mathcal{C}_2 + \alpha_s^3 \mathcal{C}_3 + \ldots)$$

requires $\alpha_s \ll 1 \quad , \quad \mathcal{C}_n \sim \mathcal{O}(1)$

But $\alpha_s^n \mathcal{C}_n \sim \frac{\alpha_s^n}{q_T^2} \log^{2n-1} \frac{M_H^2}{q_T^2}$

◉ Convergence spoiled when two scales are very different (small q_T)



LO: $\frac{d\sigma}{dq_T} \rightarrow +\infty$ as $q_T \rightarrow 0$

NLO: $\frac{d\sigma}{dq_T} \rightarrow -\infty$ as $q_T \rightarrow 0$

Logs originated by soft and collinear gluon radiation

◉ Large logs need to be resummed!

Dokshitzer, Diakonov, Troian (1978)
Parisi, Petronzio (1979)
Curci, Greco, Srivastava (1979)
Collins, Soper, Sterman (1985)

Resummation performed in b space

$$\frac{d\hat{\sigma}^{(\text{res.})}_{H,ac}}{dq_T^2}(q_T, m_H, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \int_0^\infty db\, \frac{b}{2}\, J_0(bq_T)\, \mathcal{W}^H_{ac}(b, m_H, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)$$

◉ + some improvements

Catani, deF, Grazzini (2000)
Bozzi, Catani, deF, Grazzini (2005)

Process Dependent

$$\mathcal{W}^H_N(b, m_H; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \mathcal{H}^H_N\left(m_H, \alpha_S(\mu_R^2); m_H^2/\mu_R^2, m_H^2/\mu_F^2, m_H^2/Q^2\right)$$
$$\times \exp\{\mathcal{G}_N(\alpha_S(\mu_R^2), L; m_H^2/\mu_R^2, m_H^2/Q^2)\}$$

Universal Sudakov Form Factor

Resummation scale

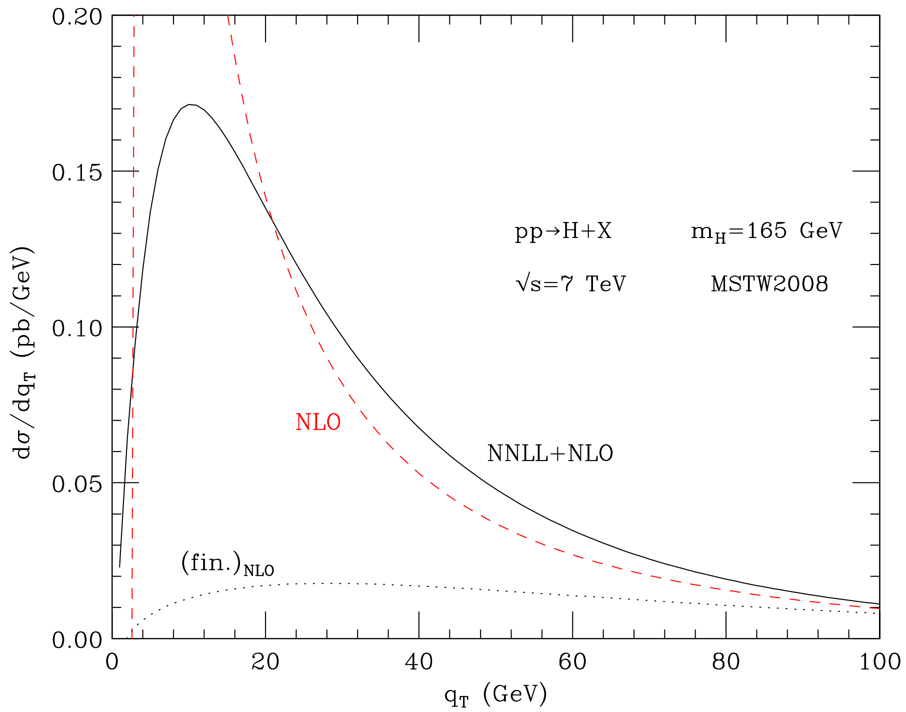
$$\tilde{L} = \ln\left(1 + Q^2 b^2/b_0^2\right)$$

impose unitarity constraint

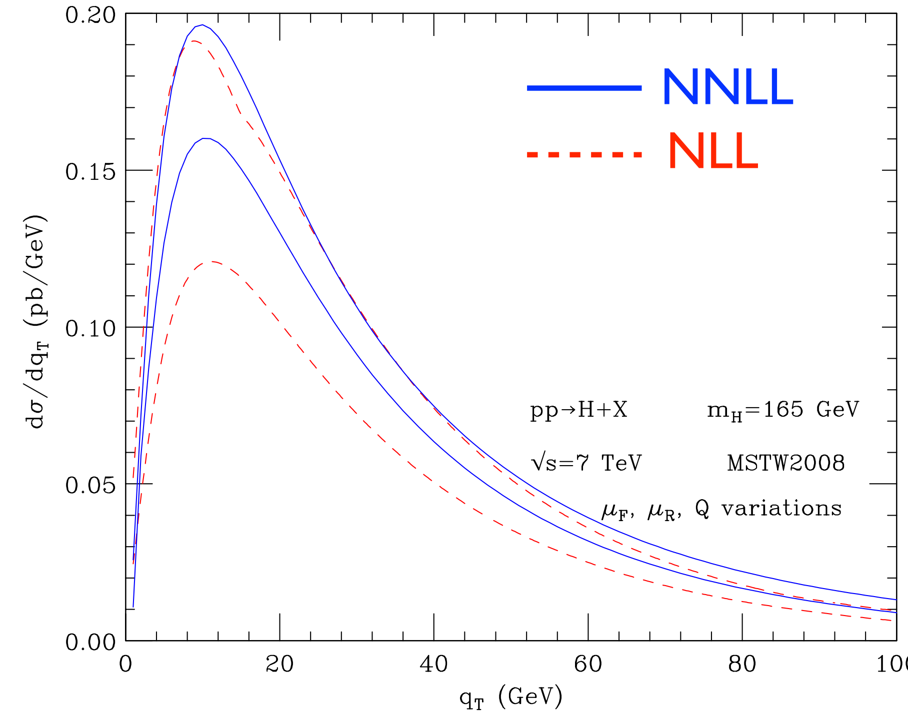
- ◉ Consistent study of perturbative uncertainties (scales)
- ◉ Full NNLL ($H^{(2)}$ coefficient)
- ◉ Matching with NLO transverse momentum distribution
- ◉ Integration over $\mathbf{q_T}$ provides exact NNLO total cross section

HqT 2.0

deF, Ferrera, Grazzini, Tommasini (2011)



Effect survives at q_T ~ 40 GeV

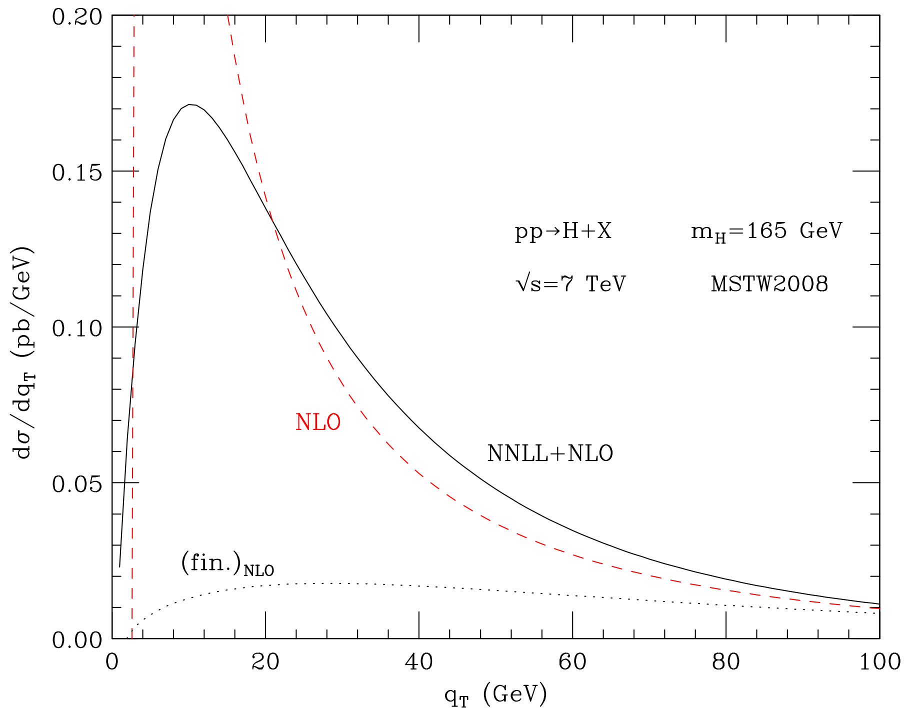


Good convergence

✓ Re-weight the spectrum of MC event generators (accurate to NLL)

HqT 2.0

deF, Ferrera, Grazzini, Tommasini (2011)



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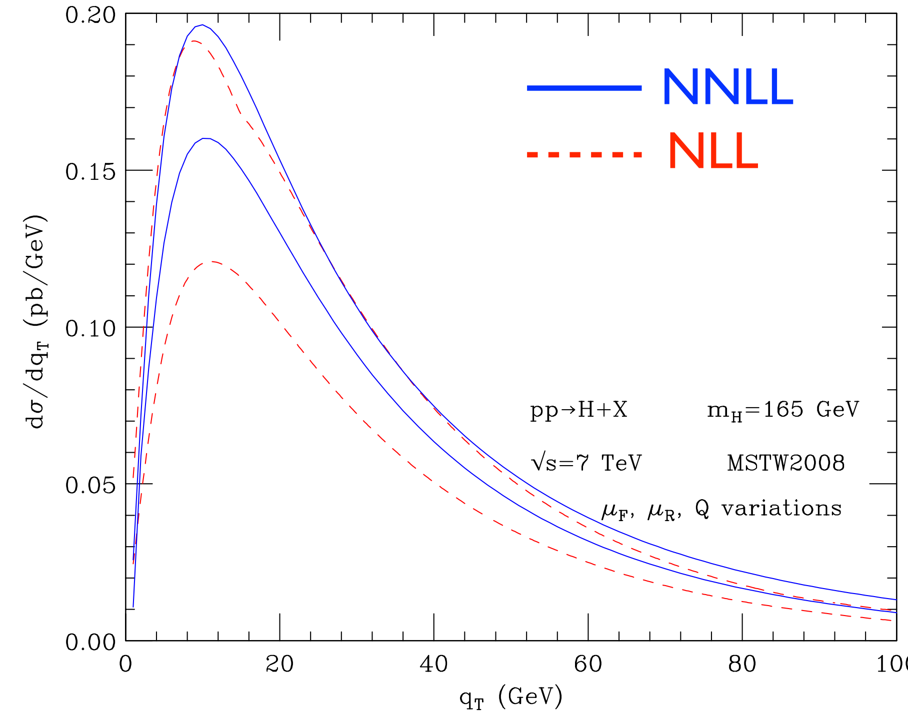

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HRes

deF, Ferrera, Grazzini, Tommasini (2012)

Include full description of Higgs decay products →

$\gamma\gamma$
$WW \to l\nu l\nu$
$ZZ \to 4l$

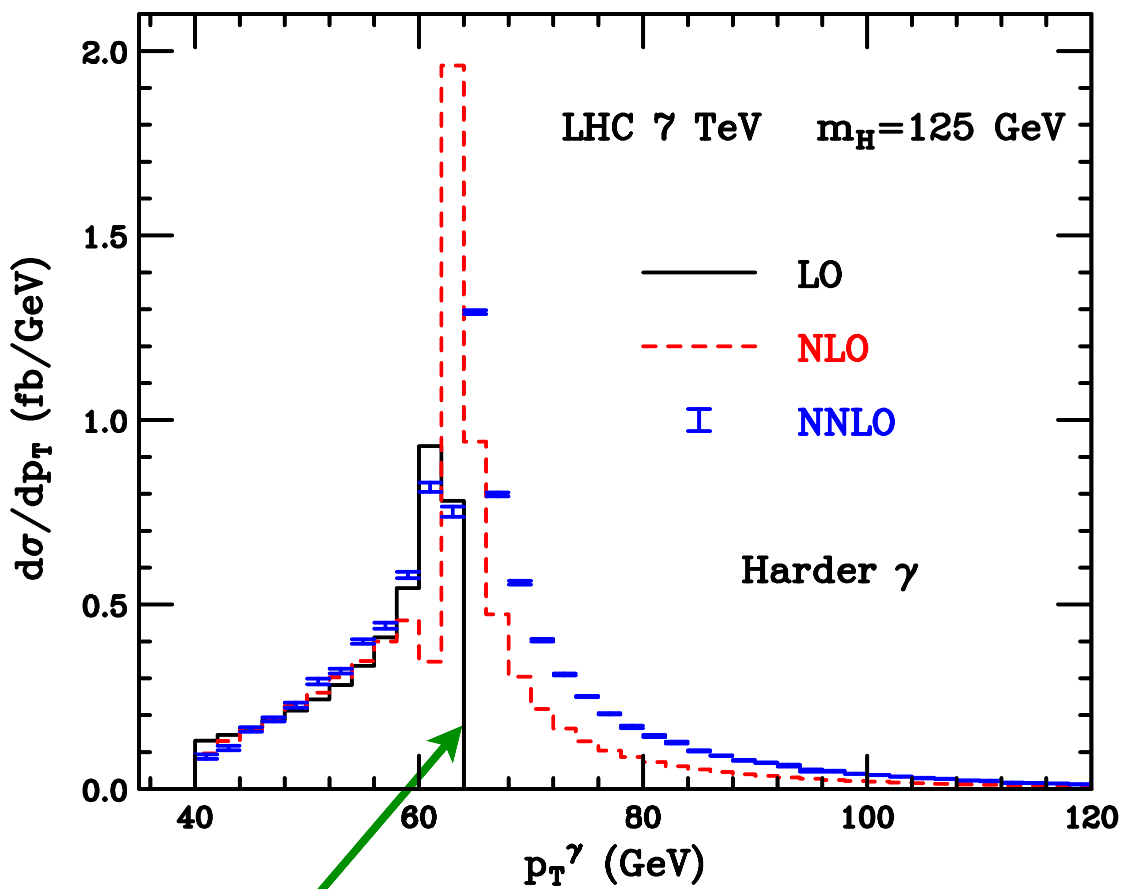
Effect from Higgs small transverse momentum propagates into more exclusive distributions

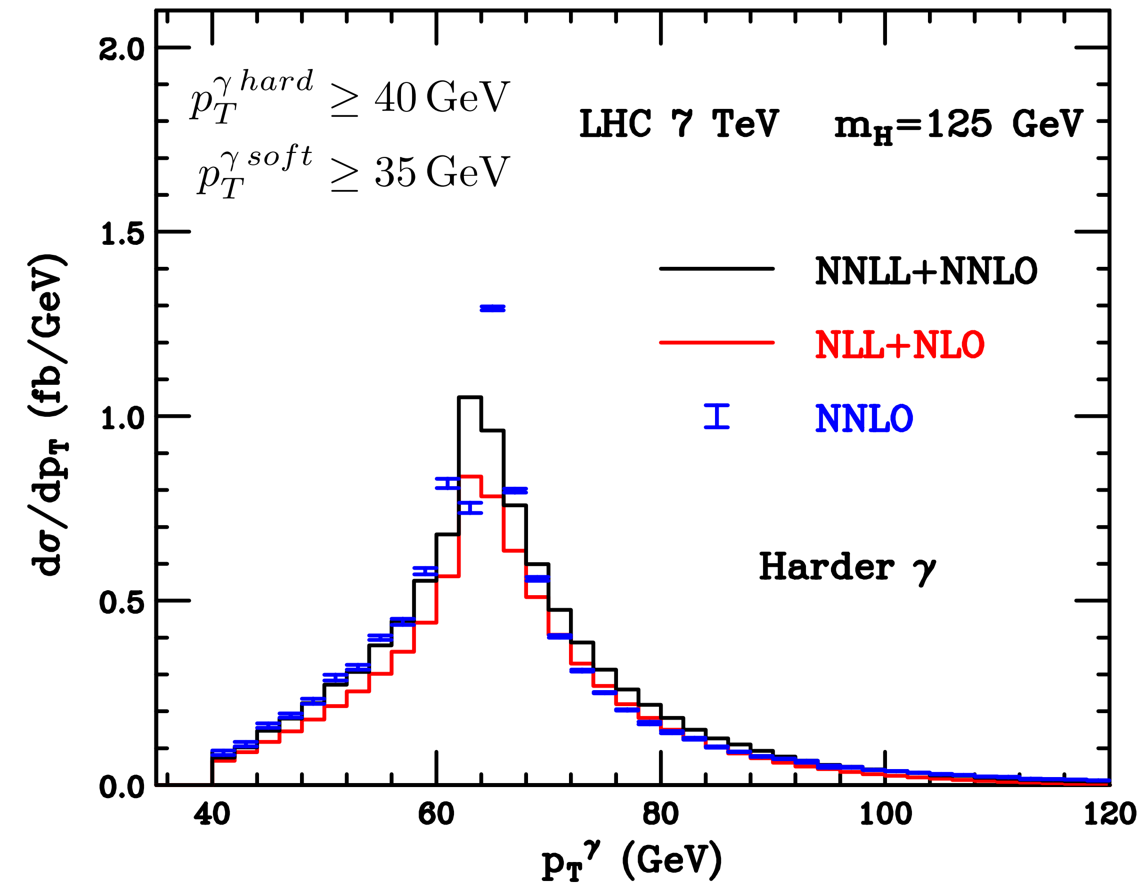
$gg \to H \to \gamma\gamma$ D.Tommasini PhD Thesis

At LO Higgs produced without transverse momentum

Photons back-to-back → kinematical boundary at $p_T^\gamma = \frac{M_H}{2}$

Higher order corrections suffer from perturbative instabilities near the Jacobian peak





Integrable logarithmic singularities
large bins to be reliable at fixed order

Catani, Webber

Resummed result smooth and stable
shape from NLL to NNLL

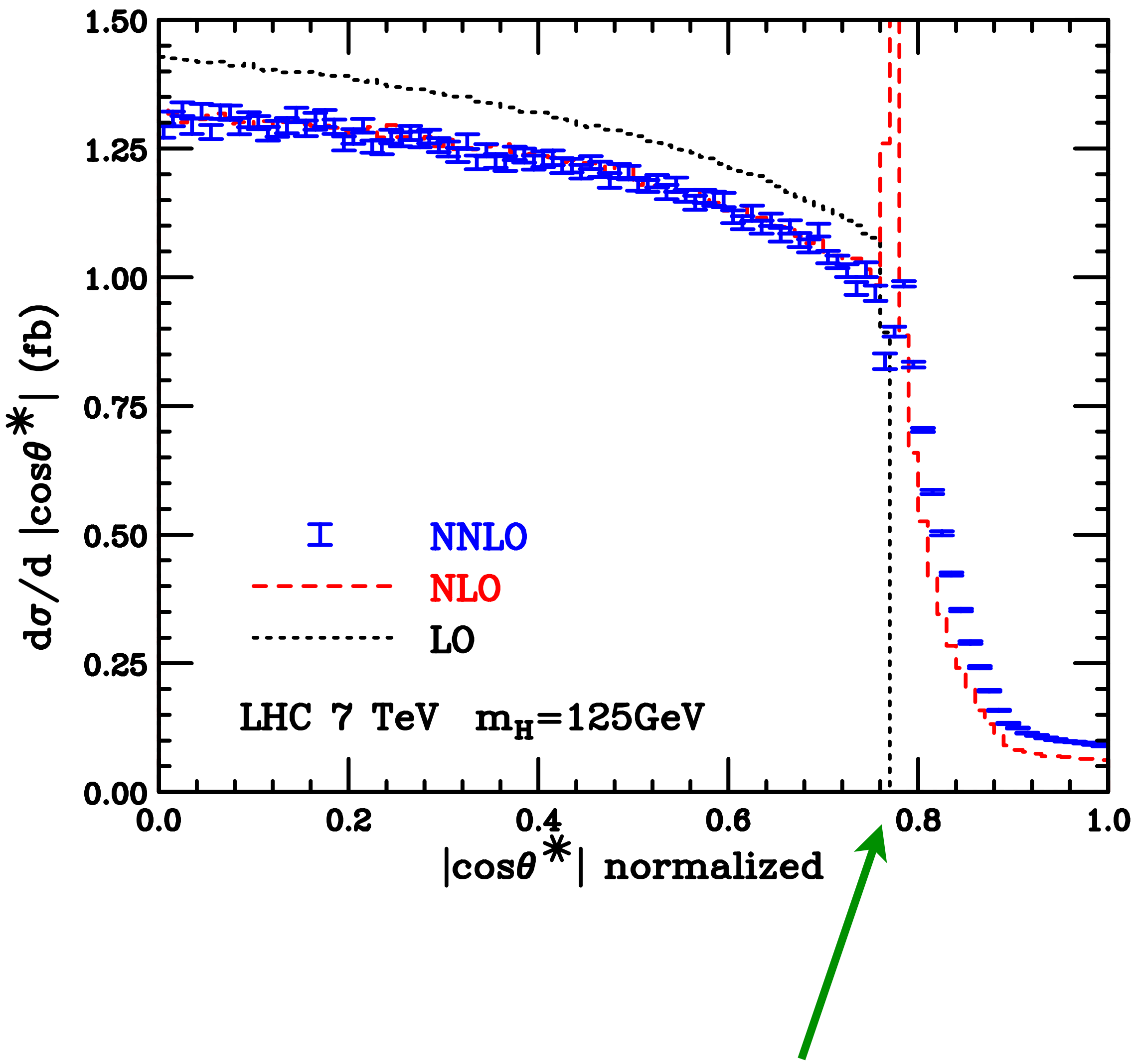
Away from the kinematical boundary recover fixed order result

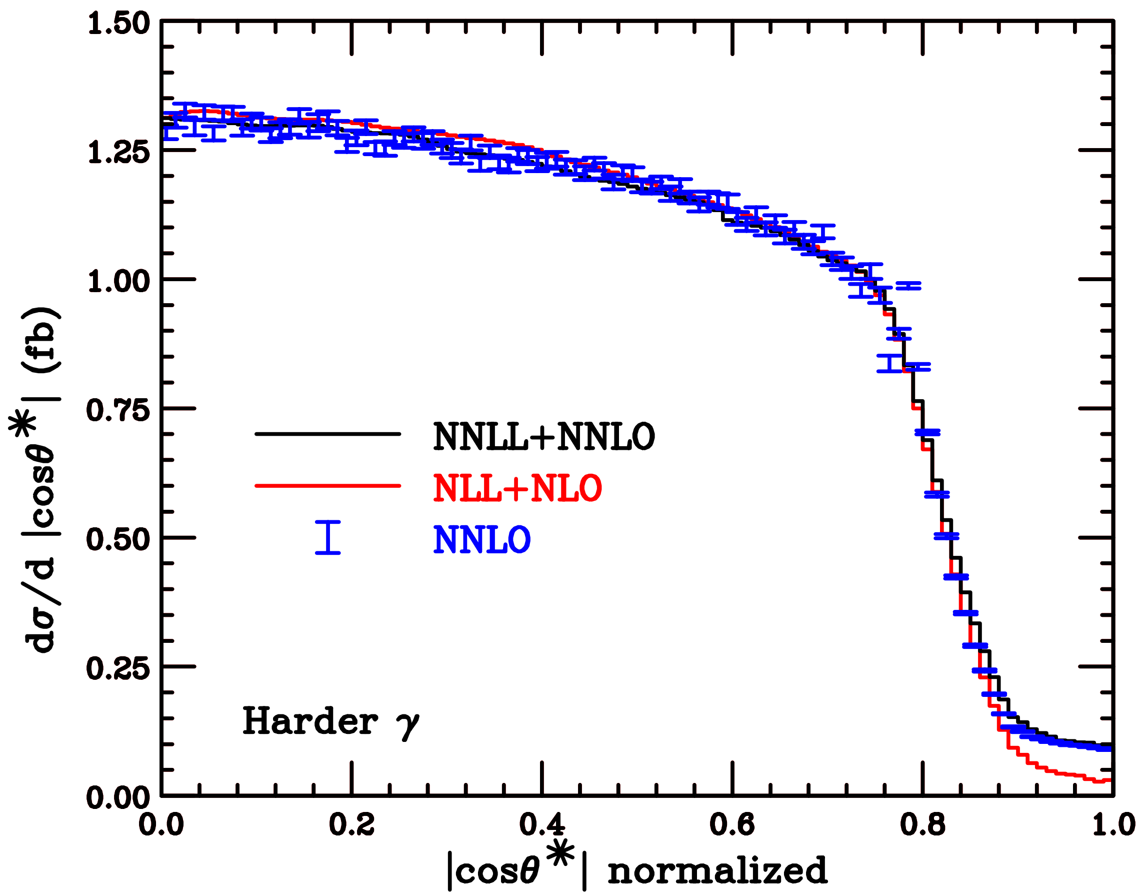
Another interesting distribution $|\cos\theta^*|$

polar angle of a photon in Higgs rest frame

at LO $|\cos\theta^*| = \sqrt{1 - \frac{4(p_T^\gamma)^2}{M_H^2}}$ → $|\cos\theta^*| \leq |\cos\theta^*_{cut}| \simeq 0.768$

$M_H = 125\,\text{GeV}$
$p_T^\gamma \geq 40\,\text{GeV}$





instabilities in the fixed order result

Smooth resummed results

Conclusions Signal

✓ NNLL $\mathbf{q_T}$ resummation exclusive on Higgs decay products

✓ Recovers full NNLO cross section after integration

✓ Sizable corrections if observable sensitive to small transverse momentum of Higgs → smooth results at edges of LO phase space

✓ Eliminate instabilities from fixed order calculations

✓ Do not modify observables when fixed order calculation is safe

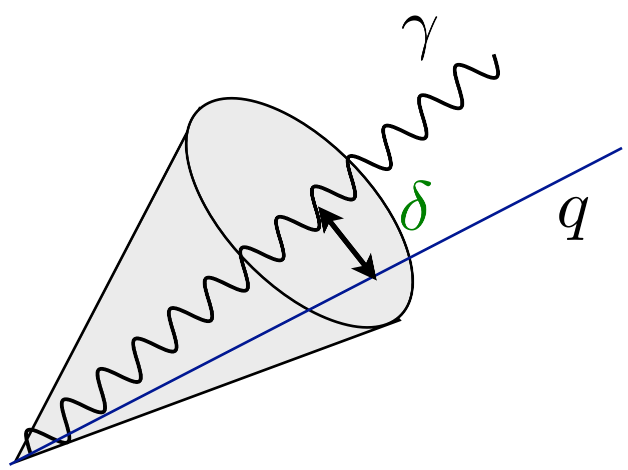
HRes

Backup Slides

Direct Contribution

Smooth Photon Isolation

S.Frixione



$$E_T^{had}(\delta) \le \chi(\delta) \text{ such that } \lim_{\delta \to 0} \chi(\delta) = 0$$

only soft emission allowed if collinear to photon

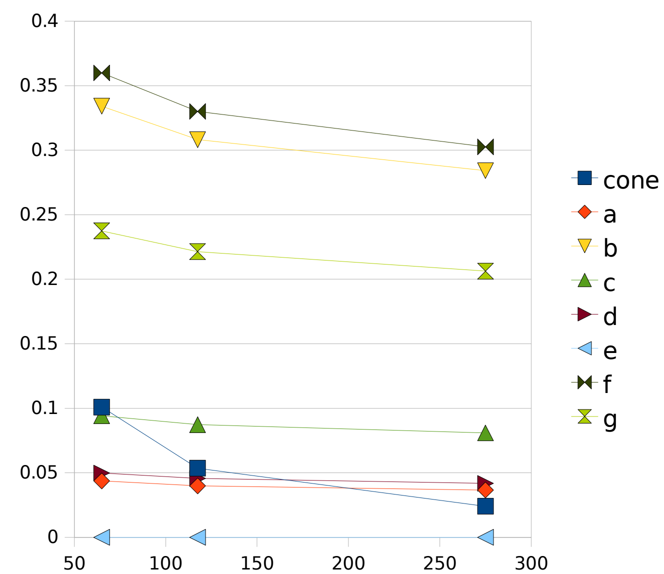
- no quark-photon collinear divergences
- no fragmentation component (only direct)
- Direct well defined by itself

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

$n = 1$
$\epsilon_\gamma = 0.5$
$R_0 = 0.4$

- Work on the discretized version $\epsilon_\gamma = 0.05$ practically eliminates frag. component

frag. fraction



Label	R0	E (GeV)	epsilon	n
a	0.4	4	0.05	0.2
b	0.4	4	1	0.2
c	0.4	4	1	1
d	0.4	4	0.5	1
e	0.4	4	0.05	1
f	0.4	4	1	0.1
g	0.4	4	1	0.5

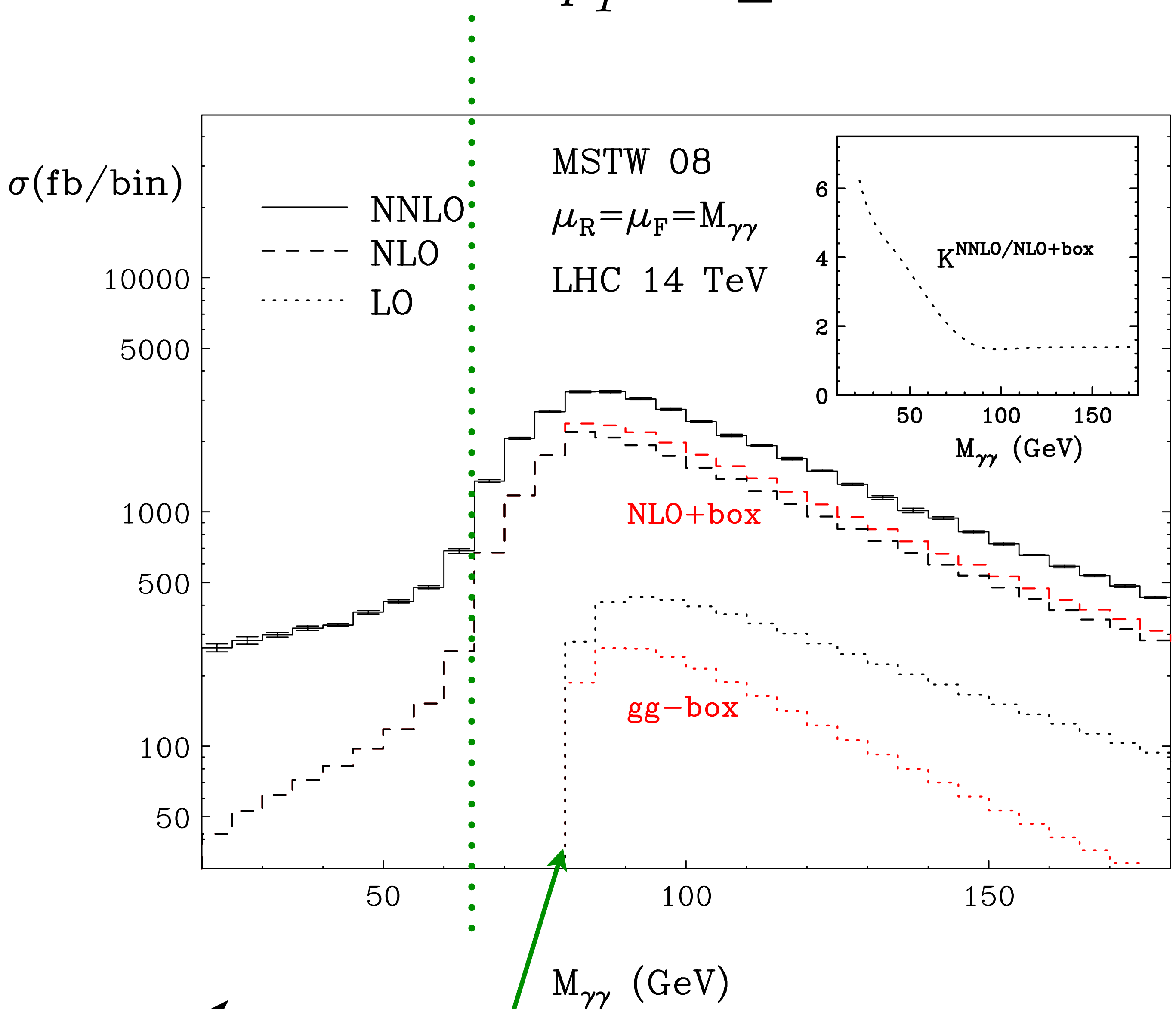
M. Stockton
Les Houches 11

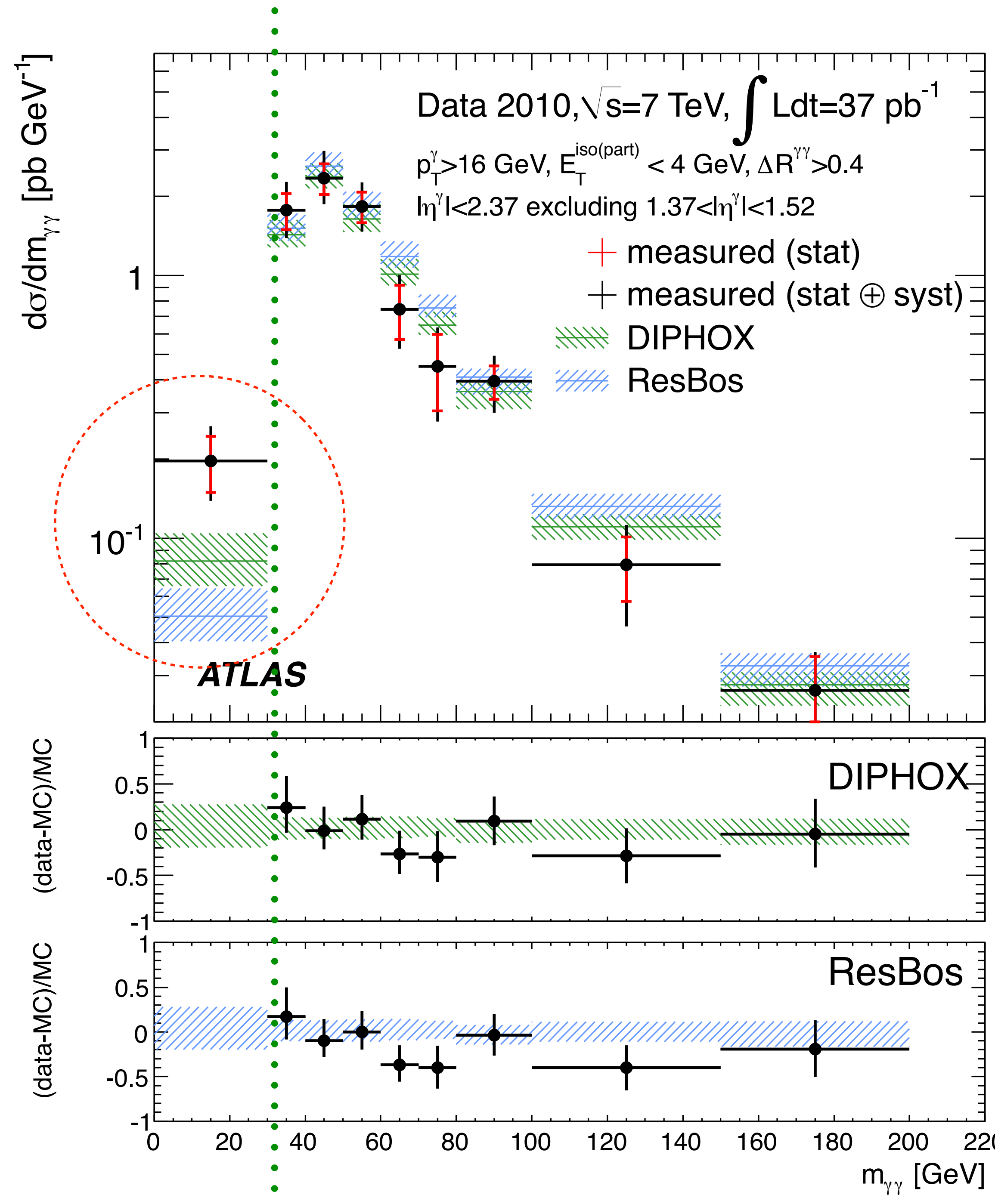
invariant mass below the LO threshold

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

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

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



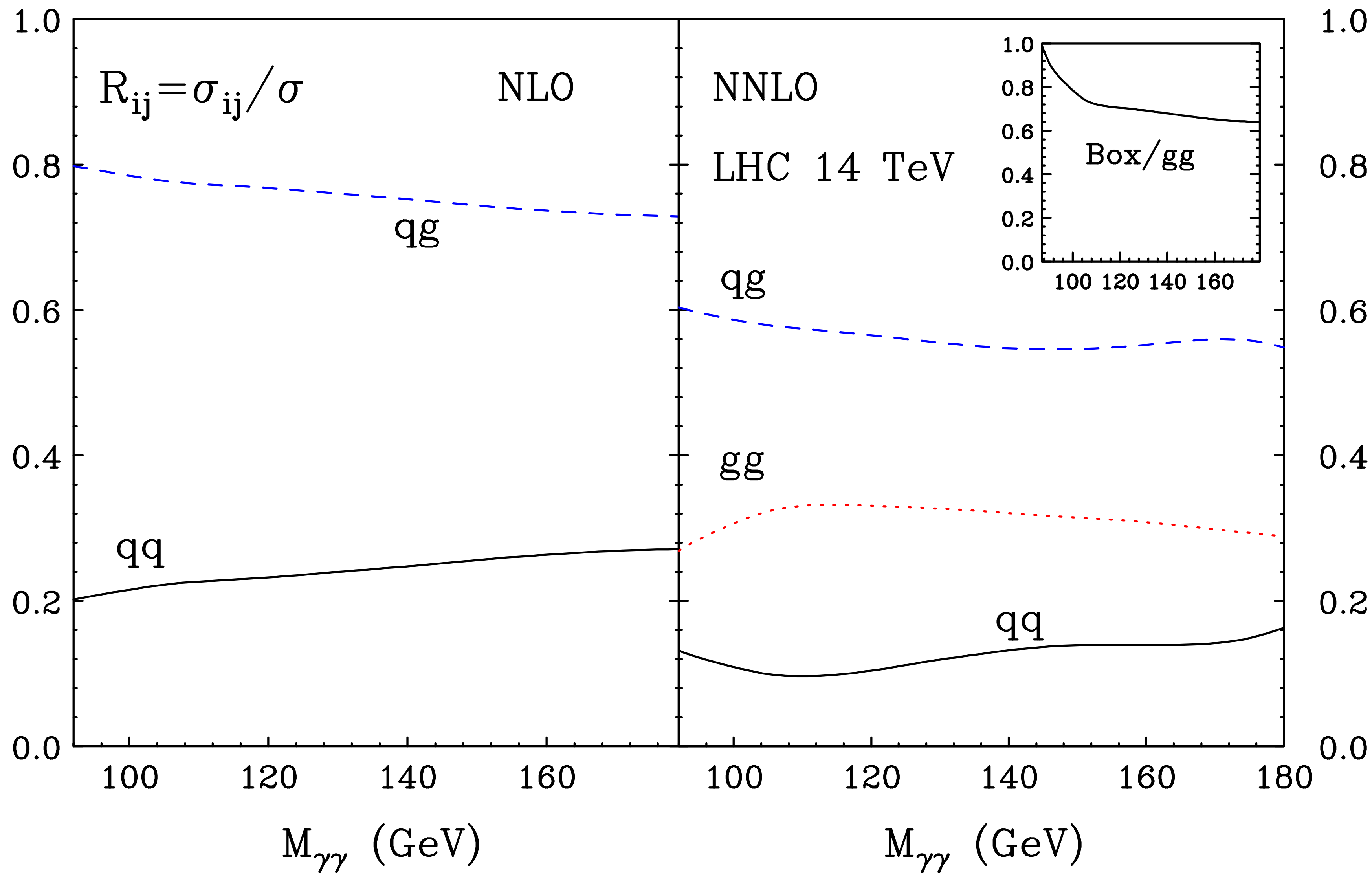


~ "collinear"

LO threshold at 80 GeV

"No back-to-back"

Channels



$R_{ij}=\sigma_{ij}/\sigma$
NLO
NNLO
LHC 14 TeV
qg
qg
gg
qq
qq
Box/gg
1.0
0.8
0.6
0.4
0.2
0.0
100
120
140
160
180
$M_{\gamma\gamma}$ (GeV)
$M_{\gamma\gamma}$ (GeV)

Comparing oranges to tangerines...

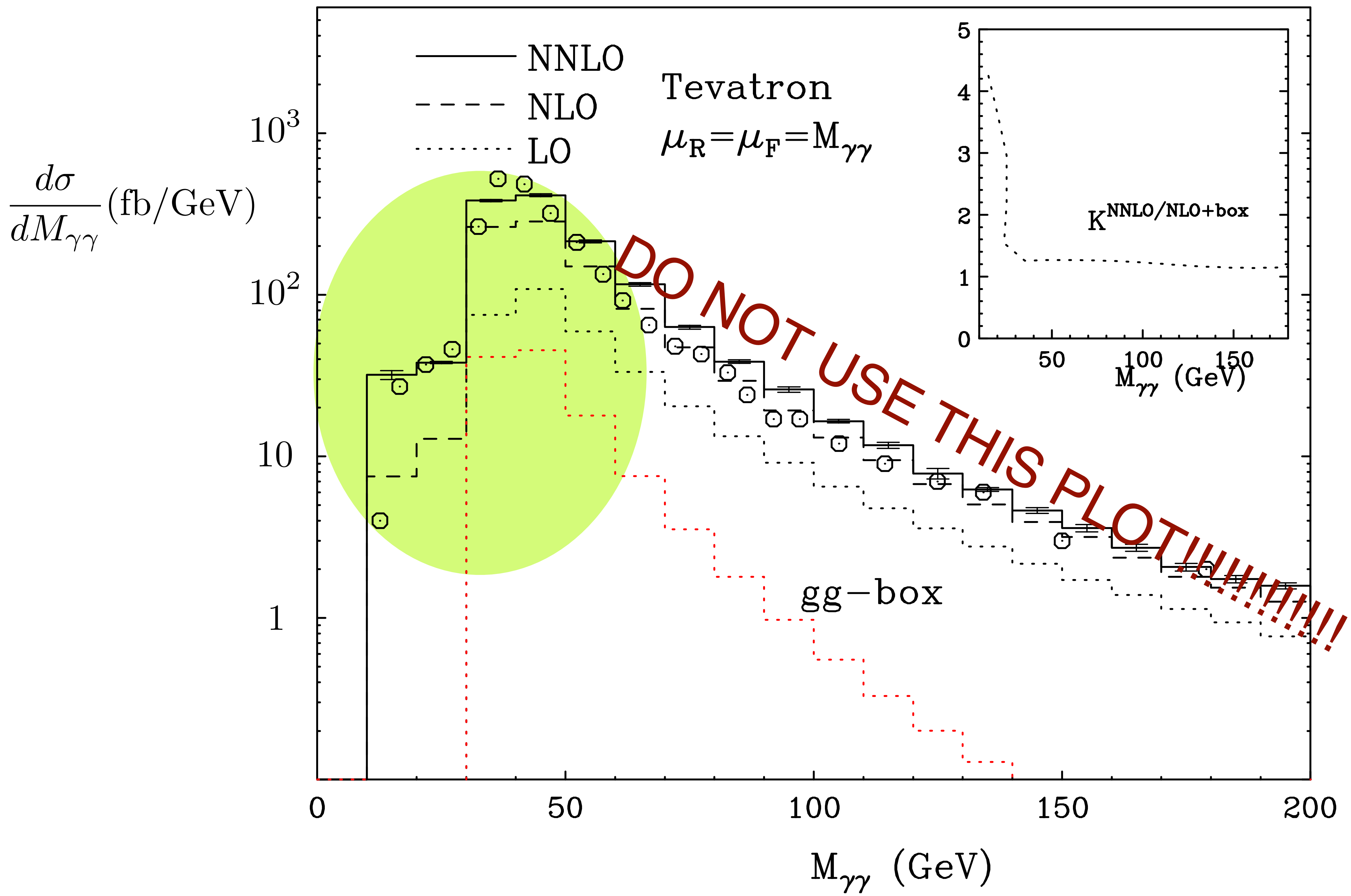
$|\eta^\gamma| \leq 1$

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

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

Tevatron data (CDF) with usual isolation

Theory with Frixione's isolation (not exactly same cuts)



Asymmetric cuts and pQCD

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

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

$R_{\gamma\gamma} > 0.45$

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

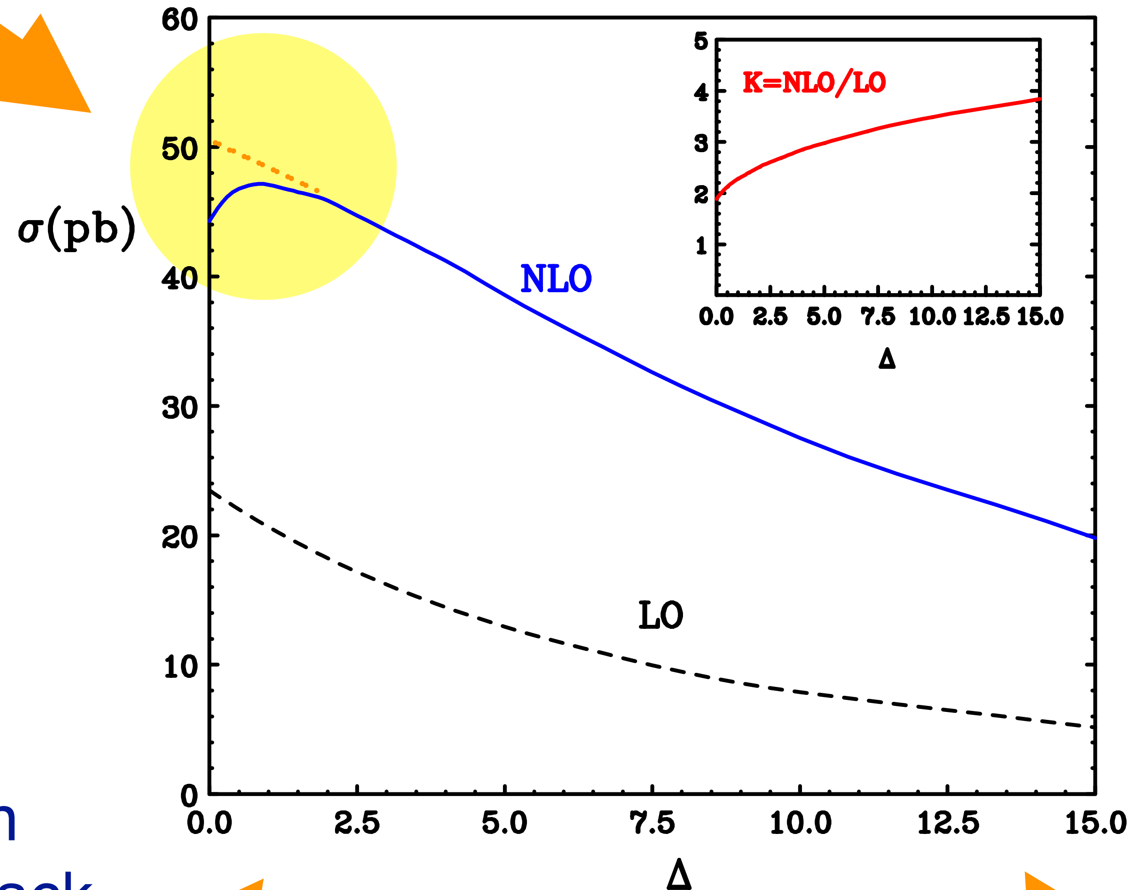
CTEQ6 NLO pdfs

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

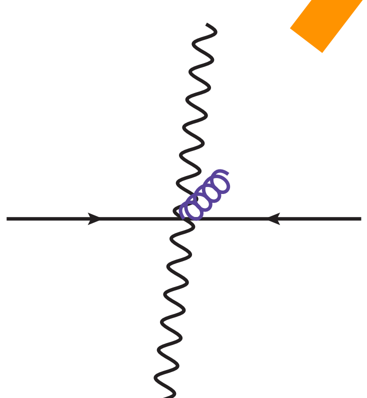
$p_T^{\gamma\, softer} \geq 20\,\mathrm{GeV}$

for jets: Frixione, Ridolfi (1997)

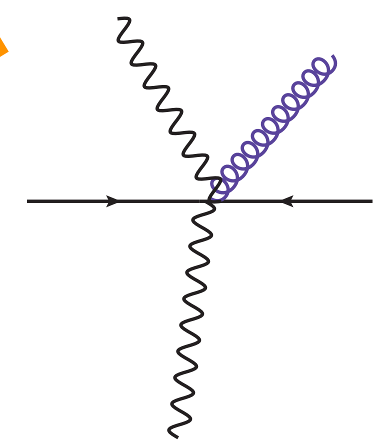
Fixed order calculation not reliable at small Δ



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



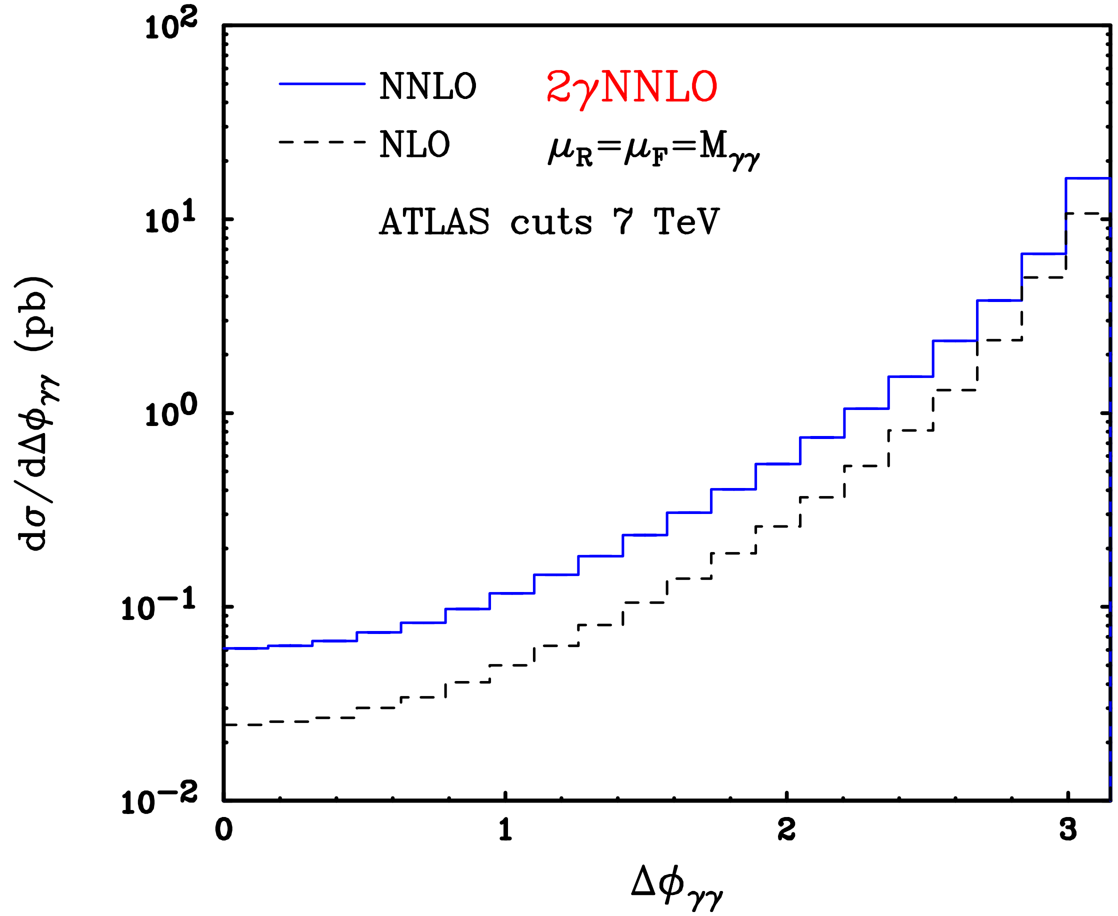
"Affected" by opening of phase space for "hard" radiation (not allowed at LO)

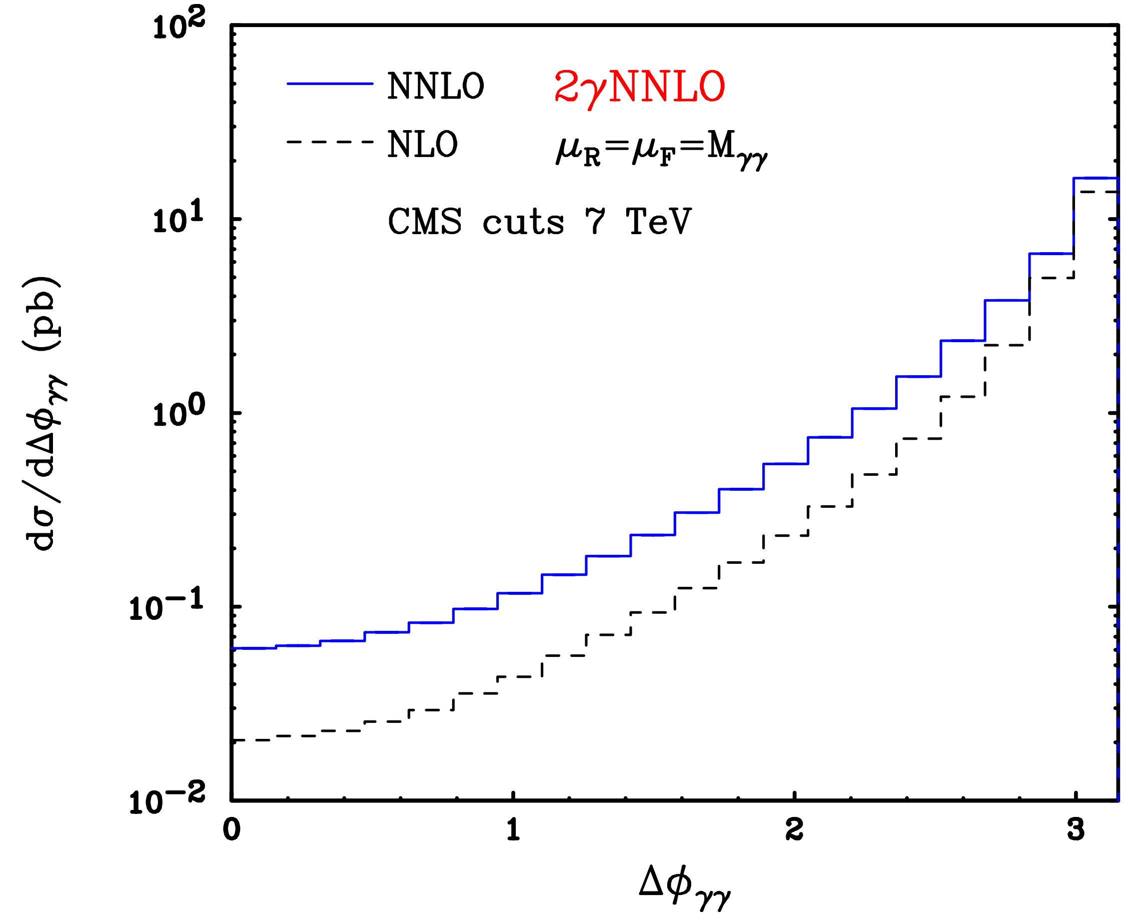


effectively LO away from back to back

damned if you do, damned if you don't

With Higgs search cuts at 7 TeV





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

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

$$|\eta^\gamma| \leq 2.37$$

excluding $1.37 \leq |\eta^\gamma| \leq 1.52$

$$\epsilon = 0.05$$

$$p_T^{\gamma\, hard} \geq 40\,\mathrm{GeV}$$
$$p_T^{\gamma\, soft} \geq 30\,\mathrm{GeV}$$

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

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

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

$$\epsilon = 0.05$$