The resummed Higgs qt spectrum

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Outline

- Why transverse momentum resummation?
- The qT resummation formalism
- The resummed Higgs qT spectrum
- The resummed qT spectrum for γγ production
- Summary

Why transverse momentum resummation?

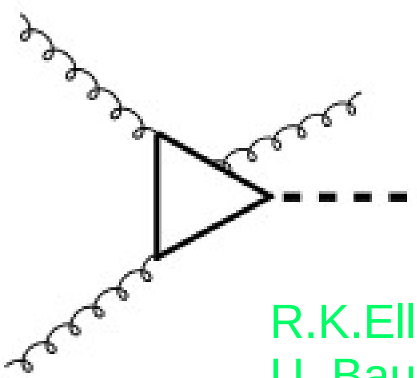
- The effects of the QCD radiation are encoded in the qT spectrum.
- Transverse momentum (qT) and rapidity identify the Higgs kinematics
- The fixed order can't describe the small qT region (qT<<M)
- In the small-qT region, where the bulk of events is produced, the convergence of the fixed-order expansion is spoiled, since the coefficients of the perturbative series in α_s are enhanced by powers of large logarithmic terms, $\ln^m(M^2/qT^2)$.

We have to distinguish two regions of transverse momenta

- $qT \sim M_H$

To have $qT \neq 0$ the Higgs boson has to recoil against at least one parton

NLO corrections are known only in the large m_{top} approximation (part of inclusive NNLO cross section !)



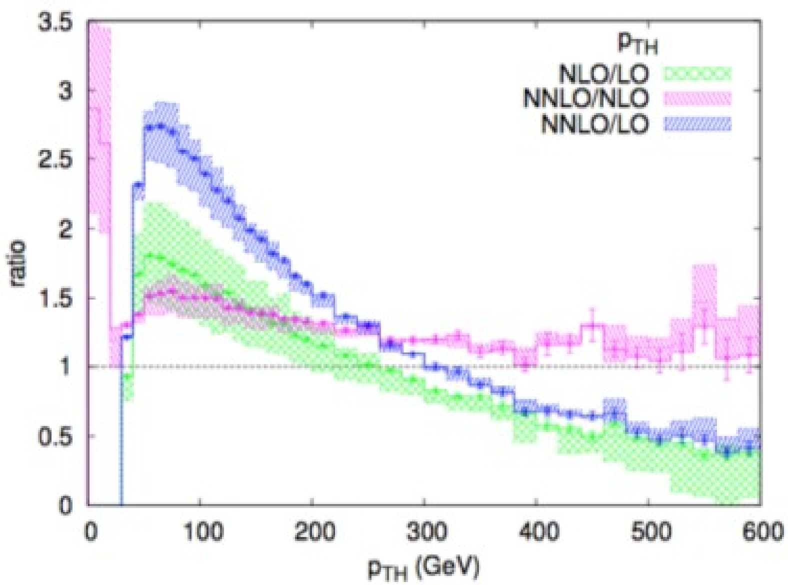
R.K.Ellis et al (1988);
U. Baur and E.W.N.Glover (1990)

D. de Florian, Z.Kunszt, MG (1999)
V.Ravindran, J.Smith, V.Van Neerven (2002)
C.Glosser, C.Schmidt (2002)

We have to distinguish two regions of transverse momenta

- $qT \sim M_H$

To have qT ≠ 0 the Higgs boson has to recoil against at least one parton



Recently NNLO (i.e. $O(\alpha_S^5)$) contribution from the gg channel has been evaluated

→ quantitative effect appears to be large

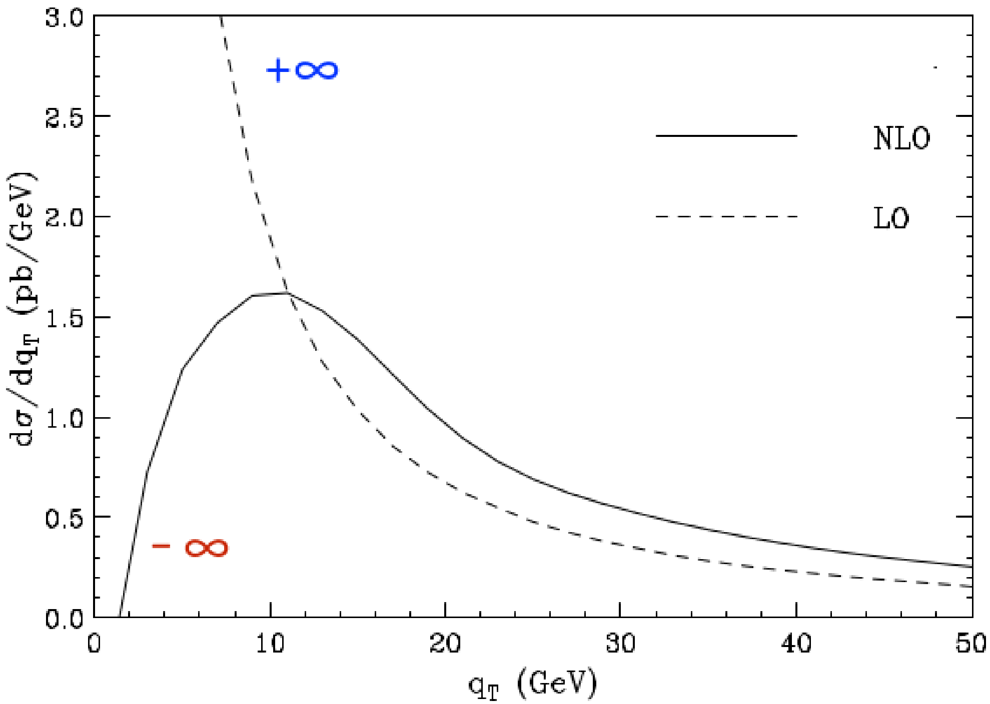
X. Chen, T. Gehrmann, E.W.N. Glover, M. Jaquier (2014)
(see also Boughezal, Caola, Petriello, Melnikov, Schulze (2013))

We have to distinguish two regions of transverse momenta

- $qT \ll M_H$

In this region large logarithmic corrections of the form $\alpha_s^m \ln^{2m}(M^2/qT^2)$ appear that originate from soft and collinear emission

- the perturbative expansion becomes not reliable



$$\text{LO:} \quad \frac{d\sigma}{dp_T} \to +\infty \quad \text{as } p_T \to 0$$

$$\text{NLO:} \quad \frac{d\sigma}{dp_T} \to -\infty \quad \text{as } p_T \to 0$$

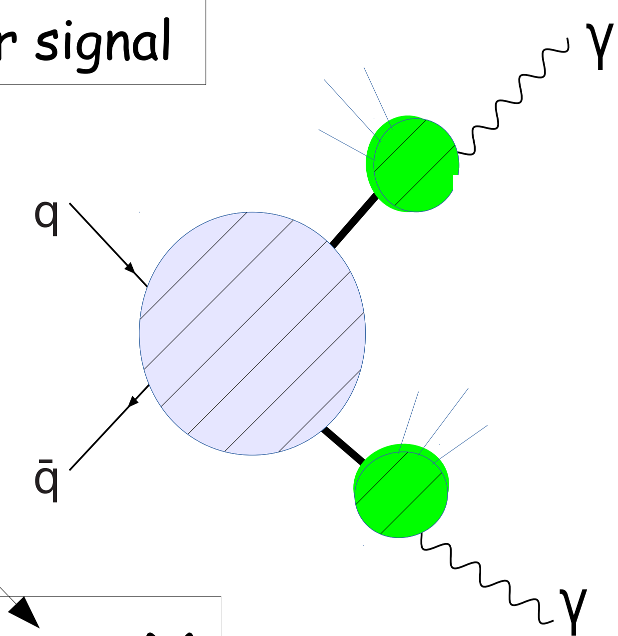
→ **Resummation Needed (effectively performed at leading log level by standard MC generators)**

Signal and background

Same perturbative features as for signal

$qT_{\gamma\gamma}$

$pp \to H + X \to \gamma\gamma + X$



$pp \to \gamma\gamma + X$

We need resummation for both

Main differences at small qT:

+) H → gg fusion

+) γγ → mostly $q\bar{q}$ and also gg

+) H peak position ~ 10 GeV

+) γγ peak position ~ 5 GeV

The qT resummation formalism

The qT resummation formalism for colorless final states

- Resummation in b-space was fully formalized by Collins, Soper and Sterman for the DY process by $q\bar{q}$ anihilation

- Process-independent universal generalization to generic colorless high-mass systems

  Catani, de Florian, Grazzini (2000)
  Bozzi, Catani, de Florian, Grazzini (2003)
  Catani-Grazzini (2010) (gg fusion sub-process)

- Universal resummation coefficients explicitly known at NLO/NLL level

  Kodaira, Trentadue (1981)
  Catani, d'Emilio, Trentadue (1988)

- And NNLO/NNLL

  Davies, Stirling, Webber (1985)
  De Florian, Grazzini (2000)
  Becher, Neubert (2010)
  Catani, Grazzini (2011) → H^2 (Higgs)
  Catani, LC, de Florian, Ferrera, Grazzini (2012) → H^2 (Higgs)
  Catani, LC, de Florian, Ferrera, Grazzini (2013) → H^2 (Univ)
  Gehrman, Lubbert, Yang (2012)

Our formalism

Catani, de Florian, Grazzini (2000)
Bozzi, Catani, de Florian, Grazzini (2005)
Catani, LC, de Florian, Ferrera, Grazzini (2013)

- Resummation performed in b-space → constraint of qT conservation

$$\frac{d\sigma_F}{dq_T^2}(q_T, M, s) = \frac{M^2}{s}\int_0^\infty db\,\frac{b}{2}\,J_0(bq_T)\,W^F(b, M, s) + \ldots$$

- $$W_N^F(b, M) = \sum_{a,b} \mathcal{W}^F_{ab,\,N}(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)\, f_{a/h_1,N}(\mu_F^2)\, f_{b/h_2,N}(\mu_F^2)$$

PDFs

- $$\frac{d\hat{\sigma}^{(\mathrm{res.})}_{F\,ab}}{dq_T^2}(q_T, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) =$$

$$\frac{M^2}{\hat{s}}\int_0^\infty db\,\frac{b}{2}\,J_0(bq_T)\,\mathcal{W}^F_{ab}(b, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)$$

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$$\mathcal{W}^{F}_{ab,\,N}(b,M;\alpha_S(\mu_R^2),\mu_R^2,\mu_F^2) = \sum_{\{I\}} \mathcal{H}^{\{I\},\,F}_{ab,\,N}\left(M,\alpha_S(\mu_R^2);M^2/\mu_R^2,M^2/\mu_F^2,M^2/Q^2\right)$$
$$\times \exp\{\mathcal{G}_{\{I\},\,N}(\alpha_S(\mu_R^2),L;M^2/\mu_R^2,M^2/Q^2)\} \;,$$

Free of large logarithmic terms (behaves as a constant in b → ∞, or qT → 0 limit).

Sudakov → includes all the large logarithmic terms in the large b limit (then small qT)

$$\mathcal{H}^F_N(M,\alpha_S;M^2/\mu_R^2,M^2/\mu_F^2,M^2/Q^2) = \sigma^{(0)}_F(\alpha_S,M)\Big[1+\frac{\alpha_S}{\pi}\,\mathcal{H}^{F\,(1)}_N(M^2/\mu_R^2,M^2/\mu_F^2,M^2/Q^2)$$
$$+\left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{F\,(2)}_N(M^2/\mu_R^2,M^2/\mu_F^2,M^2/Q^2)$$
$$+\sum_{n=3}^{+\infty}\left(\frac{\alpha_S}{\pi}\right)^n \mathcal{H}^{F\,(n)}_N(M^2/\mu_R^2,M^2/\mu_F^2,M^2/Q^2)\Big]$$

Process dependent

Universal

$$\mathcal{G}_N(\alpha_S(\mu_R^2),L;M^2/\mu_R^2,M^2/Q^2) = -\int_{b_0^2/b^2}^{Q^2}\frac{dq^2}{q^2}\left[A(\alpha_S(q^2))\,\ln\frac{M^2}{q^2}+\widetilde{B}_N(\alpha_S(q^2))\right]$$

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Bozzi, Catani, de Florian, Grazzini (2005)
Catani, LC, de Florian, Ferrera, Grazzini (2013)

$$\mathcal{G}_N(\alpha_S, L; M^2/\mu_R^2, M^2/Q^2) = L\, g^{(1)}(\alpha_S L) + g_N^{(2)}(\alpha_S L; M^2/\mu_R^2, M^2/Q^2) + \frac{\alpha_S}{\pi} g_N^{(3)}(\alpha_S L; M^2/\mu_R^2, M^2/Q^2) + \sum_{n=4}^{+\infty} \left(\frac{\alpha_S}{\pi}\right)^{n-2} g_N^{(n)}(\alpha_S L; M^2/\mu_R^2, M^2/Q^2)$$

LL: $L\, g^{(1)}$; NLL: $g_N^{(2)}$; NNLL: $g_N^{(3)}$

- With $L = \ln(1 + Q^2 b^2/b_0^2)$ and $\alpha_s = \alpha_s(\mu_R)$; $\mu_R \sim O(M)$

Resummation scale $Q \sim O(M)$

- $O(\alpha_s L) \sim 1 \rightarrow$ LL $\sim \alpha_s^n L^{n+1}$ and NLL $\sim \alpha_s^n L^n$ $\rightarrow$ NLL/LL $\sim O(\alpha_s)$
- The form factor takes the same form as in threshold resummation
- Unitarity constraint enforces correct total cross section

Our formalism

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Bozzi, Catani, de Florian, Grazzini (2005)
Catani, LC, de Florian, Ferrera, Grazzini (2013)

- $L \sim \ln(Q^2 b^2/b_0^2)$; $b\,Q \gg 1$ (large log)

  $L \ll 1$; $b\,Q \ll 1$ (small corrections)

  In particular : $L \to 0$ if $b \to 0$ (total cross section)

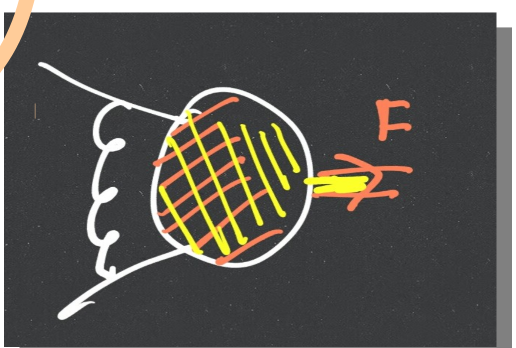
- Unitarity constraint → the integral over qT of the transverse momentum distribution gives the total Xsection

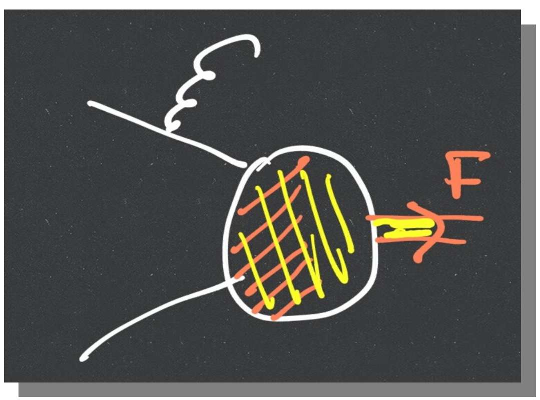
- $$\int_0^\infty dq_T^2\, \frac{d\hat{\sigma}_F^{(\mathrm{res.})}}{dq_T^2}(q_T, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2, Q^2) = \frac{M^2}{\hat{s}}\, \mathcal{H}^F\left(M, \hat{s}, \alpha_S(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2\right) ,$$

- $$\frac{d\hat{\sigma}_{F\,ab}}{dq_T^2} = \frac{d\hat{\sigma}_{F\,ab}^{(\mathrm{res.})}}{dq_T^2} + \frac{d\hat{\sigma}_{F\,ab}^{(\mathrm{fin.})}}{dq_T^2}$$

Real corrections + CT

H^F (virtuals)





Our formalism

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- The calculation can be done:
  - NLL+NLO: we need the functions $g^{(1)}$, $g_N^{(2)}$ and the coefficient $\mathcal{H}_N^{(1)}$ plus the matching at relative order α_S
  - NNLL+NNLO: we also need the function $g_N^{(3)}$ and the coefficient $\mathcal{H}_N^{(2)}$ plus the matching at relative order α_S^2

Our formalism

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- $$\frac{d\hat{\sigma}_{F\,ab}}{dq_T^2} = \frac{d\hat{\sigma}_{F\,ab}^{(\mathrm{res.})}}{dq_T^2} + \frac{d\hat{\sigma}_{F\,ab}^{(\mathrm{fin.})}}{dq_T^2}$$

- The formalism was applied at NNLL+NNLO to:

ZZ, WW, γγ, H, DY

Catani, de Florian, Ferrera,Grazzini (2015);
Bozzi, Catani, de Florian, Ferrera Grazzini (2011);
LC, Coradeschi, de Florian (2015);
de Florian, Ferrera, Tommasini, Grazzini (2011);
Grazzini, Kallweit, Rathlev, Wiesemann (2015).

Our formalism

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- $$\frac{d\hat{\sigma}_{F\,ab}}{dq_T^2} = \frac{d\hat{\sigma}_{F\,ab}^{(\mathrm{res.})}}{dq_T^2} + \frac{d\hat{\sigma}_{F\,ab}^{(\mathrm{fin.})}}{dq_T^2}$$

- Recently all-order extension of the formalism for $t\bar{t}$:

First all-order formulation of qT resummation for final states with color

Zhu, Li, Li, Shao; Yang (2012)
Zhu, Li, Li, Shao; Yang (2013)
Catani, Grazzini, Torre (2013)

The resummed Higgs qT spectrum

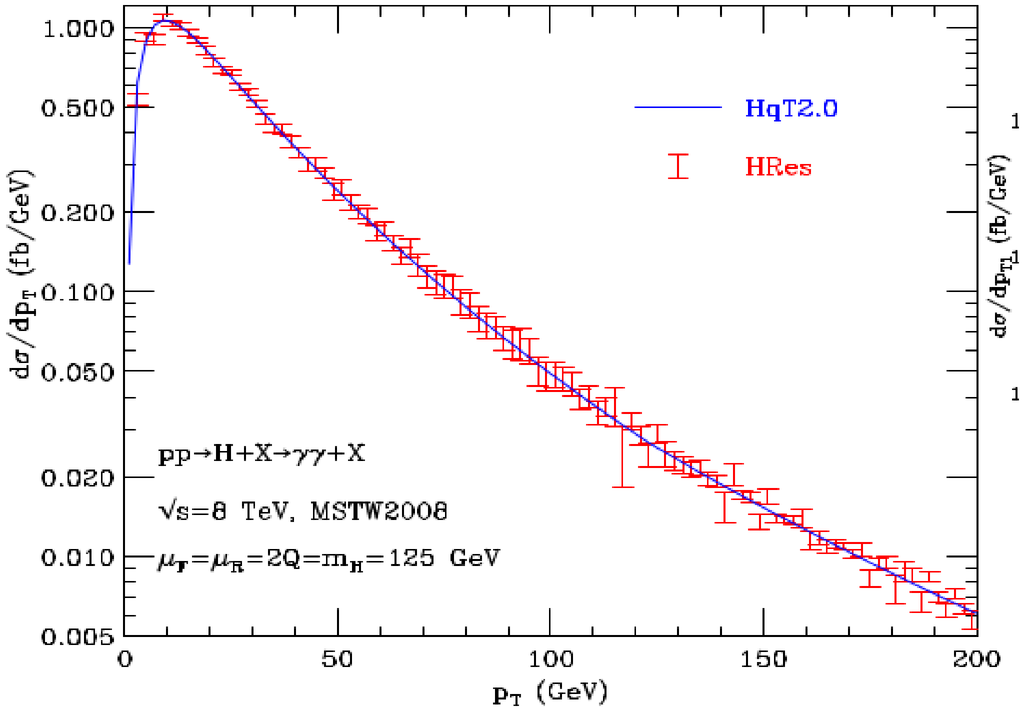
Higgs boson → HRes

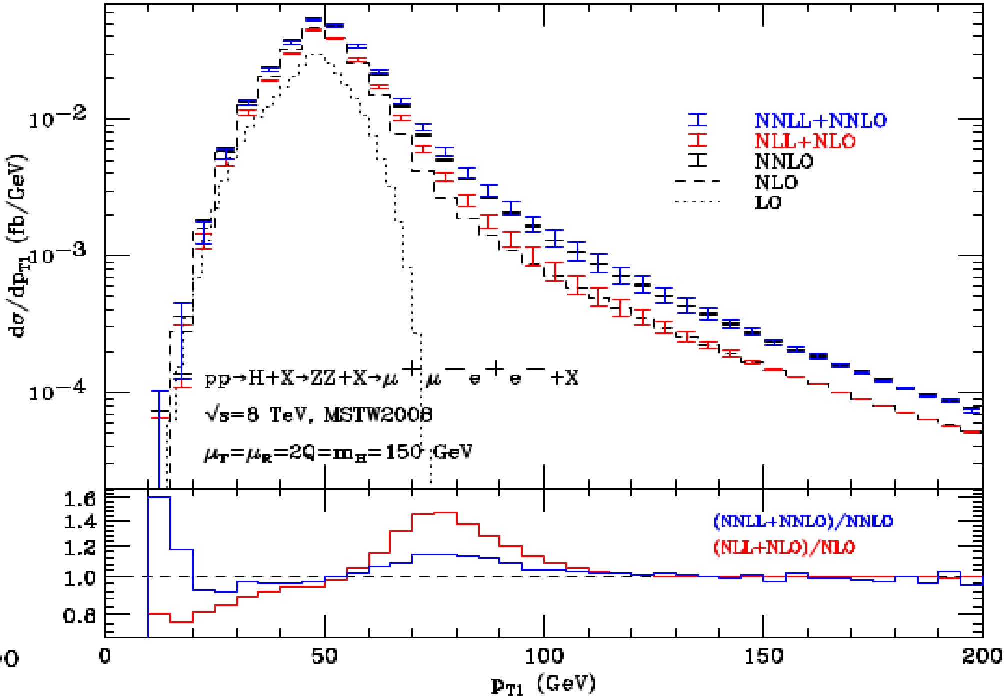
D. de Florian, G.Ferrera, D. Tommasini, M.Grazzini (2011)

- HRes combines the NNLO calculation in HNNLO with the small-qT resummation as implemented in HqT → "Higgs event generator"

  Bozzi, Catani, de Florian, Grazzini (2003)(2005)

It includes the decay H→γγ, H→WW→lνlν, H→ZZ→4l





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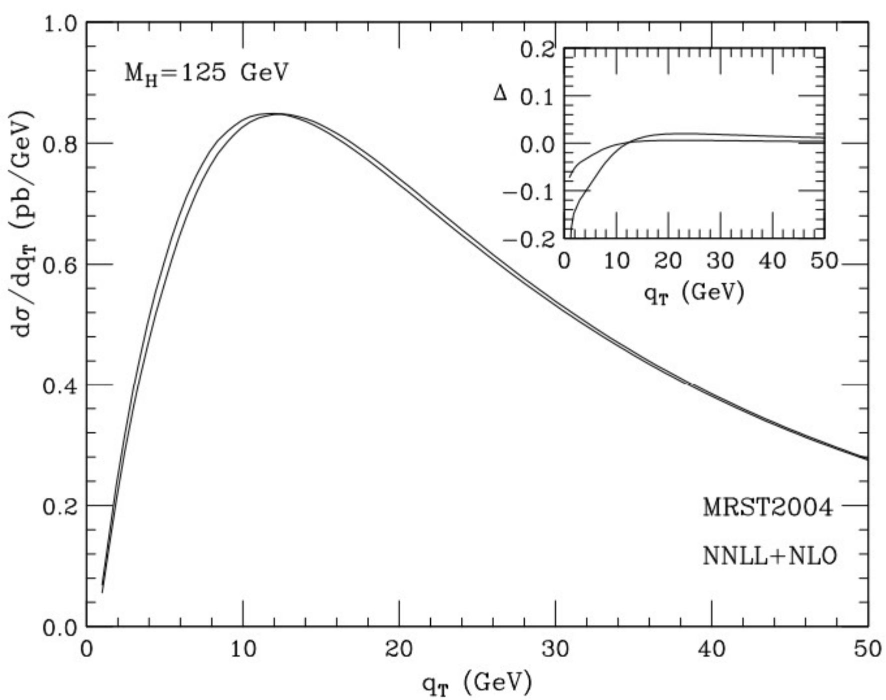
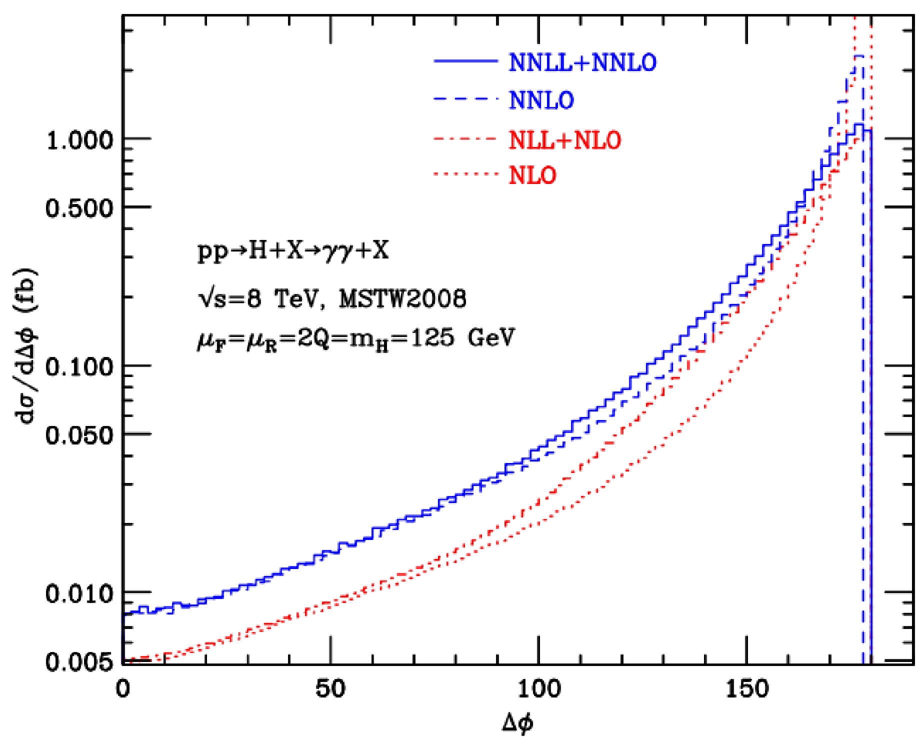


The upper (lower) curve at small q_T is obtained with $g_{NP} = 1.67\ \mathrm{GeV}^2$ ($g_{NP} = 5.64\ \mathrm{GeV}^2$)



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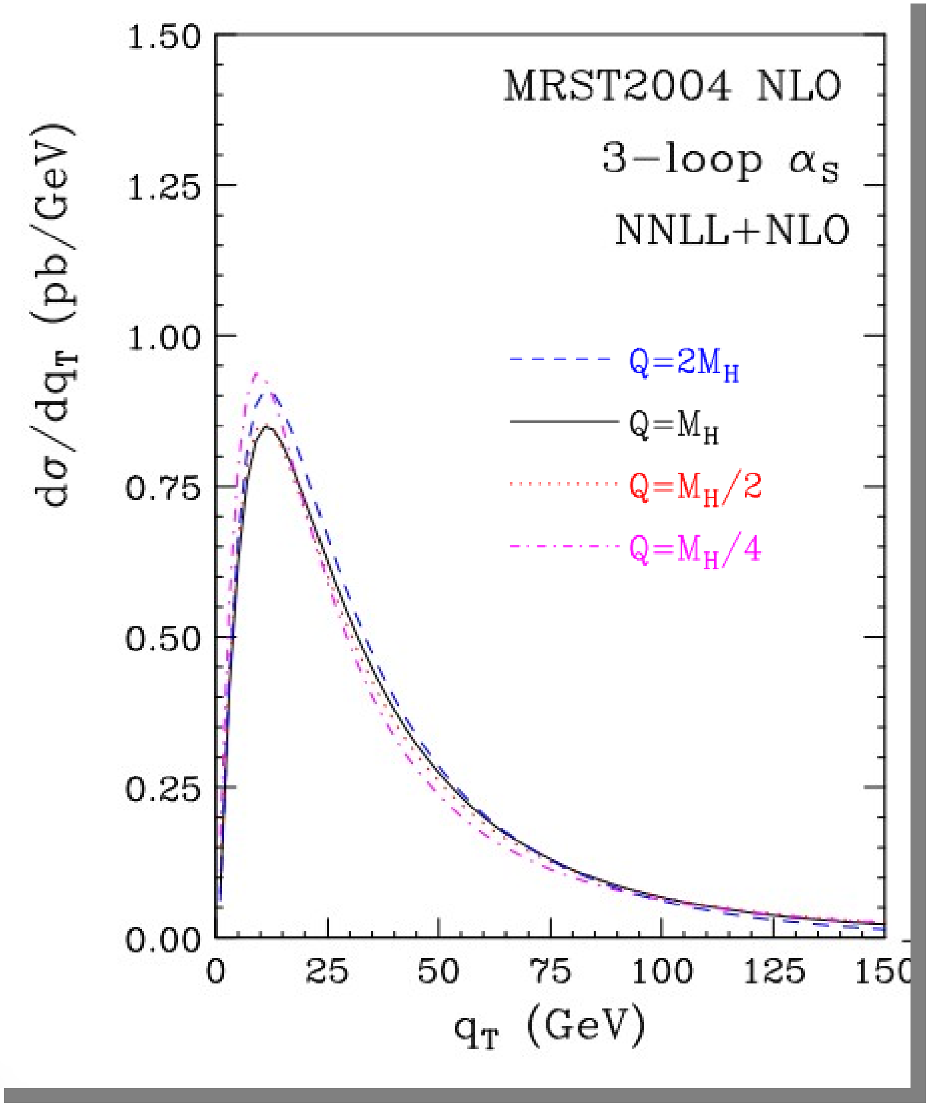
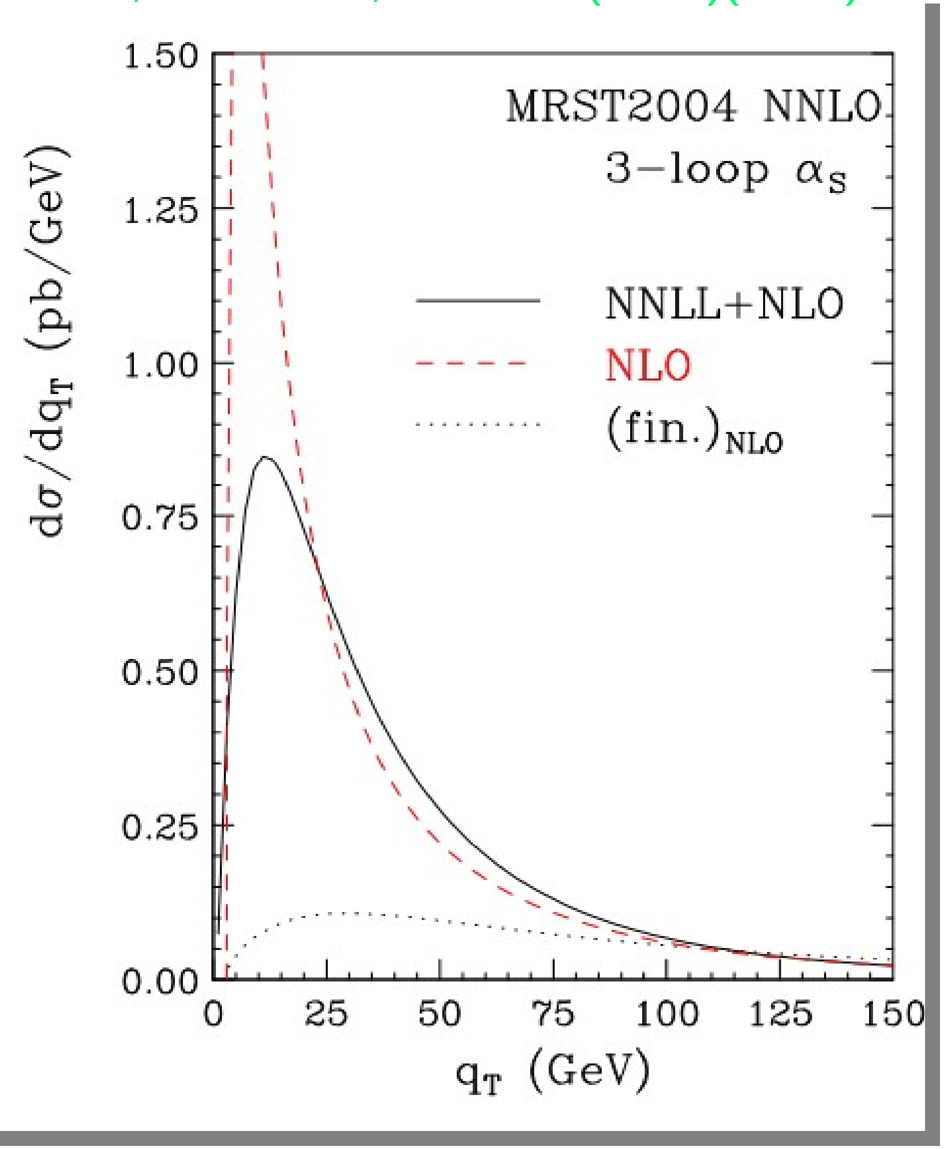
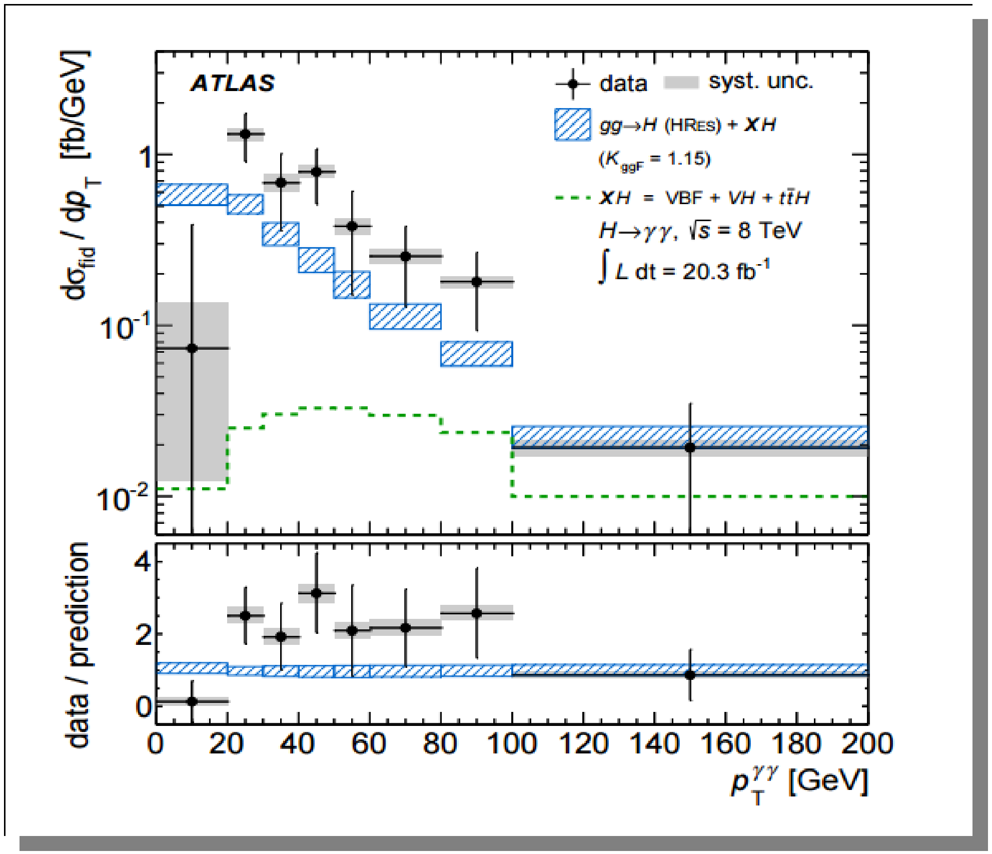
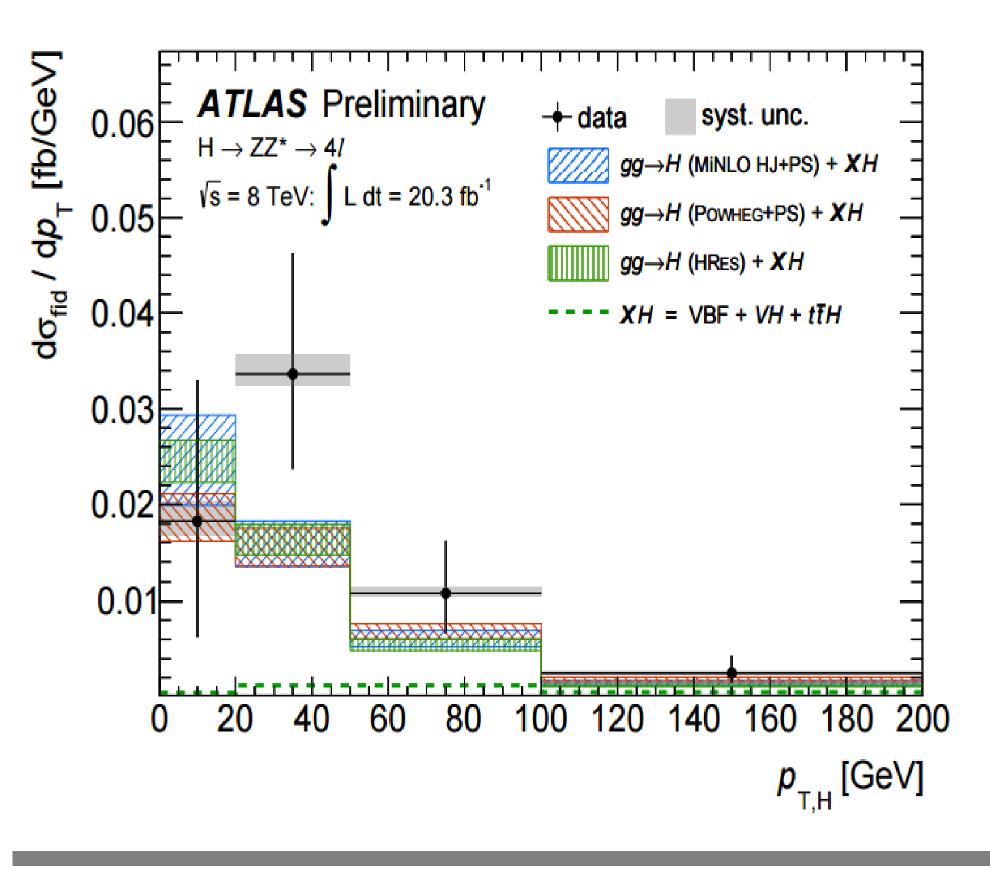




The first data



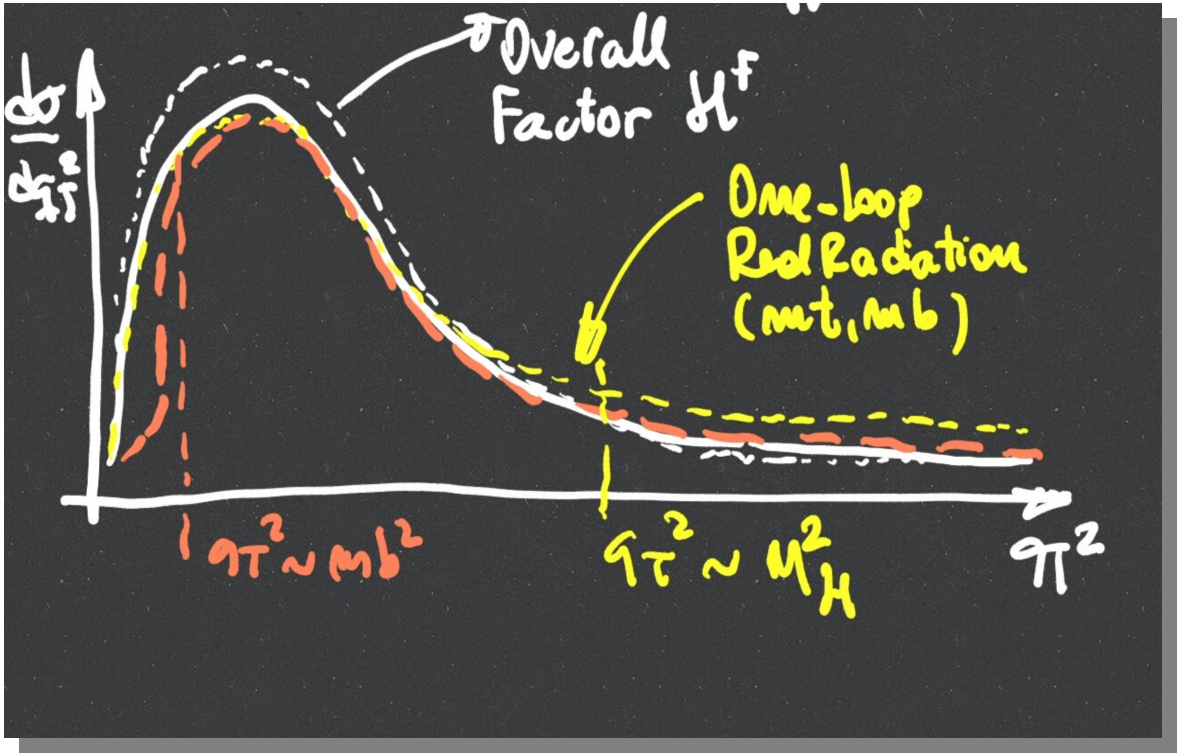
JHEP 1409 (2014) 112

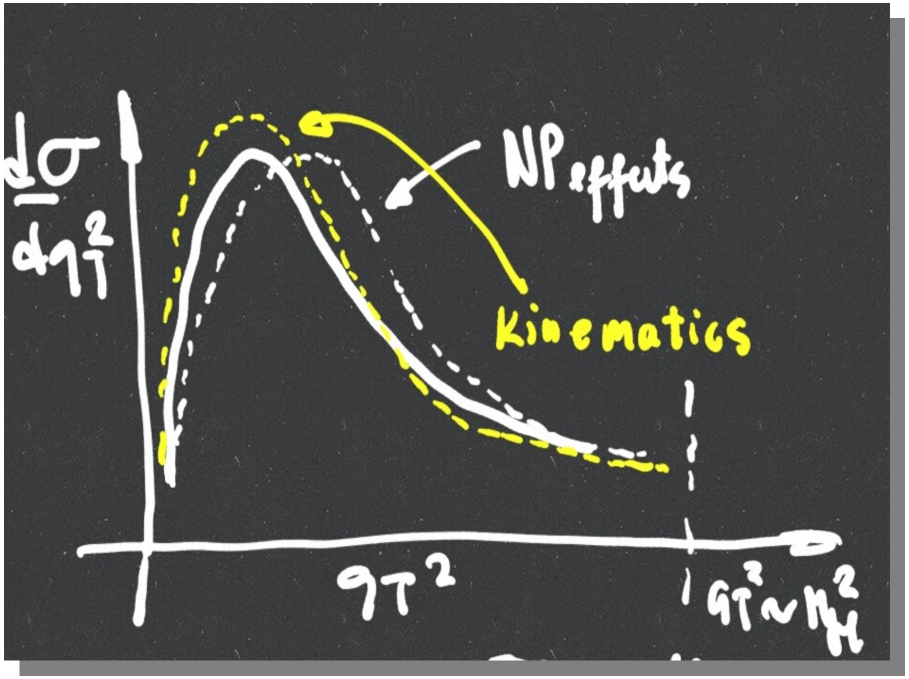


ATLAS-CONF-2014-044

ATLAS data seem to suggest a harder spectrum (but still very large uncertainties !)

Sketchy form of contributions



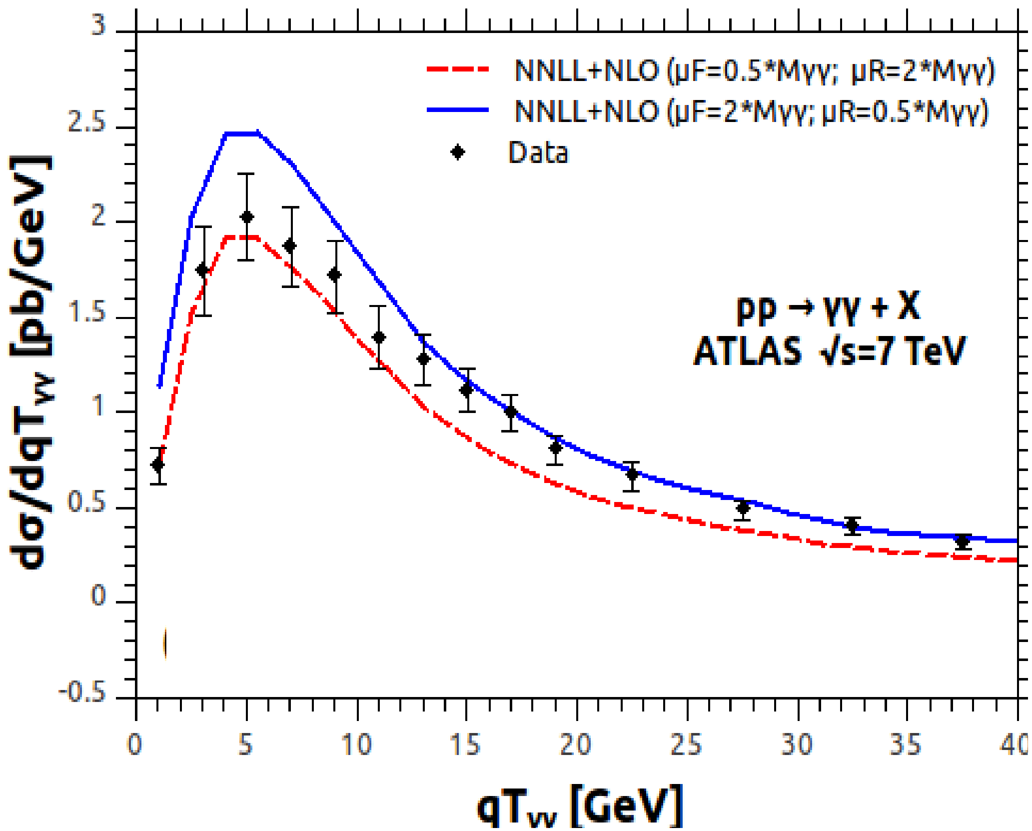


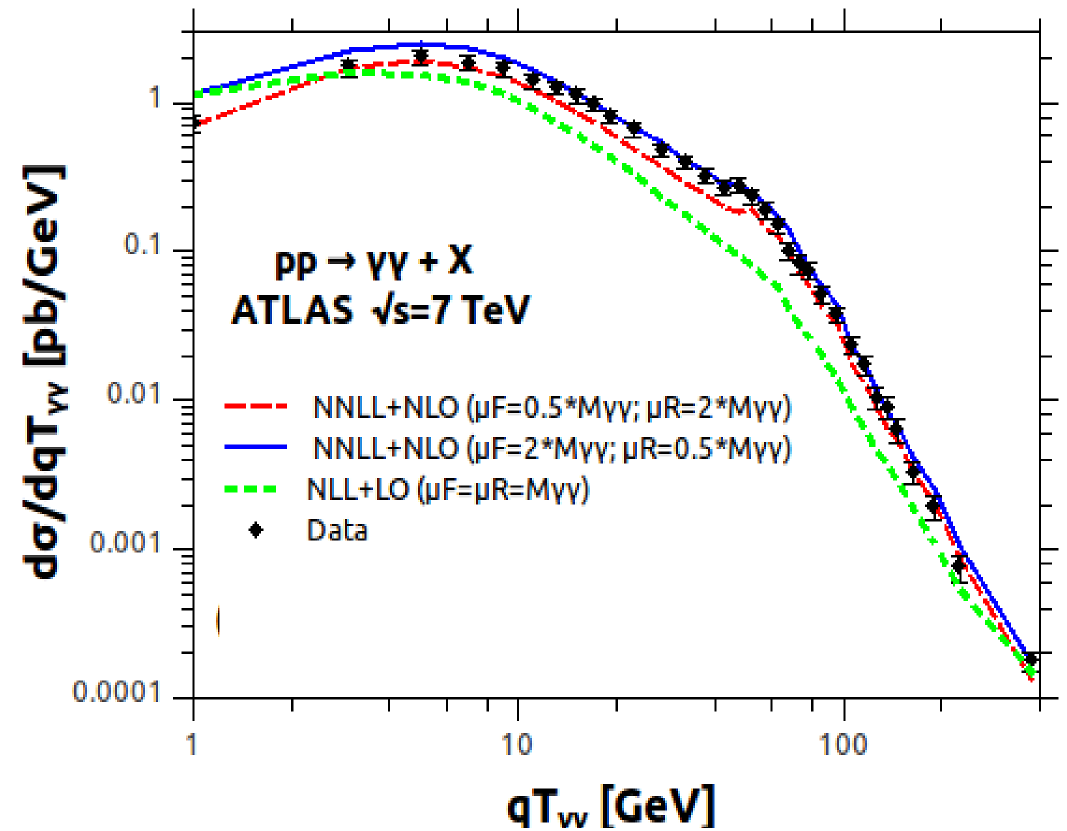
The resummed q_T spectrum for $\gamma\gamma$ production

Resummation → ATLAS γγ – (2γRes)

LC, Coradeschi, de Florian

First results!





$$S^a_{NP} = \exp(-C_a\, g_{NP}\, b^2)$$

$a = F$ for $q\bar{q}$ and $a = A$ for gg

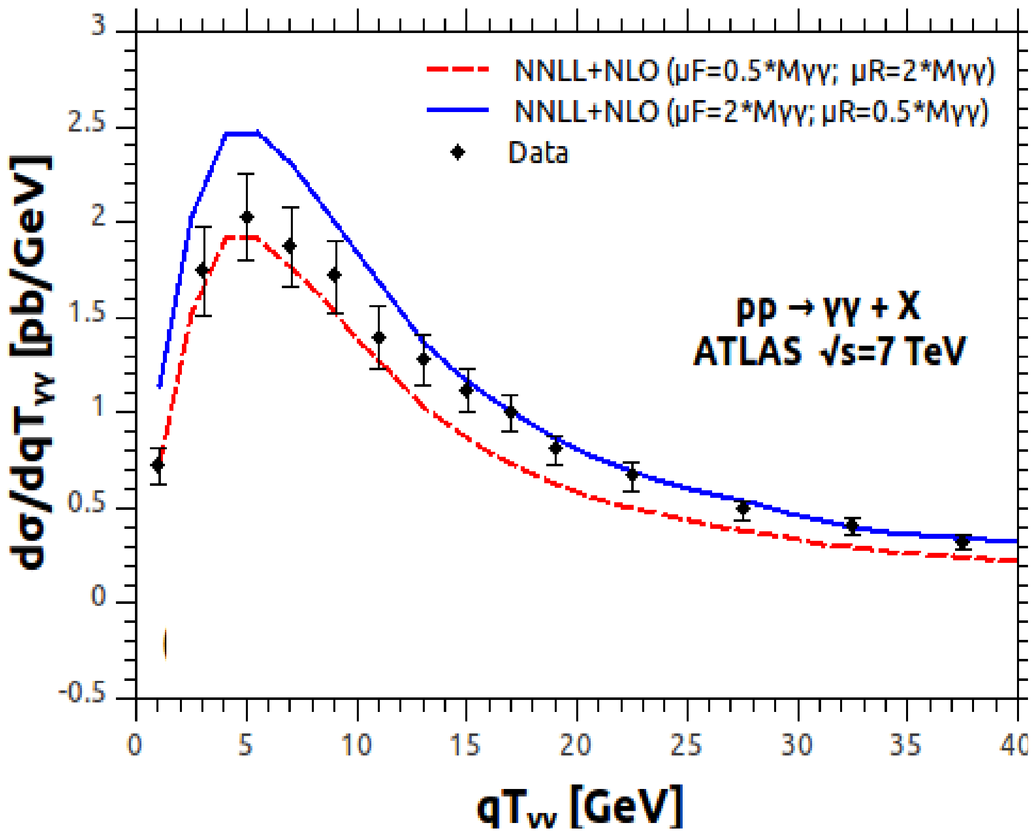
$C_F = (N_c^2 - 1)/(2N_c)$ and $C_A = N_c$

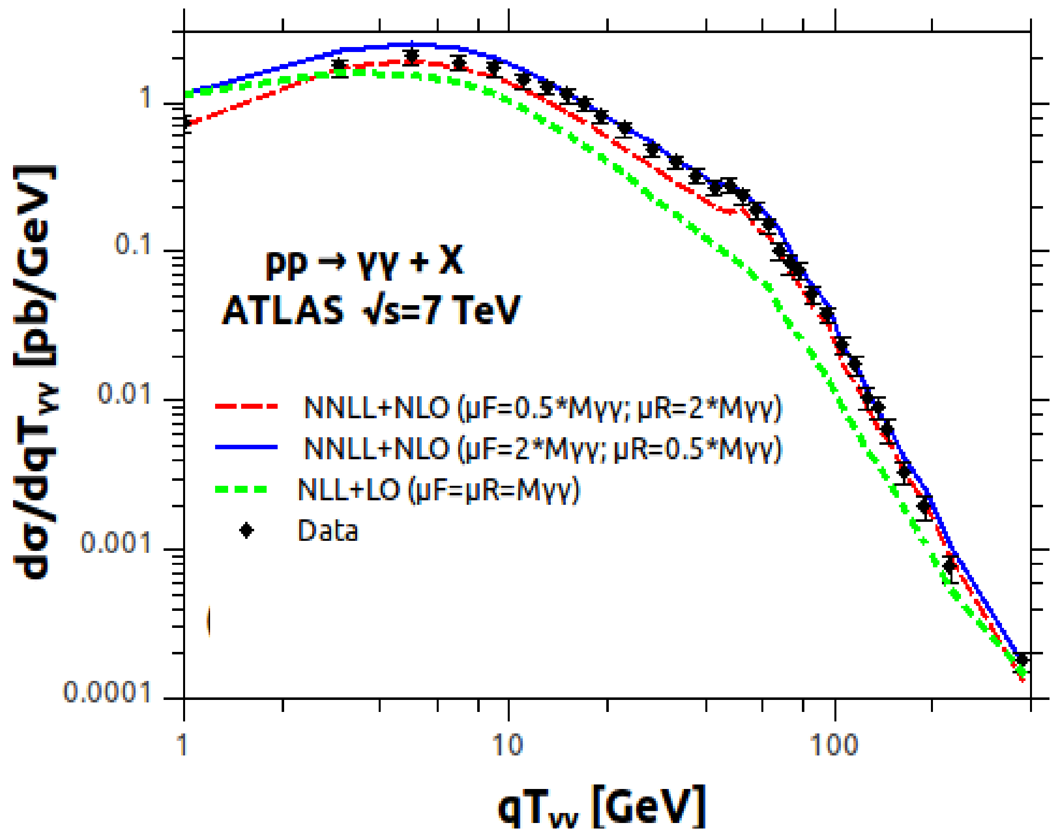
$p_T^{\text{harder}} \geq 25$ GeV, $p_T^{\text{softer}} \geq 22$ GeV,
$|y_\gamma| < 1.37 \;\vee\; 1.52 < |y_\gamma| \leq 2.37$,
$E_{T\ max} = 4$ GeV, $n = 1$, $R = 0.4$,
$R_{\gamma\gamma} = 0.4$

Resummation → ATLAS γγ – (2γRes)

LC, Coradeschi, de Florian

First results!





qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

$$p_T^{\text{harder}} \geq 25\ \text{GeV},\quad p_T^{\text{softer}} \geq 22\ \text{GeV},$$
$$|y_\gamma| < 1.37\ \vee\ 1.52 < |y_\gamma| \leq 2.37,$$
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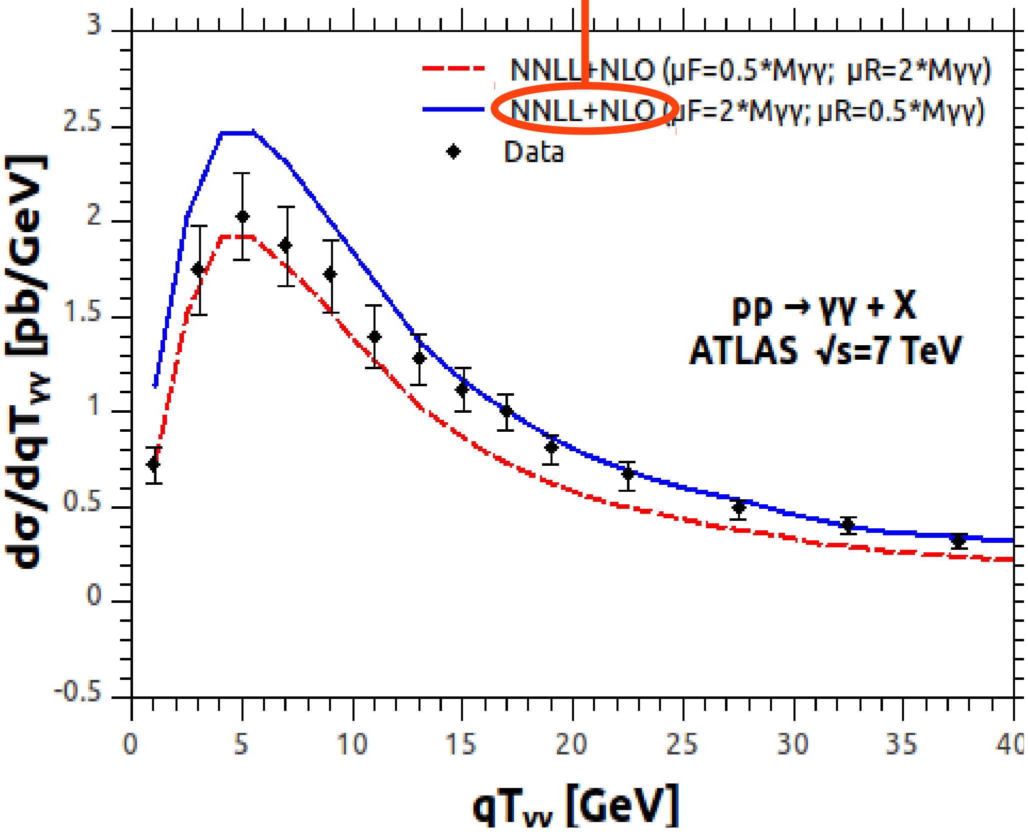
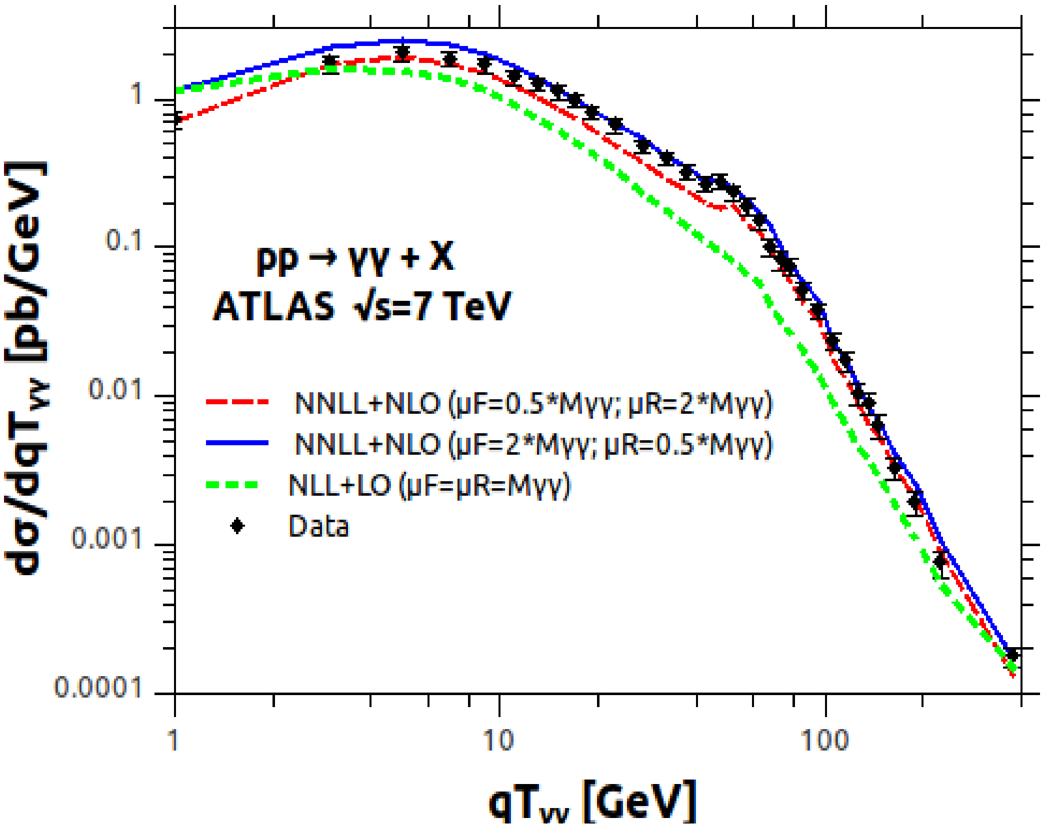
$$R_{\gamma\gamma} = 0.4$$

Resummation → ATLAS γγ – (2γRes)

LC, Coradeschi, de Florian

+) NLO here means: γγ + jet at NLO
+) γγ + jet at NLO is a part of γγ production at NNLO





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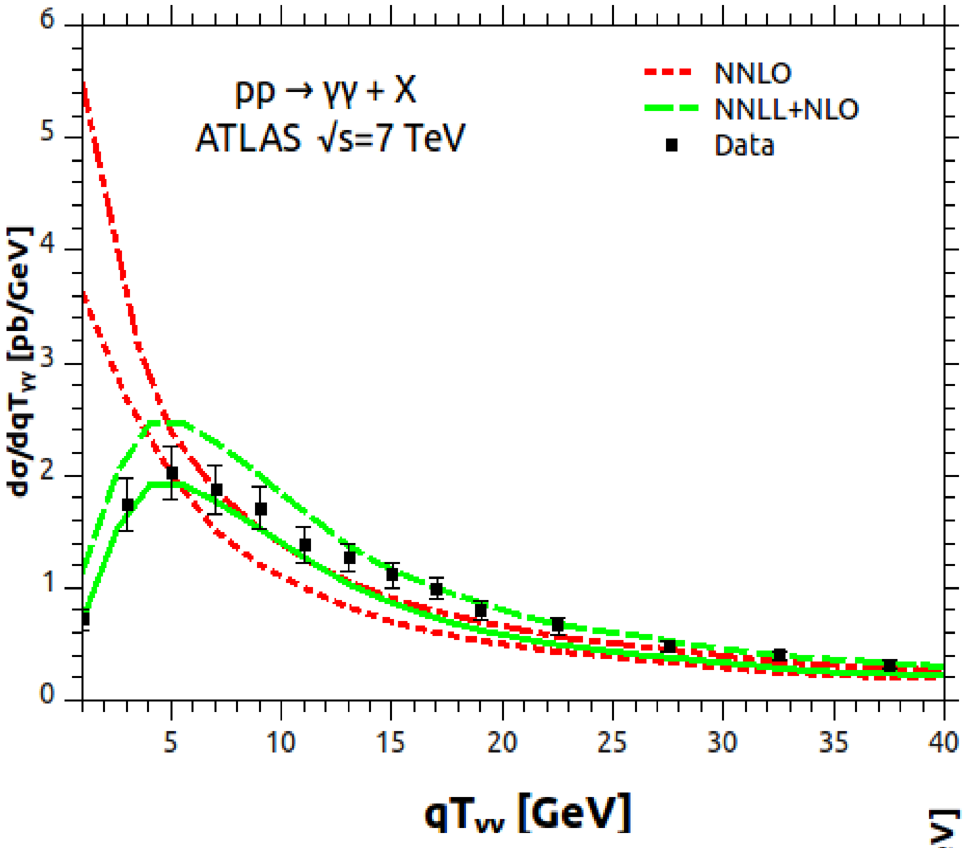
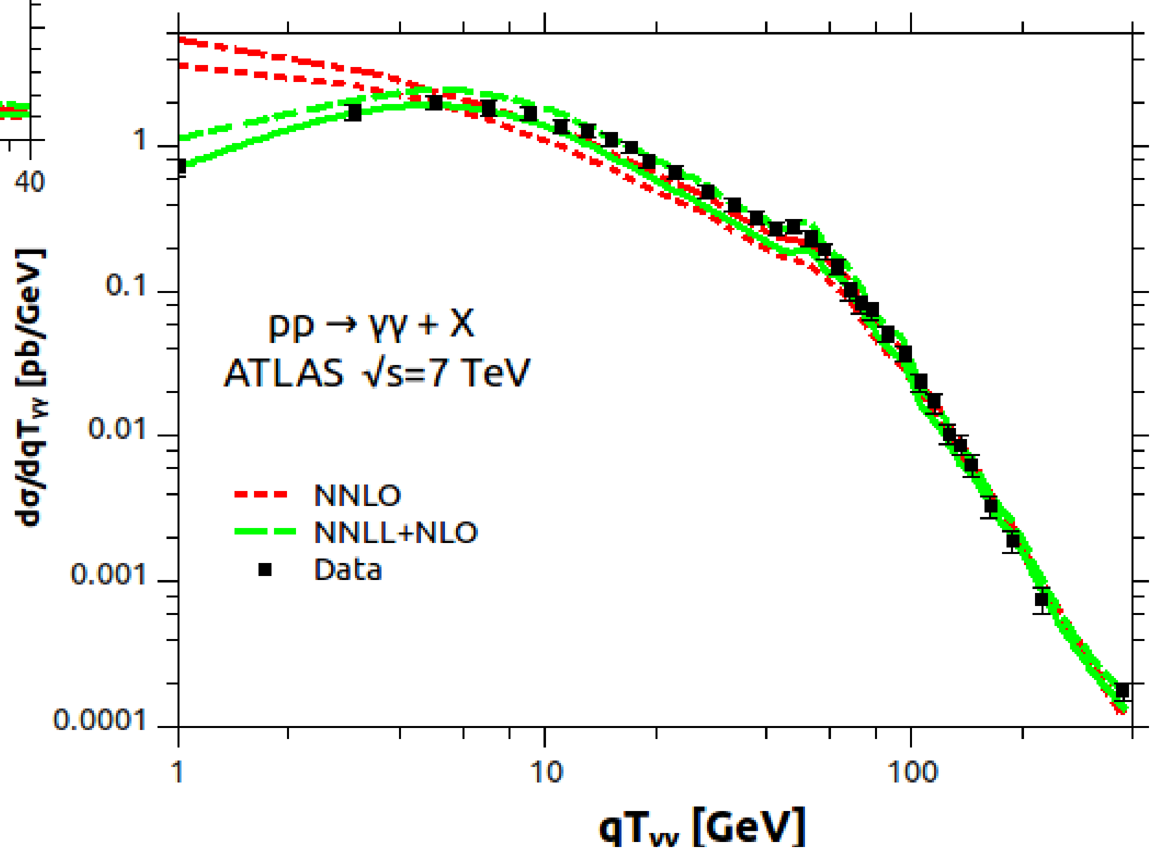
Resummation → ATLAS γγ – (2γRes)

LC, Coradeschi, de Florian



Good agreement between theory and experiment over the whole qT range.

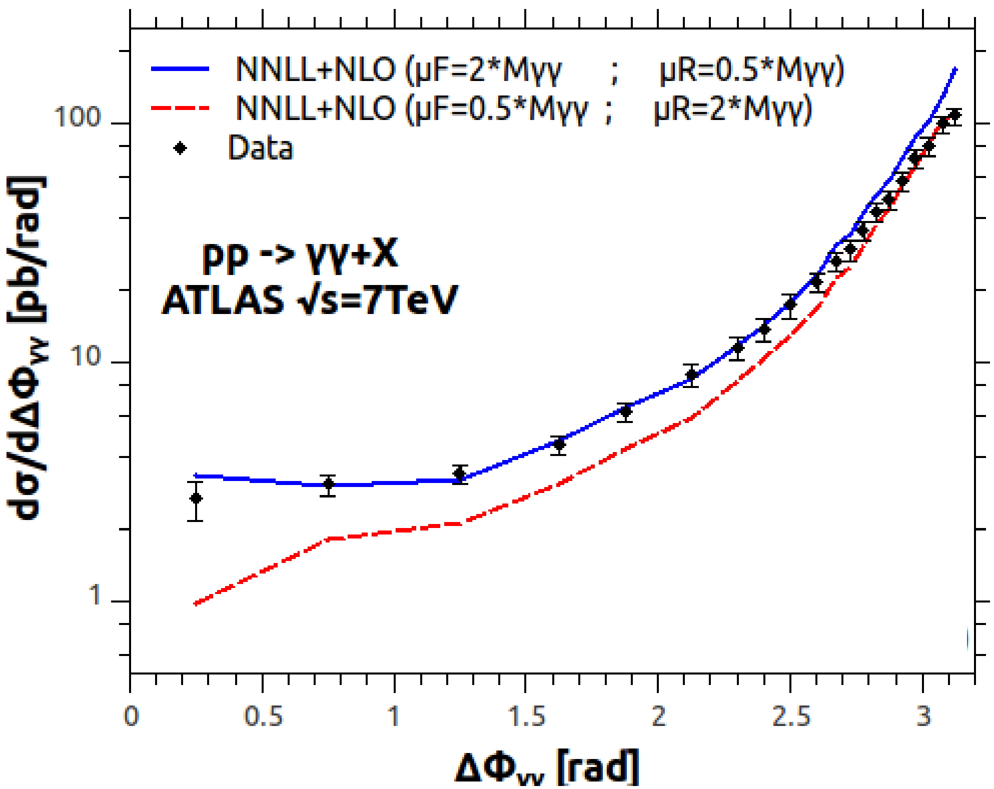
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

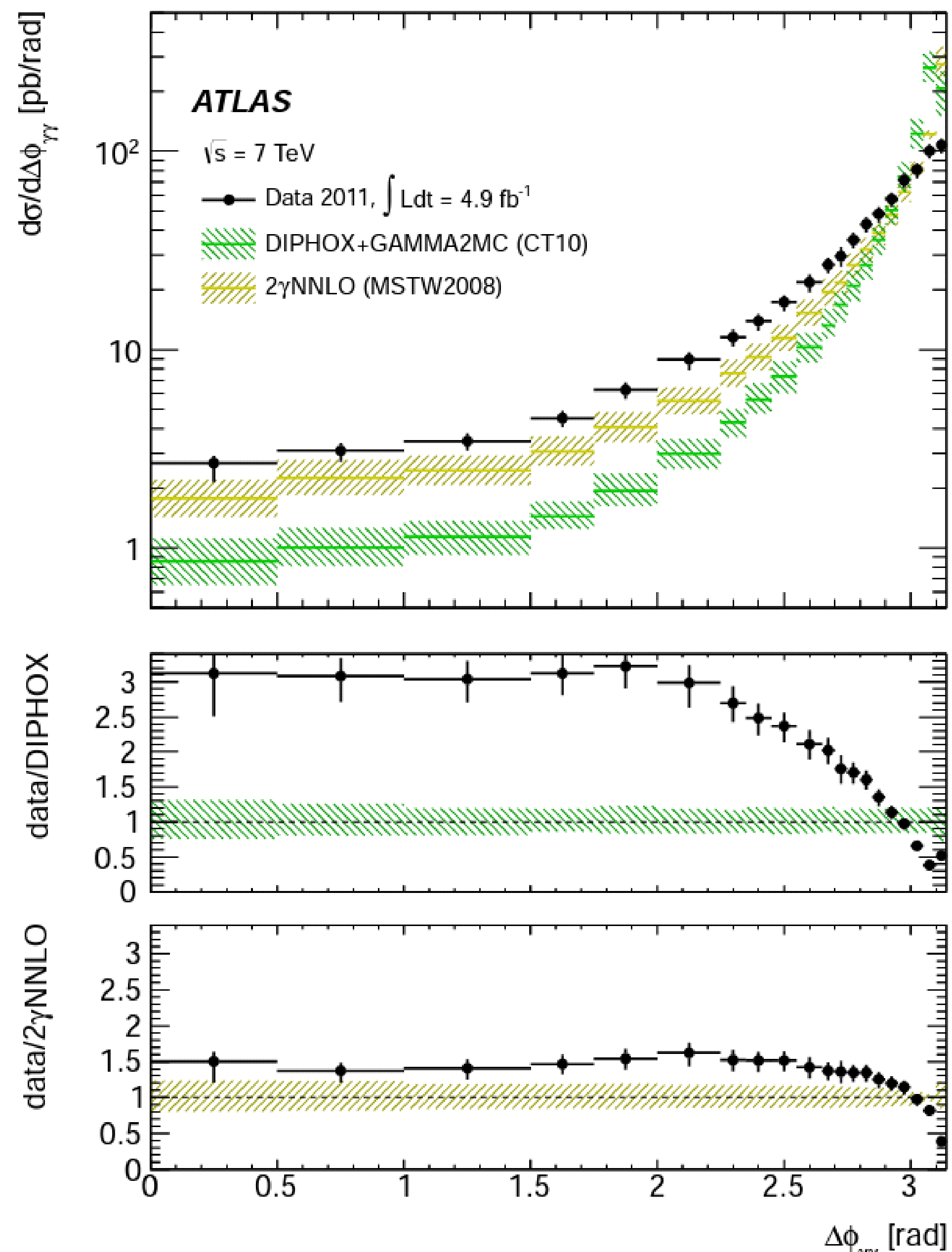


Resummation → ATLAS γγ – (2γRes)

LC, Coradeschi, de Florian

First results!





The same set-up also allows the calculation of more exclusive observable distributions

Uncertainties → 6% - 8%

Resummation → ATLAS γγ – (2γRes)

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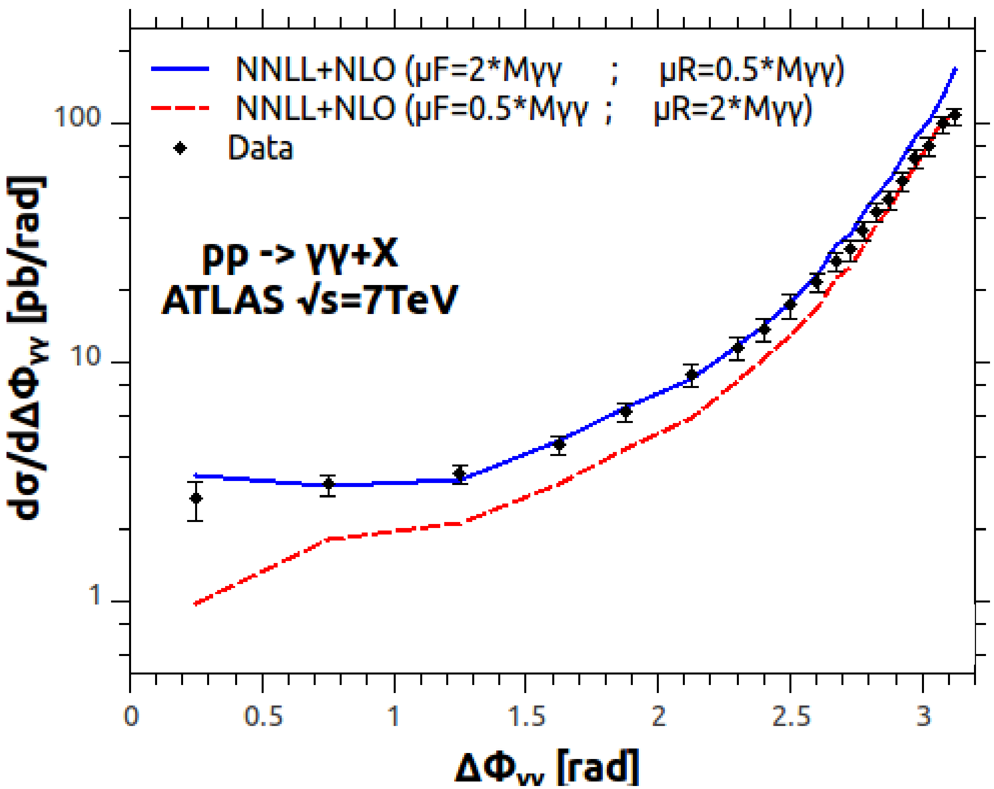
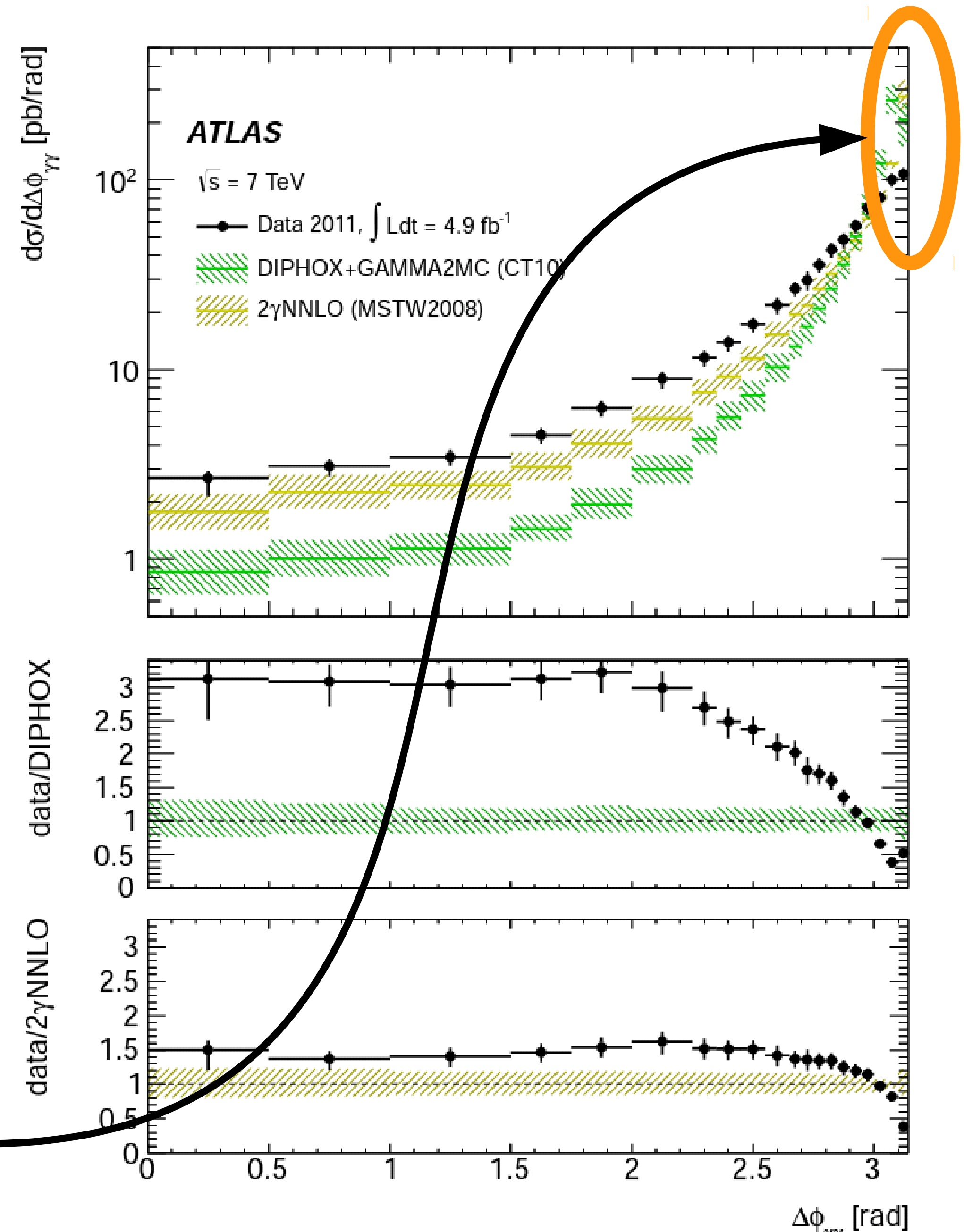
First results!





Uncertainties → 6% - 8% due to the opening of the gg channel which is "effectively" LO at NNLO

qT resummation "spreads" the uncertainties of the gg channel over the whole Δφ range

Summary

- The qT resummation is necessary (and essential) in order to reproduce the phenomenology of the measured qT spectrum
- First ATLAS data show a spectrum which is significantly harder than the SM prediction, though still with very large uncertainties
- HRes includes the finite top and bottom quark masses at full NLL+NLO accuracy. NNLL+NNLO effects are included in the large-mtop limit
- HRes allows us to retain the full kinematical information on the Higgs boson and its decay products in $H \to \gamma\gamma$, $H \to WW \to l\nu l\nu$ and $H \to ZZ \to 4l$
- Among the various kinematical distributions in $gg \to H$ the qT spectrum plays an important role: embodies main effects of QCD radiation
- First results of diphoton production at NNLL+NNLO (2γRes) show an improved agreement (respect NNLO) with the LHC data over the whole qT range.

Thank you!!!

Backup slides

Higgs p_T and BSM

Modifications of the Higgs couplings to gluons and the top quark can be parametrised as

$$\mathcal{L} = -c_t \frac{m_{top}}{v} \bar{\psi}\psi + \frac{\alpha_S}{12\pi} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu} \qquad \text{SM:} \quad c_t = 1 \quad c_g = 0$$

neglecting CP violation

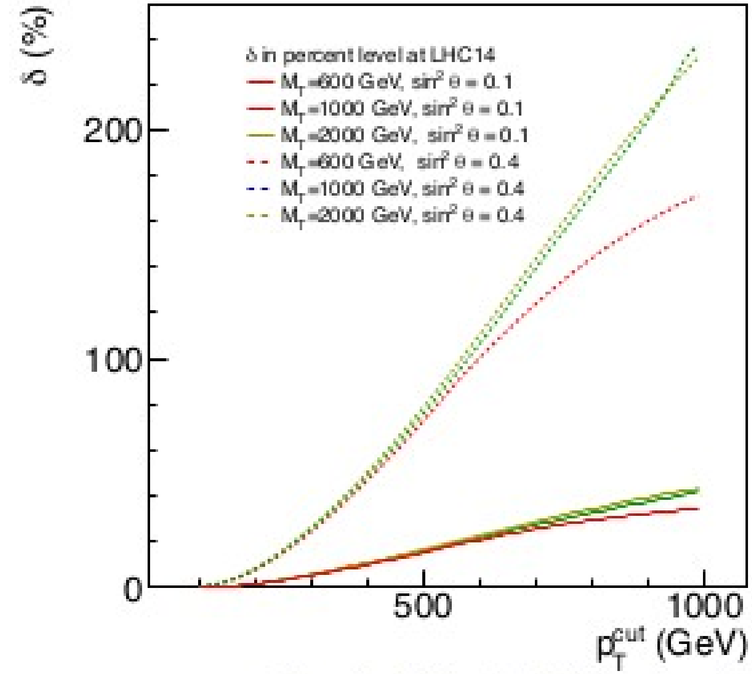
$$\sigma_H \sim |c_t + c_g|^2 \, \sigma_H^{SM}$$

→ not possible to disentangle c_t and c_g in the inclusive rate

Direct access to top Yukawa coupling is offered by tth production but low sensitivity

Looking at high-p_T events allows us to break this degeneracy

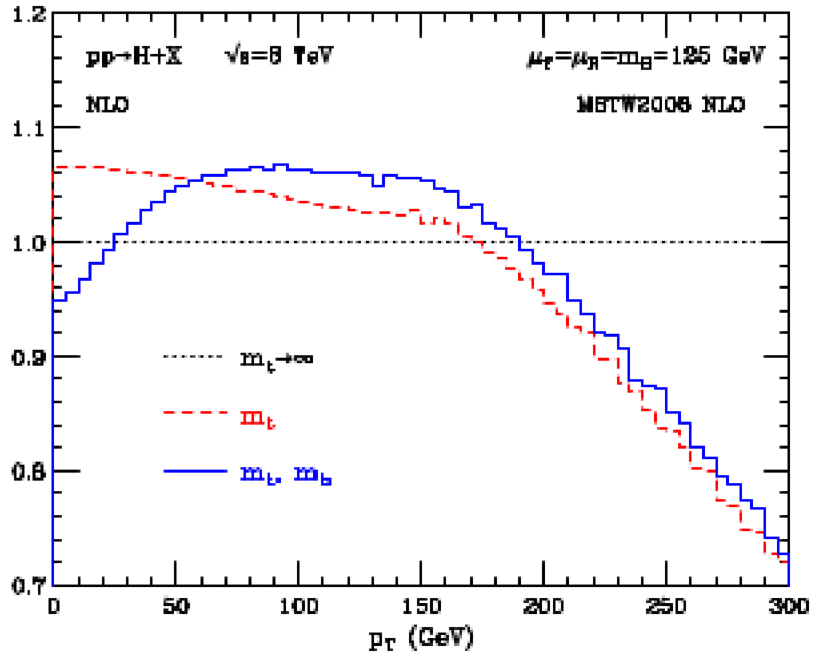
Relative effect of top partners on high-p_T cross section can be very large

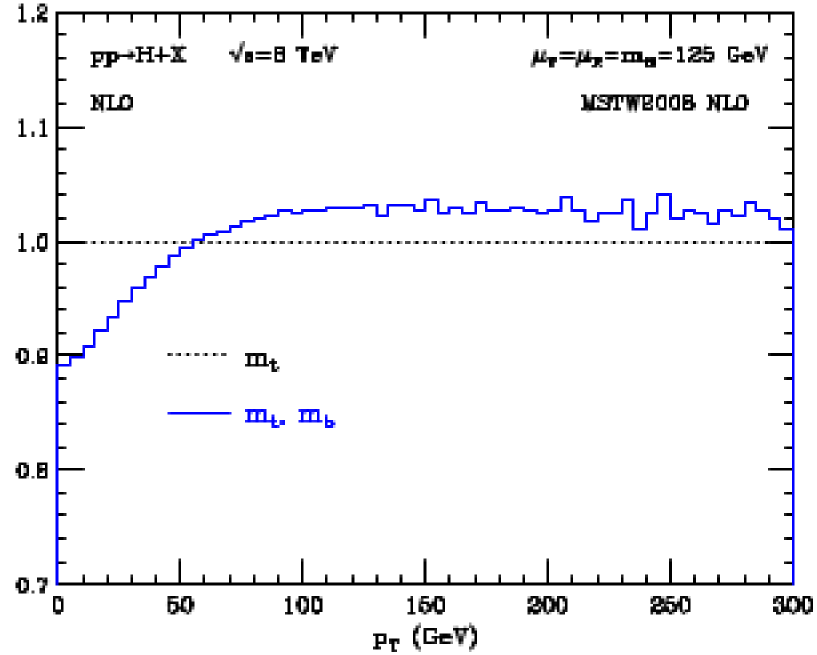


A.Banfi, A.Martin, V.Sanz (2013)

Mass effects at fixed order

Let us look at the mass effects in the NLO p_T spectrum





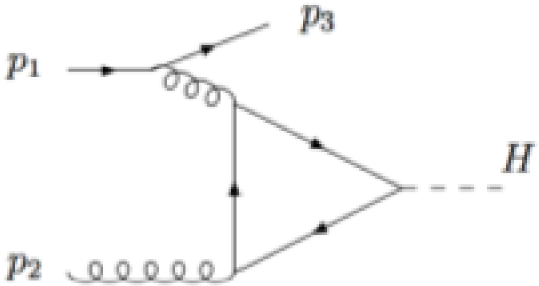
When only the top contribution is considered the shape of the spectrum in the small and intermediate p_T region is similar to the $m_t \to \infty$ result

The bottom contribution significantly distorts the spectrum in the low p_T region

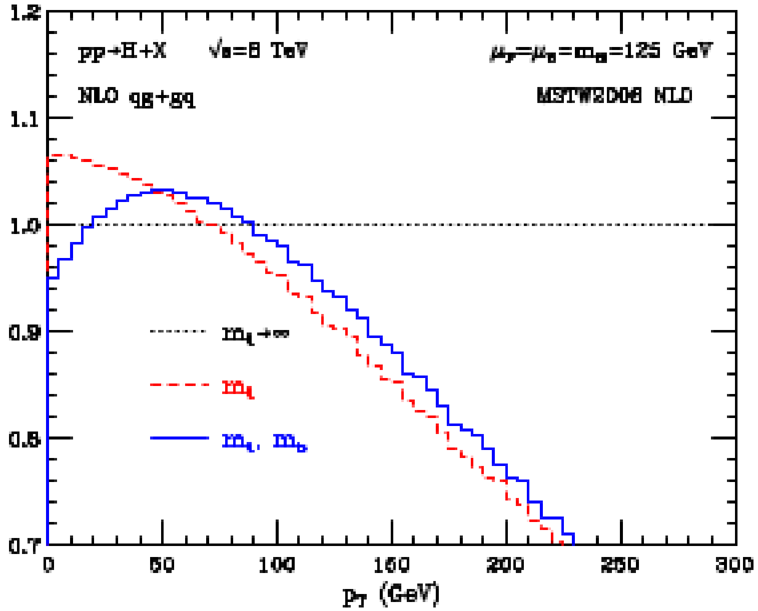
Mass effects at fixed order

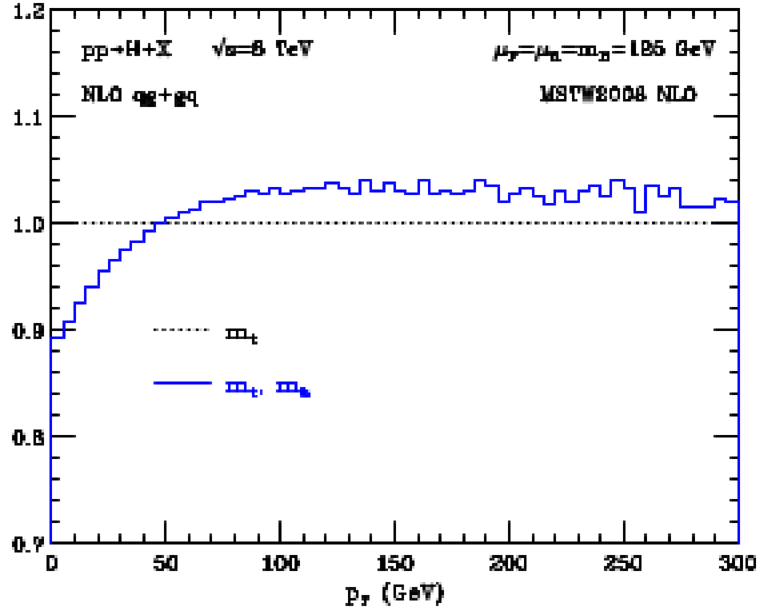
In order to understand what happens let us focus on the qg channel

We may expect that when $p_T << m_H$ the diagram should factorize naively independently on the mass of the heavy quark running in the loop



but this is not the case





Also in this channel the bottom contribution modifies the shape at small p_T

The resummation formalism

- The resummation formalism has been developed in the eighties

  Y.Dokshitzer, D.Diakonov, S.I.Troian (1978)
  G. Parisi, R. Petronzio (1979)
  G. Curci, M.Greco, Y.Srivastava(1979)
  J. Collins, D.E. Soper, G. Sterman (1985)

- As it is customary in QCD resummations one has to work in a conjugate space in order to allow the kinematics of multiple gluon emission to factorize

- Many phenomenological studies performed at different levels of theoretical accuracy

  I.Hinchliffe, S.F.Novaes (1988)
  R.P. Kauffmann (1991)
  C.P.Yuan (1992)
  C.Balazs, C.P.Yuan (2000)
  E. Berger, J. Qiu (2003)
  A.Kulezsa, J.Stirling (2003)

- Recent studies also in the context of SCET

  S.Mantry, F.Petriello (2009,2010)
  T. Becher, M.Neubert (2010)

Our formalism

Catani, de Florian, Grazzini (2000)
Bozzi, Catani, de Florian, Grazzini (2005)
Catani, LC, de Florian, Ferrera, Grazzini (2013)

- Resummation performed in b-space → constraints of qT conservation

$$\frac{d\sigma_F}{dq_T^2}(q_T, M, s) = \frac{M^2}{s} \int_0^\infty db\, \frac{b}{2}\, J_0(b q_T)\, W^F(b, M, s) + \ldots$$

- $$W_N^F(b, M) = \sum_{a,b} \mathcal{W}^F_{ab,\, N}(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)\, f_{a/h_1, N}(\mu_F^2)\, f_{b/h_2, N}(\mu_F^2)$$

PDFs

$$W_N^F(b, M) = \sum_c \sigma^{(0)}_{c\bar{c},\, F}(\alpha_S(M^2), M)\, H_c^F(\alpha_S(M^2))\, S_c(M, b) \times \sum_{a,b} C_{ca,\, N}(\alpha_S(b_0^2/b^2))\, C_{\bar{c}b,\, N}(\alpha_S(b_0^2/b^2))\, f_{a/h_1, N}(b_0^2/b^2)\, f_{b/h_2, N}(b_0^2/b^2)$$

Born Xsection

Hard coefficient → Process dependent

Collinear coefficient functions → Universal

Mass effects in the resummed spectrum

H.Sargsyan, M. Grazzini (2013)

- It is not difficult to extend the fully exclusive calculation in HNNLO to include the exact dependence on the masses of the heavy quarks up to NLO
- Two loop virtual corrections available

M.Spira et al. (1991,1995)
R.Harlander , P.Kant (2005)
U.Aglietti, R.Bonciani, G. Degrassi, A.Vicini (2006)

- One loop real corrections available

R.K.Ellis,I.Hinchliffe,M.Soldate, J. van der Bij (1988)

- Top and bottom quark contributions exactly taken into account up to NLO. At NNLO we consider only the top-quark contribution and we rescale it with the ratio $\sigma_{LO}(mt)/\sigma_{LO}(mt \to \infty)$

HNNLO now includes → NLO mass effects

Mass effects in the resummed spectrum

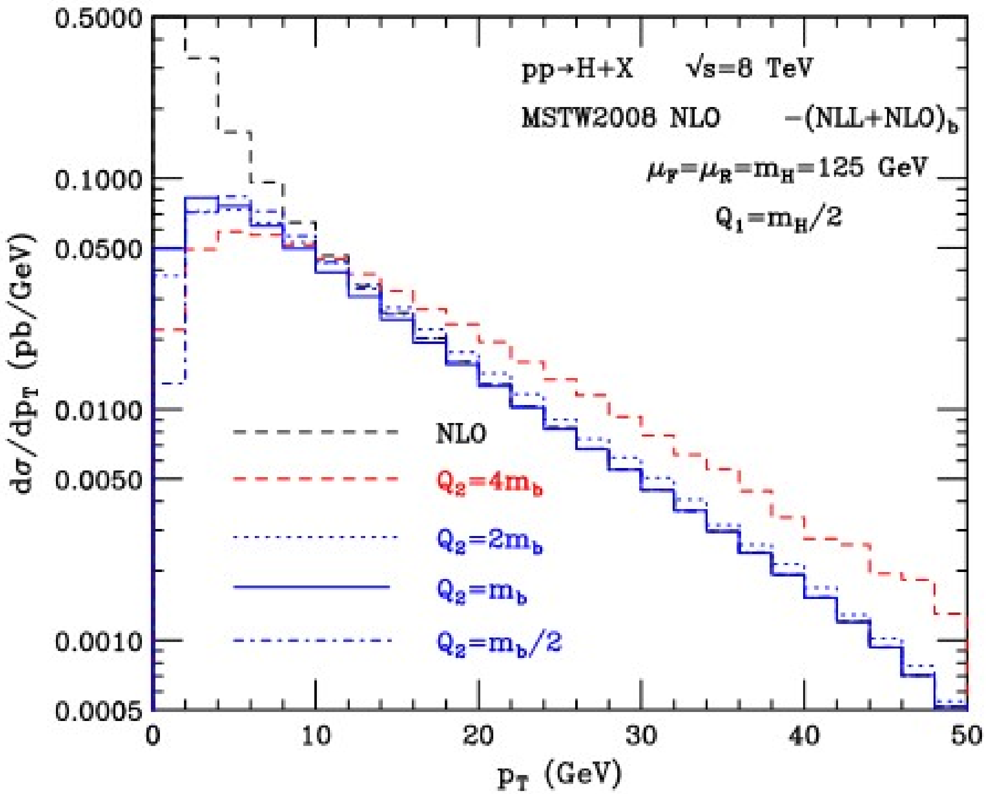
H.Sargsyan, M. Grazzini (2013)

- Studying the analytic behavior of the QCD matrix elements we find that collinear factorization is a good approximation only when $q_T \ll 2m_b$
- The standard resummation procedure cannot be straightforwardly applied to the bottom quark contribution
- How to deal with different scales:
- the top quark gives the dominant contribution to the q_T cross section and we treat it as usual with a resummation scale Q1
- the bottom contributions (and the top-bottom interference) are controlled by an additional resummation scale Q2 that we choose of the order of the b-mass

In this way we limit the resummation for the bottom contribution only to the region in which it is really justified (and needed)

Mass effects in the resummed spectrum

H.Sargsyan, M. Grazzini (2013)



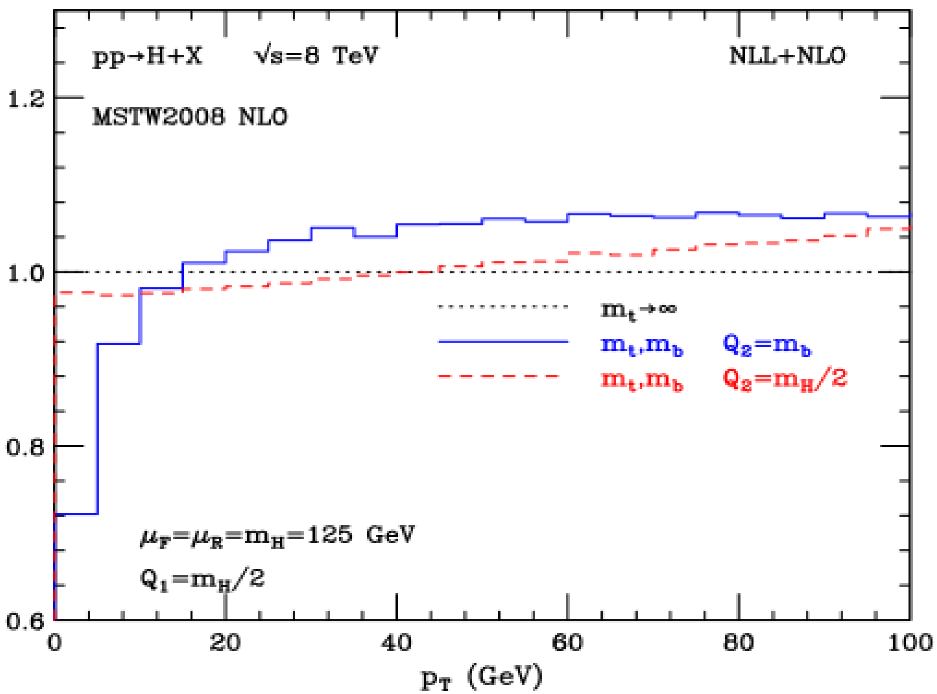
Comparison of resummed spectrum from the bottom quark
with the corresponding NLO result for different scales Q2

- We see that for Q2 =mb/2, mb, 2mb the fixed order is nicely reproduced in the region qT >10 GeV. For Q2 =4mb instead the resummation deviates from the NLO result. We thus choose Q2 =mb as central scale and proceed with the full calculation

Mass effects in the resummed spectrum

H.Sargsyan, M. Grazzini (2013)

Numerical results



Comparison of the results obtained with $Q_2=m_b$ and $Q_2=m_H/2$

→ Significant differences in the low-p_T region

The result with $Q_2=m_H/2$ is in agreement with independent calculation by Mantler-Wiesemann (and with MC@NLO)

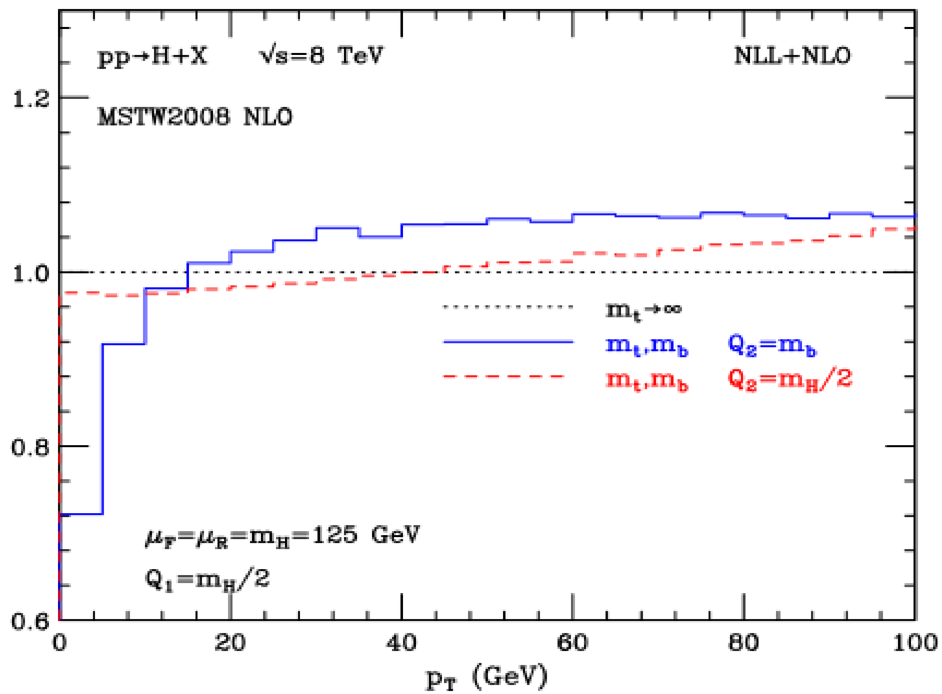
Our result for $Q_2=m_b$ somewhat more similar to POWHEG though the distortion is at smaller p_T

But in order to judge the relevance of this effect we should compare with the perturbative uncertainties affecting the NLL+NLO calculation (which are large)

Mass effects in the resummed spectrum

H.Sargsyan, M. Grazzini (2013)

Numerical results



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Mass effects in the resummed spectrum

H.Sargsyan, M. Grazzini (2013)

- Recently the choice of the central value and range of the second resummation scale has been the subject of discussion

- It has been argued that the factorisation breaking terms are small and could be treated as a finite remainder

  A.Banfi, P.F.Monni, G.Zanderighi (2013)

- This point of view has been recently taken by Harlander et al. who suggest to choose Q2 so as to let the resummed spectrum agree (with 100%) with the fixed order at $q_T \sim m_H$

  R.Harlander, R.Mantler,M.Wiesemann (2014)

- In this way one is lead to consider values of the second resummation scale Q2 larger than what suggested in the analysis of Sargsyan and Grazzini (but still smaller than Q1)

QT resummation and Higgs couplings

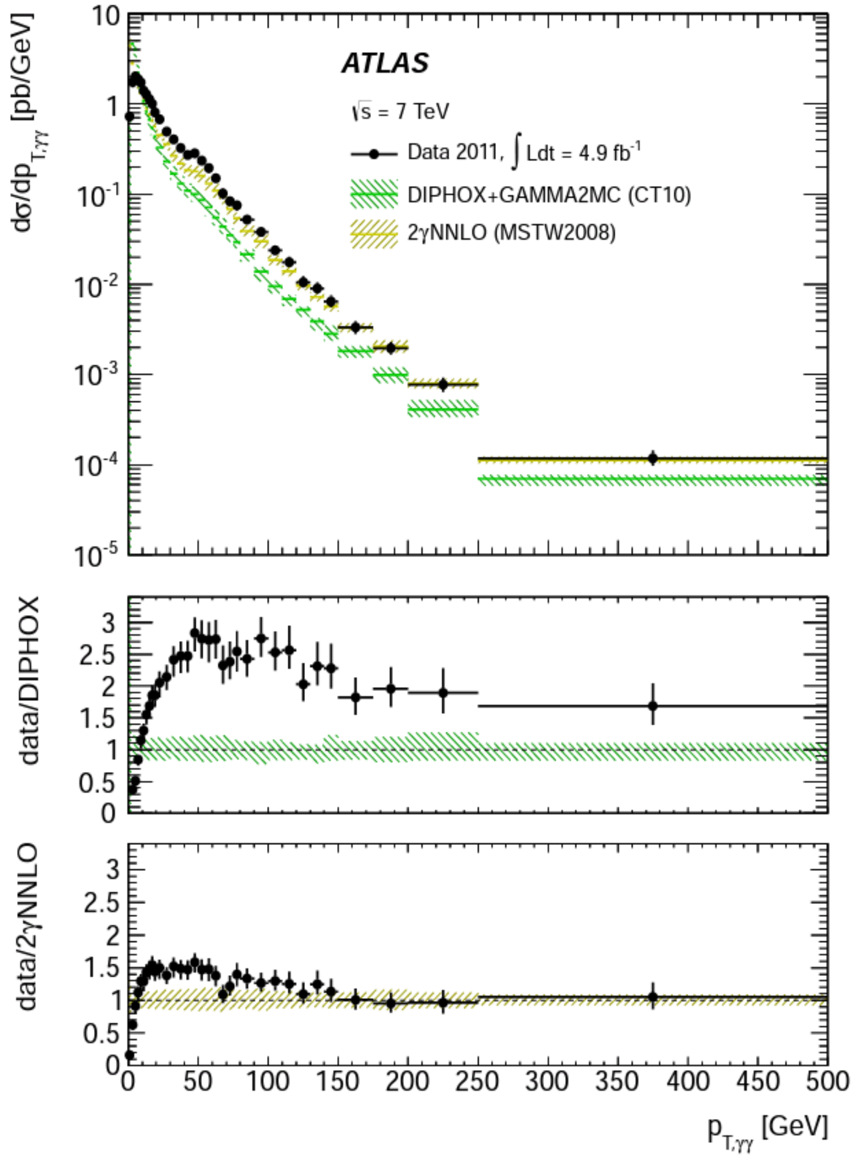
- The transverse momentum spectrum of the Higgs boson can be used to extract information about the couplings
- It has been argued that the most important region for this task is the large qT region and the total Xsection

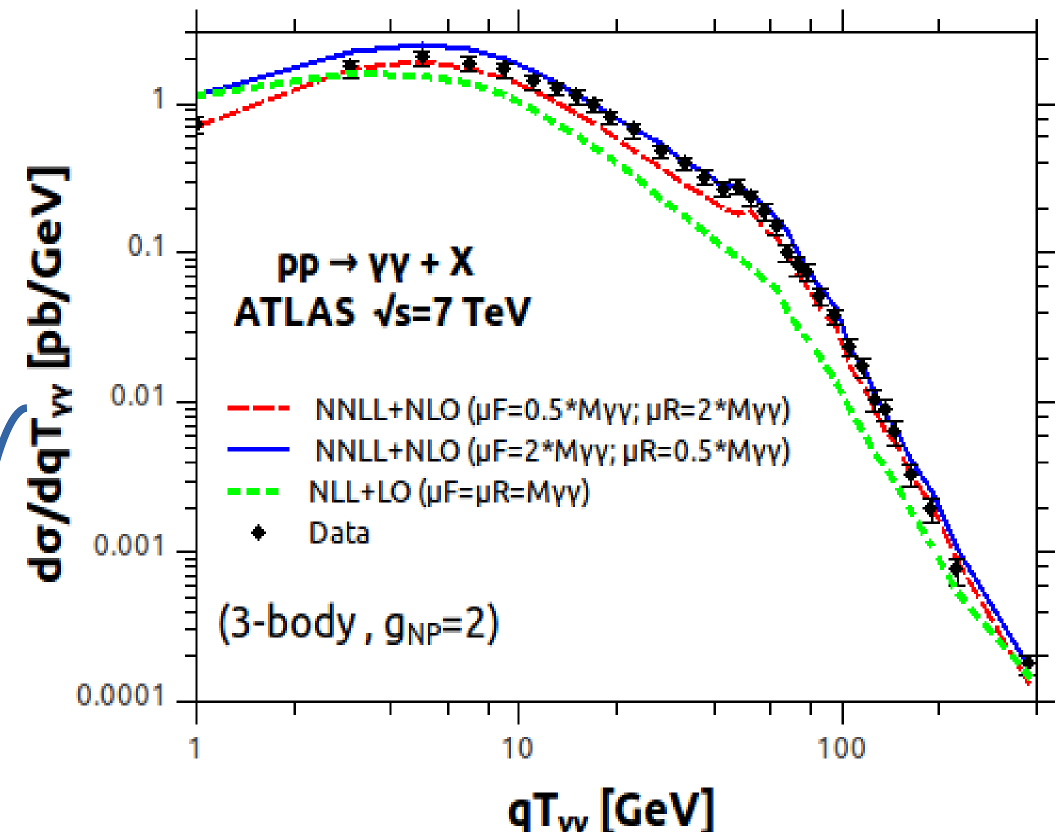
Azatov, Paul (2014);
Langenegger, Spira, Strebel (2015);
Englert,McCullough, Spannowsky (2013);
Langenegger , Spira, Starodumov, Trüb (2006);
Spira, Grazzini, Ilnicka, Wiesemann (to be published)

Resummation → ATLAS γγ

Fixed order

LC, Coradeschi, de Florian





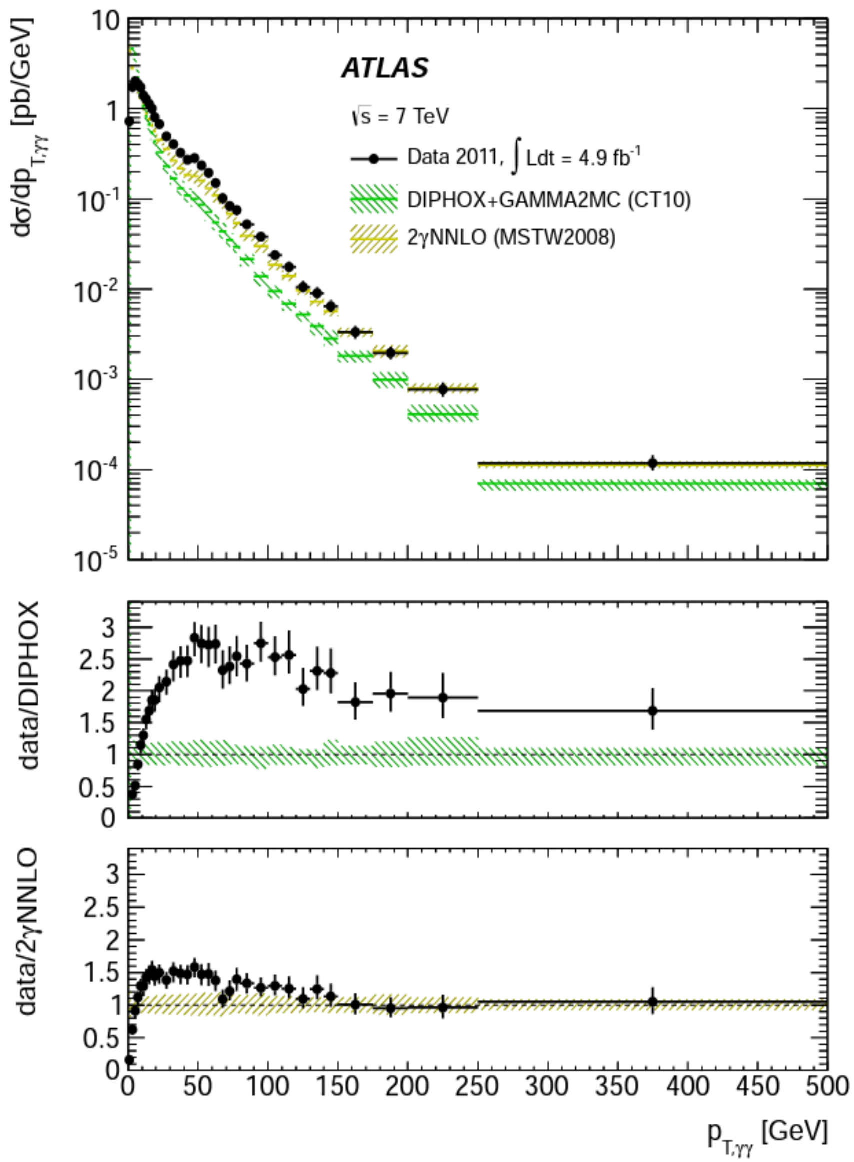
With respect to the fixed-order calculation, the present implementation provides a better description of the data and recovers the correct physical behaviour in the small qT region, with the spectrum going to zero.

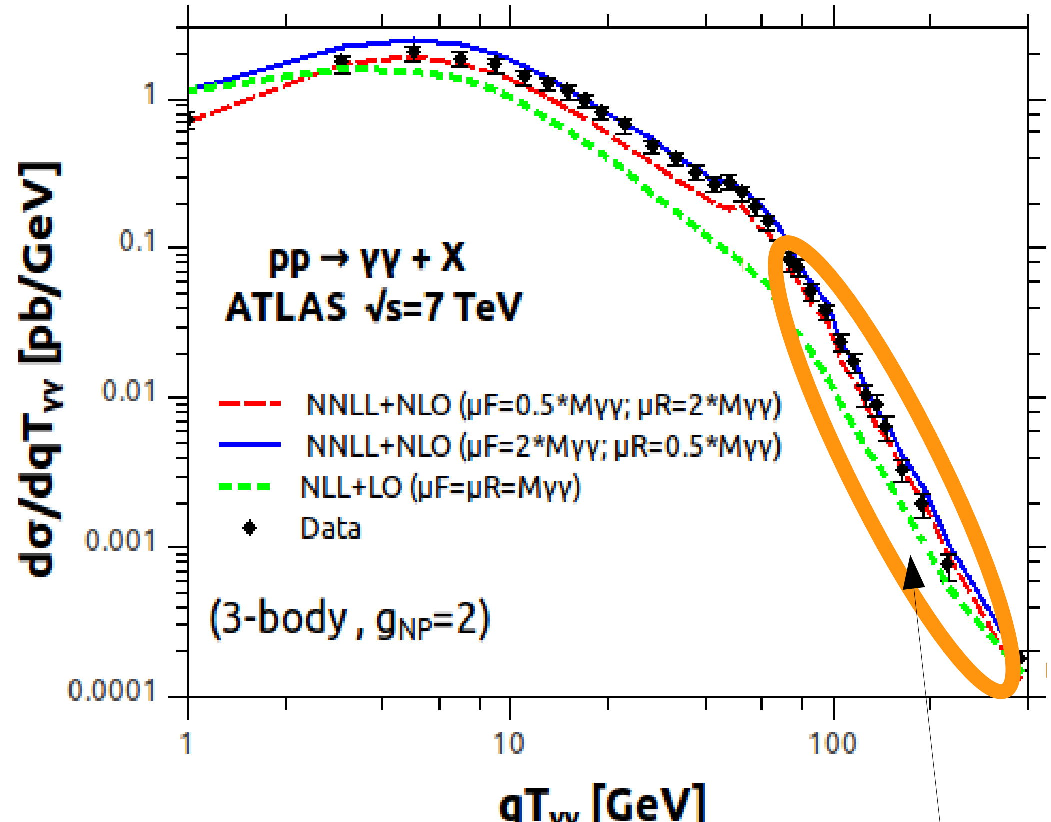
qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

Resummation → ATLAS γγ

Fixed order

LC, Coradeschi, de Florian

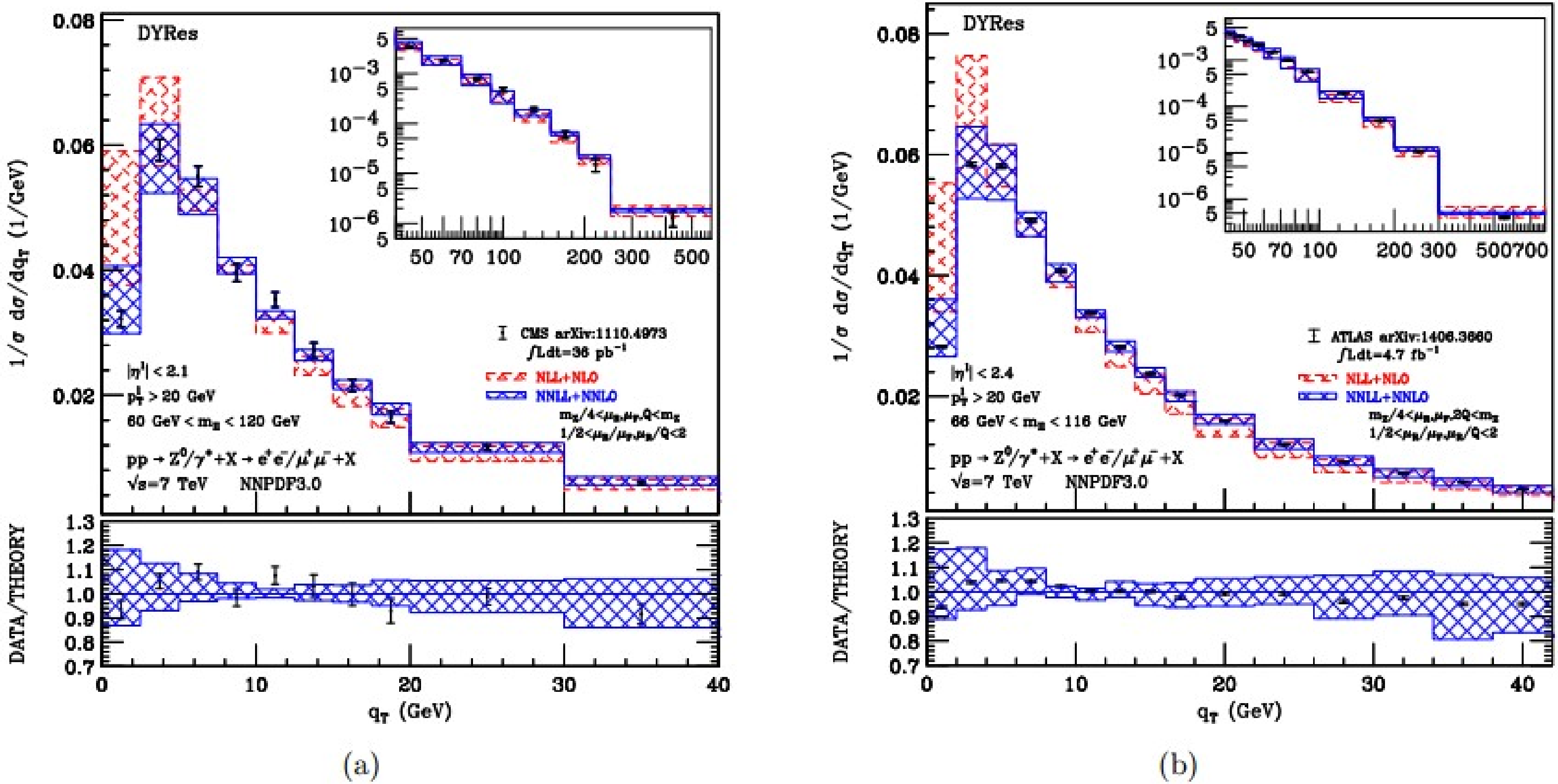




The size of the bands is proportional to the luminosity of the PDF of the gluon

qT resummation "spreads" the uncertainties of the gg channel over the whole qT range

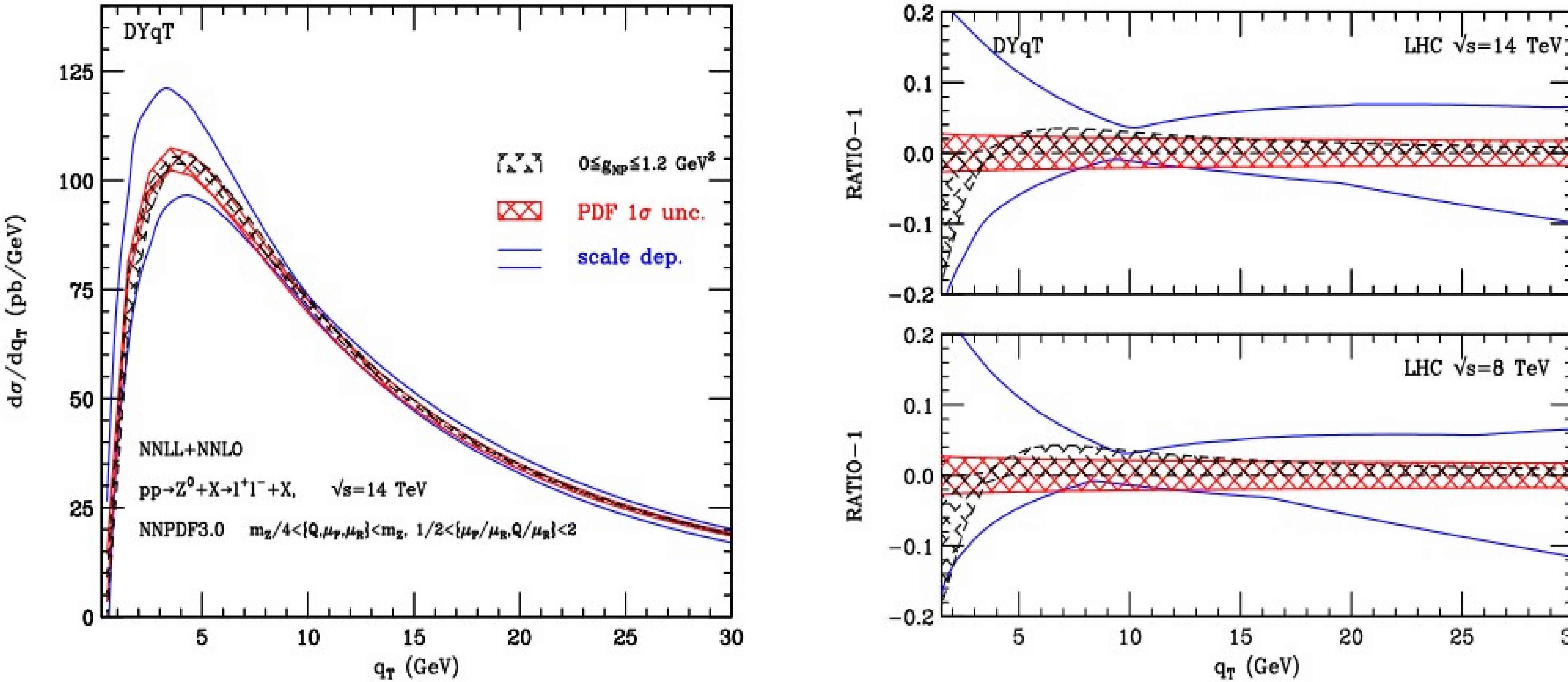
DYRes



Vector boson production at the LHC with lepton selection cuts. The NLL+NLO (red) and NNLL+NNLO (blue) normalized q_T spectra for Z/γ^* production

The inset plot shows the ratio of the data and of the scale dependent NNLL+NNLO result with respect to the NNLL+NNLO result at central values of the scales.

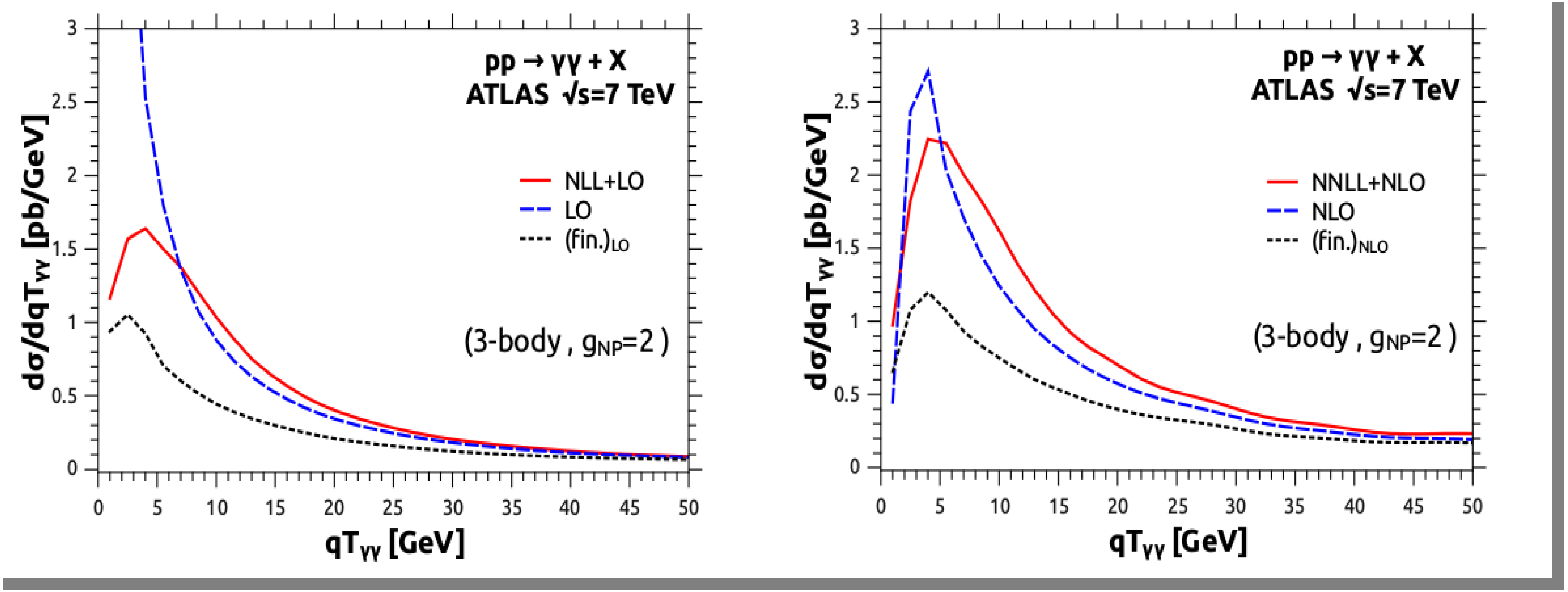
DYRes



(a) (b)

(a) The q_T spectrum at NNLL+NNLO accuracy for Z boson production at the LHC with $\sqrt{s}$ =14 TeV. Comparison of scale dependence (blue solid) and PDF (red crossed solid) uncertainties. The possible impact of NP effects is also shown (black crossed dashed). (b) The same results are normalized to the central NNLL+NNLO prediction at $\sqrt{s} = 14$ TeV (upper panel), and corresponding results are shown at $\sqrt{s} = 8$ TeV (lower panel).

2γRes


pp → γγ + X
ATLAS √s=7 TeV
NLL+LO
LO
(fin.)LO
(3-body , gNP=2)
dσ/dqTγγ [pb/GeV]
qTγγ [GeV]
pp → γγ + X
ATLAS √s=7 TeV
NNLL+NLO
NLO
(fin.)NLO
(3-body , gNP=2)
dσ/dqTγγ [pb/GeV]
qTγγ [GeV]