Higgs boson production and decay at the LHC

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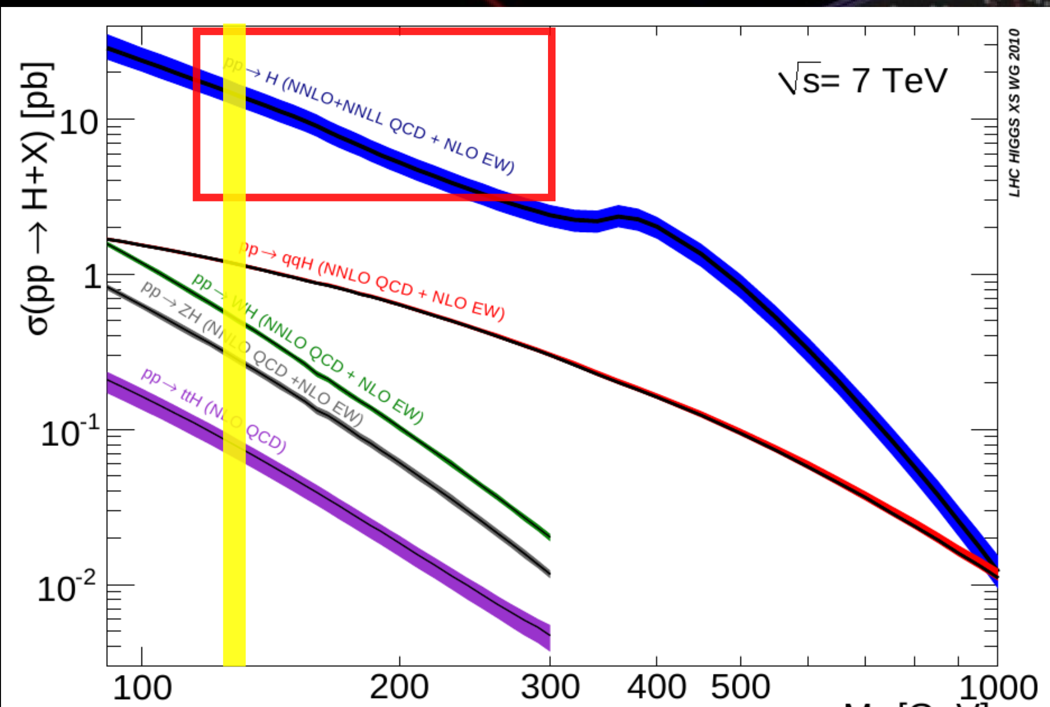
Outline

- Introduction
- Higgs boson production: transverse momentum distribution
- The inclusion of the Higgs boson decay: the program HRes
- Results for $H \to \gamma\gamma$,

  $H \to W W \to l\nu l\nu$ and $H \to ZZ \to 4l$
- New: finite quark mass effects
- Summary

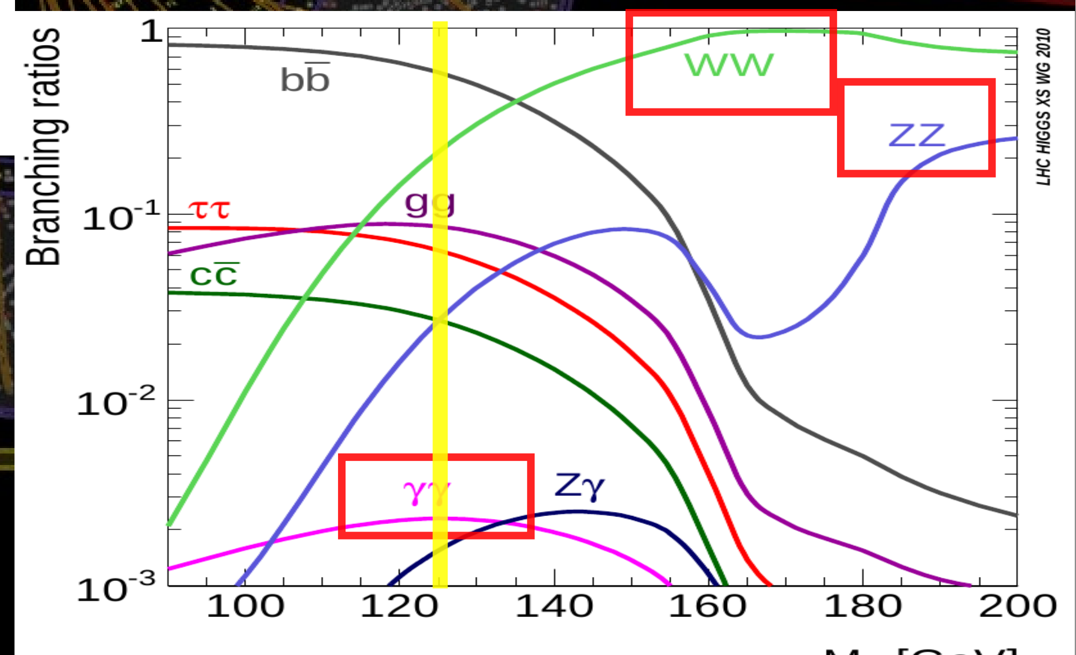
Higgs search at hadron colliders



arXiv:1101.0593v3

- One of the most important production channel is the gluon-gluon fusion (largest cross section). Calculated up to NNLL+NNLO QCD & NLO EW

- In case of gluon-gluon fusion, the most useful channels are the electroweak decays (better ratio signal/background)



arXiv:1101.0593v3

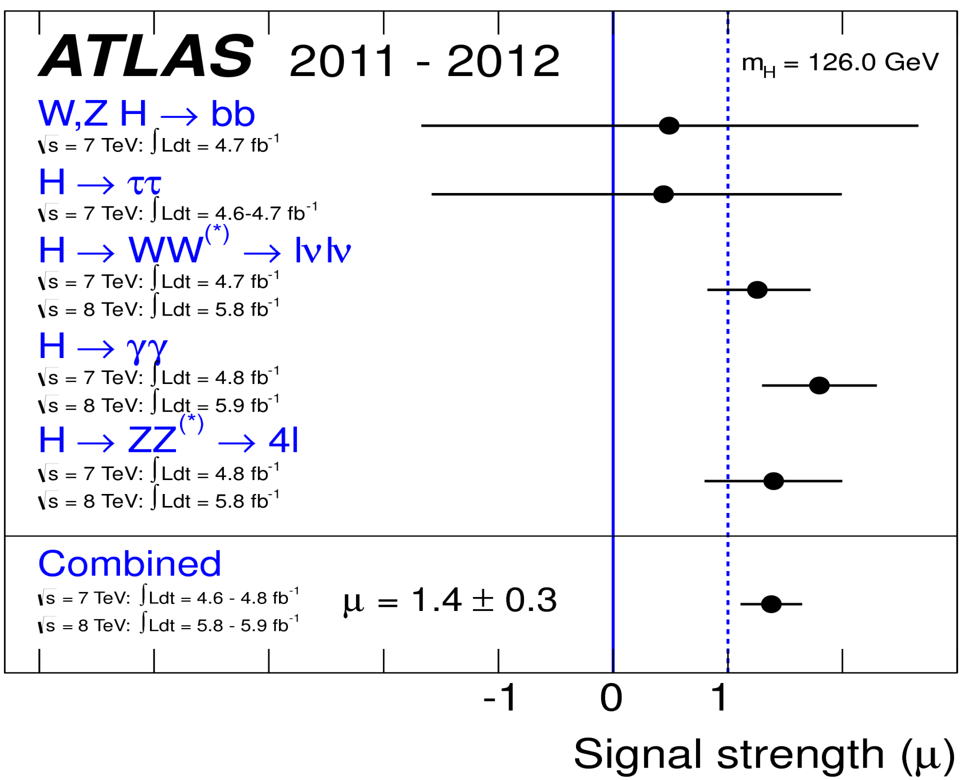
Experimental status

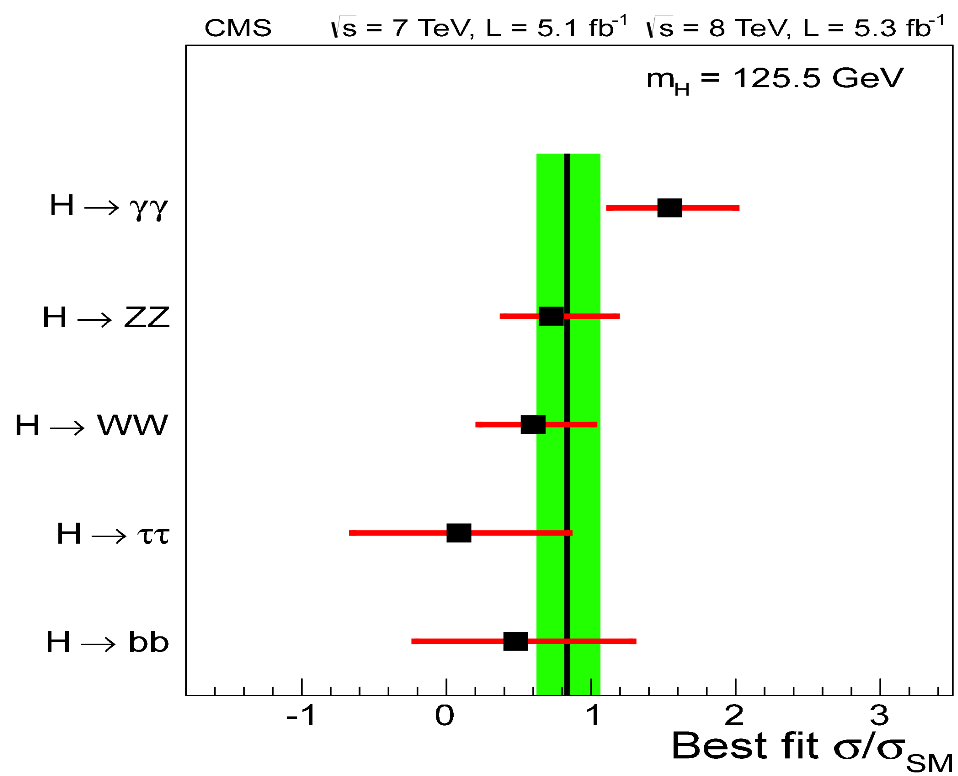
Observation of a new boson at a mass of ~126 GeV

ATLAS: 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV

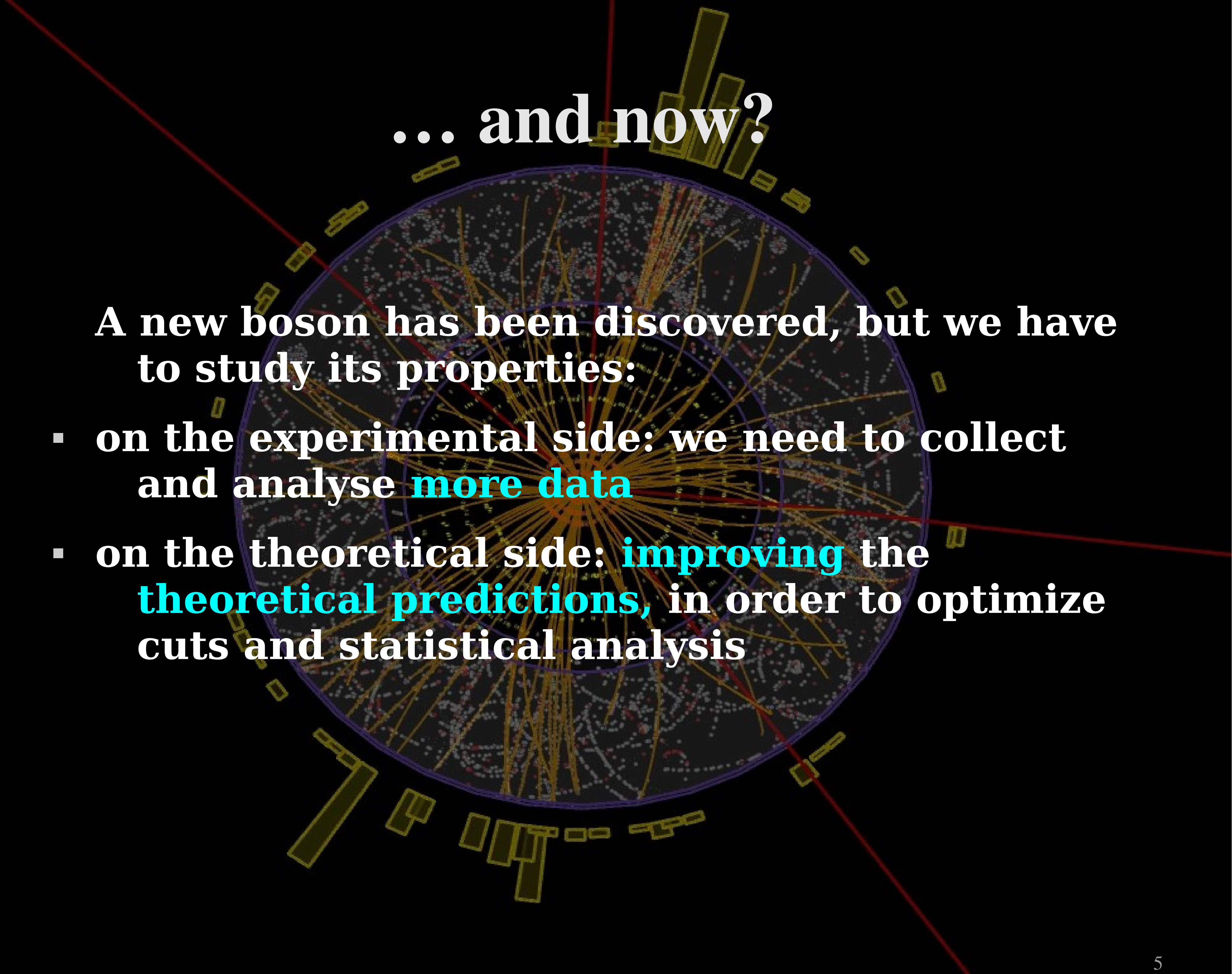
CMS: 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV

It is consistent with the SM Higgs boson.





… and now?

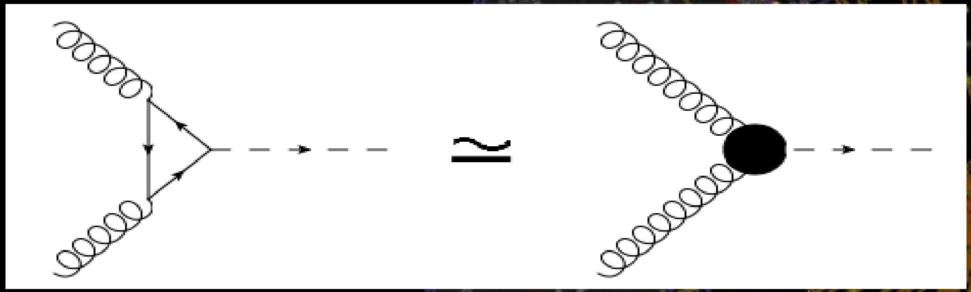


A new boson has been discovered, but we have to study its properties:

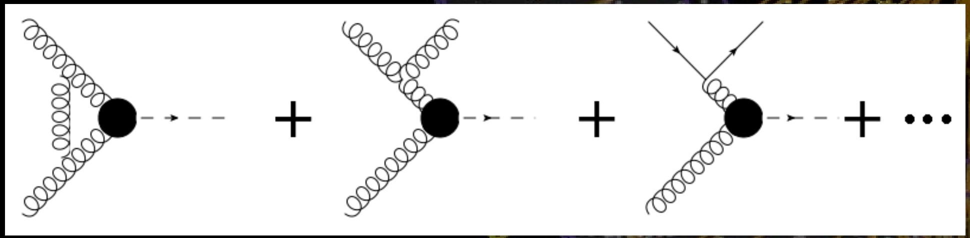
- **on the experimental side: we need to collect and analyse more data**
- **on the theoretical side: improving the theoretical predictions, in order to optimize cuts and statistical analysis**

Higgs boson production

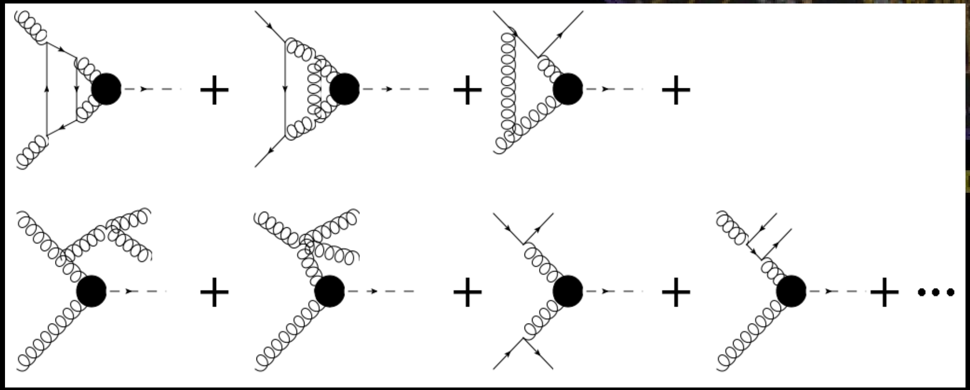
The hard cross section is calculated as perturbative serie of α_s through fixed order calculations



- LO (large top quark mass approximation: production of H via ggH effective vertex)

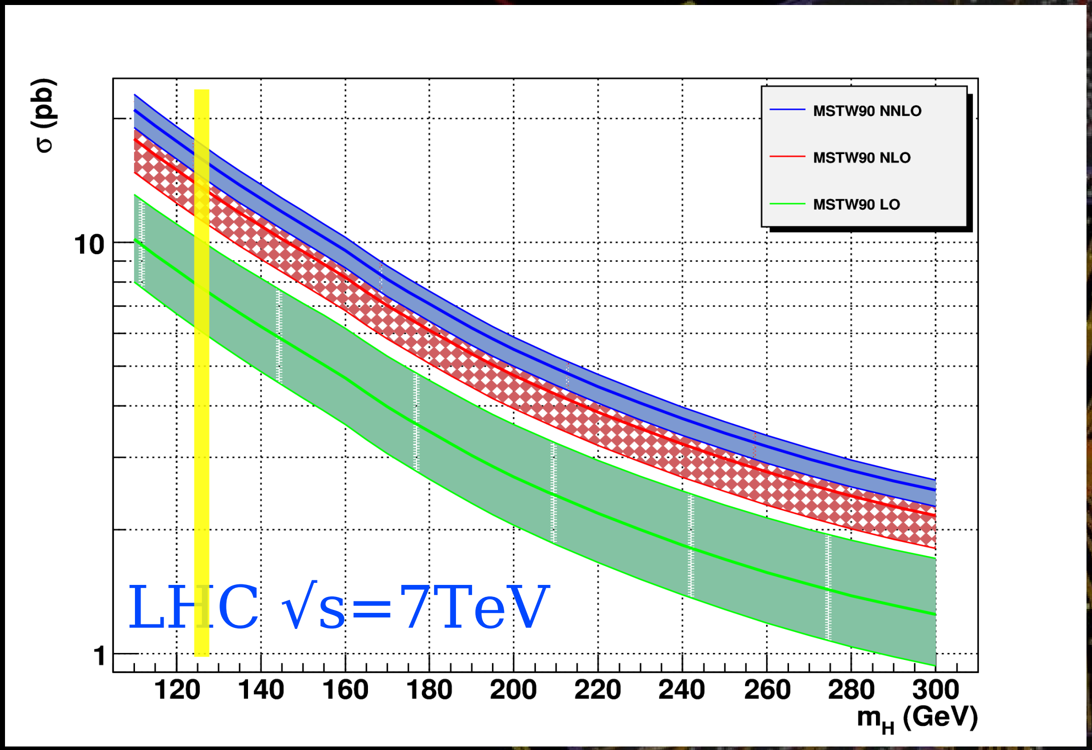


- NLO; but LO if we consider the $q_T \neq 0$ region (at least one recoiling parton: H+jet)



- NNLO; but NLO if we consider the $q_T \neq 0$ region (H+jet(s))

Gluon fusion **total** cross section calculation



- LO to NLO ~80-100% and no overlapping
- NLO to NNLO ~25% and overlapping

R.Harlander, W.B. Kilgore (2002)
C. Anastasiou, K. Melnikov (2002)
V. Ravindran, J. Smith, W.L.Van Neerven (2003)

Further improvements (smaller corrections each):

- threshold resummation at the NNLL accuracy, EW corrections, mixed QCD-EW corrections, sub-leading terms in the 1/mt expansion, real effects from EW radiation

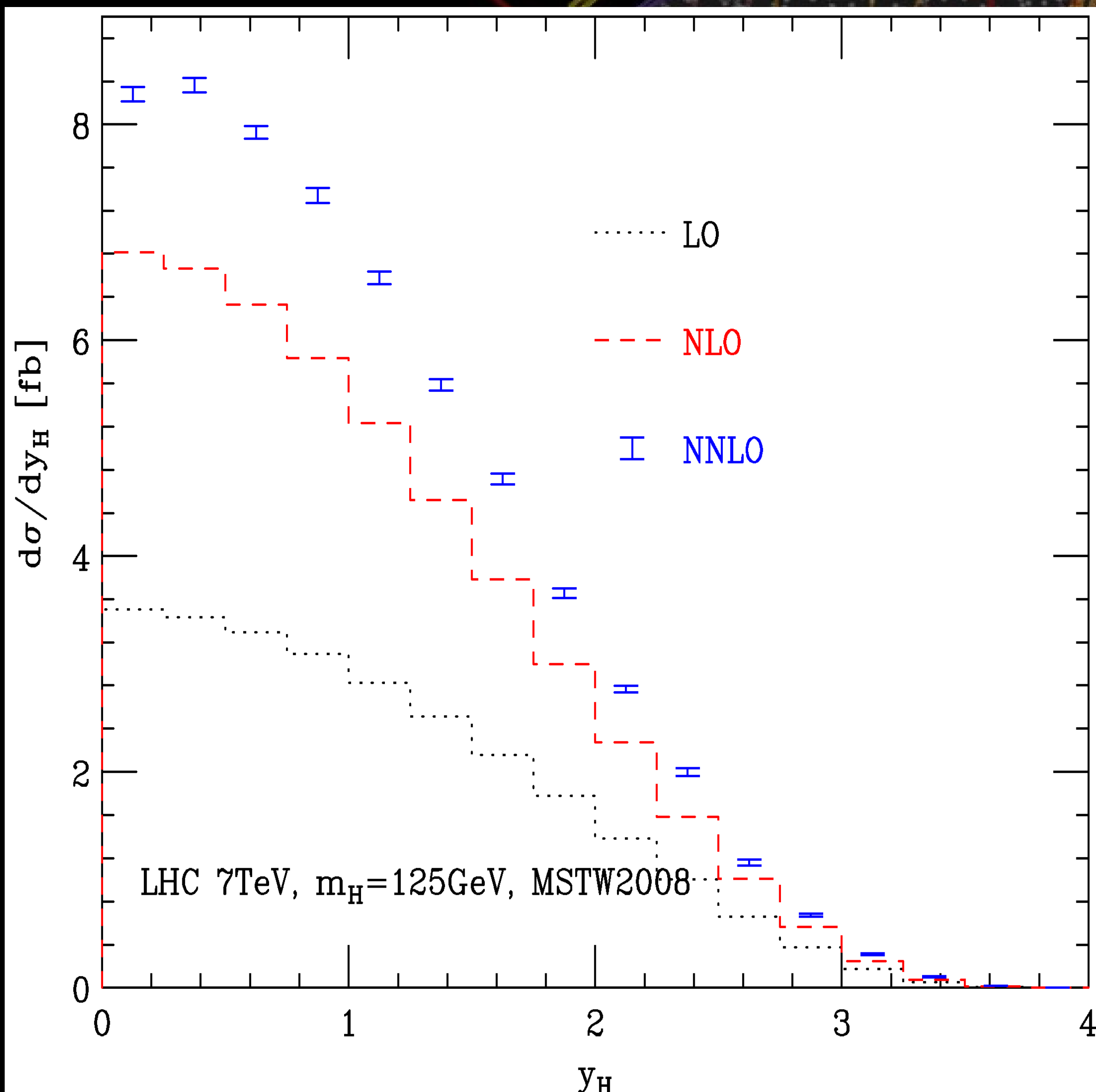
From total cross section to differential distributions

- Total cross sections are ideal quantities (the detectors have finite acceptances)
- Furthermore: optimization of the cut selection in the analysis, to improve the ratio signal/background

  ⟹ differential distributions are needed

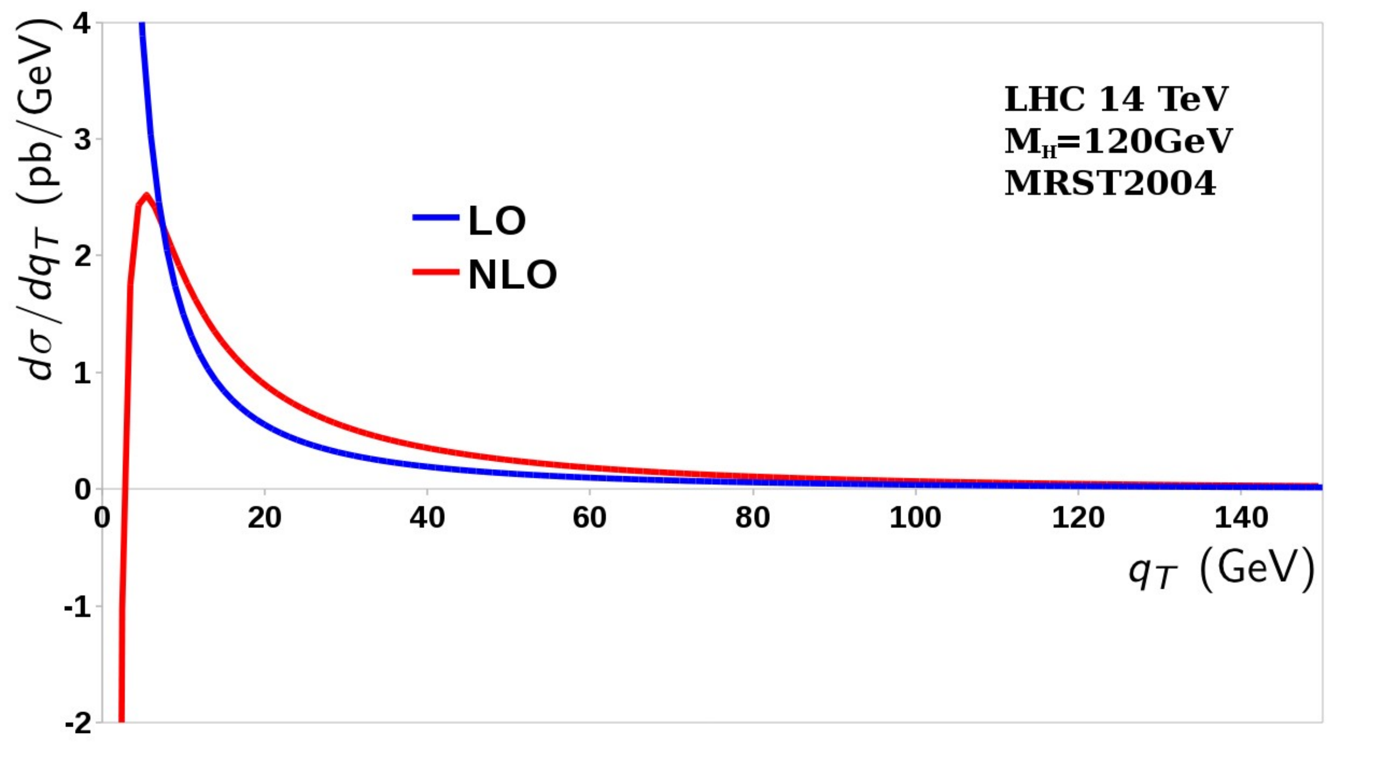
- For the Higgs boson production, the full kinematics is described by the rapidity (y) and the transverse momentum (q_T or p_T)
- Only the decay products are observable. Interesting rapidity, transverse momentum, and also angular variables

Higgs production: rapidity distribution



- The rapidity distribution for the Higgs production is mainly driven by the PDFs of the incoming hadrons.
- Rather stable shape at various perturbative orders

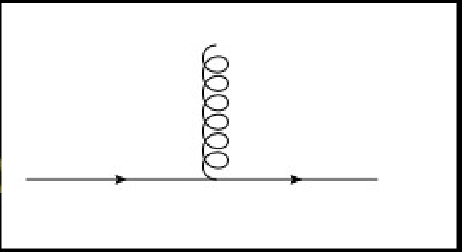
Higgs production: transverse momentum distribution



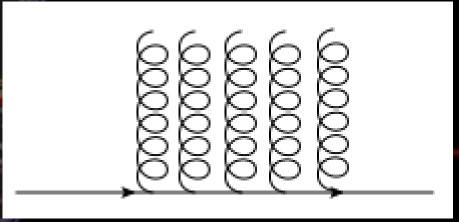
- In the limit $q_T \to 0$ the predictivity of the theory fails: at LO $d\sigma/dq_T$ diverges to $+\infty$ and at NLO there is an unphysical peak and then diverges to $-\infty$.
- The problem comes from soft gluon emission

Resummation (1)

- The problem arises from the emission of one or more soft gluons, that gives terms enhanced by powers of $L \equiv Log(M_H^2/q_T^2)$



- If $q_T \sim M_H \rightarrow L \approx 0$
- If $q_T \ll M_H \rightarrow L \gg 1$



- If we resum the emission of soft gluons, we can reorganize the series:

$$\sum_n \alpha_s^n \rightarrow \sum_{n,m} \alpha_s^n L^m$$

- Note: we can introduce a new unphysical resummation scale Q (with $Q \sim M_H$), analogous to the factorization and renormalization scales

$$Log\left(\frac{M_H^2}{q_T^2}\right) = Log\left(\frac{M_H^2}{Q^2}\right) + Log\left(\frac{Q^2}{q_T^2}\right)$$

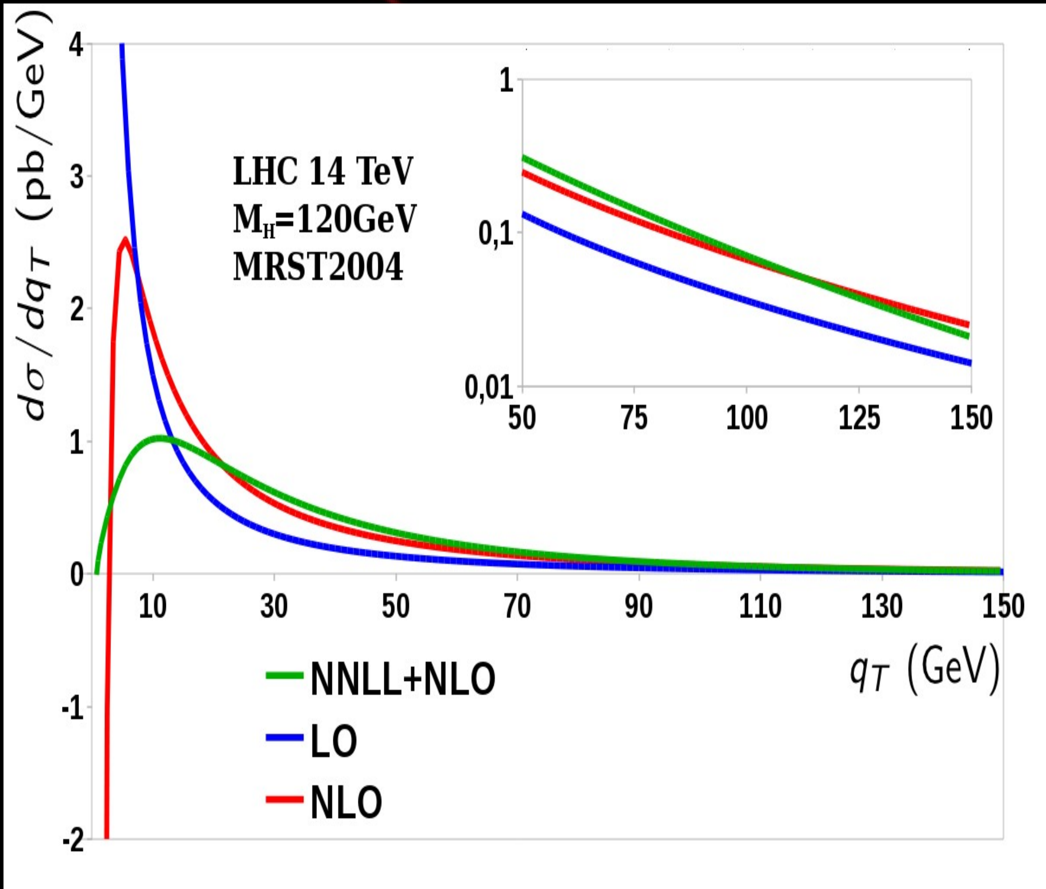
Resummation (2)

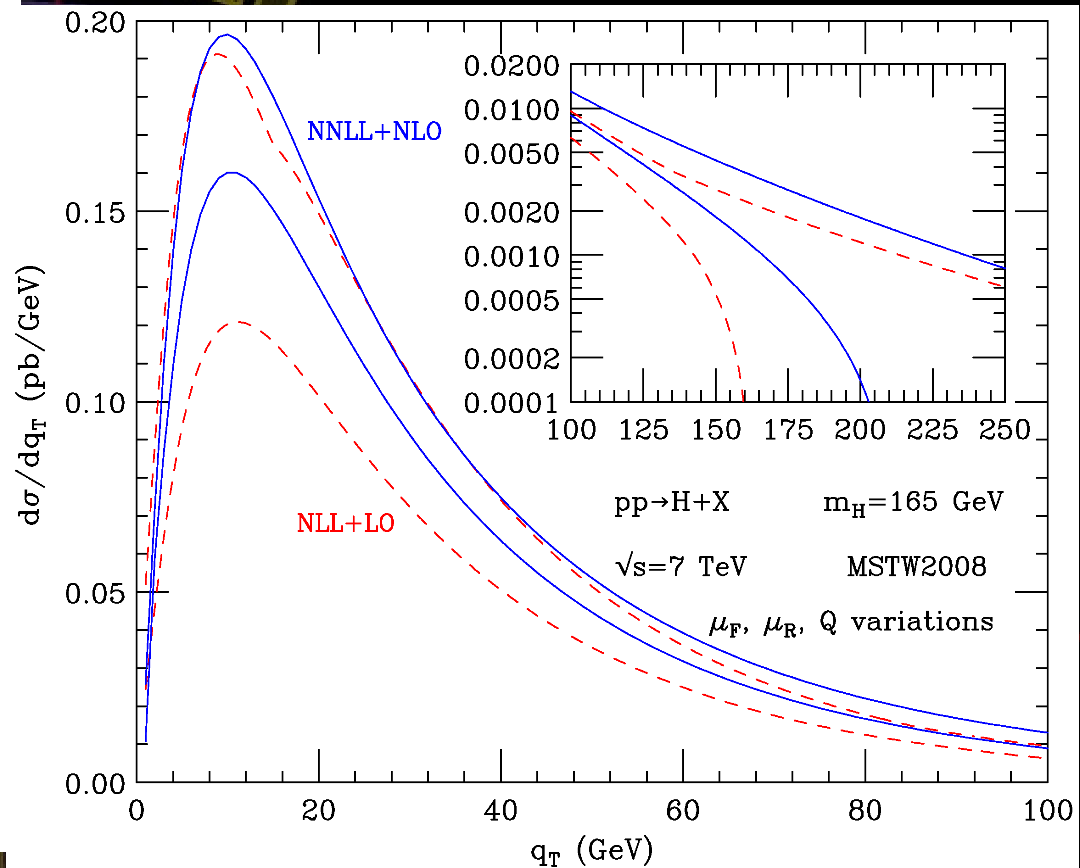
- We introduce the following decomposition of the partonic cross section

$$\frac{d\sigma}{dq_T^2} = \frac{d\sigma^{(res)}}{dq_T^2} + \frac{d\sigma^{(fin)}}{dq_T^2}$$

- The (res) term contains all the logarithmically enhanced contributions at small q_T and has to be computed by resumming them to all orders in α_S. These contribution can be organized in classes of terms (LL, NLL, NNLL...)
- The (fin) component is free of such contributions and can be evaluated by fixed order truncation of the perturbative series
- The resummed component gives the dominant contribution in the small q_T region, while the finite component dominates at large values of q_T.
- The two components have to be consistently matched at intermediate values of q_T.

HqT2.0 numerical code





- This formalism has been implemented in a numerical code named HqT. The obtained distribution has no divergences in the limit $q_T \to 0$ and no unphysical peak
- At high q_T we recover the f.o. results
- HqT widely used by the experimental collaborations at the Tevatron and the LHC to correct (reweight) the q_T distribution from MC event generators.

Higgs decay

- The q_T distribution of the Higgs boson is important, but it isn’t directly observable in the detectors; we can observe only the decay products

- It is important to extend the computation to include the Higgs decay

The new code **HRes**

- We start from the NNLL prediction for $d\sigma/dp_T dy$; extension to rapidity does not lead to substantial theoretical complications - G.Bozzi, S.Catani, D. de Florian, M.Grazzini (2007)
- Despite the extension is theoretically straightforward, the efficient generation of Higgs like events according to the resummed double differential distribution and the inclusion of the decay require substantial improvements in the computational speed
- We then match the result with the fixed order computation implemented in `HNNLO` - We thus obtain a result which is everywhere as good as the NNLO result but includes the resummation of the large logarithmic terms at small transverse momenta
- The calculation is implemented in a new numerical code name `HRes` that merges the features of `HNNLO` and `HqT`

The new code **HRes**

- 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 $H \to ZZ \to 4l$
- The user can select the cuts and the required distributions can be obtained with the same run
- Price to pay: we must be inclusive over recoiling QCD radiation

D. de Florian, G. Ferrera, M. Grazzini, DT [JHEP 06(2012)132]

http://theory.fi.infn.it/grazzini/codes.html

Effect of cuts in photon distributions

- The real detectors have a finite acceptance. We consider a realistic example at LHC $\sqrt{s}$=8TeV and m_H=125GeV

$$gg \rightarrow H + X \rightarrow 2\,\gamma + X$$

- For each event we classify the photon transverse momentum according to the minimum and maximum value:

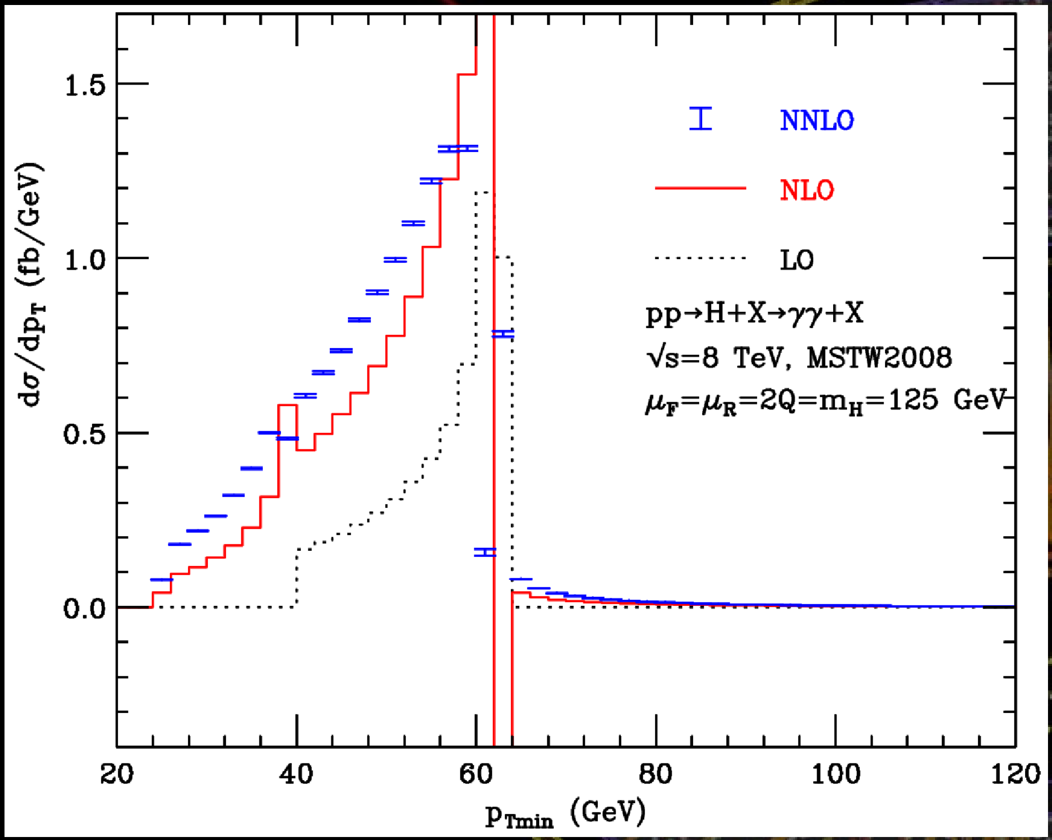
  (p_{Tmin}, p_{Tmax}) and we study the relative distributions

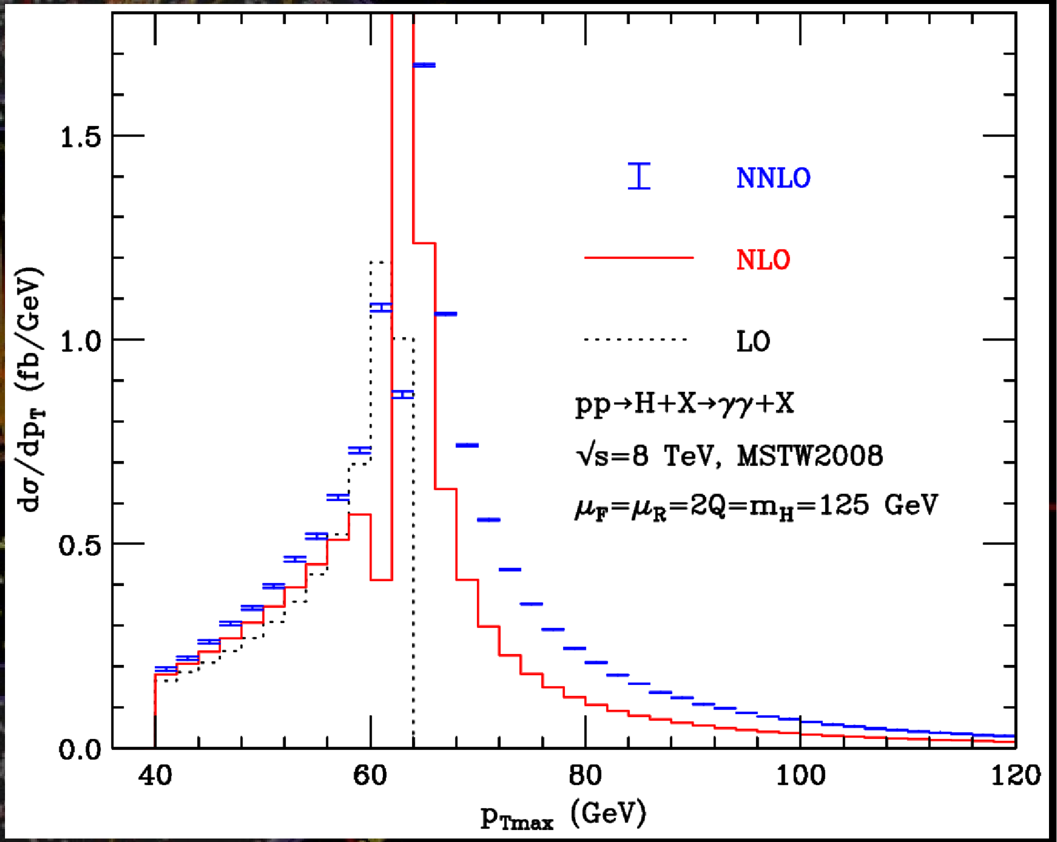
- Cuts: p_{Tmin} > 25GeV, p_{Tmax} > 40GeV, $|\eta|<2.5$

Cross section	LO	NLO	NLL+NLO	NNLO	NNLL+NNLO
Total [fb]	17.08	30.79	30.65	38.4	38.5
With cuts [fb]	11.14	21.55	21.54	27.0	27.0
Efficiency %	65.3	70.0	70.3	70.2	70.2

- Effect of these cuts on the cross section: no substantial differences between resummed and f.o. predictions

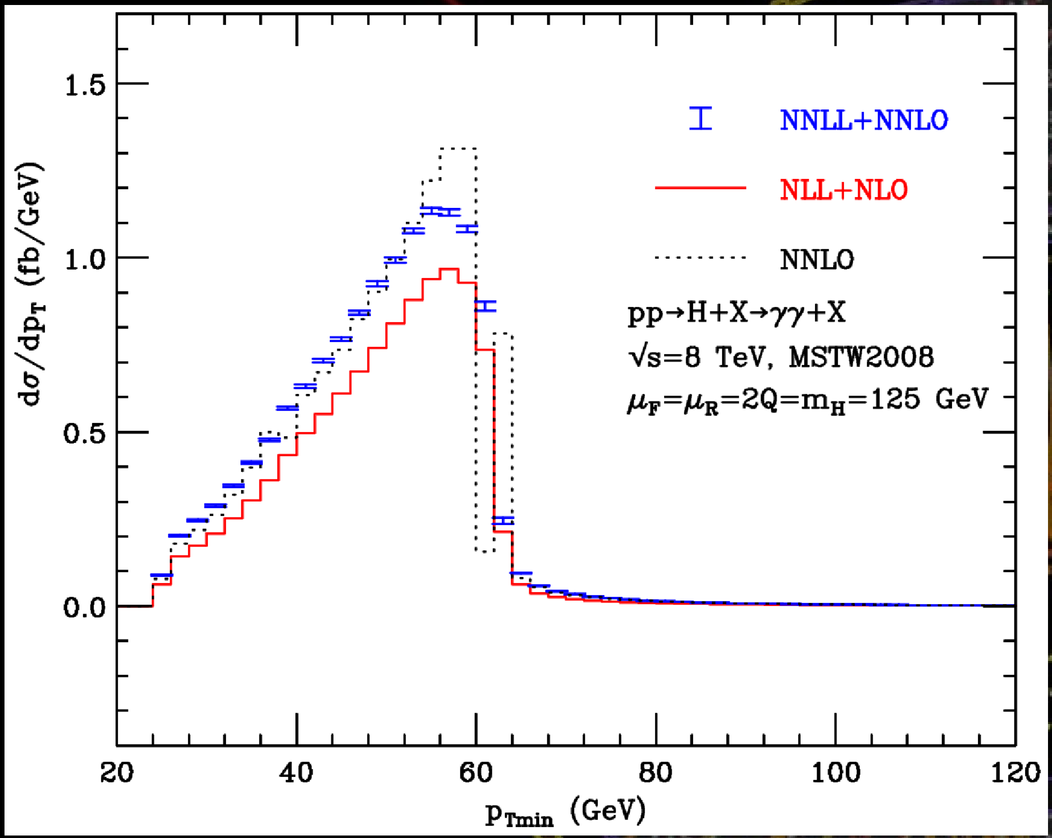
HNNLO: Photon p_{Tmin} and p_{Tmax} distributions

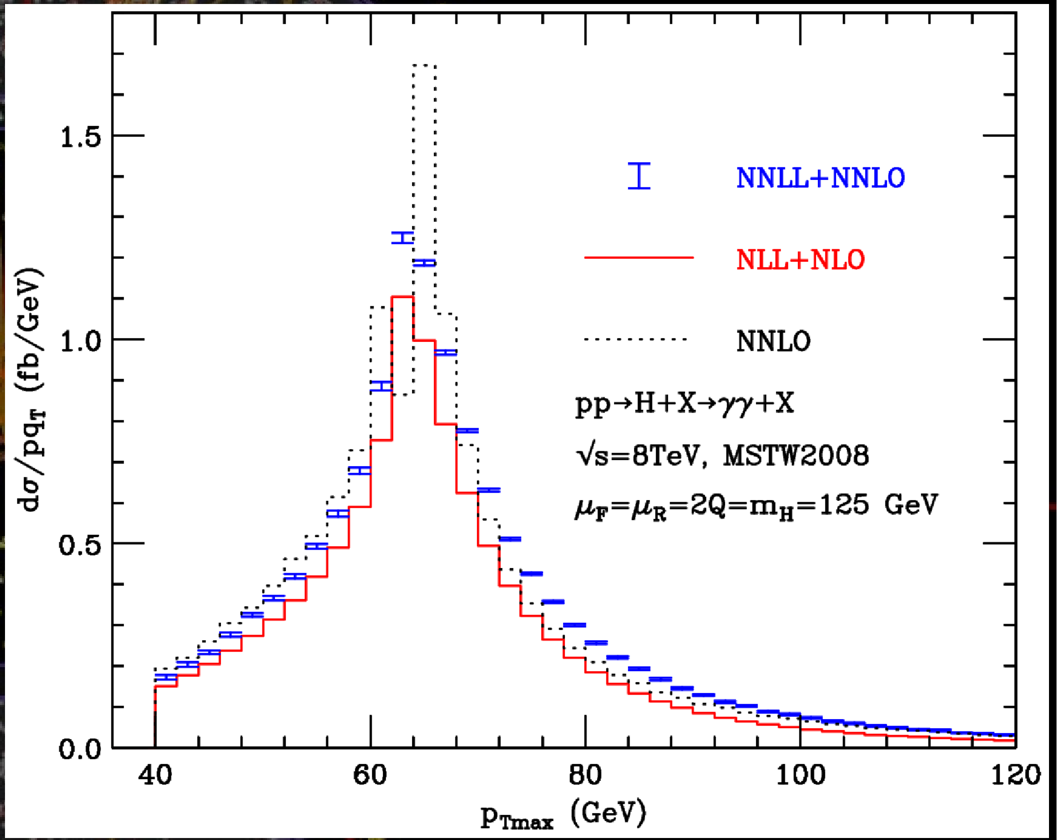




- LO: kinematical boundary at $m_H/2$
- At NLO and NNLO: enhancement almost proportional to the rising total cross section; QCD radiation allows events beyond the kinematical limit
- Fixed order calculations: around the point of discontinuity at LO, there are instabilities at (N)NLO ⇒ Sudakov shoulder [Catani, Webber '98]

HRes: Photon p_{Tmin} and p_{Tmax} distributions





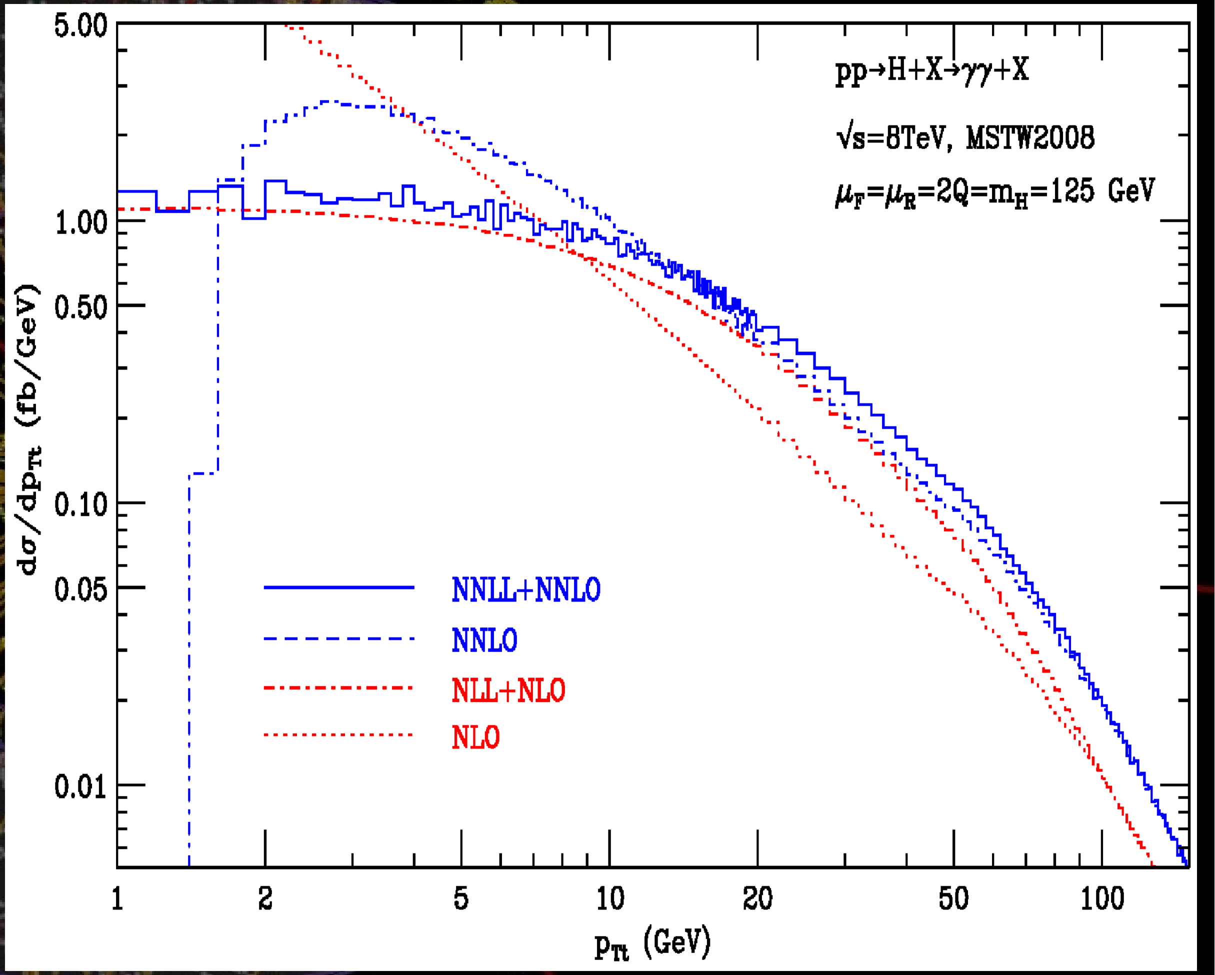
- The resummed distributions are smooth and the shape is rather stable, fixed order prediction recovered out from the unstability region

Predictions on the pTthrust distribution

$$p_{Tt} = |\vec{p}_{\mathrm{T}}^{\gamma\gamma} \times \hat{t}|$$

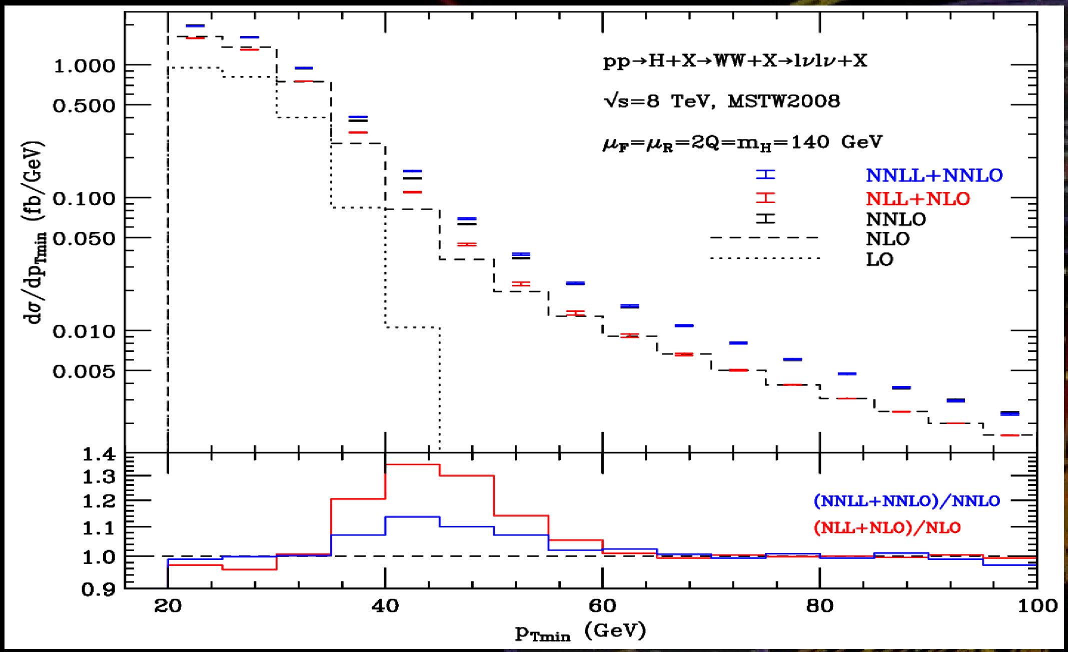
Where, the thrust versor t and the transverse momentum of the γγ diphoton system are defined as follows

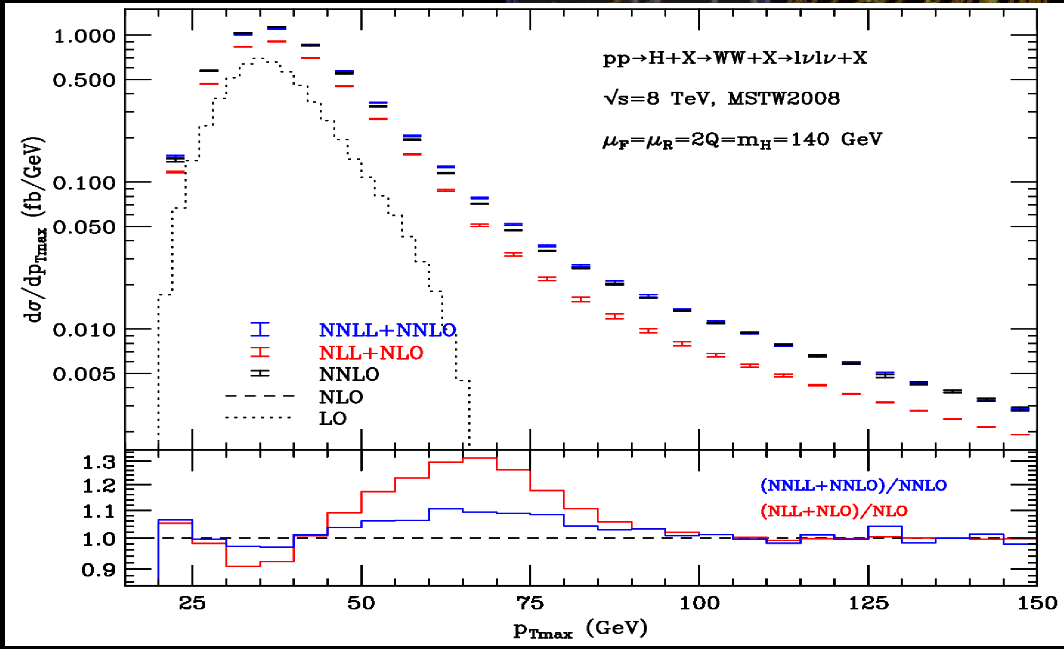
$$\hat{t} = \frac{\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}}{|\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}|}; \qquad \vec{p}_{\mathrm{T}}^{\gamma\gamma} = \vec{p}_{\mathrm{T}}^{\gamma_1} + \vec{p}_{\mathrm{T}}^{\gamma_2}$$



The pTthrust variable is used by the ATLAS analysis to classify the events into categories

$H \rightarrow WW \rightarrow l\nu l\nu$

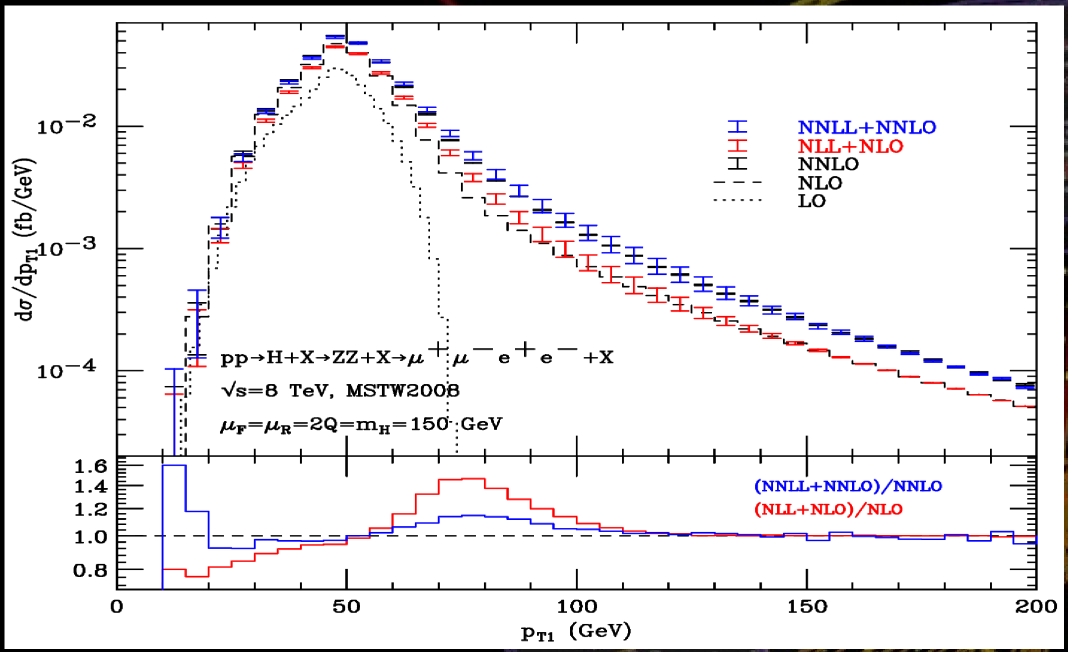


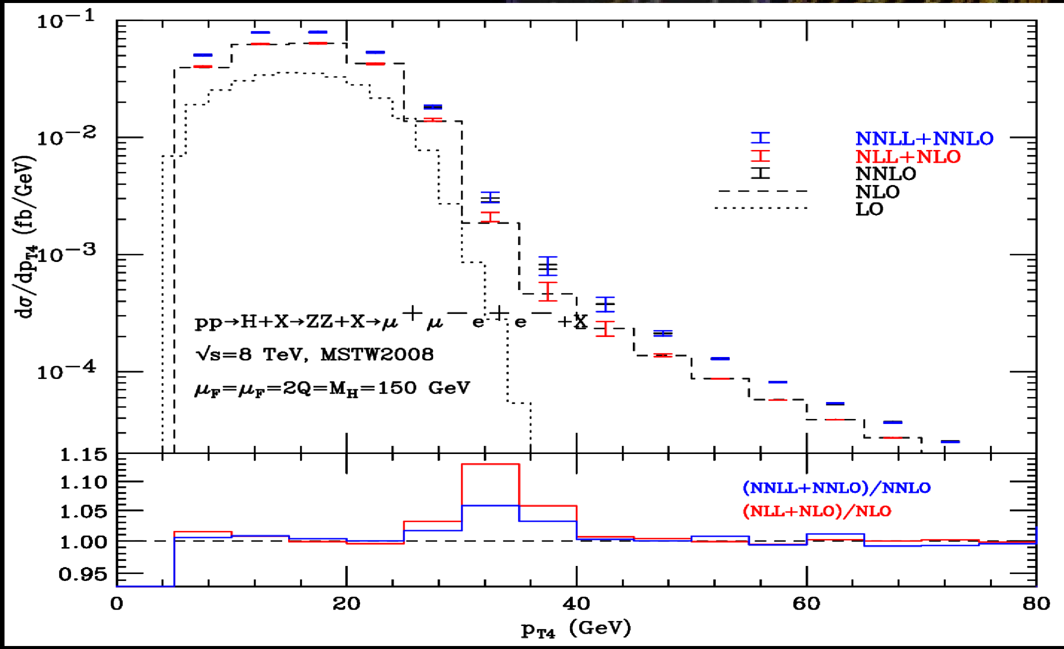


- LHC $\sqrt{s}$=8TeV, m_H=140GeV

  $gg \rightarrow WW + X \rightarrow l\nu l\nu + X$
- For each event we classify the lepton transverse momentum according to the minimum and maximum value: (p_{Tmin}, p_{Tmax})
- Cuts: lepton p_T > 20GeV & $|\eta|$<2.5, missing p_T > 30GeV, charged leptons invariant mass > 12GeV
- Resummation makes p_T distributions harder, in the intermediate region effect is about +30% at NLL+NLO and +10 % at NNLL+NNLO
- Behaviour at the kinematical boundary is smooth ⇒ no instabilities beyond LO

$H \to ZZ \to 4l$





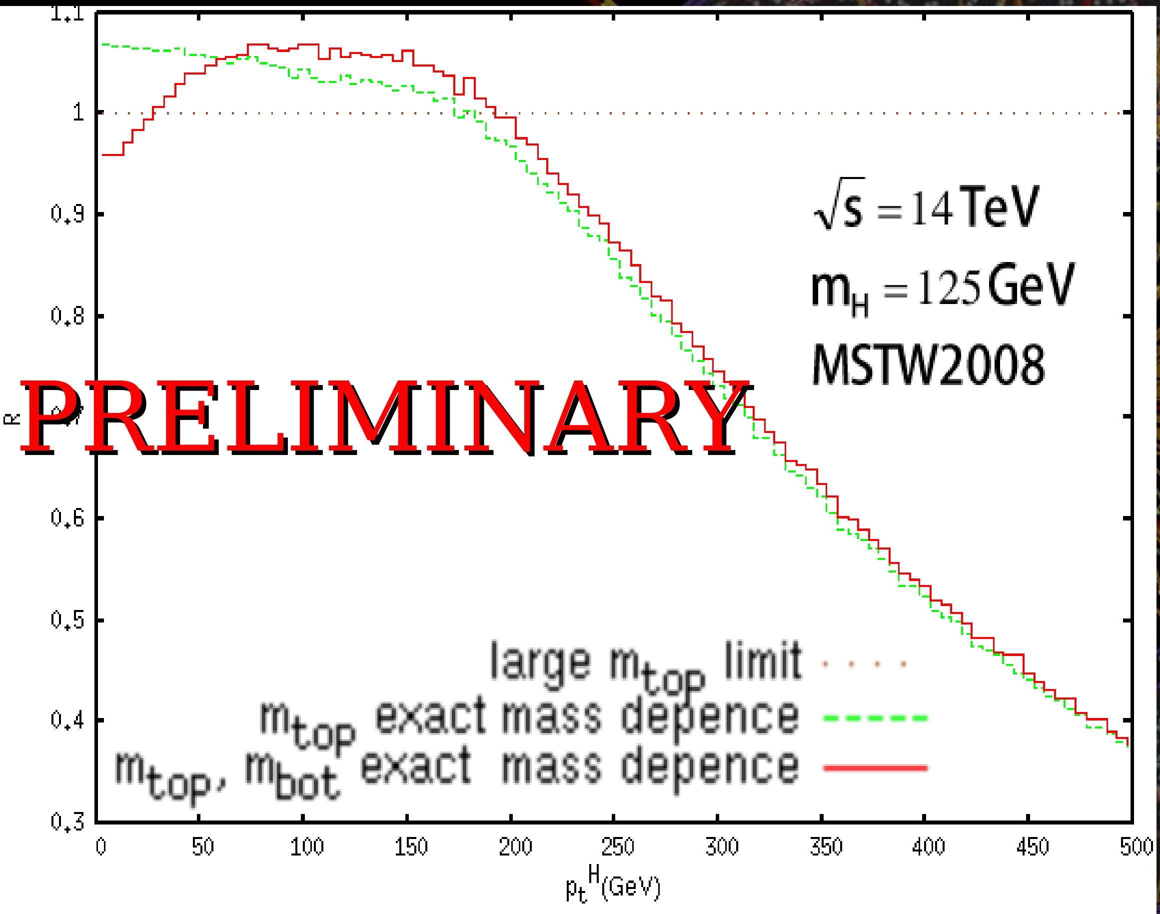
- LHC $\sqrt{s}$=8TeV, m_H=150GeV
- m_1 and m_2 are closest and next to closest to m_z invariant masses
- Cuts: $p_{Tl} > 5$ GeV; $|\eta| < 2.5$; $m_1 > 50$ GeV $m_2 > 12$ GeV
- At LO kinematical boundary:

  softest lepton $p_T > m_H/4$

  hardest lepton $p_T > m_H/2$
- As for the WW decay, resummation makes p_T distributions harder; behaviour at the kinematical boundary is smooth no instabilities beyond LO

Beyond the large-mtop approximation

Transverse momentum distribution in HNNLO at the NLO accuracy



Work in progress by H. Sargsyan

Good agreement previous works [Bagnaschi et al. 2011]

- At the large transverse momentum the top quark contribution dominates and reduces the cross section with respect to the result in the largemtop limit
- The knowledge of the exact shape of the transverse momentum distribution will be important for the boosted analysis
- Main contribution of the bottom quark in the low transverse momentum region; negative by the top-bottom interference in the Born term

Summary

- The year 2012 is the year of the SM Higgs boson. There is evidence of a new boson in the mass region around 125~126GeV.

  More data from LHC are needed

- On theoretical side, efforts are needed to improve results and reduce their uncertainties.

- New code HRes: it merges the features of HNNLO and HqT to include the resummation of the logarithmically enhanced terms at small transverse momentum and allows to obtain accurate predictions, including the effects of cuts, for the differential distributions: Higgs boson production up to NNLL+NNLO and decay in two photons and WW/ZZ to four leptons.

  Some typical pathologies of the fixed order predictions solved

- Work in progress for both HNNLO and HRes: going beyond the large-mtop approximation in the transverse momentum spectrum for NNLO and NNLL+NNLO predictions

Photon |*cos θ**| distribution

- We study the distribution on |*cos θ**|, where *θ** is the polar angle of one of the photons in the rest frame of the Higgs boson.
- The 4-momentum of the photon is $q_\gamma \equiv \left(\frac{m_H}{2}, \overrightarrow{q_T}, q_z\right)$
- At the LO, the Higgs boson has q_T=0,

  we have the two relations: $\begin{cases} (\overrightarrow{q_T})^2 + q_Z^2 = \left(\frac{m_H}{2}\right)^2 \\ |\cos\theta^*| = \frac{|q_z|}{m_H/2} \end{cases}$

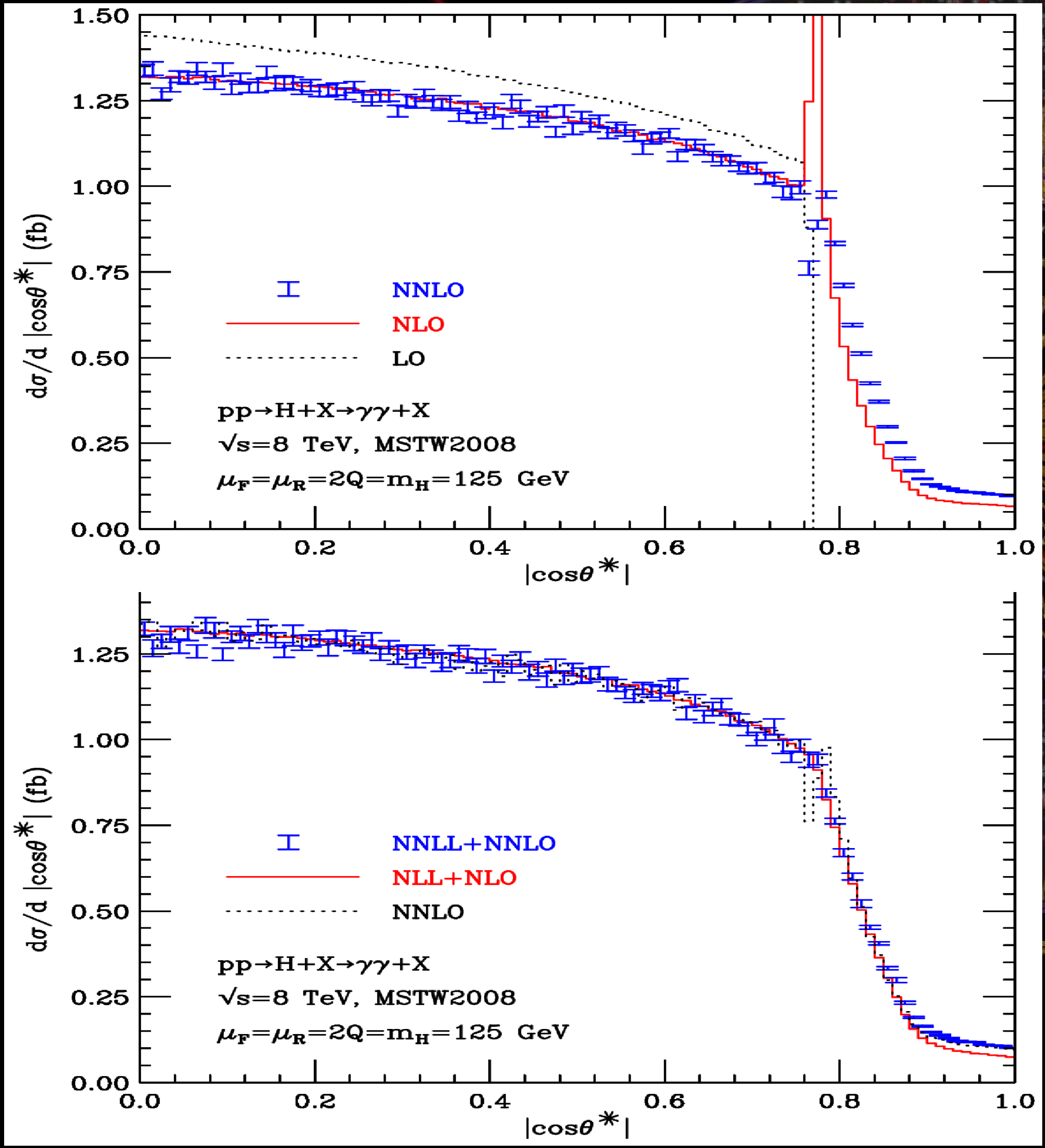
  then $q_z = \sqrt{\left(\frac{m_H}{2}\right)^2 - (\overrightarrow{q_T})^2} \;\Rightarrow\; |\cos\theta^*| = \sqrt{\left(1 - \frac{4(\overrightarrow{q_T})^2}{m_H^2}\right)}$

- If q_T > 40GeV and m_H = 125GeV, we finally obtain

  $$q_T \geq q_{Tcut} \;\Rightarrow\; |\cos\theta^*| \leq |\cos\theta^*_{cut}| \sim 0.768$$

- At NLO and NNLO the |*cos θ**| distribution suffers from perturbative instabilities in the region of the angular-cut.

Predictions on the normalized photon |cos θ*| distribution



- The f.o. results suffer from perturbative instabilities
- As before, the resummed results are smooth and more stable
- Note: perfect agreement of resummed and fixed order prediction away from the instability region