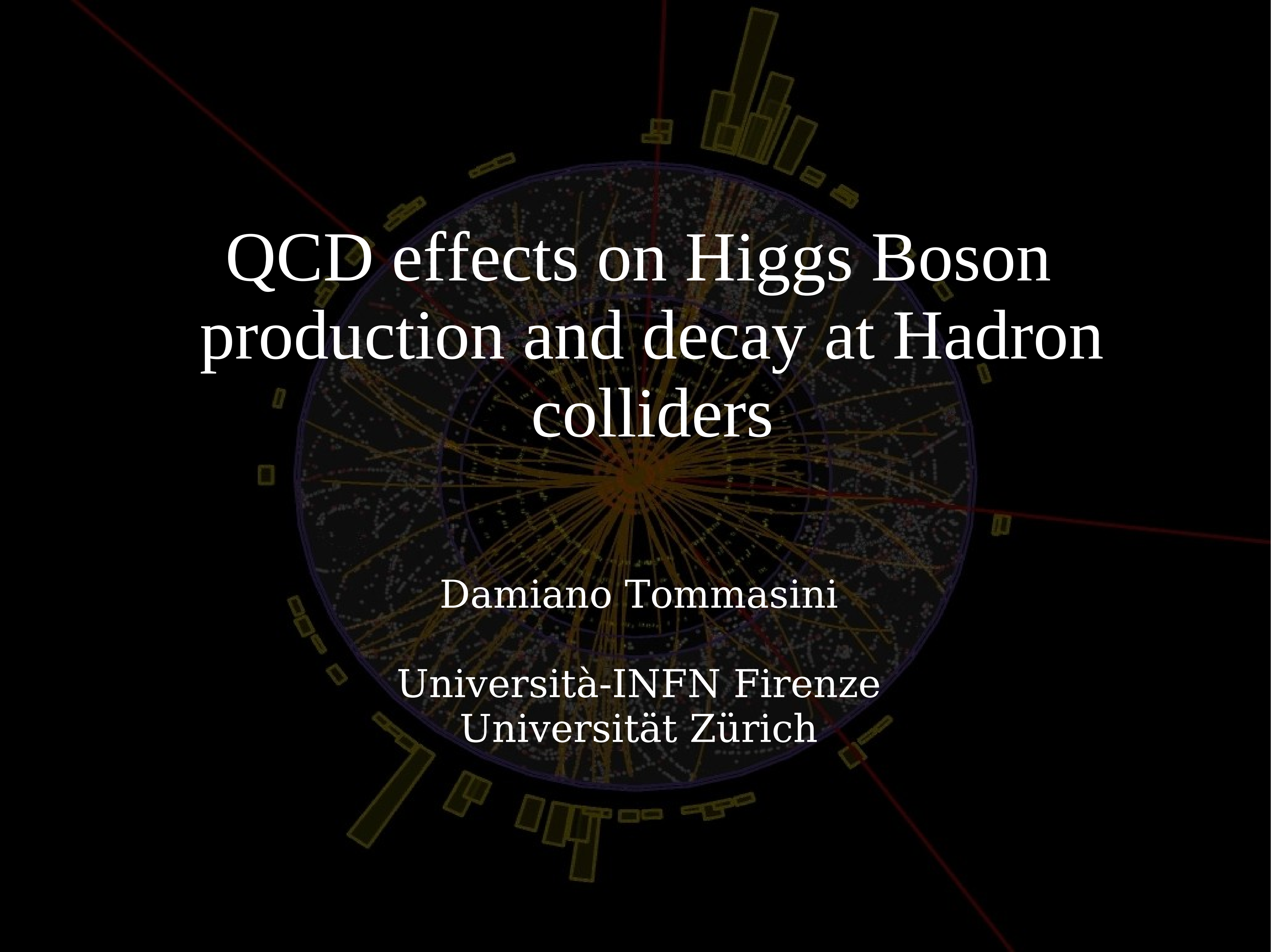

QCD effects on Higgs Boson production and decay at Hadron colliders

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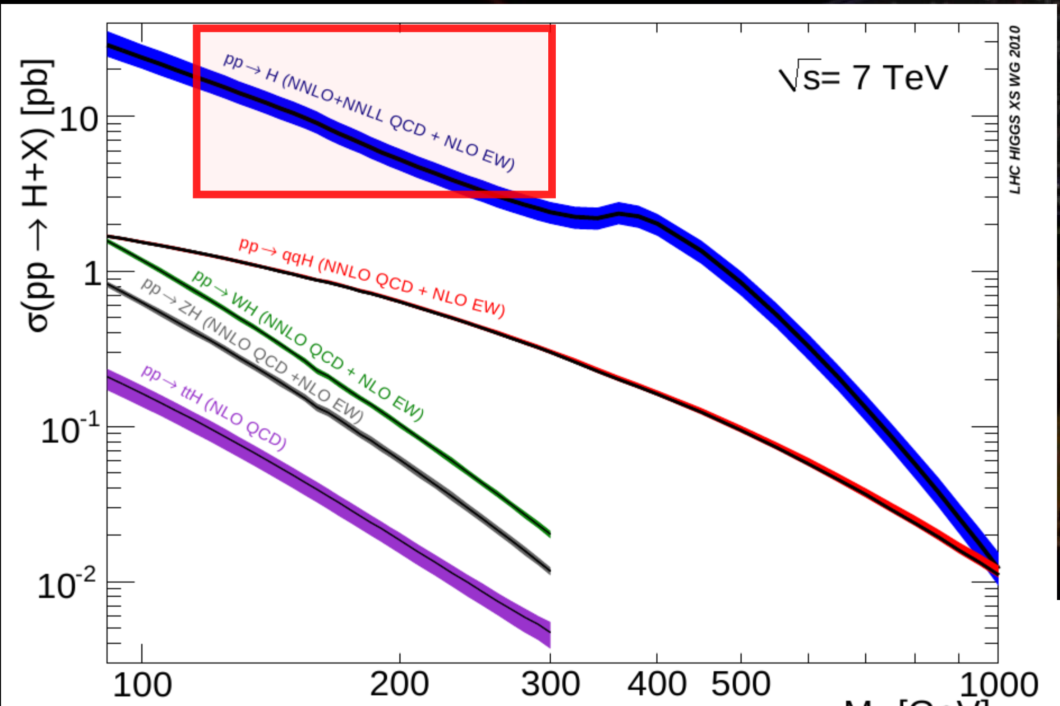
Outline

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

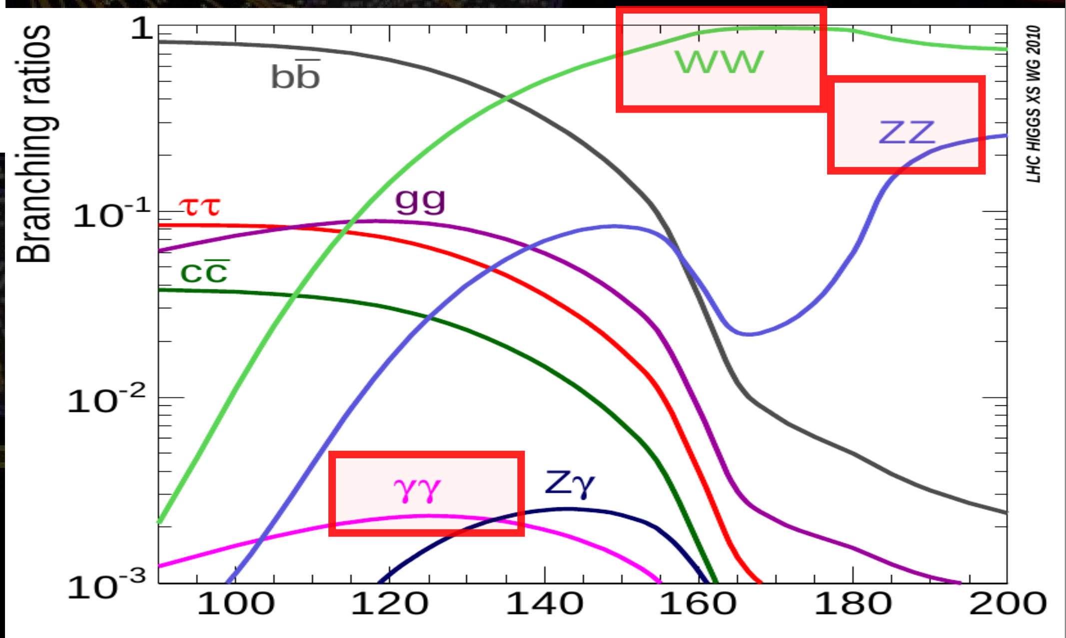
  $H \to W\,W \to l\nu l\nu$ and $H \to ZZ \to 4l$
- Summary

Higgs search at hadron colliders



arXiv:1101.0593v3 [hep-

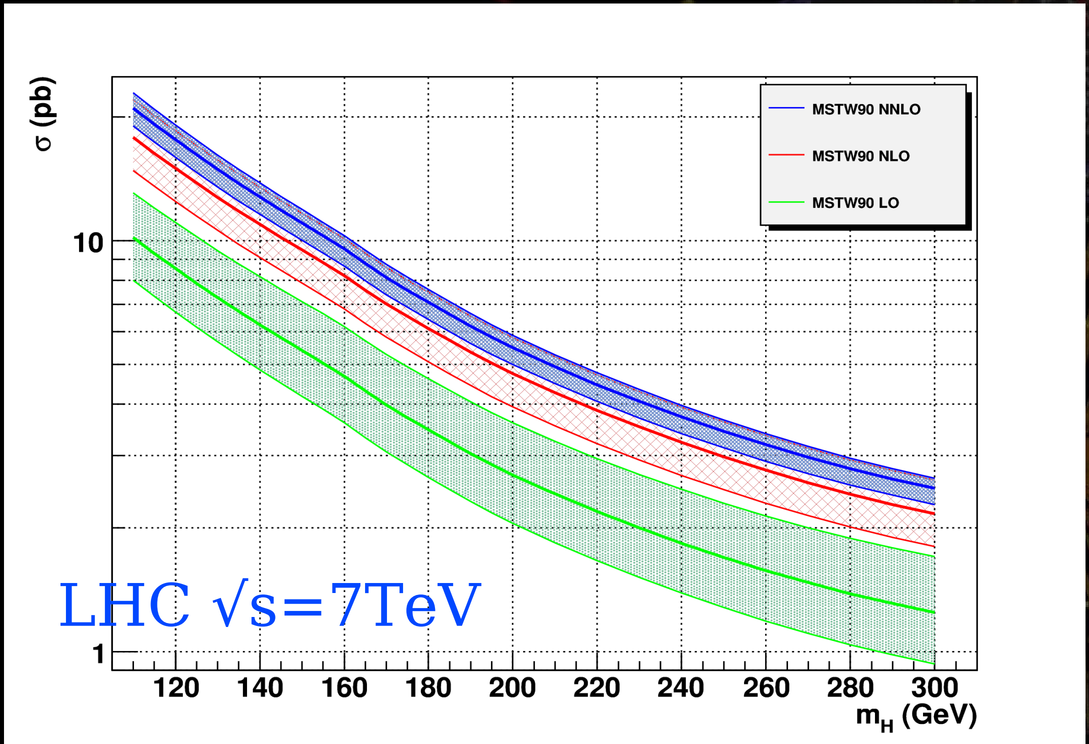
- One of the most important production channel is the gluon-gluon fusion (largest cross section). Calculated up to NNLL+NNLO QCD & NLO EW



arXiv:1101.0593v3 [hep-

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

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

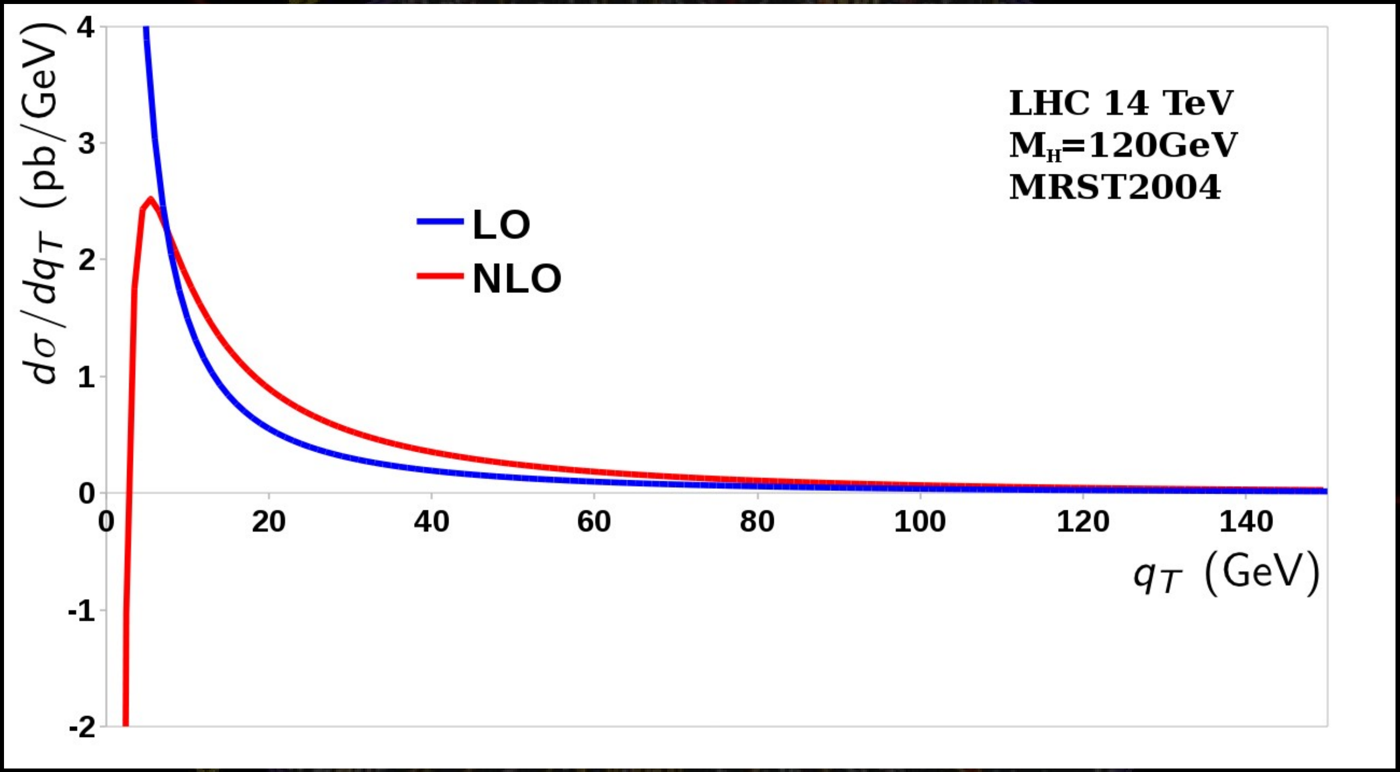
From total cross section to differential distributions

- Total cross sections are ideal quantities (the detectors have finite acceptances)
  ⟹ differential distributions are needed

- For Higgs boson production, the full kinematics is described by the rapidity (y) and the transverse momentum (q_T or p_T)
  Drell-Yan like process. See Simone Marzani's talk

- Only the decay products are observable. Interesting rapidity, transverse momentum, and also angular variables

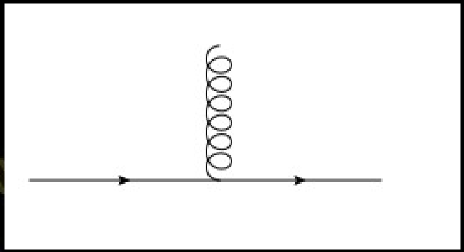
Higgs production: transverse momentum distribution



- 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

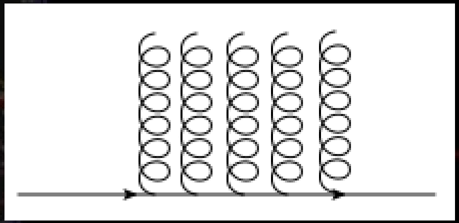
Resummation: main idea

- 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 $q_T \ll m_H \rightarrow L \gg 1$



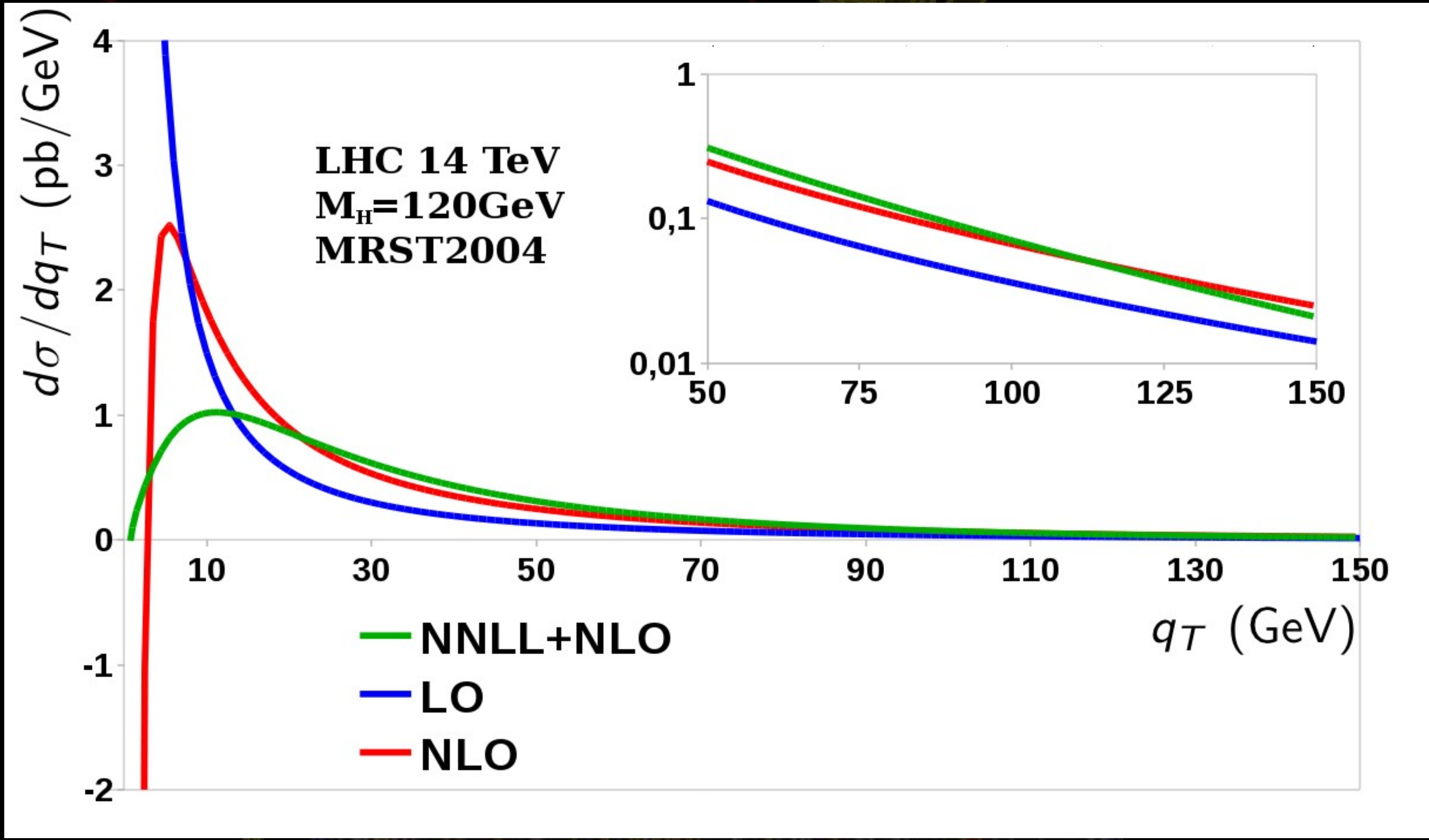
- If we resum the emission of soft gluons, we can reorganize the series:

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

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

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

HqT 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.

Upgrade from `HqT` to the new code `HqT2.0`

Limits of the previous verson of `HqT`:

- Approximations in the NNLL predictions: the $H^{(2)}$ function was estimated by the unitarity constraint and the A_3 coefficient was assumed the same as the one in the threshold resummation
- Resummation scale dependence not implemented $\Rightarrow$ there is no way to estimate the resummation uncertainties

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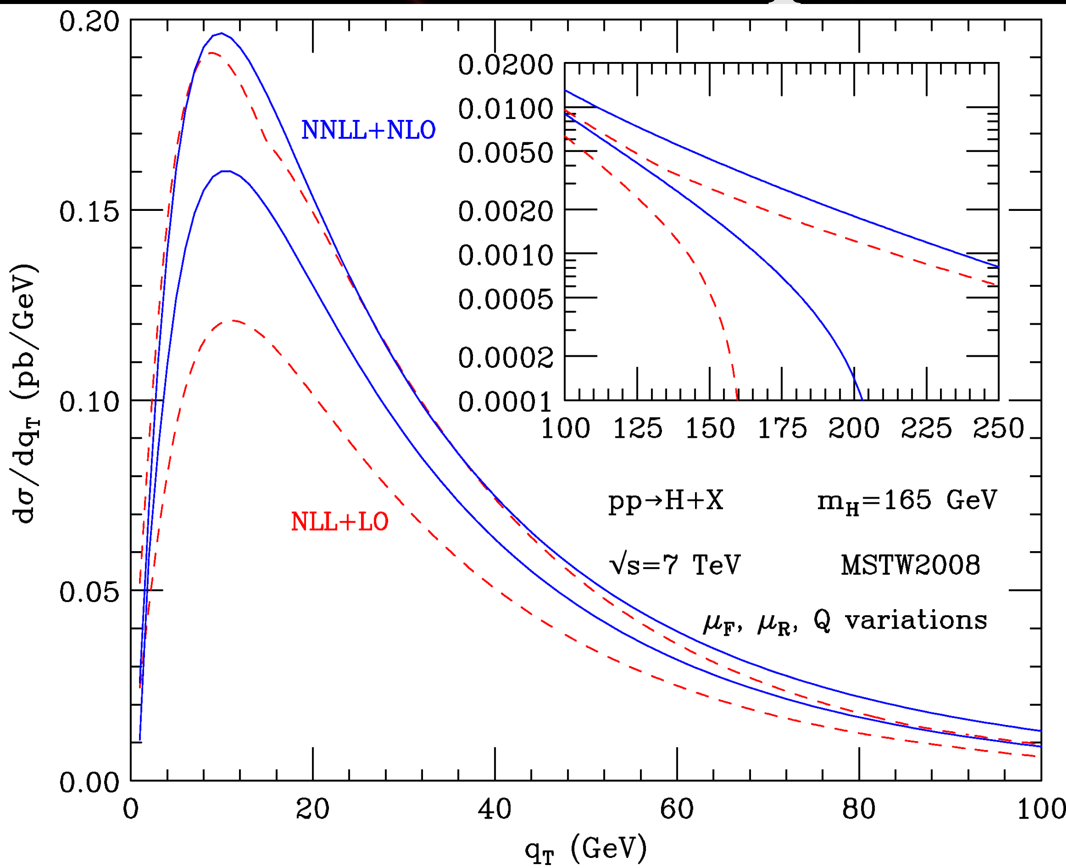
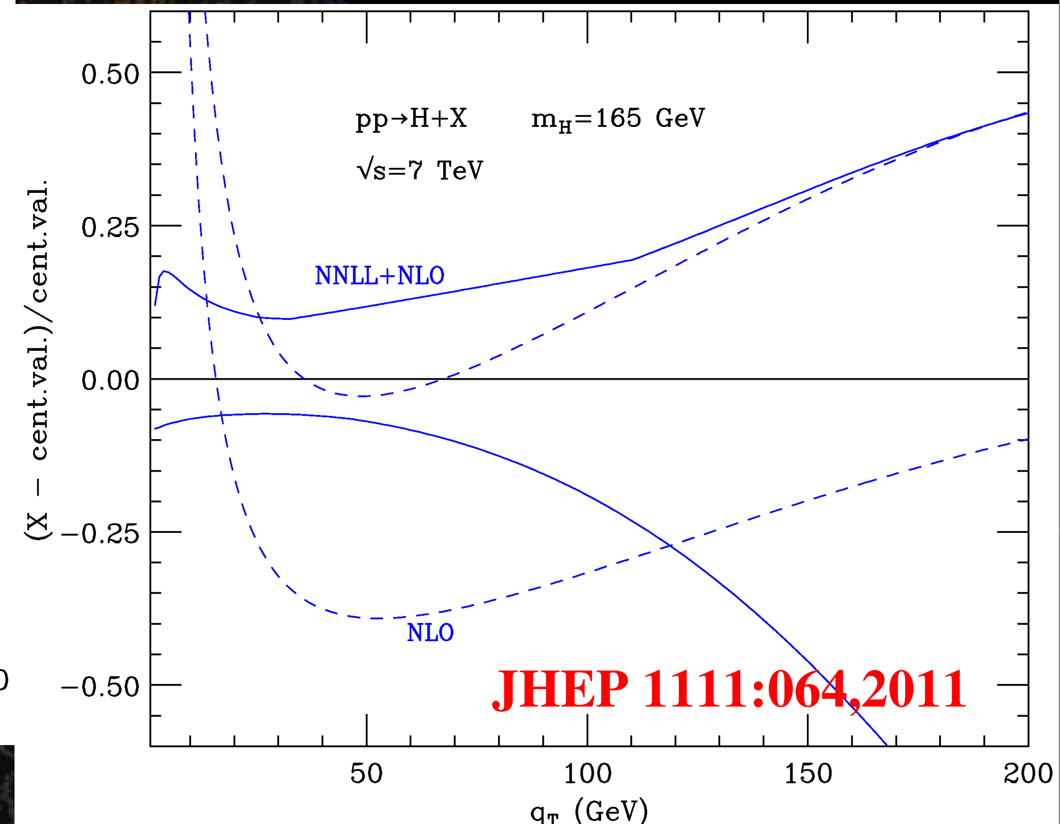
Upgrades:

- Now we know the exact form of the functions $H^{(2)}$ (Catani,Grazzini '11) and A_3 (Becher,Neubert '10) → we have computed the Mellin transform of the function $H^{(2)}$ and implemented it in the new version of the code → we obtain a slightly harder distribution (of the order ~1-2%)
- The resummation scale dependence is fully implemented → More reliable estimate of the theoretical uncertainties
- Interface with LHAPDFs and compatibility with new Fortran compilers (practical advantages)

Numerical predictions of `HqT2.0`





- Central value: $\mu_R = \mu_F = 2Q = m_H$
- Scale variations: $m_H/2 \leq \{\mu_R, \mu_F, (2Q)\} \leq 2m_H$ & $½ \leq \{\mu_R/\mu_F, \mu_R/Q\} \leq 2$
- At NNLL+NLO: in the peak region the theoretical uncertainty is of the order of 10%, at ~100GeV about 20%
- High q_T: f.o. calculations (provided by the same code) give more reliable results.

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

D. de Florian, G. Ferrera, M. Grazzini, DT (to appear)

- 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

Effect of cuts in photon distributions

- The real detectors have a finite acceptance. We consider a realistic example at LHC $\sqrt{s}$=8TeV, for the process

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

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

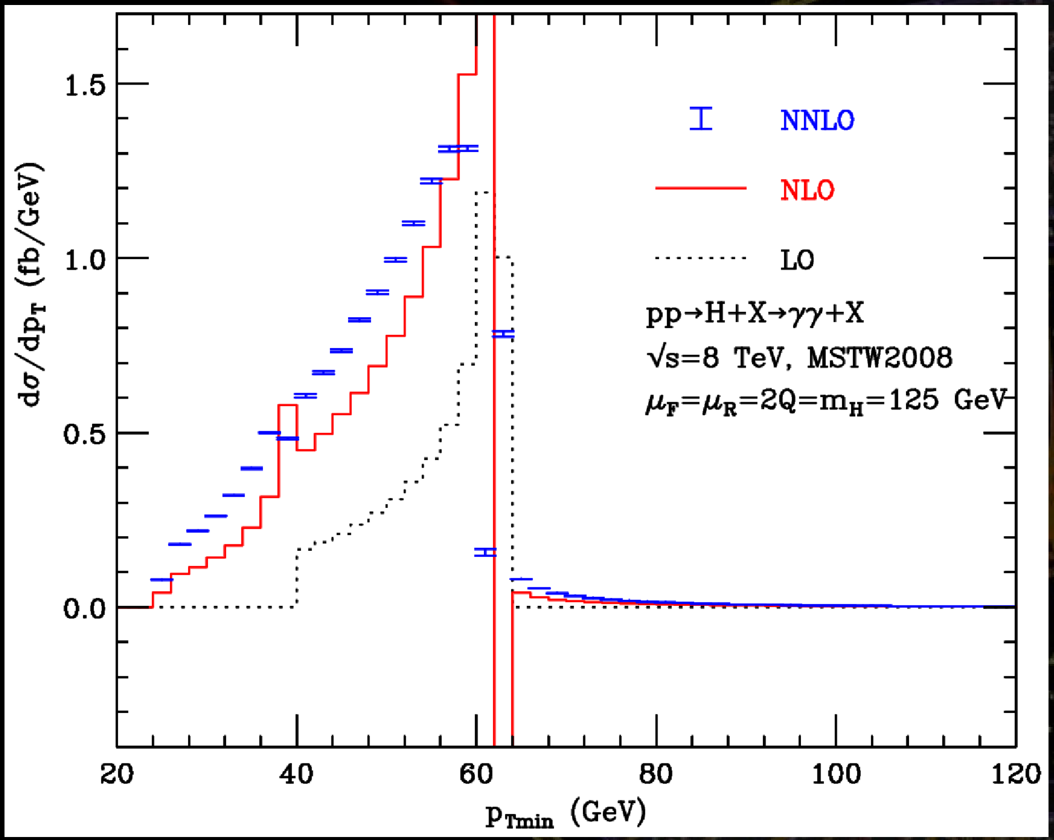
  (p_{Tmin}, p_{Tmax}) and we study the relative distributions

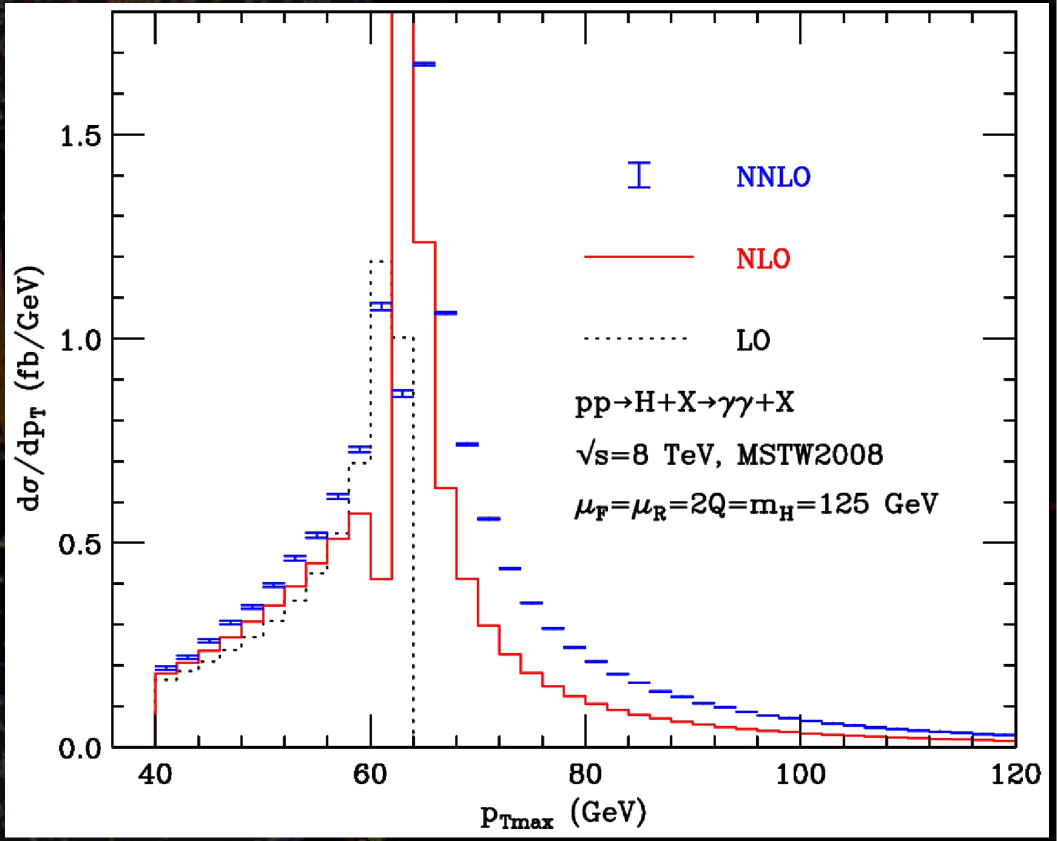
- Cuts: $p_{Tmin} > 25$GeV, $p_{Tmax} > 40$GeV, $|\eta|<2.5$

Cross section	LO	NLO	NLL+NLO	NNLO	NNLL+NNLO
Total [fb]	17.08	30.8	30.7	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

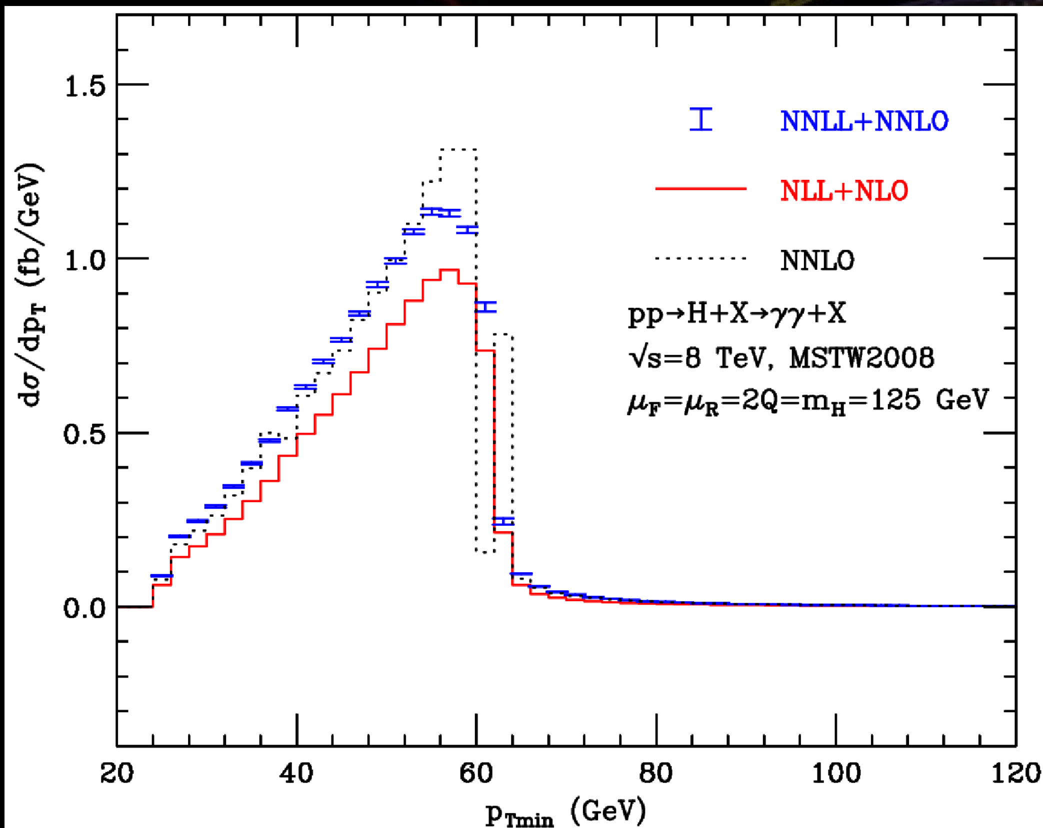
Photon p_{Tmin} and p_{Tmax} distributions

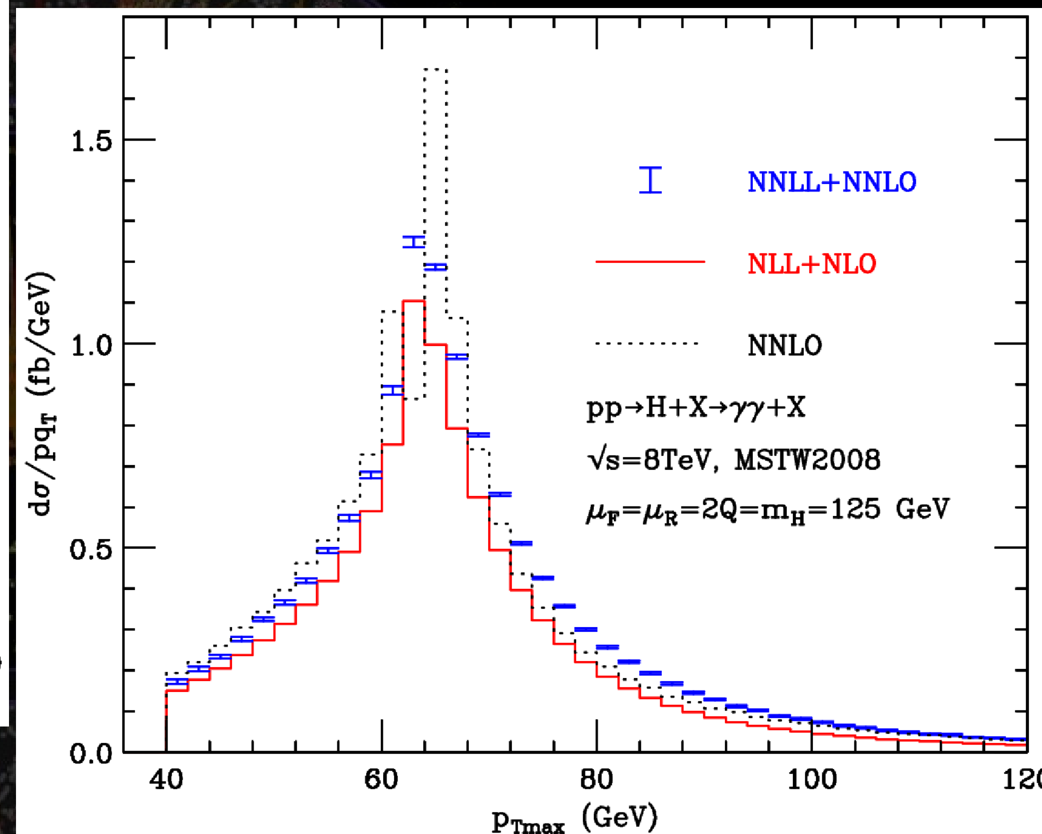




- LO: kinematical boundary at $m_H/2$
- At NLO and NNLO: enhancement almost proportional to the rising total cross section; QCD radiation allows events beyond the kinematical limit
- Around the point of discontinuity at LO, there are instabilities at (N)NLO: Sudakow shoulder (Catani, Webber '98)

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

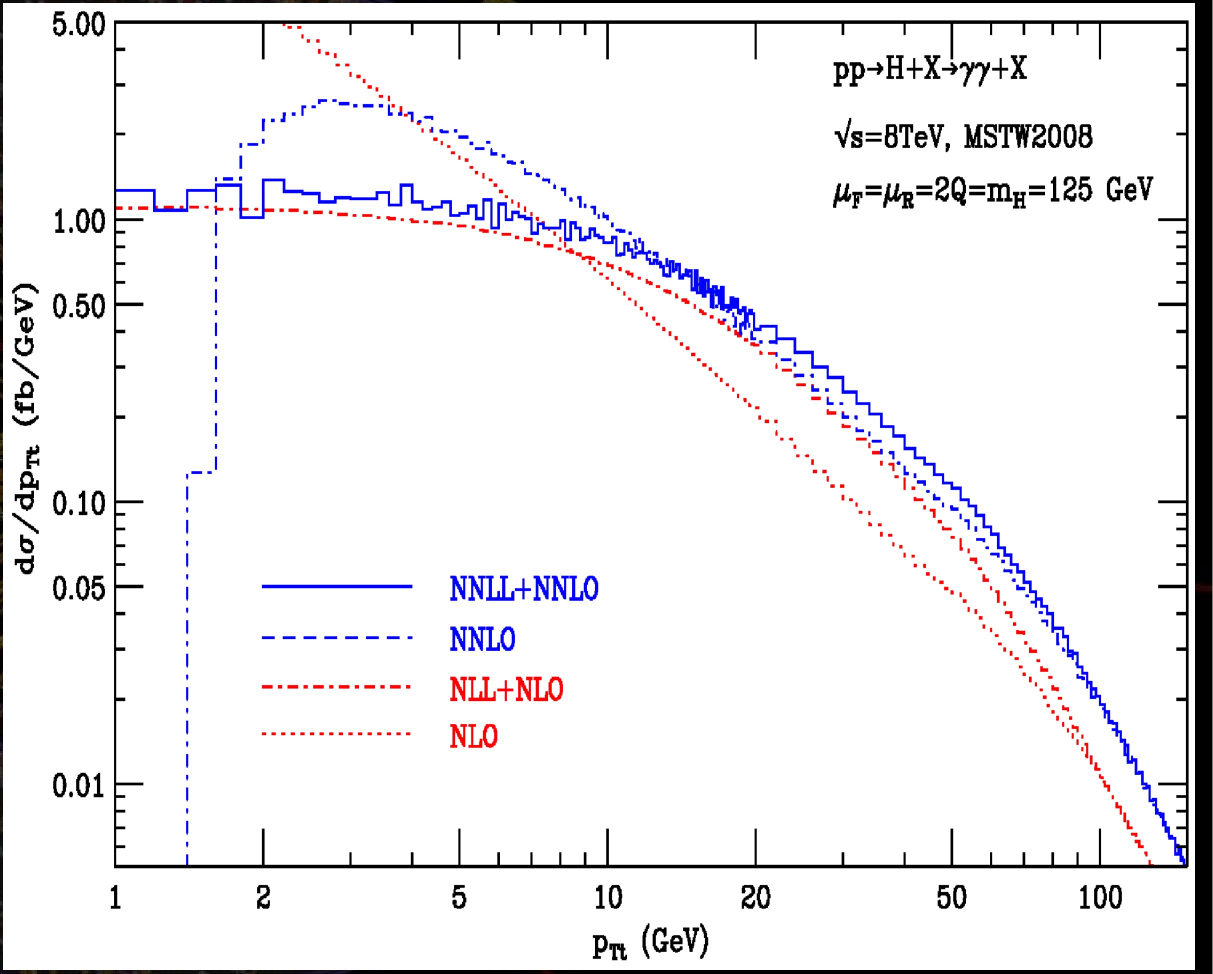
Predictions on the pTthrust distribution

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

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

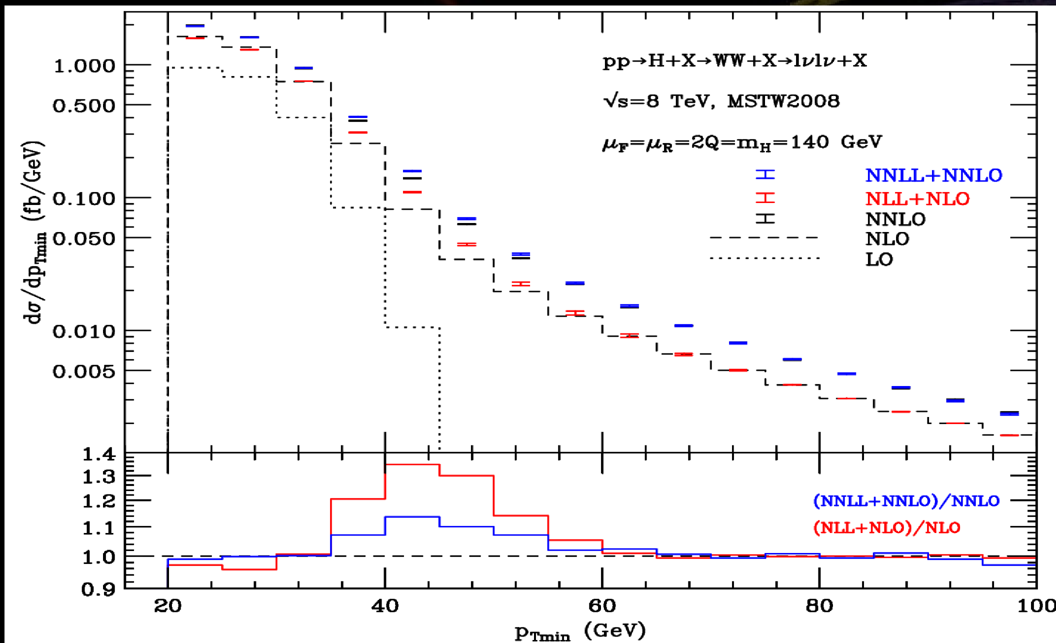
$$\hat{t} = \frac{\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}}{|\vec{p}_{\mathrm{T}}^{\gamma_1} - \vec{p}_{\mathrm{T}}^{\gamma_2}|}; \qquad \vec{p}_{\mathrm{T}}^{\gamma\gamma} = \vec{p}_{\mathrm{T}}^{\gamma_1} + \vec{p}_{\mathrm{T}}^{\gamma_2}$$

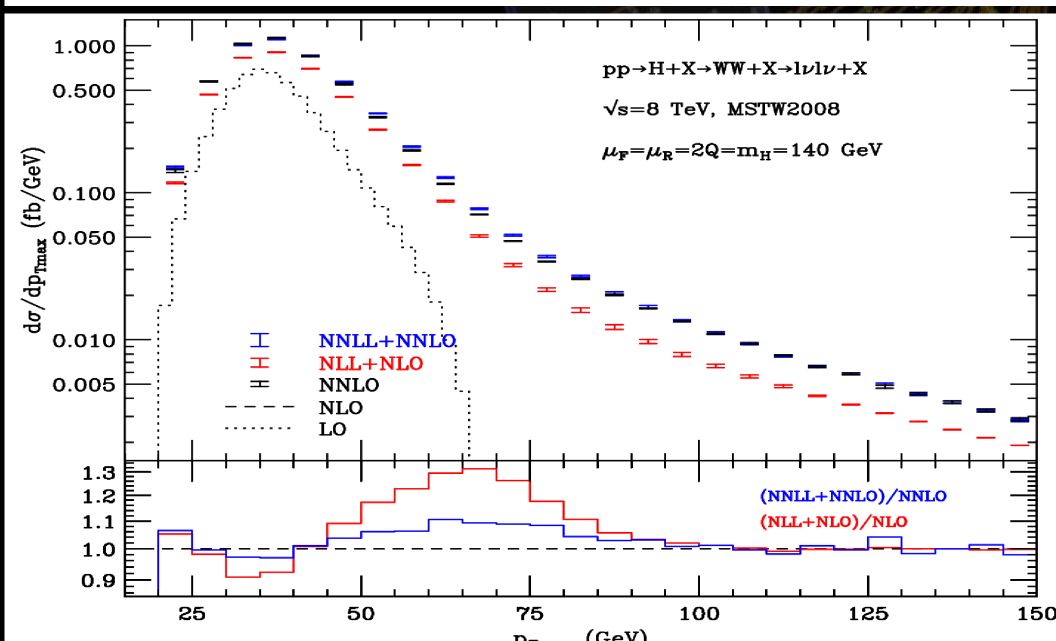
Same variable as a_T defined for the Drall-Yan process



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

$H \to WW \to l\nu l\nu$



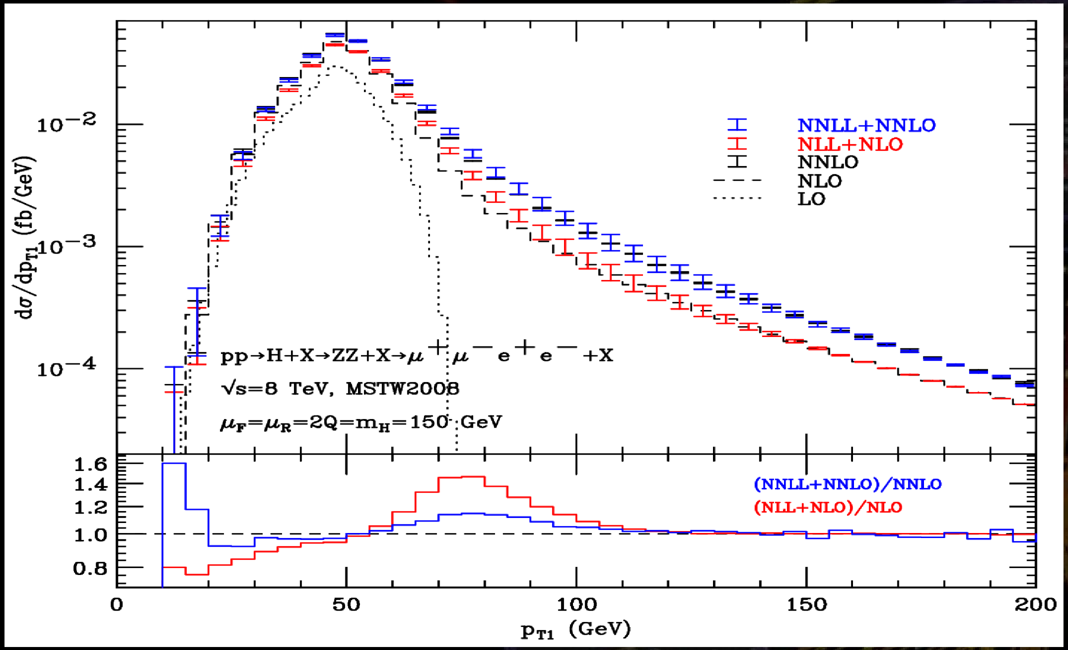


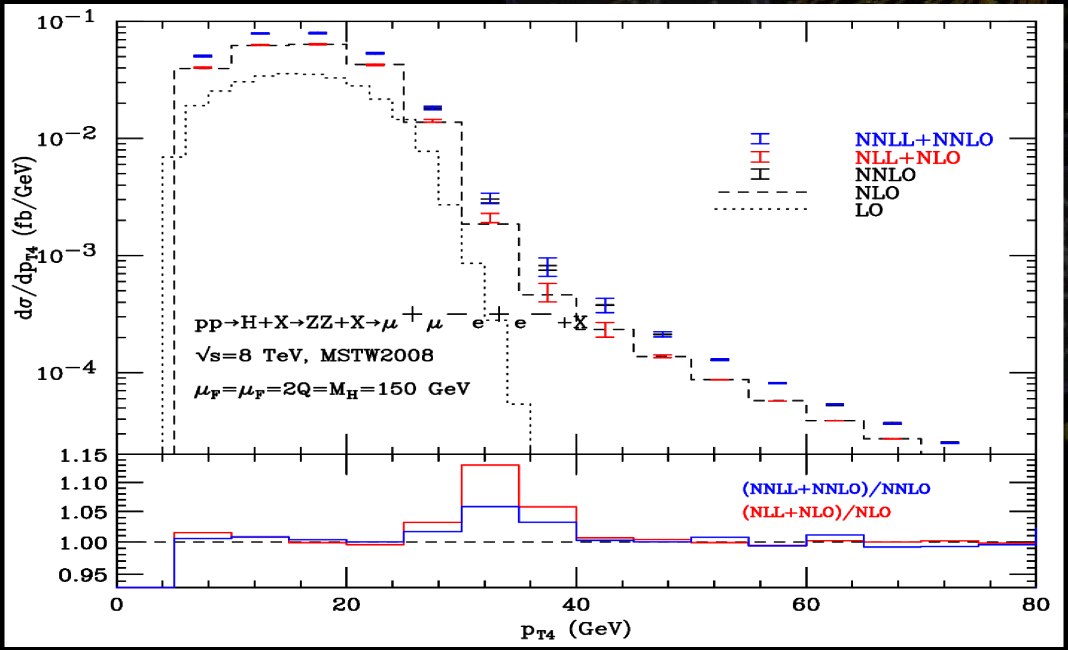
- LHC $\sqrt{s}$=8TeV, m_H=140GeV

  $gg \to WW + X \to l\nu l\nu + X$

- 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 +40% 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

Summary

- The year 2012 will be a crucial year for the SM Higgs boson. Wide region of Higgs boson masses already excluded, but still there is an excesses of events in the mass region around 125GeV

  More data from LHC are needed, in order to clarify the nature of these excesses
- One of the most important Higgs boson observables is the transverse momentum distribution (embodies effects of initial state QCD radiation, its precise knowledge can help to setup strategies to improve statistical significance)
- `HqT` is a numerical program that allows to compute the Higgs p_T spectrum to the highest accuracy possible to date
- Upgrade of `HqT`: exact expression for $H^{(2)}$ and A_3 functions, full implementation on the resummation scale dependence, LHAPDFs interfacing and new compilers compatibility, studies of theoretical uncertainties

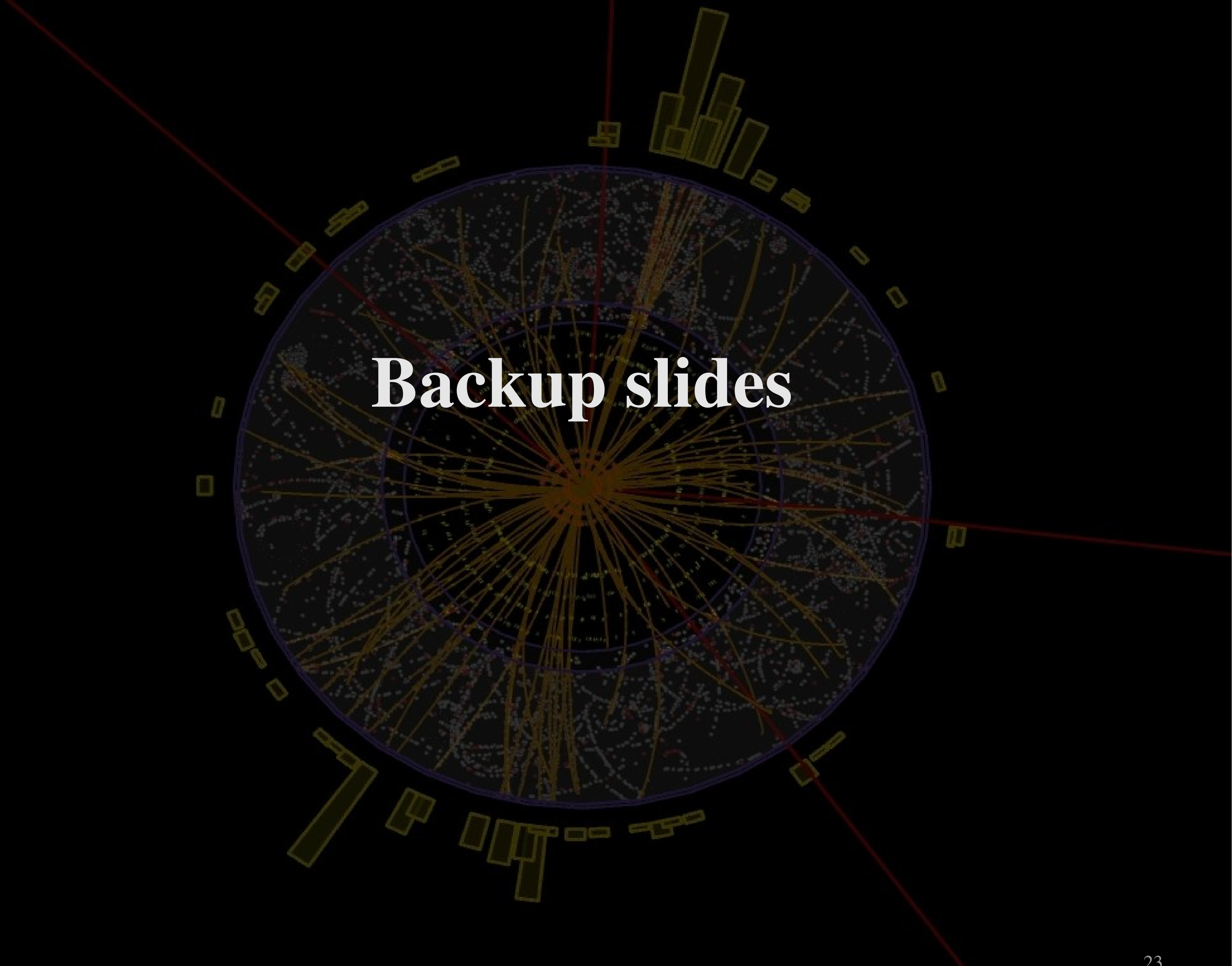
Summary

- New code `HRes`: it merges the features of `HNNLO` and `HqT` to provide predictions everywhere as good as the NNLO predictions, but that include the resummation of the logarithmically enhanced terms at small transverse momentum

- 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

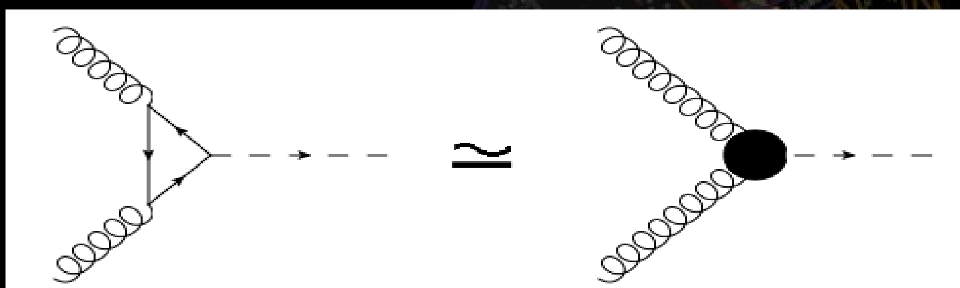
- Outlook: predictions beyond the narrow width and large m-top approximations



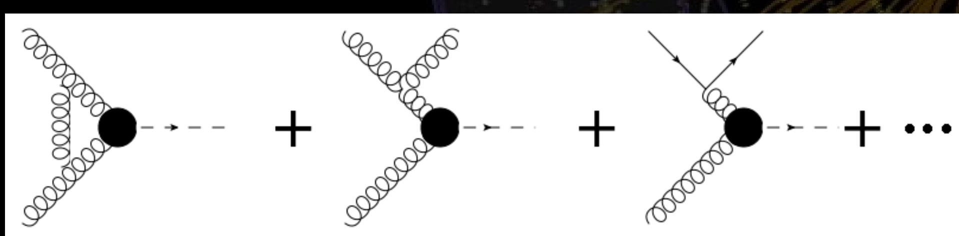
Backup slides

Higgs boson production

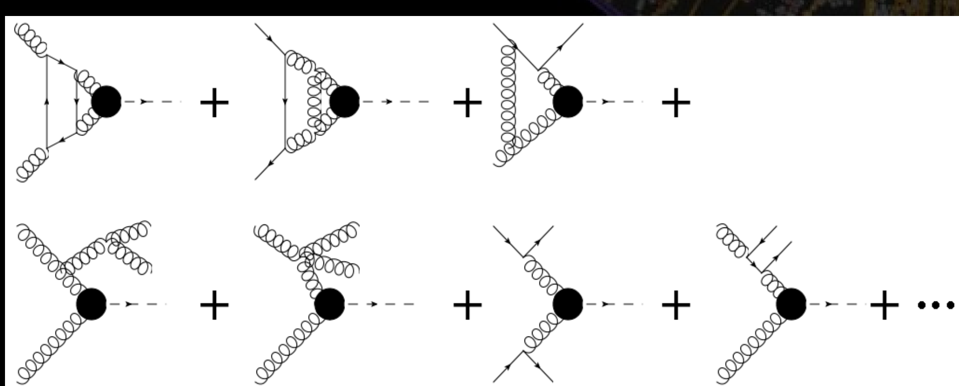
The hard cross section is calculated as perturbative serie of α_s through fixed order calculations



- LO (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))

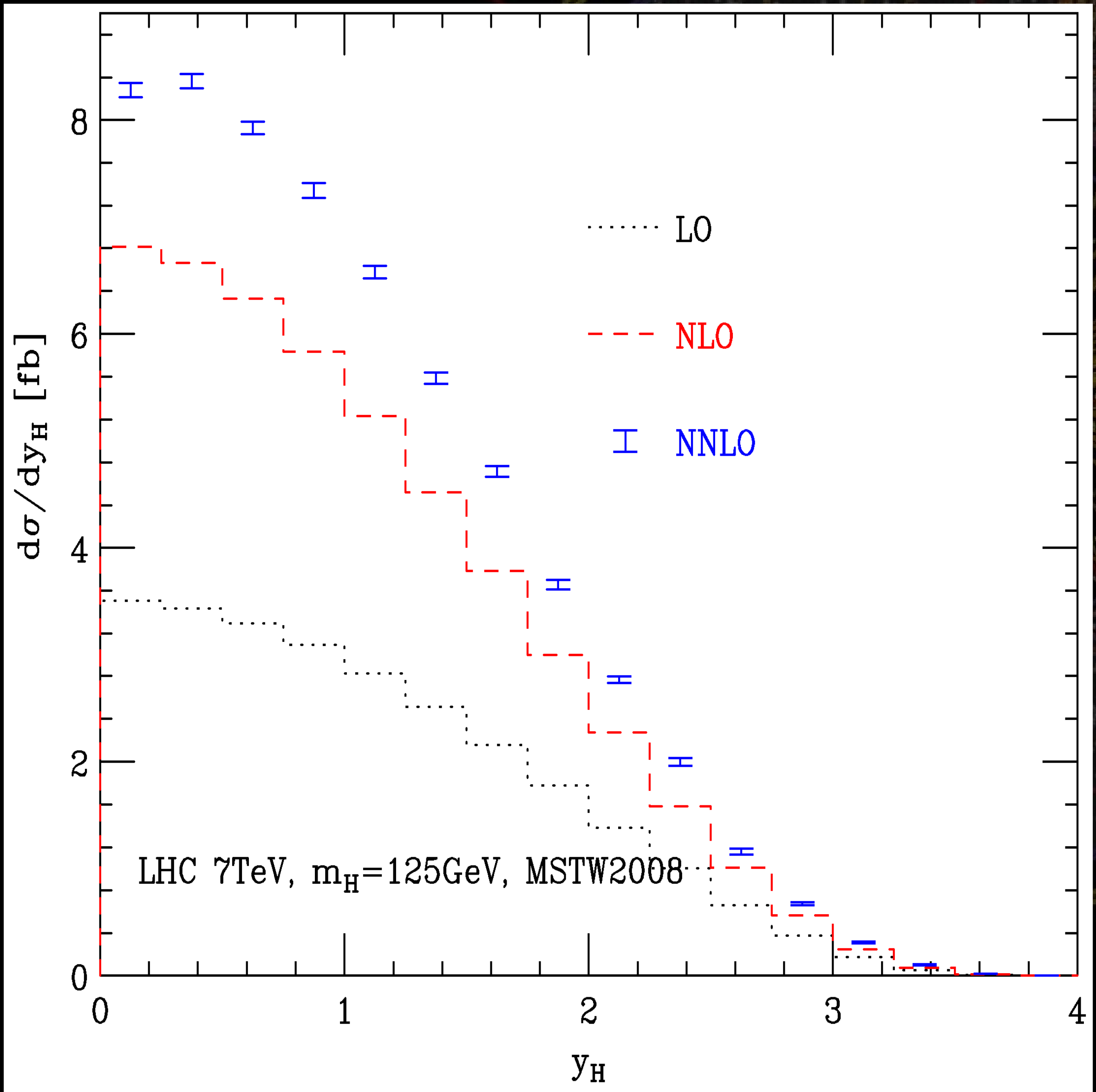
Resummation (2)

- 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.

Backup. 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