Resummation in Higgs Physics

Lorena Rothen

Deutsches Elektronen-Synchrotron (DESY)

QCD@LHC
Zurich, Switzerland
22-26 August 2016

Outline

- Introduction: Higgs Production and Resummation
- Higgs Transverse Momentum Distribution
- Higgs Production with a Jet Veto
- Summary

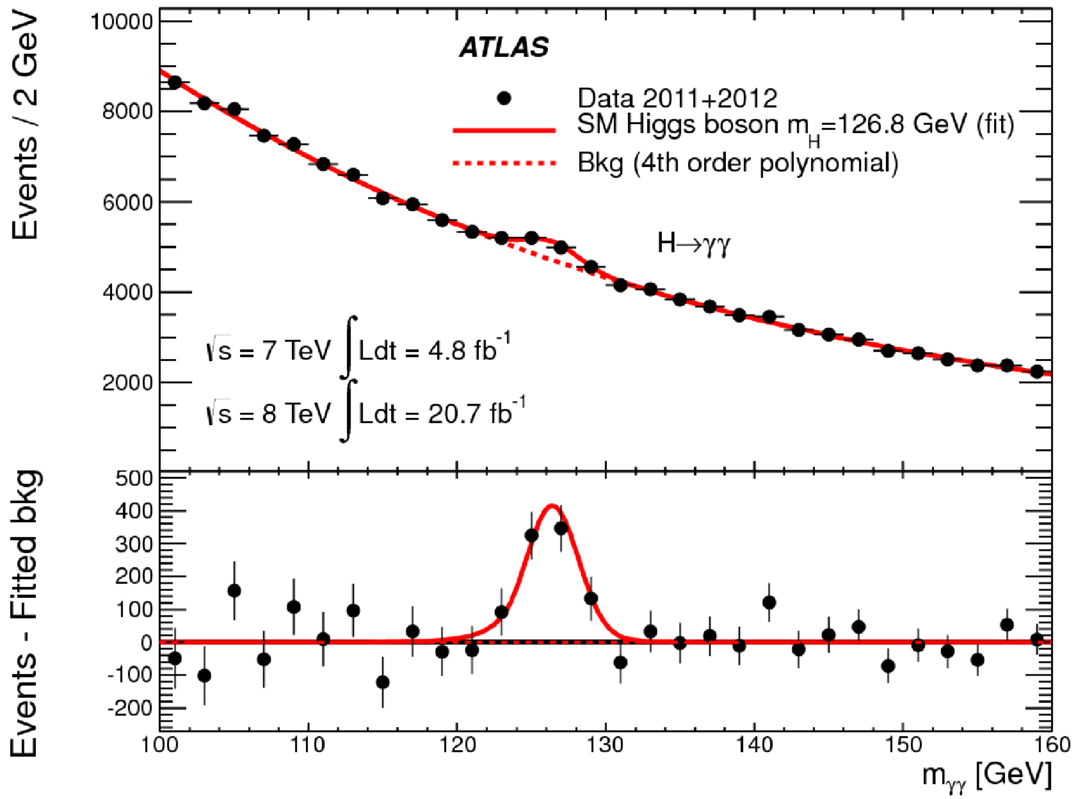
After Higgs Discovery

Higgs discovery:
Not necessarily theoretical precision physics needed.

To test Higgs properties or set exclusion limits: High accuracy in QCD (+EW) predictions

- Couplings, Mass, CP
  SM: no free parameters for the couplings
  (masses → couplings)
- Differential and exclusive measurements are of key importance

$H \to \gamma\gamma$ ATLAS on full 2011+2012 data



Depending on observable, various theoretical challenges to obtain required precision.

Resummation of Large Logarithms

- High energy physics → small coupling constant

  Perturbative expansion in the coupling (fixed order predictions).

- When we put exclusive constraints on the transverse momentum of radiation (e.g. kinematical distributions or cuts)
  - Only soft and collinear emission allowed
  - Sudakov double logarithms appear in the fixed order expansion, which can be large and spoil convergence of the series.

$$\alpha_s^n \ln(\lambda)^{2n} \sim \mathcal{O}(1) \qquad \text{for} \quad \lambda \ll 1$$

  - Need to be resummed to all orders to obtain a reliable theoretical prediction

Resummation of Large Logarithms

- Double logarithms generally exponentiate.

$$\sigma \sim \sigma_0 \exp(\alpha_s L^2 + \alpha_s L + \alpha_s^2 L + \dots)$$

LL NLL NNLL

$$L = \ln(\lambda)$$

λ : small parameter (depends on observable)

- Based on this exponentiation we can define a resummed perturbative order

$$\sigma \sim \sigma_0 (1 + \alpha_s (L^2 + L + c1) \quad \text{NLO}$$
$$+ \alpha_s^2 (L^4 + L^3 + L^2 + L + c2) \quad \text{NNLO}$$
$$+ \alpha_s^3 (\vdots + \vdots + \vdots + \vdots + \dots) \quad \text{NNNLO}$$

LL NLL NNLL

Resummed Order	Γ_{cusp}	γ, F_{gg}	$I_{g \leftarrow i}$	Matching to:
LL	1-loop	tree	-	-
NLL	2-loop	1-loop	tree	LO
NNLL	3-loop	2-loop	1-loop	NLO
N^3LL	4-loop	3-loop	2-loop	NNLO

Matching to fixed order results includes power suppressed terms

.

Resummation is crucial for many Collider Observables

- Threshold
- Transverse Momentum
- Event Shapes
- Jet Veto
- Electroweak
- Masses
- Jet Substructure
- ...

Resummation is crucial for many Collider Observables

- Threshold
- Transverse Momentum
- Event Shapes
- Jet Veto
- Electroweak
- Masses
- Jet Substructure
- ...

This Talk
(for Higgs production)

Various Tools available

Resummation by:

- Collins-Soper-Sterman (CSS) type
  [Collins, Soper, Sterman et al., Bozzi, Catani, de Florian, Ferrera, Grazzini]
- Soft-Collinear Effective Theory (SCET)
  [Bauer, Fleming, Pirjol, Stewart; Rothstein, Beneke, Chapovsky, Diehl, Feldmann]
- Branching algorithm
  [Catani, Marchesini, Webber et al.]

Factorization of the cross section allows for resummation via renormalization group evolution (RGE).

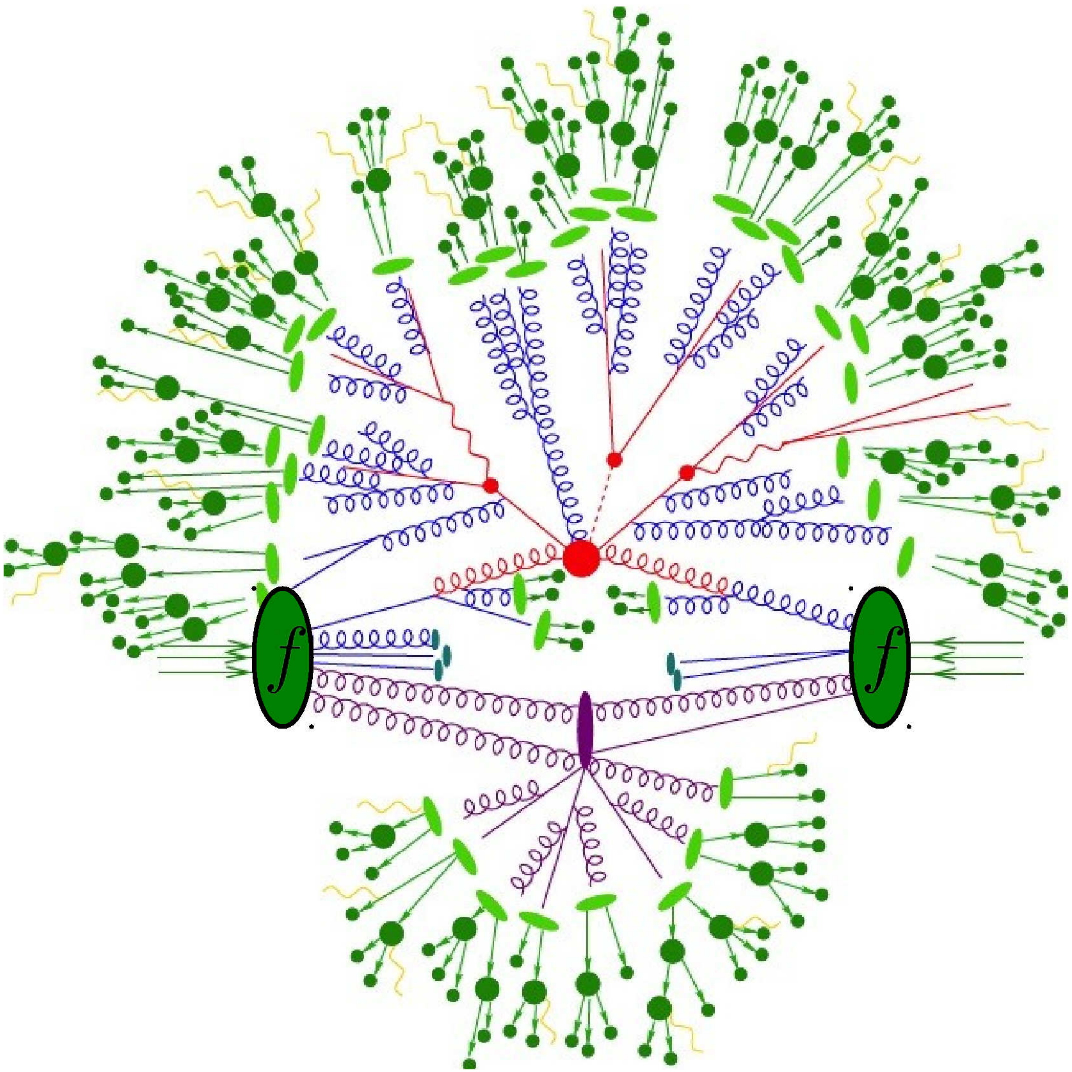
- CAESAR/ARES
  [Banfi, Salam, Zanderighi, +McAslan]

Resummation achieved by numerically simulating QCD radiation to all orders.

Collider Physics

Typical multi-scale problem!

- Hard collision
- Proton structure (non-perturbative long distance physics)
- Collinear & soft radiation



sciencenode.org/feature/sherpa-and-open-science-grid-predicting-emergence-jets.php

All LHC calculation rely on the factorization

$$d\sigma = d\hat{\sigma} \otimes f\, f$$

partonic cross section

parton distribution functions (PDFs)

Resummation by SCET

Soft-collinear effective theory (SCET) is an effective field theory of QCD:

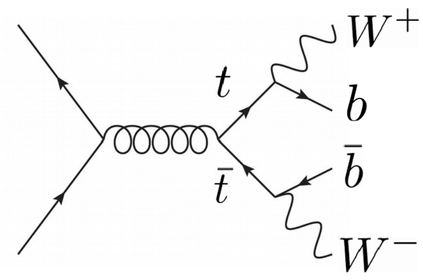
[Bauer, Fleming, Pirjol, Stewart; Rothstein, Beneke, Chapovsky, Diehl, Feldmann]

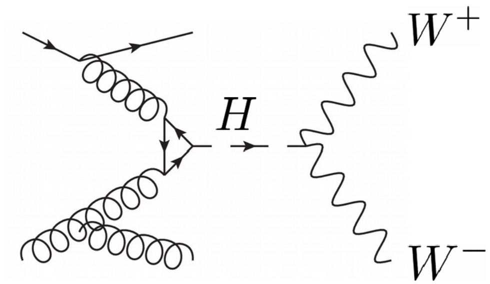
- Low-energy degrees of freedom: **Soft** and **Collinear** fields
- Off-shell modes are integrated out. Hard-scattering encoded in the **Wilson coefficents** of the operators.
- Advantages:
  - Operator definition (manifest gauge invariance).
  - Systematic scale separation. Derivation of factorization theorems.
  - Resummation by standard **RGE methods.**
  - **Power corrections** manifest at Lagrangian level.

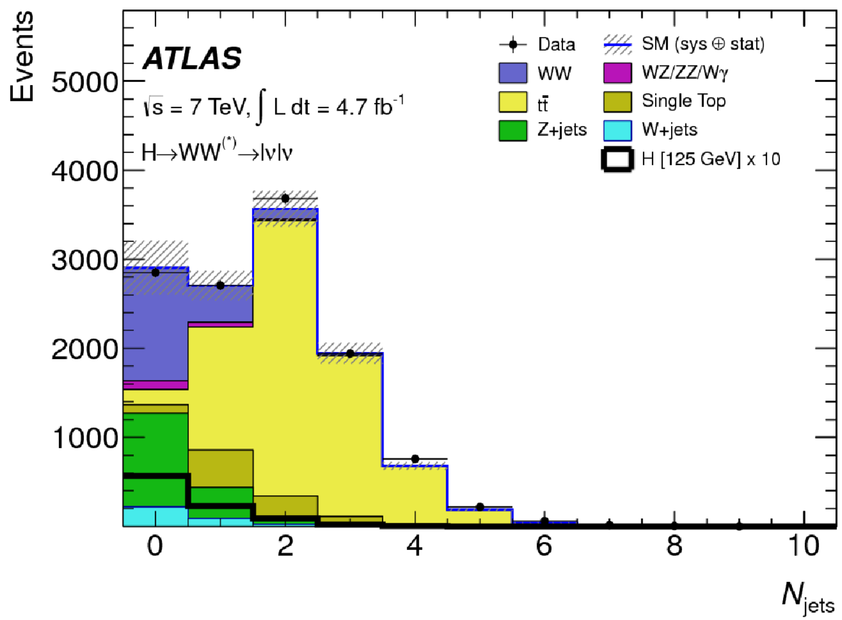
Jet Binning and the Jet Veto

Role of the Jet Veto

- Events are binned by exclusive jet multiplicity.
- Channel to check coupling to W boson $H \to W W^*$
  - Problem: large top background







  - Solution: **jet veto**
    Discard events including jets with transverse momentum:

$$p_T^{\mathrm{Jet}} > p_T^{\mathrm{veto}} \sim 15 - 30\,\mathrm{GeV}$$

- Formalism applicable to production of any color singlet (Z, WW, …)
- Initial-state discrimination → Talk by Markus Ebert

Resummation for the Jet Veto

Recent work:

- NNLL+NNLO for beam thrust: Berger, Marcantonini, Stewart, Tackmann, Waalewijn '11 [1012.4480]
- NNLL+NNLO: Banfi, Salam, Zanderighi '12 + Monni '12 [1206.4998]
- N^3LL_p+NNLO: Becher, Neubert '12 +LR '13 [1307.0025]
- NNLL'+NNLO: Tackmann, Walsh, Zuberi '12 + Stewart, Walsh '13 [1307.1808]
- Small Radius Jets: Dasgupta, Dreyer, Salam, Soyez '14 [1411.5182]
- NNLL+N^3LO+LL_R: Banfi, Caola, Dreyer, Monni, Salam, Zanderighi, Dulat '15 [1511.02886]
- Quark-mass effects: Banfi, Monni, Zanderighi '13 [1308.4634]
- Higgs plus one jet: Liu, Petriello '13 [1303.4405]
- Combination across jet bins: Bougheza, Liu, Petriello, Tackmann, Walsh '13 [1312.4535]
- Rapidity dependent jet vetos: Gangal, Stahlhofen, Tackmann '14 +Gaunt '16 [1412.4792, 1608.01999]

ATLAS vs Theory

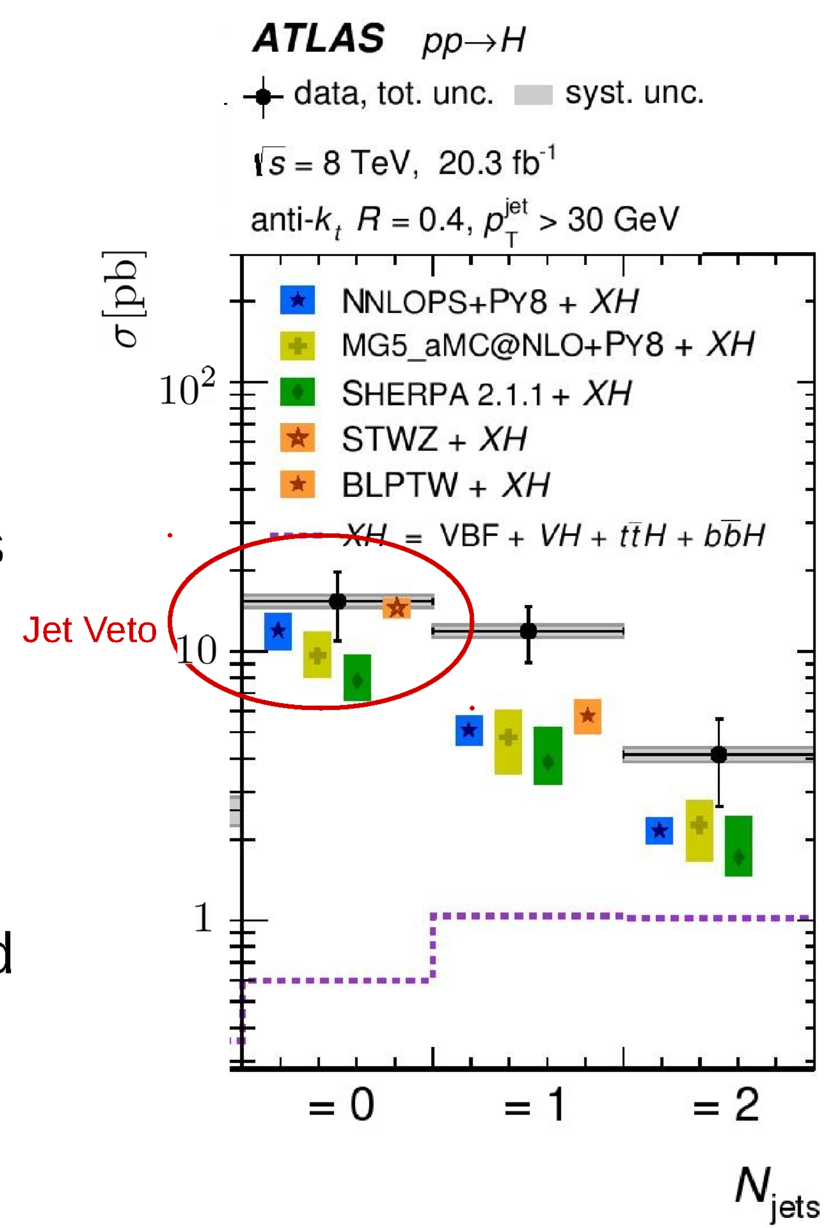
- ATLAS compared results to

  STWZ + *XH* [Stewart et al. '13]

  - NNLL'+NNLO (includes π^2 Resummation)
  - Good agreement with data
  - Compared to theoretical predictions from
    - N^{3}LL$_p$+NNLO: Becher, Neubert, LR '13
    - NNLL+NNLO: Banfi et al. '12

  results agree within error bands and similar size uncertainties are found.

[ATLAS Sept. 2015, 1504.05833]



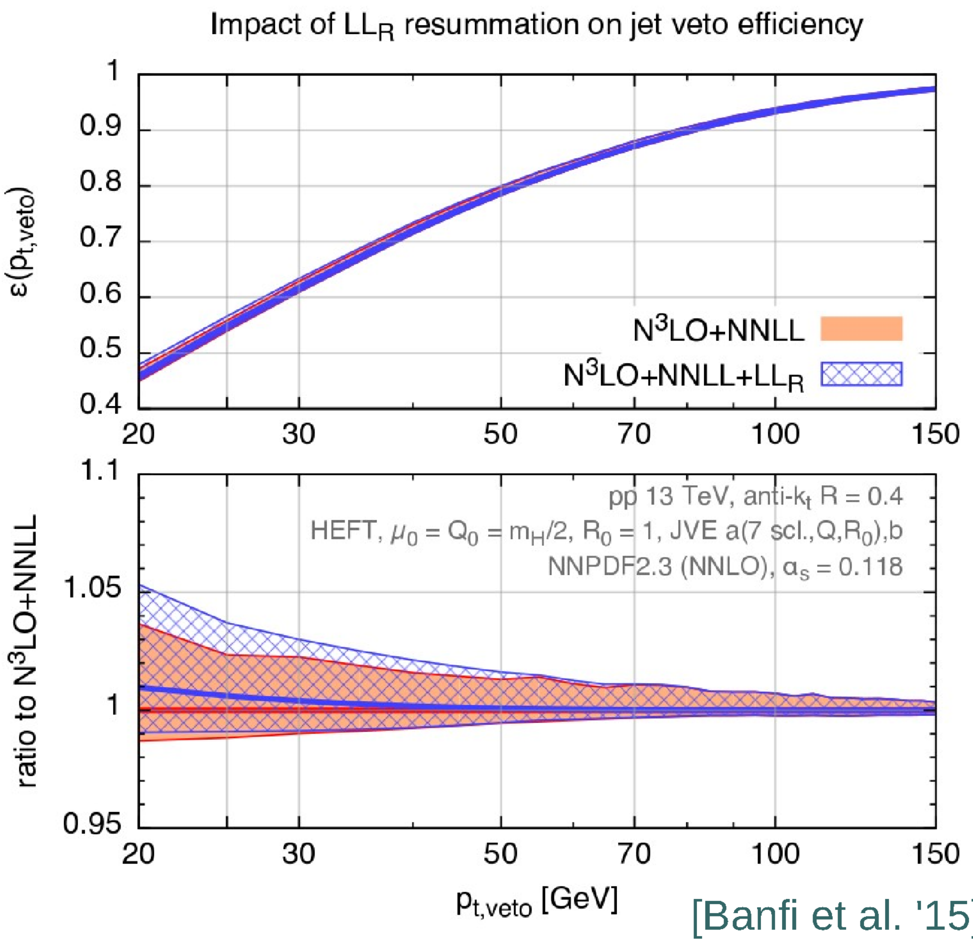
NNLL+N^{3}LO+LL$_R$ for Jet Veto

Predictions for the jet-veto efficiency and cross section at the LHC by Banfi et al. '15 [1511.02886]

- Total N^{3}LO cross section; H+1 Jet NNLO.
- Exact top- and bottom-mass effects up to NLO.
- NNLL resummation.
- Small jet radius to LL accuracy:
  - Terms like

$$\alpha_s^n \log^n \left(R^2\right)$$

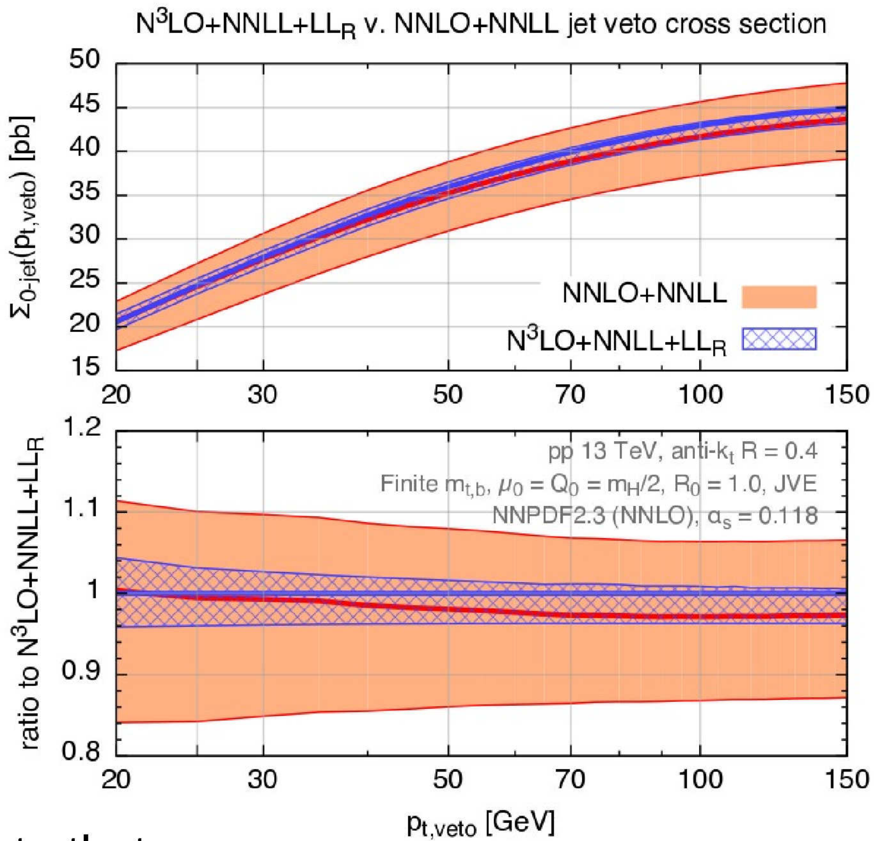
    present in the perturbative series.
  - For small values of *R* these could be large.
  - LL resummation achieved by Dasgupta et al. '14.
  - No large effect seen in Higgs produciton with a jet veto for current choices of *R.*



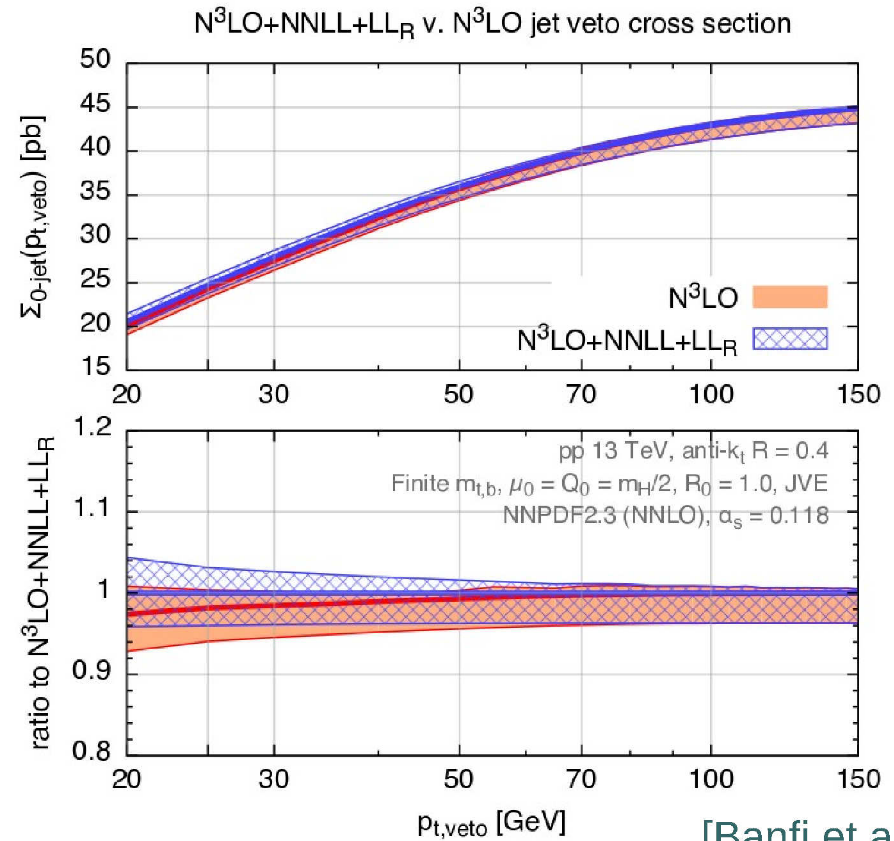
[Banfi et al. '15]

NNLL+N^{3}LO+LL$_R$ for Jet Veto

Central value change < 1%
Significant reduction in uncertainty



N^{3}LO about 2% lower
Similar uncertainty of 3-4%



[Banfi et al. '15]

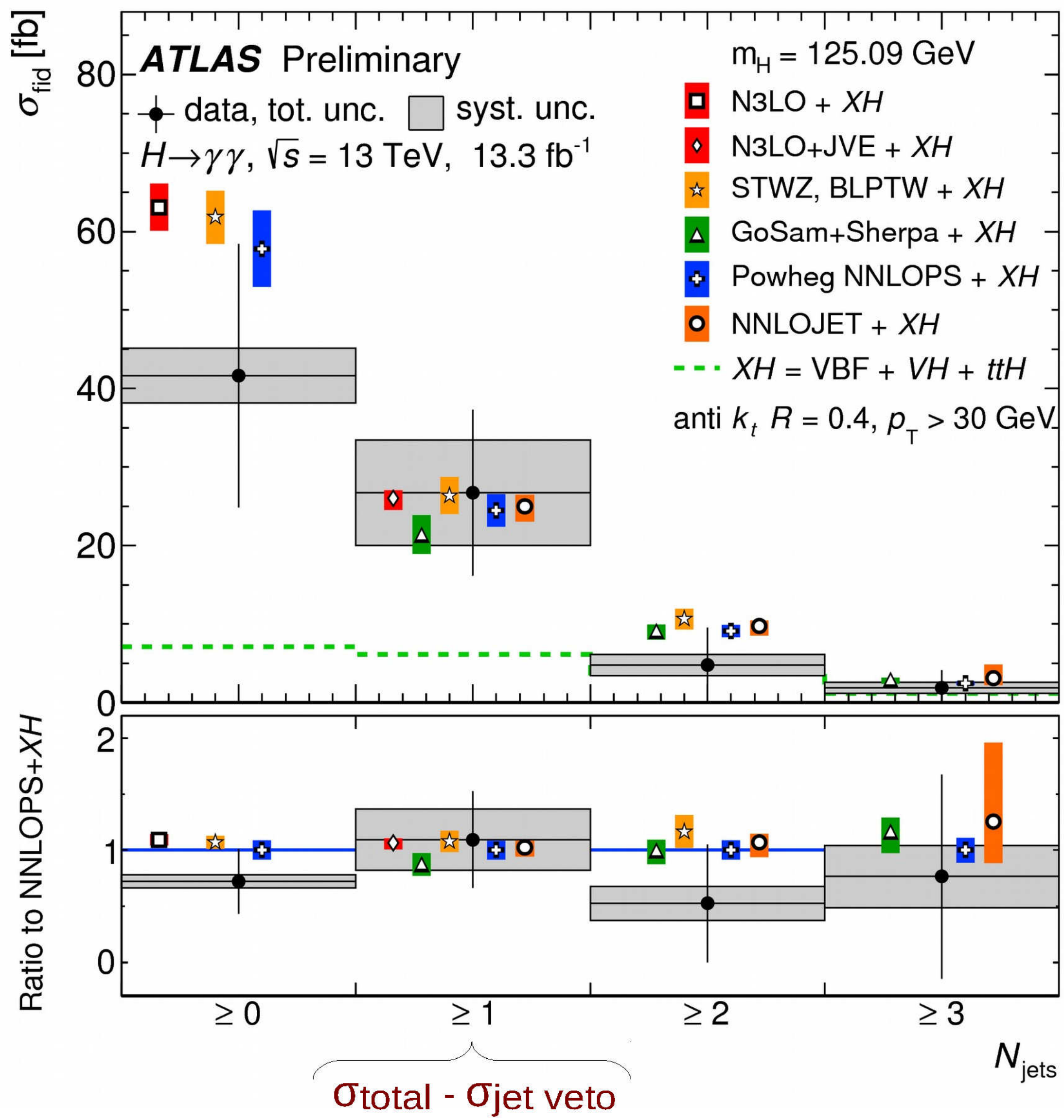
Note that

- Use more "aggressive" treatment of resummation uncertainties than [Stewart et al. '13] and [Becher et al. '13] and $\mu = m_H/2$ as the central scale (very small N^{3}LO uncertainty).
- PDF and strong coupling uncertainties are not included.
- Higher-order quark mass effect, electroweak- and non-perturbative-effects are of the same order as the uncertainty.

Run 2 Data at 13 TeV

$H \to \gamma\gamma$ in bins of inclusive jet multiplicity

- N3LO+JVE corresponds to NNLL+N³LO+LL$_R$ [Banfi et al.]
- Measured cross section a bit lower (not statistically significant)
- Except for the undershoot in the low p_T^{jet} region, good agreement.



[ATLAS-CONF-2016-067, August '16]

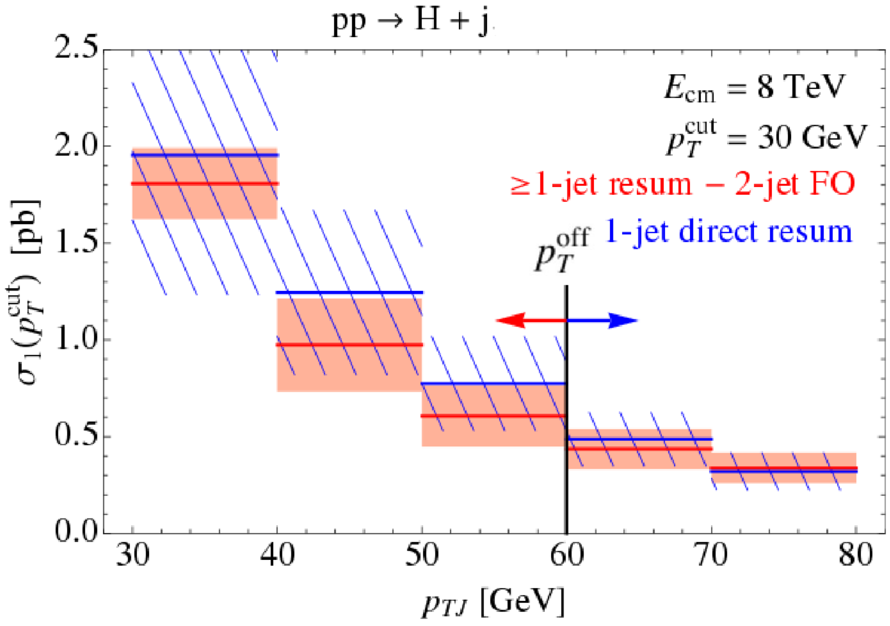
Higgs plus Jets / Multiple scales

- Exclusive 1-jet bin is a multi-scale problem

$$p_T^{\text{jet 2}} < p_T^{\text{veto}} < p_T^{\text{jet 1}} < m_H$$

- Additional scale → additional large logarithms
- Different resummation needed for each region
- Liu, Petriello '12: NLL'+NLO 1-jet bin direct resummation (resummation of $p_T^{\text{jet 2}} \ll p_T^{\text{veto}}$ and $p_T^{\text{jet 1}}$ at fixed order, valid for the high $p_T^{\text{jet 1}} \sim m_H$ region)
- Bougheza et al. '13:
  Framework to consistently combine 0-jet and 1-jet bin resummations.
  - Indirect method for resummation in the small region $p_T^{\text{jet 1}}$ given.
  - Description of uncertainty correlations (covariance matrix).
- Jet observables: Non-global logarithms

  → Talk by T. Becher



Smooth transition (independent of precise p_T^{off})

Transverse Momentum Distributions

Transverse Momentum Distributions

$$P + P \to H(q) + X$$

- The transverse momentum (q_T) spectrum of bosons is among the most basic kinematic distributions at hadron colliders.
- At fixed order logs

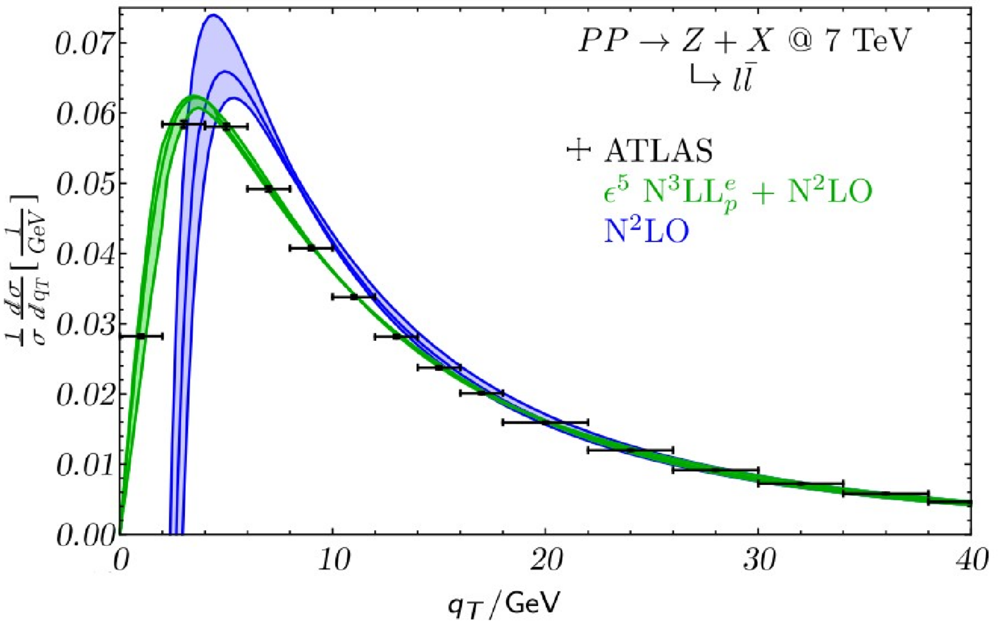
$$\alpha_s^n L^m \quad \left(L = \log\left(m_H/q_T\right),\ m \leq 2n-1\right)$$

  appear, which spoil the convergence at small q_T

- Resummation essential in the region

$$q_T \ll m_H$$

- Transition region (turn off resummation) between fixed order at large q_T and resummed result at low values.
- Transverse PDFs (Beam functions)
- CSS & SCET factorization formulas are in impact parameter space (x_T).



[Becher, Luebbert, Neubert, Wilhelm]pgr.

(Higgs) Transverse Momentum Resummation

Monte Carlos: Herwig, Pythia, Sherpa, ...

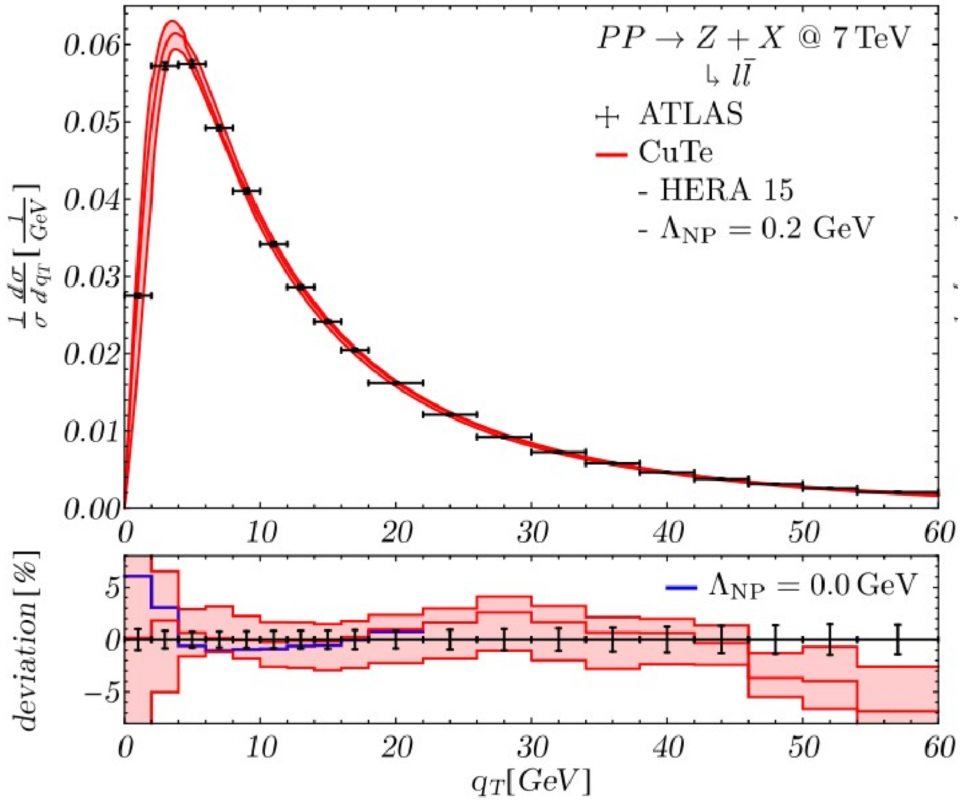
Analytic tools:

- CSS type:
  - HqT (NNLL+(N)NLO): Bozzi, Catani, de Florian, Ferrera, Grazzini, Tommasini
  - DYqT, DYRes, HRes (NNLL+NNLO) '12: Catani, Cieri, de Florian, Ferrera, Grazzini, Tommasini
- SCET:
  - NNLL+NLO (CuTe 1.0): Becher, Neubert, Wilhelm '12 [1212.2621]
  - NNLL+NNLO: Neill, Rothstein, Vaidya '15 [1503.00005]
  - Gluon TMDPDFs: Echevarria, Kasemets, Mulders, Pisano '15 [1502.05354]
  - NNLO TMDPDFs: Gehrmann, Luebbert, Yang '14 [1403.6451]
  - Rapidity anomalous dimension @ 3 loops (N^3LL): Li, Zhu '16 [1604.01404]
  - N^3LL+NNLO (CuTe 2.0): Becher, Luebbert, Neubert, Wilhelm [in progress]
- CAESAR/ARES approach: NNLL+NNLO Monni, Re, Torielli '16 [1604.02191]
- Quark-mass effects (top and bottom):
  Grazzini, Sargsyan '13 [1306.4581]; Banfi, Monni, Zanderighi '13 [1308.4634]
- Non-perturbative effects: Becher, Bell '13 [1312.5327]

N^3LL_p+NNLO with CuTe

Cute 2.0:

- ϵ^5 N^3LL_p+NNLO precision
- π^2 Resummation
- 4-loop cusp Padé approx.
- q_T matching scheme
- Smooth transit to pure fixed order for q_T between M/2 and 3M/4.
- In following plots an estimate is used for $F^{(3,0)}$. Recently computed value lies within this estimate and would lead to a bit smaller uncertainty bands.

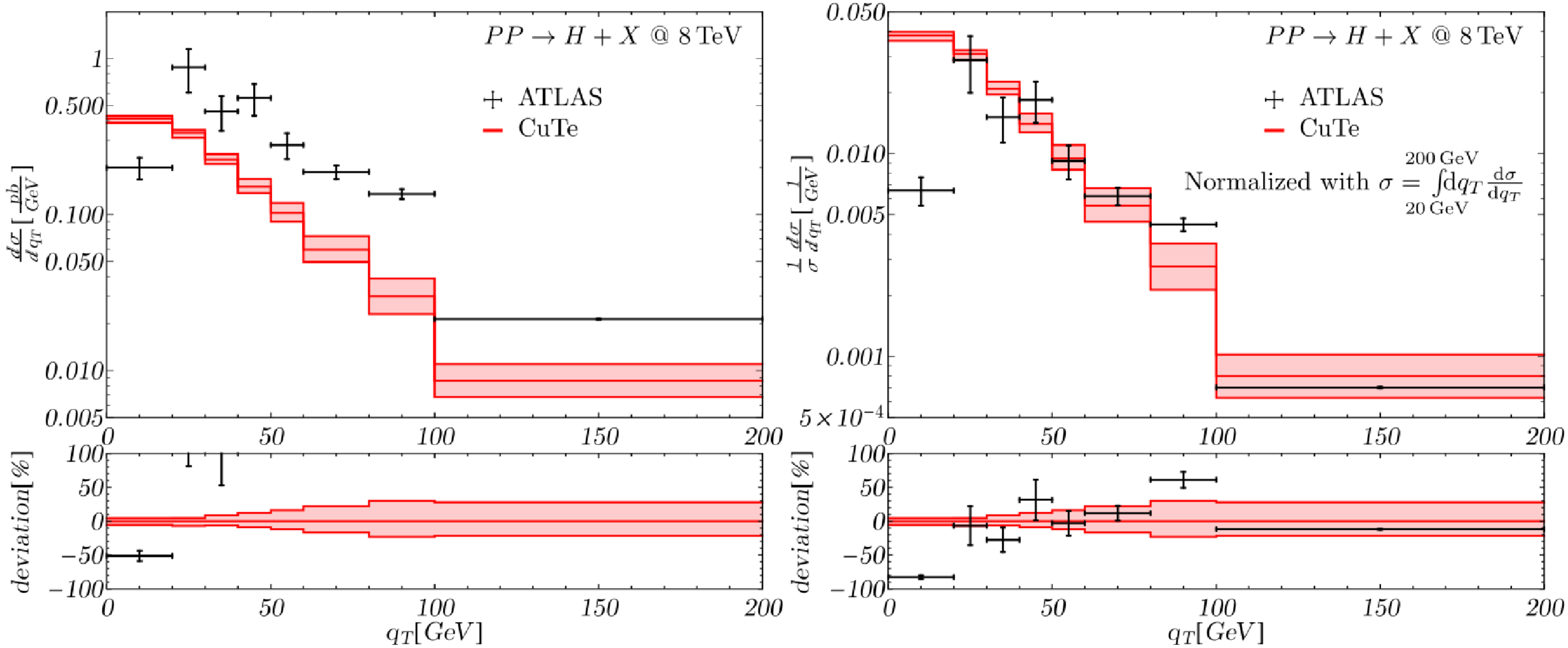


[Becher, Luebbert, Neubert, Wilhelm]$_{pgr.}$

Comparison with Z ATLAS 7 TeV data:

- Good agreement
- Uncertainties include:
  - Higher order in QCD (μ and $F^{(3,0)}$ variations); PDF uncertainty; nonperturbative effects (q_T < 3 GeV).

CuTe vs ATLAS for Higgs

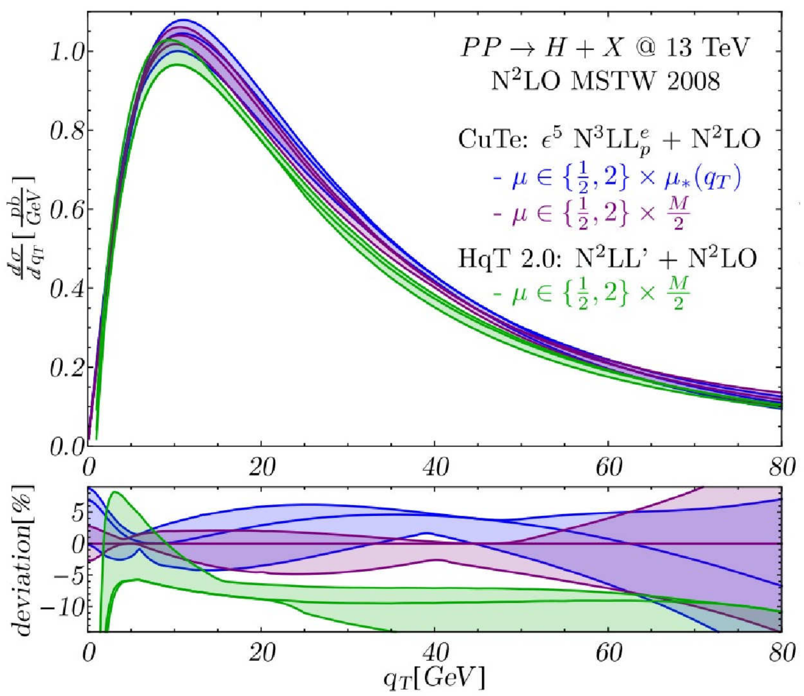


[Becher, Luebbert, Neubert, Wilhelm]pgr.

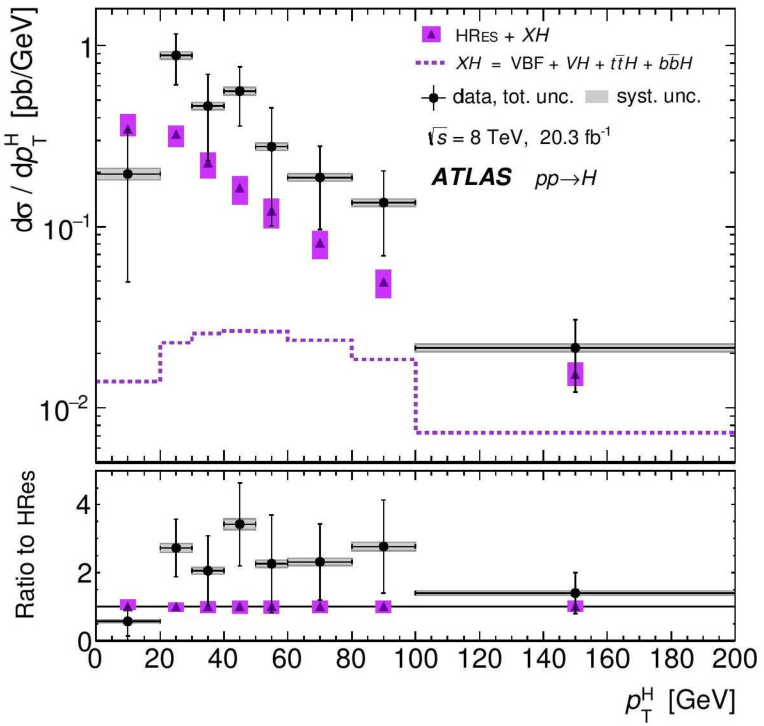
Comparison with Higgs ATLAS 8 TeV data Hep-ex/1504.05833 20.3 fb^{-1}:

- Siezable uncertainty for Higgs production: Mainly in fixed order part (high q_T region).
- Low statistics for data
  - Can the first experimental bin be trusted (right hand plot: first bin is dropped)
  - Also normalizing to total cross section of the data leads to improved agreement.
- Total Higgs boson production is larger and produced with larger transverse momentum and more associated jets than predicted by current SM calculations.

CuTe vs HqT / HRes vs ATLAS



[Becher, Luebbert, Neubert, Wilhelm]pgr.

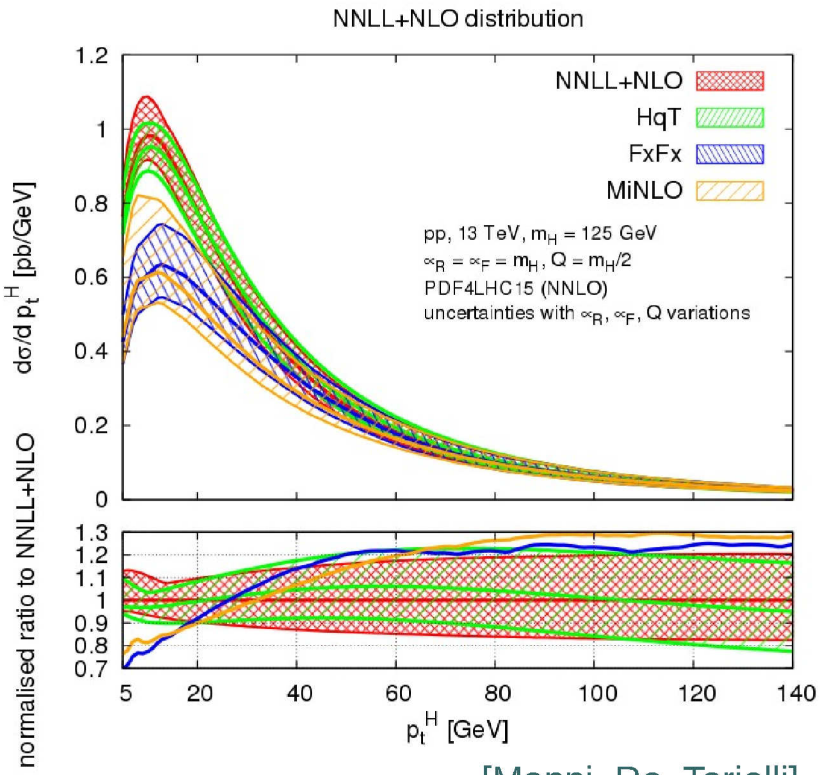


[ATLAS Sept. 2015, 1504.05833]

- Similar shape as HqT [Bozzi et al.] (slightly larger result for CuTe)
- Integrated σ
  - σ_{CuTe} = 44 pb ± 8%,
  - σ_{HqT} = 40 pb ± 6%,
  - σ_{N3LO} = 44.3 pb ± 2.6%

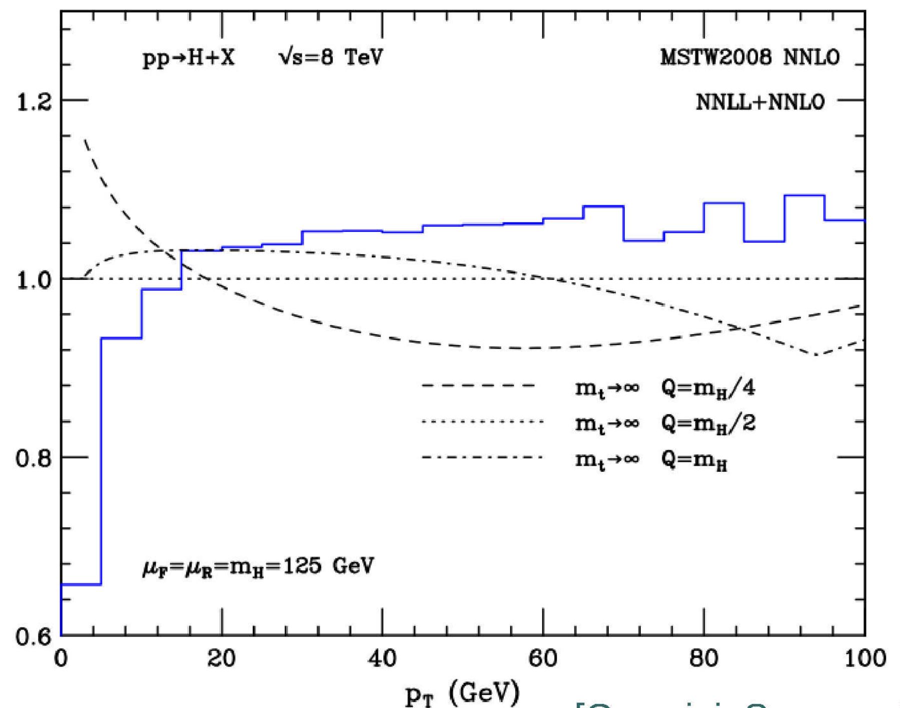
- HRes: NNLL'+NNLO
  - Includes finite top and bottom quark masses
  - Full kinematic information on Higgs and decays.
- Similar comparison to ATLAS Higgs 8 TeV data as CuTe result on previous page.

CEASAR Approach / Mass Effects



[Monni, Re, Torielli]

NNLL+NNLO with finite quark masses normalized to the $m_t \to \infty$ limit



[Grazzini, Sargsyan]

In 1604.02191: New method entirely formulated in momentum space (NNLL+NNLO).

- Does not rely on factorization theorem
- Moderately higher than HqT in the peak region

Study of impact of finite top and bottom-quark masses up to $O(\alpha_S^3)$

- Distortion of spectrum
- At NNLL+NNLO mass effects important at low q_T (10% effect $q_T < m_b$)

Automation and Resummation: a few Examples

Era of automation for higher order resummation has started for various observables (Higher precision than standard Monte Carlo + Parton Showers)

- Jet Veto: [Becher, R. Frederix, M. Neubert and LR, '15]
  - Automated framework for weak bosons production at NNLL+NLO accuracy
    - Implemented within MadGraph5_aMC@NLO (Public code)
    - Straightforward to include decays and cuts on the decay products.
- HRes [Bozzi, Catani, Cieri, de Florian, Ferrera, Grazzini, Tommasini]
  - Transverse Momentum: Retains the full kinematic information on the Higgs boson and its decay products.
- GENEVA (Drell-Yan process) [Alioli et al.]
- 2 Loop soft functions [Bell, Rahn, Talbert '15]
- NNLL Resummation for event shape observables: ARES [Banfi, McAslan, Monni, Zanderighi, '15]
- [Farhi, Feige, Freytsis, Schwartz ´15], [Gerwick, Hoeche, Marzani, Schumann ´15], ...

Summary

- Run 2 → more data available to test various Higgs properties.
- Precise theoretical predictions essential.
- Exclusive observables, kinematic distributions often suffer from large logarithms that need to be resummed (various different approaches).
- Great achievements: Up to N^3LO fixed order and up to N^3LL resummed precision reached for certain observables.

Thank you!