QCD at Hadron collider

Theoretical Standard Model Predictions

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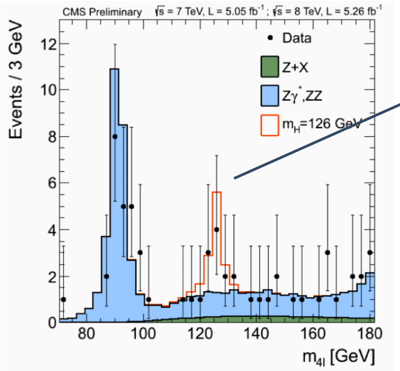
Pushing the Frontiers of Particle Physics During the LHC Run II Era,
Gordon Research Conference, Hong Kong, 25 Jun. 2017

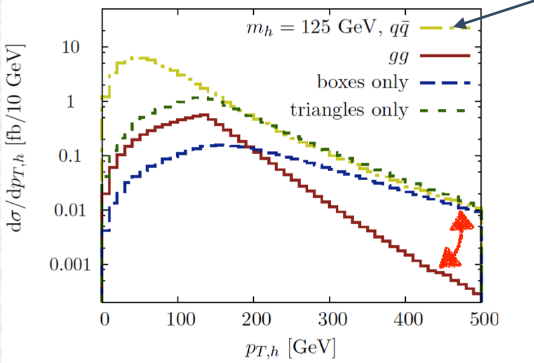
Many `vanilla' models excluded

NP and where to find it



BUMP HUNTING: little to no theoretical input needed. So far: Higgs

REQUIRE VERY GOOD CONTROL ON SM PREDICTIONS FOR SIGNALS / BACKGROUNDS



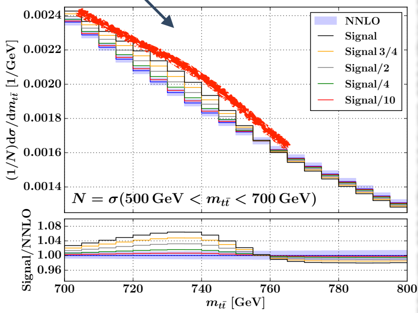
Shape distortions from high-scale NP

``Stealth scenarios''

$$\tilde{t} \to t + \mathrm{LSP}$$

$$m_{\tilde{t}} \approx m_t \gg m_{\mathrm{LSP}}$$

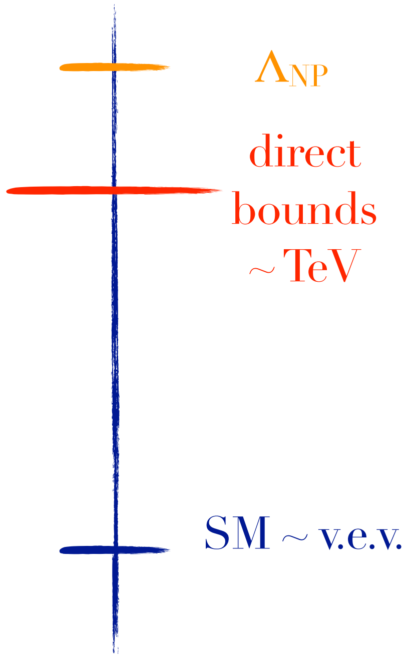
Tricky signatures



Wide resonances

+…

… ``good control'': a (rough) estimate



Λ_{NP}

direct bounds ~ TeV

SM ~ v.e.v.

Imagine to have new physics at a (heavish) scale Λ_{NP}

Typical modification to observable w.r.t. standard model prediction:

$$\delta O \sim Q^2/\Lambda_{\mathrm{NP}}^2$$

To gain over direct bounds:

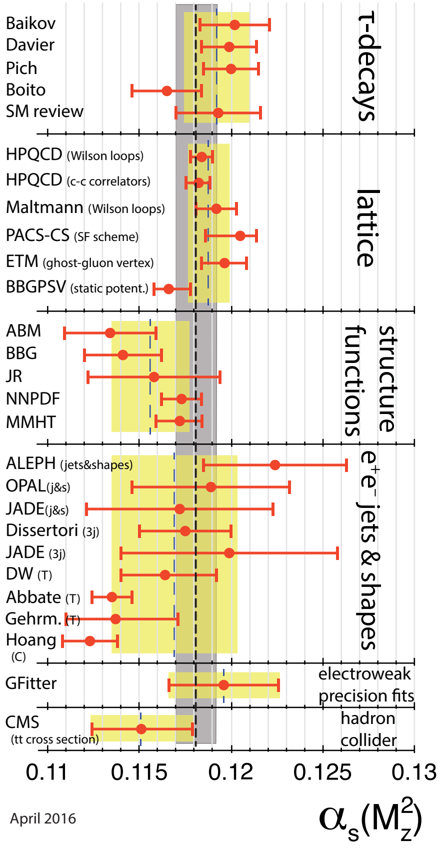
IN THE BULK:
Q~M_H → few percent

IN THE TAIL:
Q≳ 500 GEV →
~10-20%

THIS LEVEL OF PRECISION: WITHIN EXPERIMENTAL REACH OF THE (HL-)LHC

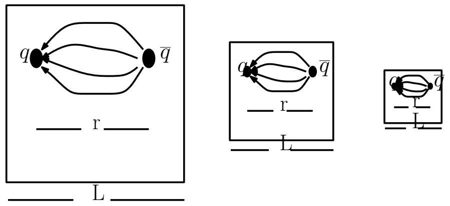
Theoretically, highly non trivial…

The precision on input parameters: α_S



$$\boxed{\alpha_s(m_Z) = 0.118 \pm 1\%}$$

- Many different determinations, (more or less) consistent
- Lattice: the best hope for improvement?
- A lot of recent developments to properly connect the non-perturbative to the perturbative regime (finite size scaling…)

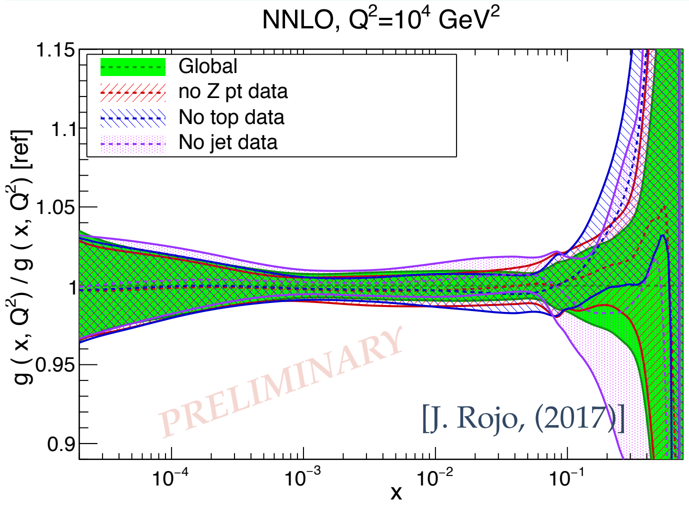


[Lüscher et al (1991), ALPHA (2017)]

0.5% precision may be possible?

PDFs: sanity checks

or how do we make sure we are not fitting new physics away…

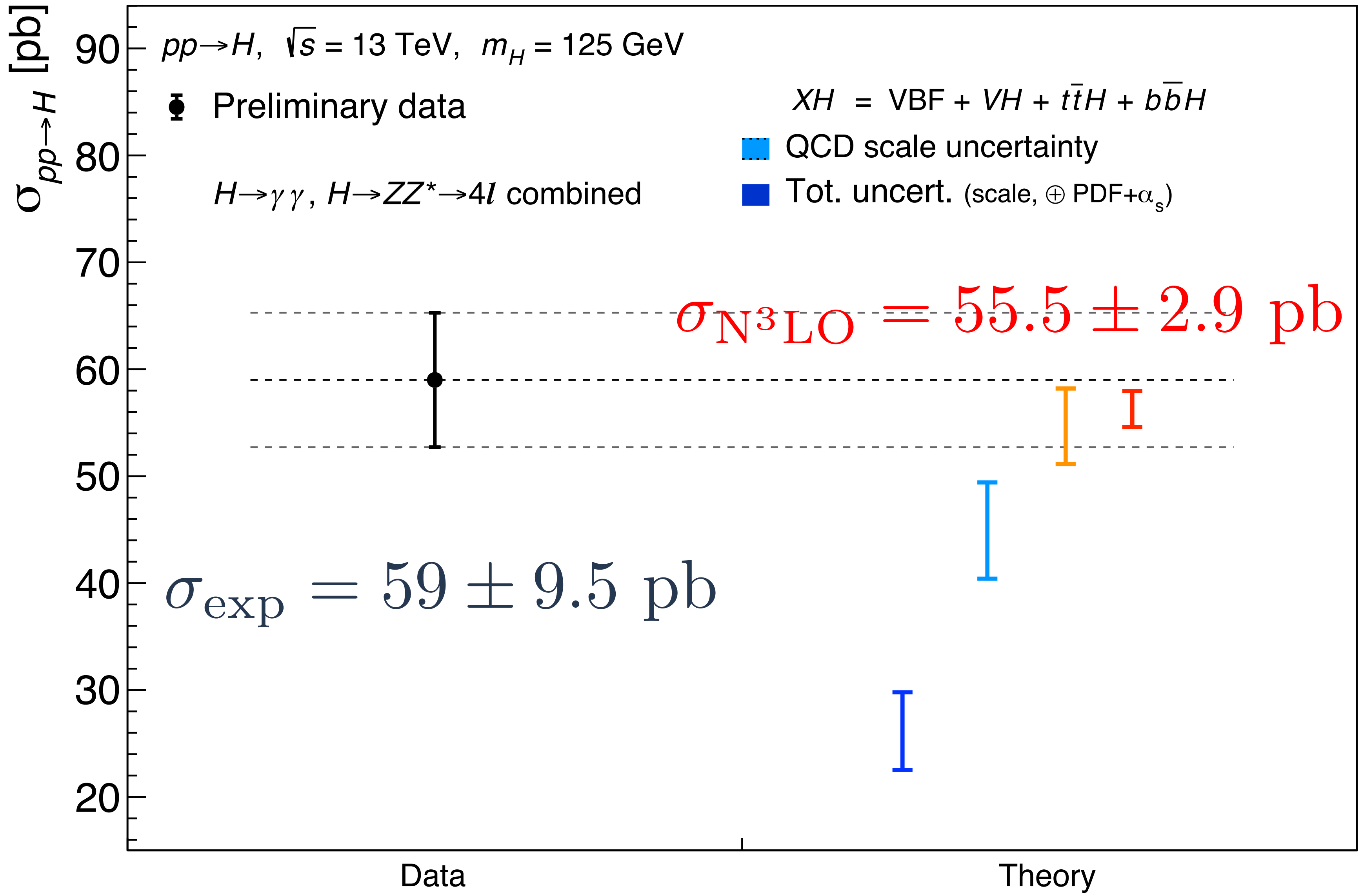


[J. Rojo, (2017)]

- Fits are stable under inclusion/exclusion of extra data-set
- Effect of new data: mostly reduction in uncertainty, small change in the central value

- With more and more data, can also try to fit ``safest'' PDF from PS regions which should be free from NP contaminations (e.g. forward jets…)…

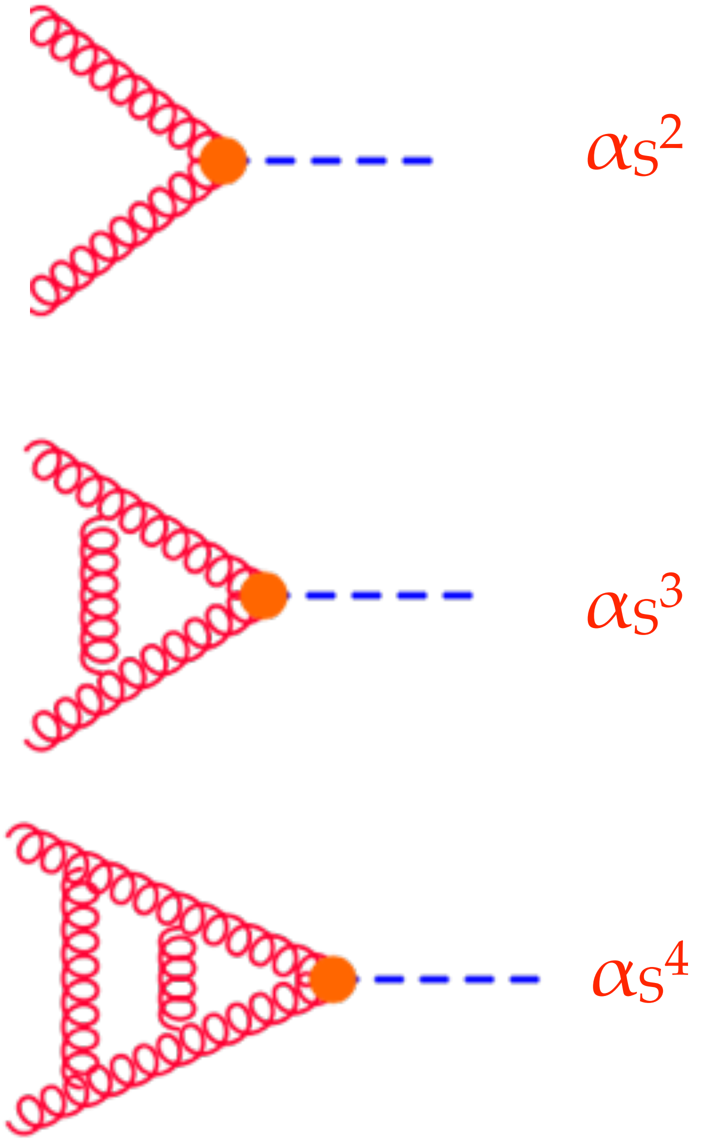
The need for higher orders: Higgs



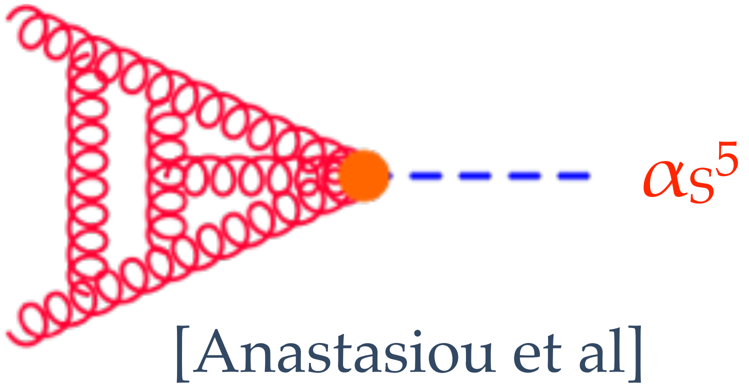
$$\sigma_{\mathrm{N^3LO}} = 55.5 \pm 2.9\ \mathrm{pb}$$

$$\sigma_{\mathrm{exp}} = 59 \pm 9.5\ \mathrm{pb}$$

N^{3}LO results needed to establish perturbative convergence / reduce residual theoretical uncertainty



[Anastasiou, Melnikov; Harlander, Kilgore]

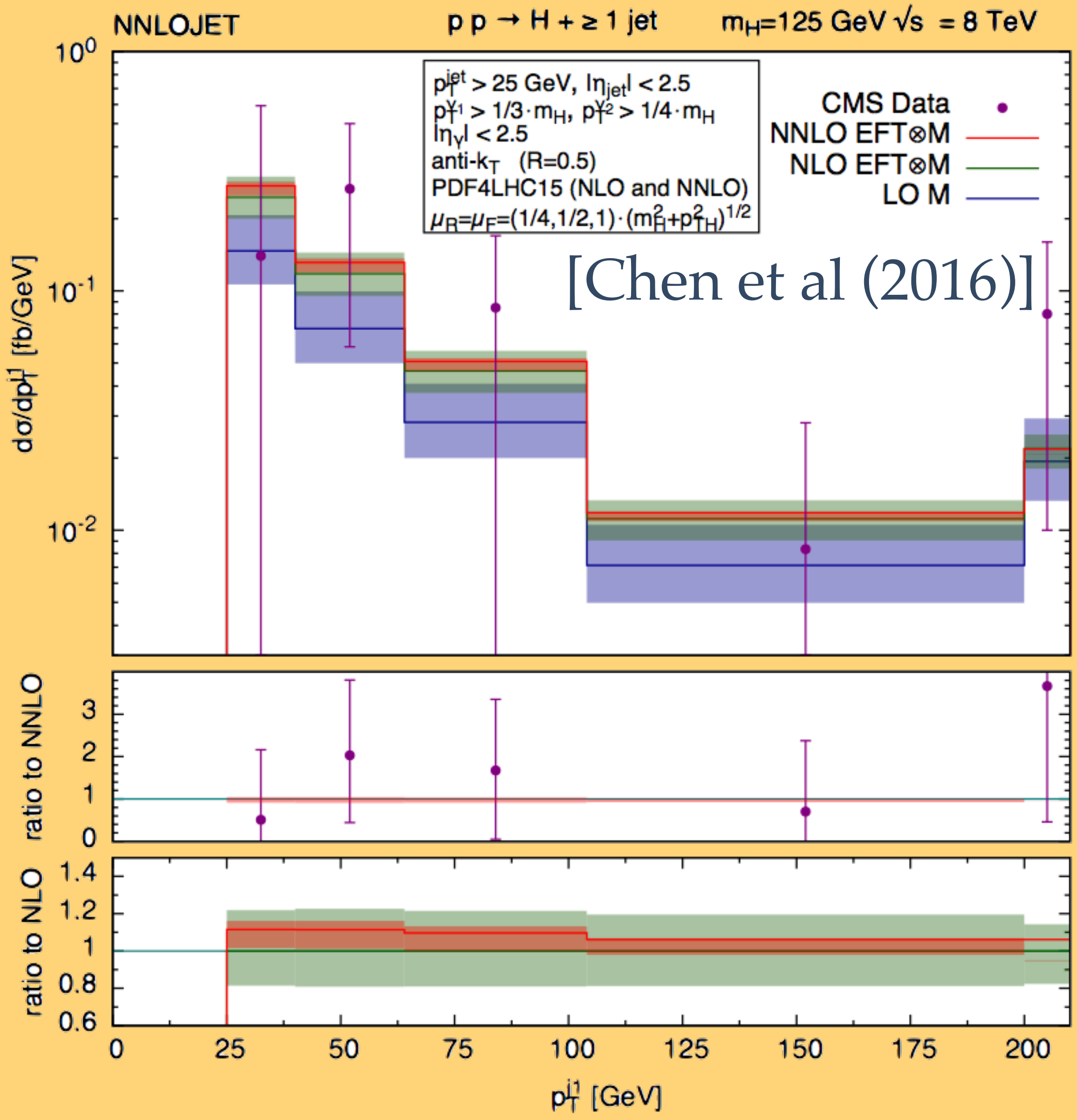


[Anastasiou et al]

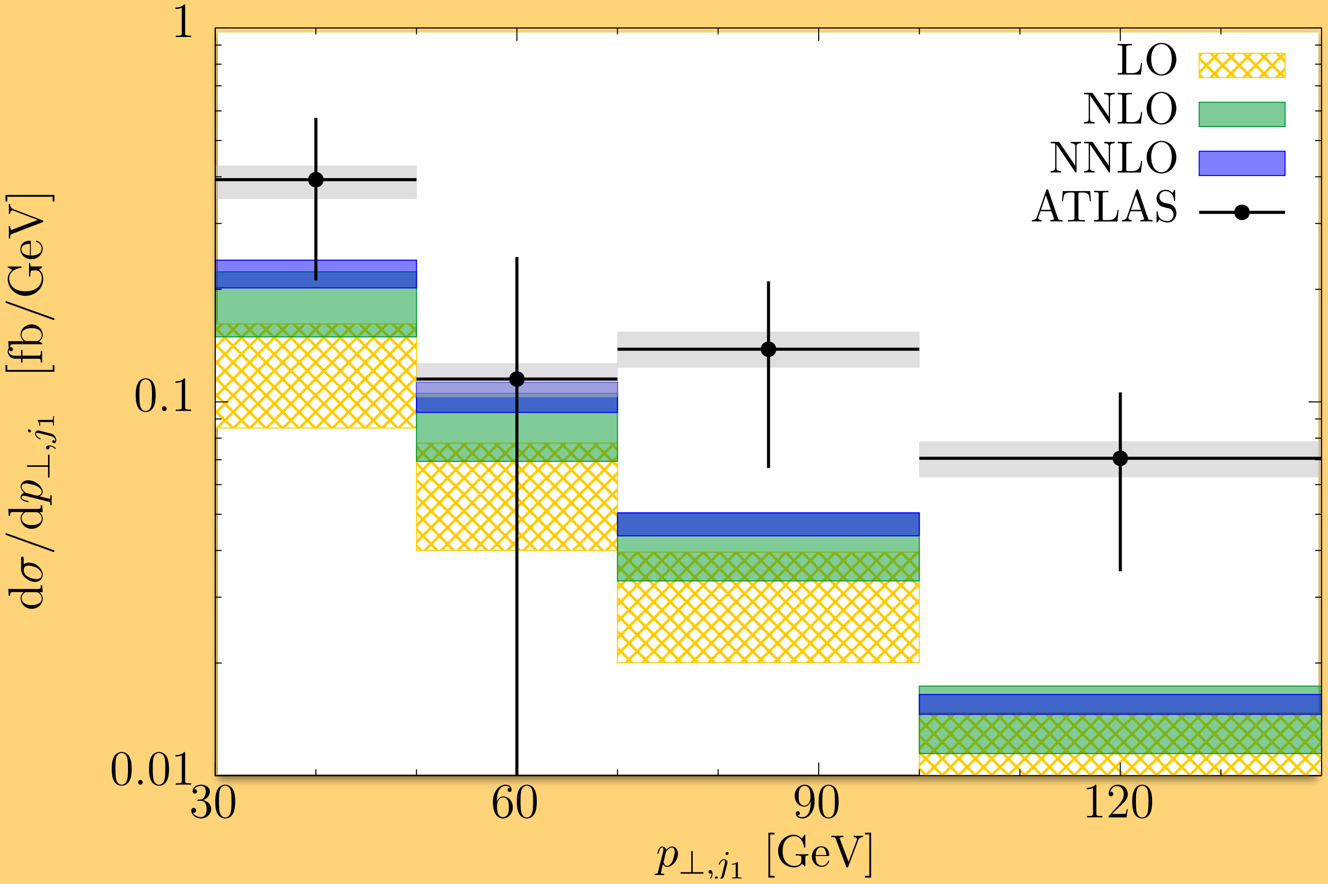
The need for higher orders: Higgs

Similar picture at the differential level:

$O(\alpha_s^5)$ [NNLO] needed to match exp. systematics



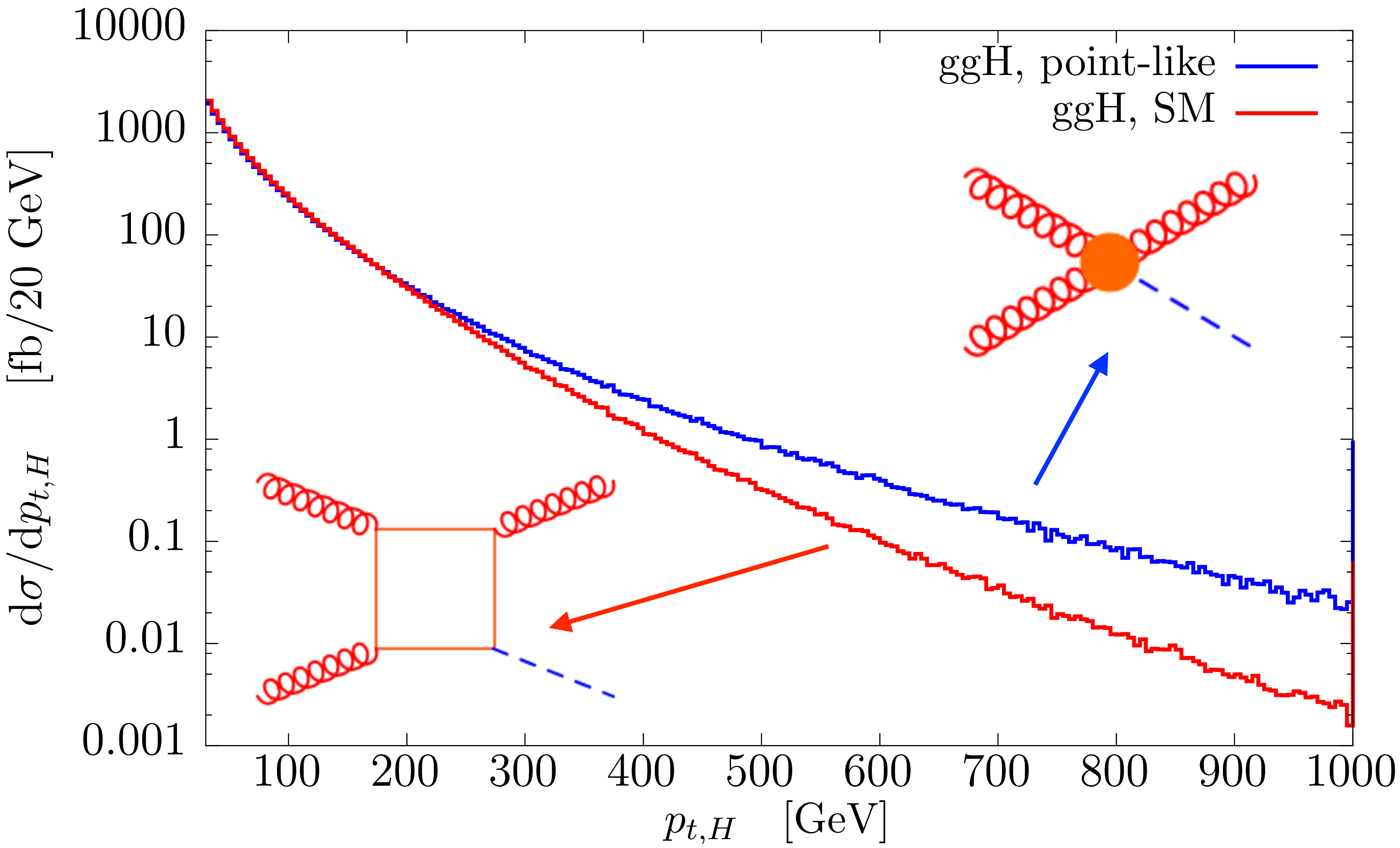
[Chen et al (2016)]



[FC, Melnikov, Schulze]

13 TeV data are coming in…

A (so far) less successful story: the Higgs tail



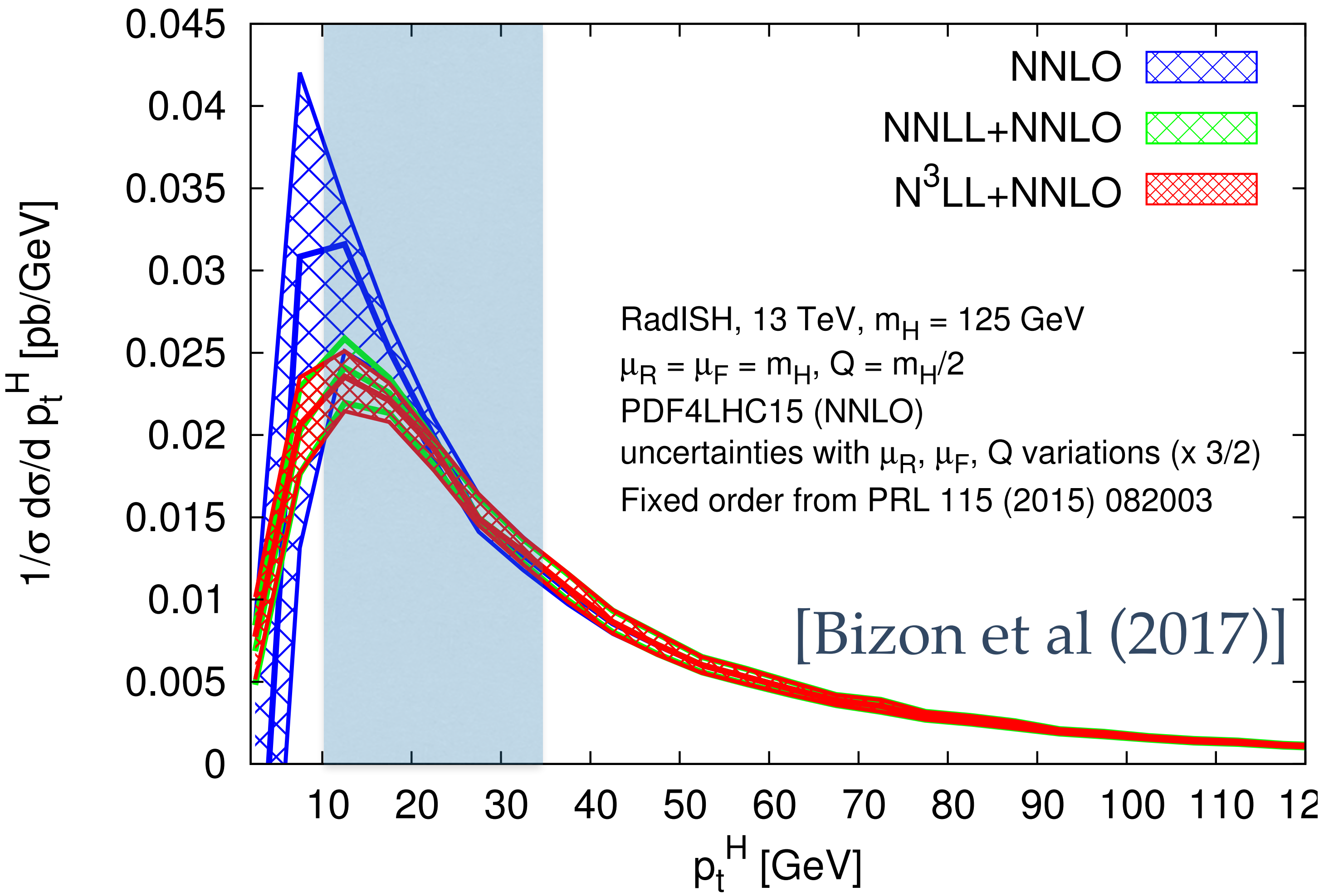
σ_{gg} ($p_t > p_{t,cut}$) =	1 fb	1 ab
bb	$p_{t,cut}$ ~ 600 GeV	$p_{t,cut}$ ~ 1.5 TeV
ττ	~ 400 GeV	~ 1.2 TeV
2l2ν	~ 300 GeV	~ 1 TeV
γγ	~ 200 GeV	~ 750 GeV
4l	~ 50 GeV	~ 450 GeV

- The LHC is starting to explore the boosted Higgs regime
- Crucial information on coupling structure, non accessible at low p_t
- TH input: ~20% would be fine
- Despite a lot of progress, [*see e.g. Bonciani et al.*] still only LO predictions there. Large p_T fully resolves the top loop, cannot neglect internal dynamics
- Similar for off-shell tail

Taming logs: the low-p_t Higgs spectrum

beyond f.o. computations

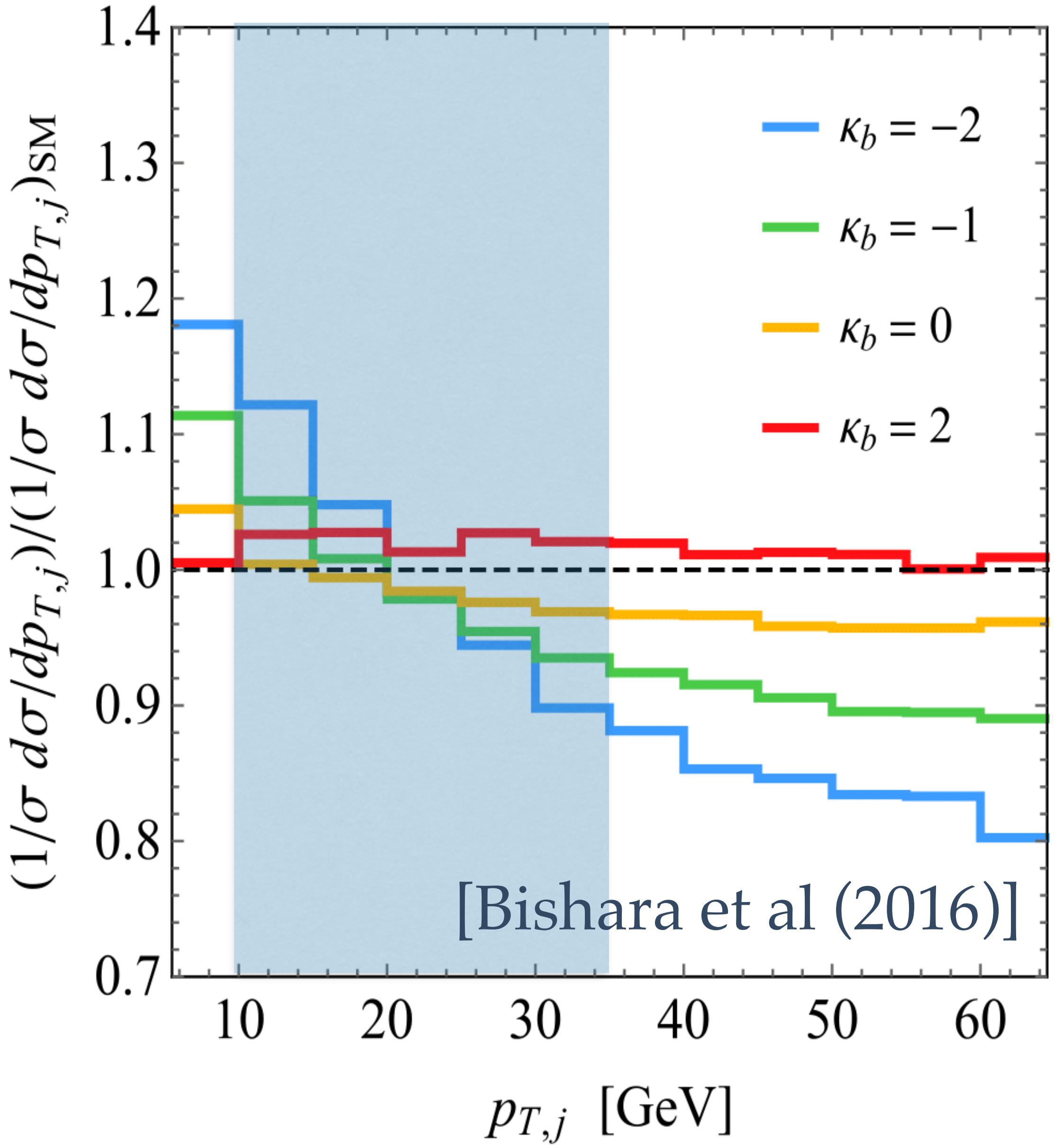
$$\alpha_s \ln^2 \frac{p_{t,H}}{M_H} \sim 0.5, \qquad p_t \sim 15 \text{ GeV}$$



RadISH, 13 TeV, m_H = 125 GeV
$\mu_R = \mu_F = m_H$, $Q = m_H/2$
PDF4LHC15 (NNLO)
uncertainties with μ_R, μ_F, Q variations (x 3/2)
Fixed order from PRL 115 (2015) 082003

[Bizon et al (2017)]

lowish p_t spectrum sensitive to non standard light Yukawa modifications



[Bishara et al (2016)]

Good understanding of the transition between (recently computed) NLO and resummation would be beneficial

Fixed-order predictions for precision observables

Thomas Gehrmann Universität Zürich

LHC Run II Gordon Research Conference, HKUST, Hong Kong,25.6.2017

NLO multi-particle production

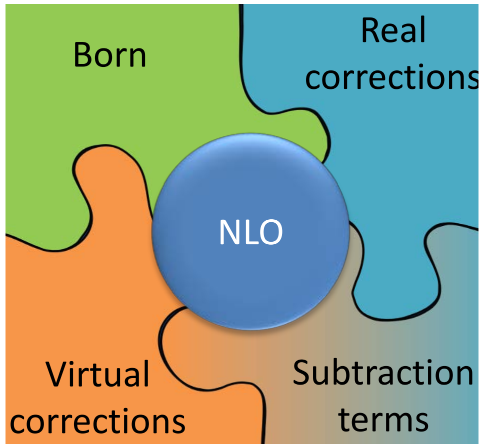
- Why NLO?
  - reduce scale uncertainty of LO theory prediction
  - reliable normalization and shape
  - accounts for effects of extra radiation
  - jet algorithm dependence
- Typical observations
  - sizable NLO corrections
  - corrections not constant, but kinematics-dependent
  - remaining uncertainty at NLO typically 10-20%

NLO multi-particle production

- Leading-order multi-purpose tools available for 25+ years
- Enormous progress in getting NLO predictions for 2→(4,5,6,…) processes over the last years
- Made possible by
  - Improved techniques for loop amplitudes
  - Crucial: a high level of automation
- Well-defined interfaces (Binoth Les Houches accord)
  - combine different ingredients from different codes

NLO automation

- One-loop amplitudes
  - BlackHat (Z. Bern, L. Dixon, F. Febres Cordero, S. Höche, H. Ita, D. Kosower, D. Maitre)
  - GoSam (G.Cullen, N.Greiner, G.Heinrich, G Luisoni, P. Mastrolia, G.Ossola, F.Tramontano)
  - RECOLA (S. Actis, A. Denner, L. Hofer, J.N. Lang, A. Scharf, S. Uccirati)
  - OpenLoops (F. Cascioli, P. Maierhöfer, S. Pozzorini)
  - NJet (S. Badger, B. Biedermann, P. Uwer, V. Yundin)
  - MadLoop/aMC@NLO (R. Frederix et al.)
  - CutTools (G. Ossola, C. Papadopoulos, R. Pittau)
- Real radiation, subtraction terms and phase space (infrastructure)
  - From event generator programs

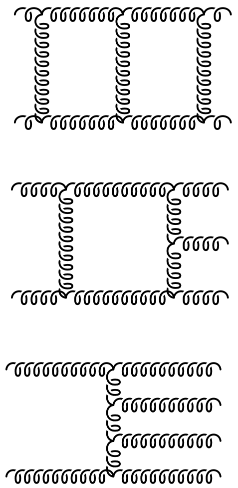


Tools for NLO calculations

- MCFM, VBFNLO (J. Campbell, K. Ellis, C. Williams; D. Zeppenfeld et al.)
  - Extensive libraries of NLO QCD processes
- MG5_aMC@NLO (F. Maltoni, S. Frixione et al.)
  - Full event generation with automation of one-loop amplitudes
  - Matching to parton shower (MC@NLO method)
- SHERPA (F. Kraus et al.)
  - Interfaces to one-loop codes (OpenLoops, BlackHat, Njet, GoSam)
  - Matching to parton shower (MC@NLO, POWHEG methods)
  - Matching of NLO multiplicities (MENLOPS)
- HERWIG (S. Gieseke, S. Plätzer, P. Richardson et al.)
  - Full event generation with one-loop from GoSam or VBFNLO
  - Matching to parton shower (MC@NLO method)

NNLO calculations

- Require three principal ingredients
  - two-loop matrix elements
    - explicit infrared poles from loop integral
      - known for all massless 2 → 2 processes
  - one-loop matrix elements
    - explicit infrared poles from loop integral
    - and implicit poles from single real emission
      - usually known from NLO calculations
  - tree-level matrix elements
    - implicit poles from double real emission
      - known from LO calculations
- Infrared poles cancel in the sum
- Challenge: combine contributions into parton-level generator

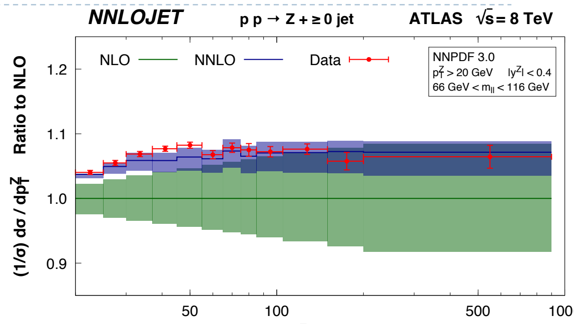


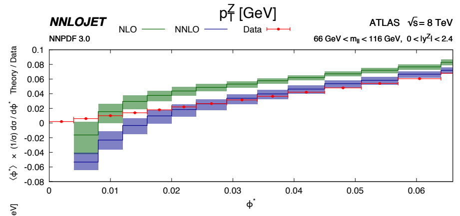
Z p_T-distribution at NNLO

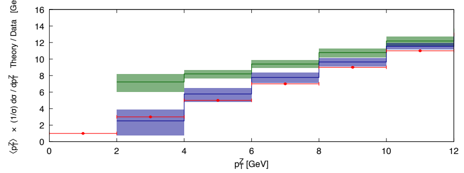
- Classical QCD observable
  - Measured: p_T= 1...1000 GeV
  - Constrains gluon distribution (R.Boughezal, A. Guffanti, F. Petriello, M. Ubiali)
  - NNLO improves description of data in shape and normalization
- Related observable

$$\phi^* = \tan\left(\frac{\pi-\Delta\phi}{2}\right)\sin(\theta^*_\eta) \approx \frac{p_T^Z}{2m_{ll}}$$

  - purely from lepton directions
  - Higher resolution at low pT
  - NNLO reliable to p_T=5 GeV
  - Challenge for numerics







Real radiation at NNLO: methods

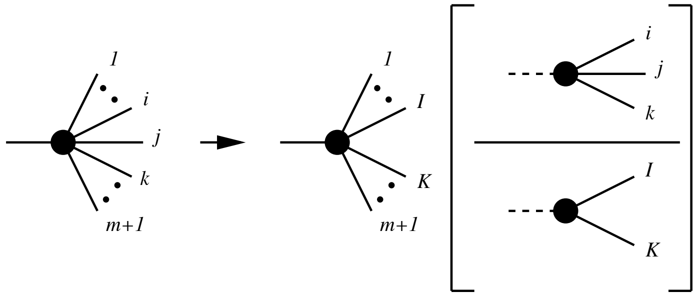
- q_T-subtraction (S. Catani, M. Grazzini)
  - Production of colourless final states at hadron colliders
  - Universal behaviour for small transverse momentum from resummation
  - Cut off real radiation phase space at small transverse momentum

$$d\sigma^F_{NNLO} = \mathcal{H}^F_{NNLO} \otimes d\sigma^F_{LO} + \left[d\sigma^{F+\text{jet}}_{NLO} - d\sigma^{CT}_{NLO} \right]$$

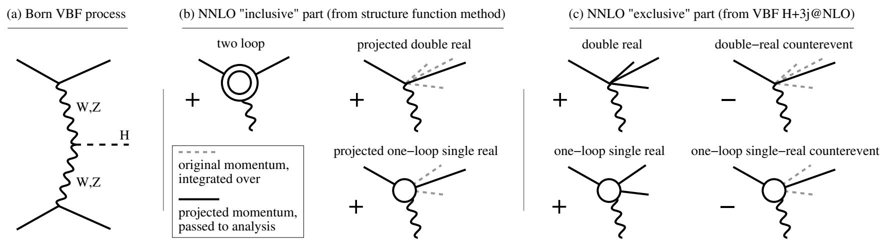
- N-jettiness subtraction (R. Boughezal, X. Liu, F. Petriello; J. Gaunt, M. Stahlhofen, F. Tackmann, J. Walsh)
  - Use N-jettiness variable as cut-off for N-jet final state

$$\tau_N = \frac{2}{Q^2}\sum_k \min\left\{q_a\cdot p_k, q_b\cdot p_k, q_1\cdot p_k, \dots q_N\cdot p_k\right\}$$

- Antenna subtraction (A. Gehrmann-De Ridder, E.W.N. Glover, TG)
  - Subtraction terms constructed from antenna functions
  - Antenna function contains all emission between two partons



- Projection-to-Born (M. Cacciari, F. Dreyer, A. Karlberg, G. Salam, G. Zanderighi)



Where do we stand?

- Witnessed an NLO revolution
  - Previously unthinkable NLO QCD+EW multi-particle calculations now feasible due to technological breakthroughs
  - High-level of automation
  - Standarization of interfaces: combine different codes (providers)
  - Interface to experiment (codes, ntuples, histograms,..)?
- Substantial progress on NNLO calculations
  - Several different methods available
  - Close interplay with resummation
  - Calculations on process-by-process basis
  - Codes typically require HPC infrastructure

Future Directions

- NNLO automation
  - Uncover analytical structures to organize calculation
  - Develop standard interfaces
  - Interface to experiment ?
- Beyond NNLO
  - N^3LO precision for benchmark processes

Status and Progress on Resummed Calculations in Soft-Collinear Effective Theory

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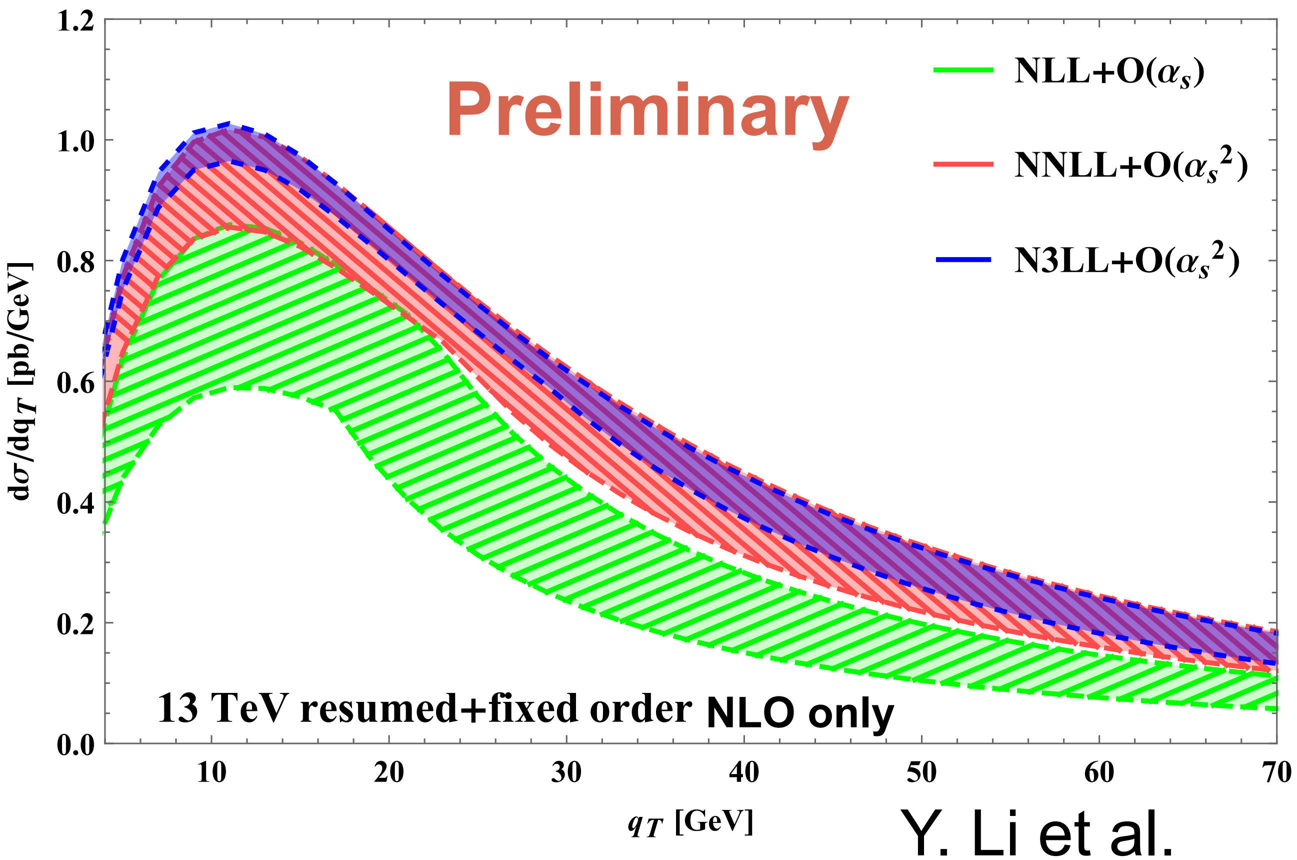
Pushing the Frontiers of Particle Physics During the LHC Run II Era
Gordon Research Conference

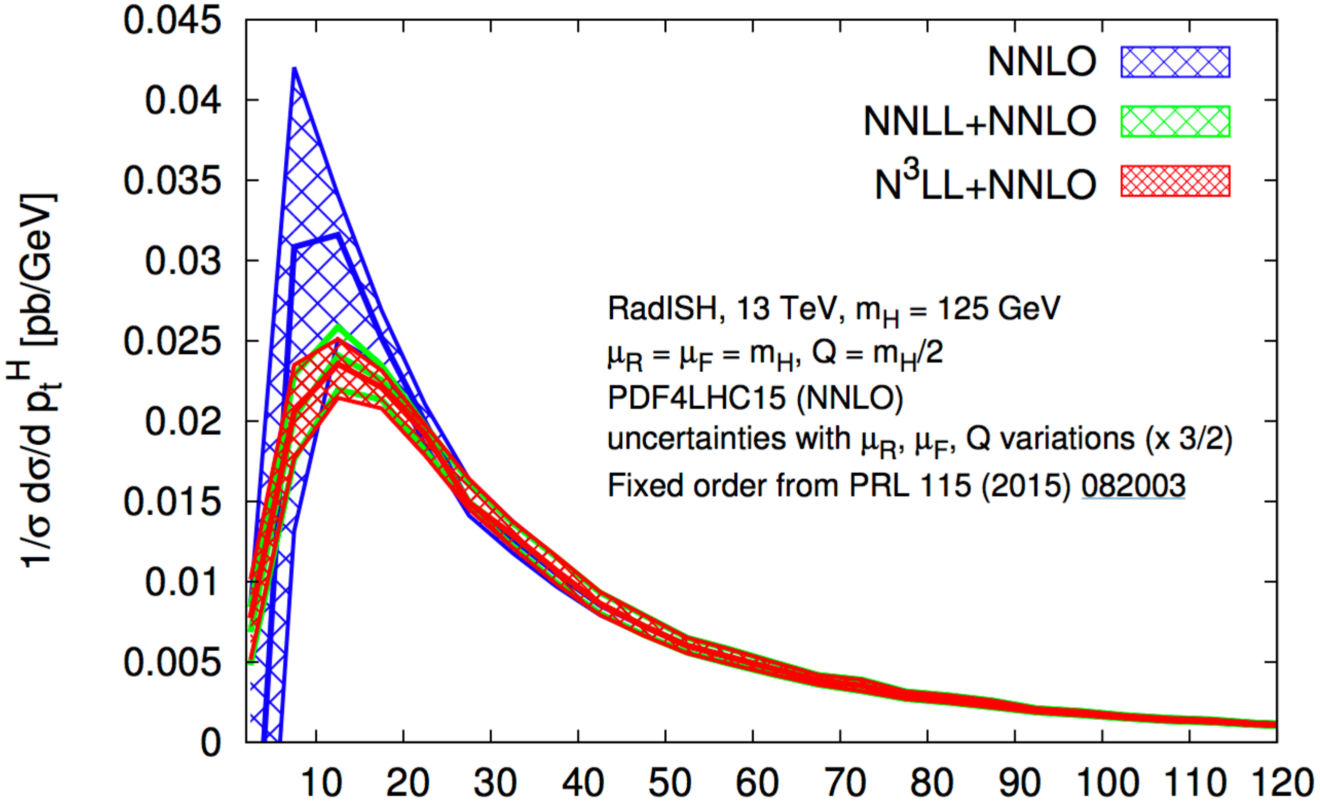
The Hong Kong University of Science and Technology
June 25th, 2017

pT resummation for Higgs at N3LL

- First example of N^3LL resummation for differential distribution at hadron collider (with the exception of 4-loop cusp anomalous dim.)
  - N^3LL resummation for thrust in e+e- in about 10 years ago [Becher, Schwartz]
  - Complications at hadron collider: PDF convolution, definition of observable, anomalous dim.
- N^3LL resummaiton in the rapidity renormalization group formalism [Y. Li et al.]
  - Good convergence of RG improved perturbation theory
  - Smooth switch between resummed and fixed order beyond NLL
- Momentum space N^3LL resummation [Bizon et al.]



Y. Li et al.



Bizon et al.

Status and Recent Advances in Monte Carlo Event Generation

Simone Alioli

Pushing the Frontiers of Particle Physics
During the LHC Run II Era

HKUST - Honk Kong
25 June 2017

State-of-the-art theoretical predictions

We currently have 3 main approaches to perturbative QCD calculations:

Fixed-Order: power expansion $\underbrace{c_0}_{LO} + \underbrace{c_1\alpha_s}_{NLO} + \underbrace{c_2\alpha_s^2}_{NNLO} + \underbrace{c_3\alpha_s^3}_{N3LO} + \ldots$

- ✓ Valid for cross sections and inclusive quantities. Systematically improvable.
- ✗ Fails for many soft-collinear emissions and “Sudakov-sensitive” observables. Unrealistic events.

Resummation: expansion in $\alpha_s^N \log^M(Q_1/Q_2)$ LL,NLL,NNLL,. . .

- ✓ Correct in exclusive regions. Systematically improvable.
- ✗ One observable at a time, no generic hadronization.

Parton-shower event generators: recursive probabilistic algorithm

- ✓ Predict all observables. Realistic events, include hadronization
- ✗ Crude approximation of QCD. Accuracy bottleneck, not easy to improve systematically.

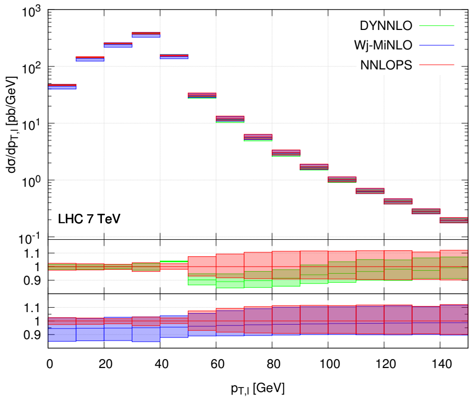
Event Generators are unavoidable tools, but the LHC experimental precision already demands better theory predictions !

$\hookrightarrow$ ***Merge the benefits of the 3 approaches***

The state of the art : NNLO + PS

- Interfacing NNLO calculations to a parton shower is more complicated: general approach presented in [SA, Bauer et al. 1311.0286]
- Three different approaches available, implemented only for color singlet production:

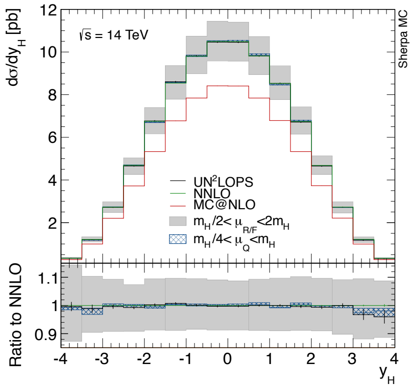
MiNLO - NNLOPS



[Hamilton,Nason et al. ’13, ’14, ’15, ’16]

- Implemented V, H, VH
- Multi-dimensional reweight to external NNLO program.
- 0-jet events (2-loop virtuals) are showered with fudge factor
- Combined with $2j$ NLO [Hamilton, Frederix ’16]

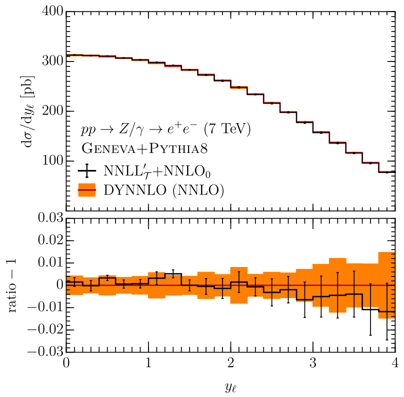
UNNLOPS



[Hoeche, Prestel et al. ’14, ’15]

- Implemented V, H
- NNLO by $N-$jettiness slicing and imposing unitarity
- Never showers 0-jet events (2-loop virtuals)

GENEVA



[SA, Bauer et al. ’13, ’15, ’16]

- Implemented V
- NNLO by $N-$jettiness subtraction.
- 0-jet events (2-loop virtuals) are showered as the resummation dictates