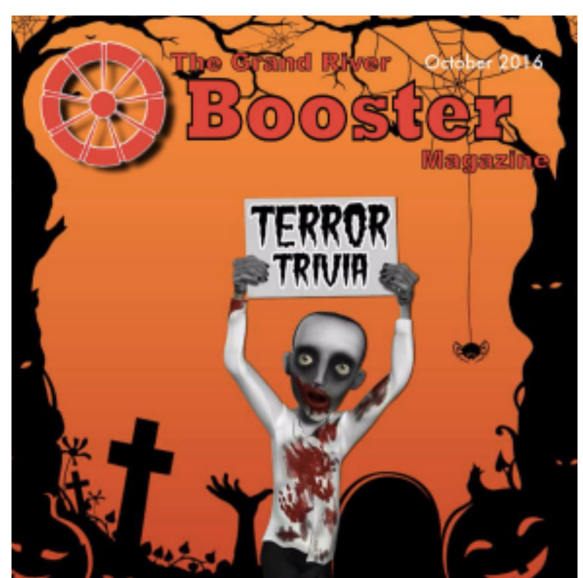
QCD at NNLO

John Campbell, Fermilab

BOOST 2017, Buffalo, July 18 2017

Personal perspective

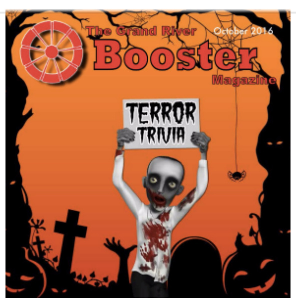
- Brief from the organizers: *“stimulate discussion on the role of higher-order corrections in the description of jet properties, perhaps in the presence of substructure algorithms”.*
- Disclaimer: I am a practitioner of higher-order corrections and have not worked on typical BOOST topics, substructure, …
- I am using opportunity to inform myself and see what I can add.
- More generally, hope to help stimulate dialogue between **boosters** and **loopers**.



CMS inclusive H→bb: a tour de force

[CMS PAS HIG-17-010](#)

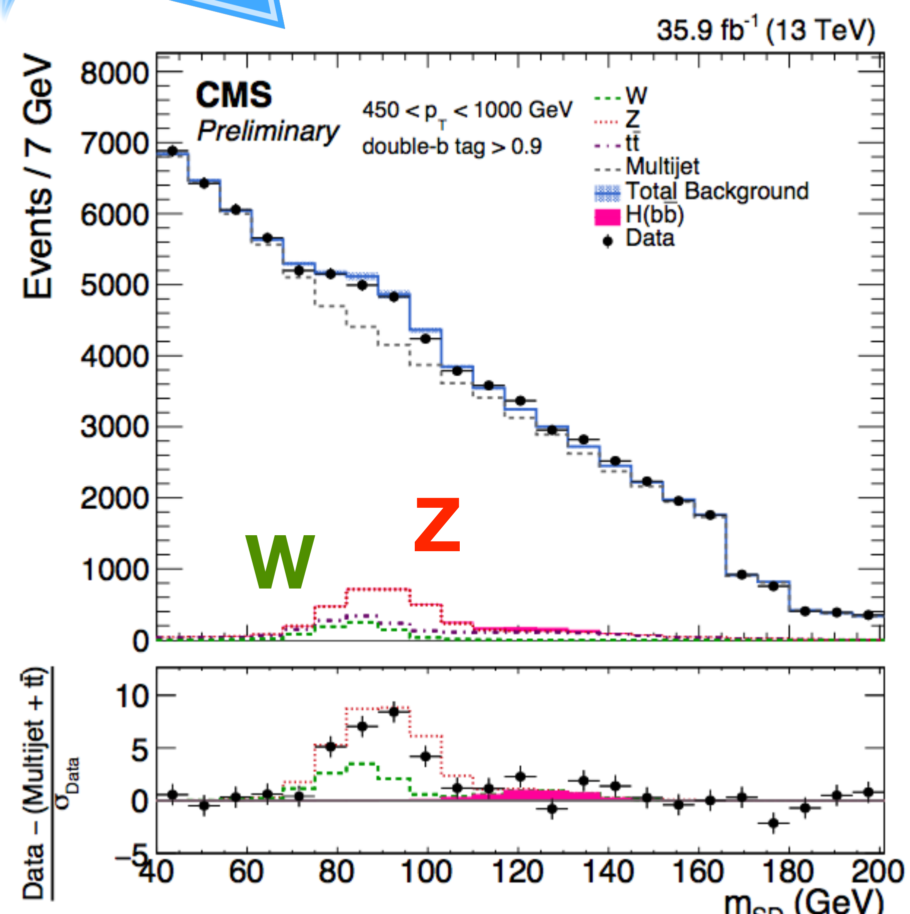
- Search for H→bb decay from Higgs boson produced at high p_T: local significance of 1.5σ.
  - Also sensitive to Z→bb decays: first observation in single-jet topology (5.1σ)!
- Exciting experimental achievement anchored by confluence of theoretical input.



jet trimming to remove soft radiation
Krohn, Thaler, Wang

soft drop algorithm to remove wide-angle radiation
Dasgupta et al , Larkoski et al

N_2^1 variable for determining two-prong substructure
Moult, Necib, Thaler
Larkoski, Salam, Thaler



POWHEG event generator
Frixione, Nason, Oleari

MG: inclusion of finite top mass effects
Hirschi & Mattelaer

$$\text{Powheg}(1\text{ jet } m_t \to \infty) \times \frac{\text{MG LO } 0-2 \text{ jet } m_t}{\text{Powheg}(1\text{ jet } m_t \to \infty)} \times \frac{\text{NLO 1 jet } m_t}{\text{LO 1 jet } m_t} \times \frac{\text{NNLO 1 jet } m_t \to \infty}{\text{NLO 1 jet } m_t \to \infty}.$$

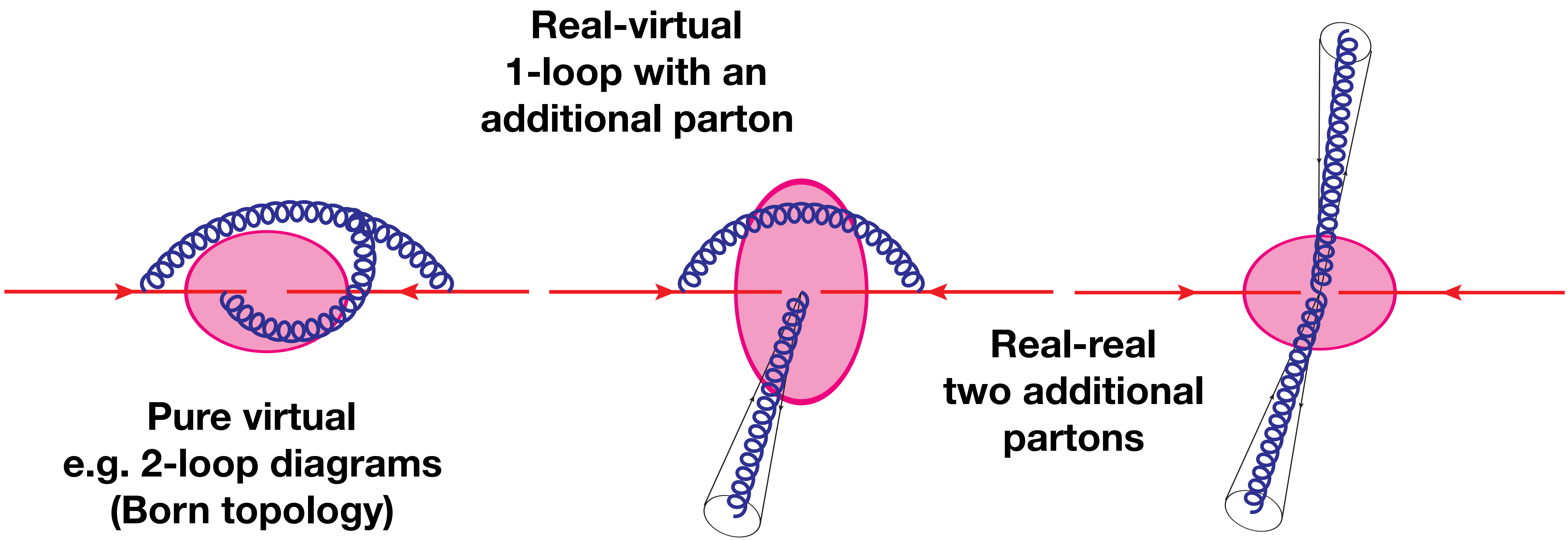
NLO corrections with finite m_t
Neumann & Williams

NNLO QCD corrections
[refs later]

Outline

- Brief survey of NNLO calculations that have been performed.
  - most theoretical work so far has been performed using analytic techniques based on resumming large logs or parton showers.
  - as far as I am aware, no real substructure analyses using NNLO.
- Overview of results from recent “jetty” NNLO calculations.
  - in most cases, there are already many phenomenological studies.
  - rather than dwell on typical features of NNLO, highlight aspects of particular relevance for boosted applications.
- A few words about suitability of calculations for further studies and related applications.

NNLO ingredients

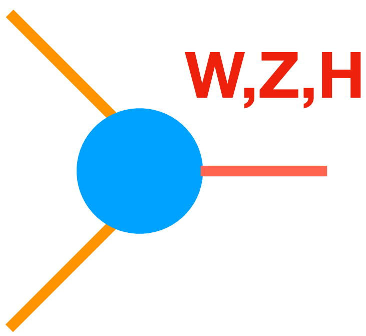


- Two main challenges
  - calculation of 2-loop diagrams with multiple scales;
  - method for isolating singularities and cancelling between contributions.

[for a recent overview see: G. Zanderighi @ EPS2017]

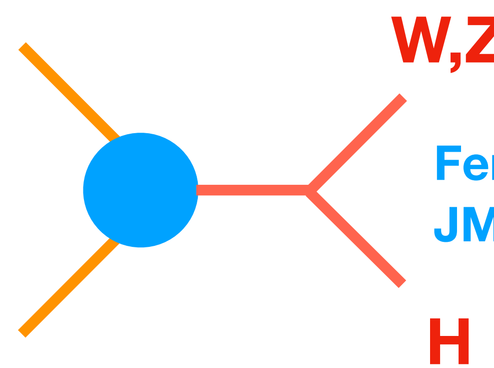
- For simplest cases (~ pre-2014) limited "jet" interest, radiation "all ISR".

NNLO: no jets

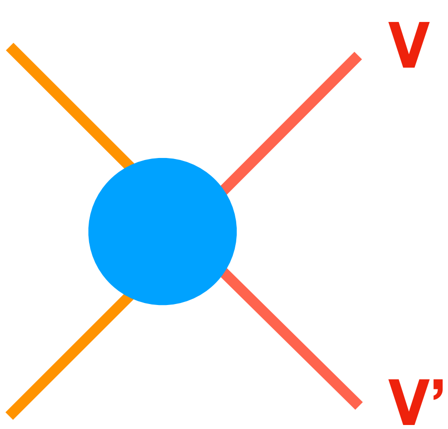


Catani et al, arXiv:0703012, arXiv:0903.2120
Petriello et al, arXiv:1201.5896
Boughezal et al, arXiv:1605.08011

N^{3}LO: Anastasiou et al, arXiv:1602.00695

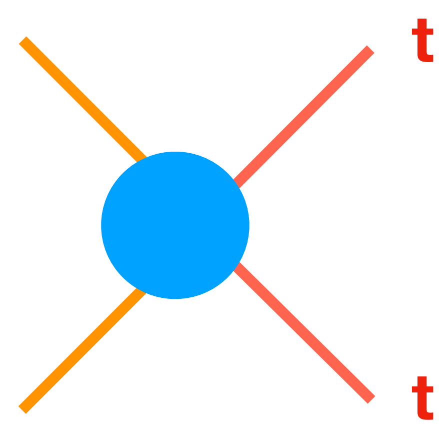


Ferrera et al, arXiv:1705.10304
JMC et al, arXiv:1601.00658



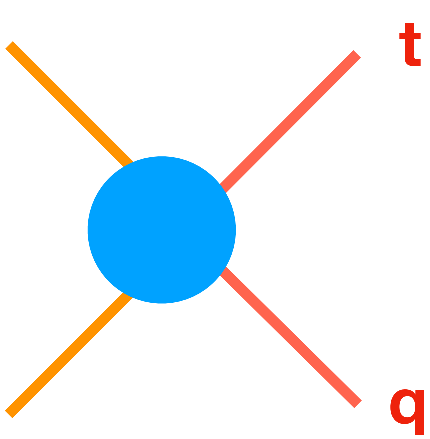
Grazzini et al, recent review:
Wiesemann et al, Proceedings

Catani et al, arXiv:1110.2375
JMC et al, arXiv:1603.02663

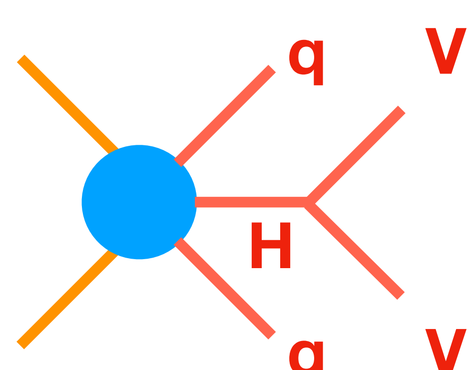


Czakon et al, recently:
arXiv:1705.04105

[see also approx. NNLO+decay, Gao & Papanastasiou, arXiv:1705.08903]



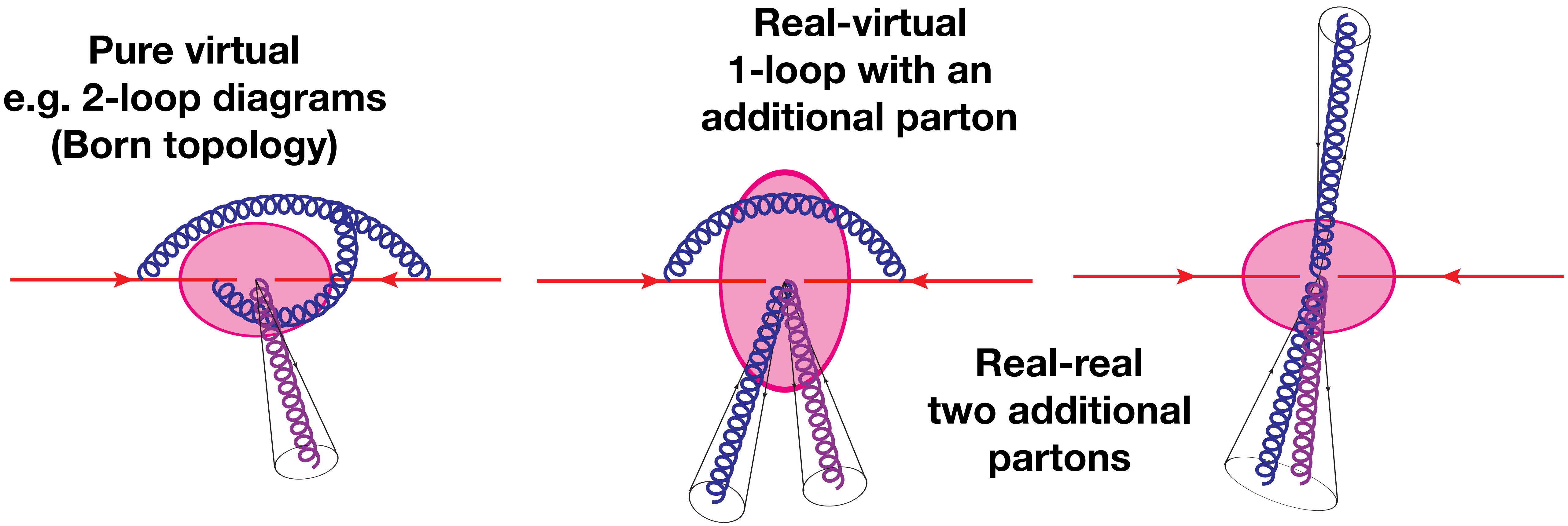
t-channel single top
(structure function, no jet)
Berger et al,
arXiv:1606.08463



VBF (structure function, no jets)
Bolzoni et al, arXiv:1003.4451

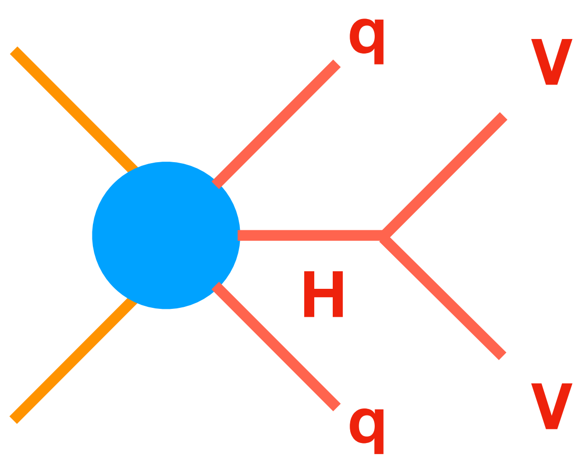
N^{3}LO: Dreyer and Karlberg,
arXiv:1606.00840

NNLO ingredients with jet(s)



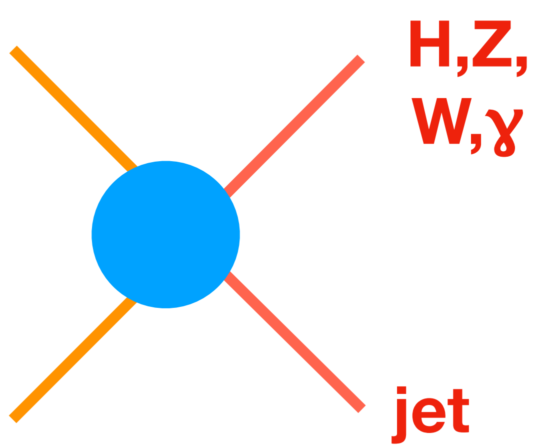
- More recently, results with jets at Born level: X+jet for EW boson X, or X=jet.
- In addition to usual NNLO benefits of theoretical control and precision, possibility of studying:
  - systems produced at high transverse momentum.
  - jet substructure with up to 3 partons in a jet, with exact ME (e.g. wide-angle emission).
  - corrections to predictions for non-trivial jet properties, e.g. jet mass.

NNLO: jet processes



VBF differential, "projection-to-Born"
[quark jets produced via EW interactions not QCD]

Cacciari et al, arXiv:1506.02660



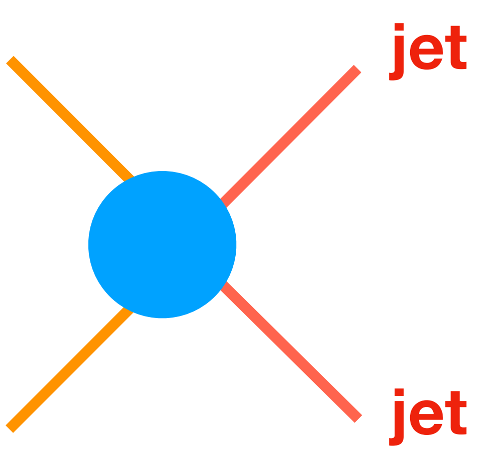
EW boson+jet

Higgs: Boughezal et al, arXiv:1505.03893, arXiv:1504.07922;
Caola et al, arXiv:1508.02684; Chen et al, arXiv:1607.08817

Z: Gehrmann-De Ridder et al, arXiv:1610.01843
Boughezal et al, arXiv:1602.08140

W: Boughezal et al, arXiv:1602.06965, arXiv:1602.05612

ɣ: JMC et al, arXiv:1703.10109

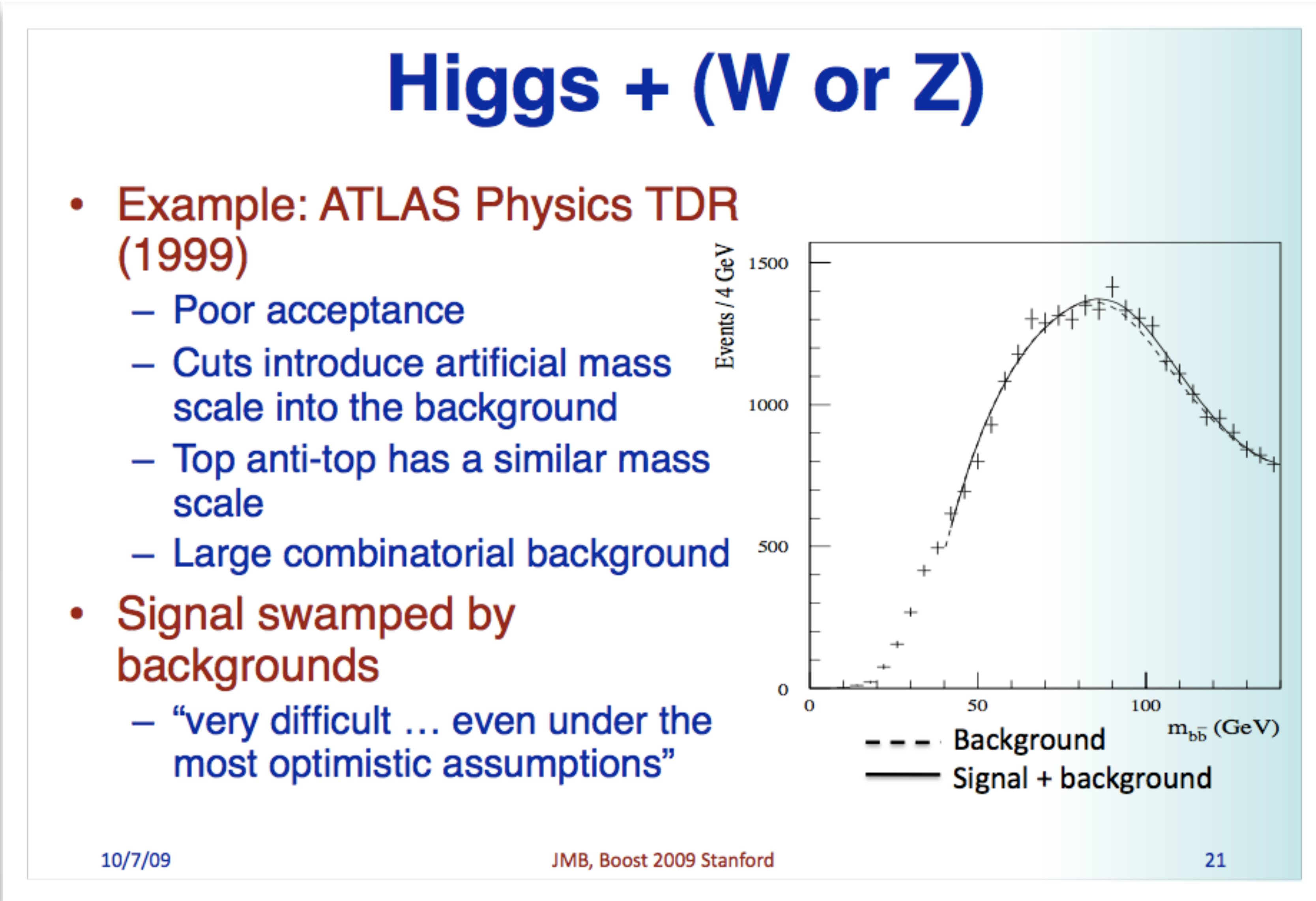


Inclusive jet, dijets

Currie et al, arXiv:1611.01460, arXiv:1705.10271,
arXiv:1705.08205

VH production: history

- Venerable boosted heritage for sensitivity to H→bb decay.



Butterworth, Davison, Rubin, Salam, arXiv:0802.2470

VH production: history

- Venerable boosted heritage for sensitivity to H→bb decay.

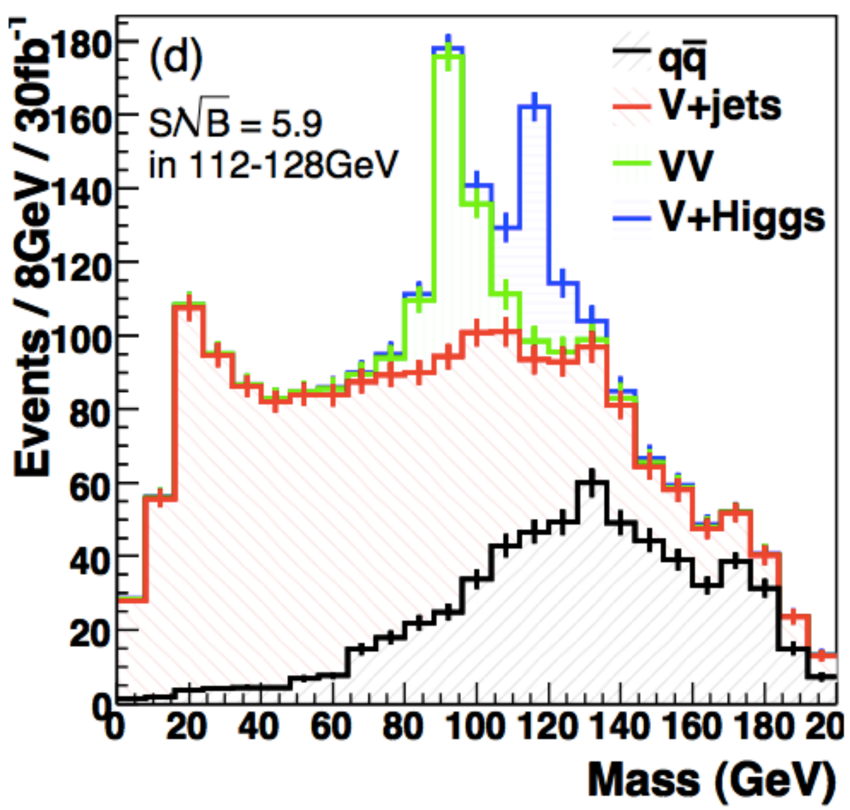
Higgs + (W or Z)

- Example: ATLAS Physics TDR (1999)
  - Poor acceptance
  - Cuts introduce artificial mass scale into the background
  - Top anti-top has a similar mass scale
  - Large combinatorial background
- Signal swamped by backgrounds
  - "very difficult … even under the most optimistic assumptions"

10/7/09 JMB, Boost 2009 Stanfo

Butterworth, Davison, Rubin, Salam, arXiv:0802.2470

Combined particle-level result



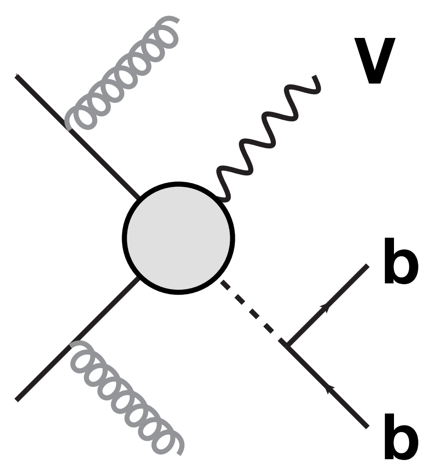
- Note excellent Z peak for calibration
- 5.9 σ; potentially very competitive
- bb branching information critical for extracting Higgs properties
  - *"Measuring the Higgs sector" Lafaye, Plehn, Rauch, D.Zerwas, Duhrssen, arXiv:0904.3866 [hep-ph]*
- Studies within ATLAS are promising and nearly public.

10/7/09 JMB, Boost 2009 Stanford 33

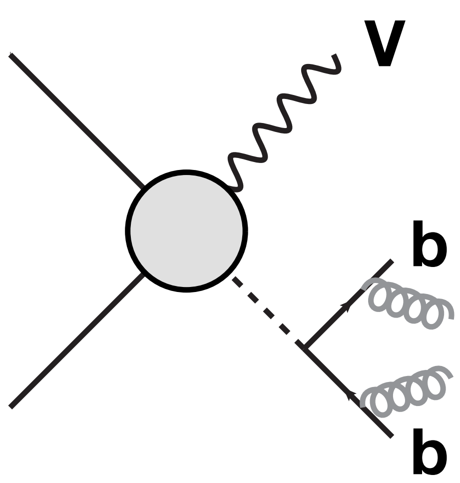
Importance of radiation in decay

- Perturbative QCD treatment should treat radiation in all parts of the process, including decay.

radiation in production



radiation in decay

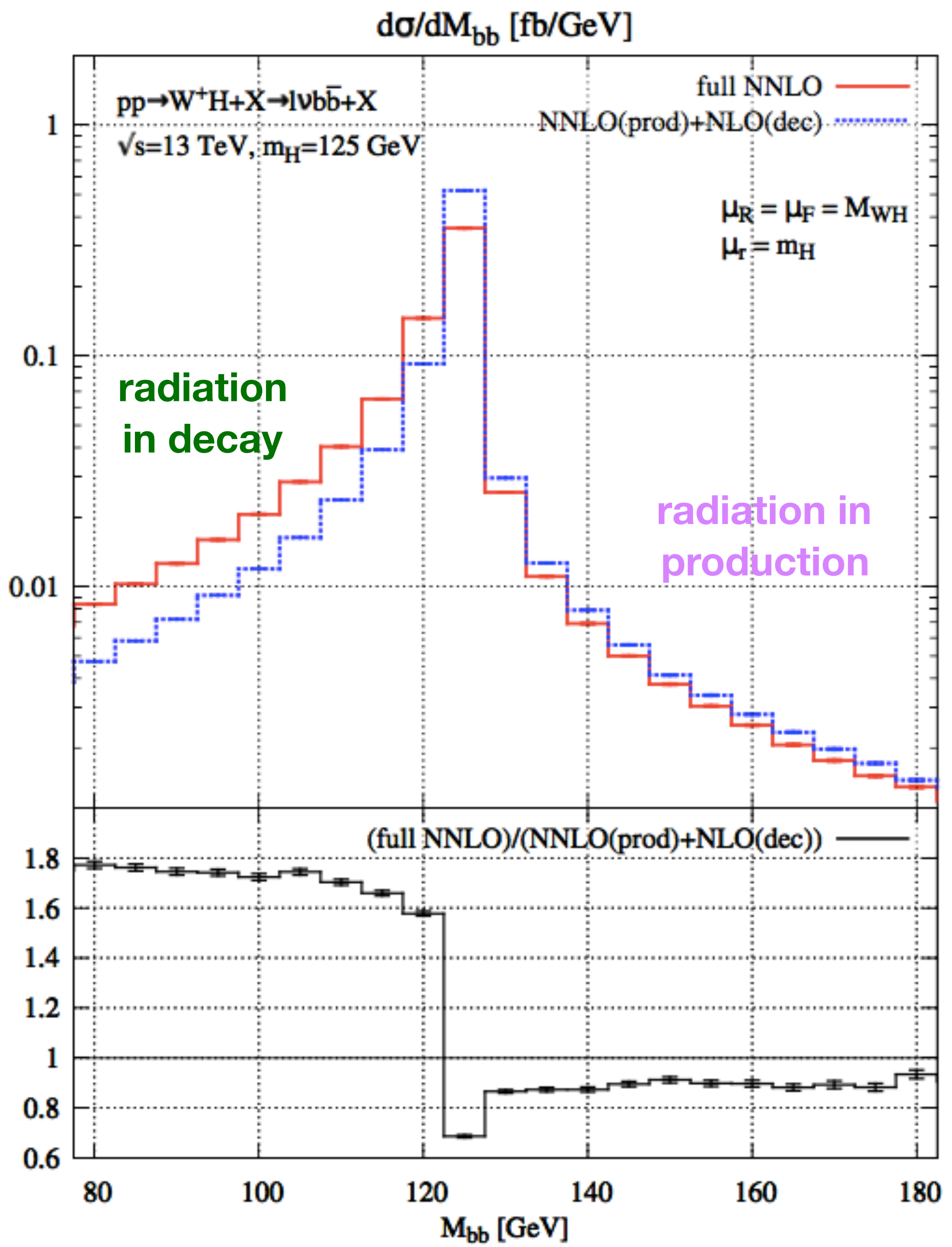


- Multiple calculations including effect of NNLO QCD in production and NLO QCD in Higgs boson decay.

  Ferrera, Grazzini, Tramontano, arXiv:1107.1164, arXiv:1312.1669, arXiv:1407.4747
  JMC, Ellis, Williams, arXiv:1601.00658

  - radiation in decay has non-trivial effect under application of experimental cuts.
  - might expect to be especially important for substructure analyses.

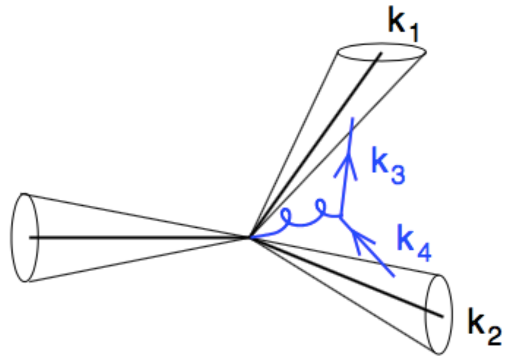
VH production in full NNLO



Ferrera, Somogyi, Tramontano, arXiv:1705.10304

- New full calculation of NNLO effects in production and decay.
- Infrared safety requires use of flavor k_T algorithm to properly define *b*-jet at this order.

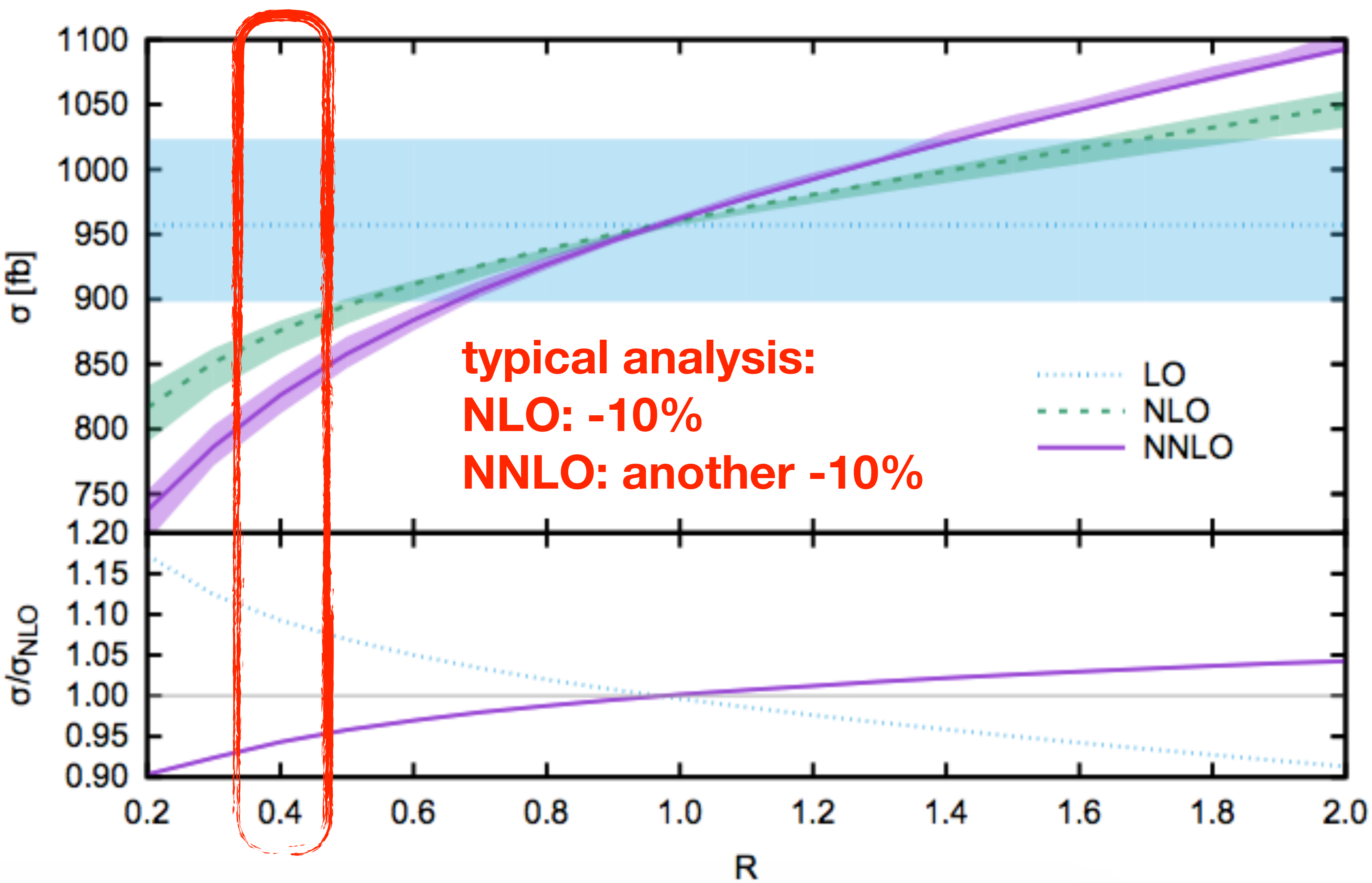
Banfi, Salam, Zanderighi, arXiv:0601139



- Effects of NNLO decay can be ~ 80%.
- Earlier studies (NLO decay) using BDRS fat jet analysis.
  - not yet updated to NNLO.
  - no recent substructure techniques.

Properties of jets in VBF

- Differential calculation reveals larger NNLO corrections (~10%) than might have been expected from inclusive calculation (~2%). Cacciari et al, arXiv:1506.02660
- New study to examine dependence on jet definition at NNLO. Rauch and Zeppenfeld, arXiv:1703.05676



Stronger R-dependence at NNLO than at NLO

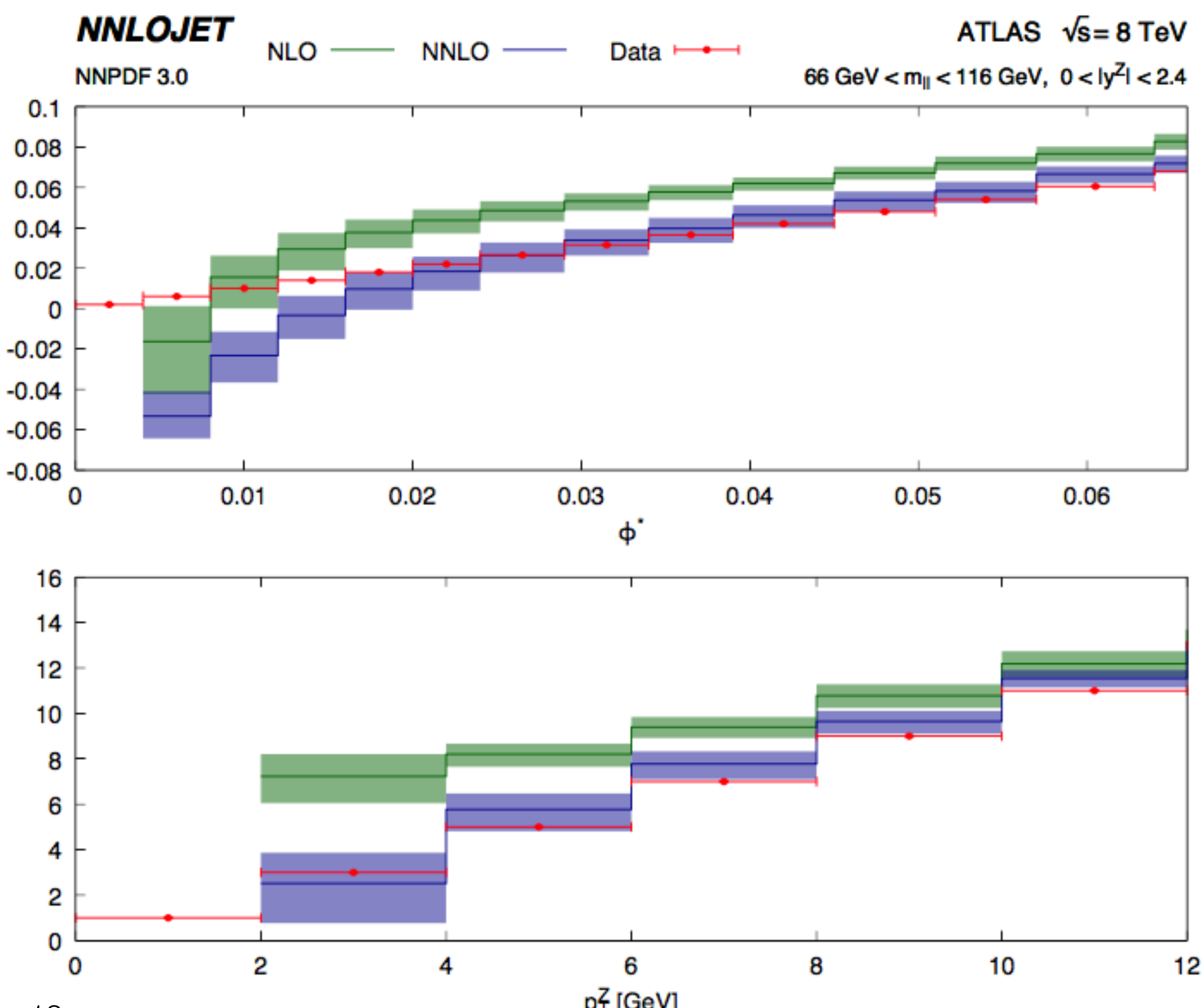
– wider energy flow within quark jets at NNLO

– larger jets capture more energy from original quark, more easily pass VBF cuts

R-dependence really only computed at NLO

Z production at low p_T

Gehrmann-De Ridder et al, arXiv:1610.01843



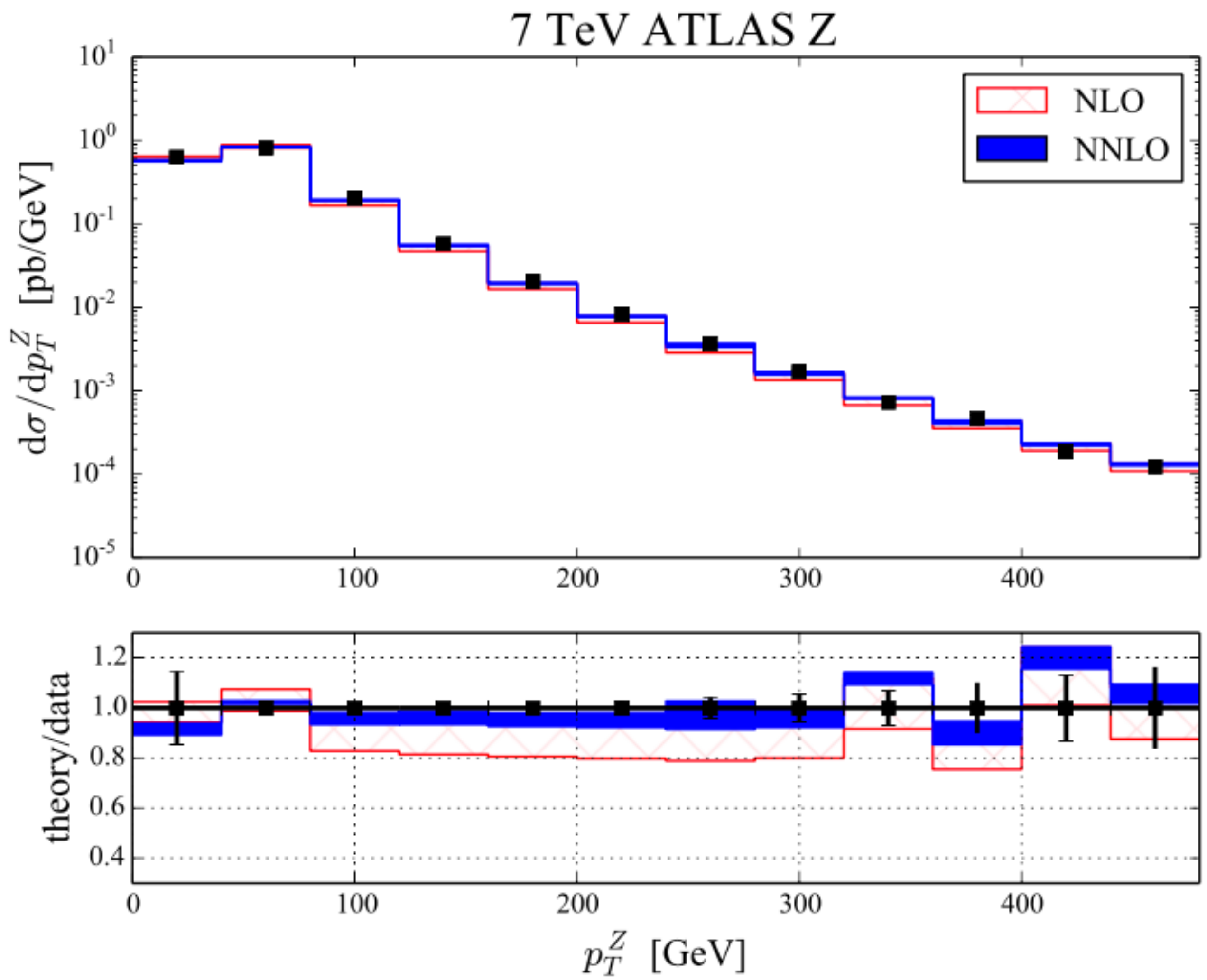
- … with apologies for being very un-BOOST-y!
- Improved description at small $p_T(Z)$, between 4 and 20 GeV.
  - Range of fixed-order validity extended at NNLO, into traditional "resummation zone".
- Note: alternative angular variable (ϕ*) measured directly from lepton directions to minimize experimental uncertainty, $p_T(Z) \sim 2m_{ll}\,\phi^*$

Banfi et al, arXiv:1009.1580

… and at moderate p_T

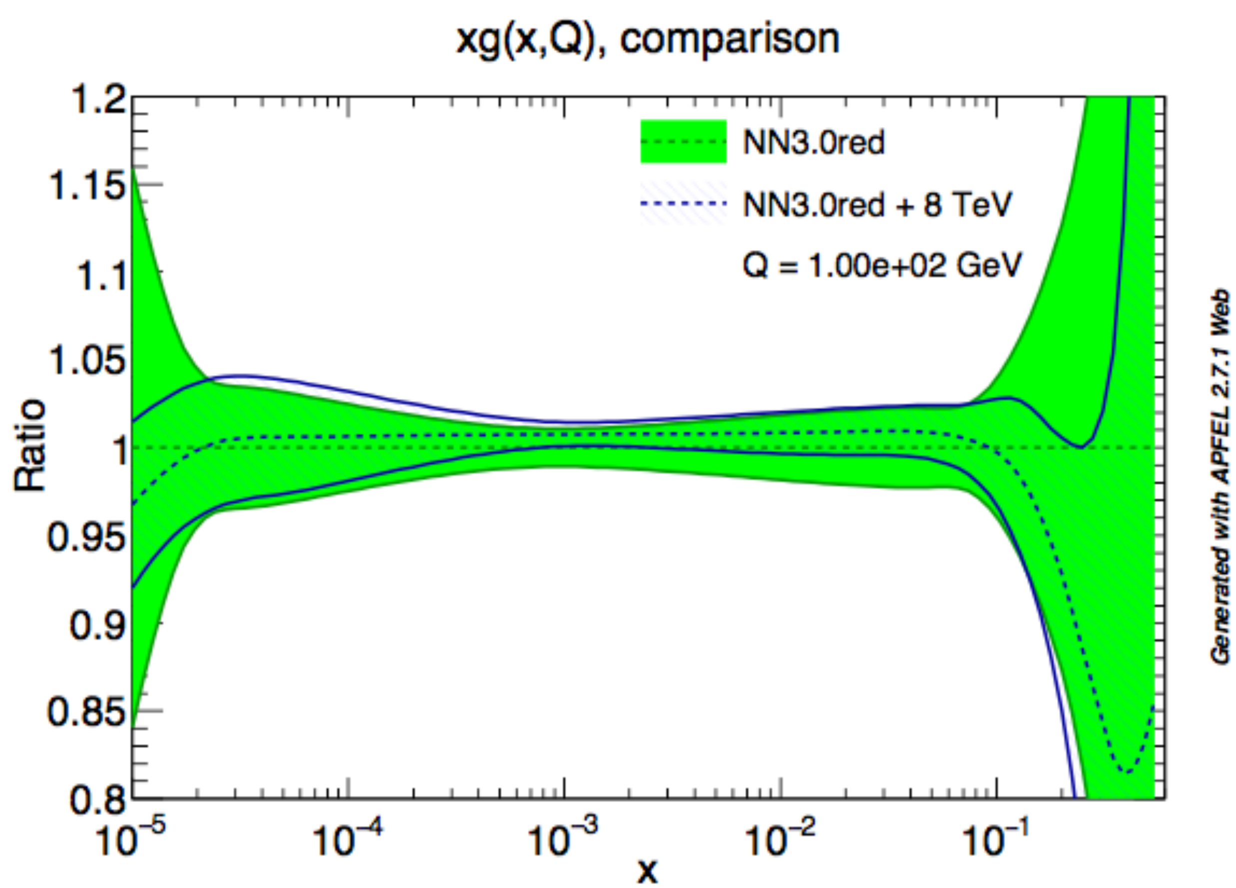
Gehrmann-De Ridder et al, arXiv:1507.02850; Boughezal et al, arXiv:1512.01291; …

- Normalized $p_T(Z)$ distribution well-described at NNLO at moderate transverse momentum.
  - can be used to reduce PDF uncertainties using global fit including LHC Run 1 data.



Boughezal et al, arXiv:1602.05612

Boughezal et al, arXiv:1705.00343



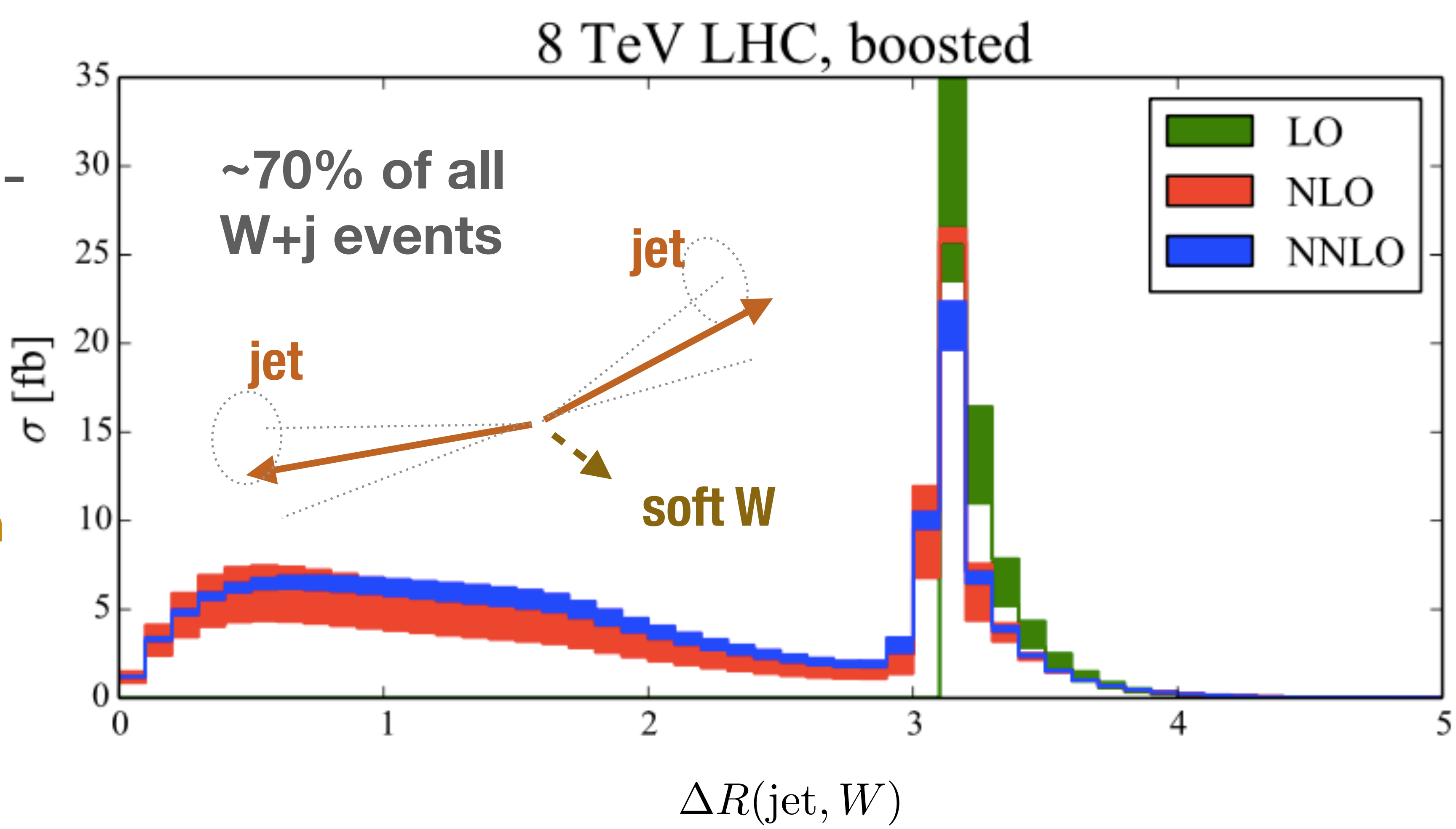
(see also: Boughezal et al, arXiv:1602.08140, arXiv:1705.00343; …)

W production at high p_T

Boughezal et al, arXiv:1504.02131, arXiv:1602.06965

- Study of NNLO correction under boosted selection:
- Large NLO corrections (~300%) due to new topology in which two jets produced back-to-back, with soft or collinear W-boson ("giant K-factor")
    - stabilized by inclusion of NNLO (~15% correction, ~5% uncertainty).

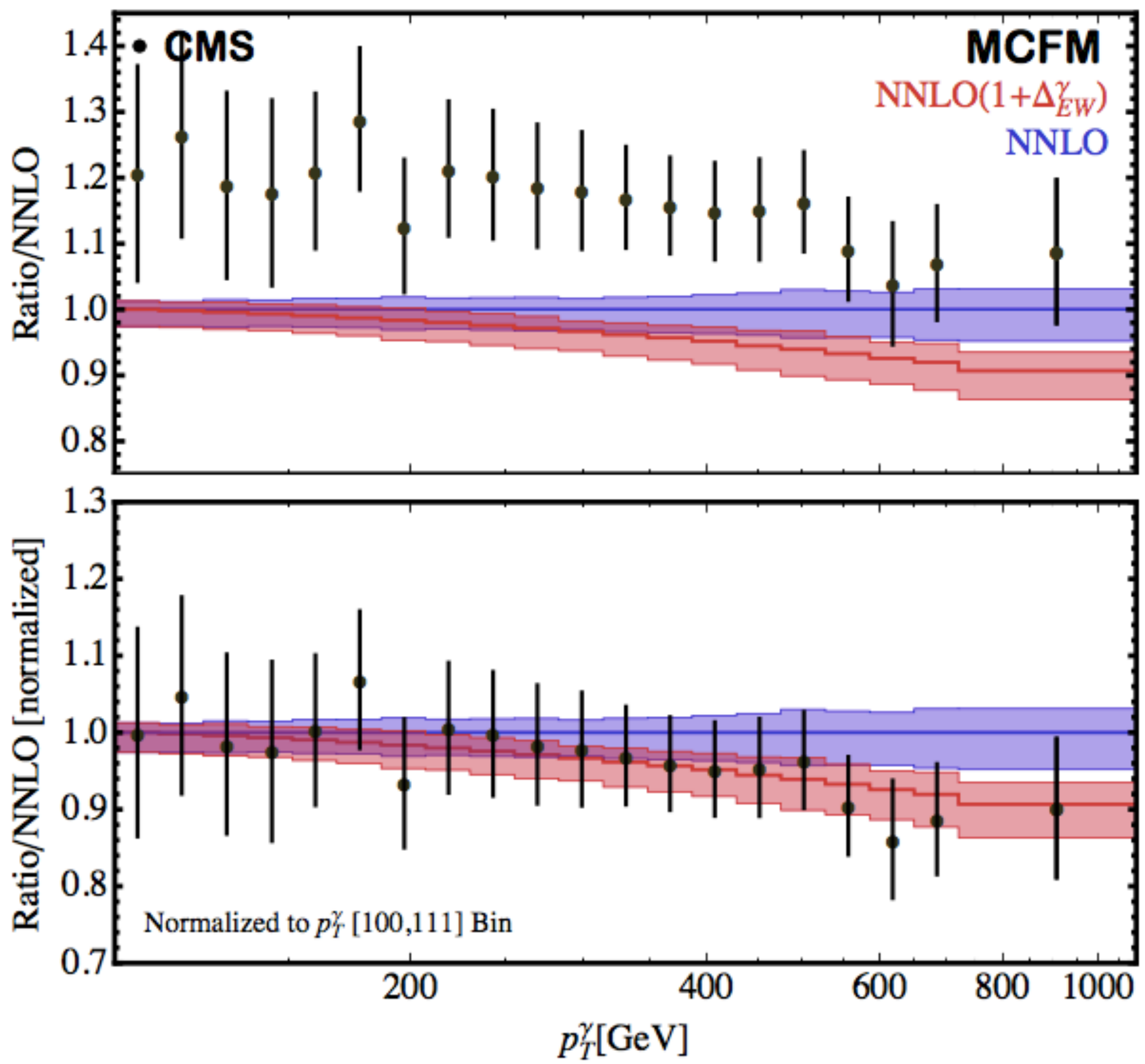
$$p_T^J > 100\,\mathrm{GeV}, \quad |\eta^J| < 2.1, \quad p_T^{J_1} > 500\,\mathrm{GeV},$$
$$p_T^{lep} > 25\,\mathrm{GeV}, \quad |\eta^{lep}| < 2.5.$$

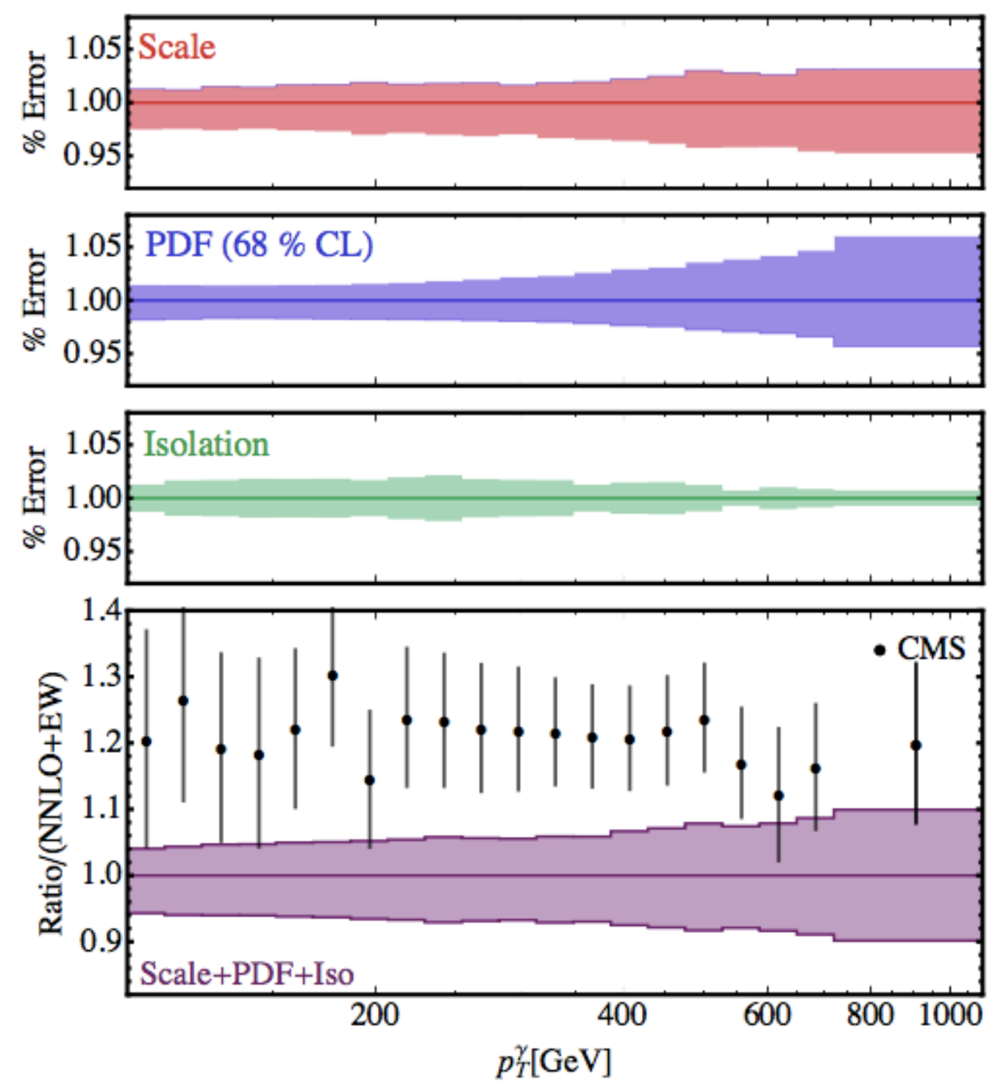


High p_T photons

JMC, Ellis, Williams, arXiv:1612.04333, arXiv:1703.10109

- Good agreement with shape of 8 TeV CMS data, especially after inclusion of suppression from EW Sudakov at high p_T.
- Tension with overall normalization, even after careful error budget. Missing systematic effect in theory, experiment or both?



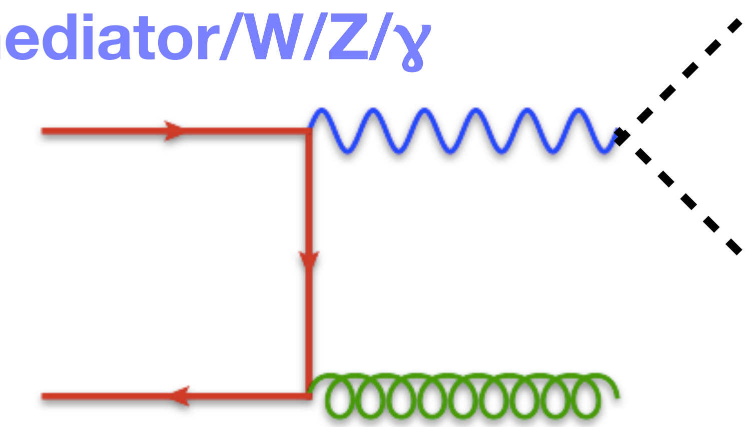


V+jet predictions for DM searches

Lindert, Pozzorini et al, [arXiv:1705.04664]

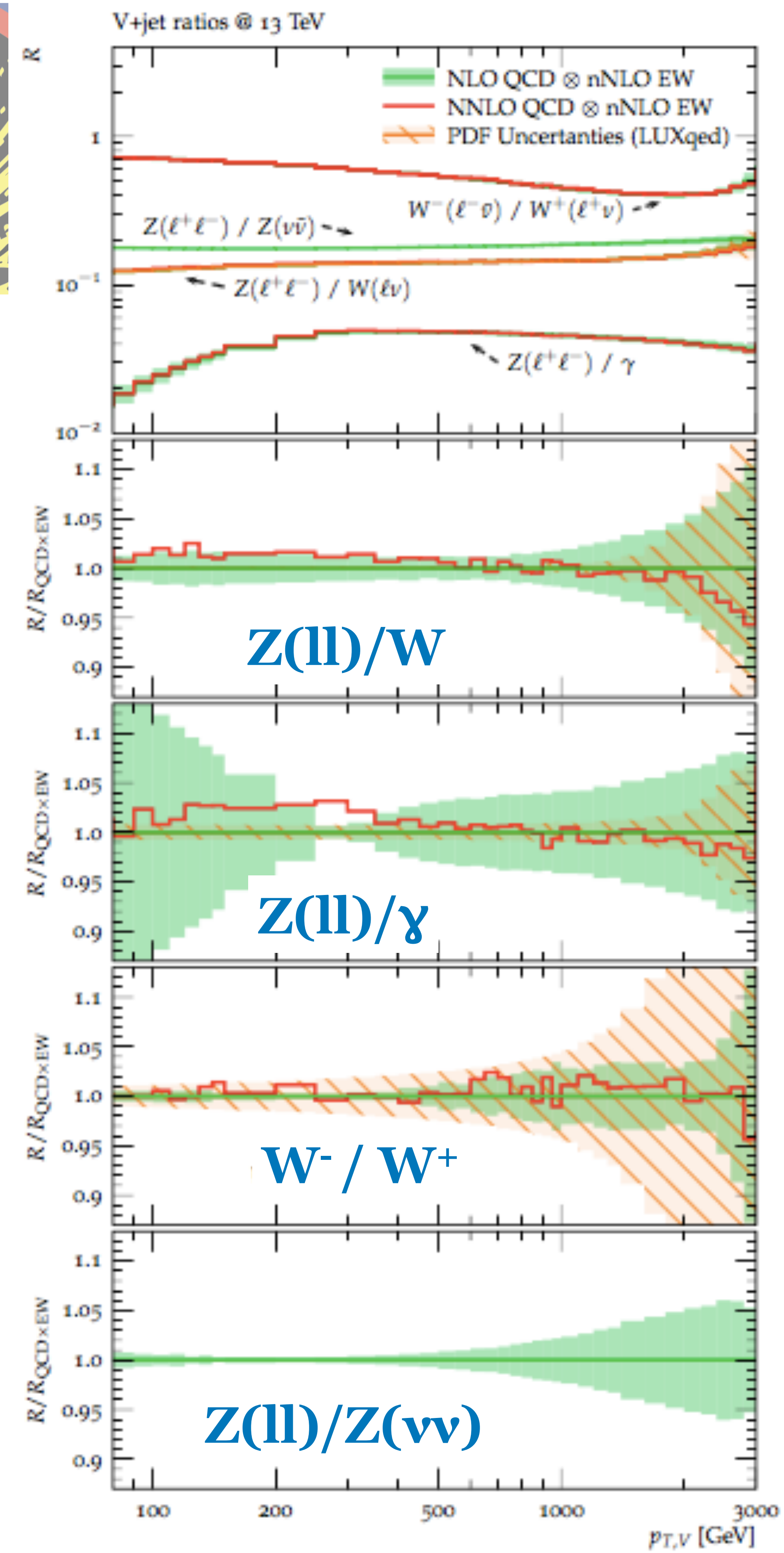
- Aim for precise predictions for leading background to MET+jet searches, Z(→νν)+jet.

mediator/W/Z/ɣ



DM/
neutrinos/
leptons

- Calibrate through visible decays of Z or W, or ɣ, + jet events.
- State-of-the-art NNLO QCD + NLO EW.
- After inclusion of NNLO QCD, leading theoretical uncertainty due to pdfs.
  - still very small in ratios, typically <5% up to 2 TeV.

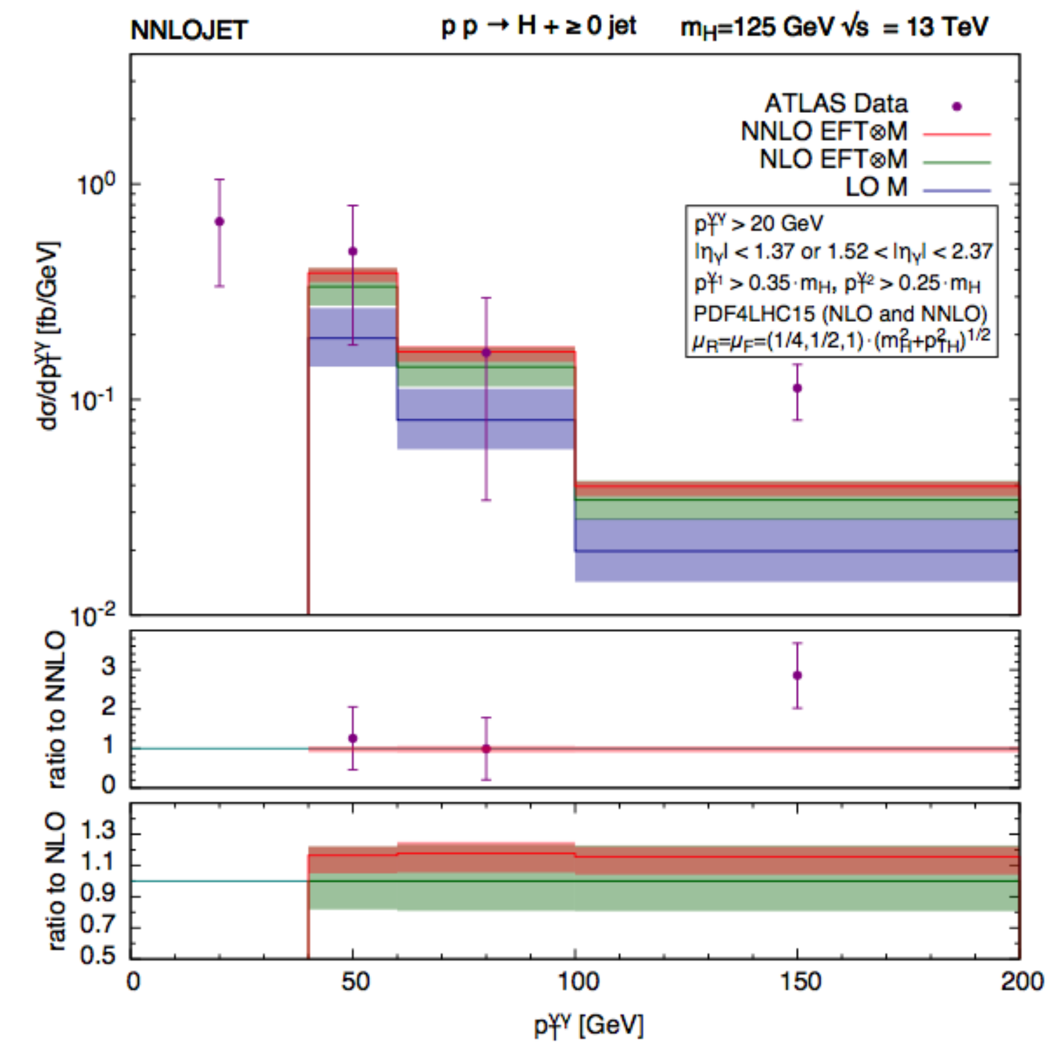


Higgs+jet: limitations of NNLO

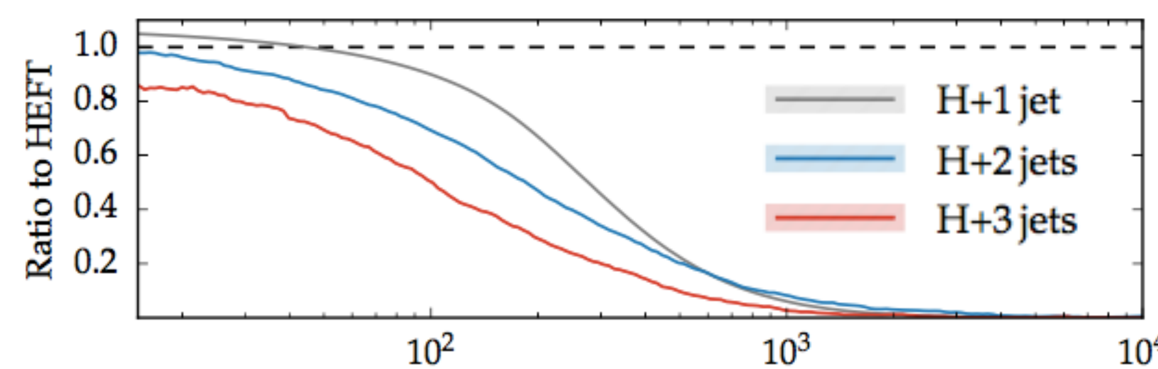
Chen et al, arXiv:1408.5325; Boughezal et al, arXiv:1505.03893, arXiv:1504.07922; Caola et al, arXiv:1508.02684; …

- Sensitive to fact that ggH coupling is not pointlike but can be resolved for Higgs $p_T > m_T$ (finite top mass).
- NNLO in hand from multiple groups.
- Limited differential information so far, from diphoton and ZZ decays of Higgs boson.
- Would benefit greatly from additional statistics, e.g. from boosted analysis of hadronic decay channels.
  - State-of-the-art in boosted region is a combination of NNLO pointlike ggH and approximate NLO with finite mt.

Neumann, Williams, arXiv:1609.00367



Chen et al, arXiv:1607.08817



Bothmann et al, arXiv:1605.00617

Dijet observables at NNLO

Currie et al, arXiv:1611.01460, arXiv:1705.10271, arXiv:1705.08205

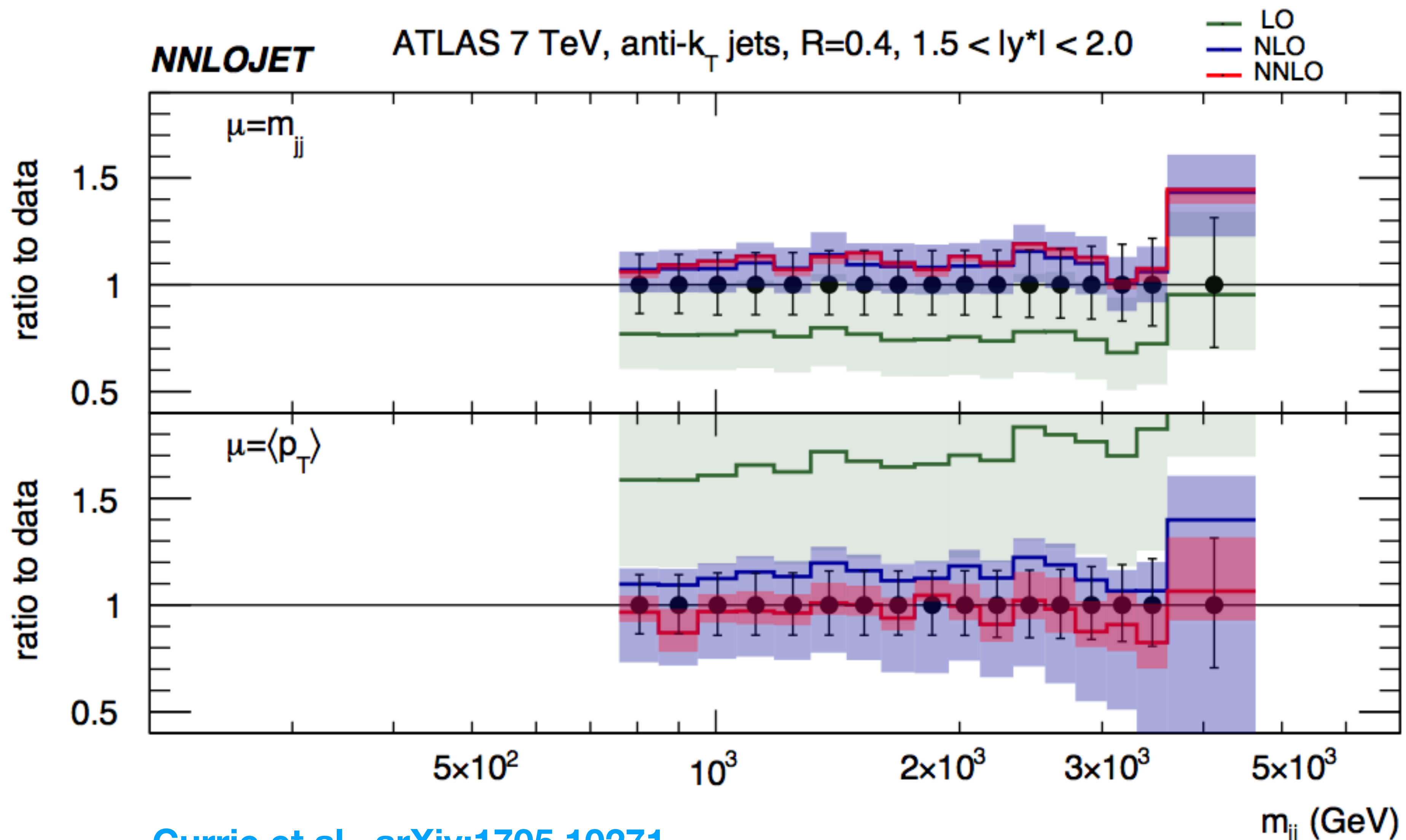
- First calculation of key observables at NNLO: dijet mass and rapidity difference.
- Yields information on convergence of perturbative series and optimal scale choice.

$\mu = m_{jj}$ (not widely used)

- overlapping uncertainty bands at each order
- good convergence and description of data

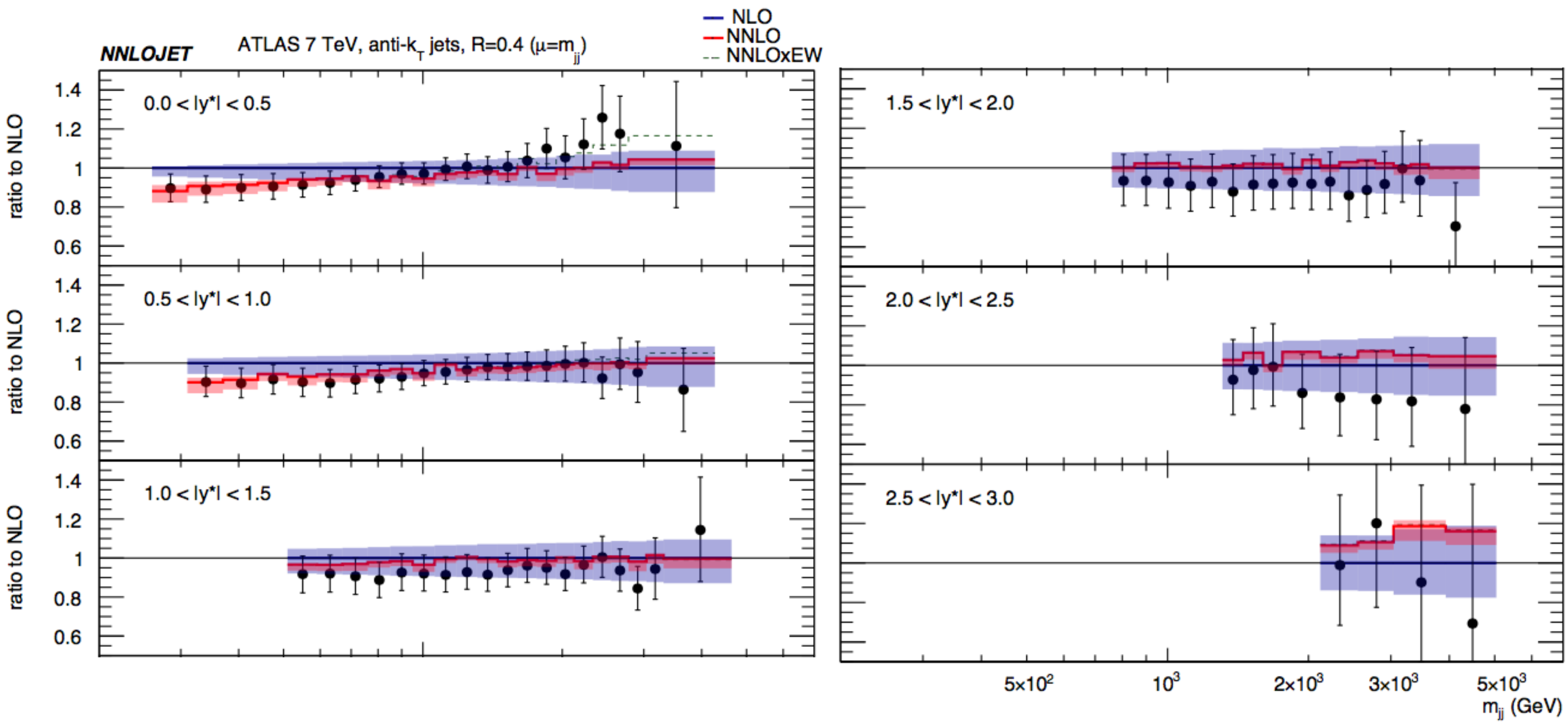
$\mu = \langle p_T \rangle$: (used by CMS, previously D0)

- large corrections at each order
- unphysical behavior
- significant residual uncertainty



Currie et al, arXiv:1705.10271

Dijet invariant mass at NNLO



- Excellent agreement in all rapidity-separation bins and across range of m_{jj}
- Corrections outside NLO uncertainty at small $|y^*|$ and m_{jj} understood

Jet production outlook

- Prime arena in which to study jet properties:
  - wealth of excellent experimental data.
  - multiple jets at Born level.
  - NNLO calculation in hand and already validated across wide range of kinematics (both inclusive and dijet).
  - Should be ready for analysis of jet properties.
- “On the to-do list” and no particular issues anticipated.

Theoretical applications

- Higher-order calculations implicitly include terms that may be useful to extract for other applications, e.g. coefficients of logarithms or finite terms for matching.
- Example: matching to NNLO soft-drop groomed two-point energy correlation function (e_2) in $e^+e^- \to$ dijets and $pp \to Z+j$.

  Frye, Larkoski, Schwartz and Yan, arXiv:1603.09338

  - incredibly computationally demanding (highly singular and complicated phase-space, fine binning required).
  - leverages techniques developed for NNLO: efficient, multi-core computations, similar phase-space sampling requirements.
- This study performed "after market" — would be useful to include suitable tools in-situ.

Outlook

- The most interesting NNLO codes for BOOST (i.e. with jets) are still private.
  - demanding computing requirements – multi-core, multi-thread, long run-times.
  - some bespoke elements – e.g. choice of slicing parameter that regularizes singularities, cross-checks that code is working as intended.
  - as far as I am aware, no applications to heavy ions program.
- Could be extra complications …
  - implementation of substructure analyses in principle "easy".
  - computing jet properties and substructure observables should probe deeper infrared regions where phase space generation and/or numerical precision requires further work.
  - "language barrier" may be best overcome by direct collaboration.