Alexander von Humboldt Stiftung/Foundation

TECHNISCHE UNIVERSITÄT MÜNCHEN

Multi-leg Hadronic Final State: calculation and simulation

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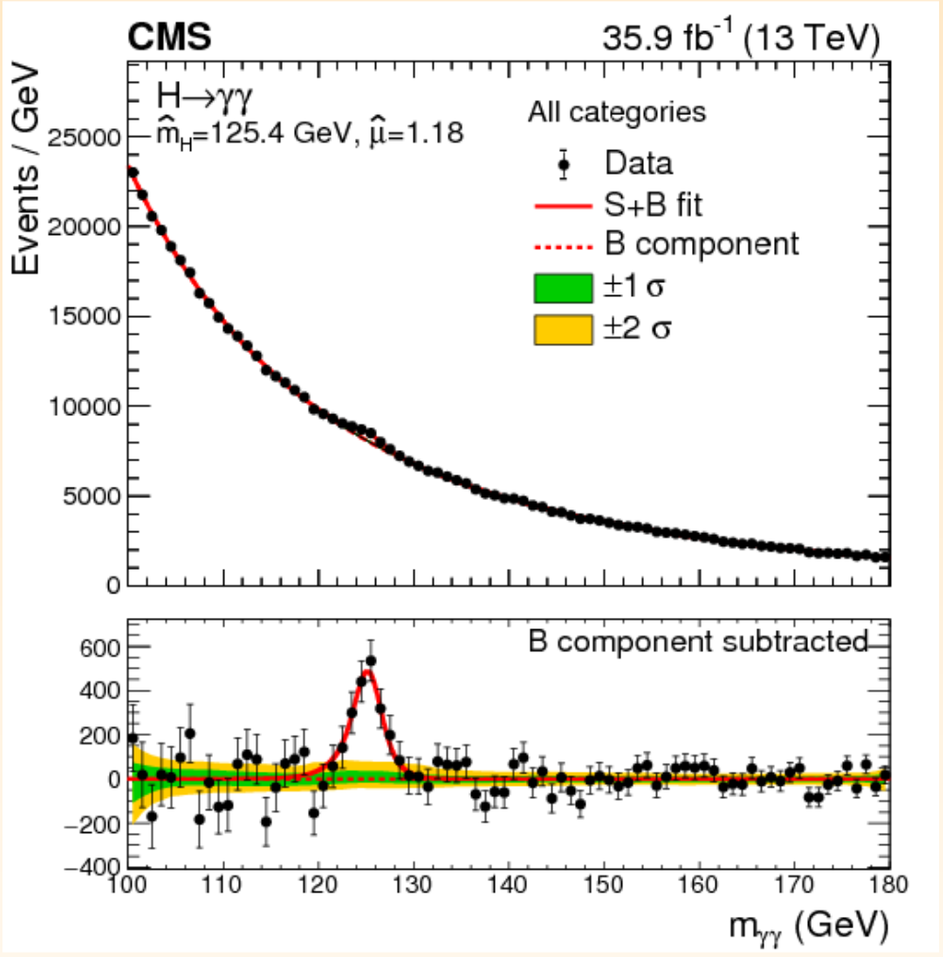
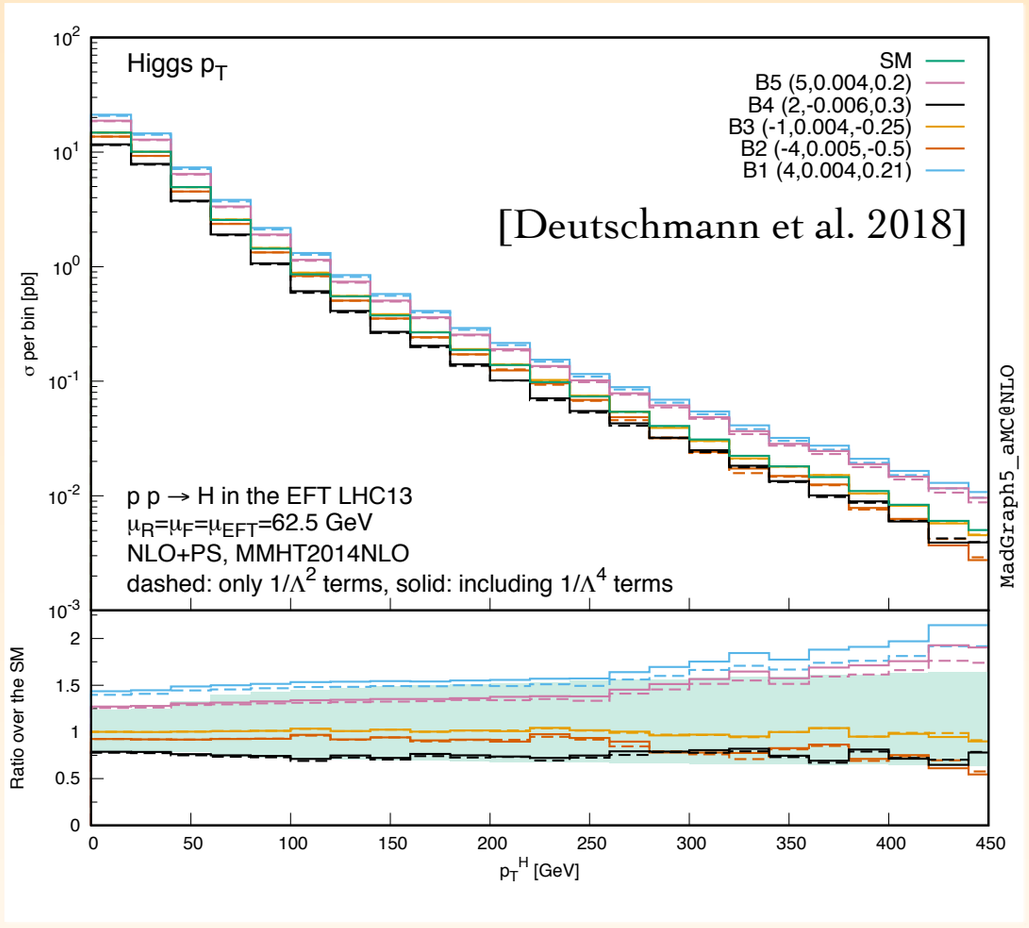
Search for New Physics

Invariant mass peak: "easy"



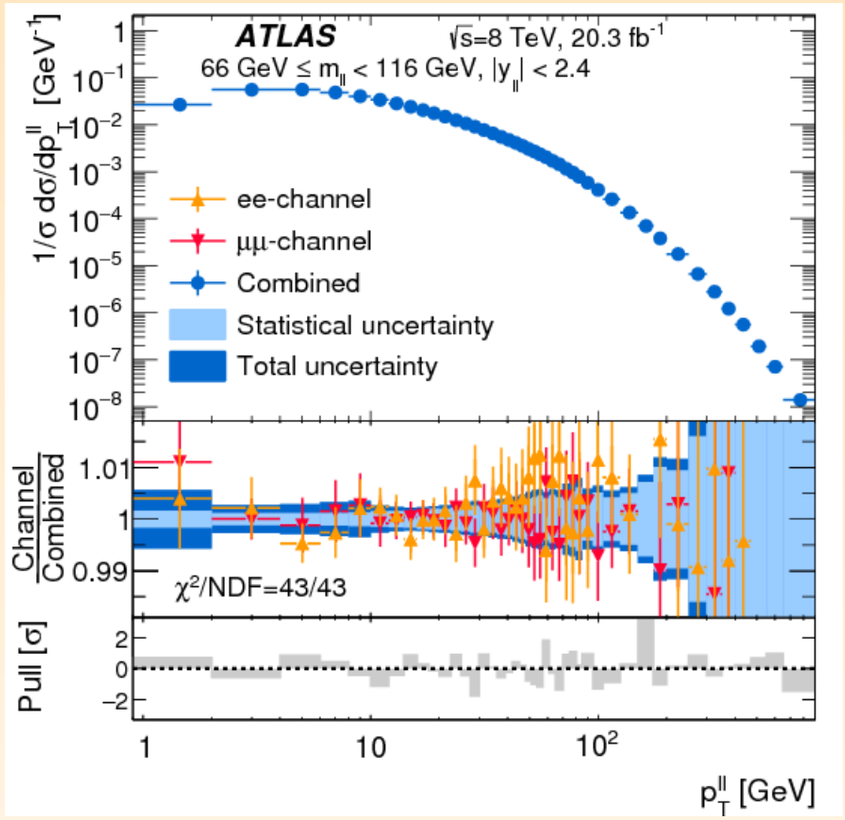
- Theory predictions not important for finding a resonance peak
- However, they do play a role in measuring its properties…

Shape variation: "hard"



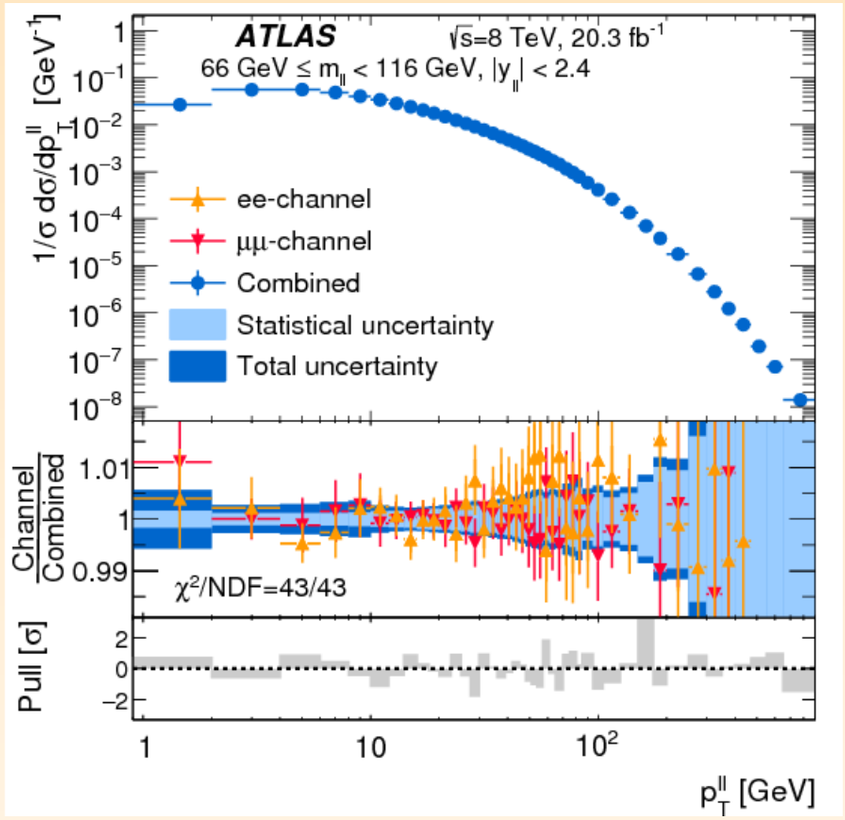
- Theory predictions fundamental in extraction of signal
- Need accuracy, including realistic theory estimates

Searching for New Physics



- LHC is touching the <1% uncertainty for some observables
- Can we match this accuracy with theory predictions to test SM?
- Might be difficult: factorisation works only up to $O(\Lambda/Q)$ power corrections

Searching for New Physics



- LHC is touching the <1% uncertainty for some observables
- Can we match this accuracy with theory predictions to test SM?
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- More exclusive phase-space regions might be more sensitive to BSM physics
  - Hard cuts/tails/jet-vetos/b-tagging/etc.
- Even though these measurements come with larger uncertainties (statistic and systematic), this is where New Physics could be found
- Need to match accuracy in measurements with accuracy in theory predictions for these exclusive phase-space regions
  - At least multi-jet NLO matched/ merged with Parton Shower MC

Current state-of-the-art

- NLO-accurate tools are the default for most SM background predictions by ATLAS and CMS. Most used are
  - POWHEG BOX
  - MadGraph5_aMC@NLO (incl. FxFx merging)
  - Sherpa+OpenLoops/BlackHat/… (incl. MEPS@NLO)
- Can we do better than NLO-QCD?
  - What about NNLO?
  - What about NLO-EW corrections?
  - What about the accuracy of the Parton Shower?

NNLO+PS

Matching NNLO QCD calculation to parton showers

✦ For example: Higgs production

Hamilton, Nason, Re, Zanderighi, 2013

Special scale setting + simple Sudakov FF

Add 'unitarising' higher order, process dependent, terms to Sudakov FF

Reweight incl. 0-jet observables (i.e. Higgs rapidity) to include NNLO

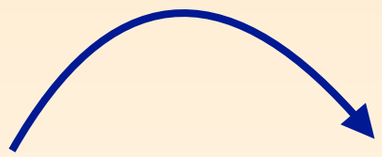
Add parton shower below scale of 2nd jet using POWHEG

NLO for H+j	**Minlo for H+j**	**Minlo' for H+j**	**NNLO for H**	**NNLO+PS for H**
0-jet: unphysical 1-jet: NLO 2-jet: LO n-jet: 0	0-jet: **LO+** 1-jet: NLO 2-jet: LO n-jet: 0	0-jet: **NLO** 1-jet: NLO 2-jet: LO n-jet: 0	0-jet: **NNLO** 1-jet: NLO 2-jet: LO n-jet: 0	0-jet: NNLO 1-jet: NLO 2-jet: LO n-jet: **PS**

✦ Alternative approach: UN²LOPS [Höche, Li, Prestel 2014]

Rethinking the 2nd step

Add 'unitarising' higher order, process dependent, terms to Sudakov FF



Minlo for H+j	**Minlo' for H+j**
0-jet: **LO+**	0-jet: **NLO**
1-jet: NLO	1-jet: NLO
2-jet: LO	2-jet: LO
n-jet: 0	n-jet: 0

- Tricky to compute these terms in practice: only known for Higgs and DY production (and related, like VH)
- Alternative approach:
  - These should be higher order in Sudakov FF -> logarithmic form known
  - Enforce unitarity to deduce them [RF, Hamilton 2015]

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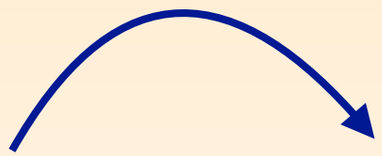

Minlo for H+j	**Minlo' H+j/jj**
0-jet: **LO+**	0-jet: **NLO**
1-jet: NLO	1-jet: NLO
2-jet: LO	2-jet: **NLO**
n-jet: 0	n-jet: 0

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n-jet: 0

NNLO for H

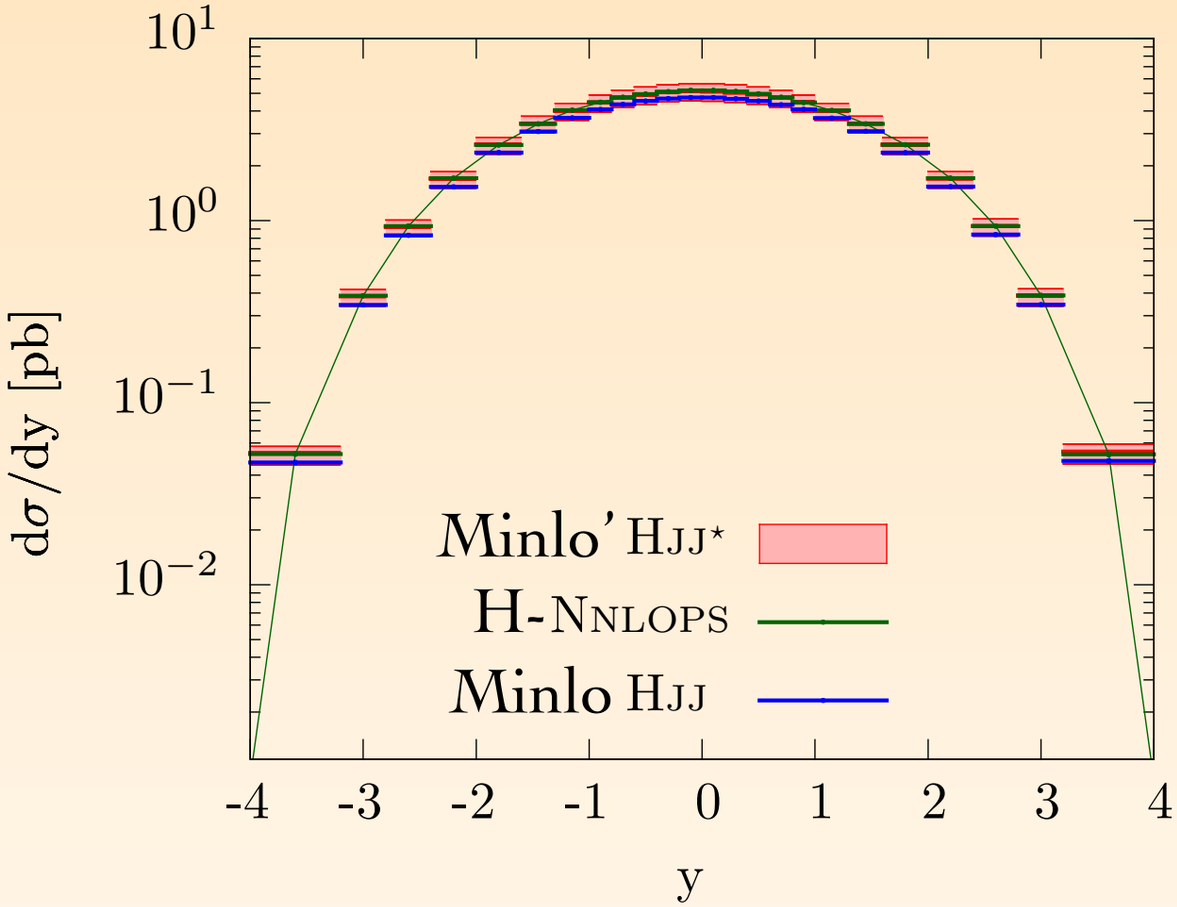
0-jet: **NNLO**
1-jet: NLO
2-jet: NLO
n-jet: 0

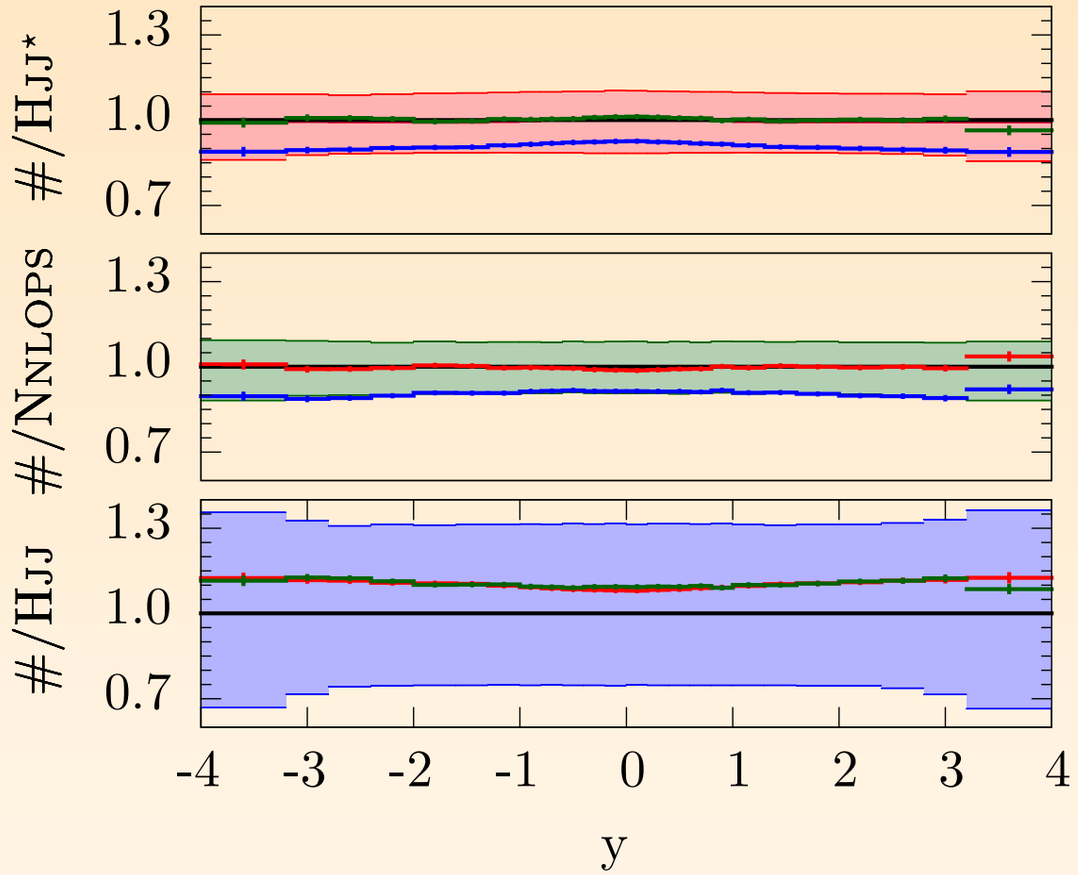
NNLO+PS for H

0-jet: NNLO
1-jet: NLO
2-jet: NLO
n-jet: **PS**

For example: H+2J

RF, Hamilton (2015)

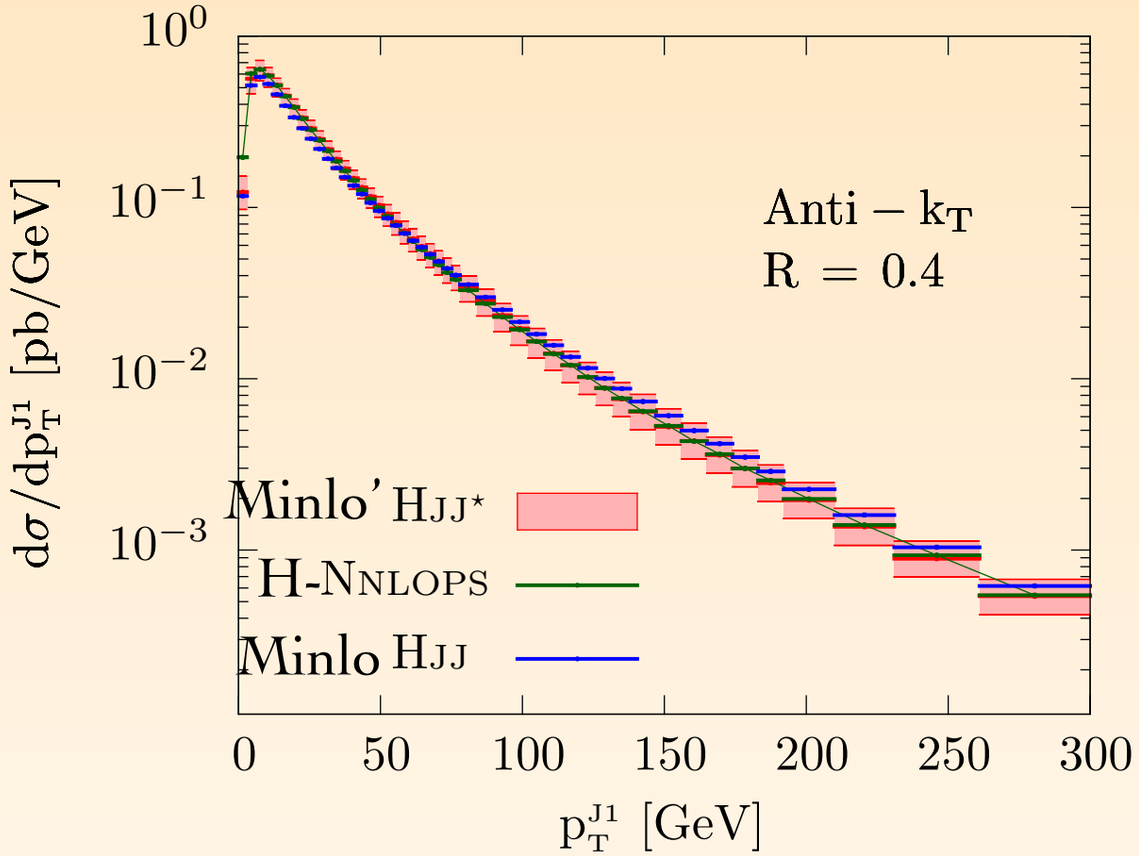


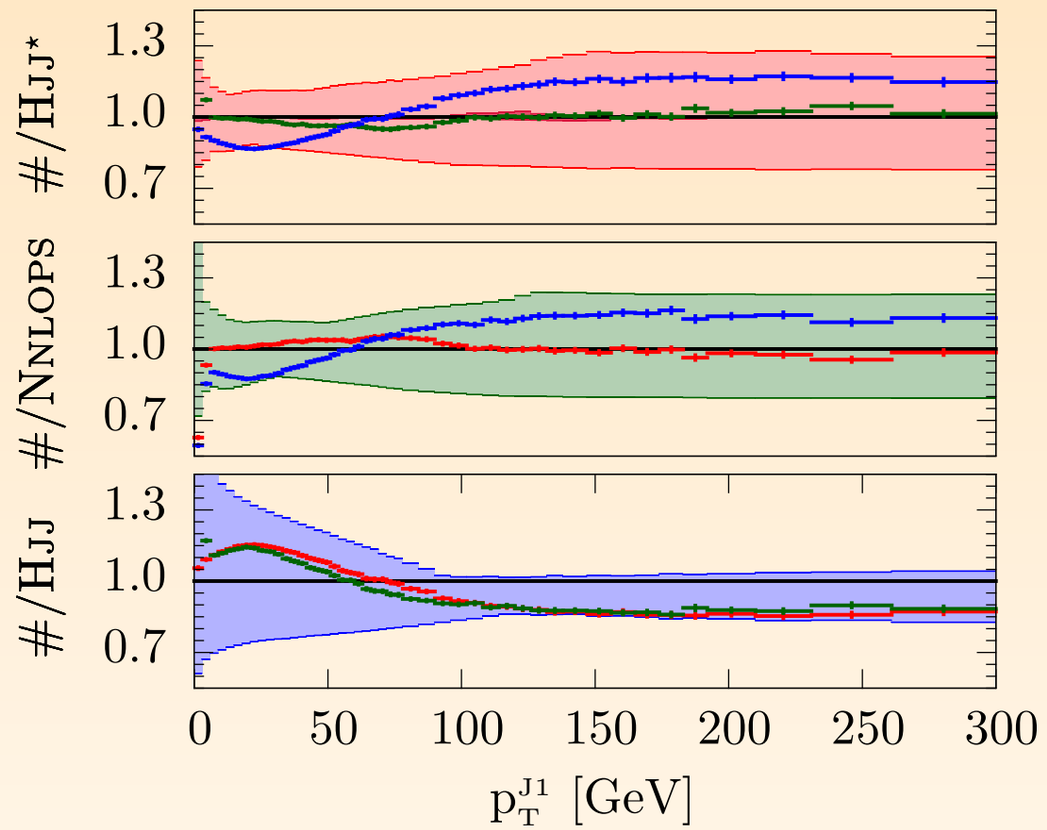


- Minlo'-HJJ*, red, formally NNLO
- H-NNLOPS, green, formally NNLO
- Minlo-HJJ, blue, formally not quite LO

Transverse momentum of the leading jet

RF, Hamilton (2015)





- Minlo'-HJJ*, red, formally NLO
- H-NNLOPS, green, formally NLO
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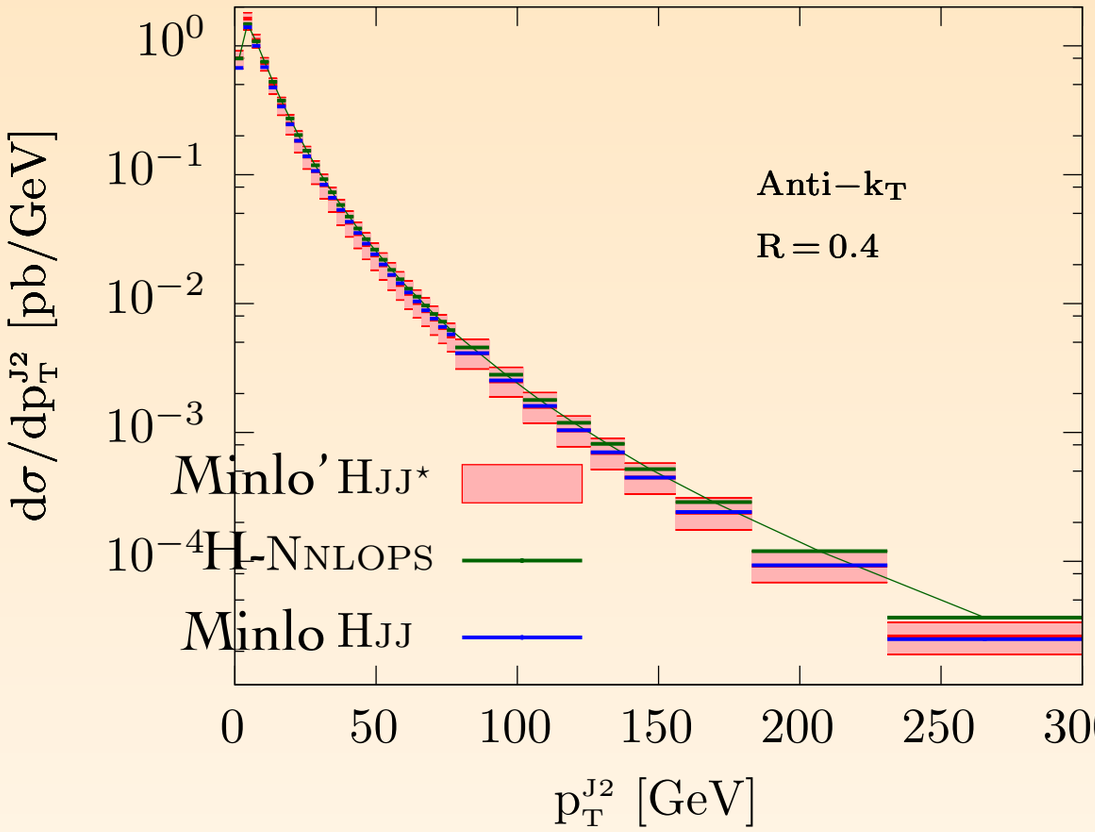
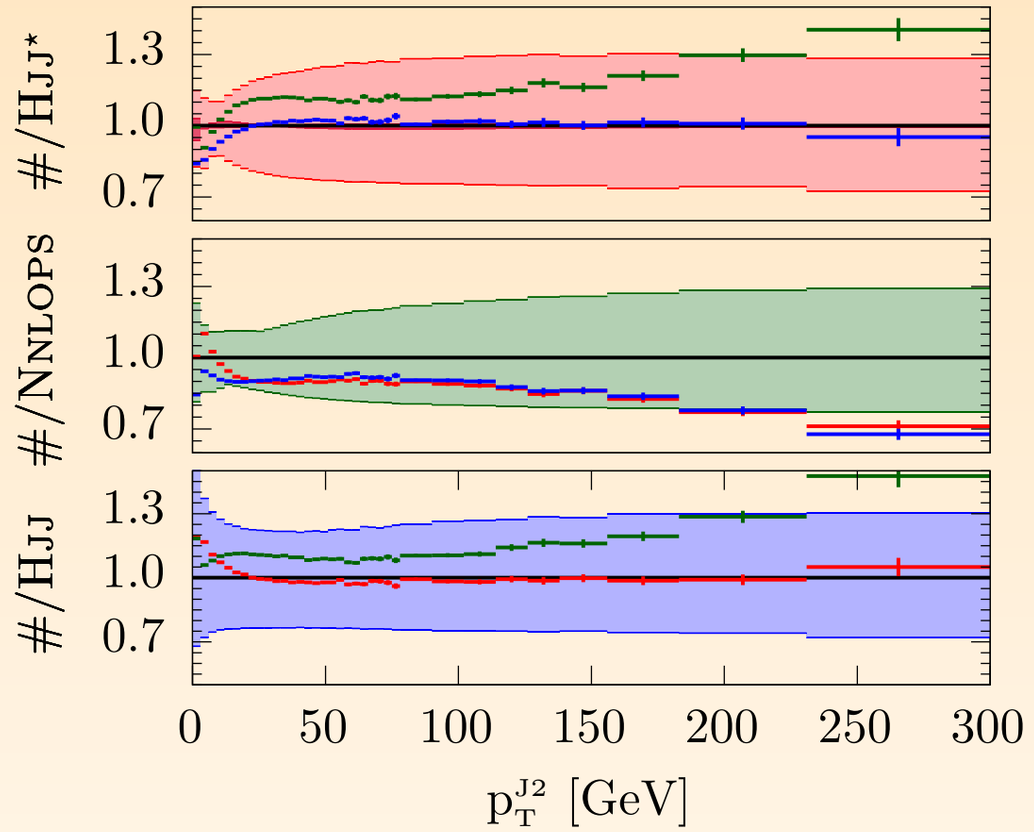
Transverse momentum of the second jet

RF, Hamilton (2015)

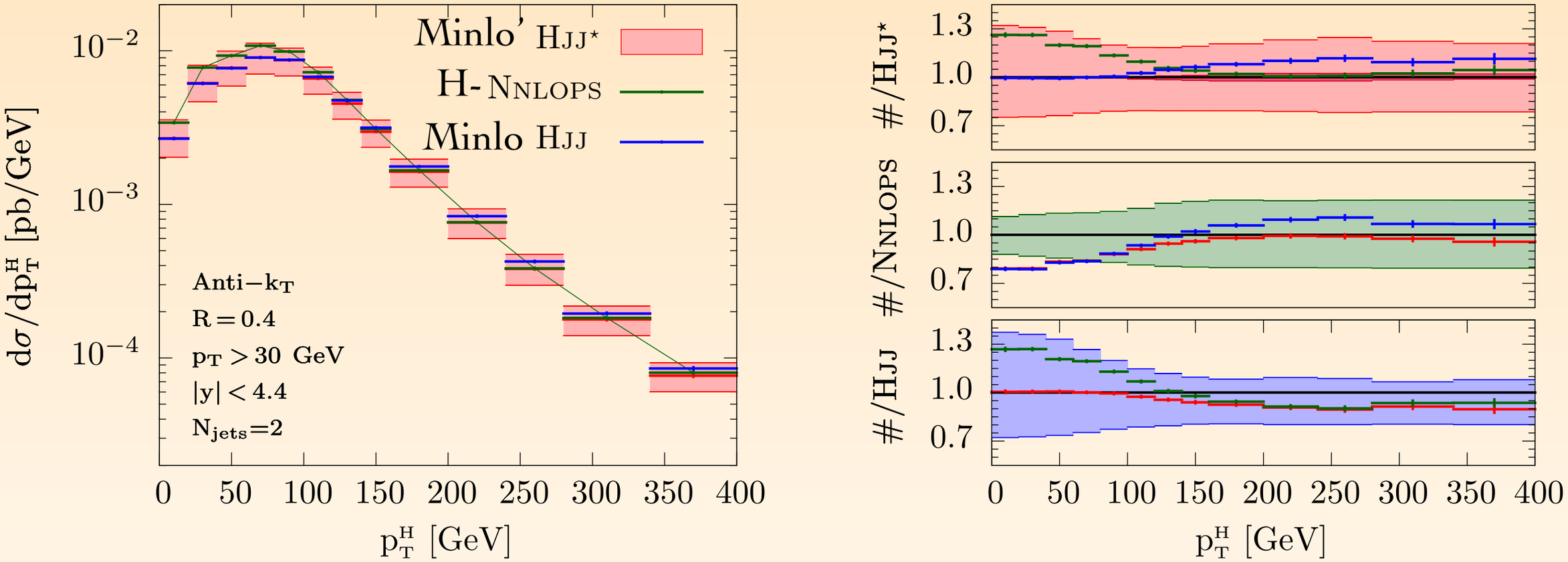




- Minlo'-HJJ*, red, formally NLO
- H-NNLOPS, green, formally LO
- Minlo-HJJ, blue, formally NLO

Higgs boson p_T in events with exactly 2 jets

RF, Hamilton (2015)



- Minlo'-HJJ*, red, formally NLO
- H-NNLOPS, green, LO at low p_T, NLO at high p_T
- Minlo-HJJ, blue, NLO at low p_T, not quite LO at high p_T

NLO+PS with EW corrections

Expected importance of EW corrections

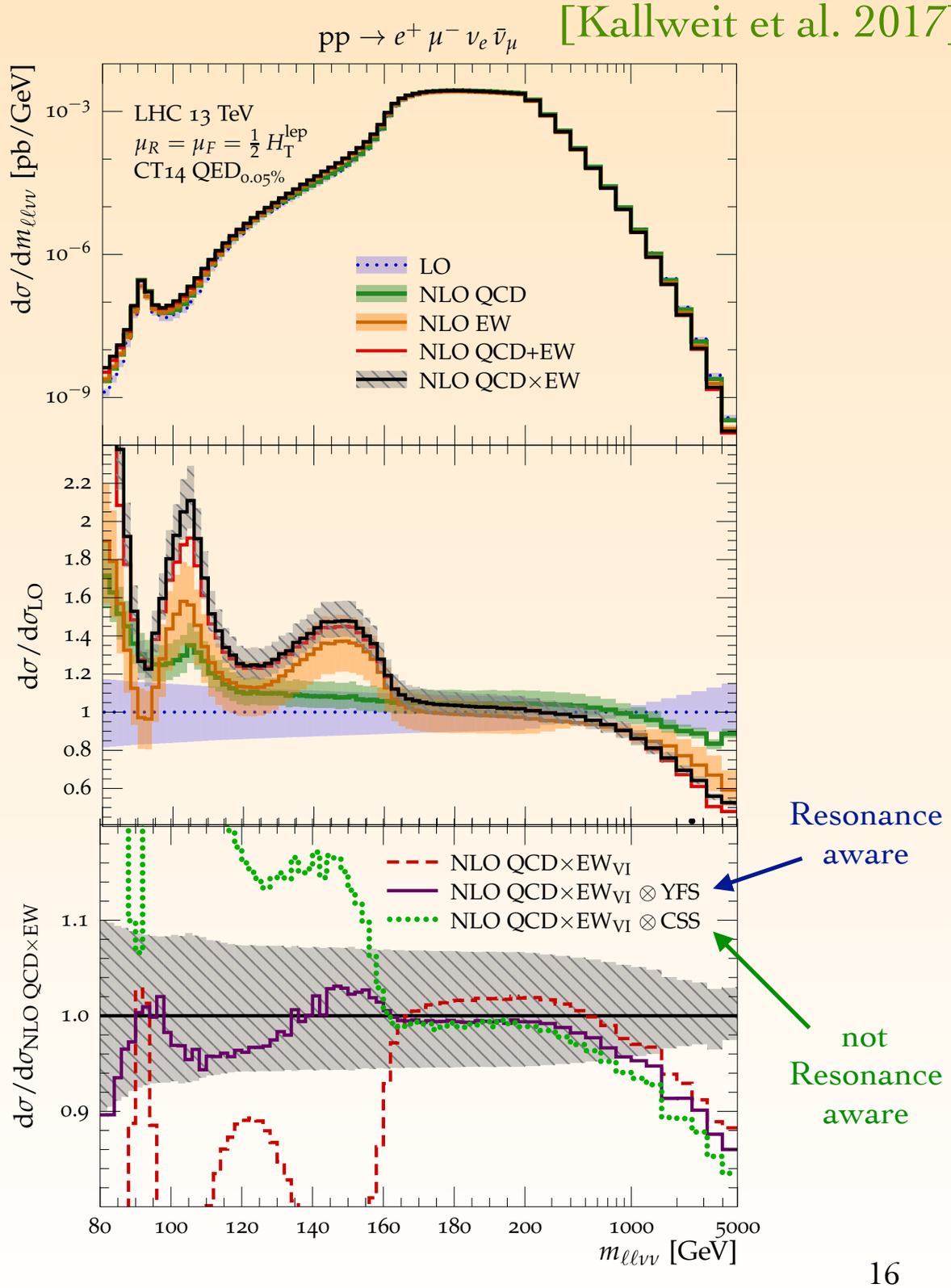
- By comparing the strength of the strong to the EW coupling, one expects that NNLO QCD corrections of similar importance to NLO EW corrections
  - On top of that, EW corrections can be enhanced in certain kinematical regions, where they can result in several tens of percents:
    - Close to EW resonances, radiation from decay products results in sizeable changes
    - Large invariants result in large EW corrections
      - Important in BSM searches, particularly when understanding shapes of backgrounds is a must

Matching NLO EW

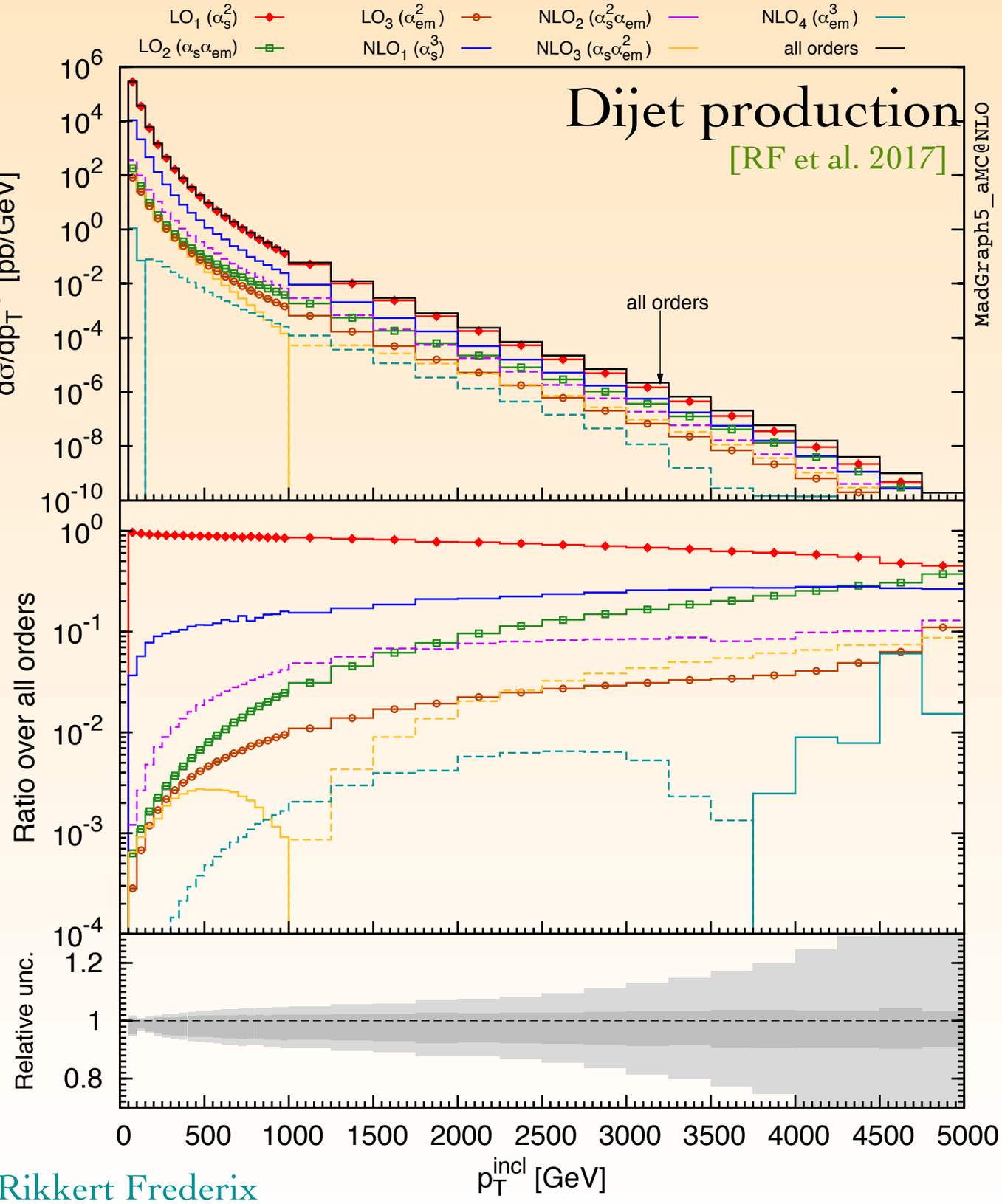
- No complete matching including EW effects exists apart from DY in the POWHEG BOX [Barzé et al. 2012, 2013; Bernaciak 2012]
- Sherpa (+Recola/Openloops/GoSam) and MadGraph5_aMC@NLO are working towards complete automation including matching to parton showers
  - Sherpa+Openloops have some approximated results
  - Resonance-aware matching an issue here

Indispensable in W-mass measurement

[Kallweit et al. 2017]



Dijet production: "Complete-NLO"



- Dijet production
- What about terms "beyond NLO EW"?
- Consider complete-NLO corrections:

$$\begin{aligned}\Sigma_{jj}^{(\mathrm{LO})}(\alpha_S,\alpha) &= \alpha_S^2\,\Sigma_{2,0} + \alpha_S\alpha\,\Sigma_{2,1} + \alpha^2\,\Sigma_{2,2} \\ &\equiv \Sigma_{\mathrm{LO}_1} + \Sigma_{\mathrm{LO}_2} + \Sigma_{\mathrm{LO}_3}\,, \\ \Sigma_{jj}^{(\mathrm{NLO})}(\alpha_S,\alpha) &= \alpha_S^3\,\Sigma_{3,0} + \alpha_S^2\alpha\,\Sigma_{3,1} + \alpha_S\alpha^2\,\Sigma_{3,2} + \alpha^3\,\Sigma_{3,3} \\ &\equiv \Sigma_{\mathrm{NLO}_1} + \Sigma_{\mathrm{NLO}_2} + \Sigma_{\mathrm{NLO}_3} + \Sigma_{\mathrm{NLO}_4}\,,\end{aligned}$$

- Size of corrections mostly follows what one expects from the coupling combinations
  - Apart from the tail where NLO_3 is larger then one would expect

Towards NLO Parton Showers

Parton showers beyond Leading Order

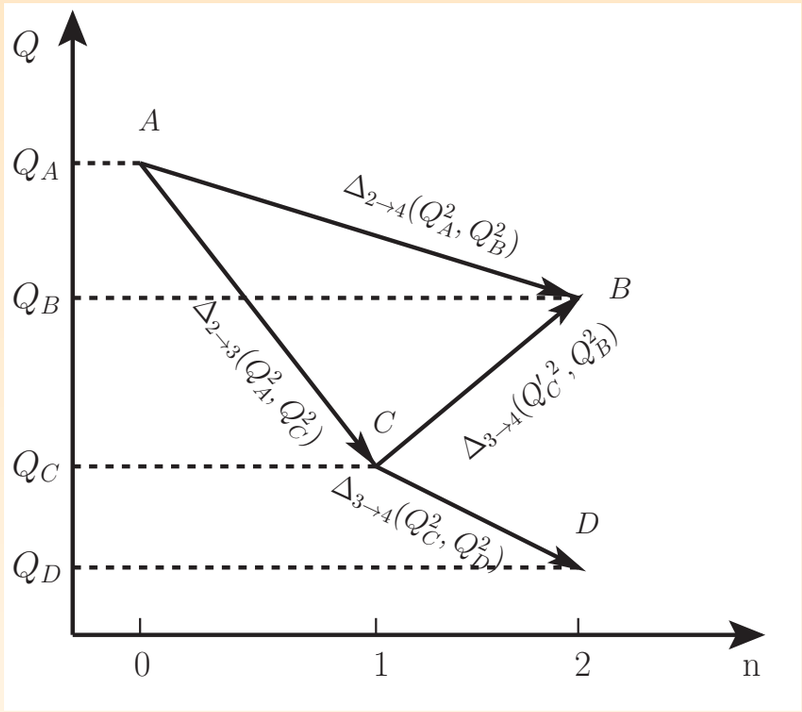
- All Parton Showers are based on LO splitting functions
  - Some universal NLO terms are included (through angular ordering and $\alpha_S(..)$ scale choice)
- Formal accuracy of Parton Shower is only Leading Logarithmic, although most important NLL terms are included as well

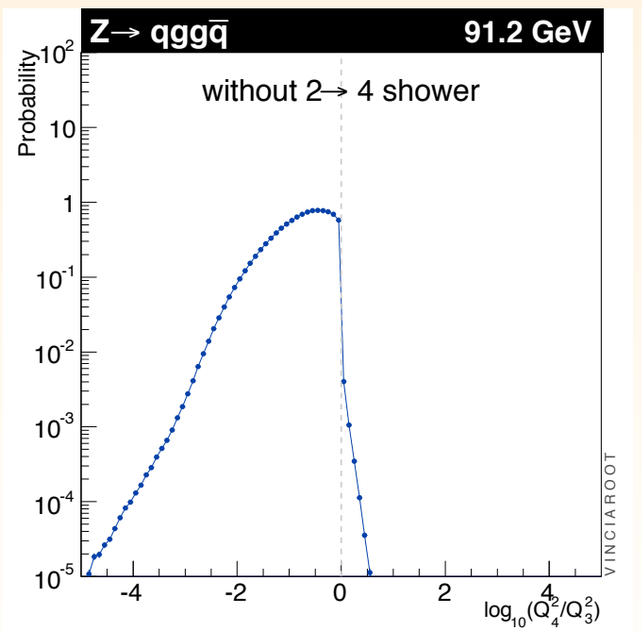
- Some progress is being made for including complete NLO corrections to the DGLAP shower splitting functions
  - requires one to move away from the traditional 1->2 branchings (or 2->3 in case of dipole shower)

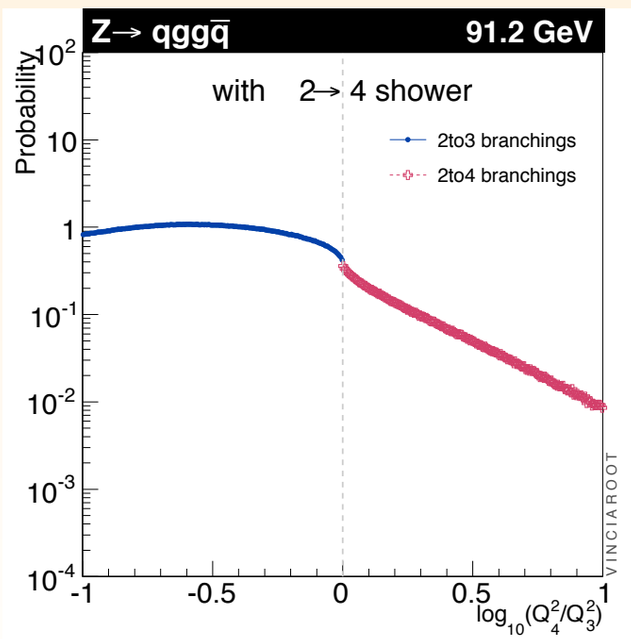
VINCIA

Li & Skands 2016

- Formalism allows for iterated NLO 2->3 branchings combined with LO 2->4 branchings
- 2->4 branchings enlarge the phase-space of the shower emissions beyond what can be reached by ordered, iterated 2->3 branchings
- Smooth/consistent description and implementation

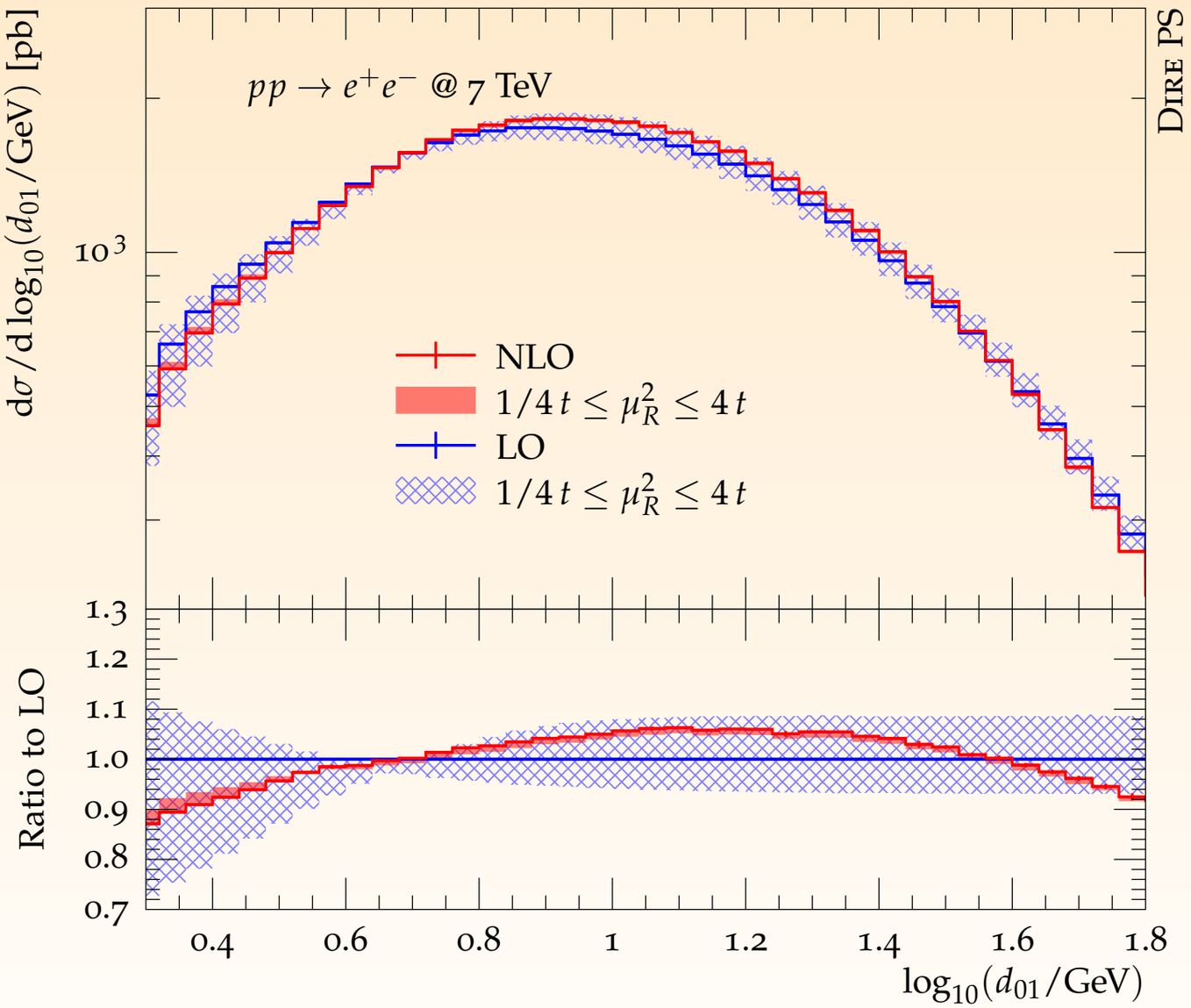






Dire

Hoeche, Krauss & Prestel 2017



- First steps also in the DIRE Parton Shower (available Sherpa & Pythia8)
- NLO DGLAP evolution implemented
- However, still leading-colour and soft emissions are only at LO accuracy
- Note: bands are not uncertainty estimates, but rather simply the scale dependence in the shower evolution

Conclusions

- In the last couple of years the accuracy of event generation has greatly improved, and full automation has been achieved at NLO accuracy
  - NLO accuracy in multiple regions of phase-space, separated by a merging scale
- Currently studying the possibilities for inclusion of NNLO QCD, NLO EW matrix elements, and higher order Parton Showers
- A lot of freedom in tuning has been replaced by accurate theory descriptions:
  - More predictive power
  - Better control on uncertainties in predictions
  - Greater trust in the measurements