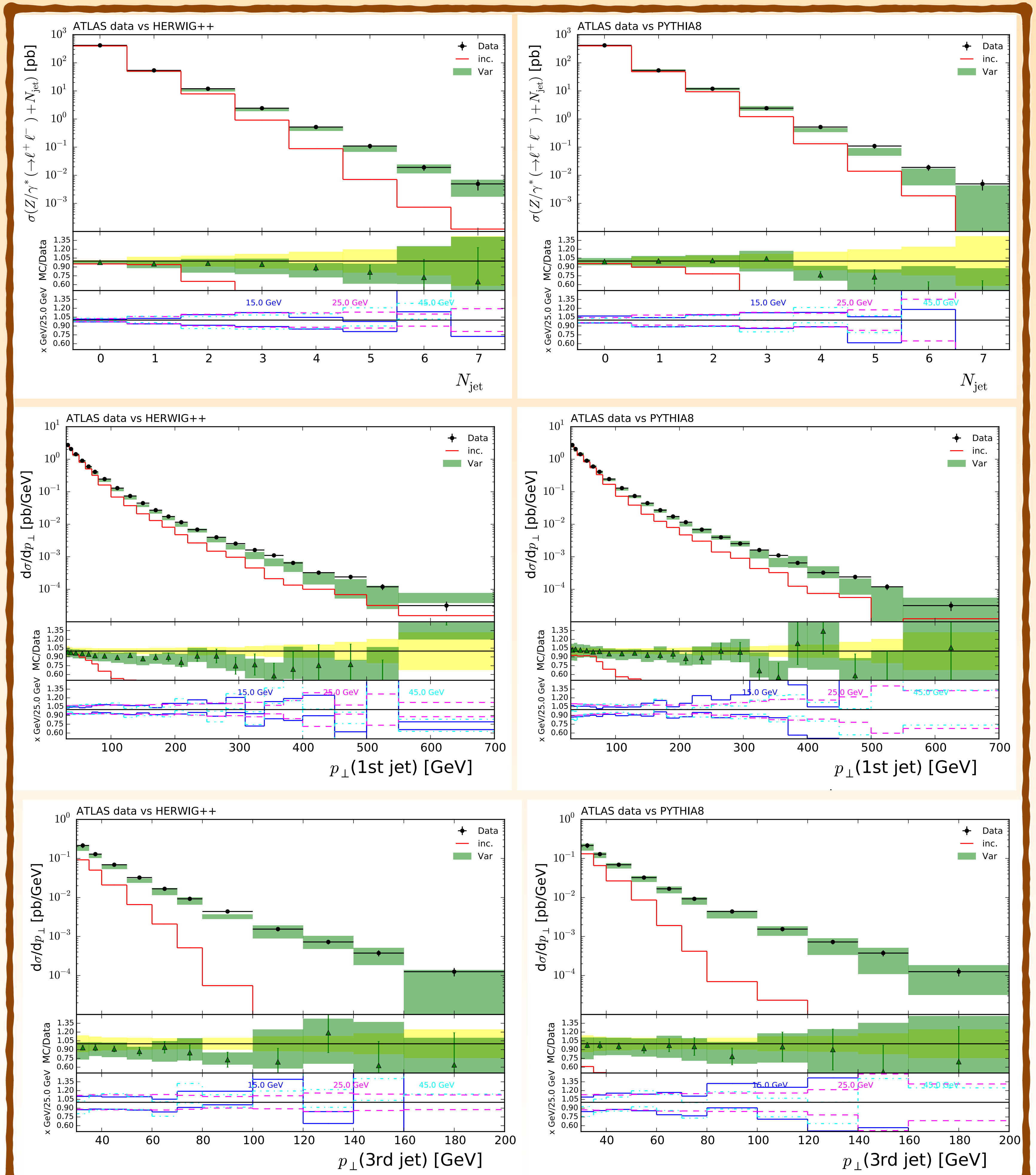
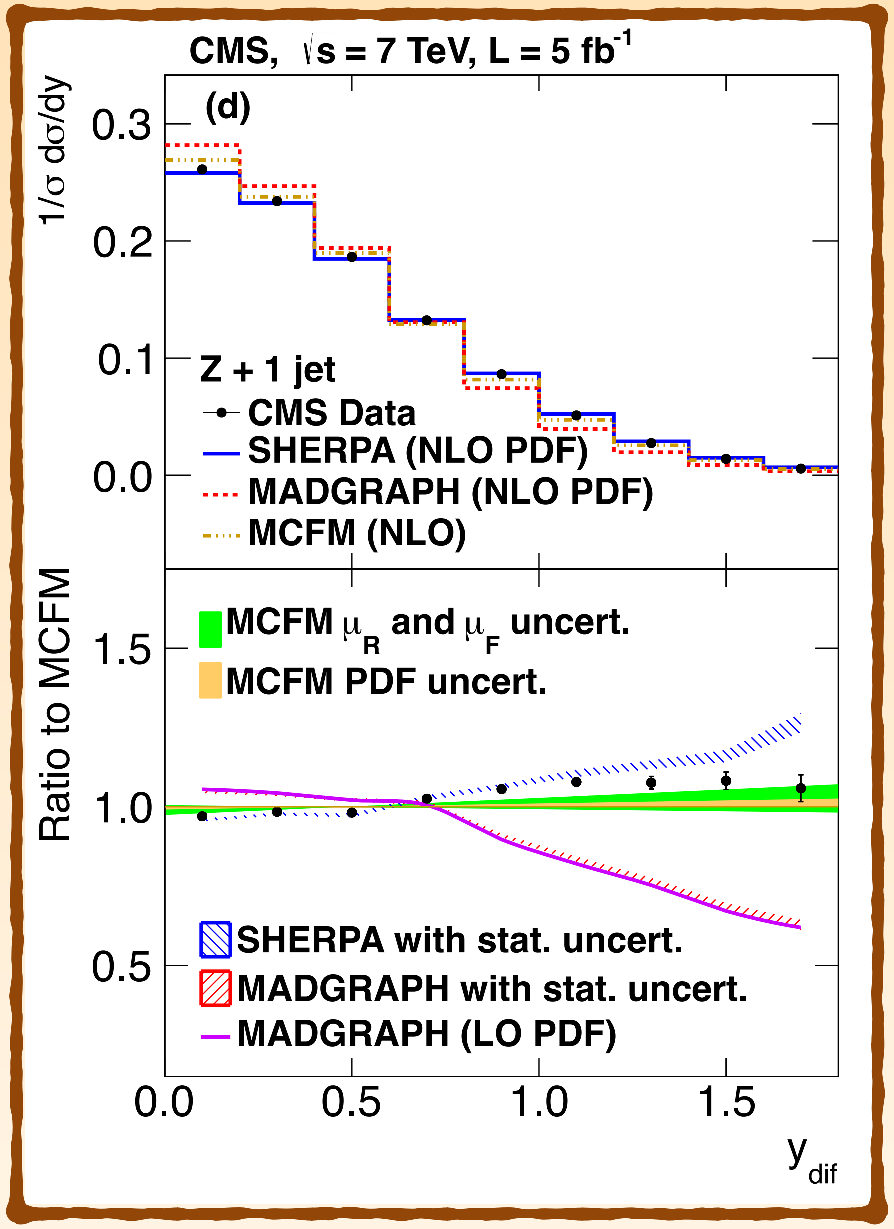
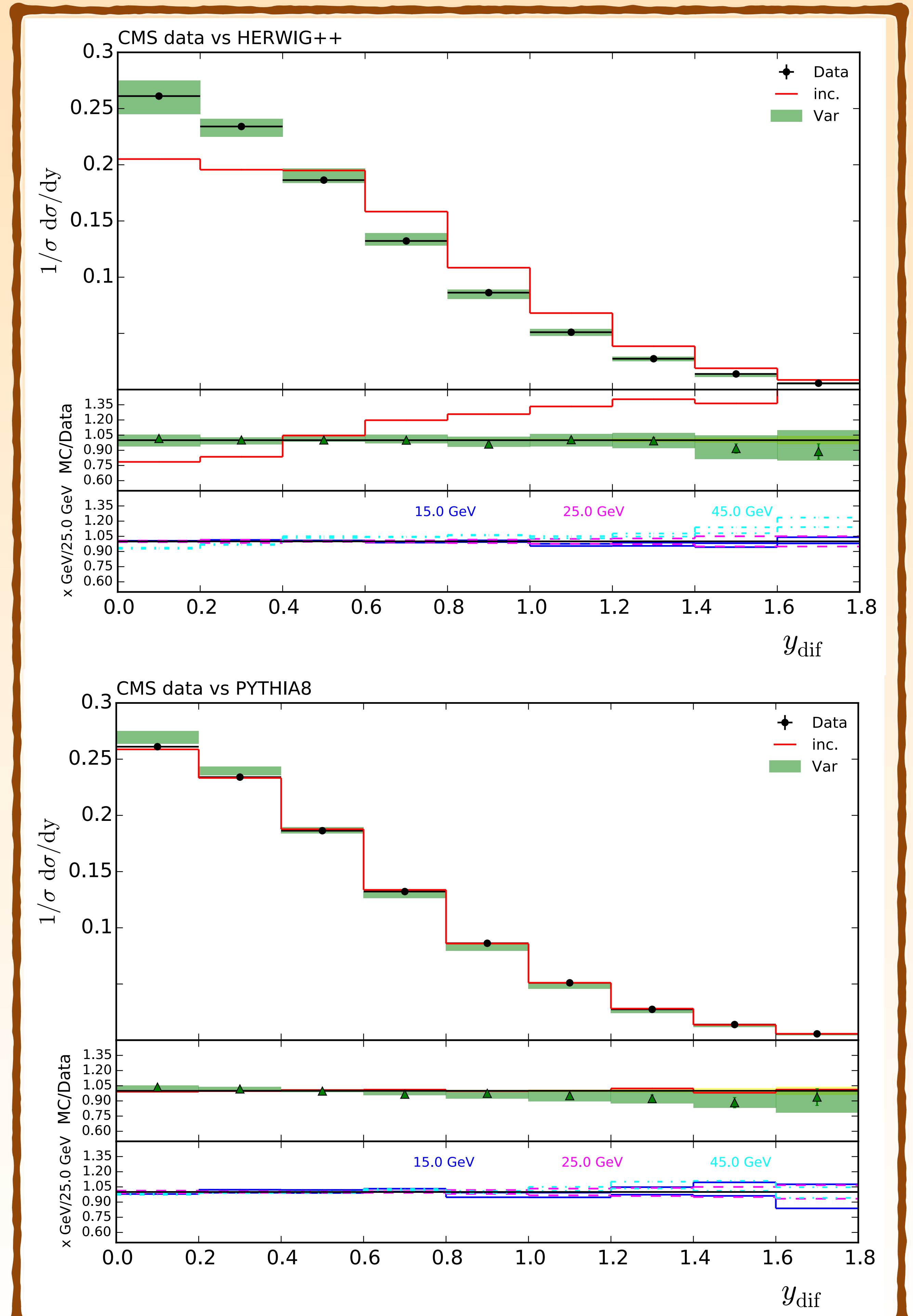
- Z+jets
- Exclusive jet multiplicity and hardest and 3rd hardest jet pT spectra
- Uncertainty band contains ren. & fac. scale, PDF & merging scale dependence
- Rather good agreement between data and theory



Rikkert Frederix





- Rapidity difference between Z-boson and hardest jet.
- Sensitive to higher multiplicity matrix elements
- LO predictions off (in particular MadGraph)
- No discrepancies at NLO

- W+jets
- Agreement between FxFx merged results, matched to Herwig++ and Pythia8, and Atlas and CMS data is rather good
- Where data and theory differ, also differences between the results matched to HW++ and PY8 differ

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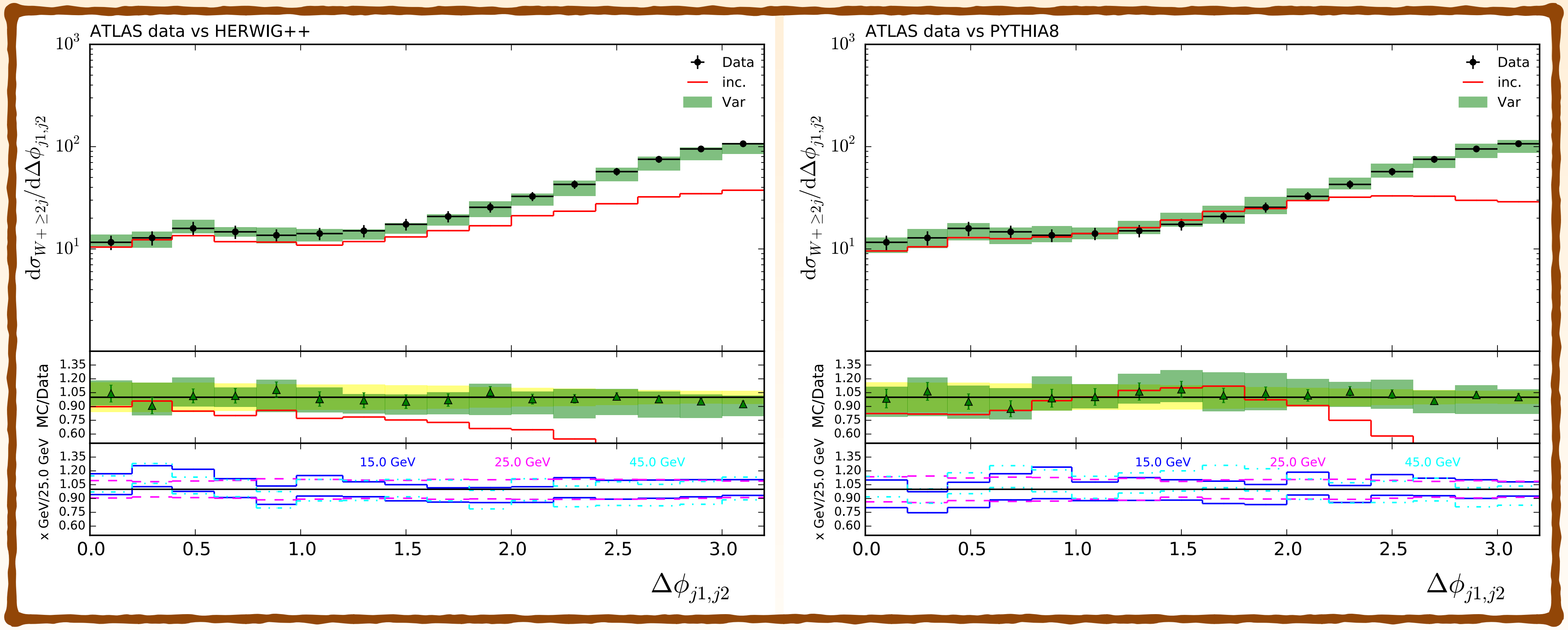

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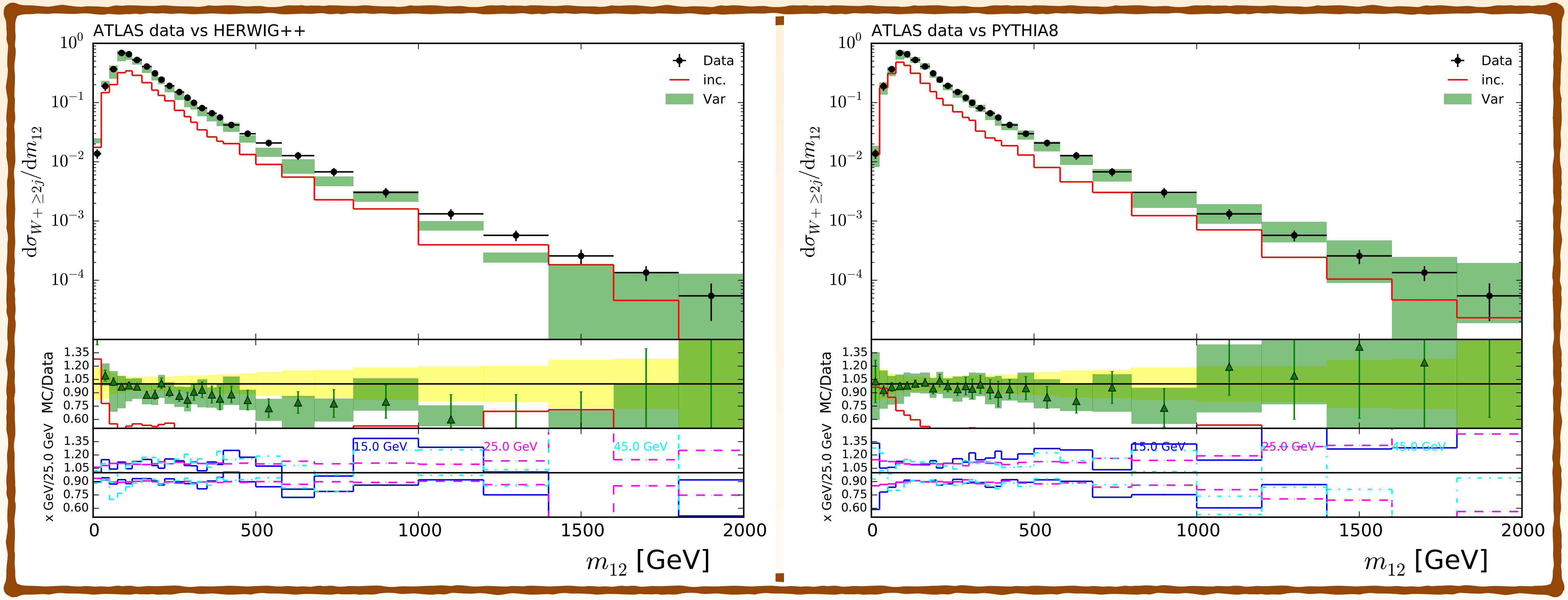
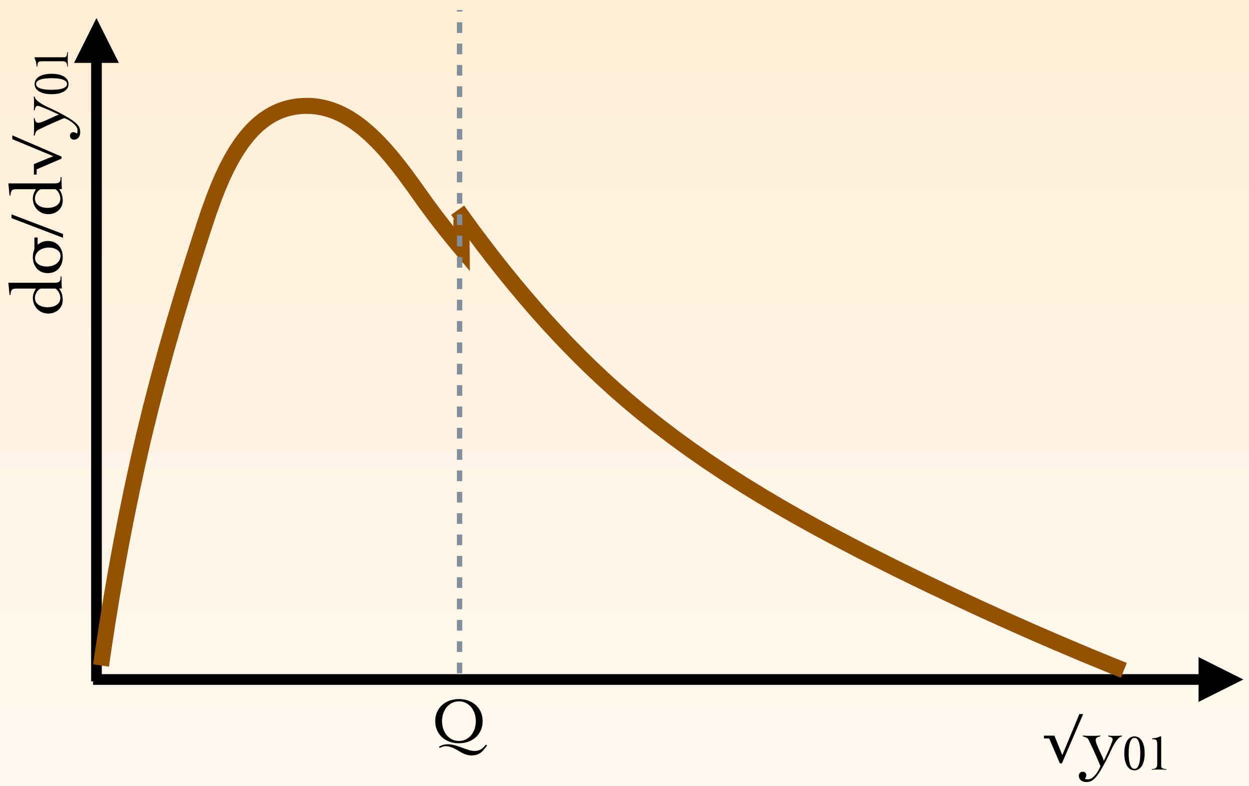


FxFx / Meps@nlo: V & V+1j merging

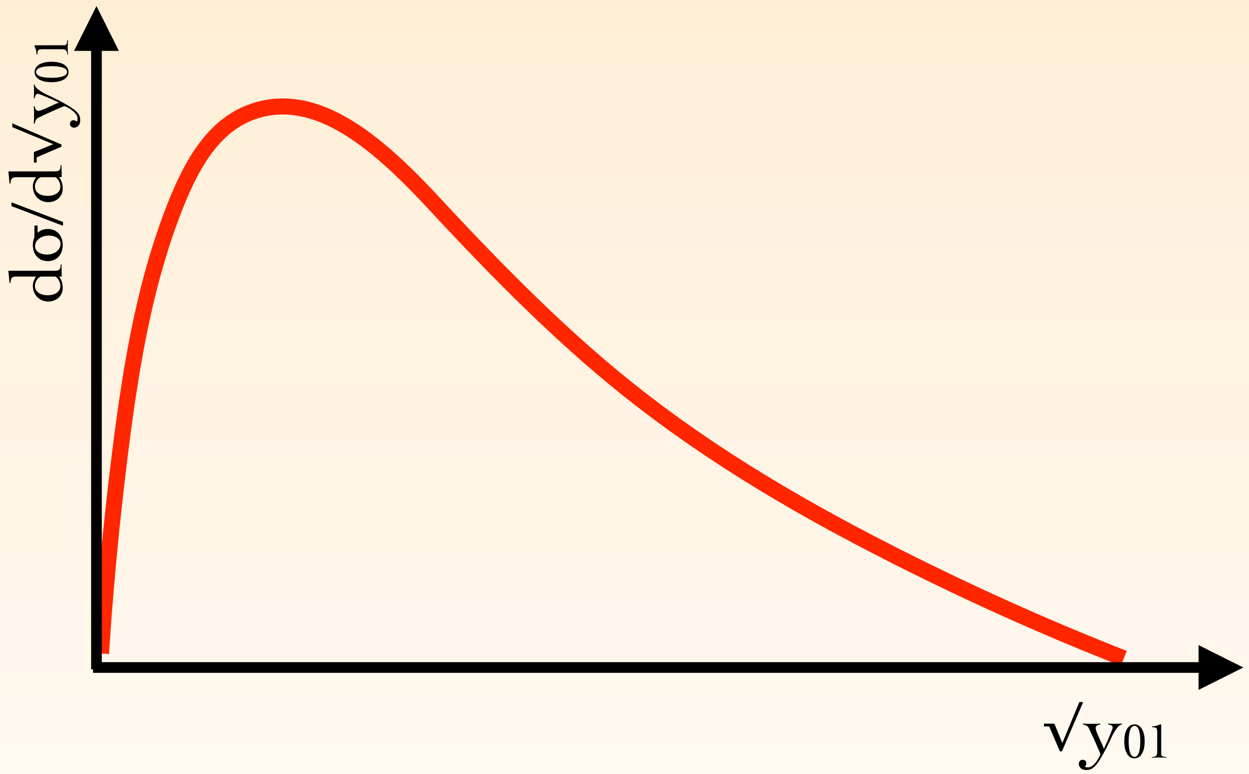


FxFx: [RF, Frixione (2012)]
MEPS@NLO: [Hoeche, Krauss, Schonherr, Siegert; +Gehrmann (2012)]

- Merge NLO+PS for V with Minlo for V+1j, at "merging scale" Q
- Above Q the tail is NLO accurate
- For not-too-small Q, integral is NLO accurate
- Used by ATLAS & CMS for LHC run II analyses

Physical curve	"Yes"
Tail	NLO
Integral	"NLO" (depending on Q)
Extendible to multi-jet	Yes

Minlo-Revisited V+1J



[Hamilton, Nason, Oleari, Zanderighi (2012); Hamilton, Nason, Re, Zanderighi (2013); RF, Hamilton (2015)]

- Much simpler as Geneva
- Like Minlo V+1j, include Sudakov form factors to make distribution physical at low p_T
- **Modify the Sudakov form factors with subleading, process dependent terms such that total integral becomes NLO accurate**
- Can include NNLO corrections for V

Physical curve	Yes
Tail	NLO
Integral	(N)NLO
Extendible to multi-jet	Yes

Minlo accuracy for (inclusive) 0-jet observables

✦ An explicit comparison between the diff.-jet-rate-resummation formula (which integrates to the correct NLO 0-jet diff. cross section) and Minlo shows that they differ by terms of order

[Banfi, Salam, Zanderighi (2005); Dokshitzer, Diakonov, Troian (1980)]

$$\frac{d\sigma_{\mathcal{MR}}}{d\Phi dL} = \frac{d\sigma_0}{d\Phi} \exp\left[-R(v)\right] \prod_{\ell=1}^{n_i} \frac{q^{(\ell)}\left(x_\ell, \mu_F^2 v\right)}{q^{(\ell)}\left(x_\ell, \mu_F^2\right)} \left[\bar{\alpha}_{\mathrm{S}}^2 \left(K_R^2\, y\right) \left[\widetilde{R}_{21}\, L + \widetilde{R}_{20}\right] + \bar{\alpha}_s^3 \left(K_R^2\, y\right) L^2\, \widetilde{R}_{32}\right]$$

✦ After integration over the logarithm L (taking R_{21}=0, which is okay for the processes considered here) this results into terms of

$$\int dL' \frac{d\sigma_{\mathcal{MR}}}{d\Phi dL'} = -\frac{d\sigma_0}{d\Phi} \left[\widetilde{R}_{20} - \bar{\beta}_0 \mathcal{H}_1\left(\mu_R^2\right)\right] \sqrt{\frac{\pi}{2}} \frac{1}{\left|2G_{12}\right|^{1/2}} \bar{\alpha}_{\mathrm{S}}^{3/2} \left(1 + \mathcal{O}\left(\sqrt{\bar{\alpha}_{\mathrm{S}}}\right)\right)$$

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It's process dependent and not a constant in phase-space

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Can either be done analytically or numerically by enforcing unitarity

- Hence, diff. NLO-0jet cross section not correct with NLO-1jet Minlo

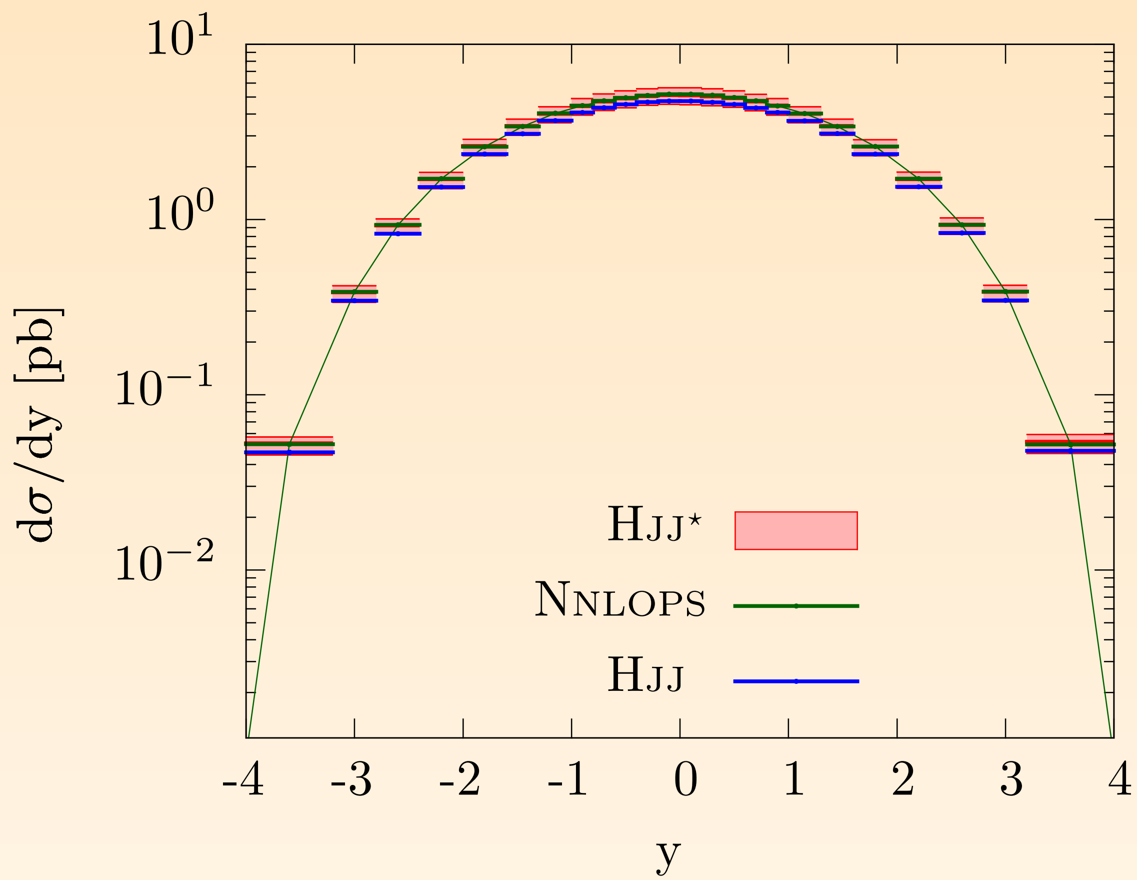
[Hamilton, Nason, Oleari, Zanderighi (2012); RF, Hamilton (2015)]

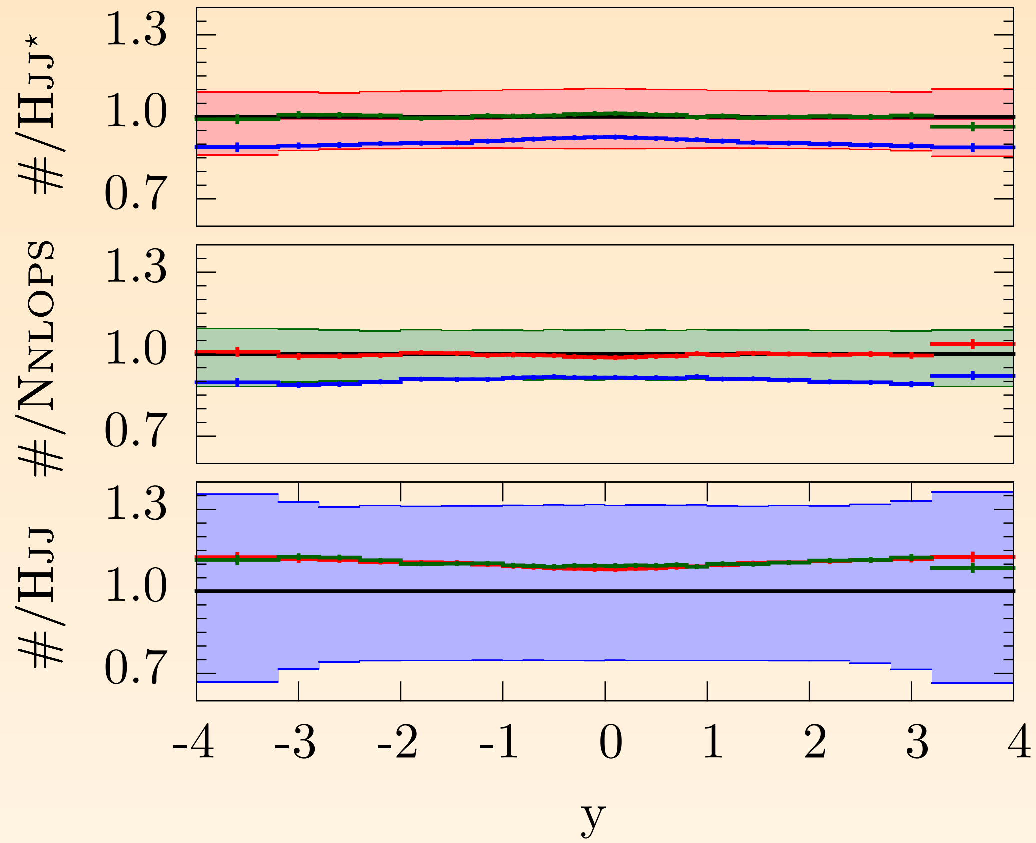
Proof-of-concept

[RF, Hamilton (2015)]

- Apply the method to **Higgs production by gluon fusion** in the infinite top quark limit (which is not a good approximation at high scales, but not a problem for a proof of concept)
- Start from H+J Minlo', corrected to include NNLO for H. Already available in the POWHEG BOX [Hamilton, Nason, Re, Zanderighi (2013)]
- Apply the extended Minlo' method to HJJ at NLO to get
  - NLO+PS predictions for inclusive HJJ observables
  - NLO+PS predictions for inclusive HJ observables
  - NNLO+PS predictions for inclusive H observables
- Study renormalisation/factorisation scale dependence and dependence on freezing parameter ρ (which we vary $\rho=\{1, 3, 9, 18, 27\}$)

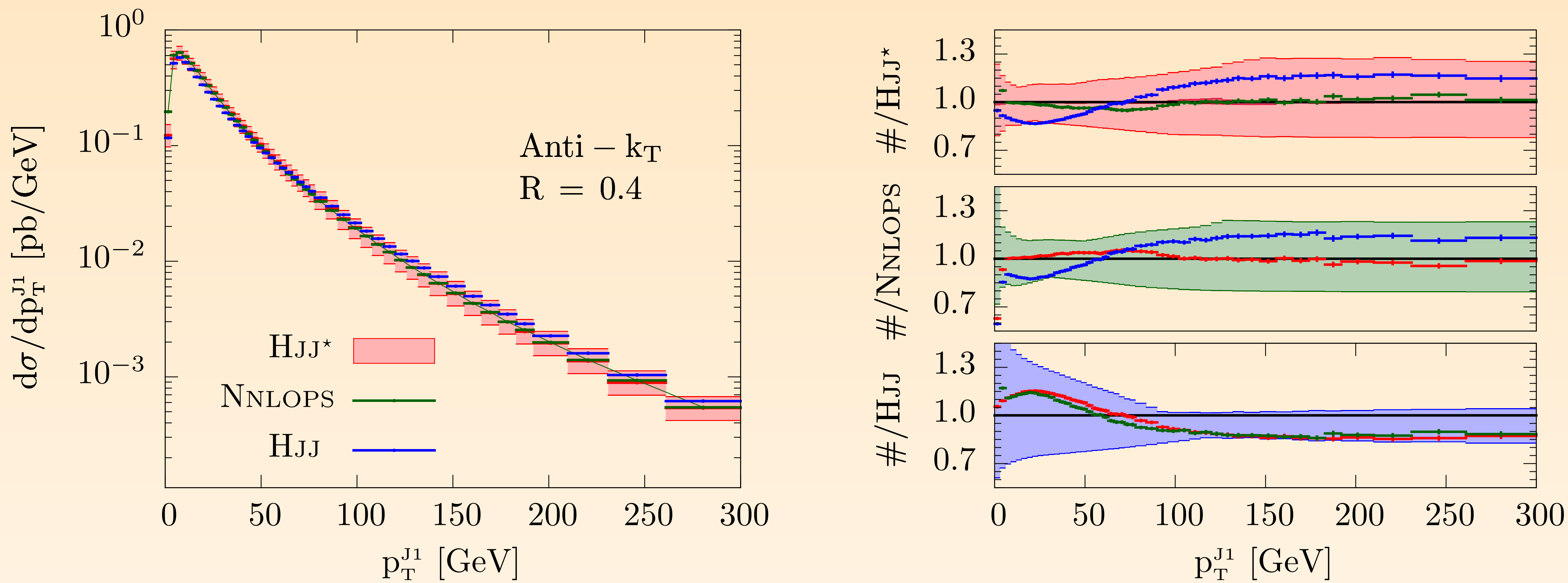
Rapidity of the Higgs boson





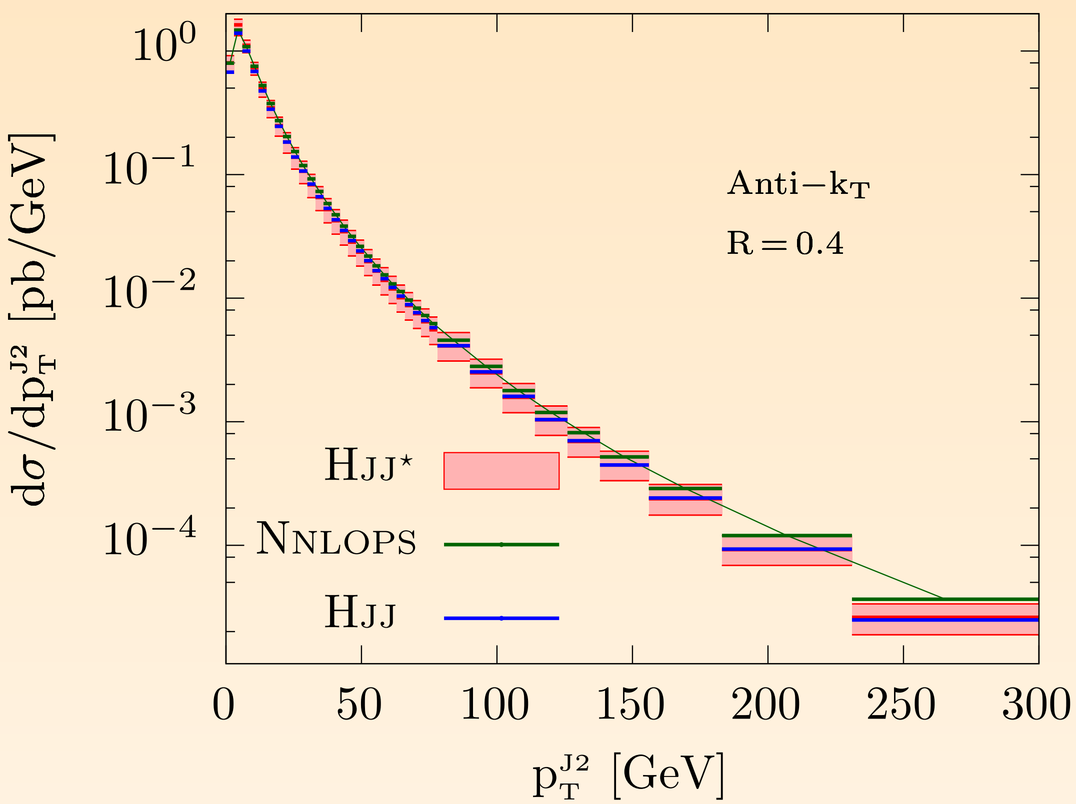
- ✦ Only observable truly NNLO correct
- ✦ Extended Minlo' method (HJJ*) agrees with NNLOPS by construction
- ✦ Normal HJJ Minlo shows larger uncertainty bands and different central value: it's only LO accurate for this observable

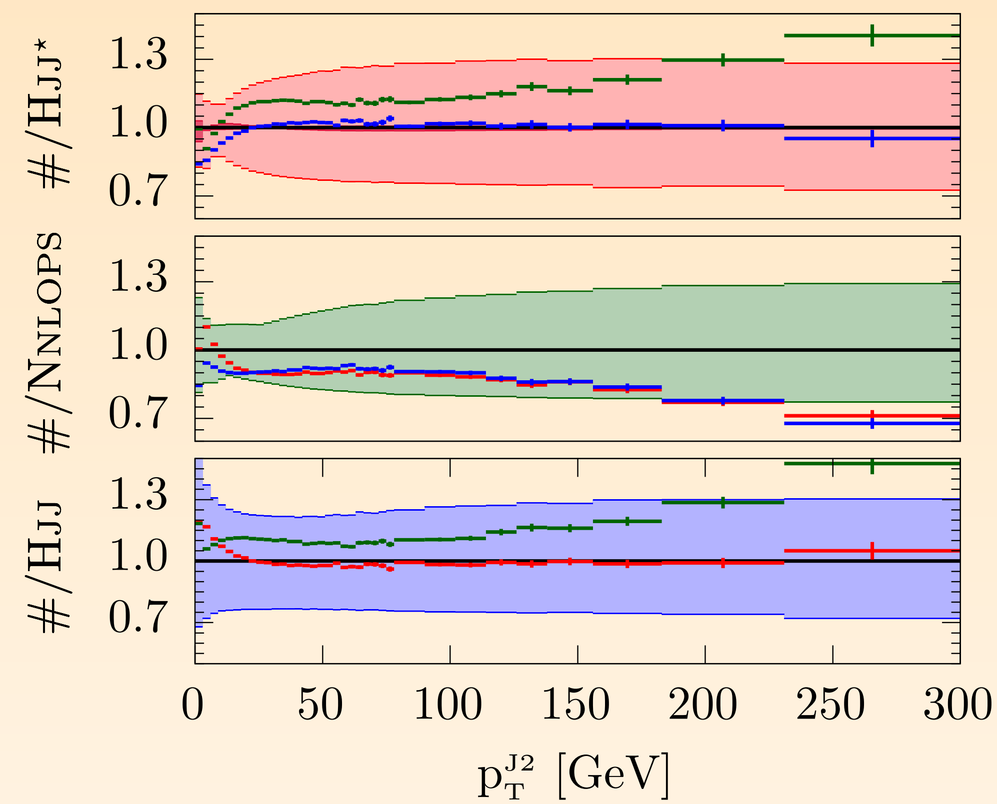
Transverse momentum of the leading jet



- Extended Minlo' method (HJJ★) agrees with NNLOPS by construction.
  - apart from p_T<5 GeV region: grid-granularity to compute δ not fine enough
  - Also region 60<p_T<80 GeV shows 3-5% deviations: pT derivative of the numerator of δ changes very rapidly
- Normal HJJ Minlo shows unphysical uncertainty band. Formally only LO for this observable

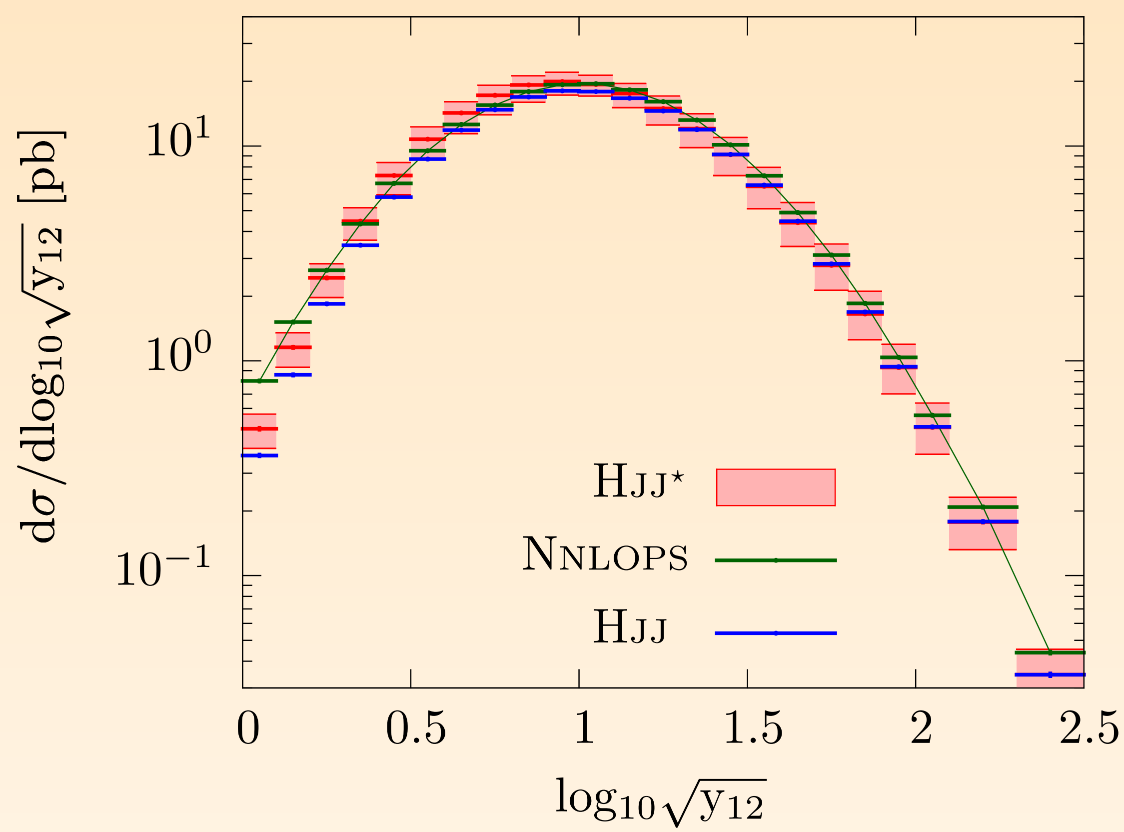
Transverse momentum of the second jet

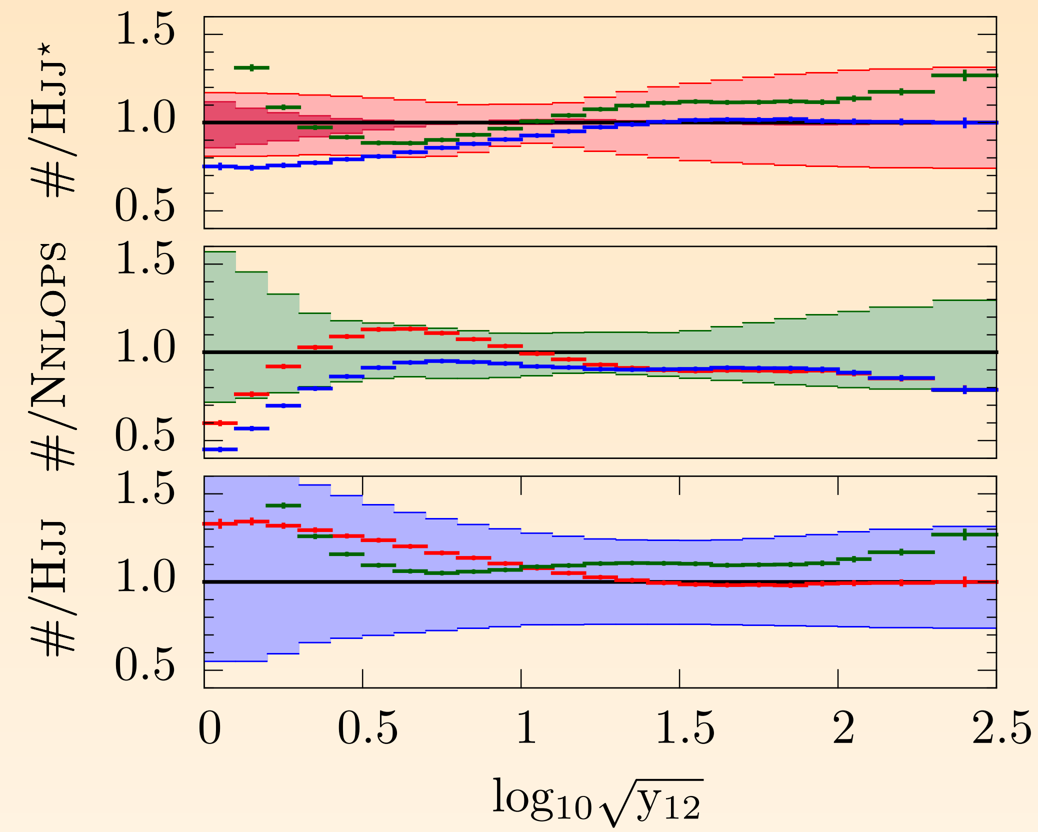




- ✦ Extended Minlo' method HJJ⋆ agrees with Minlo HJJ, as expected
  - ○ apart close to the Sudakov peak: the difference between HJJ⋆ and HJJ is beyond LL/NNLL$_\sigma$ accuracy, which is important close to the Sudakov peak
- ✦ NNLOPS only LO accurate for this observable: uncertainty band is too small (this is due to the POWHEG method)

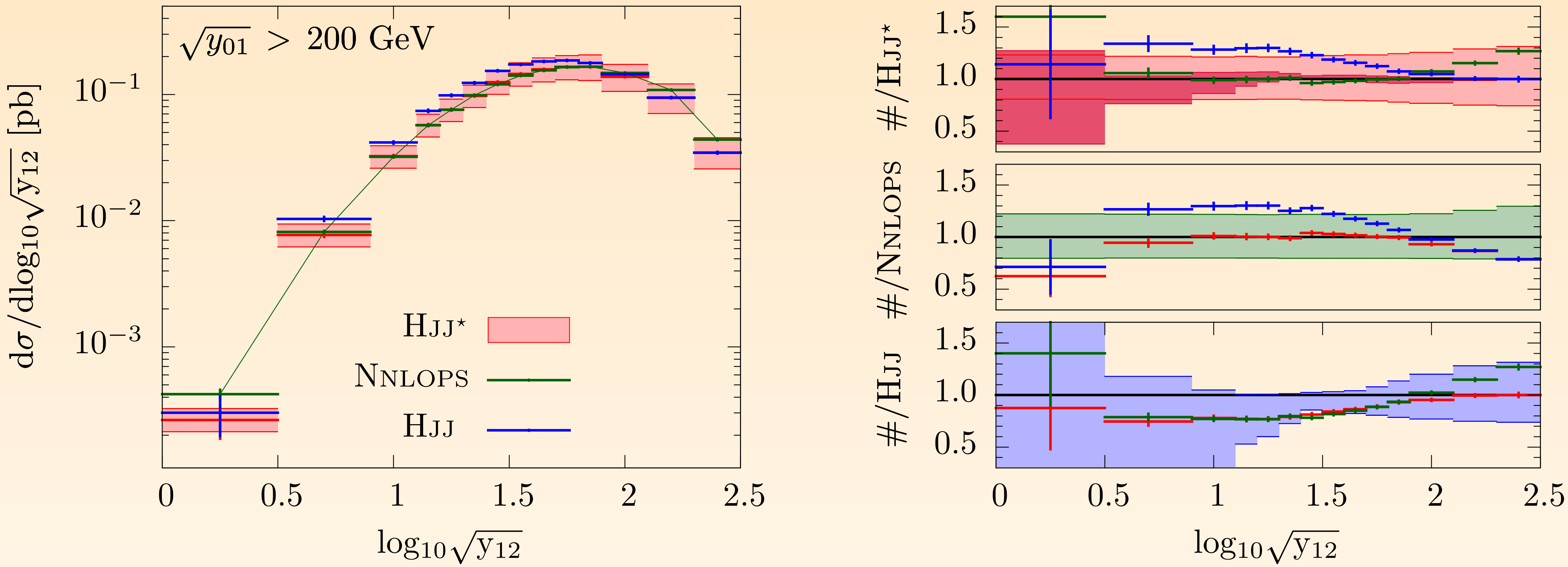
Y_{12} RESOLUTION PARAMETER





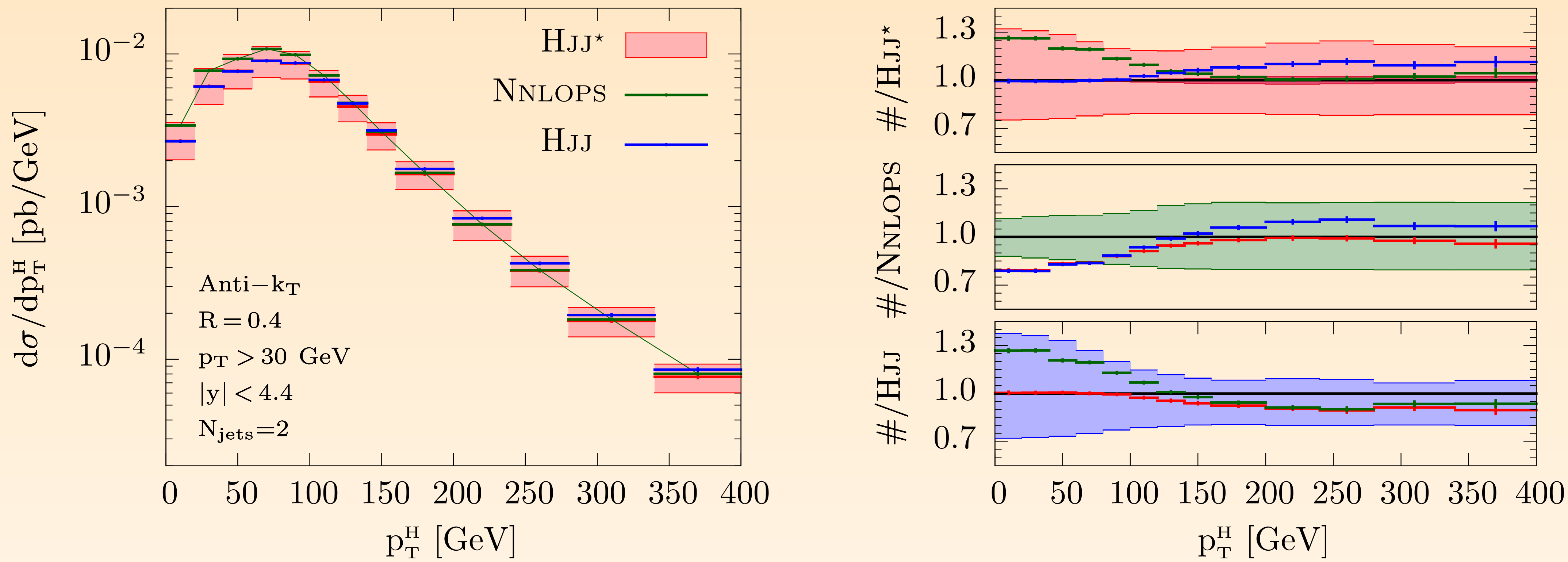
- ✦ Similar picture as for $p_T(j_2)$, but low p_T region easier to see due to logarithmic x-axis
- ✦ First observable where we see some non-zero dependence on the freezing parameter ρ (red solid). Well below the Sudakov peak where higher-logarithmic corrections are large as well as non-perturbative corrections

y_{12} resolution parameter with $\sqrt{y_{01}} > 200$ GeV



- At very large y_{12}, all scales are large and of the same order —> the Minlo method switches off: HJJ⋆ agrees with HJJ
- When $y_{12} \ll y_{01}$, large logarithms build up, and the extended Minlo' method brings the HJJ⋆ to the NNLOPS

Higgs boson p_T in events with exactly 2 jets



- At small p_T, all scales are of the same order. The Minlo method does not do much: HJJ★ agrees with HJJ

- At large p_T, HJJ★ agrees with NNLOPS dominated by events with one hard jet ($p_T(j_1) \sim p_T(H)$) and one soft jet: a 30 GeV jet comes basically for free
  - The pT(H) spectrum with N_{jets}=2 becomes essentially N_{jets}≥1 pT(H) distribution

Conclusions

- In the last couple of years the accuracy of event generation has greatly improved, and full automation has been achieved at NLO accuracy
  - FxFx Merging is one of the methods to combine NLO matrix elements of various multiplicities with the parton shower
  - NLO accuracy in multiple regions of phase-space, separated by a merging scale
- 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
- One of the latest developments, 'Minlo revisited', allows for similar accuracy as FxFx in multi-jets, but without the introduction of a merging scale and with the possibility to include NNLO. Only proof-of-concept so far.