ME+PS merging at NLO

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MadGraph meeting 2012, Natal Brazil, Sep. 30 - Oct. 8, 2012

General idea

- Merge aMC@NLO samples for S+0j, S+1j, S+2j, S+...j consistently without double counting (where S can be a Higgs, a ttbar pair, a W-boson, di-jet, etc.)
- Use techniques from CKKW/MLM and multi-scale improved fixed order NLO or "MINLO" (Hamilton, Nason & Zanderighi, 2012) to define **exclusive event samples** for S+0j, S+1j, etc.
  - In such a way that the exclusive samples can simply be combined to one big event sample
- Special care for the highest multiplicity sample

A BIT MORE DETAIL

- To make a LO prediction exclusive in the number of jets, we need to multiply it by a Sudakov damping factor; this is MLM or CKKW:

$$\sigma^{\mathrm{LO}}_{n,\ \mathrm{excl}} = B\,\Theta(Q_n - Q_{\mathrm{cut}})\,\Delta_n(Q_{\mathrm{cut}}, Q_{\mathrm{max}})$$

This gives makes the prediction exclusive at leading logarithmic accuracy

- Similarly we can make an NLO prediction exclusive at leading logarithm

$$\sigma^{\mathrm{NLO}}_{n,\ \mathrm{excl,\ LL}} = \left\{B + V + \int d\Phi_1\, R\right\}\Theta(Q_n - Q_{\mathrm{cut}})\,\Delta_n(Q_{\mathrm{cut}}, Q_{\mathrm{max}})$$

- We can improve here and use the real-emission matrix elements instead of just the Sudakov:

$$\sigma^{\mathrm{NLO}}_{n,\ \mathrm{excl}} = \left\{B + V + \int_0^{Q_{\mathrm{cut}}} d\Phi_1\, R - B\Delta^{(1)}_n(Q_{\mathrm{cut}}, Q_{\mathrm{max}})\right\}$$
$$\Theta(Q_n - Q_{\mathrm{cut}})\,\Delta_n(Q_{\mathrm{cut}}, Q_{\mathrm{max}})$$

Exclusive MC@NLO

- Exclusive (in the number of jets) predictions within the MC@NLO procedure

$$\mathbb{S}\text{-events:} \quad \left\{ B + V - B\Delta_n^{(1)}(Q_{\rm cut}, Q^B_{\rm max}) + \int_0^{Q_{\rm cut}} d\Phi_1 \, {\rm MC} \right\} \Theta(Q_n^B - Q_{\rm cut}) \, \Delta_n(Q_{\rm cut}, Q^B_{\rm max})$$

$$\mathbb{H}\text{-events:} \quad \left\{ R\,\Theta(Q_n^R - Q_{\rm cut}) - {\rm MC}\,\Theta(Q_n^B - Q_{\rm cut}) \right\} \Theta(Q_{\rm cut} - Q_{n+1}^R) \, \Delta_n(Q_{\rm cut}, Q^R_{\rm max})$$

- That doesn't look very hard...

  Why did it took you so long to have this working?

The devil is in the details...

- What to choose for the renormalization scale (it does not only enter as argument of the strong coupling at NLO)?
- What to choose for the factorization scale (it does not only enter in the PDFs at NLO)?
- What to do for the PDF reweighting (NLO PDF counter terms)?
- What to choose for the starting scales of the parton shower?
- How to apply the Sudakov suppression (MLM or CKKW)?
- How to treat the extra parton in the real-emission? Do we need a Sudakov?
- What to do with the matching scale (fixed or a smooth function)?
- ...

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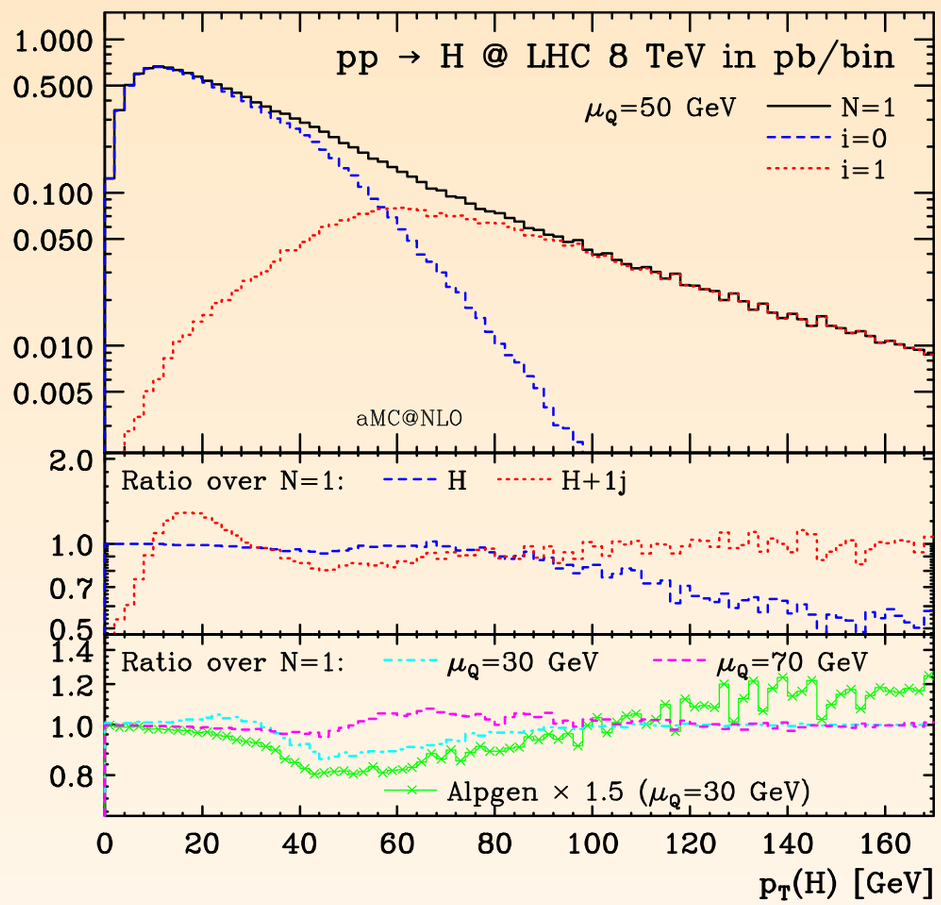
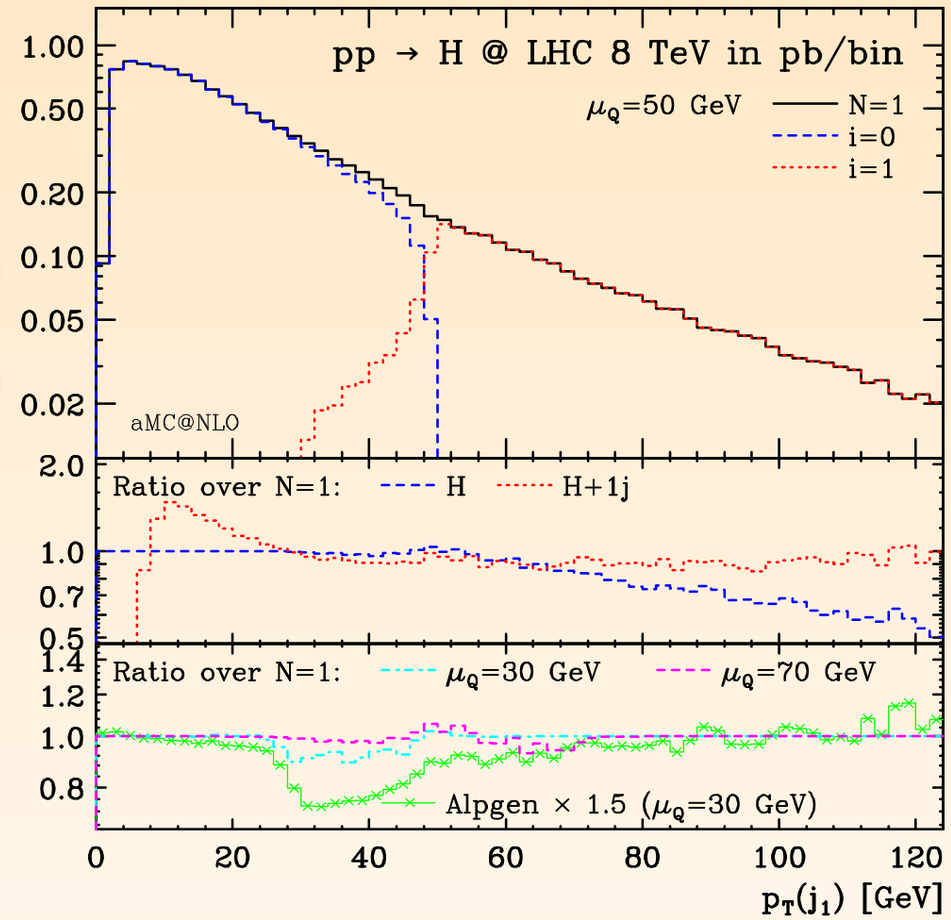
A lot of "freedom"; we have found a way that seems to be working

Some results: Higgs

RF & Frixione, 2012





- Transverse momentum of the Higgs and of the 1st jet.
- Agreement with H+0j at MC@NLO and H+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale
- Alpgen shows larger kinks

Some results: Higgs

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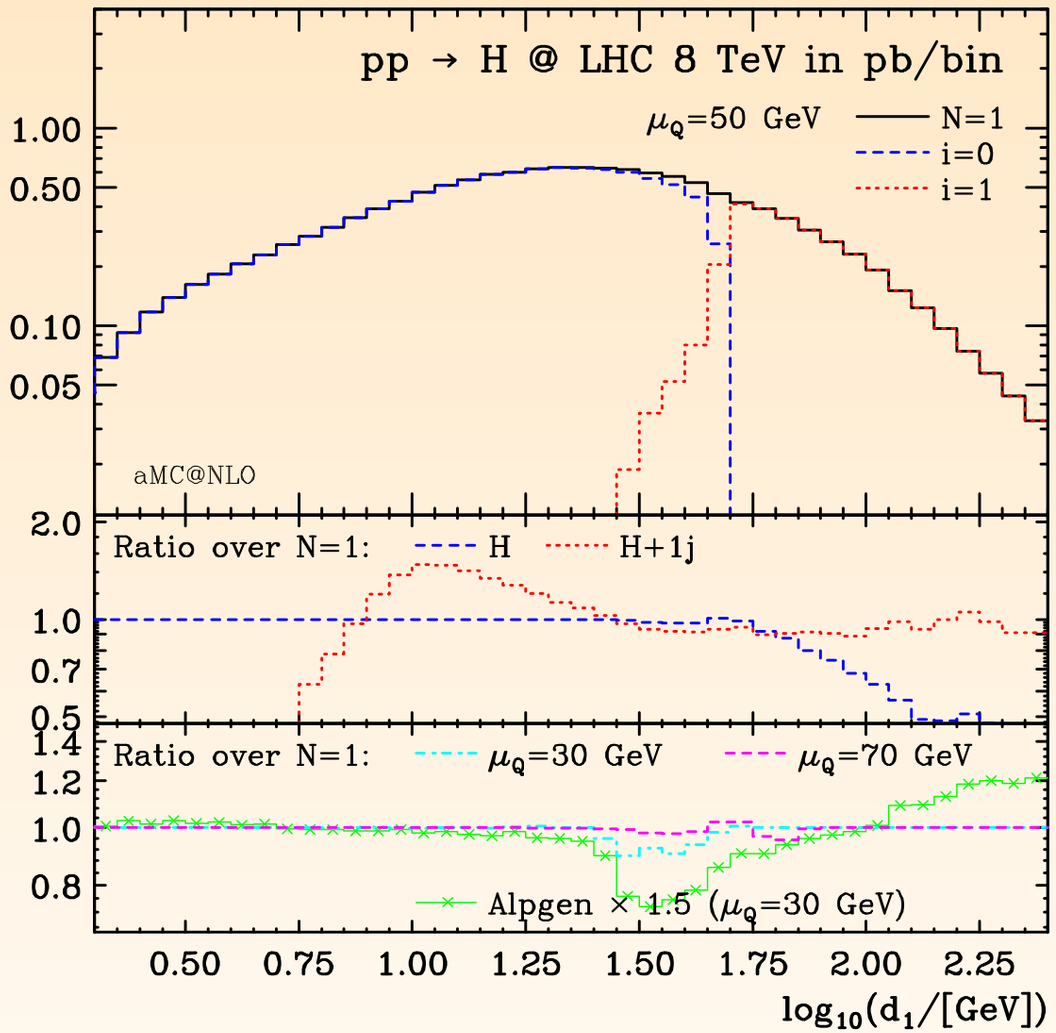
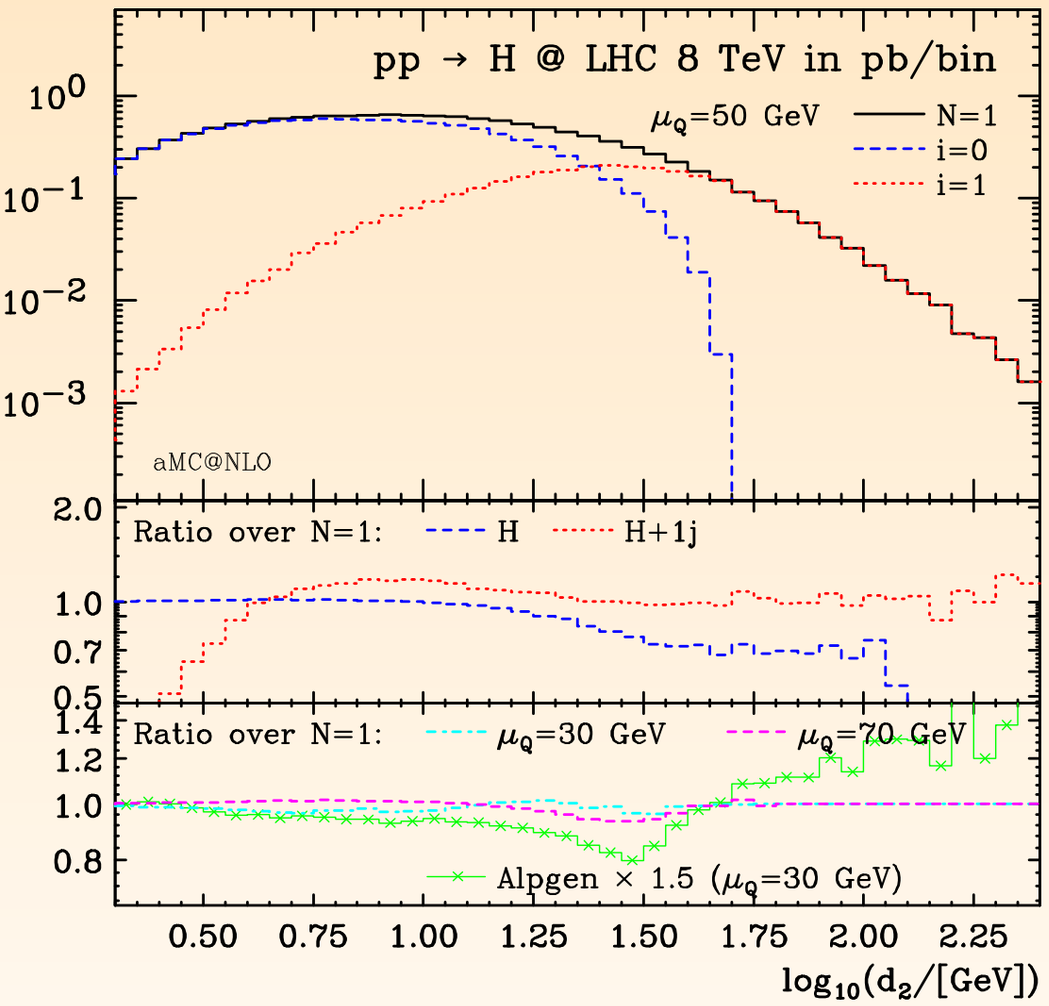
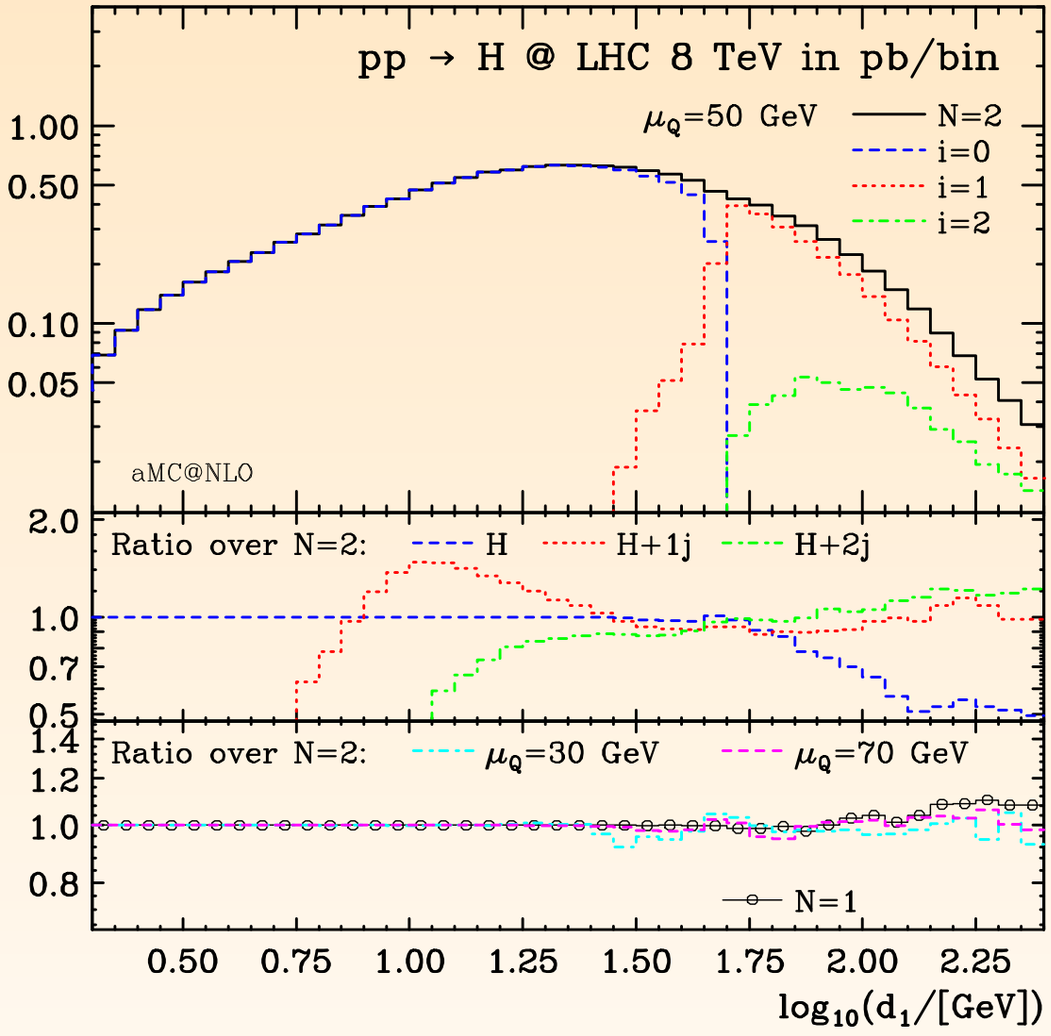


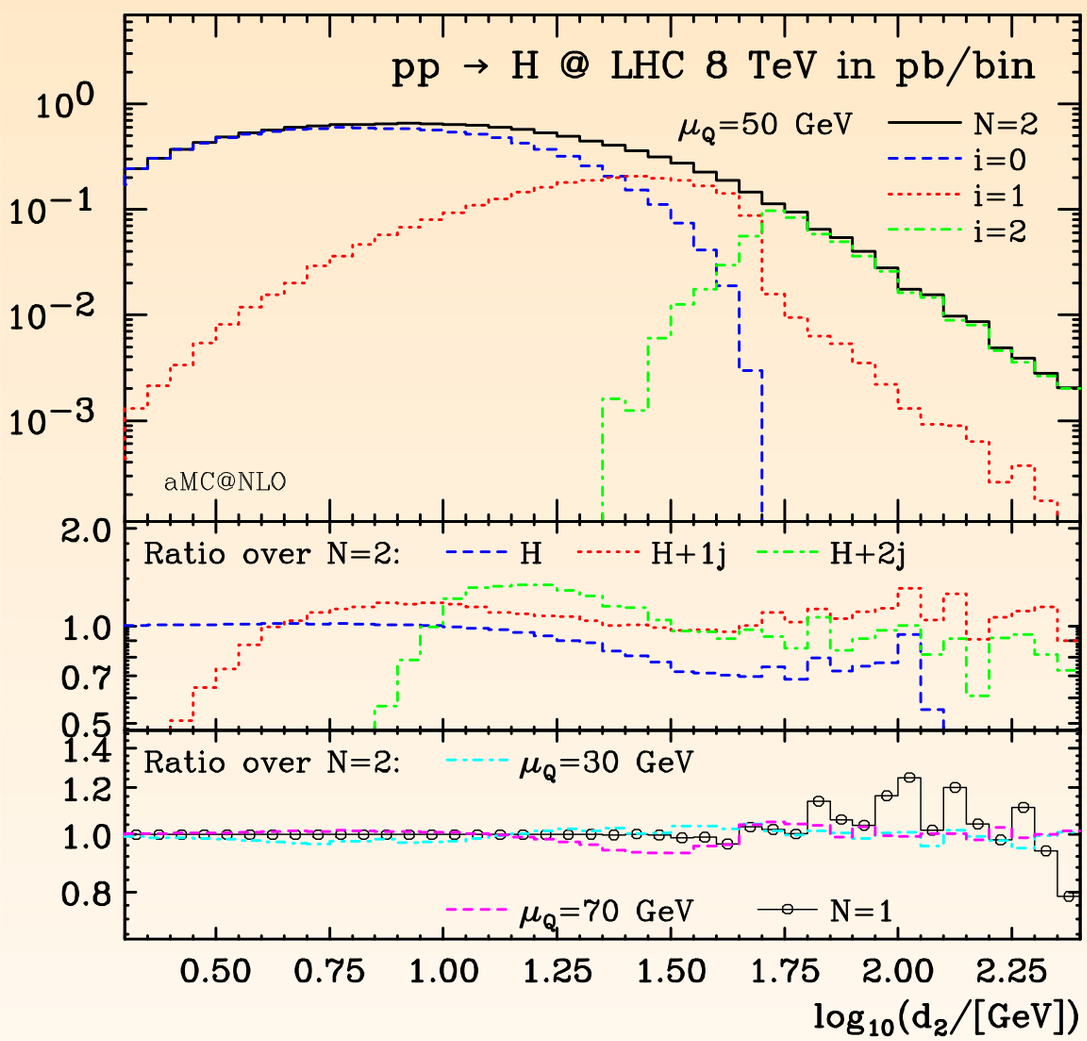


- Differential jet rates for 1->0 and 2->1

Some results: Higgs

RF & Frixione, 2012

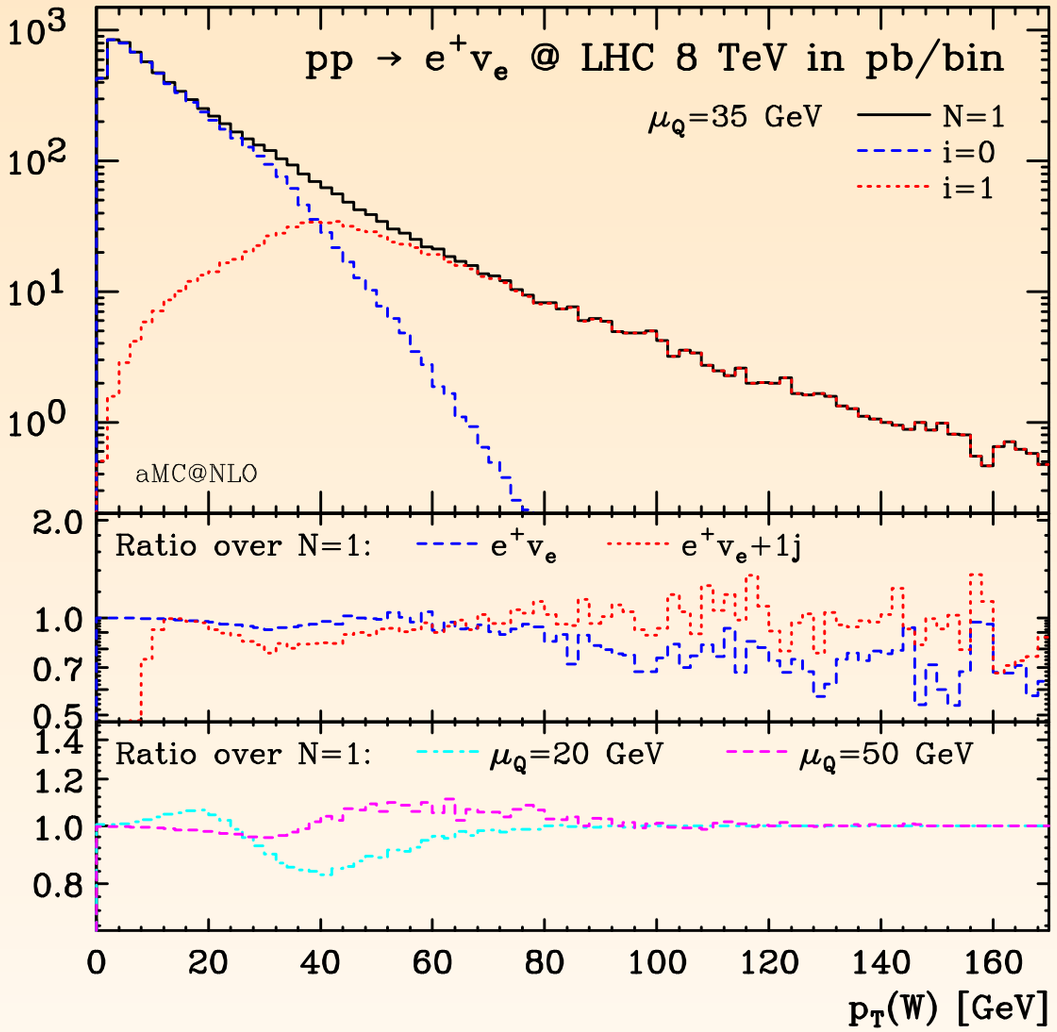


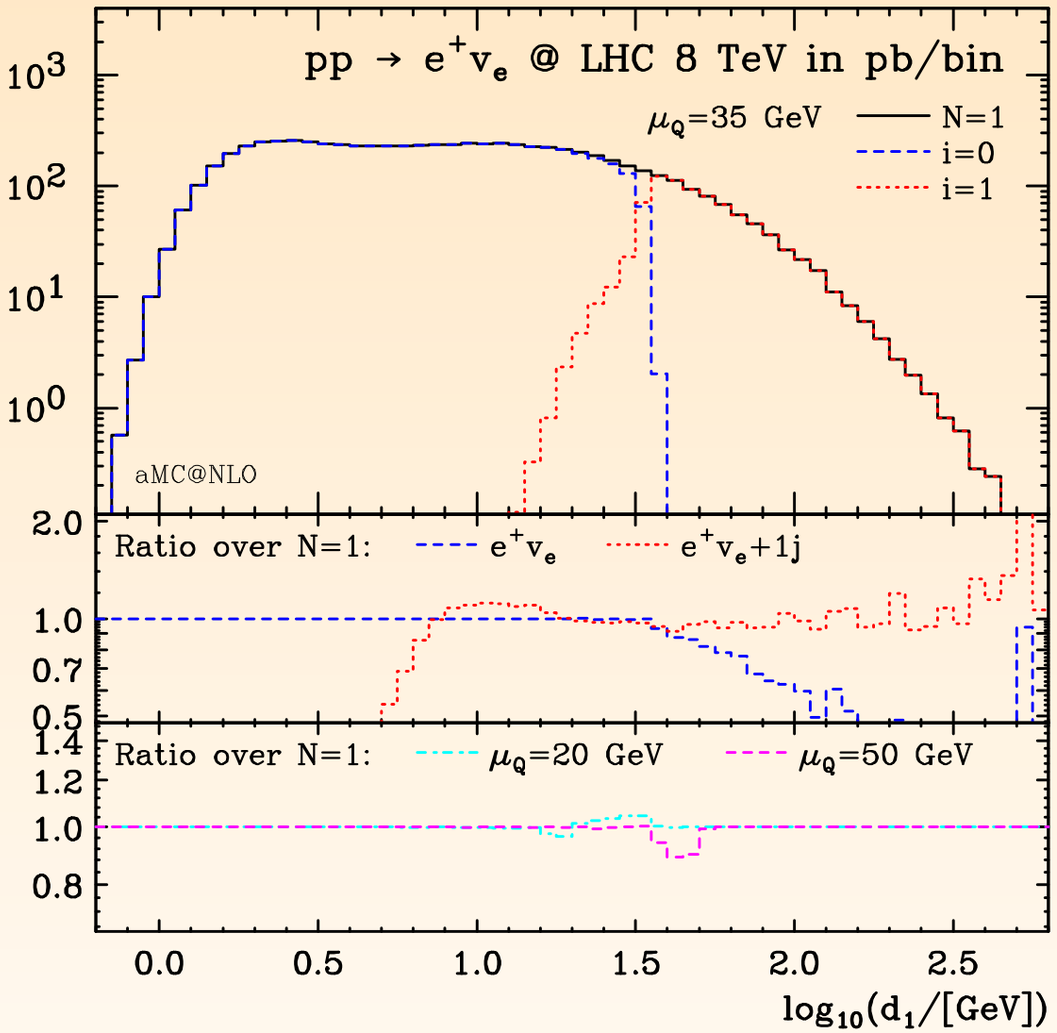


- Differential jet rates
- Matching up to 2 jets at NLO
- Results very much consistent with matching up to 1 jet at NLO

Some results: W-boson

RF & Frixione, 2012

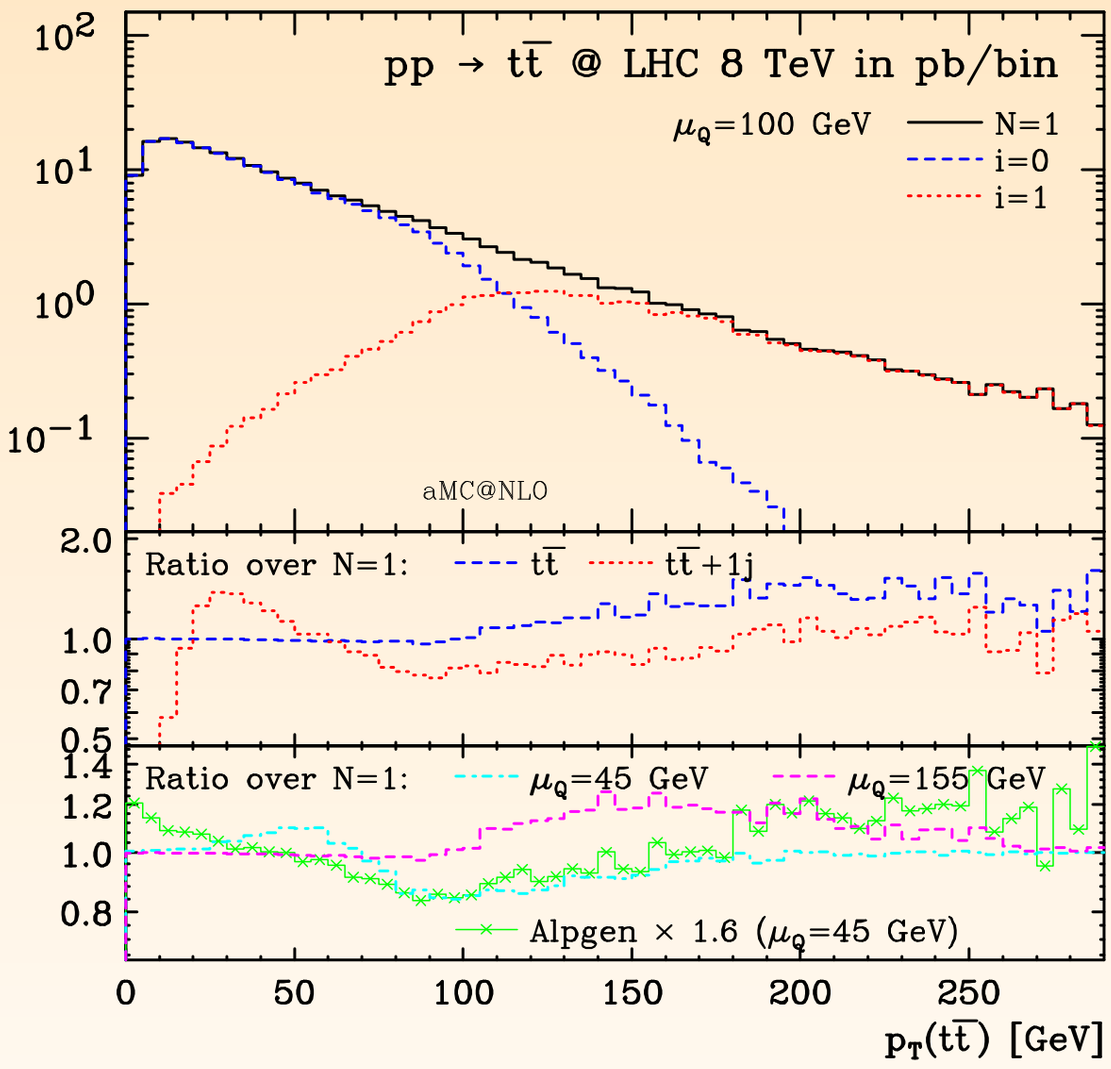


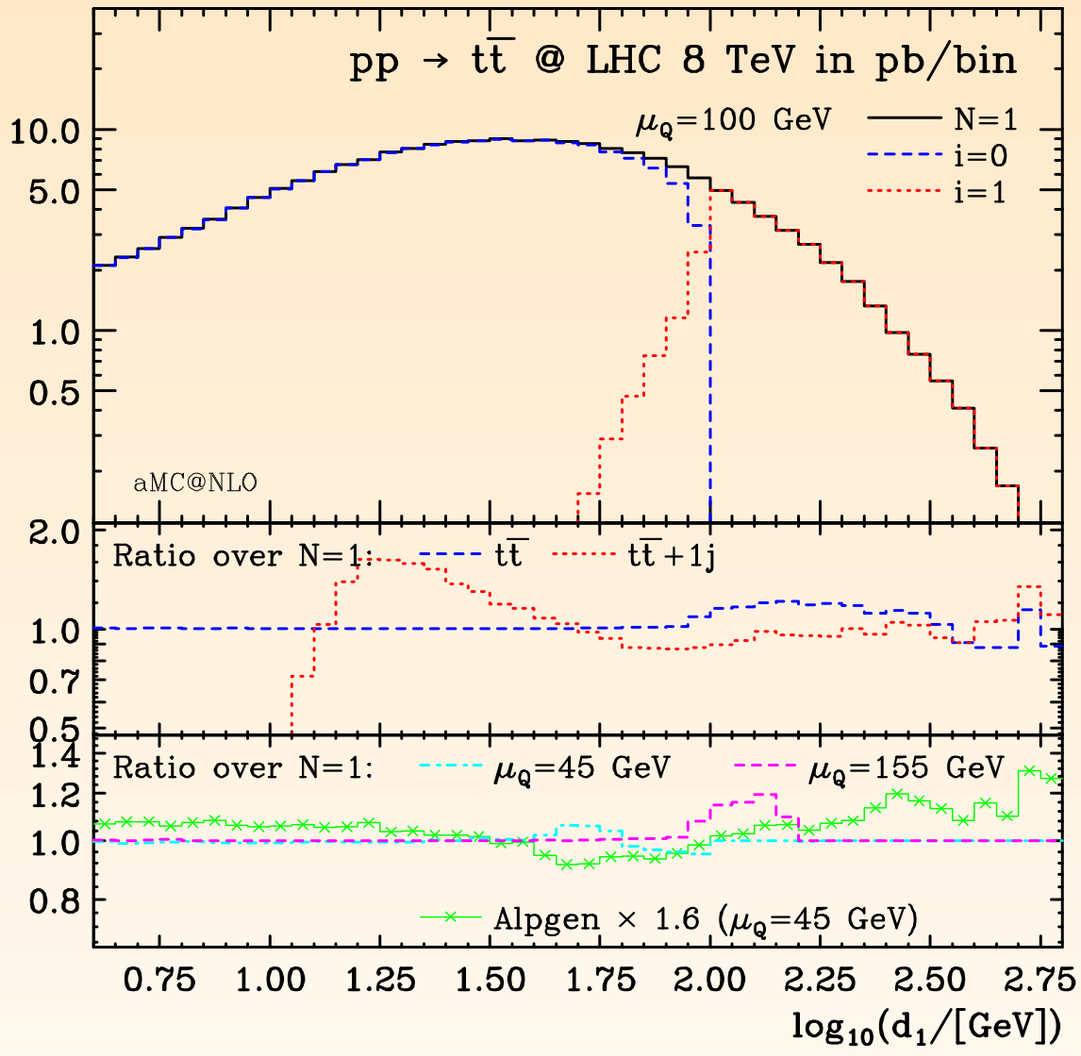


- Similar results for W-boson production

Some results: ttbar

RF & Frixione, 2012





- and top pair production
- Only for VERY large scales tt+1j at MC@NLO is larger than than tt+0j at MC@NLO

What still needs to be done

- **Automation**: so far, applying the Sudakov factors was done in a non-automatic way
  - Can we take the CKKW/MLM cluster.f and reweight.f that is already there for the LO and port it to the NLO code?
    - Discussion with Johan already started
    - Some difficulties, because at NLO there are also the real-emission matrix elements that are clustered in a different way (in the real-emission one step needs to be skipped; not all information is readily available)
- Processes with **jets at the lowest multiplicity Born** (e.g. t-channel single top): is there anything special needed?

Physics applications

- Most interesting right now might be Higgs production by VBF and VBF+1j, to be able to study in detail the uncertainties in the central jet veto:
  - how well are they modeled at LO and
  - what are the uncertainties coming from the matching
- Extension to include b quarks (Wbb and Wbb+1j)
- Higgs production by gluon fusion and NLO spin correlations (spin-2 Higgs)
- And many, many more...