NNLOPS

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UCL

Outline

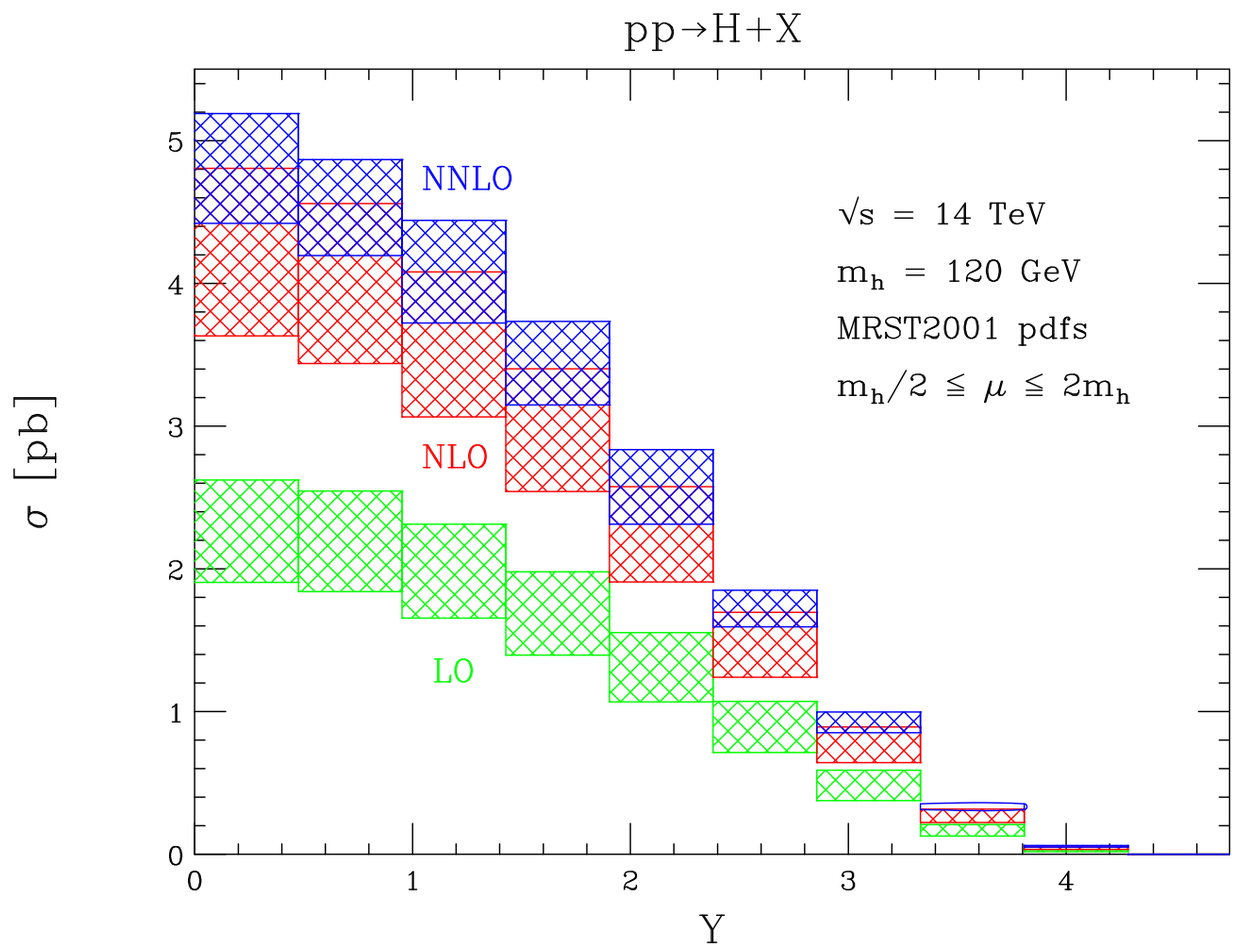
- MOTIVATION
- MiNLO: Multiscale improved NLO

  Nason, Zanderighi, k.h. - JHEP 1210
  Nason, Oleari, Zanderighi, k.h. - JHEP 1305
- NNLOPS

  Nason, Zanderighi, Re, k.h. - JHEP 1310/JHEP 1505
  Karlberg, Re, Zanderighi - JHEP 1409
- RESULTS
- SUMMARY

Motivation: NNLO

- NNLO needed for processes where NLO/LO corrs are large ...
- E.g. Higgs production

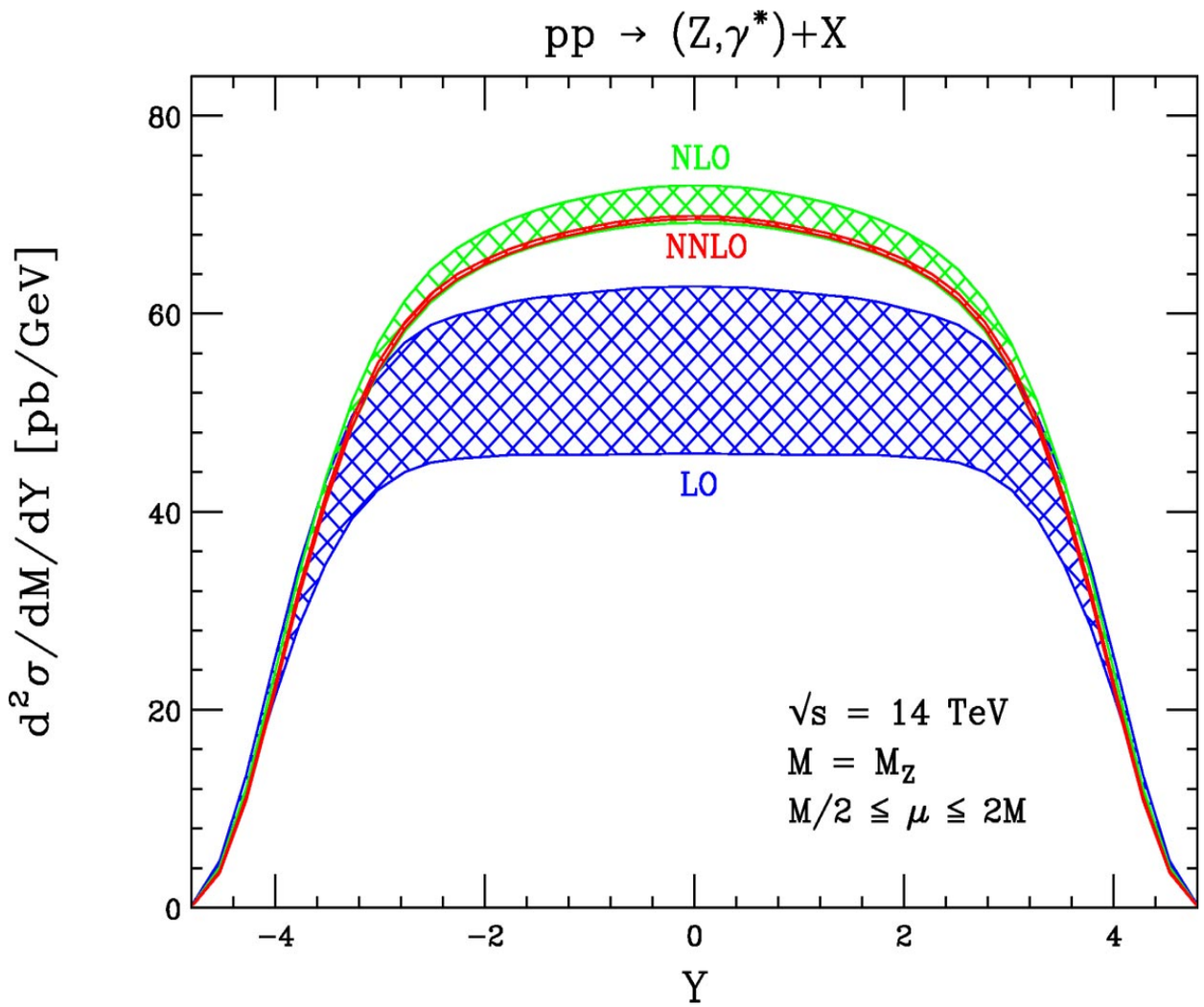


- For exploiting Higgs data we rather know the NNLO than NLO/LO ...

Left: Anastasiou, Melnikov, Petriello 2005 NPB 724 Right: CMS arXiv:1307.7135

Motivation: NNLO

- NNLO needed for HIGH precision signal measurements ...
- E.g. DY : constrains PDFs, detector calibrat^n, BSM searches



- You'd rather know this with O(1%) than O(10%) unc ...

Left: Anastasiou, Dixon, Melnikov, Petriello 2004 PRD 69 Right: ATLAS PLB 725

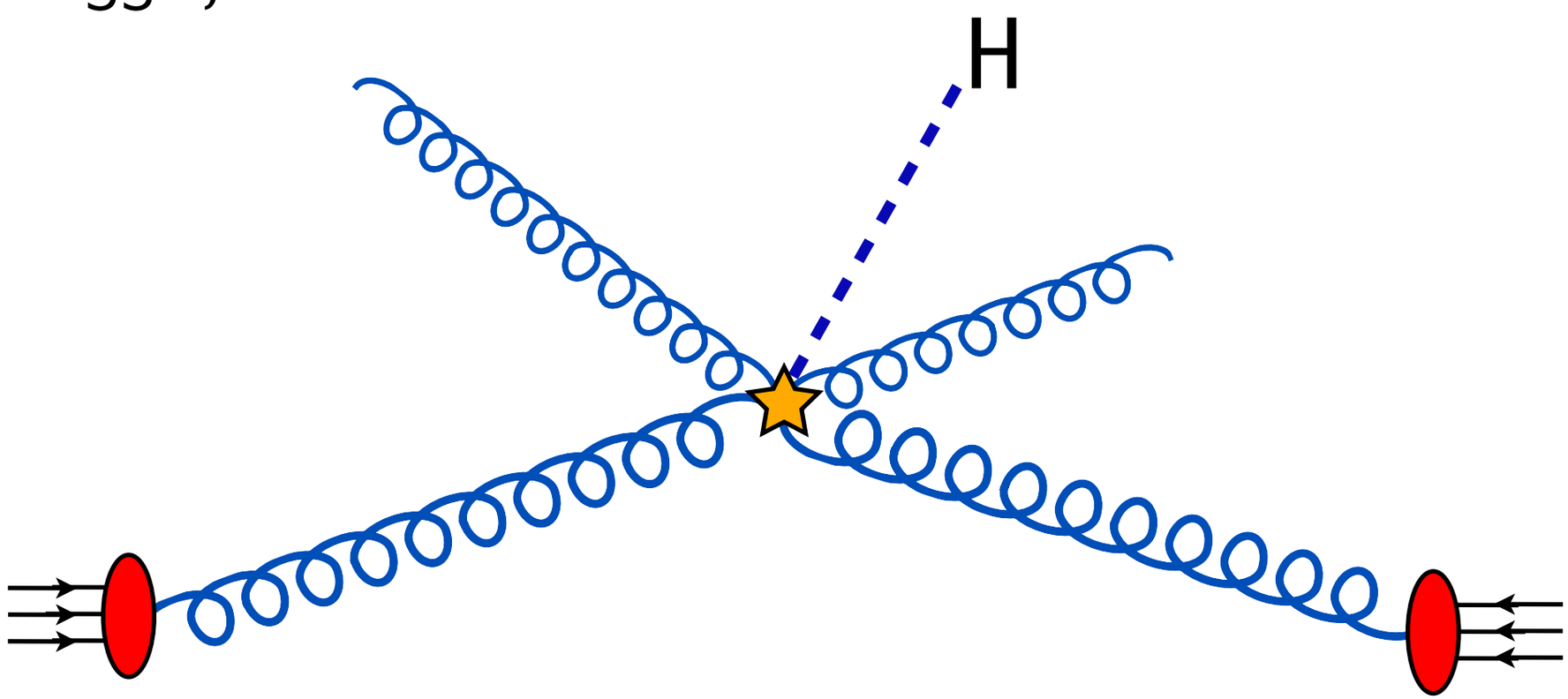
Motivation: NNLOPS

- Differential NNLO DY and gg → Higgs achieved ~10yrs ago

  Anastasiou, Dixon, Melnikov, Petriello ; Catani, Grazzini
  Generalised in more recent years:
  Del Duca, Somogyi, Trocsanyi ; Gehrmann, Glover, Pires et al. ; Czakon ;
  Boughezal, Caola, Melnikov, Petriello, Schulze ; Boughezal, Focke, Giele, Liu, Petriello ;
  Gaunt, Stahlhofen, Tackmann, Walsh

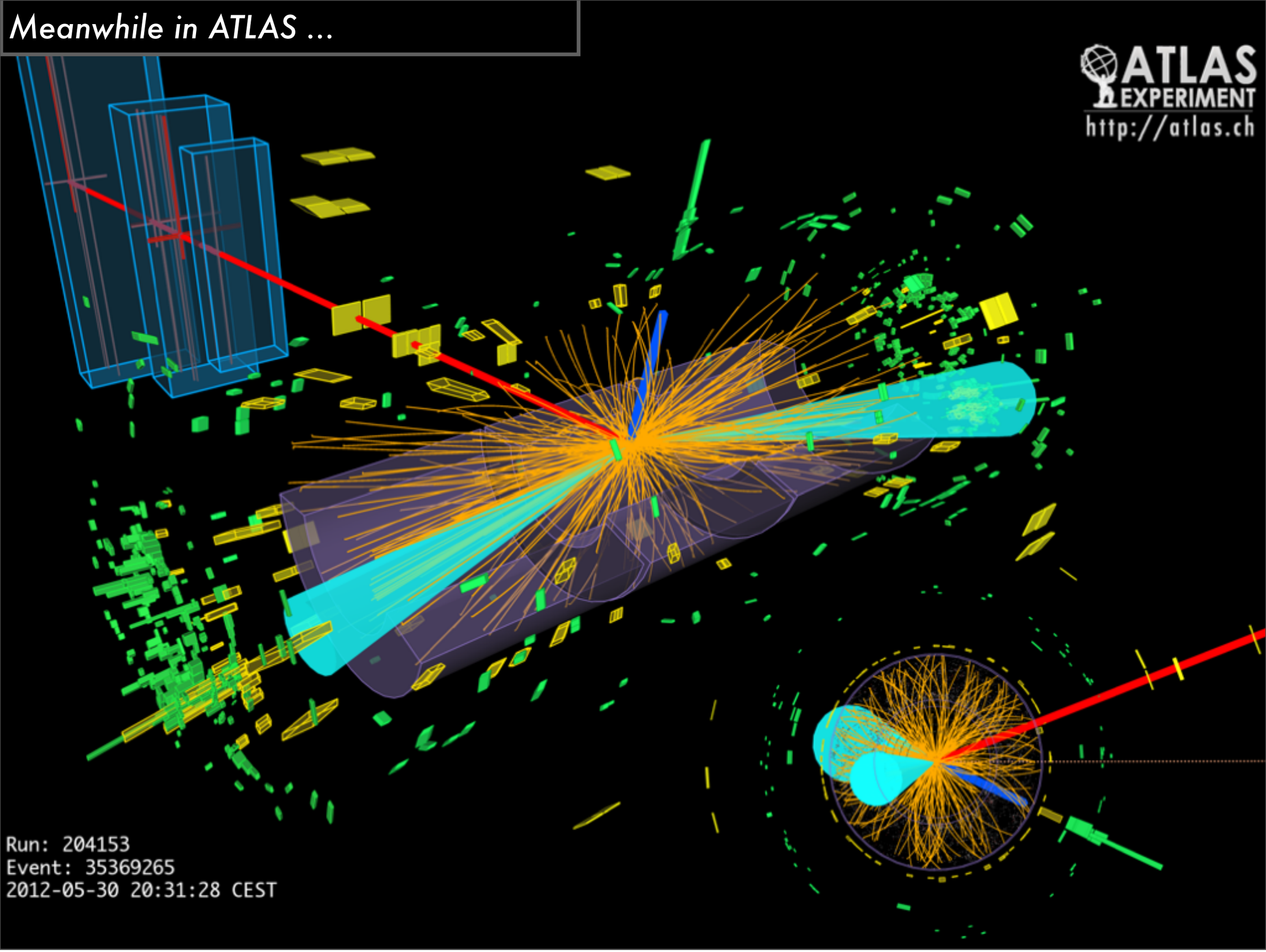
- Unquestionably outstanding & progress

- Description of highest multiplicity events in e.g. NNLO gg → Higgs, is



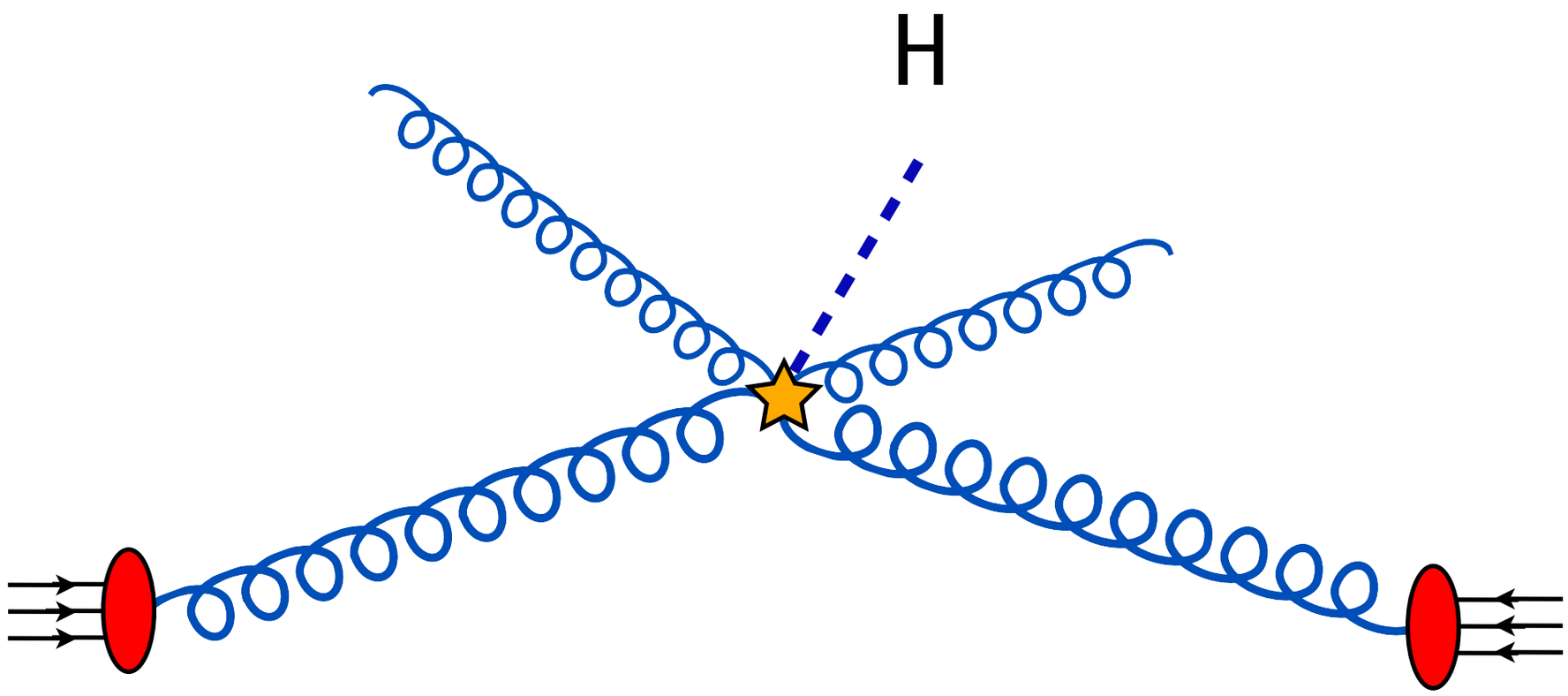
Anastasiou, Dixon, Melnikov, Petriello 2003 PRL 91 Catani, Grazzini 2007 PRL 98

Meanwhile in ATLAS ...



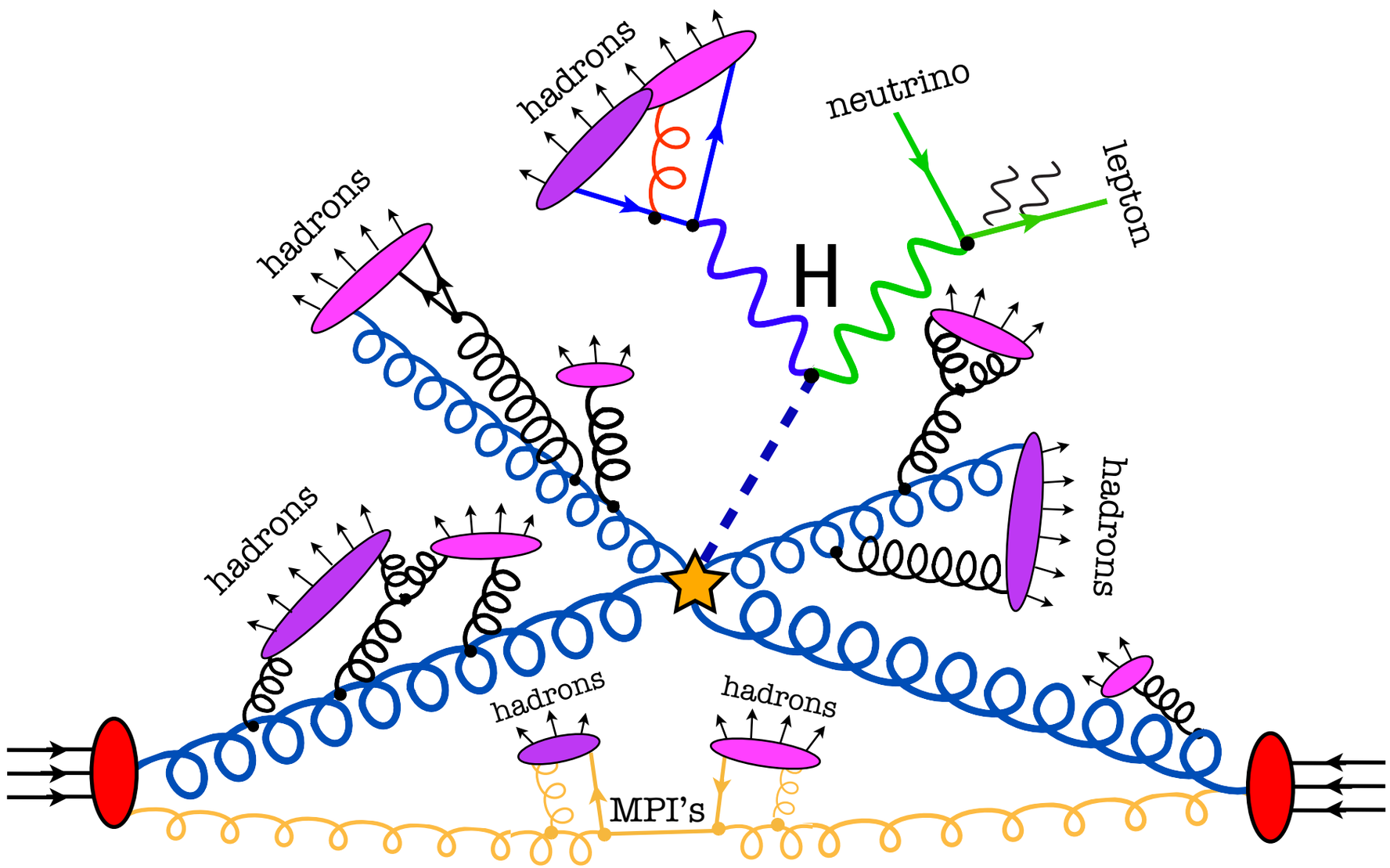
Motivation: NNLOPS

- NNLOPS takes fully inclusive fixed order NNLO as input ...



Motivation: NNLOPS

- NNLOPS outputs NNLO+[N]LL resummed, hadronized, fully exclusive, particle-level, unweighted events, with MPI, with QED ...



- No need for extrapolations, acceptance corr^{n}s, effy corr^{n}s, shower corr^{n}s, non-perturbative corr^{n}s, MPI, QED ...

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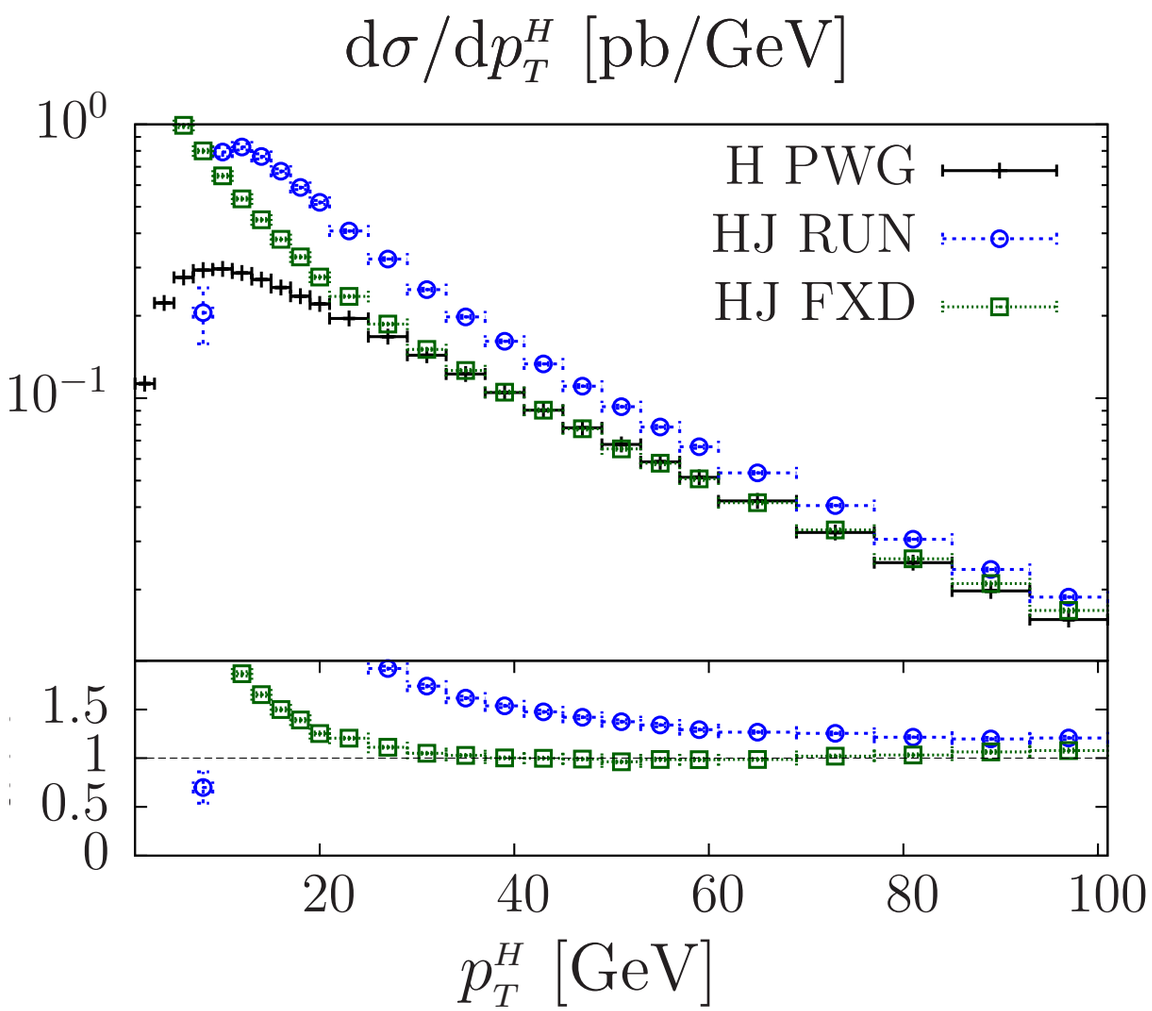
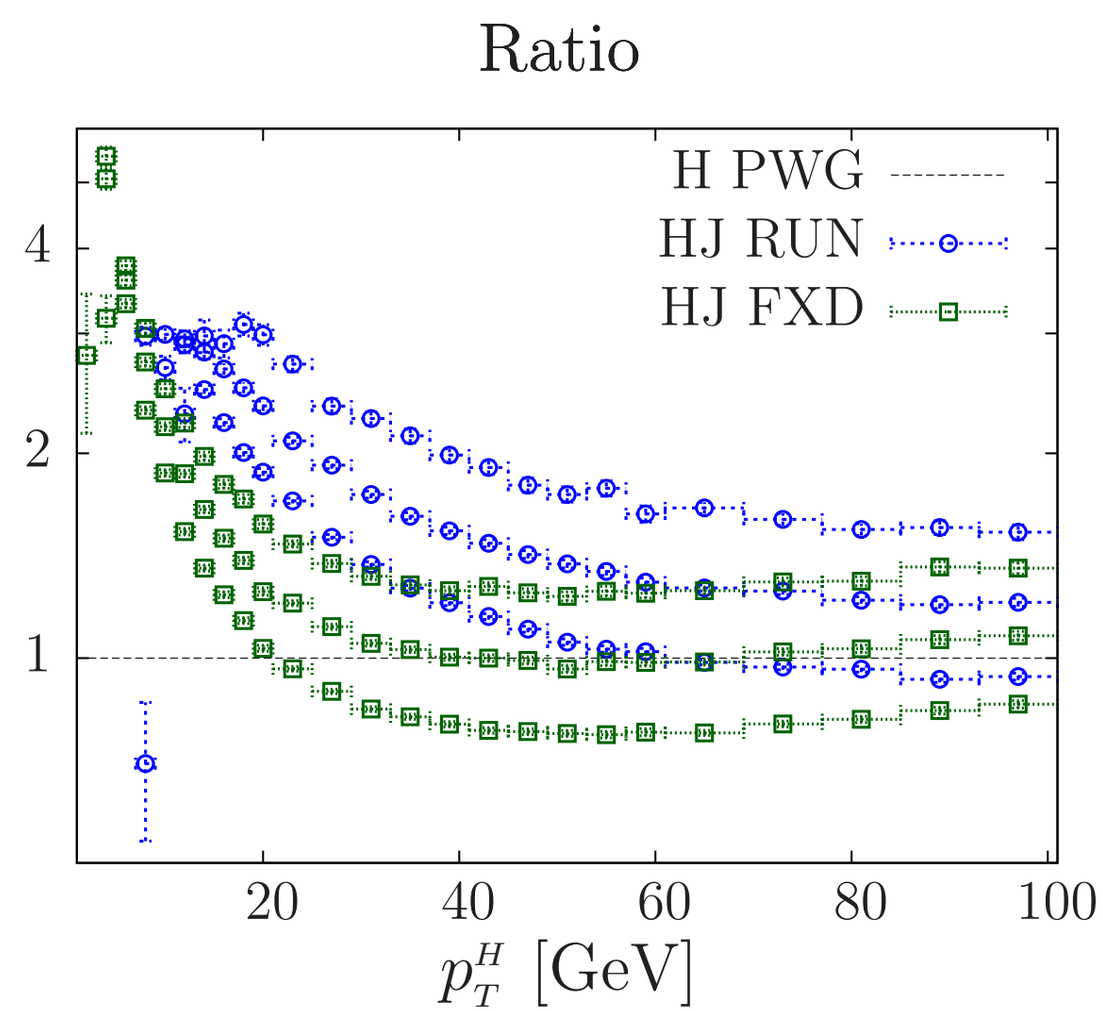
Conventional NLO H + jet vs NLOPS H





- H PWG: gg → Higgs at NLO Powheg+Pythia
- HJ RUN: NLO H+1 jet with $\mu_R = \mu_F = p_{T,H}$
- HJ FXD: NLO H+1 jet with $\mu_R = \mu_F = M_H$
- Conventional HJ calc^{n}s diverge to -infinity as $p_T \to 0$

Nason, Zanderighi, k.h. 2012 JHEP 1210

MiNLO H + jet in a nutshell

- In a nutshell MiNLO adds Sudakov resummation to H + jet configs

- MiNLO recipe applied to the NLO H + jet goes

$$L = \log \frac{Q^2}{p_{\mathrm{T}}^2}$$

$$\frac{d\sigma_{\mathcal{M}}}{dp_{\mathrm{T}}^2 dy} = \Delta^2\left(Q, p_{\mathrm{T}}\right) \frac{\alpha_{\mathrm{S}}\left(p_{\mathrm{T}}\right)}{\alpha_{\mathrm{S}}\left(Q\right)} \left[\frac{d\sigma}{dp_{\mathrm{T}}^2 dy} + \left.\frac{d\sigma}{dp_{\mathrm{T}}^2 dy}\right|_{\mathrm{LO}} \alpha_{\mathrm{S}}^{\mathrm{NLO}} \left[A_1 L^2 + 2B_1 L - b_0 L\right]\right]$$

Sudakov form factor

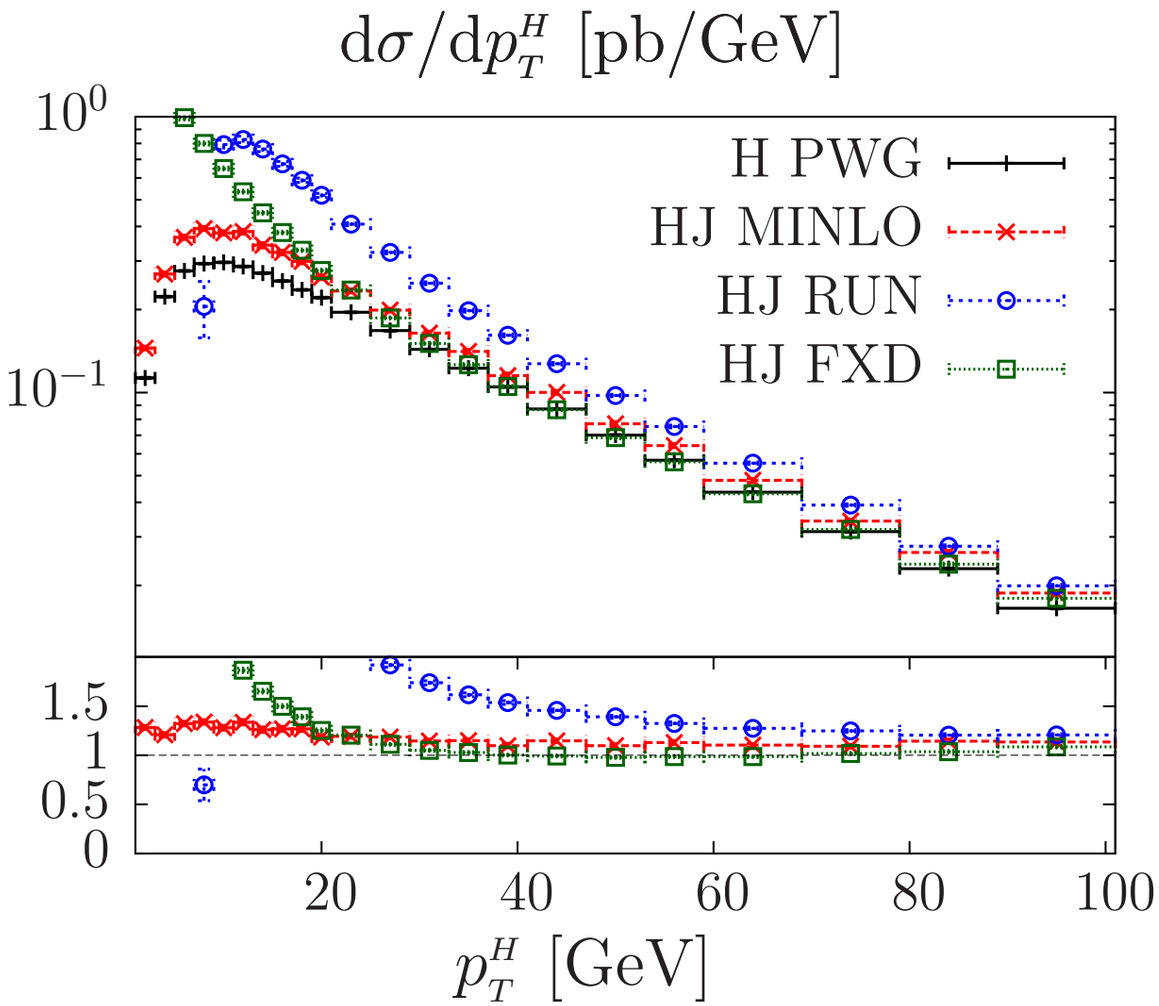
Resum b_0 logs in α_S

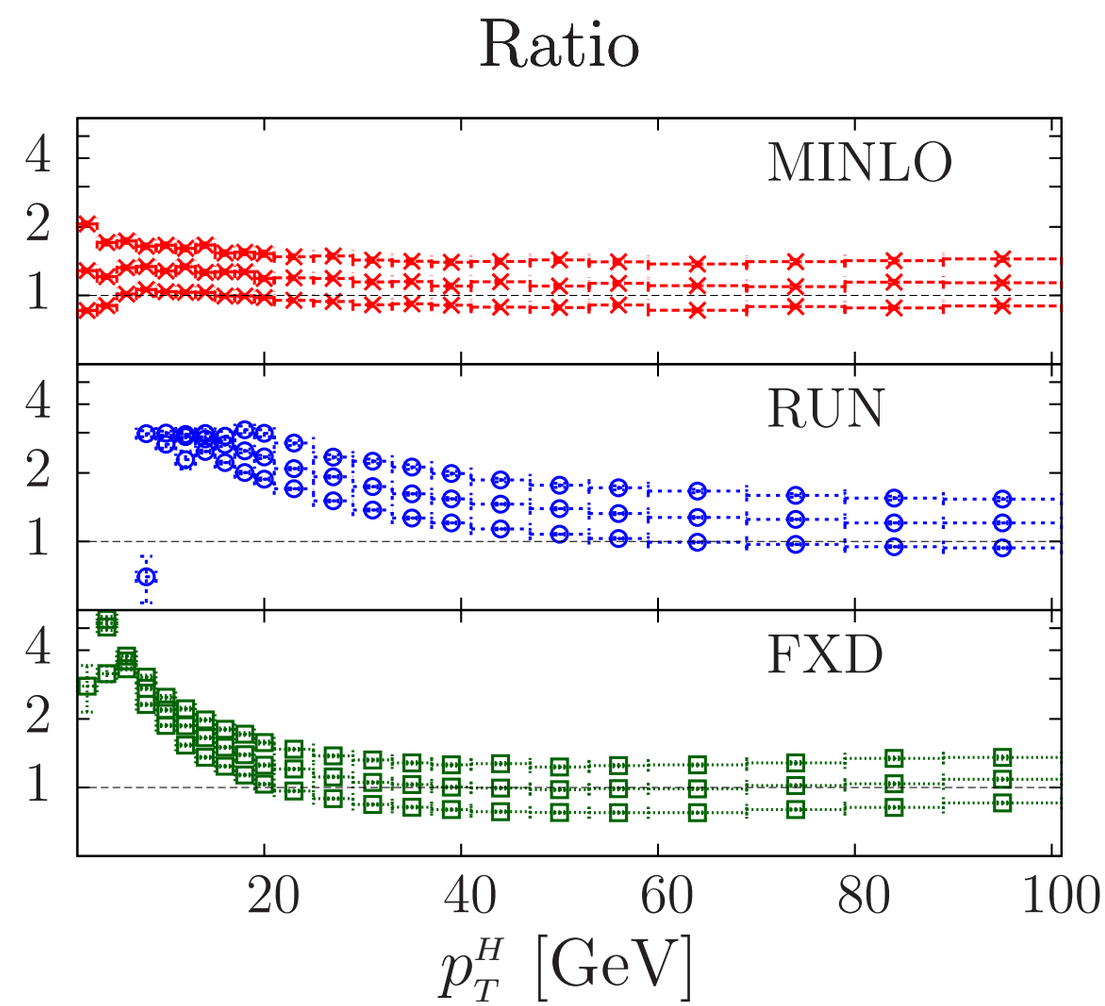
NLO xsec
$\mu_R = Q$
$\mu_F = p_T$

Maintain F.O. expansion to NLO

- With MiNLO, the initial $pp \to H$ + jet kinematic goes from being divergent as $p_T \to 0$ to having physical Sudakov suppression

MiNLO H + jet v Conventional NLO v NLOPS H

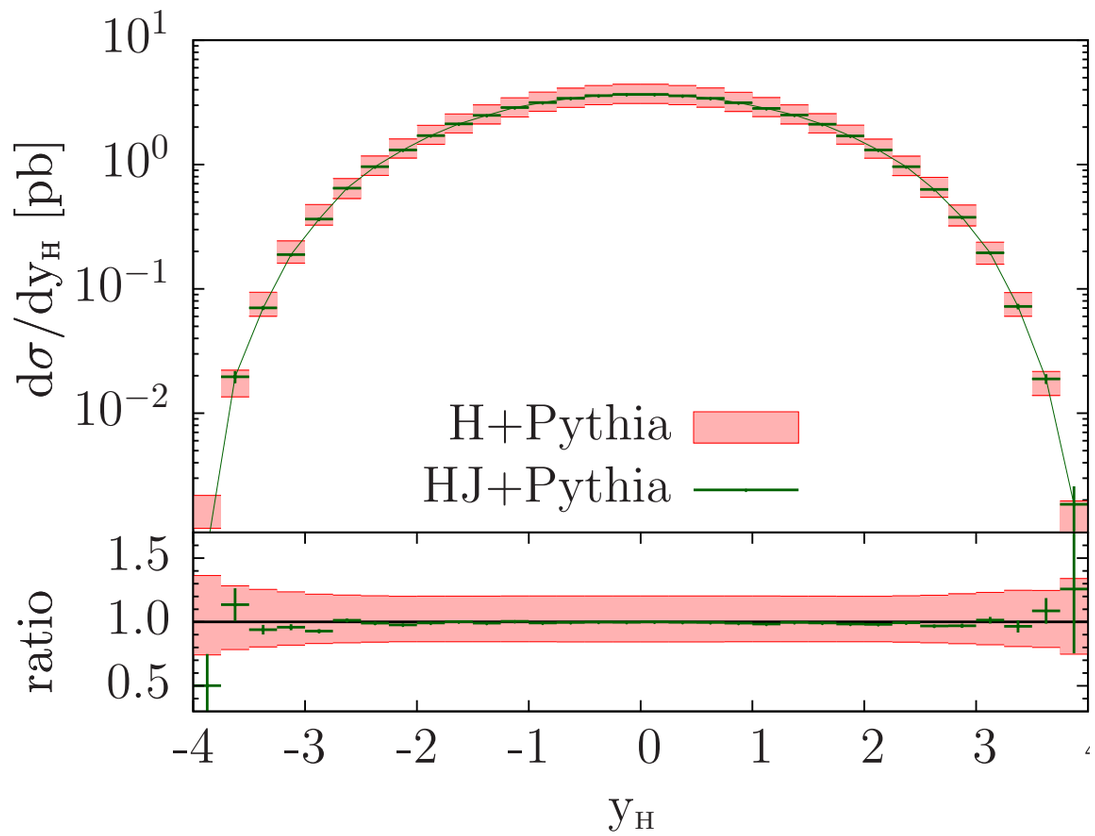




- H PWG: Essentially parton shower x NLO K-fact [≡ 1 in ratios]
- HJ RUN: NLO H + 1 jet with $\mu_R = \mu_F = p_{T,H}$
- HJ FXD: NLO H + 1 jet with $\mu_R = \mu_F = M_H$
- HJ-MiNLO conventional NLO H + 1 jet at high p_T
- HJ-MiNLO parton shower result at low p_T, no divergences
- HJ-MiNLO sensible scale unc. band [doesn't shrink as $p_T \to 0$]

MiNLO H + jet: NLO for H + jet & NLO for H

- MiNLO gives physical predictⁿs for multi-jet spectra all through p_T spectra [as opposed to ∞] so it gives physical predictⁿs for fully inclusive Higgs observables too



- JHEP 1305 proved with the NNLL$_\sigma$ Sudakov of Ellis & Veseli HJ-MiNLO is NLO for H + jet AND inclusive Higgs observables: two NLO calcⁿs from one [“NLO x NLO”]

Nason, Oleari, Zanderighi, k.h. 2012 JHEP 1305 Ellis, Veseli 1997 NPB 503

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NNLOPS

- HJ NLO:
  - Unphysical NLO 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - 0 everything else

- HJ-MINLO [NLO x NLO]:
  - NLO 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - 0 everything else

- HJ-MINLO + PS for $q<q_0$:
  - NLO 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - PS everything else

- NNLOPS:
  - NNLO 0-jet obs
  - NLO 1-jet obs
  - LO 2-jet obs
  - PS everything else

- Achieved by NNLO/NLO rwgting the NLO x NLO version of HJ-MiNLO

Nason, Oleari, Zanderighi, k.h. 2012 JHEP 1305 Nason, Re, Zanderighi, k.h. JHEP 1310

vanilla NNLOPS

- In its most basic form:

  $$d\sigma_{NNLOPS} = d\sigma_{MiNLO} \times W(y_H) \quad \text{with} \quad W(y_H) = \frac{\frac{d\sigma_{NNLO}}{dy_H}}{\frac{d\sigma_{MiNLO}}{dy_H}}$$

- Since $\frac{d\sigma_{MiNLO}}{dy_H} = \frac{d\sigma_{NNLO}}{dy_H}$ at NLO ⟶ $W(y_H) = 1+O(\alpha_S^2)$

  so $W(y_H)$ factor only affects $d\sigma_{MiNLO}$ by NNLO terms

- So multiplying $d\sigma_{MiNLO}$ by the $W(y_H)$ factor for NNLO accuracy doesn't spoil NLO accuracy already in $d\sigma_{MiNLO}$ for ≥ 1 jet obs!

- If $\frac{d\sigma_{MiNLO}}{dy_H} \neq \frac{d\sigma_{NNLO}}{dy_H}$ at NLO $W(y_H)$ spoils NLO of $d\sigma_{MiNLO}$ for ≥ 1 jet obs

- Apart from NNLO calc^n, catch for NNLOPS is making the NLO x NLO MiNLO calc^n ...

HNNLO is fixed order NNLO code of Catani, Grazzini, Sargsyan 2007/2013 PRL 98/JHEP 1309]

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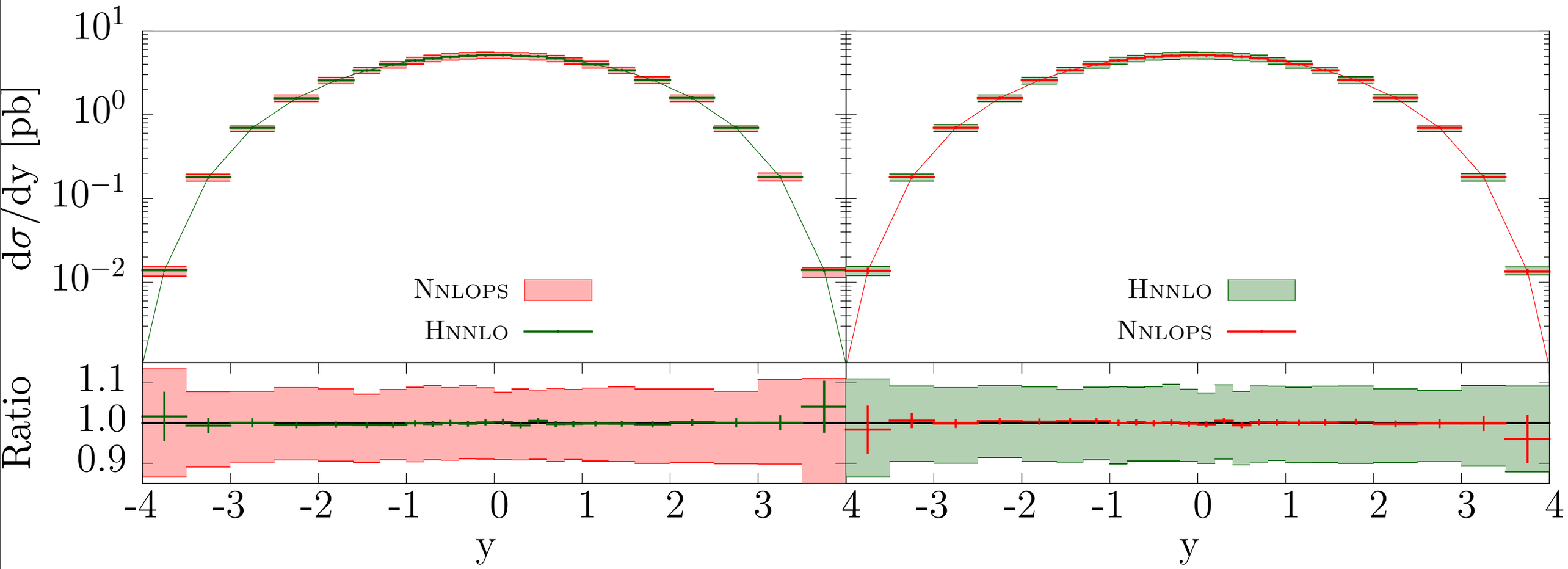
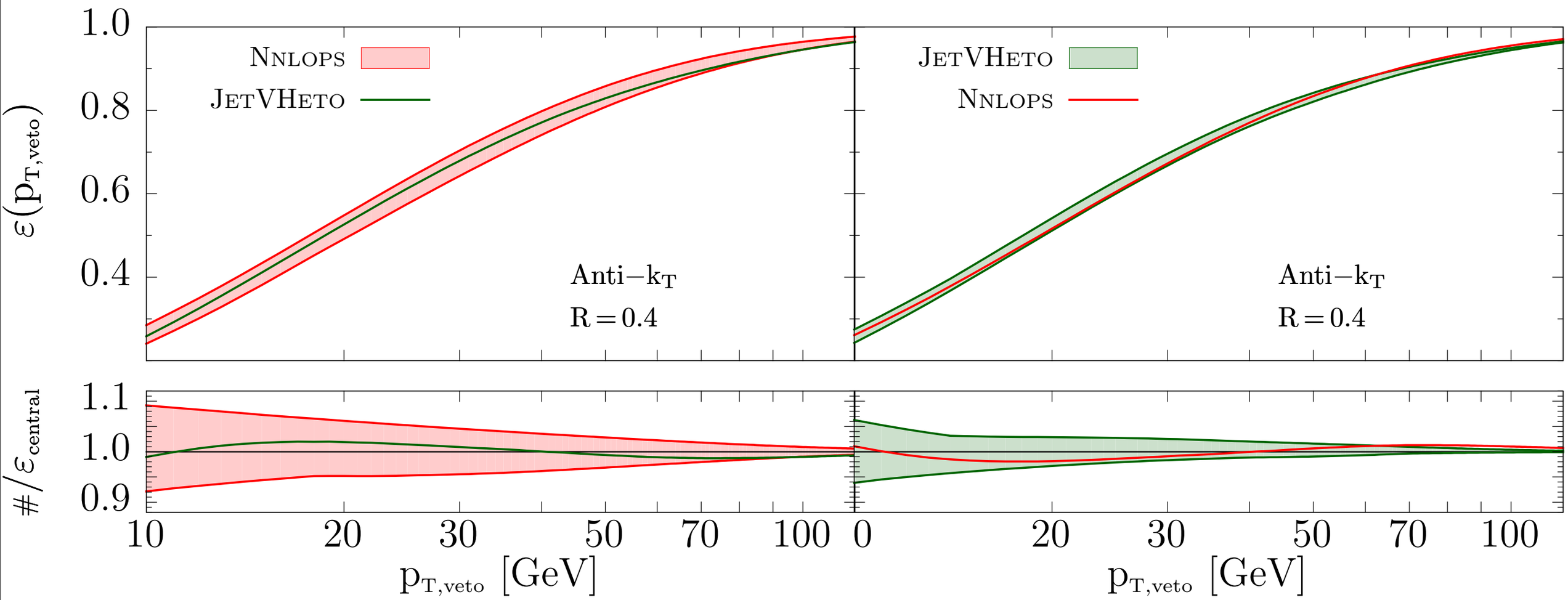
Higgs rapidity: HNNLOPS vs NNLO



- HNNLO: state-of-the-art fixed order Higgs production calculation [Catani, Grazzini, Sargsyan 2007/2013 PRL 98/JHEP 1309]
- HNNLOPS: as above but with resummed, parton showered, fully exclusive, realistic, hadron level, final-states

Nason, Re, Zanderighi, k.h. JHEP 1310

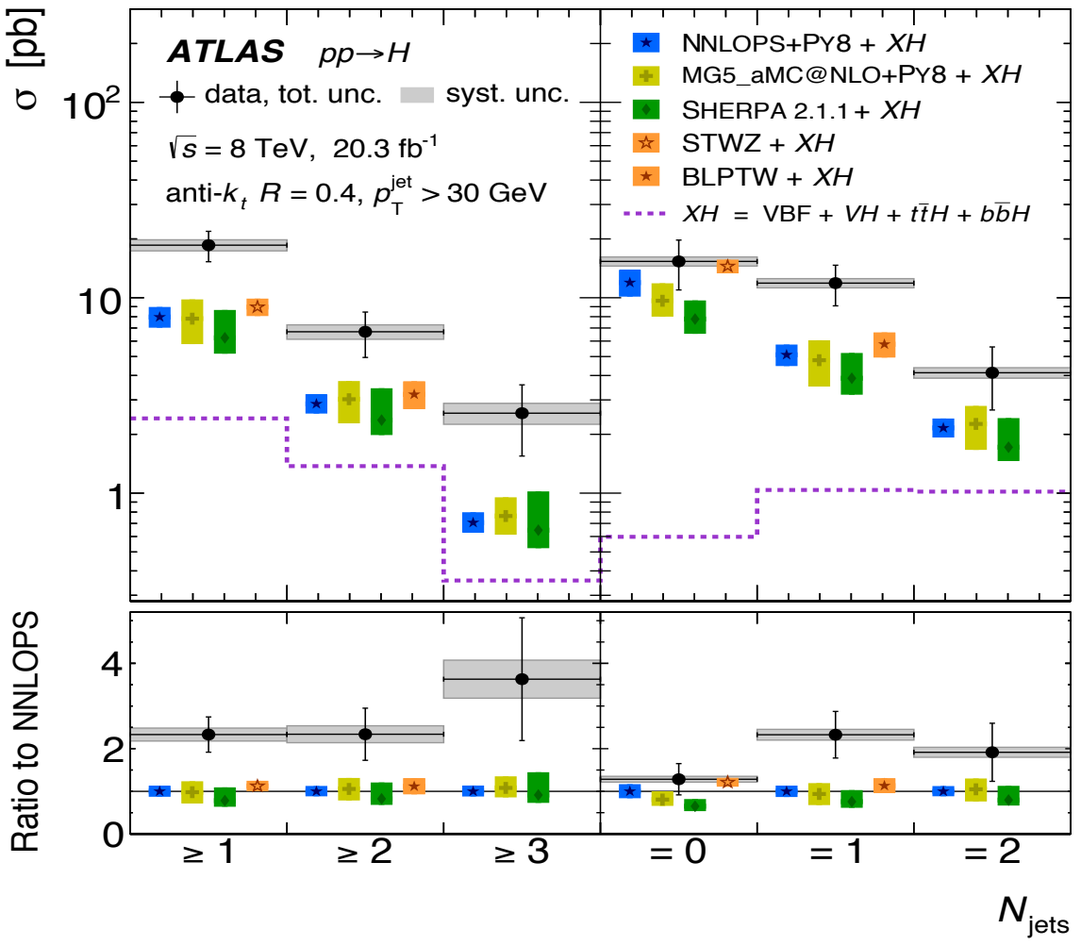
Jet veto efficiency: HNNLOPS vs NNLO+NNLL

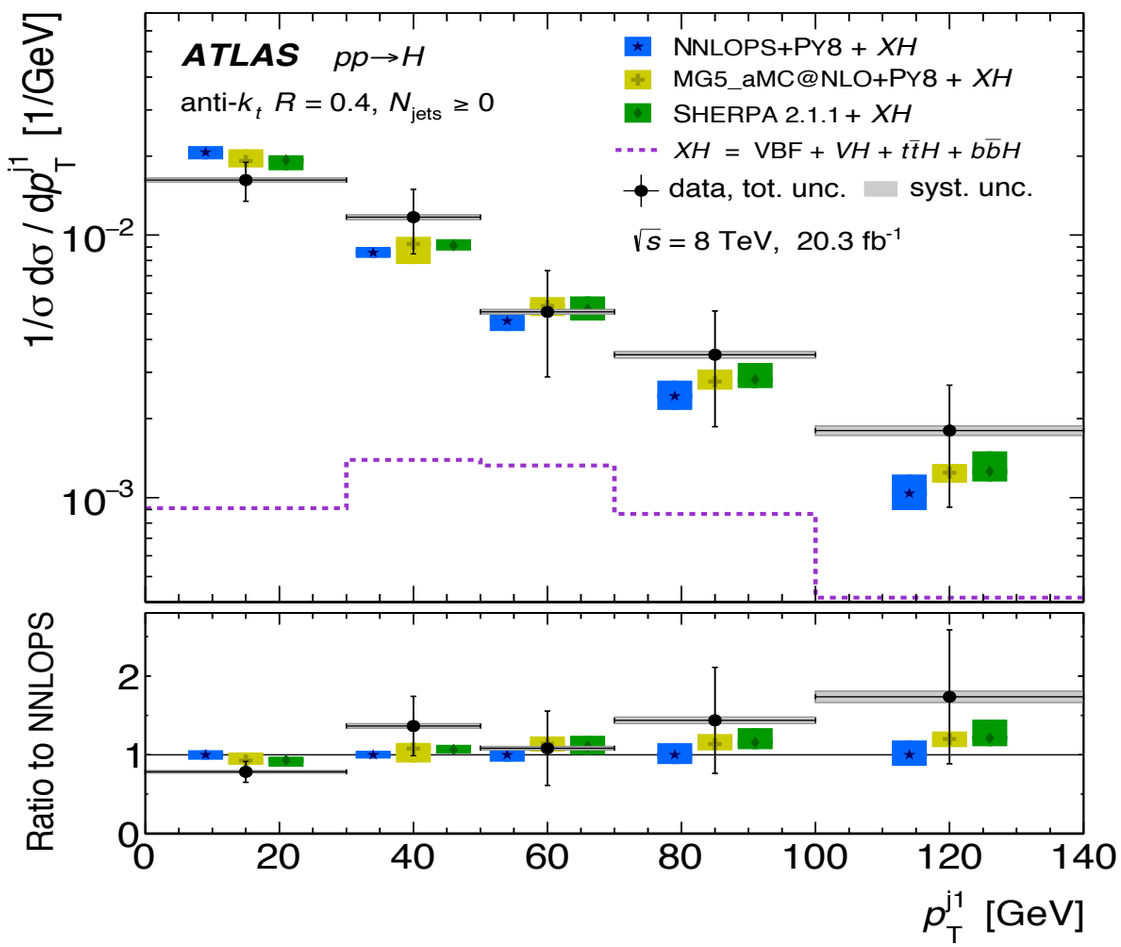


- 0-jet xsec efficiency: $\varepsilon(p_{T,veto}) = \sigma(p_{T,veto}) / \sigma_{tot}$
- JETVHETO: state-of-the-art NNLO+NNLL 0-jet xsec effy
  [Banfi, Monni, Salam, Zanderighi 2012 PRL 109]
- HNNLOPS: agreement at level of ≤ 3% everywhere

Nason, Oleari, Zanderighi, k.h. 2012 JHEP 1305 Nason, Re, Zanderighi, k.h. JHEP 1310

Jet bins & Jet p_T : HNNLOPS vs ATLAS data



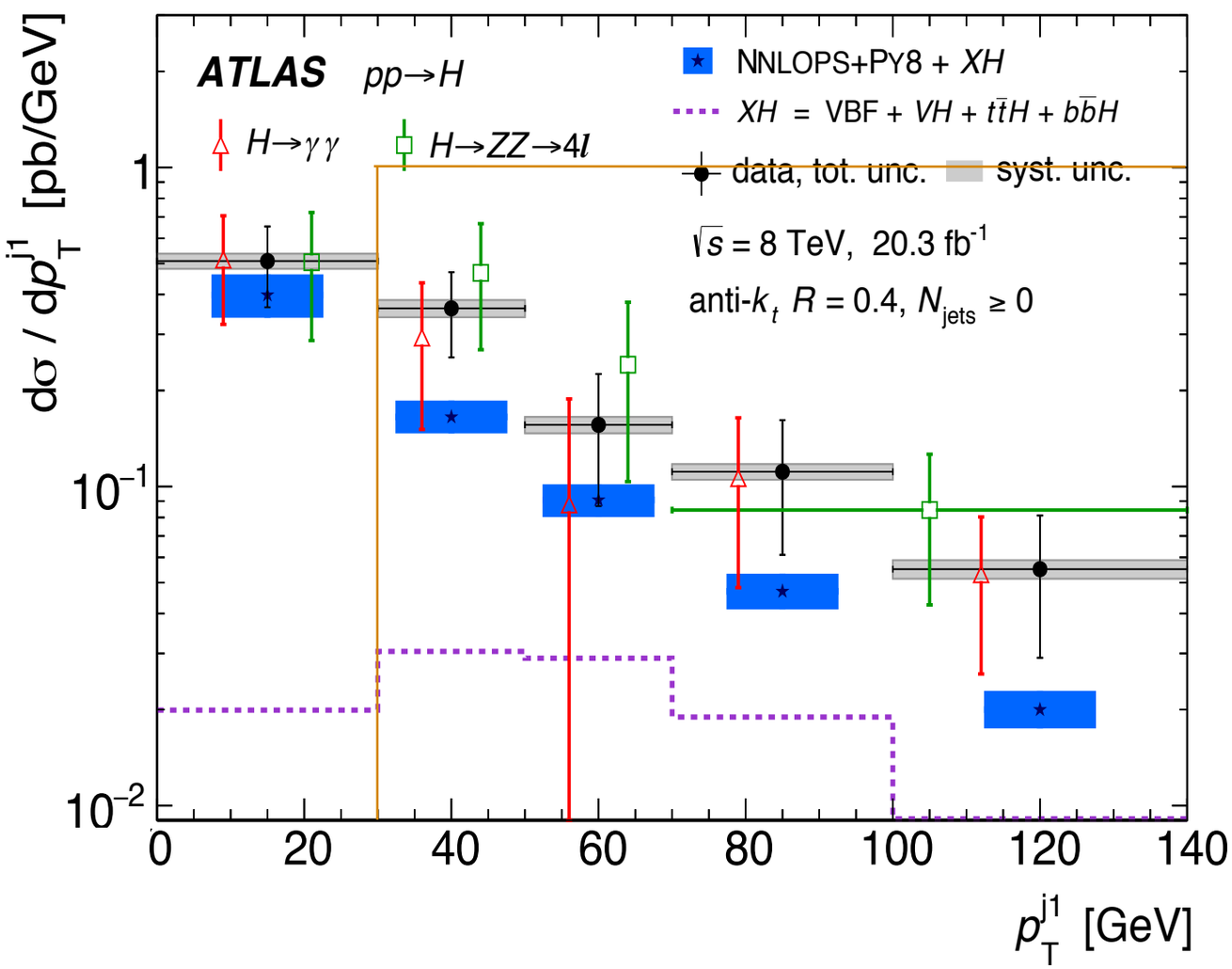


- Jet bins low for all MCs ; HNNLOPS expectedly better in 0-jet bin
- " ... poorest agreement with data ... in the inclusive and exclusive 1-jet bins, with p-values ranging between 0.1% and 3.6%."
- <u>Normalised</u> lead jet p_T agreeing well between data & all MCs

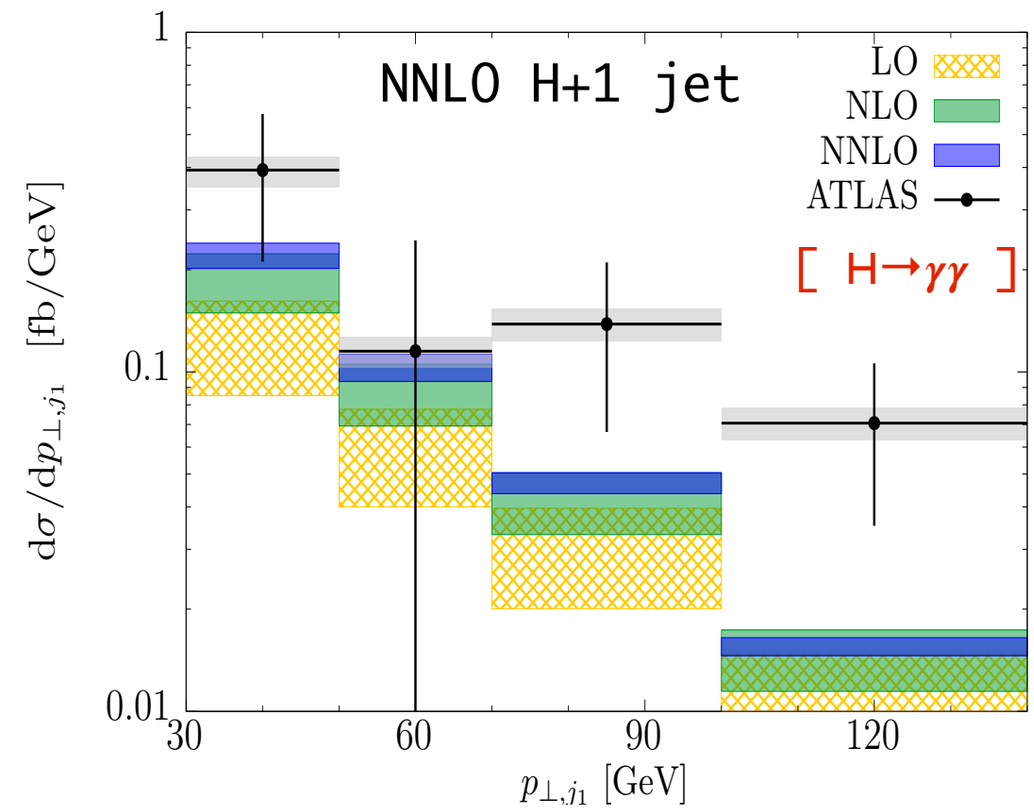
Nason, Re, Zanderighi, k.h. JHEP 1310 ATLAS arXiv:1504.05833

Jet p_T : HNNLOPS vs ATLAS data

ATLAS PRL 2015



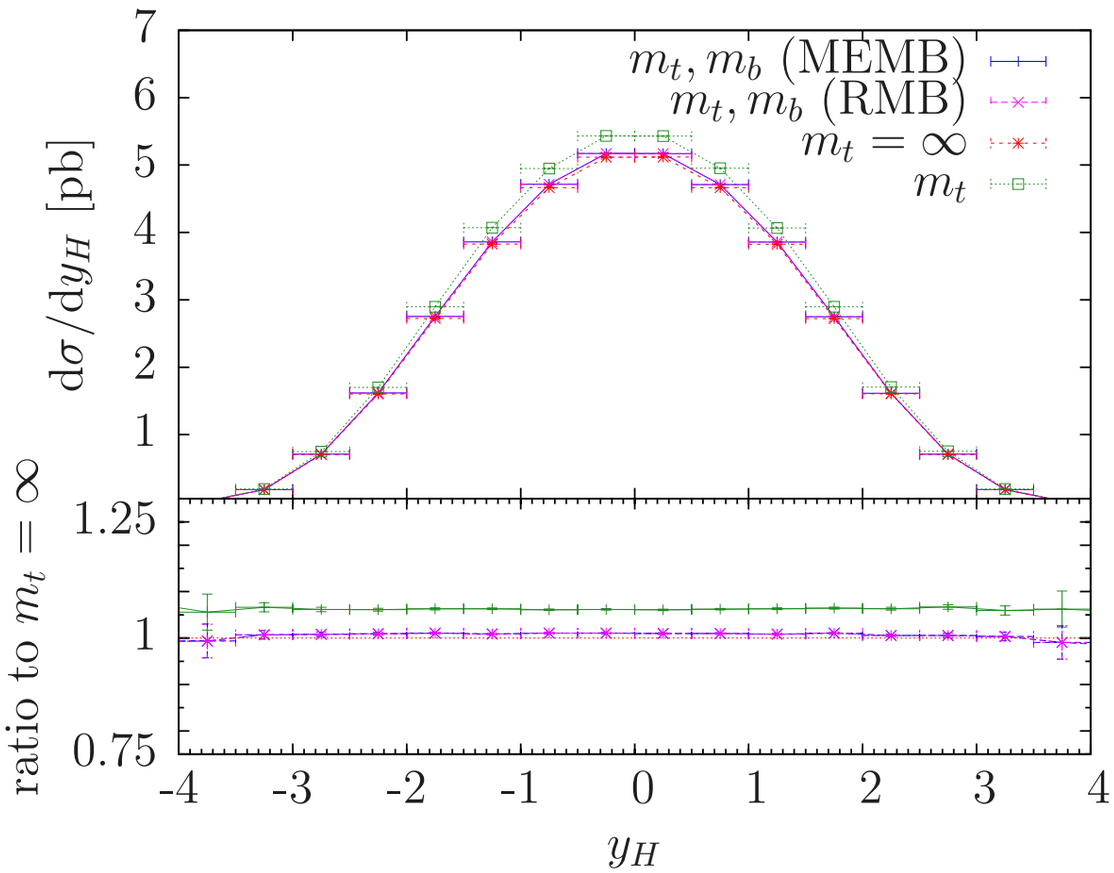
Caola, Melnikov, Schulze
ATLAS JHEP 1409

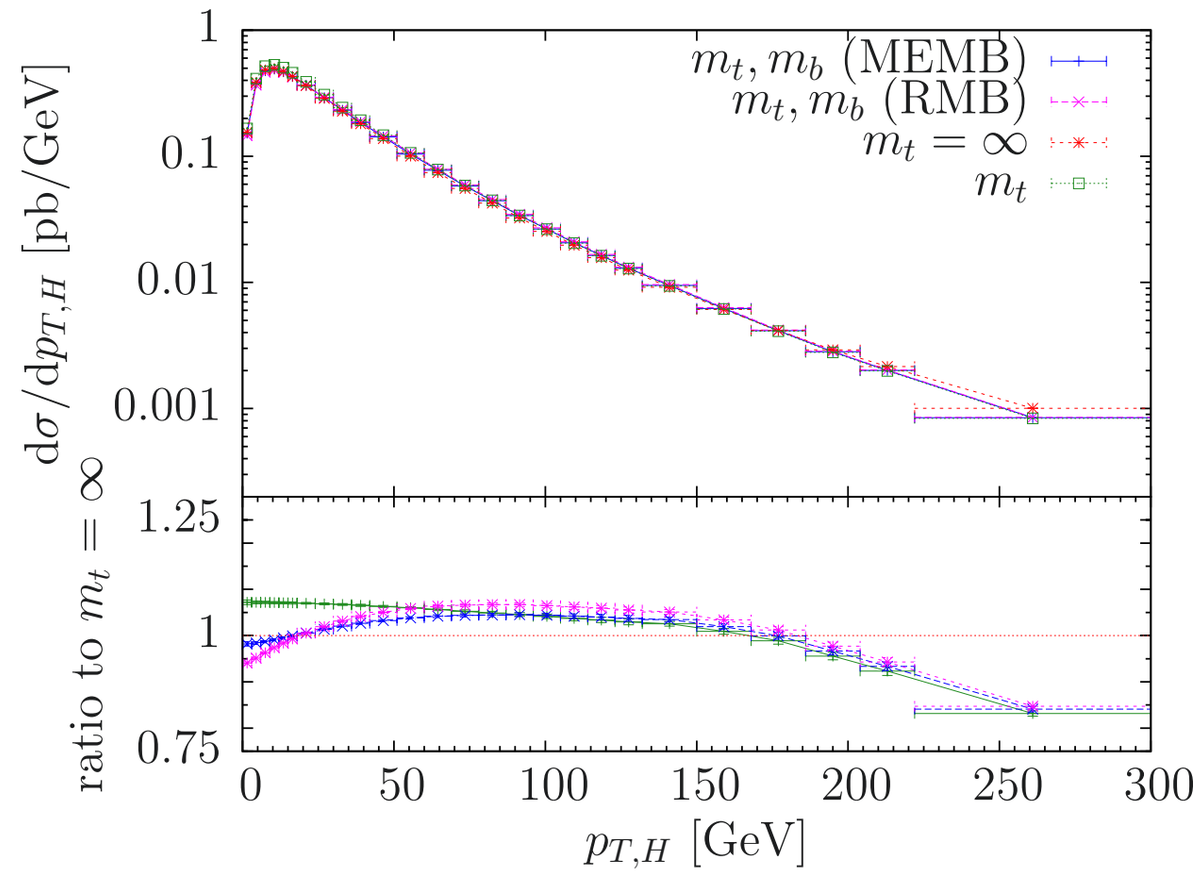


- Left : NNLOPS vs 20.3 fb^{-1} ATLAS PRL 2015, H → $\gamma\gamma$ △, H → ZZ □, H → ZZ ⊕ $\gamma\gamma$ ✚
- Right : NNLO H+1 jet vs 20.3 fb^{-1} ATLAS JHEP 1409 H → $\gamma\gamma$
- HNNLOPS & state-of-the-art NNLO H+1 jet calc^n appear to do a similar job for lead jet p_T w.r.t data

Left ATLAS & Nason, Re, Zanderighi, k.h. JHEP 1310 Right: Caola, Melnikov, Schulze arXiv:1508.02684

y_H $p_{T,H}$: HNNLOPS t & b mass effects

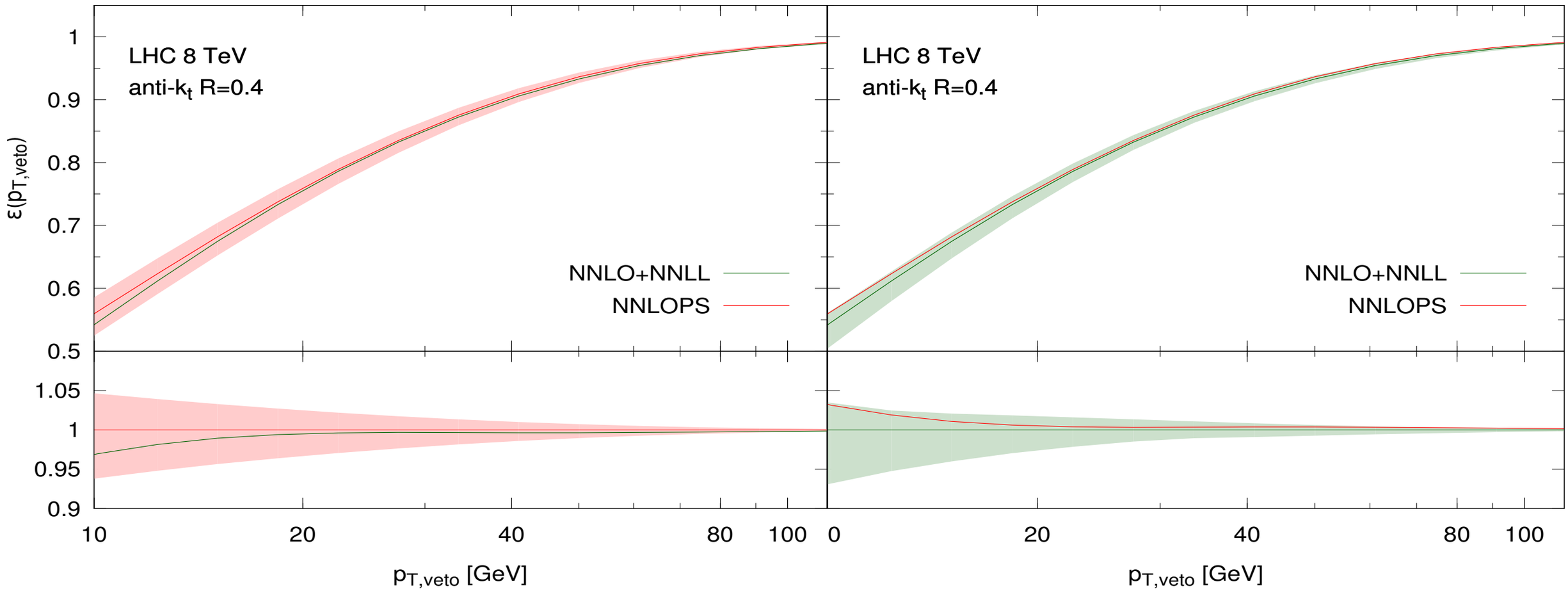




- y_H : mass effect flat, finite m_t → +6%, finite m_t+m_b → +6-6% = 0%
- $p_{T,H}$ < 120 GeV: m_t effect mild and ~flat
- $p_{T,H}$ > 220 GeV: m_t effect sizable, -ve & NOT flat w.r.t large m_t
- $p_{T,H}$ > 70 GeV: m_b effect v.small [t-b-loop interference v.small]
- $p_{T,H}$ < 40 GeV: m_b effect sizable but not far from large m_t limit

Nason, Zanderighi, k.h. 2015 JHEP 1501

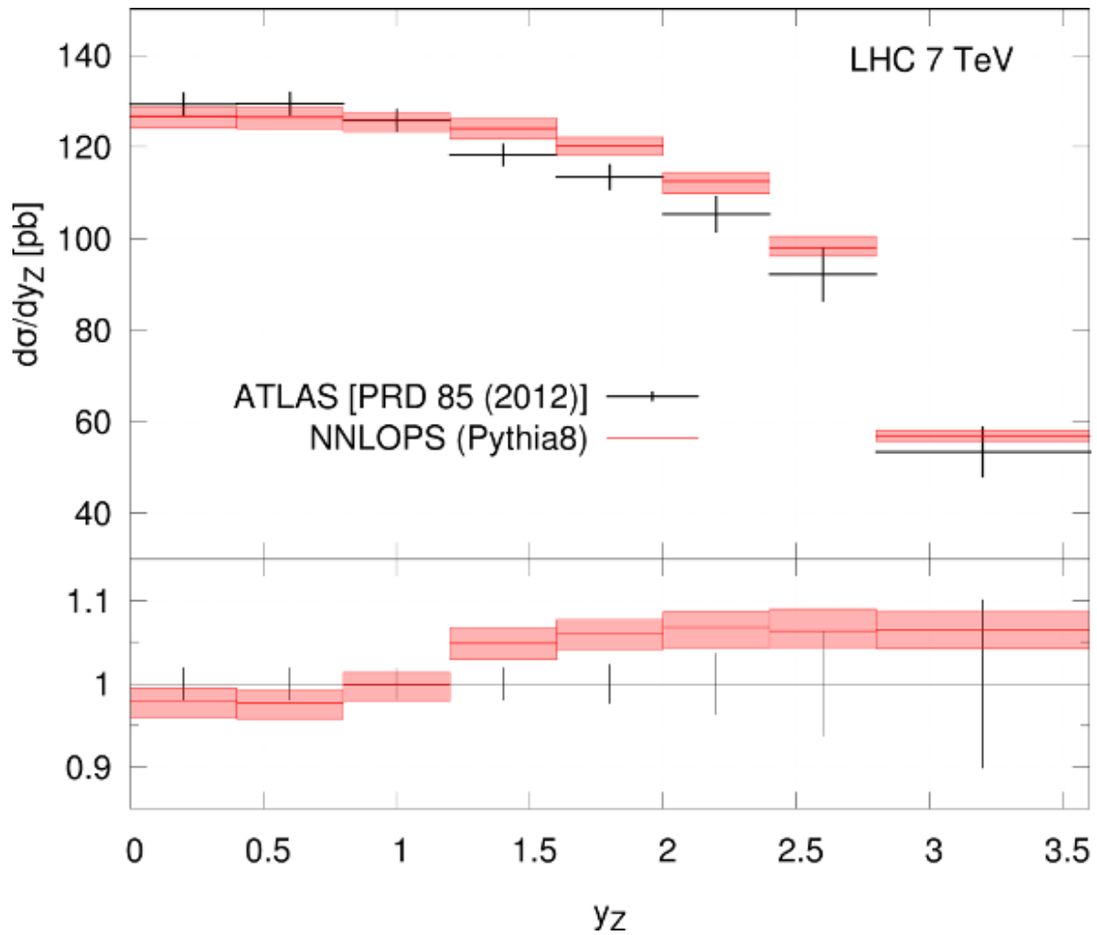
Jet veto efficiency: DYNNLOPS vs NNLO+NNLL

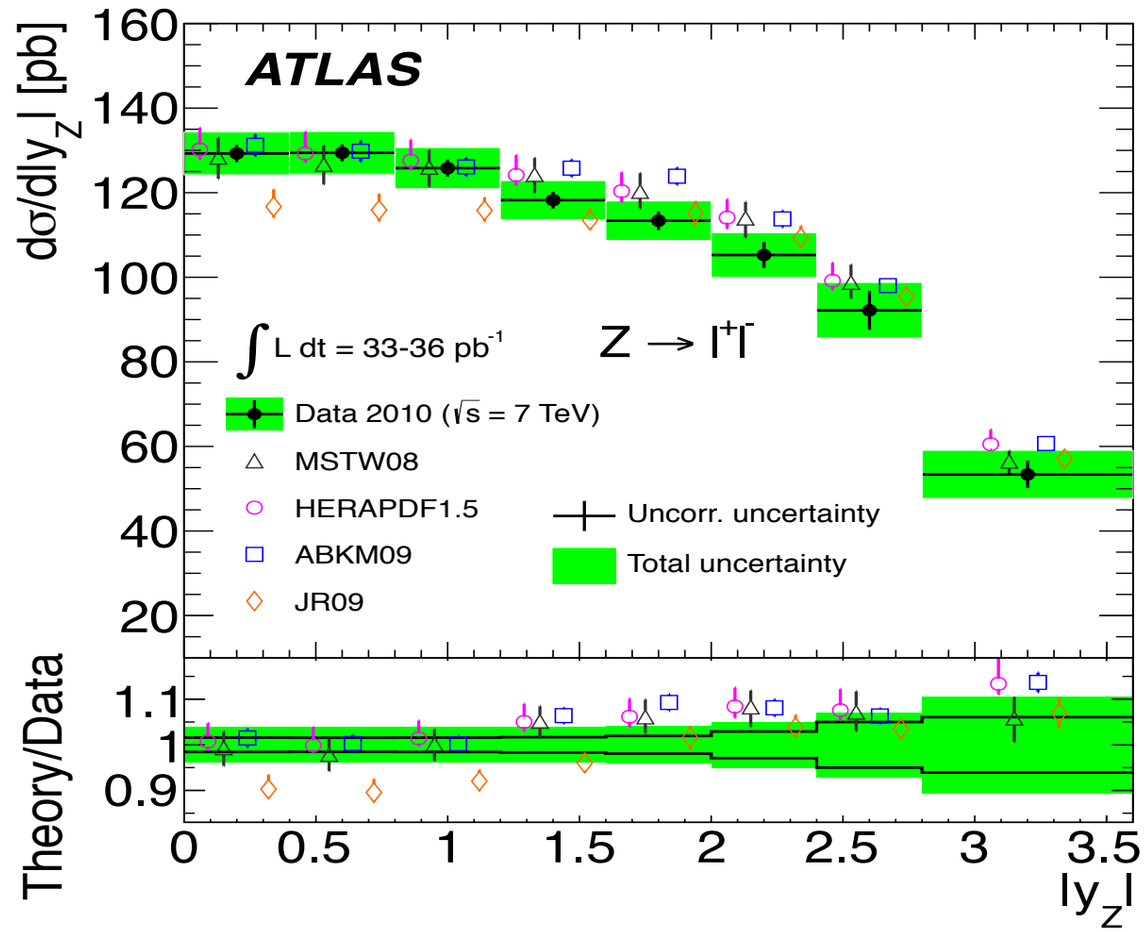


- 0-jet xsec efficiency: $\varepsilon(p_{T,veto}) = \sigma(p_{T,veto}) / \sigma_{tot}$
- JETVHETO: state-of-the-art NNLO+NNLL 0-jet xsec effy
  [Banfi, Monni, Salam, Zanderighi 2012 PRL 109]
- DYNNLOPS: agreement at level of ≤ 3% everywhere [as for HNNLOPS]

Karlberg, Re, Zanderighi 2014 JHEP 1409

Z rapidity: DYNNLOPS on ATLAS data





- ATLAS late 2011 incl. Z analysis PRD 85
- Left: DYNNLOPS v data. Right: FEWZ with various PDFs v data ...
- Good agreement for central region, less so at high $|y_Z|$
- DYNNLOPS v.compatible with independent fixed order FEWZ NNLO

Karlberg, Re, Zanderighi 2014 JHEP 1409 ATLAS 2011 PRD 85

Summary

- **MOTIVATION**

  Maximising reach & potential of NNLO & NLO calc^{n}s requires matching to fully excl. resummation, hadronization, MPI, QED, particle-level PS's

- **MiNLO: Multiscale improved NLO**

  Get NLO for lower multiplicity calc^{n}s 'for free' from higher multiplicity ones: exponentiate NNNLL$_\sigma$ soft terms in NLO xsecn

- **NNLOPS**

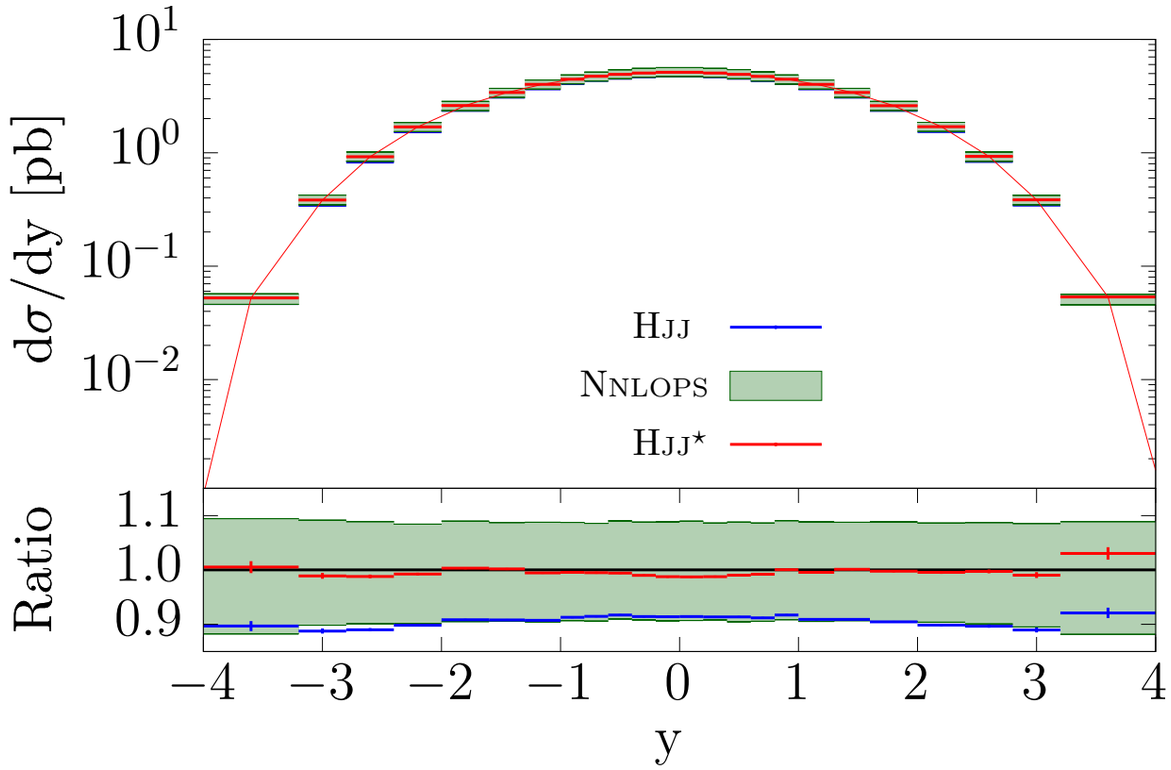
  <u>Depends</u> on NNLO code from NNLO groups

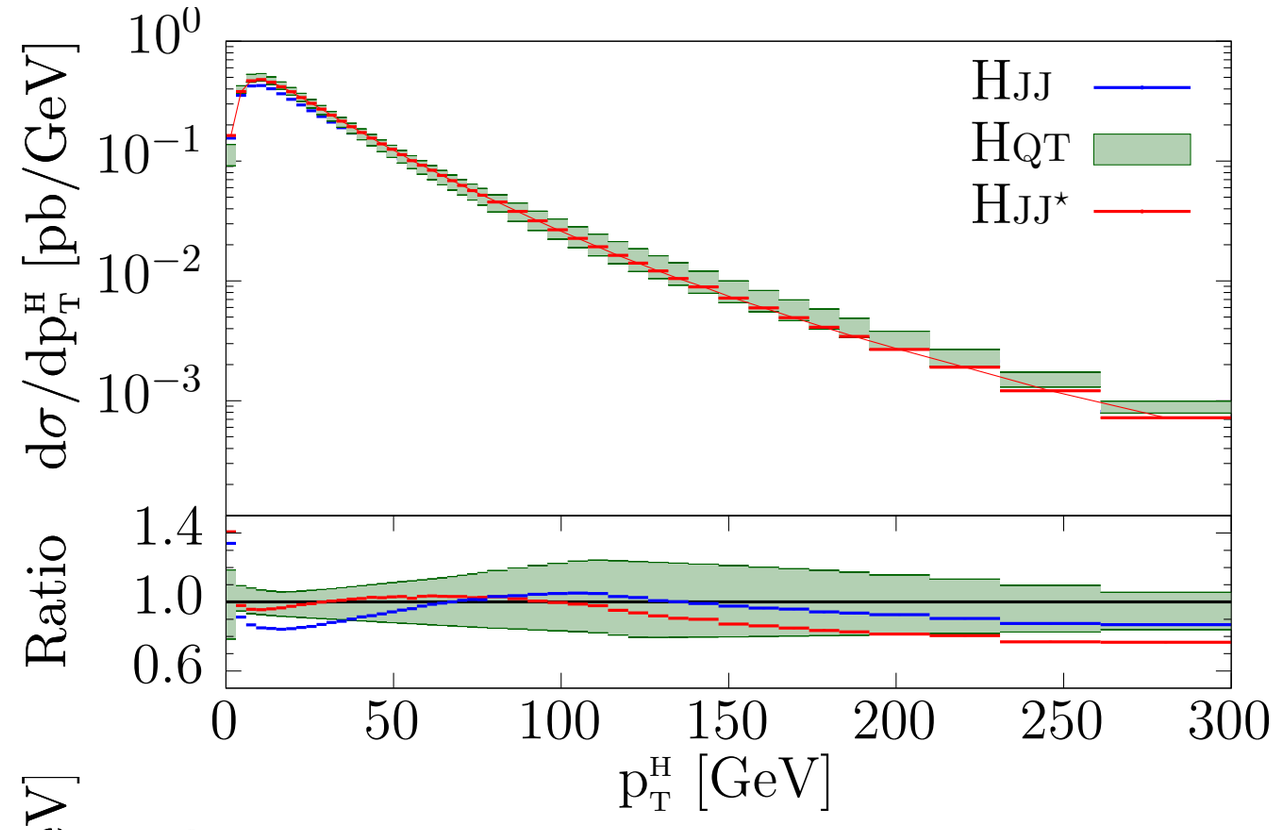
  In its most basic variant: $d\sigma_{NNLOPS} = d\sigma_{MiNLO} \times \dfrac{\frac{d\sigma_{NNLO}}{d\Phi_B}}{\frac{d\sigma_{MiNLO}}{d\Phi_B}}$

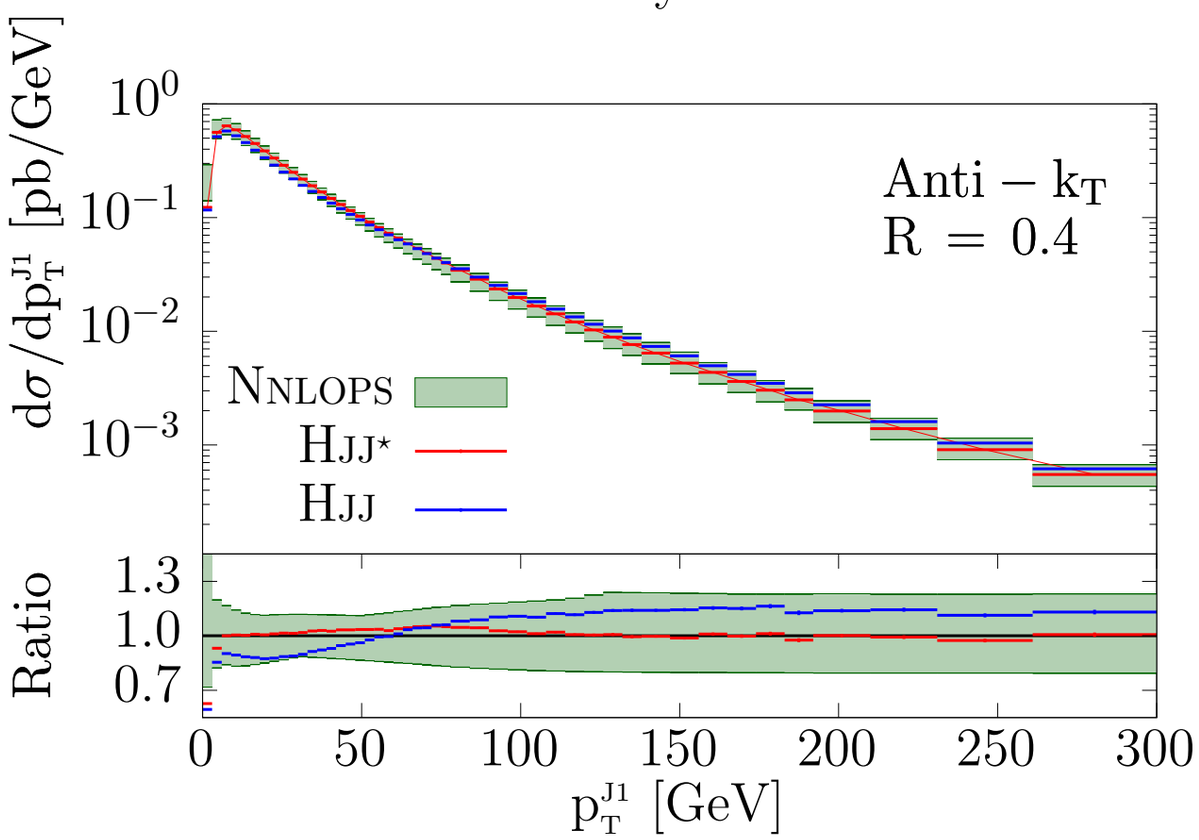
- **RESULTS**

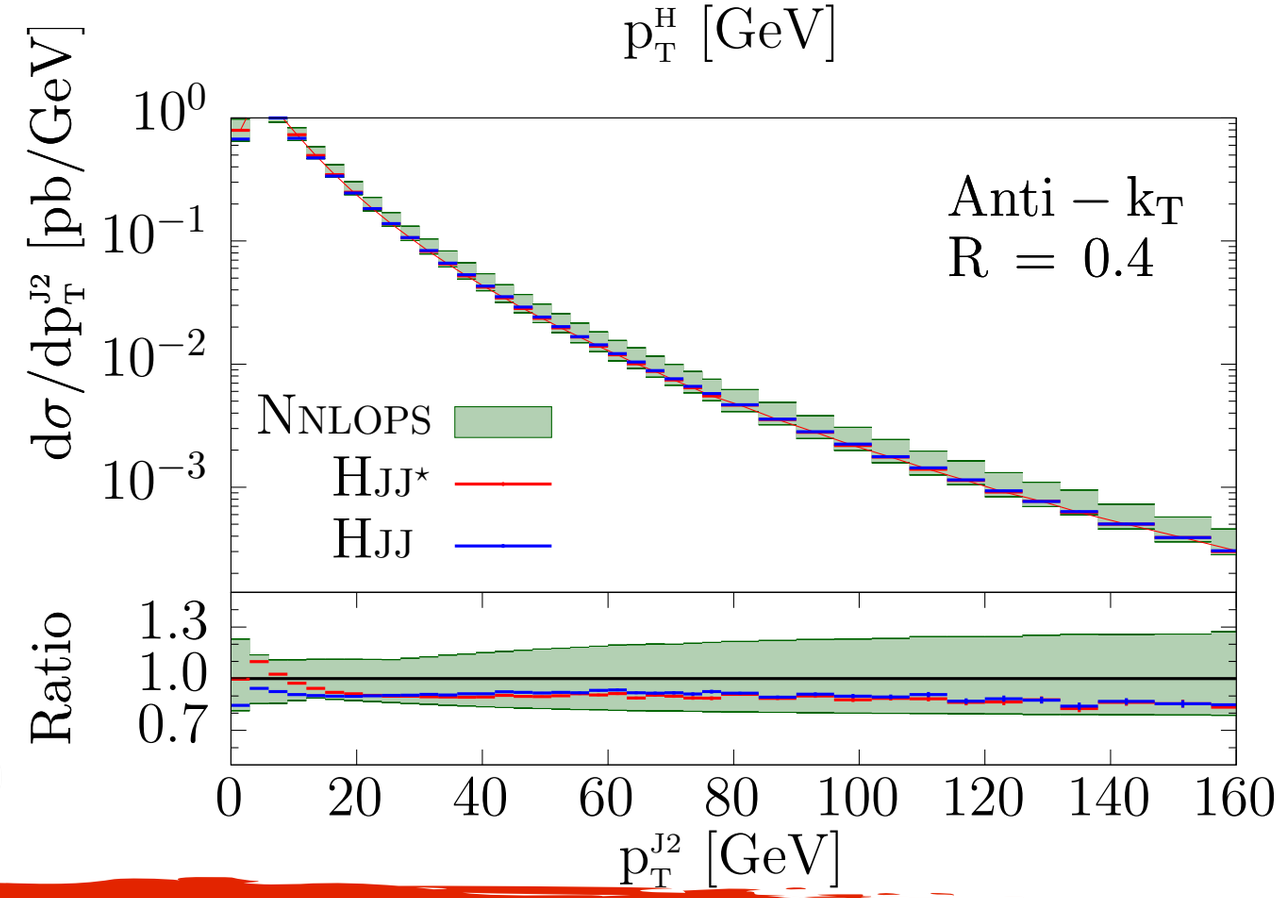
  Someone will have a new idea/extend this idea but NNLOPS does the job today & it does it well

improving HJJ → HJJ⋆





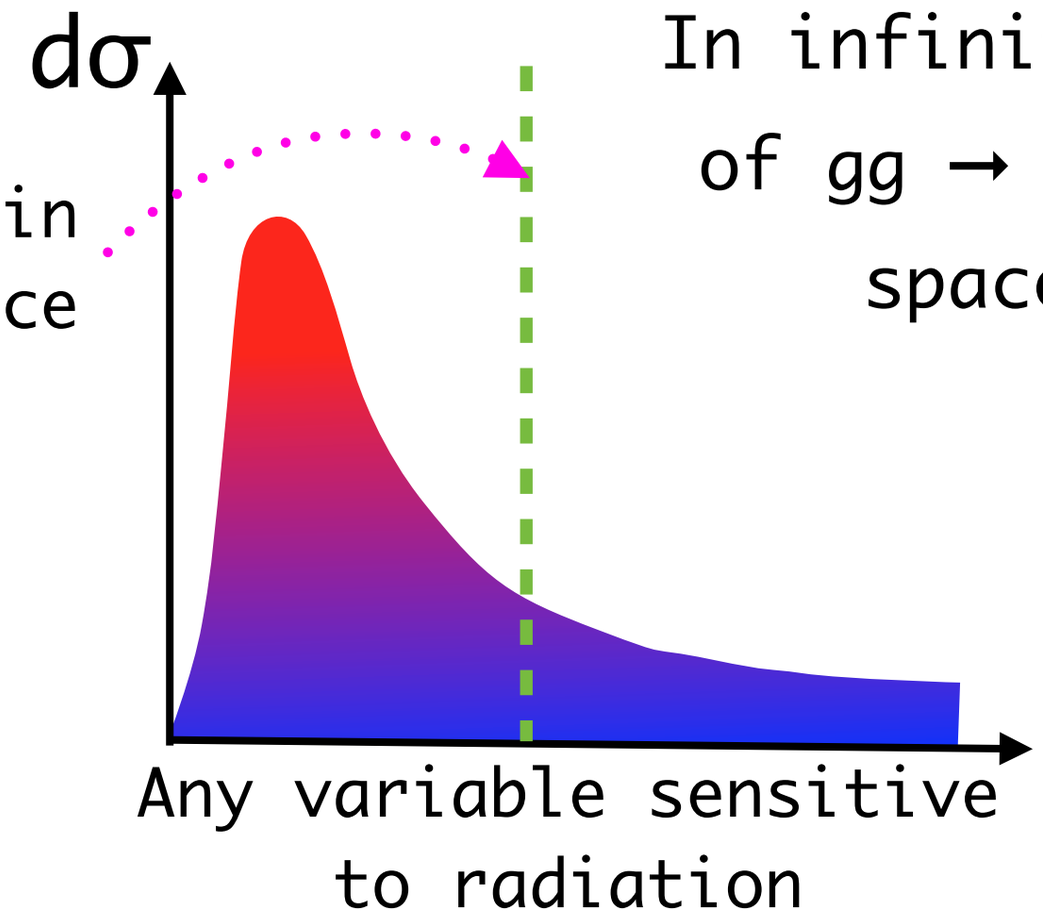




In pipeline, Rikkert Frederix, k.h.

Why that gives NNLO for everything? Sketch ...

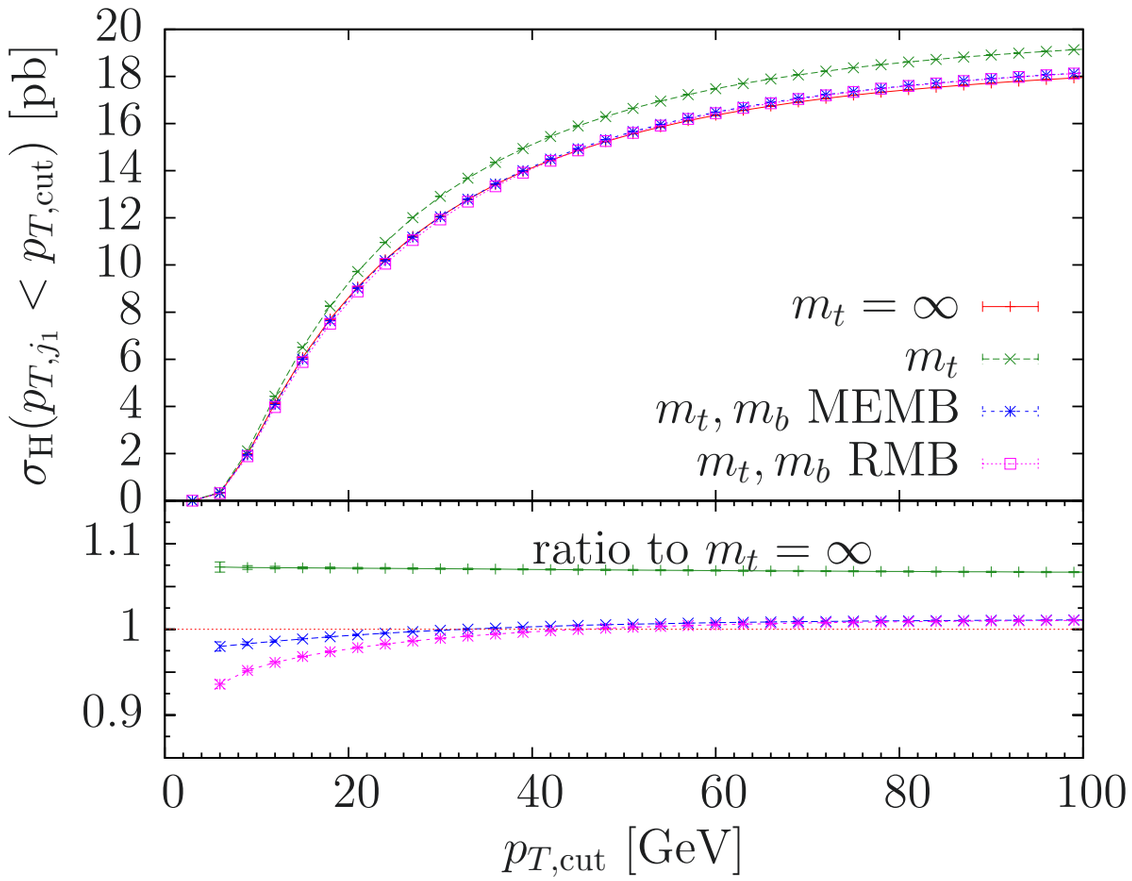
Some arbitrary cut in radiation phase space

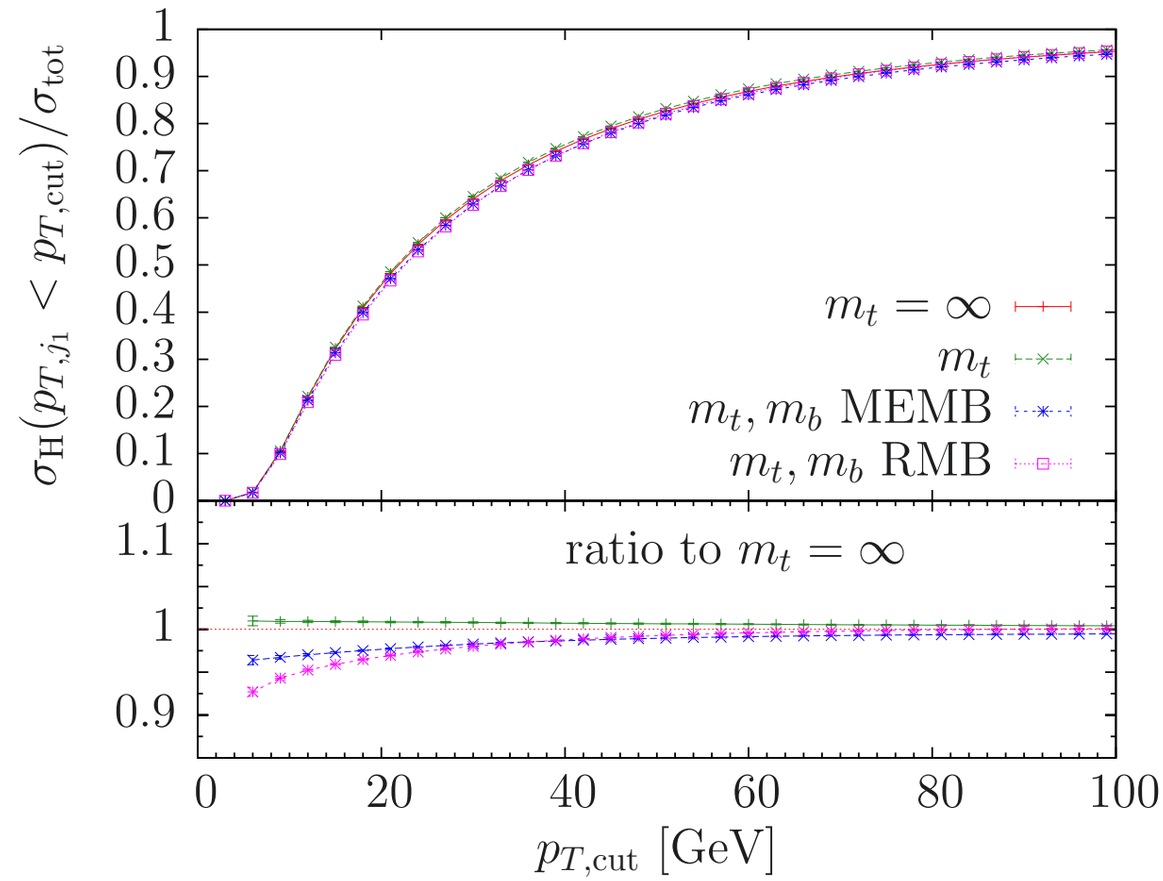


In infinitesimal element of gg → Higgs Born ph. space [y, y+dy]

- Suppose MC gives integral at NNLO i.e. including $O(\alpha_S^4)$ terms [HJ-MiNLO rwgted to HNNLO [Catani, Grazzini] dσ/dy does this]
- Suppose MC also predicts spectrum at NLO i.e. distribution to right of green cut including $O(\alpha_S^4)$ terms [HJ-MiNLO does this]
- Plainly the MC then also gives the area to the left at NNLO i.e. including $O(\alpha_S^4)$ terms [HJ-MiNLO rwgted to NNLO dσ/dy does this]

0-jet xsec^n : HNNLOPS t & b mass effects





- 0-jet xsec^n and 0-jet xsec^n effy: net effect of finite m_t + m_b corrections is very small [2-3%] in region of practical interest
- Little difference on exponentiating [RMB] or not [MEMB] non-factorizing terms
- Cumulative nature of observables diminishes m_b effect at low p_T

Nason, Zanderighi, k.h. 2015 JHEP 1501