NLOPS H from NLOPS HJ-MiNLO

P.Nason C.Oleari G.Zanderighi E.Re KH

JHEP 1210 (2012) 155, JHEP 1305 (2013) 082

Outline

- The goal
- Preliminary ideas:
  1. HJ Powheg
  2. HJ-MiNLO
  3. HJ NLO v HJ-MiNLO
- NLOPS H from NLOPS HJ-MiNLO
- Results
- Conclusion

The goal

- < 4 yrs ago NLOPS limited to colourless F.S.'s [at Born level]
- Since then aMC@NLO, POWHEG and SHERPA all have NLOPS for colourless + 0,1 [2] jets e.g.
- NLOPS H:
  - NLO 0-jet inc obs
  - LO 1-jet inc obs
  - PS everything else
- NLOPS HJ:
  - Unphysical 0-jet inc obs
  - NLO 1-jet inc obs
  - LO 2-jet inc obs
  - PS everything else
- Degree of complementarity alone already begs for way to consistently combine colourless + jets NLOPS simulations
- I.E. NLO extension of CKKW LOPS merging algorithm

The goal

- You would like to combine strengths, somehow.
- NLOPS H jet:
  - NLO 0-jet inc obs
  - LO 1-jet inc obs
  - PS everything else
- NLOPS HJ:
  - Unphysical 0-jet inc obs
  - NLO 1-jet inc obs
  - LO 2-jet inc obs
  - PS everything else
- Merged / matched NLOPS H $\cup$ HJ:
  - NLO 0-jet inc obs
  - NLO 1-jet inc obs
  - LO 2-jet inc obs
  - PS everything else
- And you'd like it for free, of course. No hidden charges.

Outline

- The goal
- Preliminary ideas:
  1. HJ Powheg
  2. HJ-MiNLO
  3. HJ NLO v HJ-MiNLO
- NLOPS H from NLOPS HJ-MiNLO
- Results
- Conclusion

Preliminary #1/3: HJ Powheg

- Powheg defines underlying Born [U.B.] vars ϕ_B specifying pp → HJ 2 → 2 kinematics

- Roughly speaking event generation happens in three steps:

  1. U.B. config. is generated acc. to NLO $d\sigma/d\phi_B$

  2. Hardest rad^n attached by unitary PS-type mechanism to the U.B. kinematic [incl. relevant HJ →HJJ Sudakov suppression]

  3. Subsequent softer emissions generated by feeding these hardest rad^n events to a [vetoed] parton shower

- NLO $d\sigma/d\phi_B$ is divergent & unphysical for $p_T \to 0$; regulated by an unphysical gen. cut well below experimental jet p_T threshold

Preliminary #2/3: HJ-MiNLO

- By HJ-MiNLO we mean improvement of the NLO xsec determining the starting U.B. config. [i.e. modify step 1 on last slide]

- In a nutshell MiNLO adds Sudakov resummation to HJ U.B. configs

- MiNLO recipe applied to the NLO HJ 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

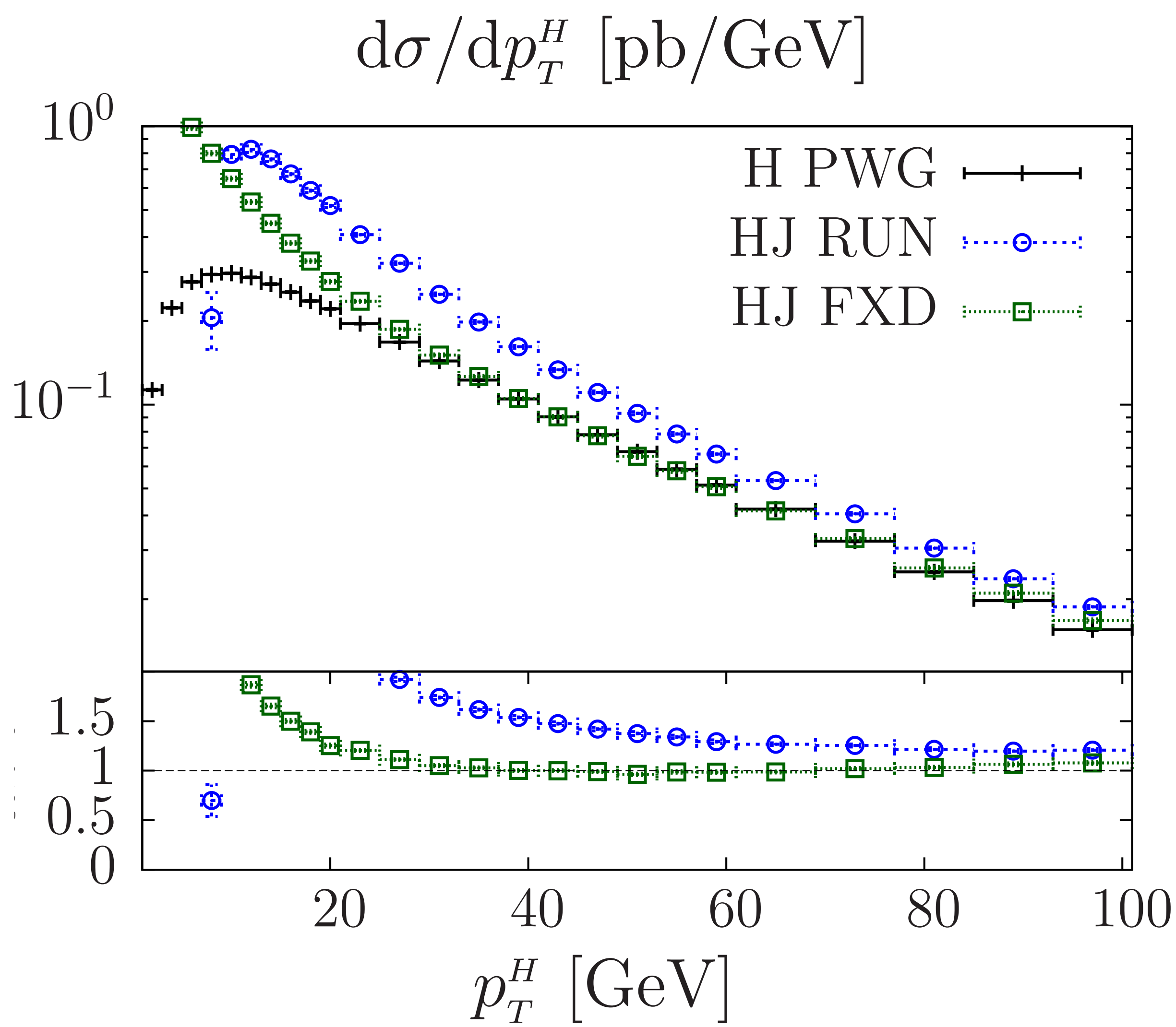
Resum b_0 logs in α_S

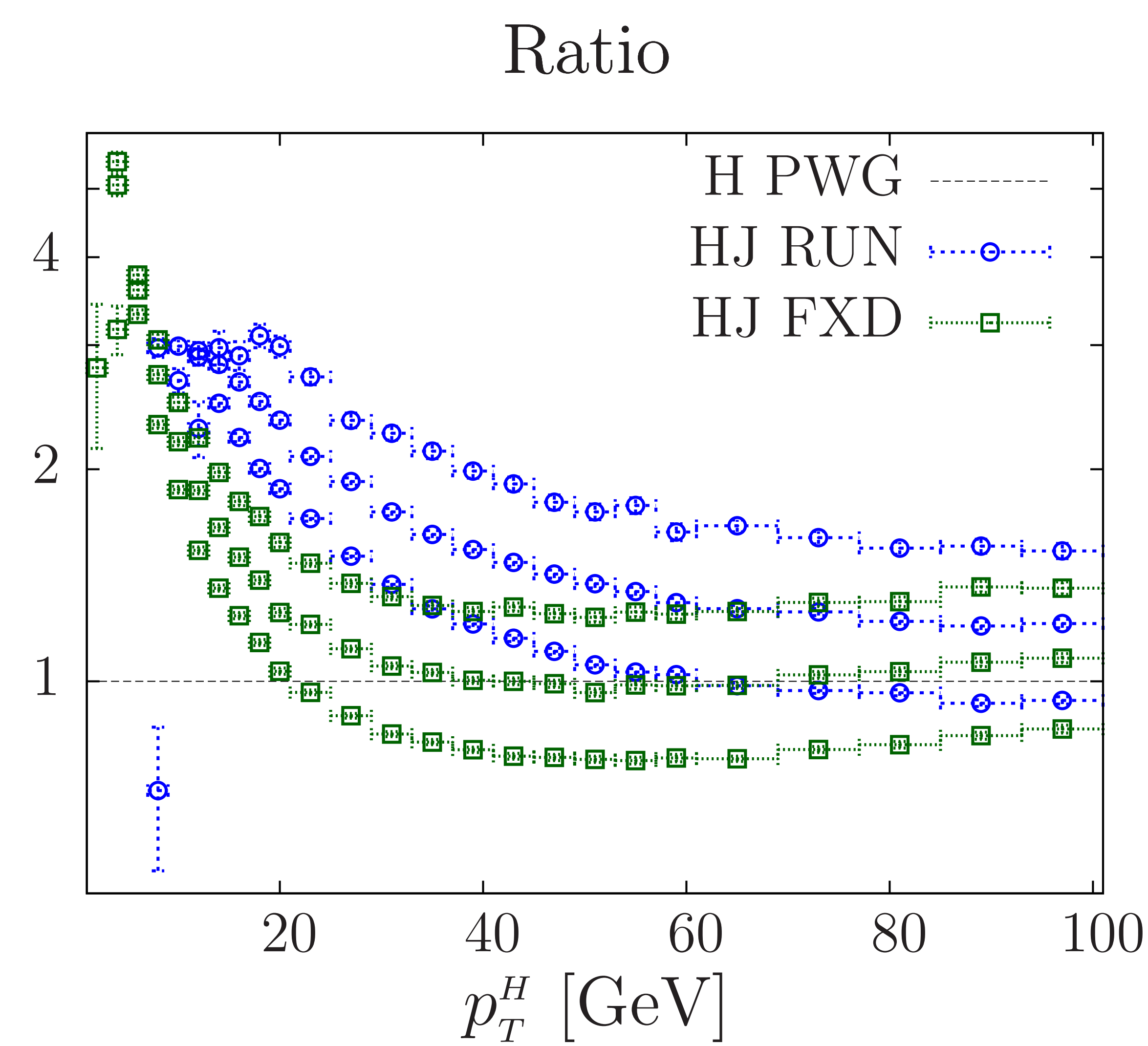
NLO xsec
$\mu_R = Q$
$\mu_F = p_T$

Maintain F.O. expansion to NLO

- Again, with MiNLO, the initial U.B. $pp \to HJ$ kinematic goes from being divergent as $p_T \to 0$ to having physical Sudakov suppression

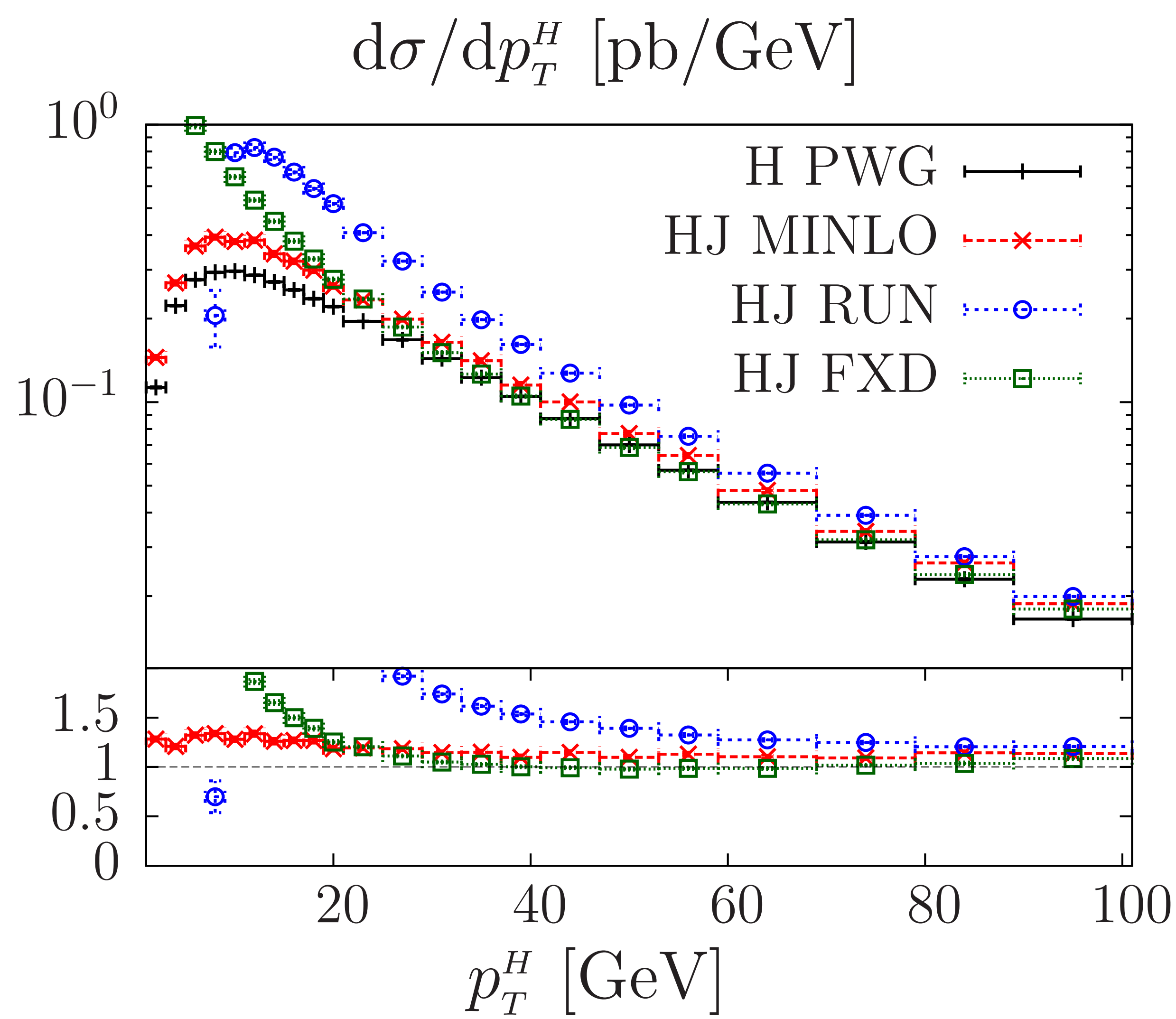
Preliminary #3/3: HJ-NLO v [old] HJ-MiNLO

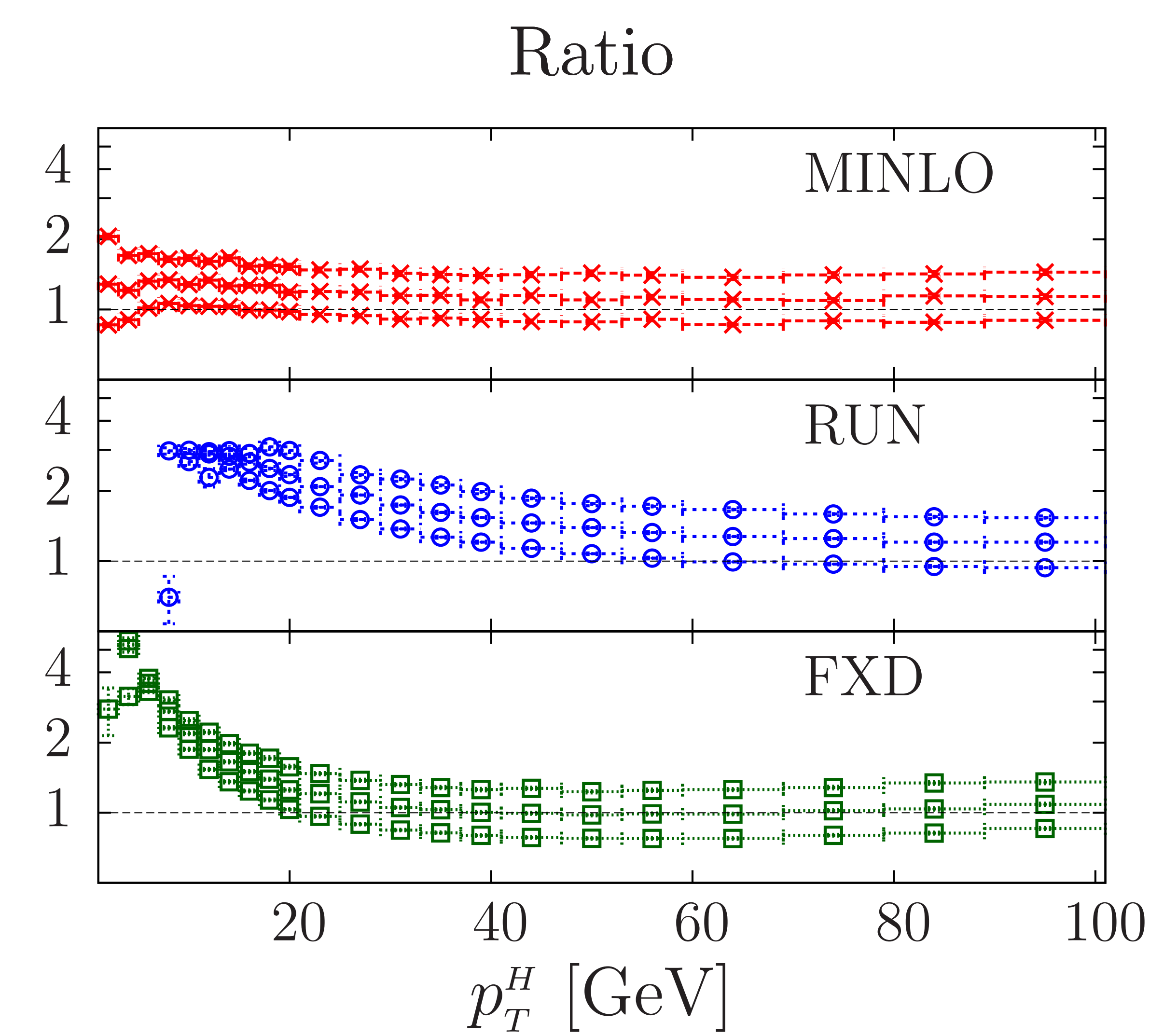




- H PWG: $gg \to$ Higgs at NLO Powheg+Pythia
- HJ RUN: NLO HJ jet with $\mu_R = \mu_F = p_{T,H}$
- HJ FXD: NLO HJ jet with $\mu_R = \mu_F = M_H$
- The ref. line for ratios is NLO $gg \to$ H Powheg+Pythia

Preliminary #3/3: HJ-NLO v [old] HJ-MiNLO





- HJ-MiNLO agrees w.other HJ NLO calcs at high p_T as promised
- HJ-MiNLO within 40% of NLOPS H simulation in deep Sudakov region
- HJ-MiNLO scale uncertainty doesn't shrink towards low p_T
- 'Normal' bands shrink to 0 by having first Sudakov log only
- Shrinking envelope as $p_T \to 0$ surely a bad sign

Outline

- The goal
- Preliminary ideas:
  1. HJ Powheg
  2. HJ-MiNLO
  3. HJ NLO v HJ-MiNLO
- NLOPS H from NLOPS HJ-MiNLO
- Results
- Conclusion

NLOPS H from NLOPS HJ-MiNLO: 0/5

- Inclusion of Sudakov resummation means removal of generation cuts and physical behaviour all over phase space
- MiNLO X+jets computat^{n}s therefore also gives sensible predict^{n}s for fully incl. obs. [where conventional NLO X+jets gives garbage]
- Quantify 'sensible' : 2nd MiNLO paper showed HJ-MiNLO different to NLO for incl. obs. by $O(\alpha_S^{1.5})$ terms relative to LO H prod.
- In particular, 2nd MiNLO shows by including B_2 coefficient in Sudakov HJ-MiNLO gets promoted to NLO accuracy for incl. obs.
- Next slides show how this comes about

NLOPS H from NLOPS HJ-MiNLO: 1/5

1. Establish $p_T \to 0$ singular behaviour of NLO HJ xsec

- Write NLO HJ xsec as sum of $p_T \to 0$ sing. & non-sing. parts

$$\frac{d\sigma}{dp_{\mathrm{T}}^2 dy} = \frac{d\sigma_{\mathcal{S}}}{dp_{\mathrm{T}}^2 dy} + \frac{d\sigma_{\mathcal{F}}}{dp_{\mathrm{T}}^2 dy}$$

- Sing. part is given in literature as sum of terms ~ $\alpha_{\mathrm{S}}^r L^s / p_{\mathrm{T}}^2$ where $L = \log \frac{Q^2}{p_{\mathrm{T}}^2}$ and Q^2 is the Higgs virtuality

$$\frac{d\sigma_{\mathcal{S}}}{dp_{\mathrm{T}}^2 dy} = \frac{N}{p_{\mathrm{T}}^2} \sum_{r=1}^{2} \sum_{s=0}^{2r-1} \left(\frac{\alpha_{\mathrm{S}}}{2\pi}\right)^r {}_rD_s\, L^s$$

- $d\sigma_{\mathcal{S}}$ defined to vanish when $p_{\mathrm{T}} > Q$ i.e. $d\sigma = d\sigma_{\mathcal{F}}$ there
- N defined s.t. at LO $d\sigma/dy = N f_i\, f_j$

NLOPS H from NLOPS HJ-MiNLO: 2/5

2. Improve the NLO HJ xsec according to MiNLO prescription

   [i.e. add into NLO HJ p_T resummation]

(a) Apply μ_R and μ_F scale choices

- All μ_F's replaced by p_T
- All μ_R's replaced by Q
- Except the one in the NLO power of α_S: $\alpha_S^{\mathrm{NLO}} = \alpha_S(p_T)$
- Choice of μ_F's absorbs couple of terms in the ${}_r D_s$'s in the PDFs

NLOPS H from NLOPS HJ-MiNLO: 2/5

2. Improve the NLO HJ xsec according to MiNLO prescription

   [i.e. add into NLO HJ p_T resummation]

(b) Match on to p_T space Sudakov form factor

- Multiply NLO HJ xsec by Sudakov [includes B_2]

$$\log \Delta\left(Q, p_{\mathrm{T}}\right) = -\int_{p_{\mathrm{T}}^2}^{Q^2} \frac{dq^2}{q^2} \sum_{i=1}^{2} \alpha_{\mathrm{S}}^i\left(q\right) \left[A_i \log\frac{Q^2}{q^2} + B_i \right]$$

- Multiply NLO HJ xsec by ratio $\alpha_{\mathrm{S}}\left(p_{\mathrm{T}}\right)/\alpha_{\mathrm{S}}\left(Q\right)$

- Subtract their α_S expansions maintaining NLO F.O. expansion

- This gives HJ-MiNLO xsec, exactly, no approximations:

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

NLOPS H from NLOPS HJ-MiNLO: 3/5

3. Establish leading $p_T \to 0$ behaviour of HJ-MiNLO xsec

- Write HJ-MiNLO xsec as sum of $p_T \to 0$ leading & subleading parts

$$\frac{d\sigma_{\mathcal{M}}}{dp_{\rm T}^2 dy} = \frac{d\sigma_{\mathcal{MS}}}{dp_{\rm T}^2 dy} + \frac{d\sigma_{\mathcal{MF}}}{dp_{\rm T}^2 dy}$$

- Plug exp. for sing. part of NLO HJ, $d\sigma_{\mathcal{S}}$, into HJ-MiNLO one, $d\sigma_{\mathcal{M}}$

$$\frac{d\sigma_{\mathcal{MS}}}{dp_{\rm T}^2 dy} = \Delta^2(Q, p_{\rm T}) \, \frac{N}{p_{\rm T}^2} \sum_{r=1}^{2} \sum_{s=0}^{1} \alpha_{\rm S}^{r}\,{}_{r}E_s \, L^s + \{i \leftrightarrow j\}$$

- Subleading part also from plugging $d\sigma_{\mathcal{F}}$ into $d\sigma_{\mathcal{M}}$ expression on last slide [not singular, $O(\alpha_S^3)$ before & after p_T integrat^n].

- Note r=2, s=0,1 not 0,1,2,3 : r=2, s=2,3 absorbed in Sud. & PDFs

NLOPS H from NLOPS HJ-MiNLO: 3/5

3. Establish leading $p_T \to 0$ behaviour of HJ-MiNLO xsec

- In full the four coefficients are

$$
\begin{aligned}
{}_1E_1 &= A_1\, f_i\, f_j\,, \\
{}_1E_0 &= B_1\, f_i\, f_j + [P_{ik} \otimes f_k]\, f_j\,, \\
{}_2E_1 &= A_2\, f_i\, f_j + 2A_1 \left[C^{(1)}_{ik} \otimes f_k\right] f_j\,, \\
{}_2E_0 &= B_2\, f_i\, f_j + 2B_1 \left[C^{(1)}_{ik} \otimes f_k\right] f_j + \left[P^{(2)}_{ik} \otimes f_k\right] f_j \\
&\quad + \left[C^{(1)}_{ik} \otimes f_k\right] [P_{jl} \otimes f_l] + \left[C^{(1)}_{ik} \otimes P_{kl} \otimes f_l\right] f_j - b_0 \left[C^{(1)}_{ik} \otimes f_k\right] f_j
\end{aligned}
$$

- $C^{(1)}_{ik}$ are NLO corrections to the H prod^n coeff. f^{n}s, C_{ik} , in well known b-space resummation formula

- $P^{(2)}_{ik}$ are NLO corrections to the relevant AP splitting f^{n}s, $P_{ik}(z)$

- $d\sigma_{\mathcal{MS}}$ is exactly the leading $p_T \to 0$ part of HJ-MiNLO jet xsec

NLOPS H from NLOPS HJ-MiNLO: 4/5

4. Determine integral of HJ-MiNLO p_T spectrum at $O(\alpha_S^3)$ accuracy

- Not hard to show w. fixed coupling & double log Sudakov terms

$$\Delta^2\left(Q,p_{\mathrm{T}}\right)\,\frac{N}{p_{\mathrm{T}}^2}\,\alpha_{\mathrm{S}}^r\,L^s$$

w. $s \leq 2r-5$ [$\propto N\,\alpha_S^3 L$, $N\,\alpha_S^4 L^3$, ...] integrate to $O(\alpha_S^4)$ terms*

- Knowing this can use RGE & DGLAP to write up to $O(\alpha_S^4)$ ambiguity

$$\int dp_{\mathrm{T}}^2\,\frac{d\sigma_{\mathcal{M}}}{dp_{\mathrm{T}}^2 dy}=\int dp_{\mathrm{T}}^2\left[N\,\frac{d}{dp_{\mathrm{T}}^2}\,\Delta^2(Q,p_{\mathrm{T}})\,\left[C_{ik}\otimes f_k\right]\,\left[C_{jl}\otimes f_l\right]+\frac{d\sigma_{\mathcal{M}\mathcal{F}}}{dp_{\mathrm{T}}^2 dy}\right]$$

- If no B_2 in Sudakov you get extra junk on RHS $\sim\Delta^2\left(Q,p_{\mathrm{T}}\right)\,\frac{N}{p_{\mathrm{T}}^2}\,\alpha_{\mathrm{S}}^2\,B_2$ which integrates up to $O(N\,\alpha_S^{1.5})$

* Can also do running α_S upper bound w. saddle point approx to integral

NLOPS H from NLOPS HJ-MiNLO: 5/5

5. Compare to conventional NLO

- Considering C_{ik} are [essentially by definition] related to the conventional NLO xsec differential in y as

$$\frac{d\sigma}{dy} = N\,[C_{ik}\otimes f_k]\,[C_{jl}\otimes f_l] + \int dp_{\mathrm{T}}^2\,\frac{d\sigma_{\mathcal{F}}}{dp_{\mathrm{T}}^2\,dy} + \mathcal{O}\left(\alpha_{\mathrm{S}}^4\right)$$

- And $d\sigma_{\mathcal{F}}$ equals $d\sigma_{\mathcal{MF}}$ up to $O(\alpha_S{}^4)$ terms
- The p_T-integrated MiNLO xsec

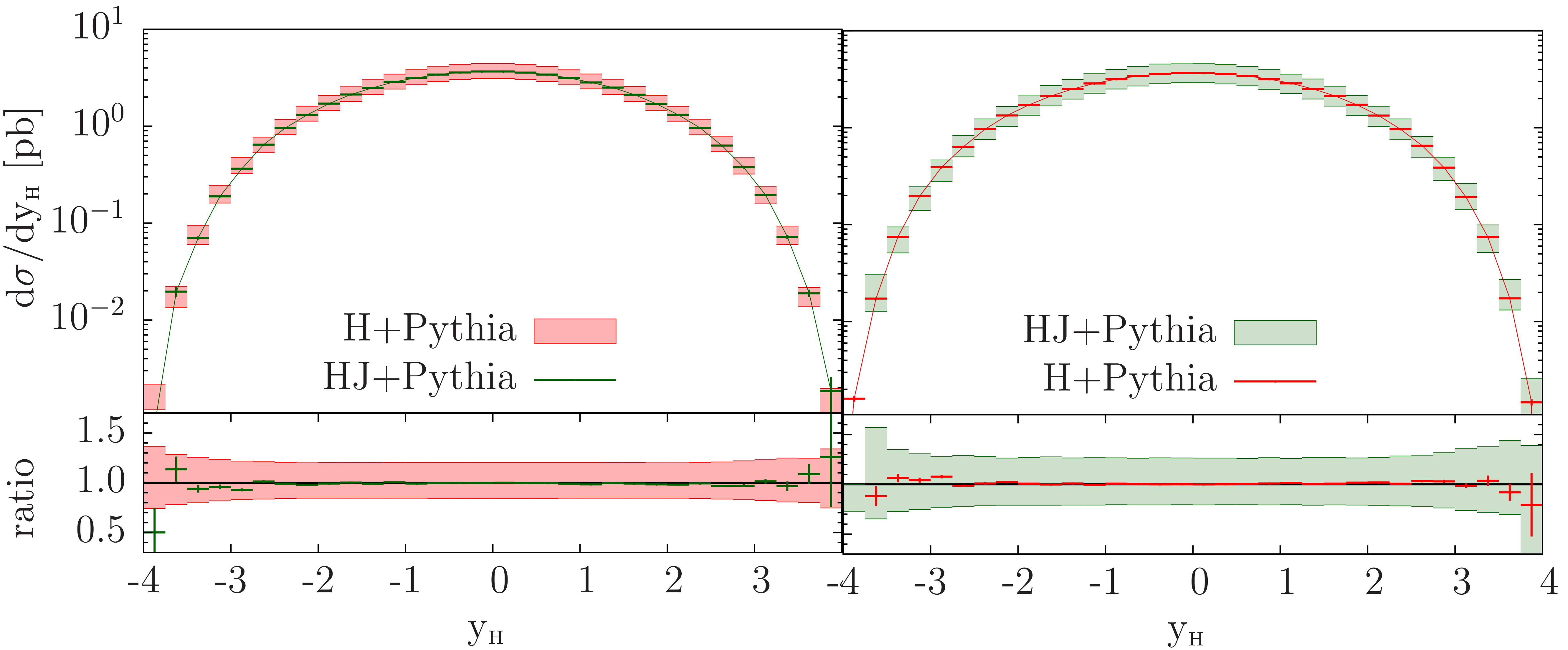
$$\int dp_{\mathrm{T}}^2\,\frac{d\sigma_{\mathcal{M}}}{dp_{\mathrm{T}}^2\,dy} = \int dp_{\mathrm{T}}^2\left[N\,\frac{d}{dp_{\mathrm{T}}^2}\,\Delta^2(Q,p_{\mathrm{T}})\,[C_{ik}\otimes f_k]\,[C_{jl}\otimes f_l] + \frac{d\sigma_{\mathcal{MF}}}{dp_{\mathrm{T}}^2\,dy}\right]$$

is the same, up to $O(\alpha_S{}^4)$ terms as the conventional NLO xsec differential in y

Outline

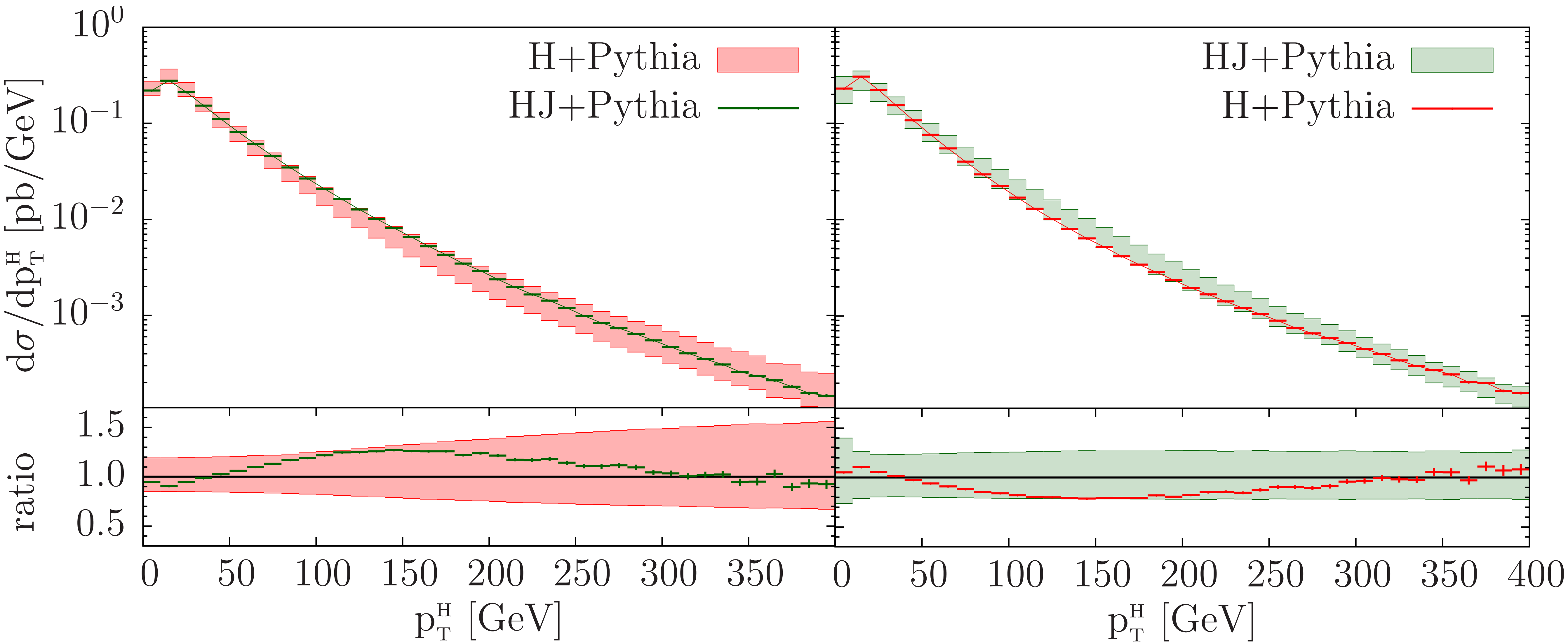
- The goal
- Preliminary ideas:
  1. HJ Powheg
  2. HJ-MiNLO
  3. HJ NLO v HJ-MiNLO
- NLOPS H from NLOPS HJ-MiNLO
- Results
- Conclusion

Results: NLOPS H v NLOPS HJ-MiNLO



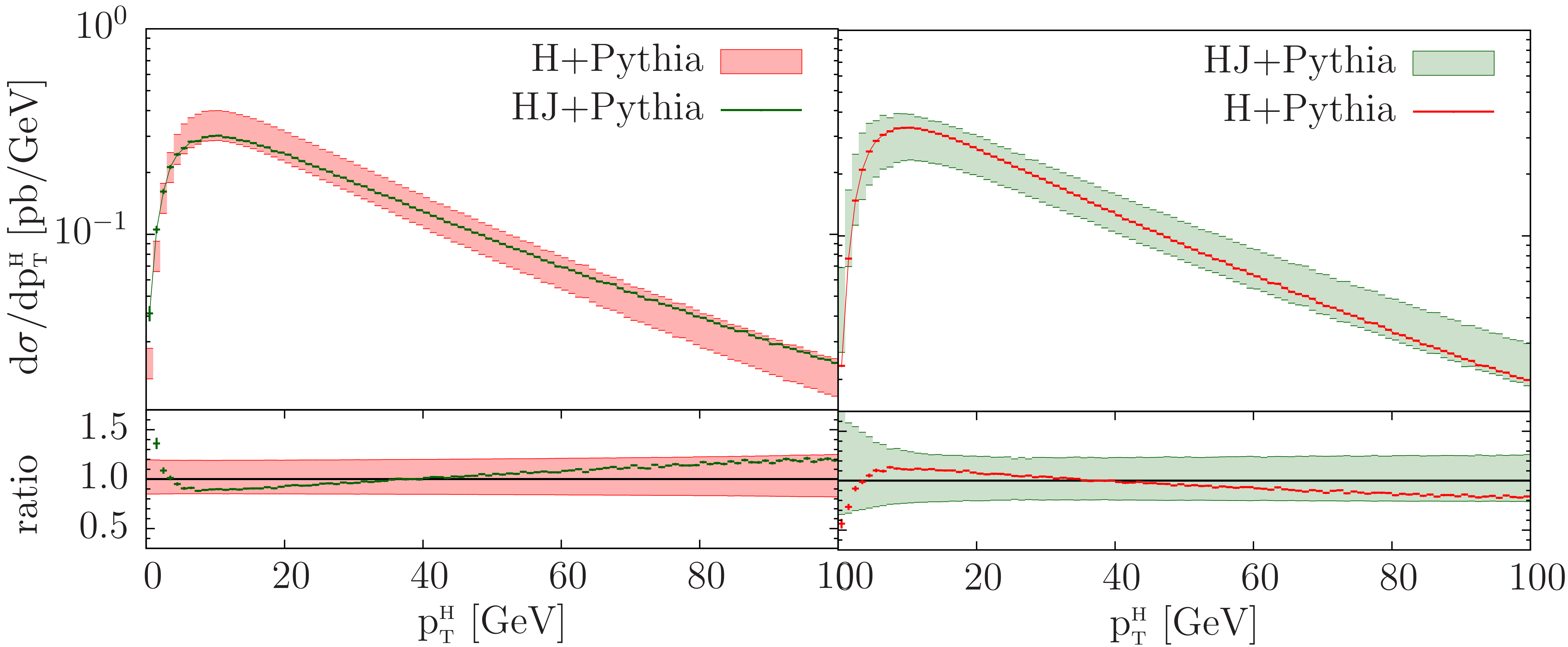
- Left NLO H PWG uncertainty w. HJ-MiNLO inset as green +'s
- Right HJ-MiNLO uncertainty w. NLO H inset in red +'s
- 7 pt independent μ_R , μ_F scale variation bands

Results: NLOPS H v NLOPS HJ-MiNLO



- Again, central values in good agreement
- HJ-MiNLO is NLO for HJ and H inclusive
- Powheg H only NLO for H inclusive
- HJ-MiNLO band expectedly smaller at high p_T

Results: NLOPS H v NLOPS HJ-MiNLO



- HJ-MiNLO band widens at p_T ; approaching strong coupling
- H band not realistic as $p_T \to 0$; reflects tot. x-sec unc.
- Different shape as $p_T \to 0$ due to different Sudakovs: extra NNLL terms in HJ-MiNLO, finite ones in Powheg H

Conclusion

- NLOPS HJ:
  - Unphysical 0-jet inc obs
  - NLO 1-jet inc obs
  - LO 2-jet inc obs
  - PS everything else
- HJ-MiNLO ⊇ H:
  - NLO 0-jet inc obs
  - NLO 1-jet inc obs
  - LO 2-jet inc obs
  - PS everything else
- NLOPS acc. for H all from within NLOPS HJ-MiNLO: <u>no merging</u>
- NLO H xsec present in NLO HJ via factorisation of 0- & 1-loop MEs in [multiple] soft / coll. limits [see e.g. dFG NPB 2001]
- This is v.new, still only getting started really ...

  much to investigate understand better: extensions, uncertainties, resummation, does it generalise, &c &c