Precision calculations and simulations

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1. what the talk is about
2. calculating without a bad feeling
3. matching with parton showers
4. advanced trickery: multi-jet merging
5. where we are and where we (should/could/would) go

motivation & introduction

motivation: aim of the exercise

- review the state of the art in precision calculations/simulations

  (personal selection)

- provide a personal outlook on the future

  (we will all die)

- trigger a lively discussion

  (and **not** be provocative)

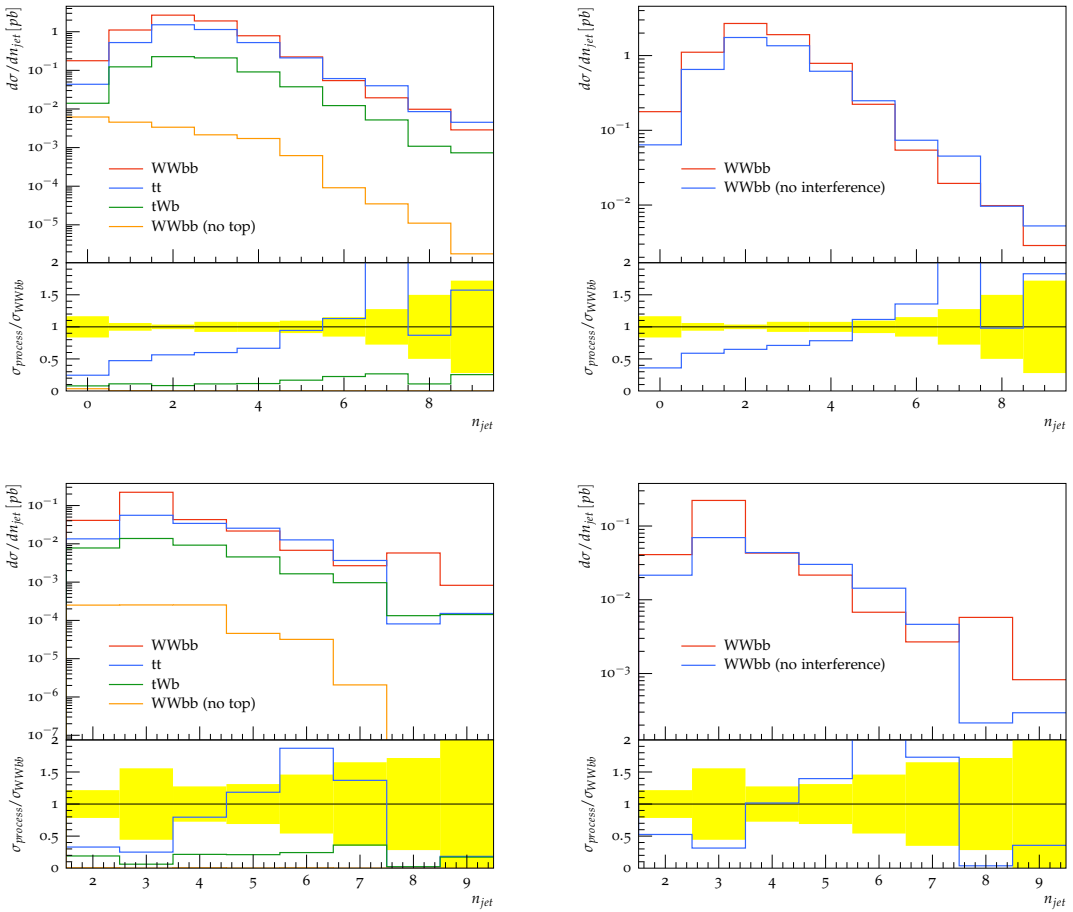
fixed-order and its limits

the fate of revolutions

- NLO (QCD) revolution "over": revolutionists becoming establishment
  - BlackHat, GoSam, MadGraph, Njet, OpenLoops, Recola + automated IR subtraction methods (MadGraph, Sherpa)
  - first full NLO (EW) results with such tools
- consolidating the establishment
  - higher multis, speed, integration efficiency
  - easier handling, PDF/α_S reweighting etc.
  - check MINLO (shower-motivated scale setting procedure)
- steep learning curve still ahead: "NLO phenomenology"
  - establishing and using methods for estimates of uncertainties

    (scales and their definitions, PDFs, non-perturbative effects)
  - loop–induced processes: LO merging available, but no MC@NLO
  - interplay of processes, interference/spin effects, etc. (example: $t\bar{t}$ vs. $b\bar{b}WW$)

- example above $t\bar{t}$ vs. $b\bar{b}WW$ for Les Houches study at LO
- N_{jets} before (upper) and after (lower) WBF cuts, coherent vs. incoherent sums (right) of individual contributions (right)



the looming revolution: NNLO

- H in ggF at N^{3}LO (Anastasiou, Duhr and others)
- explosive growth in NNLO (QCD) $2 \to 2$ results

(apologies for any unintended omissions)

  - $t\bar{t}$ (Czakon, Mitov)
  - single-t (Brucherseifer, Caola, Melnikov)
  - VV (Gehrmann, Grazzini, Kallweit, Maierhöfer, vManteuffel, Pozzorini, Rathlev, Tancredi)
  - VH (Ferrera, Grazzini, Tramontano; Campbell, Ellis, Williams)
  - WBF (Cacciari, Dreyer, Karlberg, Salam, Zanderighi)
  - $V\gamma$ (Grazzini, Kallweit, Rathlev)
  - $\gamma\gamma$ (Catani, Cieri, de Florian, Ferrera, Grazzini; Campbell, Ellis, Li, Williams)
  - Vj (Gehrmann^2, Glover, Huss, Morgan; Boughezal, Focke, Liu, Petriello; Boughezal, Campbell, Ellis, Focke, Liu, Giele, Petriello)
  - Hj (Chen, Gehrmann, Glover, Jacquier; Boughezal, Caola, Melnikov, Petriello; Boughezal, Focke, Giele, Liu, Petriello; Caola, Melnikov, Schulze)
  - jj (Currie, Gehrmann^2, Glover, Pires, Wells)

- different IR subtraction schemes:
  N-jettiness slicing, antenna subtraction, sector decomposition,

challenging the revolution

- technical issues:
  - stability of automated NLO in divergent regions
  - robustness under integration - subtraction vs. slicing
  - public release of code(s)
- going to higher multis:
  - first $2 \to 3$ amplitudes appear
  - new issues (IR subtraction, robust integrals, ...?)
- more scales (internal or external) complicated – need integrals
- going to higher power of N often driven by need to include larger FS multiplicity – maybe not the most efficient method
- structural questions concerning convergence/importance (see below)

matching @ (N)NLO

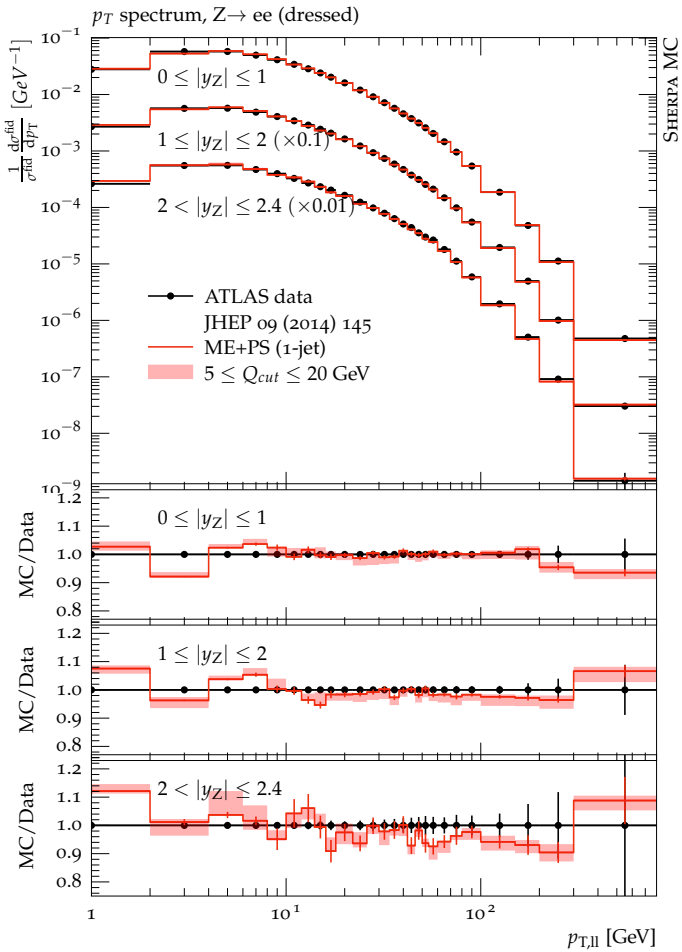
matching fixed order and resummation

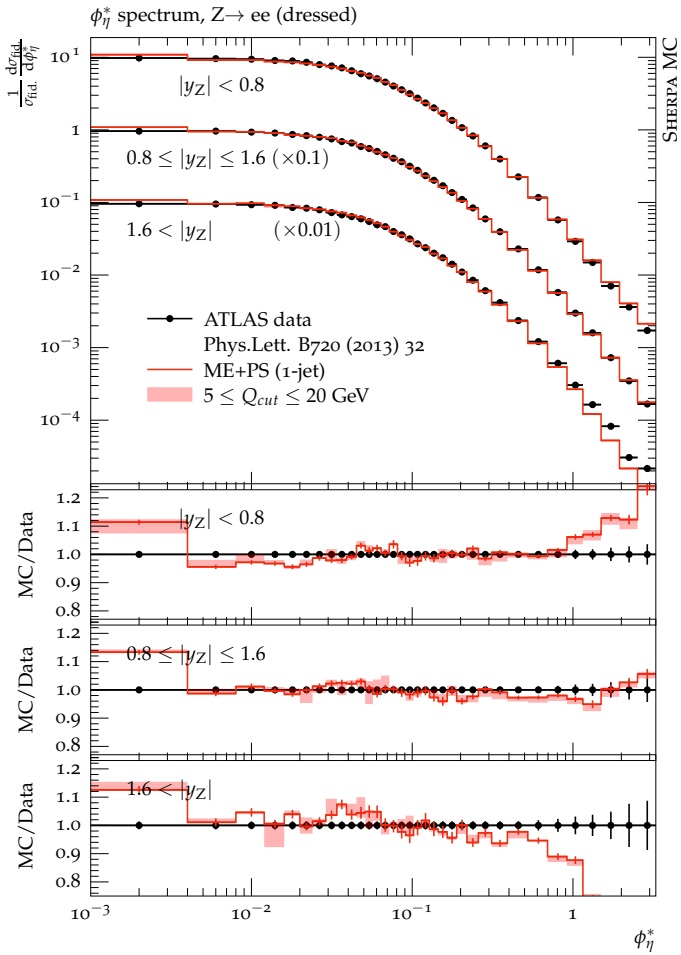
- more or less ignore analytic resummation
  - various schemes for various logs
- concentrate on parton shower instead
  - parametric accuracy by comparing with q_T resummation: showers usually include terms $A_{1,2}$ and B_1 (NLL)

    (this is for the Sudakov form factor)
  - only for processes with known resummation (singlet production)
  - A_2 often realised by pre-factor multiplying scale $\mu_R \simeq k_\perp$

some parton shower fun with DY

(follow up from yesterday - Vicini - and past week: this is the kind of precision observable/study)





- two schemes at NLO: POWHEG and MC@NLO

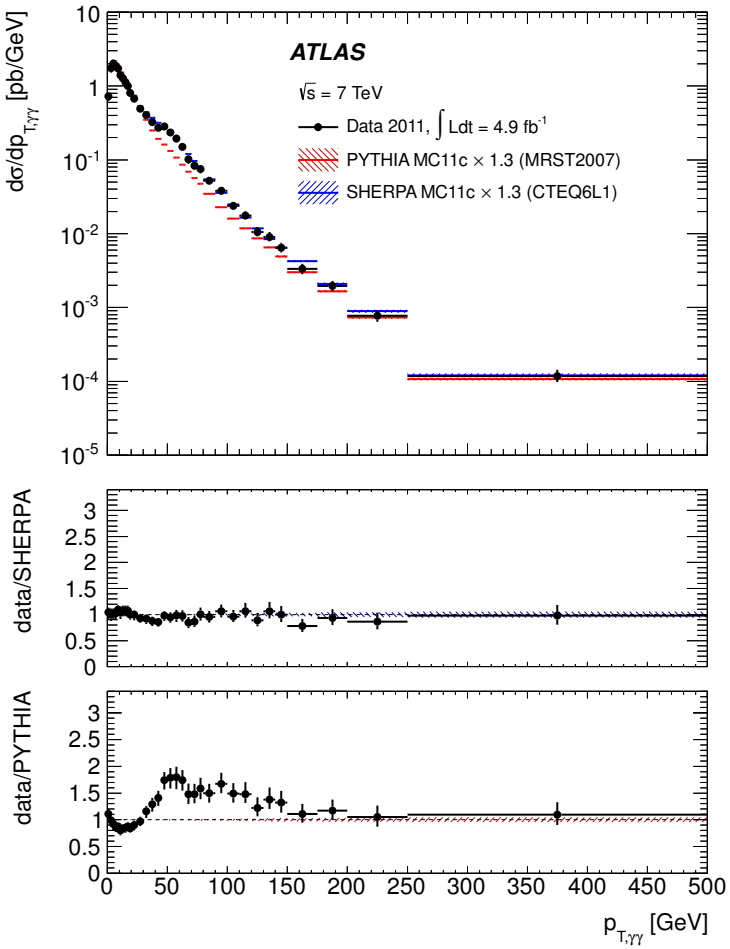
(see yesterday's talk by Vicini)

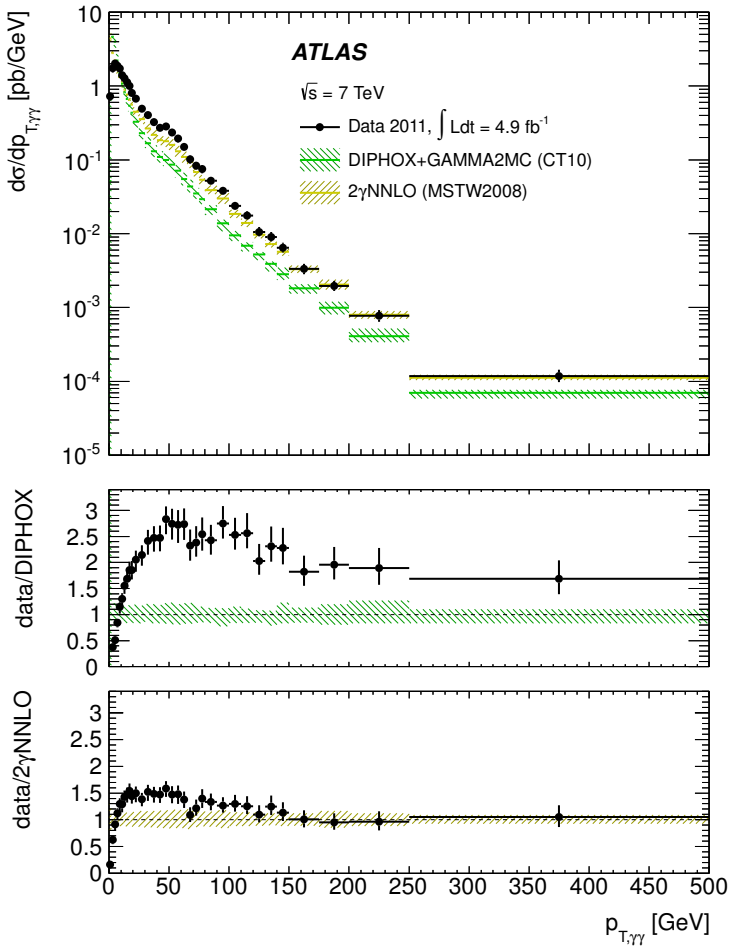
  - only one matching scheme given by kinematics of process in original version of MC@NLO (also implemented in SHERPA)
  - leads to structures due to mismatch of K factors in transition region to hard jet emissions
- two schemes at NNLO: MINLO & UNNLOPS (singlets S only)
  - different ways to avoid double-counting of emissions with shower and Sudakov rejection
  - MINLO pushes $S+j$ at NLO to $p_T^{(S)} \to 0$ and captures divergences by reweighting internal line with analytic Sudakov, NNLO accuracy ensured by reweighting with full NNLO calculation for S production
  - UNNLOPS identifies and subtracts and adds parton shower terms at FO from $S+j$ contributions, maintaining unitarity

multijet-merging @ (N)LO

example: $p_{\perp,\gamma\gamma}$ in MEPS@LO vs. NNLO

(arXiv:1211.1913 [hep-ex])





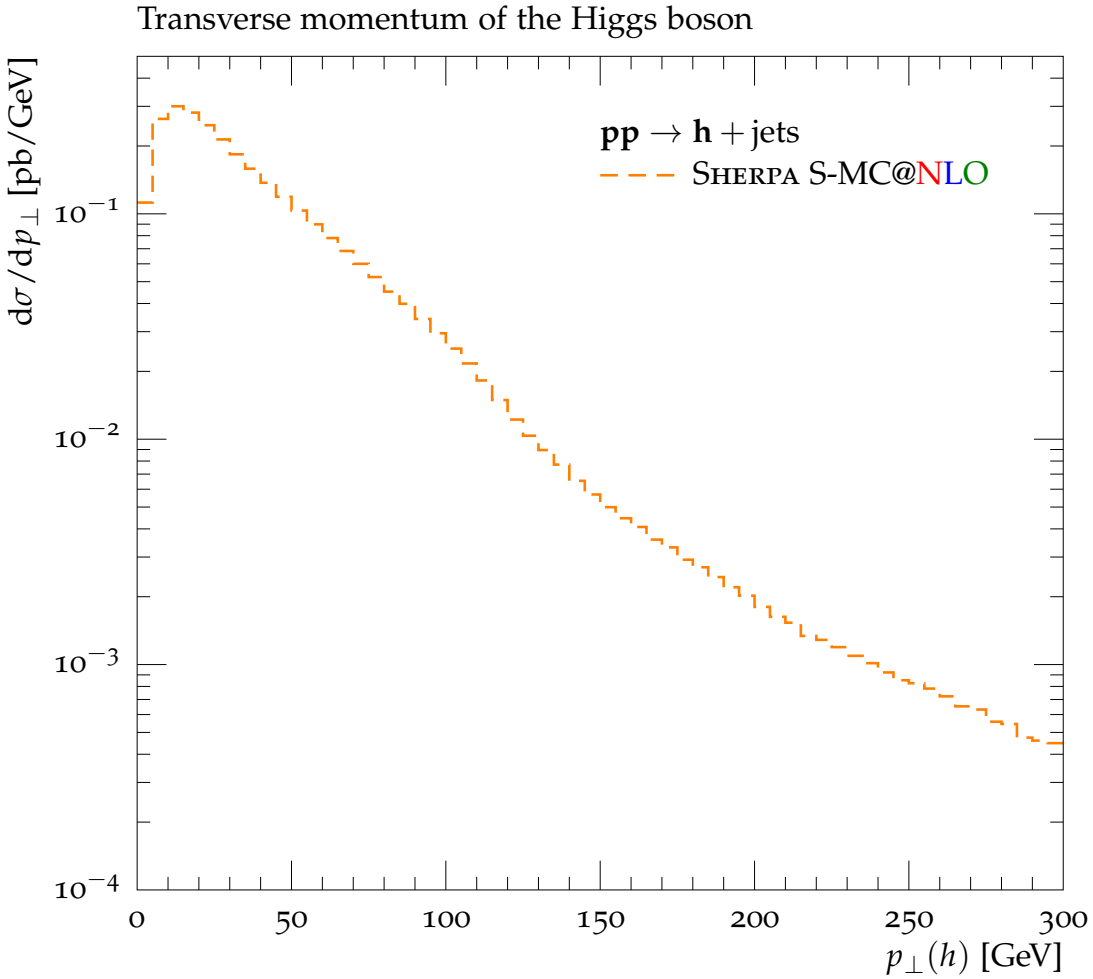
multijet-merging at NLO

- sometimes "more legs" wins over more loops
- basic idea like at LO: towers of MEs with increasing jet multi (but this time at NLO)
- combine them into one sample, remove overlap/double-counting
- maintain NLO and LL accuracy of ME and PS
- this effectively translates into a merging of MC@NLO simulations and can be further supplemented with LO simulations for even higher final state multiplicities
- different implementations, parametric accuracy not always clear

(MEPS@NLO, FXFX, UNLOPS)

- starts being used, still lacks careful cross-validation

illustration: $p_\perp^H$ in MEPS@NLO



- first emission by MC@NLO

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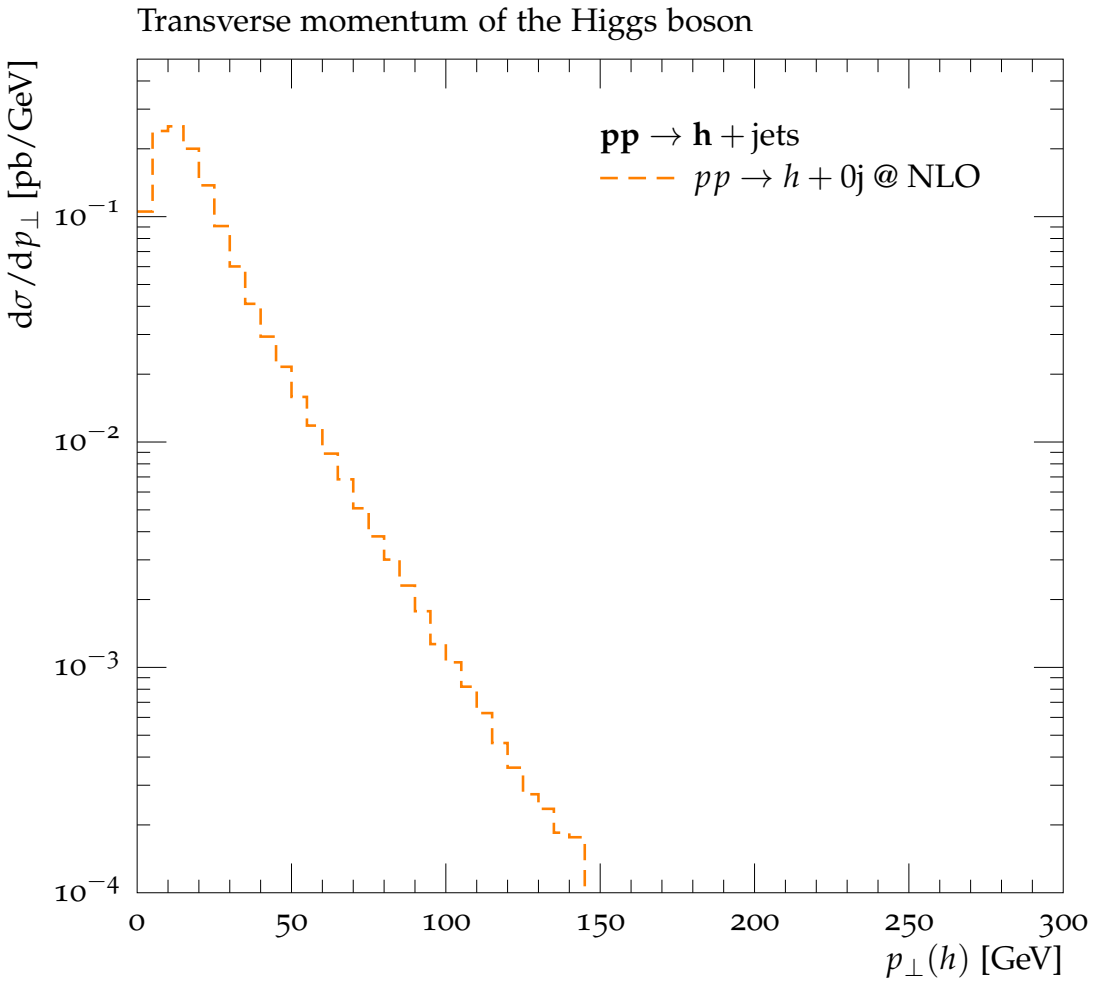

- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$

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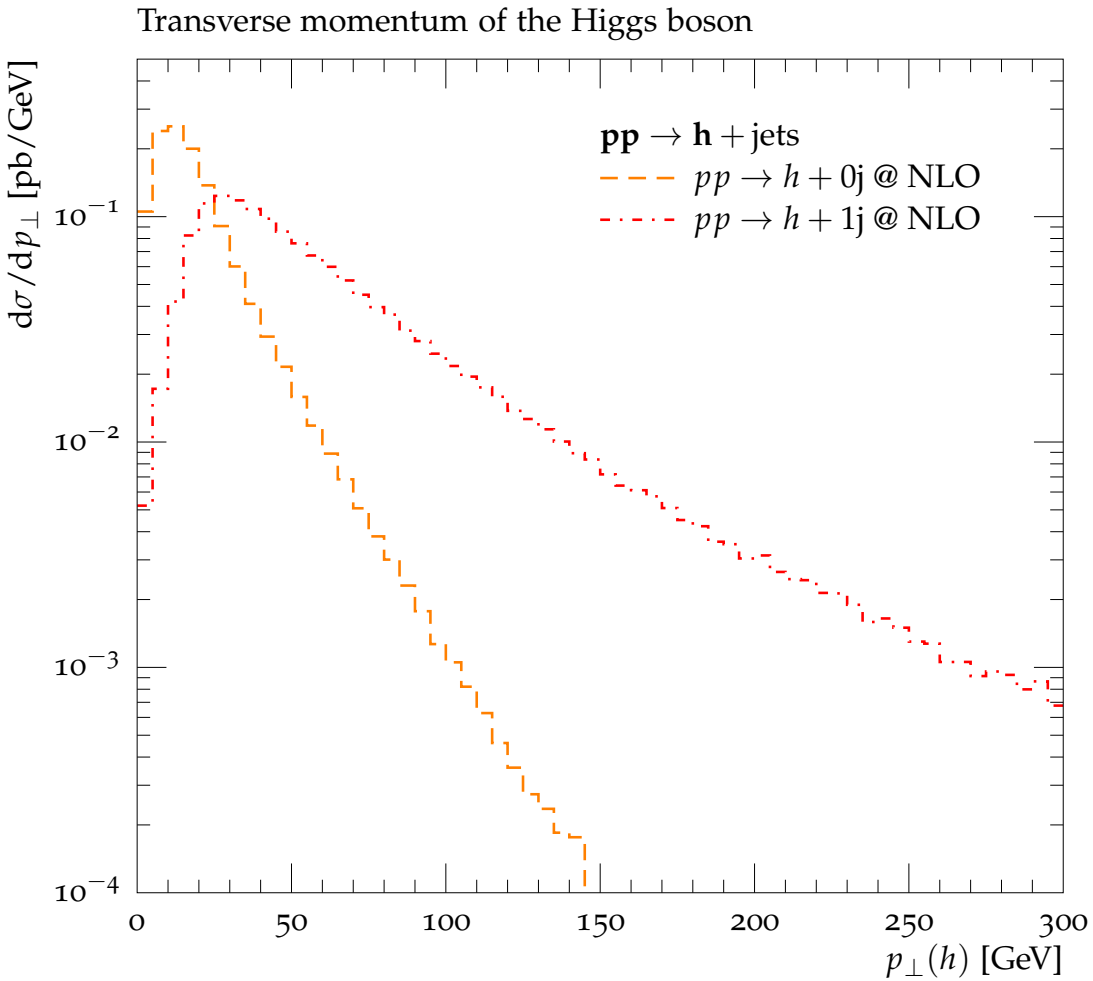

- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$

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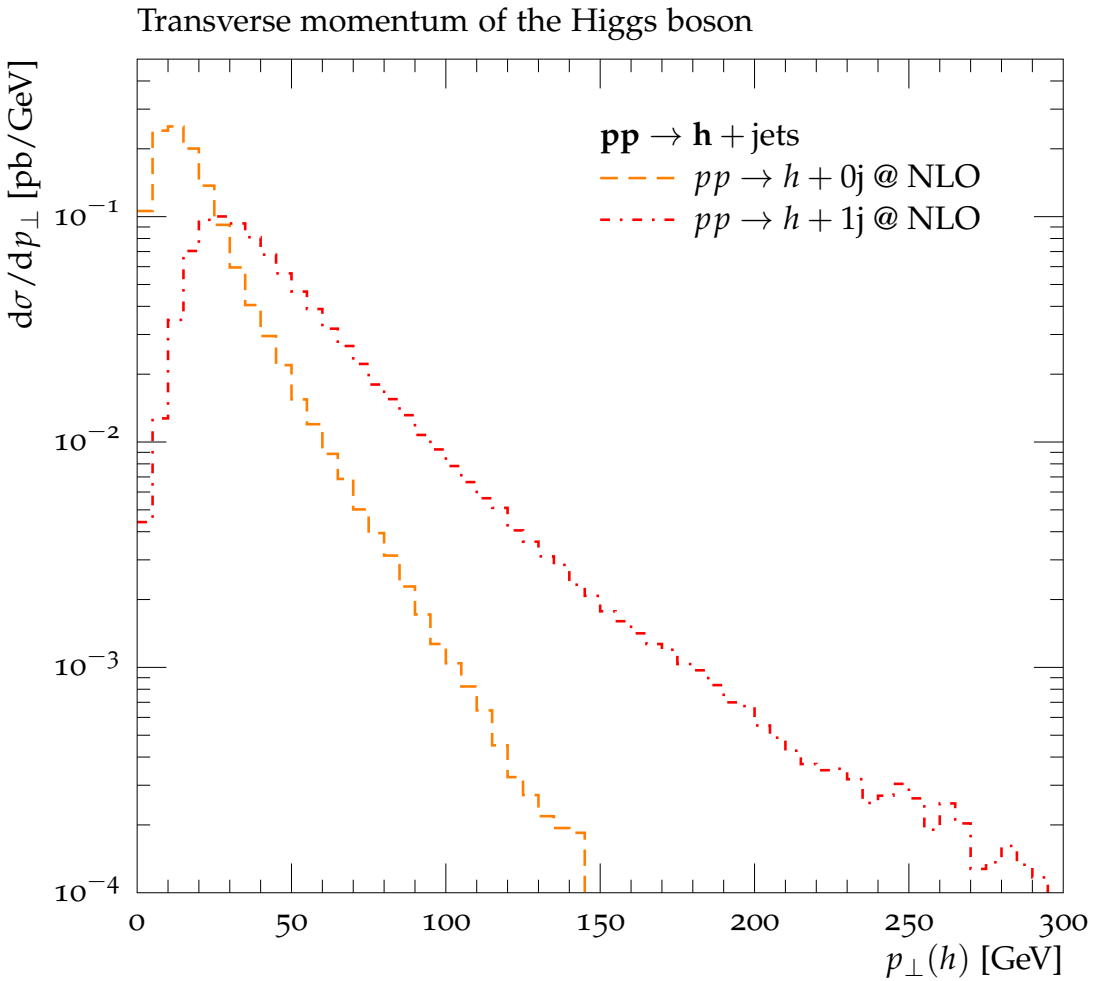

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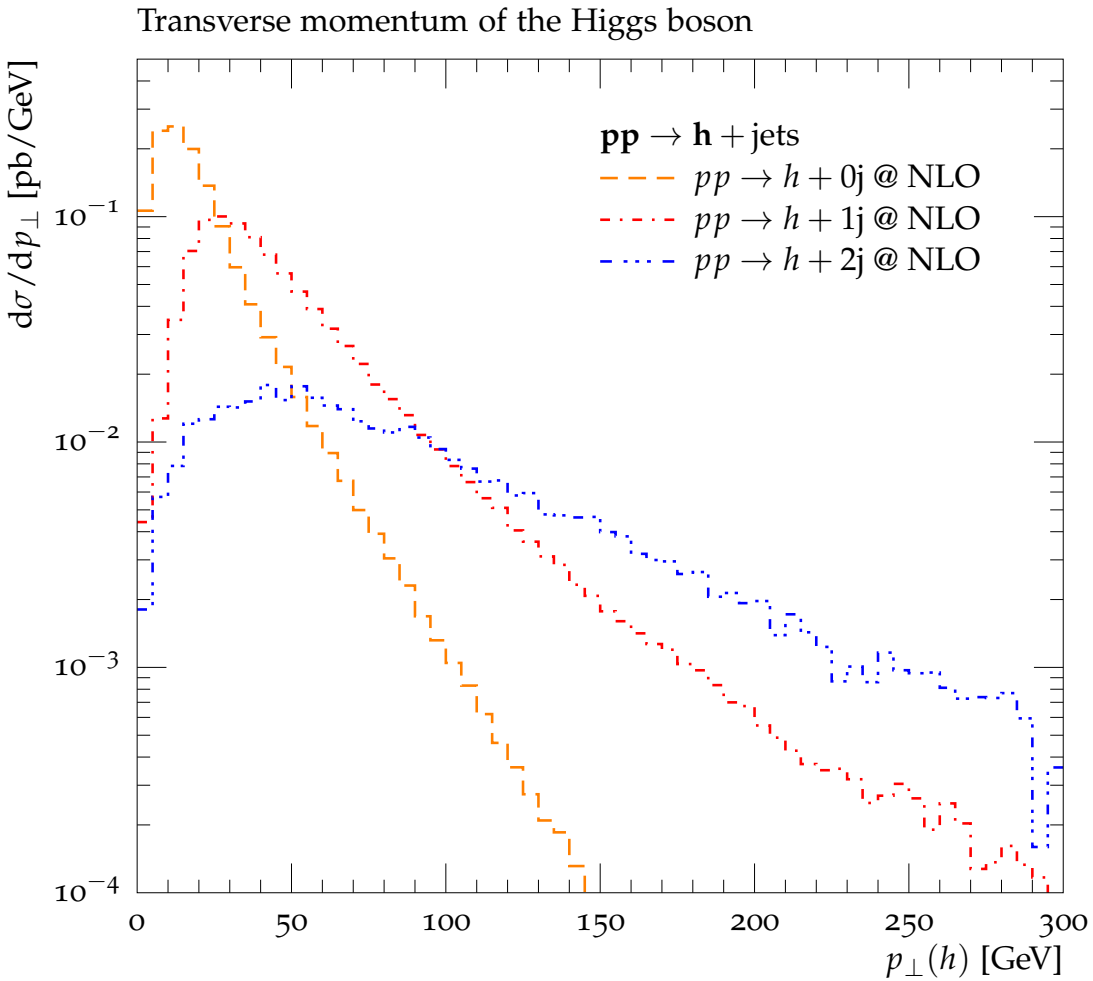

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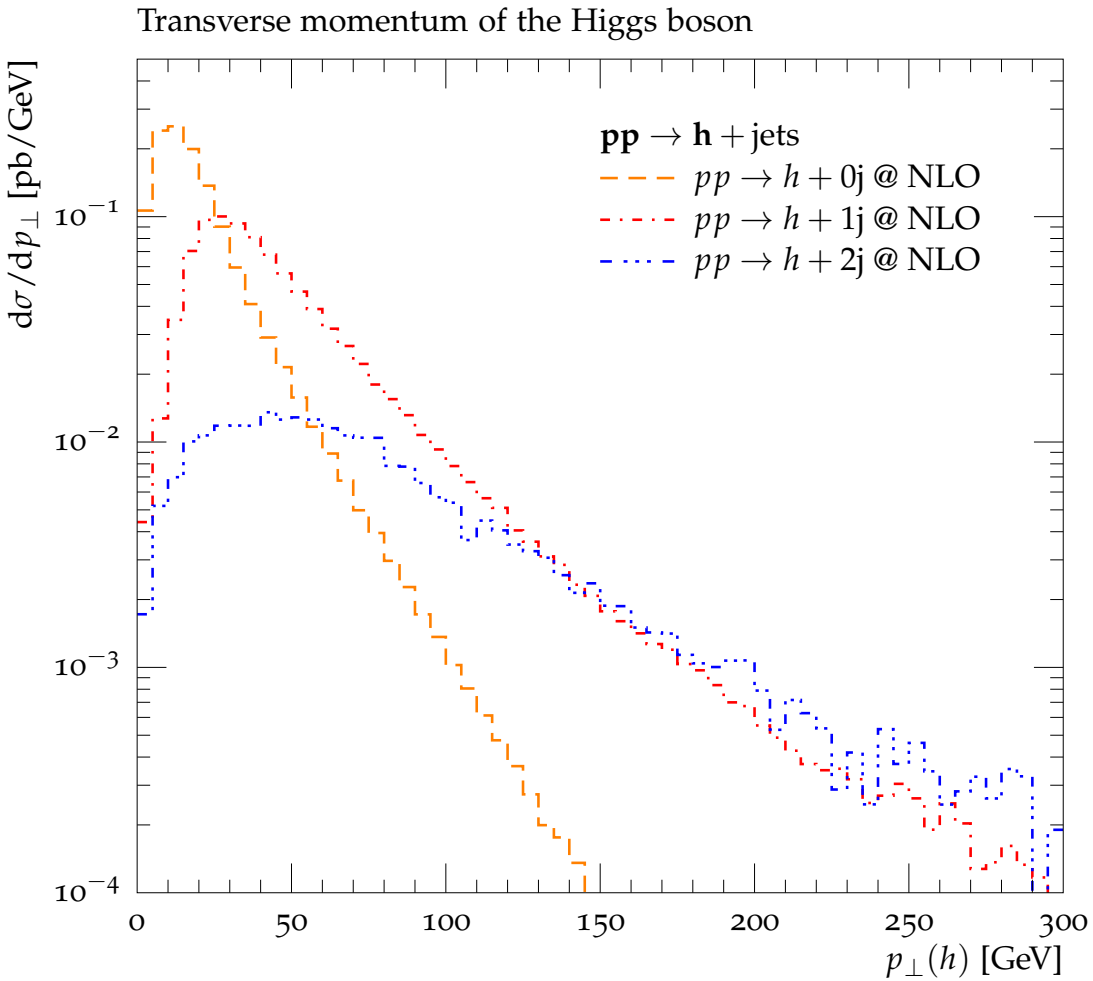
illustration: $p_\perp^H$ in MEPS@NLO



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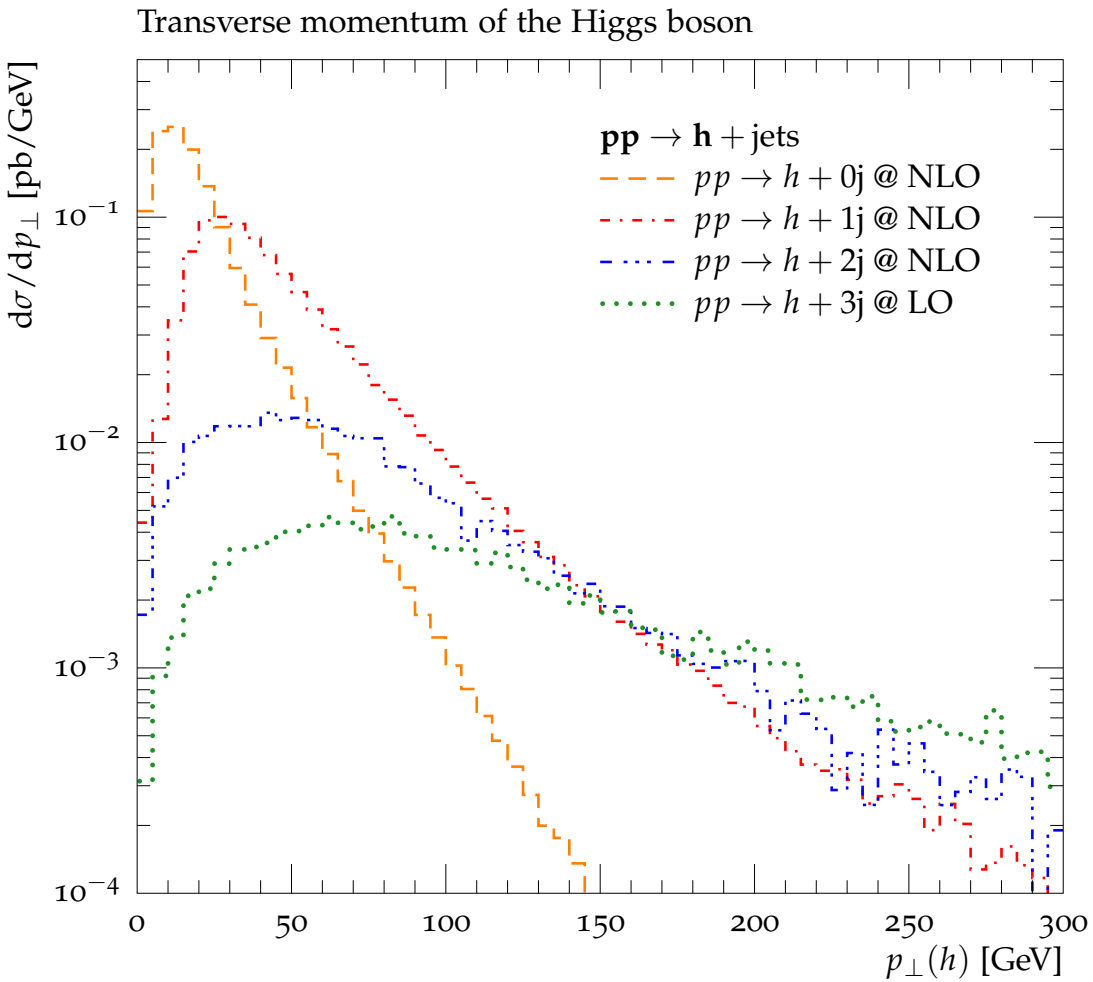

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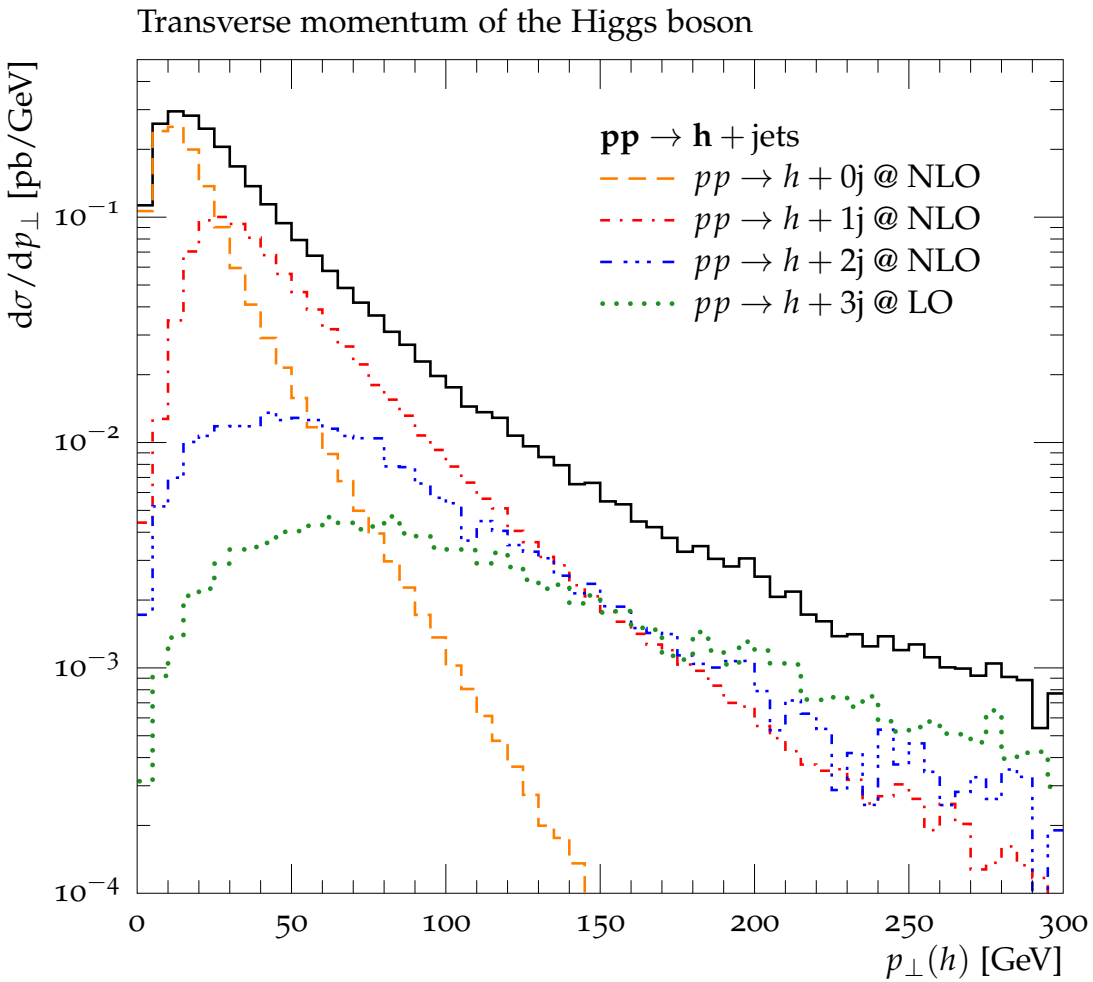

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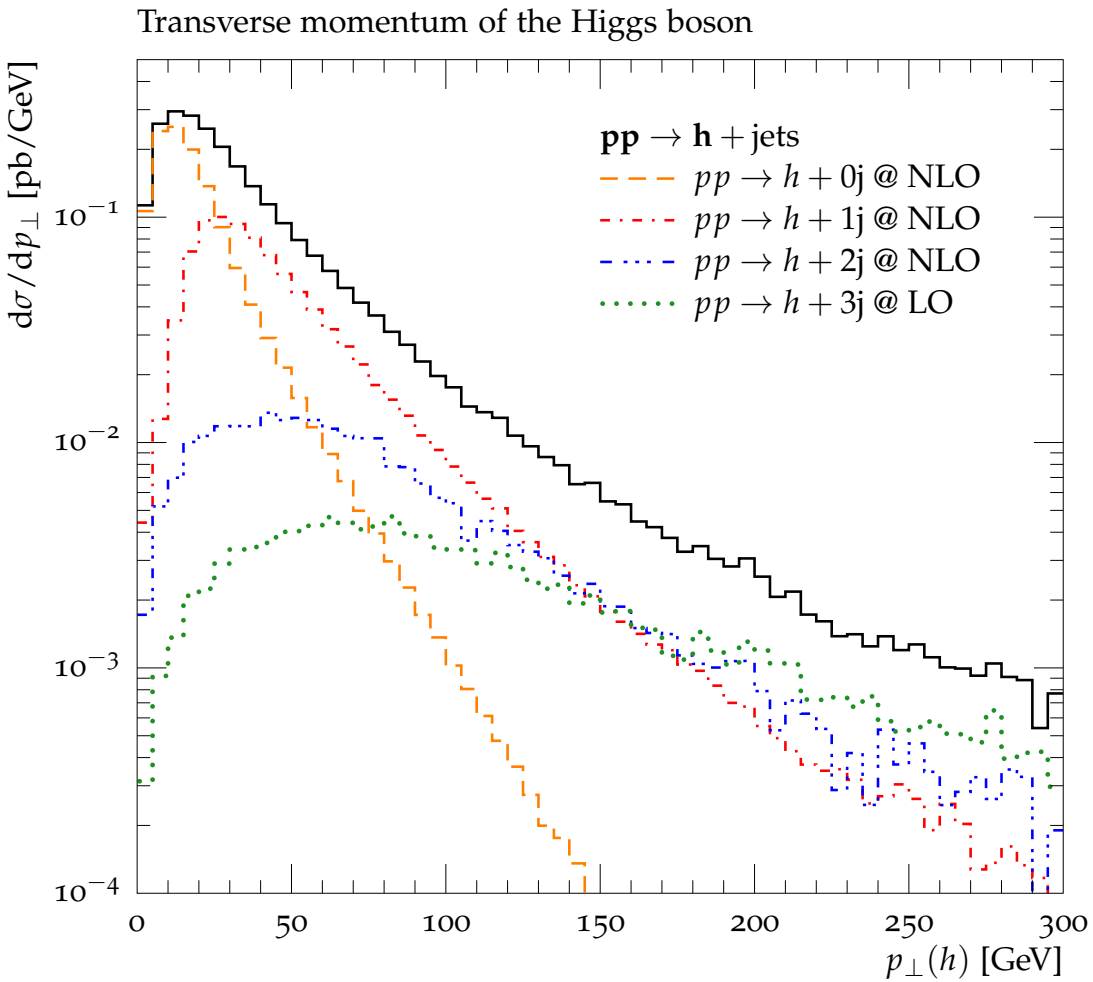

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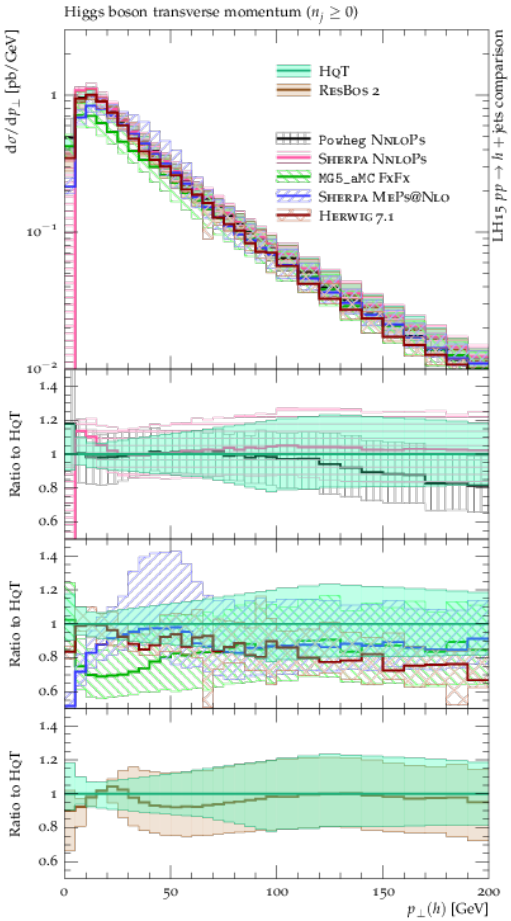
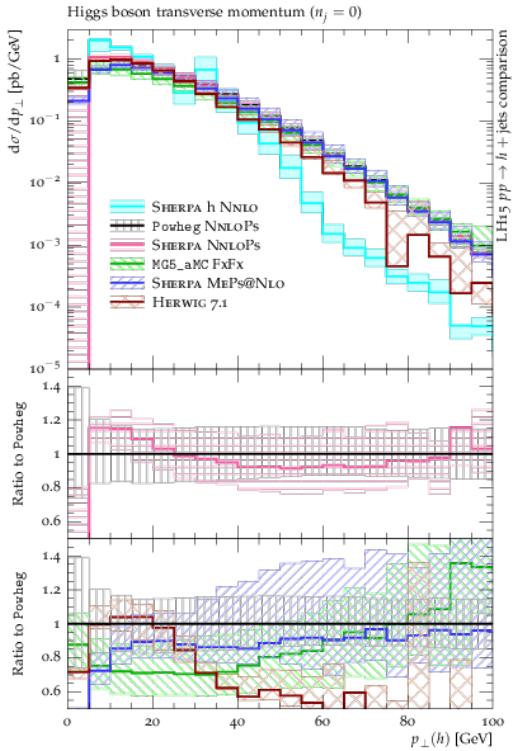
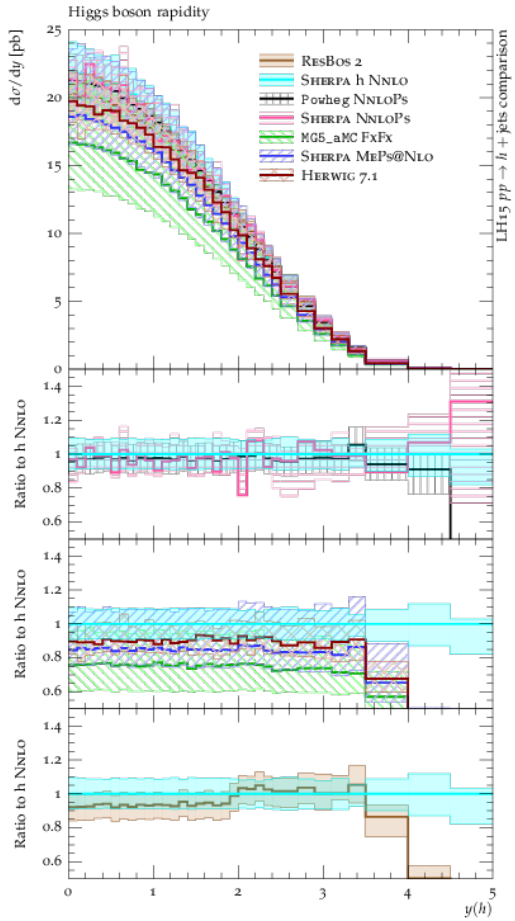
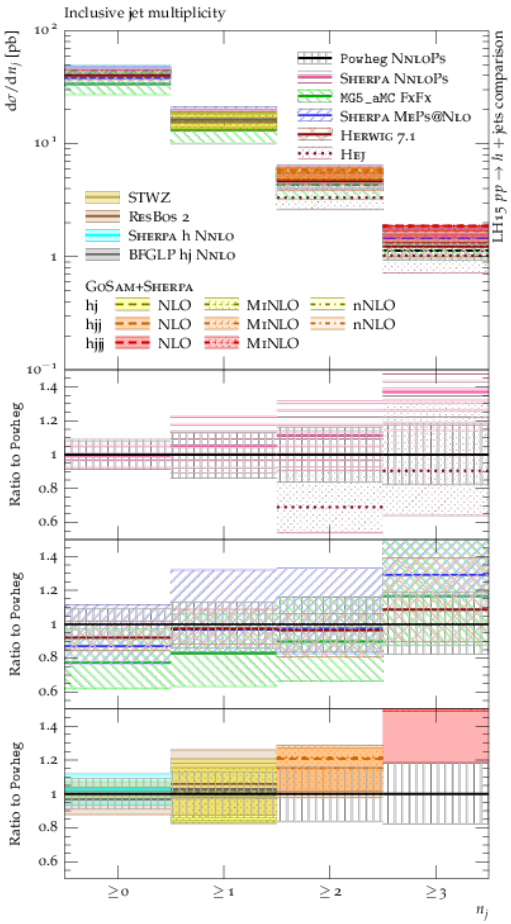
- iterate
- sum all contributions
- eg. $p_\perp(h)$>200 GeV has contributions fr. multiple topologies

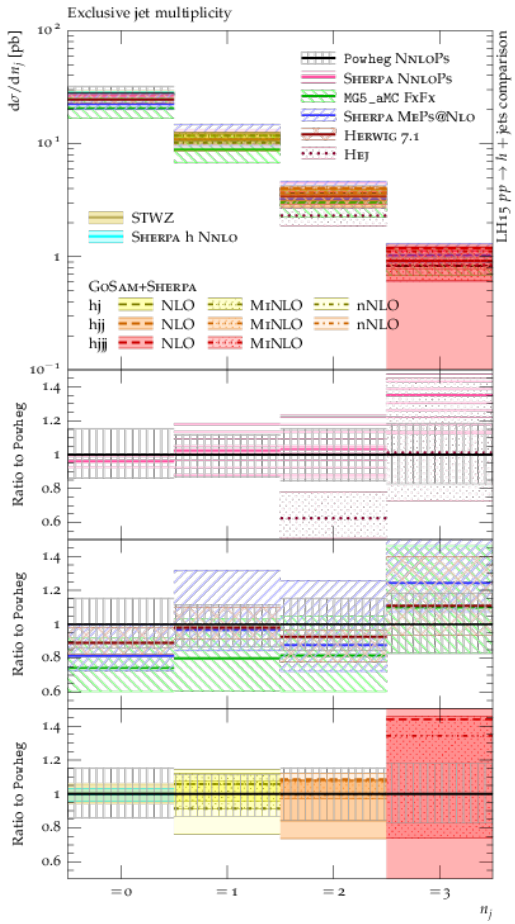
results from various schemes in H+jets through ggF








Inclusive jet multiplicity
Powheg NNLOPS
SHERPA NNLOPS
MG5_aMC FxFx
SHERPA MEPS@NLO
HERWIG 7.1
HEJ
STWZ
RESBOS 2
SHERPA h NNLO
BFGLP hj NNLO
GOSAM+SHERPA
hj NLO MINLO nNLO
hjj NLO MINLO nNLO
hjjj NLO MINLO
LH15 $pp \to h +$ jets comparison
$d\sigma/dn_j$ [pb]
Ratio to Powheg
n_j


Exclusive jet multiplicity
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SHERPA NNLOPS
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HERWIG 7.1
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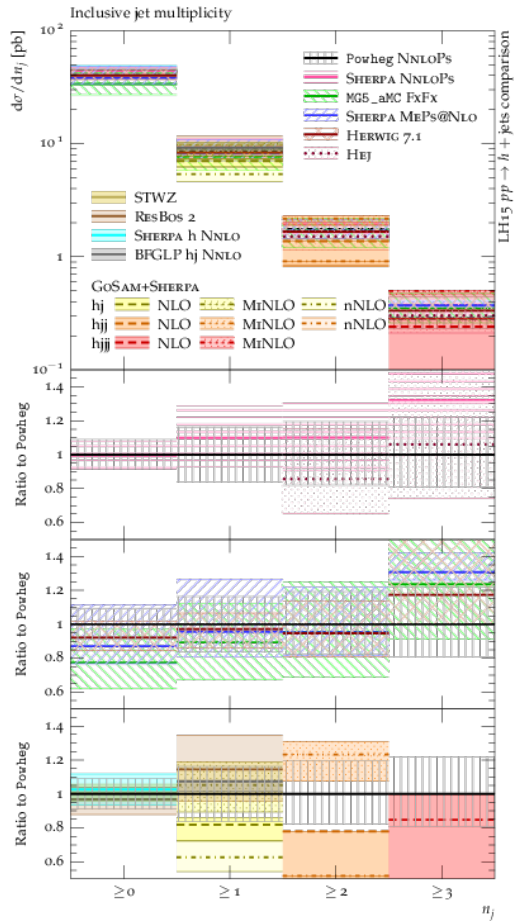
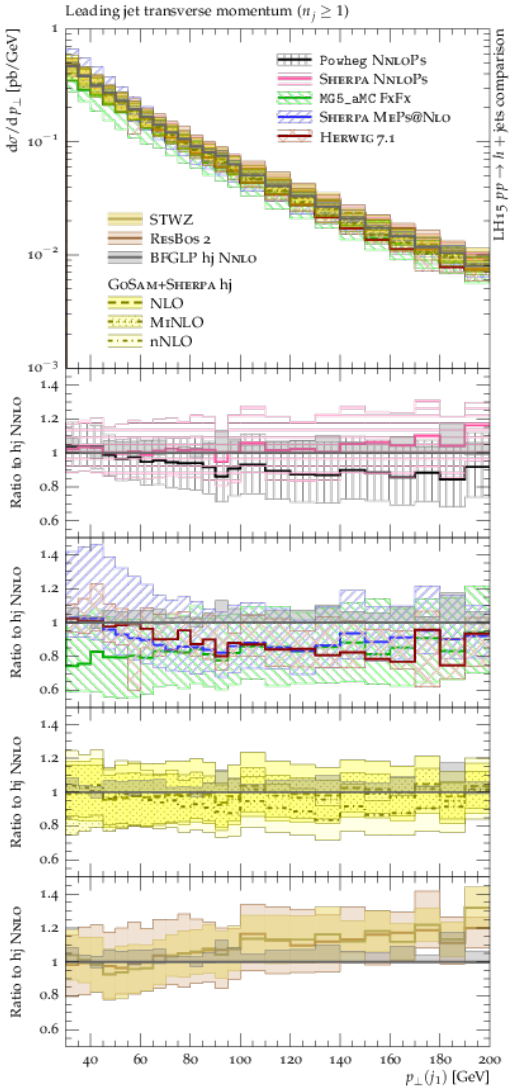
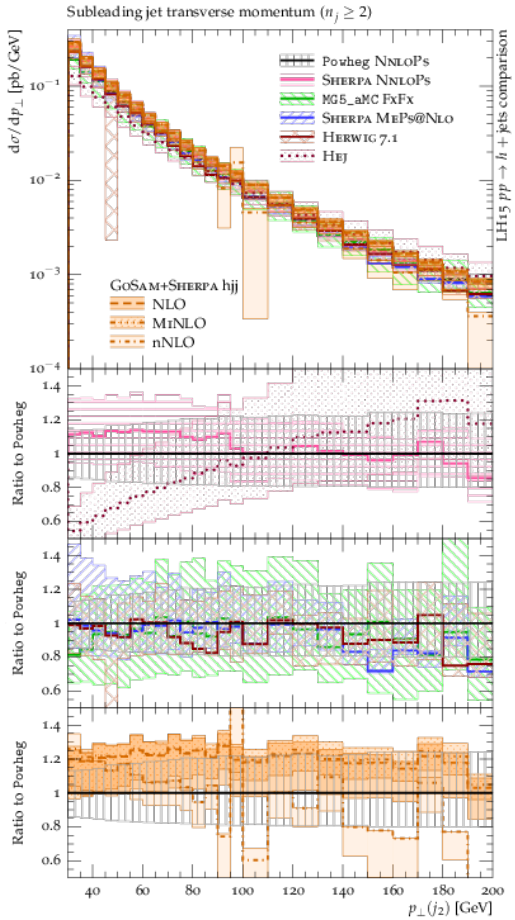
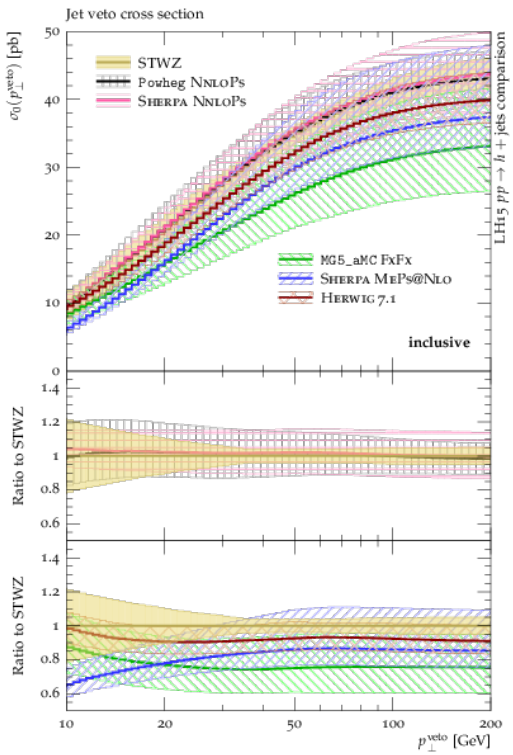
SHERPA h NNLO
GOSAM+SHERPA
hj NLO MINLO nNLO
hjj NLO MINLO nNLO
hjjj NLO MINLO
LH15 $pp \to h +$ jets comparison
$d\sigma/dn_j$ [pb]
Ratio to Powheg
n_j


Inclusive jet multiplicity
Powheg NNLOPS
SHERPA NNLOPS
MG5_aMC FxFx
SHERPA MEPS@NLO
HERWIG 7.1
HEJ
STWZ
RESBOS 2
SHERPA h NNLO
BFGLP hj NNLO
GOSAM+SHERPA
hj NLO MINLO nNLO
hjj NLO MINLO nNLO
hjjj NLO MINLO
LH15 $pp \to h +$ jets comparison
$d\sigma/dn_j$ [pb]
Ratio to Powheg
n_j


Leading jet transverse momentum ($n_j \geq 1$)
Powheg NNLOPS
Sherpa NNLOPS
MG5_aMC FxFx
Sherpa MEPs@NLO
Herwig 7.1
STWZ
ResBos 2
BFGLP hj NNLO
GoSam+Sherpa hj
NLO
MiNLO
nNLO
LH15 $pp \to h +$ jets comparison
Ratio to hj NNLO
$p_\perp(j_1)$ [GeV]


Subleading jet transverse momentum ($n_j \geq 2$)
Powheg NNLOPS
Sherpa NNLOPS
MG5_aMC FxFx
Sherpa MEPs@NLO
Herwig 7.1
Hej
GoSam+Sherpa hjj
NLO
MiNLO
nNLO
LH15 $pp \to h +$ jets comparison
Ratio to Powheg
$p_\perp(j_2)$ [GeV]


Jet veto cross section
STWZ
Powheg NNLOPS
Sherpa NNLOPS
MG5_aMC FxFx
Sherpa MEPs@NLO
Herwig 7.1
inclusive
LH15 $pp \to h +$ jets comparison
Ratio to STWZ
$p_\perp^{\text{veto}}$ [GeV]

plans

state of the game at half-time

- NLO (QCD) "revolution" consolidated:
  - lots of routinely used tools for large FS multis (4 and more)
  - incorporation in MC tools done, need comparisons, critical appraisals and a learning curve in their phenomenological use
  - to improve: description of loop–induced processes
- amazing success in NNLO (QCD) calculations:
  - emergence of first round of $2 \to 2$ calculations
  - next revolution imminent (with question marks)
  - first MC tools for simple processes ($gg \to H$, DY), more to be learnt by comparison etc. (see above)
- first N^{3}LO calculation in $gg \to H$, more to come (?)
- attention turning to NLO (EW)
  - first benchmarks with new methods (V+3j)
  - calculational setup tricky
  - need maybe faster approximation for high-scales (EW Sudakovs)

anticipating the second half

- practical limitations/questions to be overcome:
  - dealing with IR divergences at NNLO: slicing vs. subtracting

    (I'm not sure we have THE solution yet)
  - how far can we push NNLO? are NLO automated results stable enough for NNLO at higher multiplicity?
  - users of codes: higher orders tricky $\rightarrow$ training needed

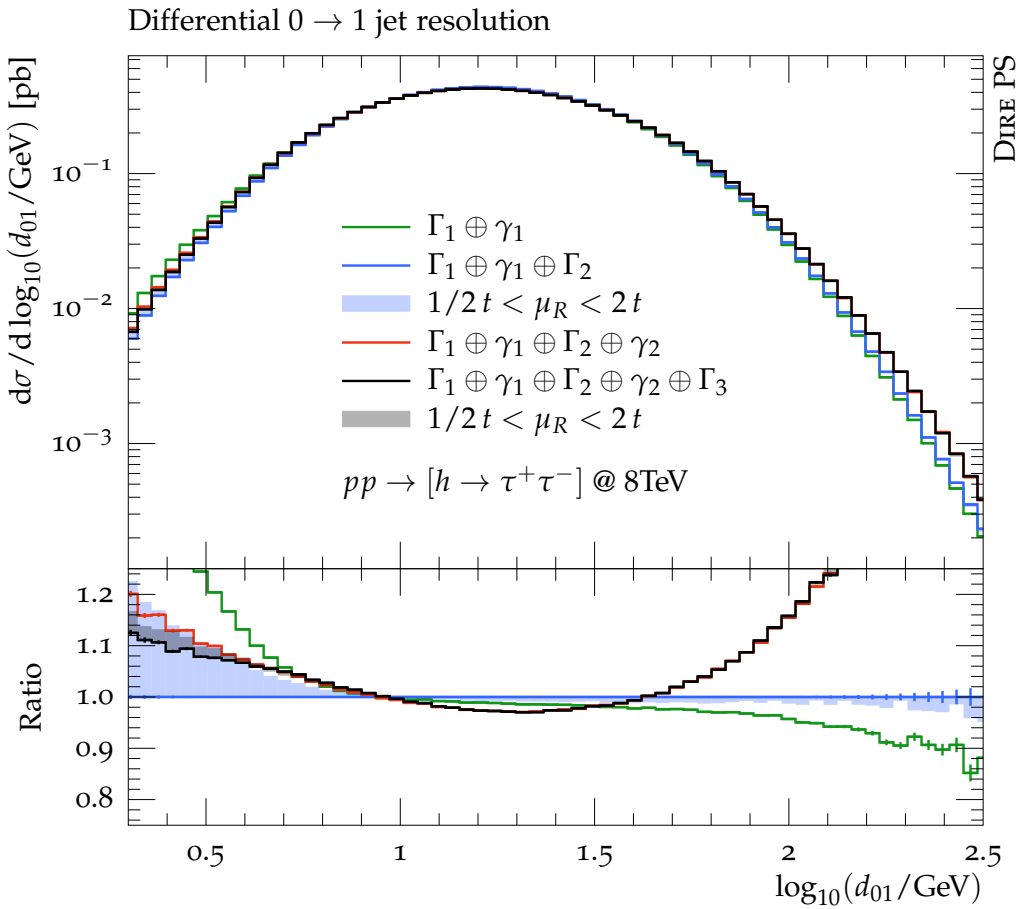
    (MC = black box attitude problematic - a new brand of pheno/experimenters needed?)
- limitations of perturbative expansion:
  - breakdown of factorisation at HO (Seymour et al.)
  - higher-twist: compare $(\alpha_S/\pi)^n$ with $\Lambda_{\rm QCD}/M_Z$

    (see Melnikov's talk last week)
- limitations in analytic resummation: process- and observable-dependent
  - first attempts at automation (CAESAR and some others) – checks/cross-comparison necessary
- showering needs to be improved

  (for NNLO the "natural" accuracy is NNLL)

second half, last minute

- first steps towards improvement of parton showers
- example below: μ_R uncertainty in $p_\perp^{(\mathrm{emit})}$ in ggF



overtime

- we have constructed lots of tools for precision physics at LHC
  but we did not cross-validate them careful enough (yet)
  but we did not compare their theoretical foundations (yet)
- we also need unglamorous improvements:
  - systematically check advanced scale-setting schemes (MINLO)
  - automatic (re-)weighting for PDFs & scales (ME: ✓, PS: -)
  - scale compensation in PS is simple (implement and check)
  - PDFs: to date based on FO vs. data — will we have to move to resummed/parton showered?

(reminder: LO* was not a big hit, though)

- ... and maybe we will have to go to the "dirty" corners:
  higher-twist, underlying event, hadronization, ...

(many of those driven by experiment)

penalties

(being German: I like them)

and maybe all of this is obsolete by summer . . .