MC Tools and NLO Monte Carlos

or

The Good, the Bad & the Ugly

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- what the talk is about
- the cutting edge in theory inputs
- matching & merging with parton showers
- where we are and where we (should/could/would) go

motivation & introduction

motivation: the need for (more) accurate tools

- to date no survivors in searches for new physics & phenomena

  (a pity, but that's what Nature hands to us)

- push into precision tests of the Standard Model

  (find it or constrain it!)

- statistical uncertainties approach zero

  (because of the fantastic work of accelerator, DAQ, etc.)

- systematic experimental uncertainties decrease

  (because of ingenious experimental work)

- theoretical uncertainties are or become dominant

  (it would be good to change this to fully exploit LHC's potential)

$\Longrightarrow$ more accurate tools for more precise physics needed!

motivation: aim of the exercise

- review the state of the art in precision simulations

  (celebrate success)

- highlight missing or ambiguous theoretical ingredients

  (acknowledge failure)

- suggest some further studies – experiment and theory

  (. . .)

reminder: fixed-order and its limits

the aftermath of the NLO (QCD) revolution

- establishing a wide variety of automated tools for NLO calculations

  BlackHat, GoSam, MadGraph, NJet, OpenLoops, Recola + automated IR subtraction methods (MadGraph, Sherpa)
- first full NLO (EW) results with such tools
- technical improvements still mandatory

  (higher multis, higher speed, higher efficiency, easier handling, . . .)
- start discussing scale setting prescriptions

  (simple central scales for complicated multi-scale processes? test smarter prescriptions?)
- steep learning curve still ahead: "NLO phenomenology"

  (example: methods for uncertainty estimates beyond variation around central scale)

the looming revolution: going beyond NLO

- 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)

  - $t\bar{t}$ (1303.6254; 1508.03585;1511.00549)
  - single-t (1404.7116)
  - VV (1507.06257; 1605.02716;1604.08576; 1605.02716)
  - HH (1606.09519)
  - VH (1407.4747; 1601.00658)
  - $V\gamma$ (1504.01330)
  - $\gamma\gamma$ (1110.2375; 1603.02663)
  - Vj (1507.02850; 1512.01291; 1602.06965)
  - Hj (1408.5325; 1504.07922; 1505.03893; 1508.02684)
  - jj (1310.3993)
- WBF at NNLO and N^{3}LO (1506.02660 and N^{3}LO 1606.00840)
- different IR subtraction schemes:
  N-jettiness slicing, antenna subtraction, sector decomposition,

challenging the revolution

- some technical issues at NNLO (and beyond)

  (stability of automated NLO, robustness under integration, subtraction vs. slicing)
- 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
- 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)

matching @ (N)NLO

merging @ (N)LO

prequel: parton showers vs. resummation calculations

- various schemes for various logs in analytic resummation
- concentrate on parton shower instead $\longleftrightarrow$ compare with Q_T resummation

(transverse momentum of Higgs boson etc.)

- parametric accuracy by comparing Sudakov form factors:

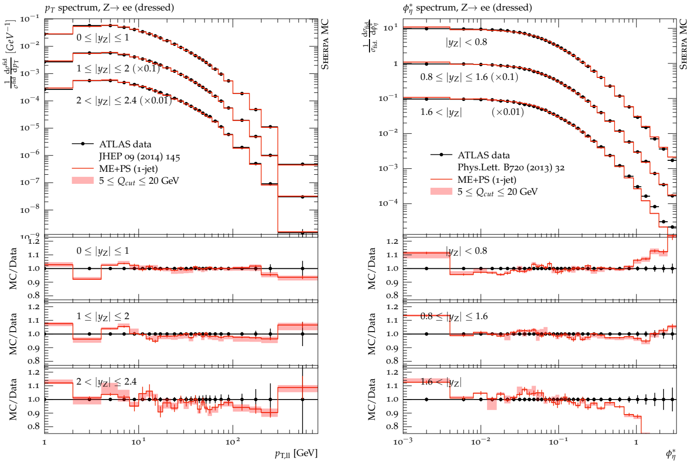
$$\Delta = \exp\left\{-\int \frac{\mathrm{d}k_\perp^2}{k_\perp^2}\left[A\log\frac{k_\perp^2}{Q^2}+B\right]\right\},$$

where A and B can be expanded in $\alpha_S(k_\perp^2)$

- showers usually include terms $A_{1,2}$ and B_1 (NLL)
- A_2 often realised by pre-factor multiplying scale $\mu_R \simeq k_\perp$

some parton shower fun with DY

(example of accuracy in description of standard precision observable)



matching at NLO and NNLO

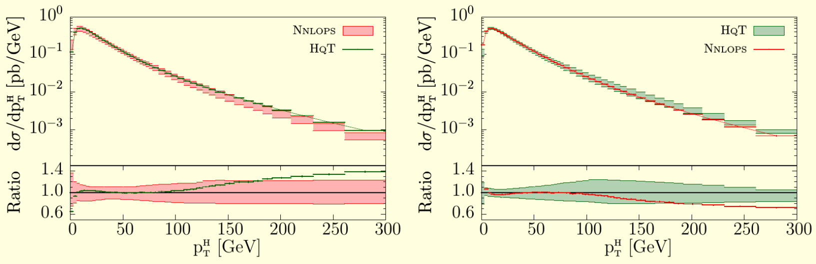
- avoid double-counting of emissions
- two schemes at NLO: MC@NLO and POWHEG
  - mismatches of K factors in transition to hard jet region
  - MC@NLO: $\longrightarrow$ visible structures, especially in $gg \to H$
  - POWHEG: $\longrightarrow$: high tails, cured by h dampening factor
  - well-established and well-known methods

(no need to discuss them any further)

- two schemes at NNLO: MINLO & UN^{2}LOPS (singlets S only)
  - different basic ideas
  - MINLO: $S + j$ at NLO with $p_T^{(S)} \to 0$ and capture divergences by reweighting internal line with analytic Sudakov, NNLO accuracy ensured by reweighting with full NNLO calculation for S production
  - UN^{2}LOPS identifies and subtracts and adds parton shower terms at FO from $S + j$ contributions, maintaining unitarity
  - available for two simple processes only: DY and $gg \to H$

NNLOPs for H production: MINLO

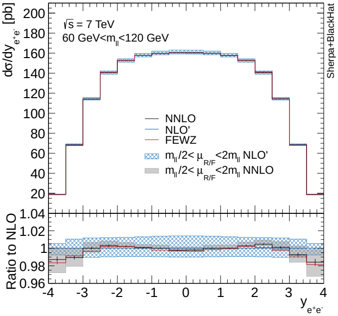
K. Hamilton, P. Nason, E. Re & G. Zanderighi, JHEP 1310

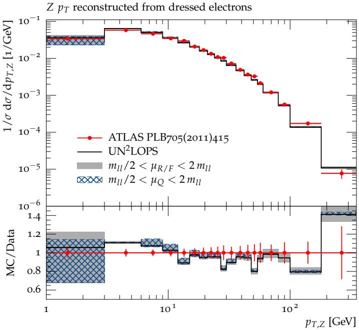


- also available for Z production

NNLOPs for Z production: UN^{2}LOPs

S. Hoche, Y. Li, & S. Prestel, Phys.Rev.D90 & D91





- also available for H production

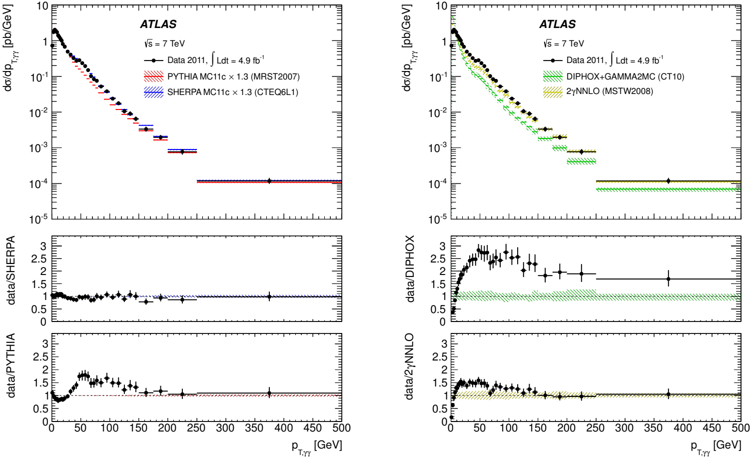
NNLOPS: shortcomings/limitations

- MINLO relies on knowledge of B_2 terms from analytic resummation
  $\longrightarrow$ to date only known for colour singlet production
- MINLO relies on reweighting with full NNLO result
  $\longrightarrow$ one parameter for H (y_H), more complicated for Z, ...

- UN^{2}LOPS relies on integrating single- and double emission to low scales and combination of unresolved with virtual emissions
  $\longrightarrow$ potential efficiency issues, need NNLO subtraction
- UN^{2}LOPS puts unresolved & virtuals in "zero-emission" bin
  $\longrightarrow$ no parton showering for virtuals (?)

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

(arXiv:1211.1913 [hep-ex])



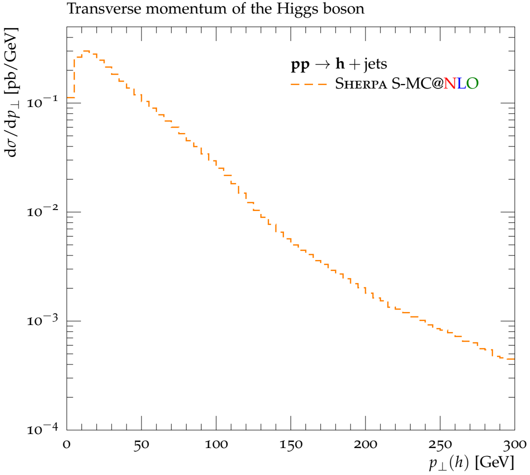
multijet-merging at NLO

- 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)

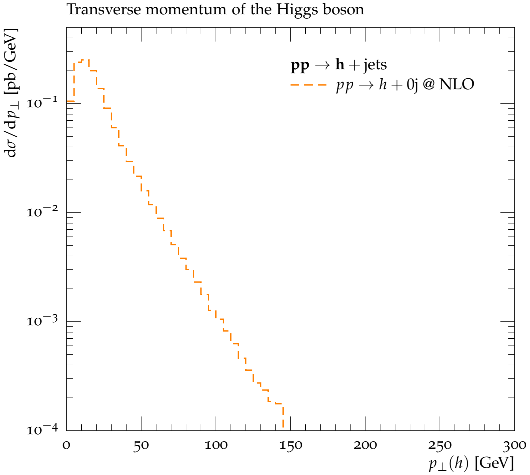
- starts being used, still lacks careful cross-validation

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



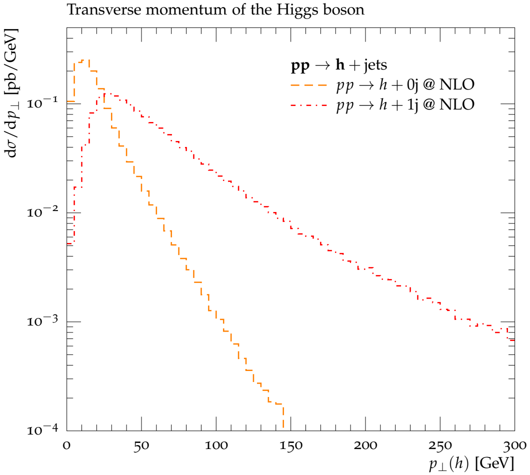
- first emission by MC@NLO

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



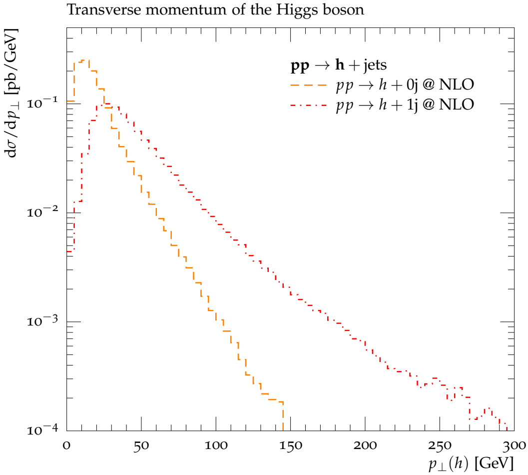
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$

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



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

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



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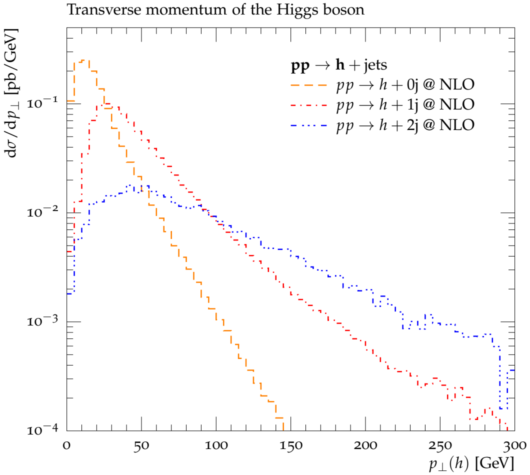

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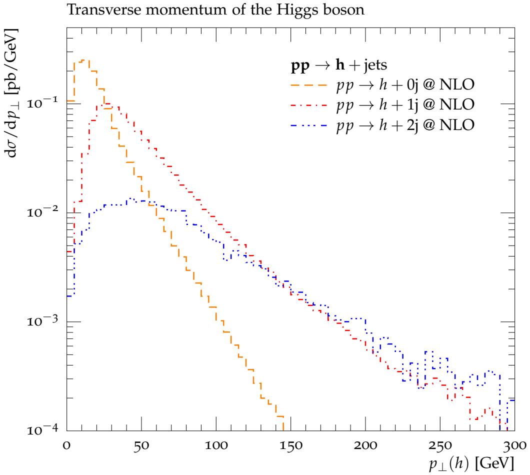
illustration: $p_\perp^H$ in MEPS@NLO



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- iterate

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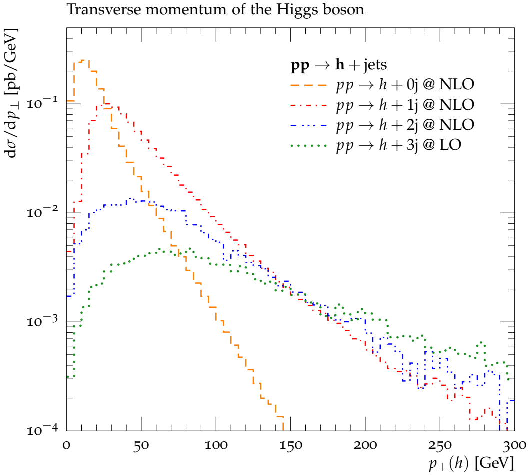

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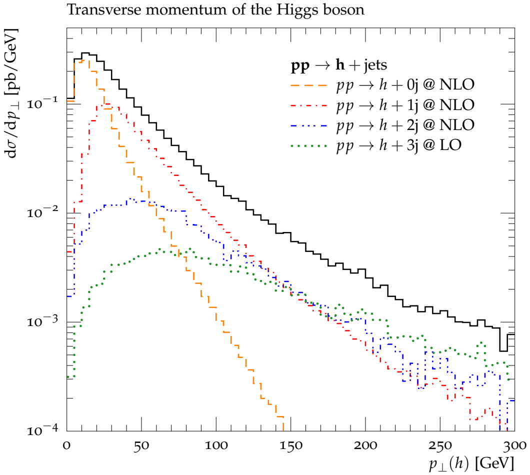

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- sum all contributions

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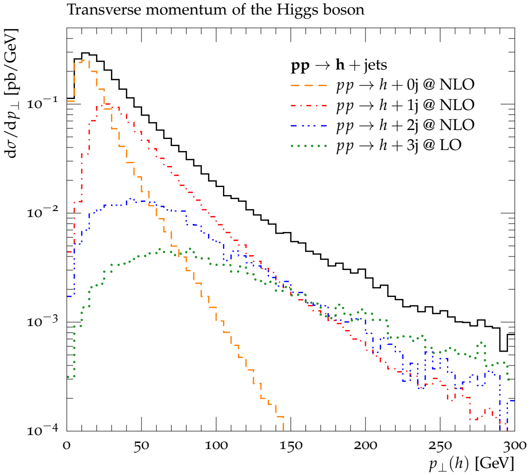

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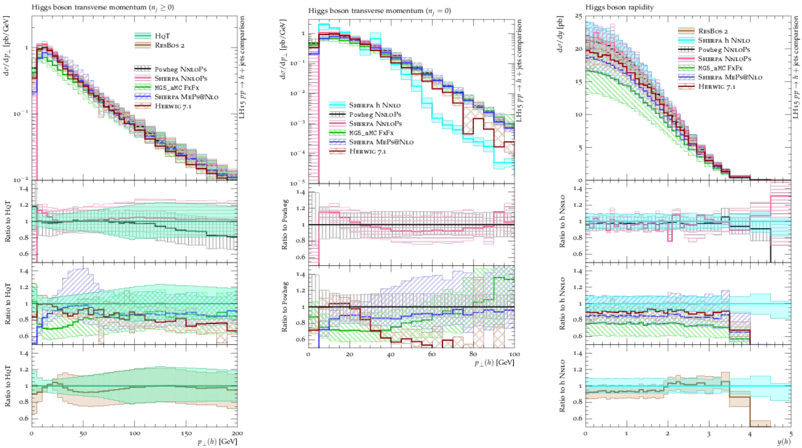
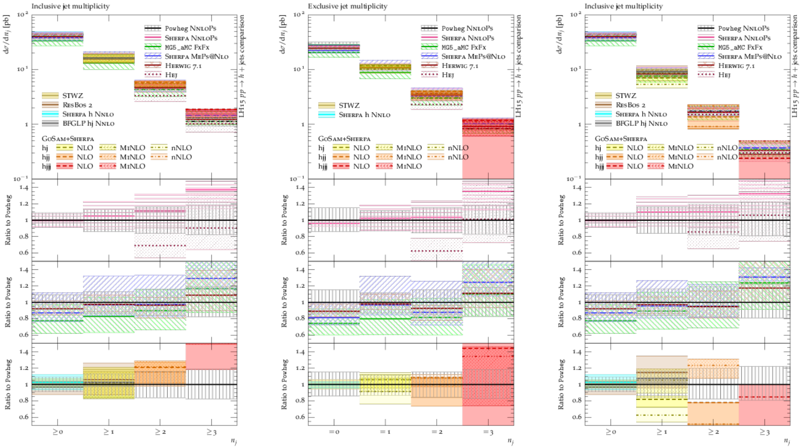
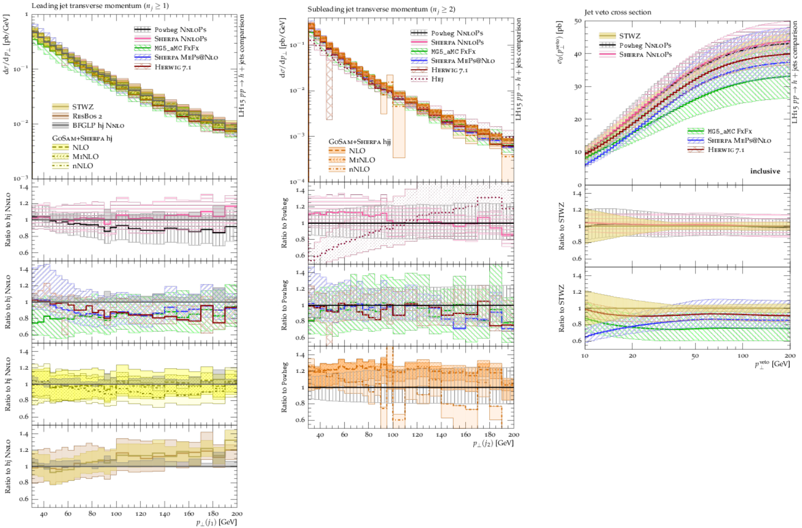
- MC@NLO $pp \to h + $2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate
- sum all contributions
- eg. $p_\perp(h) > 200$ GeV has contributions fr. multiple topologies

results from various schemes in H+jets through ggF

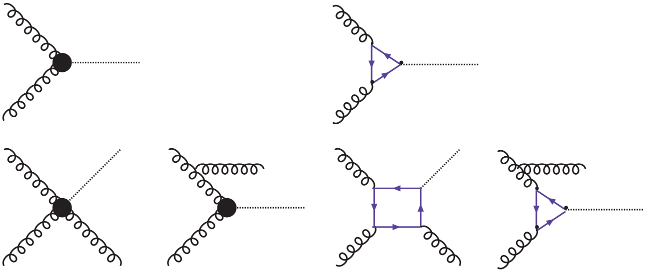



Inclusive jet multiplicity
Exclusive jet multiplicity
Inclusive jet multiplicity
dσ/dn_j [pb]
Powheg NNLOPs
Sherpa NNLOPs
MG5_aMC FxFx
Sherpa MePs@Nlo
Herwig 7.1
Hej
STWZ
ResBos 2
Sherpa h Nnlo
BFGLP hj Nnlo
GoSam+Sherpa
hj NLO MiNLO nNLO
hjj NLO MiNLO nNLO
hjjj NLO MiNLO
LH15 pp → h + jets comparison
Ratio to Powheg
≥0 ≥1 ≥2 ≥3
=0 =1 =2 =3
n_j


Leading jet transverse momentum ($n_j \geq 1$)
$d\sigma/dp_\perp$ [pb/GeV]
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 ($n_j \geq 2$)
HEJ
GoSam+Sherpa hjj
Ratio to Powheg
$p_\perp(j_2)$ [GeV]
Jet veto cross section
$\sigma_0(p_\perp^{veto})$ [pb]
inclusive
Ratio to STWZ
$p_\perp^{veto}$ [GeV]

aside: quark mass effects

- include effects of quark masses



- reweight NLO HEFT with LO ratio:

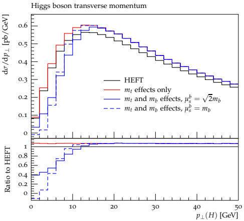
(reweight virtual with Born ratio, real with real ratio)

$$\mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{mass}} \approx \mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{HEFT}} \times \frac{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{mass}}}{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{HEFT}}}$$

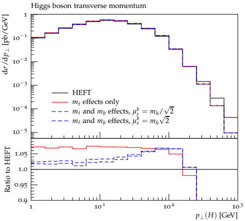
b–mass effects: playtime

- use LO multijet merging for tb-interference

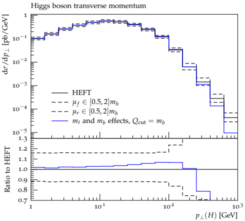
vary around $\mu_Q = m_b$



vary around $\mu_Q = m_h$ with $Q_{\rm cut} = m_b$ fixed



vary $\mu_{F,R}$



limitations of full simulations

- lots of routinely used tools for large FS multis (4 and more) at NLO accuracy, but
  $\longrightarrow$ not many detailled comparisons

  (critical appraisals and learning curve in their phenomenological use still in infancy)

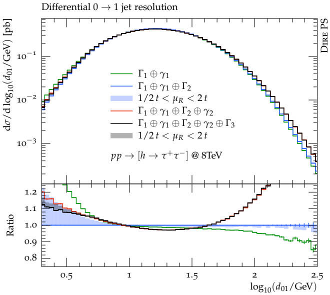
  $\longrightarrow$ no standard way of estimating uncertainties (yet?)
- to improve: description of loop–induced processes
  $\longrightarrow$ potentially important for new physics searches
- users of codes: higher orders tricky $\rightarrow$ training needed

  (MC = black box attitude problematic - a new brand of pheno/experimenters needed?)

a systematic uncertainty

- showering a source of uncertainty
  $\longrightarrow$ (N)LL only, scale variations?

  (quite often just used as black box)
- maybe include higher orders?
- example right:
  μ_R uncertainty in $p_\perp^{\rm (emit)}$ in ggF



limitations

theory limitations/questions

- we have constructed lots of tools for precision physics at LHC
  $\longrightarrow$ but we did not cross-validate them careful enough (yet)
  $\longrightarrow$ but we did not compare their theoretical foundations (yet)
- will NNLO (or beyond) become as automated as NLO?
  $\longrightarrow$ or more precisely: when and how?
- we also need unglamorous improvements on existing tools:
  - systematically check advanced scale-setting schemes (MINLO)
  - automatic (re-)weighting for PDFs & scales
  - scale compensation in PS is simple (implement and check)
- 4 vs. 5 flavour scheme $\longrightarrow$ really?
- how about α_S: range from 0.113 to 0.118

(yes, I know, but still - it still bugs me)

$\longrightarrow$ is there any way to settle this once and for all (measurements?)

more theory uncertainties/issues?

- with NNLOPS approaching 5% accuracy or better:
  - non-perturbative uncertainties start to matter:
    $\longrightarrow$ PDFs, MPIs, hadronization, etc.
  - question (example): with hadronization tuned to quark jets (LEP)
    $\longrightarrow$ how important is the "chemistry" of jets for JES?
    $\longrightarrow$ can we fix this with measurements?
  - example PDFs: to date based on FO vs. data
    $\longrightarrow$will we have to move to resummed/parton showered?

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

- $g \to q\bar{q}$ at accuracy limit of current parton showers:
  $\longrightarrow$ how bad are $\sim$ 25% uncertainty on $g \to b\bar{b}$?
  $\longrightarrow$ can we fix this with measurements?

plan

achievable goals in fixed order calculations: a roadmap (?)

- 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?
  - matching for generic processes at NNLO?

    (MINLO or UN^{2}LOPS or something new?)
- NLO for loop-induced processes:
  - fixed-order starting, MC@NLO tedious but straightforward
- EW NLO corrections with tricky/time-consuming calculational setup
  - but important at large scales: effect often $\sim$ QCD, but opposite sign
  - need maybe faster approximation for high-scales (EW Sudakovs)

"curable" bottleneck: colours/spins in parton showers

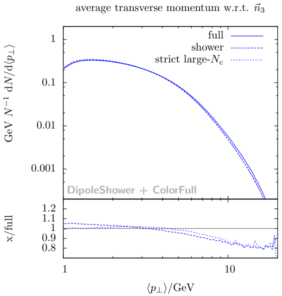
- parton shower usually is spin-averaged, leading colour, (next-to) leading log
- start including next-to leading colour

(first attempts by Platzer & Sjodahl; Nagy & Soper)

- no big effects in $e^-e^+ \to$ hadrons seen maybe more exclusive observables?
- aside: can also include spin-correlations important for EW emissions

(maybe relevant for ultra-high energies)

- HO being implemented at nthe moment



outlook

- will need precision for ballistics of smoking guns