The Quest for Precision in Simulations for the LHC

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- what the talk is about
- fixed order & matching & merging with parton showers
- revisiting 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

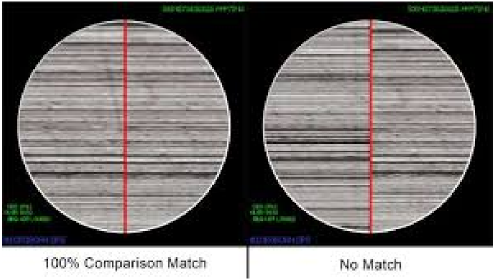
  (because of the fantastic work of accelerator, DAQ, etc.)

- 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) need more precise & accurate tools for more precise physics



matching @ (N)NLO

and

merging @ (N)LO

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 automated 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)

matching at NLO and NNLO

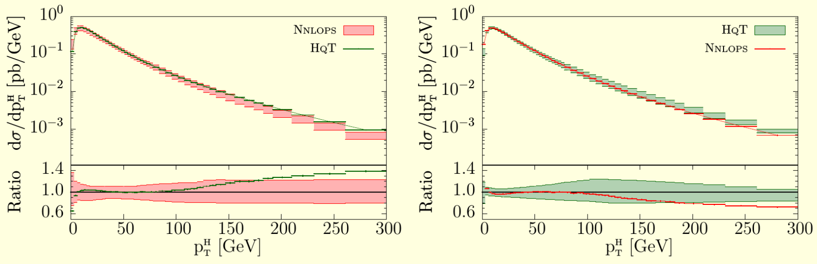
- avoid double-counting of emissions
- two schemes at NLO: MC@NLO and POWHEG
  - mismatches of K factors in transition to hard jet region
  - MC@NLO: $\longrightarrow$ visible structures, especially in $gg \to H$
  - POWHEG: $\longrightarrow$ high tails, cured by h dampening factor
  - well-established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

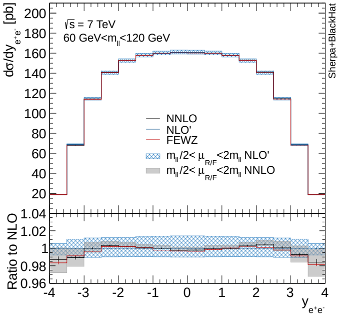
K. Hamilton, P. Nason, E. Re & G. Zanderighi, JHEP 1310

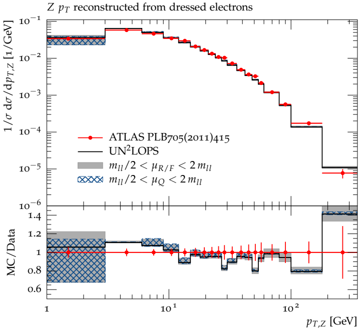


- also available for $Z/W/VH$ production

NNLOPs for Z production: UN^{2}LOPs

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





- also available for H production

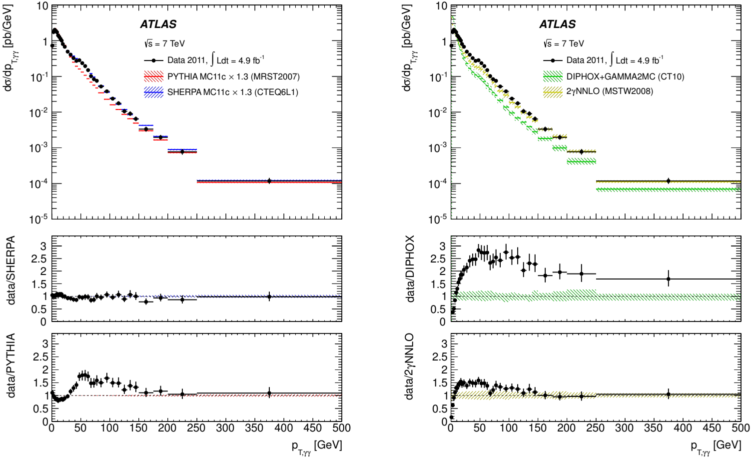
NNLOPS: shortcomings/limitations

- 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])

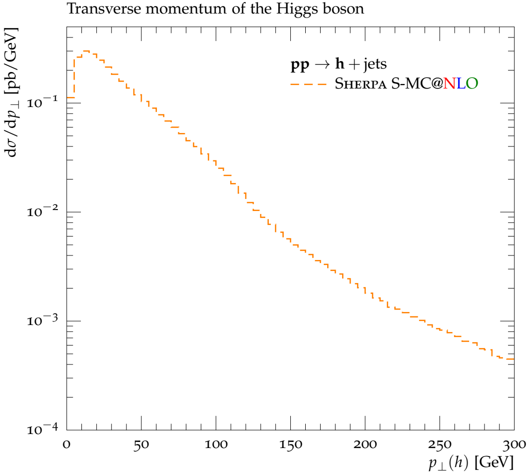


multijet-merging at NLO

- 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

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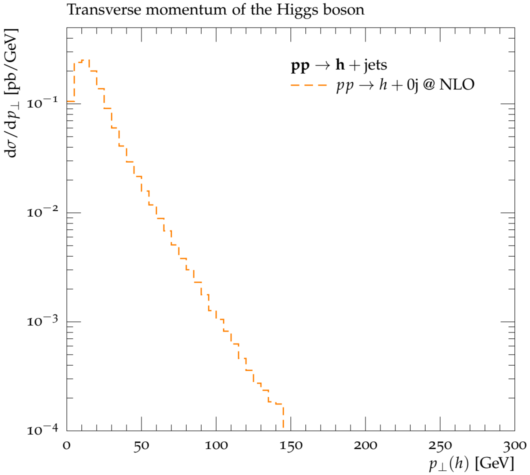

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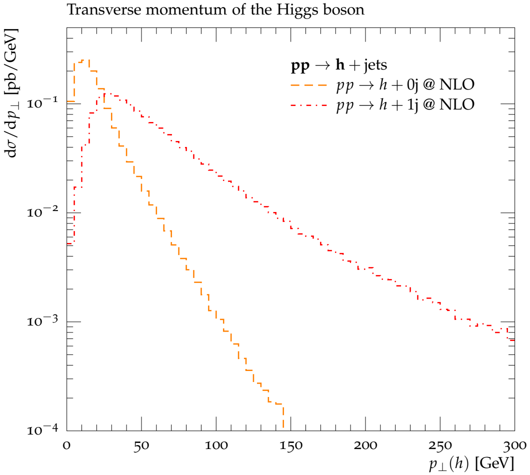

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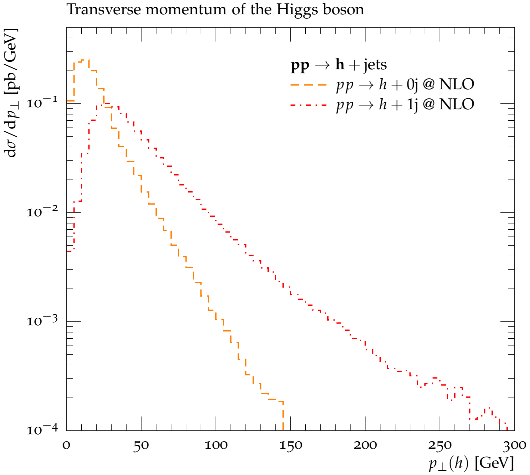

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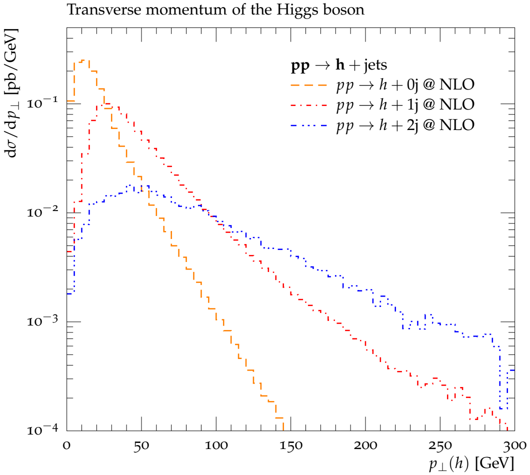

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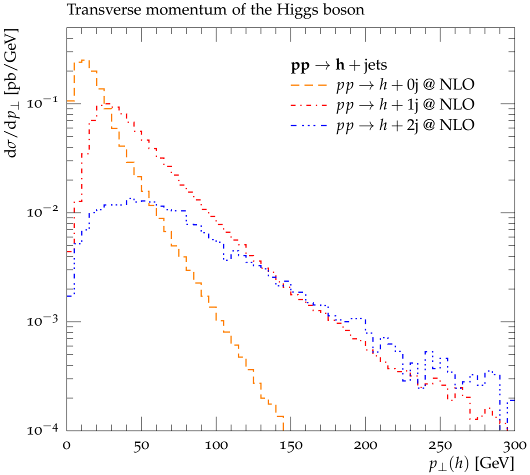

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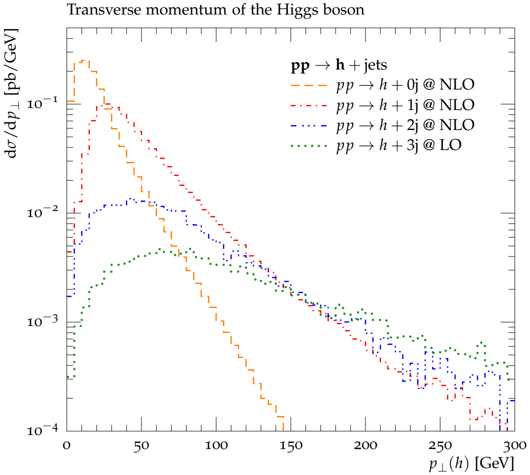

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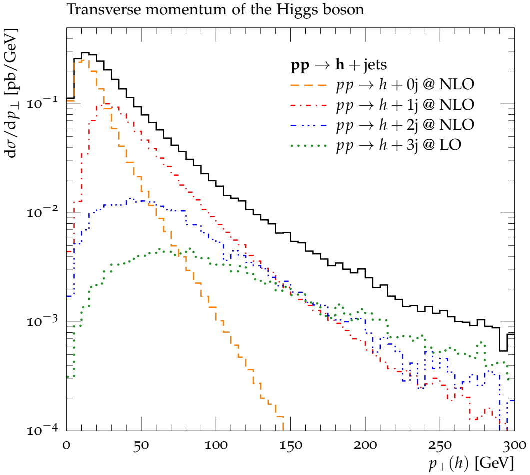

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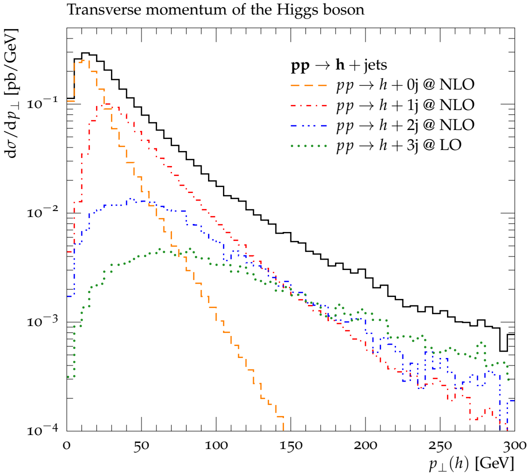

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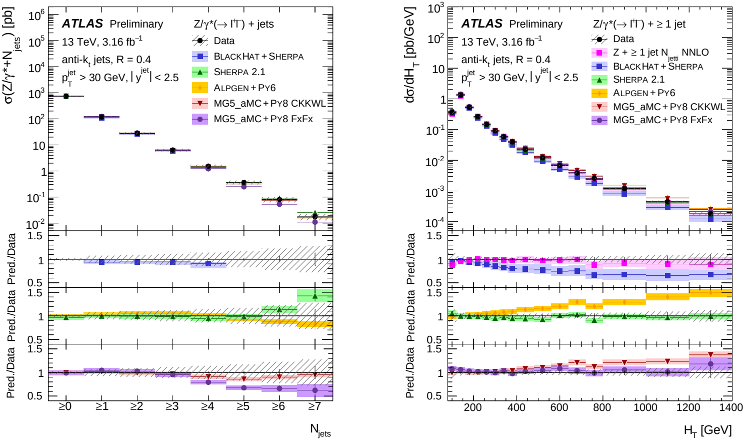
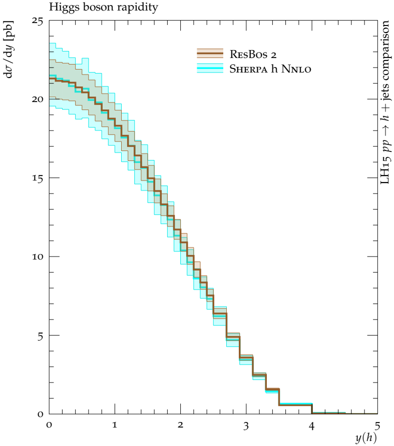
- sum all contributions
- eg. $p_\perp(h)$>200 GeV has contributions fr. multiple topologies

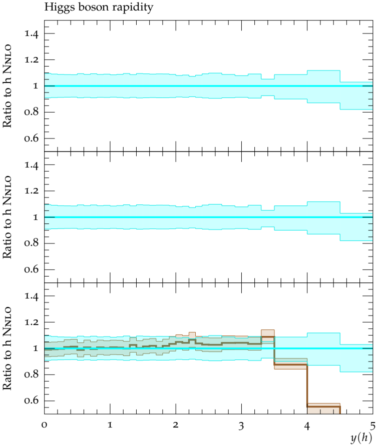
Z+jets at 13 Tev: comparison with ATLAS data

- various merging codes at LO and NLO



inclusive Higgs boson rapidity





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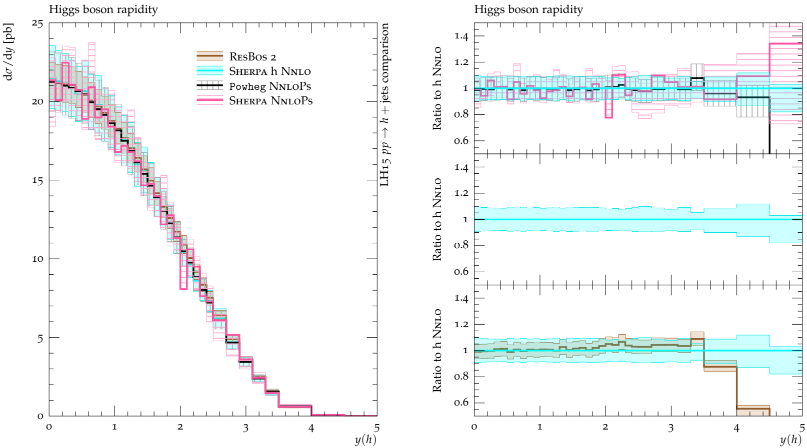

- excellent agreement between NNLO and NNLOPs

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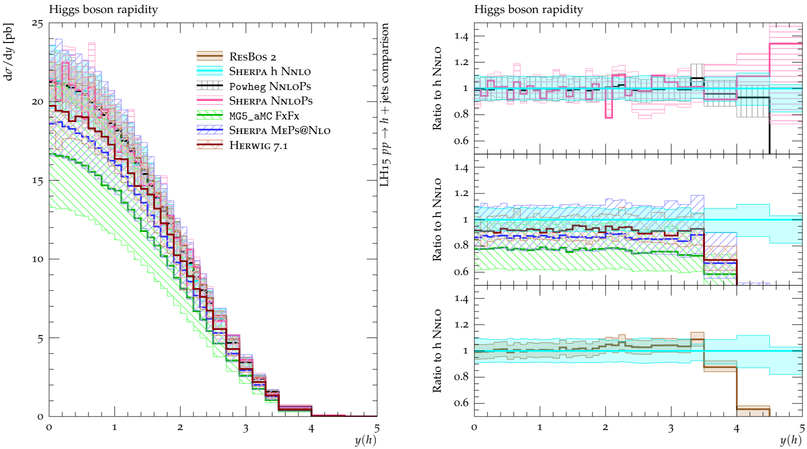
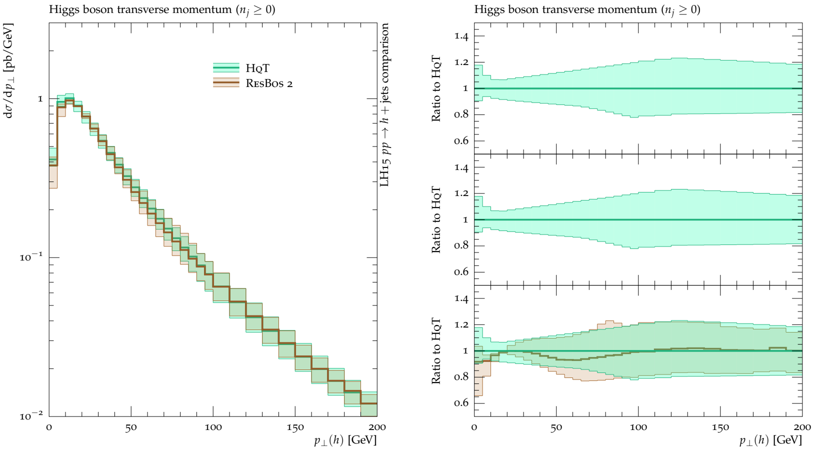


- excellent agreement between NNLO and NNLOPs
- multijet merged with NLO normalisation, PDF effects

Higgs boson transverse momentum ($n_j \geq 0$)



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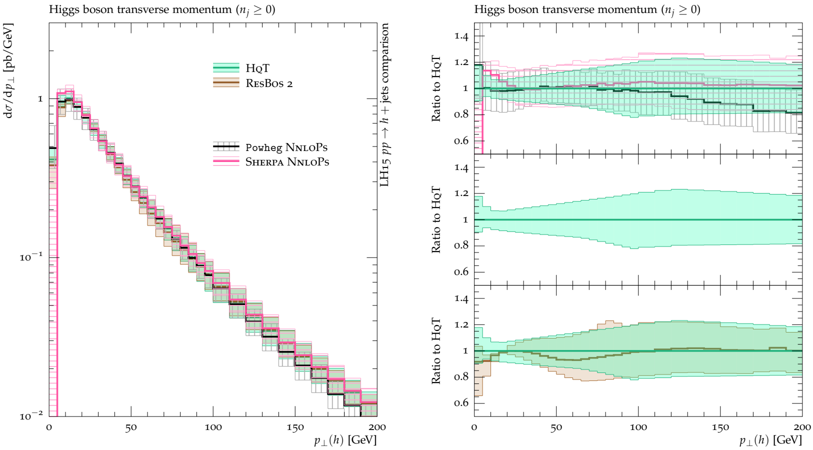

- good agreement between HqT and NNLOPs, scale choice at high $p_\perp$

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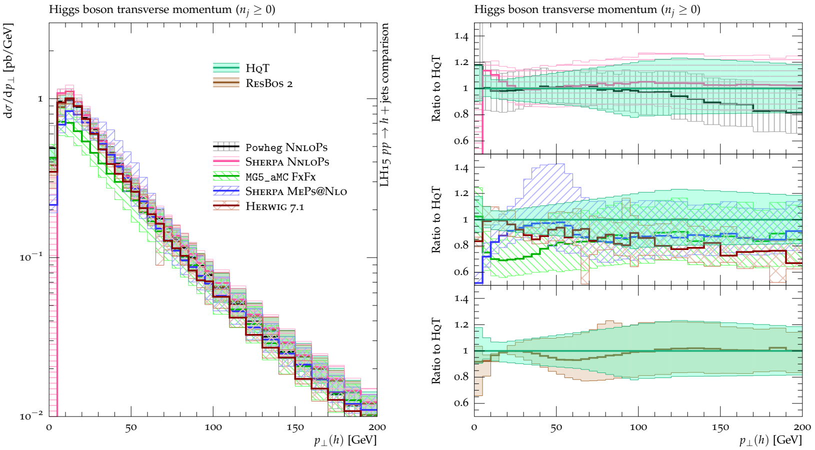
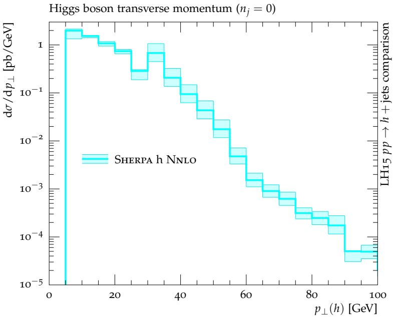


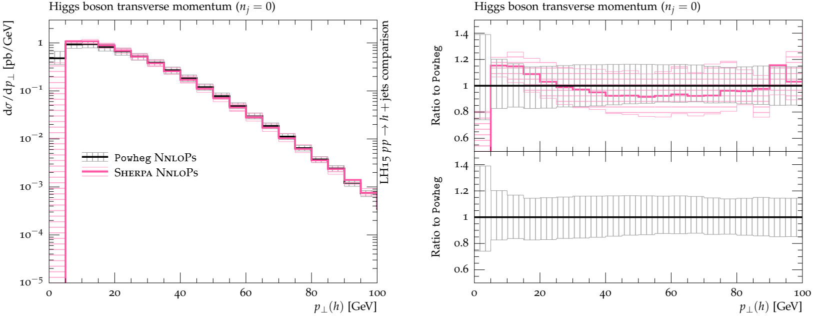
- good agreement between HqT and NNLOPs, scale choice at high $p_\perp$
- multijet merged with NLO normalisation, very different at low $p_\perp$

Higgs boson transverse momentum ($n_j = 0$)



- fixed-order has various unphysical features

Higgs boson transverse momentum ($n_j = 0$)



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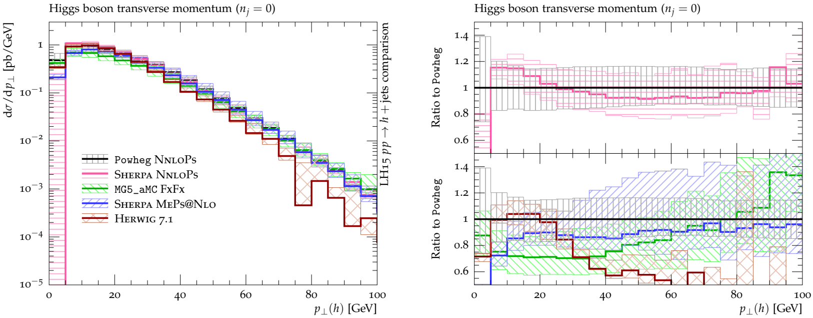
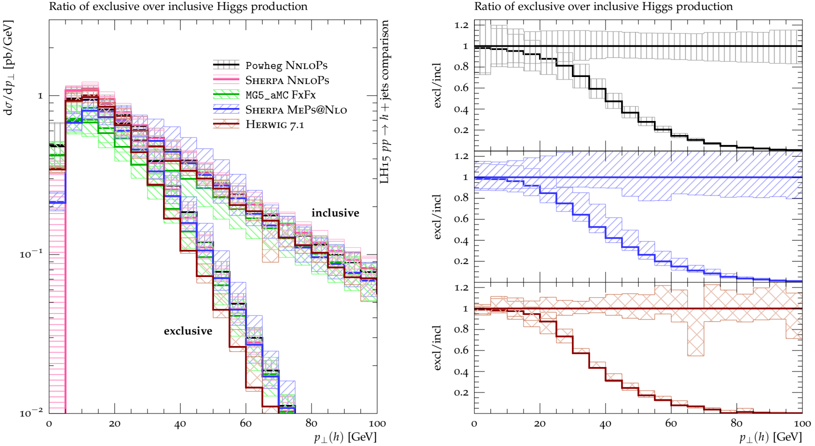


- fixed-order has various unphysical features
- good agreement between the NNLOPs
- multijet merged with NLO normalisation, HERWIG7 has much less soft radiation

exclusive over inclusive rate



- $\approx 20\%$ of Higgs with $p_\perp = 60\,\text{GeV}$ are not accompanied by a jet

including EW corrections

EW corrections

- EW corrections sizeable $\mathcal{O}(10\%)$ at large scales: must include them!
- but: more painful to calculate
- need EW showering & possibly corresponding PDFs

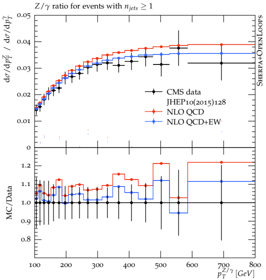
(somewhat in its infancy: chiral couplings)

- example: Z/γ vs. p_T (right plot)

(handle on $p_\perp^Z$ in $Z \to \nu\bar{\nu}$)

(Kallweit, Lindert, Pozzorini, Schoenherr for LH'15)

- difference due to EW charge of Z
- no real correction (real V emission)
- improved description of $Z \to \ell\ell$



NLO EW subtraction in SHERPA

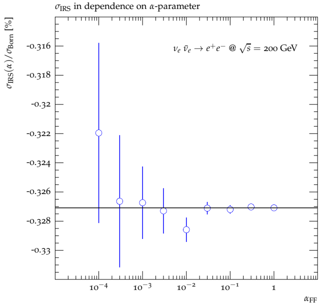
(M. Schoenherr in preparation)

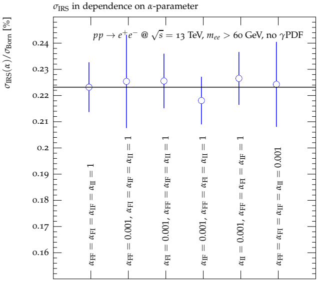
- adapt QCD subtraction (spl. fns. and colour-/spin-correlated MEs)

(Catani, Dittmaier, Seymour, Trocsanyi Nucl.Phys.B627(2002)189-265)

- replacements: $\alpha_s \to \alpha,\ C_F \to Q_f^2,\ C_A \to 0,$
  $T_R \to N_{c,f}\, Q_f^2,\ n_f\, T_R \to \sum_f N_{c,f}\, Q_f^2,$

$$\frac{\mathbf{T}_{ij}\cdot\mathbf{T}_k}{\mathbf{T}_{ij}^2} \longrightarrow \frac{Q_{ij}Q_k}{Q_{ij}^2}$$





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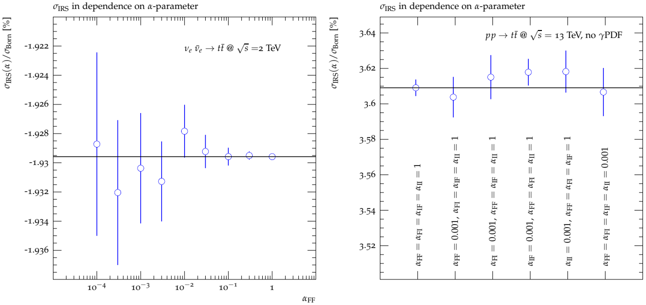

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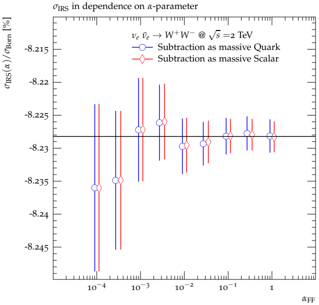
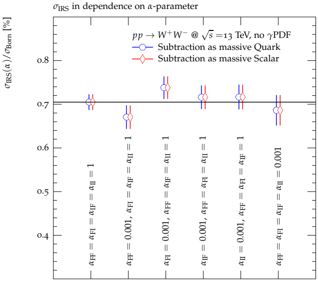




inclusion of electroweak corrections in simulation

- incorporate approximate electroweak corrections in MEPS@NLO
  1. using electroweak Sudakov factors

$$\tilde{\mathrm{B}}_n(\Phi_n) \;\approx\; \tilde{\mathrm{B}}_n(\Phi_n)\,\Delta_{\mathrm{EW}}(\Phi_n)$$

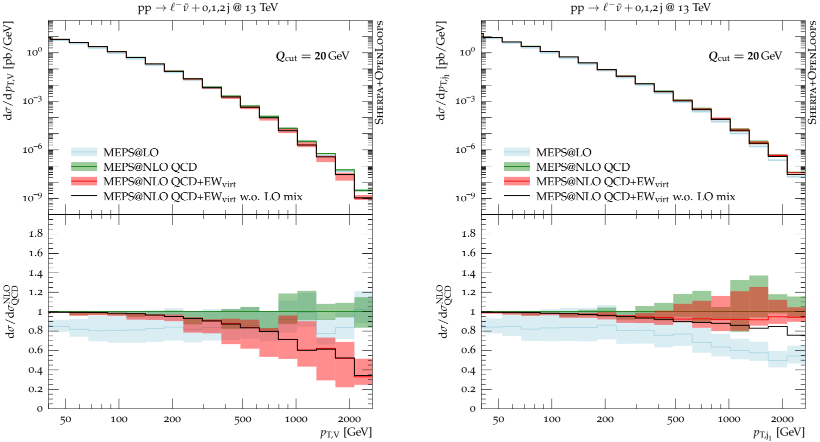
  2. using virtual corrections and approx. integrated real corrections

$$\tilde{\mathrm{B}}_n(\Phi_n) \;\approx\; \tilde{\mathrm{B}}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD$\oplus$EW matching and merging
  $\to$ validated at fixed order, found to be reliable,
  difference $\lesssim 5\%$ for observables not driven by real radiation

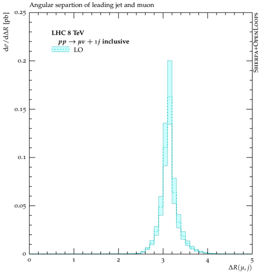
results: $pp \to \ell^- \bar{\nu} + \text{jets}$

(Kallweit, Lindert, Maierhöfer, Pozzorini, Schoenherr JHEP04(2016)021)



$\Rightarrow$ particle level events including dominant EW corrections

NLO EW predictions for $\Delta R(\mu, j_1)$



measure collinear W emission?

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$

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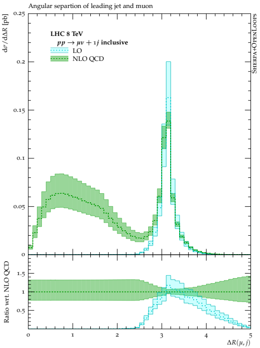

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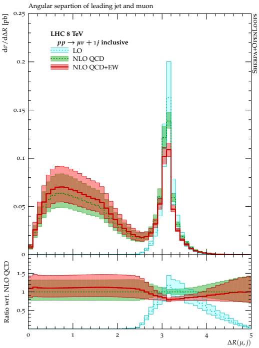

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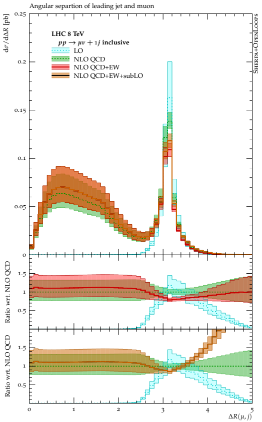

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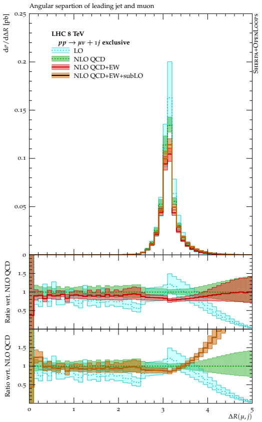

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- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV

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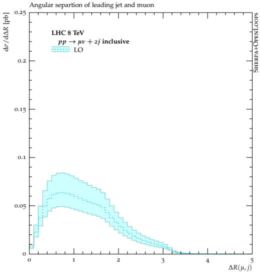

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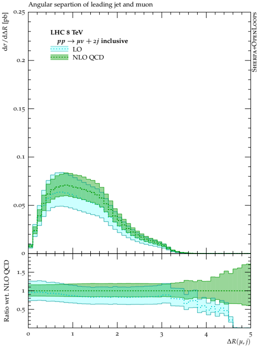
- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV

NLO EW predictions for $\Delta R(\mu, j_1)$



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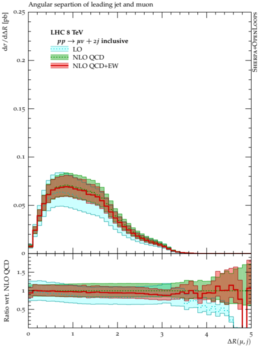

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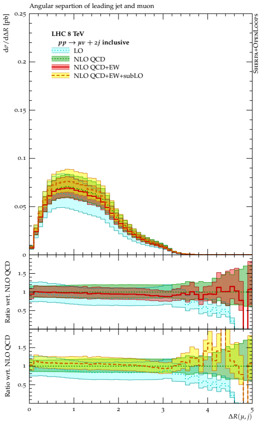

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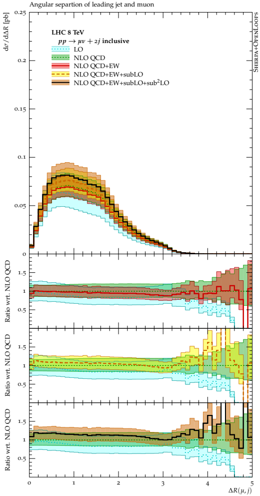

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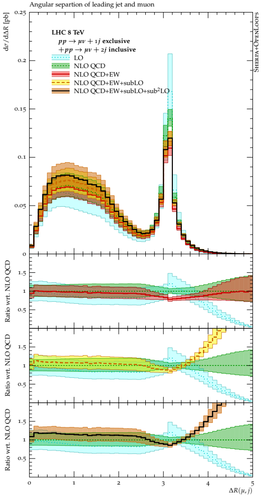

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- merge using exclusive sums

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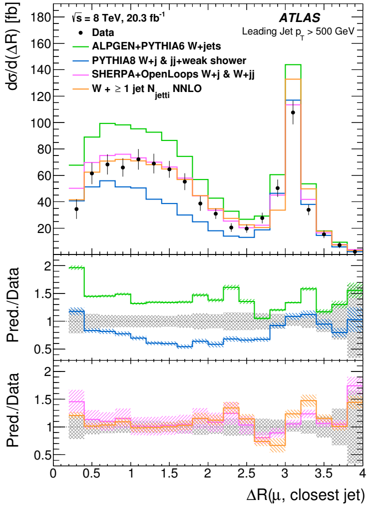

Data comparison

(M. Wu ICHEP'16, ATLAS arXiv:1609.07045)

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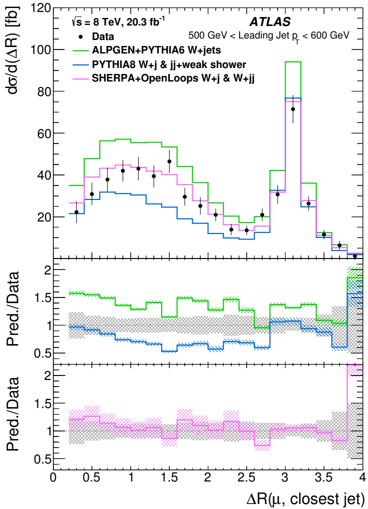

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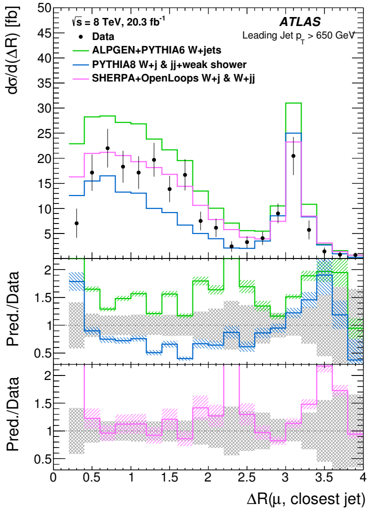

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improving parton showers

motivation: why care?

- QCD radiation omnipresent at the LHC
- enters as signal (and background) in high-$p_\perp$ analyses
  - multi-jet signatures

    $\longrightarrow$ multijet merging & higher-order matching (not the topic today)
  - inner-jet structures e.g. from "fat jets"

    $\longrightarrow$ parton shower algorithms
- begs the question:

  can we improve on parton showers and increase their precision?

(keep in mind: accuracy vs. precision)

another systematic uncertainty

- parton showers are approximations, based on

  leading colour, leading logarithmic accuracy, spin-average
- 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 $\alpha_S(k_\perp^2)$
- Q_T resummation includes $A_{1,2,3}$ and $B_{1,2}$

  (transverse momentum of Higgs boson etc.)
- showers usually include terms $A_{1,2}$ and B_1

  A = cusp terms ("soft emissions"), $B \sim$ anomalous dimensions γ

connection to fragmentation functions

- DGLAP for FFs:

$$\frac{\mathrm{d}\, xD_a(x,\ t)}{\mathrm{d}\log t} = \sum_{b=q,g}\int\limits_0^1 \mathrm{d}\tau \int\limits_0^1 \mathrm{d}z\, \delta(x-\tau z)\, \frac{\alpha_S}{2\pi}\, [zP_{ab}(z)]_+\, \tau D_b(\tau, t)\,.$$

- rewrite for definition of "+"-function, $[zP_{ab}(z)]_+ = \lim\limits_{\epsilon\to 0} zP_{ab}(z,\epsilon)$:

$$P_{ab}(z,\epsilon) = P_{ab}(z)\,\Theta(1-z-\epsilon) - \delta_{ab}\sum_{c=q,g}\frac{\Theta(1-z-\epsilon)}{\epsilon}\int\limits_0^1 \mathrm{d}\xi\, \xi P_{ac}(\xi)$$

$$\frac{\mathrm{d}\,\log D_a(x,t)}{\mathrm{d}\,\log t} = \underbrace{-\sum_{c=q,g}\int\limits_0^{1-\epsilon}\mathrm{d}\xi\,\frac{\alpha_S}{2\pi}\,\xi P_{ac}(\xi)}_{\text{derivative of Sudakov}} + \sum_{b=q,g}\int\limits_x^{1-\epsilon}\frac{\mathrm{d}z}{z}\,\frac{\alpha_S}{2\pi}\,P_{ac}(z)\,\frac{D_b(\frac{x}{z},t)}{D_a(x,t)}$$

- re-introduce Sudakov form factor

$$\Delta_a(t,t_0) = \exp\left\{-\int\limits_{t_0}^{t}\frac{\mathrm{d}t'}{t'}\sum_{c=q,g}\int\limits_0^{1-\epsilon}\mathrm{d}\xi\,\frac{\alpha_S}{2\pi}\,\xi P_{ac}(\xi)\right\}$$

to express equation above through generating functional $\mathcal{D}_a(x,t,\mu^2) = D_a(x,t)\Delta_a(\mu^2,t)$:

$$\frac{\mathrm{d}\,\log\mathcal{D}_a(x,t,\mu^2)}{\mathrm{d}\,\log t} = \sum_{b=q,g}\int\limits_x^{1-\epsilon}\frac{\mathrm{d}z}{z}\frac{\alpha_S}{2\pi}\,P_{ac}(z)\,\frac{D_b(\frac{x}{z},t)}{D_a(x,t)}$$

- add initial states (PDFs) & arrive at argument(s) for Sudakov form factors when jets not measured

$$\sum_{i\in IS}\sum_{b=q,g}\int\limits_{x_i}^{1-\epsilon}\frac{\mathrm{d}z}{z}\frac{\alpha_S}{2\pi}\,P_{ba_i}(z)\,\frac{f_b(\frac{x_i}{z},t)}{f_{a_i}(x,t)}+\sum_{j\in FS}\sum_{b=q,g}\int\limits_{x_i}^{1-\epsilon}\mathrm{d}z\,z\frac{\alpha_S}{2\pi}\,P_{a_jb}(z)\,.$$

subtle symmetry factors

- observations for LO PS in final state:
  - only $P_{qq}^{(0)}$ used but not $P_{qg}^{(0)}$
  - $P_{gg}^{(0)}$ comes with "symmetry factor" 1/2
- challenge this way of implementing symmetry through:

(Jadach & Skrzypek, hep-ph/0312355)

$$\sum_{i=q,g}\int\limits_0^{1-\epsilon}\mathrm{d}z\,z\,P_{qi}^{(0)}(z) = \int\limits_\epsilon^{1-\epsilon}\mathrm{d}z\,P_{qq}^{(0)}(z)+\mathcal{O}(\epsilon)$$

$$\sum_{i=q,g}\int\limits_0^{1-\epsilon}\mathrm{d}z\,z\,P_{gi}^{(0)}(z) = \int\limits_\epsilon^{1-\epsilon}\mathrm{d}z\,\left[\frac{1}{2}P_{gg}^{(0)}(z)+n_f P_{gq}^{(0)}(z)\right]+\mathcal{O}(\epsilon)$$

- net effect: replace symmetry factors by parton marker z

implementation in DIRE

- evolution and splitting parameter $((ij) + k \to i + j + k)$:

$$\kappa^2_{j,ik} = \frac{4(p_i p_j)(p_j p_k)}{Q^4} \quad \text{and} \quad z_j = \frac{2(p_j p_k)}{Q^2}\,.$$

- splitting functions including IR regularisation

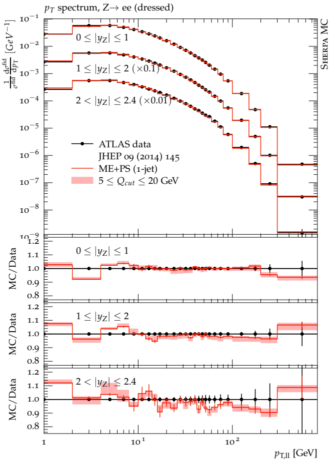
(a la Curci, Furmanski & Petronzio, Nucl.Phys. B175 (1980) 27-92)

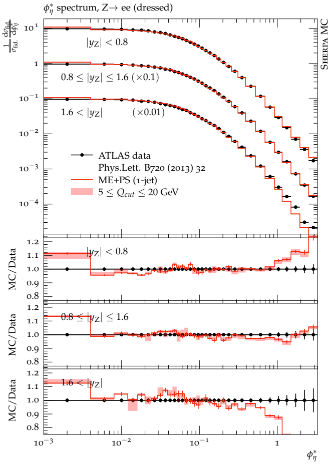
$$\begin{aligned}
P^{(0)}_{qq}(z,\kappa^2) &= 2C_F\left[\frac{1-z}{(1-z)^2+\kappa^2} - \frac{1+z}{2}\right]\,,\\
P^{(0)}_{qg}(z,\kappa^2) &= 2C_F\left[\frac{z}{z^2+\kappa^2} - \frac{2-z}{2}\right]\,,\\
P^{s(0)}_{gg}(z,\kappa^2) &= 2C_A\left[\frac{1-z}{(1-z)^2+\kappa^2} - 1 + \frac{z(1-z)}{2}\right]\,,\\
P^{(0)}_{gq}(z,\kappa^2) &= T_R\left[z^2+(1-z)^2\right]
\end{aligned}$$

- renormalisation/factorisation scale given by $\mu = \kappa^2 Q^2$
- combine gluon splitting from two splitting functions with different spectators $k \to$ accounts for different colour flows

LO results for Drell-Yan

(example of accuracy in description of standard precision observable)





including NLO splitting kernels

including NLO splitting kernels

(Hoeche, FK & Prestel, 1705.00982, and Hoeche & Prestel, 1705.00742)

- expand splitting kernels as

$$P(z,\,\kappa^2)\;=\;P^{(0)}(z,\,\kappa^2)\,+\,\frac{\alpha_S}{2\pi}\,P^{(1)}(z,\,\kappa^2)$$

- aim: reproduce DGLAP evolution at NLO
  include all NLO splitting kernels
- three categories of terms in $P^{(1)}$:
  - cusp (universal soft-enhanced correction) (already included in original showers)
  - corrections to $1\to 2$
  - new flavour structures (e.g. $q\to q'$), identified as $1\to 3$
- new paradigm: two independent implementations

implementation details: $1 \to 2$ splittings

- problem: new pole structure $1/z$ appears
- in final-state shower: symmetrisation yields extra factor z

  (such a factor is present in IS shower)
- this factor accounts for $1/2$ typically applied to $g \to gg$
- include also $q \to gq$ splitting
- physical interpretation:
  - "unconstrained" (without) vs. "constrained" evolution

    (DGLAP evolution for fragmentation functions)
  - factor z explicitly guarantees (momentum) sum rules
  - it also identifies final state particle

- symmetry factors not so clear at NLO $\longrightarrow$ more care needed

$$\sum_{b=q,g,b\neq a}\int\limits_0^{1-\epsilon}\mathrm{d}z_1\int\limits_0^{1-\epsilon}\mathrm{d}z_2\,\frac{z_1z_2}{1-z_1}\,\Theta(1-z_1-z_2)$$

$$\times\left[P_{a\to ba\bar{b}}(z_1,z_2,\dots)+P_{a\to b\bar{b}a}(z_1,z_2,\dots)\right]$$

$$=\quad\sum_{b=q,g,b\neq a}\int\limits_0^{1-\epsilon}\mathrm{d}z_1\int\limits_0^{1-z_1}\mathrm{d}z_2\,\frac{1}{\prod\limits_{i=q,g}n_i!}\,P_{a\to ba\bar{b}}(z_1,z_2,\dots)+\mathcal{O}(\epsilon)$$

$1 \to 3$ flavour changing kernels

(Hoeche & Prestel, 1705.00742)

- start with triple-collinear splitting functions

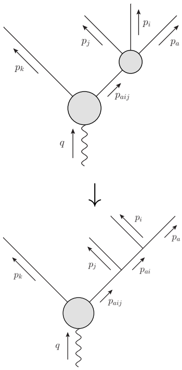
  (Campbell & Glover, hep-ph/9710255 & Catani & Grazzini, hepph/9908523)

- re-interpret splitting as sequential:
  $(aij) + k \to (ai) + j + k \otimes (ai) + k \to a + i + k$
- kinematic mappings from CDST

  (Catani, Dittmaier, Seymour & Trocsanyi, hep-ph/0201036)

- evolution and splitting parameters:

$$\begin{aligned} t &= \frac{4(p_j p_{ai})(p_{ai} p_k)}{q^2 - m_{aij}^2 - m_k^2}\,, \quad z_a = \frac{2 p_a p_k}{q^2 - m_{aij}^2 - m_k^2} \\ s_{ai} &= 2 p_a p_i + m_a^2 + m_i^2\,, \quad x_a = \frac{p_a p_k}{p_{ai} p_k} \end{aligned}$$



- phase space factorised by successive s-channels:

(Dittmaier, hep-ph/9904440)

$$d\Phi_{+2} = \left[\frac{1}{4(2\pi)^3}\frac{dt}{t}dz_a d\phi_j J_{FF}^{(1)}\right]\left[\frac{1}{4(2\pi)^3}ds_{ai}\frac{dx_a}{x_a}d\phi_i J_{FF}^{(2)}\,(2p_{ai}p_j)\right]$$

- combine with ME in coll. limit $\longrightarrow$ diff. branching probability:

$$\frac{d\,\log\Delta^{1\to 3}_{(aij)a}}{d\,\log t} = \int dz_a \int ds_{ai} \int \frac{dx_a}{x_a} \int \frac{d\phi}{2\pi}\left(\frac{\alpha_S}{2\pi}\right)^2 \frac{z_a z_i}{1-z_a}\frac{P_{(aij)a}(p_a,p_i,p_j)}{s^2_{aij}/(2p_a p_j)}$$

with $P_{(aij)a}$ = triple-collinear splitting function

subtractions

- must subtract spin-correlated iterated $1 \to 2$ splittings

$$\frac{\mathrm{d}\ \log \Delta^{(1\to 2)^2}_{(aij)a}}{\mathrm{d}\ \log t} = \int \mathrm{d}z_a \int \frac{\mathrm{d}s_{ai}}{s_{ai}} \int \frac{\mathrm{d}\xi}{\xi} \left(\frac{\alpha_S}{2\pi}\right)^2 \frac{z_a z_i}{1-z_a} \frac{P^{(0)}_{(aij)(ai)}(\xi)\, P^{(0)}_{(ai)a}(\frac{z_a}{\xi})}{s_{aij}/(2p_a p_j)}$$

- must subtract convolution of one-loop matching coefficient with fixed-order renormalisation of fragmentation function, $\mathcal{I}$

$$\mathcal{I}_{qq'}(z) = 2C_F \int\limits_z \frac{\mathrm{d}x}{x} \left(\frac{1+(1-x)^2}{x} \log[x(1-x)] + x \right) P^{(0)}_{gq'}(\frac{z}{x})$$

(this is the finite part of convoluting $1 \to 2$ in D dimensions with another $1 \to 2$ in 4 dimensions)

final result

- arrive at final expression, ready for MC implementation

$$P_{qq'}(z) = \left(I + \frac{1}{\epsilon}\mathcal{P} - \mathcal{I}\right)_{qq'}(z) + \int \mathrm{d}\Phi_{+1}\left(R - S\right)_{qq'}(z, \Phi_{+1}),$$

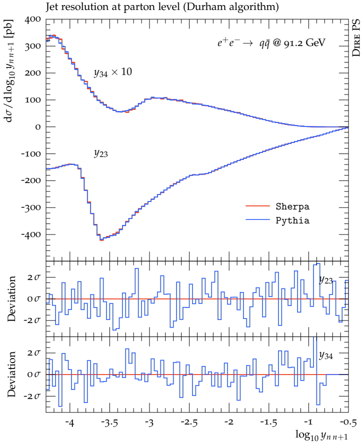
where

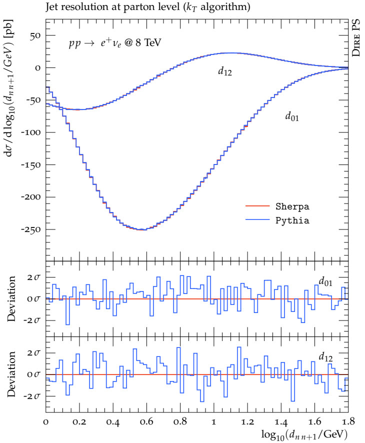
$$\begin{aligned}\left(I + \frac{1}{\epsilon}\mathcal{P}\right)_{qq'}(z) &= \int \mathrm{d}\Phi_{+1}\, S_{qq'}(z, \Phi_{+1})_{\mathrm{finite}} \\ R_{qq'}(z, \Phi_{+1}) &= P^{1\to 3}_{qq'}(z, \Phi_{+1}) \\ S_{qq'}(z, \Phi_{+1}) &= \frac{s_{aij}}{s_{ai}}\left(P^{(0)}_{qg} \otimes P^{(0)}_{gq'}\right)(z, \Phi_{+1})\end{aligned}$$

- this looks like MC@NLO inside the Sudakov exponent

validation of $1 \to 3$ splittings

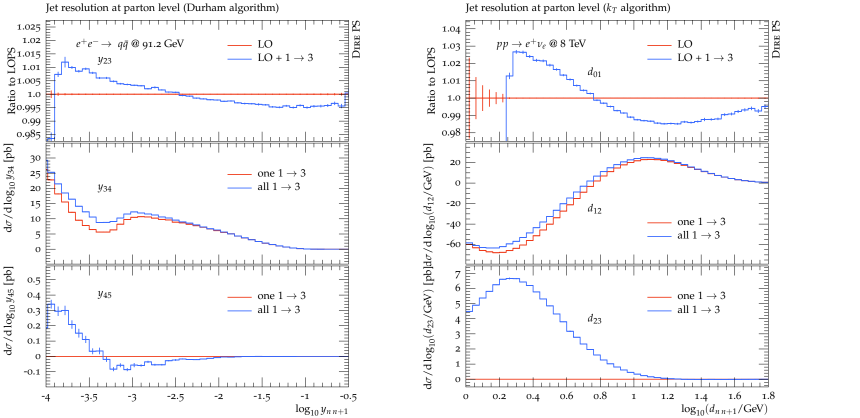
(Hoeche & Prestel, 1705.00742)





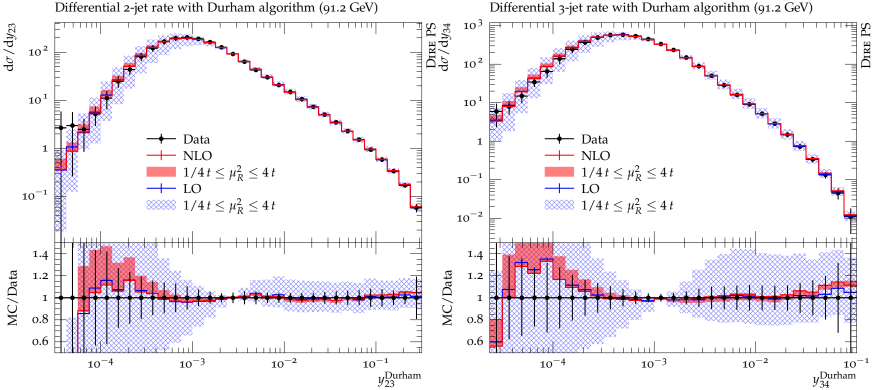
impact of $1 \to 3$ splittings

(Hoeche & Prestel, 1705.00742)



physical results: $e^-e^+ \to$ hadrons

(Hoeche, FK & Prestel, 1705.00982)



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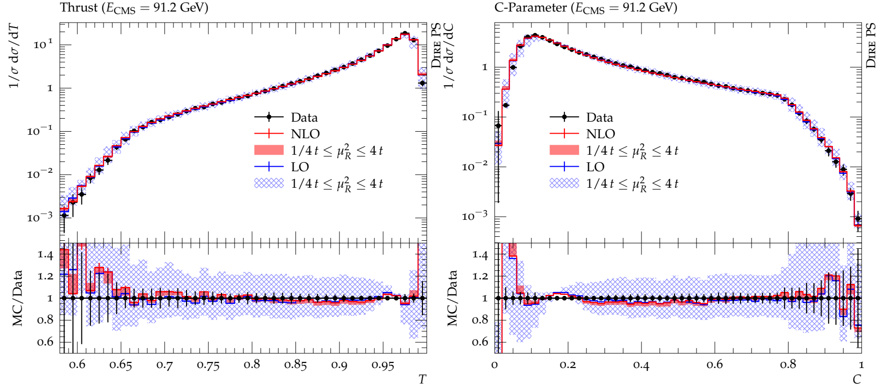
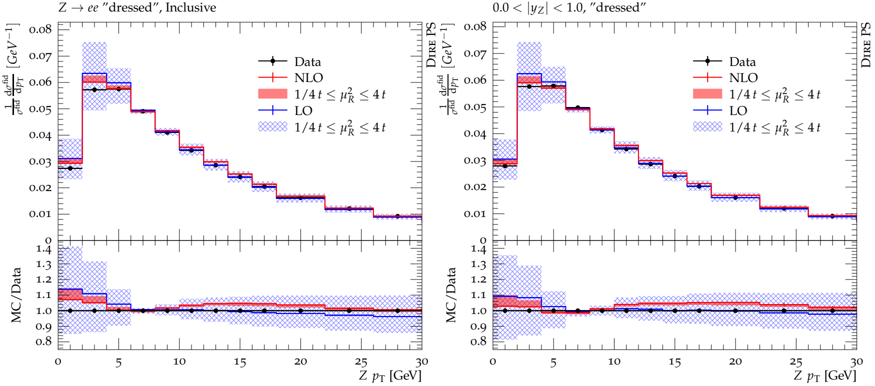


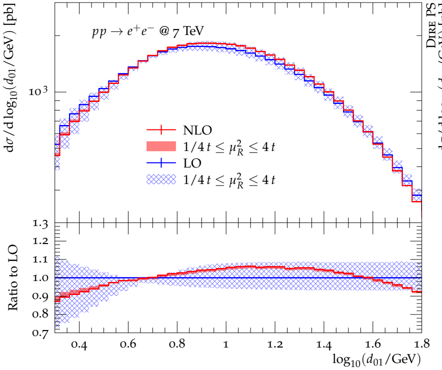
physical results: DY at LHC

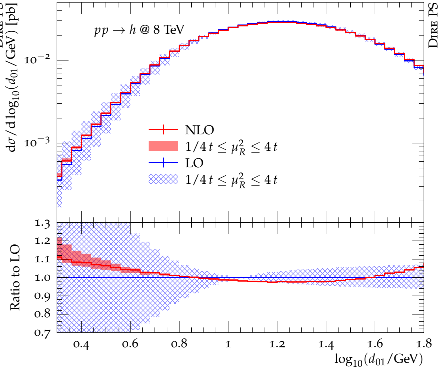
(Hoeche, FK & Prestel, 1705.00982)



physical results: diff. jet rates at LHC

(Hoeche, FK & Prestel, 1705.00982)





limitations

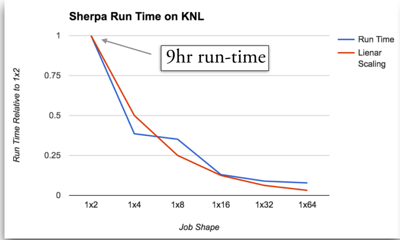
and

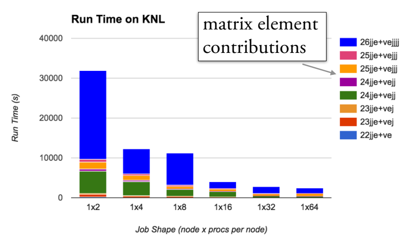
future challenges

limitation: computing short-distance cross sections – LO

(Childers, Uram, LeCompte, Benjamin, Hoeche, CHEP 2016)

- challenge of efficiency on tomorrow's (& today's) computers
- 2000's paradigm: memory free, flops expensive
  (example: 16-core Xeon, 20MB L2 Cache, 64GB RAM)
- 2020's paradigm: flops free, memory expensive & must be managed
  (example: 68-core Xeon KNL, 34MB L2 Cache, 16GB HBM, 96GB RAM)
- may trigger rewrites of code to account for changing paradigm





(figures stolen from Taylor-Childers' talk at CHEP)

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)
- we also need unglamorous improvements on existing tools:
  - account for new computer architectures and HPC paradigms
  - 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 bugs me)

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

achievable goals (I believe we know how to do this)

- NLO for loop-induced processes:
  - MC@NLO tedious but straightforward → around the corner
- EW NLO corrections with tricky/time-consuming calculation setup
  - but important at large scales: effect often ∼ QCD, but opposite sign
  - need maybe faster approximation for high-scales (EW Sudakovs)
  - work out full matching/merging instead of approximations
- improve parton shower:
  - beyond (next-to) leading log, leading colour, spin-averaged
  - HO effects in shower and scale uncertainties

    → NLO DGLAP done, now soft?
  - start including next-to leading colour
  - include spin-correlations → important for EW emissions

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?

$g \to Q\bar{Q}$ — a systematic nightmare

- parton showers geared towards collinear & soft emissions of gluons

  (double log structure)

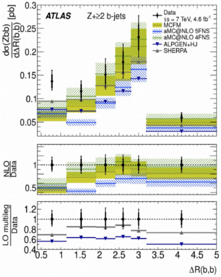
- $g \to q\bar{q}$ only collinear

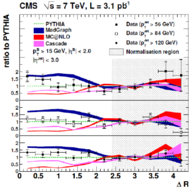
- old measurements at LEP of $g \to b\bar{b}$ and $g \to c\bar{c}$ rate
- fix this at LHC for modern showers

  (important for $t\bar{t}b\bar{b}$)

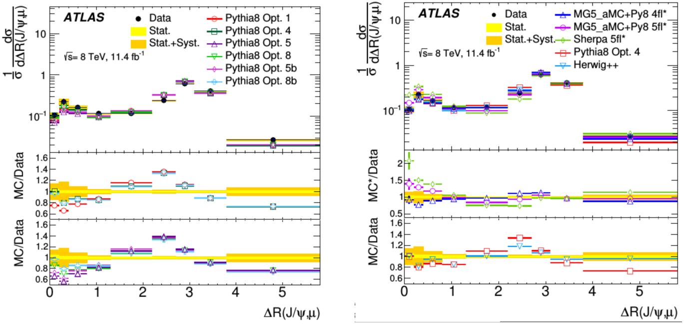
- questions: kernel, scale in α_S

  (example: $k_\perp$ vs. m_{bb})





- ATLAS measurement in $b\bar{b}$ production
- use decay products in $B \to J/\Psi(\mu\mu) + X$ and $B \to \mu + X$
- use muons as proxies, most obvious observable $\Delta R(J\Psi, \mu)$



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;1605.08011)
  - $V\gamma$ (1504.01330)
  - $\gamma\gamma$ (1110.2375; 1603.02663)
  - Vj (1507.02850; 1512.01291; 1602.06965; 1605.04295; 1610.07922)
  - Hj (1408.5325; 1504.07922; 1505.03893; 1508.02684; 1607.08817)
  - jj (1310.3993; 1611.01460)
- NLO corrections to $gg \to VV$ (1605.04610)
- WBF at NNLO (1506.02660) and N^{3}LO (1606.00840)
- different IR subtraction schemes:
  N-jettiness slicing, antenna subtraction, sector decomposition,

living with the revolution

- we will include them into full simulations

  (I am willing to place a bet: 5 years at most!)

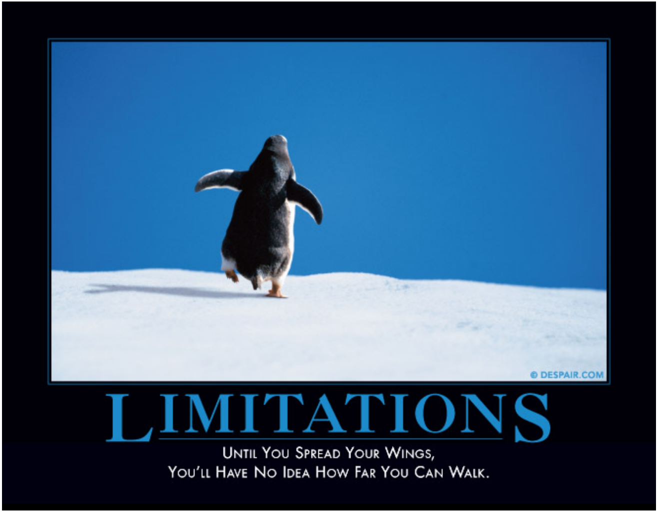
- practical limitations/questions to be overcome:
  - dealing with IR divergences at NNLO: slicing vs. subtracting

    (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?)
  - more scales (internal or external) complicated – need integrals
- philosophical questions:
  - going to higher power of N often driven by need to include larger FS multiplicity – maybe not the most efficient method
  - limitations of perturbative expansion:

    $\longrightarrow$ breakdown of factorisation at HO (Seymour et al.)

    $\longrightarrow$ higher-twist: compare $(\alpha_S/\pi)^n$ with $\Lambda_{\rm QCD}/M_Z$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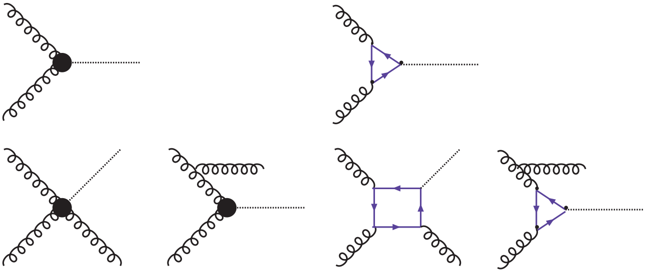
LIMITATIONS
Until You Spread Your Wings,
You'll Have No Idea How Far You Can Walk.

extra: quark mass effects in GGF

- include effects of quark masses

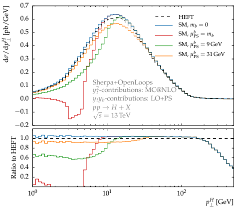


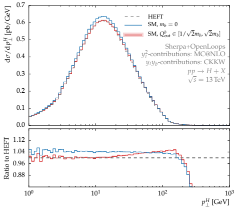
- reweight NLO HEFT with LO ratio:

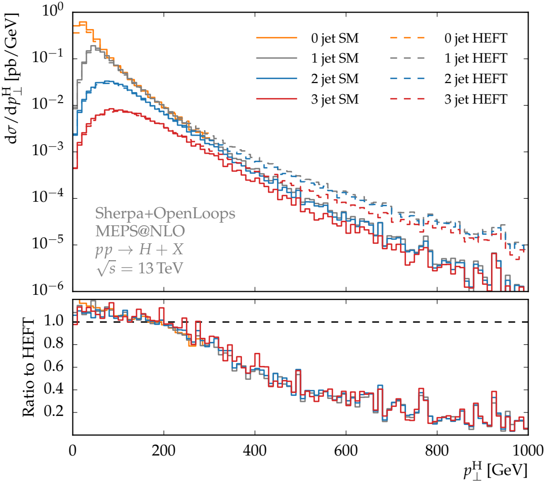
(reweight virtual with Born ratio, real with real ratio)

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

- example: mass effects in $gg \to H$ (LO merging for b contribution)





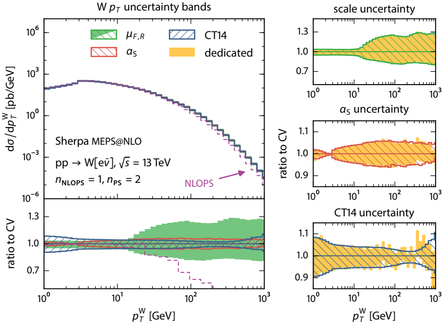


extra: event generation (on-the-fly scale variations, LO only)

- basic idea: want to vary scales to assess uncertainties
- simple reweighting in matrix elements straightforward
- reweighting in parton shower more cumbersome
  - shower is probabilistic, concept of weight somewhat alien
  - introduce relative weight
  - evaluate (trial-)emission by (trial-)emission

extra: weight variation for W+jets with MEPS@NLO

- uncertainties in $p_\perp^W$



- CPU budget