Monte Carlo

The Quest for Precision

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- what the talk is about
- parton showers I: accuracy and issues
- fixed-order improvements: matching and merging
- electroweak corrections
- parton showers II: showering @ NLO
- summary

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)

- not covered: status of BSM simulations:
  UFO routinely used in MADGRAPH, HERWIG7, & SHERPA

(my apologies)

- not covered: tun-ology

(boring and to some degree meaningless to me)

parton showers I

accuracy and unresolved issues

reminder: how parton showers work

- 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

a new shower implementation — DIRE

(S.Höche & S.Prestel, Eur.Phys.J. C75 (2015) 461)

- 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

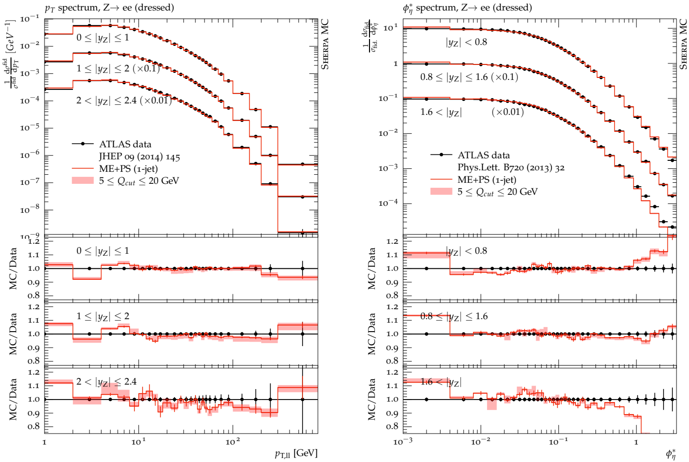
(a la Curci, Furmanski & Petronzio, Nucl.Phys. B175 (1980) 27-92)

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

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

LO results for Drell-Yan

(example of accuracy in description of standard precision observable)



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

- parton showers geared towards collinear & soft emissions of gluons

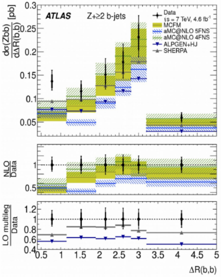
  (double log structure)

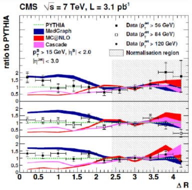
- $g \to q\bar{q}$ only collinear
- old measurements at LEP of $g \to b\bar{b}$ and $g \to c\bar{c}$ rate
- fix this at LHC for modern showers

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

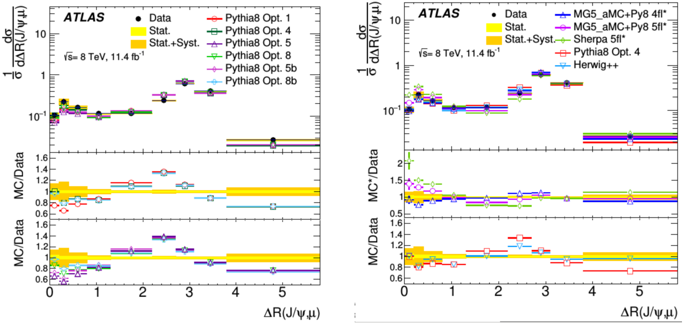
- questions: kernel, scale in α_S

  (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 $\Delta R(J\Psi, \mu)$



fixed-order improvements

matching and merging

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

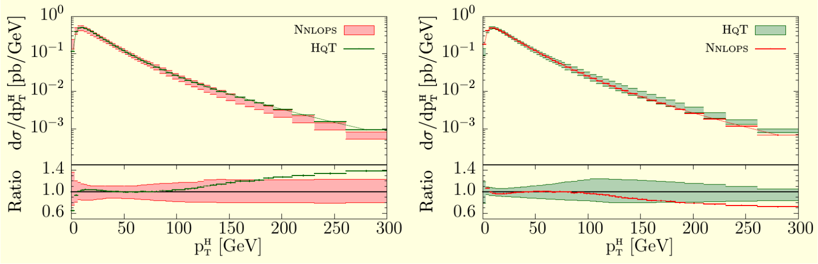
- avoid double-counting of emissions
- two schemes at NLO: MC@NLO and POWHEG
  - mismatches of K factors in transition to hard jet region
  - MC@NLO: $\longrightarrow$ visible structures, especially in $gg \to H$
  - POWHEG: $\longrightarrow$ high tails, cured by h dampening factor
  - well-established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

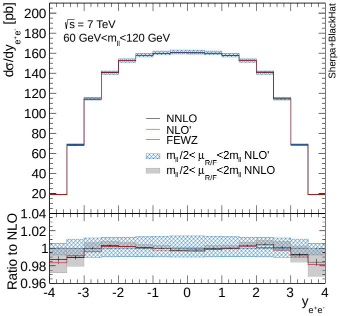
K. Hamilton, P. Nason, E. Re & G. Zanderighi, JHEP 1310

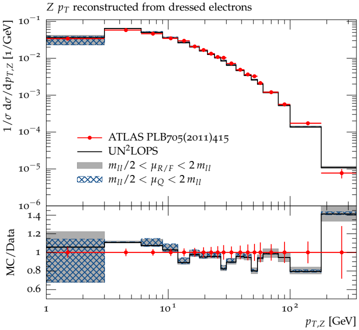


- also available for $Z/W/VH$ production

NNLOPs for Z production: UN^{2}LOPs

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





- also available for H production

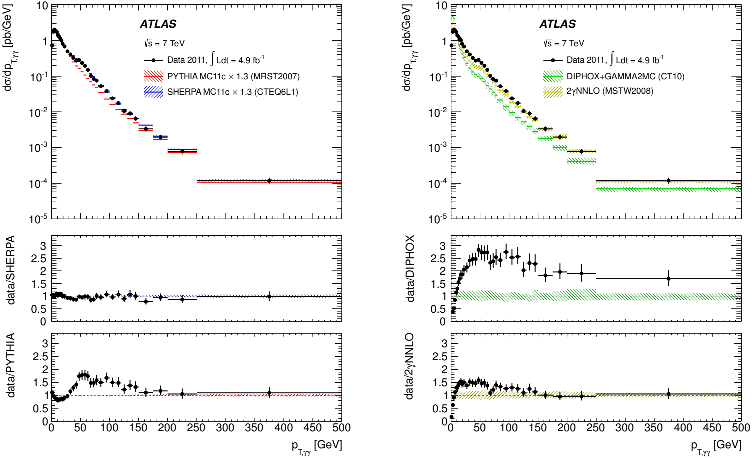
NNLOPS: shortcomings/limitations

- 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])

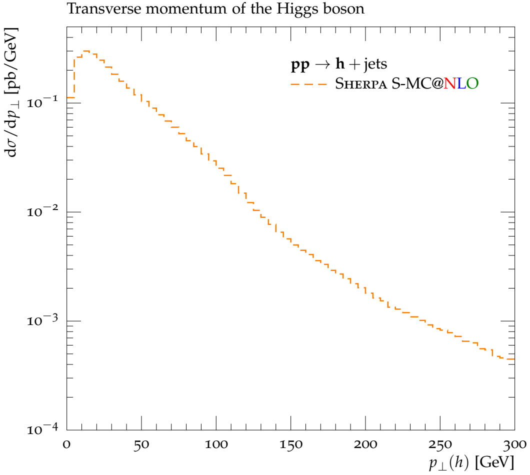


multijet-merging at NLO

- 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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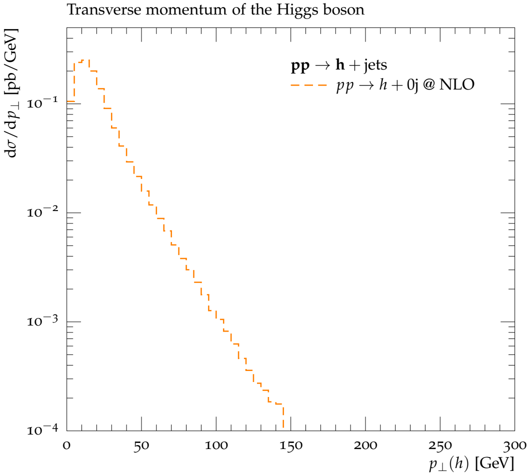

- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$

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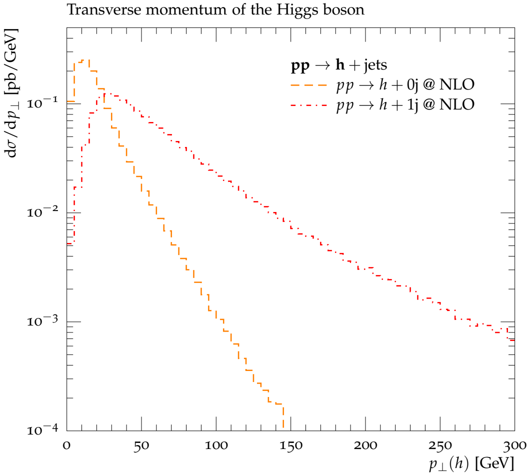

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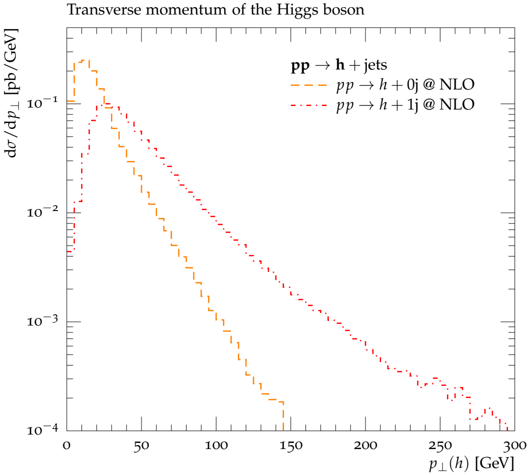

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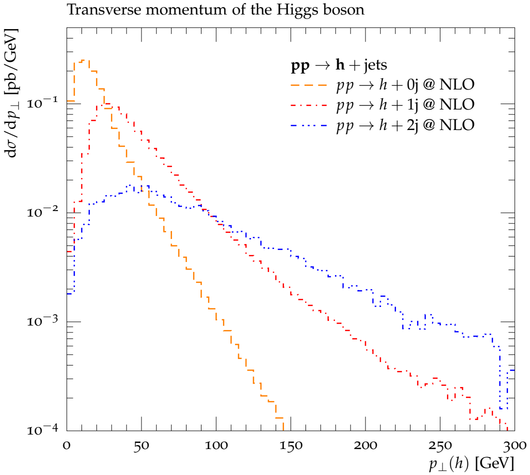

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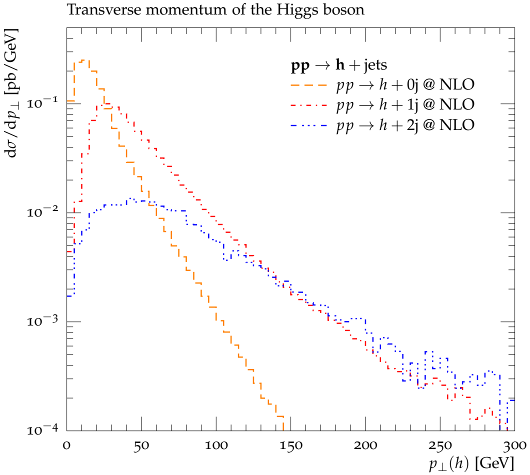

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- iterate

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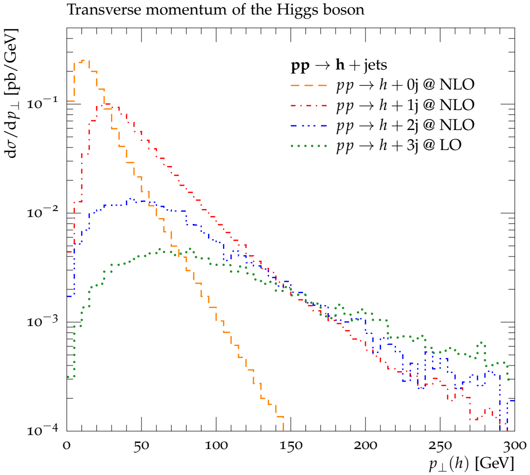

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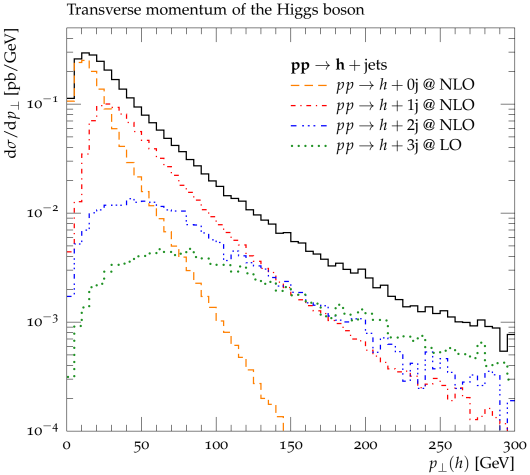

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- sum all contributions

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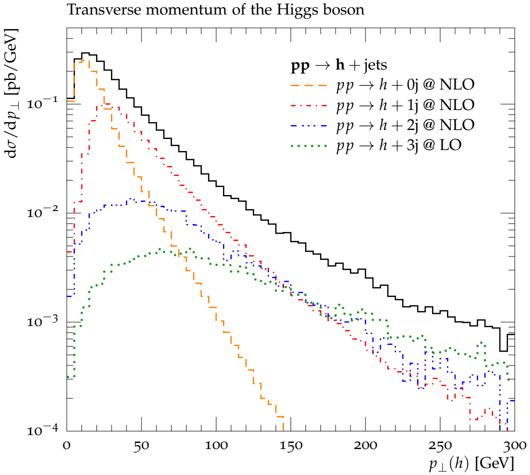

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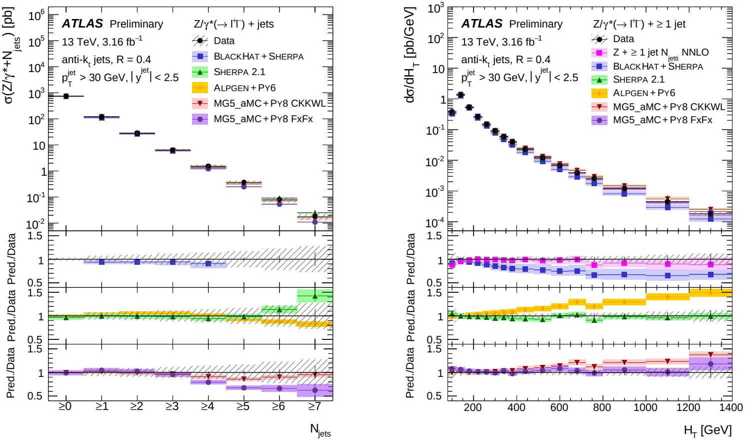
- iterate
- sum all contributions
- eg. $p_\perp(h) > 200$ GeV has contributions fr. multiple topologies

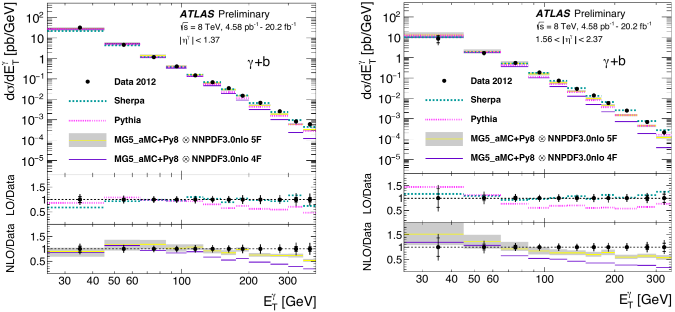
Z+jets at 13 Tev: comparison with ATLAS data

- various merging codes at LO and NLO



$\gamma + Q$ production

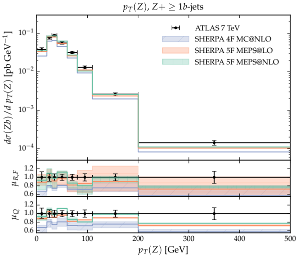
- compare 4F and 5F schemes, NLO and multijet merging at LO

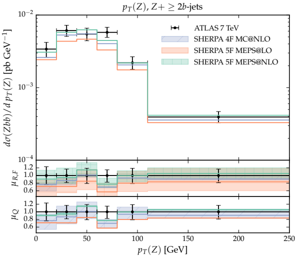


$Z + b$ production

- compare 4F and 5F schemes, MC@NLO, MEPS@LO and MEPS@NLO
- theory uncertainties from varying μ_F, μ_R, μ_Q

(μ_Q = parton shower starting scale)





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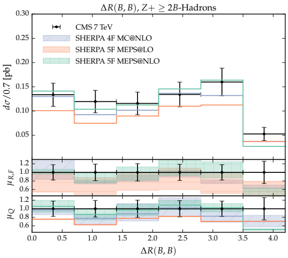
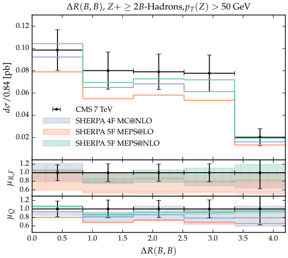




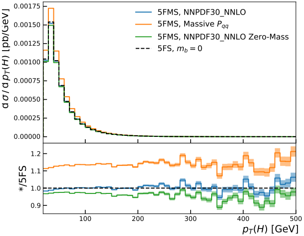
aside: massive 5FS ?

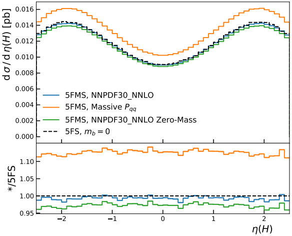
- LO finding: massive 5FS performs best

  (with $\alpha_S(m_{bb})$ for $g \to bb$ and $\alpha_S(p_\perp)$ for $b \to bg$)
- but: IR subtraction not fully worked out for massive IS

  (work in prep. by Napoletano and FK)
- interesting problem: massive (?) PDFs — scheme choice

  (it feels as if this is a higher-twist correction)
- some snapshot results for $b\bar{b} \to H$ below


5FMS, NNPDF30_NNLO
5FMS, Massive P_{qq}
5FMS, NNPDF30_NNLO Zero-Mass
5FS, $m_b = 0$
$d\sigma / d\, p_T(H)$ [pb/GeV]
*/5FS
$p_T(H)$ [GeV]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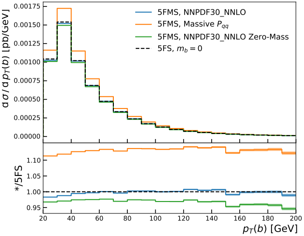
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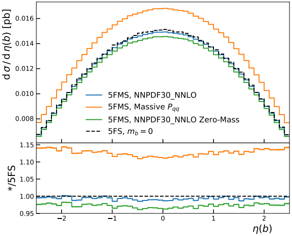
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including EW corrections

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

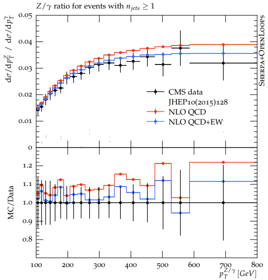
(somewhat in its infancy: chiral couplings)

- example: $Z\gamma$ 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 $Z\to\ell\ell$



inclusion of electroweak corrections in simulation

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

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

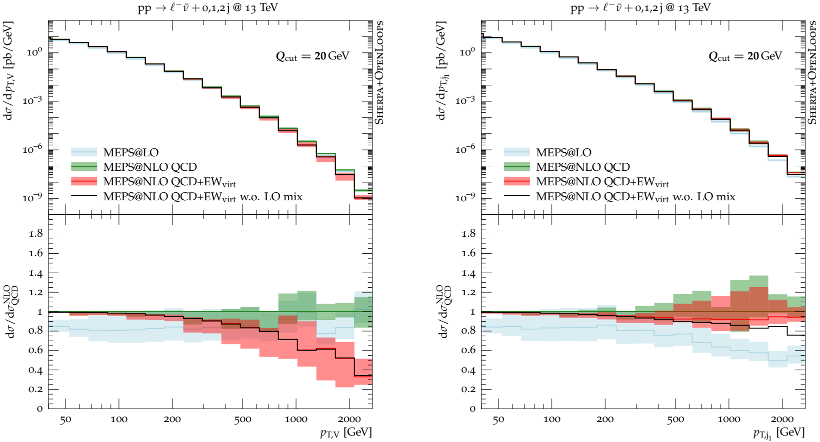
  2. using virtual corrections and approx. integrated real corrections

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

- 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

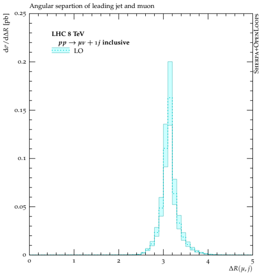
results: $pp \to \ell^- \bar{\nu} + \text{jets}$

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



⇒ particle level events including dominant EW corrections

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

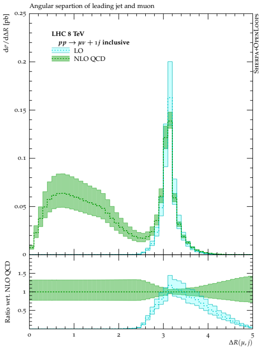


measure collinear W emission?

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

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

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



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  large $pp \to Wjj$ component opening PS

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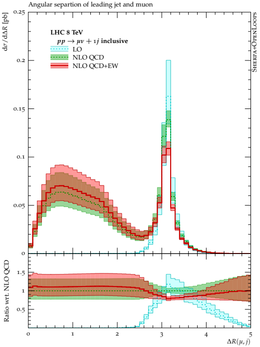

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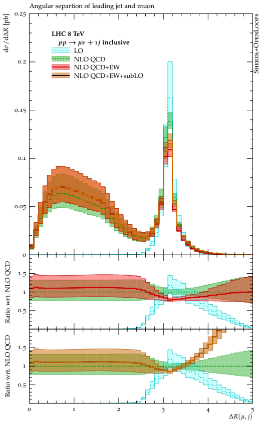

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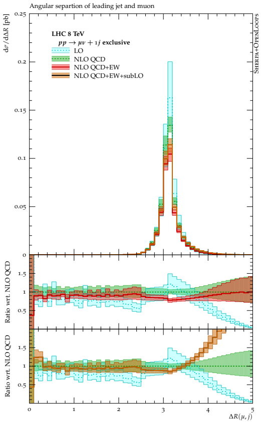
- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- sub-leading Born (γPDF) at large ΔR

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



measure collinear W emission?

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

- 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 $p_\perp^{j_2} > 100\,\text{GeV}$

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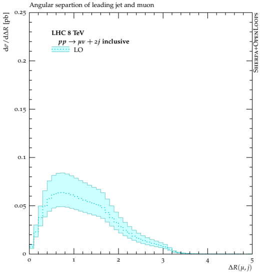

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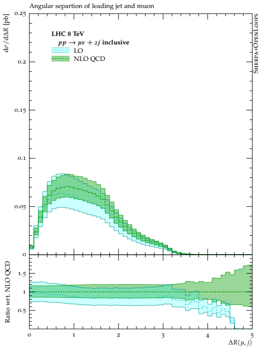

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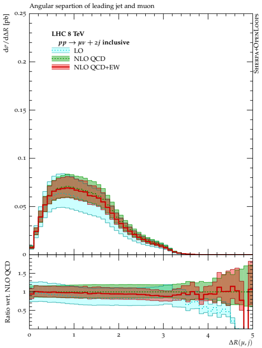

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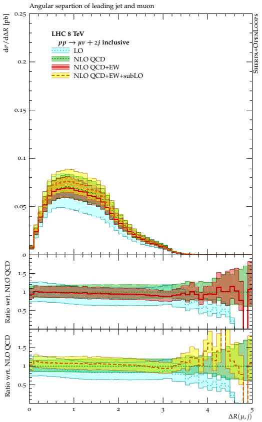

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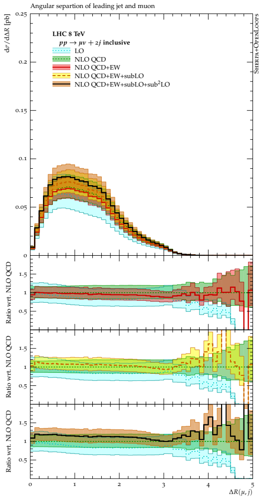

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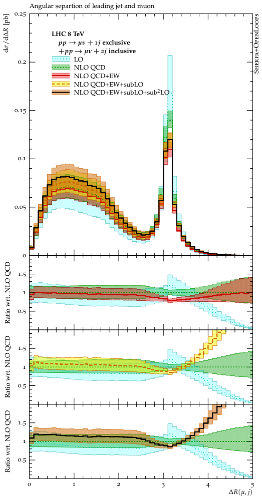

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  $\to$ possible double counting with BG
- merge using exclusive sums

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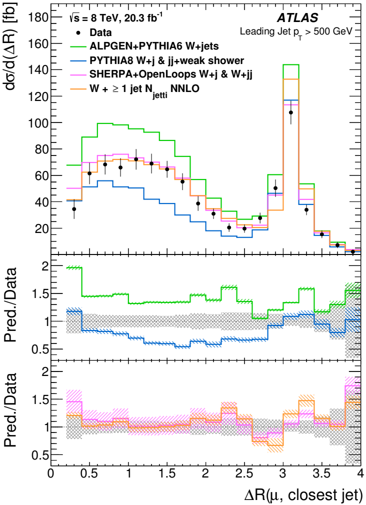

Data comparison

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

- ALPGEN+PYTHIA
  $pp \to W+$jets MLM merged
  (Mangano et.al., JHEP07(2003)001)
- PYTHIA 8
  $pp \to Wj$ + QCD shower
  $pp \to jj$ + QCD+EW shower
  (Christiansen, Prestel, EPJC76(2016)39)
- SHERPA+OPENLOOPS
  NLO QCD+EW+subLO
  $pp \to Wj/Wjj$ excl. sum
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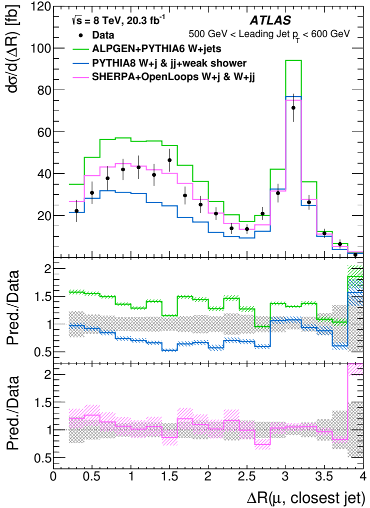

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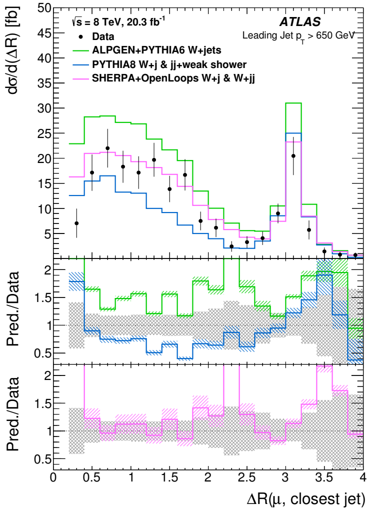

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parton showers II

showering @ NLO

Including NLO splitting kernels

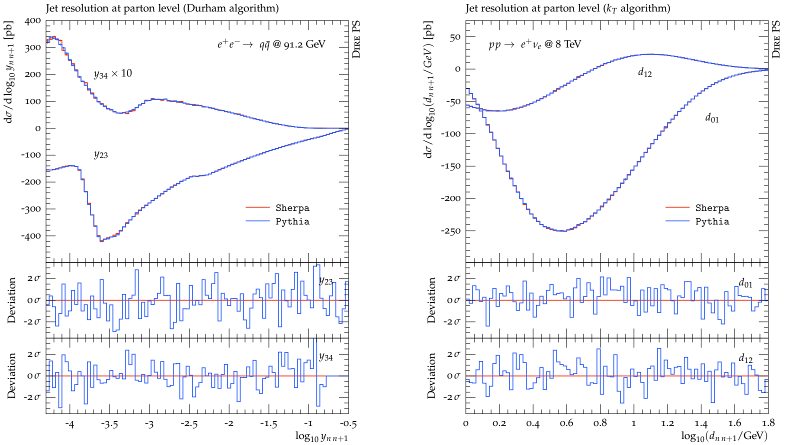
(Hoeche, FK & Prestel, 1705.00982, and Hoeche & Prestel, 1705.00742)

- expand splitting kernels as

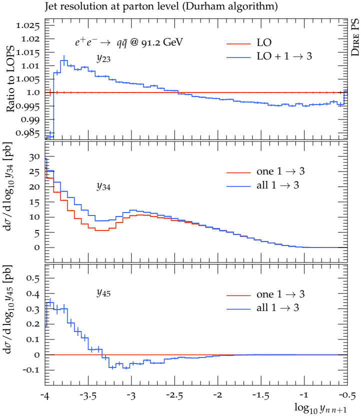
$$P(z,\,\kappa^2)\;=\;P^{(0)}(z,\,\kappa^2)\,+\,\frac{\alpha_S}{2\pi}\,P^{(1)}(z,\,\kappa^2)$$

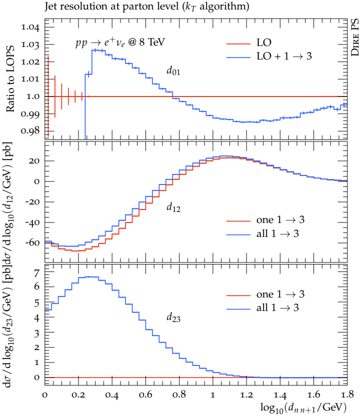
- aim: reproduce DGLAP evolution at NLO
  include all NLO splitting kernels
- three categories of terms in $P^{(1)}$:
  - cusp (universal soft-enhanced correction) (already included in original showers)
  - corrections to $1\to 2$
  - new flavour structures (e.g. $q\to q'$), identified as $1\to 3$
-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

validation of $1 \to 3$ splittings



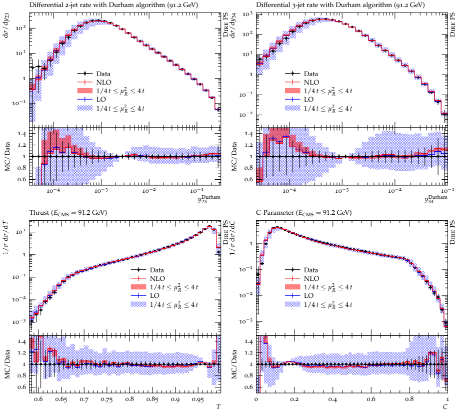
impact of $1 \to 3$ splittings





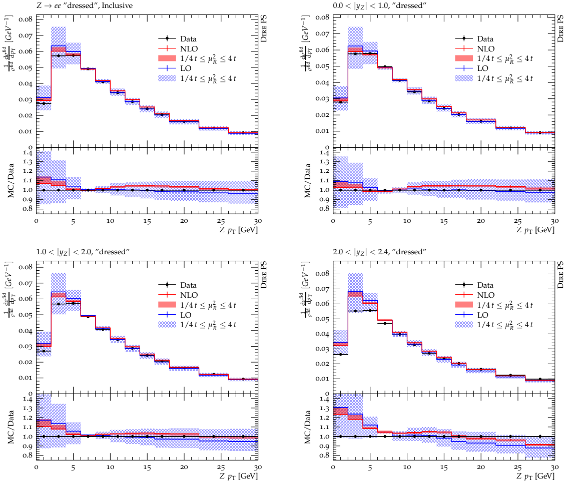
physical results: $e^-e^+ \to$ hadrons

(Hoeche, FK & Prestel, 1705.00982)

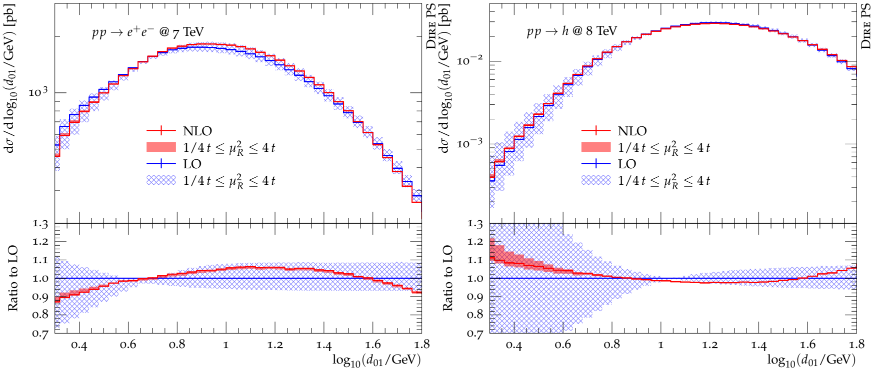


physical results: DY at LHC

(untuned showers vs. 7 TeV ATLAS data)



physical results: differential jet rates at LHC



summary

fixed-order accuracy

- amazing progress in NLO automation for QCD and EW

lots of tools and public codes: use them!

- NNLO QCD for $2 \to 2$ processes more or less complete
- will trigger a new wave of MC@NNLO beyond MINLO and UN^{2}LOPS
- steep learning curve still ahead of us

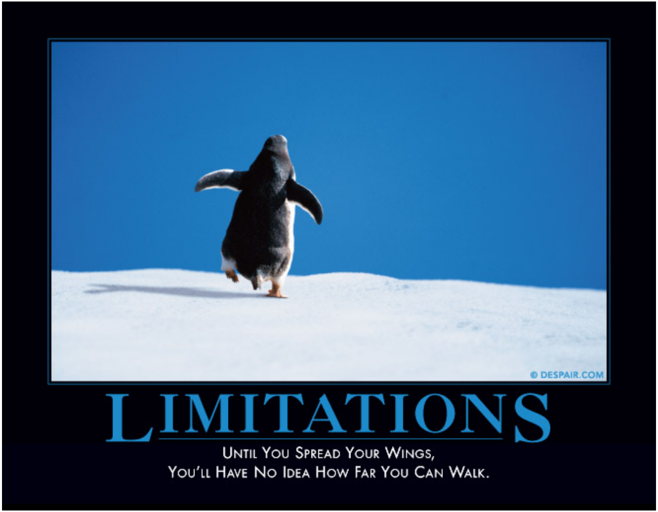
(N)NLO Phenomenology

more subtleties, more work, more detail

more reward

shower accuracy

- parton showering now limiting factor in quest for precision
- implemented NLO DGLAP kernels into two independent showers
  will allow cross checks/validation of NP effects
- cross-validated implementations PYTHIA $\longleftrightarrow$ SHERPA
- matching to NNLO/multijet merging at NLO ongoing work
- extension to include loop-corrections to $1to2$ straightforward
  will allow to use triple-collinear splitting functions throughout
- future plans: soft-gluon emissions and non-trivial colour correlations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LIMITATIONS
Until You Spread Your Wings,
You'll Have No Idea How Far You Can Walk.