

The Quest for Precision in Simulations for the LHC

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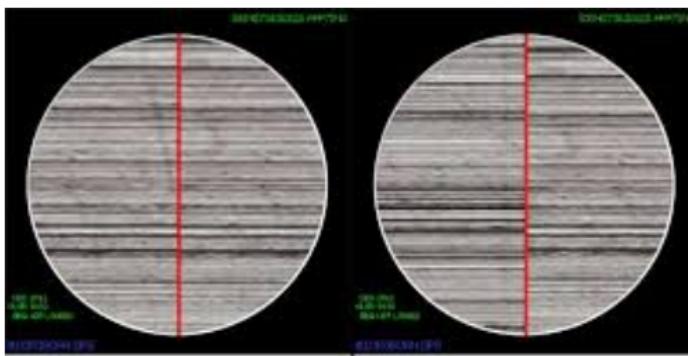
- what the talk is about
- fixed order & matching & merging with parton showers
- revisiting parton showers
- where we are and where we (should/could/would) go

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

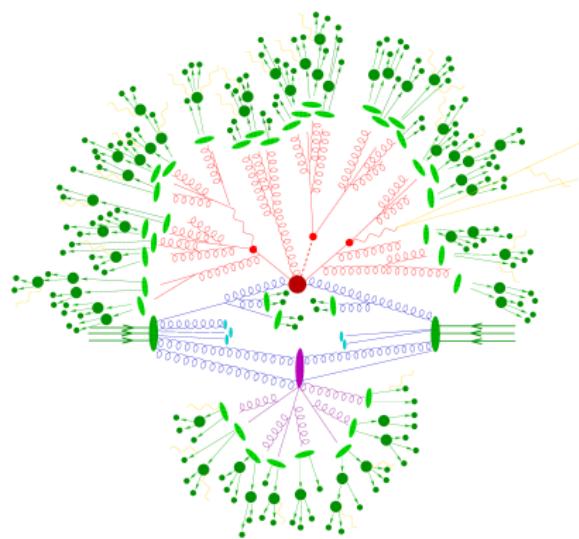


No Match

embedding precision in full simulations

- fixed-order perturbation theory does not give full picture of $p\bar{p}$ collisions at LHC.
- more particles produced by
 - radiation of secondaries
 - all-orders PT in approximation
 - transition from quarks & gluons to hadrons
 - decays of unstable hadrons & QED radiation
 - multiple interactions
- all in numerical simulation

combination of first principles PT, effective theories, heavy modelling, and fitting to data



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

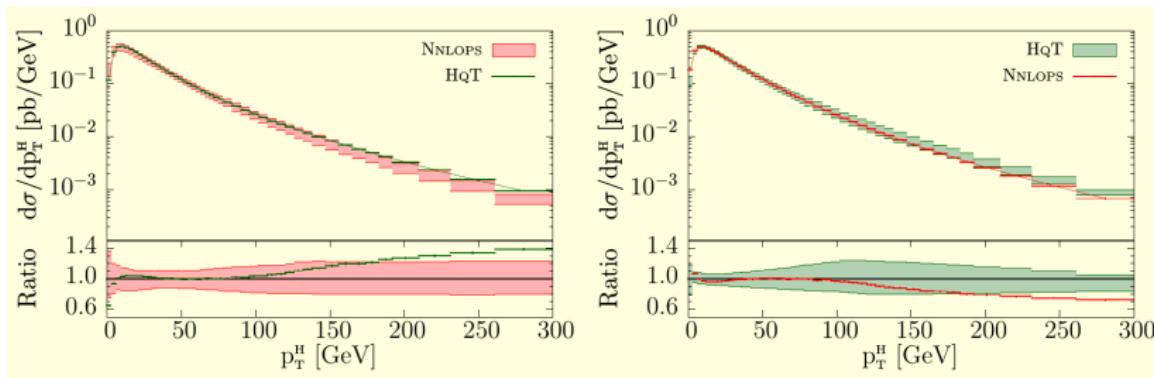
- avoid double-counting of emissions
- two schemes at NLO: Mc@NLO and POWHEG
 - mismatches of K factors in transition to hard jet region
 - Mc@NLO: → visible structures, especially in $gg \rightarrow H$
 - POWHEG: → high tails, cured by h dampening factor
 - well-established and well-known methods

(no need to discuss them any further)

- two schemes at NNLO: MINLO & UN²LOPs (singlets S only)
 - different basic ideas
 - MINLO: $S + j$ at NLO with $p_T^{(S)} \rightarrow 0$ and capture divergences by reweighting internal line with analytic Sudakov, NNLO accuracy ensured by reweighting with full NNLO calculation for S production
 - UN²LOPs identifies and subtracts and adds parton shower terms at FO from $S + j$ contributions, maintaining unitarity
 - available for two simple processes only: DY and $gg \rightarrow H$

NNLOPs for H production: MINLO

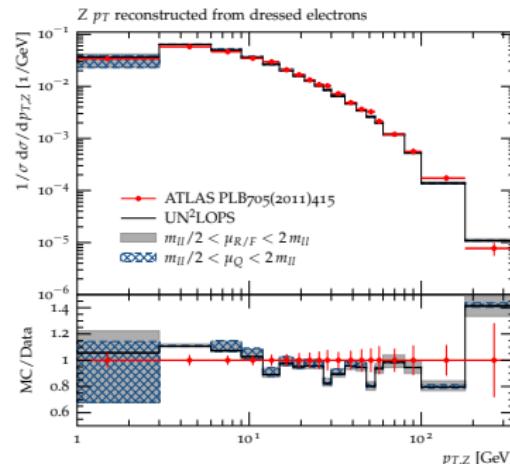
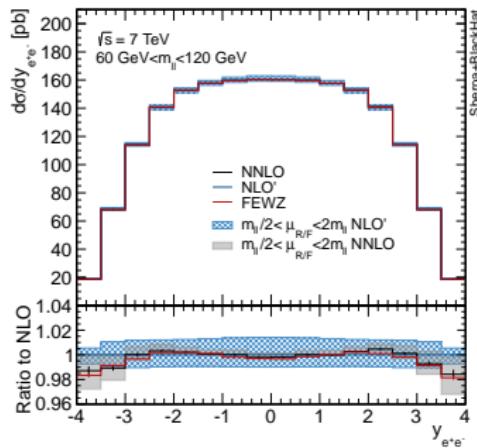
K. Hamilton, P. Nason, E. Re & G. Zanderighi, JHEP 1310



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

NNLOPs for Z production: UN²LOPs

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



- also available for H production

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

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

(arXiv:1211.1913 [hep-ex])

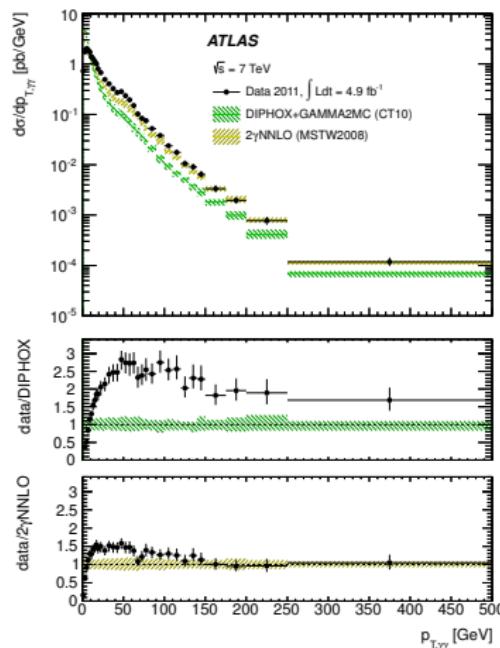
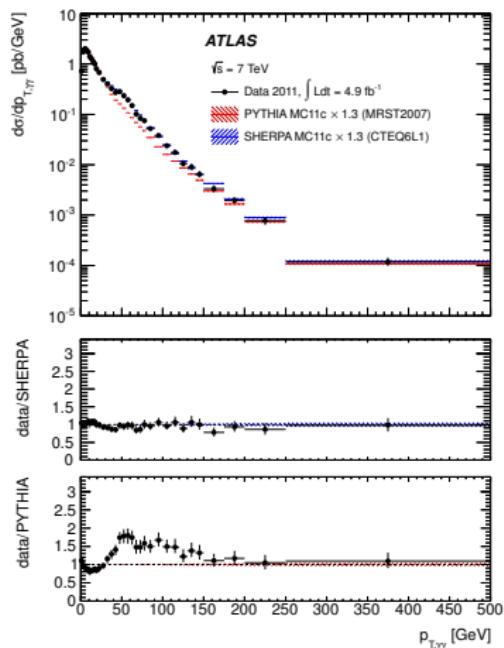


illustration: p_T^H in MEPS@NLO

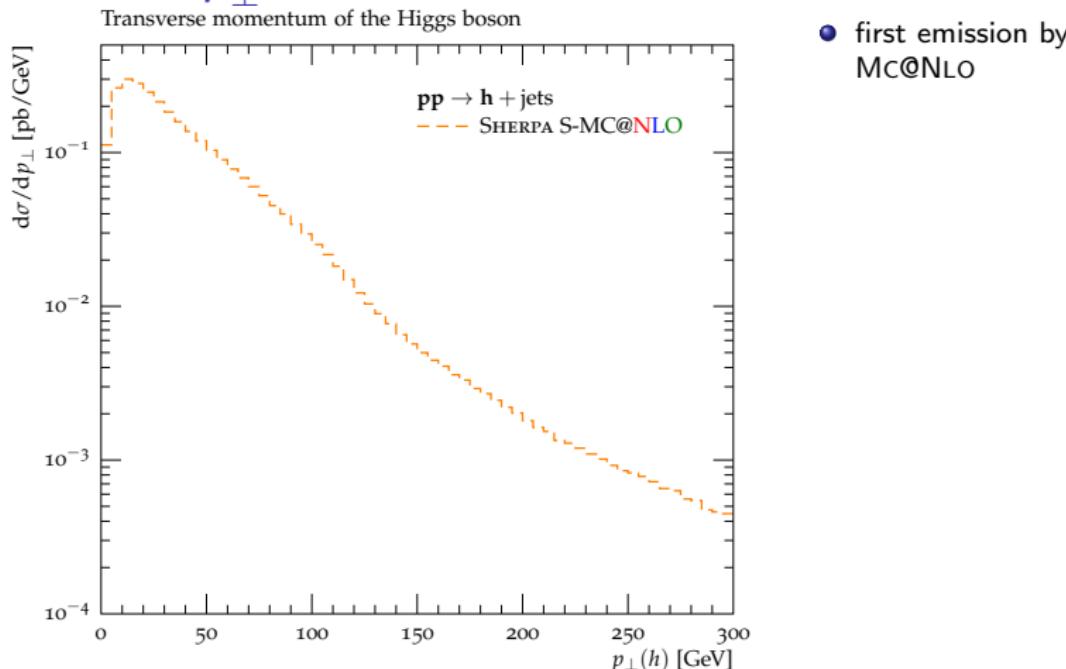
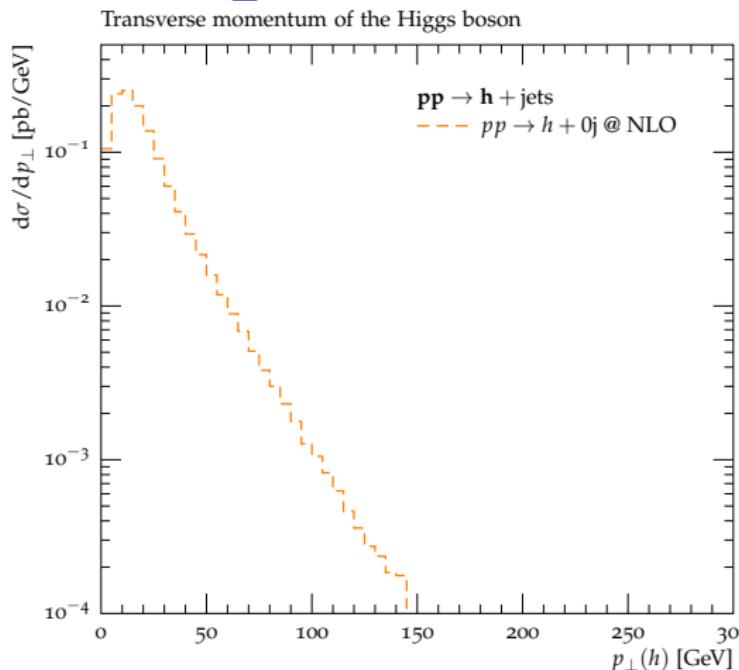
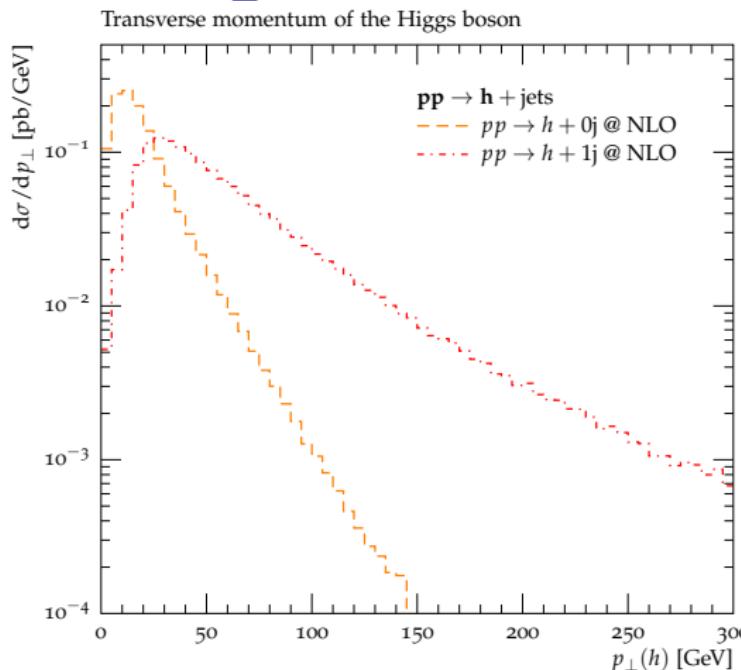


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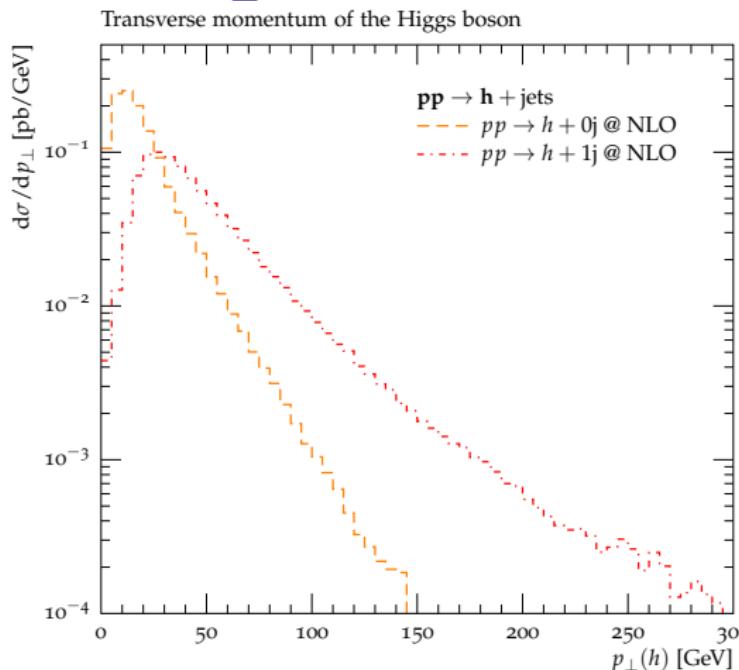
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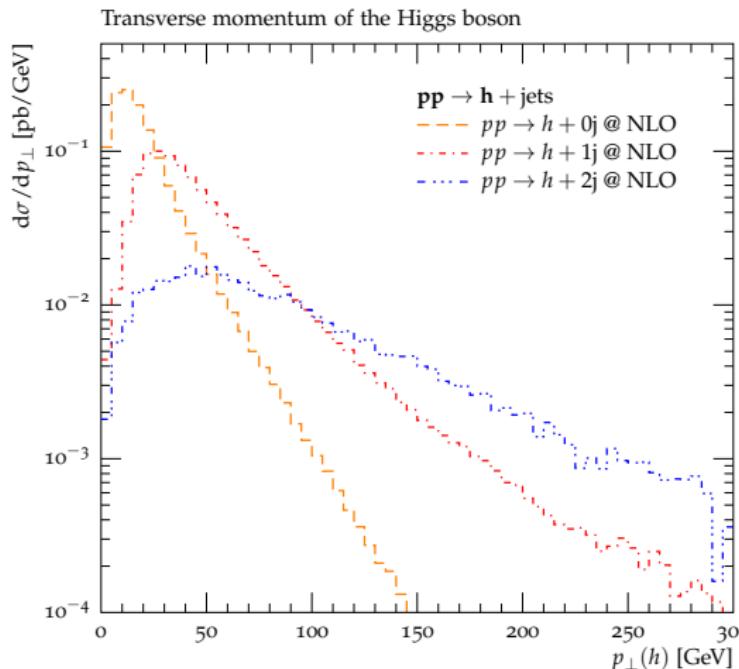
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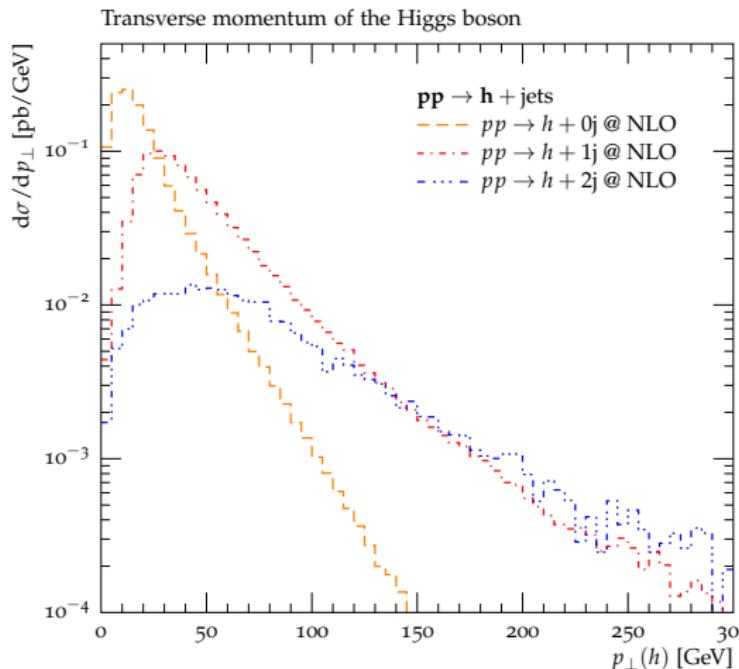
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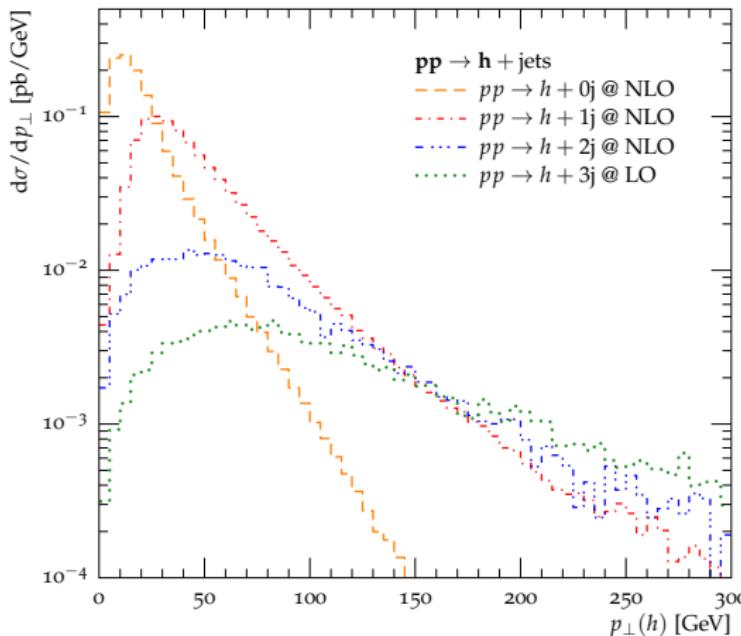
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- iterate

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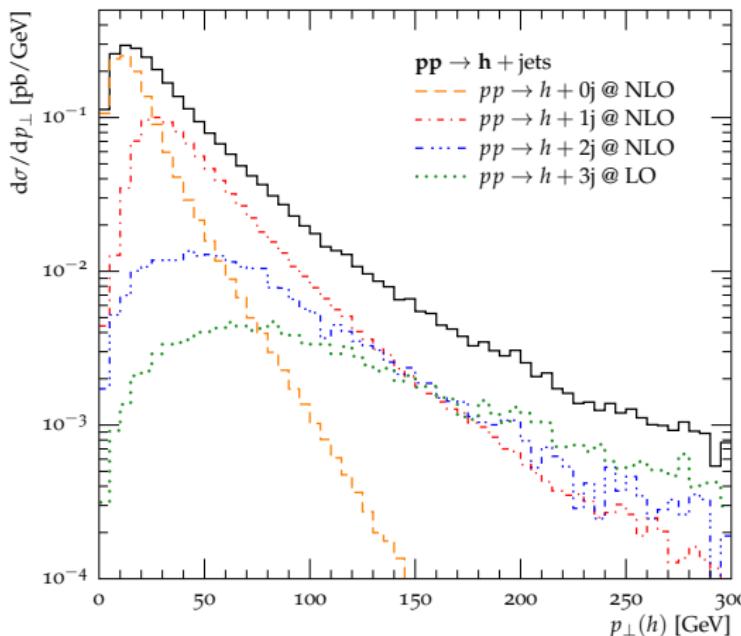
Transverse momentum of the Higgs boson



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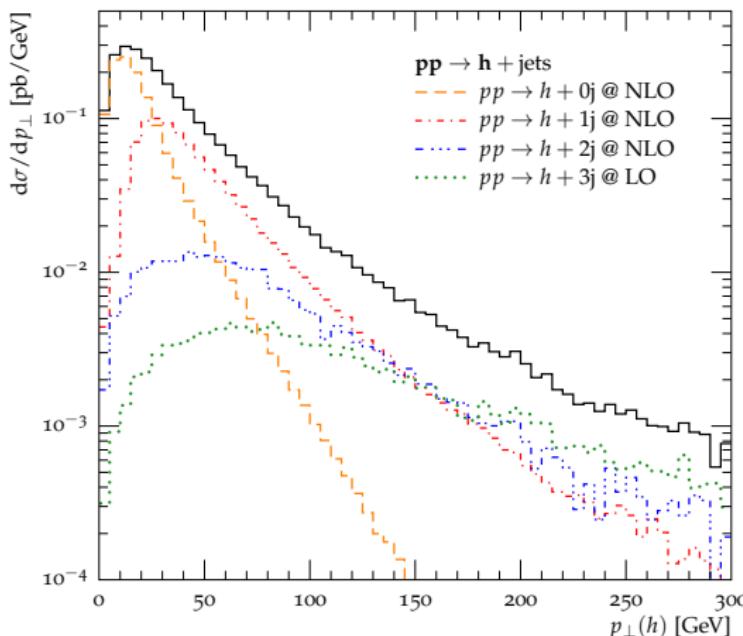
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- sum all contributions

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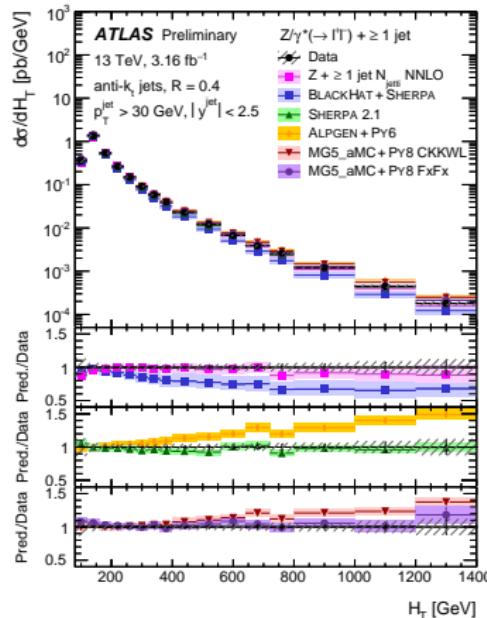
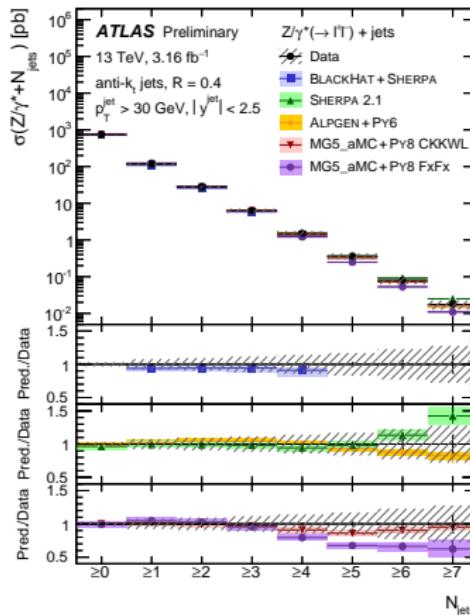
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- iterate
- sum all contributions
- eg. $p_\perp(h) > 200 \text{ GeV}$ has contributions fr. multiple topologies

Z+jets at 13 Tev: comparison with ATLAS data

- various merging codes at LO and NLO



including EW corrections

EW corrections

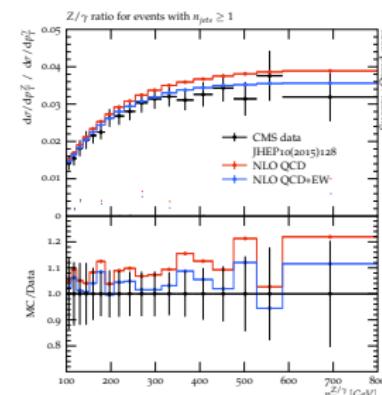
- EW corrections sizeable $\mathcal{O}(10\%)$ at large scales: **must include them!**
- but: more painful to calculate
- need EW showering & possibly corresponding PDFs

(somewhat in its infancy: chiral couplings)

- example: Z/γ vs. p_T (right plot)
 (handle on p_{\perp}^Z in $Z \rightarrow \nu\bar{\nu}$)

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

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



inclusion of electroweak corrections in simulation

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

$$\tilde{B}_n(\Phi_n) \approx \tilde{B}_n(\Phi_n) \Delta_{\text{EW}}(\Phi_n)$$

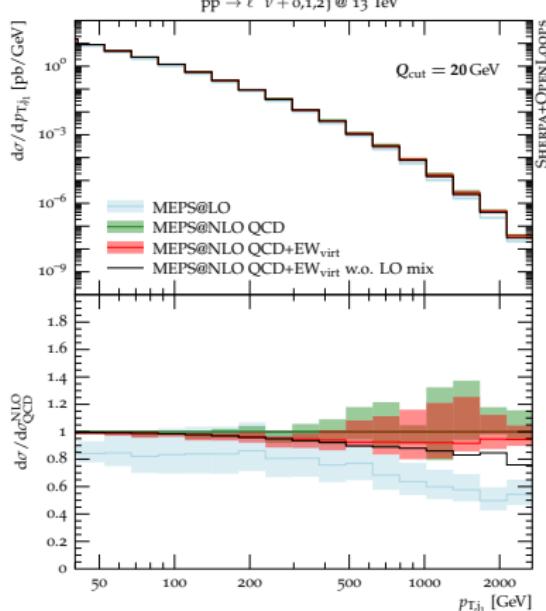
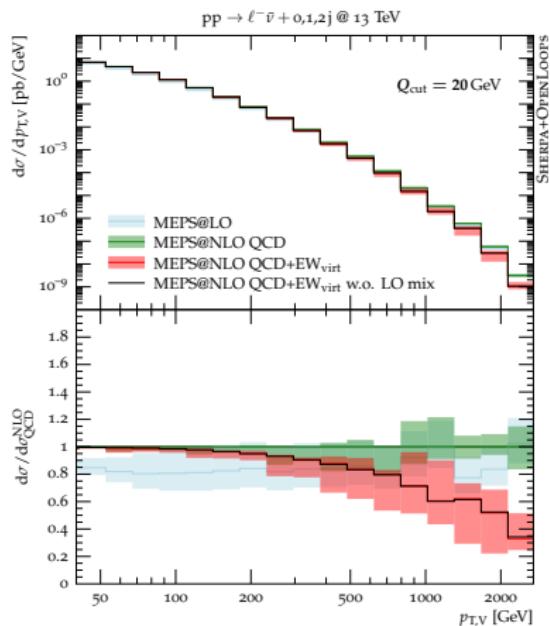
- ② using virtual corrections and approx. integrated real corrections

$$\tilde{B}_n(\Phi_n) \approx \tilde{B}_n(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

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

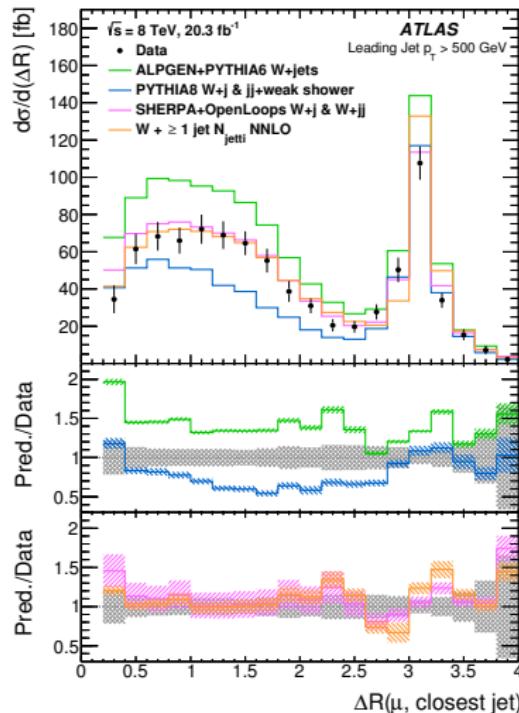
results: $pp \rightarrow \ell^-\bar{\nu} + \text{jets}$

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



⇒ particle level events including dominant EW corrections

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

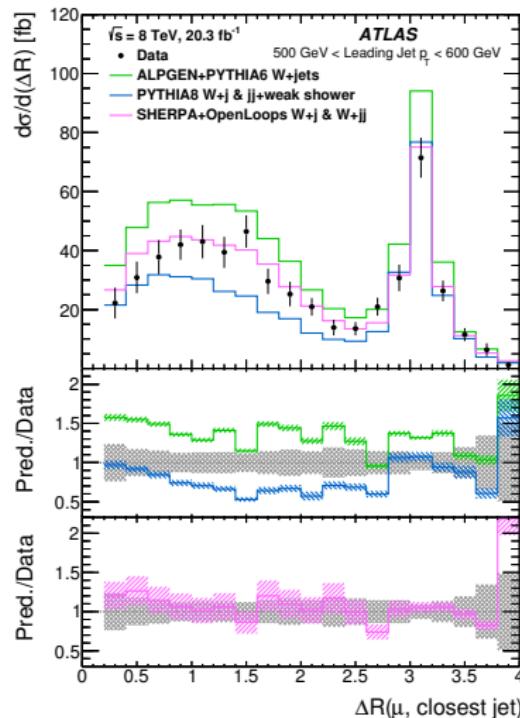


Data comparison

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

- ALPGEN+PYTHIA
 $pp \rightarrow W + \text{jets}$ MLM merged
(Mangano et.al., JHEP07(2003)001)
- PYTHIA 8
 $pp \rightarrow Wj + \text{QCD shower}$
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(Christiansen, Prestel, EPJC76(2016)39)
- SHERPA+OPENLOOPS
NLO QCD+EW+subLO
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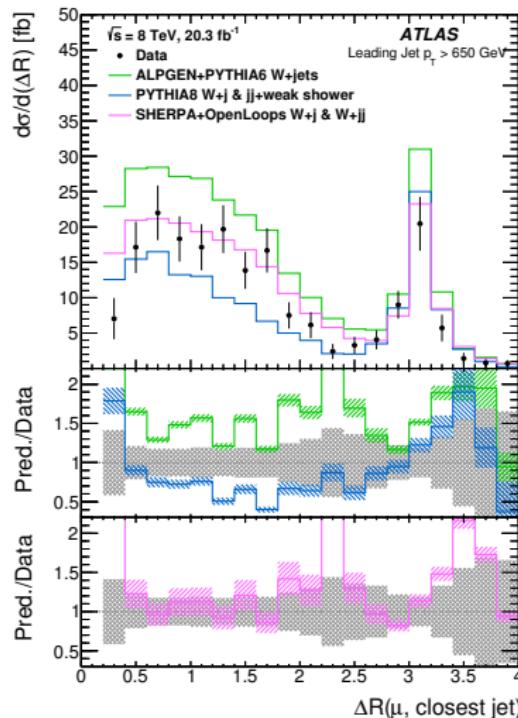


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improving parton showers

motivation: why care?

- QCD radiation omnipresent at the LHC
- enters as signal (and background) in high- p_{\perp} analyses
 - multi-jet signatures
 - multijet merging & higher-order matching (not the topic today)
 - inner-jet structures e.g. from “fat jets”
 - 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:

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

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

implementation in DIRE

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

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

- splitting functions including IR regularisation

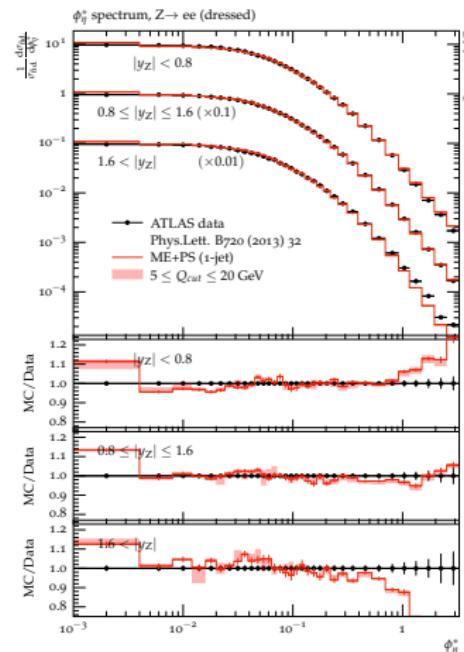
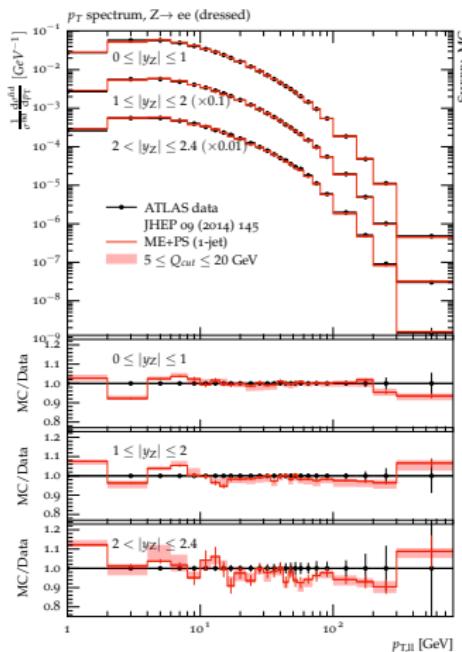
(a la Curci, Furmanski & Petronzio, Nucl.Phys. B175 (1980) 27-92)

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

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

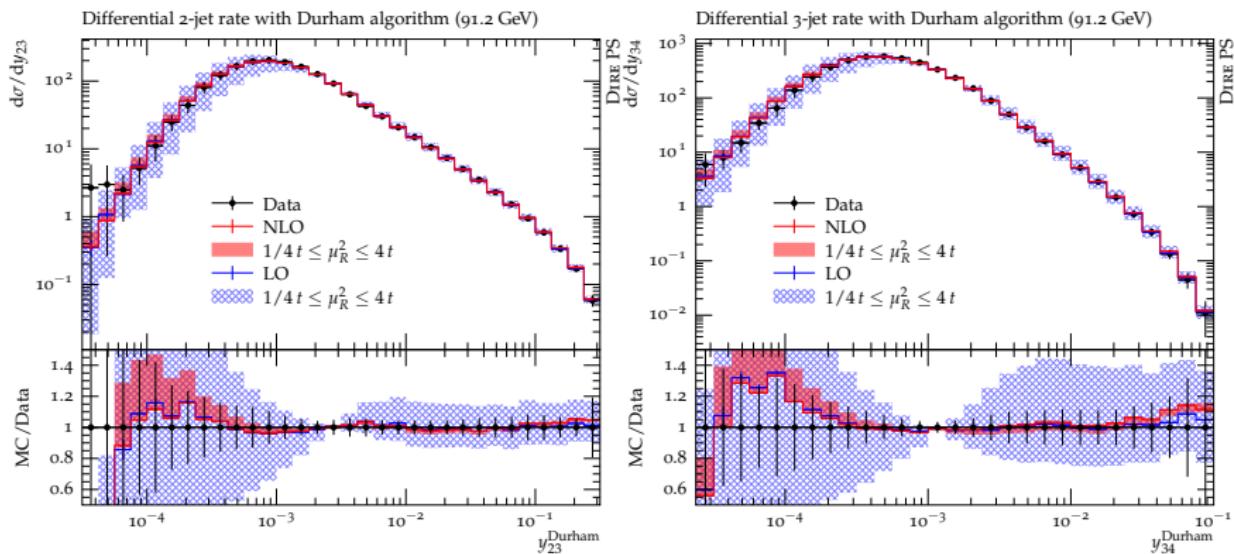
$$P(z, \kappa^2) = P^{(0)}(z, \kappa^2) + \frac{\alpha_s}{2\pi} P^{(1)}(z, \kappa^2)$$

- 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 $1 \rightarrow 2$
 - new flavour structures (e.g. $q \rightarrow q'$), identified as $1 \rightarrow 3$
- new paradigm: two independent implementations

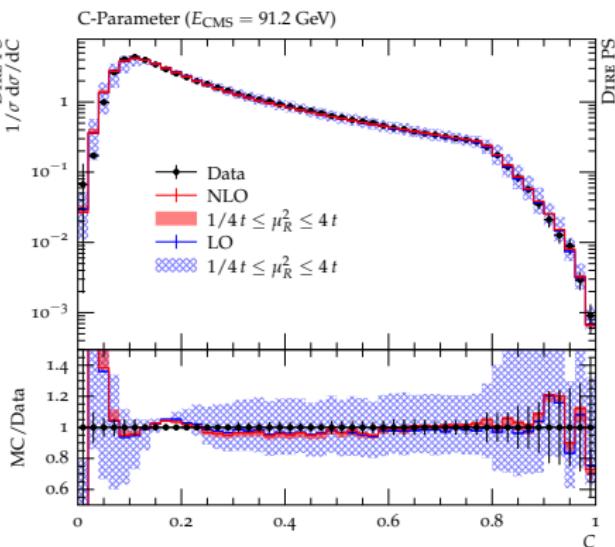
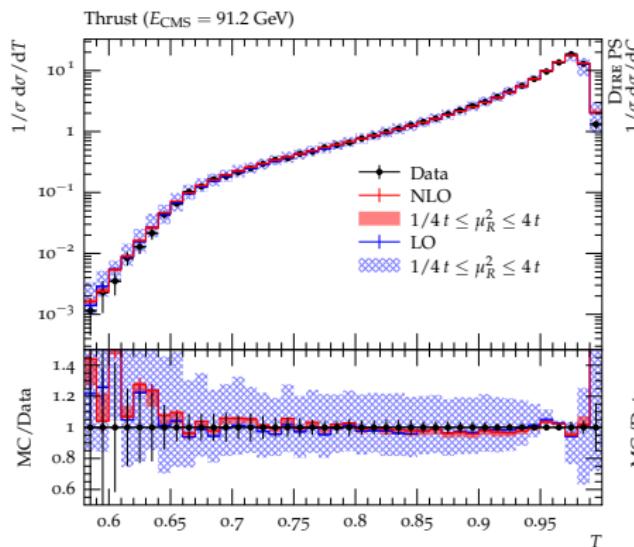
physical results: $e^-e^+ \rightarrow \text{hadrons}$

(Hoeche, FK & Prestel, 1705.00982)



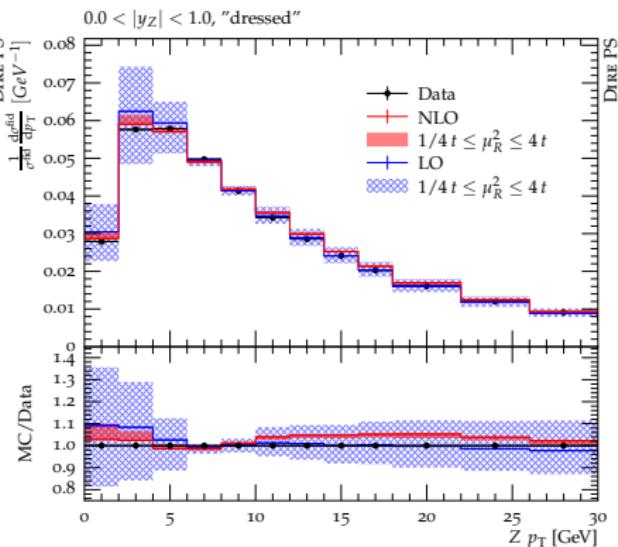
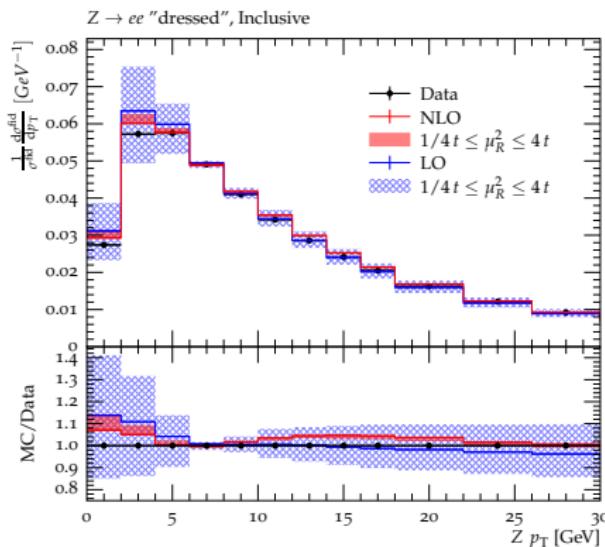
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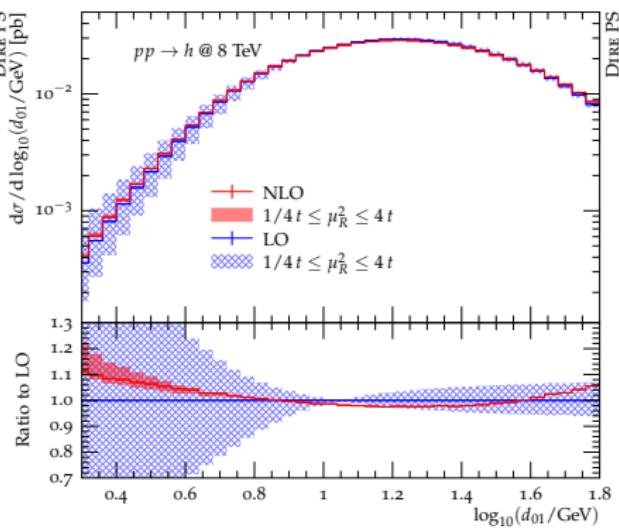
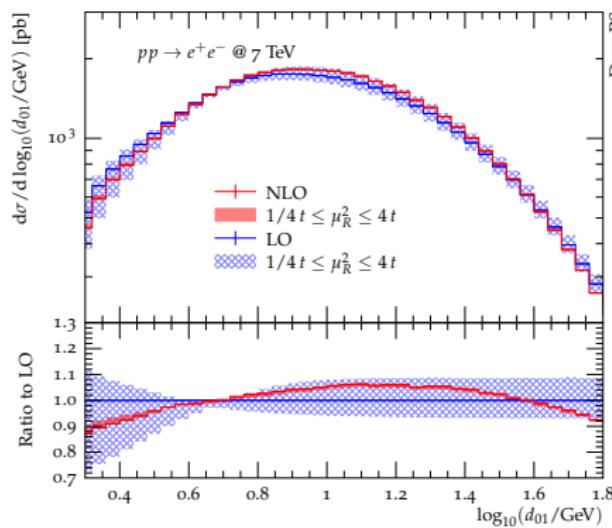
physical results: DY at LHC

(Hoeche, FK & Prestel, 1705.00982)



physical results: diff. jet rates at LHC

(Hoeche, FK & Prestel, 1705.00982)



limitations

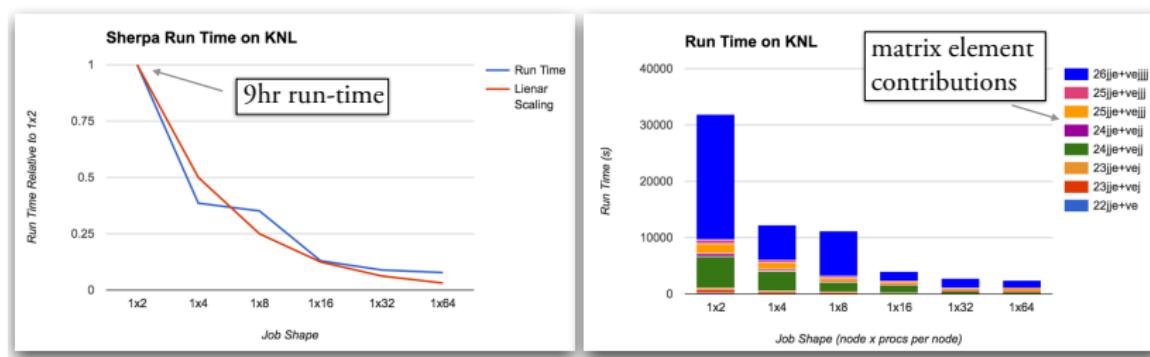
and

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
 - **but** we did not cross-validate them careful enough (yet)
 - **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 → **really?**
- how about α_S : range from 0.113 to 0.118

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

→ 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 \sim 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:
→ PDFs, MPIs, hadronization, etc.
 - question (example): with hadronization tuned to quark jets (LEP)
→ how important is the “chemistry” of jets for JES?
→ can we fix this with measurements?
 - example 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)

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

the looming revolution: going beyond NLO

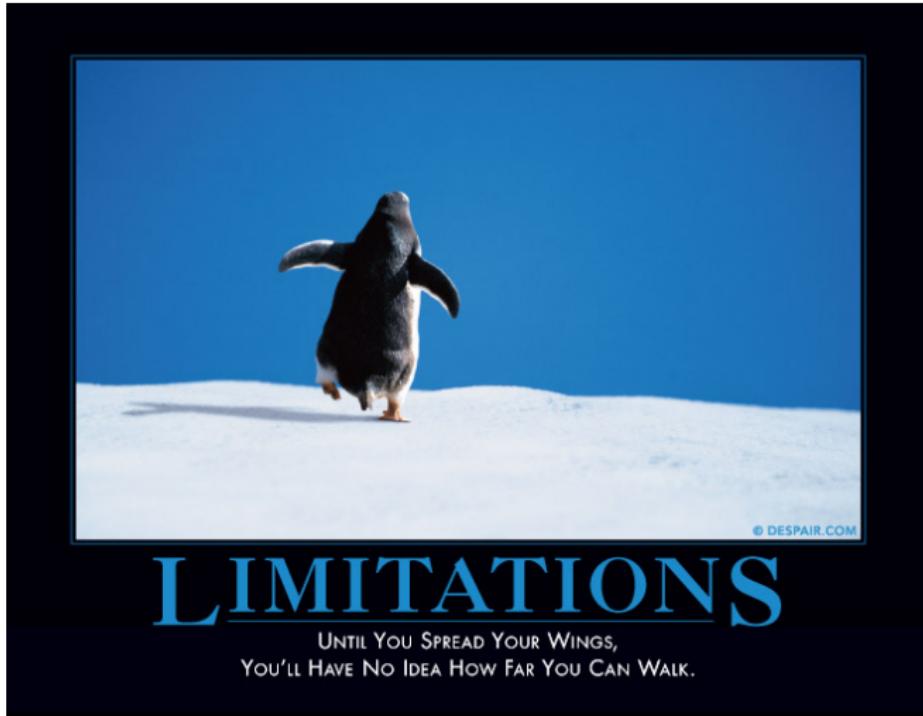
- H in ggF at $N^3\text{LO}$ (Anastasiou, Duhr and others)
- explosive growth in NNLO (QCD) $2 \rightarrow 2$ results

(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 $gg \rightarrow VV$ ([1605.04610](#))
- WBF at NNLO ([1506.02660](#)) and $N^3\text{LO}$ ([1606.00840](#))
- different IR subtraction schemes:
N-jettiness slicing, antenna subtraction, sector decomposition,

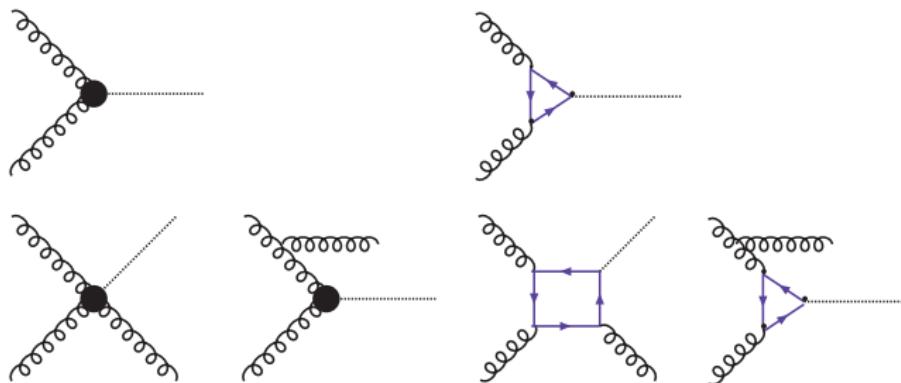
living with the revolution

- 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 UN²LoPs 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:
 - breakdown of factorisation at HO (Seymour et al.)
 - higher-twist: compare $(\alpha_S/\pi)^n$ with Λ_{QCD}/M_Z



extra: quark mass effects in GGF

- include effects of quark masses

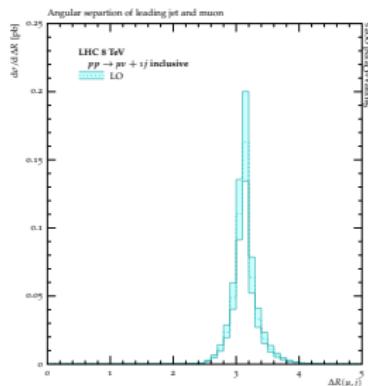


- reweight NLO HEFT with LO ratio:

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

$$d\sigma_{\text{mass}}^{(\text{NLO})} \approx d\sigma_{\text{HEFT}}^{(\text{NLO})} \times \frac{d\sigma_{\text{mass}}^{(\text{LO})}}{d\sigma_{\text{HEFT}}^{(\text{LO})}}$$

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

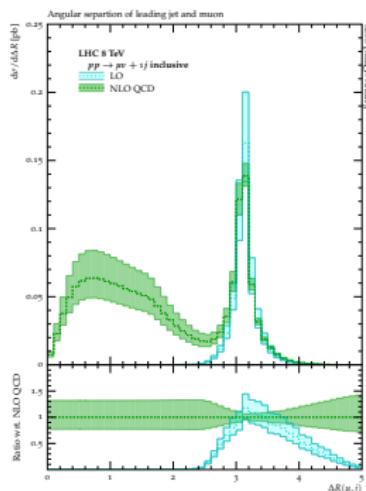


measure collinear W emission?

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

- LO $p p \rightarrow W j$ with $\Delta\phi(\mu, j) \approx \pi$

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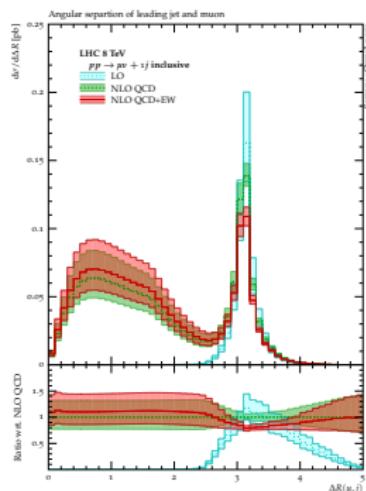


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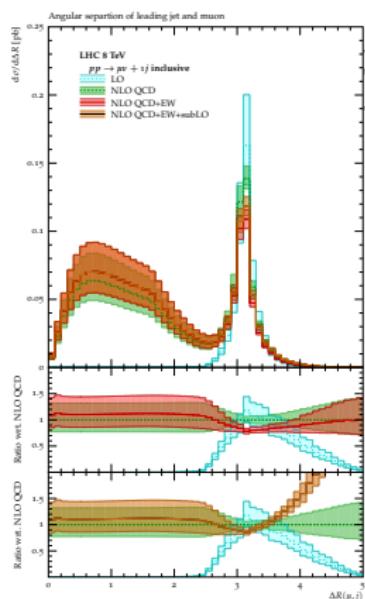


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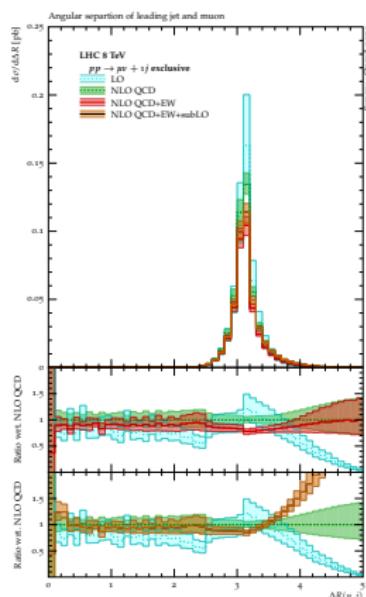


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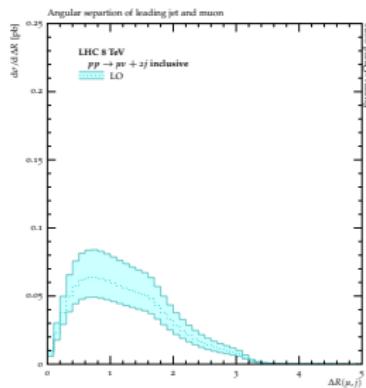


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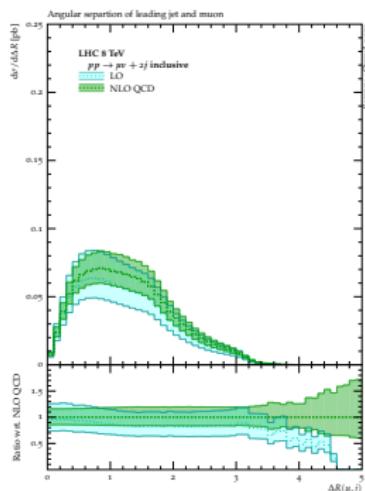


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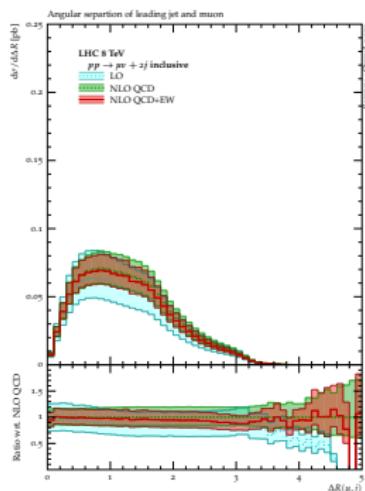


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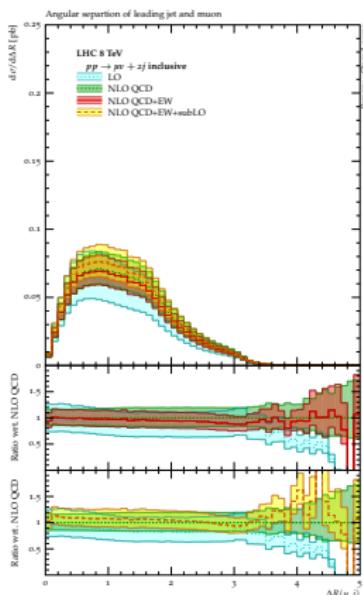
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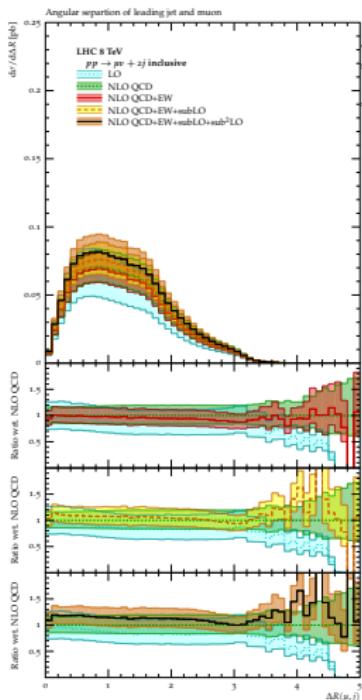


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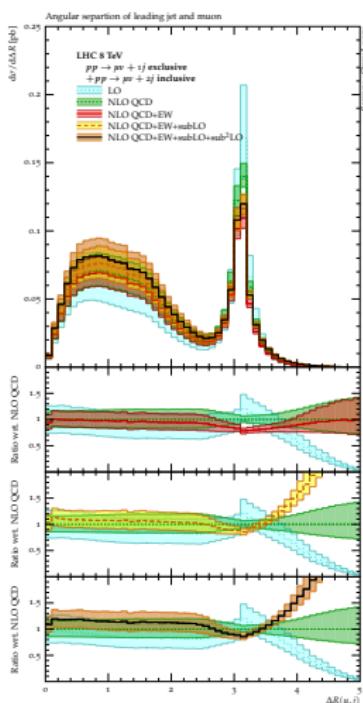
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 \rightarrow possible double counting with BG



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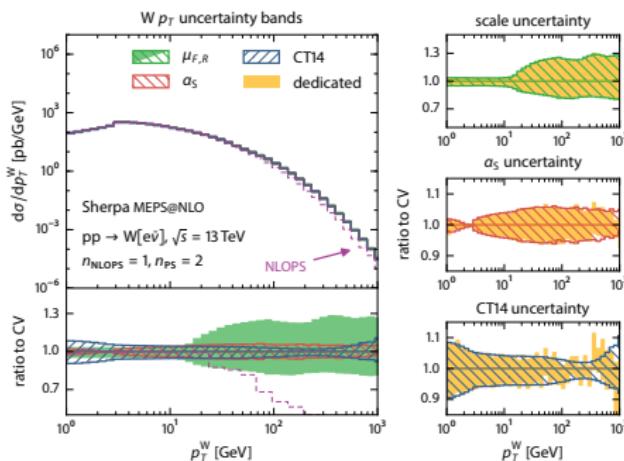
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 - merge using exclusive sums

extra: weight variation for $W+\text{jets}$ with MEPS@NLO

- uncertainties in p_T^W



- CPU budget

