The Edge of Precision in Simulations for the LHC

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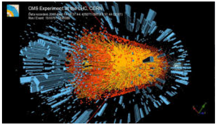
- why precision tools?
- current precision
- improving parton showers
- persistent problems
- summary & outlook

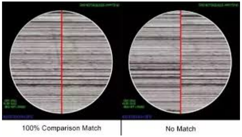
why precision

(carrying coal to Newcastle)

motivation: the need for (more) accurate tools

- to date no discovery of new physics (BSM) (a pity, but that's Nature)
- hope for "simple" discoveries is waning (don't expect anything glaringly obvious)
- push into precision tests of the Standard Model (find it or constrain "subtle"!)
- statistical uncertainties approach zero (because of fantastic work of accelerator, DAQ, etc.)
- systematic exp. uncertainties decrease (because of ingenious experimental work)
- theoretical uncertainties are or become dominant (obstacle to full explitation of LHC)





CSI LHC: need precise & accurate tools for precision physics

how to build an event generator

- paradigm: "divide et impera"
- divide simulation in distinct phases, with (logarithmically) separated scales
- start with signal event

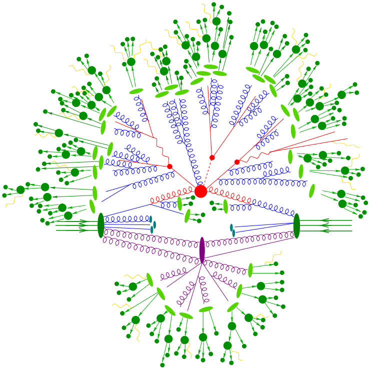
  (fixed order perturbation theory)
- dress partons with parton shower

  (resummed perturbatkon theory)
- add underlying event

  (phenomenological models)
- hadronize partons

  (phenomenological models)
- decay hadrons

  (effective theories, simple symmetries & data)



current precision

(where we are)

fixed-order accuracy

(apologies for any omissions in active field with ≈ 100 publications/past 5 years)

- N^{3}LO for single-boson production (1503.06056 …1802.00833, 1807.11501)
  for DIS, and for VBF H-production in double DIS (1803.09973; 1606.00840)
- NNLO for practically all $2 \to 2$ (and some $2 \to 3$) processes:
  - jj (1705.10271, 1905.09047, …)
  - Vj, γj, Hj (1408.5325, 1504.02131, 1504.07922, 1505.03893, 1705.04664, 1901.11041, 1905.13738, …)
  - tt & single top (1303.6254, 1511.00549; 1404.7116, …)
  - VV and $\gamma\gamma$ (1408.5243, 1504.01330, 1507.06257, 1604.08576, 1605.02716, 1708.02925, 1711.06631, …)
  - VBF (1506.02660, 1802.02445, …)
  - dijets in DIS (1804.05663, …)
- virtual $2 \to \geq 3$ amplitudes (1511.05409, 1511.09404, 1604.06631, 1712.02229, 1811.11699, …)
- relative size argument: $\alpha_s^2 \approx \alpha_W$:
  must include NLO EW corrections for $\mathcal{O}(1-10\%)$ accuracy
  $\Longrightarrow$ automated in OpenLoops, Recola, aMC@Nlo _MadGraph

(1705.00598, 1704.05783, 1405.0301)

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SM precision simulation in a nutshell: Drell-Yan

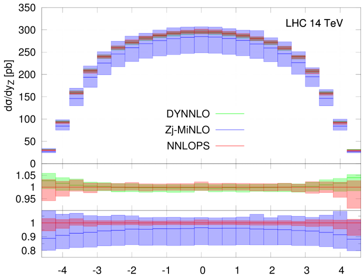
- current "accuracy standard(s)":
  - matching: NNLOPS for inclusive V
  - merging: MEPS@NLO for $V+\leq 2$ jets at NLO $V+\geq 3$ jets at LO
- dominating QCD effects: $\mathcal{O}(10\text{-}30\%)$
  - low-$p_\perp$ region dominated by parton shower
  - high-$p_\perp$ region dominated by (multi-) jet topologies
  - higher accuracy in rate (and some shapes) through NNLO matching
- must add EW corrections for %-level precision
  - EW correction at large scales $\mathcal{O}(10\%)$
  - QED FSR + EW for V line shapes at $\mathcal{O}(1\%)$

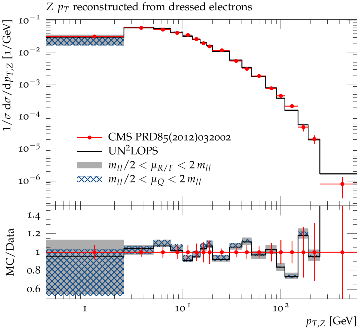
matching at NLO and NNLO

- avoid double-counting of emissions
- two schemes at NLO: MC@NLO and POWHEG
- two schemes at NNLO: MINLO & UNNLOPS (singlets S only)
- MINLO:
  - use POWHEG for $S + j$ with $p_T^{(S)} \to 0$,
  - capture divergences by reweighting with analytic Sudakov form factor
  - NNLO accuracy by reweighting with full NNLO calculation
- UNNLOPS:
  - subtract and add parton shower terms at FO from $S + j$ contributions
  - maintaining unitarity using zero-$p_\perp$ bin
- both available for two simple processes only
- common limitiation: **accuracy of parton showers**

NNLOPS for Z production: MINLO & UNNLOPS

(1407.2904, 1405.3607)

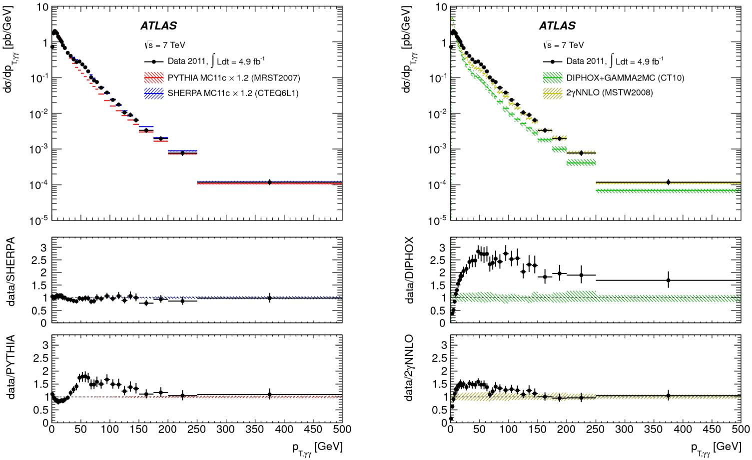




- different logic of achieving NNLO precision
- available for H, V production (both) and VV production (MINLO)

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

(arXiv:1211.1913 [hep-ex])

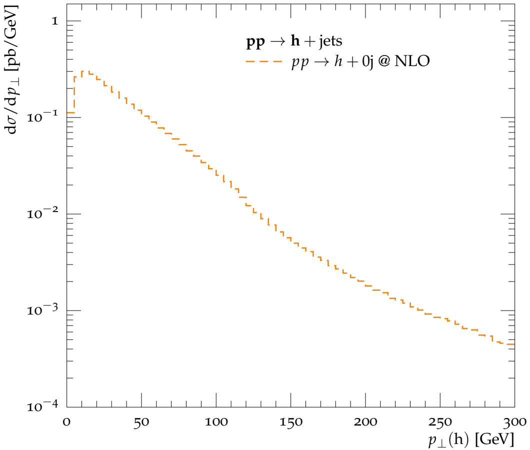


multijet-merging at NLO

- 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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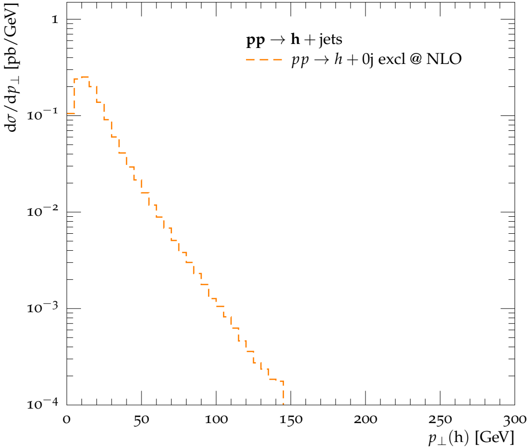

- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$

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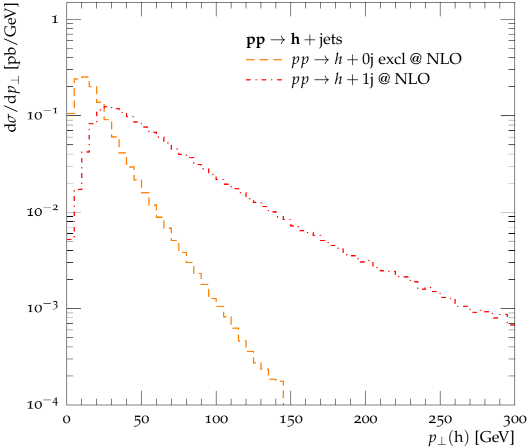

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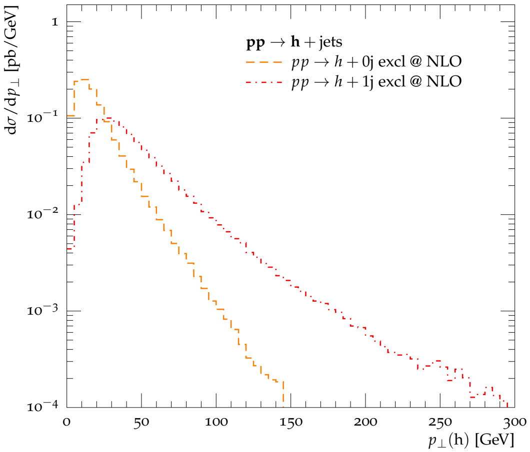

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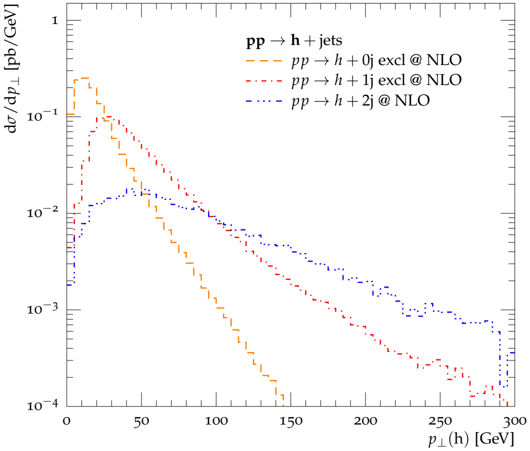

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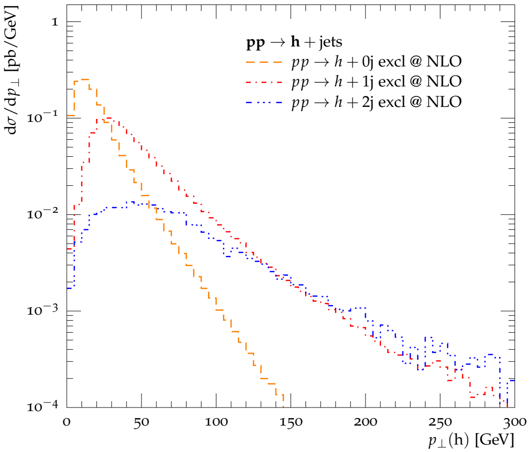

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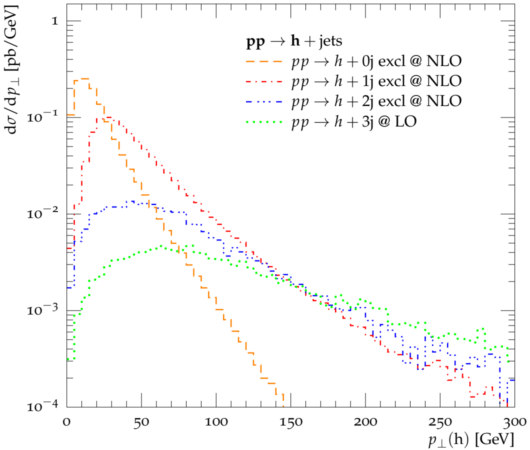

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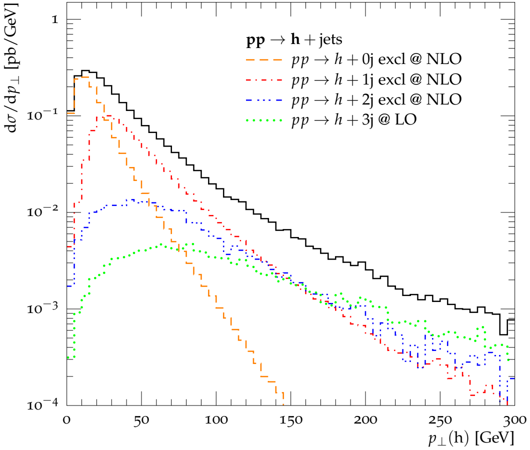

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- sum all contributions

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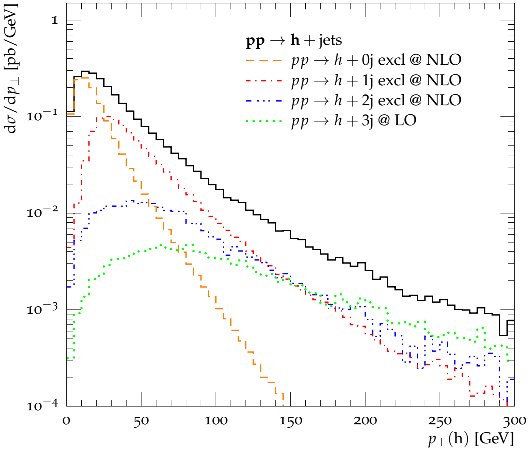

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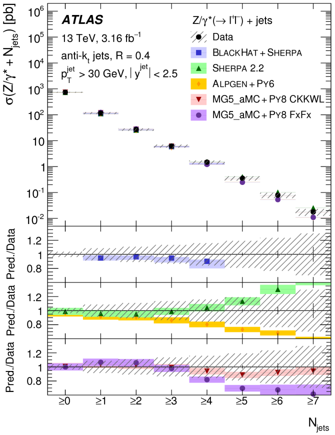
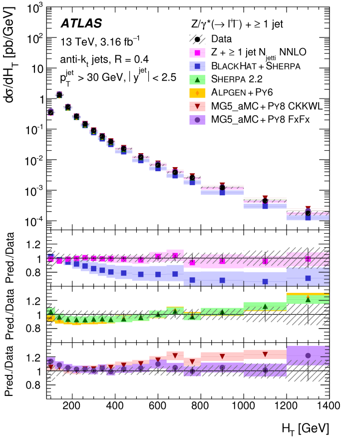
- MC@NLO $pp \to h +$ 2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate
- sum all contributions
- eg. $p_\perp(h)$>200 GeV has contributions fr. multiple topologies

MEPS@NLO for Z+jets: ATLAS data (13 TeV)

(arXiv:1702.05725 [hep-ex])

- various merging codes at LO and NLO



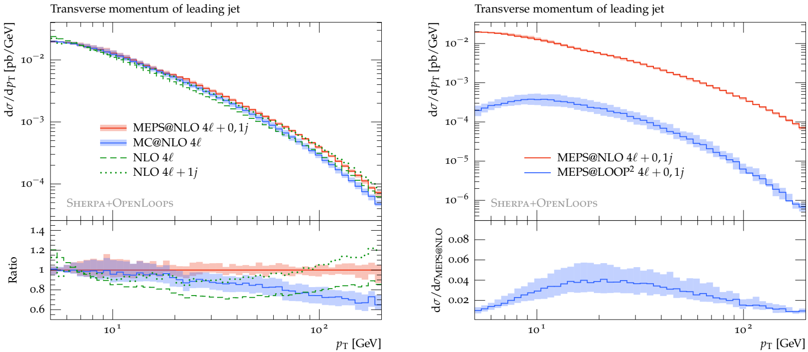


adding loop-induced processes: *WW* production

(arXiv:1309.0500 [hep-ph])

- combine MEPS@NLO for "direct" *WW* production with LO merging for $gg \to WW$

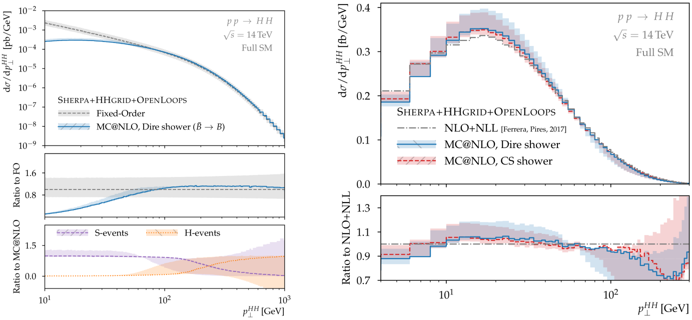
("tagged" by light-quark box)



MC@NLO for loop-induced processes (*HH* production)

(arXiv:1703.09252 & 1711.03319 [hep-ph])

- technology ready for loop-induced NLO (effectively parts of NNLO) combined with parton shower
- two implementations: aMC@NLO _MADGRAPH & SHERPA



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

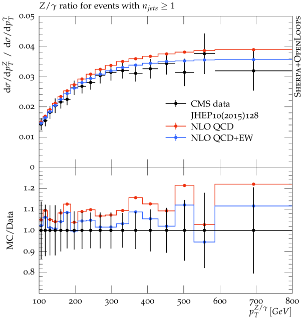
  (somewhat in its infancy: chiral couplings)

- example: Z/γ vs. p_T (right plot)

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

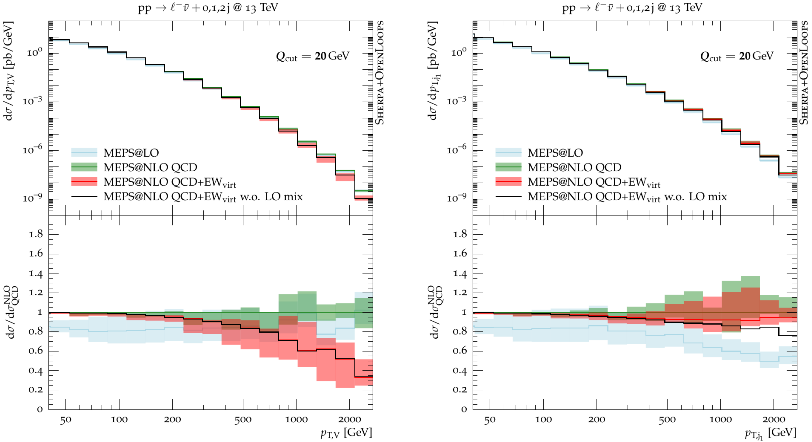
  (Kallweit, Lindert, Pozzorini, Schoenherr for LH'15)

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



EW corrections in $pp \to \ell^- \bar{\nu} +$ jets

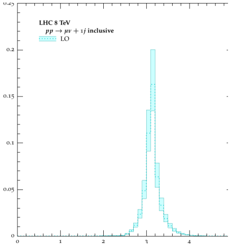
(arXiv:1511.08692 [hep-ph])



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

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

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



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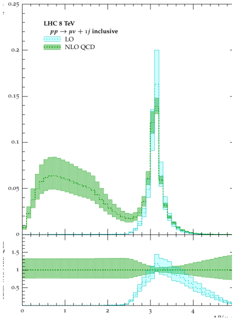

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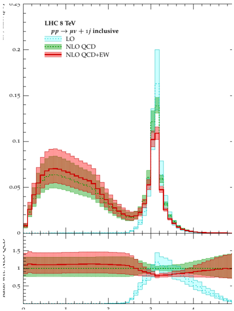

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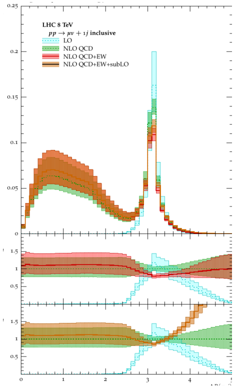

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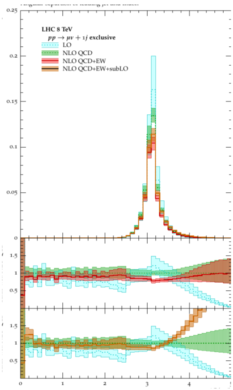

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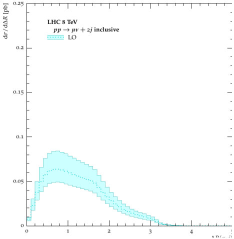

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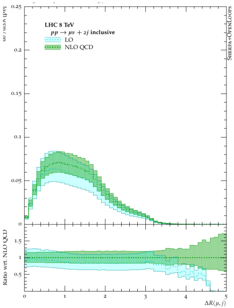

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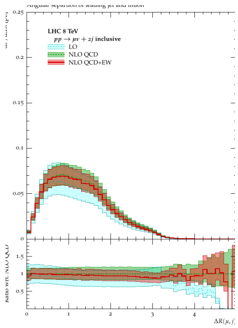

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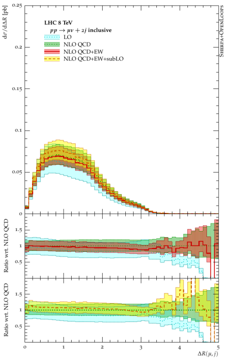

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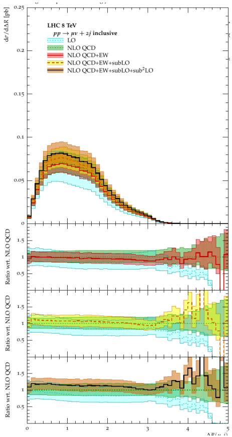

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  $\to$ possible double counting with BG

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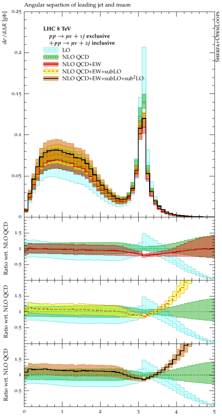

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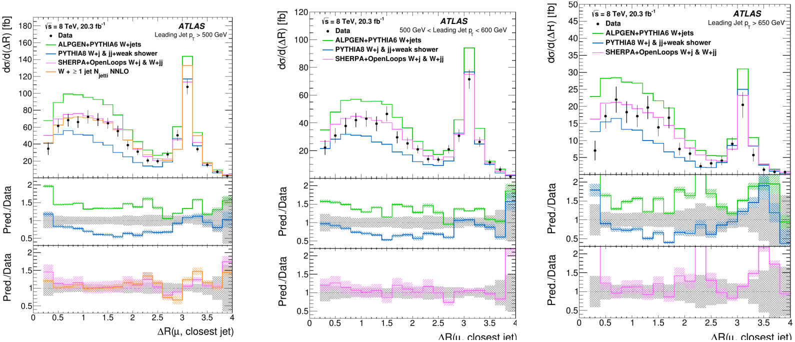
  $\to$ possible double counting with BG
- merge using exclusive sums

. . . and the measurement

(arXiv:1609.07045 [hep-ex])

- different fixed order and simulation tools



another systematic uncertainty: parton showering

- parton showers are approximations, based on

  leading colour, leading logarithmic accuracy, spin-average
- parametric accuracy by comparing Sudakov form factors:

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

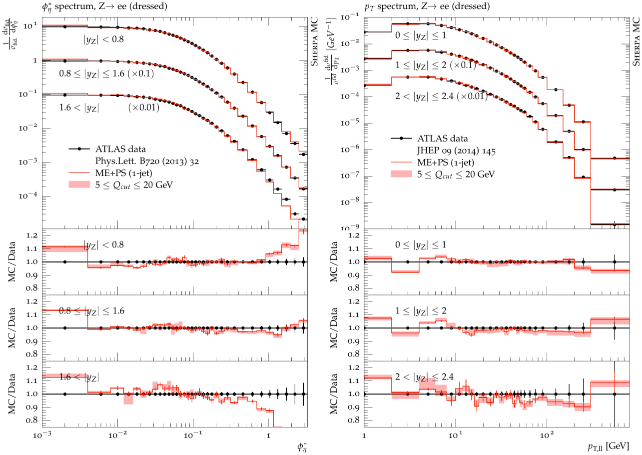
  where A and B can be expanded in $\alpha_s(k_\perp^2)$
- Q_T resummation includes $A_{1,2,3}$ and $B_{1,2}$

  (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

LO results for Drell-Yan

(example of accuracy in description of standard precision observable, 1506.05057)



improving parton showers

(going beyond “plumbing”)

including NLO splitting kernels

(1705.00982, 1705.00742)

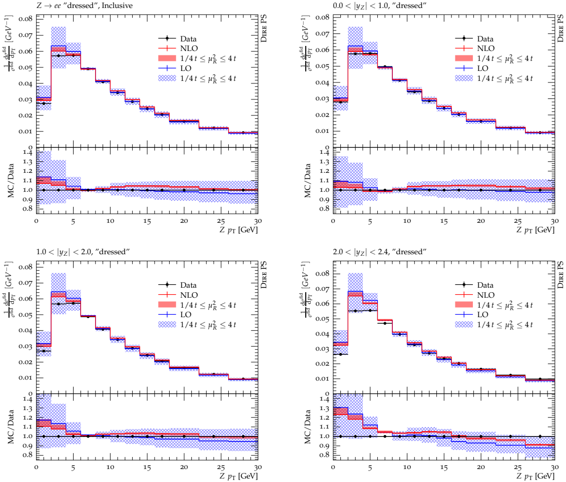
- expand splitting kernels as

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

- 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

physical results: DY at LHC

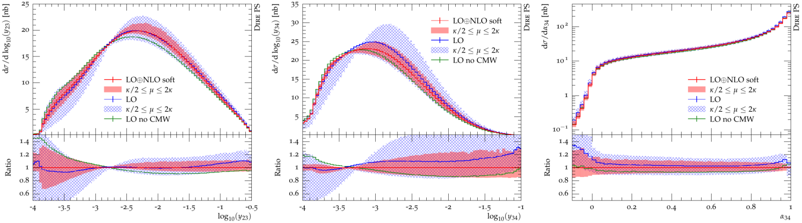
(untuned showers vs. 7 TeV ATLAS data, optimistic scale variations)



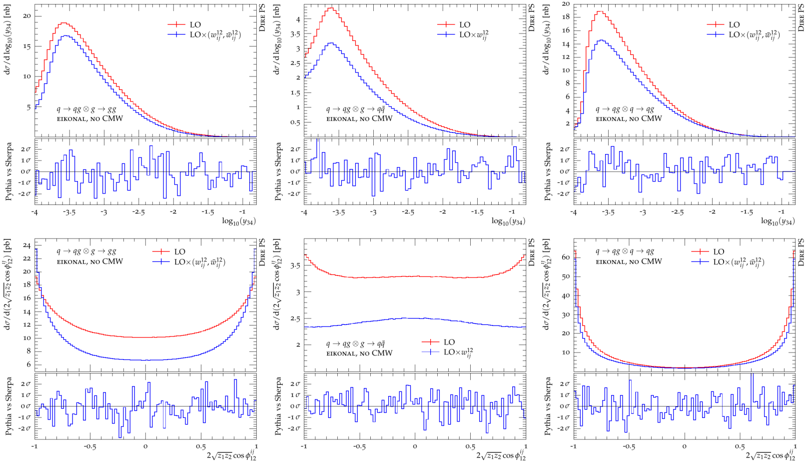
leading colour differential two-loop soft corrections

(1805.03757)

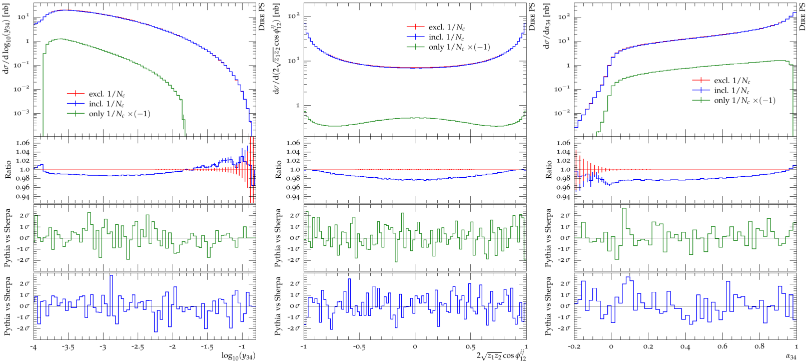
- compare two-emission soft contribution with iterated single emissions
- capture effect by reweighting original parton shower, with
  - accounting for finite recoil
  - including first $1/N_c$ corrections (another way to solve problems in 1805.09327)
  - incorporating spin correlations
- resulting scale dependence (pessimistic estimate) below



reweighting



including $1/N_c$ effects



how to assess formal precision?

- PS proven to be NLL accurate for simple observables, provided

  Catani, Marchesini, Webber, NPB349 (1991) 635

  - soft double-counting removed ($\nearrow$ before) and
  - 2-loop cusp anomalous dimension included
- not entirely clear what this means numerically, because
  - parton shower is momentum conserving, NLL is not
  - parton shower is unitary, NLL approximations break this
- differences can be quantified by
  - designing an MC that reproduces NLL exactly
  - removing NLL approximations one-by-one
  - employ well-established NLL result as example (technical discussion in 1711.03497)
- recent study: issues with 2$^{\rm nd}$ emission in modern showers (1805.09327)
  known problem (and solved for ARIADNE in, e.g., Nucl.Phys. B392 (1993) 251)

persistent problems

(not everything is rosy)

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

- parton showers geared towards collinear & soft emissions of gluons

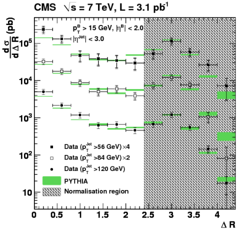
  (double log structure)

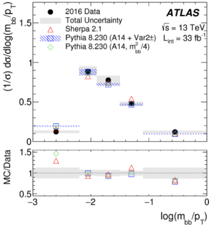
- $g \to q\bar{q}$ only collinear
- old measurements at LEP of $g \to b\bar{b}$ and $g \to c\bar{c}$ rate
- fix this at LHC for modern showers

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

- questions: kernel, scale in α_s

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

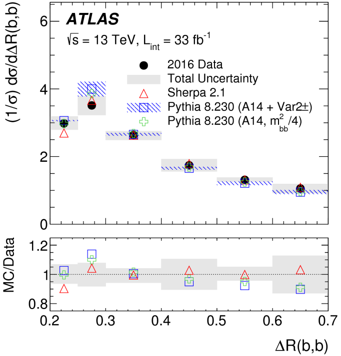


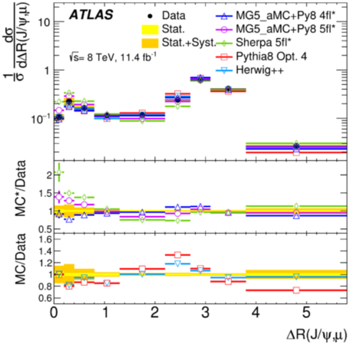


latest ATLAS measurements

(arXiv:1812.09283, 1705.03374 [hep-ex])

- use b-tagged jets with $R = 0.2$ (left)
- use muons in $B \to J/\Psi(\mu\mu) + X$ and $B \to \mu + X$ as proxies (right)





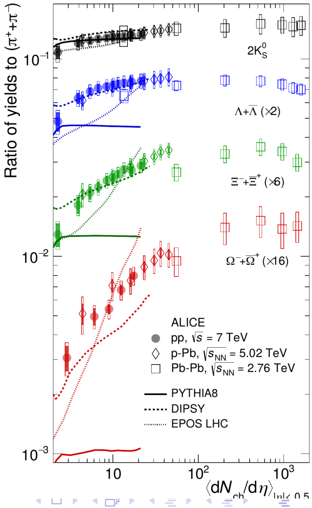
massive quarks are tricky - encore

- heavy quarks also problematic in initial state:
  no PDF support for $Q^2 \leq m_Q^2 \longrightarrow$ quarks stop showering
- possible solutions:
  - naive: ignore and leave for beam remnants (SHERPA)
  - better: enforce splitting in region around m_Q^2 (PYTHIA)
    $\longrightarrow$ effectively produces collinear Q and gluon in IS
- will need to check effect on precision obsevables: $p_\perp^{(W)}/p_\perp^{(Z)}$

soft physics: strange strangeness

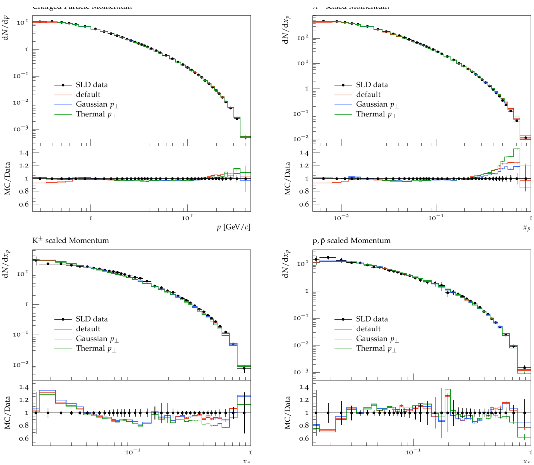
- universality of hadronization assumed
- parameters tuned to LEP data
  in particular: strangeness suppression
- for strangeness: flat ratios
  but data do not reproduce this
- looks like $SU(3)$ restoration
  not observed for protons
- needs to be investigated (see next)

(plot from arXiv:1606.07424 [hep-ex])



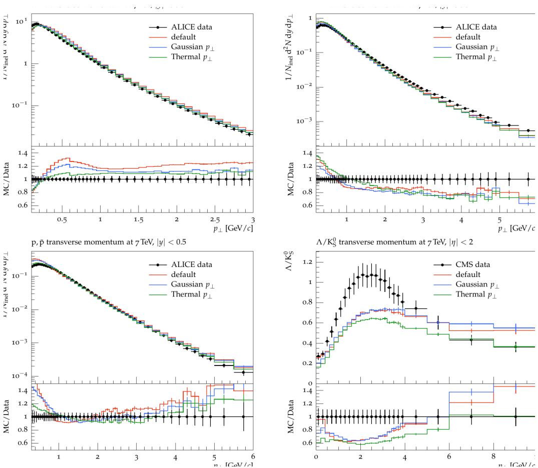
hadronization issues

(illustrative plots from arXiv:1610.09818 [hep-ph])



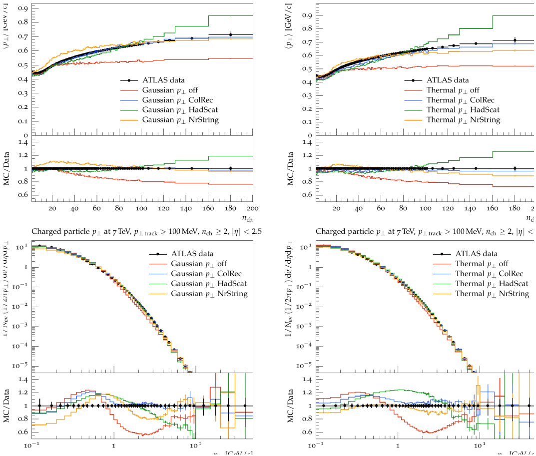
hadronization issues

(illustrative plots from arXiv:1610.09818 [hep-ph])



hadronization issues

(illustrative plots from arXiv:1610.09818 [hep-ph])

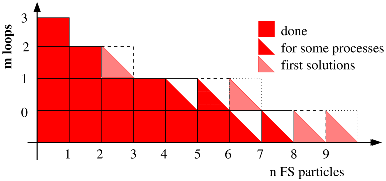


summary & outlook

(successes, wild dreams, & heretical thoughts)

successes & questions

- program of precision calculations (HO QCD) successful:



- NNLO QCD calculations consolidated for $2 \to 2$ processes

(but: not yet available in full simulations, necessary for investigations at $\mathcal{O}(< 10\%)$ accuracy)

- combine (N)NLO QCD and NLO EW corrections?

(investigate additive vs. multiplicative, maybe with calculations like 1511.08016)

- consolidated MC simulation at NLO

(MC@NLO, MEPS@NLO & friends, addition of EW effects)

(but: still steep learning curve ahead)

wild dreams for upcoming LHC run(s)

(things that I think are feasible in next 5 years)

- NNLO (QCD) $\oplus$ NLO (EW) for all $2 \to 2$ SM processes
- NNLO (QCD) for first "real" $2 \to 3$ SM processes
- parton shower at $\mathcal{O}(\alpha_s^2)$

(interesting interplay with subtraction at NNLO)

- "proper" NNLOPS (MC@NNLO) for all $2 \to 2$ processes

(plus multijet merging with (N)NLO)

- $\mathcal{O}(1\%)$ control over inclusive/precision observables: inclusive xsecs; $p_\perp$ spectrum of W, Z, H; ...
- fix treatment of heavy flavours in FS & IS

(important for Higgs precision/BSM searches, "higher-twist" corrections to simple factorisation, role of PDFs)

(problems at $\mu_F^2 < m_Q^2 \longrightarrow$ forced transitions to gluons at/around mass threshold)

summary: some heretical thoughts

- massive efficiency issues with HO calculations

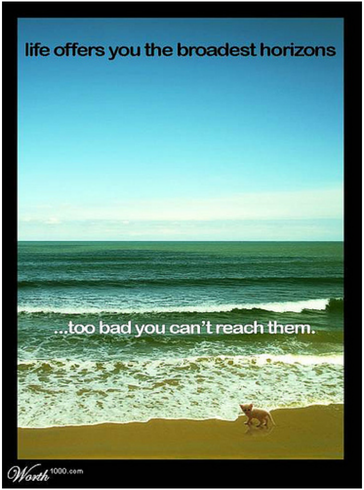
(must learn to use tools in smarter ways)

- is there a limit to our perturbative precision programme?
  - discuss non-perturbative effects: compare $\Lambda_{\rm QCD}/Q$-effects with α_s
  - improvement scales like ratio of "exponent" n in N^{n}LO/N^{n-1}LO?

($= \infty$ for LO$\to$ NLO, 100% for NLO$\to$NNLO, 50% for NNLO$\to$NNNLO, ...)

- soft/non-perturbative physics will be the biggest uncertainty for many observables/measurements

(but practically nobody works on it)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