QCD at the Energy Frontier

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WE Heraeus School on
“QCD – Old Challenges and New Opportunities”

- what the talk is about
- lessons from the LHC
- the quest for precision
- anticipating the future
- summary

motivation & introduction

motivation

- QCD = well understood theory with subtle effects
- QCD radiation omnipresent at the LHC
- enters as signal (and background) in high-$p_\perp$ analyses
  - multi-jet signatures

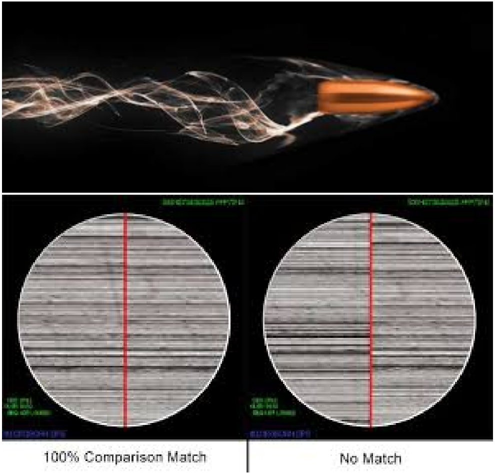
    $\longrightarrow$ multijet merging & higher-order matching
  - inner-jet structures e.g. from "fat jets"

    $\longrightarrow$ parton shower algorithms
- begs the question: can we improve our understanding?

  (keep in mind: accuracy vs. precision)
- in addition: interesting physics in QCD alone

  (think about multi-parton interactions, collective phenomena, etc.)

- will need precision for ballistics of smoking guns



lessons from the LHC

lessons from the LHC

- jets are ubiquitous: QCD fills phase space if available:
  n-jet rates may scale beyond α_S^n
- if emissions well-separated: fixed order QCD
  $\longrightarrow$ works amazingly well
- however: subtle effects when emission logarithms become large
  $\longrightarrow$ QCD beyond fixed order!
- conceptual problems still open: mainly soft QCD
  hadronization, multiple parton interactions, the "ridge"

perturbation theory works!

factorization: calculating observables for the LHC

- master formula

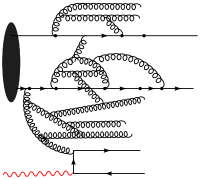
$$\mathrm{d}\sigma_{pp\to X} = \sum_{ij}\int_0^1 \mathrm{d}x_1\mathrm{d}x_2 f_i(x_1,\mu_F)\, f_j(x_2,\mu_F) \int \mathrm{d}\Phi_X\, \hat{\sigma}_{ij\to X}(\{p_X\};\mu_F,\mu_R)$$

relating parton-level $\hat{\sigma}$ with particle-level (observable) cross section σ

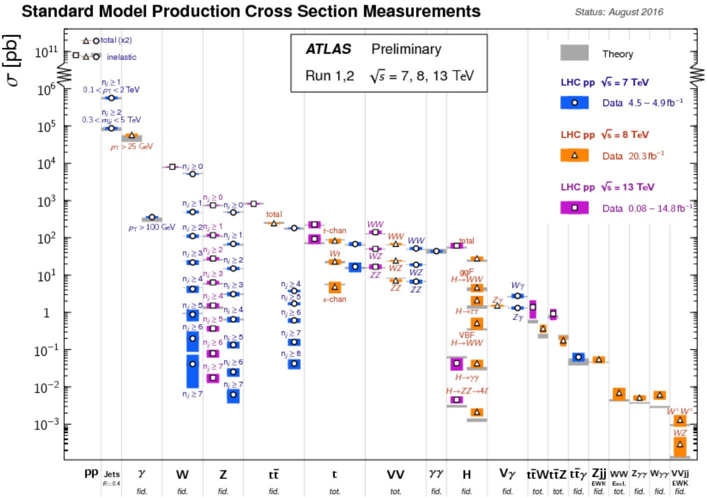
(partons = quarks and gluons)

- based on "factorization":
  parton distribution function $f_i(x,\,\mu_F)$
  process-independent if typical momentum scale $Q \approx \mu_F \gg m_{\rm proton}$

(PDF = probability to find one parton of type i with energy fraction x at factorization scale μ_F in proton)



overall agreement with data



soft QCD questions

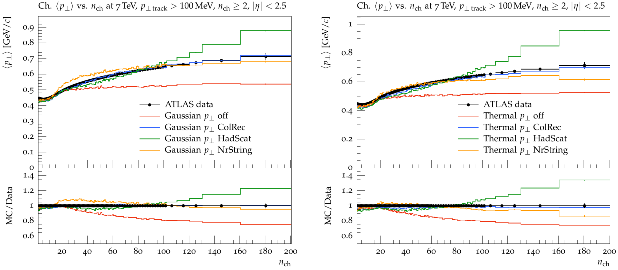
colour reconnections and friends

(Fischer, Sjostrand, 1610:09818)

Collective flow observed in pp at LHC. Partly unexpected.
New mechanisms required; could also (partly) replace CR.

Active field, e.g. N. Fischer & TS, arXiv:1610:09818 [hep-ph]:

- Thermal $exp(-p_\perp/T) \to exp(-m_\perp/T)$ hadronic spectrum.
- Close-packed strings $\Rightarrow$ increased string κ or T.
- Dense hadronic gas $\Rightarrow$ hadronic rescattering.

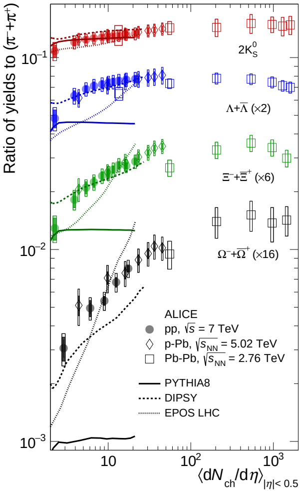


(slide stolen from Torbjorn Sjostrand)

strange strangeness

- universality of hadronisation 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

(ALICE collaboration)



beyond factorization

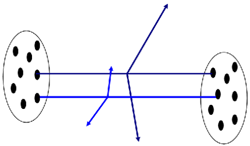
example: multi-parton interactions

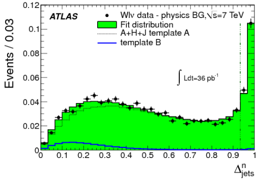
- protons = extended objects
  $\longrightarrow$ possibility of more parton pairs interacting
  resulting final states may be hard
  in "perturbative regime" $p_\perp \geq$ few GeV
- but: no factorization theorem available
  $\longrightarrow$ no first-principles theory
- simplistic parameterization

$$\sigma^{(DPS)}_{X+Y} = \frac{\sigma_X \otimes \sigma_Y}{\sigma_{\rm eff}}$$

with $\sigma_{\rm eff} \approx 15$ mb (measured)

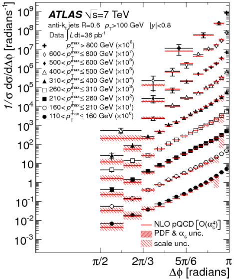
($\sigma_{\rm tot} \approx 100$ mb $= 10^{-29}$m^2 at LHC)



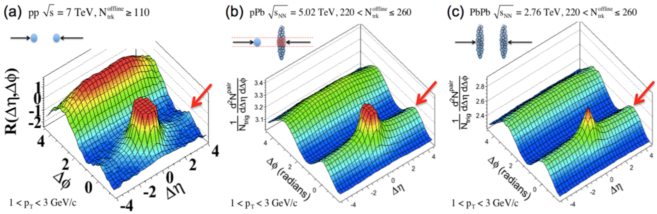


example: the ridge

- momentum conservation in transverse plane:
  $\longrightarrow$ in $2 \to 2$ collisions particles produced "back-to-back"
  $\longrightarrow$ decorrelation by additional radiation
- well understood in pert.QCD



- however: surprising structure in high-multiplicity *pp* cannot be reproduced in standard pert.QCD Monte Carlo



- typically explained as "collective effect"
  in heavy-ion collisions: "hydrodynamics"
  in *pp*: colour-ropes, "glasma"

(colour-glass condensate = non-pert. in weak coupling, glasma = Bose enhancement + Pauli blocking)

- conceptually different from textbook perturbation theory

the quest for precision

precision at fixed order

complex inputs I: parton distribution functions

- PDFs not known from first principles, only their scaling with μ_F

  (from the Altarelli-Parisi equations)

- fitted from data at different processes, at different, μ_F, at different experiments, with different systematics
- current accuracy: next-to–next-to–leading order (NNLO)

  (various collaborations: CTEQ, MMHT, NNPDF, ABM, GRV, HeraPDF)

- needs NNLO calculations and three-loop kernels driving the evolution

  (4-loop kernels partially known; Moch et al., 1707.08315)

- but: α_S^2 is $\mathcal{O}(1\%)$ – must also include electromagnetic and weak evolution at (N)LO

  (current frontier: LUXqed; Manohar PRL 117 (2016) 242002)

determining reliable PDFs — a complex endeavour

complex inputs II: partonic cross sections $\hat{\sigma}$

- fully automated evaluation of $\hat{\sigma}$ at LO and NLO,
  integral over phase space $\mathrm{d}\Phi_X$ with $3n-2$ dimensions for n particles
  $\longrightarrow$ Monte Carlo methods with involved sampling strategies
- problem beyond LO: occurrence of divergent structures when
  - momenta $k\to\infty$ ("ultraviolet divergence")
    regularization and renormalization
  - or $k\to 0$ ("infrared divergence")
    regularization and exact cancellation between contributions

    (Kinoshita–Lee–Nauenberg theorem)
- regularization by analytic continuation $\mathrm{d}^4k\to\mathrm{d}^Dk$ with $D=4+2\epsilon$
  divergences manifest as poles $1/\epsilon$
- straightforward for UV divergences but tricky for IR divergences:
  cancellation is between contributions of different multiplicity

  (and phase space integrals are usually done with Monte Carlo methods)

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, . . .)

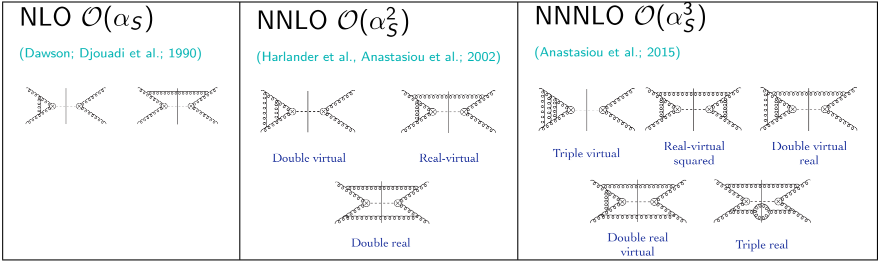
- start discussing scale setting prescriptions

  (simple central scales for complicated multi-scale processes? test smarter prescriptions?)

- steep learning curve still ahead: "NLO phenomenology"

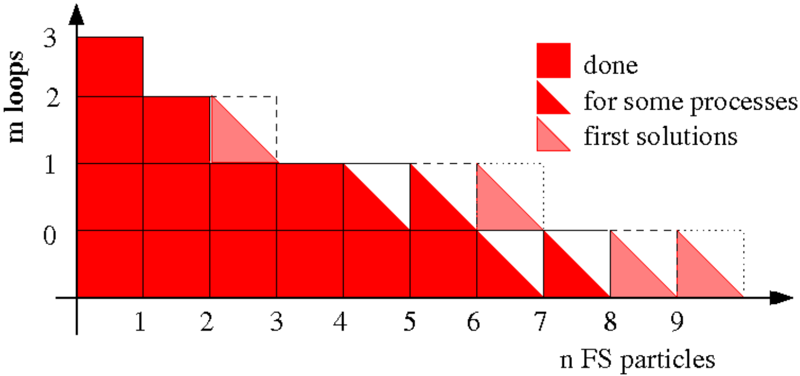
  (example: methods for uncertainty estimates beyond variation around central scale)

pushing the perturbative order: $gg \to H$



- $\sim$ 1,000 Feynman diagrams at NNLO
- $\sim$ 100,000 Feynman diagrams at N^{3}LO
  reduced to $\sim$ 1000 master integrals $\longrightarrow$ "Symbols"

technological/complexity limit



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: 3 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?

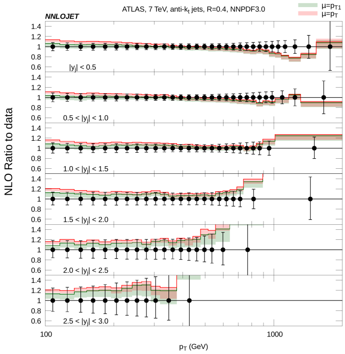
    (MINLO or UN^{2}LOPS or something new?)

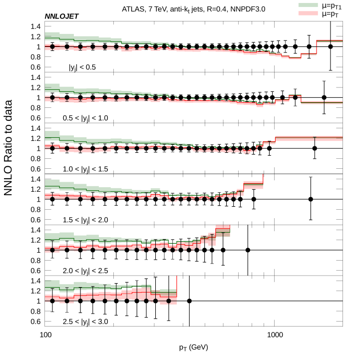
  - more scales (internal or external) complicated – need integrals
- more philosophical questions:
  - going to higher power of N often driven by need to include larger FS multiplicity – maybe not the most efficient method
  - limitations of perturbative expansion:
    $\longrightarrow$ breakdown of factorisation at HO (Seymour et al.)
    $\longrightarrow$ higher-twist: compare $(\alpha_S/\pi)^n$ with $\Lambda_{\rm QCD}/M_Z$

a scale puzzle at NNLO

J. Currie et al., Acta Phys.Polon. B48 (2017) 955

- common lore: higher orders stabilise/reduce scale dependence
- but: look at inclusive jet-$p_\perp$





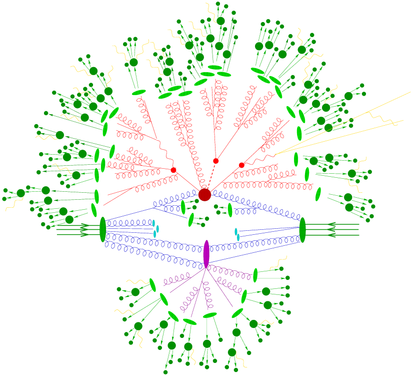
status of precision simulations

embedding in full simulations

- fixed-order perturbation theory does not give full picture of *pp* 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



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 $((ij)+k\to i+j+k)$:

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

- splitting functions including IR regularisation

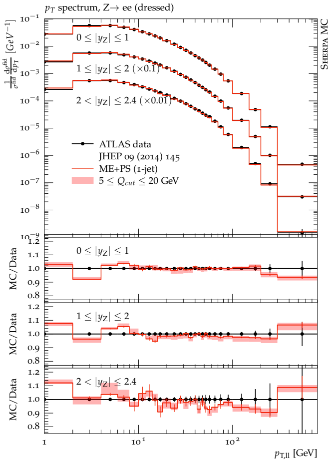
(a la Curci, Furmanski & Petronzio, Nucl.Phys. B175 (1980) 27-92)

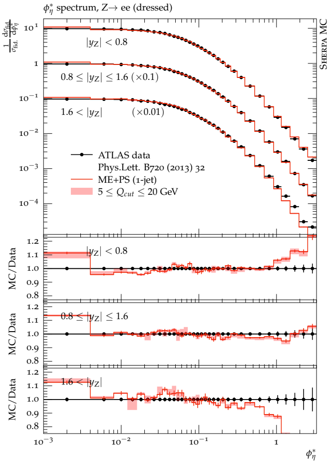
$$\begin{aligned}
P^{(0)}_{qq}(z,\kappa^2) &= 2C_F\left[\frac{1-z}{(1-z)^2+\kappa^2}-\frac{1+z}{2}\right],\\
P^{(0)}_{qg}(z,\kappa^2) &= 2C_F\left[\frac{z}{z^2+\kappa^2}-\frac{2-z}{2}\right],\\
P^{s(0)}_{gg}(z,\kappa^2) &= 2C_A\left[\frac{1-z}{(1-z)^2+\kappa^2}-1+\frac{z(1-z)}{2}\right],\\
P^{(0)}_{gq}(z,\kappa^2)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

- renormalisation/factorisation scale given by $\mu=\kappa^2Q^2$
- 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)





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

- parton showers geared towards collinear & soft emissions of gluons

(double log structure)

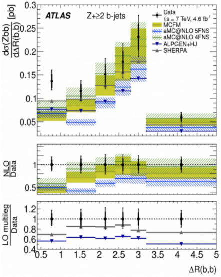
- $g \to q\bar{q}$ only collinear

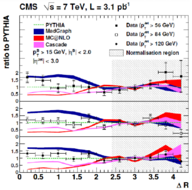
- old measurements at LEP of $g \to b\bar{b}$ and $g \to c\bar{c}$ rate
- fix this at LHC for modern showers

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

- questions: kernel, scale in α_S

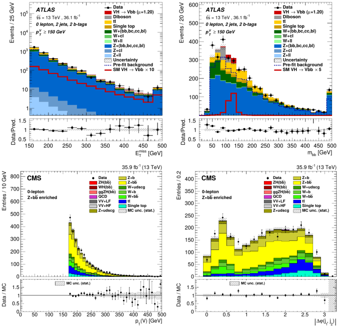
(example: $k_\perp$ vs. m_{bb})



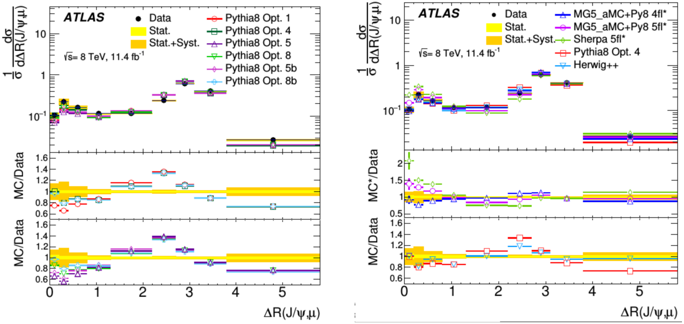


- flagship measurements: $VH_{\to b\bar{b}}$, $t\bar{t}H_{\to b\bar{b}}$, ...
- many searches with b's
- influences b-tag rate

  ("double"-b jets = gluon jets)
- can cause problems in highly boosted regime



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



matching at NLO and NNLO

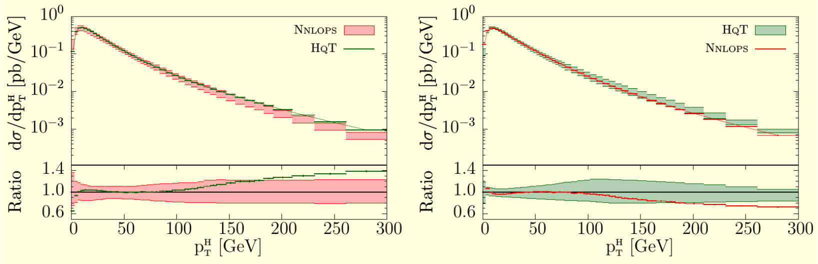
- avoid double-counting of emissions
- two schemes at NLO: MC@NLO and POWHEG
  - mismatches of K factors in transition to hard jet region
  - MC@NLO: $\longrightarrow$ visible structures, especially in $gg \to H$
  - POWHEG: $\longrightarrow$ high tails, cured by h dampening factor
  - well-established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

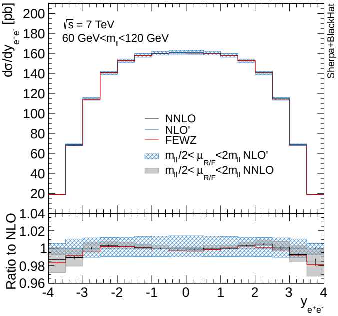
K. Hamilton, P. Nason, E. Re & G. Zanderighi, JHEP 1310

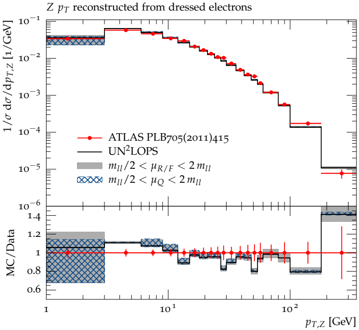


- also available for $Z/W/VH$ production

NNLOPs for Z production: UN^{2}LOPs

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





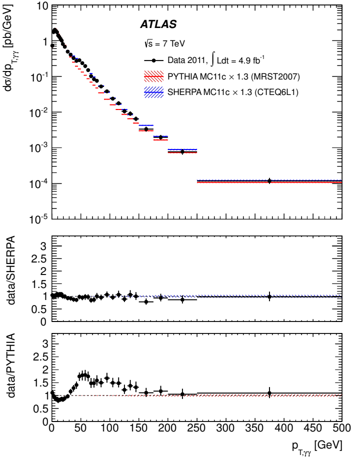
- also available for H production

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])

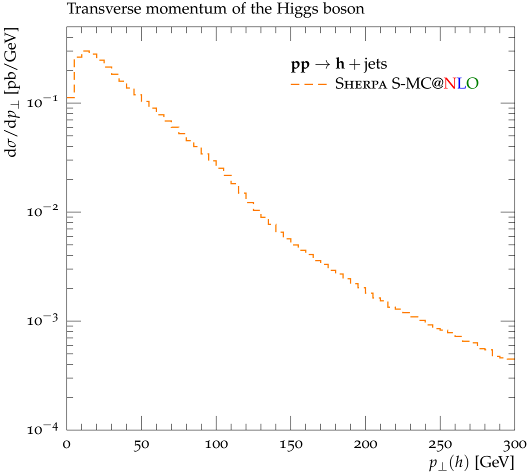


multijet-merging at NLO

- 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

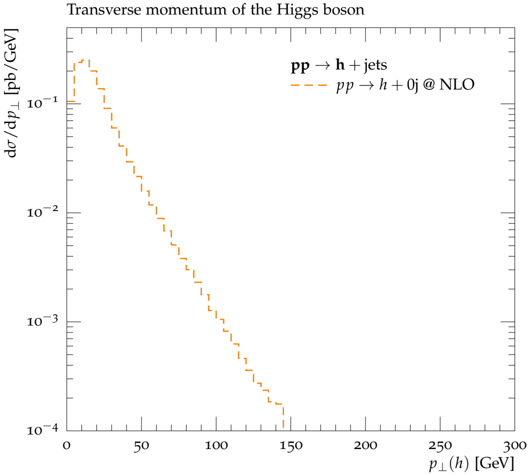
  (MEPS@NLO, FxFx, UNLOPS)
- starts being used, still lacks careful cross-validation

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



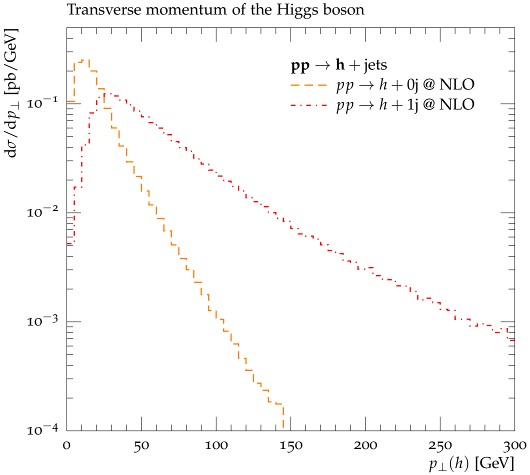
- first emission by MC@NLO

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



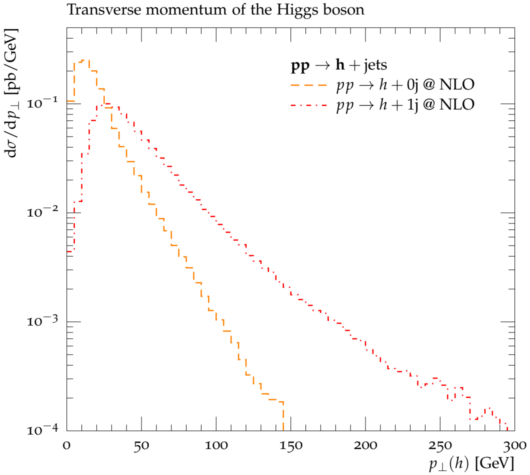
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$

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



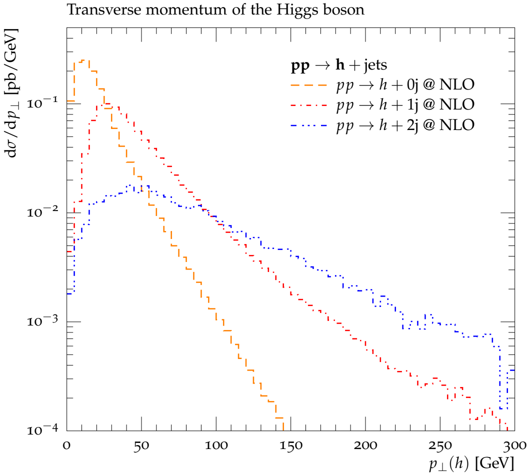
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$

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



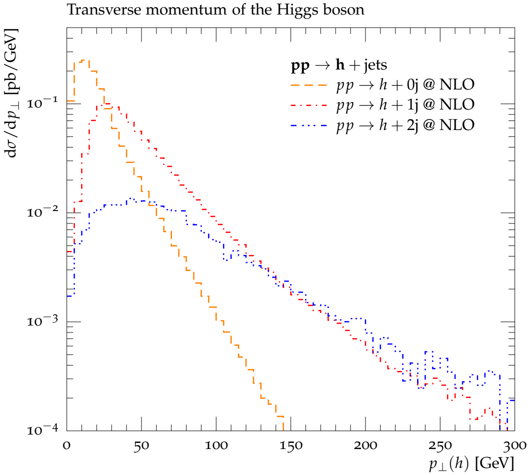
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$

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



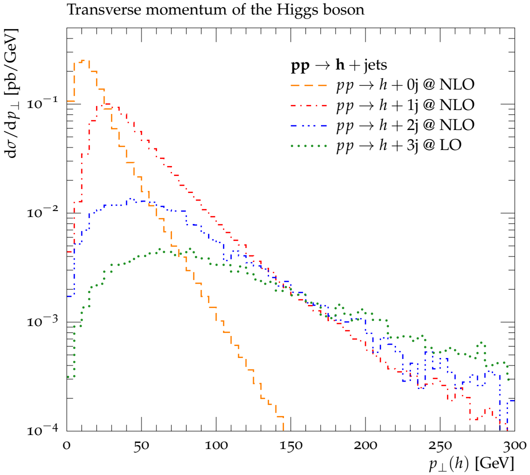
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\rm cut}$

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



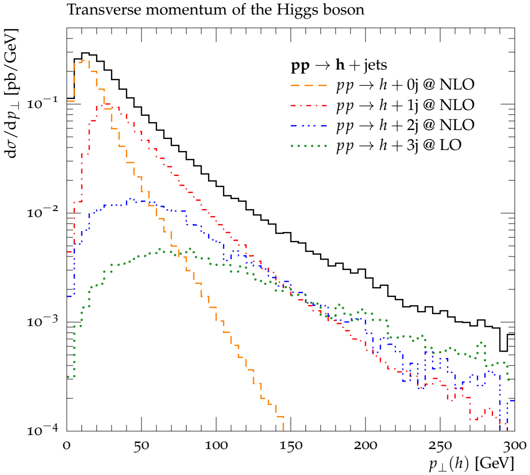
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h+$jet for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h+$jet to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h+$2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate

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



- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h +$ jet for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h +$ jet to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h +$ 2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate

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



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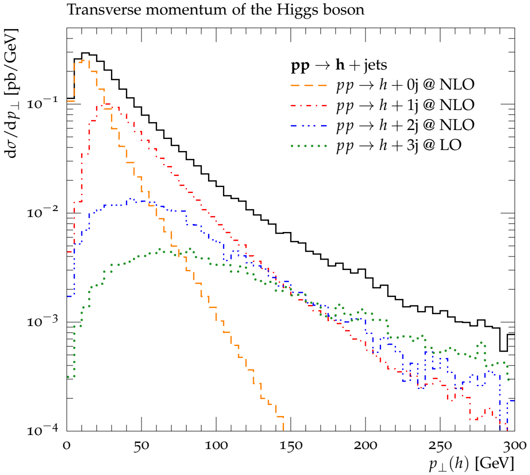

- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
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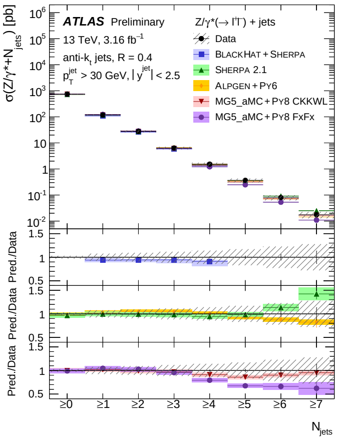
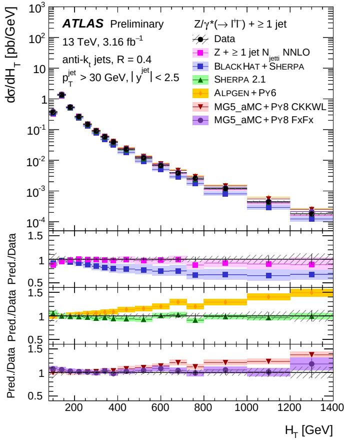
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\rm cut}$
- iterate
- sum all contributions
- eg. $p_\perp(h) > 200$ GeV has contributions fr. multiple topologies

Z+jets at 13 Tev: comparison with ATLAS data

- various merging codes at LO and NLO





pushing the envelope:
showering at NLO accuracy

Including NLO splitting kernels

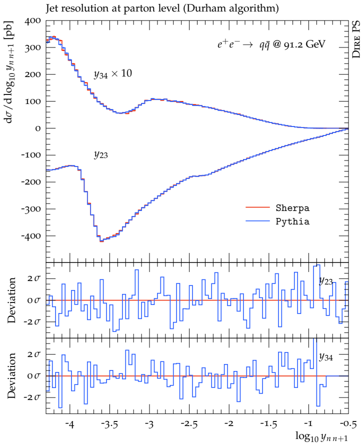
(Hoeche, FK & Prestel, 1705.00982, and Hoeche & Prestel, 1705.00742)

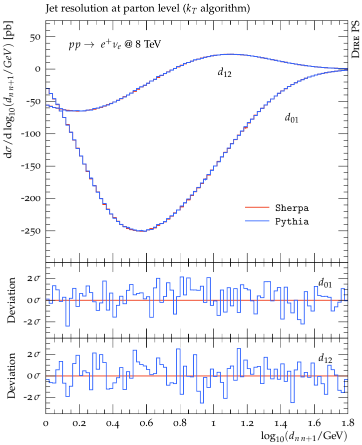
- expand splitting kernels as

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

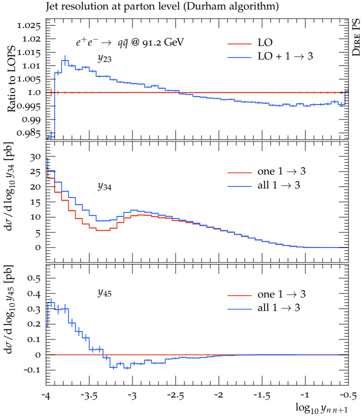
- aim: reproduce DGLAP evolution at NLO
  include all NLO splitting kernels
- three categories of terms in $P^{(1)}$:
  - cusp (universal soft-enhanced correction) (already included in original showers)
  - corrections to $1 \to 2$
  - new flavour structures (e.g. $q \to q'$), identified as $1 \to 3$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

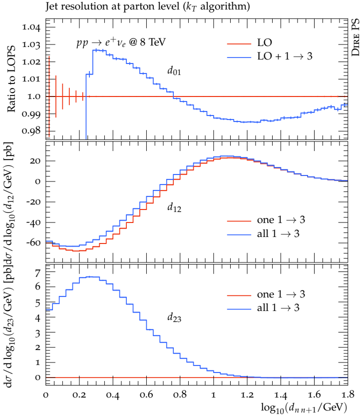
validation of $1 \to 3$ splittings





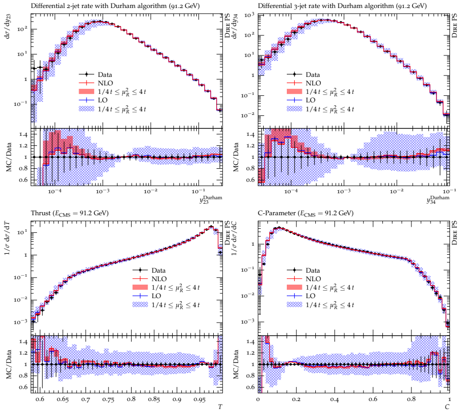
impact of $1 \to 3$ splittings





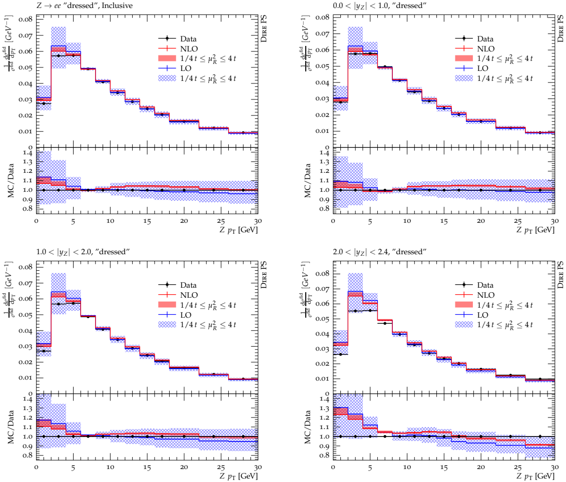
physical results: $e^- e^+ \to$ hadrons

(Hoeche, FK & Prestel, 1705.00982)

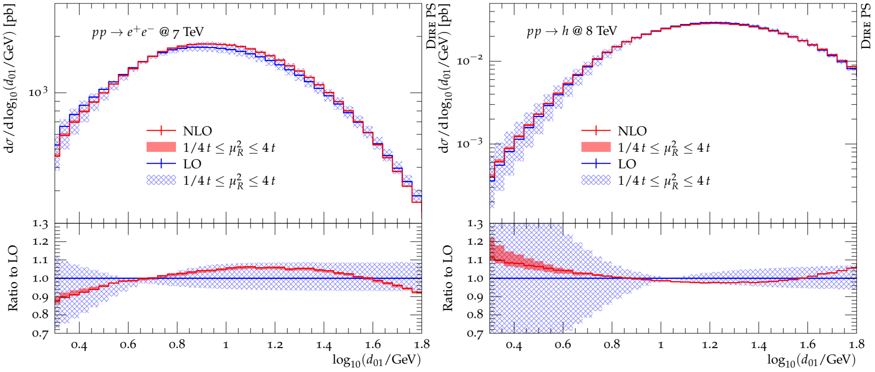


physical results: DY at LHC

(untuned showers vs. 7 TeV ATLAS data)



physical results: differential jet rates at LHC



limitations

and

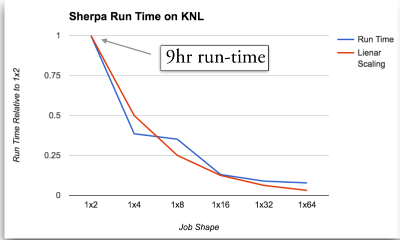
future challenges

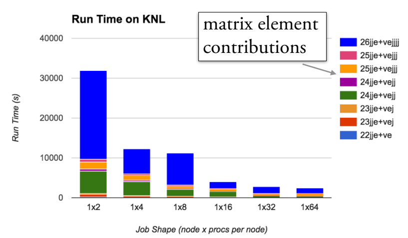
theory challenges

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:
  - fixed-order starting, MC@NLO tedious but straightforward
- 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
  - start including next-to leading colour
  - include spin-correlations $\rightarrow$ 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)

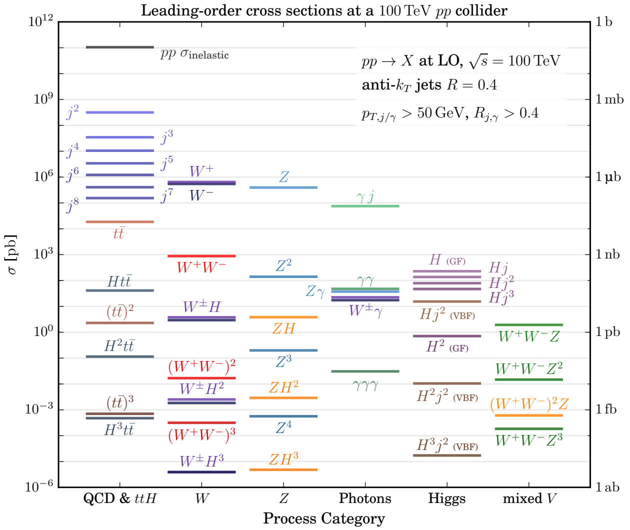
- $g \to q\bar{q}$ at accuracy limit of current parton showers:
  $\longrightarrow$ how bad are $\sim 25\%$ uncertainty on $g \to b\bar{b}$?
  $\longrightarrow$ can we fix this with measurements?

opportunities at 100 TeV

some general observations

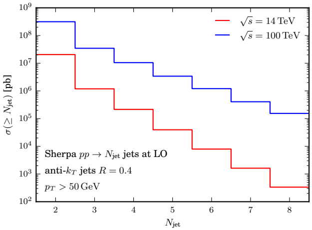
- (sea-) parton luminosities go with $x^{-\lambda}$
  $\longrightarrow$ steep increase in soft jet production
  $\longrightarrow$ "soft @ LHC" $\neq$ "soft @ 100 TeV"
- interesting opportunities for double-parton scattering
- ridge with 10 GeV $p_\perp$ hadrons?
  $\longleftrightarrow$ interface perturbative – non-perturbative?
- jets will be more collimated – challenges for sub-jet measurements

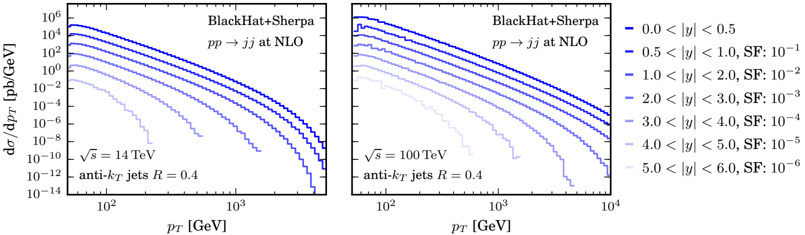
cross sections potpourri



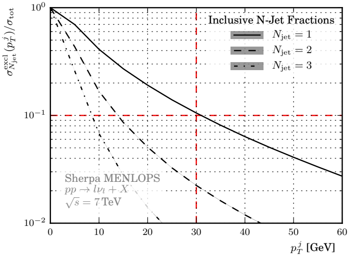
scaling of jet rates with c.m. energy

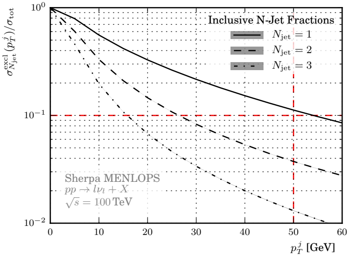
- more jets
- higher transverse momenta
- jets more collimated
- $\sigma(p_\perp \geq 10\text{TeV}) \approx 100$ ab
- different scaling patterns





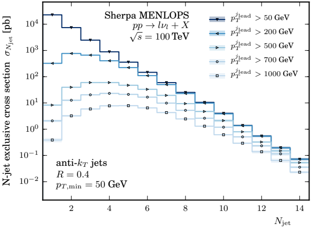
"typical" jet-$p_\perp$ in $W+$ jets



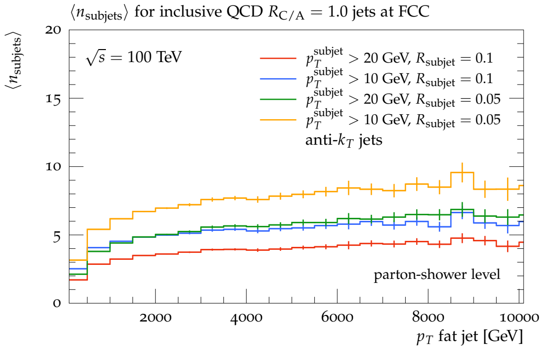


staircase to Poisson

- scaling patterns in multijet production
- may provide insight where precise calulcations fail
- two extreme cases:
  staircase vs. Poissonian



jet substructure



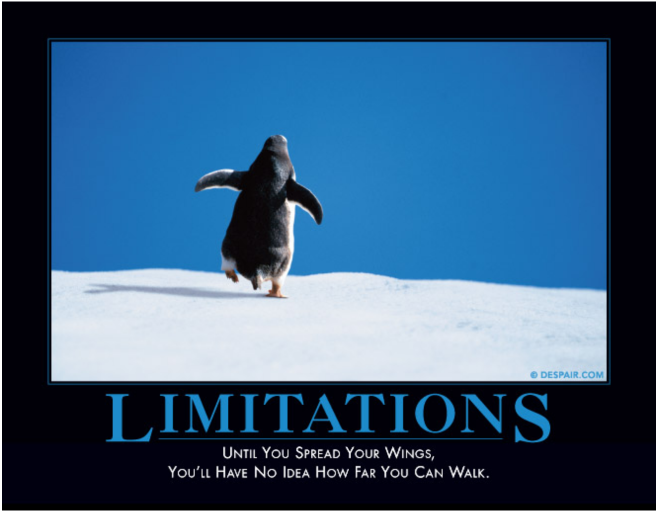
summary

summary

- QCD at energy frontier full of challenges & surprises
- increasing accuracy and precision of LHC drives
  - rapid development of calculational techniques

    (with a lot of exciting mathematical developments)
  - rapid development of ever more detailed simulations

    (stress-testing computational abilities in soft- and hardware)
- first measurements with boosted topologies
  $\longrightarrow$ jet substructures become analysis tool
- not covered, but: novel analysis methods (ML & friends)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LIMITATIONS
UNTIL YOU SPREAD YOUR WINGS,
YOU'LL HAVE NO IDEA HOW FAR YOU CAN WALK.