Perturbative QCD in event generators

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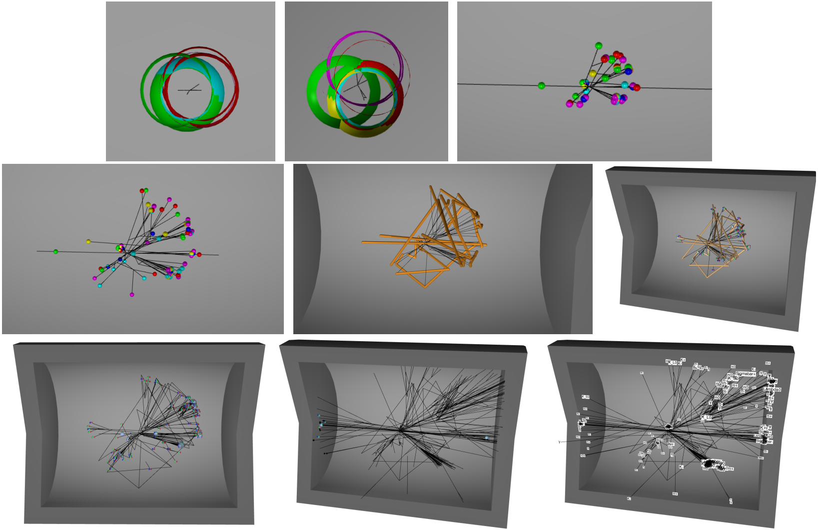
What do you do when you measure something that you don't find a theory plot for?
You ask an event generator.

Event generators are **publicly available** software tool in which **somebody has coded** theory knowledge.

Event generators produce **events**
Each momentum configuration required for the prediction is numerically sampled, with Monte-Carlo methods.



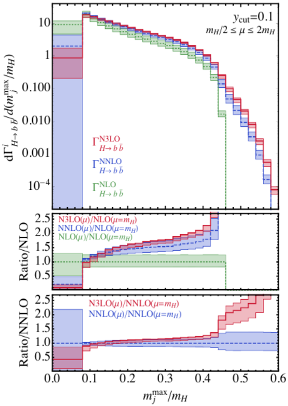
Events allow to disentangle calculation and analysis.

An extension of the concept of "event" beyond leading order – to produce low-uncertainty predictions – has been a major focus of the generator community.

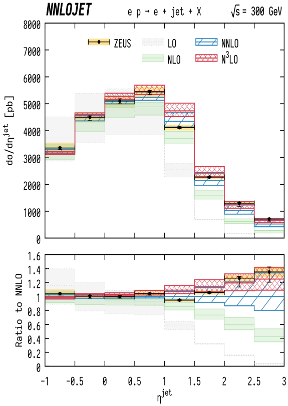
Why should we care about precision perturbative QCD?

more data ~~,better theory~~ → inconclusive analyses

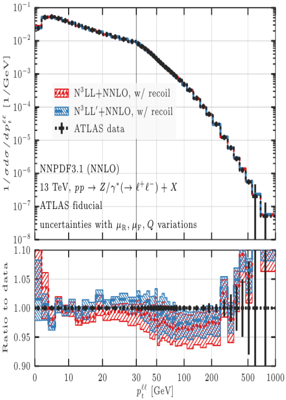
more data, better theory → conclusive i.e. better analyses



arXiv:1904.08960



arXiv:1803.09973



arXiv:2104.07509

We don't want to be left with inconclusive measurements!

Precision in MCs =

Precise fixed-order prediction $\underset{\text{matching}}{\otimes}$ precise shower

Fixed order: Sets correct rates (to NLO, NNLO, N3LO result), including virtuals.

Shower: Describes fully differential evolution.

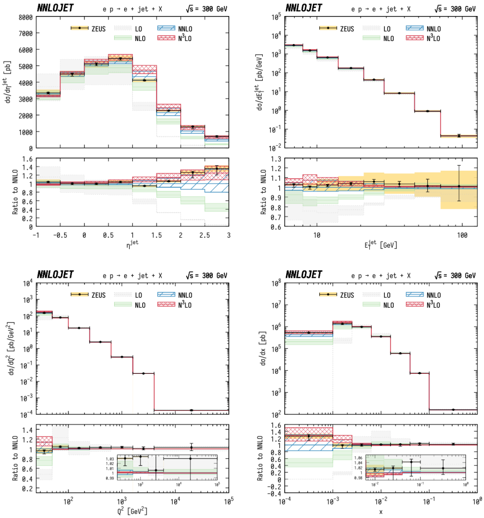
In matched calculations, shower acts as IR regularization of (hard) fixed-order coefficient – shower must recover all singularities appropriately.

Apologies if your favorite generator is not mentioned below. May be an oversight, or because it does not fall under the “precision QCD” umbrella...

Unpolarized DIS known fully differentially at third order (N3LO)

Describes most of HERA data – w/o effects outside collinear PDF evolution.

May allow N3LO PDF fits.



NNLO calculations for *polarized* DIS available fully differentially

NNLO result often outside of the NLO error estimate.

Could be starting-point for precision polarized event generators.

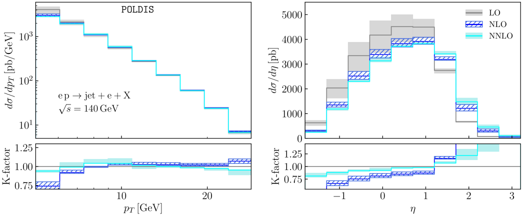


FIG. 1: Single-jet pseudorapidity and transverse momentum unpolarized distributions at LO, NLO and NNLO. The bands refle the variation in the cross-section when changing the scales as $\mu_R = \mu_F = [1/2, 2]Q$. The lower inset shows the correspondi $K-$factors as defined in the main text.

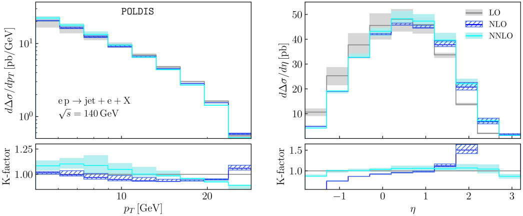
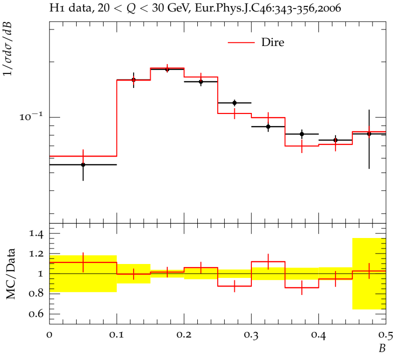


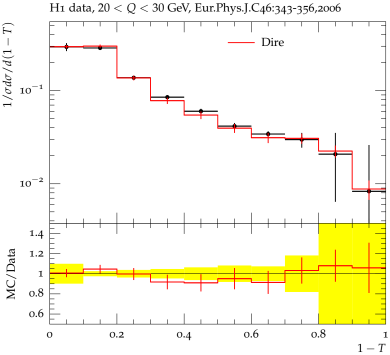
FIG. 2: Same as Fig 1 but for *polarized* deep inelastic scattering.

DIS-like configurations can be handled by all general-purpose event generators (HERWIG7, SHERPA, PYTHIA8).

Each offers at least two distinct shower models, to be considered uncertainties.

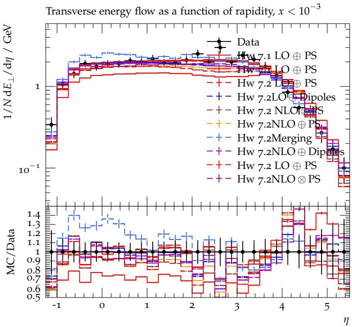
The description of HERA data is generally okay. Disclaimer: Statement needs to be confirmed independently.

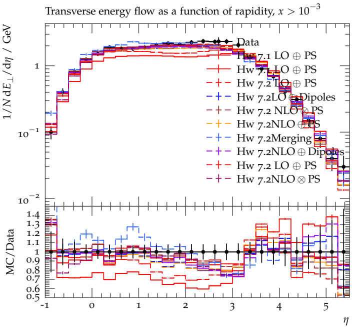




With the flexibility of an LHC-hardened generator come many precision perks:

See e.g. HERWIG7, from `herwig.hepforge.org/plots`



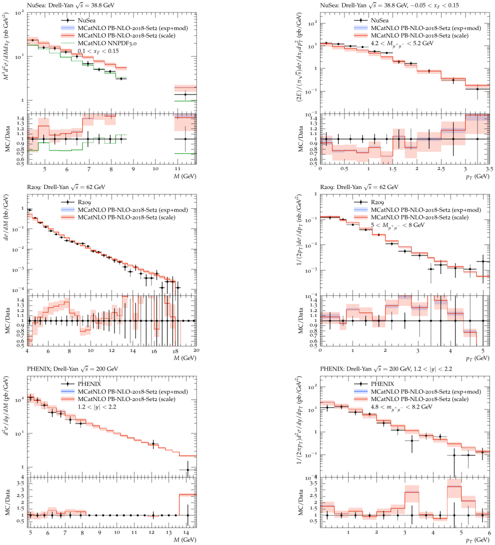


...which offers many different precision improvements.

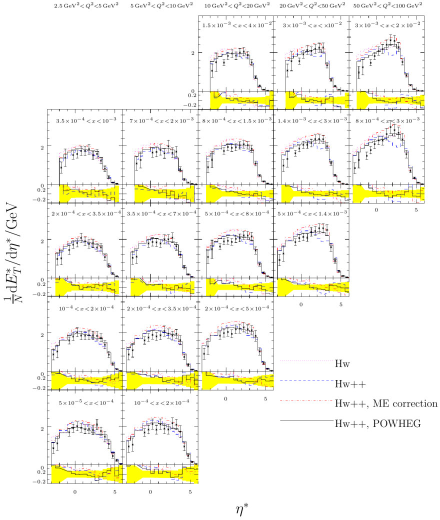
Recently, showers relying on an "pragmatic" definition of TMDs introduced at LHC. This also seems to work at low E_{CM}.

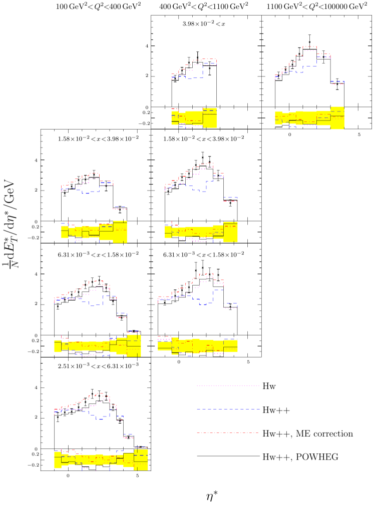
Shower based on TMD operator definitions still unsolved.

Current model (CASCADE3) not yet operational for DIS.



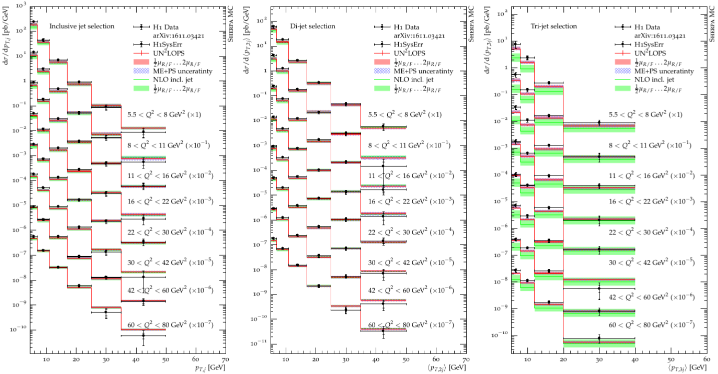
Precision generators need at least NLO+PS matching, e.g. HERWIG ships POWHEG for DIS:





NLO reaches new regions of phase space $\rightarrow$ enough to describe high-Q^2 or forward regions. No BFKL resummation needed.

Sherpa even offers an NNLO+PS calculation

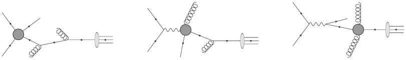


Impressive agreement with data + small residual uncertainty.

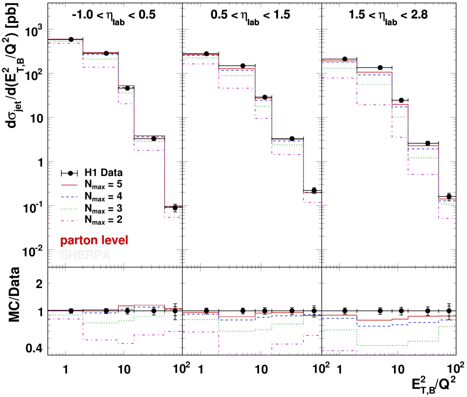
…and if more (than three) jets are needed, do multi-jet merging…

Interesting feature of DIS: The highest momemtum transfer need not be ins DIS process.

⇒ Combine many “core processes”, e.g. DIS- and photo-production-like events.



(a) (b) (c)



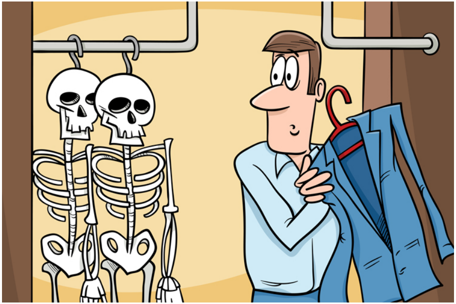
New phase space in forward direction described by fixed-order corrections.

Warning:

ISR shower evolution $\stackrel{!}{=}$ input PDF evolution

...typically not true due to

- recoil, soft gluon complications
- difficultly to define ISR beyond leading order



Showers beyond LL have received much attention lately. Three main schools of thought:

NLO showers

- Desire to match singularities of *event classes*
- Improve by new kernels
- Dates back to 80s; proponents: NLLjet[1], KRKMC[2], Vincia[3], Dire[4]
- Some work applicable to DIS

[1] e.g. CPC 64 (1991) 67-97, Z.Phys.C 54 (1992) 397-410

[2] e.g. arXiv:1103.5015, arXiv:1606.01238

[3] arXiv:1611.00013

[4] arXiv:1705.00982, arXiv:1705.00742, arXiv:1805.03757

NLL showers

- Desire to match logarithms of (large) *observable classes*
- Improve by assessing/correcting LL choices
- Extending historical discussion angular vs. pT ordering; proponents: PanScales[a], Cvolver/Herwig[b]

[a] arXiv:2002.11114, arXiv:2011.10054, arXiv:2103.16526

[b] arXiv:1904.11866, arXiv:2003.06400, arXiv:2011.15087

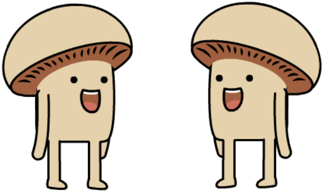
Amplitude-level PS

- Desire to match singularities for *diagram classes*
- Closely related to multi-differential factorization proofs
- Includes Glauber phases; proponents: Deductor[α], Cvolver[β]

[α] e.g. arXiv:1605.05845, arXiv:1908.11420, arXiv:1905.07176

[β] e.g. arXiv:1905.08686, arXiv:2007.09648

...so lots of progress!



...but there's also a to-do list...

TODO: Differential evolution beyond LO

Complications:

- at least fully-differential-NNLO-subtraction hard
- will require updated factorization theorems
- no room for numerical errors – you exponentiate an NLO calculation

$$\Delta(t_0,t_1) = e^{-\int_{t_1}^{t_0} \frac{dt}{t} \int d\tilde{z} \left[\underbrace{\left(\mathrm{I}+\frac{1}{\varepsilon}\,\mathcal{P}-\mathcal{I}\right)(\tilde{z})}_{\text{virtual + mass factorization + subtraction}} + \int \mathrm{d}\Phi_{+1} \underbrace{(\mathrm{R}-\mathrm{S})(\tilde{z},\Phi_{+1})}_{\text{real - subtraction}} \right]}$$

TODO: Polarized evolution

Note: Spin-dependent (frame-dependent) algorithms known since 80s; recently resurrected for FSR. No progress on ISR.

Complications:

- hard to prove simultaneous unpolarized DGLAP if spins are not measured.
- IR structure of QCD richer due to azimuthal correlations, e.g. no obvious angular ordering

TODO: Differential treatment of soft gluons in transverse-momentum-dependent evolution

Note: Showers treat emission momenta differentially.

Problem: At odds with CSS. Need more complex factorization theorems to constrain differential soft-gluon evolution. This will also mean new operator definitions of TMDs

TODO: Combination of DIS, photoproduction, diffractive DIS (...) in one common perturbative framework.

Note: Merging provides blueprint on how to combine presumably distinct processes, but assumes similar non-perturbative structure.

DIS framework should also take into account different non-perturbative structure.

NB: No such framework exists for LHC either. They manage by measuring only in restricted phasespace regions.

TODO: The **I** in E**I**C is absent from precision QCD generators.

Note: Basic assumption: Ion modelling factorizes from hard-scattering modelling.
i.e. use high-precision calculation only for highest-momentum transfer.

Worry: At LHC, initial-state modelling does not always factorize from hard-scattering, cf. multiparton interactions.

High-precision generators will require more resources.

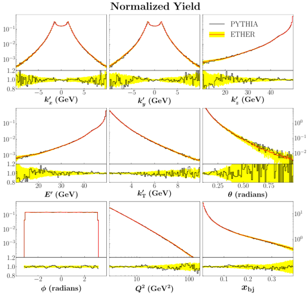


FIG. 3. Phase space distributions (with yield normalized to unity) for inclusive ep scattering from PYTHIA (black) and ETHER (red with yellow bands) trained on the electron momenta k'_i $(i = x, y, z, \mathrm{T})$ and energy E', with predictions for the reconstructed variables θ, ϕ, Q^2 and $x_{\rm bj}$ (vertical scales for θ and $x_{\rm bj}$ are given on the right hand sides of the panels). The ratios of the ETHER distributions to PYTHIA are shown at the bottom of each panel, with the uncertainty bands for ETHER generated via bootstrap.

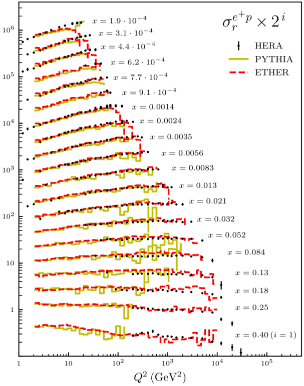


FIG. 4. Comparison of the neutral current inclusive ep (reduced) cross section $\sigma_r^{e^+p}$ (scaled by a factor 2^i) from the HERA collider [24] (black points) with data generated from PYTHIA [1] (yellow solid lines) and the trained ETHER (red

Use machine-learning-based, fast, high-fidelity representations of precision pseudo-data (cf. ETHER `arXiv:2008.03151`) for day-to-day operations?

Precision pQCD generators could form the backbone of the EIC program

LHC-hardened general-purpose generators offer state-of-the-art perturbative predictions: They are precision (collinear factorization) background calculations for new QCD dynamics signals.

However, QCD is complicated: There's still much to do, in collinear factorization and beyond.

I'm looking forward to many successful MC4EIC workshops!