Event Generators for High-Energy Physics

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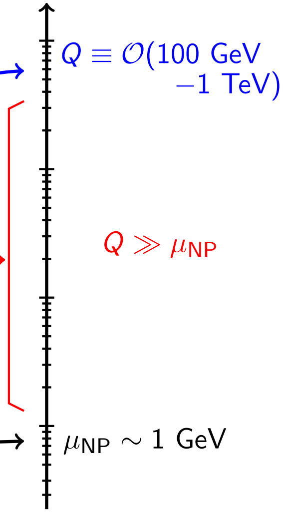
Plan

- Importance of Event generators
- Challenges and progress
  - at the Hard scale (see e.g. talk by Thomas Gehrmann)
  - between hard and soft scales i.e. in parton showers
  - at small scales (see e.g. talk by Valentina Zaccolo)



Importance of Event Generators

What do Event Generators provide?

Event Generators

Simulate events using Monte-Carlo techniques

- All-purpose generators simulating a "full event"
  Pythia, Herwig, Sherpa
- more specific tools (e.g. fixed-order, parton shower)
  e.g. aMC@NLO, POWHEG, Vincia, Dire, ...

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Main advantage: versatility

- “realistic” and very generic aspects of all-purpose generators
  (including combination with detector simulation)
- broad range of analyses (any phase-space cut, observable, ...)

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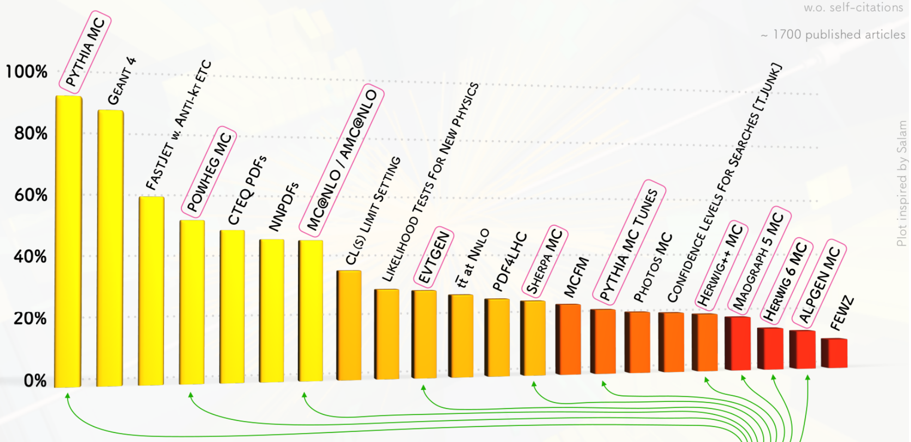
Beware! each part/component of the "simulation" has its own capabilities/limitations and its own accuracy

Event Generators are among us!

- % of ATLAS+CMS+LHCb papers citing some article/group in Jan '14 → May '20



- PS MC is a central, everyday, part of the LHC physics programme

Both "fixed-order" and "parton-shower/all-purpose" generators

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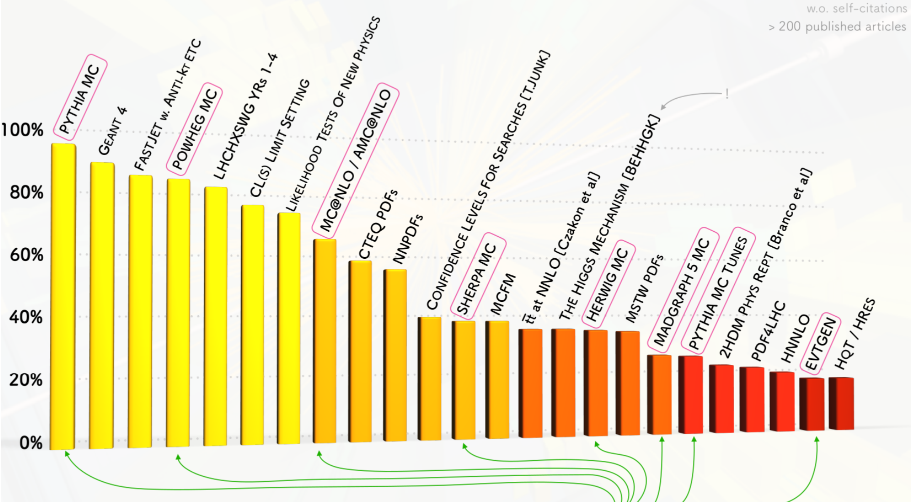
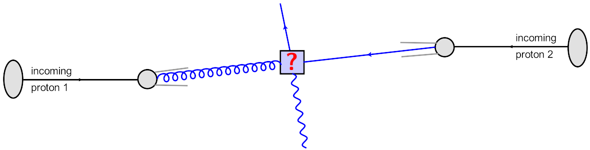


- PS / NLO+PS MC ubiquitous in Higgs analysis

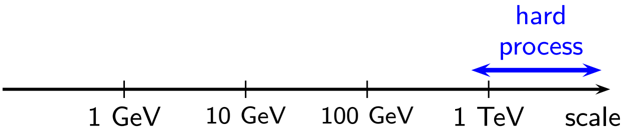
[thanks to Keith Hamilton]

Anatomy of a high-energy collision



Simulating a high-energy collision requires several ingredients

- A hard process



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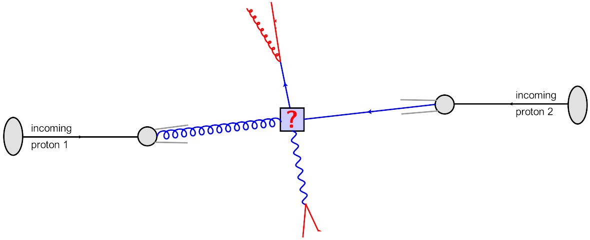

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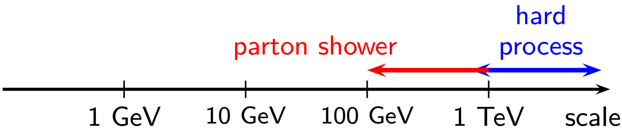
- Parton shower (initial and final-state)



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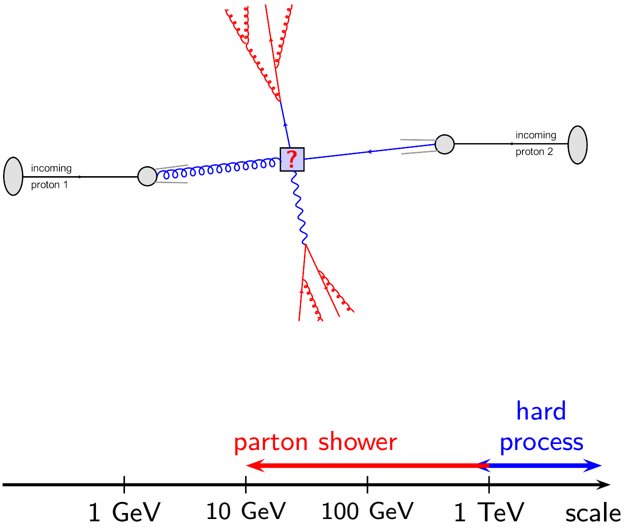

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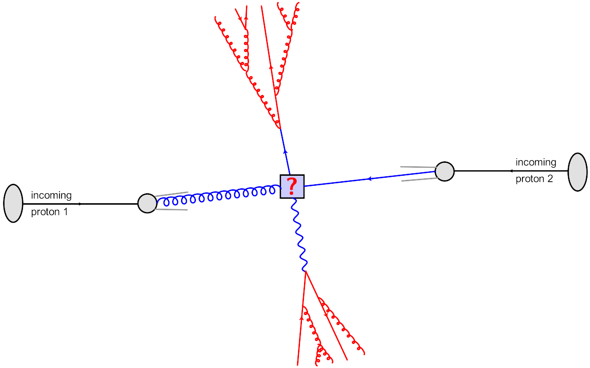
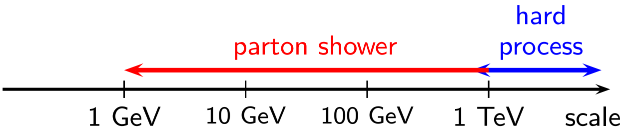


Simulating a high-energy collision requires several ingredients

- A hard process
- Parton shower (initial and final-state)
- Hadronisation



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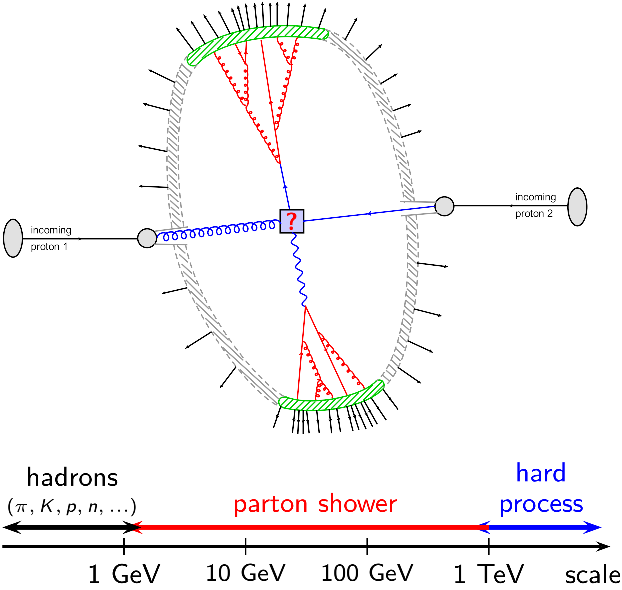

Simulating a high-energy collision requires several ingredients

- A hard process
- Parton shower (initial and final-state)
- Hadronisation
- Multi-parton interactions
- ...

Challenges and progress

perturbative physics at the hard scale

Fixed-order generators

Recent progress has been phenomenal

- NLO readily available for all processes we want (with rare exceptions)
- NNLO is the next frontier and progress is good

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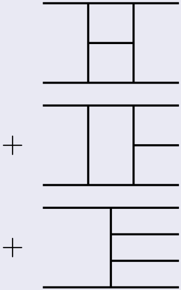
To watch for (in the context of fixed-order event generators)

- NNLO = "2-loop virtual" + "real-virtual" + "double real"

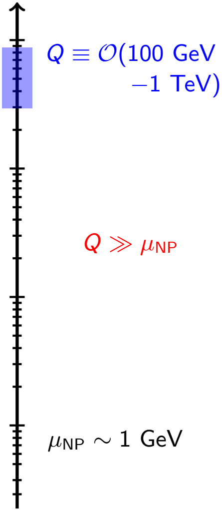


- Subtle cancellation of IR singularities
  (beyond capabilities to calculate the 2-loop part)
  Still room for improvement
- Processes with coloured final-states more delicate
- NNLO is computationally (very) CPU-hungry

Matching/merging

Main idea

Connect fixed-order ((N)(N)LO, Hard scales)
with parton shower ("intermediate scales")



Recent progress:

- NNLO matching for colour-singlet production
  - MiNNLO$_{\rm PS}$: POWHEG framework, no reweighting [Monni,Nason,Re,Wiesemann,Zanderighi,19]
  - GenEvA: SCET-based [Bauer,Tackmann,Thaler,08]
  - UNLOPS: SHERPA framework [Höche,Prestel,14]
- uncertainty assessment: e.g. [Gellersen, Prestel, 20]

Challenges: *pp* processes with light jets

Challenges and progress

perturbative physics of parton showers

Dipole/Antenna showers

Many showers (Pythia, Sherpa, Vincia, Dire, ...) are dipole/antenna showers (main exception: Herwig)

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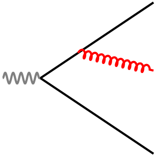
Idea #1:

gluon emission ≡ dipole splitting

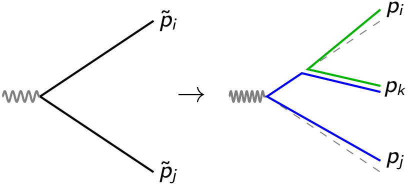
$(ij) \to (ik)(kj)$

- captures the soft/collinear limits
- key ingredient: mapping

$$\underbrace{\tilde{p}_i, \tilde{p}_j}_{\text{before split}} \to \underbrace{p_i, p_j, p_k}_{\text{after split}}$$



viewed as



Dipole/Antenna showers

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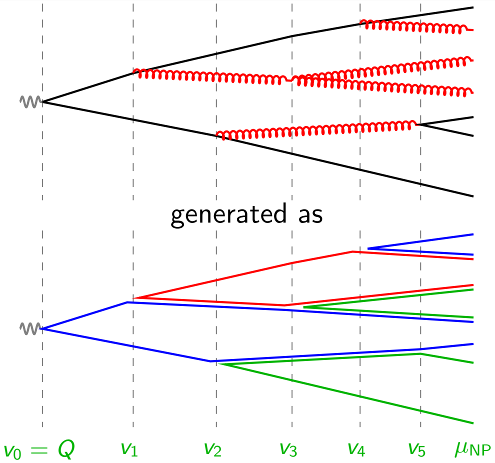


Idea #2:

iterate dipole splittings
(populate the full phase space with multiple emissions)

Several challenges:

- ordering variable
- beyond large/leading-N_c
- treat recoil properly
- assess/improve accuracy

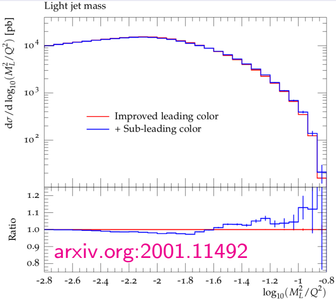
Beyond leading colour

Challenges

- most showers (except Herwig) are leading colour (even at leading-log) (see e.g. [Dasgupta,Dreyer,Hamilton,Monni,Salam,18])
- very complex structure for multiple soft-gluon emissions

Recent progress

- Amplitude-level showers
  in contrast to approached based on squared matrix-elements
  see e.g. [Forshaw,Holguin,Plätzer,19]
- Beyond leading-N_c/full colour
  see e.g. [Nagy,Soper,12], [Höche,Reichelt,20], [Forshaw,Holguin,Plätzer,20]



arxiv.org:2001.11492

Electroweak showers

Main challenges

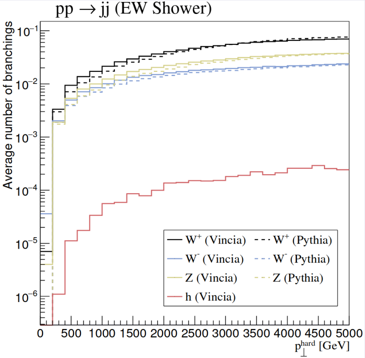
- Splitting functions more involved than standard Altarelli-Parisi
- Explicit dependence on chirality/spin$^{(*)}$

Recent progress

Implementation in Vincia, based on the spinor-helicity formalism

[Kleiss,Verheyen,20]

phenomenological relevance at large p_t



$^{(*)}$ Technically, this is also the case for QCD showers

Challenges: parton-shower accuracy

WHAT DOES ACCURACY MEAN?

- parton showers are anchored in perturbative QCD
- disparate scales $Q \gg \Lambda_{\mathrm{QCD}} \implies$ logs resummed to all orders
- **accuracy means logarithmic accuracy**
  well-defined and systematically improvable

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(Cumulative) distributions can (often) be written as ($L = log(v)$)

$$\Sigma(v) = \exp\left[\underbrace{g_1(\alpha_s L)L}_{\text{leading log}(LL)} + \underbrace{g_2(\alpha_s L)}_{\text{next-to-leading log}(NLL)} + \underbrace{g_3(\alpha_s L)\alpha_s}_{NNLL} + \dots \right]$$

Idea for testing: NLL accuracy requires

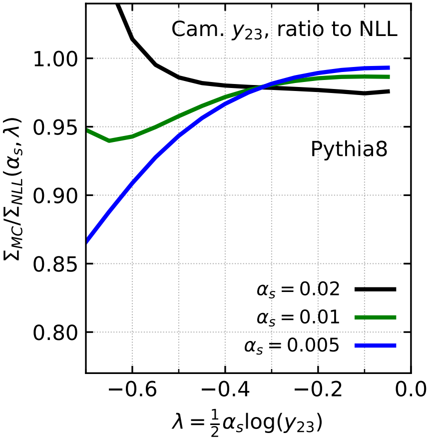
$$\frac{\Sigma_{MC}(\lambda=\alpha_s L, \alpha_s)}{\Sigma_{NLL}(\lambda=\alpha_s L, \alpha_s)} \xrightarrow{\alpha_s \to 0} 1$$

at fixed $\lambda = \alpha_s L$

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]

Example: Cambridge/Aachem(C/A) y_{23}

- e^+e^- event
- cluster with C/A (angular-ordered)
- keep clustering with maximum (relative) transverse momentum: $\sqrt{y_{23}} = \max_i k_{ti}$



Study

$$\frac{\Sigma_{MC}(\lambda=\alpha_s L, \alpha_s)}{\Sigma_{NLL}(\lambda=\alpha_s L, \alpha_s)} \text{ for } \alpha_s \to 0.$$

Assessing accuracy

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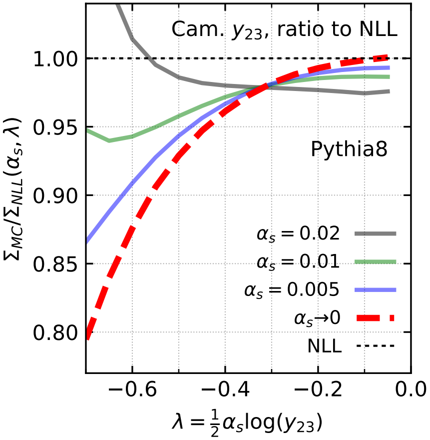

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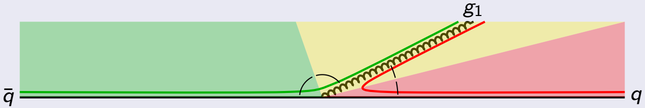
PanScales showers

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]

Key element 1: how to associate colour and recoil to dipoles?

Expected rad^n from $qg_1\bar{q}$ $[(qg_1) + (g_1\bar{q})]$



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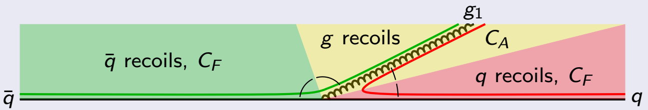

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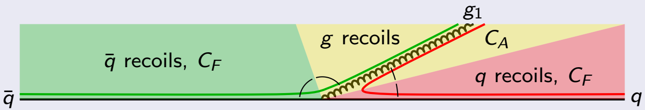
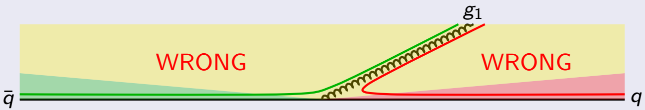


Pythia:



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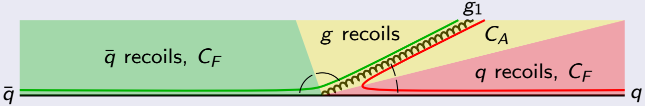

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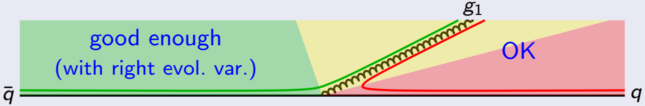

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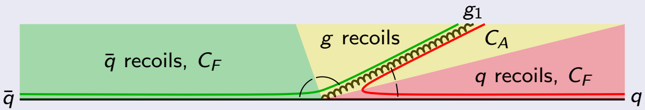

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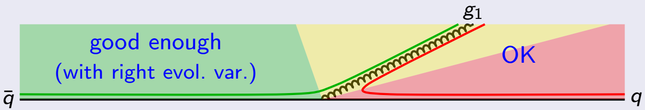

Key element 2: choice of evolution variable

$v \sim k_{t,ik}\theta_{ik}^{\beta}$ $\qquad (0 < \beta < 1)$

Idea: emissions with commensurate k_t radiated with successively smaller angles

Assessing accuracy

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]

Example: C/A y_{23}

$$\sqrt{y_{23}} = \max_i k_{ti}$$

Study

$$\frac{\Sigma_{MC}(\lambda{=}\alpha_s L, \alpha_s)}{\Sigma_{NLL}(\lambda{=}\alpha_s L, \alpha_s)} \text{ for } \alpha_s \to 0.$$

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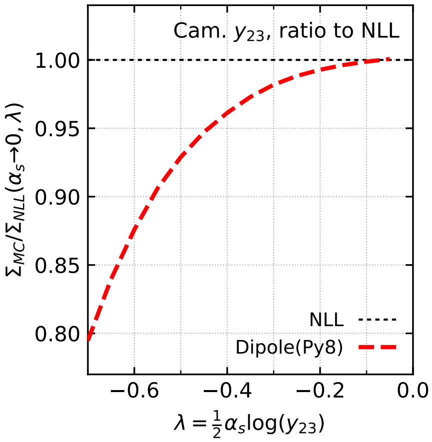

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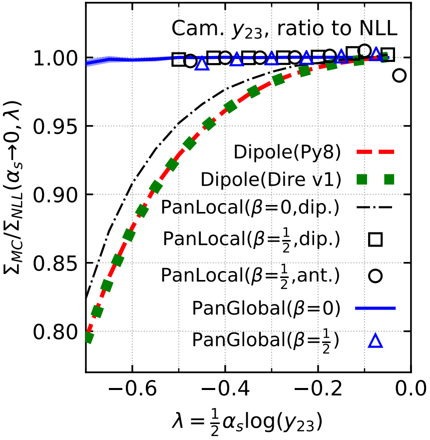
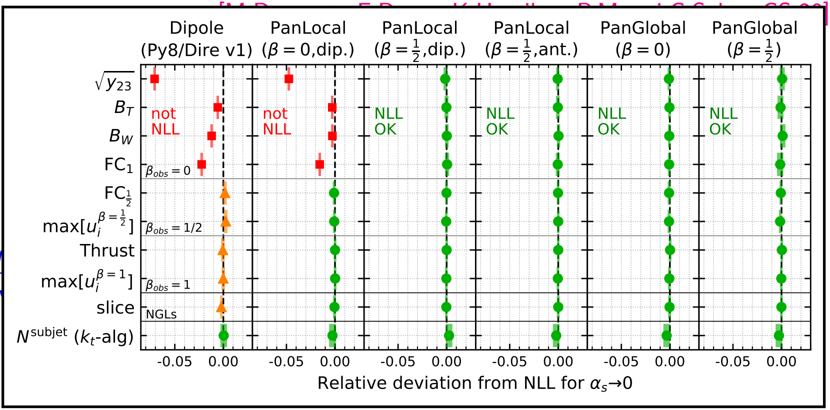


× Pythia8 deviates from NLL
✓ PanLocal($0 < \beta < 1$) OK
✓ PanGlobal($0 \leq \beta < 1$) OK

Assessing accuracy

Examp

Study



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✓ PanLocal($0 < \beta < 1$) OK

✓ PanGlobal($0 \leq \beta < 1$) OK

global observables

non-global observables

multiplicities

Tested against a series of observables (expected 0)

(green: OK at NLL; orange: issues at fixed order; red issues at fixed and all orders)

Challenges and progress

non-perturbative physics at the soft scales

Watch out

BASIC TAKE-HOME MESSAGE

Outside the reach of perturbative QCD $\Longrightarrow$ **rely on models**

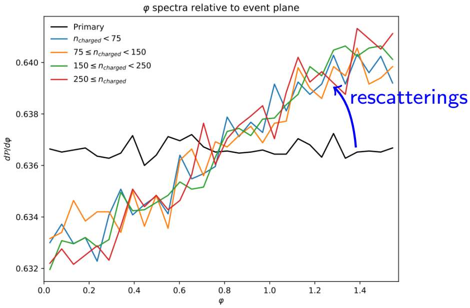
- Model parameters have to be "tuned" (mostly to data)
  e.g. LEP data strongly constrain hadronisation
  Dedicated LHC (and Tevatron) measurements for MPI
- Can try to develop theoretical frameworks, use lattice QCD, ...
- Open question: Systematic way of assessing uncertainty?

Example #1

[Sjostrand, Utheim, 20]

framework for hadron rescatterings in Pythia

- main impact: various "flows" of hadrons
- Possible applications to pA and AA collisions (e.g. via Angantyr [Bierlich, Gustafson, Lönnblad,Shah,18])

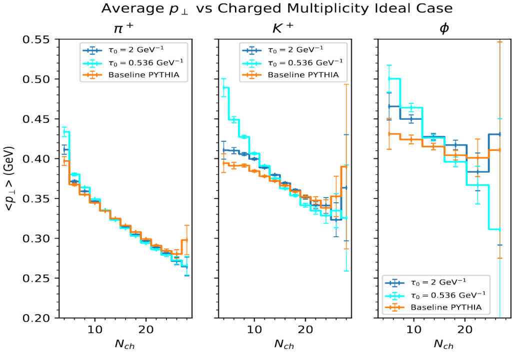


Example #2

[Hunt-Smith, Skands, 20]

Lund string fragmentation with time-dependent tension (Pythia)

- motivated by lattice considerations
- main impact: larger p_t & more strangeness



Summary

MCs used everywhere! Immensely relied upon at the LHC

Full event simulation requires coverage of a wide range of scales

Scale	Realm	Progress	Challenges
Hard	Fixed-order (LO,NLO,NNLO,...) Matching/merging	Towards NNLO subtraction methods MiNNLO	More complex colour ampl $\rightarrow d\sigma/dX$ CPU cost?
Parton shower	All-orders (LL,,NLL,NNLL,...)	Assessing accuracy NLL-accurate showers Improved colour electroweak showers	new (N)NLL showers better uncertainties
Soft	Non-perturbative models	more realistic models "collectivity" (cf. AA)	How far can one go? Assess uncertainties?

Common effort needed in the quest towards precision