

ALARIC

SHERPA's new precision parton shower

Frank Krauss

Institute for Particle Physics Phenomenology
Durham University

QCD Seminar, Jyväskylä, 22.10.2026



- introduction
- issues in parton showers
- constructing ALARIC
- comparison with data from LEP and LHC
- soft physics
- summary

setting the scene

(we theorists did pretty well, didn't we?)

preface: 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 perturbation theory)

- add **underlying event**

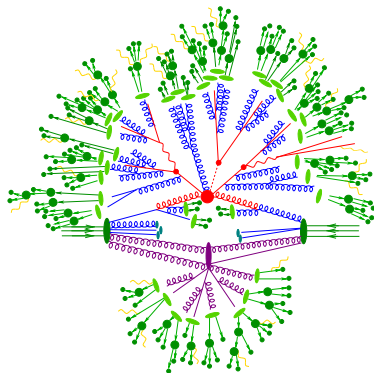
(phenomenological models)

- **hadronize** partons

(phenomenological models)

- **decay** hadrons

(effective theories, simple symmetries & data)



executive summary: theory precision

(apologies to any paper/author I didn't mention – this is a rich and highly successful & diverse field)

- ✓ scattering processes: $2 \rightarrow 1$ @ $N^3\text{LO}(\text{QCD})$
(e.g. 1503.06056, ...)
- ✓ scattering processes : $2 \rightarrow 1$ @ mixed two-loop $\text{QCD} \otimes \text{EW}$
(e.g. 0811.3458, 2005.10221, 2009.10386, 2203.11237, 2401.15682, ...)
- ✓ scattering processes : $2 \rightarrow 2$ @ $\text{NNLO}(\text{QCD})$
(e.g. 1303.6254, 1408.5243, 1408.5325, 1611.01460, 2102.13583, 2105.00954, 2110.12992, 2204.10173, 2311.14991, ..., MCFM)
- ✓ first two-loop cross sections for $2 \rightarrow 3$ @ $\text{NNLO}(\text{QCD})$
(e.g. 1310.1051, 1712.02229, 1911.00479, 2102.02516, 2105.06940, 2205.01687, 2304.06682, 2404.12325, 2409.08146, ...)
- ✓ $2 \rightarrow n$ scattering processes @ $\text{NLO}(\text{QCD or EW})$ automated
(OPENLOOPS/RECOLA +SHERPA, MADGRAPH, MCFM)
- ✓ $\text{NNLO}+\text{NNLL}$ singlet production
(e.g. 0705.3887, 1007.2351, 1007.4005, 1109.2109, 1507.02565, 2009.11437, 2210.10724, 2301.11768, ...)

executive summary: Monte Carlo perturbative precision

- ✓ NNLO $\otimes$ parton shower for colour singlet production
(MINNLO: 1309.4634, 1407.2940, ... , 2208.12660; UNNLOPs: 1405.4607, 1407.3773)
- ✓ NNLO $\otimes$ parton shower for heavy quark production
(MINNLO: 2112.04168 ($t\bar{t}$), 2302.01645 ($b\bar{b}$))
- ✓ MEPS@NLO: NLO multijet merging
(SHERPA: 1207.5030; MADGRAPH: 1209.6215; PYTHIA: 1211.7278; HERWIG: 1705.06700 plus follow-ups & refinements)
- ✓ all of the above including EW@NLO
(explicit: 1511.08692, 1705.00598, ... , 2204.07652, ... ; Sudakov approximation: hep-ph/0010201, 2111.13453)
- ✓ (N)NLO $\otimes$ N^{1,2,3}LL $\otimes$ parton shower
(GENEVA: 1211.7049, 1508.01475, 2102.08390, ...)
- ✗ but: no genuine MC@NNLO due to absence of $\mathcal{O}(\alpha_s^2)$ parton shower
- ▶ improving parton showers
(logarithmic accuracy (see below); higher orders 1705.00982, ... & amplitude evolution: 1802.08531, ... (not covered here))

a new approach: PANSCALES

(resolving persistent issues)

issues with existing/frequently used parton showers

- comparison with fixed-order results

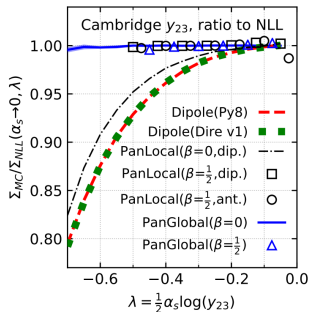
(PANSCALES: 1805.09327, 2205.02237)

issues with existing/frequently used parton showers

- comparison with fixed-order results
- logarithmic accuracy in FS showering

(PANSCALES: 1805.09327, 2205.02237)

(PANSCALES: 2002.11114, 2011.10054)



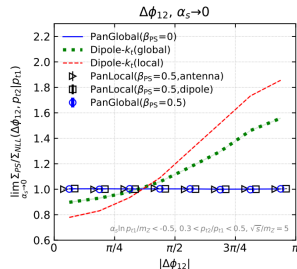
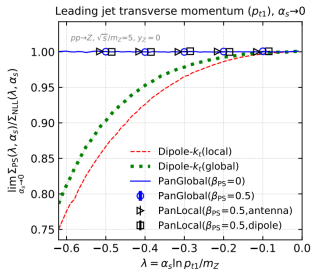
issues with existing/frequently used parton showers

- comparison with fixed-order results
- logarithmic accuracy in FS showering
- logarithmic accuracy in IS showering

(PANSCALES: 1805.09327, 2205.02237)

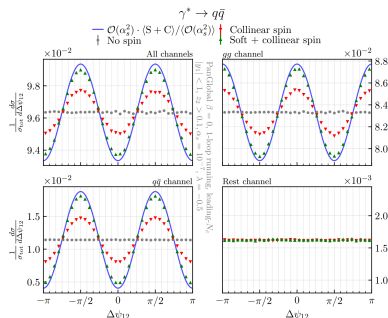
(PANSCALES: 2002.11114, 2011.10054)

(PANSCALES: 2207.09467)



issues with existing/frequently used parton showers

- comparison with fixed-order results (PANSCALES: 1805.09327, 2205.02237)
- logarithmic accuracy in FS showering (PANSCALES: 2002.11114, 2011.10054)
- logarithmic accuracy in IS showering (PANSCALES: 2207.09467)
- spin correlations (NPB 310 (1988) 571, hep-ph/0110108, PANSCALES: 2103.16526, 2111.01161)



issues with existing/frequently used parton showers

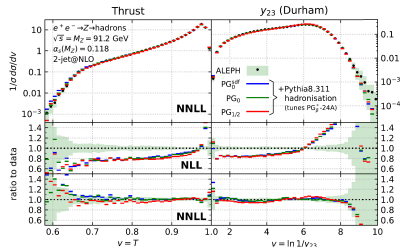
- comparison with fixed-order results (PANSCALES: 1805.09327, 2205.02237)
- logarithmic accuracy in FS showering (PANSCALES: 2002.11114, 2011.10054)
- logarithmic accuracy in IS showering (PANSCALES: 2207.09467)
- spin correlations (NPB 310 (1988) 571, hep-ph/0110108, PANSCALES: 2103.16526, 2111.01161)

✓ PANSCALES encodes massless parton showers at NLL accuracy

(1st matching e^+e^- : 2301.09645 & $pp \rightarrow H, Z$: 2504.05377)

✗ but: weird pattern in data comparison:

(2406.02661)



constructing ALARIC

or: rethinking parton showers

step 1: embedding color coherence

factorization of amplitudes

- collinear:

$$n\langle 1, \dots, n | 1, \dots, n \rangle_n \xrightarrow{i \parallel j} \sum_{\lambda, \lambda' = \pm} n-1 \left\langle 1, \dots, \check{\lambda}(ij), \dots, \check{\lambda}', \dots, n \left| \frac{8\pi\alpha_s}{2p_i p_j} P_{(ij)i}^{\lambda\lambda'}(z) \right| 1, \dots, \check{\lambda}(ij), \dots, \check{\lambda}', \dots, n \right\rangle_{n-1},$$

with spin-dependent splitting function $P_{(ij)i}^{\lambda\lambda'}(z)$

- soft:

$$n\langle 1, \dots, n | 1, \dots, n \rangle_n \xrightarrow{p_j \rightarrow 0} -8\pi\alpha_s \sum_{i, k \neq j} n-1 \left\langle 1, \dots, \check{\lambda}, \dots, n \left| \mathbf{T}_i \mathbf{T}_k w_{ik,j} \right| 1, \dots, \check{\lambda}, \dots, n \right\rangle_{n-1}$$

with colour-insertion operators $\mathbf{T}_{i,k}$ & soft eikonal

$$w_{ik,j} = \frac{p_i p_k}{(p_i p_j)(p_j p_k)} = \frac{W_{ik,j}}{E_j^2} = \frac{1}{E_j^2} \frac{1 - \cos \theta_{ik}}{(1 - \cos \theta_{ij})(1 - \cos \theta_{jk})}$$

(obviously, frame-dependent when expressed by energies & angles)

soft eikonals, decomposed

- textbook decomposition (pink bible): $W_{ik,j} = \tilde{W}_{ik,j}^i + \tilde{W}_{ki,j}^k$
with “radiator functions” $\tilde{W}_{ik,j}^i$: (identify “splitters” to combine with collinear terms)

$$\tilde{W}_{ik,j}^i = \frac{1}{2} \left(\frac{1 - \cos \theta_{ik}}{(1 - \cos \theta_{ij})(1 - \cos \theta_{jk})} + \frac{1}{1 - \cos \theta_{ij}} - \frac{1}{1 - \cos \theta_{jk}} \right)$$

- express θ_{jk} for use in i -splitter term:

$$\cos \theta_{jk} = \cos \theta_{ij} \cos \theta_{ik} + \sin \theta_{ij} \sin \theta_{ik} \cos \phi_{jk}^i \dots$$

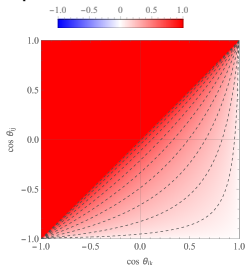
- ... and average over azimuth ϕ_{jk}^i :

$$\frac{1}{2\pi} \int_0^{2\pi} d\phi_{jk}^i \tilde{W}_{ik,j}^i = \frac{\tilde{I}_{ik,j}^i}{1 - \cos \theta_j^i}, \quad \text{where} \quad \tilde{I}_{ik,j}^i = \begin{cases} 1 & \text{if } \theta_j^i < \theta_k^i \\ 0 & \text{else} \end{cases}$$

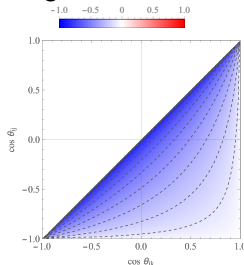
(this is the well-known source of angular ordering)

- azimuthally integrated radiator function (normalised to 2π):

positive contributions



negative contributions



- need to include azimuthal modulation, if observables sensitive to it
- but: naive inclusion bound to fail (MC efficiency $\rightarrow 0$)

soft eikonals, decomposed again

- define **positive definite** radiators:

(borrowing from Catani & Seymour, Nucl. Phys. B485 (1997) 291)

$$\bar{W}_{ik,j}^i = \frac{1 - \cos \theta_{ik}}{(1 - \cos \theta_{ij})(2 - \cos \theta_{ij} - \cos \theta_{jk})}$$

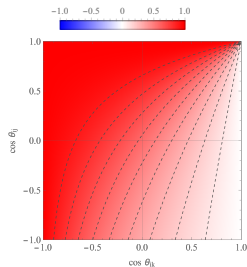
- same result after azimuthal averaging, but $\tilde{l}_{ik,j}^i \rightarrow \bar{l}_{ik,j}^i$ with

$$\bar{l}_{ik,j}^i = \frac{1}{\sqrt{(\bar{A}_{ij,k}^i)^2 - (\bar{B}_{ij,k}^i)^2}}$$

where

$$\bar{A}_{ij,k}^i = \frac{2 - \cos \theta_{ji}(1 + \cos \theta_{ki})}{1 - \cos \theta_{ki}}, \quad \bar{B}_{ij,k}^i = \frac{\sqrt{(1 - \cos^2 \theta_{ji})(1 - \cos^2 \theta_{ki})}}{1 - \cos \theta_{ki}}$$

integrated radiator, $\bar{l}_{ik,j}^i$



matching with collinear terms

- collinear limit of eikonal factors:

$$w_{ik,j} \xrightarrow{i||j} w_{ik,j}^{(\text{coll})}(z) = \frac{1}{2p_i p_j} \frac{2z}{1-z}, \quad \text{where} \quad z \xrightarrow{i||j} \frac{E_i}{E_i + E_j}$$

(can express energies E_{ij} as scalar products of four-momenta)

- compare with leading $(1-z)$ -terms of splitting functions

($1/z$ term in $g \rightarrow gg$ captured with other “dipole”)

$$P_{qq}(z) = C_F \left(\frac{2z}{1-z} + (1-z) \right),$$

$$P_{gg}(z) = C_A \left(\frac{2z}{1-z} + z(1-z) \right),$$

$$P_{gq}(z) = T_R (1 - 2z(1-z)).$$

→ defines “collinear remnant”

step 2: a new kinematic map

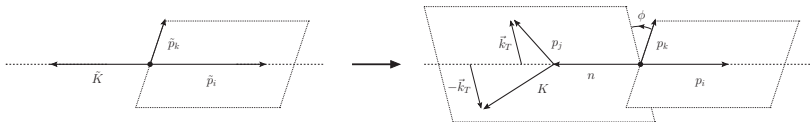
birds-eye view

- kinematics as main obstacle to NLL accuracy in dipole showers: recoil of subsequent soft emissions may change “NLL history”
- construct new mapping $\{\tilde{p}_I\} \longrightarrow \{p_I\}$

(inspired by Catani & Seymour's treatment of identified hadrons)

- logic: disentangle colour spectator $\tilde{p}_k$ and recoil partner $\tilde{K}$

(i.e. define a **global** recoil scheme, use spectator for eikonal/azimuth)



constructing the kinematics

- splitter $\tilde{p}_i \rightarrow p_i = z\tilde{p}_i$, spectator $\tilde{p}_k \rightarrow p_k$ (splitter and spectator keep direction)
- introduce orientation n to define splitting variable $z = \frac{p_i n}{(p_i + p_j)n}$
- with recoil momentum $\tilde{K}$: $n = \tilde{K} + (1 - z)\tilde{p}_i$
- construct emitted momentum and recoil partner after splitting:
(demand $\tilde{K}^2 = K^2$ & $p_j^2 = m_j^2 = 0$)

$$\begin{aligned} p_j &= \nu \bar{n} + \frac{1}{\nu} \frac{k_\perp^2}{2\tilde{p}_i \tilde{K}} \tilde{p}_i - k_\perp \\ K &= (1 - \nu) \bar{n} + \frac{1}{1 - \nu} \frac{k_\perp^2 + \tilde{K}^2}{2\tilde{p}_i \tilde{K}} \tilde{p}_i + k_\perp. \end{aligned}$$

with $\nu = \frac{p_i p_j}{p_i K}$ and additional direction $\bar{n} = n - \frac{n^2}{2\tilde{p}_i n} \tilde{p}_i$

- transverse momentum vanishes for $p_i \parallel p_j$

$$k_\perp^2 = \nu(1 - \nu) 2p_j K - \nu^2 K^2 = \nu(1 - \nu)(1 - z) 2\tilde{p}_i \tilde{K} - \nu^2 \tilde{K}^2$$

constructing the kinematics

- boost every momentum in recoil partner to new system $\tilde{K} \rightarrow K$:

$$p_l^\mu \rightarrow \Lambda_\nu^\mu(K, \tilde{K}) p_l^\nu \text{ with } \Lambda_\nu^\mu(K, \tilde{K}) = g_\nu^\mu - \frac{2(K + \tilde{K})^\mu (K + \tilde{K})_\nu}{(K + \tilde{K})^2} + \frac{2\tilde{K}^\mu K_\nu}{K^2}$$

- construct emission phase space:
 - obtain by factorising 3-body phase space, result:

$$d\Phi_{+1}^{(\text{FI})}(-\tilde{K}; \tilde{p}_1, \dots, \tilde{p}_{j-1}, \tilde{p}_{j+1}, \dots, \tilde{p}_n; p_j) = \frac{-2\tilde{p}_i \tilde{K}}{16\pi^2} dv dz z \frac{d\phi}{2\pi}$$

- note: azimuthal angle expressed through scalar products
→ PS Lorentz-invariant
- IS kinematics from FS through crossing relations

parton evolution

- define evolution parameter:

$$t = 2E_j^2 (1 - \cos \theta_j^i) = v(1 - z) 2\tilde{p}_i \tilde{K}$$

and therefore soft evolution given by

$$dP_{ik,j}^{i(\text{soft})}(t, z, \phi) = d\Phi_{+1}(\{\tilde{p}\}, p_j) 8\pi\alpha_s C_i \bar{w}_{ik,j}^i = dt dz \frac{d\phi}{2\pi} \frac{\alpha_s}{2\pi t} 2C_i \bar{W}_{ik,j}$$

- same for collinear evolution, but could evolve in virtuality or similar

step 3: checks

analytic considerations

- analyse Lorentz boost (*i.e.* impact on previous emissions)
- decompose new recoil momentum as

$$K^\mu = \tilde{K}^\mu - X^\mu = \tilde{K}^\mu - [p_j - (1-z)\tilde{p}_i]^\mu$$

(X^μ will go to zero for soft/collinear emissions)

- write Lorentz transformation as

$$\Lambda_\nu^\mu(K, \tilde{K}) = g_\nu^\mu + \tilde{K}^\mu A_\nu + X^\mu B_\nu$$

with

$$A^\nu = 2 \left[\frac{(\tilde{K} - X)^\nu}{(\tilde{K} - X)^2} - \frac{(\tilde{K} - X/2)^\nu}{(\tilde{K} - X/2)^2} \right], \quad \text{and} \quad B^\nu = \frac{(\tilde{K} - X/2)^\nu}{(\tilde{K} - X/2)^2}$$

- follow CAESAR formalism and analyse behaviour under scaling

(A. Banfi, G. P. Salam, & G. Zanderighi, JHEP **03** (2005) 073)

$$k_{t,l} \rightarrow k'_{t,l} = k_{t,l} \rho^{(1-\xi_l)/(a+\xi_l/(a+b))}, \quad \eta_l \rightarrow \eta'_l = \eta - \xi_l \frac{\ln \rho}{a+b}, \text{ where } \xi = \frac{\eta}{\eta_{\max}}$$

- impact of recoil in Lund plane under global rescaling must vanish
- boost in $\rho \rightarrow 0$ limit:

$$A^\nu \xrightarrow{\rho \rightarrow 0} 2 \frac{\tilde{K} X}{\tilde{K}^2} \frac{\tilde{K}^\nu}{\tilde{K}^2} - \frac{X^\nu}{\tilde{K}^2} \text{ and } B^\nu \xrightarrow{\rho \rightarrow 0} \frac{\tilde{K}^\nu}{\tilde{K}^2}$$

and

$$\Delta p_l^\mu = 2 \frac{\tilde{K} X}{\tilde{K}^2} \frac{\tilde{p}_l \tilde{K}}{\tilde{K}^2} \tilde{K}^\mu - \frac{\tilde{p}_l X}{\tilde{K}^2} \tilde{K}^\mu + \frac{\tilde{p}_l \tilde{K}}{\tilde{K}^2} X^\mu$$

- colour-singlet decay or production ($e^-e^+ \rightarrow \text{hadrons}, q\bar{q} \rightarrow V$)
 $\longrightarrow \tilde{K} = \text{c.m.-momentum, only energy component (not rescaled)}$
- assume emitter $\tilde{p}_i$ is soft (and for ALARIC $a = 1, b = 0$)

$$\tilde{p}_i \tilde{K} \sim \rho^{1-\xi_i} \text{ and } \tilde{p}_i X \sim \rho^{2-\xi_i-\max(\xi_i, \xi_j)}$$

and therefore, in components

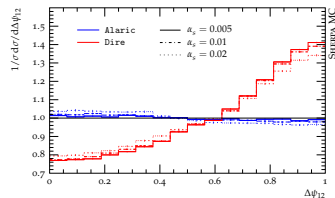
$$\begin{array}{llll} \Delta p_i^0 & \sim & \rho^{1-\xi_i} X^0 + \rho^{2-\xi_i-\max(\xi_i, \xi_j)} \tilde{K}^0 + \rho^{1-\xi_i} X^0 & \sim & \rho^{2-\xi_i-\max(\xi_i, \xi_j)} \\ \Delta p_i^3 & \sim & \rho^{1-\xi_i} X^3 & \sim & \rho^{2-\xi_i-\max(\xi_i, \xi_j)} \\ \Delta p_i^{1,2} & \sim & \rho^{1-\xi_i} X^{1,2} & \sim & \rho^{2-\xi_i} \end{array}$$

- therefore: impact of subsequent emissions vanishes with ρ

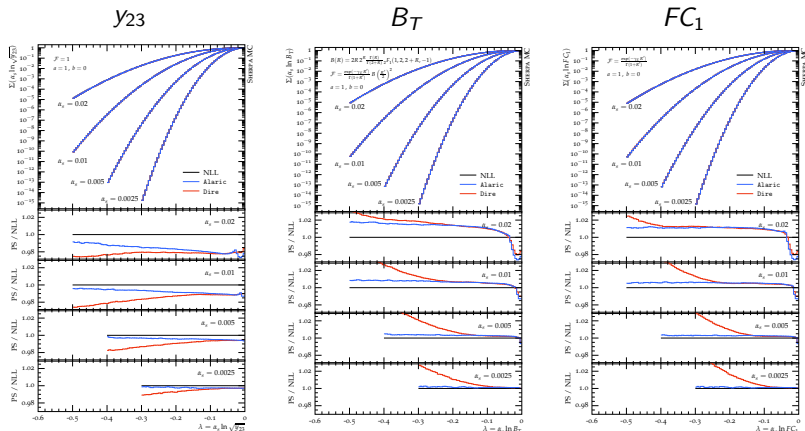
set-up of numerical tests

- compare results in $\alpha_S \rightarrow 0$ limit with NLL result
- set-up for checks
 - fixed α_S
 - leading colour $C_A = 2C_F = 3$
 - all partons massless
- example: azimuthal angle between two leading Lund-plane declusterings

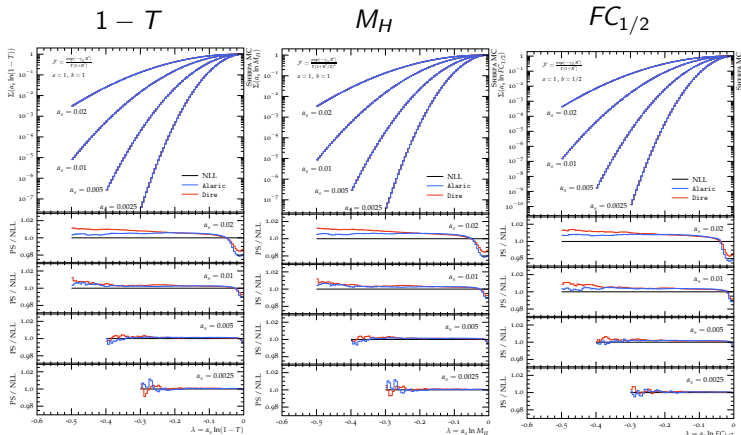
(should be $\Delta\Psi_{12} = 0$)



numerics: event shapes



more event shapes



data comparison

the ultimate arbiter

LEP: LO+NLL

set-up & data comparison

(2208.06057)

- compare hadron-level results with LEP data
- perturbative set-up
 - no higher orders (no matching or merging)
 - running two-loop α_S with $\alpha_S(M_Z) = 0.118$
 - use CMW scheme for soft eikonal parts
 - all partons massless, masses emulated through simplistic thresholds
 - leading colour $C_A = N_c = 3$, $C_F = \frac{N_c^2 - 1}{2N_c}$
- non-perturbative set-up

- needed to use PYTHIA hadronization

(ALARIC not yet ready for heavy hadron decays)

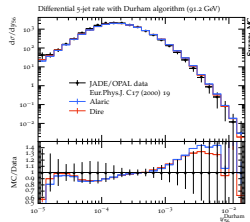
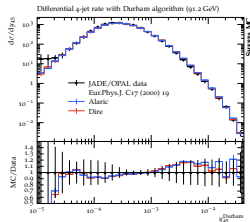
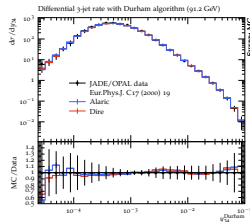
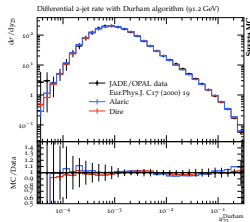
- default parameters of PYTHIA 6.4, exceptions:

$\text{PARJ}(21) = 0.3$, $\text{PARJ}(41) = 0.4$, $\text{PARJ}(42) = 0.36(\text{ALARIC})/0.45(\text{DIRE})$

set-up & data comparison

(2208.06057)

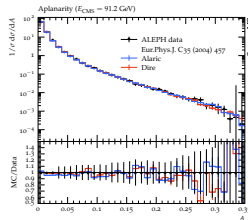
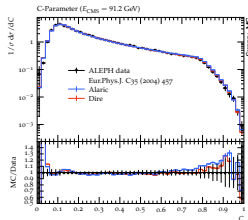
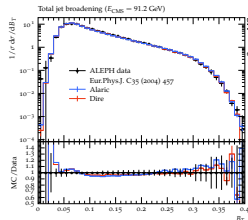
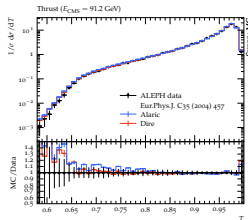
- differential jet rates



set-up & data comparison

(2208.06057)

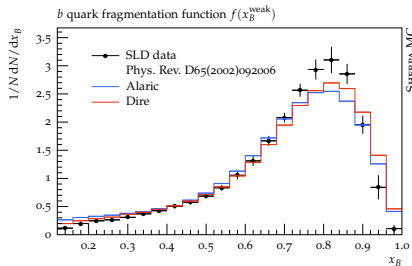
• some event shapes



set-up & data comparison

(2208.06057)

- b -quark fragmentation
 - emulation of quark masses with naive thresholds in $g \rightarrow q\bar{q}$:
stop evolution if $t \leq (2m_q)^2$
 $\implies$ must include quark masses also in $q \rightarrow qg$
 - quick plausibility check: b -quark fragmentation function



LEP: MC@NLO

set-up & data comparison

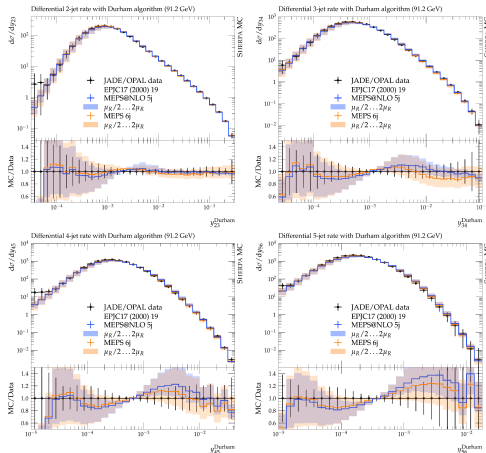
(2507.22837)

- perturbative set-up
 - MEPS@LO (up to 6 jets)
 - running two-loop α_S with $\alpha_S(M_Z) = 0.118$
 - use CMW scheme for soft eikonal parts
 - all partons massless, masses emulated through simplistic thresholds
 - leading colour $C_A = N_c = 3$, $C_F = \frac{N_c^2 - 1}{2N_c}$
 - scale variations by factor of 2
- non-perturbative set-up
 - use (tuned) AHADIC hadronization, no colour reconnections

set-up & data comparison

(2507.22837)

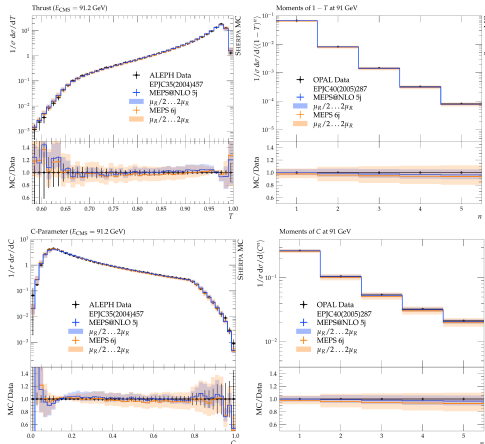
• differential jet rates



set-up & data comparison

(2507.22837)

● some event shapes



LHC: MEPS@Lo

set-up & data comparison

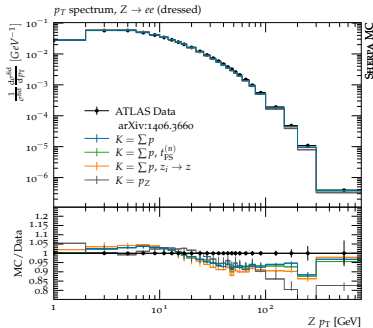
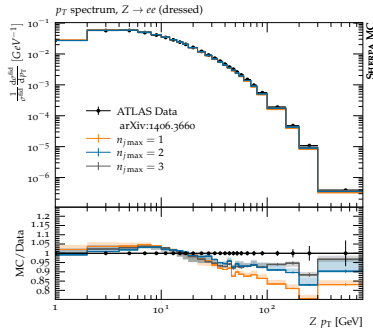
(2404.14360)

- perturbative set-up
 - MEPS@LO (up to 6 jets)
 - α_S from PDF, CMW scheme for soft eikonal parts
 - leading colour $C_A = N_c = 3$, $C_F = \frac{N_c^2 - 1}{2N_c}$
 - scale variations by factor of 2, Q_{cut} variations as indicated
- non-perturbative set-up
 - use (tuned) AHADIC hadronization
 - use (tuned) MPI model

set-up & data comparison

(2404.14360)

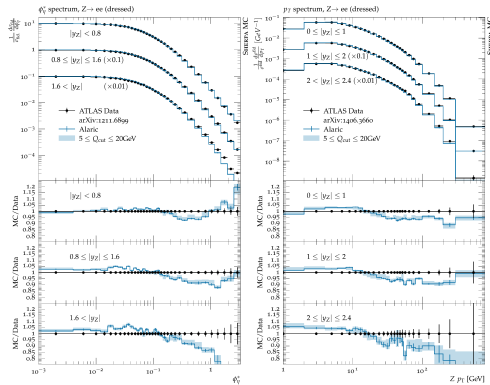
- Z+jets: impact of $n_{\text{max}}^{\text{jet}}$ and kinematics scheme



set-up & data comparison

(2404.14360)

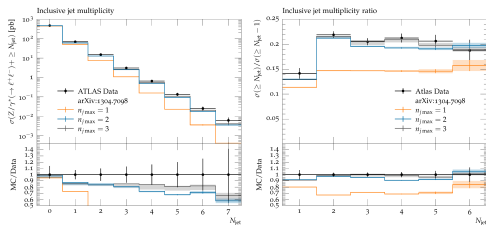
- Z +jets: impact of Q_{cut} on inclusive observables



set-up & data comparison

(2404.14360)

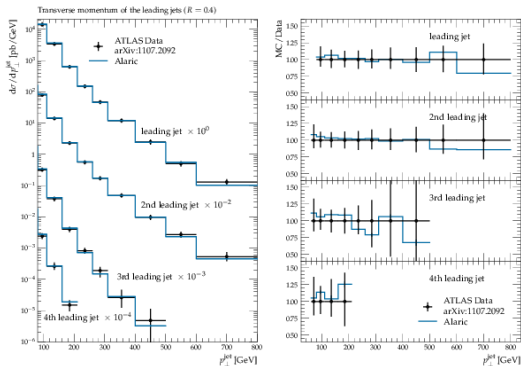
- Z +jets: impact of $n_{\text{max}}^{\text{jet}}$ on jet multiplicities



set-up & data comparison

(2404.14360)

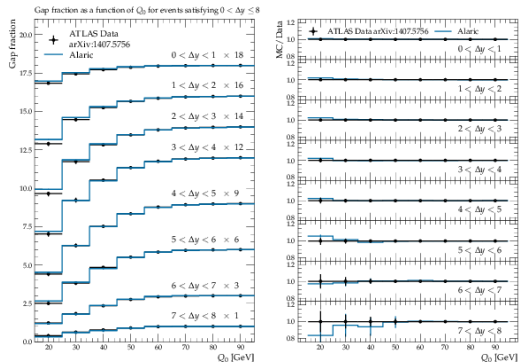
- inclusive jets (LO $\otimes$ PS only): $p_\perp$ spectra



set-up & data comparison

(2404.14360)

- inclusive jets (LO $\otimes$ PS only): rapidity gaps



higher twist: (hard) double parton scattering (DPS)

- example: same-sign W -pair production
 - interesting final state, probes lots of gauge structures
 - $EW \approx QCD, qq' \rightarrow \bar{q}q' W^\pm W^\pm$ finite $\forall p_\perp^q$
 - no need to tag forward jets – different to backgrounds
 - but: $\sigma_{\text{direct}} \approx \sigma_{DPS}$, double-parton scattering

supreme testing ground for double-parton scattering

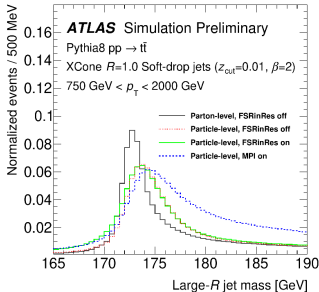
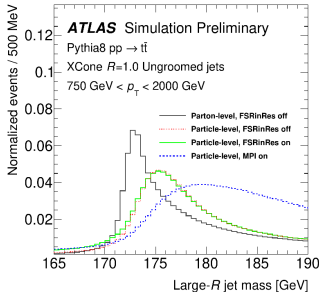
- DPS significant in many other processes (e.g. Wjj production), effect more pronounced in certain phase spaces
- first steps towards first-principles understanding of DPS and its interplay with multi-parton PDFs

(see e.g. 1708.03528, 2305.09716, ...)

(multi-parton PDF DGLAP evolution tend to ignore impact of spatial distance)

higher twist: multi-parton interactions (MPIs)

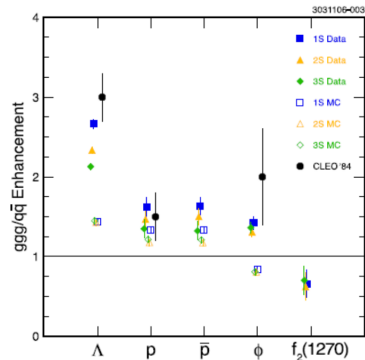
- even without **really** hard secondary scatters: clear evidence for MPIs
 - due to proton = extended objects, contain multiple partons
 - overall: deposit energy/particles everywhere, change jet shapes
- example: impact on top mass in boosted tops (below, from ATL-PHYS-PUB-2021-034)



a potential hadronization issue: gluon fragmentation

(from 0704.2766, just an example for more issues)

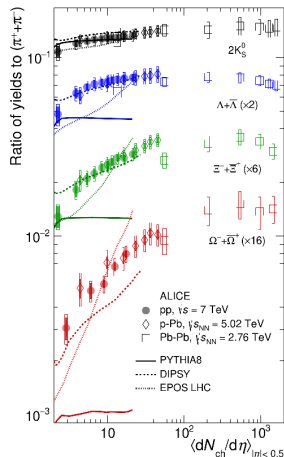
- tunes dominated by LEP 1
(10M Z events are hard to argue with)
- but: mainly quarks
- to have handle on gluons: flavour-tagged Mercedes-star events
(they are rare!)
- alternatively: decays of vector mesons ($Q\bar{Q}$)
(see right)
(either $V \rightarrow ggg$ (QCD) or $V \rightarrow f\bar{f}$ (QED))
- issues with strangeness/baryons?



hadronization issues: strange strangeness

- models date back to the 1970's/80's based on
 - linear QCD potential (strings) or
 - Local Parton Hadron Duality (clusters)
- hadronization universality **assumed**
- parameters tuned to LEP data in particular: strangeness suppression
- for strangeness: **flat ratios** in the “usual” multi-purpose MC's but data do not reproduce this
 - needs “colour ropes” or some such
- looks like $SU(3)$ restoration not observed for protons

(from 1606.07424, just another example for more issues)

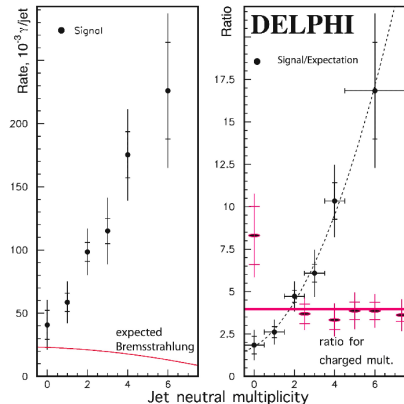


another thing that doesn't work: soft photons

(from 1004.1587)

- DELPHI expectation:
0.02 soft photons/jet flat
(dependent on isolation cuts)
- but: strong scaling with neutral hadron multiplicity (see right)
- possible explanations:
 - (magnetic) dipole emissions?
 - enhanced radiation off quarks during hadronization?
 - ...

so far unable to reproduce data

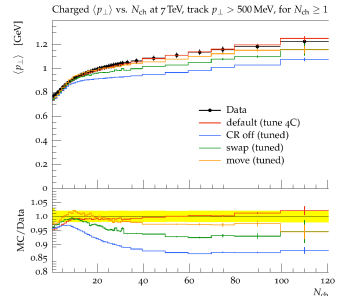


another nuisance: colour reconnections

(they certainly exist – implementation through various ad-hoc models)

- origins of colour reconnections:
 - $N_c = 3$ vs. $N_c \rightarrow \infty$
(used in parton showers)
 - soft, non-perturbative “gluons”
- modelling colour reconnections:
 - reshuffle colours after parton shower
(exhibiting non-pert. nature)
 - “shuffle” probabilities based on phase-space distances
- models quite ad-hoc
first-principles models needed!

- effect on particle spectra in MinBias:



(from 1407.6653)

...and another nuisance: Bose–Einstein correlations

(they certainly exist – so far only ad-hoc models in PYTHIA)

- quantum statistics of identical particles

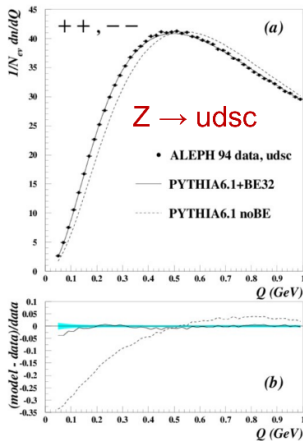
(produced at “same” point)

- effect: identical particles i and j
“want” to be closer in phase space
closeness parametrised by
 $Q^2 = -(p_i - p_j)^2$

- correlation function
 $f_2(Q^2) = 1 + \lambda \exp(-Q^2 R^2)$

(with $\lambda \sim 1$, $R \sim 0.5$ fm)

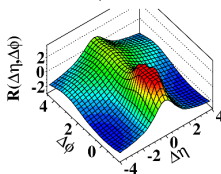
- so far only implemented in PYTHIA
as phenomenological “after-burner”
by shifting hadron momenta



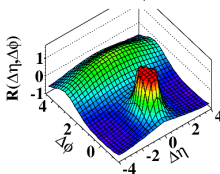
unsolved: the emergence of collectivity

(from 1009.4122, I am not aware of any genuine first-principles solution)

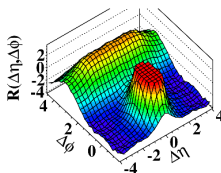
(a) CMS MinBias, $p_T > 0.1 \text{ GeV/c}$



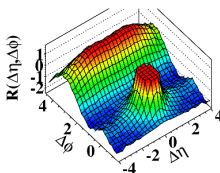
(b) CMS MinBias, $1.0 \text{ GeV/c} < p_T < 3.0 \text{ GeV/c}$



(c) CMS N ≥ 110, $p_T > 0.1 \text{ GeV/c}$



(d) CMS N ≥ 110, $1.0 \text{ GeV/c} < p_T < 3.0 \text{ GeV/c}$



summary

my prediction: future “attractions”

- solvable (and probably solved within the decade):
practically everything at the precision frontier
 - NNLO (QCD) for $2 \rightarrow n$ processes
 - (N)NLL parton showers and their matching to NNLO
 - two-loop mixed QCD $\otimes$ EW for $2 \rightarrow 2$ processes
- extremely tricky (and probably not solved within the decade):
practically everything with non-perturbative physics

main obstacles:

- lack of people power – not attractive for ECRs
- lack of compelling ideas
- absence of systematic treatment (“eigen-tunes”):
perception of sufficient approach to extracting non-pert.
uncertainties by merely “flicking” through tunes

final thoughts

- perception/common narrative (I):
HL-LHC and results are a “done deal” – certainly overly naive!
(still a lot of work to be done – conceptually, methodologically, implementation, validation, ...)
- perception/common narrative (II):
higher theoretical accuracy $\leftrightarrow$ decreasing experimental uncertainties
(this reduces theory to indispensable help for experimental data analysis)
- challenge reductionist approach:
which new things can we learn/decipher with precision?
(“rediscover” precision theory as input to design of new analyses/measurements)
- also: is there something beyond “more N’s”?
we may want/need to look at non-perturbative effects
(it is conceivable that they may become the largest impediment for theory accuracy of some measurements)



© DESPAIR.COM

LIMITATIONS

UNTIL YOU SPREAD YOUR WINGS,
YOU'LL HAVE NO IDEA HOW FAR YOU CAN WALK.