Challenges and progress with parton showers
simulating events from ee to AA collisions

Gregory Soyez

with PanScales: M.van Beekveld, M.Dasgupta, B.El-Menoufi, F.Dreyer, S.Ferrario Ravasio, K.Hamilton, A.Karlberg, R.Medves, P.Monni, G.Salam, L.Scyboz, A.Soto-Ontoso, R.Verheyen;

and with P.Caucal, E.Iancu, A.H.Mueller

IPhT, CNRS, CEA Saclay

Strong and Electroweak Matter 2022

Intro: event generators for high-energy collisions

(Fairly) generic example

Most observables/measurements can take the following form:

$$\mathcal{O} = \sum_n \int [d\Psi_n] \, \frac{d^n\sigma}{dk_1 \ldots dk_n} \, \mathcal{O}_n(k_1, \ldots, k_n)$$

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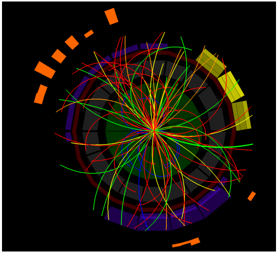
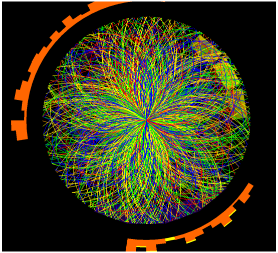
- Outrageously complex in general



Alice (pp)



Alice ($PbPb$)

Even for pheno calculations this quickly grows out of control

(Fairly) generic example

Most observables/measurements can take the following form:

$$\mathcal{O} = \underbrace{\sum_n \int [d\Psi_n] \frac{d^n\sigma}{dk_1 \ldots dk_n}}_{\text{simulate numerically}} \underbrace{\mathcal{O}_n(k_1, \ldots, k_n)}_{\text{observable}}$$

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- Idea: simulate numerically
  sample “randomly” using a **Monte Carlo event generator**

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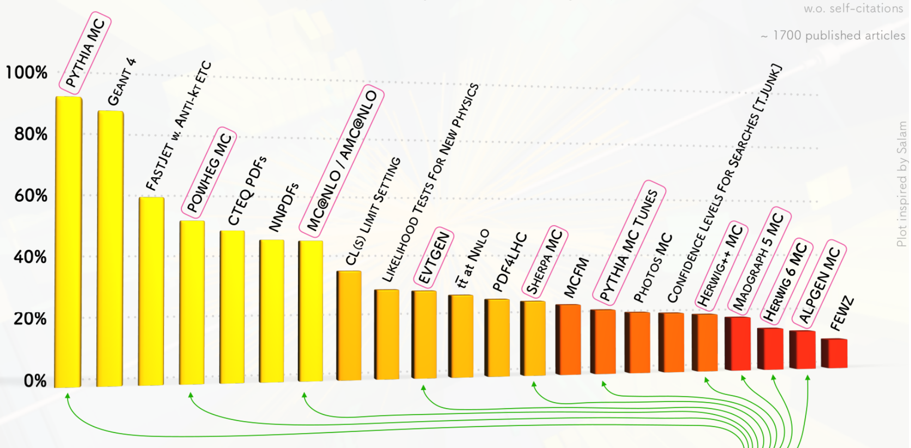
- Outrageously complex in general
- Idea: simulate numerically
  sample "randomly" using a **Monte Carlo event generator**
- **Main advantage: works for basically any observable**

Event Generators are among us!

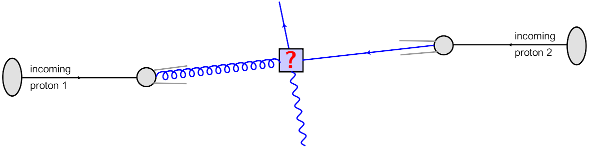
- % of ATLAS+CMS+LHCb papers citing some article/group in Jan '14 → May '20



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

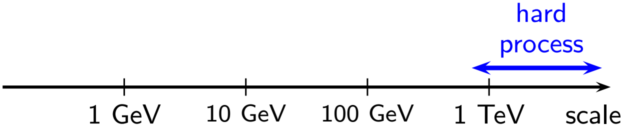
[plot by Keith Hamilton]

Anatomy of a high-energy collision



Simulating a high-energy collision requires several ingredients

- A hard process



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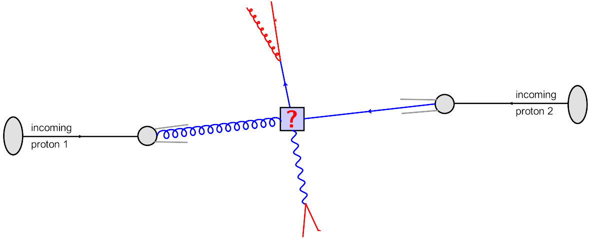
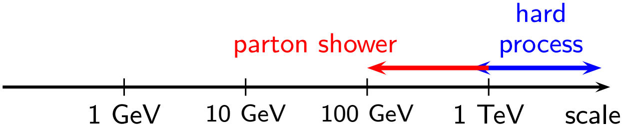


Simulating a high-energy collision requires several ingredients

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



hard process

parton shower

1 GeV

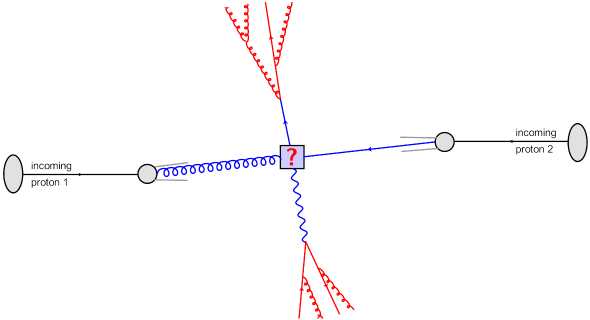
10 GeV

100 GeV

1 TeV

scale

Anatomy of a high-energy collision



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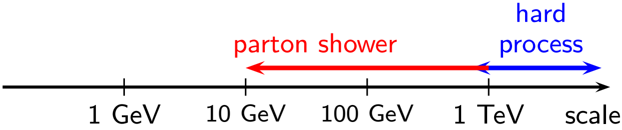

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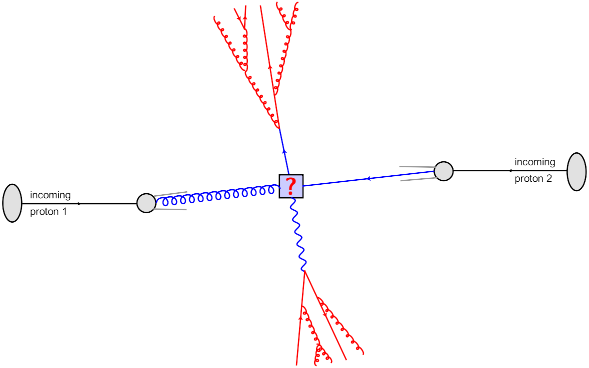
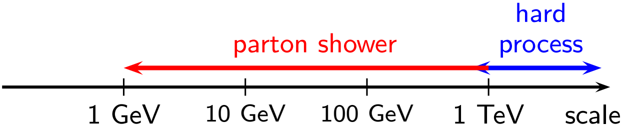


Simulating a high-energy collision requires several ingredients

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



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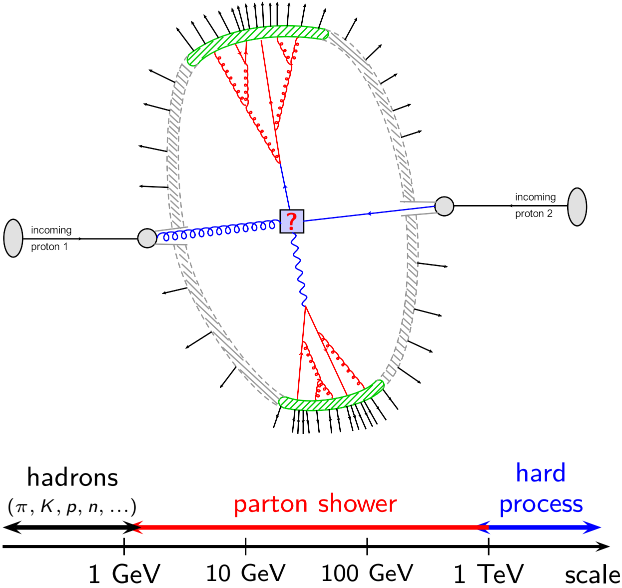

Simulating a high-energy collision requires several ingredients

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

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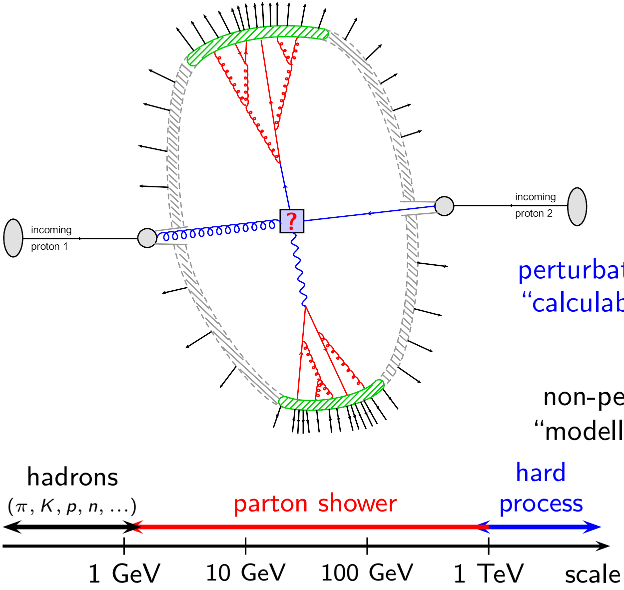


Simulating a high-energy collision requires several ingredients

perturbative
"calculable"

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

non-pert.
"modelled"

- Hadronisation
- Multi-parton interactions
- ...

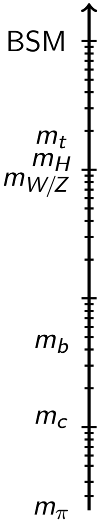
Basic message #2: physics at all scales

physics probed across many scales

$Q \equiv$ 100 GeV $\to$ 1 TeV

$Q \gg \mu_{\mathrm{NP}}$

$\mu_{\mathrm{NP}} \sim$ 1 GeV



BSM

m_t

m_H

$m_{W/Z}$

m_b

m_c

m_π

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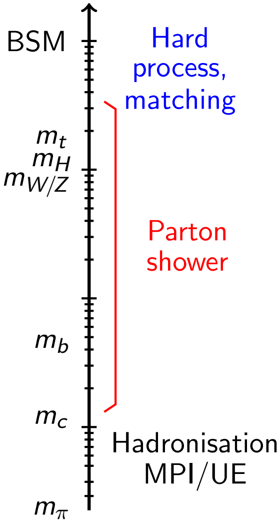

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Hard process, matching

Parton shower

Hadronisation MPI/UE

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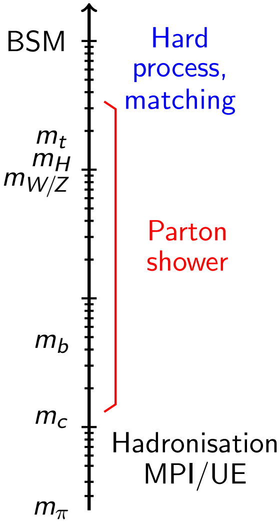
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A lot of work in past 20 years:

- "Amplitudes"
- MadGraph, aMC@NLO, POWHEG, MCFM, ...
- MLM, CKKW, Mi(N)NLO UNNLOPS, Geneva, ...

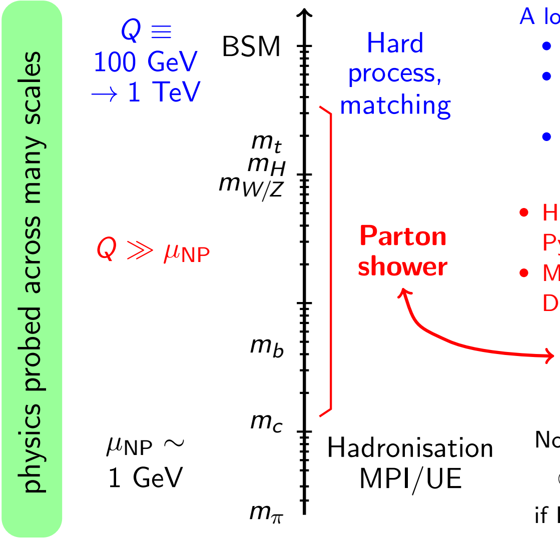
- Historical showers: Pythia,Herwig,Sherpa
- More recent work: Dire, Vincia, Deductor, **PanScales**...

Nonperturbative modelling

$$\propto (\mu_{NP}/Q)^{\#}$$

if IRC-safe

Basic message #2: physics at all scales



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This Talk

Nonperturbative modelling

$$\propto (\mu_{NP}/Q)^{\#}$$

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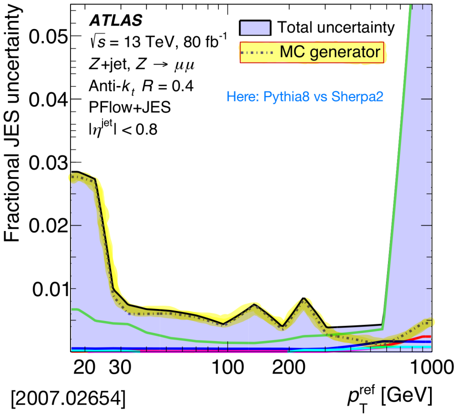
Plan

✓ Motivate the importance of event generators

- Parton showers in “the vacuum” (*ee* and *pp* collisions)
  - **Goal: achieve precision (across all scales)**
  - How is it built?
  - progress within PanScales (assessing and improving accuracy)
- Parton showers in the medium (*AA* collisions)
  - **Get a meaningful physical picture**
Qualitative (slowly moving towards quantitative)
  - the “Saclay”/JetMed factorised picture

A nice illustrative example for precision needs



[2007.02654]

Uncertainty on the reconstruction of the jet energy in ATLAS:

Dominant source comes from MC generator (Sherpa v. Pythia)

Critical!

This affects ALL the measurements involving jets

Parton showers in the "vacuum" (*ee*&*pp*)

"Accuracy"?

Parton showers cover a large range of scales

Disparate scales $\Rightarrow$ logs $\Rightarrow$ all-order resummation

(Cumulative) distributions can (often) be written as ($L \equiv \ln 1/v_{\text{cut}}$)

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

Examples for the observable v:

- Thrust $T = \max_{|\vec{u}|=1} \frac{\sum_i |\vec{p}_i \cdot \vec{u}|}{\sum_i |\vec{p}_i|}$
- Cambridge y_{23} ($\approx$ largest k_t in an angular-ordered clustering)
- angularities
- Z transverse momentum in Drell-Yan
- Jet vetos

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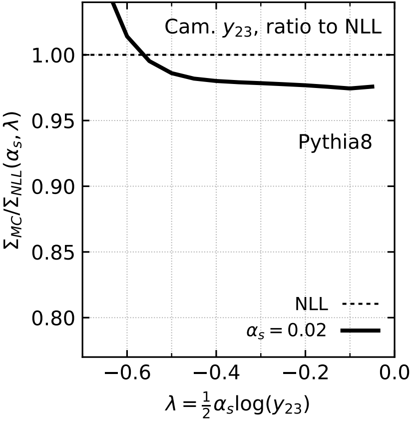
$$\mathcal{O}(1/\alpha_s) \qquad \mathcal{O}(1) \qquad \mathcal{O}(\alpha_s)$$

in resummation regime:

$$\alpha_s \ll 1, \qquad L \gg 1, \qquad \lambda \equiv \alpha_s L \sim 1$$

We should control at least $\mathcal{O}(1)$ contributions

Testing accuracy



Idea for testing:

$$\frac{\Sigma_{MC}(\lambda{=}\alpha_s L,\alpha_s)}{\Sigma_{NLL}(\lambda{=}\alpha_s L,\alpha_s)} \quad \text{v.} \quad 1$$

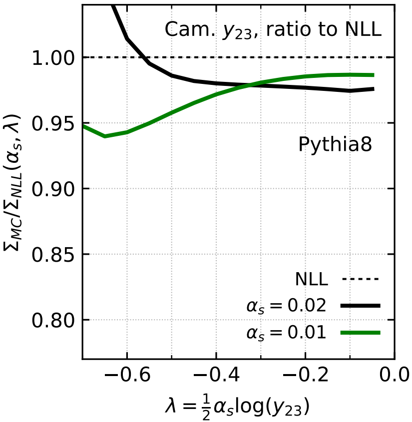
with $\lambda = \alpha_s L$

NLL deviations

or

subleading effects?

Testing accuracy



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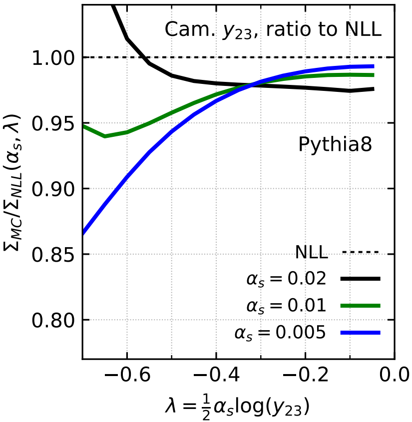

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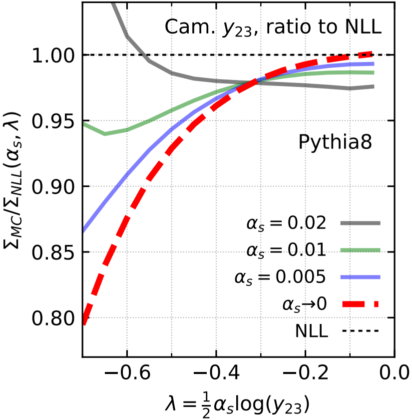

Idea for testing:

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at fixed $\lambda = \alpha_s L$

NLL deviations

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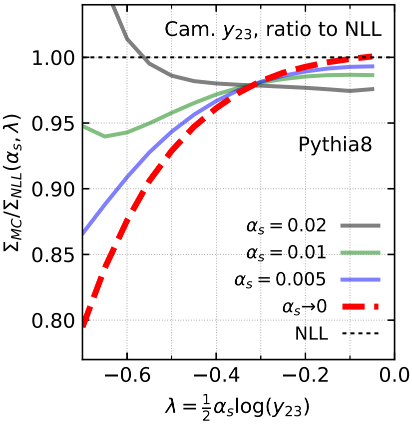

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Next slides: get to NLL accuracy

Parton showers in the “vacuum” (ee&pp)

How do parton showers work?

Dipole/Antenna showers: ingredients

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

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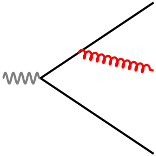
Idea #1:

gluon emission ≡ dipole splitting

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

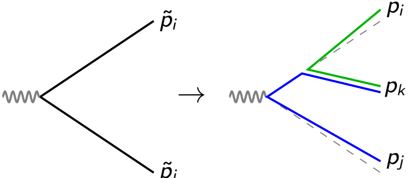


ingredient 1: mapping

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

includes recoil
& energy-mom conservation

viewed as



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ingredient 2: emission probability

Captures the soft/collinear limits

$$d\mathcal{P}_{\tilde{\imath}\tilde{\jmath}\to ijk} \approx \frac{\alpha_s^{(\mathrm{CMW})}}{\pi} \frac{dv}{v} d\bar{\eta} \times$$
$$\times \left[g(\bar{\eta}) z_i P_{\tilde{\imath}\to ik}(z_i) \right.$$
$$\left. + g(-\bar{\eta}) z_j P_{\tilde{\jmath}\to jk}(z_j) \right]$$

$v(\ll 1) \equiv$ ordering variable

(measures "softness", e.g. k_t)

$\bar{\eta} \equiv$ rapidity along the dipole

(could also use $\ln z$)

Dipole/Antenna showers: ingredients

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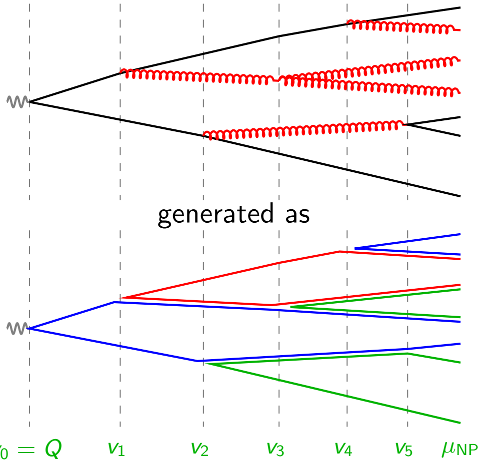

Idea #2:

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

Rooted in QCD factorisation

$n, n+1$ particles probabilities

$$P_{n+1}(v_{n+1}) = e^{-\Delta_n(v_0,v)} |M^2|(v) P_n(v_n)$$

Sudakov
≡"no emissions"
(virtuals)

real emission

Dipole/Antenna showers: ingredients

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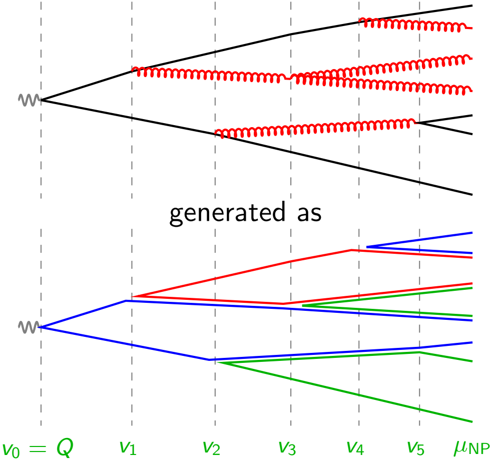

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Main benefits:

- automatic soft-gluon (antenna) pattern
- automatic angular ordering (coherence)
- easy collinear branchings

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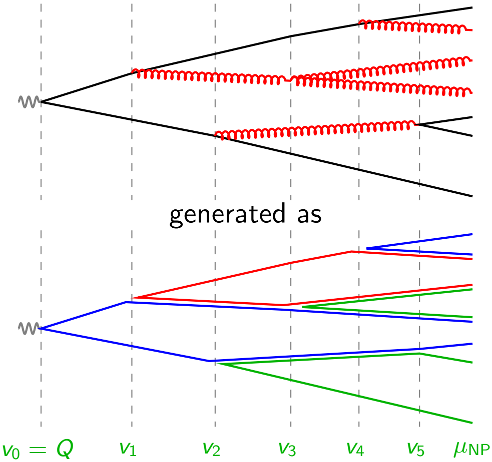

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Several challenges:

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

Towards NLL accuracy with the PanScales showers

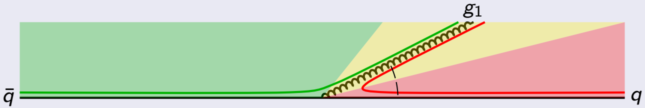
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,arXiv:2002:11114]

PanScales showers

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

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

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



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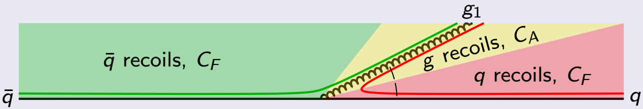

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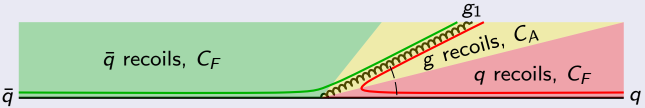
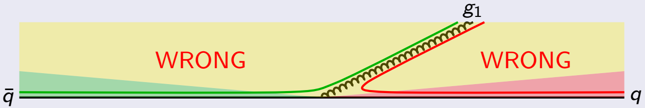


Pythia:

recoiler decided in
dipole rest frame



Notes:

- Say the two emissions have transverse momentum k_{t1} and k_{t2}
- "WRONG" only problematic if $k_{t2} \sim k_{t1}$
- Pythia is k_t-ordered $\Rightarrow$ wrong IS problematic

PanScales showers

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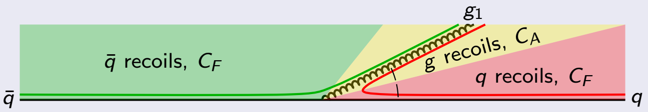
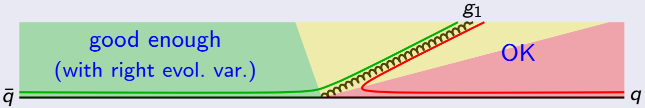


PanScales:
recoiler decided in
event frame



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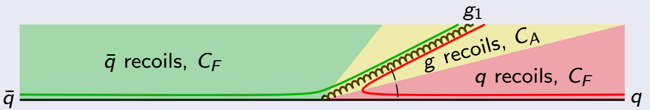
- PanScales with k_t-ordering still expected wrong

PanScales showers

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

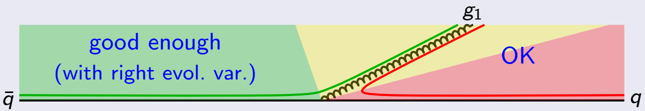
Key element 1: how to associate colour and transverse recoil to dipoles?

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



PanScales:

recoiler decided in
event frame



Key element 2: choice of evolution variable

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

Idea: emissions with commensurate k_t radiated with successively smaller angles

Assessing accuracy: y_{23}

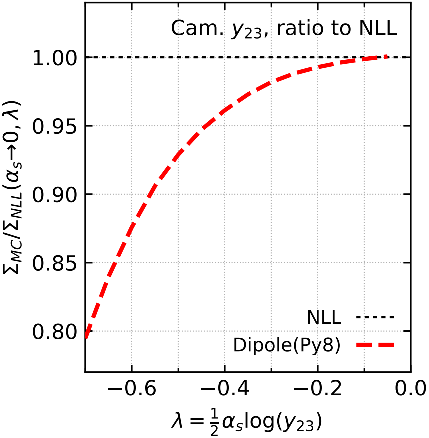
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]

Example: C/A $y_{23} \equiv \max_i k_{ti}$

Study

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

× Pythia8 deviates from NLL



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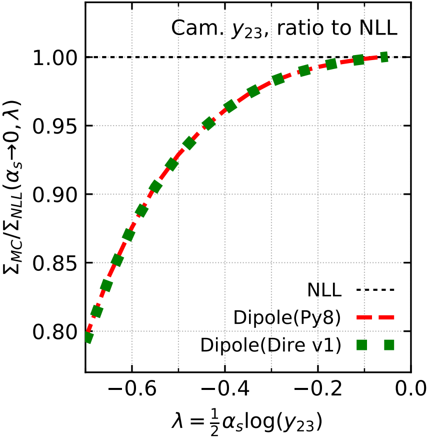
- × Dire(v1) same as Pythia8



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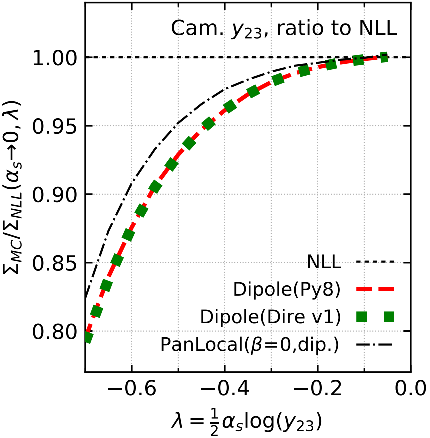
× Dire(v1) same as Pythia8

× PanLocal($\beta = 0$) still deviates
(issue of k_t ordering remains)



PanLocal $\equiv$ momentum conservation "local" in kinematic map

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

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- × Dire(v1) same as Pythia8
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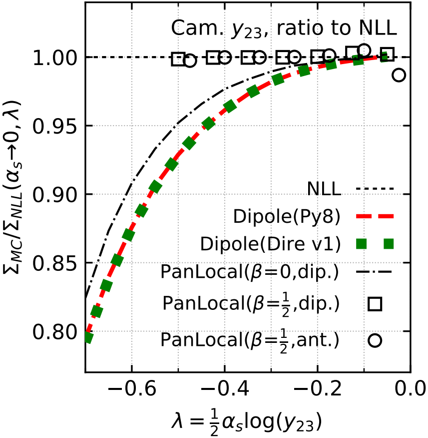
  (issue of k_t ordering remains)
- ✓ PanLocal($0 < \beta < 1$) OK
  (issue of k_t ordering remains)



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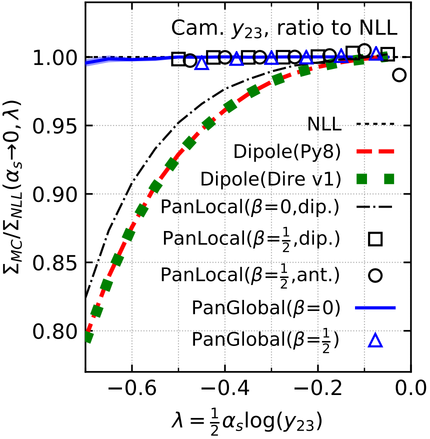
$$\frac{\Sigma_{MC}(\lambda{=}\alpha_s L,\alpha_s)}{\Sigma_{NLL}(\lambda{=}\alpha_s L,\alpha_s)} \text{ for } \alpha_s \to 0.$$

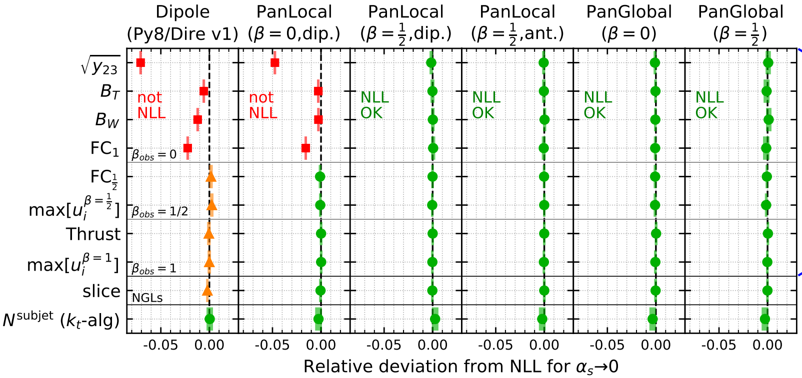
- × Pythia8 deviates from NLL
- × Dire(v1) same as Pythia8
- × PanLocal($\beta = 0$) still deviates (issue of k_t ordering remains)
- ✓ PanLocal($0 < \beta < 1$) OK (issue of k_t ordering remains)
- ✓ PanGlobal($0 \leq \beta < 1$) OK (global recoil allows also for $\beta = 0$)



PanLocal $\equiv$ momentum conservation "local" in kinematic map
PanGlobal $\equiv$ momentum conservation "globally (global rescaling+Boost)

Assessing accuracy: extensive observable list

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,2002.11114]



global event shapes (different scalings)

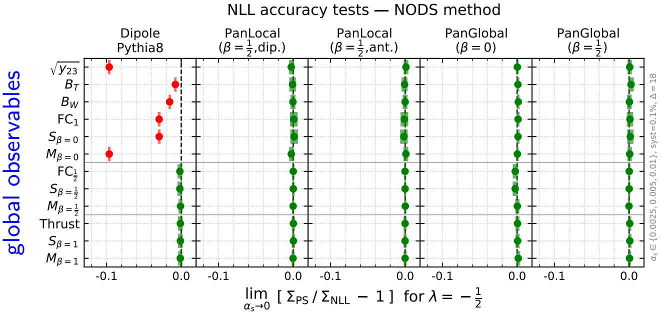
non-global

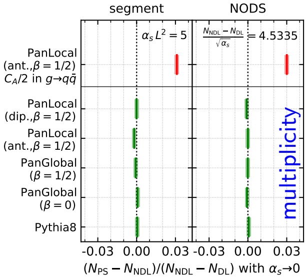
multiplicity

PanLocal($0 < \beta < 1$) and PanGlobal($0 \leq \beta < 1$) get expected NLL (i.e. 0)

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

Assessing accuracy: extension beyond leading N_c



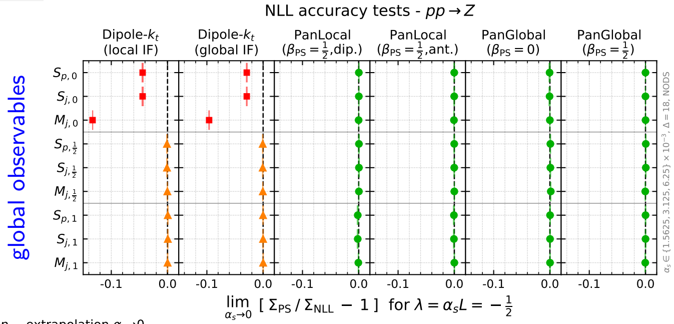


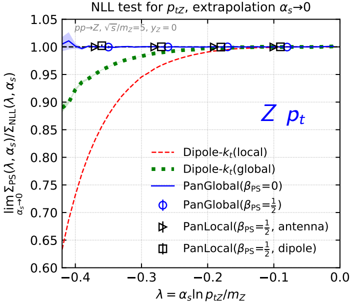
PanLocal($0 < \beta < 1$) & PanGlobal($0 \leq \beta < 1$)
get expected NLL

Two methods beyond leading N_c
("segment" and NODS)

[K.Hamilton,R.Medves,G.P.Salam,
L.Scyboz,GS,2011.10054]

Assessing accuracy: extension to hadron collisions



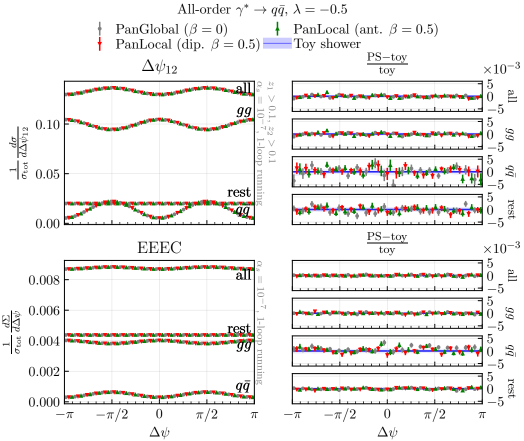


PanLocal($0 < \beta < 1$) &
PanGlobal($0 \leq \beta < 1$)
get expected NLL

For now only colour-singlet production

[M.van Beekveld,S.Ferrario Ravasio,G.P.Salam, A.Soto-Ontoso,GS,R.Verheyen,2205.02237]

Assessing accuracy: spin correlations



Spin correlations enter at NLL:

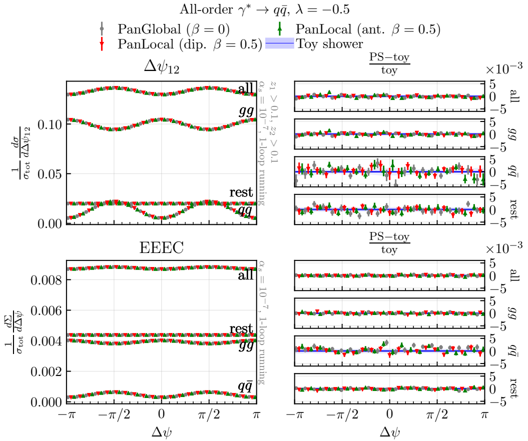
① consecutive "hard" collinear splittings

② soft gluon + hard collinear splitting

PanLocal$(0 < \beta < 1)$ & PanGlobal$(0 \leq \beta < 1)$ get expected NLL

[A.Karlberg,G.P.Salam,L.Scyboz, R.Verheyen,2103.16526]
[K.Hamilton,+same,2111.01161]

Assessing accuracy: spin correlations



Spin correlations enter at NLL:

1. consecutive “hard” collinear splittings
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[A.Karlberg,G.P.Salam,L.Scyboz, R.Verheyen,2103.16526]
[K.Hamilton,+same,2111.01161]

Overall result: first NLL parton shower

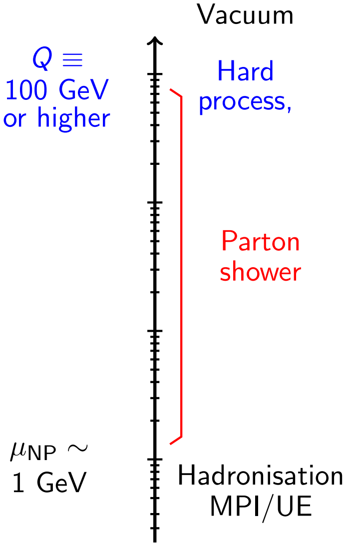
Parton shower in the Quark-Gluon Plasma

Main/leading picture

with P. Caucal, E. Iancu, A.H. Mueller
1801.09703, 1907.04866, 2005.05852, 2012.01457

Another look at scales

LHC probes physics across many scales



Vacuum

$Q \equiv$ 100 GeV or higher

Hard process,

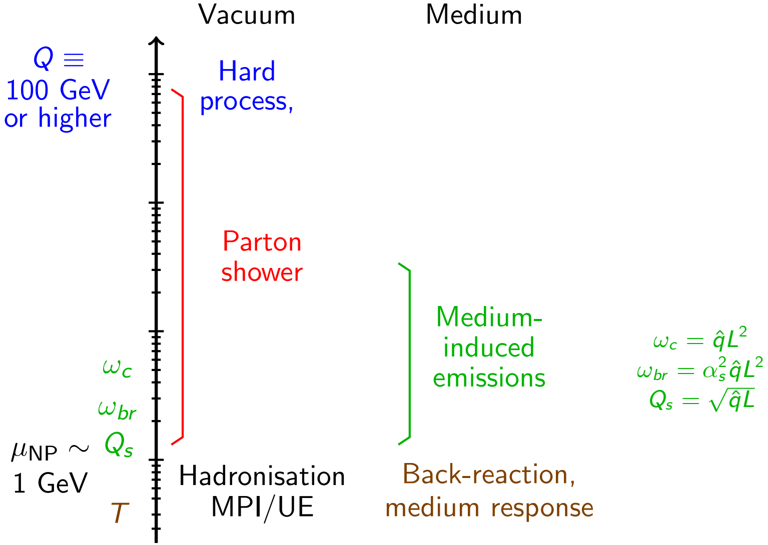
Parton shower

$\mu_{\rm NP} \sim$ 1 GeV

Hadronisation MPI/UE

Another look at scales

LHC probes physics across many scales



Vacuum

Medium

$Q \equiv$
100 GeV
or higher

Hard
process,

Parton
shower

Medium-
induced
emissions

$\omega_c = \hat{q}L^2$
$\omega_{br} = \alpha_s^2\hat{q}L^2$
$Q_s = \sqrt{\hat{q}L}$

ω_c

ω_{br}

Q_s

$\mu_{\text{NP}} \sim$
1 GeV

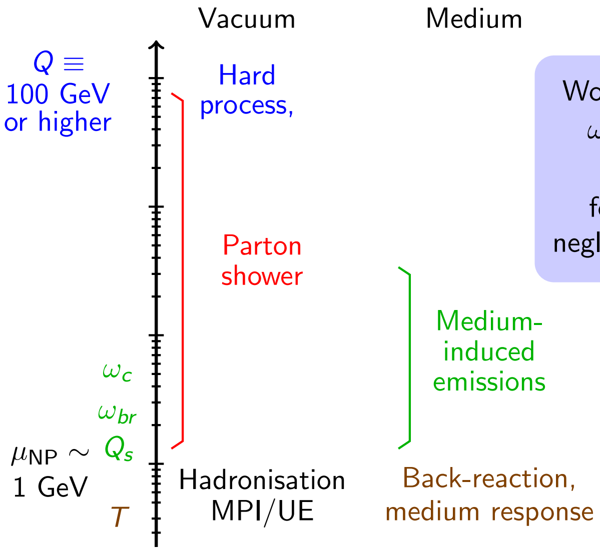
T

Hadronisation
MPI/UE

Back-reaction,
medium response

Another look at scales

LHC probes physics across many scales



Working assumption

$\omega_c, \omega_{\text{br}}, Q_s \gg T$

$\Downarrow$

focus on shower

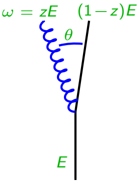
neglect thermalisation

$\omega_c = \hat{q}L^2$

$\omega_{br} = \alpha_s^2\hat{q}L^2$

$Q_s = \sqrt{\hat{q}L}$

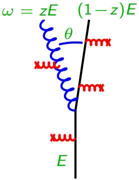
2 types of emissions



Standard "DGLAP" splitting rate:

$$d^2\mathcal{P}_{\text{vle}} = \frac{\alpha_s(k_\perp)}{\pi} P(z)dz \frac{d\theta}{\theta} \approx \frac{2\alpha_s(k_\perp)C_R}{\pi} \frac{dz}{z} \frac{d\theta}{\theta}$$

- ✓ includes soft&collinear divergence
- ✓ Iterated (Markovian process) for successive branchings with angular ordering $\theta_{i+1} < \theta_i$



Medium interactions ⇒ additional emissions

BDMPS-Z spectrum ($\omega_c = \frac{1}{2}\hat{q}L^2$)

$$d^2\mathcal{P}_{\text{mie}} \approx \frac{\alpha_{s,\text{med}}C_R}{\pi} \sqrt{\frac{2\omega_c}{E}} \frac{dz}{z^{3/2}} \mathcal{P}_{\text{broad}}(\theta,\omega)$$

- ✓ strong peak at small z, no collinear div.
- ✓ Here: assume θ from Gaussian $k_\perp$ broadening
- ✓ Iterated (Markovian process) for successive branchings in formation time $t_f = \frac{2}{\omega\theta^2}$
- ✓ NO ANGULAR ORDERING

Combining vacuum and medium-induced emissions

compare the transverse momenta over the formation time: $t_f = \frac{2}{\omega\theta^2}$

$$k^2_{\perp,\text{vac}} = \omega^2\theta^2$$

$$k^2_{\perp,\text{med}} = \hat{q}t_f = \frac{2\hat{q}}{\omega\theta^2}$$

Combining vacuum and medium-induced emissions

compare the transverse momenta over the formation time: $t_f = \frac{2}{\omega\theta^2}$

$$k_{\perp,\mathrm{vac}}^2 = \omega^2\theta^2$$

$$k_{\perp,\mathrm{med}}^2 = \hat{q}t_f = \frac{2\hat{q}}{\omega\theta^2}$$

Double-logarithmic approximation: 2 possible cases:

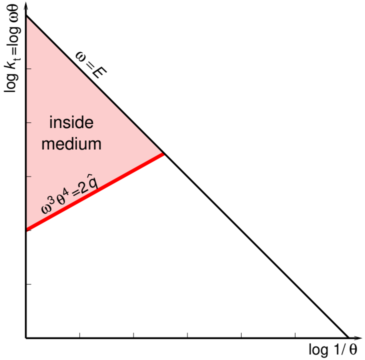
- $k_{\perp,\mathrm{vac}}^2 \gg k_{\perp,\mathrm{med}}^2$: vacuum-like emission (VLE)
- $k_{\perp,\mathrm{med}}^2 \gg k_{\perp,\mathrm{vac}}^2$: medium-induced emission (MIE)

transition at $k_{\perp,\mathrm{med}}^2 = k_{\perp,vac}^2$ i.e. $\omega^3\theta^4 = 2\hat{q}$

Factorised physical picture

Double-log accuracy:

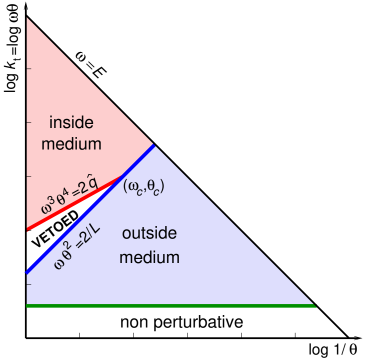
- in-medium VLEs



Factorised physical picture

Double-log accuracy:

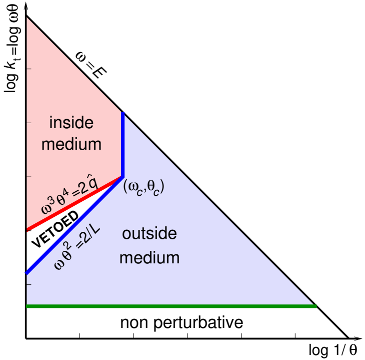
- in-medium VLEs
- medium length
- VLEs vetoed in between



Factorised physical picture

Double-log accuracy:

- in-medium VLEs
- medium length
- VLEs vetoed in between
- colour (de)coherence
  - in-medium has $\theta > \theta_c$
  - in-medium: angular-ordered
  - in→out jump: no ordering



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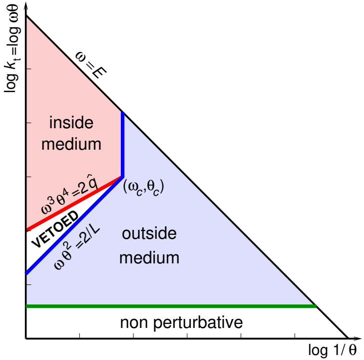
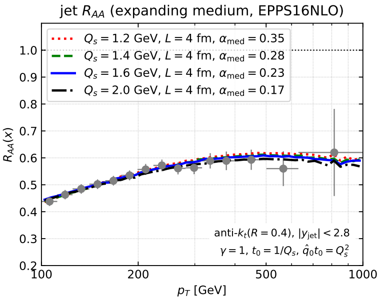


Full picture: parton shower factorised in 3 stages

1. in-medium angular-ordered VLEs
2. each VLE sources MIEs propagating through the medium
3. out-medium VLEs with first emission at any angle

Basic results

- Easily implemented in a Monte-Carlo generator
- Generalised to longitudinally-expanding medium



- R_{AA}: "flatness" explained

  Higher p_t

  $\Rightarrow$ larger "in-medium" vac. phase-sp.

  $\Rightarrow$ more sources for MIEs

  $\Rightarrow$ E_{loss} increased

Basic results

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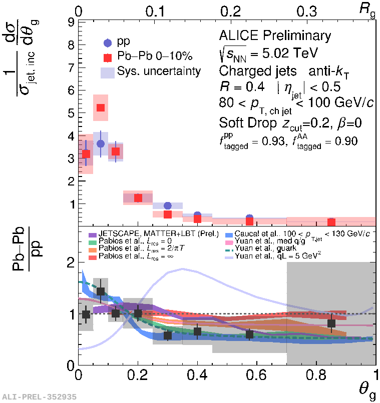

- R_{AA}: "flatness" explained
- θ_g: clear transition around θ_c

  Expectedly more smeared in the data

Basic results

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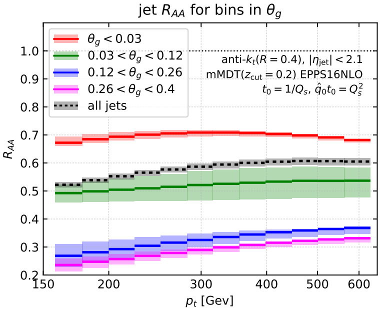
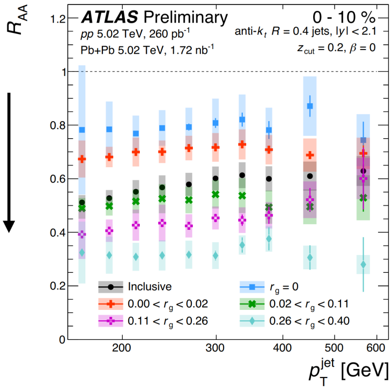


- R_{AA}: "flatness" explained
- θ_g: clear transition around θ_c
- New idea: R_{AA} in bins of θ_g

  smaller θ_g
  - $\Rightarrow$ less vacuum radiation
  - $\Rightarrow$ less $E_{\rm loss}$ sources
  - $\Rightarrow$ smaller R_{AA}

Basic results

- Easily implemented in a Monte-Carlo generator
- Generalised to longitudinally-expanding medium



sourge: A.Sickles QM2022 talk

- R_{AA}: “flatness” explained
- θ_g: clear transition around θ_c
- New idea: R_{AA} in bins of θ_g

  smaller θ_g

  $\Rightarrow$ less vacuum radiation

  $\Rightarrow$ less E_{loss} sources

  $\Rightarrow$ smaller R_{AA}

  Clearly observed by ATLAS

Conclusions

Monte Carlo generators (with parton showers at their core) are a key tool in HEP

Parton showers in *pp* collisions

→ Need for precision (to match the precision quest of the LHC)

✓ New way to define and test accuracy (systematically improvable)

✓ First NLL shower

? TODO: Z+jets, dijets in *pp*, NNLL, ...

Parton showers in *AA* collisions

→ Many effect, e.g. vacuum and medium-induced emissions

✓ New factorised approach (at double-log accuracy)

✓ Easy explanation for many quenching phenomena

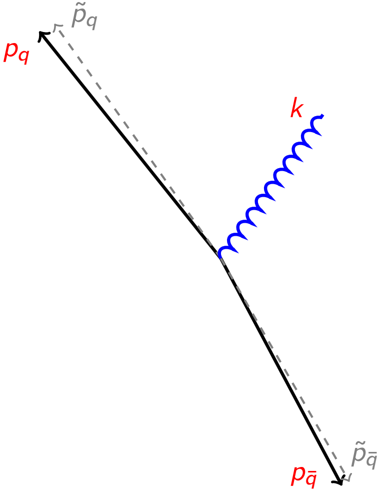
? TODO: beyond double log, geometry, "$\mathcal{O}(T)$" phenomena

? TODO: be more quantitative?

Backup

Basic features of QCD radiations

Take a gluon emission from a $(q\bar{q})$ dipole



Emission $(\tilde{p}_q\tilde{p}_{\bar{q}}) \to (p_q k)(k p_{\bar{q}})$:

$$k^\mu \equiv z_q \tilde{p}_q^\mu + z_{\bar{q}} \tilde{p}_{\bar{q}}^\mu + k_\perp^\mu$$

3 degrees of freedom:

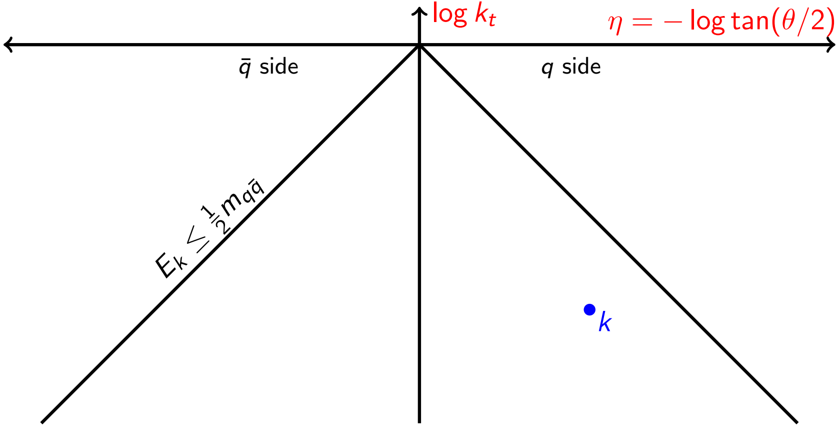
- Rapidity: $\eta = \frac{1}{2} \log \frac{z_q}{z_{\bar{q}}}$
- Transverse momentum: $k_\perp$
- Azimuth: ϕ

In the soft-collinear approximation

$$d\mathcal{P} = \frac{\alpha_s(k_\perp) C_F}{\pi^2} \, d\eta \, \frac{dk_\perp}{k_\perp} \, d\phi$$

Basic features of QCD radiations: the Lund plane

Lund plane: natural representation uses the 2 “log” variables η and $\log k_\perp$



Basic features of QCD radiations: the Lund plane

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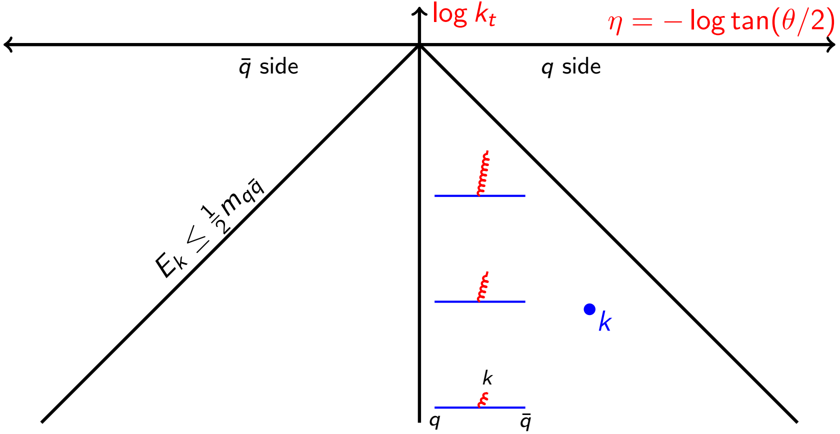

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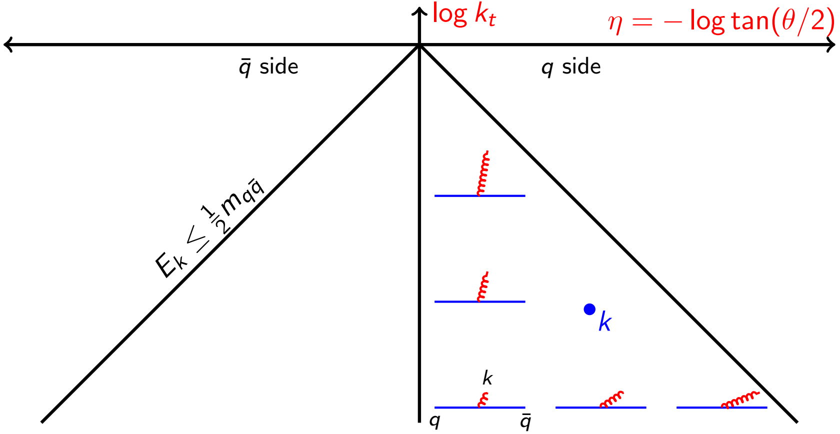

Basic features of QCD radiations: the Lund plane

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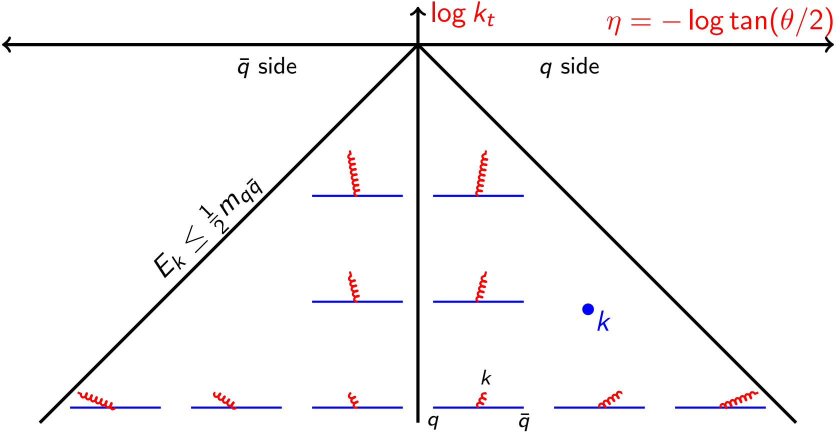
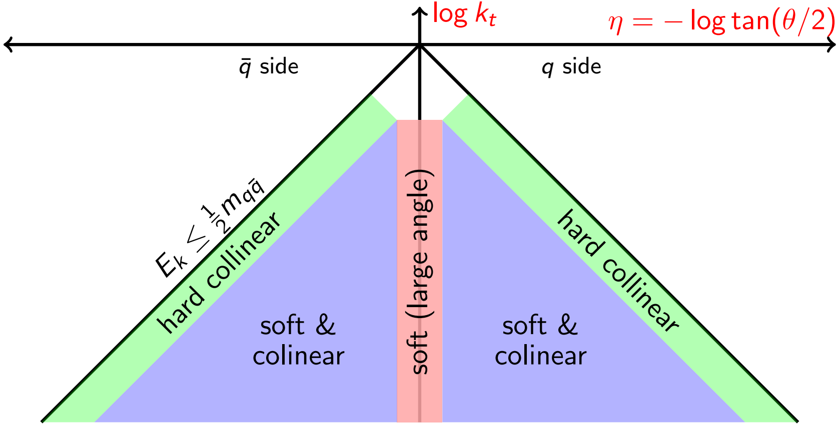
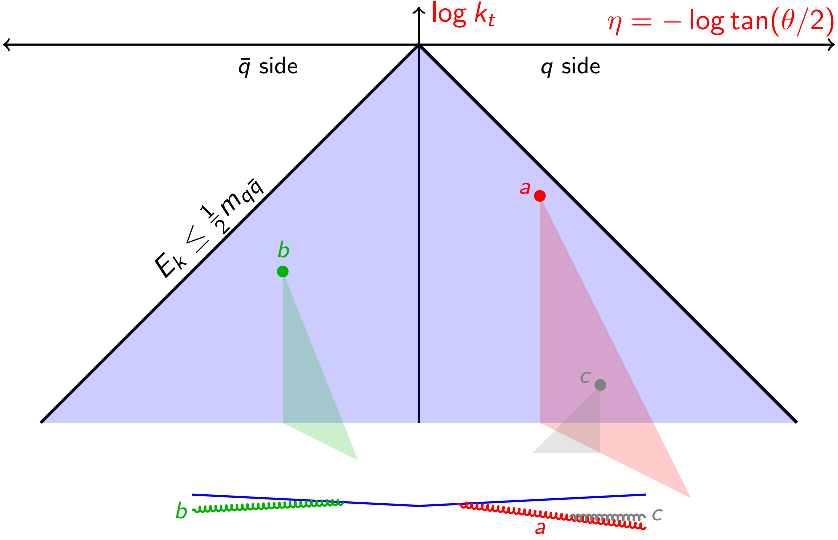


Basic features of QCD radiations: the Lund plane

Lund plane: natural representation uses the 2 "log" variables η and $\log k_\perp$

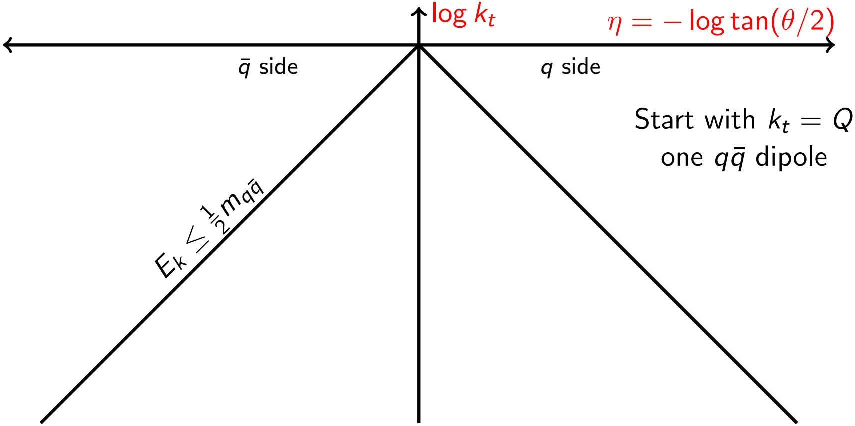


Multiple emissions in the Lund plane



Parton shower in the Lund plane

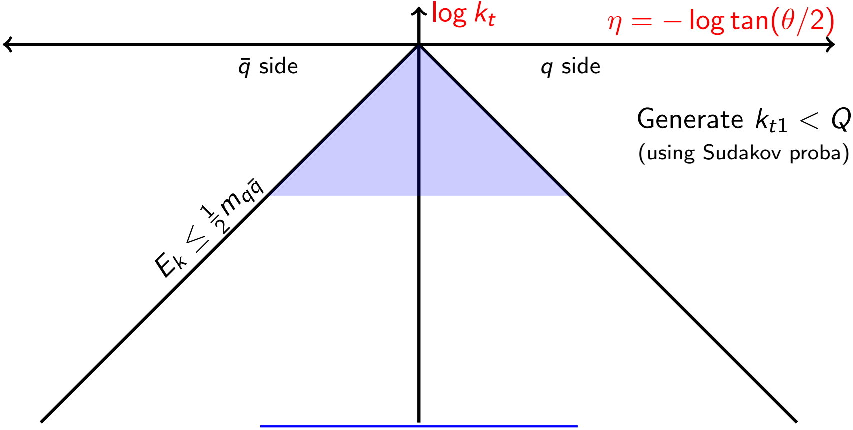
Ordering variable: transverse momentum k_t



Start with $k_t = Q$
one $q\bar{q}$ dipole

Parton shower in the Lund plane

Ordering variable: transverse momentum k_t

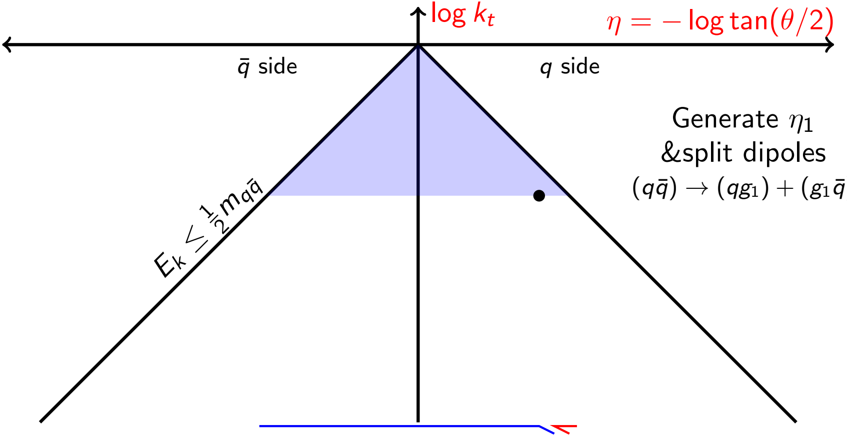


Generate $k_{t1} < Q$

(using Sudakov proba)

Parton shower in the Lund plane

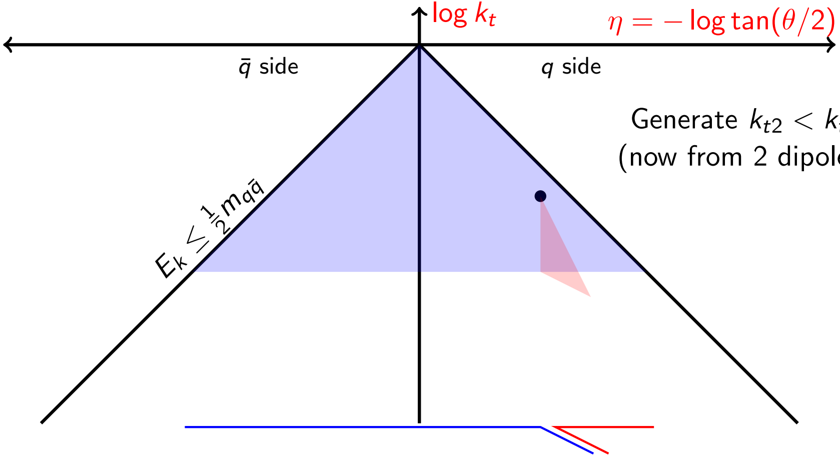
Ordering variable: transverse momentum k_t



Generate η_1
&split dipoles
$(q\bar{q}) \to (qg_1) + (g_1\bar{q})$

Parton shower in the Lund plane

Ordering variable: transverse momentum k_t



Generate $k_{t2} < k_{t1}$
(now from 2 dipoles)

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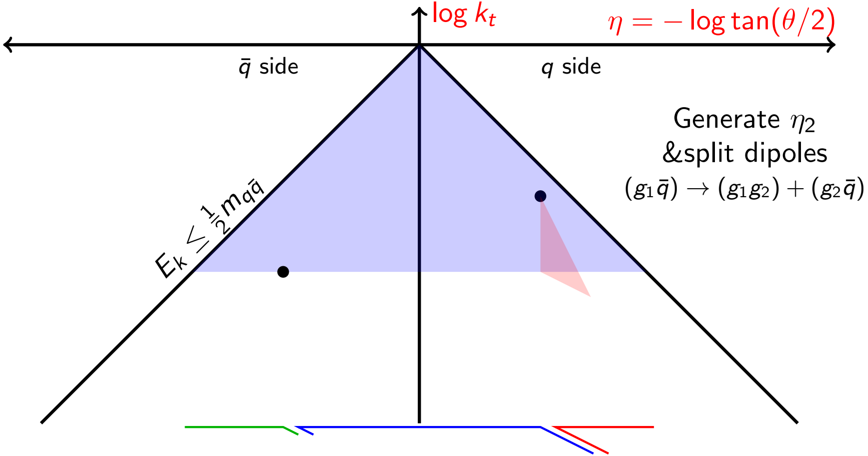
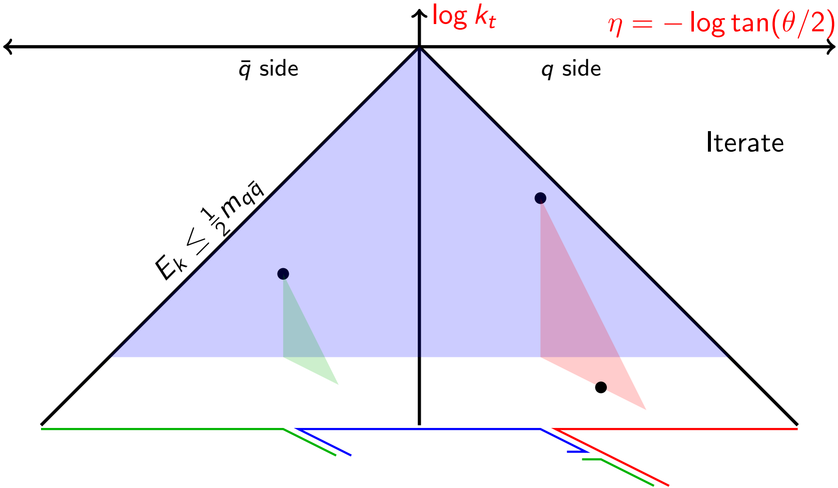


Generate η_2
&split dipoles
$(g_1\bar{q}) \to (g_1 g_2) + (g_2\bar{q})$

Parton shower in the Lund plane

Ordering variable: transverse momentum k_t



Parton shower in the Lund plane

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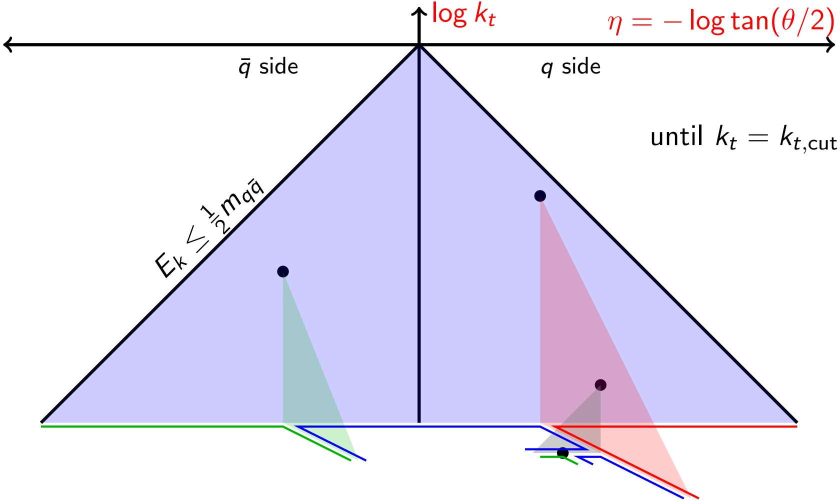
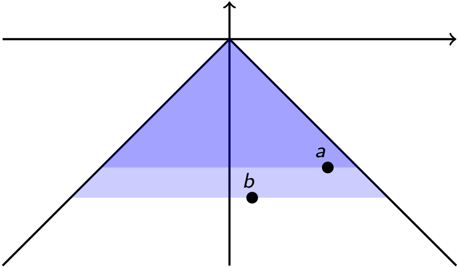


Different ordering variables...

... can lead to different emission orderings

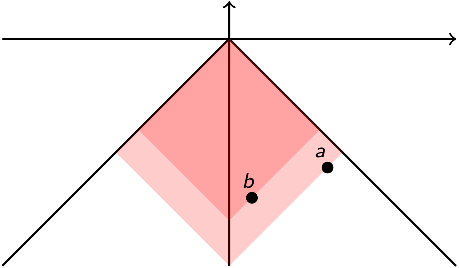
k_t (transv. mom.) ordering



$k_{ta} > k_{tb}$

$\Rightarrow$ a emitted before b

q (virtuality) ordering



$q_b > q_s$

$\Rightarrow$ b emitted before a

Our targeted accuracy

NLL accuracy for a range of observables

- global event shapes
    - thrust
    - jet rates
    - angularities
    - broadening
    - ...
- non-global observables

  e.g. energy in slice
- multiplicity

  (NLL is $\alpha_s^n L^{2n-1}$)

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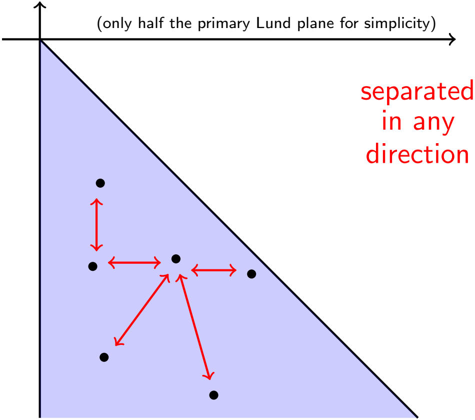
Correct matrix elements for N well separated emissions in the Lund plane



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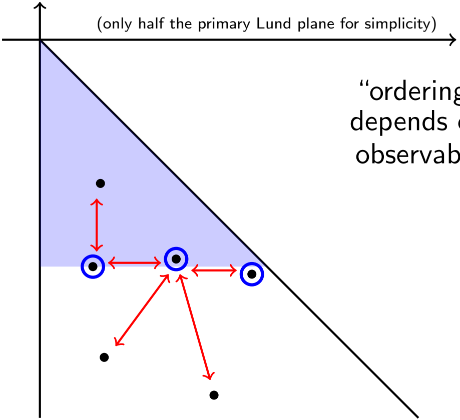

“ordering” depends on observable

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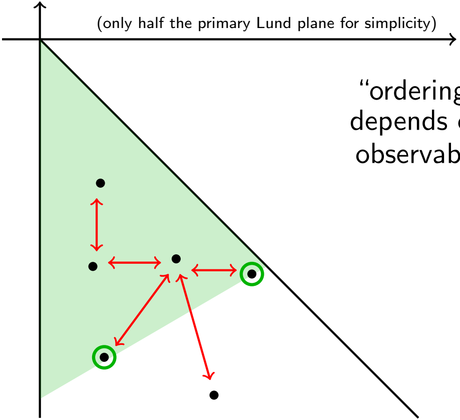

(only half the primary Lund plane for simplicity)

"ordering" depends on observable

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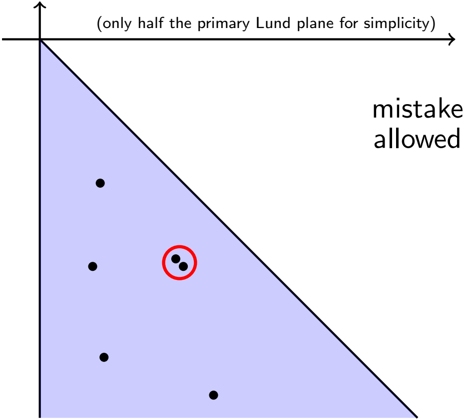
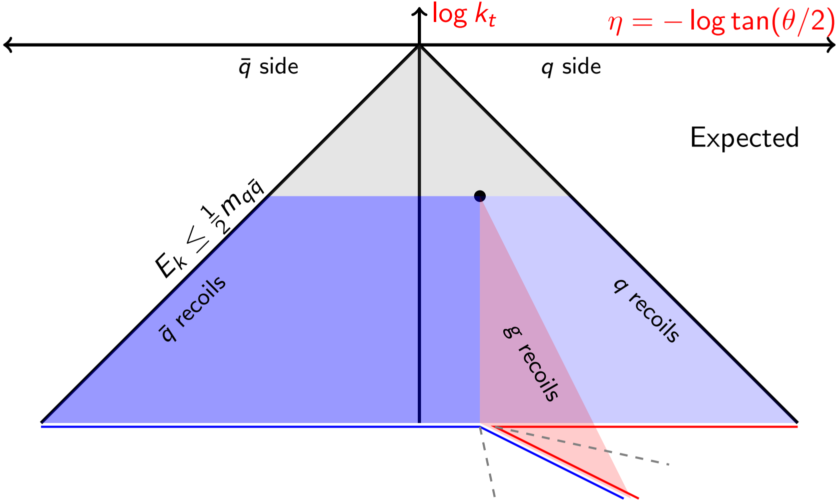


Lund-plane representation: transverse recoil boundaries



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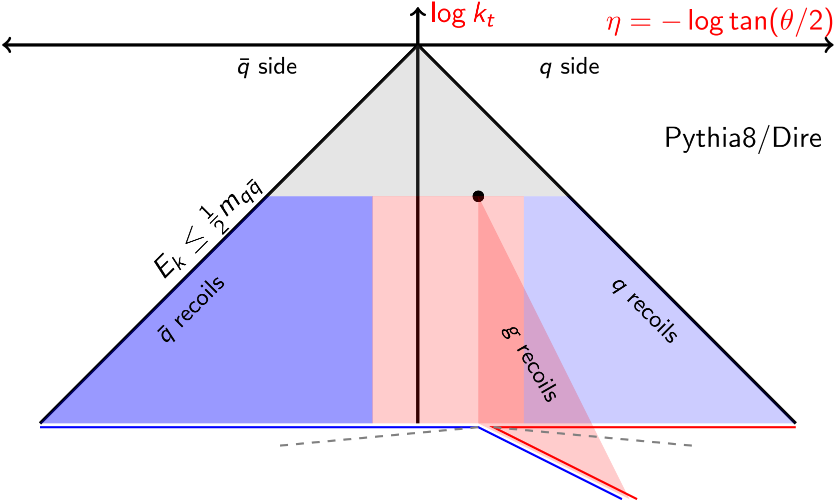

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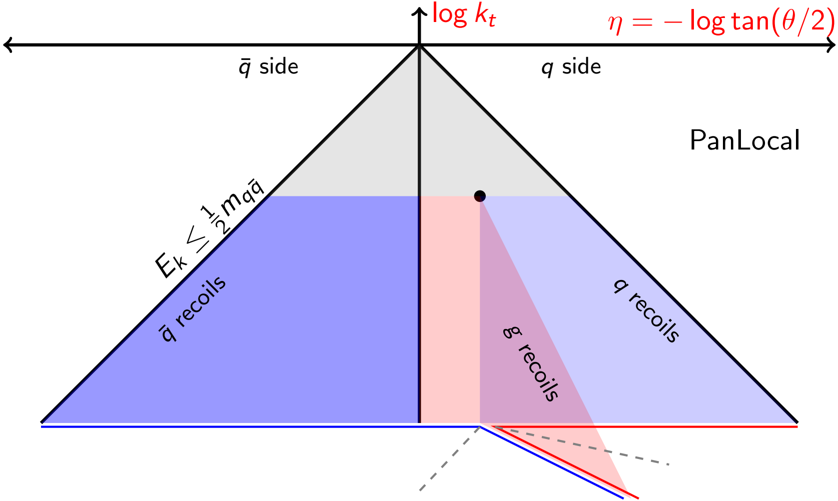
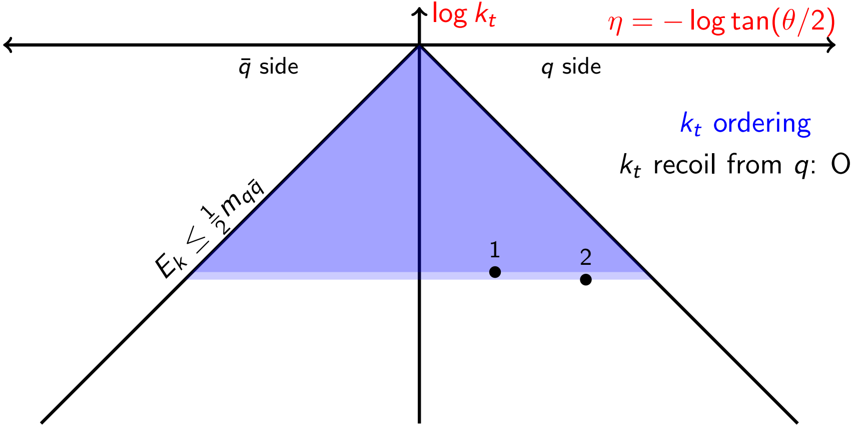


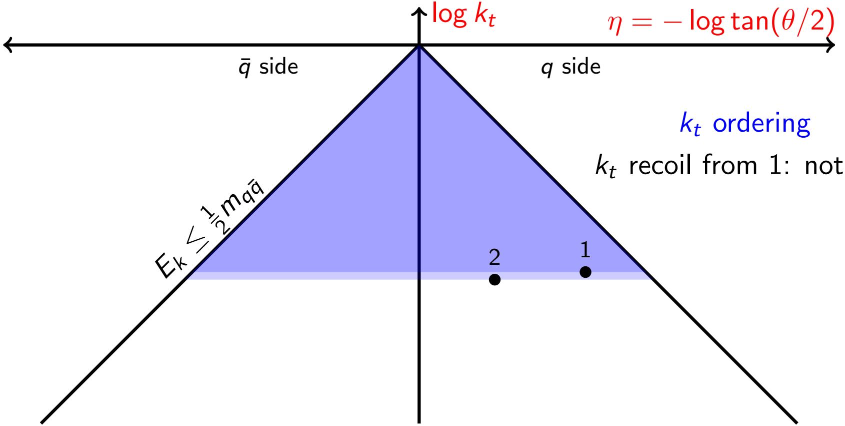
Lund-plane representation: PanLocal evolution variable



k_t ordering

k_t recoil from q: OK

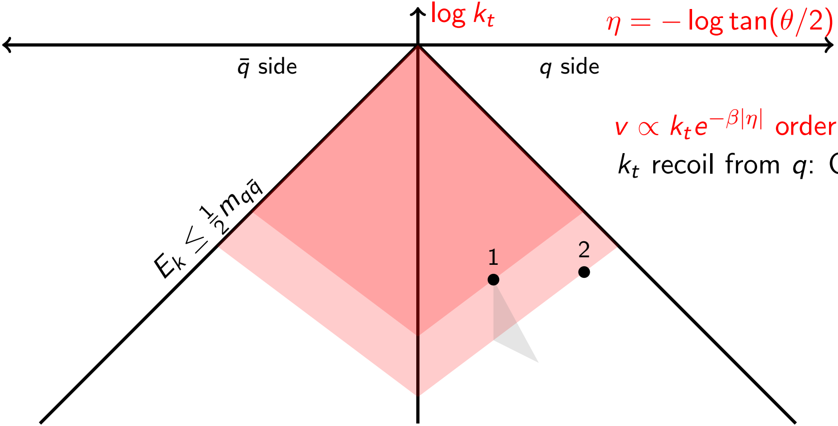
Lund-plane representation: PanLocal evolution variable



k_t ordering

k_t recoil from 1: not OK

Lund-plane representation: PanLocal evolution variable



$v \propto k_t e^{-\beta|\eta|}$ ordering

k_t recoil from q: OK

Kinematic map

(just to give an idea of what it takes)

$$
\begin{aligned}
p_k &= a_k \tilde{p}_i + b_k \tilde{p}_j + k_\perp \\
p_i &= a_i \tilde{p}_i + b_i \tilde{p}_j - f\, k_\perp \\
p_j &= a_j \tilde{p}_i + b_j \tilde{p}_j - (1 - f) k_\perp
\end{aligned}
$$

f decides where to put recoil

- $f \to 1$ when $k \to i$
- $f \to 0$ when $k \to j$

Where to put the transition?

- Pythia8/Dire: equal angles in dipole rest frame
- PanLocal: equal angles in event frame

Kinematic map

(just to give an idea of what it takes)

$$p_k = a_k\tilde{p}_i + b_k\tilde{p}_j + k_\perp$$
$$p_i = a_i\tilde{p}_i + b_i\tilde{p}_j - f\, k_\perp$$
$$p_j = a_j\tilde{p}_i + b_j\tilde{p}_j - (1-f)k_\perp$$

with (PanLocal(β), variables v and $\tilde{\eta}$)

$$|k_\perp| = \rho\, v\, e^{\beta|\tilde{\eta}|} \qquad \rho = \left(\frac{2\tilde{p}_i.Q\,\tilde{p}_j.Q}{Q^2\,\tilde{p}_i.\tilde{p}_j}\right)^{\beta/2}$$

$$a_k = \sqrt{\frac{\tilde{p}_j.Q}{2\tilde{p}_i.Q\,\tilde{p}_i.\tilde{p}_j}}\,|k_\perp|\,e^{+\tilde{\eta}},$$

$$b_k = \sqrt{\frac{\tilde{p}_i.Q}{2\tilde{p}_j.Q\,\tilde{p}_i.\tilde{p}_j}}\,|k_\perp|\,e^{-\tilde{\eta}},$$

$f \approx \Theta(\tilde{\eta})$ and E-mom conservation

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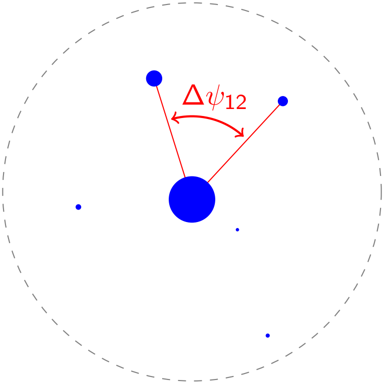
A last example

- Look at angle $\Delta\psi_{12}$ between two hardest "emissions" in jet
  (defined through Lund declusterings)



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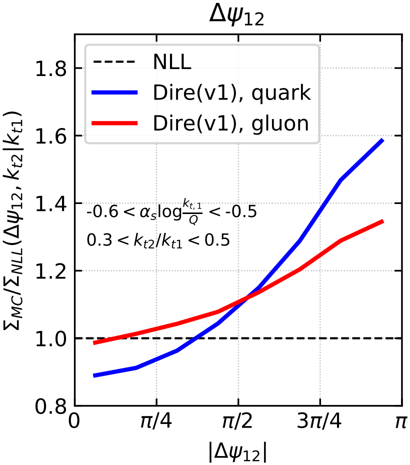
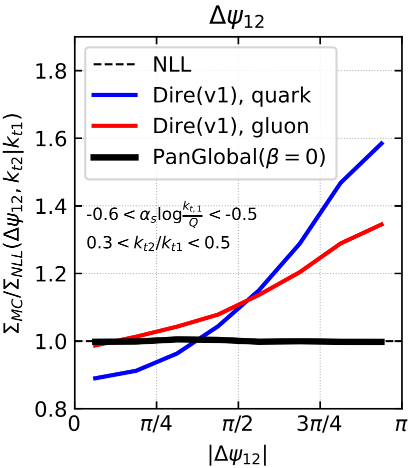
- Look at angle $\Delta\psi_{12}$ between two hardest "emissions" in jet (defined through Lund declusterings)

- quite large NLL deviations in current dipole showers
- differences between quark and gluon jets



A last example

- Look at angle $\Delta\psi_{12}$ between two hardest "emissions" in jet (defined through Lund declusterings)
- quite large NLL deviations in current dipole showers
- differences between quark and gluon jets
- PanGlobal gets correct NLL



JetNed vs. other HI generators

Monte-Carlo	**JetMed**	`MARTINI`	`MATTER+LBT`	`Q-PYTHIA`	`JEWEL`	Hybrid
Fact. scale	✓	✓	✓	✗	✗	✗
Decoherence	✓	✗	✗	✗	✗	✗
LPM effect	✓	✓	✗$^{(1)}$	✓	✓	✗
Multiple branching	✓	?	✗	✗	?	✗
Hadronisation	✗	✓	✓	✓	✓	✓
Medium geom/expnd.	✗	✓	✓	✗$^{(2)}$	✓	✓
Hard scatterings	✗	✓	✓	✗	✓	✗
Medium response	✗	✗	✓	✗	✓	✓
HT splitting functions	✗	✗	✓	✗	✗	✗
Strongly coupled E_{loss}	✗	✗	✗	✗	✗	✓

Notes:
(1) A modified-Boltzmann approach has been proposed to take into account the LPM regime.
(2) `Q-PYTHIA` can be interfaced to an optical Glauber model

[P.Caucal,PhD,2010.02874]