PanScales: the quest for precision across scales

Gregory Soyez
within PanScales: Melissa van Beekveld, Mrinal Dasgupta, Frederic Dreyer, Basem El Menoufi, Silvia Ferrario Ravasio, Keith Hamilton, Jack Helliwell, Alexander Karlberg, Rok Medves, Pier Monni, Gavin Salam, Ludovic Scyboz, Alba Soto-Ontoso, Rob Verheyen

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Intro: event generators for high-energy collisions

(Fairly) generic example

Most observables/measurements can take the following form:

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

(Fairly) generic example

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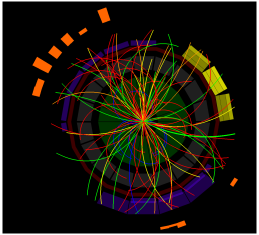
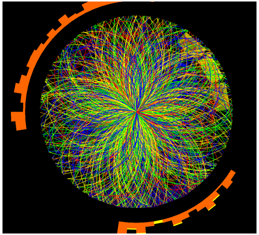
- Outrageously complex in general





source: Alice
pp(left), $PbPb$(right)

Even for simple pheno processes this quickly grows out of control

(Fairly) generic example

Most observables/measurements can take the following form:

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

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

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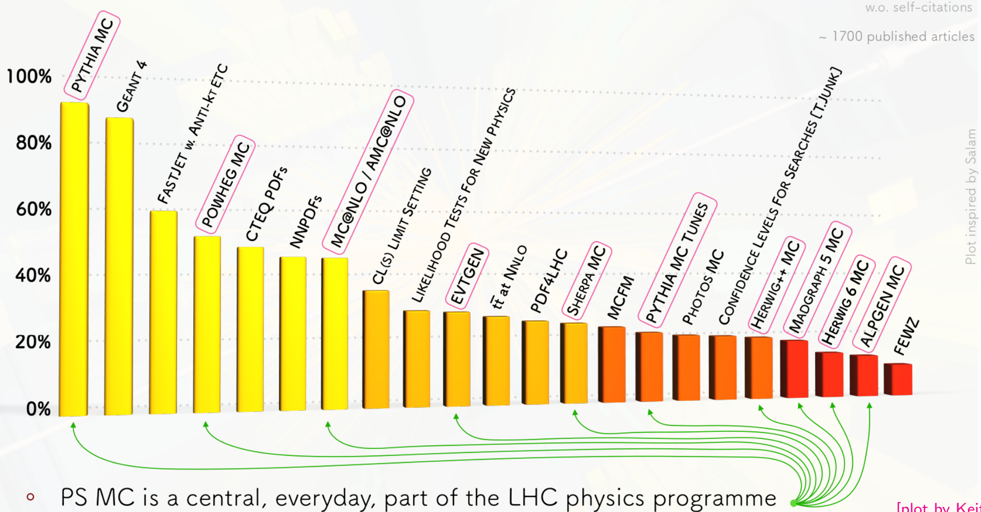
- Outrageously complex in general
- Idea: simulate numerically
  sample "randomly" using a **Monte Carlo event generator**
- **Main advantage: works for basically any observable**

Basic message #1: Event Generators are among us!

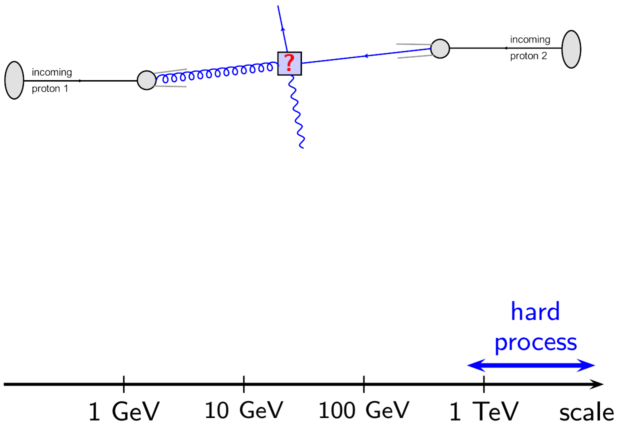
- % of ATLAS+CMS+LHCb papers citing some article/group in Jan '14 → May '20



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

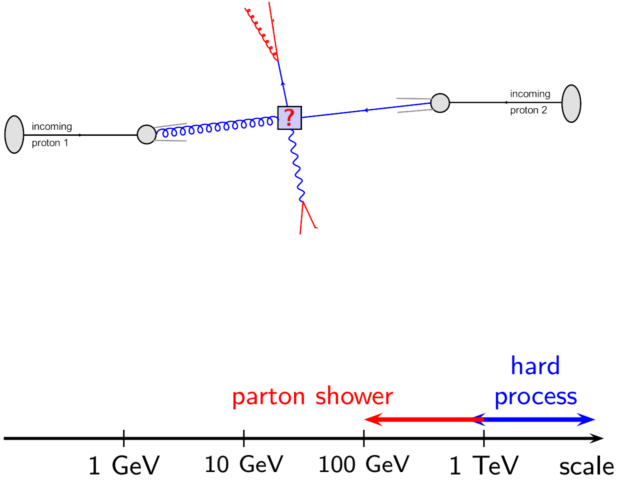
[plot by Keith Hamilton]

Anatomy of a high-energy collision



Simulating a high-energy collision requires several ingredients

- A hard process



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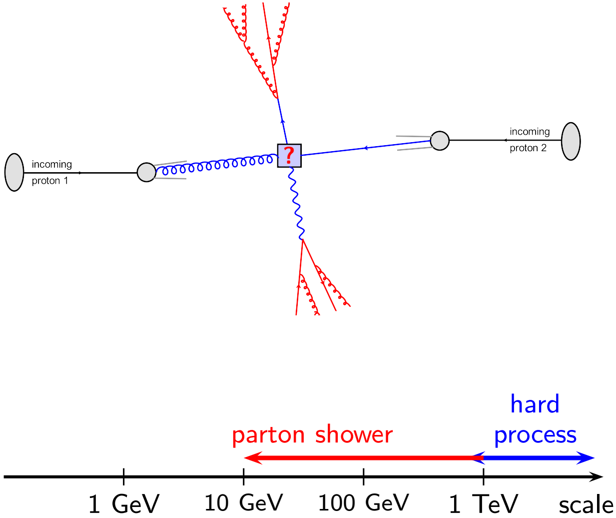
- A hard process
- Parton shower (initial and final-state)

Anatomy of a high-energy collision



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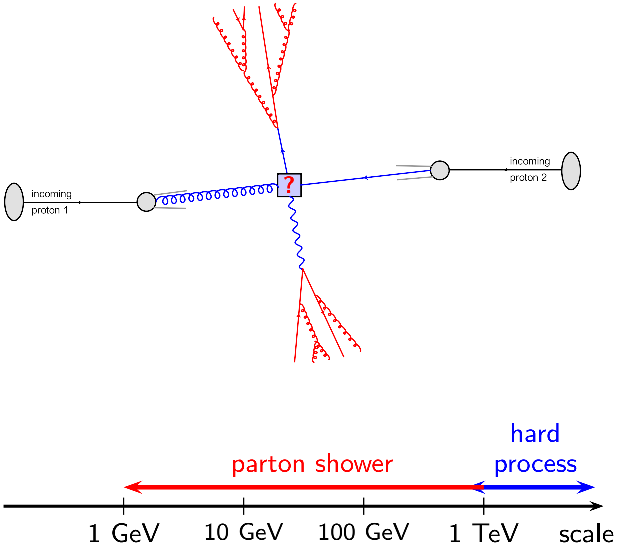

Simulating a high-energy collision requires several ingredients

- A hard process
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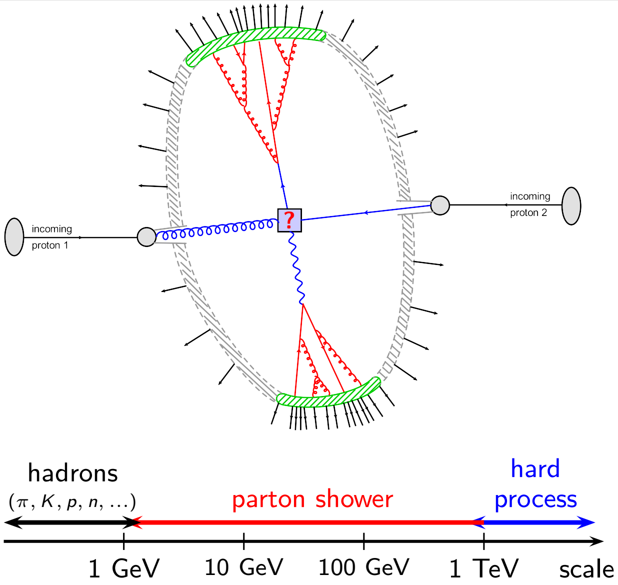
- Hadronisation



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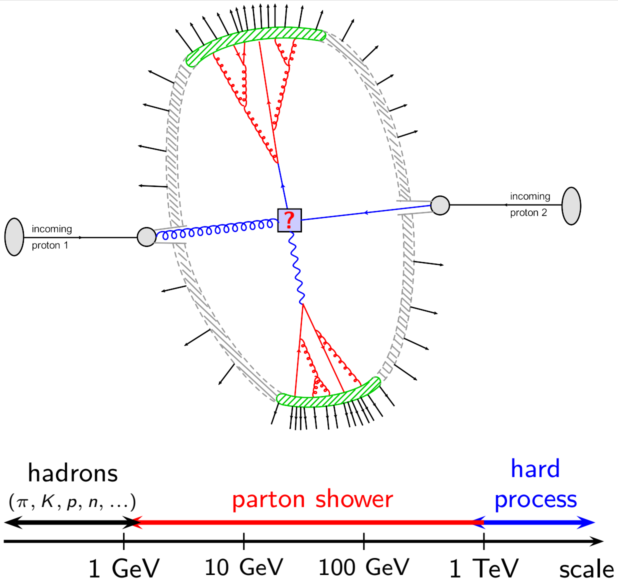


Simulating a high-energy collision requires several ingredients

perturbatively "calculable"

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

non-pert. "modelled"

- Hadronisation
- Multi-parton interactions

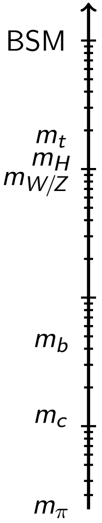
Basic message #2: physics at all scales

physics probed across many scales

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

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

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



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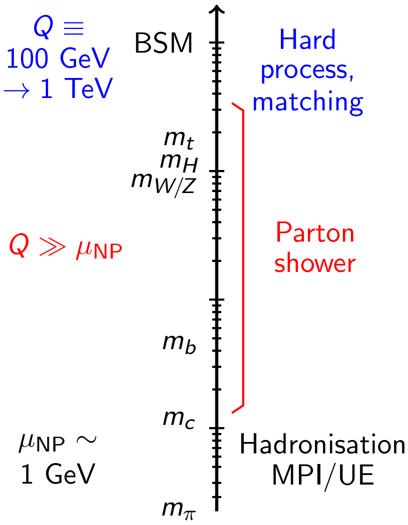

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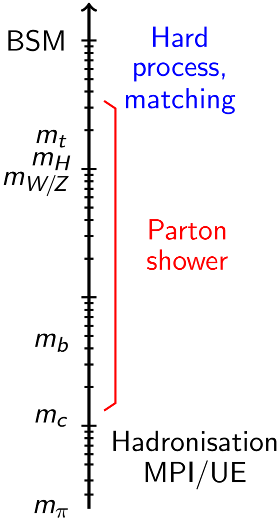

"Standard" perturbative expansion

$$\alpha_s(Q) f_1(v) + \alpha_s^2(Q) f_2(v) + \alpha_s^3(Q) f_3(v) + \dots$$

LO NLO NNLO

expect logs between disparate scales

$$\alpha_s \log^2 Q/\mu_{\rm NP},\ \alpha_s \log Q/\mu_{\rm NP}$$

(double, single,...) logs to resum

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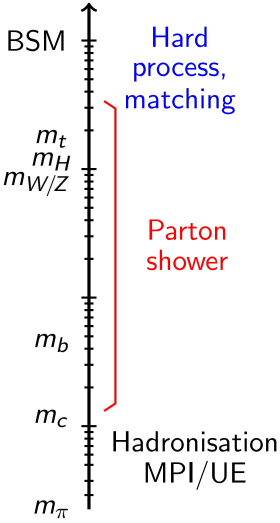

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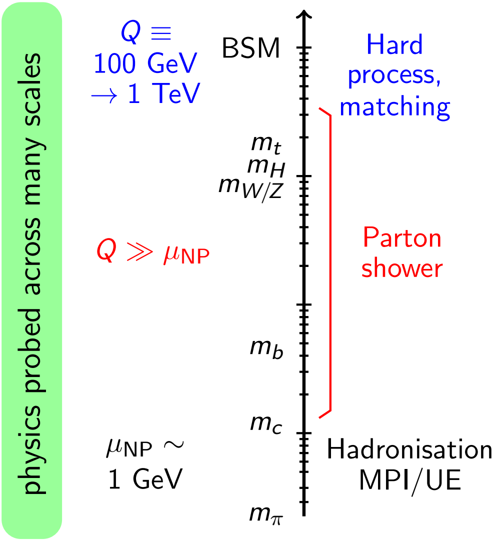
(double, single,...) logs to resum

accuracy means logarithmic

LL, NLL, N^{2}LL, ...

well-defined & systematically improvable

Basic message #2: physics at all scales



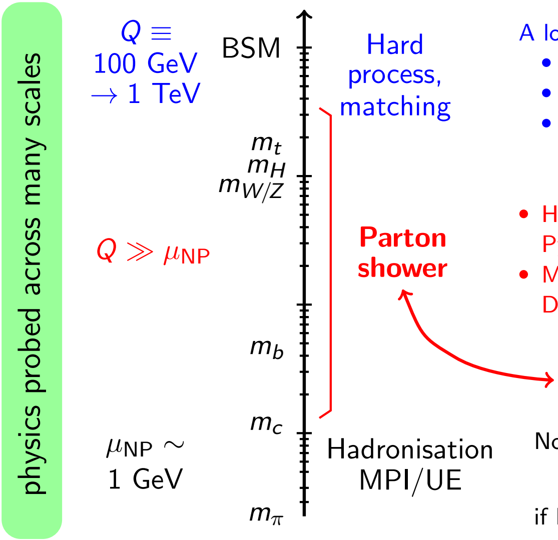
A lot of work in past 20 years:

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

- Historical showers: Pythia, Herwig, Sherpa
- More recent work: Dire, Vincia, Deductor, Alaric, **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 $\propto (\mu_{NP}/Q)^{\#}$ if IRC-safe

Simulate events using Monte-Carlo techniques

- All-purpose generators simulating a "full event"
  3 main tools: Pythia, Herwig, Sherpa

- more specific tools (e.g. fixed-order, parton shower)
  long list of tools: e.g. aMC@NLO, POWHEG, MiNLO, Dire, Deductor,...

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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, ...)

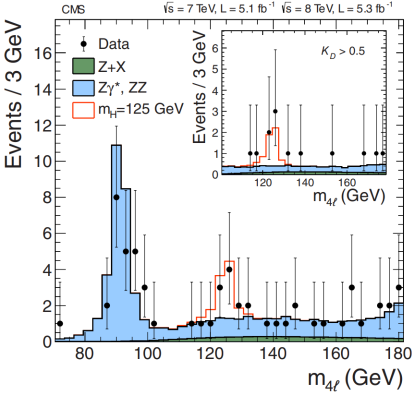
What do Event Generators provide?

Broad range of applications

Searches

Background (and signal) estimate

Example:
$H \to ZZ \to 4\ell$
[CMS, arXiv:1207.7235]



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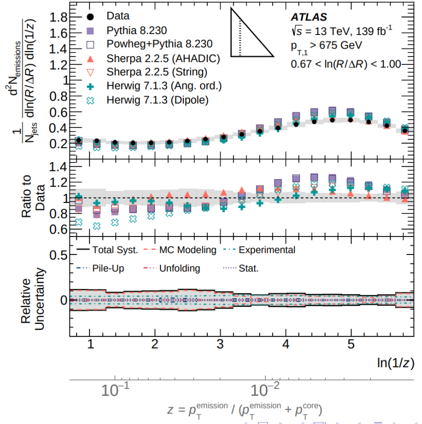
Measurements



[ATLAS, arXiv:2004.03540]

<u>Idea</u>: data v. MC

- allows the use of MC as modelling tool
- helps developing better MC

What do Event Generators provide?

Broad range of applications

Searches

Measurements & modelling

Tool to estimate uncertainties

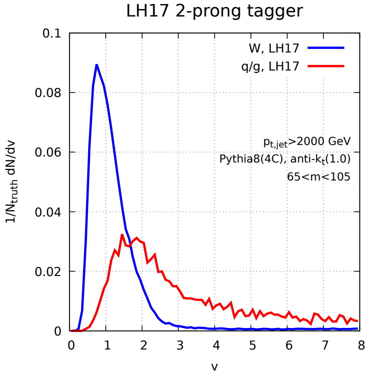
Example:
top mass measurement
[ATLAS-CONF-2019-046]

Source	Unc. on m_t [GeV]	Stat. precision [GeV]
Data statistics	0.40	
Signal and background model statistics	0.16	
Monte Carlo generator	0.04	±0.07
Parton shower and hadronisation	0.07	±0.07
Initial-state QCD radiation	0.17	±0.07
Parton shower α_S^{FSR}	0.09	±0.04
b-quark fragmentation	0.19	±0.02
HF-hadron production fractions	0.11	±0.01
HF-hadron decay modelling	0.39	±0.01
Underlying event	< 0.01	±0.02
Colour reconnection	< 0.01	±0.02
Choice of PDFs	0.06	±0.01
W/Z+jets modelling	0.17	±0.01
Single top modelling	0.01	±0.01
Fake lepton modelling ($t \to W \to \ell$)	0.06	±0.02
Soft muon fake modelling	0.15	±0.03
Jet energy scale	0.12	±0.02
Soft muon jet p_T calibration	< 0.01	±0.01
Jet energy resolution	0.07	±0.05
Jet vertex tagger	< 0.01	±0.01
b-tagging	0.10	±0.01
Leptons	0.12	±0.00
Missing transverse momentum modelling	0.15	±0.01
Pile-up	0.20	±0.05
Luminosity	< 0.01	±0.01
Total systematic uncertainty	0.67	±0.04
Total uncertainty	0.78	±0.03

What do Event Generators provide?

Broad range of applications

- Searches
- Measurements & modelling
- Pheno studies



Long list of applications:

- New tools & observables (incl. substructure)
- Comparison to analytics
- Comparison to data
- BSM models

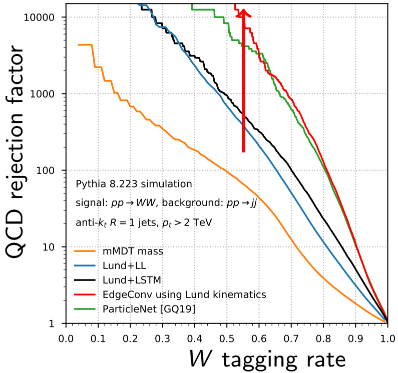
What do Event Generators provide?

Broad range of applications

Searches | Measurements & modelling | Pheno studies | Machine learning

- Deep Learing increasingly used at the LHC
- Training often done on MCs
- Shows interesting performance
- Example: boosted $W \to q\bar{q}$ v. QCD jet

[plot from Frederic Dreyer]



Need for precision

Basic message #3

Precision increasingly required for LHC physics (and future colliders)

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↓ Search for tiny deviations

↓ precise background estimates

↓ Amplitudes NNLO, ... (+resummations)

↓ deep learning picks all details

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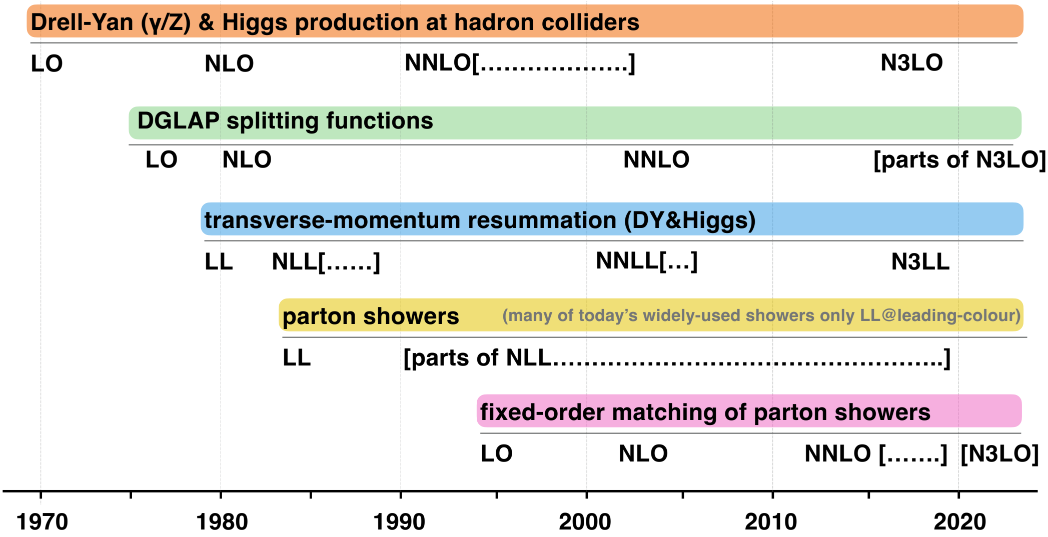
A key question in this talk: accuracy of parton showers?

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

selected collider-QCD accuracy milestones

[slide from Gavin Salam (Moriond QCD 2023)]



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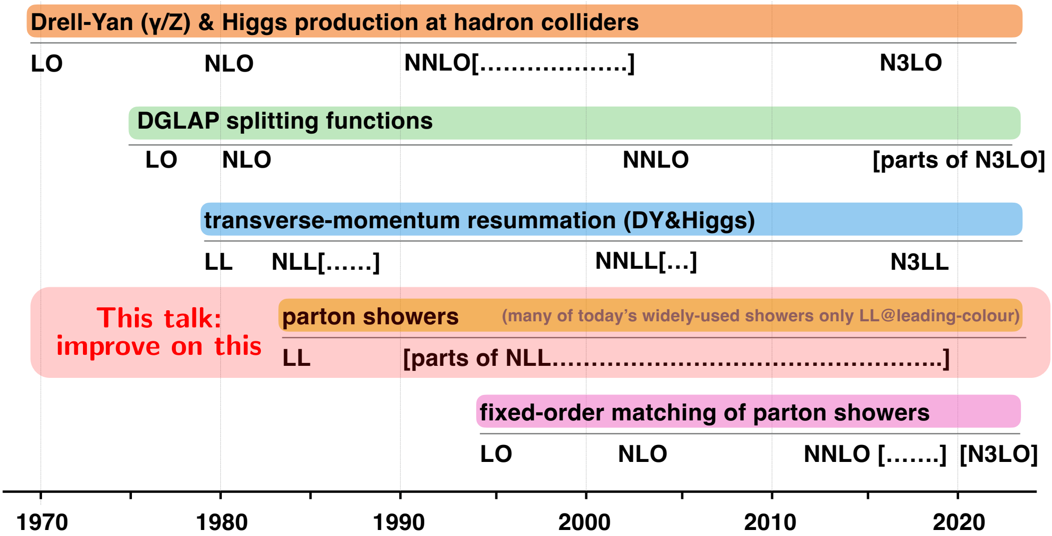

How do parton showers work?

Dipole/Antenna showers: ingredients

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

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Idea #1:

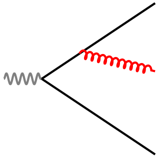
gluon emission ≡ dipole splitting

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

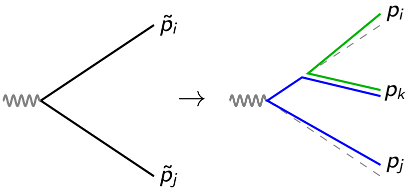
- captures the soft/collinear limits
- key ingredient: mapping

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

includes recoil
& energy-mom conservation



viewed as



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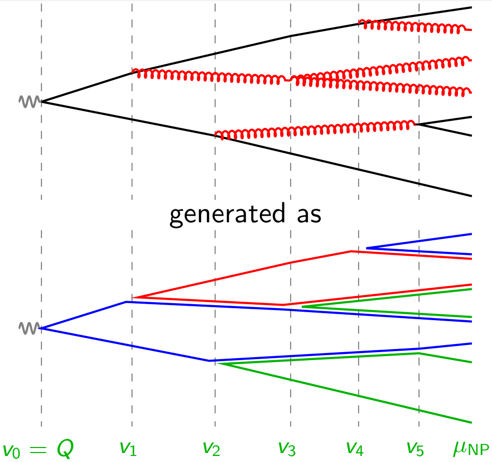

Idea #2:

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

Rooted in QCD factorisation

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

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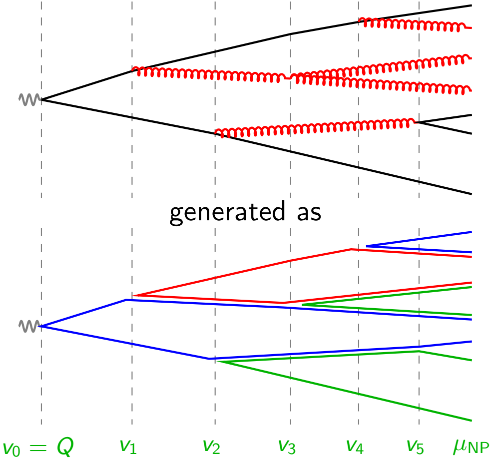

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- P_{n+1}, P_n: n, $n+1$ particles probabilities
- $e^{-\Delta_n(v_0,v)}$: Sudakov ≡"no emissions" (virtuals)
- $|M^2|(v)$: real emission

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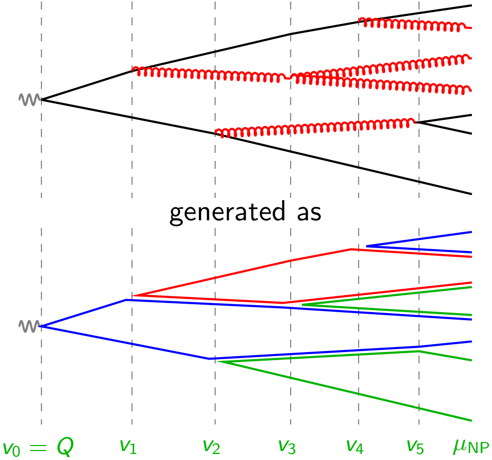

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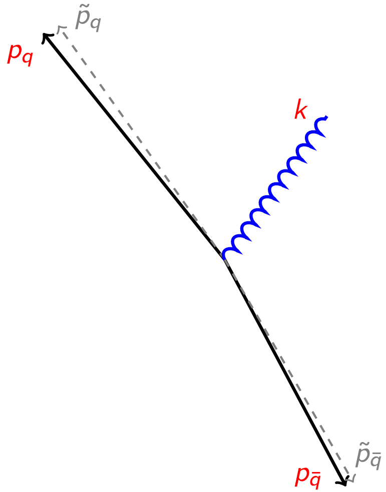
Several challenges:

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

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:

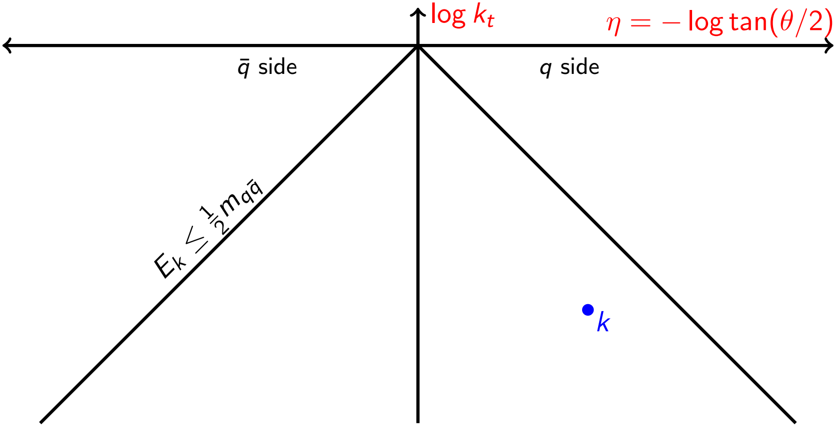
- Rapidity: $\eta = \frac{1}{2}\log\frac{z_q}{z_{\bar{q}}}$
- Transverse momentum: $k_\perp$
- Azimuth: ϕ

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 $\log k_\perp$



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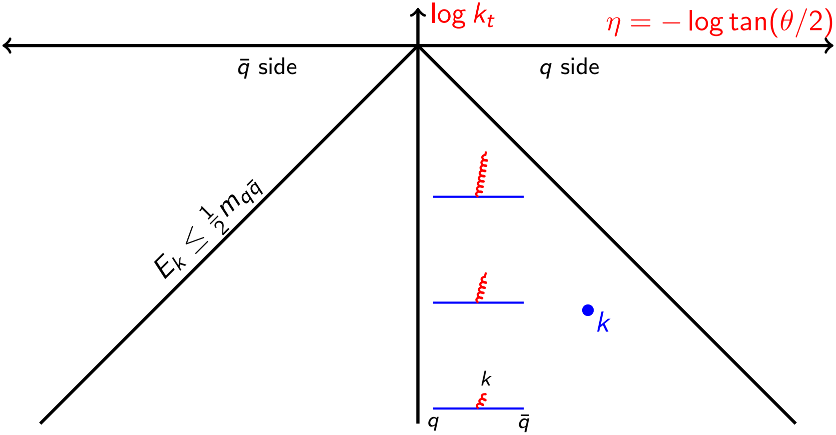

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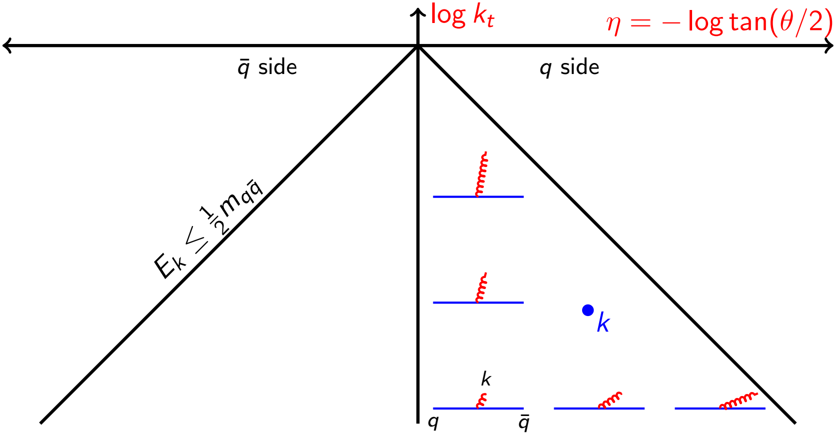

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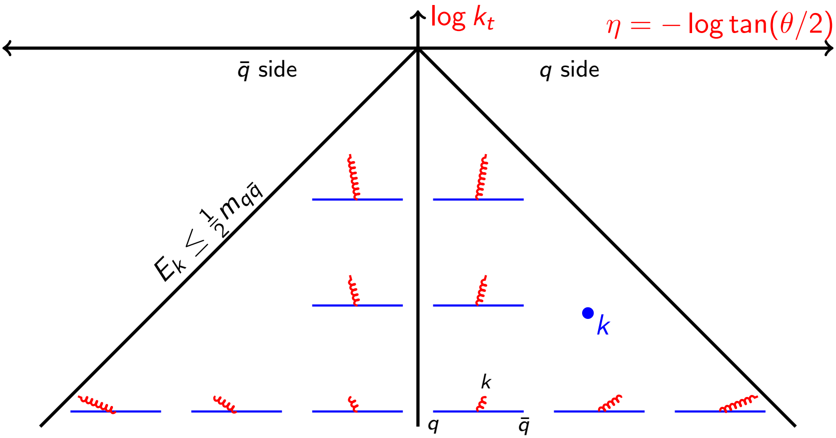

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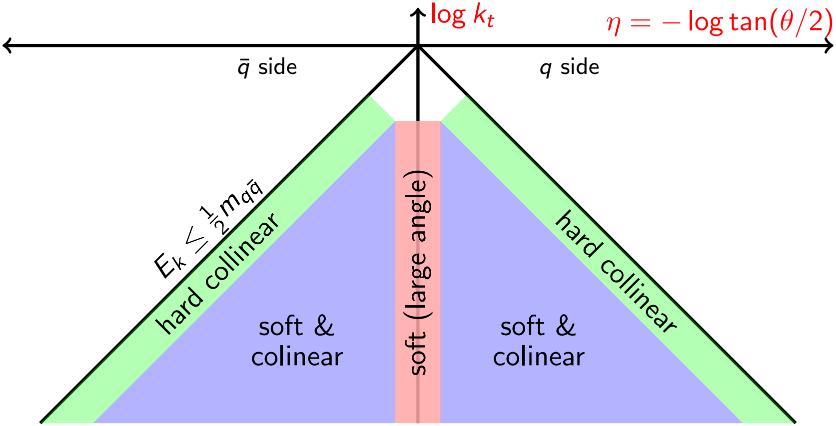
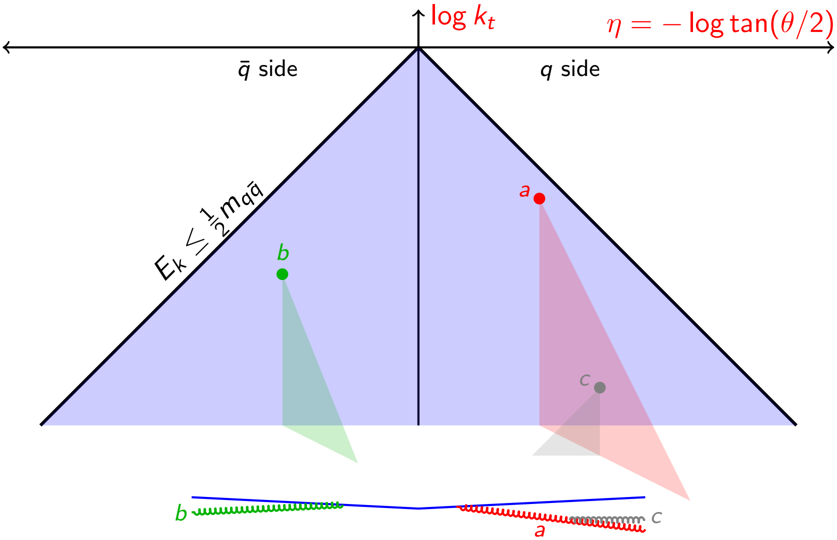
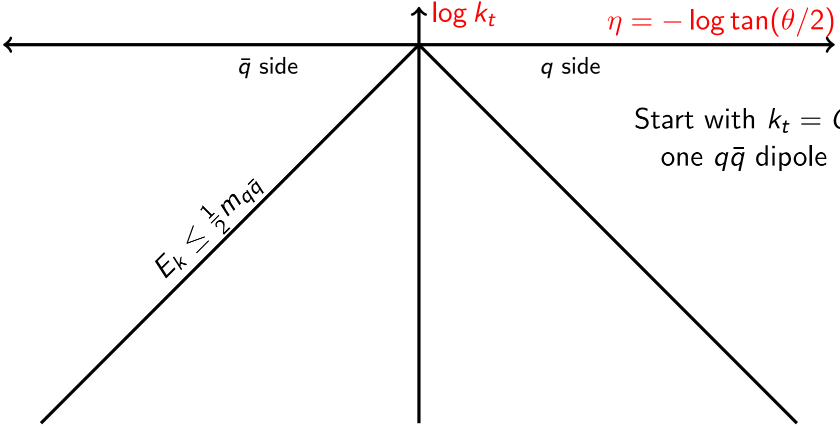


Multiple emissions in the Lund plane



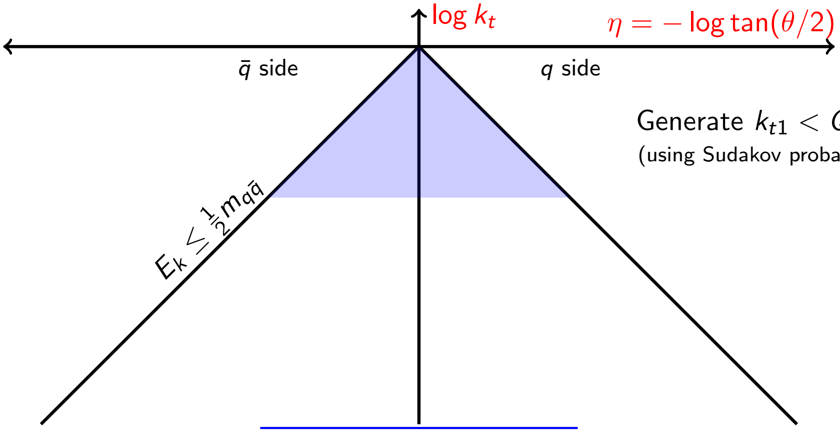
Ordering variable: transverse momentum k_t



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

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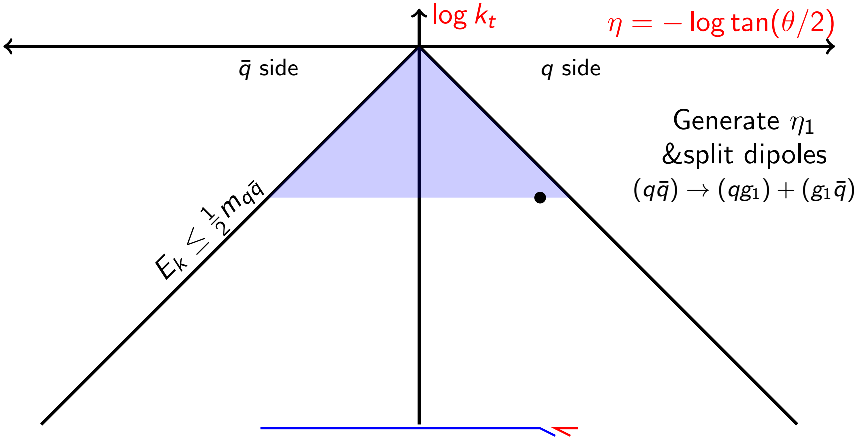

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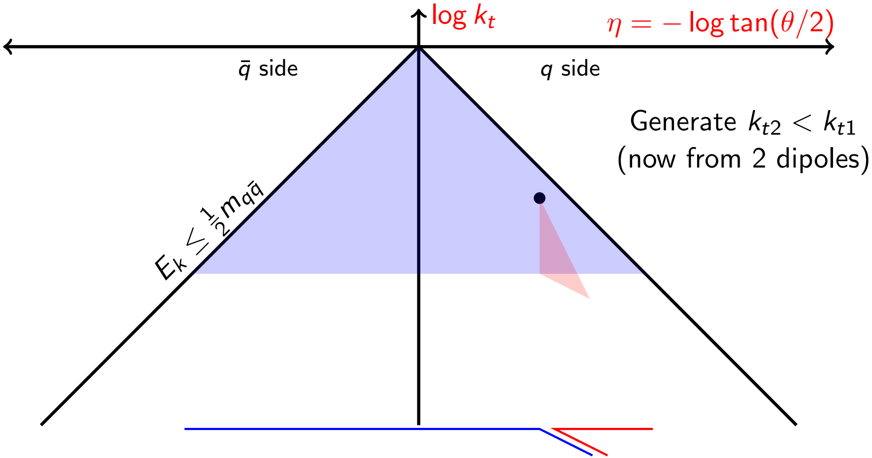

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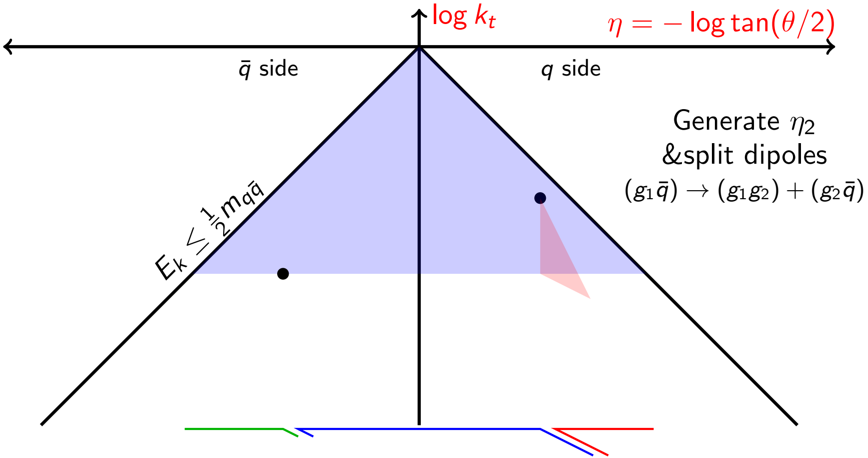

Parton shower in the Lund plane

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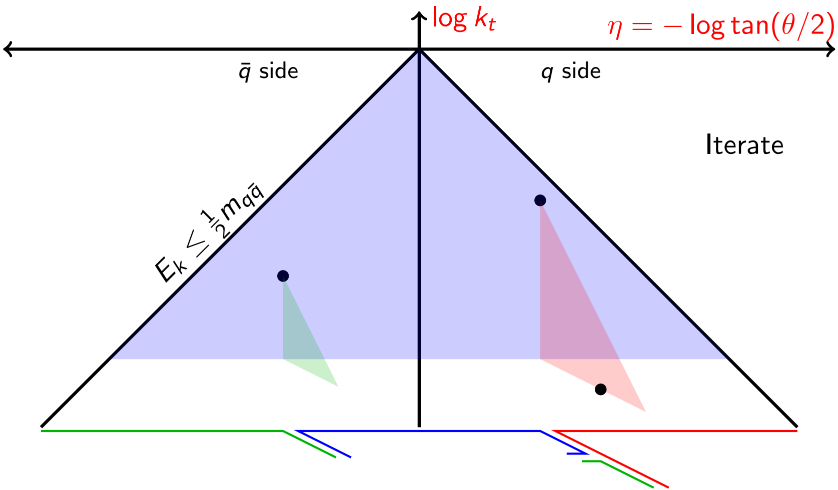

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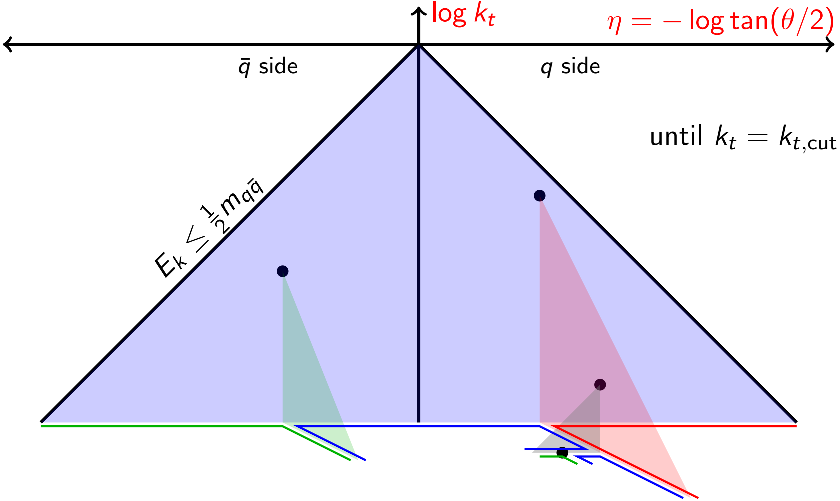
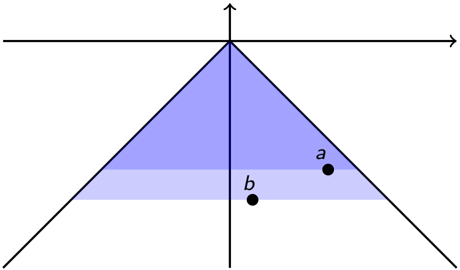


Different ordering variables...

... can lead to different emission orderings

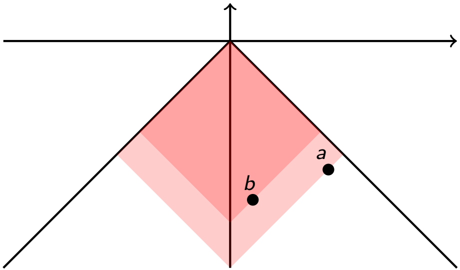
k_t (transv. mom.) ordering



$k_{ta} > k_{tb}$

$\Rightarrow$ a emitted before b

q (virtuality) ordering



$q_b > q_s$

$\Rightarrow$ b emitted before a

Recent progress (for completeness)

Lots of progress in several key directions over the past years:

- (subleading) $1 \to 3$ splitting functions (example: Dire(v2)).
  See e.g. [Jadach *et al*,16], [Li,Skands,16], [Höche,Krauss,Prestel,17], [Höche,Prestel,17]
- Subleading colour
  - most showers are leading colour (even at leading-log)
  - complex soft-gluon patterns
  - see e.g. [Nagy,Soper,12], [Gieseke,Kirchgaesser,Plätzer,Siodmock,18], [Höche,Reichelt,20], [Forshaw,Holguin,Plätzer,20]
- Amplitude-level showers, see e.g. [Forshaw,Holguin,Plätzer,19]
- Electroweak showers
  - more involved splitting kernels than in QCD
  - explicit chirality/spin depenence
  - see e.g. [Kleiss,Verheyen,20], [Bauer,Ferland,Webber,17-18], [Bauer,DeJong,Nachman,Provasoli,19]

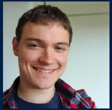
PanScales

[slide from Alba Soto and Gavin Salam]

Oxford


Melissa van Beekveld


Jack Helliwell


Rok Medves


Frederic Dreyer


GPS


Ludo Scyboz

UCL


Keith Hamilton


Rob Verheyen

Manchester


Basem El-Menoufi

CERN


Mrinal Dasgupta


Gregory Soyez


Pier Monni


Alexander Karlberg


Alba Soto Ontoso


Silvia Ferrario Ravasio

PanScales

A project to bring logarithmic understanding and accuracy to parton showers

PanScales

Assessing accuracy?

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,arXiv:1805.09327]
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,arXiv:2002:11114]

Testing the shower logarithmic accuracy

(Cumulative) distributions can (often) be written as

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

Examples:

- Thrust $\quad T = \max_{|\vec{u}|=1} \frac{\sum_i |\vec{p}_i \cdot \vec{u}|}{\sum_i |\vec{p}_i|}$
- Cambridge y_{23} ($\approx$ largest k_t in an angular-ordered clustering)
- angularities
- ...

Note: substructure techniques (e.g. Lund-plane based) can help design more observables

Testing the shower logarithmic accuracy

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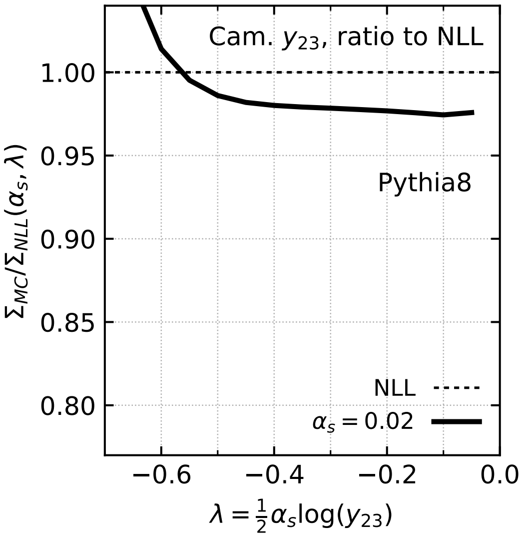
$\mathcal{O}(1/\alpha_s)$ $\mathcal{O}(1)$ $\mathcal{O}(\alpha_s)$

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

Novel approach for 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?

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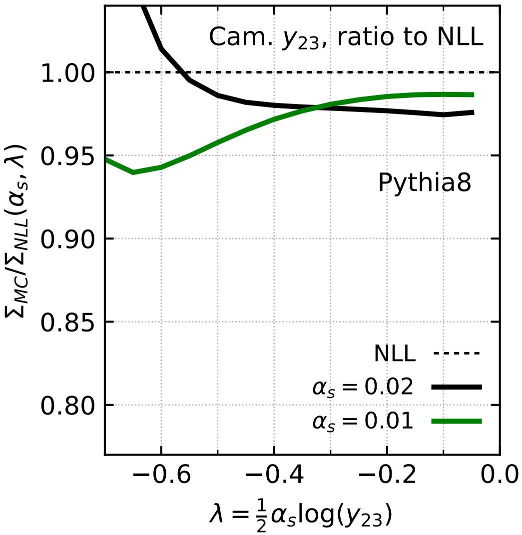

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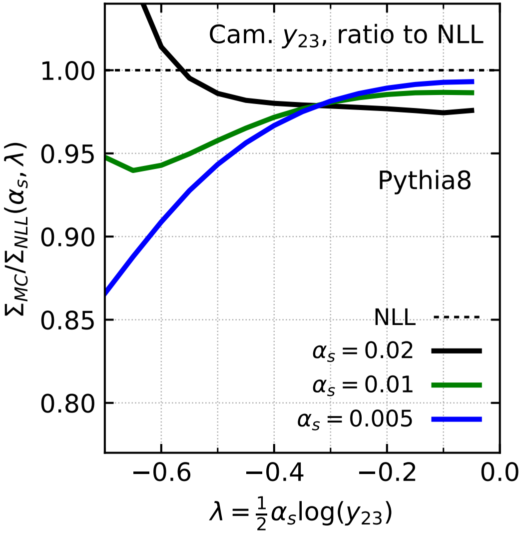

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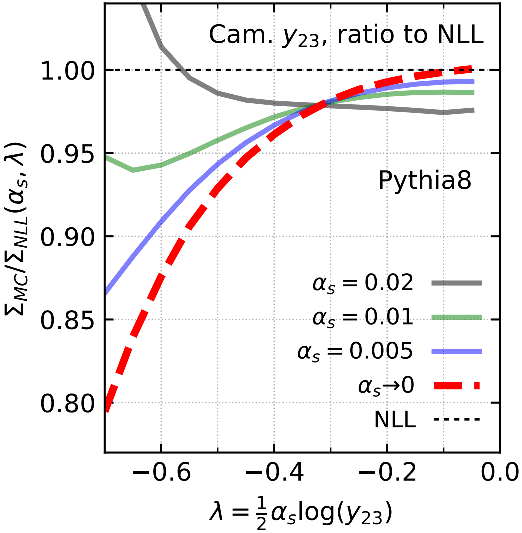

Idea for testing:

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

at fixed $\lambda = \alpha_s L$

NLL deviations

or

~~subleading effects?~~

PanScales

Key building principles?

Towards NLL: addressing recoil

[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,arXiv:1805.09327]

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

Fundamental principles to target NLL 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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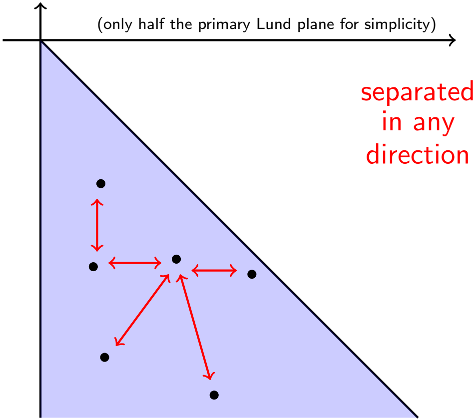
Correct matrix elements for N well separated emissions in the Lund plane



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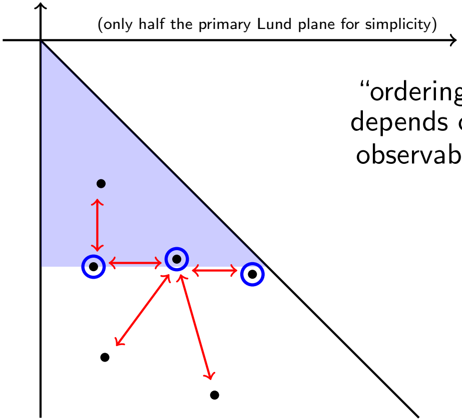

“ordering” depends on observable

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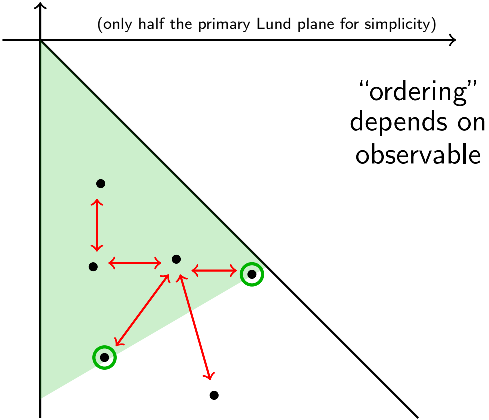

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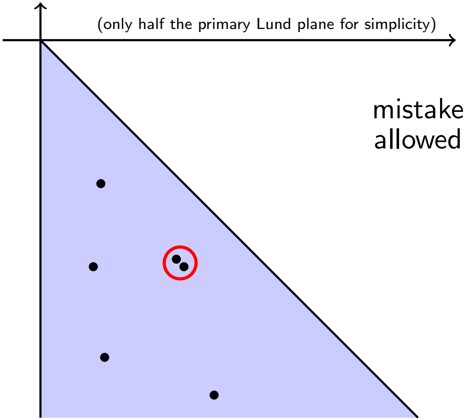
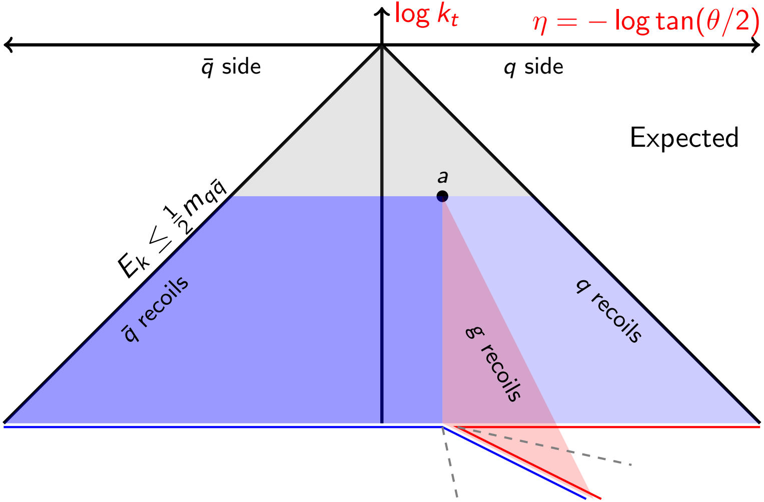


Lund-plane representation: transverse recoil boundaries



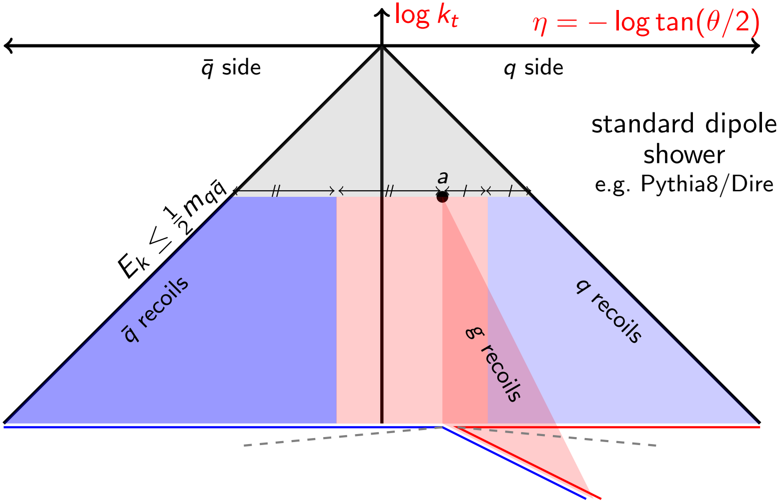
gluon a radiated at scale k_{ta} and angle θ_a

gluon b radiated at scale $k_{tb} \leq k_{ta}$

Expected

a takes recoil iff $\theta_{ab} < \theta_a$

Lund-plane representation: transverse recoil boundaries



gluon a radiated at scale k_{ta} and angle θ_a

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Expected

a takes recoil iff $\theta_{ab} < \theta_a$

standard dipole shower

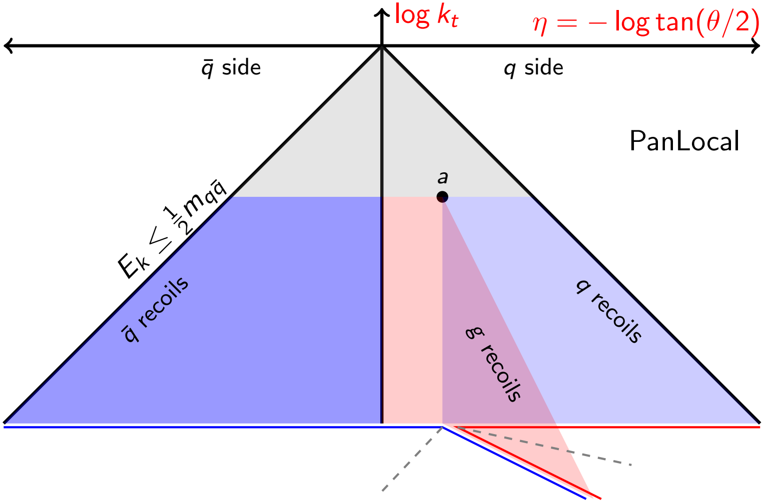
decided in dipole frame:

a takes recoil if

$$\theta_{bg}^{(\text{dip})} < \theta_{bq}^{(\text{dip})}$$

WRONG!

Lund-plane representation: transverse recoil boundaries



gluon a radiated at scale k_{ta} and angle θ_a

gluon b radiated at scale $k_{tb} \leq k_{ta}$

Expected

a takes recoil iff $\theta_{ab} < \theta_a$

PanLocal (step 1)

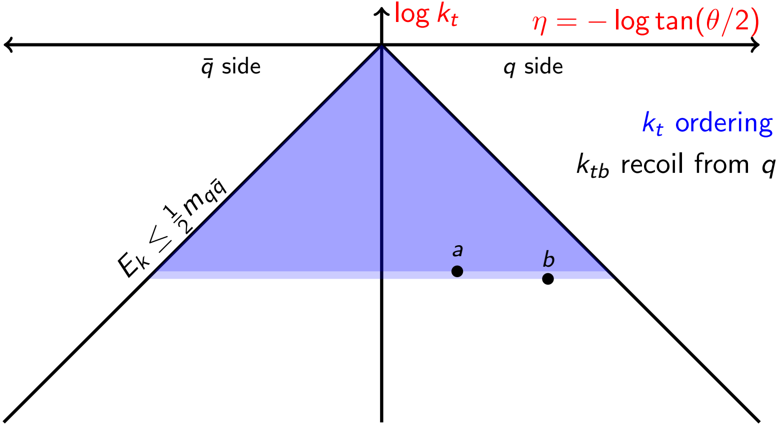
decided in event frame:

a takes recoil if

$$\theta_{bg} < \theta_{bq}$$

better but still WRONG!

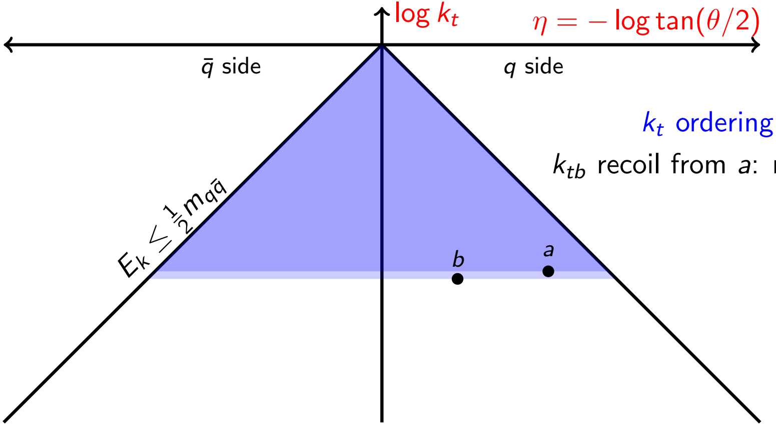
Lund-plane representation: PanLocal evolution variable



k_t ordering

k_{tb} recoil from q: OK

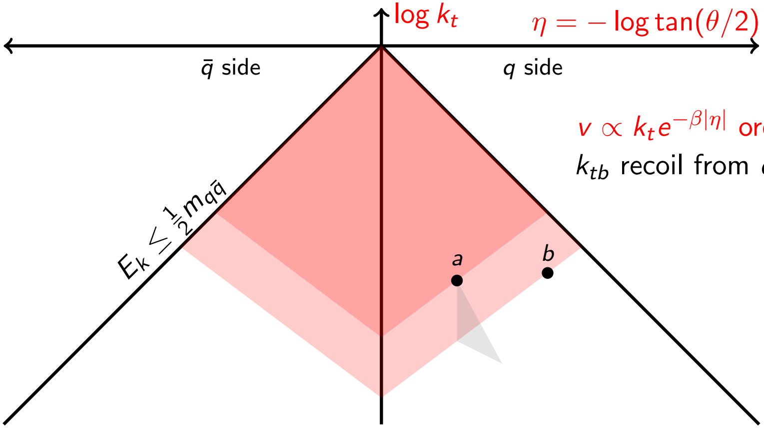
Lund-plane representation: PanLocal evolution variable



k_t ordering

k_{tb} recoil from a: not OK

Lund-plane representation: PanLocal evolution variable



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

k_{tb} recoil from q: OK

commensurate k_t emissions generated from central to forward rapidities

$\Rightarrow$ no recoil issue

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

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

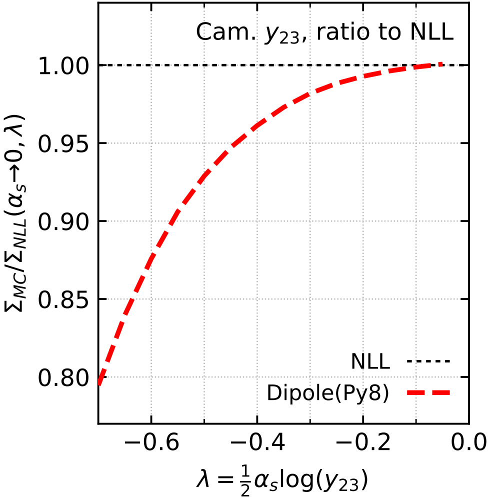
Assessing accuracy: y_{23}

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

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

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

× Pythia8 deviates from NLL



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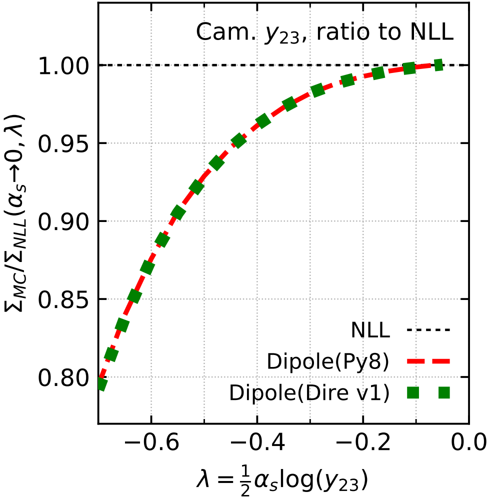

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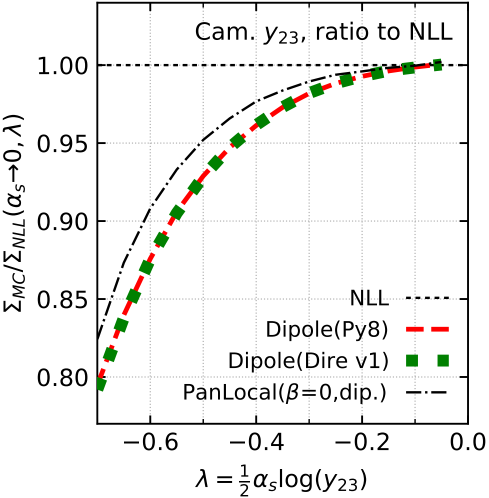
Study $$\frac{\Sigma_{MC}(\lambda=\alpha_s L,\alpha_s)}{\Sigma_{NLL}(\lambda=\alpha_s L,\alpha_s)} \text{ for } \alpha_s \to 0.$$

- × Pythia8 deviates from NLL
- × Dire(v1) same as Pythia8
- × PanLocal($\beta = 0$) still deviates
  (issue of k_t ordering remains)



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× Pythia8 deviates from NLL

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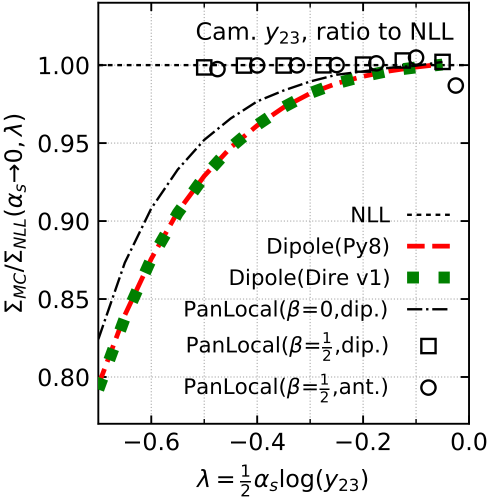
✓ PanLocal($0 < \beta < 1$) OK
(issue of k_t ordering disappears)



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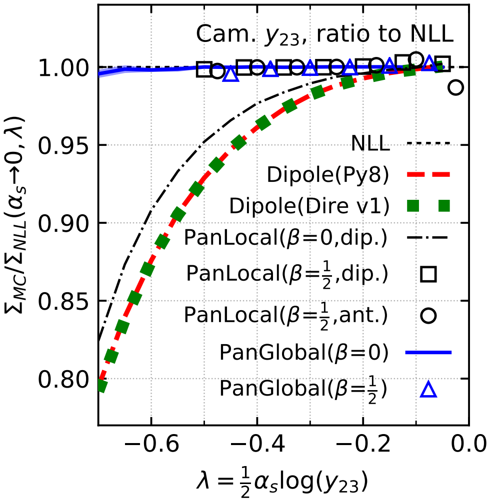
Example: C/A $y_{23} \equiv \max_i k_{ti}$

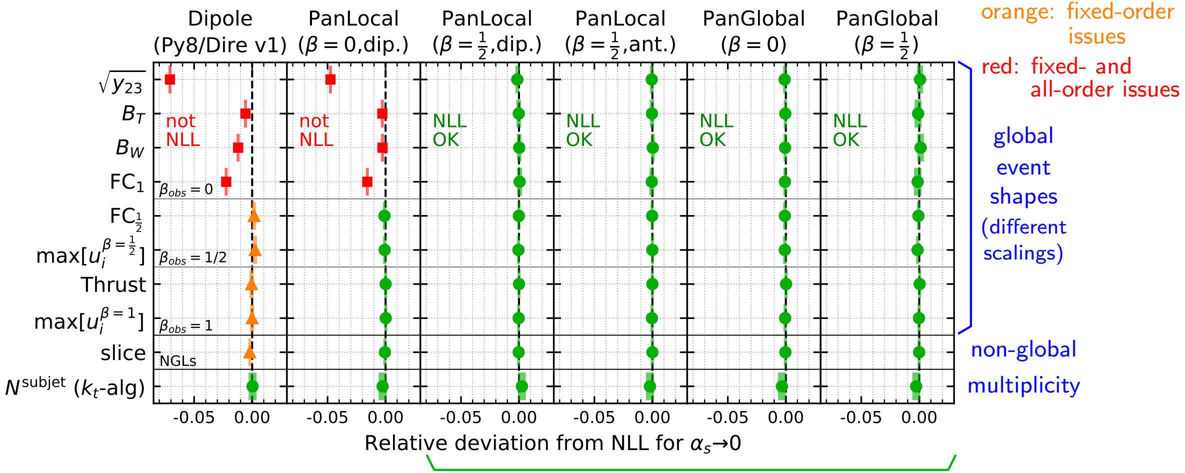
Study $\dfrac{\Sigma_{MC}(\lambda=\alpha_s L,\alpha_s)}{\Sigma_{NLL}(\lambda=\alpha_s L,\alpha_s)}$ for $\alpha_s \to 0$.

- × 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 disappears)
- ✓ PanGlobal($0 \leq \beta < 1$) OK
  (global recoil allows also for $\beta = 0$)



Assessing accuracy: extensive observable list

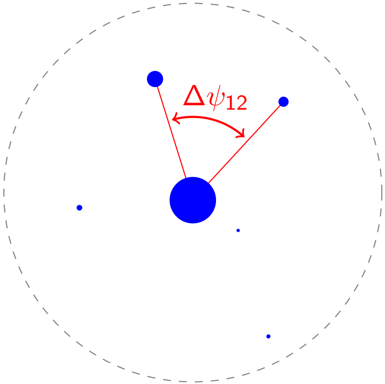
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]



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

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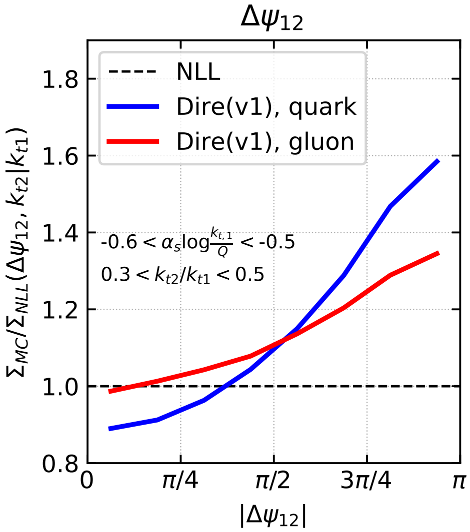
- quite large NLL deviations in current dipole showers
- differences between quark and gluon jets



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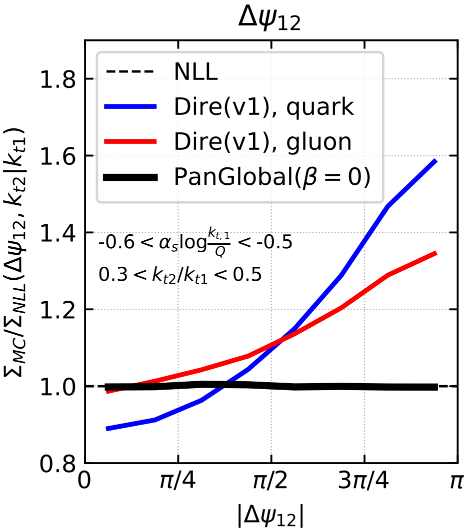

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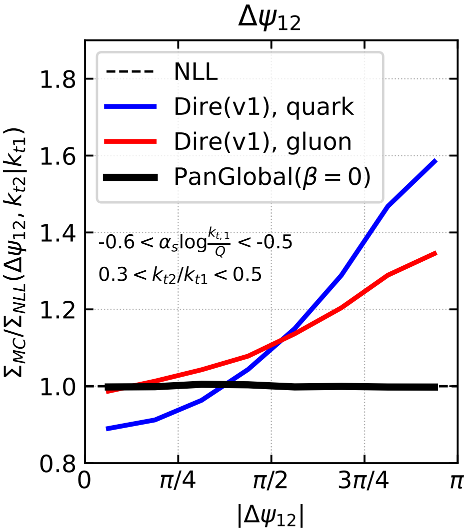
- quite large NLL deviations in current dipole showers
- differences between quark and gluon jets
- PanScales showers (here PanGlobal) get the correct NLL
- ML could "wrongly/correctly" learn this



Summary up to this point

Take-home messages

- Novel method to test parton shower accuracy (i.e. logarithmic accuracy)
- Standard showers (like Pythia8 or Dire) fail to deliver NLL accuracy (spurious k_t recoil)
- Two new showers: PanLocal and PanGlobal with NLL accuracy
- So far: large-N_c, no spin correlations, e^+e^- collisions

PanScales

Towards full NLL

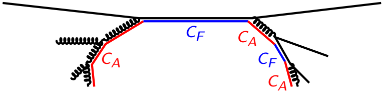
[K.Hamilton,R.Medves,G.Salam,L.Scyboz,GS,arXiv:2011.10054]
[K.Hamilton.A.Karlberg,G.Salam,L.Scyboz,R.Verheyen,arXiv:2103.16526]
[K.Hamilton.A.Karlberg,G.Salam,L.Scyboz,R.Verheyen,arXiv:2111.01161]
[M.van Beekveld,S.Ferrario Ravasio,G.Salam,A.Soto-Ontoso,GS,arXiv:2205.02237]
[M.van Beekveld,S.Ferrario Ravasio,K.Hamilton,G.Salam,A.Soto-Ontoso,GS,arXiv:2207.09467]

Note: quick overview to get the overall picture, ask for more details if you want

Beyond large N_c

Physics:

Keep track of the C_F–$C_A/2$ transitions



First generate assuming $C_A(/2)$, then correct in one of 2 ways:

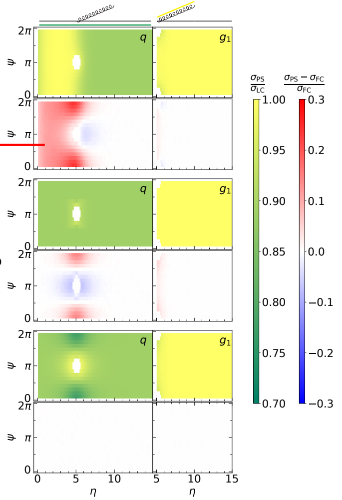
1. segment
   factor $2C_F/C_A$ if in quark segment
   OK in the angular-ordered limit
2. NODS
   (soft) $q\bar{q}g$ matrix-element correction
   also OK for 2 emissions at $\sim$ angles

Fixed-order tests:

as in pythia

WRONG
similar to
recoi earlier

perform as
expected



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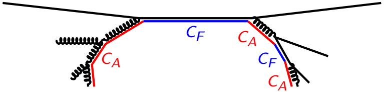

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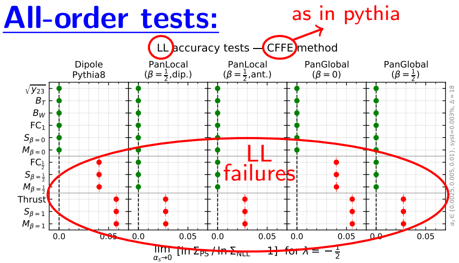
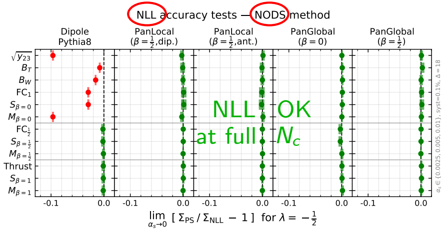
All-order tests:





Non-global logs: large-N_c + (full-N_c at $\mathcal{O}(\alpha_s^2)$)

(Collinear) spin correlations

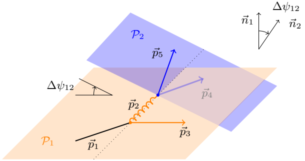
Beyond large N_c

(collinear & soft) spin correlations

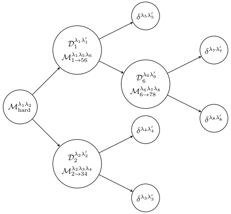
hadronic collisions

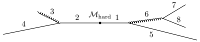
Physics:

$\Delta\psi$ distribution due to spin correlations



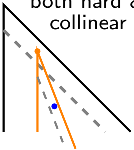
Solution: adapt the Collins-Knowles alg.



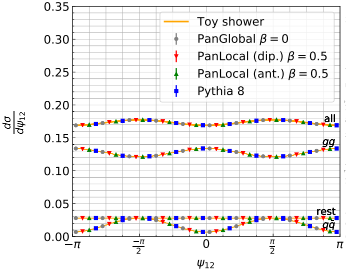


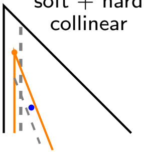
build and update a spin correlation tree as shower progresses

Tests:

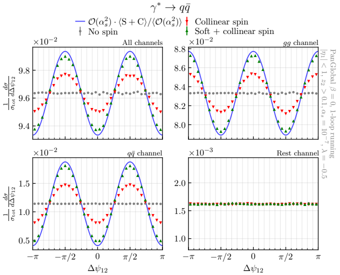


also EEEC v. analytics





first all-order result



Beyond large N_c

(collinear & soft) spin correlations

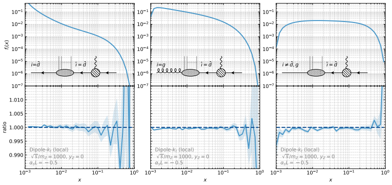
hadronic collisions

Physics:

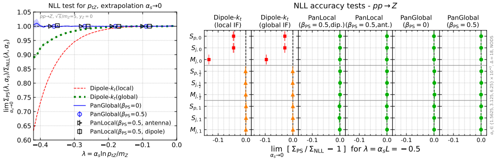
- hadron collision
  $\Rightarrow$ initial-state radiation
- Consider Drell-Yan
- existing showers have the same recoil issue as for final state
  earlier emission takes recoil instead of the Z
- fix is essentially the same
  (modulo kinematic differences)
- includes colour and spin
- so far limited to colour singlet production

Tests:

explicit test of DGLAP



+ usual tests: Z-boson p_t, event shapes



+ multiplicity, non-globals, beyond large-N_c, spin

PanScales

Beyond NLL: matching

[K.Hamilton.A.Karlberg,G.Salam,L.Scyboz,R.Verheyen,arXiv:2301.09645]

Matching within PanScales

Matching = exact fixed-order generator + parton shower resumming logs

Physics

Focus on e^+e^- collisions. We want

✓ exact $q\bar{q}g$ ($\mathcal{O}(\alpha_s)$) distributions

✓ maintain NLL accuracy

Benefit: "NNDL" accuracy for event shapes$^{(*)}$

$$\Sigma(L) = \underbrace{h_1(\alpha_S L^2)}_{\text{DL}} + \underbrace{\sqrt{\alpha_s} h_2(\alpha_s L^2)}_{\text{NDL}} + \underbrace{\alpha_s h_3(\alpha_s L^2)}_{\text{NNDL}} + \dots$$

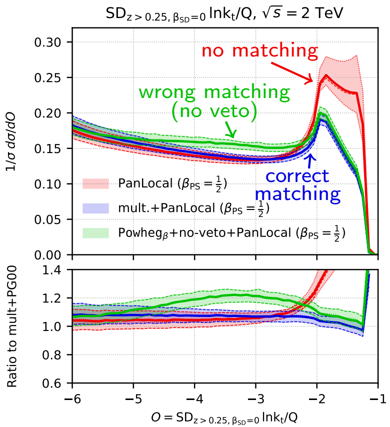
Implementation

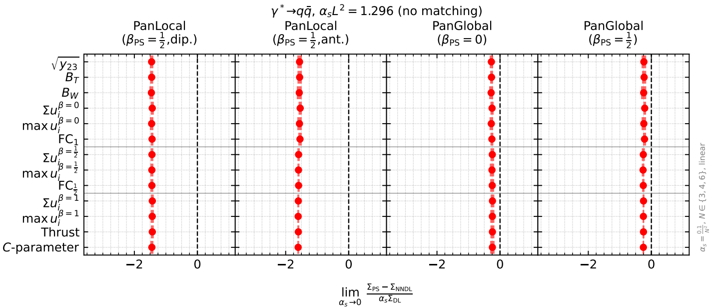
Several possibilities:

- simple multiplicative matching (accept first emission with probability $P_{\text{exact}}/P_{\text{shower}}$)
- MC@NLO-like matching
- POWHEG-like matching (with β scaling and careful veto to avoid double-counting when switching from POWHEG to the shower)

$^{(*)}$ Note: N^{k}LL expands $\ln \Sigma(\alpha_s L, \alpha_S)$ for "exponentiating" observables; N^{k}DL directly expands $\Sigma(\alpha_s L^2, \alpha_s)$
alternative viewpoint: NLL requires an arbitrary number of single-logs ($(\alpha_s L)^n$); NDL requires only one ($(\alpha_s L)(\alpha_s L^2)^n$)

Accuracy tests

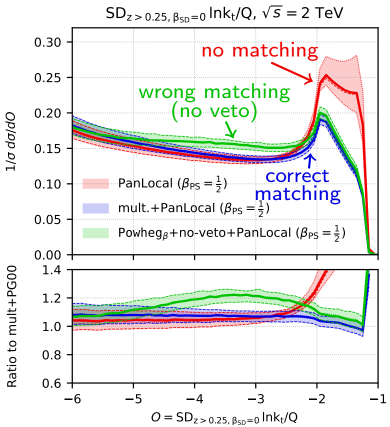


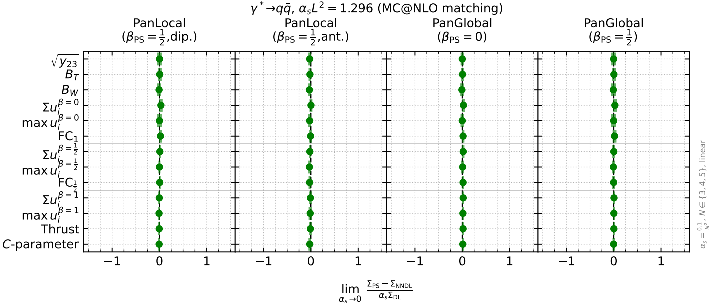


- no matching $\Rightarrow$ wrong NNDL

- visible effect at large k_t (right)
- spurious effect if not careful
- "correct" matching OK everywhere

Accuracy tests





- visible effect at large k_t (right)
- spurious effect if not careful
- "correct" matching OK everywhere

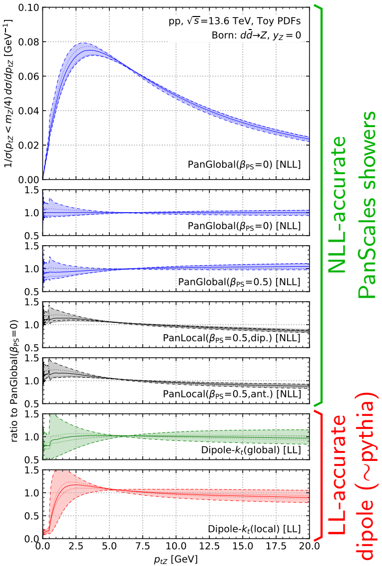
- no matching ⇒ wrong NNDL
- with matching ⇒ OK at NNDL

PanScales

Preliminary phenomenology

[M.van Beekveld,S.Ferrario Ravasio,K.Hamilton,G.Salam,A.Soto-Ontoso,GS,arXiv:2207.09467]
[K.Hamilton.A.Karlberg,G.Salam,L.Scyboz,R.Verheyen,arXiv:2301.09645]
+ preliminary

Example #1: Z-boson transverse momentum



Uncertainties:

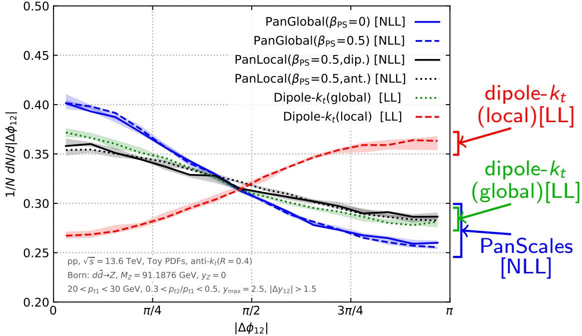
- renormalisation scale variation:
  for NLL-accurate showers include compensation term to maintain 2-loop running for soft emissions
- factorisation scale variations (note: use of toy PDFs)
- term associated with lack of matching for $k_t \sim M_Z$
- for LL showers: a term associated with spurious recoil for commensurate k_t's

Observations: Differences are relatively small except

- at very small k_t for dipole-k_t (esp. w global recoil)
- NLL brings significant uncertainty reduction

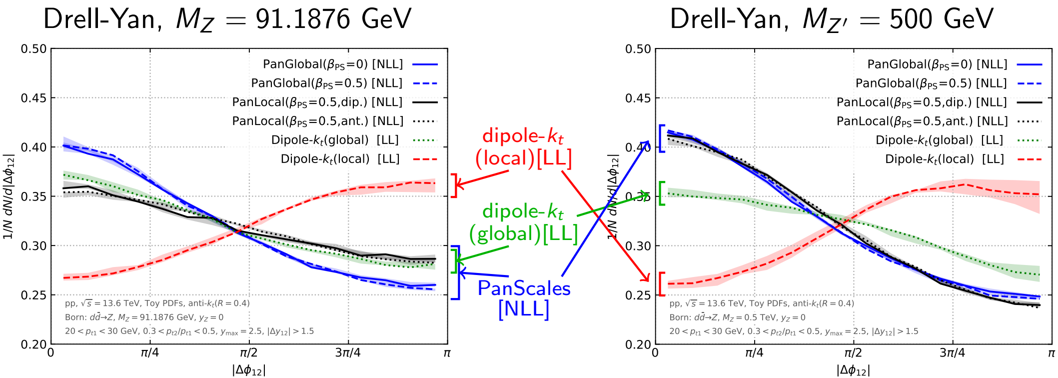
Example #2: $\Delta\psi_{12}$

Drell-Yan, $M_Z = 91.1876$ GeV



- Dipole-k_t with global recoil (LL) quite off
- All others [local dipole-k_t(LL) and PanScales(NLL)] similar

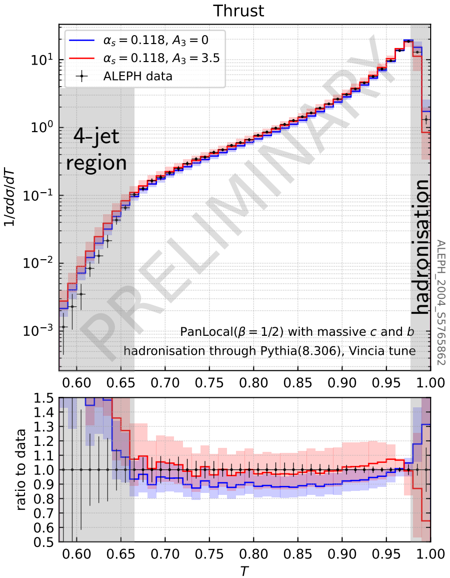
Example #2: $\Delta\psi_{12}$



- Dipole-k_t with global recoil (LL) quite off
- All others [local dipole-k_t(LL) and PanScales(NLL)] similar

- At higher scale: dipole-k_t(LL) $\neq$ PanScales(NLL)
- DANGER: false sense of control from lower-energy info!

Example #3: towards LEP phenomenology



Details:

- PanLocal($\beta = 1/2$) dipole shower
- heavy quarks (preliminary, $m_c = 1.5$ GeV, $m_b = 4.8$ GeV)
- multiplicative matching
- extra A_3 ($\alpha_s \equiv \alpha_s^{(CMW)} + A_3\alpha_s^3$)
- interfaced as a Pythia8 plugin
- hadronisation from Pythia8 (Vincia tune)

Observations:

- Promising start
- further tuning needed
- 4-jet matching would greatly help
- what about NNLL?

Conclusions

Basics

Parton showers are extensively relied upon and need to be brought to high accuracy

PanScales

- Recoil issue limits standard generators to LL (and large N_c)
- Fixed in our PanScales (PanLocal($0 < \beta < 1$) and PanGlobal($0 \leq \beta < 1$)) showers
- Including beyond large-N_c, spin correlations, hadronic collisions, (ee) 3-jet matching
- Pheno effect mostly reduction of uncertainty at $Q \sim 100$ GeV, can be larger at $Q \sim 1$ TeV

Future

- Beyond Drell-Yan (pp) and 3 jets (ee)
- Investigate phenomenology
- provide public code
- push to NNLL