PanScales: the quest for precision across scales

Gregory Soyez

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

arXiv:2011.10054 K. Hamilton, R.Medves, G. Salam, L. Scyboz, GS

arXiv:2103.16526 A.Karlberg, G.Salam, L.Scyboz, R.Verheyen

arXiv:2111.01161 K.Hamilton, A.Karlberg, G.Salam, L.Scyboz, R.Verheyen

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

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Plan

Importance of event generators and parton showers

- Motivate the importance of event generators and parton showers
- Basics of parton showers
  - How parton showers are built
  - parton shower accuracy
- The PanScales showers
  - Solving current issues
  - Reaching NLL accuracy
- (A brief look into) bringing more elements in the PanScales showers
  - beyond leading-N_c
  - Spin correlations
  - hadronic collisions

Importance of Event Generators

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, Vincia, Dire, ...

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Main advantage: versatility

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

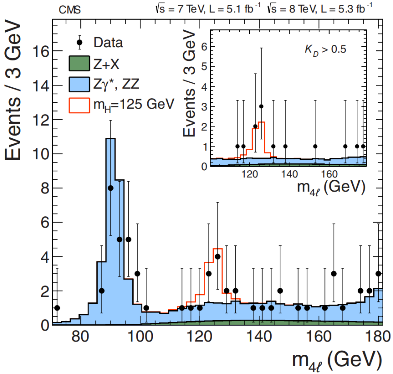
What do Event Generators provide?

Broad range of applications

Searches

Background (and signal) estimate

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



What do Event Generators provide?

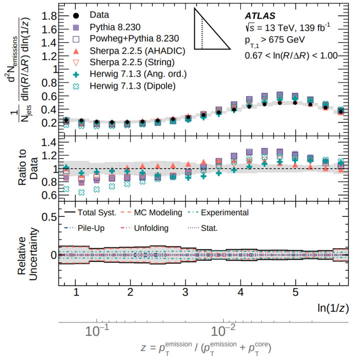
Broad range of applications

Searches

Measurements

Idea: data v. MC

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



[ATLAS, arXiv:2004.03540]

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

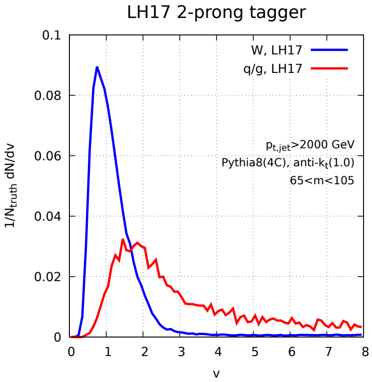
What do Event Generators provide?

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

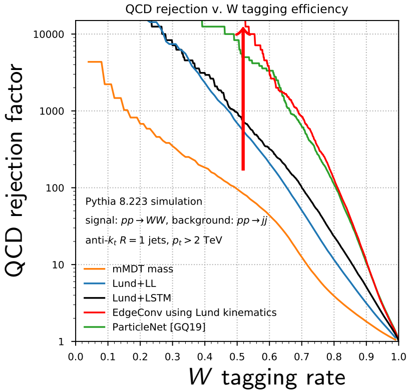
What do Event Generators provide?

Broad range of applications

- Searches
- Measurements & modelling
- Pheno studies
- Machine learning

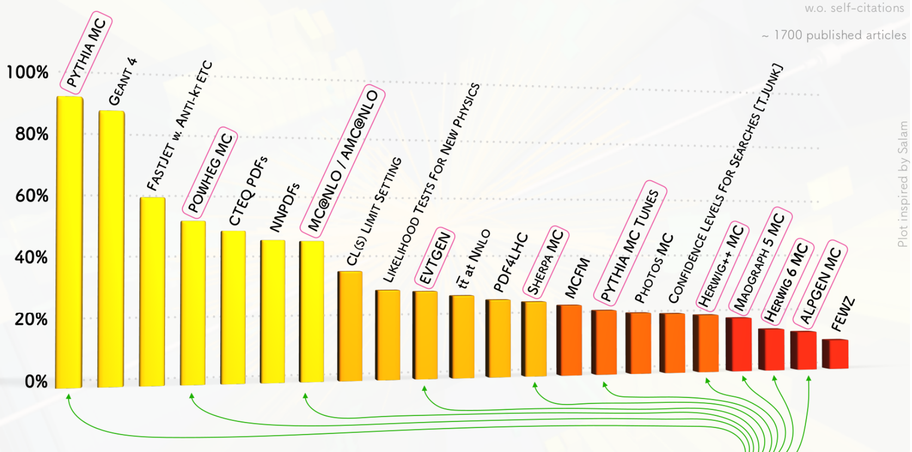
- Deep Learing increasingly used at the LHC
- Shows interesting performance
- Example: boosted $W \to q\bar{q}$ v. QCD jet
- Training often done on MCs.

[plot from Frederic Dreyer]



Event Generators are among us!

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

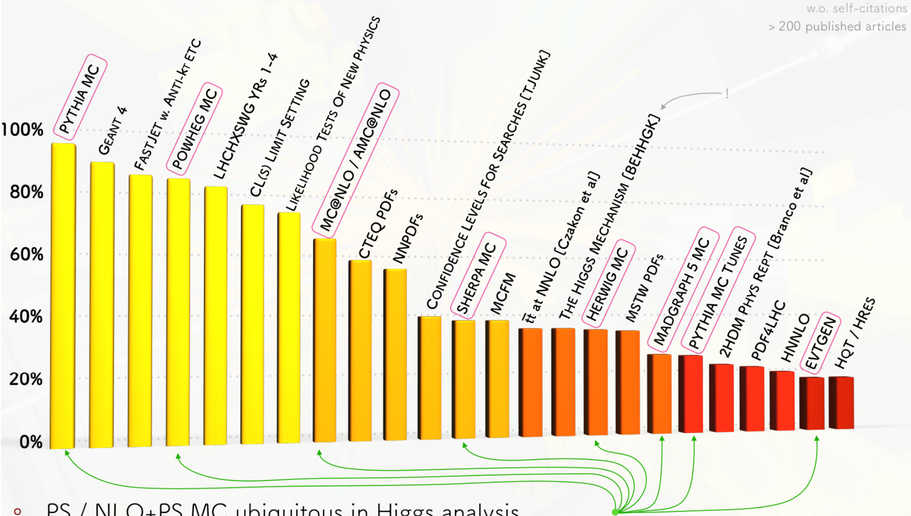


- PS MC is a central, everyday, part of the LHC physics programme

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

Event Generators are among us!

- % of ATLAS+CMS+LHCb papers citing an article/group in Jan '14 → Oct '19



- PS / NLO+PS MC ubiquitous in Higgs analysis

[thanks to Keith Hamilton]

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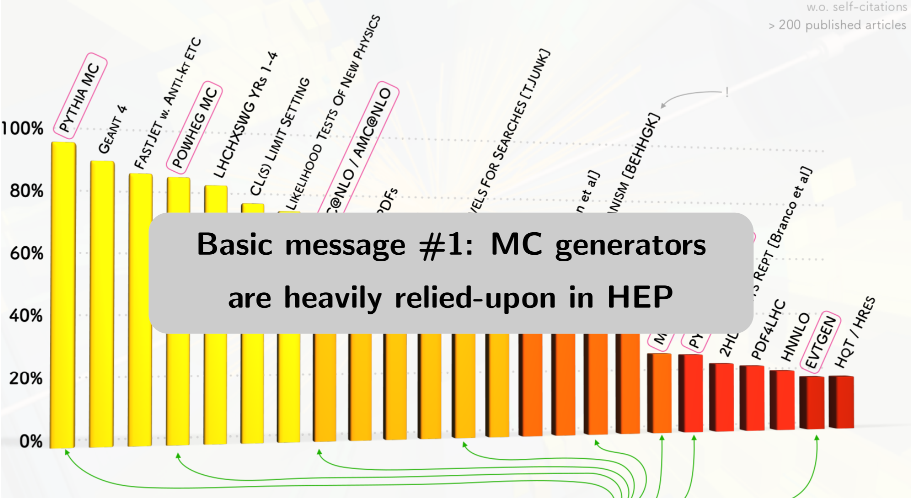
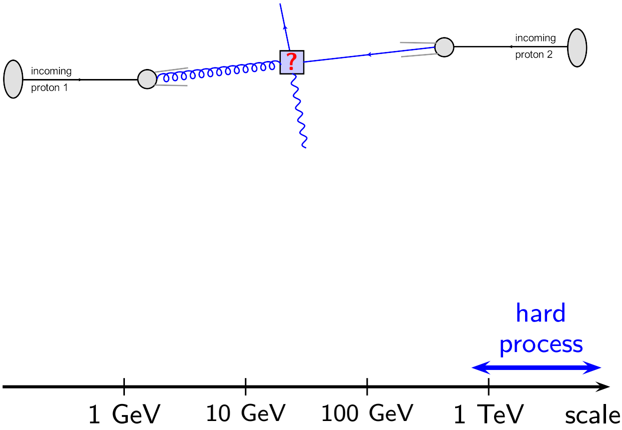


Basic message #1: MC generators are heavily relied-upon in HEP

- PS / NLO+PS MC ubiquitous in Higgs analysis

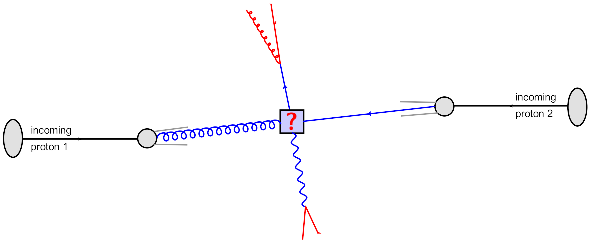
[thanks to Keith Hamilton]



Simulating a high-energy collision requires several ingredients

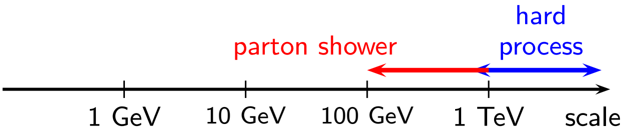
- A hard process

Anatomy of a high-energy collision



Simulating a high-energy collision requires several ingredients

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



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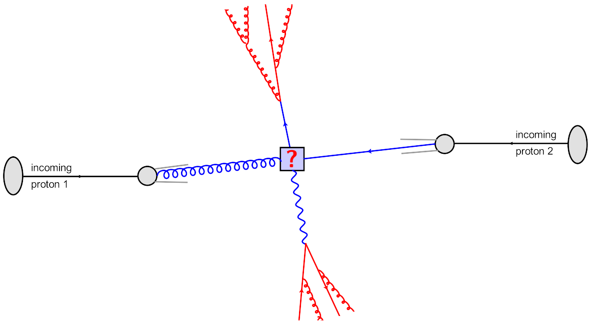

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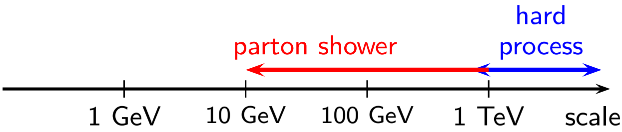
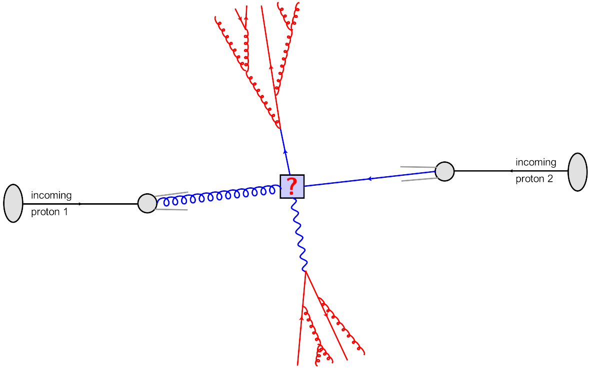
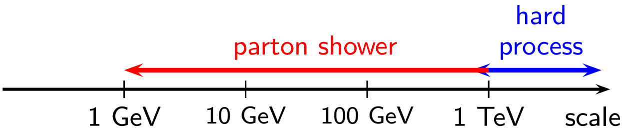




Simulating a high-energy collision requires several ingredients

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



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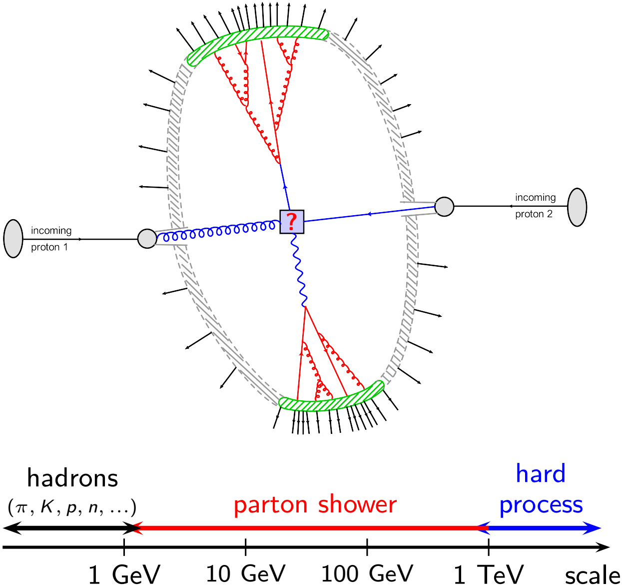


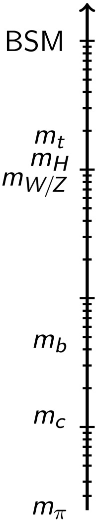
Simulating a high-energy collision requires several ingredients

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

Basic message #2: physics at all scales

LHC probes physics across many scales

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



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

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

Basic message #2: physics at all scales

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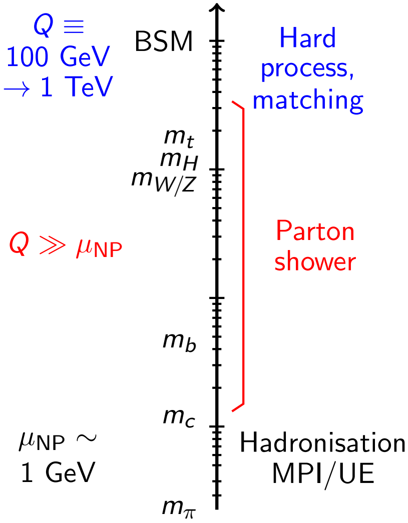

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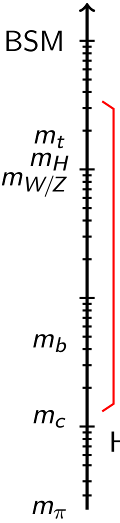

Hard process, matching

A lot of work in past 20 years:

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

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

Parton shower

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

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

Hadronisation MPI/UE

Nonperturbative modelling

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

if IRC-safe

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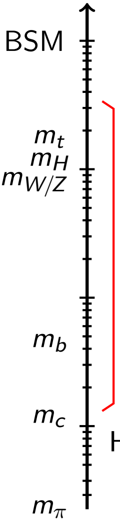

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$Q \gg \mu_{\text{NP}}$

Parton shower

- Historical showers: Pythia,Herwig,Sherpa
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This Talk

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

Hadronisation MPI/UE

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Need for precision

Basic message #3

LHC increasingly goes into precision

$\Rightarrow$ event generators need precision

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$\Rightarrow$ event generators need precision

- Search for tiny deviations
- precise background estimates
- Amplitudes NNLO, ... (+resummations)
- deep learning picks all details

Need for precision

Basic message #3

LHC increasingly goes into precision
$\Rightarrow$ event generators need precision

↓ Search for tiny deviations

↓ precise background estimates

↓ Amplitudes NNLO, ... (+resummations)

↓ deep learning picks all details

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

How do parton showers work?

Dipole/Antenna showers: ingredients

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

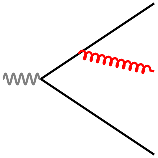
Dipole/Antenna showers: ingredients

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

Idea #1:

gluon emission ≡ dipole splitting

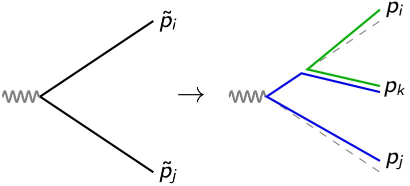
$$(ij) \to (ik)(kj)$$



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

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

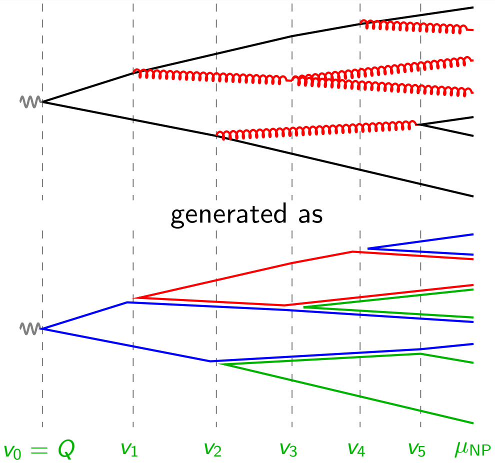
viewed as



includes recoil
& energy-mom conservation

Dipole/Antenna showers: ingredients

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



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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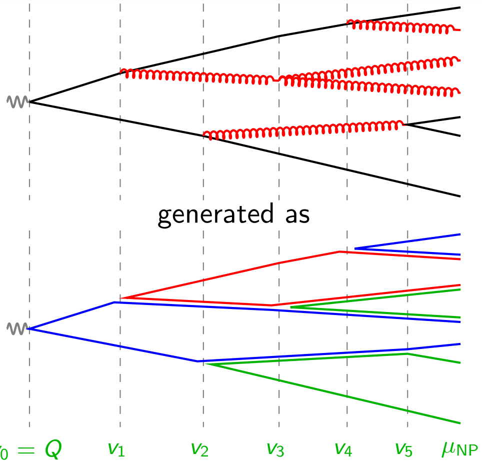

Idea #2:

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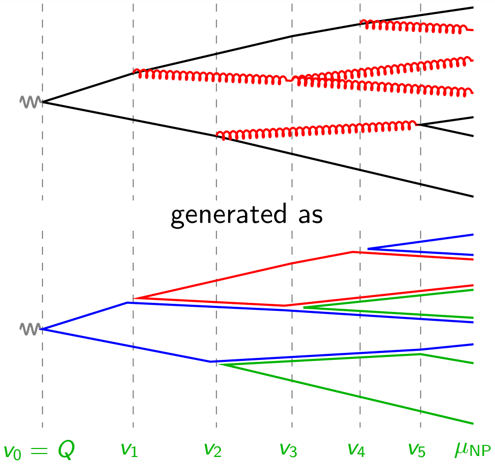
Rooted in QCD factorisation

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

- 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

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



Idea #2:

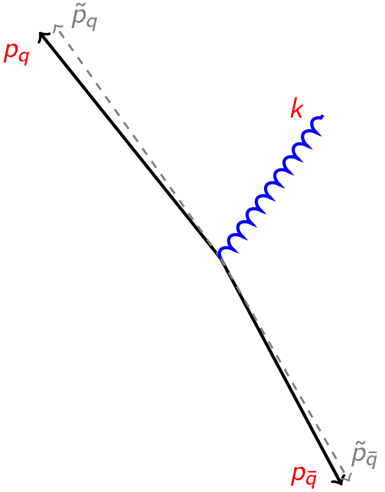
iterate dipole splittings (populate the full phase space with multiple emissions)

Several challenges:

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

Basic features of QCD radiations

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



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

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

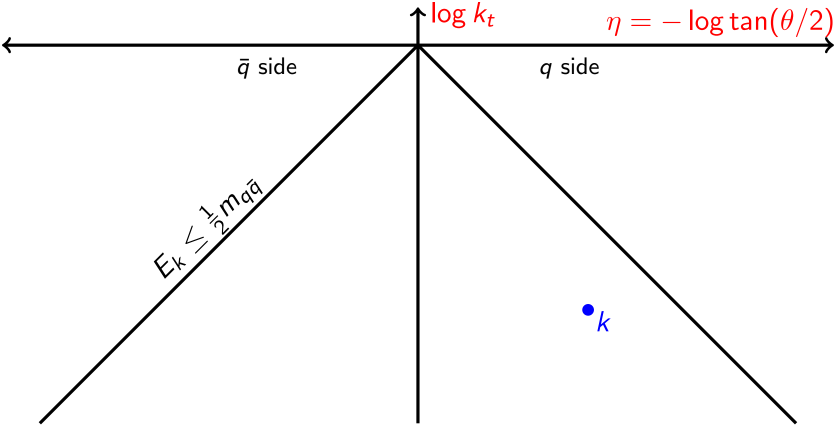
3 degrees of freedom:

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

In the soft-collinear approximation

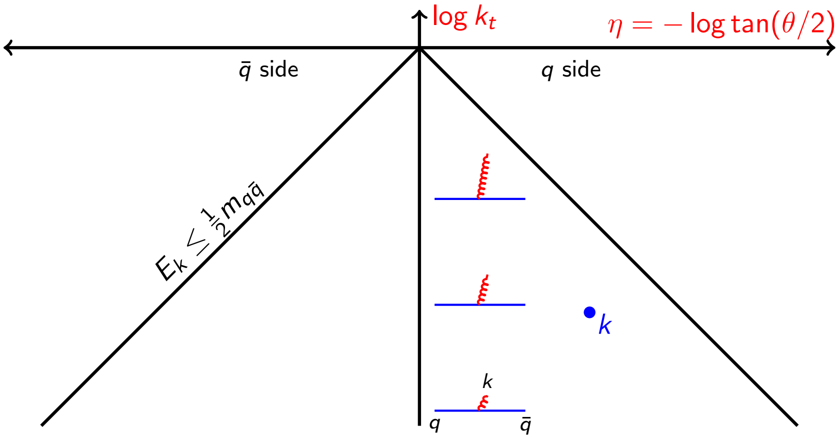
$$d\mathcal{P} = \frac{\alpha_s(k_\perp) C_F}{\pi^2} \, d\eta \, \frac{dk_\perp}{k_\perp} \, d\phi$$

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



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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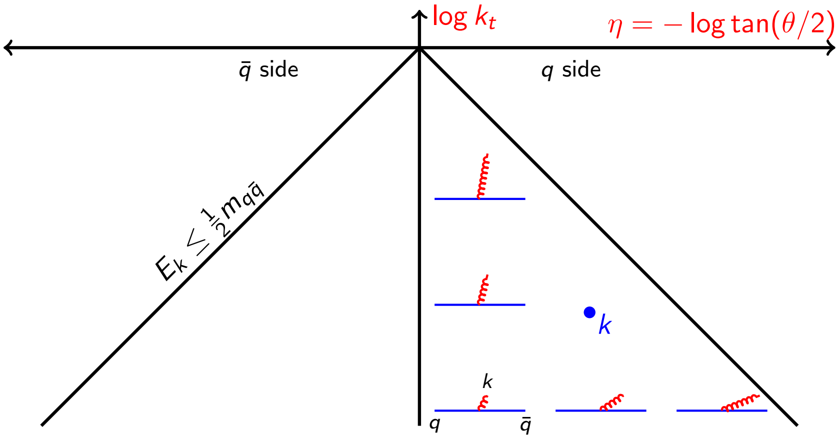

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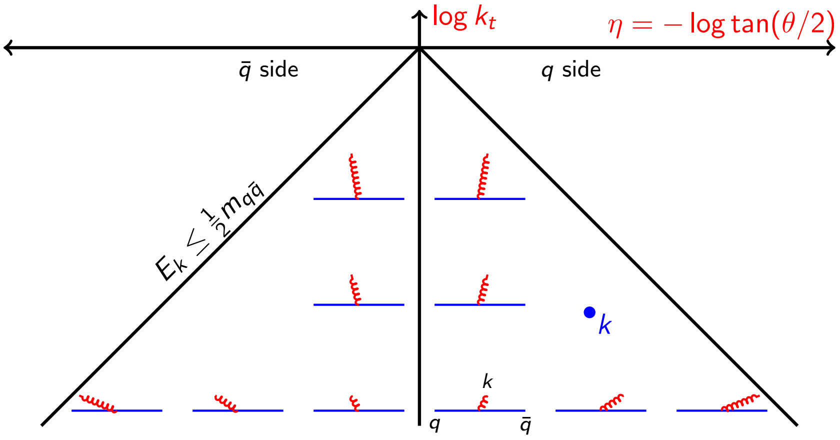

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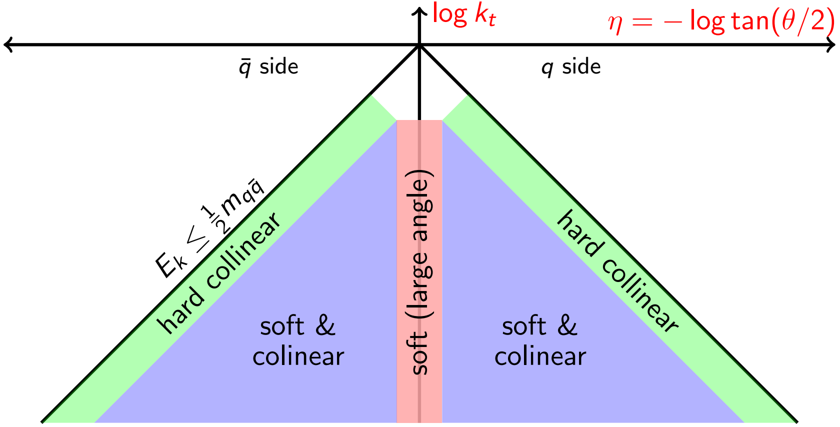
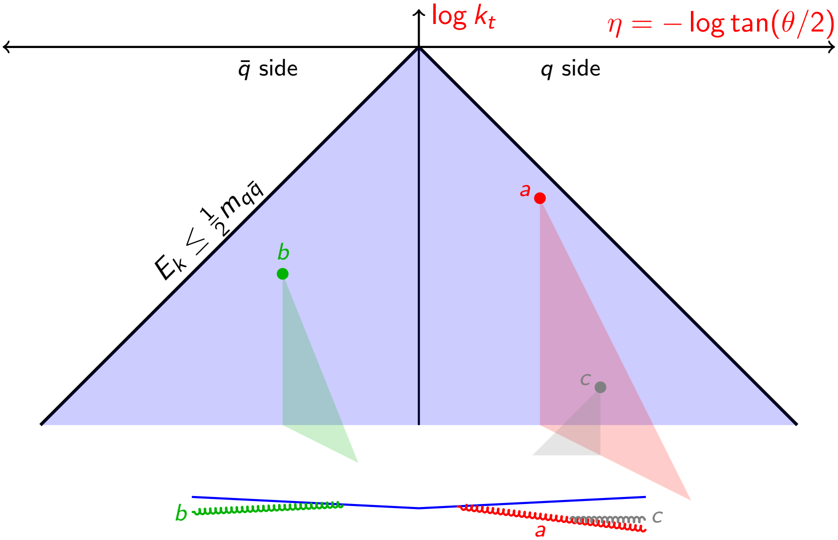
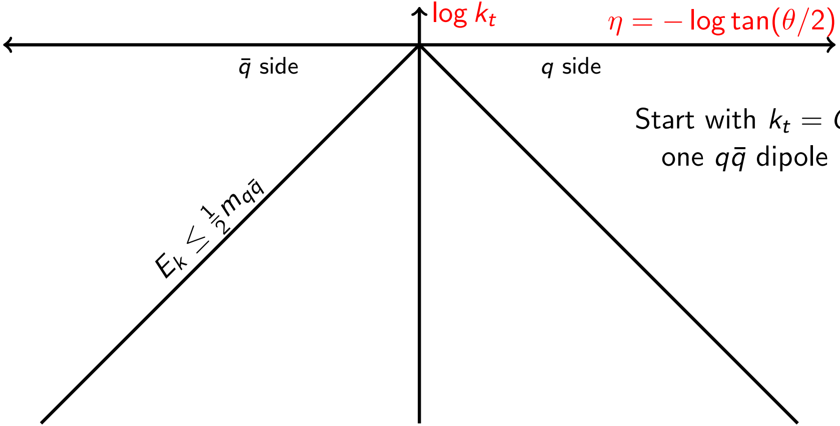


Multiple emissions in the Lund plane



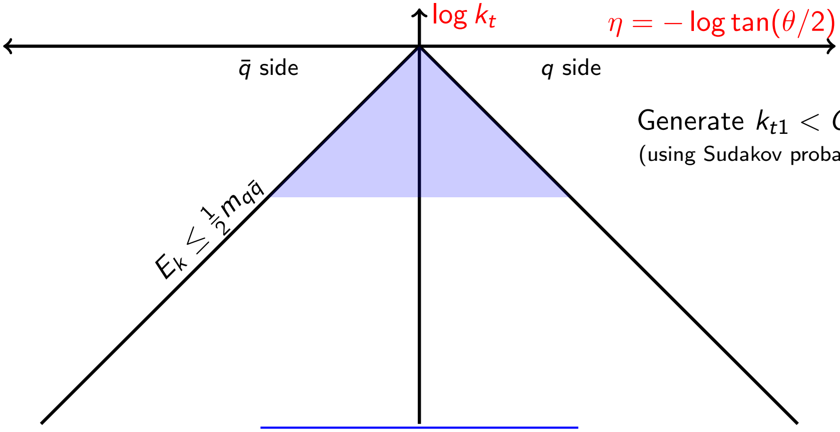
Parton shower in the Lund plane

Ordering variable: transverse momentum k_t



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

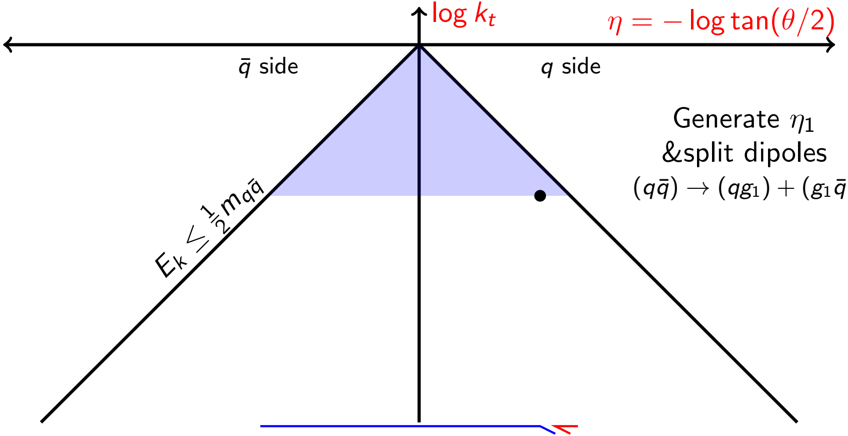
Ordering variable: transverse momentum k_t



Generate $k_{t1} < Q$
(using Sudakov proba)

Parton shower in the Lund plane

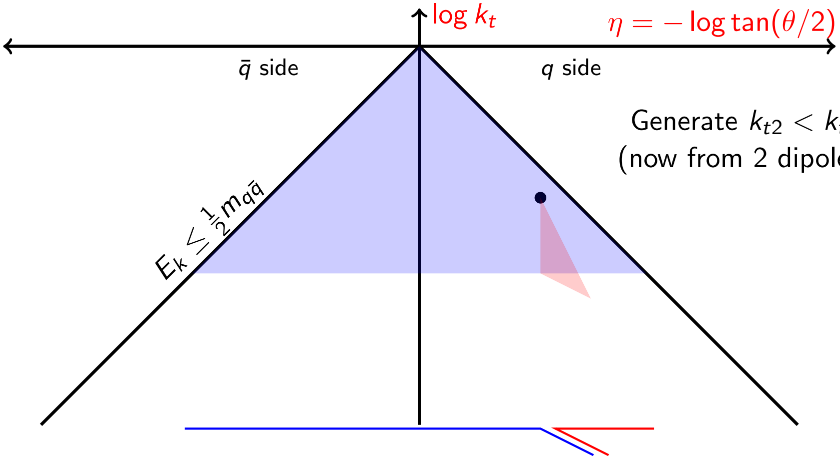
Ordering variable: transverse momentum k_t



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

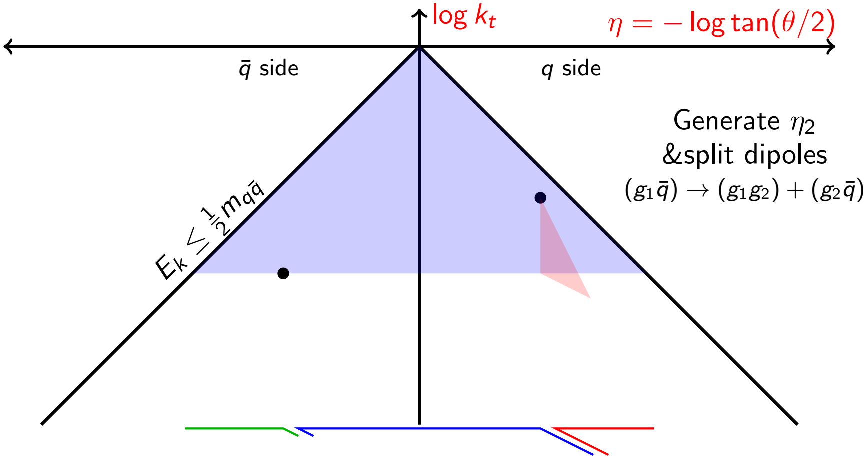
Parton shower in the Lund plane

Ordering variable: transverse momentum k_t



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

Ordering variable: transverse momentum k_t



Parton shower in the Lund plane

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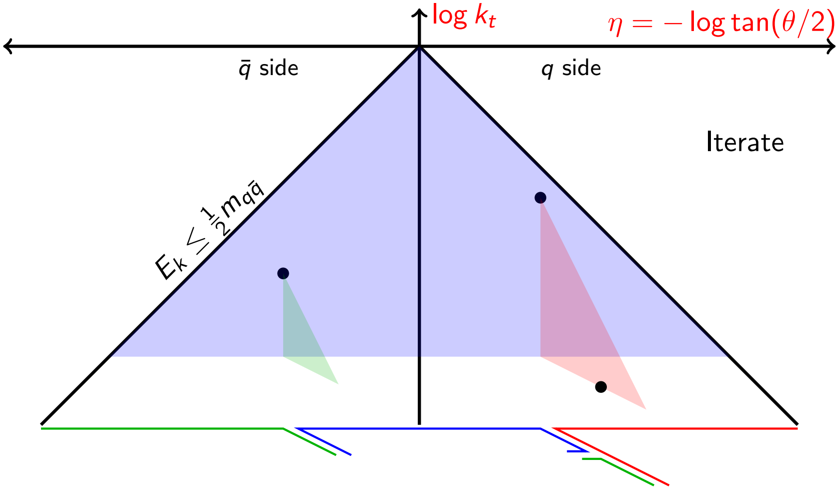

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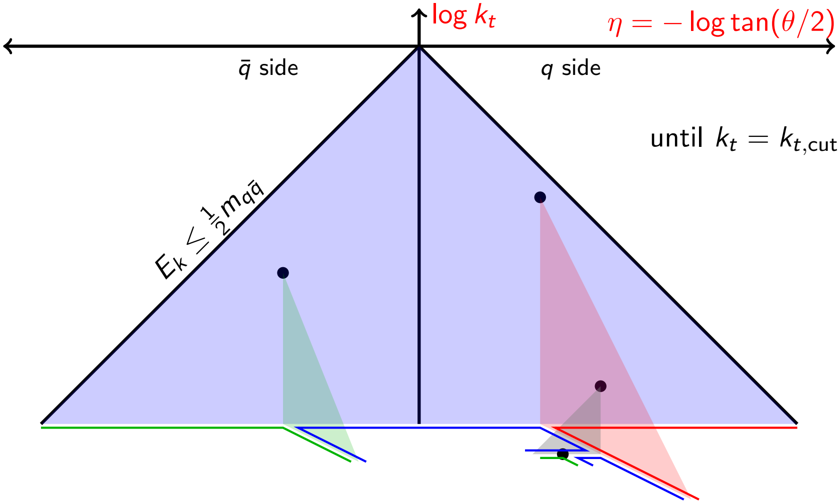
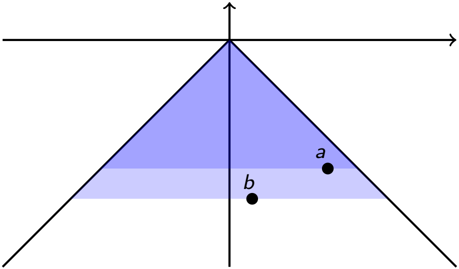


Different ordering variables...

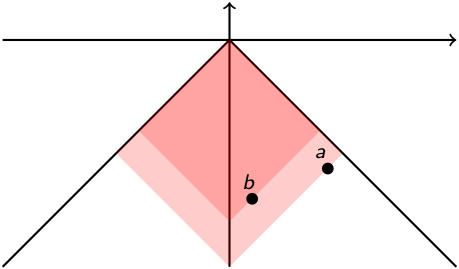
... can lead to different emission orderings

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:

- $1 \to 3$ 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]

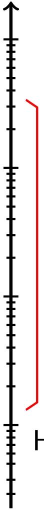
- Amplitude-level showers, see e.g. [Forshaw,Holguin,Plätzer,19]

- 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]

Parton-shower accuracy?

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

What does shower accuracy mean?



$Q \equiv$ 100 GeV $\to$ 1 TeV — Hard process, matching

$Q \gg \mu_{\rm NP}$ — Parton shower

$\mu_{\rm NP} \sim$ 1 GeV — Hadronisation MPI/UE

"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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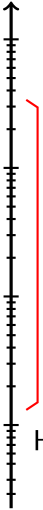

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(double, single,...) logs to resum

accuracy means logarithmic accuracy: LL, NLL, N^{2}LL, ...

well-defined
+ systematically improvable

Testing shower accuracy

(Cumulative) distributions can (often) be written as

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

Examples:

- 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
- ...

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

Testing shower accuracy

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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

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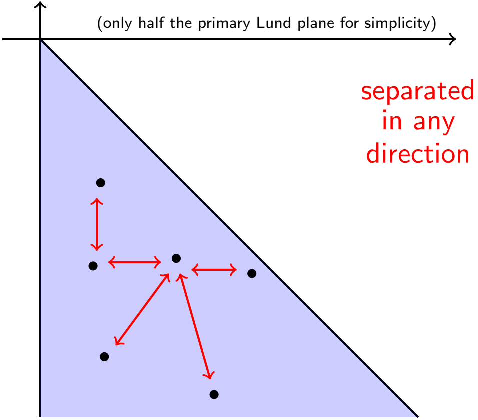
Correct matrix elements for N well separated emissions in the Lund plane



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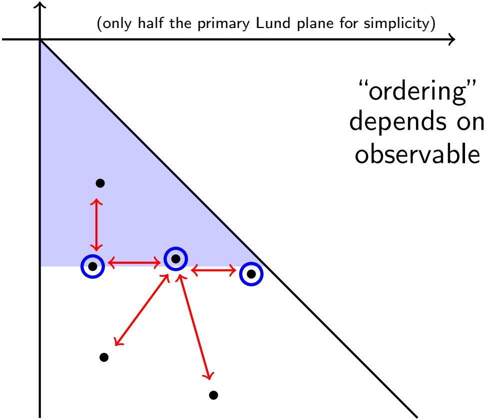

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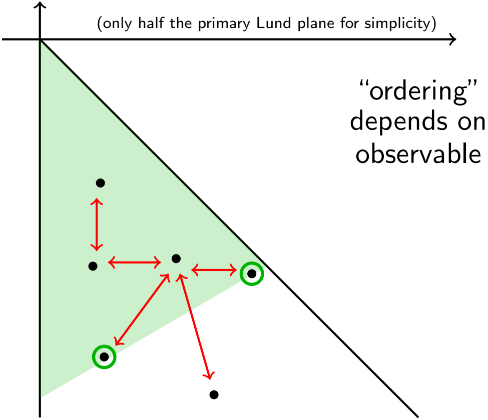

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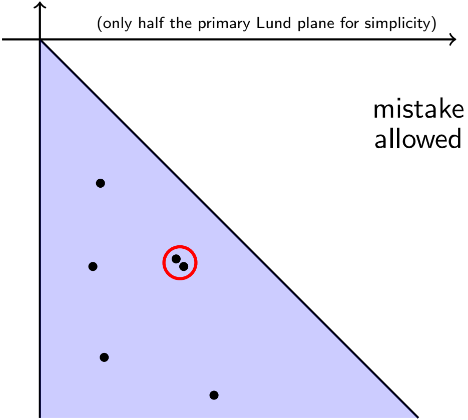


Towards NLL accuracy with the PanScales showers

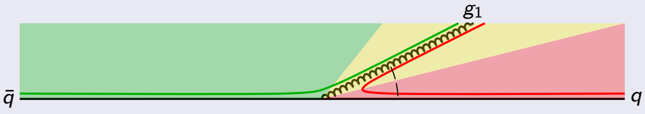
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,arXiv:2002:11114]

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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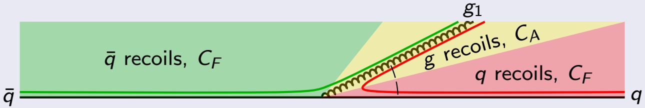

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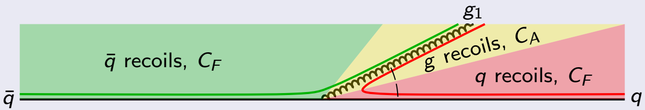
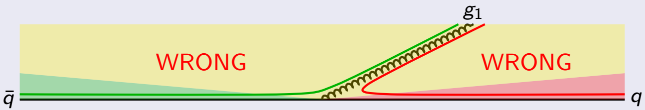


Pythia:



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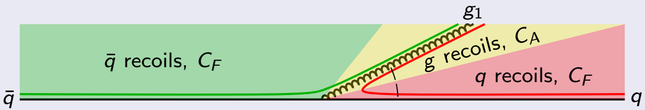

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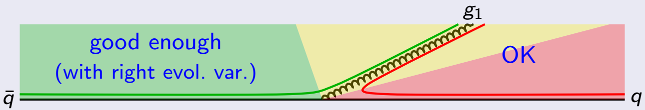

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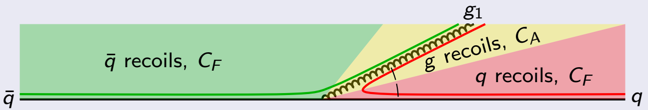

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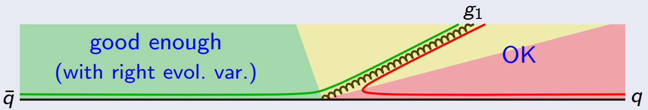
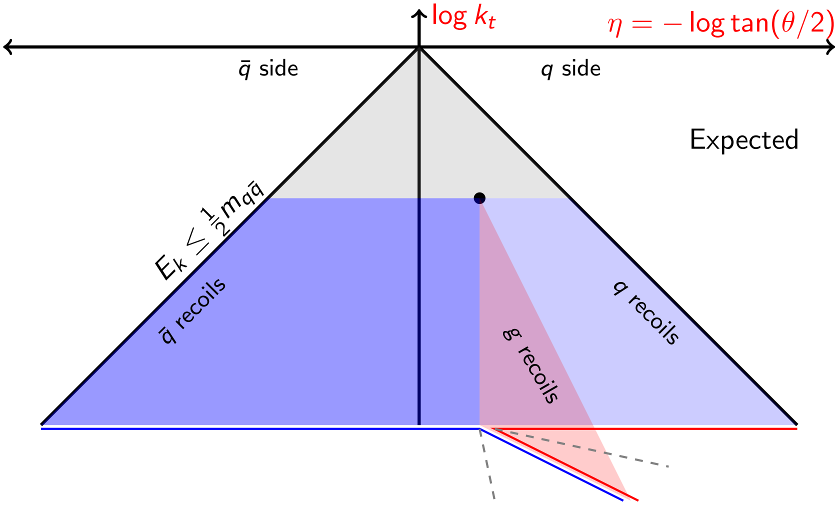


Key element 2: choice of evolution variable

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

Idea: emissions with commensurate k_t radiated with successively smaller angles

Lund-plane representation: transverse recoil boundaries



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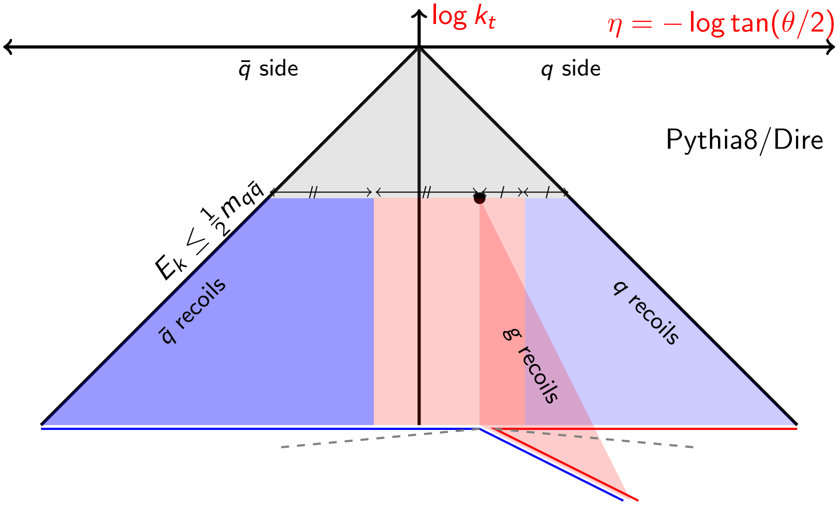
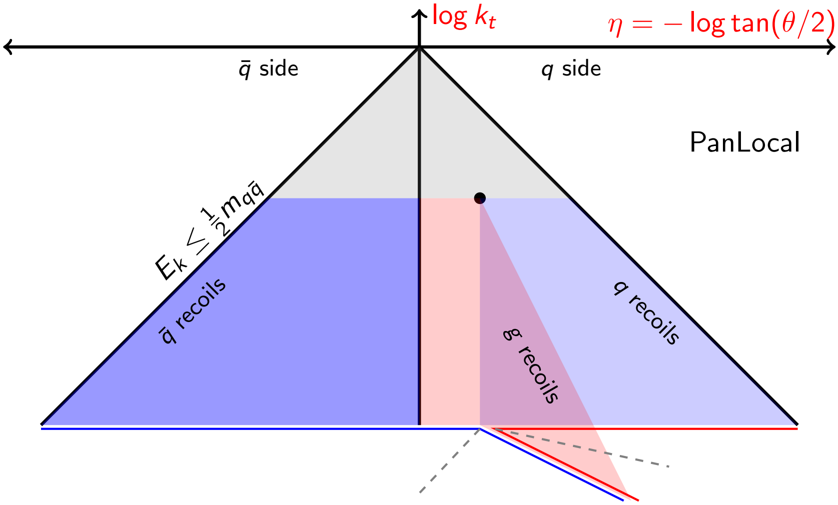
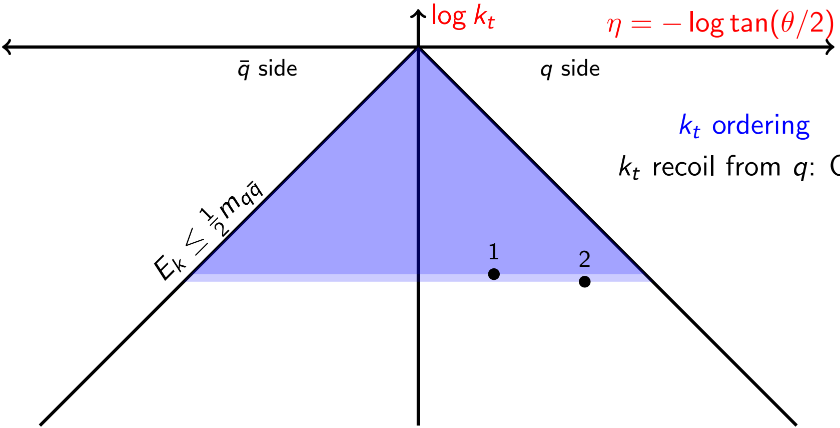


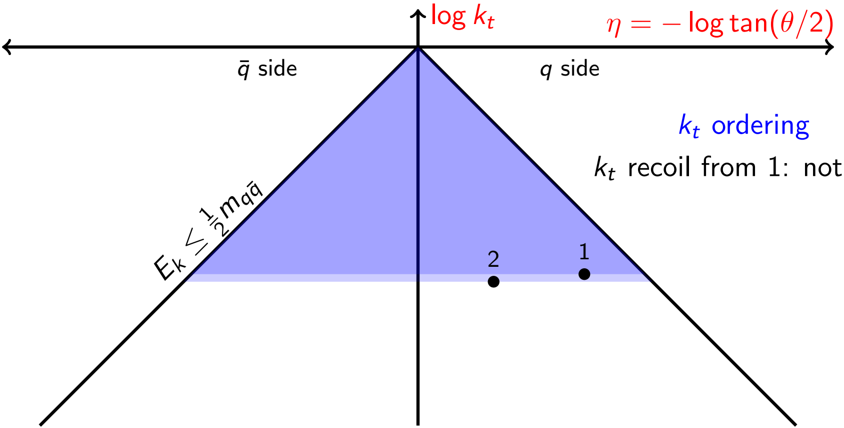

log k_t
$\eta = -\log\tan(\theta/2)$
$\bar{q}$ side
q side
PanLocal
$E_k \leq \frac{1}{2} m_{q\bar{q}}$
$\bar{q}$ recoils
g recoils
q recoils



k_t ordering

k_t recoil from q: OK

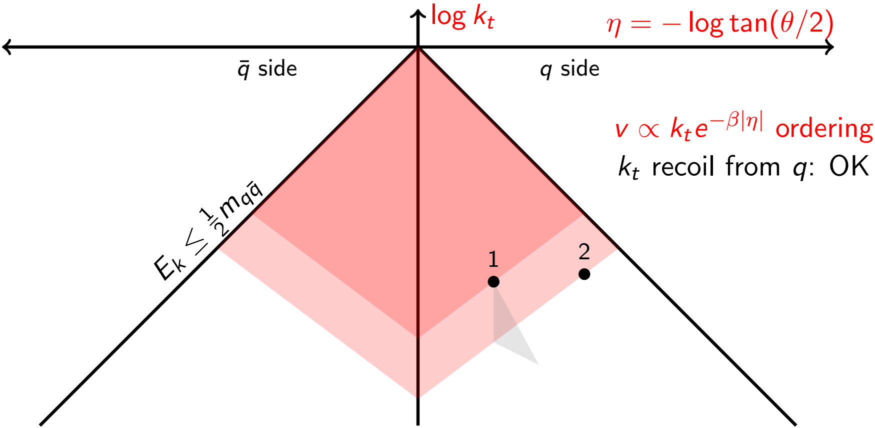
Lund-plane representation: PanLocal evolution variable



k_t ordering

k_t recoil from 1: not OK

Lund-plane representation: PanLocal evolution variable



commensurate k_t emissions generated from central to frward rapidities

$\Rightarrow$ no recoil issue

Kinematic map

(just to give an idea of what it takes)

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

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

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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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Testing the shower accuracy

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

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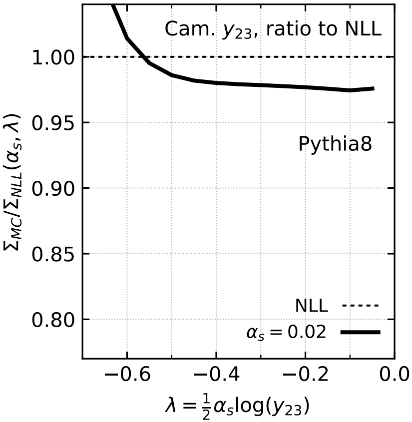


Idea for testing:

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

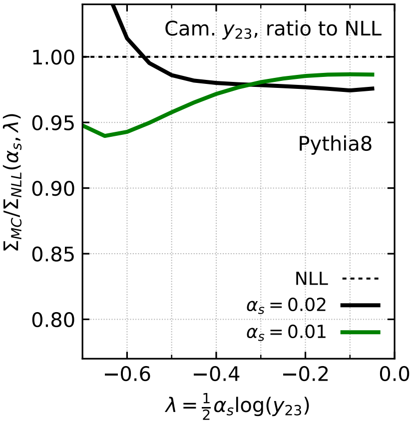
with $\lambda = \alpha_s L$

NLL deviations

or

subleading effects?

Testing accuracy



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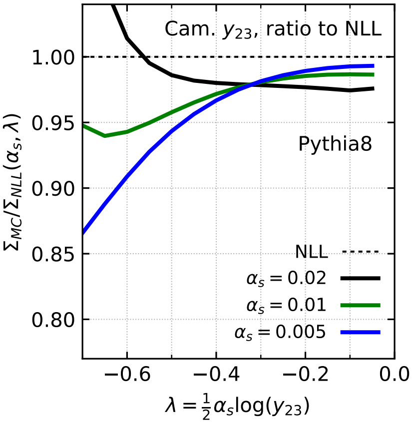

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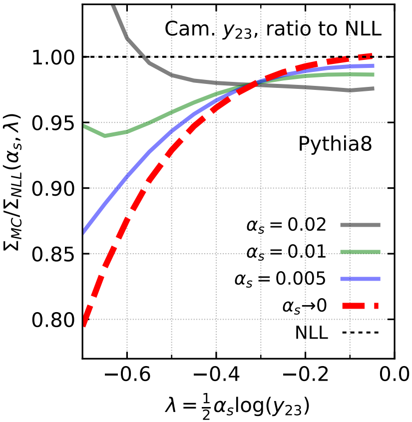


Idea for testing:

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

at fixed $\lambda = \alpha_s L$

NLL deviations

or

~~subleading effects?~~

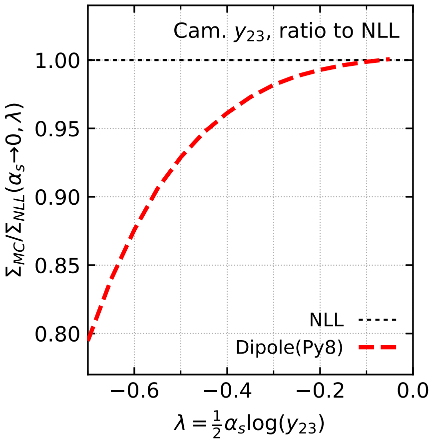
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]

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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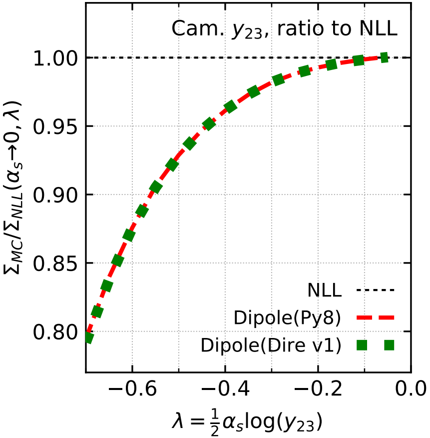

× Pythia8 deviates from NLL

× Dire(v1) same as Pythia8

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

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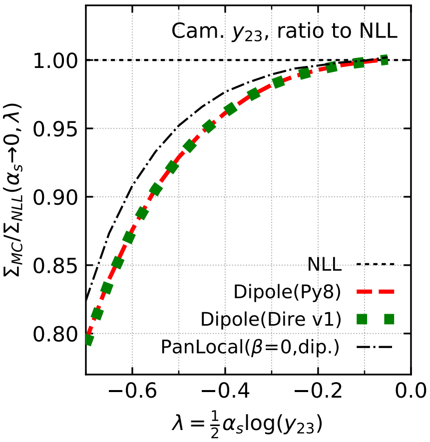
- × PanLocal($\beta = 0$) still deviates
  (issue of k_t ordering remains)



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

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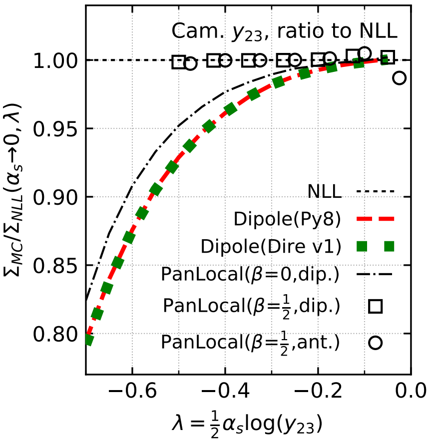
- × Dire(v1) same as Pythia8
- × PanLocal($\beta = 0$) still deviates (issue of k_t ordering remains)
- ✓ PanLocal($0 < \beta < 1$) OK (issue of k_t ordering remains)



Assessing accuracy: y_{23}

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

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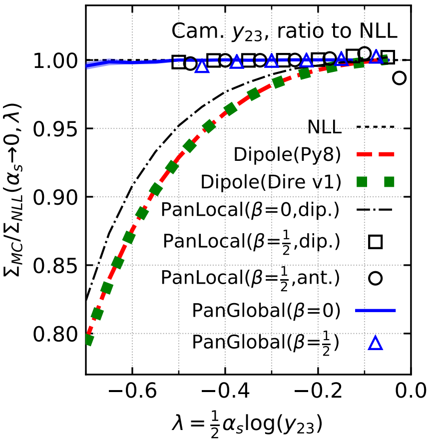
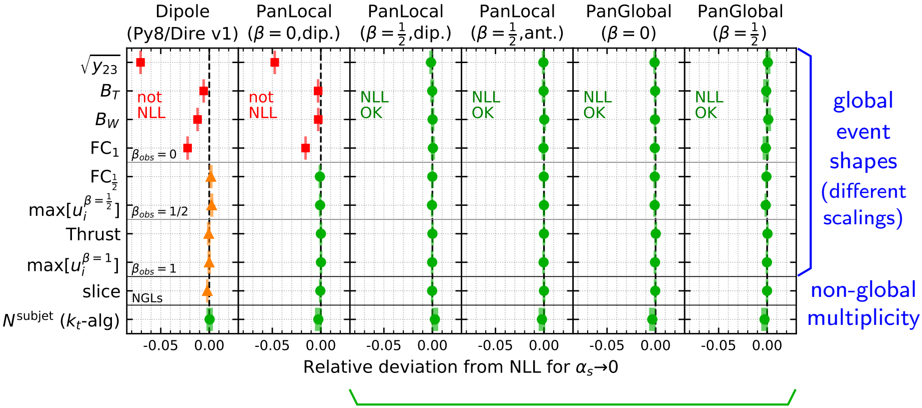
- × PanLocal($\beta = 0$) still deviates
  (issue of k_t ordering remains)
- ✓ PanLocal($0 < \beta < 1$) OK
  (issue of k_t ordering remains)
- ✓ PanGlobal($0 \leq \beta < 1$) OK
  (global recoil allows also for $\beta = 0$)



Assessing accuracy: extensive observable list

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

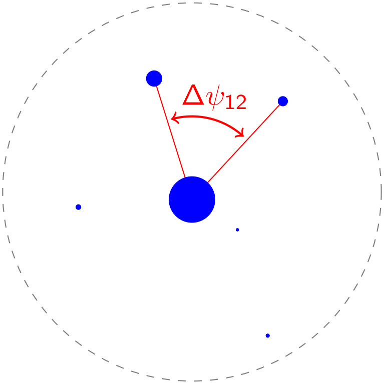


PanLocal($0 < \beta < 1$) and PanGlobal($0 \leq \beta < 1$) get expected NLL (i.e. 0)

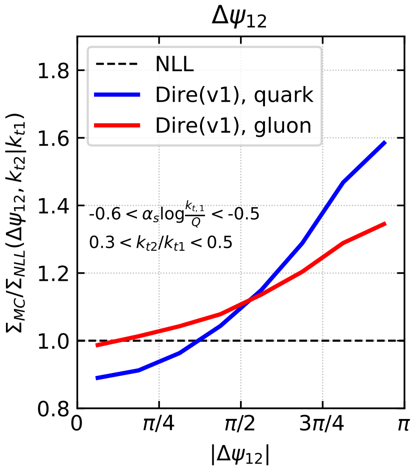
(green: OK at NLL; orange: issues at fixed order; red issues at fixed and all orders)

A last example

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



- 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

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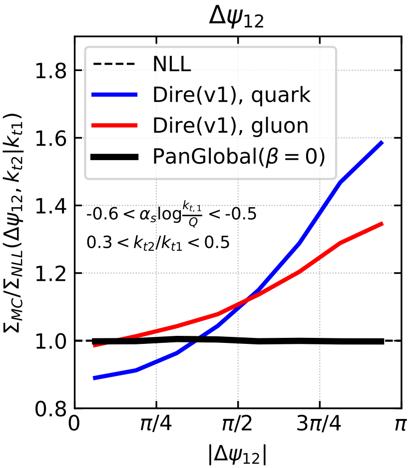
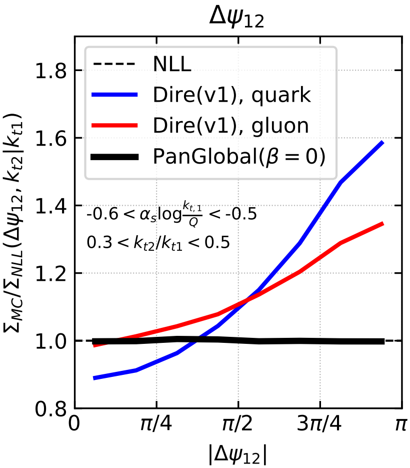


A last example

- 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
- ML could "wrongly/correctly" learn this



Summary up to this point

Take-home messages

- parton shower accuracy $\equiv$ logarithmic accuracy
- Standard showers (like Pythia8 or Dire) fail to deliver NLL accuracy (due to spurious k_t recoil)
- Two new showers: PanLocal and PanGlobal with NLL accuracy

Limitations:

- large-N_c
- no spin correlations
- e^+e^- collisions
- NLL

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Limitations:

- large-N_c
- no spin correlations
- e^+e^- collisions
- NLL

Next steps:

- ✓ beyond large-N_c
- ✓ add spin correlations
- ≈ DIS and pp collisions
- × get to NNLL

Beyond large-N_c

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

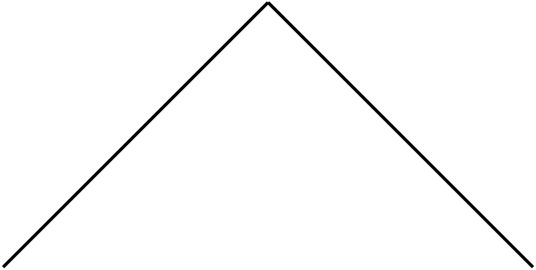
Generic context

Generic idea

- Going beyond large N_c is complex due to the intricate nature of multiple soft gluon emissions
- MC strategies beyond leading N_c usually either inaccurate or complex
- We want a simple prescription to go beyond leading N_c

Standard parton showers (e.g. Py8) determine C_F or C_A based on emitter

This leads to incorrect leading (double) logarithm contributions



Generic context

Generic idea

- Going beyond large N_c is complex due to the intricate nature of multiple soft gluon emissions
- MC strategies beyond leading N_c usually either inaccurate or complex
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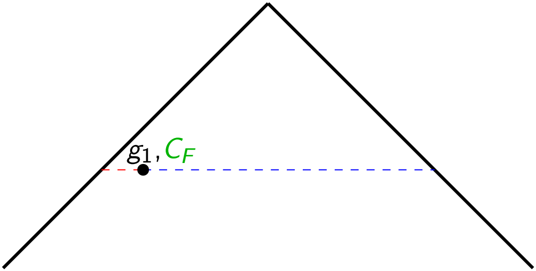

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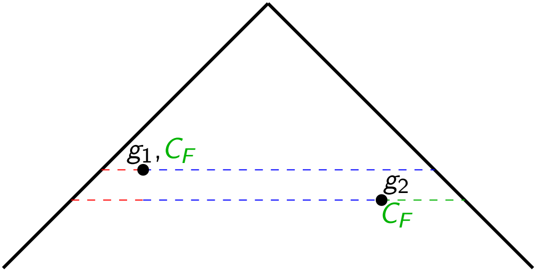

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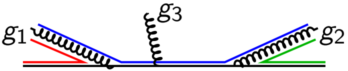

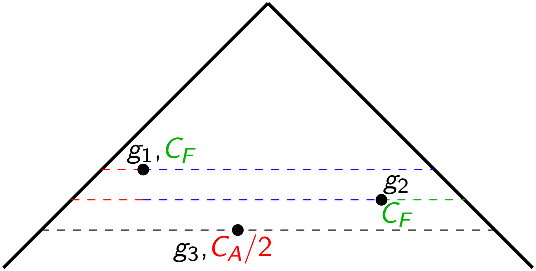

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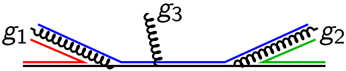
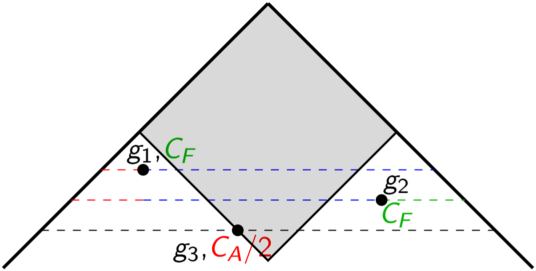
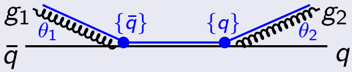




WRONG Thrust at LL

Main idea:

Keep track of the transitions between C_F and $C_A/2$ along any dipole

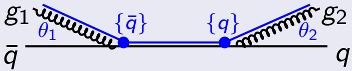


$$\left[-\infty; \frac{C_A}{2}; -\log\frac{\theta_1}{2}; C_F; \log\frac{\theta_2}{2}; \frac{C_A}{2}; \infty\right]$$

Sketching solutions

Main idea:

Keep track of the transitions between C_F and $C_A/2$ along any dipole



$$\left[-\infty; \frac{C_A}{2}; -\log\frac{\theta_1}{2}; C_F; \log\frac{\theta_2}{2}; \frac{C_A}{2}; \infty\right]$$

Segment method

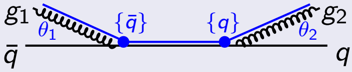
Colour factor based on the rapidity of the emission

$$\begin{aligned} \eta < -\log\frac{\theta_1}{2} &: \quad C_A/2 \\ -\log\frac{\theta_1}{2} < \eta < \log\frac{\theta_2}{2} &: \quad C_F \\ \log\frac{\theta_2}{2} < \eta &: \quad C_A/2 \end{aligned}$$

Sketching solutions

Main idea:

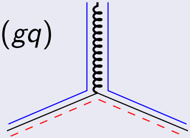
Keep track of the transitions between C_F and $C_A/2$ along any dipole



$$\left[-\infty; \frac{C_A}{2}; -\log\frac{\theta_1}{2}; C_F; \log\frac{\theta_2}{2}; \frac{C_A}{2}; \infty\right]$$

NODS method

Apply a matrix-element correction for two soft emissions:

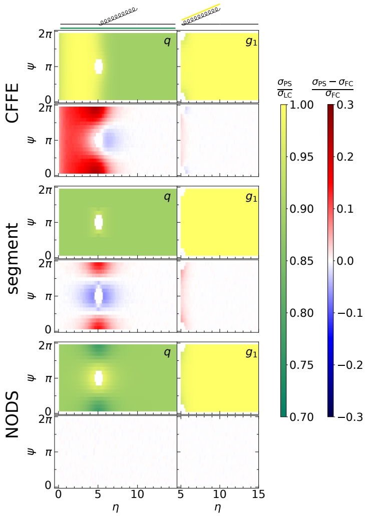


- Say we have a $q\bar{q}g$ system with 2 dipoles: $(\bar{q}g)$ and (gq)
- Soft radiation of gluon k takes the form
  $\frac{C_A}{2}(k|\bar{q}g) + \frac{C_A}{2}(k|gq) + \left(C_F - \frac{C_A}{2}\right)(k|\bar{q}q)$
- rewrite as $\frac{C_A}{2} w_{\bar{q}g;q}(k|\bar{q}g) + \frac{C_A}{2} w_{gq;\bar{q}g}(k|gq)$ with $0 < w_{ab,c} < 1$

Accuracy tests

This gets you

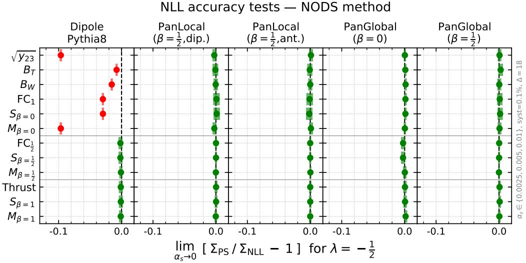
Matrix-element tests



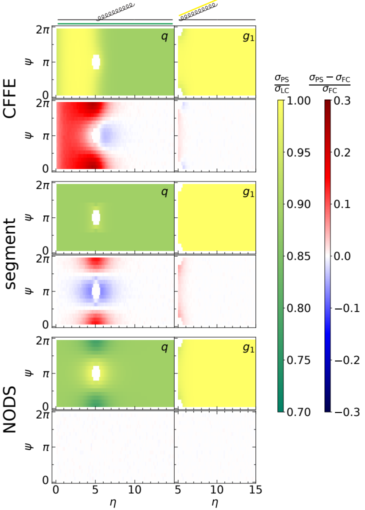
Accuracy tests

This gets you

- Full-colour NLL accuracy for global event shapes and multiplicity



Matrix-element tests

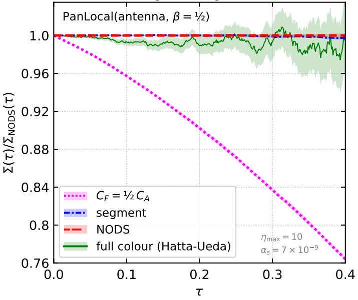


Accuracy tests

This gets you

- Full-colour NLL accuracy for global event shapes and multiplicity
- Not NLL for non-global obs but
  - NODS OK for any number of E-ordered comm.-angle pairs of em.
  - in good numerical agreement w full-colour results from Hatta&Ueda.

Energy in a slice $\frac{\pi}{3} < \theta < \frac{2\pi}{3}$ - ratio to NODS



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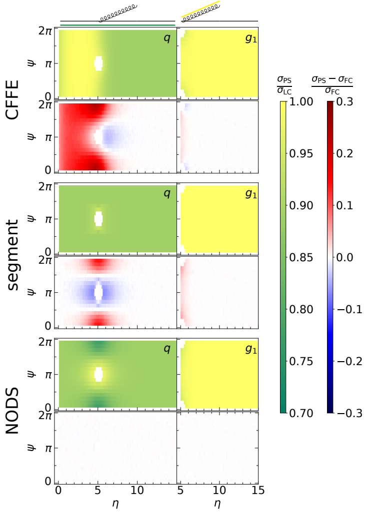


Spin correlations at NLL

[A.Karlberg, G.Salam, L.Scyboz, R.Verheyen, arXiv:2103.16526]
[K.Hamilton,A.Karlberg,G.Salam,L.Scyboz,R.Verheyen,arXiv:2111.01161]

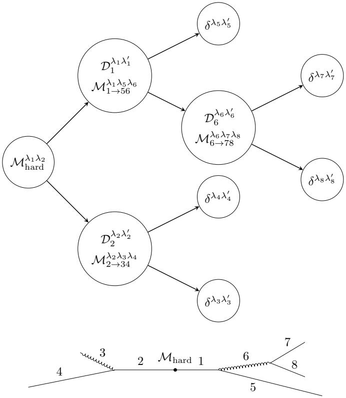
Main idea

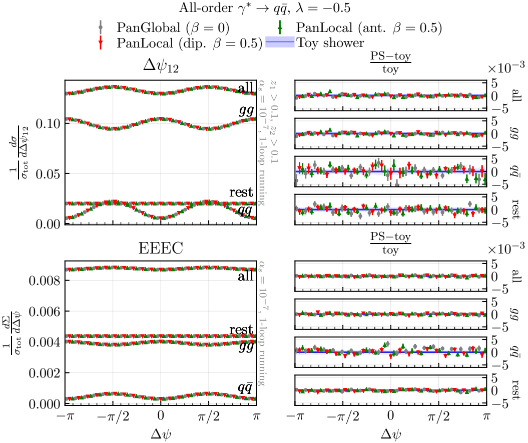
Spin correlations at NLL in two kinematic configurations
(i) 2 hard-collinear splittings; (ii) hard-collinear splitting of soft emission

Solution

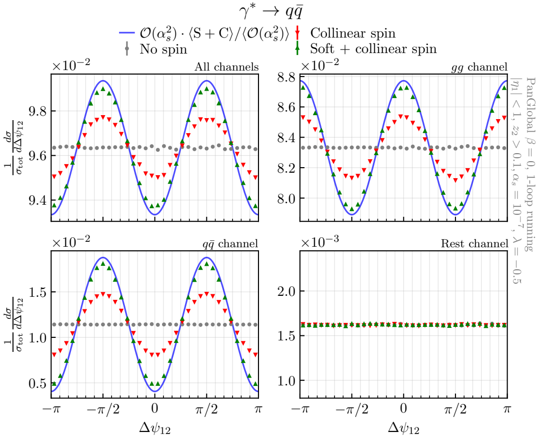
Adapt the Collins-Knowles algorithm to dipole showers

1. compute analytically amplitudes $\mathcal{M}$ in each partinic channel
2. for each event, keep a tree of spin-density and decay matrices (information propagated to the root of the tree at each emission)
3. the density matrix gives an acceptance probability for the azimuthal angle





- Very few spin-dependent observ. known at all orders [H.Chen,I.Moult,H.Zhu,2011.02492]
- Helpful jet substructure insight (e.g. Lund plane)
- PanScales shower include spin correlations at NLL



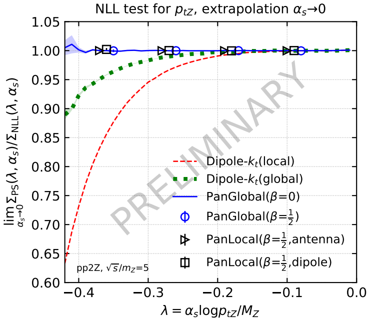
- Very few spin-dependent observ. known at all orders [H.Chen,I.Moult,H.Zhu,2011.02492]
- Helpful jet substructure insight (e.g. Lund plane)
- PanScales shower include spin correlations at NLL
- First MC inclusion of soft spin
- No all-order observables known for soft spin

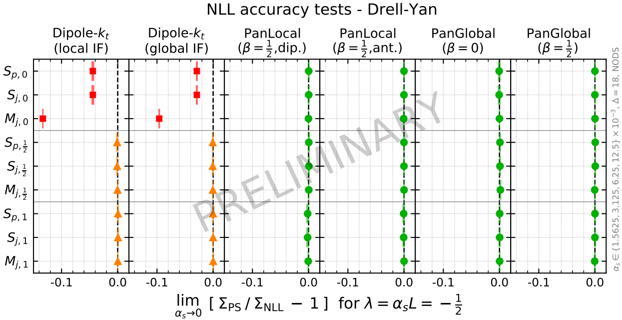
Interesting for future studies and measurements at colliders!

Hadronic collisions

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

- Standard "dipole-k_t" pp showers (either with local or global recoil for initial-state radiation) also have spurious recoil
- Adapting the PanScales showers involves a few subtleties





Preliminary results look good

stay tuned!

The quest for precision across scales

Project and people

PanScales

E.Slade, R.Medves; M. van Beekveld, F.Dreyer, B.El-Menoufi, S.Ferrario-Ravasio, A.Karlberg, L.Scyzboz, A.Soto-Ontoso, R.Verheyen; M.Dasgupta, K.Hamilton, P.Monni, G.Salam, GS

Main achievements so far

Deepen the understanding & improve parton showers (core at colliders)

1st results: accuracy assessment, NLL e^+e^- shower (incl. colour and spin), *pp* progress.

What next?

- finalise *pp*
- prepare the ingredients for NNLL
- Longer run: investigate phenomenology, go public, full NNLL