Parton showering meets perturbative QCD

Gregory Soyez

mostly based on work within PanScales:

arXiv:1805.09327, arXiv:1807.04758, arXiv:2002.11114, arXiv:2007.10355, arXiv:2011.10054, arXiv:2103.16526, arXiv:2109.07496, arXiv:2111.01161, arXiv:2205.02237, arXiv:2205.02861, arXiv:2207.09467, arXiv:2212.05076, arXiv:2301.09645, arXiv:2305.08645, arXiv:2307.11142

IPhT, CNRS, CEA Saclay

QCD Meets Gravity, CERN, December 11-15 2023

Melissa van Beekveld
NIKHEF

Mrinal Dasgupta
Manchester

Basem El-Menoufi
Monash

Silvia Ferrario Ravasio
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Keith Hamilton
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Jack Helliwell
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Pier Monni
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Gavin Salam
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Ludovic Scyboz
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Alba Soto-Ontoso
CERN

Grégory Soyez
IPhT, Saclay

PanScales

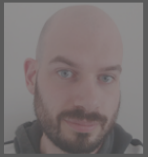
A project to bring logarithmic understanding and accuracy to parton showers

Silvia Zanoli
Oxford

Former members

Frédéric Dreyer

Rok Medves

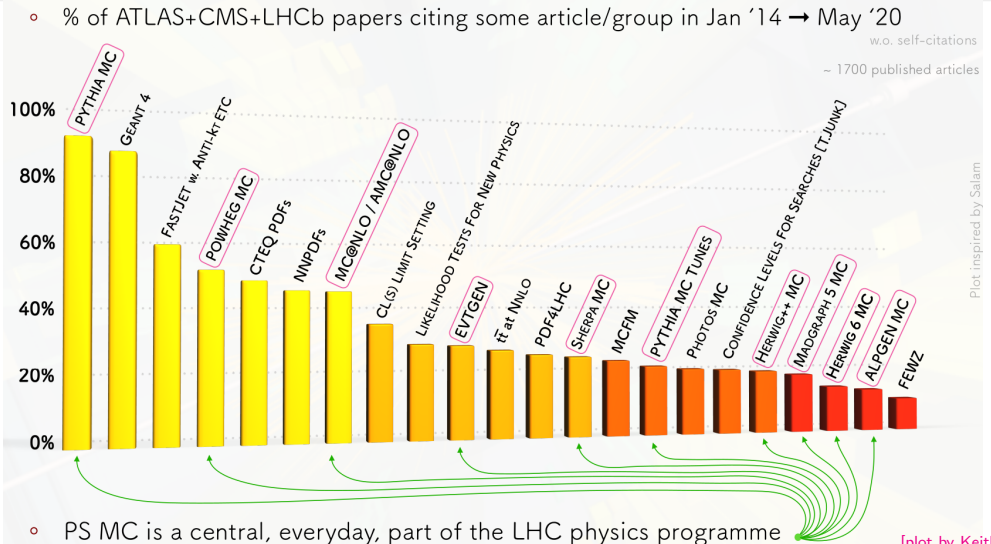


Rob Verheyen

Scarlett Woolnough

Basic message #1: Event Generators are among us!

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



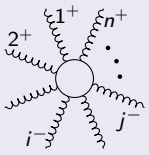
- PS MC is a central, everyday, part of the LHC physics programme

[plot by Keith Hamilton]

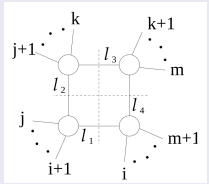
What makes them so successful/useful?

From fundamental theory...

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + Y_{ij} \bar{\psi}_i \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

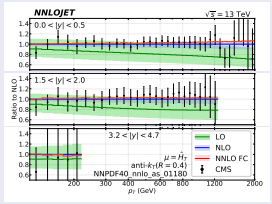


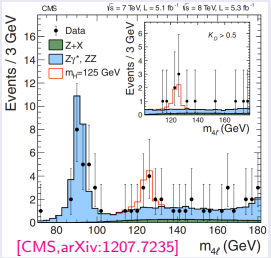
$$= \frac{\langle ij \rangle^4}{\langle 12 \rangle \langle 23 \rangle \cdots \langle n1 \rangle}$$



...to a spectrum of applications

Basic idea: getting practical numbers





Applications:

- pheno studies ("run Pythia to test a pheno idea")
- measurements (compare data/theory)
- modelling (systematic uncertaintes)
- searches (estimate backgrounds)
- AI training (e.g. supervised classification)
- ...

What makes them so successful/useful?

Benchmark feature: versatility

- ranges from "fixed-order" parton-level to realistic full-event simulations (incl. detector)
- wide range of applications
- can compute any observable, fiducial cuts, ...

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Precision challenge

Precision is increasingly required for LHC physics (and future colliders)

- Get precise background estimates
- Search for tiny deviations/rare processes
- Get precise predictions and small uncertainties
- Avoid AI picking up spurious effects

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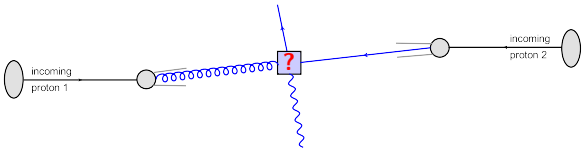
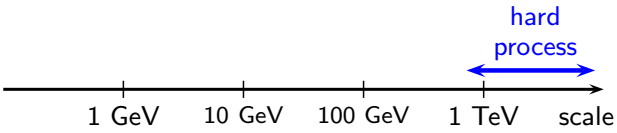
This requires control over the full chain: from the amplitude to the detector

Anatomy of a high-energy collision

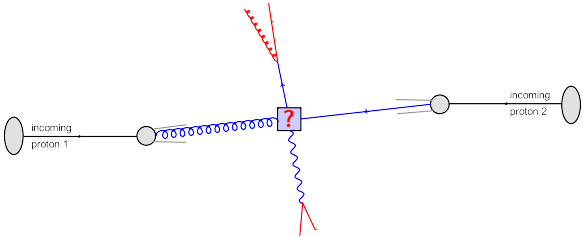


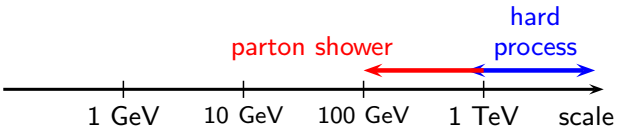


Simulating a high-energy collision requires several ingredients

- 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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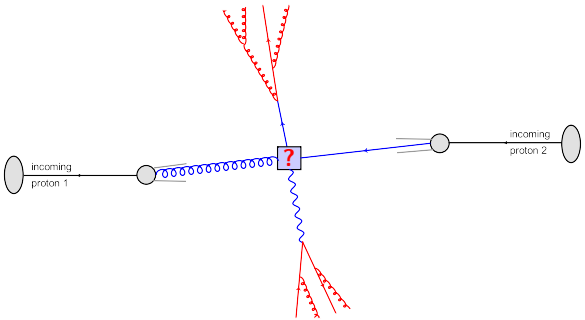

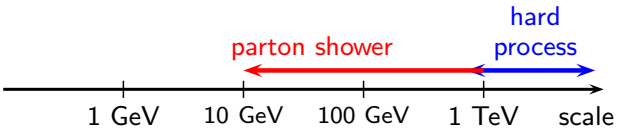

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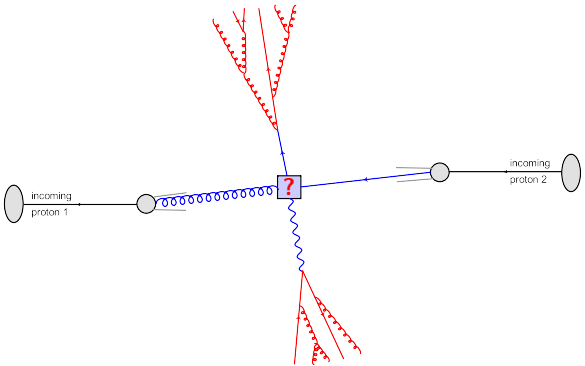
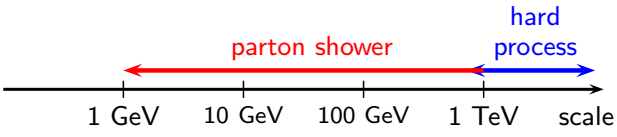
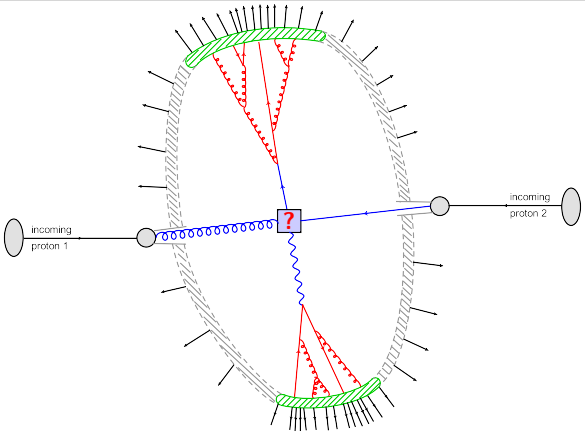


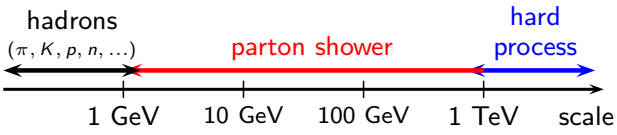


Simulating a high-energy collision requires several ingredients

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

Anatomy of a high-energy collision





Simulating a high-energy collision requires several ingredients

- A hard process
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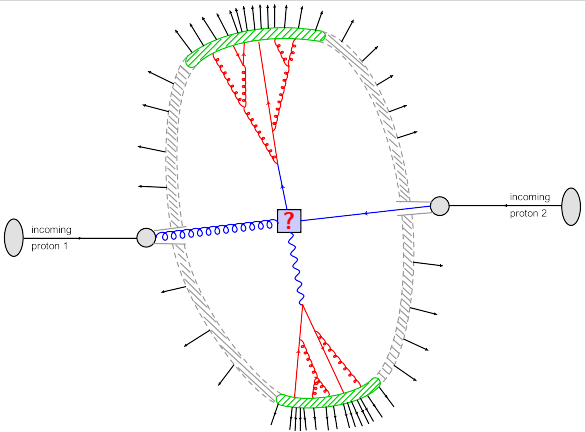
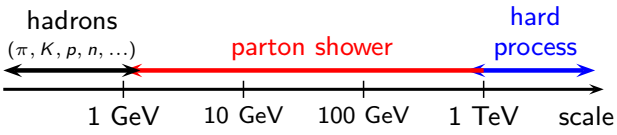
- Hadronisation
- Multi-parton interactions

Anatomy of a high-energy collision





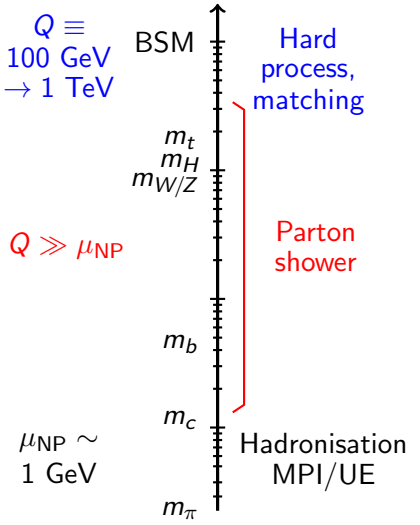
Simulating a high-energy collision requires several ingredients

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



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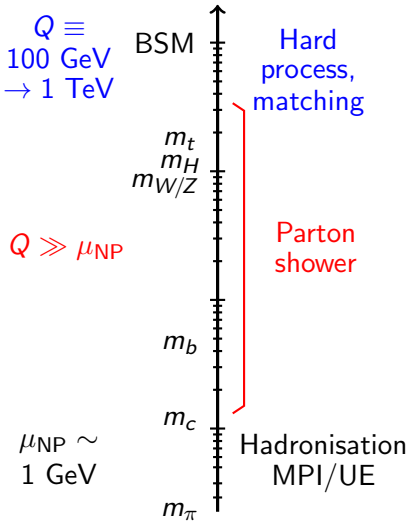


"Standard" perturbative expansion

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

LO NLO NNLO

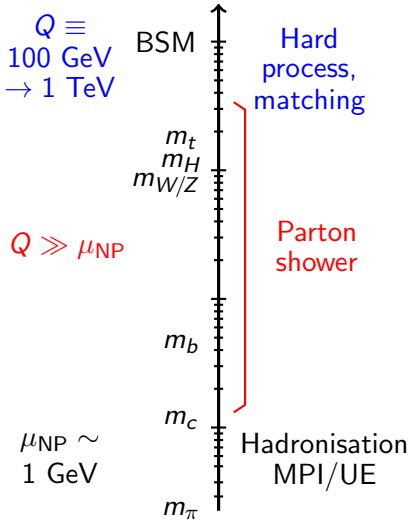
expect logs between disparate scales

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

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

Basic message #2: physics at all scales, **a shower resums logs**

physics probed across many scales



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

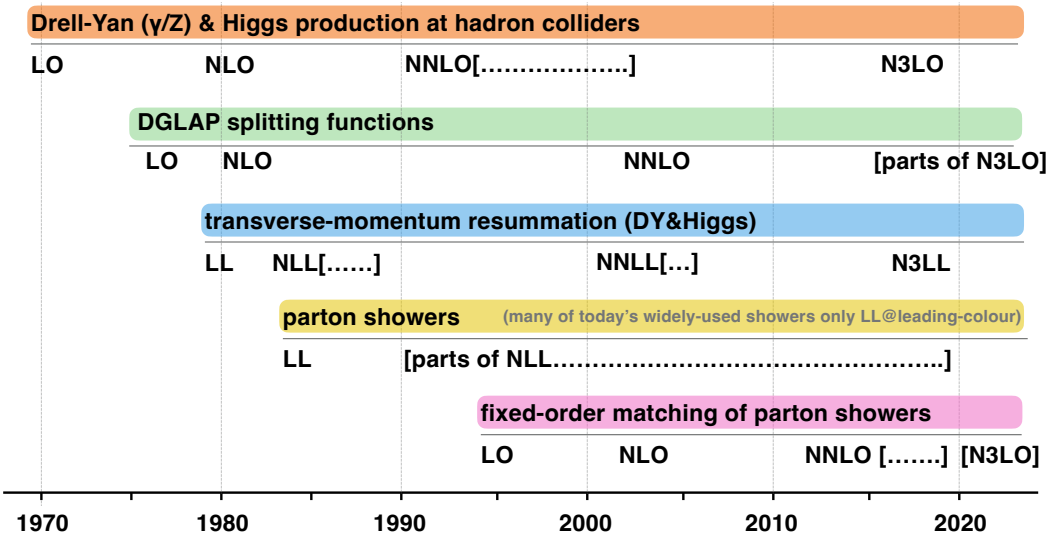
shower accuracy means logarithmic

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

well-defined & systematically improvable

selected collider-QCD accuracy milestones

[slide from Gavin Salam (Moriond QCD 2023)]



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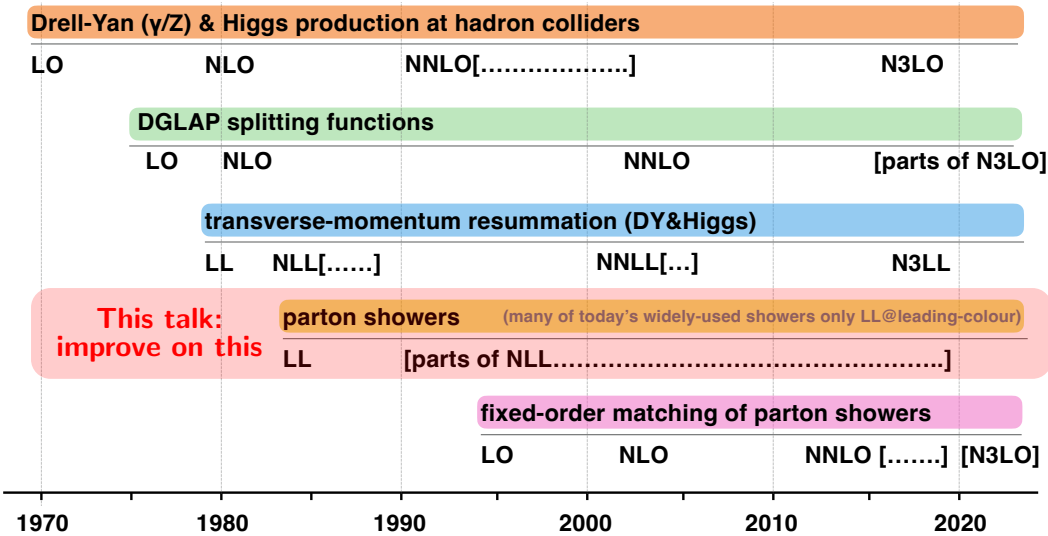
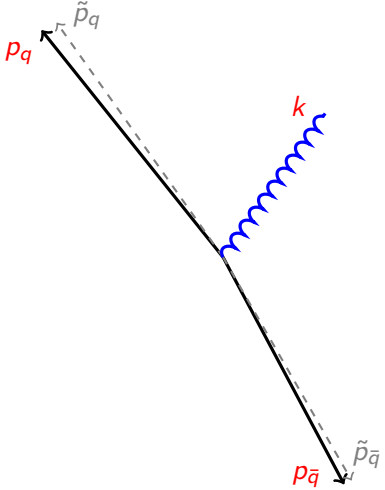


An “easy” graphical representation

Lund plane(s)

Basic features of QCD radiation

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:

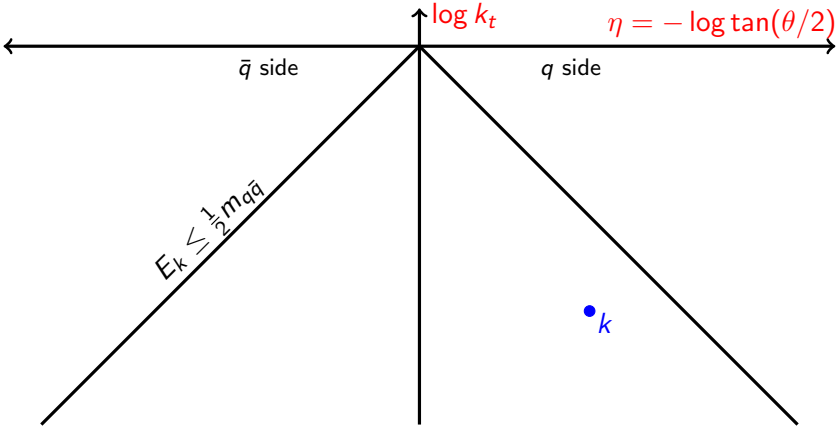
- Rapidity: $\eta = \frac{1}{2} \log \frac{z_q}{z_{\bar{q}}}$
- Transverse momentum: $k_\perp$
- Azimuth: ϕ

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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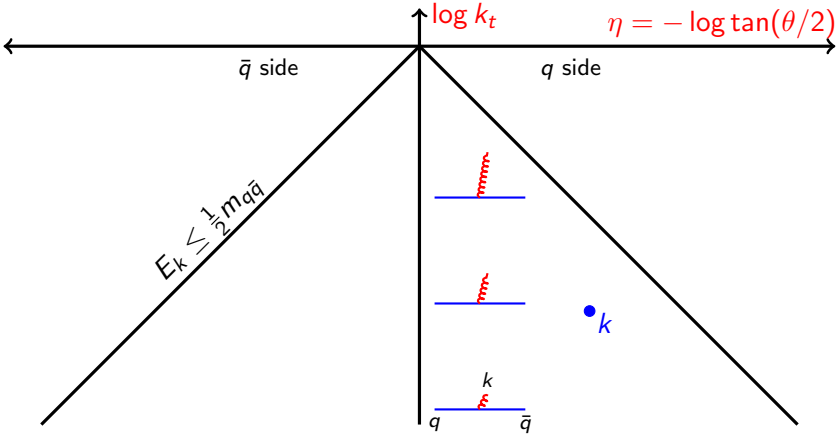

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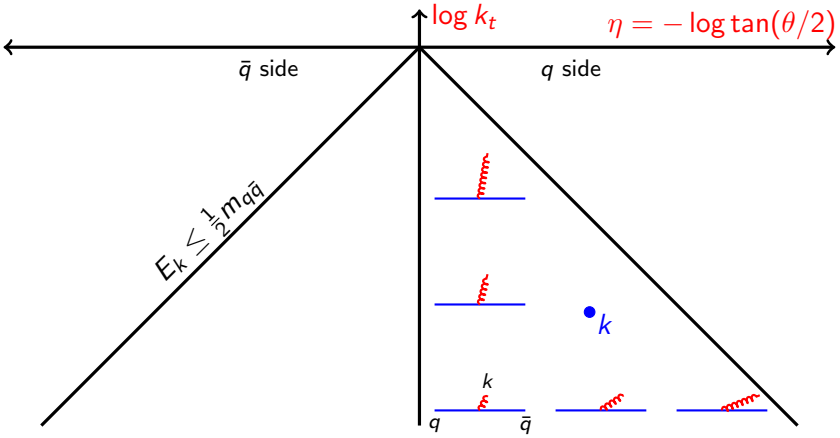

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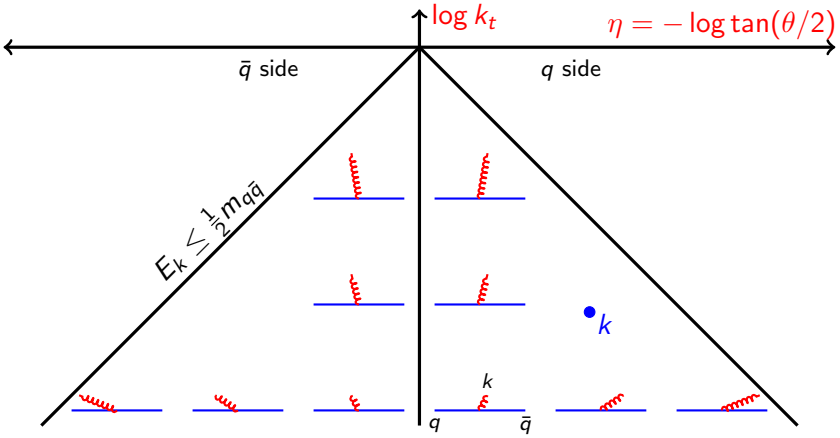

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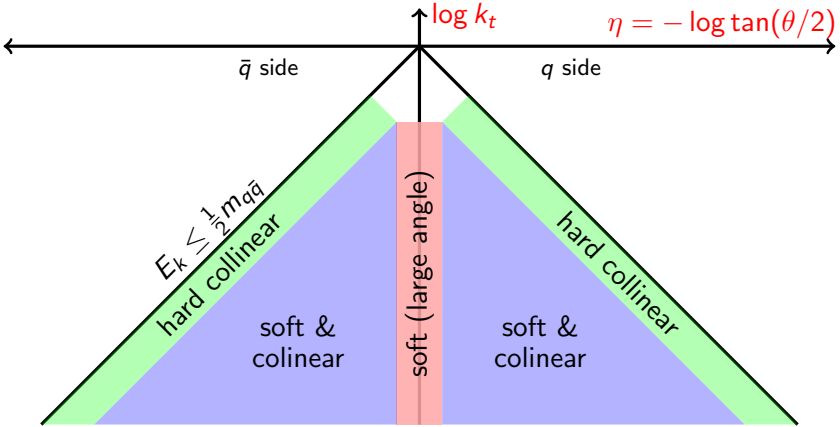
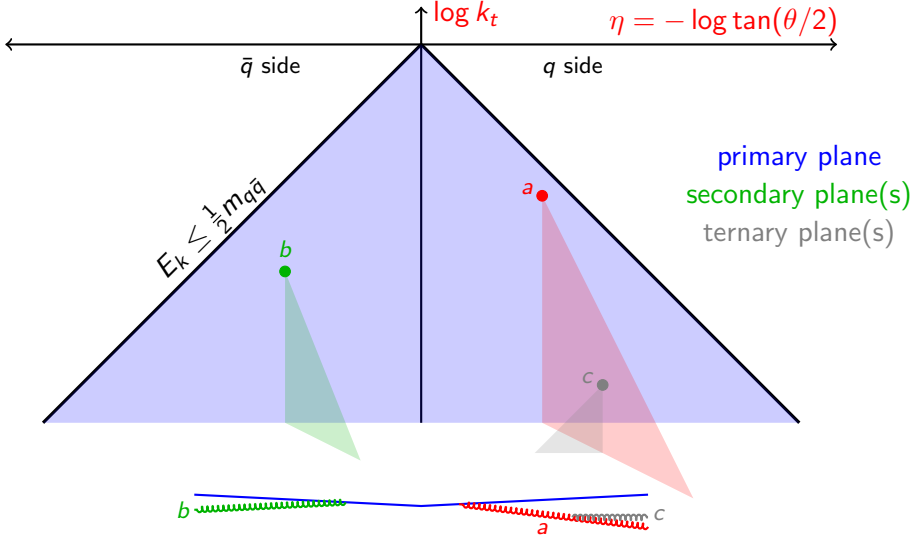
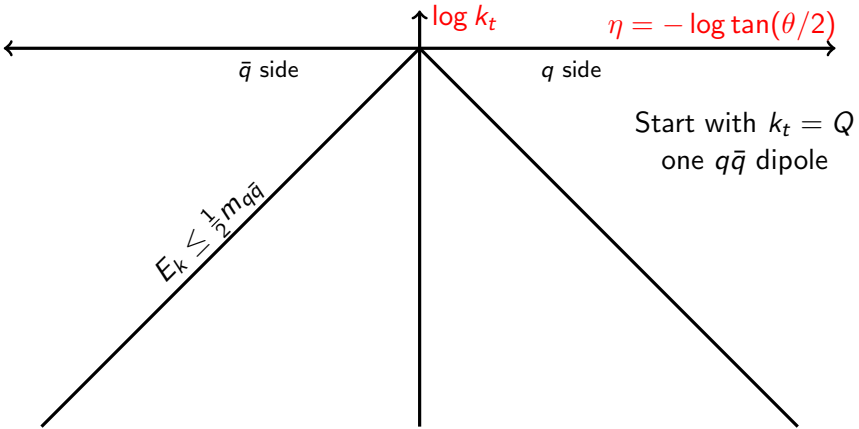


Multiple emissions in the Lund plane



(Dipole) parton shower in the Lund plane

Ordering variable: transverse momentum k_t



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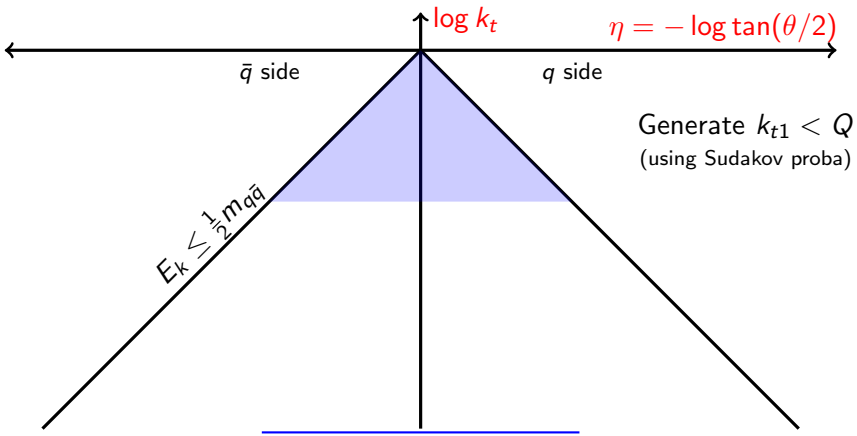

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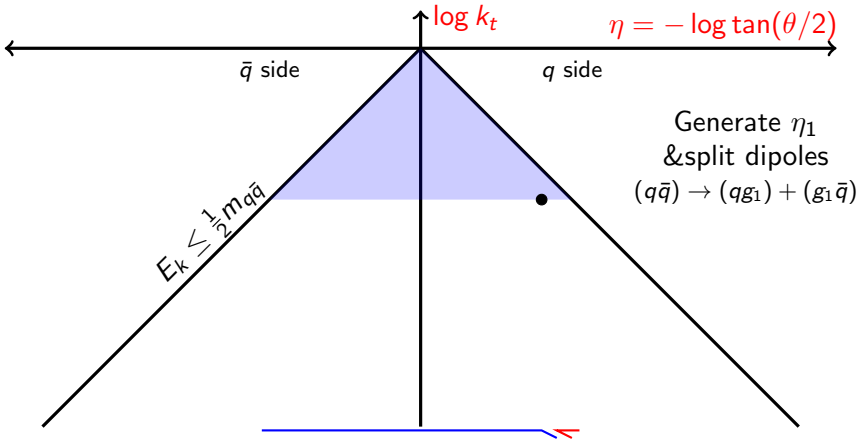

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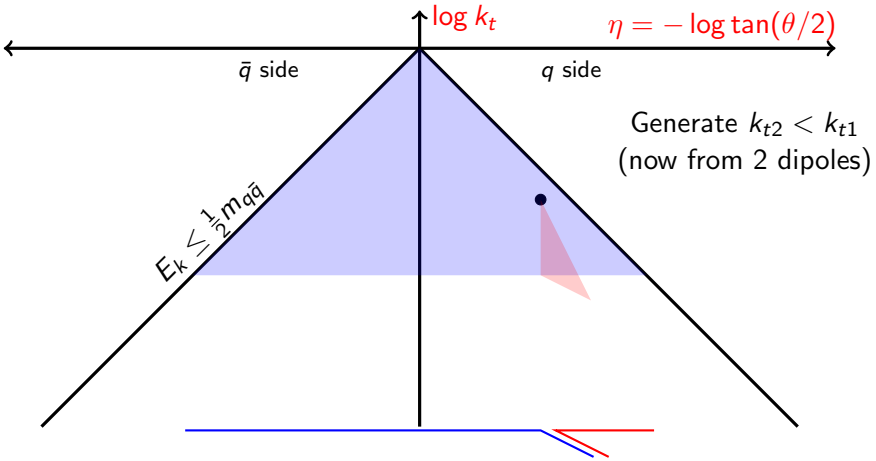

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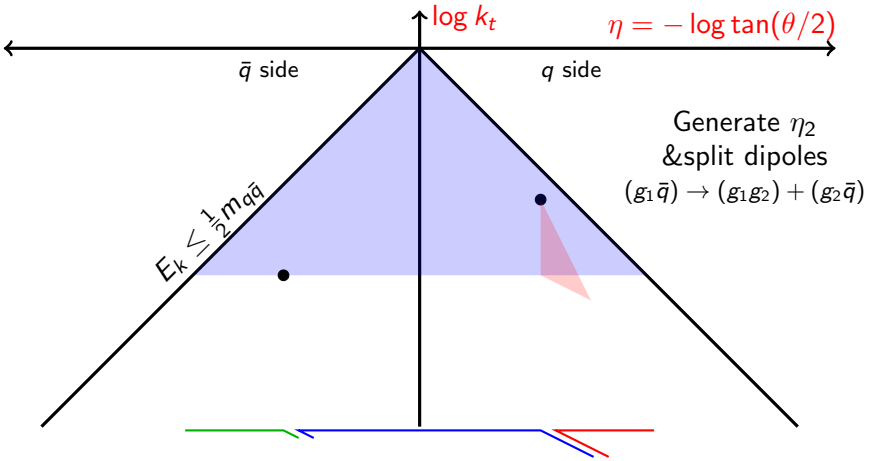

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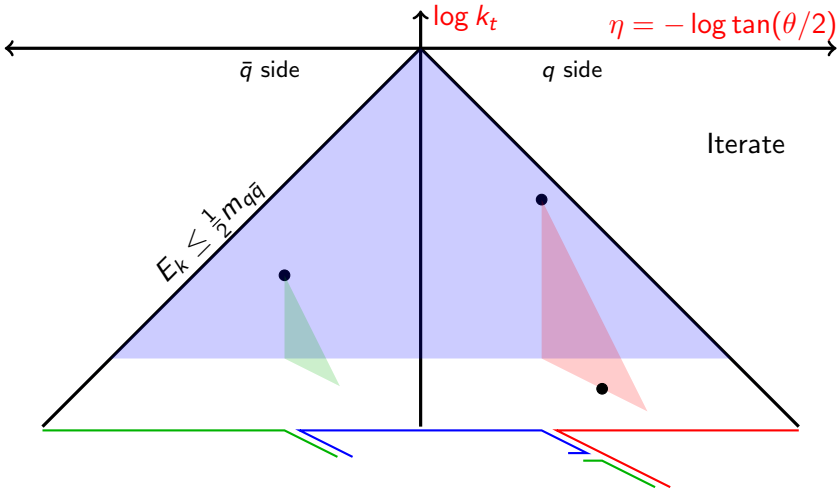

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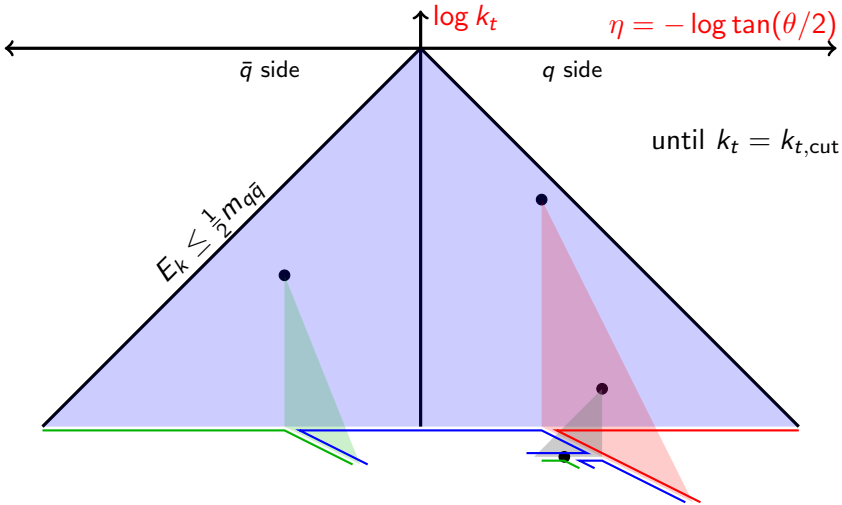


Physics result #1: an organising principle:

at a given (all-order) accuracy, what physics do we need to get right?

Accuracy $\leftrightarrow$ reproducing sets of MEs

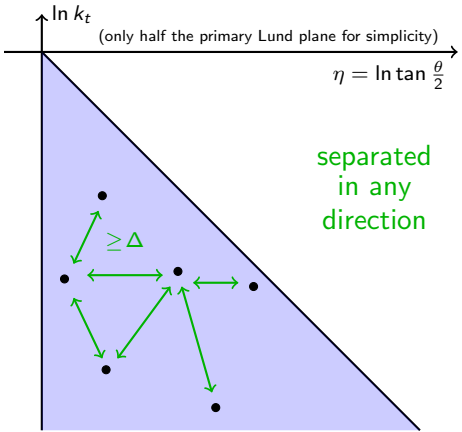
handles disparate scales
all-order perturbative QCD

$\Downarrow$

minimum: get the ME for an arbitrary number of well-separated emissions

- If "log distance" Δ emissions factorise up to $\mathcal{O}(e^{-\Delta})$ corrections
- this achieves NLL accuracy

  i.e. all-order NLL is like fixed-order LO
- In particular, in a parton showers, an emission should not be affected by subsequent distant emissions



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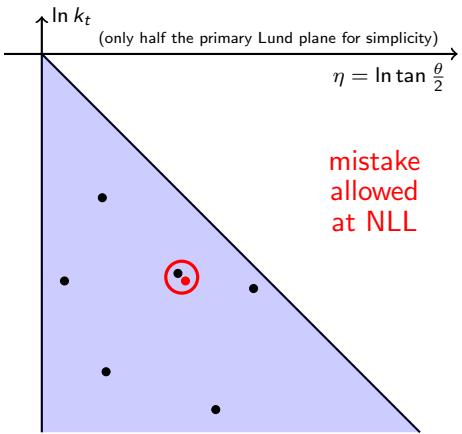


Accuracy $\leftrightarrow$ reproducing sets of MEs

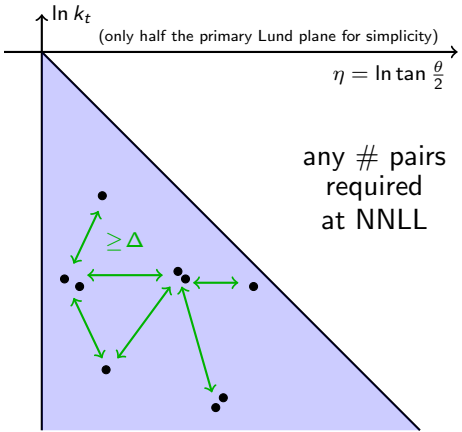
handles disparate scales
all-order perturbative QCD

$\Downarrow$

minimum: get the ME for an arbitrary number of well-separated emissions (NLL!)

Beyond NLL

- At NNLL we also want an arbitrary number of pairs of emissions
- N^{3}LL also requires triplets, etc...



Accuracy $\leftrightarrow$ reproducing sets of MEs

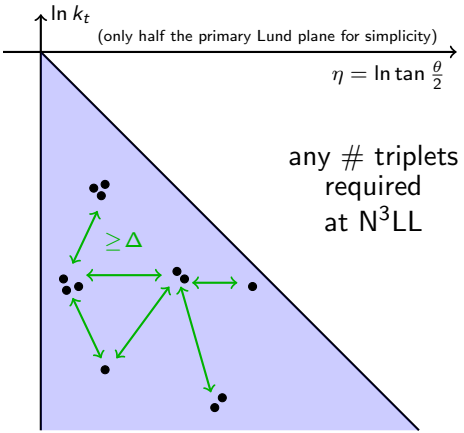
handles disparate scales
all-order perturbative QCD

$\Downarrow$

minimum: get the ME for an arbitrary number of well-separated emissions (NLL!)

Beyond NLL

- At NNLL we also want an arbitrary number of pairs of emissions
- N^{3}LL also requires triplets, etc...



For resummation experts:
- N^{k}LL counts exponentiating observables: $\Sigma(v) = e^{g_1(\alpha_s L)L + g_2(\alpha_s L) + g_3(\alpha_s L)\alpha_s + \dots}$
  NNLL requires any number of well-separated pairs, triplets for N^{3}LL, ...
- N^{k}DL counts observable logs: $\Sigma(v) = h_1(\alpha_s L^2) + h_2(\alpha_s L^2)\sqrt{\alpha_s} + h_3(\alpha_s L^2)\alpha_s + \dots$
  DL has only soft&collinear, NDL has a unique single-log,
  NNDL has a unique pair or two single-logs, etc...

Accuracy ↔ reproducing sets of MEs

handles disparate scales
all-order perturbative QCD

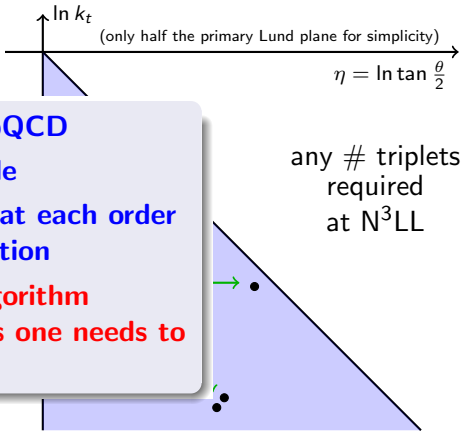
⇓

minimum: get the M
of well-separat

Beyond NLL

- At NNLL we also
  pairs of emissions
- N^{3}LL also requires

- **Robust construction in pQCD**
- **Systematically improvable**
- **"only" a handful of ME at each order thanks to QCD factorisation**
- **difficulty: the shower algorithm generates spurious terms one needs to avoid/correct for**



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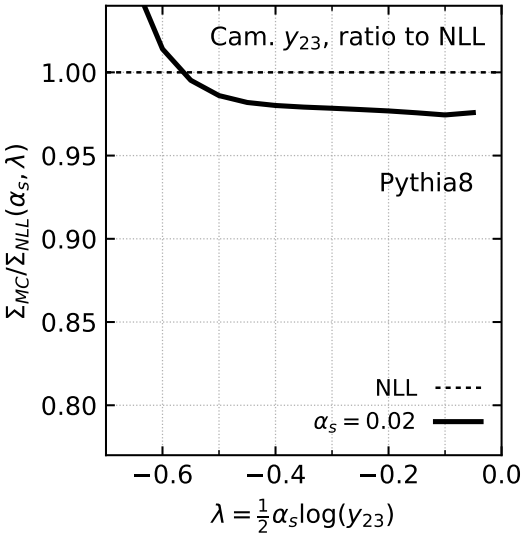
Physics result #2: NLL-accurate showers

Novel approach for testing accuracy



Resummation regime: $\alpha_s \log(v) \sim 1$, $\alpha_s \ll 1$

Idea for NLL testing:

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

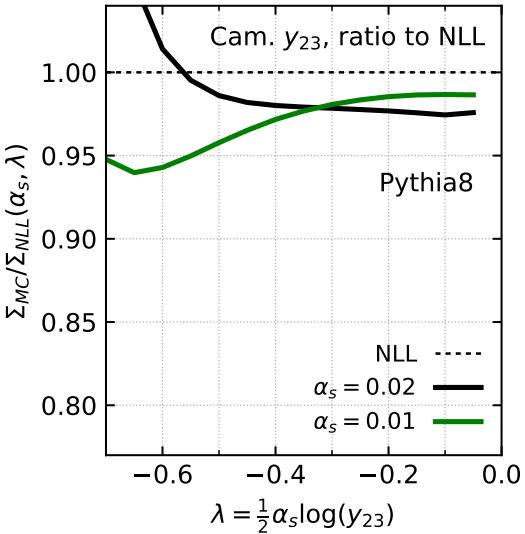
with $\lambda = \alpha_s L$

NLL deviations

or

subleading effects?

Novel approach for testing accuracy



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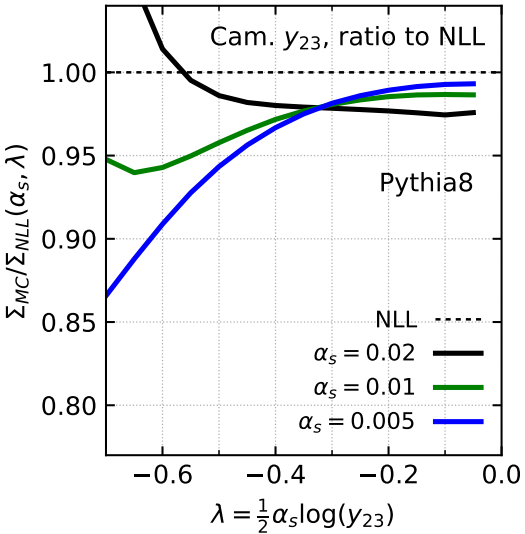

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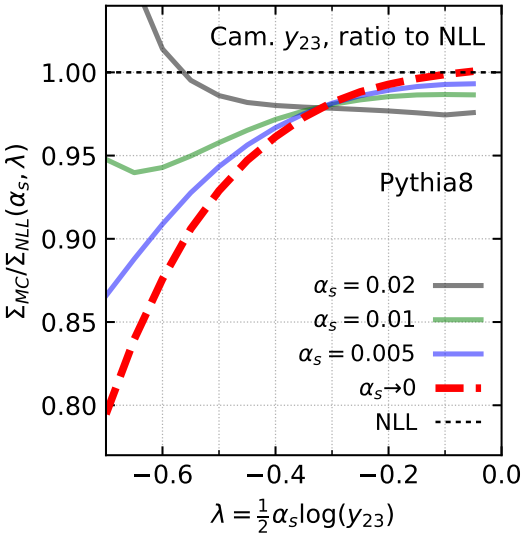


Resummation regime: $\alpha_s \log(v) \sim 1$, $\alpha_s \ll 1$

Idea for NLL 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?~~

Assessing accuracy: y_{23}

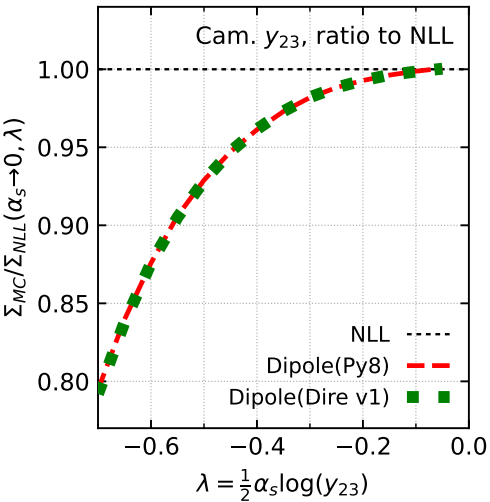
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]

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

Failure of standard dipole showers

Pythia8, Dire(v1) deviate from NLL

Reason:
spurious recoil for commensurate-k_t emissions at disparate angles violates our NLL ME requirement



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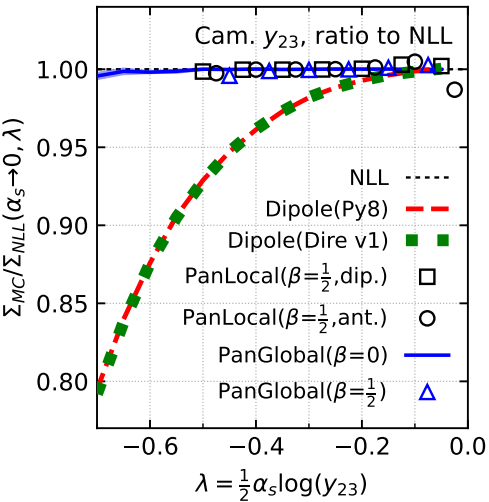
Failure of standard dipole showers

Pythia8, Dire(v1) deviate from NLL

New series of NLL-accurate showers

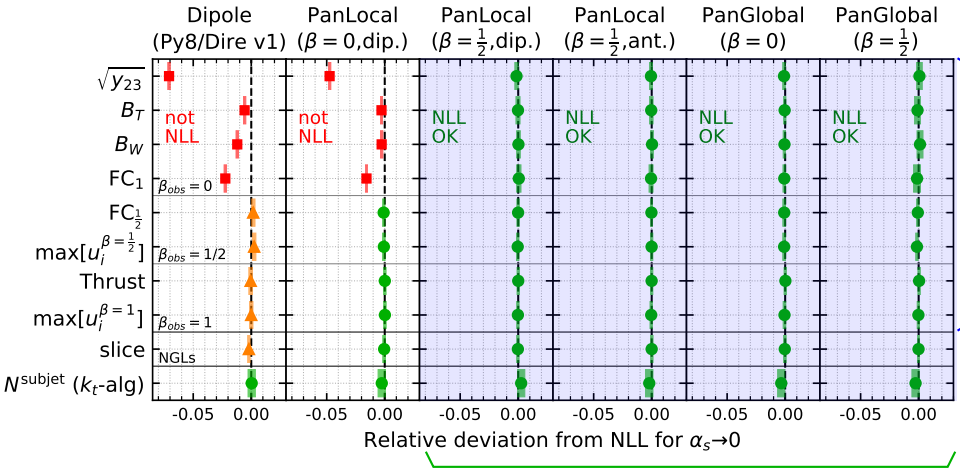
PanLocal($0 < \beta < 1$): local recoil (dipole or antenna)

PanGlobal($0 \leq \beta < 1$): global recoil



Assessing accuracy: extensive observable list

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



green: OK at NLL

orange: fixed-order issues

red: fixed- and all-order issues

global event shapes (different scalings)

non-global

multiplicity

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

More progress with NLL-accurate showers

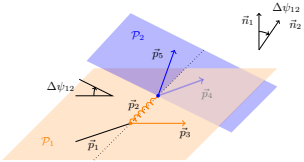
Beyond large N_c (backup)

(collinear & soft) spin correlations

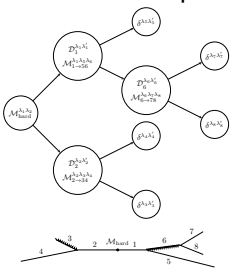
hadronic collisions DIS/VBF (backup)

Physics:

$\Delta\psi$ distribution due to spin correlations

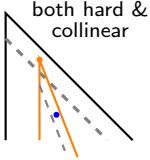


Solution: adapt the Collins-Knowles alg.

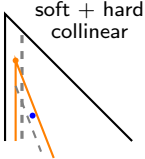


build and update a spin correlation tree as shower progresses

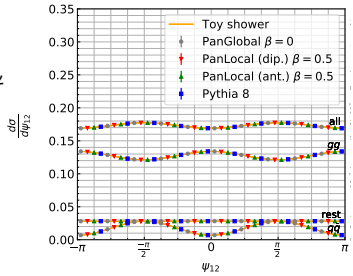
Tests:

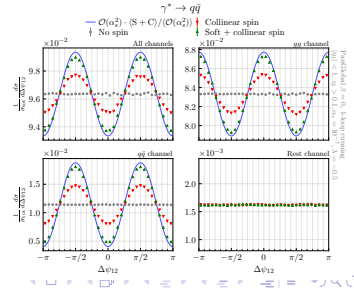


also EEEC v. analytics



first all-order result

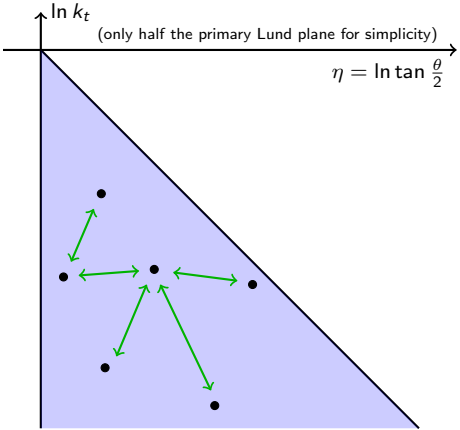




Physics result #3: towards NNLL-accurate showers

(NNLL) accuracy $\leftrightarrow$ reproducing (extra) sets of MEs

NNLL: include pairs of emissions



(NNLL) accuracy $\leftrightarrow$ reproducing (extra) sets of MEs

NNLL: include pairs of emissions

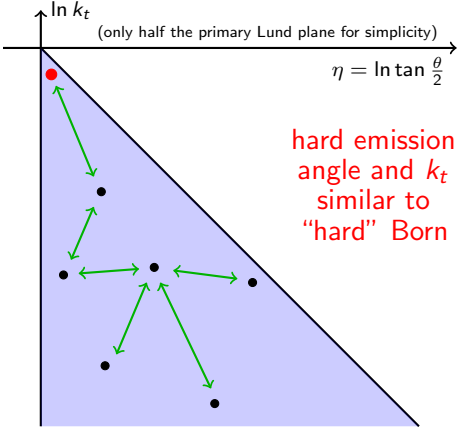
Matching

Get exact 3-jet LO (2-jet NLO) ME

$\equiv$ one hard emission (pair with the hard event)

Standard approaches work but require care to preserve NLL accuracy

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



(NNLL) accuracy $\leftrightarrow$ reproducing (extra) sets of MEs

NNLL: include pairs of emissions

Matching

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

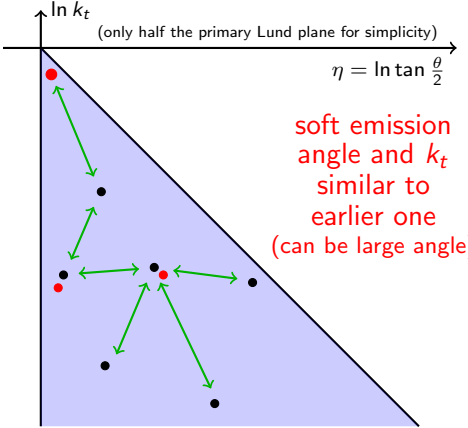
Double-soft corrections

Two soft emissions at commensurate angles and k_t
(not necessarily collinear)

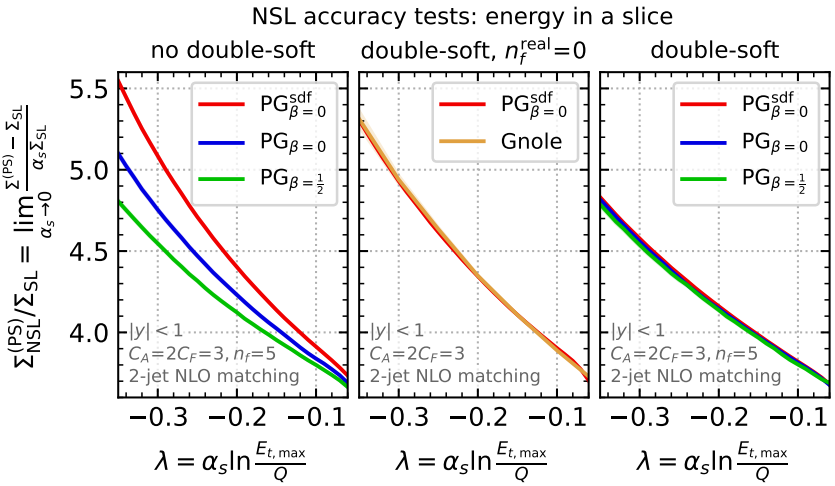
- Correction spurious shower ME $\rightarrow$ correct ME
  watch out for flavour channels and colour flows
- Need to get the correct virtual contributions
  (done through a modified K_{CMW})

Gain: state-of-the-art (next-to-single-log) non-global logs

[S.Ferrario Ravasio,K.Hamilton,A.Karlberg,G.P.Salam,L.Scyboz,GS,arXiv:2307.11142]



Beyond NLL: double-soft corrections



Successfully reproduce next-to-single (non-global) logs for emissions in a slice

Conclusions and perspectives

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
- Included at NLL: subleading-N_c, spin correlations, hadron collisions
- First NNLL ingredients: (ee) 3-jet matching, double-soft corrections
- Prelim pheno effect: reduction of uncertainty at $Q \sim 100$ GeV (larger effects at $Q \sim 1$ TeV)

Future

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

Parton shower meets gravity?

Open question

Can this have connections with "gravity"?

I am definitely not sure...
... but parton showers likely apply for weekly-coupled problems with widely separated scales.

Can that be helpful for extreme mass ratios? Is there some $\log(v/c)$ enhancements?

Backup

What do Event Generators provide?

Broad range of applications

↓

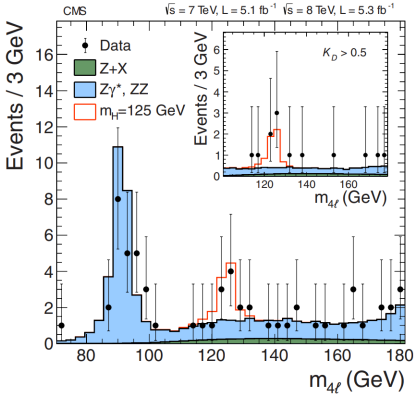
Searches

Background (and signal) estimate

Example:

$H \to ZZ \to 4\ell$

[CMS, arXiv:1207.7235]



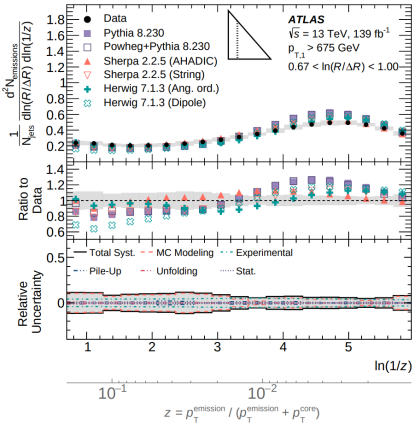
What do Event Generators provide?

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

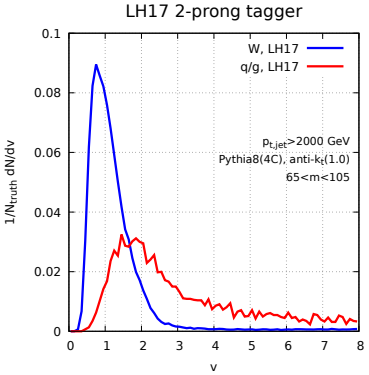
Example:
top mass measurement
[ATLAS-CONF-2019-046]

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^{ISR}	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

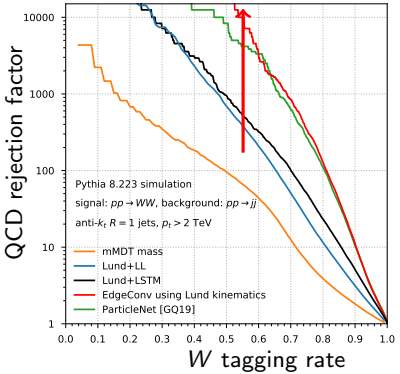
What do Event Generators provide?

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]



Dipole/Antenna showers: ingredients

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

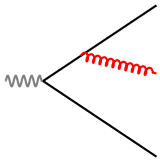
Dipole/Antenna showers: ingredients

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

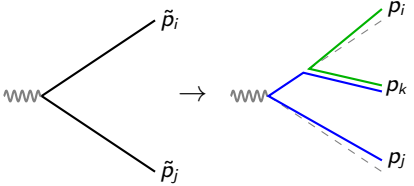
Idea #1:

gluon emission $\equiv$ dipole splitting

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



viewed as



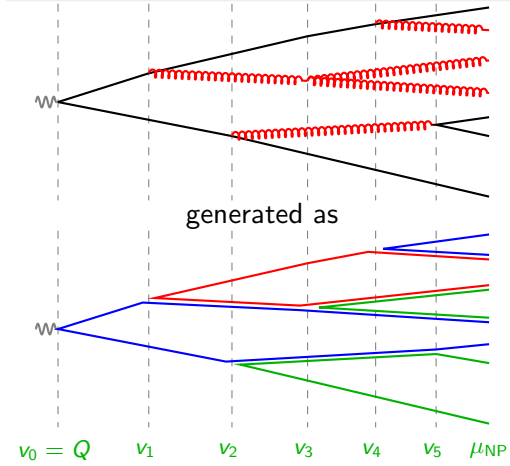
- captures the soft/collinear limits
- key ingredient: mapping

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

includes recoil
& energy-mom conservation

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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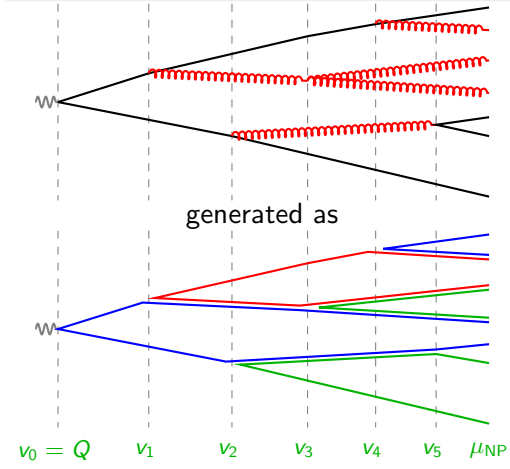

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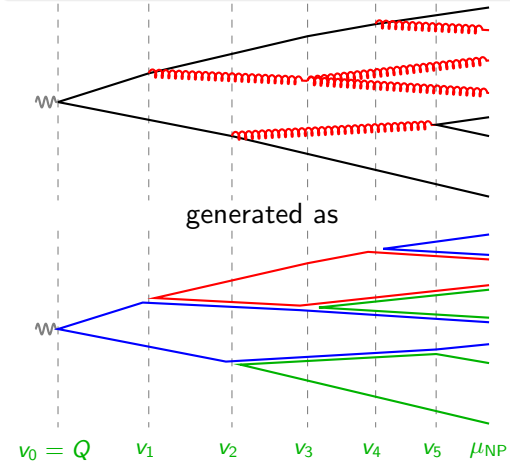
Rooted in QCD factorisation

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

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

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)

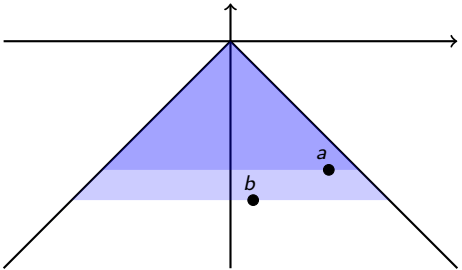
Several challenges:

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

Different ordering variables...

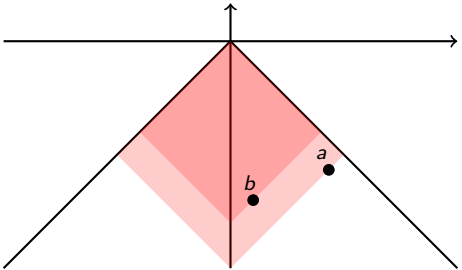
... can lead to different emission orderings

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]

Testing the shower logarithmic 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 the shower logarithmic accuracy

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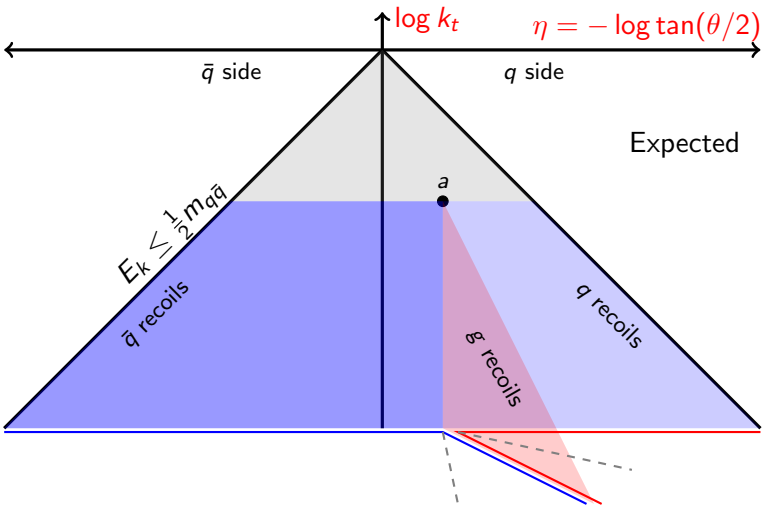
$$\mathcal{O}(1/\alpha_s) \qquad \mathcal{O}(1) \qquad \mathcal{O}(\alpha_s)$$

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

Lund-plane representation: transverse recoil boundaries



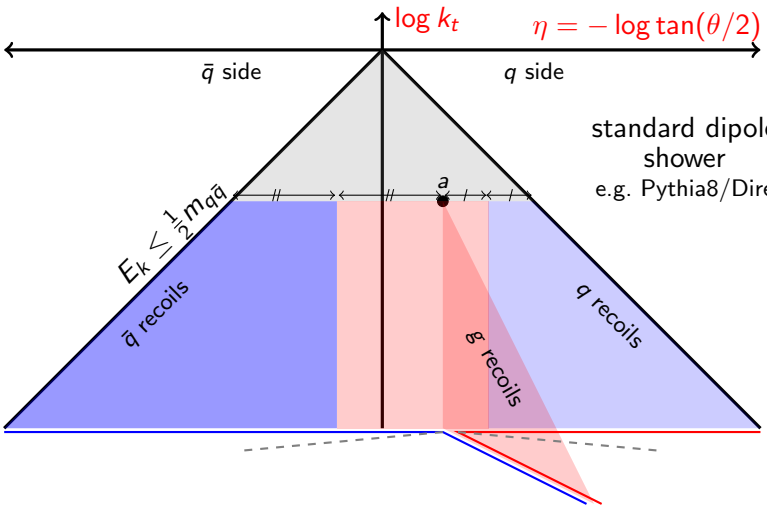
gluon a radiated at scale k_{ta} and angle θ_a

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



standard dipole shower
e.g. Pythia8/Dire

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

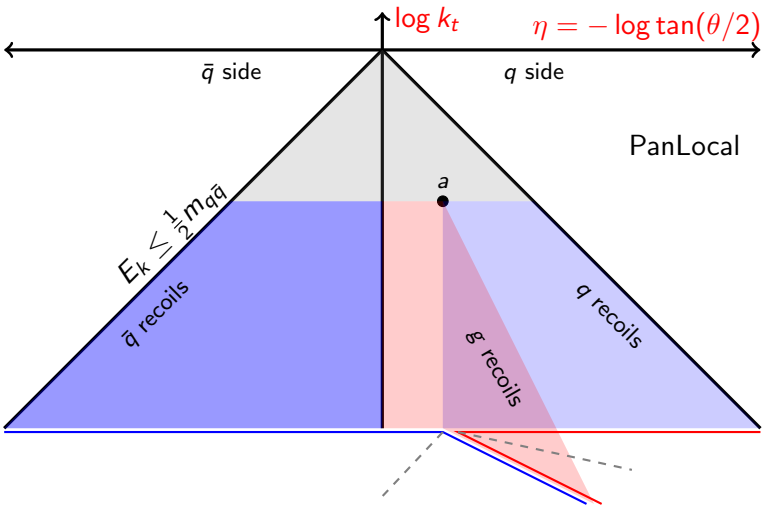
standard dipole shower

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 $\theta_{ab} < \theta_a$

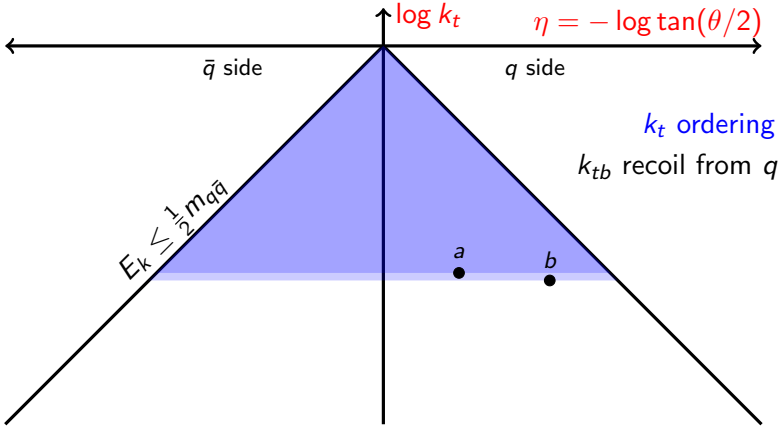
PanLocal (step 1)

decided in event frame:
a takes recoil if

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

better but still WRONG!

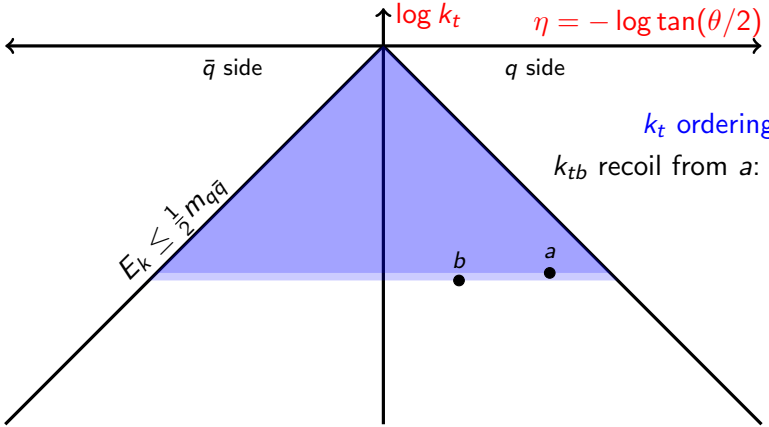
Lund-plane representation: PanLocal evolution variable



k_t ordering

k_{tb} recoil from q: OK

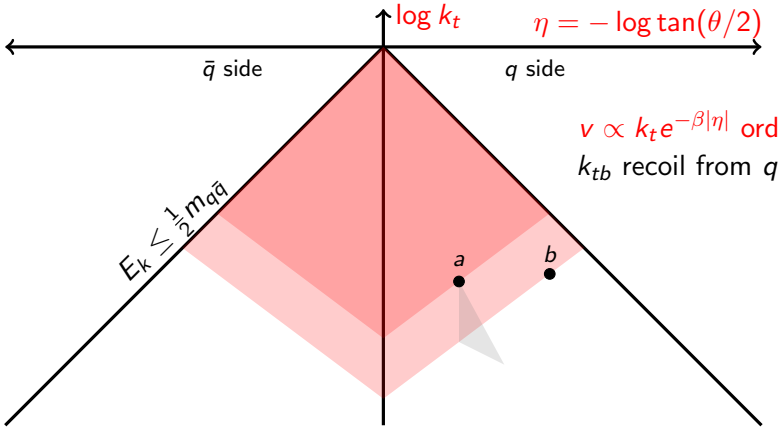
Lund-plane representation: PanLocal evolution variable



k_t ordering

k_{tb} recoil from a: not OK

Lund-plane representation: PanLocal evolution variable



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 $\tilde{\eta}$)

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

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

f decides where to put recoil

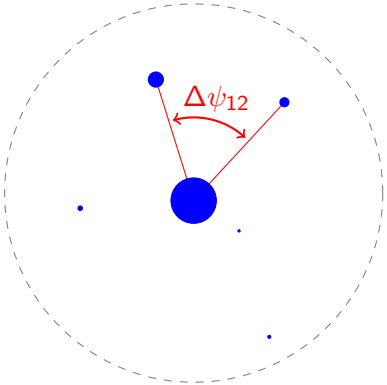
- $f \to 1$ when $k \to i$
- $f \to 0$ when $k \to j$

Where to put the transition?

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

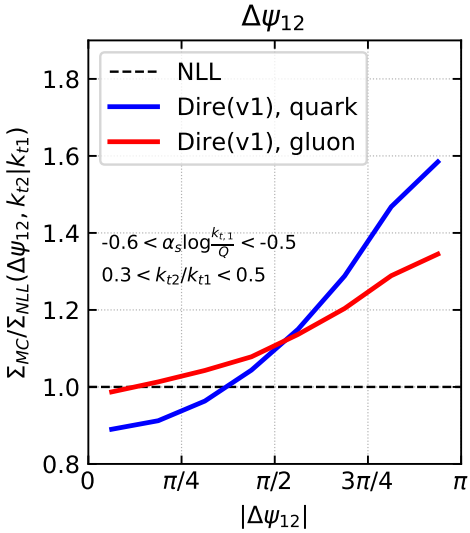
A last example

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



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



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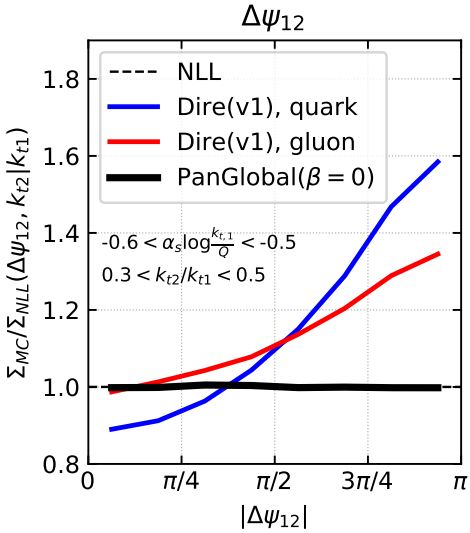

A last example

- Look at angle $\Delta\psi_{12}$ between two hardest "emissions" in jet
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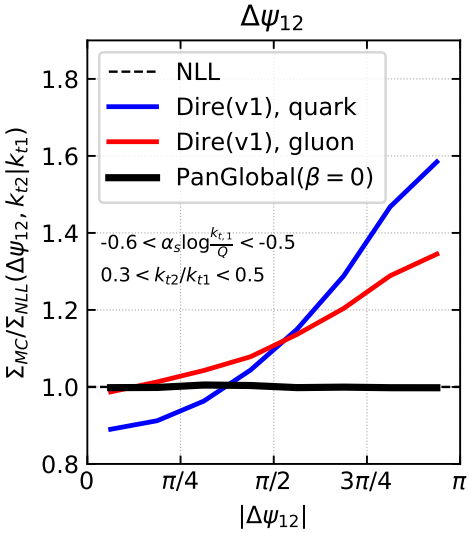
- quite large NLL deviations in current dipole showers
- differences between quark and gluon jets
- PanScales showers (here PanGlobal) get the correct NLL
- ML could "wrongly/correctly" learn this



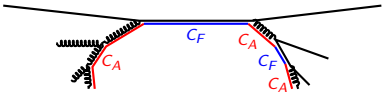
Beyond large N_c

(collinear & soft) spin correlations

hadronic collisions

Physics:

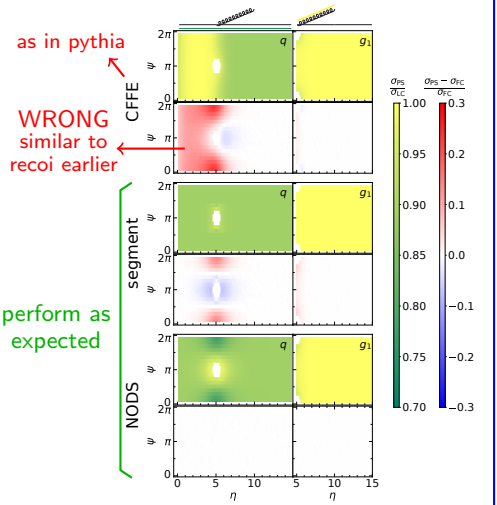
Keep track of the C_F–$C_A/2$ transitions



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:



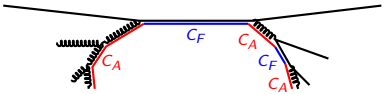
Beyond large N_c

(collinear & soft) spin correlations

hadronic collisions

Physics:

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



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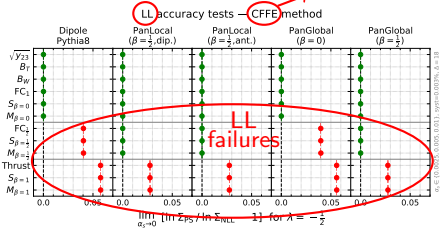
   (soft) $q\bar{q}g$ matrix-element correction
   also OK for 2 emissions at $\sim$ angles

All-order tests:

as in pythia



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

(Collinear) spin correlations

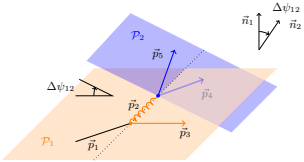
Beyond large N_c

(collinear & soft) spin correlations

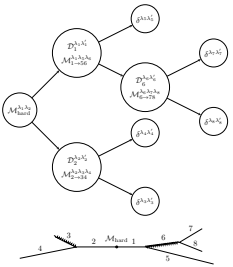
hadronic collisions

Physics:

$\Delta\psi$ distribution due to spin correlations



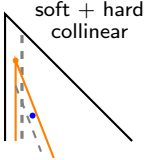
Solution: adapt the Collins-Knowles alg.



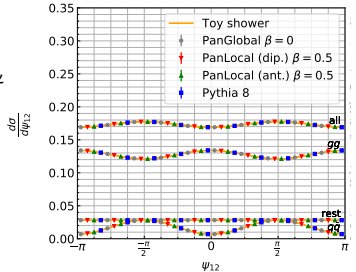
build and update a spin correlation tree as shower progresses

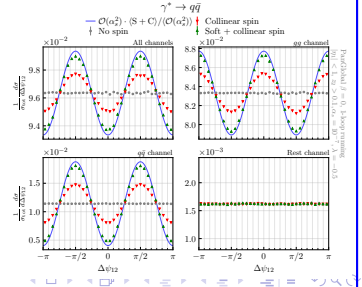
Tests:

also EEEC v. analytics



first all-order result





Beyond large N_c

(collinear & soft) spin correlations

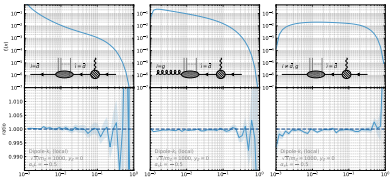
hadronic collisions

Physics:

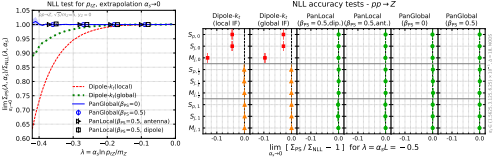
- hadron collision
  $\Rightarrow$ initial-state radiation
- Consider Drell-Yan
- existing showers have the same recoil issue as for final state
  earlier emission takes recoil instead of the Z
- fix is essentially the same
  (modulo kinematic differences)
- includes colour and spin
- so far limited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

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$^{(*)}$

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

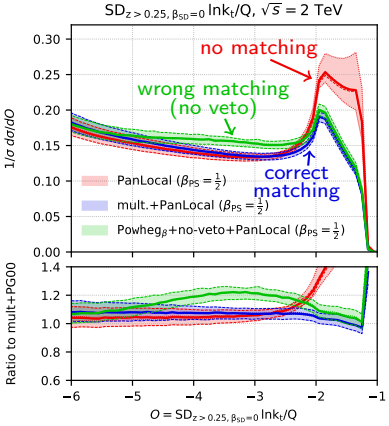
Implementation

Several possibilities:

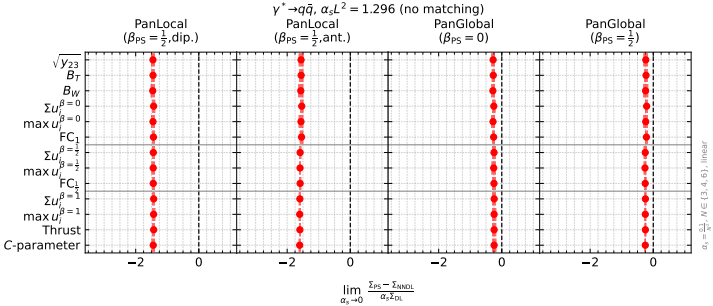
- simple multiplicative matching (accept first emission with probability $P_{\text{exact}}/P_{\text{shower}}$)
- MC@NLO-like matching
- POWHEG-like matching (with β scaling and careful veto to avoid double-counting when switching from POWHEG to the shower)

$^{(*)}$ 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

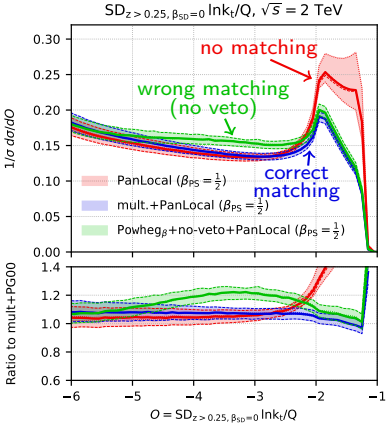


- visible effect at large k_t (right)
- spurious effect if not careful
- "correct" matching OK everywhere



- no matching ⇒ wrong NNDL

Accuracy tests



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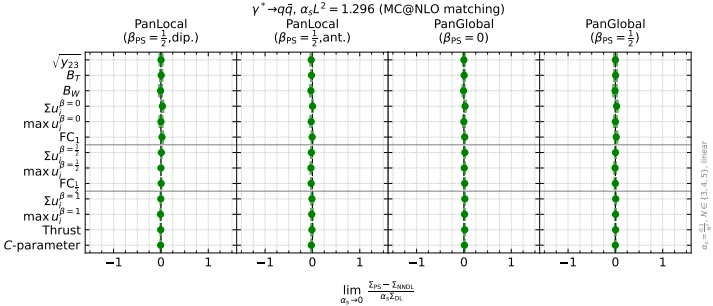
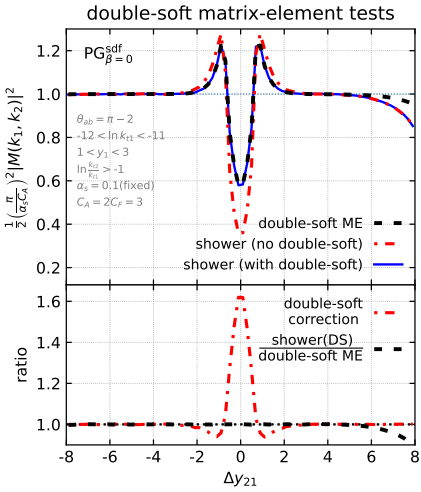
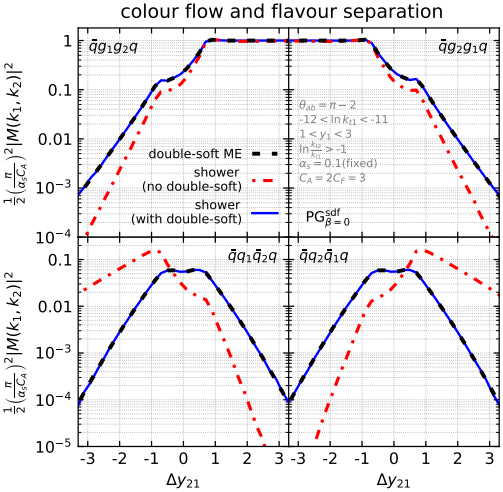


- no matching ⇒ wrong NNDL
- with matching ⇒ OK at NNDL

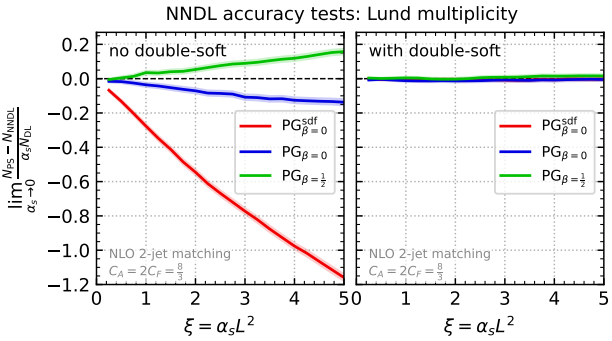
Extra double-soft results: matrix-element tests



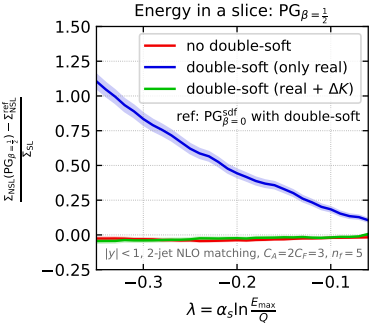


Correct reproduction of the double-soft matrix elements

Extra double-soft results: multiplicity, δK

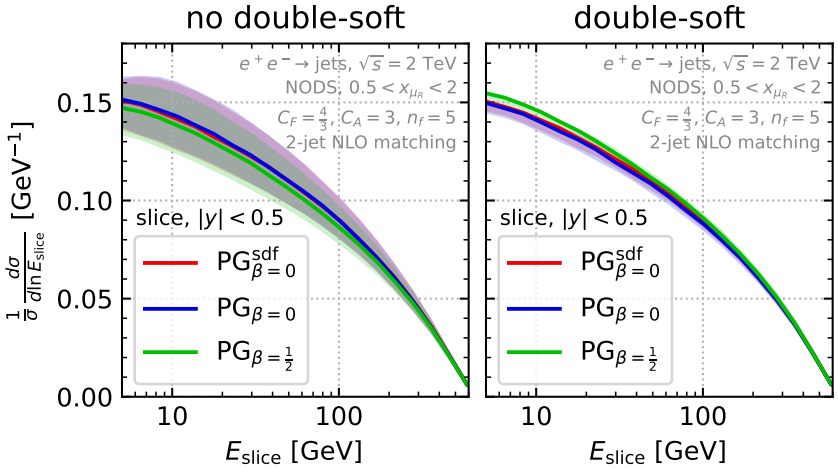


Reproduces NNDL multiplicity



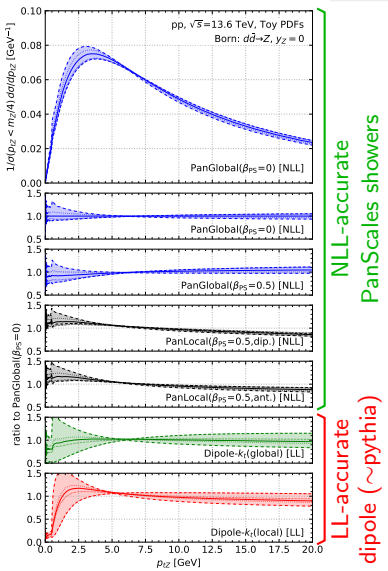
Requires the correct K_{CMW} prescription

Extra double-soft results: multiplicity, δK



No large shift of central value but large reduction of the uncertainty estimates

Example #1: Z-boson transverse momentum



Uncertainties:

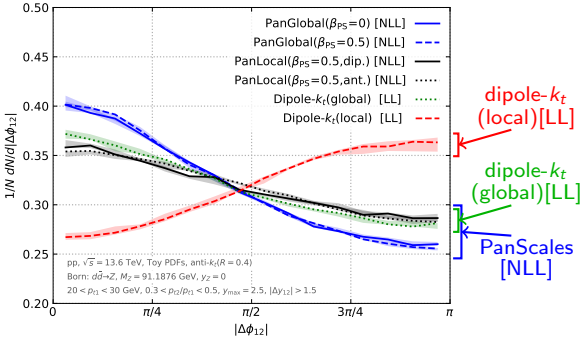
- renormalisation scale variation:
  for NLL-accurate showers include compensation term to maintain 2-loop running for soft emissions
- factorisation scale variations (note: use of toy PDFs)
- term associated with lack of matching for $k_t \sim M_Z$
- for LL showers: a term associated with spurious recoil 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: $\Delta\psi_{12}$

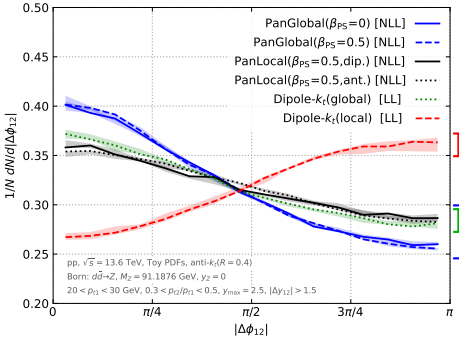
Drell-Yan, $M_Z = 91.1876$ GeV



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

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

Drell-Yan, $M_Z = 91.1876$ GeV

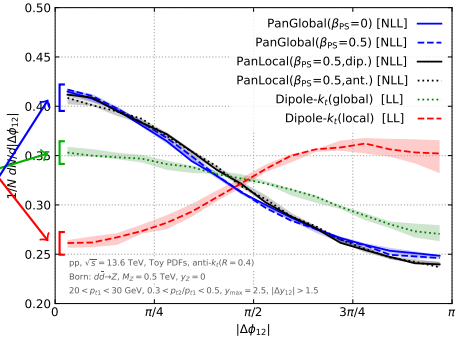


dipole-k_t (local)[LL]

dipole-k_t (global)[LL]

PanScales [NLL]

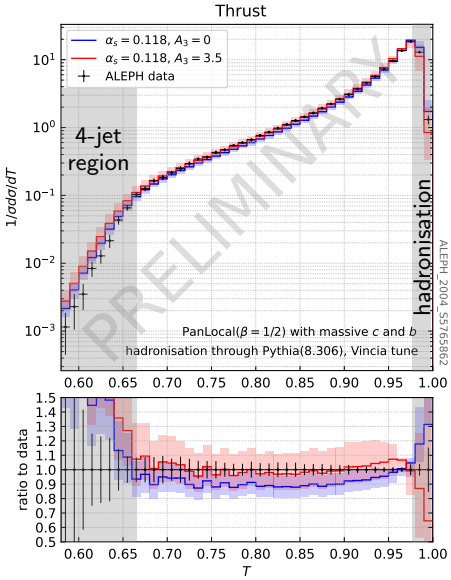
Drell-Yan, $M_{Z'} = 500$ GeV



- 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?