# The quest for precision across scales

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

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Brookhaven National Lab, June 12 2020

# Plan

- Motivate the importance of event generators
- Parton showers
  - What physics goes in?
  - How is it built?
  - Some recent progress
- Assessing parton shower accuracy
- the PanScales showers
  - Solving current issues
  - NLL accuracy

# 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, ...)

Broad range of applications

↓

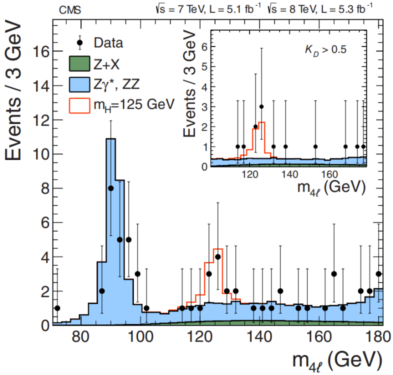
Searches

Background (and signal) estimate

Example:

$H \to ZZ \to 4\ell$

[CMS, arXiv:1207.7235]



# What do Event Generators provide?

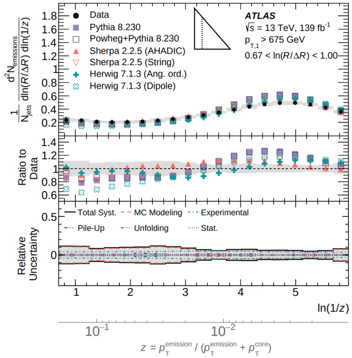
Broad range of applications

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

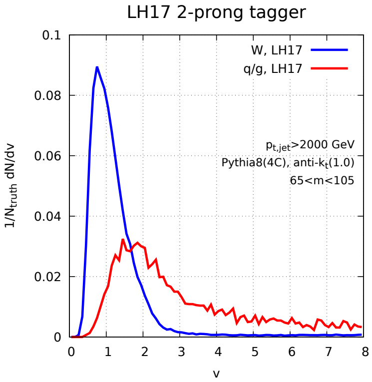
Example:
top mass measurement
[ATLAS-CONF-2019-046]

| 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 $\alpha_S^{FSR}$ | 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

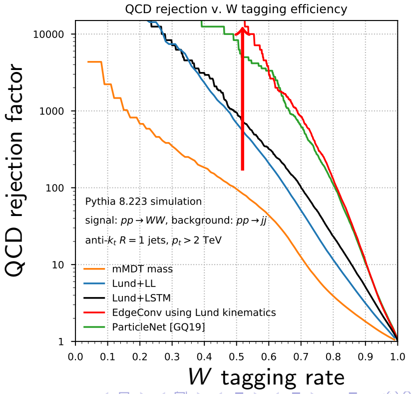
# What do Event Generators provide?

Broad range of applications

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

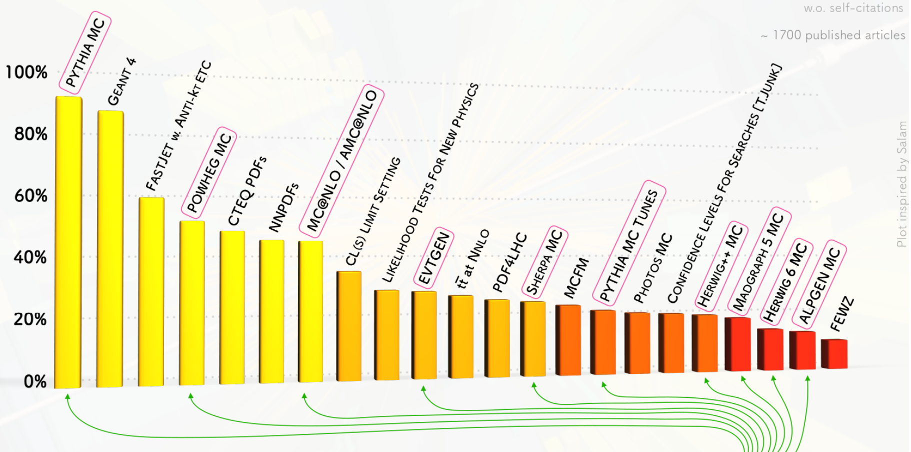
- Deep Learing increasingly used at the LHC
- Shows interesting performance
- Example: boosted $W \to q\bar{q}$ v. QCD jet
- Training often done on MCs.

[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

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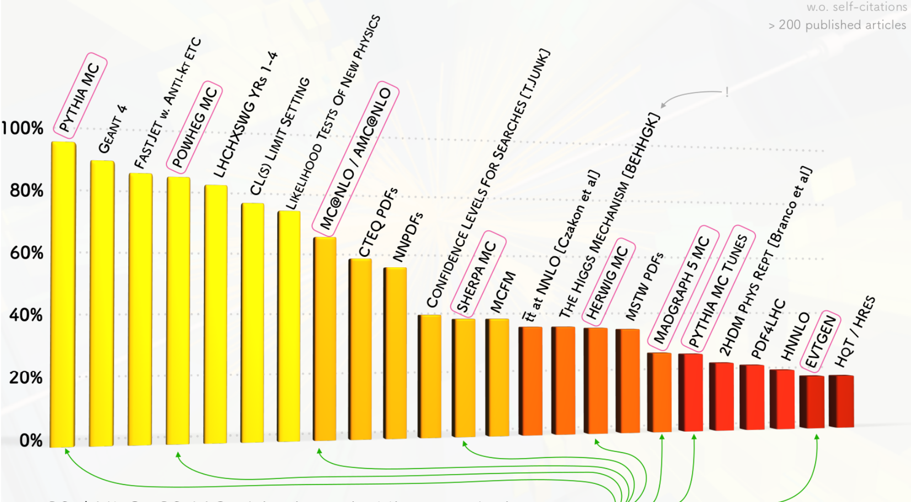


- PS / NLO+PS MC ubiquitous in Higgs analysis

[thanks to Keith Hamilton]

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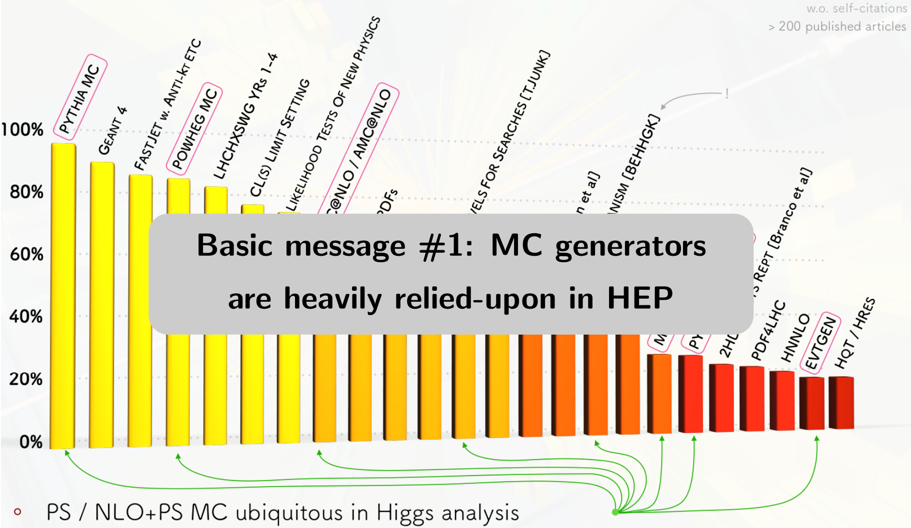


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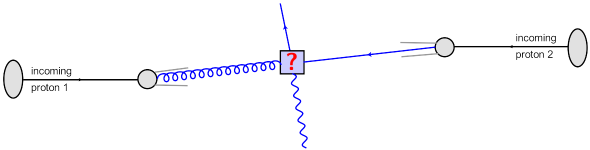
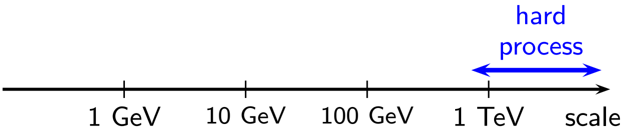
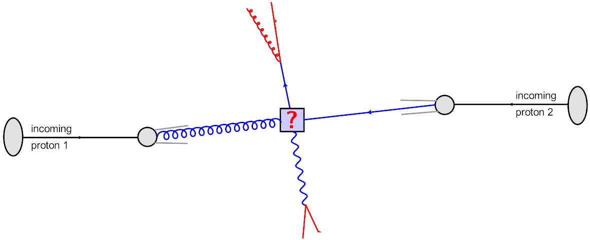
# Anatomy of a high-energy collision




**Simulating a high-energy collision requires several ingredients**

- A hard process




**Simulating a high-energy collision requires several ingredients**

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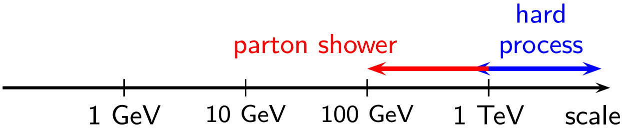

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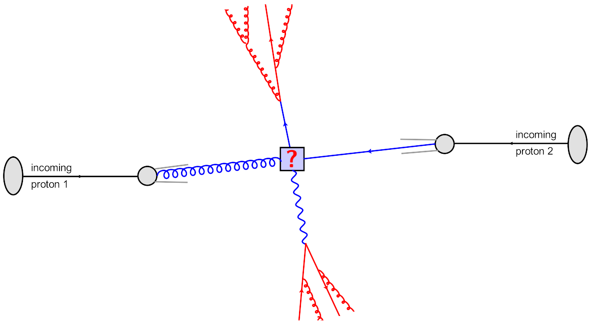


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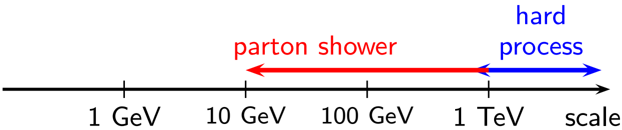

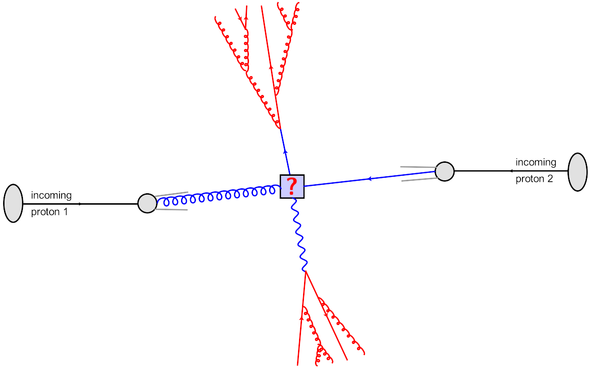


**Simulating a high-energy collision requires several ingredients**

- A hard process
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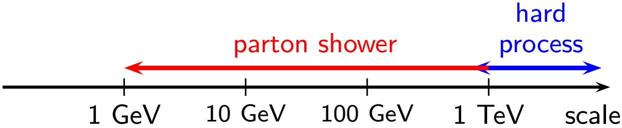
- Hadronisation



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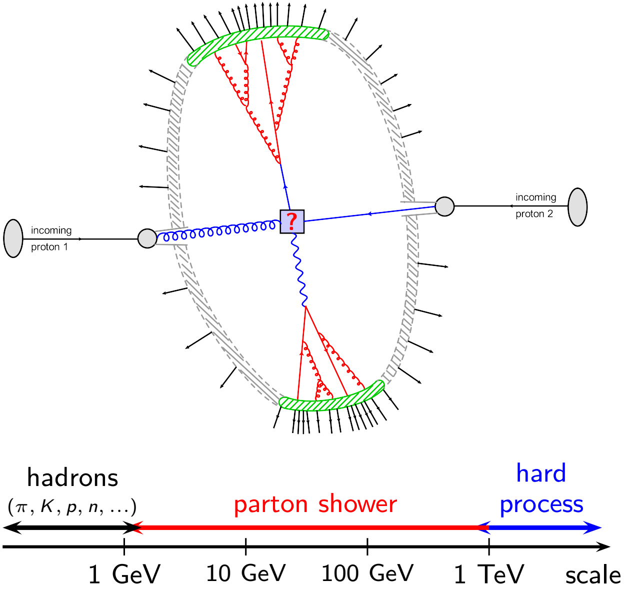



**Simulating a high-energy collision requires several ingredients**

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

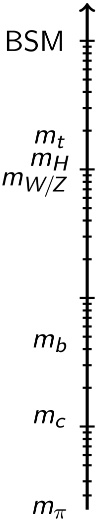
# Basic message #2: physics at all scales

LHC probes physics across many scales

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

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

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



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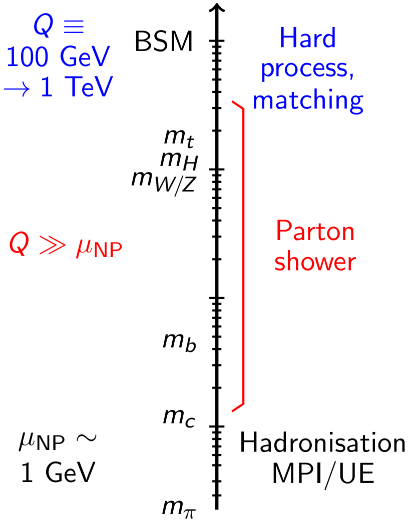

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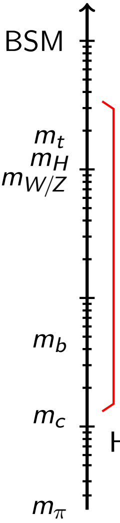


Hard process, matching

Parton shower

Hadronisation MPI/UE

A lot of work in past 20 years:

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

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

Nonperturbative modelling

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

if IRC-safe

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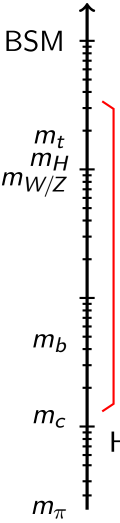


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**This Talk**

Nonperturbative modelling $\propto (\mu_{NP}/Q)^{\#}$ if IRC-safe

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**Basic message #3**

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

# Need for precision

**Basic message #3**

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$\Rightarrow$ 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)

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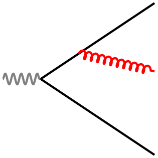
**Idea #1:**

gluon emission $\equiv$ dipole splitting

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

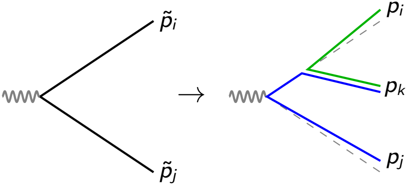


- captures the soft/collinear limits
- key ingredient: mapping

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

includes recoil
& energy-mom conservation

viewed as



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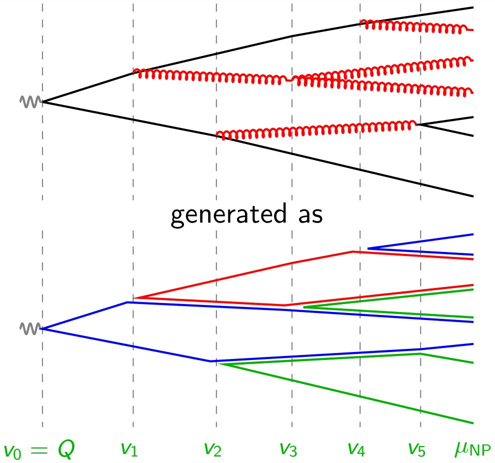


**Idea #2:**

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

Rooted in QCD factorisation

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

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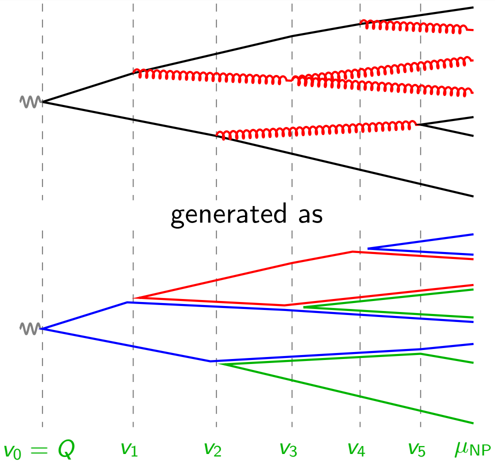


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- $n$, $n+1$ particles probabilities
- Sudakov ≡"no emissions" (virtuals)
- real emission

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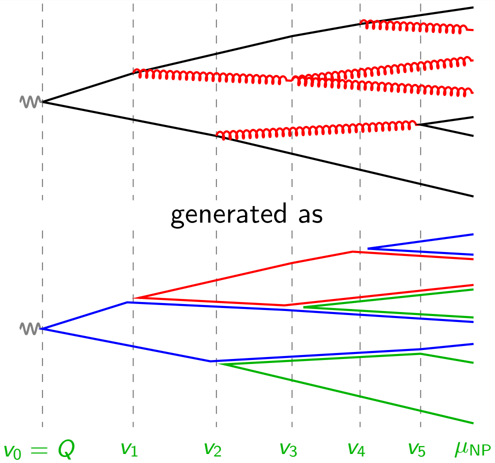



**Idea #2:**

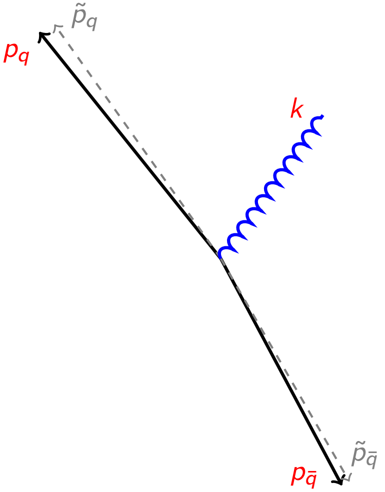
iterate dipole splittings (populate the full phase space with multiple emissions)

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

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

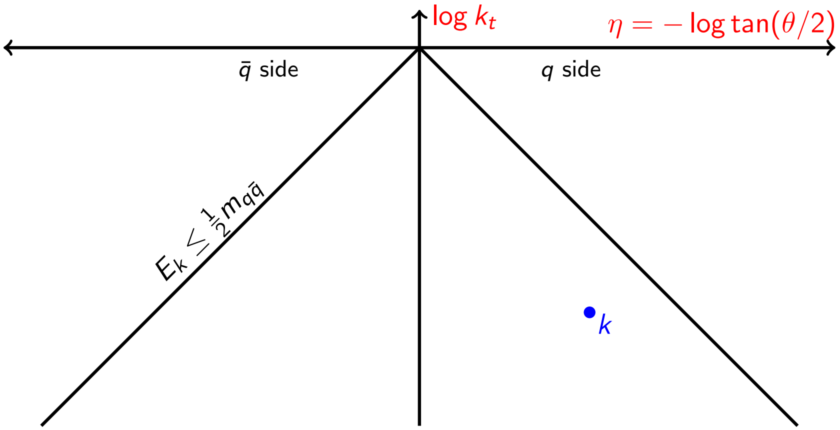
3 degrees of freedom:

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

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 $\eta$ and $\log k_\perp$



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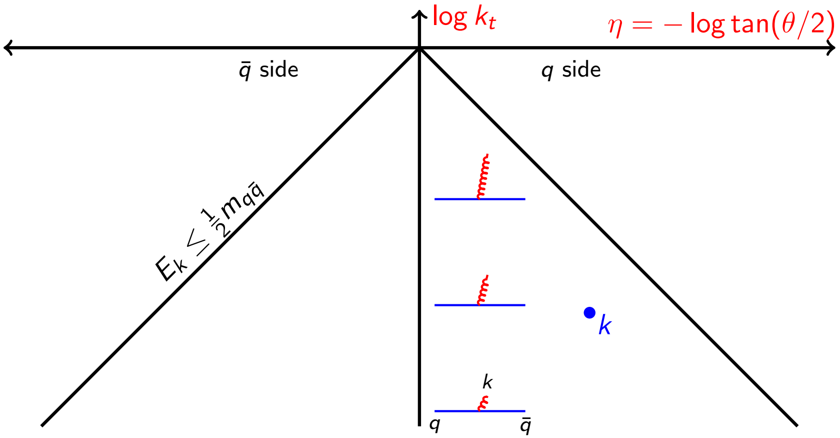

# Basic features of QCD radiations: the Lund plane

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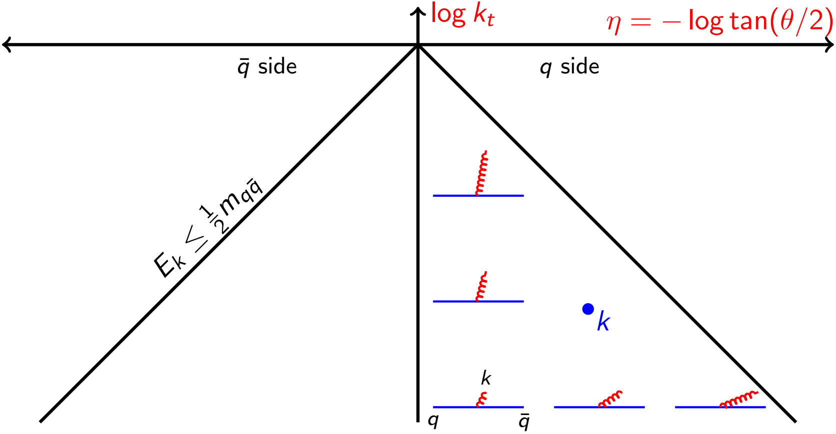

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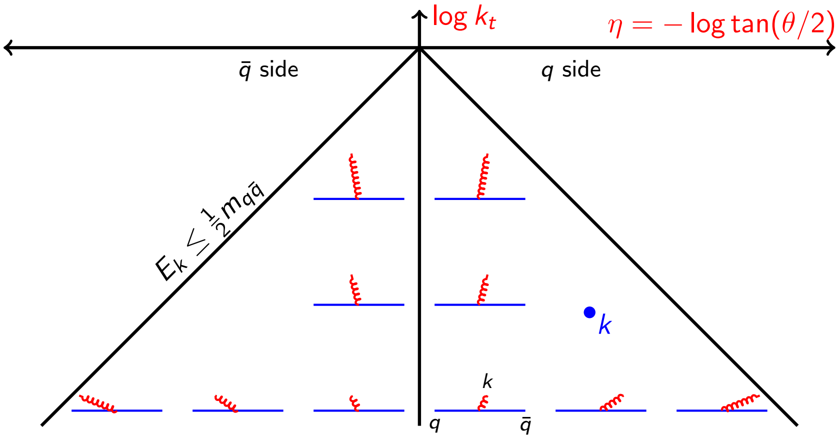

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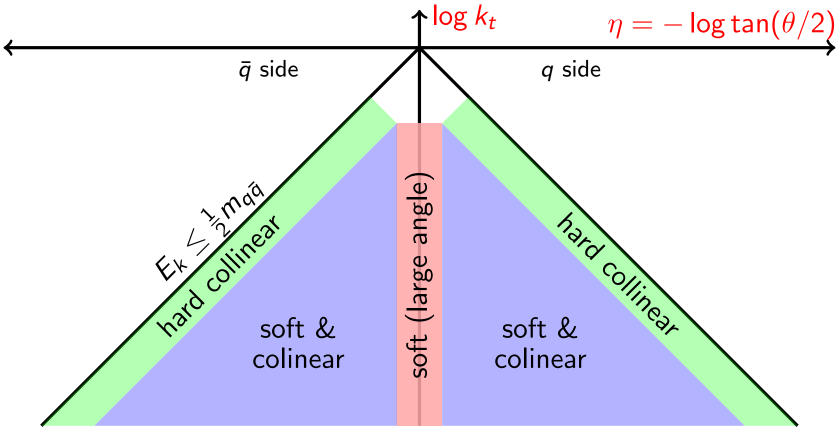
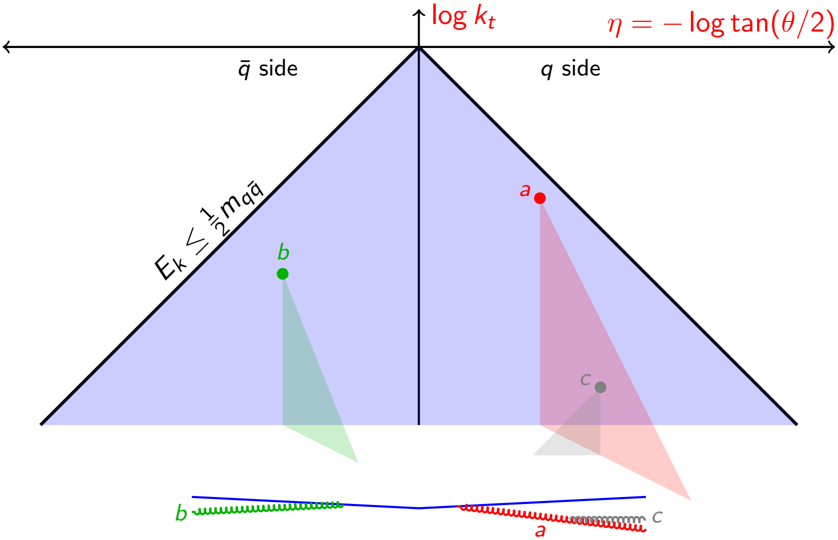
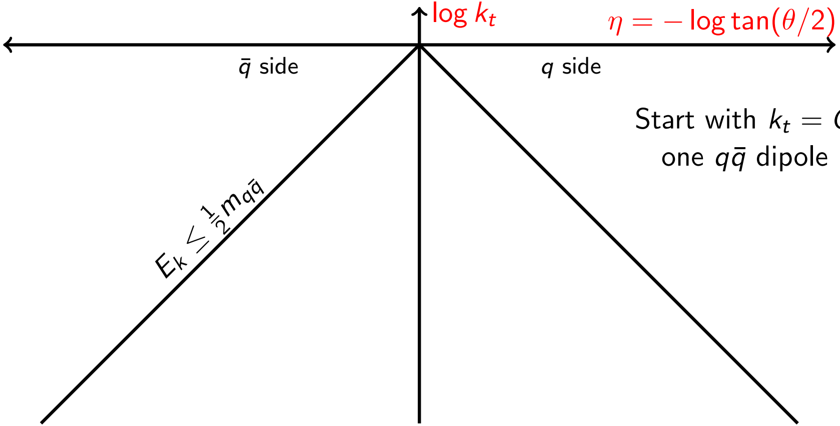


# Multiple emissions in the Lund plane



# Parton shower in the Lund plane

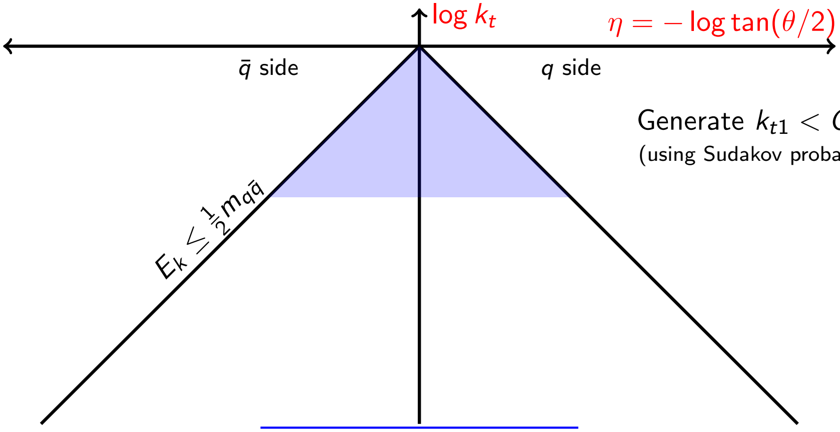
Ordering variable: transverse momentum $k_t$




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

# Parton shower in the Lund plane

Ordering variable: transverse momentum $k_t$




Generate $k_{t1} < Q$

(using Sudakov proba)

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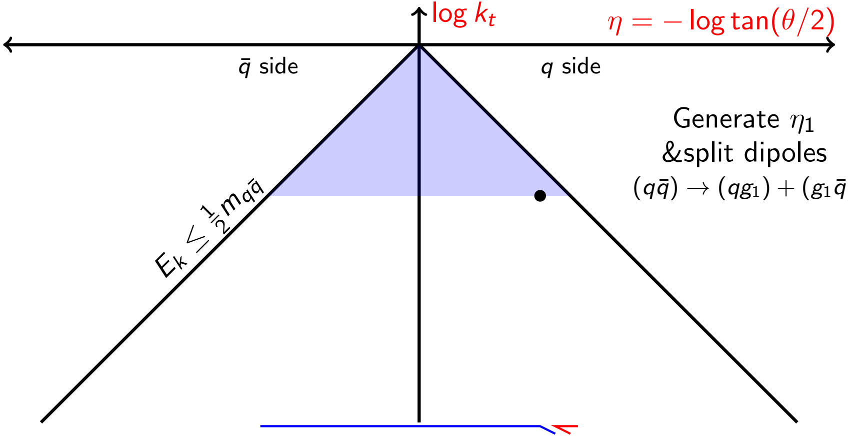
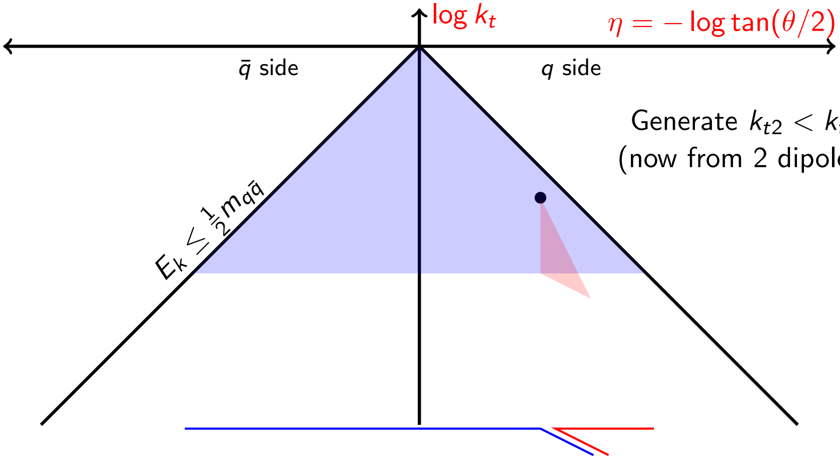
Ordering variable: transverse momentum $k_t$




Generate $\eta_1$
&split dipoles
$(q\bar{q}) \to (qg_1) + (g_1\bar{q})$

# Parton shower in the Lund plane

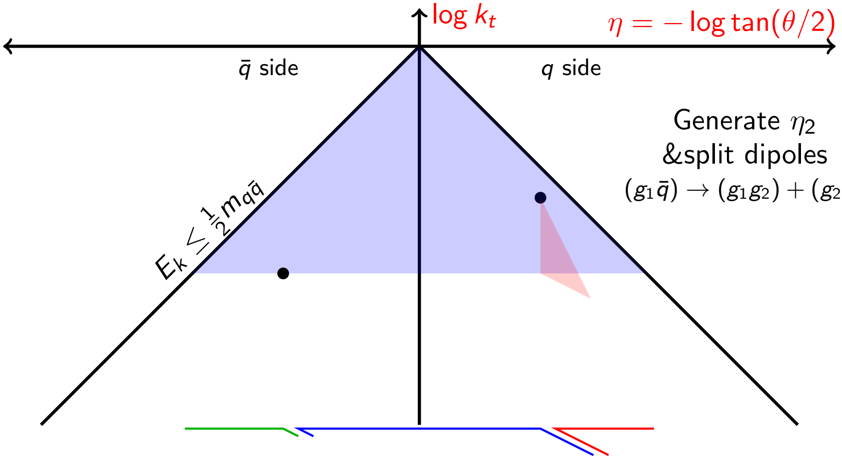
Ordering variable: transverse momentum $k_t$




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

# Parton shower in the Lund plane

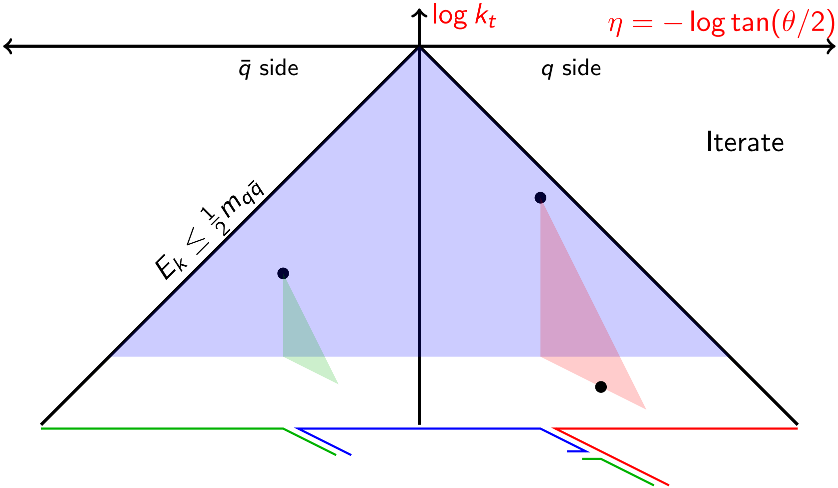
Ordering variable: transverse momentum $k_t$




Generate $\eta_2$
&split dipoles
$(g_1\bar{q}) \to (g_1 g_2) + (g_2\bar{q})$

# Parton shower in the Lund plane

Ordering variable: transverse momentum $k_t$



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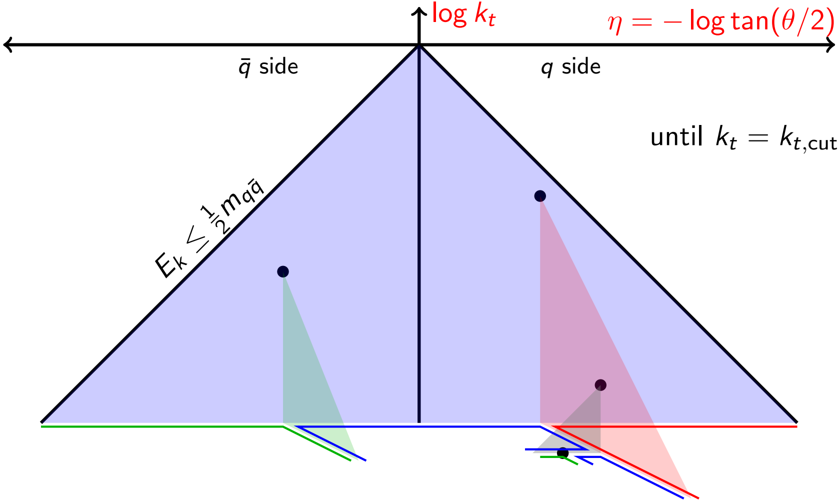
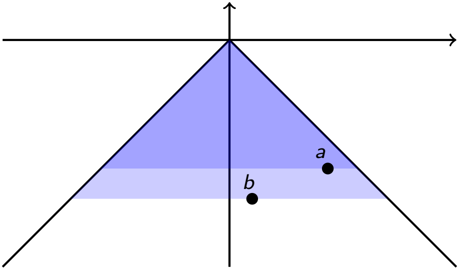


# Different ordering variables...

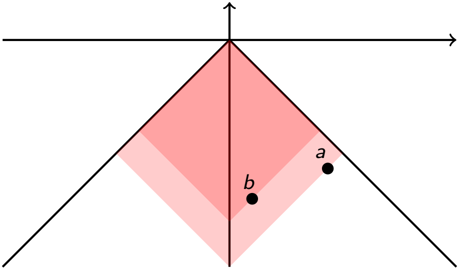
... can lead to different emission orderings

$k_t$ (transv. mom.) ordering




$k_{ta} > k_{tb}$
$\Rightarrow$ $a$ emitted before $b$

$q$ (virtuality) ordering




$q_b > q_s$
$\Rightarrow$ $b$ emitted before $a$

## (a glimpse at) recent progress?

# $1 \to 3$ splitting functions

**Idea**

ingredients towards NLO DGLAP

- Implements $1 \to 3$ splittings $2 \to 4$ in terms of dipoles
- Example: Dire(v2)

See e.g.

[Jadach *et al*,16]
[Li,Skands,16]
[Höche,Krauss,Prestel,17]
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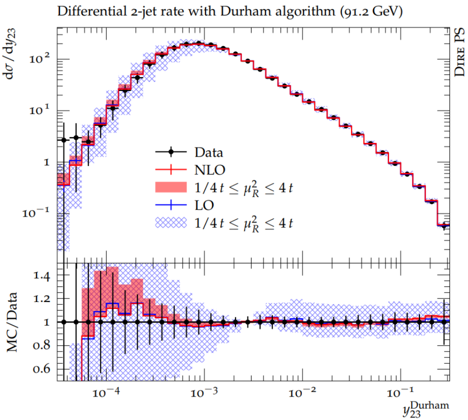



[Höche,Krauss,Prestel,17]

# Beyond leading colour

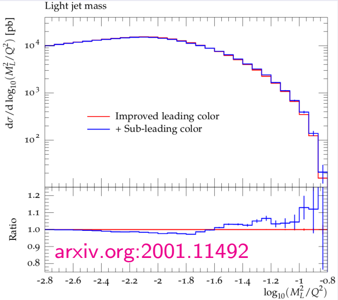
## Challenges

- most showers (except Herwig) are leading colour (even at leading-log) (see e.g. [Dasgupta,Dreyer,Hamilton,Monni,Salam,18])
- very complex structure for multiple soft-gluon emissions

## Recent progress

- Amplitude-level showers
  in contrast to approached based
  on squared matrix-elements
  see e.g. [Forshaw,Holguin,Plätzer,19]

- Beyond leading-$N_c$/full colour
  see e.g. [Nagy,Soper,12],[Höche,Reichelt,20],
  [Gieseke,Kirchgaesser,Plätzer,Siodmock,18],
  [Forshaw,Holguin,Plätzer,20]



# Electroweak showers

## Main challenges

- Splitting functions more involved than standard Altarelli-Parisi
- Explicit dependence on chirality/spin$^{(*)}$

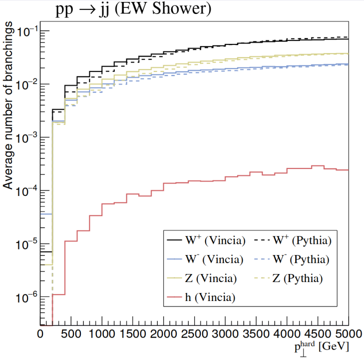
## Recent progress

Implementation in Vincia, based on the spinor-helicity formalism

[Kleiss,Verheyen,20]

phenomenological relevance at large $p_t$

see also:
[Bauer,Ferland,Webber,17-18]
[Bauer,DeJong,Nachman,Provasoli,19]

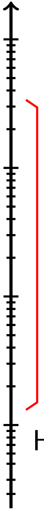



$^{(*)}$ Technically, this is also the case for QCD showers

# Parton-shower accuracy?

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

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



Hard process, matching

"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

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

Parton shower

expect logs between disparate scales

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

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

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

Hadronisation MPI/UE

# What does shower accuracy mean?

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

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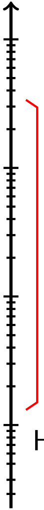
$Q \gg \mu_{\rm NP}$

Parton shower

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

Hadronisation MPI/UE



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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

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

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

in resummation regime:

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

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

# Our targeted accuracy

**NLL accuracy for a range of observables**

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

  e.g. energy in slice
- multiplicity

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

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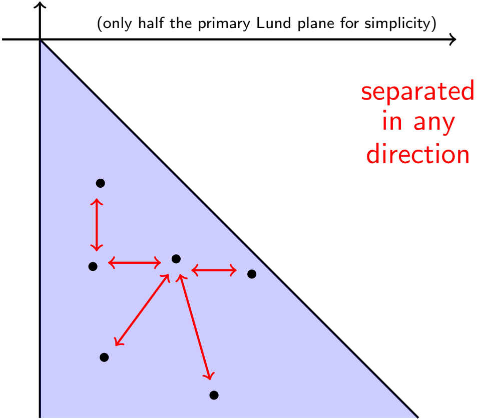
**Correct matrix elements for $N$ well separated emissions in the Lund plane**



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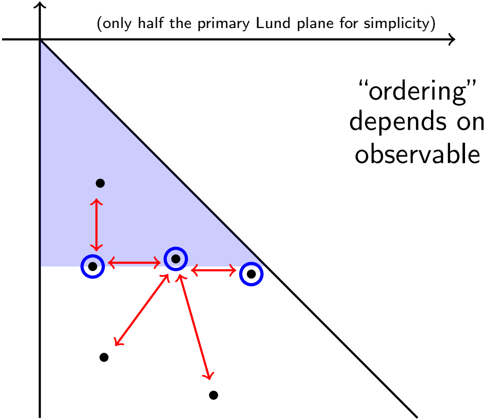

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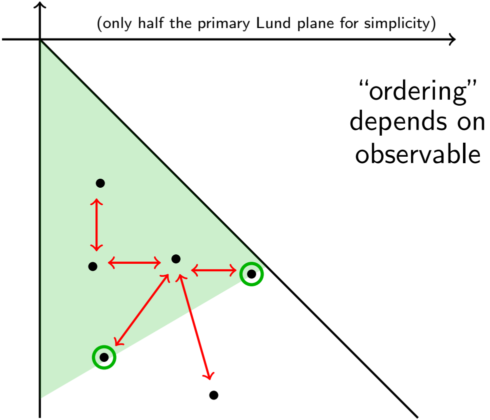

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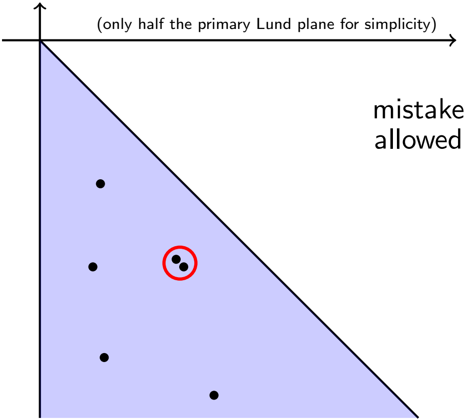
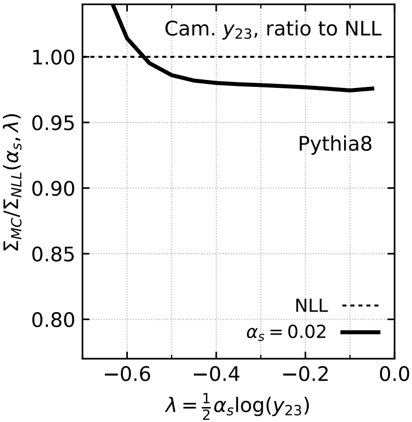


# Testing accuracy




Idea for testing:

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

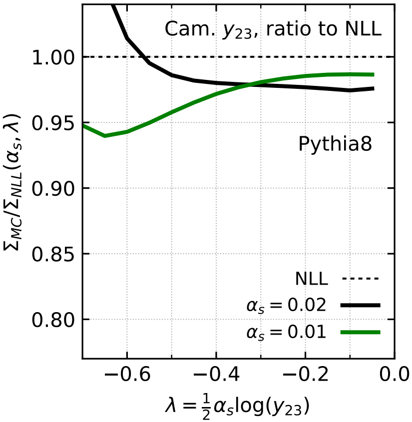
with $\lambda = \alpha_s L$

NLL deviations

or

subleading effects?

# Testing accuracy

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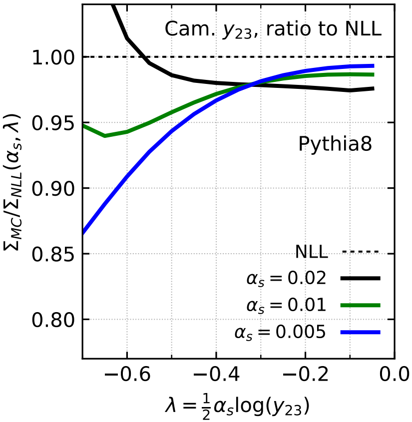


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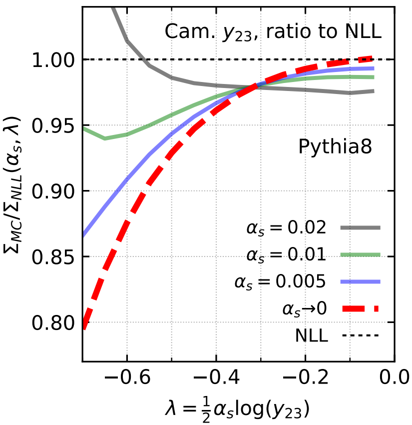



Idea for testing:

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

at fixed $\lambda = \alpha_s L$

NLL deviations

or

~~subleading effects?~~

# Towards NLL accuracy with the PanScales showers

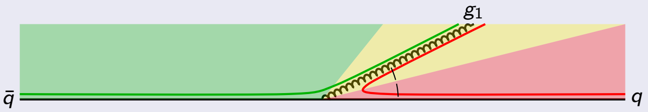
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,arXiv:2002:11114]

# 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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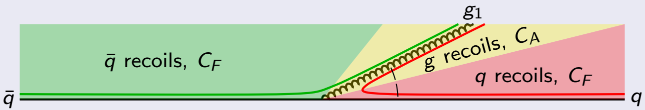

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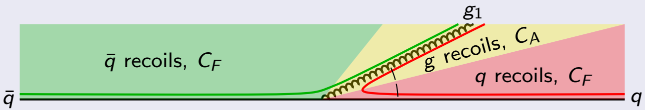
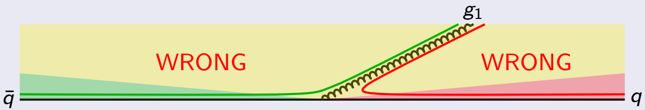



Pythia:



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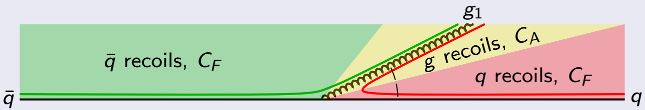


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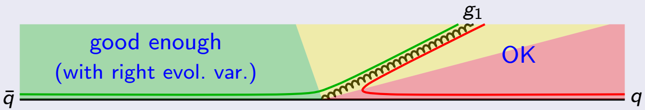

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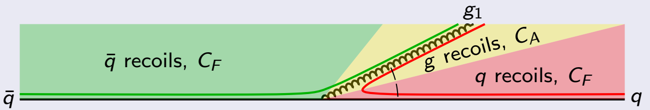


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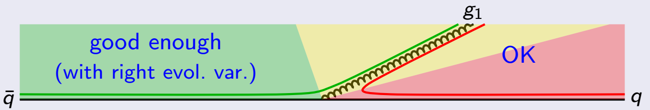
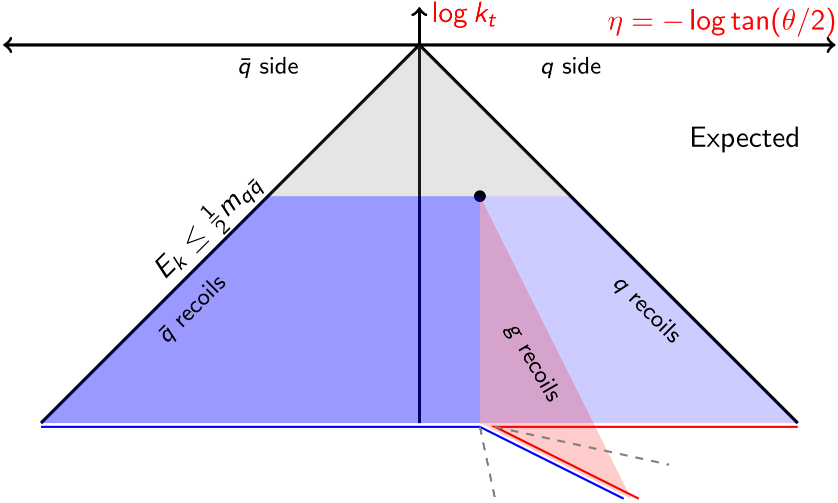



## Key element 2: choice of evolution variable

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

Idea: emissions with commensurate $k_t$ radiated with successively smaller angles

# Lund-plane representation: transverse recoil boundaries



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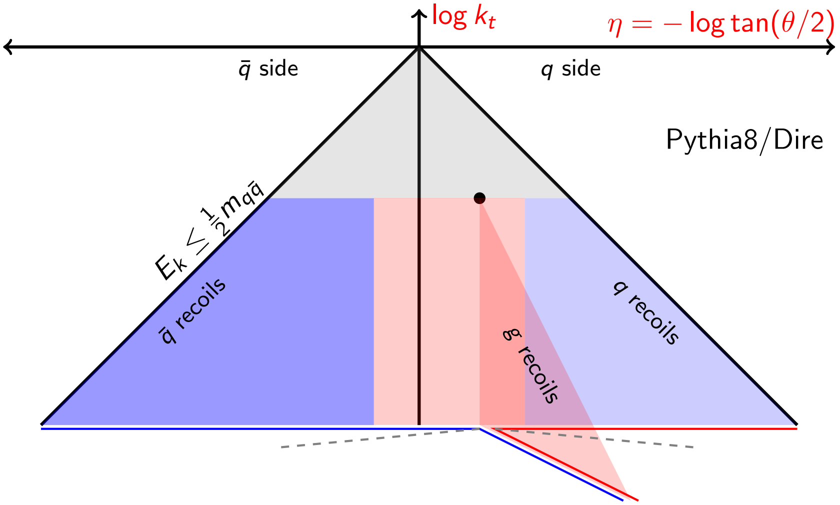

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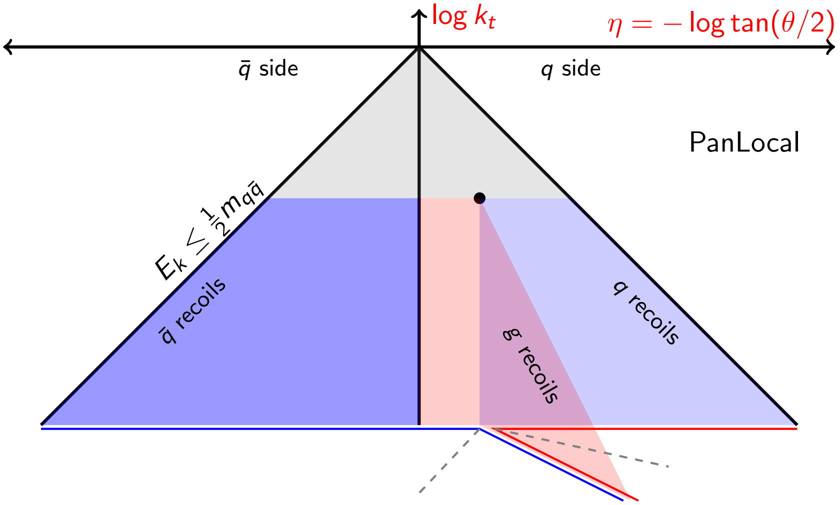
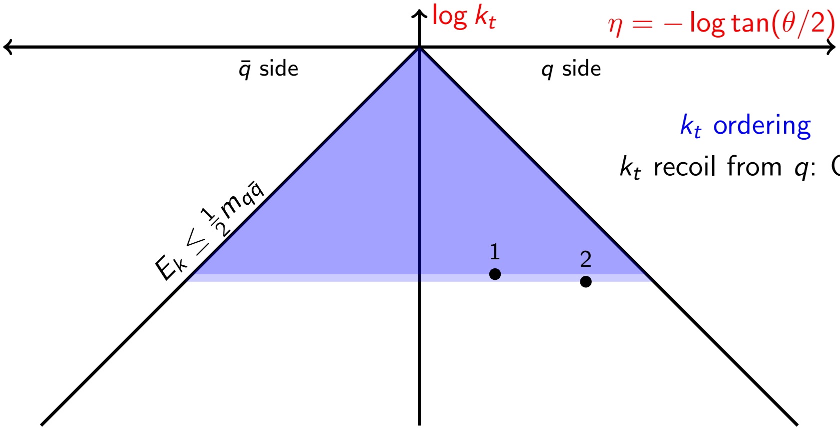


# Lund-plane representation: PanLocal evolution variable




$k_t$ ordering

$k_t$ recoil from $q$: OK

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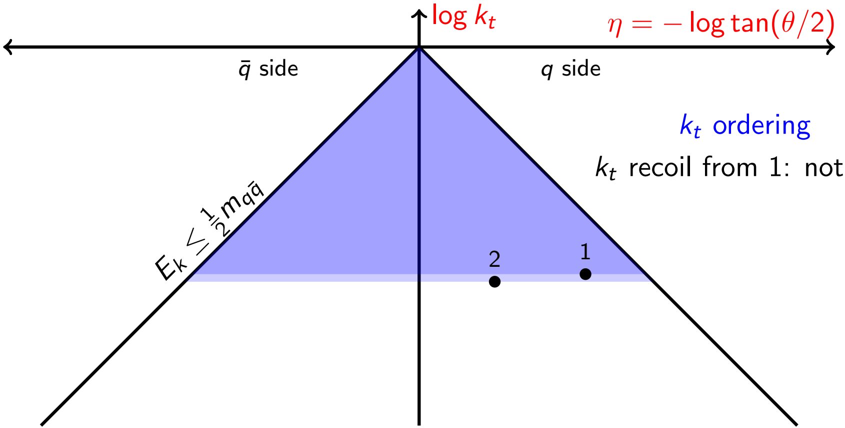
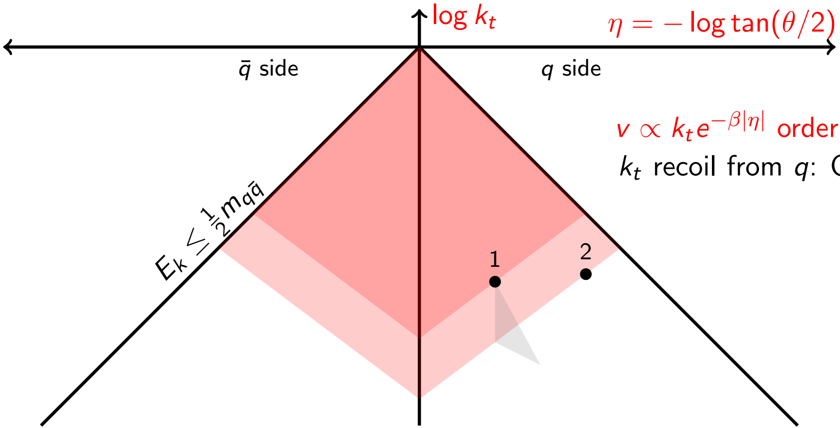



$k_t$ ordering

$k_t$ recoil from 1: not OK

# Lund-plane representation: PanLocal evolution variable




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

$k_t$ recoil from $q$: OK

# Kinematic map

(just to give an idea of what it takes)

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

$f$ 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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$$p_j = a_j \tilde{p}_i + b_j \tilde{p}_j - (1-f) k_\perp$$

with (PanLocal($\beta$), 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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Where to put the transition?

- Pythia8/Dire: equal angles in dipole rest frame
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# Assessing accuracy: $y_{23}$

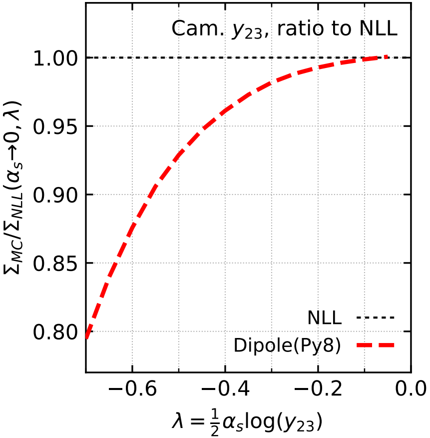
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]

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

Study

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

× Pythia8 deviates from NLL



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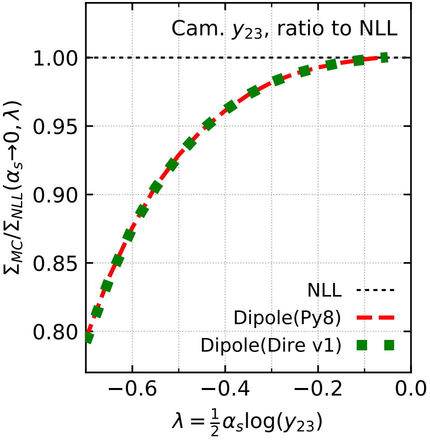
- × Pythia8 deviates from NLL
- × Dire(v1) same as Pythia8



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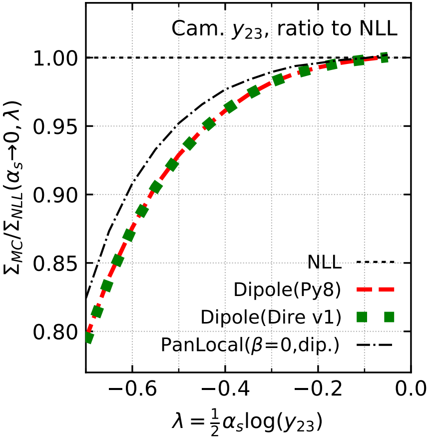
× Pythia8 deviates from NLL
× Dire(v1) same as Pythia8
× PanLocal($\beta = 0$) still deviates
(issue of $k_t$ ordering remains)



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Study

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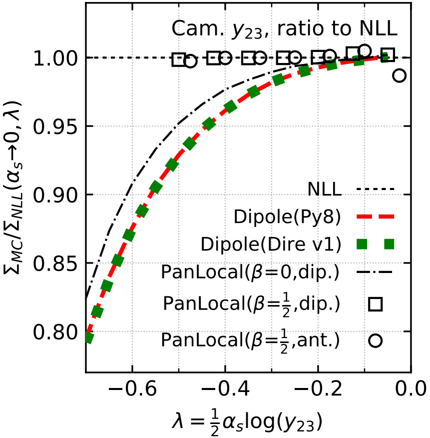
- × Pythia8 deviates from NLL
- × Dire(v1) same as Pythia8
- × PanLocal($\beta = 0$) still deviates (issue of $k_t$ ordering remains)
- ✓ PanLocal($0 < \beta < 1$) OK (issue of $k_t$ ordering remains)



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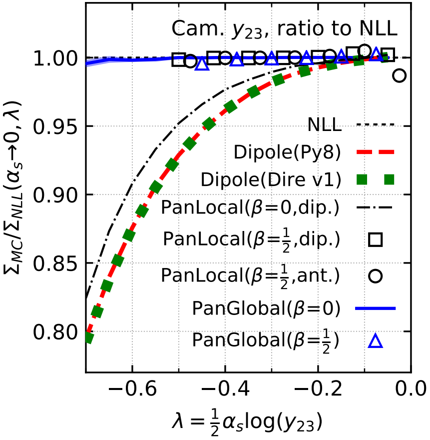
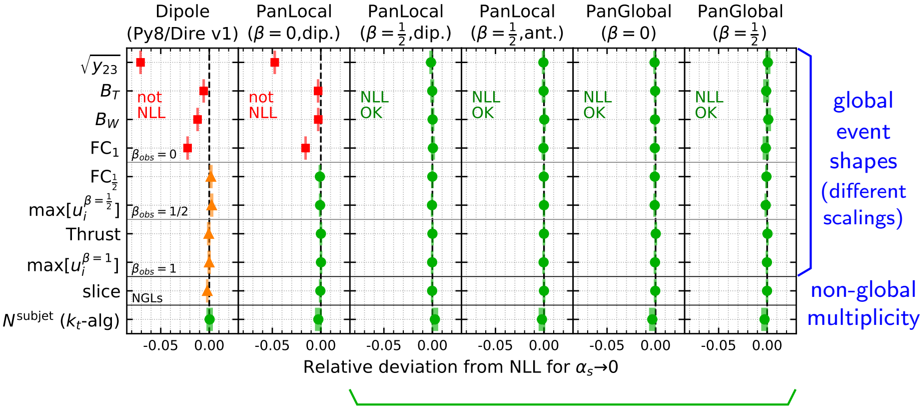



- × Pythia8 deviates from NLL
- × Dire(v1) same as Pythia8
- × PanLocal($\beta = 0$) still deviates
  (issue of $k_t$ ordering remains)
- ✓ PanLocal($0 < \beta < 1$) OK
  (issue of $k_t$ ordering remains)
- ✓ PanGlobal($0 \leq \beta < 1$) OK
  (global recoil allows also for $\beta = 0$)

# Assessing accuracy: extensive observable list

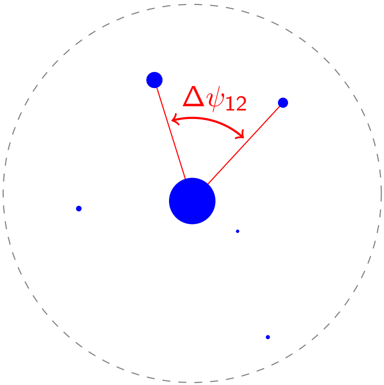
[M.Dasgupta,F.Dreyer,K.Hamilton,P.Monni,G.Salam,GS,20]




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

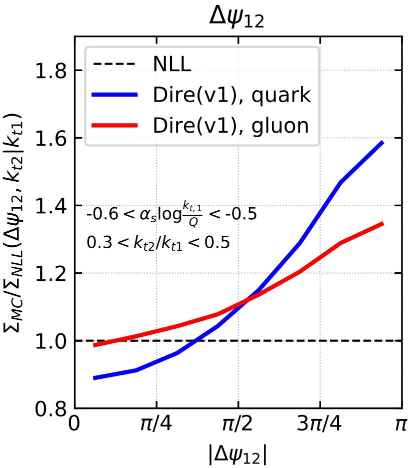
(green: OK at NLL; orange: issues at fixed order; red issues at fixed and all orders)

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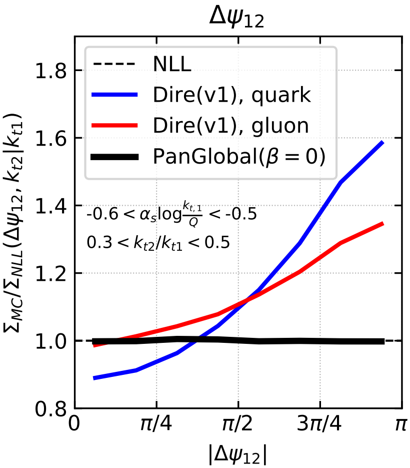
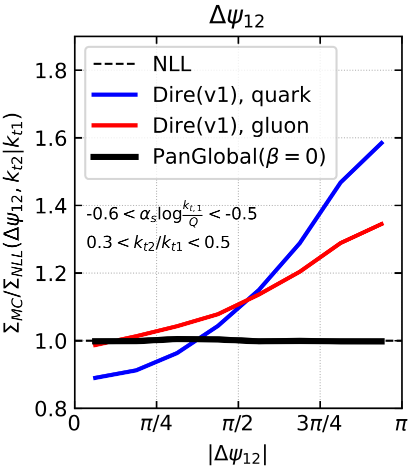
- quite large NLL deviations in current dipole showers
- differences between quark and gluon jets
- PanGlobal gets correct NLL



# 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



# The quest for precision across scales

## What is your name?

**PanScales**

E.Slade, R.Medves; F.Dreyer, B.El-Menoufi, A.Karlberg, L.Scyzboz, R.Verheyen; M.Dasgupta, K.Hamilton, P.Monni, G.Salam, GS

## What is your quest?

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

1st step presented here: accuracy assessment + first (towards) NLL $e^+e^-$ shower

## What is your favourite colour?

- still at large $N_C$, in $e^+e^-$ and without spin correlations
- Next (obvious) steps:
  beyond large-$N_c$, extend to $pp$, include spin correlations
- Longer run: investigate phenomenology, go public, explore NNLL