QCD at all orders: parton-shower resummation

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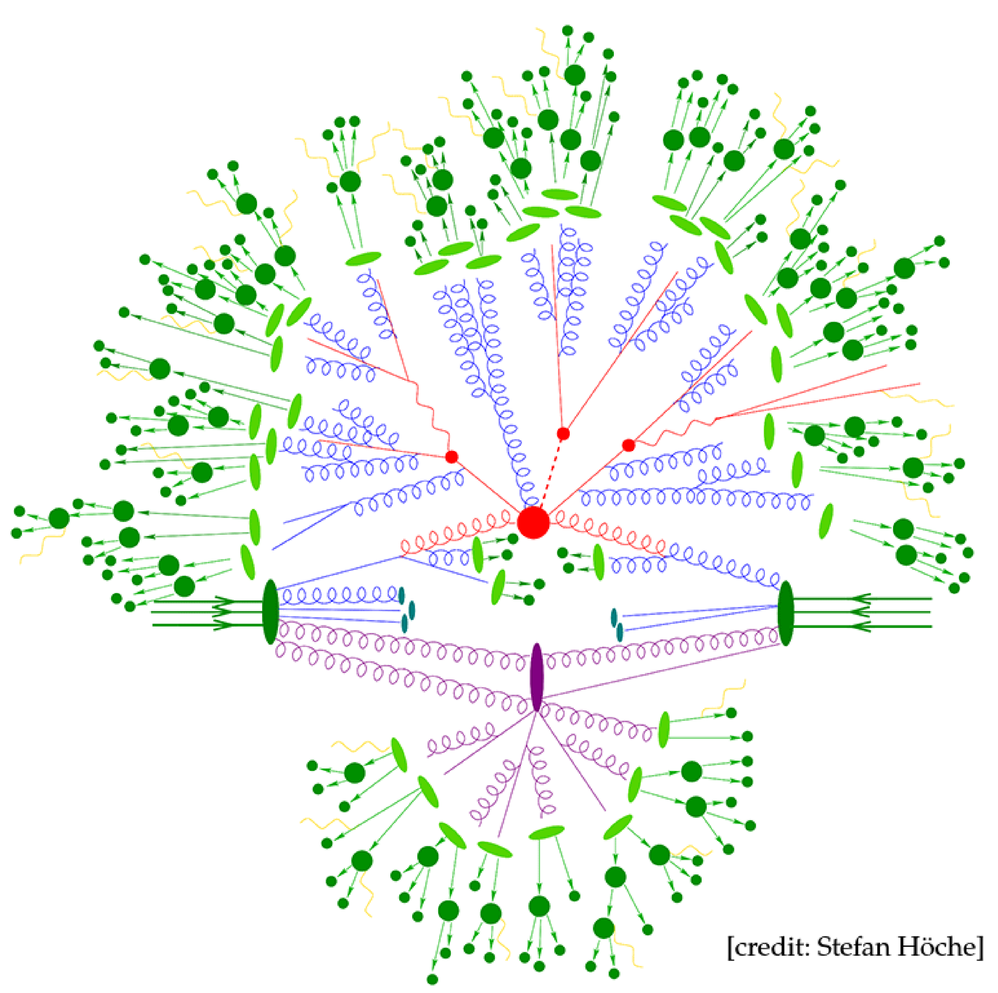
A collision at the Large Hadron Collider

Most analyses at the LHC rely on simulations of real-life proton-proton collisions: this allows us to draw conclusions about the validity of our theory of particles and their interactions, **the Standard Model**.



Programs, called **Monte-Carlo event generators**, perform these simulations by breaking the problem into simpler pieces. Each of these main pieces is an ingredient of the simulation:

- Parton distribution functions (PDF): proton content
- Hard interaction: fixed-order calculation (in QCD $\equiv 1 + \mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2) + \dots$)
- All-order radiative corrections: parton shower emissions
- Hadronisation from confinement property (quarks and gluons cannot live individually for long)
- Multiple parton interactions (MPI)
- Hadron decays

Large logarithms at all orders

Logarithms (L) of ratios of relevant scales at every order
$\rightarrow$ spoil the convergence of the perturbative series where $L \gg 1$

Example: Z-boson transverse momentum p_T, with $L = \ln \frac{m_Z}{p_t}$

$$\frac{d\sigma}{dp_T} \sim \delta(p_T) \qquad (= \text{LO})$$

$$+ F_1 \left[\alpha_s L^2 + \alpha_s L + \alpha_s\right] \qquad (= \text{NLO})$$

$$+ F_2 \left[\alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \dots\right] \qquad (= \text{NNLO})$$

$$+ \dots$$

$$\simeq \exp\left[\underbrace{L g_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\text{NNLL}} + \dots\right] \qquad \textit{resummed}$$

where LL means *leading* $\left(\sum \alpha_s^n L^{n+1}\right)$, NLL *next-to-leading* $\left(\sum \alpha_s^n L^n\right)$, NNLL *next-to-next-to-leading* $\left(\sum \alpha_s^n L^{n-1}\right)$ logarithms.

Resummation in practice

- Fixed order divergent as $p_t \to 0$ (i.e. as $\ln \frac{m_Z}{p_t} \to \infty$)
- Resummation (LL or NLL) gives finite results in regions of small p_t
- Some resummation is needed to restore agreement with data!

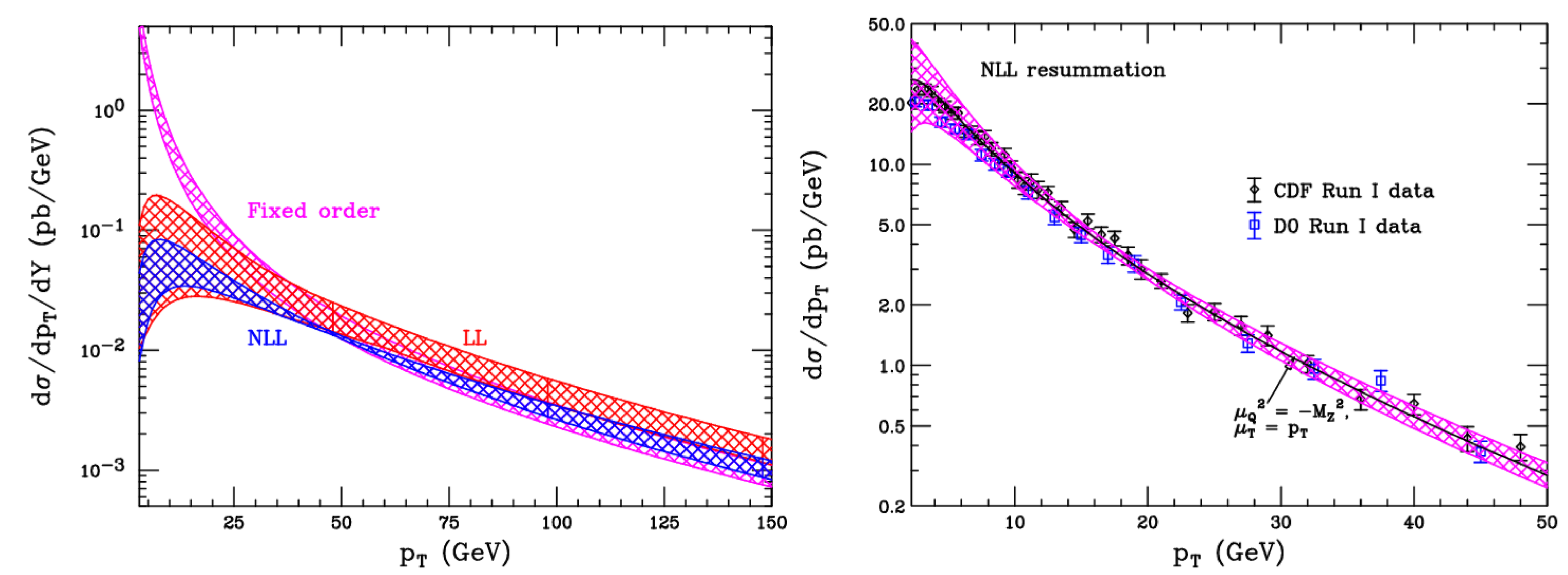


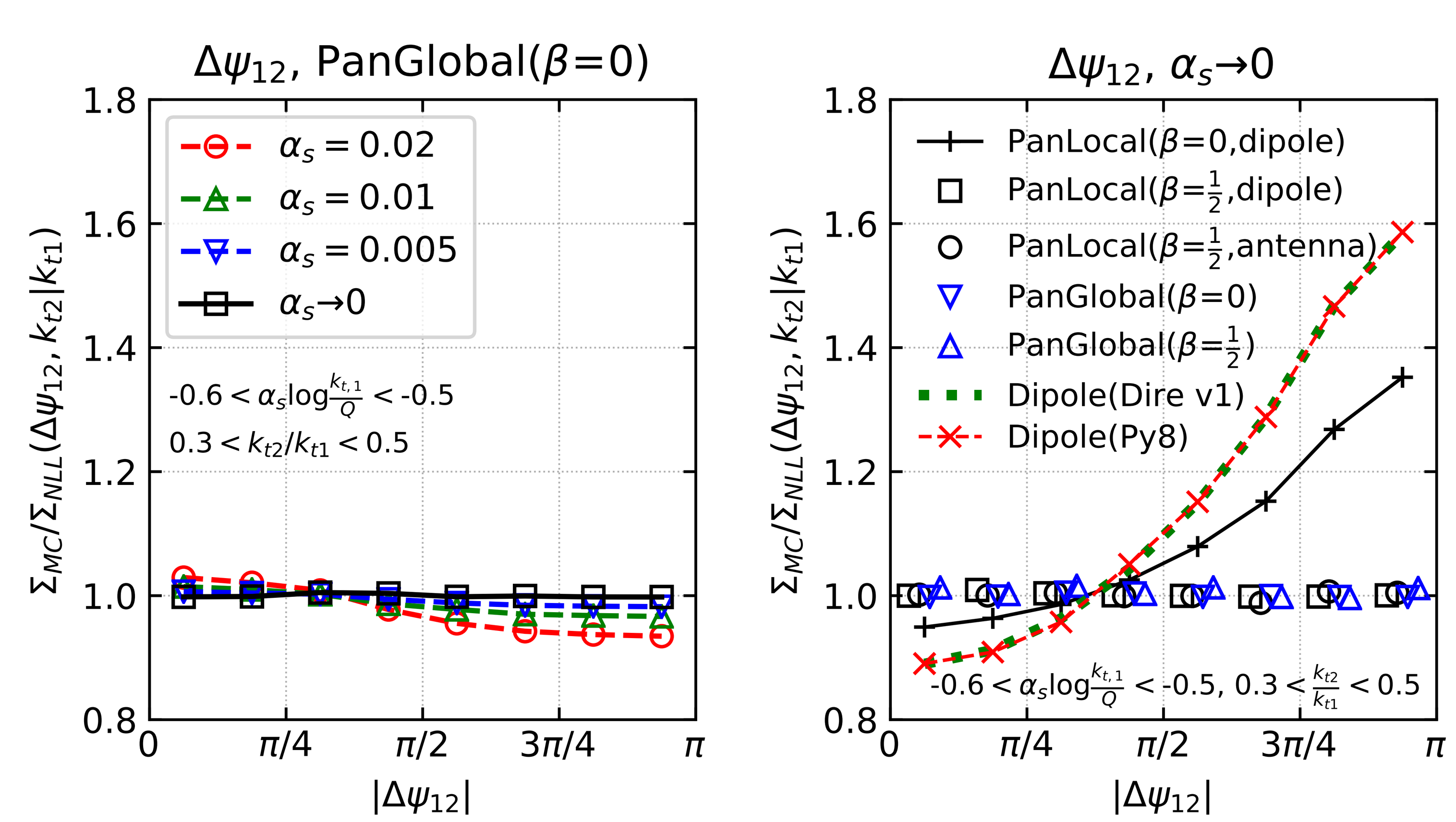
Figure 1. Adapted from Mantry & Petriello, Int.J.Mod.Phys.Conf.Ser. 04 (2011) 106

Analytic (diagram-based / Soft-Collinear Effective Theory / Mellin transform / ...)	Numerical
✗ Specific to one observable/process	✓ Fully differential ($\rightarrow$ more generic)
✓ High accuracy (N^{3}LL or even N^{4}LL)	✗ Low accuracy (typically LL, now NLL)
✗ *Ad hoc* hadronisation corrections	✓ Natural connection to hadronisation

The PanScales parton showers

- PanScales $\equiv$ family of new showers, which were the first to be **NLL-accurate** (correctly reproduce g_1 and g_2 in the exponent) for many classes of observables.
- Developed a numerical framework to test the logarithmic accuracy of (in principle) any parton shower,

$$\text{(schematically)} \qquad \lim_{\alpha_s \to 0} \frac{\text{parton-shower prediction}}{\text{independent NLL prediction}} \equiv 1$$

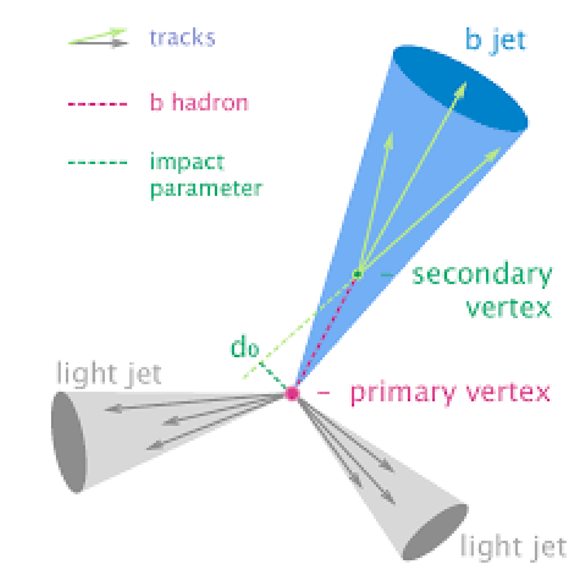


Flavoured jet algorithms

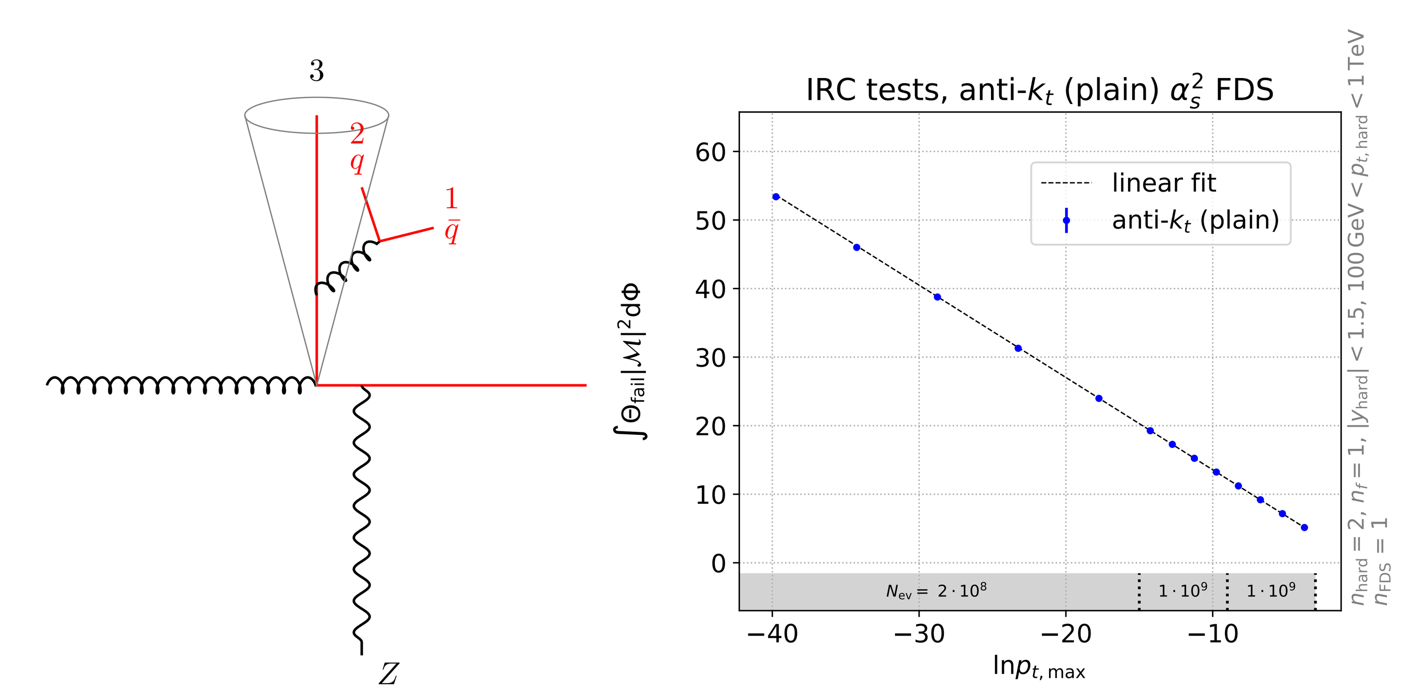
- Jets, in QCD, are defined through an algorithm (most often a *sequential recombination algorithm*)

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

- A longstanding question is how to define "flavour" in QCD jets?
  - Especially "heavy" flavour (b/c quarks), because these can be distinguished experimentally from "light" quarks ($u/d/s$)



- ... in a way that is infrared and collinear safe (i.e. non-divergent)?



- New flavoured jet algorithm called **interleaved flavour neutralisation** (IFN) plugin for anti-k_t
- ... and a numerical framework for testing IRC safety