MANCHESTER 1824

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Jet properties and substructure

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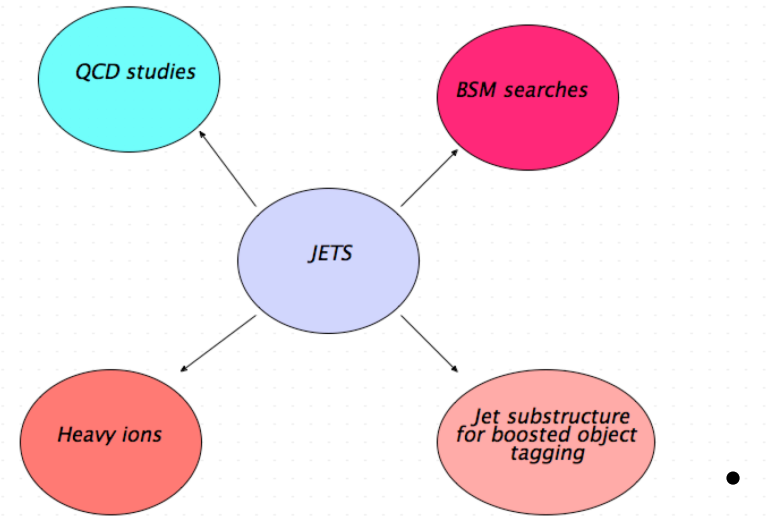
University of Manchester

LHCP 2021, 7-12 June, online

European Research Council

Established by the European Commission

Jets : a key tool at LHC



Jets have always been a key tool with numerous applications at colliders.

Butterworth, Davison, Rubin and Salam 2008

- Jet substructure emerged as a vibrant field since pioneering work in 2008.
- Provided momentum for several recent developments with impact on other areas too.

Annual “Boost” workshop series dedicated to boosted object studies.

Boosted object studies

Boosted regime implies studying particles with $p_T >> M$. Hadronic decays often reconstructed as a single jet.

Use **substructure properties** to distinguish QCD jets from jets originating from boosted W, Z,H, t etc.

Several tools for tagging W/Z/H/t jets and for grooming (removal of UE/ISR, pile-up)

Some substructure tools over past decade *

Jet declustering

Mass drop + Filtering

Pruning *Trimming*

modified Mass Drop *Soft Drop*

HEP Top Tagger *JH Top Tagger*

Shower Deconstruction *Qjets*

Lund Plane

Jet-shape/energy-flow

N subjettiness

Energy Correlation Functions

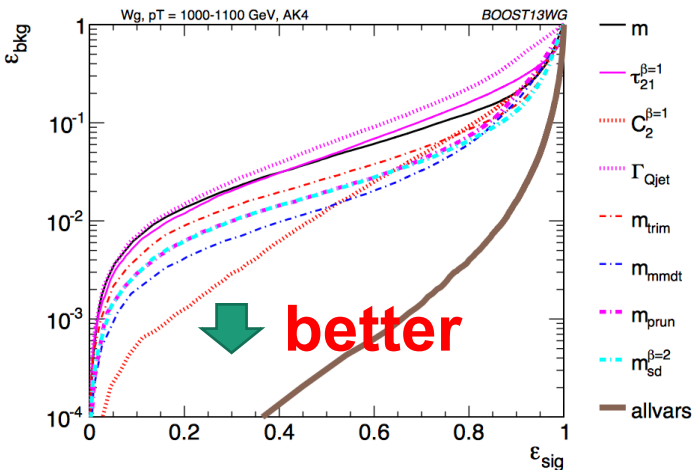
Angularities

Energy Flow Polynomials

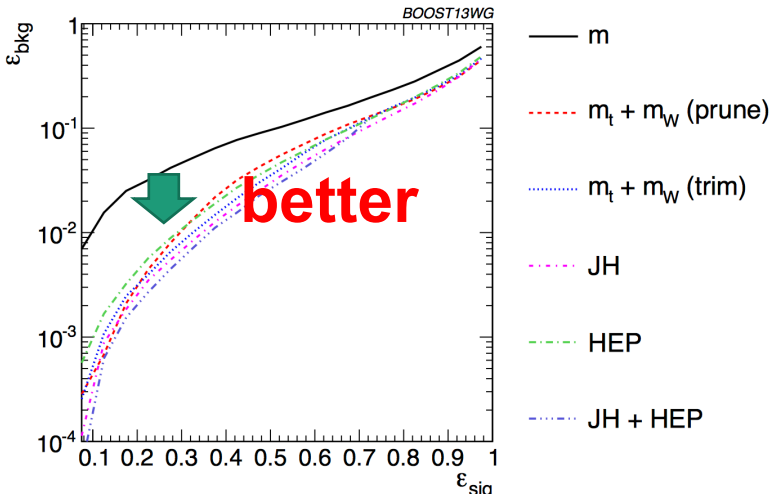
* Not an exhaustive list

Substructure : early years and key questions

Boost 2013 WG



Quark-Gluon discrimination



Top tagging

Marked by the creation of many tools studied exclusively via Monte Carlo simulations.

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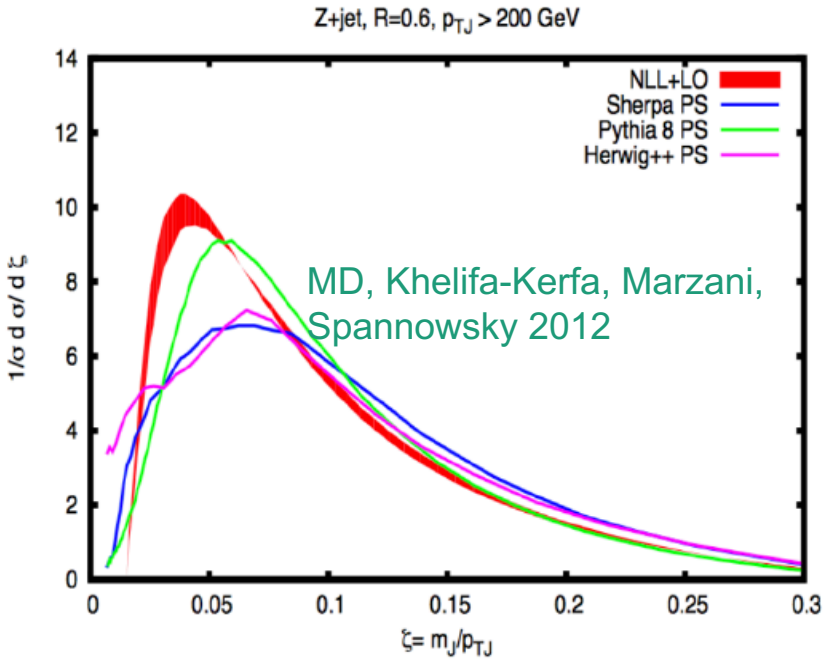
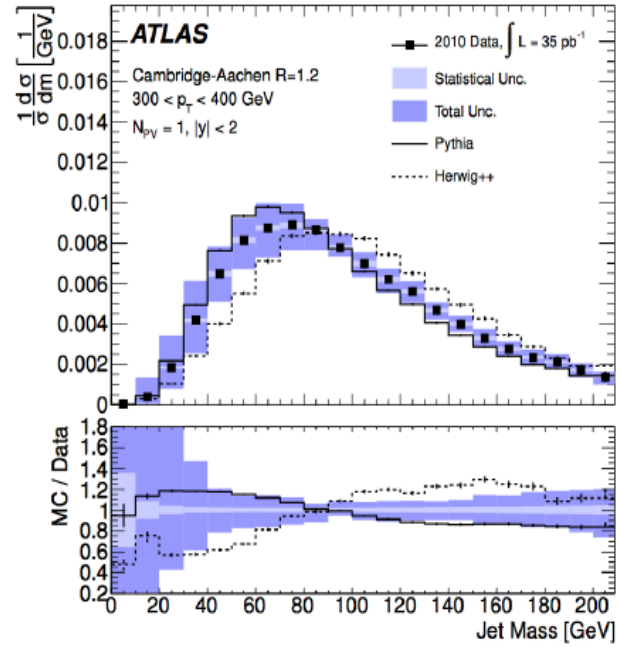
Substructure : early years and key questions





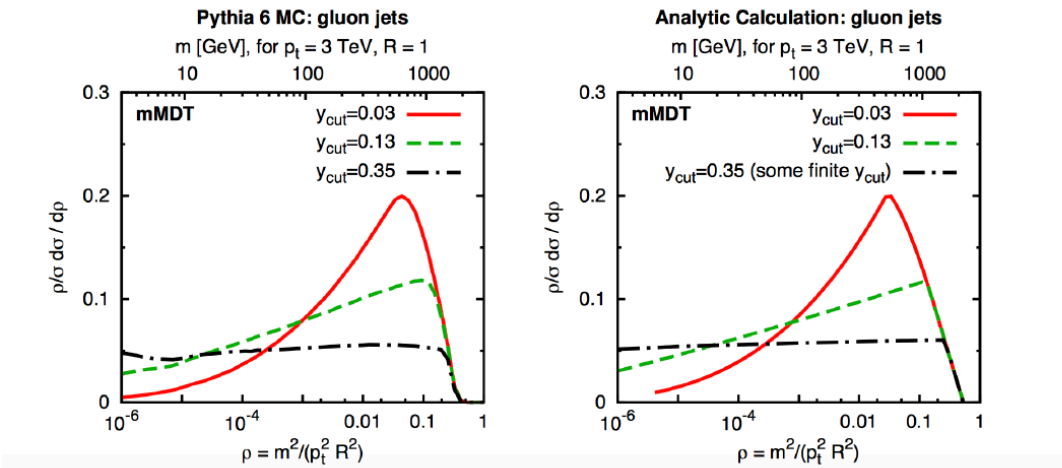
ATLAS collaboration 2012

Substantial spread in shower predictions. Concerns about treatment of soft radiation and role of poorly understood non-perturbative effects.

– How accurately is jet substructure described by state-of-the-art Monte Carlo tools?

Proceedings of Boost 2012 Valencia

Analytic understanding of substructure



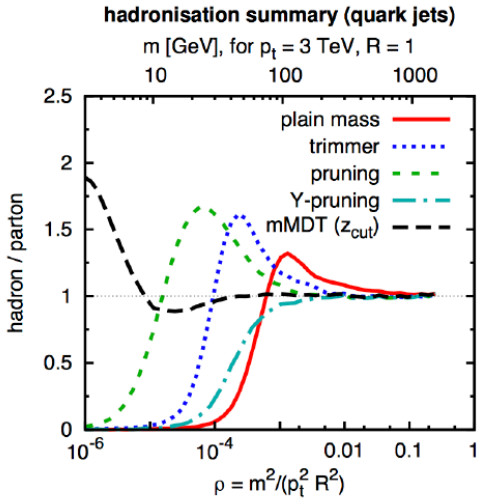
2013 saw emergence of first analytic understanding of tools.

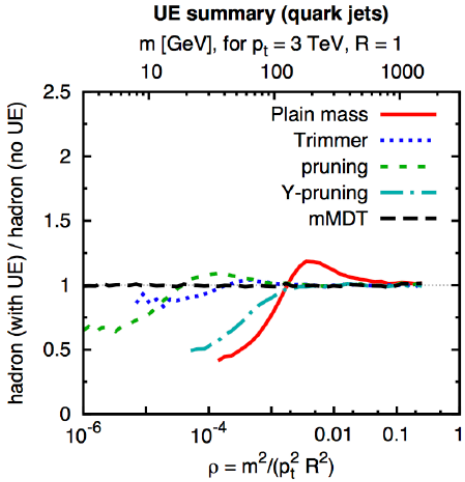
MD, Fregoso, Marzani, Salam 2013

– Can jet substructure be predicted by first-principle QCD calculations and compared to data in a meaningful way?

Boost 2012 Valencia proceedings

mMDT – a unique jet observable



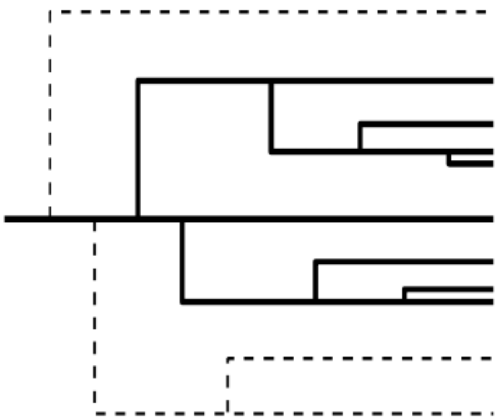


MD, Fregoso, Marzani, Salam 2013

- Free from complex class of soft gluon effects (non-global logarithms)
- Small non-perturbative corrections

→ Precise analytic calculations & phenomenology

Soft Drop : a robust and flexible tool



$$z = \frac{\min(p_{t,i}, p_{t,j})}{p_{t,i} + p_{t,j}}$$

C/A decluster jet following harder branch until branching satisfies

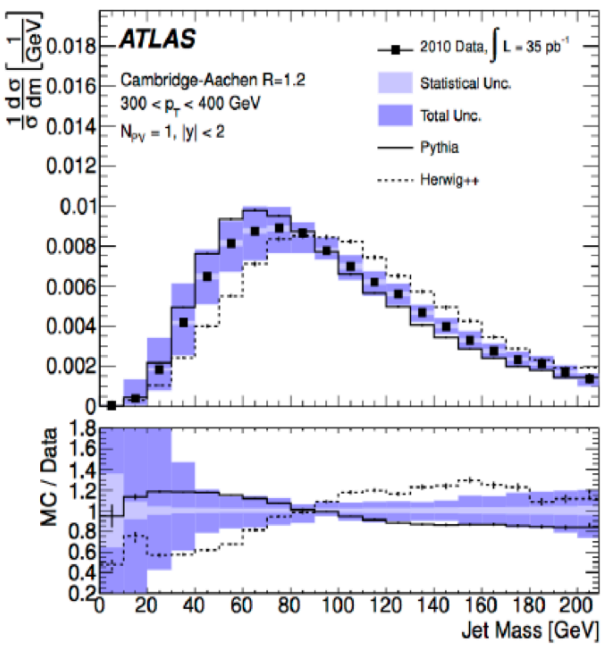
$$z > z_{\mathrm{cut}} \theta^{\beta}$$

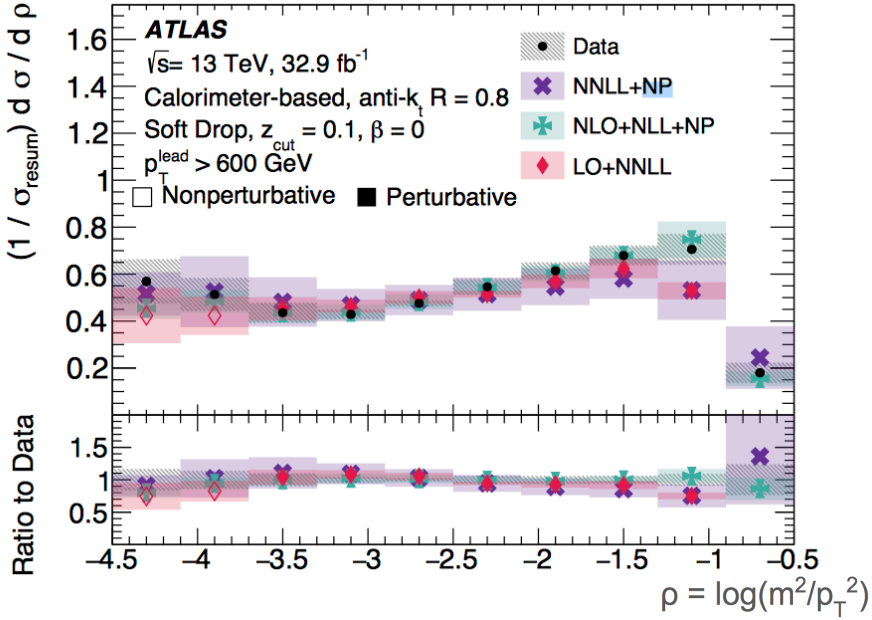
Larkoski, Marzani, Soyez, Thaler 2014

Generalises mMDT. **Robust** and **flexible** grooming tool which inherits the key properties of mMDT.

Today's standard jet grooming tool with extensive applications in LHC experiments.

Substructure and precision QCD

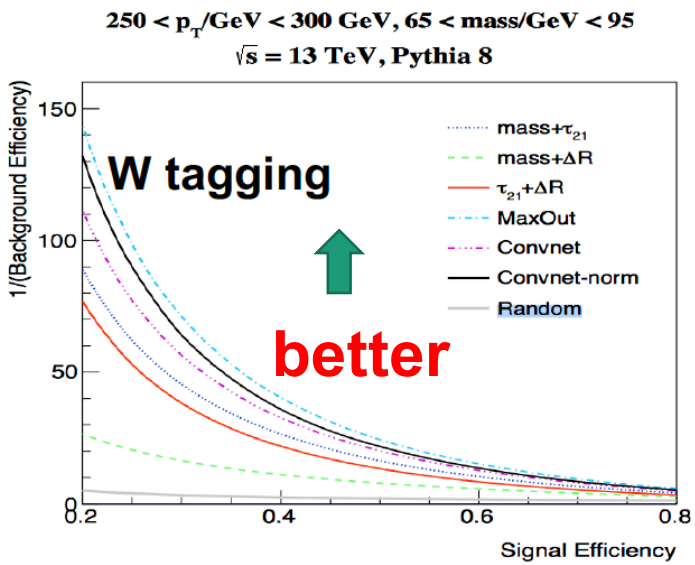




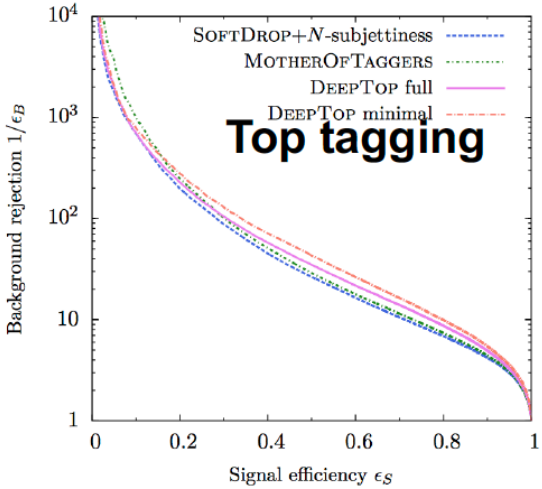
- Soft Drop jet mass is most precisely calculated substructure observable.
- QCD predictions cover several orders of magnitude in jet mass
- **Similar studies from CMS** arXiv:1807.05974

Frye, Larkoski, Schwartz, Yan 2016
Marzani, Soyez, Schunk, 2017, 2018
Kang, Lee, Liu, Ringer 2018

Tagger performance and deep learning approaches



De Oliveira, Kagan, Mackey, Nachman, Schwartzmann 2016



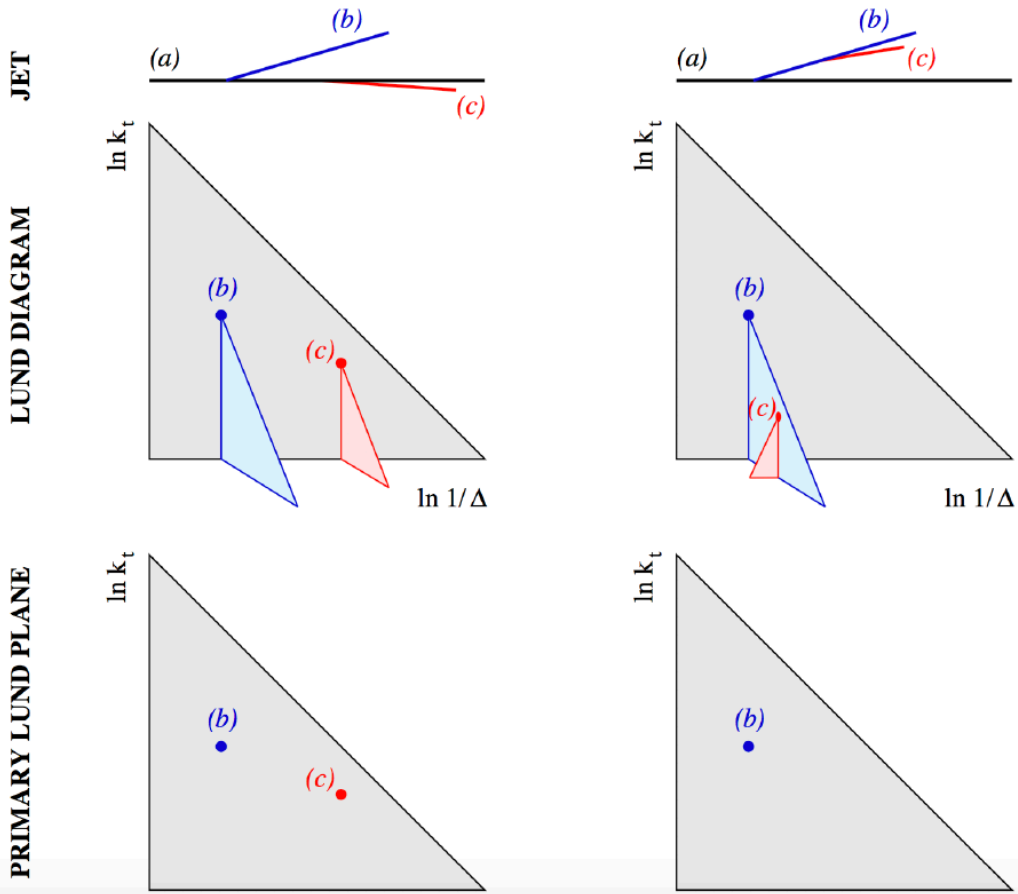
Kasieczka, Plehn, Russell. Schell 2016

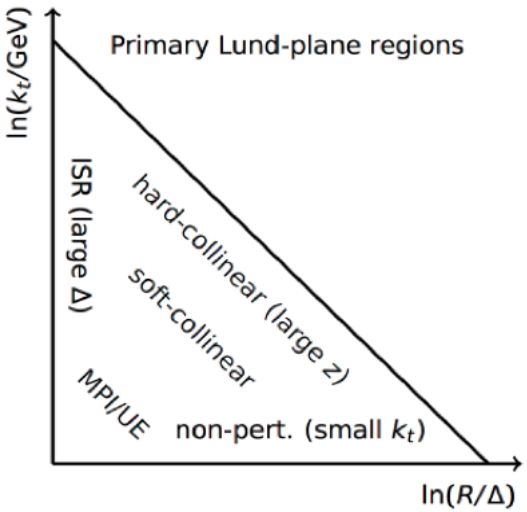
- Very active area with ML tools giving very high performance. Outperformed standard taggers.
- What features are learnt and are they well modeled by showers and detector simulations? How to get a handle on this?

The Lund plane

Gustafson, Lonnblad, Andersson, Pettersson 1989

Useful way of representing emissions in a jet





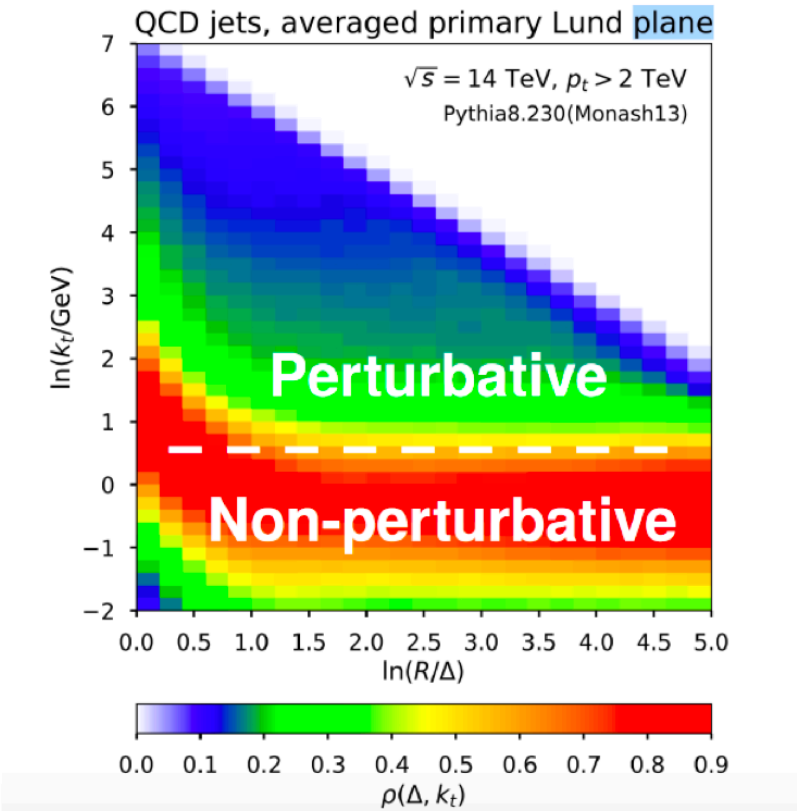
Dreyer, Salam, Soyez, 2018

Density of emissions in primary Lund plane well understood theoretically.

At the heart of analytic approaches and parton showers. Can be used as an input to ML.

Bridges the gap between Deep learning and "Deep thinking" approaches?

QCD jets in the Lund plane



Dreyer, Salam, Soyez, 2018

Simple observable

Lund plane density:

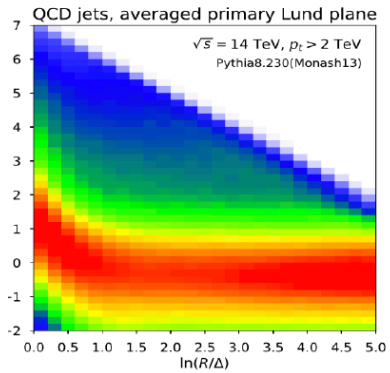
$$\rho = \frac{1}{N_{\text{jet}}} \frac{d^2 N}{d \ln 1/\Delta \, d \ln k_t}$$

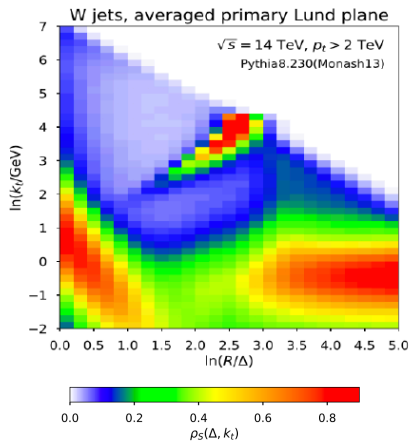
At LO in soft-collinear limit

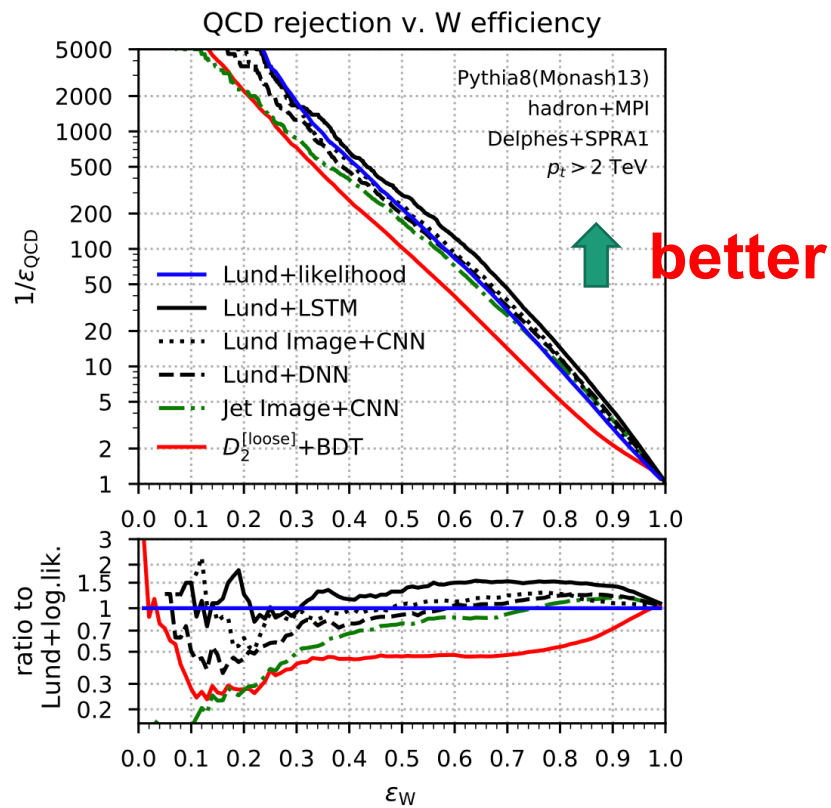
$$\rho \sim 2 C_F \frac{\alpha_s(k_t)}{\pi}$$

- Well understood theoretically
- Applications range from constraining event generator models to machine learning

Lund plane for tagging







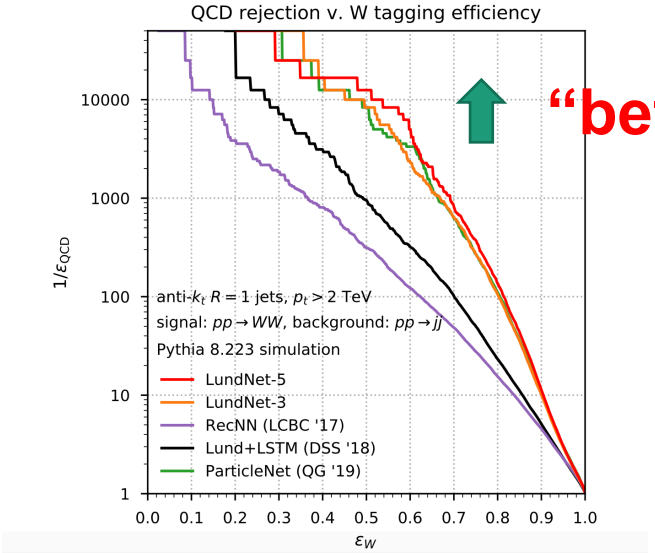
Used both log-likelihood and machine learning approach.

Dreyer, Salam, Soyez, 2018

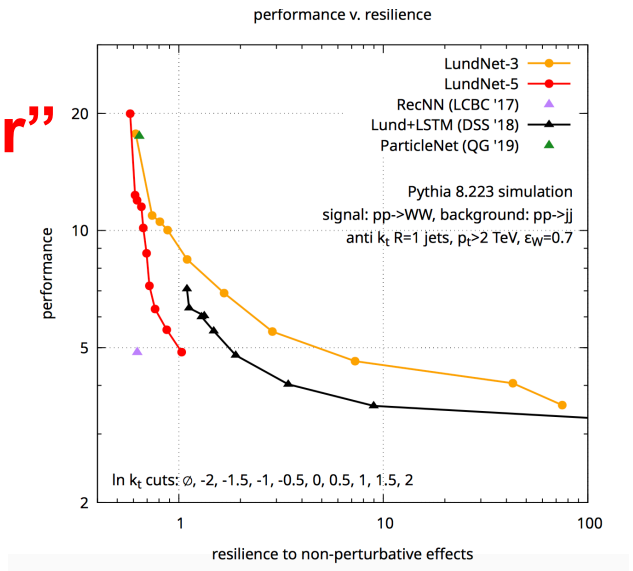
Based on Properties at each vertex

$$\mathcal{T}_i = \{\theta_i \equiv \Delta_i, k_{t,i}, z_i, \varphi_i, \ldots\}$$

Performance and resilience



"better"

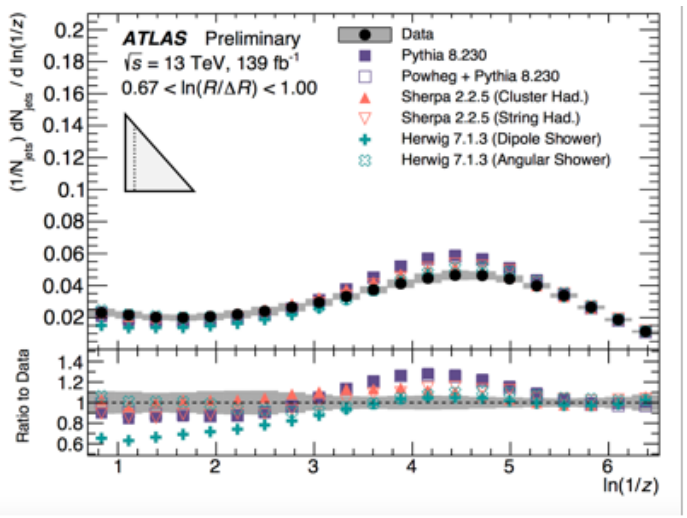


Dreyer and Qu 2021

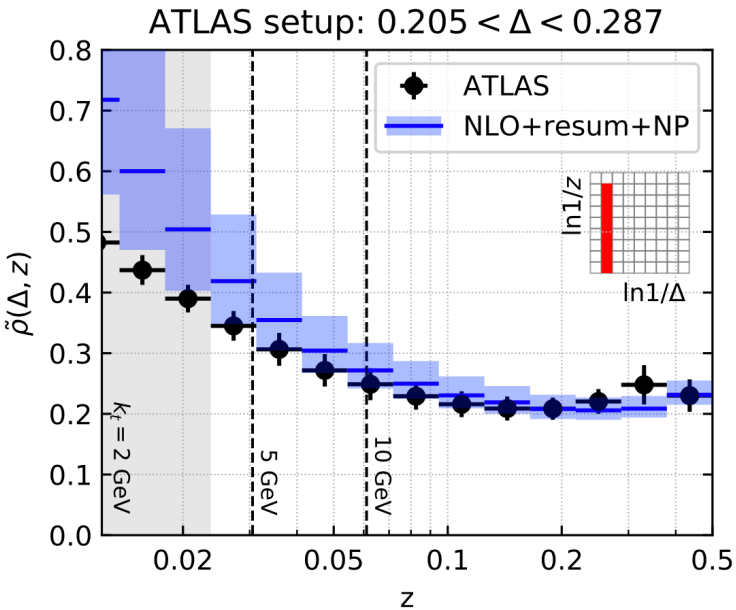
$$\zeta = \left(\frac{\Delta\epsilon_W^2}{\langle\epsilon\rangle_W^2} + \frac{\Delta\epsilon_{\mathrm{QCD}}^2}{\langle\epsilon\rangle_{\mathrm{QCD}}^2} \right)^{-\frac{1}{2}}$$

- Using information from full Lund tree gives significant performance gains.
- Trade off between performance and resilience to non-pert. effects
- Lund plane gives handle to increase resilience via a k_t cut

Lund plane phenomenology



ATLAS 2004.03540



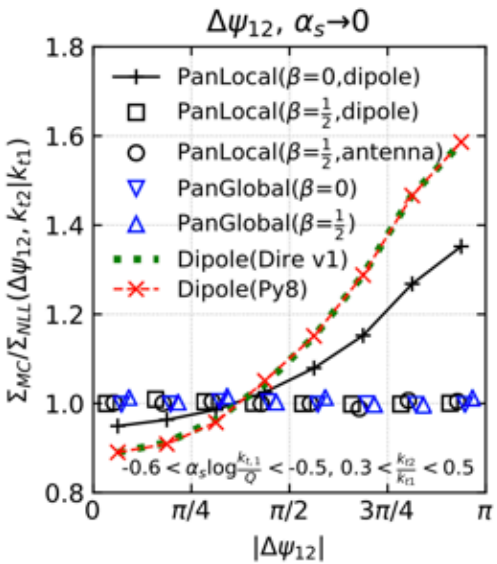
Includes resummation of single logarithmic terms matched to fixed-order

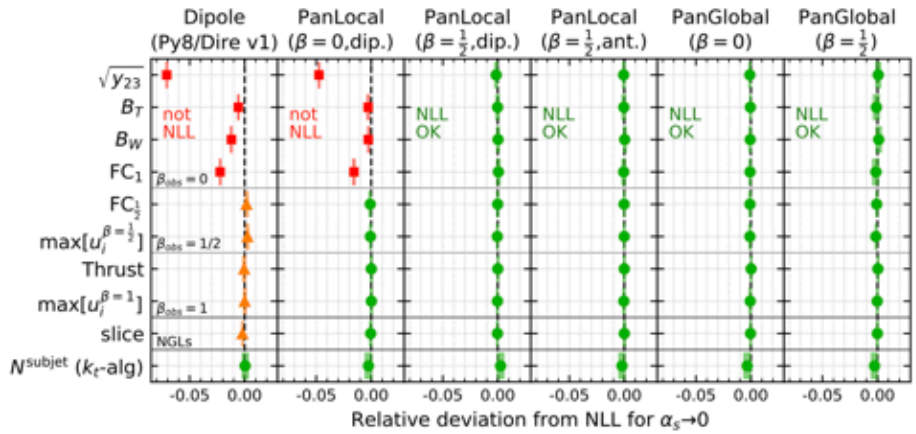
Lifson, Salam and Soyez 2020

Lund plane is a versatile tool.

- Useful to explore differences between parton showers
- Amenable to analytic calculations

Rethinking showers



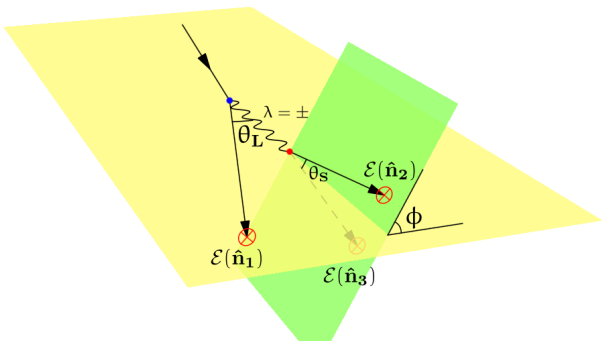


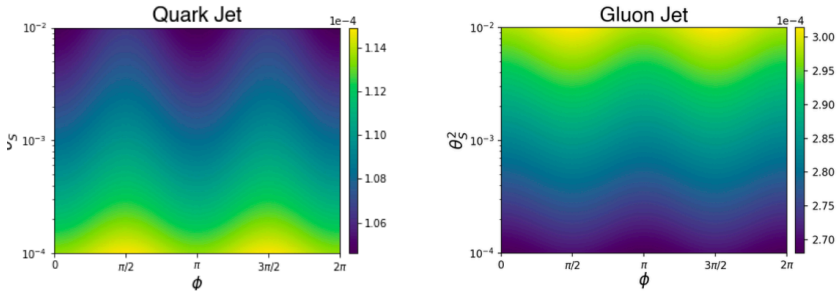
Dasgupta, Dreyer, Hamilton, Monni, Salam, Soyez 2020

- PanScales : a set of new dipole showers that remove issues seen with previous dipole showers (e.g. Pythia and DiRe v1 showers)
- First proven NLL accurate showers.
- Should represent a significant step for more reliable/accurate substructure description.

For extensions to include subleading colour and spin correlations : 2011.10054 and 2103.16526

Quantum interference effects in jet substructure





$$\langle \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)\mathcal{E}(\hat{n}_3)\rangle \quad \theta_S \ll \theta_L$$

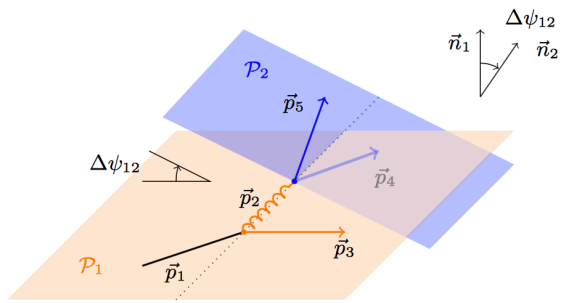
$\cos 2\phi$ ripples modulated by resummation

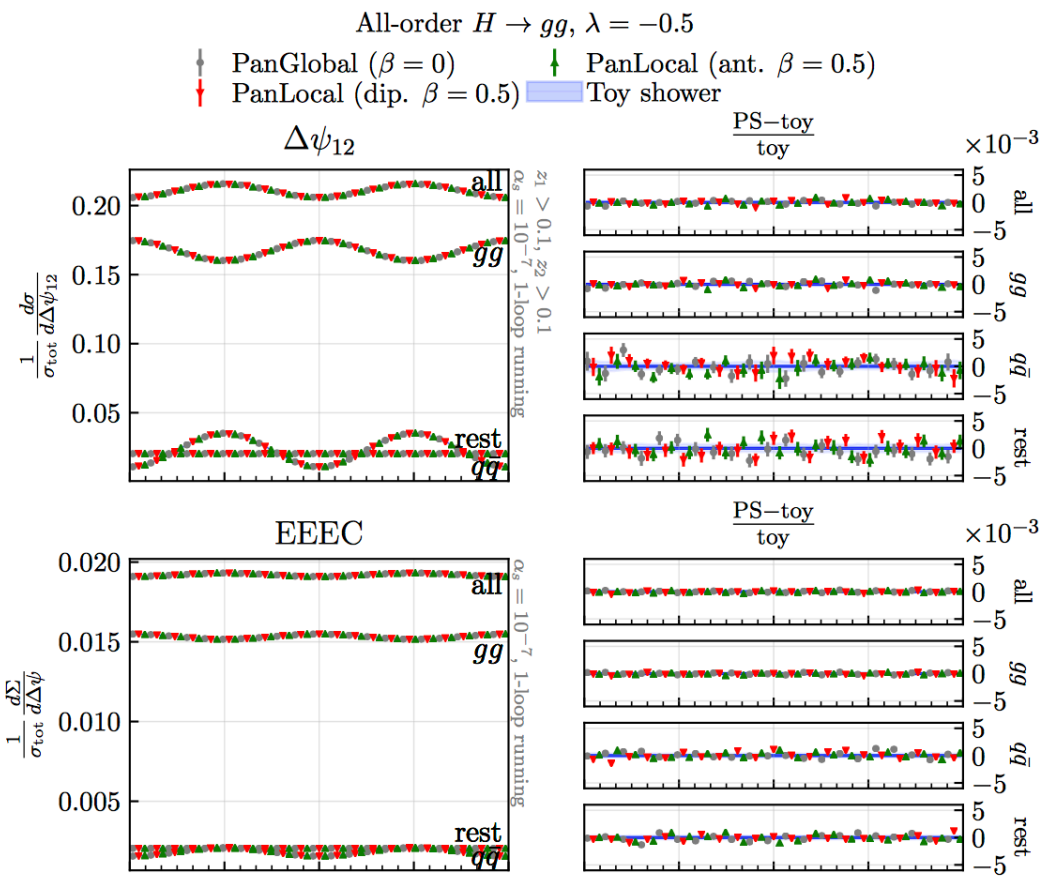
- EEEC observable probes QM interference effects within jets
- The azimuthal angle dependence reflects the role of spin correlations
- Analytic collinear resummation using light ray OPE formalism

Intrinisic theoretical interest

Chen, Moult, Zhu 2020

Spin sensitive observables and parton showers

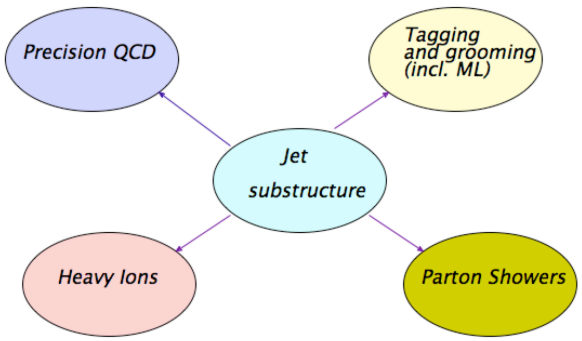




- Azimuthal correlations defined using leading k_t splitting in primary and secondary Lund plane
- New variables to test spin corr. in showers
- PanScales shower resummation for EEEC agrees with analytic.

Karlberg, Salam, Verheyen, Scyboz 2021

Summary

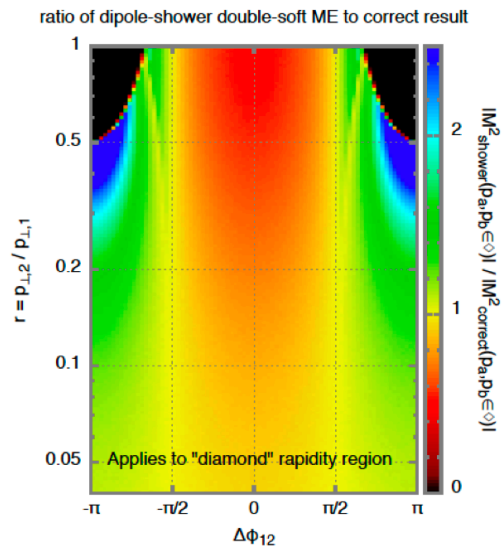


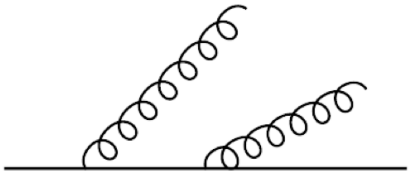
- Jet substructure has a central place in today's LHC phenomenology
- Push and pull between desire for new powerful tools and reliability/robustness brings results (Soft Drop, Lund Plane…..)
- A rich phenomenology program with many interesting studies to come (**talks by D. Recihelt (Theory), M. Seidel (CMS), R. Newhouse (ATLAS) and J.Mulligan (ALICE) at this meeting)**
- Worth keeping an eye on ongoing developments in parton showers which are key to describing substructure

Extra Slides

Showers and substructure

MD, Dreyer, Hamilton, Monni, Salam 2018





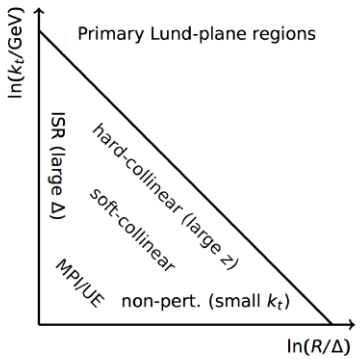
- Standard dipole showers fail to reproduce QCD emission probability even for 2 emissions.
- A worry for methods that exploit correlation between emissions given by showers?

The Lund plane

Andersson, Gustafson, Lonnblad, Pettersson 1989

Lund diagrams in the $(\ln z\theta, \ln \theta)$ plane are a very useful way of representing emissions.

Dreyer, Salam, Soyez 2018



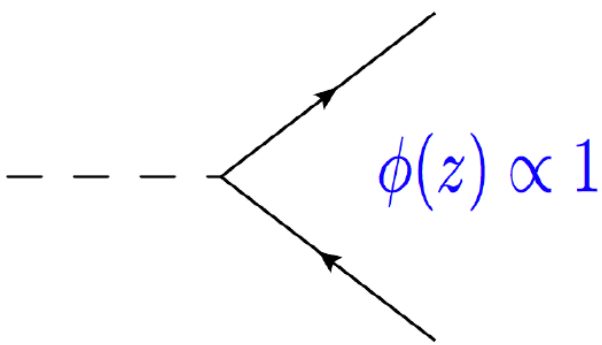
Separation of different physics effects inluding non-pert.

Density of emissions in primary Lund plane well understood theoretically.

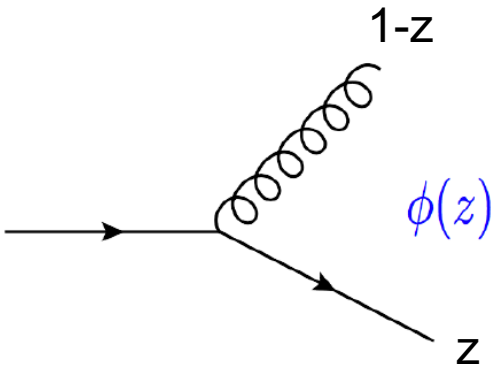
At the heart of analytic approaches and parton showers. Can be used as an input to ML.

Bridges the gap between Deep learning and “Deep thinking” approaches?

Basics: tagging and grooming



$\phi(z) \propto 1$



$\phi(z) \propto \frac{1+z^2}{1-z}$

Simple underlying ideas behind many tools:

- Use asymmetric nature of QCD splitting. Single pronged QCD jet versus multi-pronged jets.
- Exploit singlet nature of W/Z/H suppresses soft large angle radiation.
- **Groom** jets to remove uncorrelated soft radiation : ISR, UE/pile-up