Small-radius jets to all orders

Rencontre de Physique des Particules, 15 January 2015

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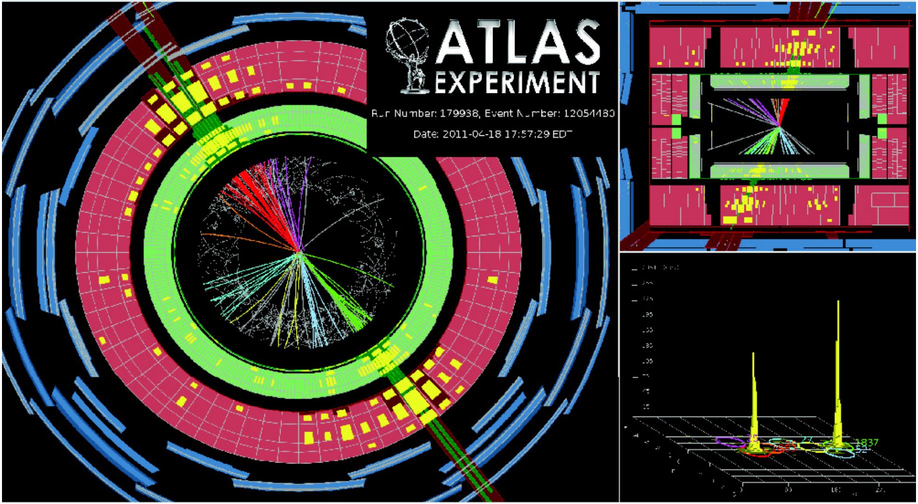
INTRODUCTION

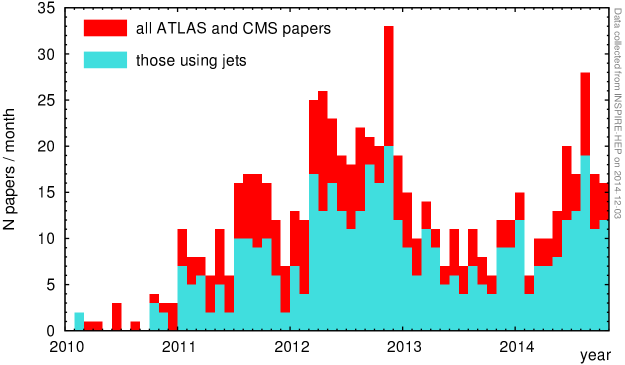
What constitutes a jet?

Jets are collimated bunches of particles produced by hadronization of a quark or gluon.



Why are jets important?

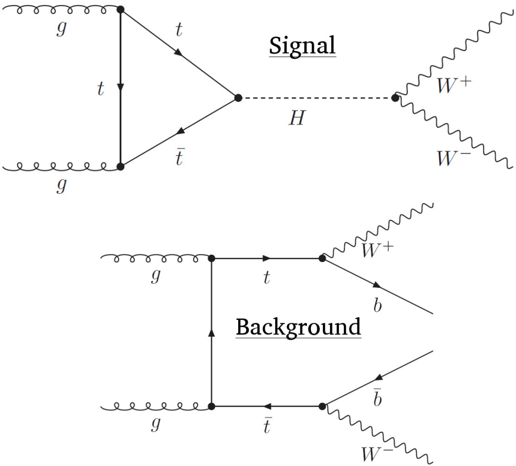
- QCD processes are at the heart of modern hadron colliders.
- Most of CMS and ATLAS searches make use of jets.
- The increase in energy and pileup at the LHC is raising the necessity for a deeper understanding of jet processes.



Example: background discrimination in Higgs production

Main background to Higgs production via gluon fusion (with W^+W^- decay) is $t\bar{t}$ production.

$\Longrightarrow$ background can be separated with veto on hard jets.



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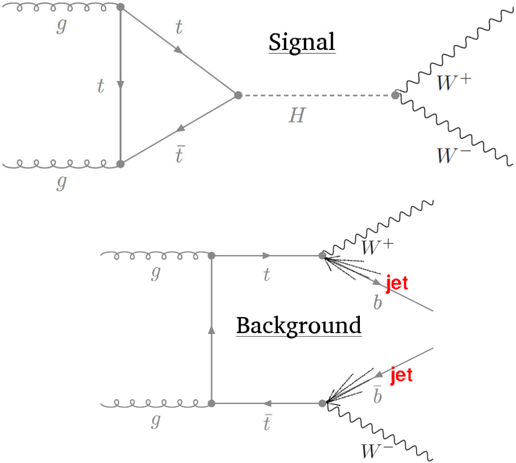


Jet algorithms and the jet radius

A jet algorithm maps final state particle momenta to jet momenta.

$$\underbrace{\{p_i\}}_{\text{particles}} \Longrightarrow \underbrace{\{j_k\}}_{\text{jets}}$$

This requires an external parameter, the jet radius R, which specifies an angular scale.

The jet radius R defines up to which point separate partons are recombined into a single jet.

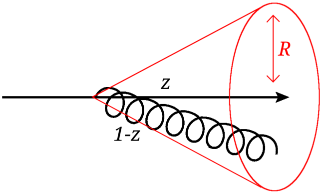


Figure – Gluon emission and emitting quark combined into a single jet.

Cambridge/Aachen algorithm with incoming hadrons

Basic idea is to invert QCD branching process, clustering pairs which are closest in metric defined by the divergent structure of the theory

Definition

1. For any pair of particles i, j find the minimum of

$$\Delta R_{ij} = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

2. If the minimum value $\min_{i,j}(\Delta R_{ij}^2) > R^2$ then particle i is removed from the list and defined as a jet, otherwise i and j are merged.
3. Repeat until no particles are left.

Most algorithms used nowadays at hadron colliders follow this pattern, with some variations in the distance measure (eg. the anti-k_t algorithm).

Perturbative properties: quark energy ≠ jet energy

Jet properties will be affected by gluon radiation and $g \to q\bar{q}$ splitting.

Average energy difference between hardest final state jet and initial quark, considering emissions beyond the reach of the jet

$$\langle \Delta z \rangle_q^{\text{hardest}} = \frac{\alpha_s}{\pi} C_F \left(2 \ln 2 - \frac{3}{8} \right) \ln R + \mathcal{O}(\alpha_s)$$

This is because emissions outside of the jet reduce the jet energy.

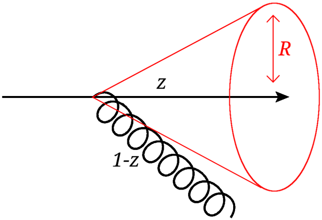


Figure – Gluon emission beyond the reach of the jet.

How relevant are small-R effects?

In recent years, jet radii have become ever smaller.

Most common choice is $R = 0.4$, but in substructure tools and heavy ions, values down to $R = 0.2$ are used.

We can evaluate numerically how important the effect of perturbative $\ln R$ terms is on the microjet p_t.

Taking $R = 0.2$ we find that

- quark-induced jets have a hardest microjet $p_t \sim 5 - 10\%$ smaller than the original quark,
- gluon-induced jets have a hardest microjet $p_t \sim 15 - 25\%$ smaller than the original gluon.

Resummation of $(\alpha_s \ln R)^n$ terms

"In the small R limit, new clustering logarithms [. . .] arise at each order and cannot currently be resummed."

— Tackmann, Walsh & Zuberi (arXiv:1206.4312)

How important can contributions from higher orders be, e.g. $(\alpha_s \ln R)^n$, especially at smaller values of R ?

We aim to resum all leading logarithmic $(\alpha_s \ln R)^n$ terms in the limit of small R for a wide variety of observables.

We will approach this question using generating functionals.

GENERATING FUNCTIONALS

Evolution variable t

Start with a parton and consider emissions at successively smaller angular scales.

Use an evolution variable t corresponding to the integral over the collinear divergence weighted with α_s

$$t = \int_{R^2}^{1} \frac{d\theta^2}{\theta^2} \frac{\alpha_s(p_t\theta)}{2\pi} = \frac{1}{b_0} \sum_{n=1}^{\infty} \frac{1}{n} \left(\frac{\alpha_s b_0}{2\pi} \ln \frac{1}{R^2} \right)^n$$

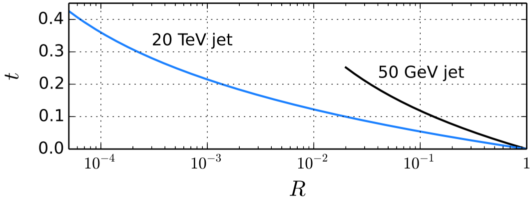


Figure – Plot of t as a function of R down to $Rp_t = 1\,\text{GeV}$ for $p_t = 0.01 - 20\,\text{TeV}$.

Generating functional

Definition

$Q(x, t_1, t_2)$ is the generating functional encoding the parton content one would observe when resolving a quark with momentum xp_t at scale t_1 on an angular scale $t_2 > t_1$ (ie. $R_2 < R_1$).

Mean number of quark microjets of momentum fraction z produced from a quark

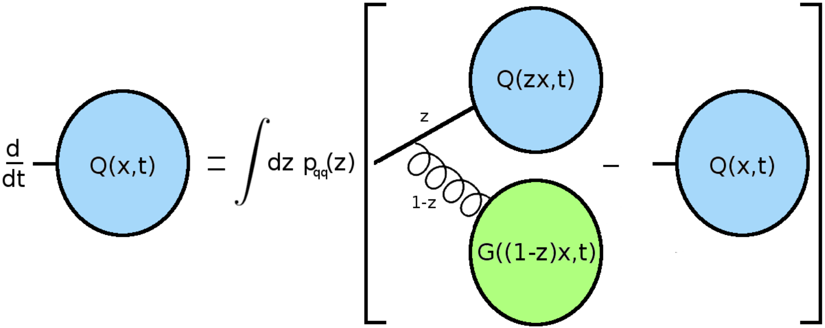
$$\frac{dn_{q(z)}}{dz} = \frac{\delta Q(1, 0, t_2)}{\delta q(z)}\Bigg|_{\forall q(z)=1, g(z)=1}$$

We can formulate an evolution equation for the generating functionals

$$Q(x, 0, t) = Q(x, \delta_t, t)\left(1 - \delta t \int dz\, p_{qq}(z)\right) + \delta_t \int dz\, p_{qq}(z)\Big[Q(zx, \delta_t, t)G((1-z)x, \delta_t, t)\Big].$$

Gluon generating functional $G(x, t_1, t_2)$ defined the same way.

We can rewrite the evolution equation of the quark generating functional in graphical form, representing a differential equation



Here the blobs represent the generating functionals at a scale t.

The quark and gluon evolution equations allow us to resum observables to all orders numerically.

OBSERVABLES

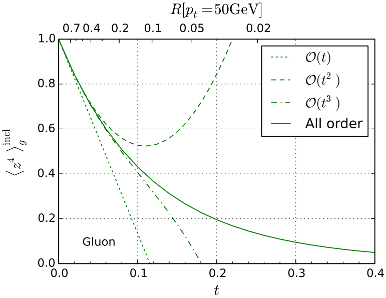
Jet spectrum from microjet fragmentation function

Jet spectrum can be obtained from the partonic spectrum

$$\frac{d\sigma_{\text{jet}}}{dp_t} \simeq \frac{d\sigma_i}{dp_t} \int_0^1 dz\, z^{n-1} f^{\text{incl}}_{\text{jet}/i}(z,t) \equiv \frac{d\sigma_i}{dp_t} \langle z^{n-1} \rangle_i^{\text{incl}}.$$

Small-R terms are important, around $30-50\%$ effect on gluonic inclusive spectrum (with $n=5$).

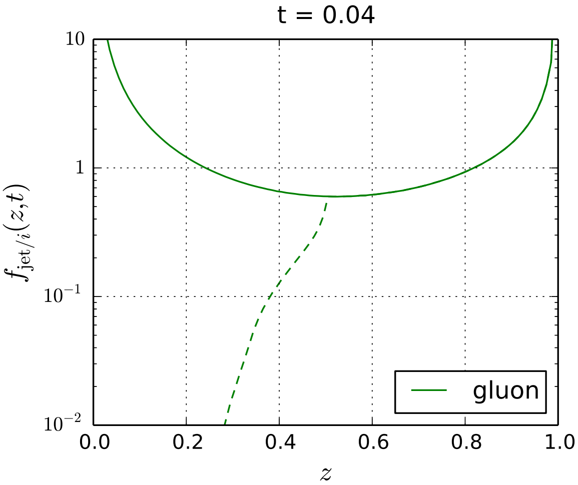
Convergence is slow: the $\mathcal{O}(t^2)$ corrections (ie. NNLO) deviate noticeably from all-orders results below $R = 0.3$



Microjet fragmentation function

Solid line: inclusive microjet fragmentation function.

Dashed line: hardest microjet fragmentation function.



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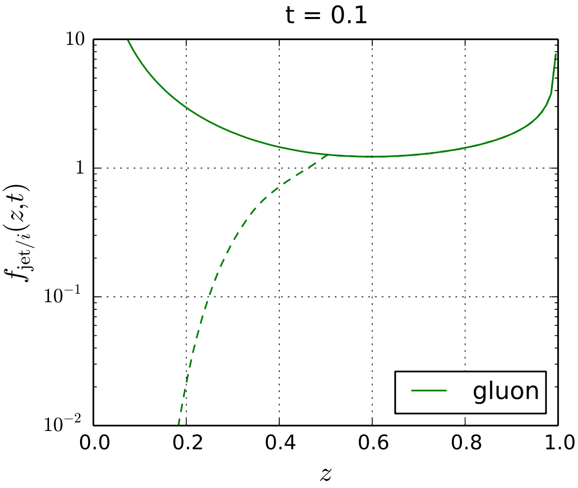

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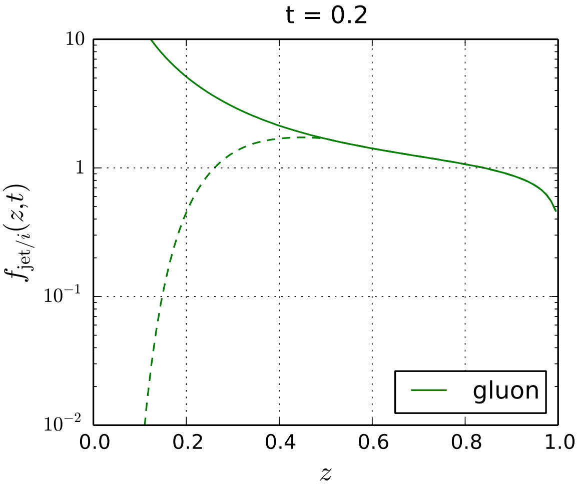

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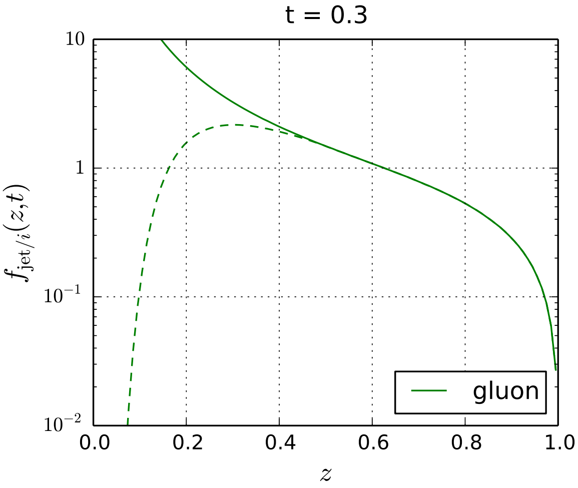

CONCLUSION

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- Using generating-functional approach, carried out numerical leading logarithmic resummation of $\ln R$ enhanced-terms in small-R jets.
- Studied inclusive microjet spectrum and identified the spectrum of hardest microjet emerging from parton fragmentation.
- Small-R effects can be substantial, for example reducing the inclusive jet spectrum by $30 - 50\%$ for gluon jets for $R = 0.4 - 0.2$.
- Study of phenomenological implications for Higgs physics and inclusive jet spectrum are forthcoming.

further reading on arXiv:1411.5182

BACKUP SLIDES

Evolution equations

We can write the complete evolution equations as differential equations, for the quark the previous graph corresponds to

Quark

$$\frac{dQ(x,t)}{dt} = \int dz\, p_{qq}(z)\,[Q(zx,t)\,G((1-z)x,t) - Q(x,t)]\,.$$

In the gluon case we find,

Gluon

$$\frac{dG(x,t)}{dt} = \int dz\, p_{gg}(z)\,[G(zx,t)G((1-z)x,t) - G(x,t)] + \int dz\, n_f\, p_{qg}(z)\,[Q(zx,t)Q((1-z)x,t) - G(x,t)]\,.$$

Microjet vetoes

Jet veto resummations are a context where all-order small-R corrections could be important.

Writing the probability of no gluon emissions above a scale p_t as

$$P(\text{no primary-parton veto}) = \exp\left[-\int_{p_t}^{Q} \frac{dk_t}{k_t} \bar{\alpha}_s(k_t) 2 \ln \frac{Q}{k_t}\right],$$

one can show that including small-R corrections and applying the veto on the hardest microjet, we have

$$\mathcal{U} \equiv P(\text{no microjet veto})/P(\text{no primary-parton veto})$$
$$= \exp\left[-2\bar{\alpha}_s(p_t) \ln \frac{Q}{p_t} \int_0^1 dz\, f^{\text{hardest}}(z, t(R, p_t)) \ln z\right].$$

The R-dependent correction generates a series of terms

$$\alpha_s^{m+n}(Q) \ln^m(Q/p_t) \ln^n R.$$

Logarithmic moment $\langle \ln z \rangle$

The logarithmic moment of f^{hardest} is, as seen previously

$$\langle \ln z \rangle^{\text{hardest}} \equiv \int_0^1 dz\, f^{\text{hardest}}(z) \ln z\,.$$

This seems to have a particularly stable perturbative expansion.