Jets: seeing quarks, gluons and more at the LHC

Grégory Soyez

IPhT, CEA Saclay

October 21-31, 2014

Brief plan

- Lecture 1: *Jets $\sim$ QCD parton*
  basic concepts
- Lecture 2: *How close is a jet to a parton?*
  Analytic estimates of perturbative and non-perturbative effects between a parton and a jet
- Lecture 3: *A jet can be something else too!*
  Boosted jets and jet substructure

Now that you got some rest...

Do you have any question?

FINALLY:
A reason to love
Mondays.

Question 1

In the IR, QCD amplitudes are

- Finite
- Divergent (infinite)

Question 1

In the IR, QCD amplitudes are

- Divergent (infinite)

Question 2

In pQCD, well-defines observables should be

- Finite
- Divergent (infinite)

Question 2

In pQCD, well-defines observables should be

- Finite

Consequence

- Divergences in real emissions cancel against virtual corrections
- Observables should be **infrared-and-collinear safe**
- Observables should not be sensitive to coll. branchings and soft em.

Question 3

A jet is a proxy to

- Leptons
- Quark and gluons
- Neutrinos

Question 3

A jet is a proxy to

- Quark and gluons

Physics idea

Because of the collinear divergence, "q/g" appear as collinear sprays of hadrons, **jets**

Question 4

What jet algorithm is used at the LHC?

- k_t
- anti-k_t
- the ATLASCone and the CMSIterativeCone
- SISCone

Question 4

What jet algorithm is used at the LHC?

- anti-k_t

The anti-k_t algorithm

- From all the objects, define the distances

$$d_{ij} = \min(p_{t,i}^{-2}, p_{t,j}^{-2})(\Delta y_{ij}^2 + \Delta\phi_{ij}^2), \qquad d_{iB} = p_{t,i}^{-2} R^2$$

- repeatedly find the minimal distance
  if d_{ij}: recombine i and j into $k = i + j$
  if d_{iB}: call i a jet

Question 5

Is the anti-k_t algorithm IRC safe?

- Yes
- No

Question 5

Is the anti-k_t algorithm IRC safe?

- Yes

Question 6

Is the following statement correct?
“For my analysis, I use jets reconstructed with the anti-k_t algorithm.”

- Yes
- No

Question 6

Is the following statement correct?

"For my analysis, I use jets reconstructed with the anti-k_t algorithm."

- No

The algorithm alone is not enough: one has to specify the parameters (here, R)

Question 7

As Bruno said, people get inventive: *"we measure the number of jets associated with the Higgs."*
Is that IRC-safe?

- Yes
- No
- It depends

Question 7

As Bruno said, people get inventive: *"we measure the number of jets associated with the Higgs."*
Is that IRC-safe?

- It depends

The "total" number of jets is not!

But one imposes a p_t cut so things are fine (quote the cut!)

Question 8

For IRC-safe observables, soft/collinear emissions are (otfen) giving

- 0
- constant correction
- logarithmic corrections
- power corrections

Question 8

For IRC-safe observables, soft/collinear emissions are (otfen) giving

- constant correction
- logarithmic corrections

Reminiscent of the $d\theta^2/\theta^2$ or dz/z emission rates

Question 9

For IRC-safe observables, non-perturbative corrections are (usually) giving

- 0
- constant correction
- logarithmic corrections ($\log(Q/\Lambda_{\rm QCD})$)
- power corrections ($(\Lambda_{\rm QCD}/Q)^k$)

Question 9

For IRC-safe observables, non-perturbative corrections are (usually) giving

- power corrections ($(\Lambda_{\mathrm{QCD}}/Q)^k$)

Mostly a cancellation of the “log” due to IRC safety

Question 10

Do you also have collinear and soft emissions in QED?

- Yes
- No

Question 10

Do you also have collinear and soft emissions in QED?

- Yes

Same $d\theta^2/\theta^2$ or dz/z divergences when emitting a photon from an electron!

Question 11

Why do we have QCD (q/g) jets and no e^-/photon jet?

Question 11

Why do we have QCD (q/g) jets and no e^-/photon jet?

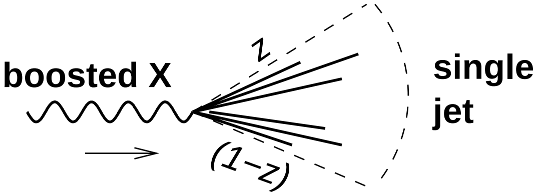
- $\alpha_e \ll \alpha_s$
- In other words $\alpha_e \log(1/R)$ or $\alpha_e \log(1/z)$ only relevant at "unresolved" scales
- And no IR divergence in the coupling

Jet substructure

concept, importance, main ideas

Boosted jets

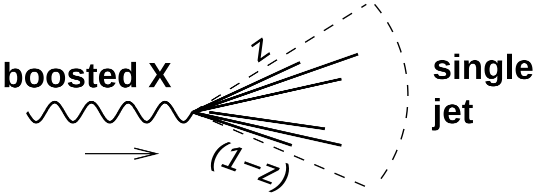
Object X decaying to hadrons



$$R \gtrsim \frac{m}{p_t} \frac{1}{\sqrt{z(1-z)}}$$

Boosted jets

Object X decaying to hadrons



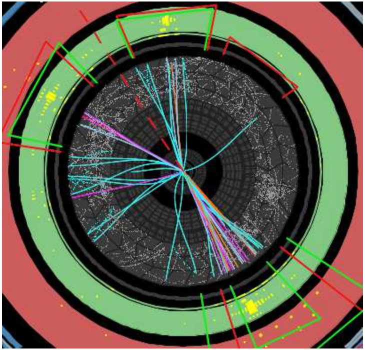
$$R \gtrsim \frac{m}{p_t}\frac{1}{\sqrt{z(1-z)}}$$

If $p_t \gg m$, reconstructed as a single jet

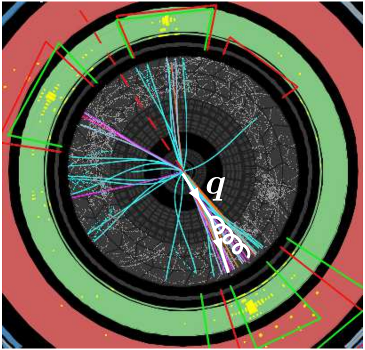
How to disentangle that from a QCD jet?

An illustration

What jet do we have here?



An illustration



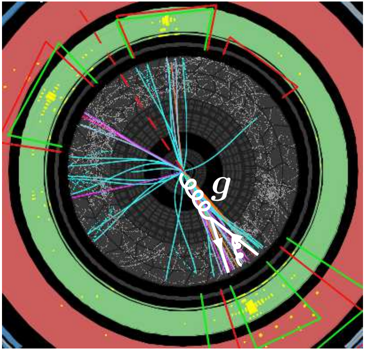
What jet do we have here?

- a quark?

An illustration

What jet do we have here?

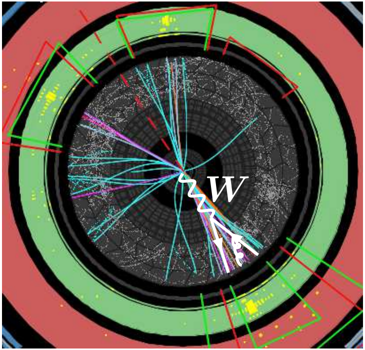
- a quark?
- a gluon?



An illustration

What jet do we have here?

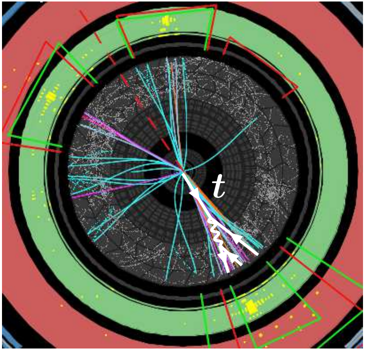
- a quark?
- a gluon?
- a W/Z (or a Higgs)?



An illustration

What jet do we have here?

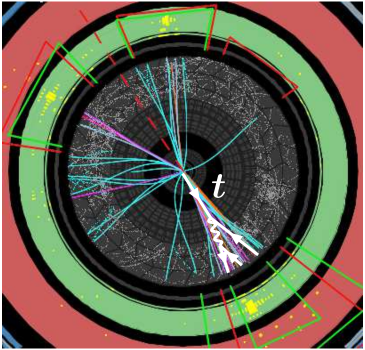
- a quark?
- a gluon?
- a W/Z (or a Higgs)?
- a top quark?



An illustration

What jet do we have here?

- a quark?
- a gluon?
- a W/Z (or a Higgs)?
- a top quark?



Source: ATLAS boosted top candidate

Question 12

Can I just look at the jet mass?

- Yes
- No

Question 12

Can I just look at the jet mass?

- No

I'll show you why later

Question 13

Does it make sense to speak about the "mass" of a jet?

- Yes
- No

Question 13

Does it make sense to speak about the "mass" of a jet?

- Yes

Th: Of course! it's a "simple" 4-vector sum!
Exp: a bit more complicated but fine (ask me or Murilo for details)

Boosted jets

Many applications: (examples)

- 2-pronged decay: $W \to q\bar{q}$, $H \to b\bar{b}$
- 3-pronged decay: $t \to qqb$, $\tilde{\chi} \to qqq$
- busier combinations: $t\bar{t}H$
- new physics: *e.g.* R-parity violating $\chi \to qqq$, boosted tops in SUSY

Boosted jets

Many applications: (examples)

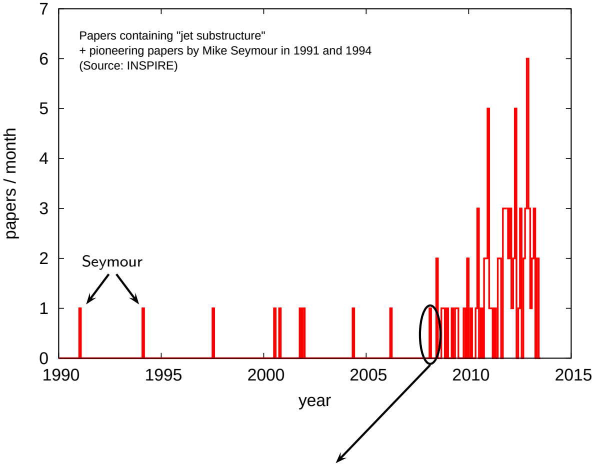
- 2-pronged decay: $W \to q\bar{q}$, $H \to b\bar{b}$
- 3-pronged decay: $t \to qqb$, $\tilde{\chi} \to qqq$
- busier combinations: $t\bar{t}H$
- new physics: *e.g.* R-parity violating $\chi \to qqq$, boosted tops in SUSY

Increasingly important:

- Increasing LHC energy
- Increasing bounds
- More-and-more discussions about yet higher-energy colliders

More and more boosted jets
Needs to be under control

A lot of activity since 2008



Jet substructure as a new Higgs search channel at the LHC

Jon Butterworth, Adam Davison, Mathieu Rubin, Gavin Salam, 0802.2470

Two major ideas: Idea 1

Find $N = 2, 3$ hard cores in a jet

Question 14

Why does that work? (say we look at W v. q jets)

- Because there is no gluon in a W jet
- Because the splitting $W \to q\bar{q} \neq q \to qg$
- Because W and q do not have the same charge
- Becasue W and q do not have the same colour

Two major ideas: Idea 1

Find $N = 2, 3$ hard cores in a jet

Question 14

Why does that work? (say we look at W v. q jets)

- Because the splitting $W \to q\bar{q} \neq q \to qg$

$$P(z) \propto 1/z \quad \Rightarrow \quad \text{dominated by soft emissions}$$

$$\Rightarrow \quad \text{QCD jets mostly have a “single” hard core}$$

Two major ideas: Idea 1

Constrain radiation patterns in the jet

Question 15

Why does that work? (say we look at W v. q jets)

- Because there is no gluon in a W jet
- Because the splitting $W \to q\bar{q} \neq q \to qg$
- Because W and q do not have the same charge
- Becasue W and q do not have the same colour

Two major ideas: Idea 1

Constrain radiation patterns in the jet

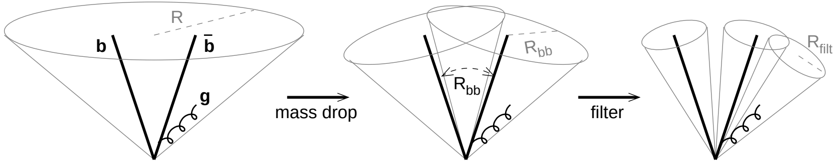
Question 15

Why does that work? (say we look at W v. q jets)

- Becasue W and q do not have the same colour

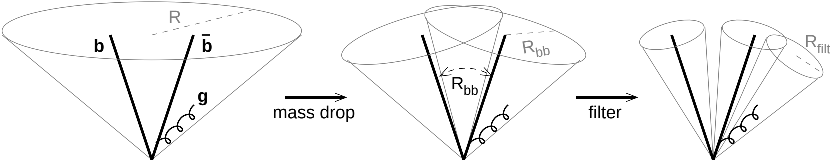
Radiation is different for colourless, quarks or gluons
Radiation patterns is different for $W \to q\bar{q}$ or $g \to q\bar{q}$

Many tools



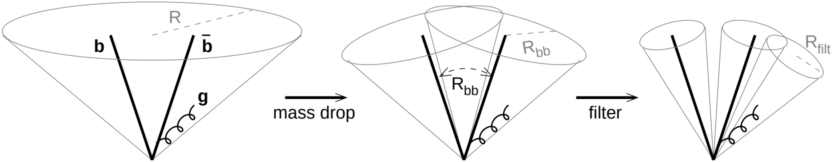
- Two major ideas:
  1. Find $N = 2, 3$ hard cores in a jet
     QCD jets typically have a single core + soft radiation
  2. constrain the radiation pattern in jets
     q/g jets radiate soft gluons differently from, *e.g.* $W \to q\bar{q}$

Many tools



- Two major ideas:
  1. Find $N = 2, 3$ hard cores in a jet
     QCD jets typically have a single core + soft radiation
  2. constrain the radiation pattern in jets
     q/g jets radiate soft gluons differently from, *e.g.* $W \to q\bar{q}$
- Many approaches:
  1. uncluster the jet into subjets/investigate the clustering history
  2. use jet shapes (functions of jet constituents),...

Many tools



- Two major ideas:
  1. Find $N = 2, 3$ hard cores in a jet
     QCD jets typically have a single core + soft radiation
  2. constrain the radiation pattern in jets
     q/g jets radiate soft gluons differently from, *e.g.* $W \to q\bar{q}$
- Many approaches:
  1. uncluster the jet into subjets/investigate the clustering history
  2. use jet shapes (functions of jet constituents),...
- Many tools: mass drop; filtering, trimming, pruning; soft drop; N-subjettiness, planar flow, energy correlations, pull; template methods; Johns Hopkins top tagger, HEPTopTagger; ...

Generic status

current status

methods are

- tested on Monte-Carlo simulations
- validated on LHC data (QCD backgrounds)

disclaimer

I cannot realistically cover everything

$\Rightarrow$ I will just show a few examples

Jet substructure

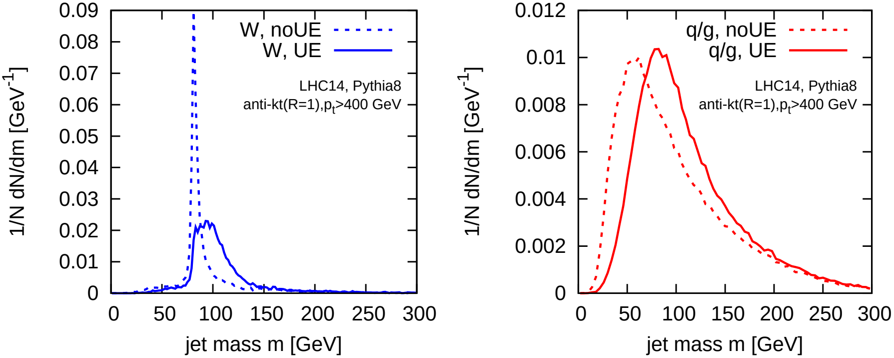
A deeper look at a few tools

Fat Jets

Fat Jets

One usually work with large-R jets ($R \sim 0.8 - 1.5$)

$\Rightarrow$ large sensitivity to UE (and pileup)



Grooming

Grooming

One usually work with large-R jets ($R \sim 0.8 - 1.5$)

$\Rightarrow$ large sensitivity to UE (and pileup)

$\Rightarrow$ "grooming" techniques reduce sensitivity to soft-and-large-angle

Grooming

Grooming

One usually work with large-R jets ($R \sim 0.8 - 1.5$)

$\Rightarrow$ large sensitivity to UE (and pileup)

$\Rightarrow$ "grooming" techniques reduce sensitivity to soft-and-large-angle

Filtering/trimming

- re-cluster the jet with the k_t algorithm, $R = R_{\rm sub}$
- Filtering: keep the $n_{\rm filt}$ hardest subjets [J.Buterworth,A.Davison,M.Rubin,G.Salam,08]
- Trimming: keep subjets with $p_t > f_{\rm trim} p_{t,\rm jet}$ [D.Krohn,J.Thaler,L-T.Wang,10]

Grooming

Grooming

One usually work with large-R jets ($R \sim 0.8 - 1.5$)

$\Rightarrow$ large sensitivity to UE (and pileup)

$\Rightarrow$ "grooming" techniques reduce sensitivity to soft-and-large-angle

Filtering/trimming

- re-cluster the jet with the k_t algorithm, $R = R_{\text{sub}}$
- Filtering: keep the n_{filt} hardest subjets
  [J.Buterworth,A.Davison,M.Rubin,G.Salam,08]
- Trimming: keep subjets with $p_t > f_{\text{trim}} p_{t,\text{jet}}$ [D.Krohn,J.Thaler,L-T.Wang,10]

pruning

- re-cluster the jet with the k_t algorithm [S.Ellis,C.Vermillion,J.Walsh,2009]
- when recombining $j_1 + j_2 \to j$, if $\theta_{12} > R_{\text{prune}} = f_{\text{prune}} m/p_t$ and $\min(p_{t1}, p_{t2}) < z_{\text{prune}} p_t$, keep only the hardest of j_1 and j_2.

Methods for finding hard cores

(modified) mass-drop tagger ((m)MDT)

- start with a jet clustered with Cambridge/Aachen
- undo the last splitting $j \to j_1 + j_2$
- if $\max(p_{t1}, p_{t2}) > z_{\rm cut} p_t$, j_1 and j_2 are the 2 hard cores
  otherwise, continue with the hardest subjet
- Original version also imposed a mass-drop: $\max(m_1, m_2) < \mu m$

[J.Buterworth,A.Davison,M.Rubin,G.Salam,08; M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

Methods for finding hard cores

(modified) mass-drop tagger ((m)MDT)

- start with a jet clustered with Cambridge/Aachen
- undo the last splitting $j \to j_1 + j_2$
- if $\max(p_{t1}, p_{t2}) > z_{\text{cut}} p_t$, j_1 and j_2 are the 2 hard cores
  otherwise, continue with the hardest subjet
- Original version also imposed a mass-drop: $\max(m_1, m_2) < \mu m$

[J.Buterworth,A.Davison,M.Rubin,G.Salam,08; M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

SoftDrop

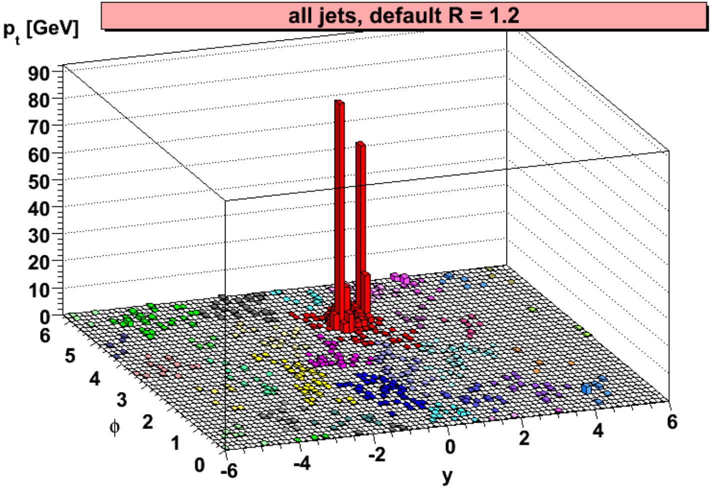
Same de-clustering procedure as the mMDT but angular-dependent cut

$$\max(p_{t1}, p_{t2}) > z_{\text{cut}} p_t (\theta_{12}/R)^{\beta}$$

[A.Larkoski,S.Marzani,J.Thaler,GS,14]

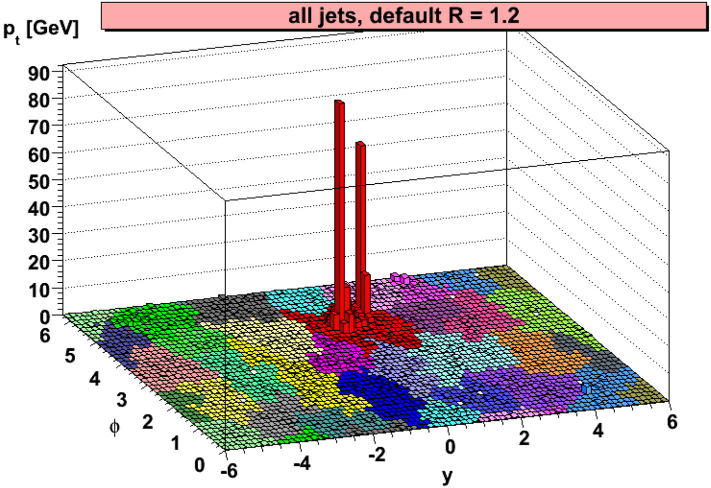
MassDrop+Filtering in action

Start with the jets in an event



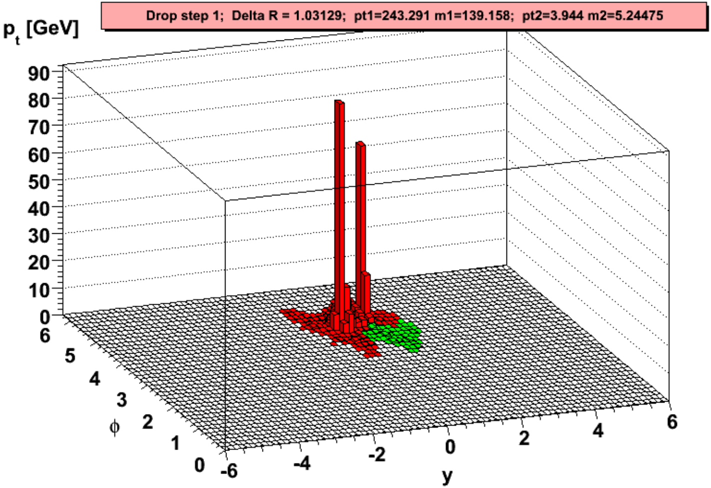
MassDrop+Filtering in action

This is what they look like with their area



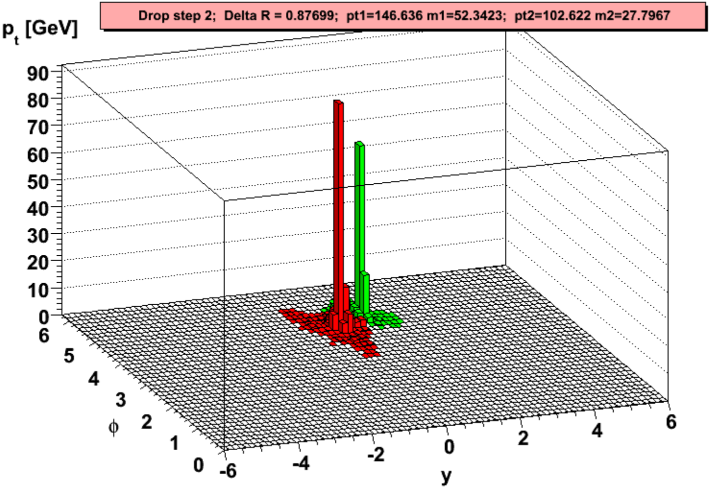
MassDrop+Filtering in action

Take the hardest, apply a step of mass-drop



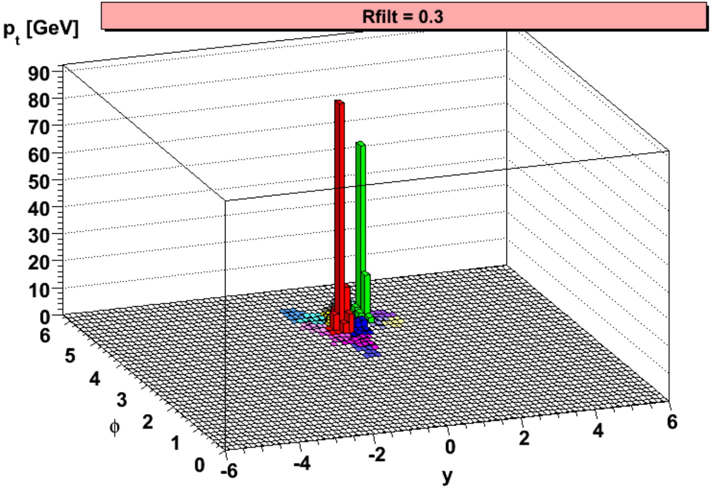
MassDrop+Filtering in action

Failed... iterate the mass drop



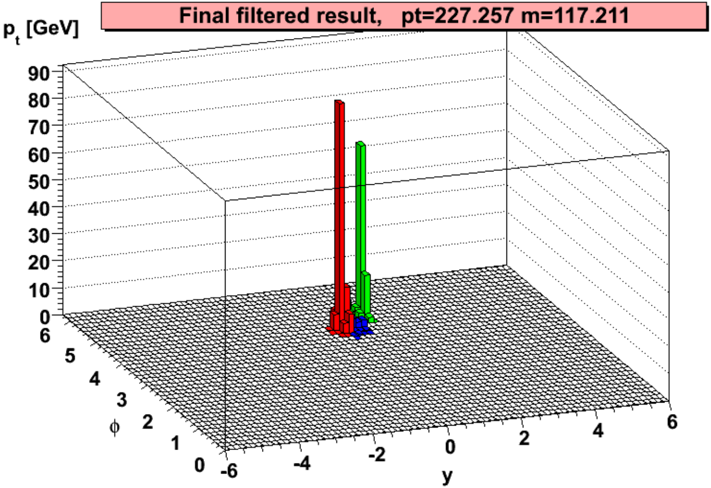
MassDrop+Filtering in action

Good... Now recluster what is left with a smaller R



MassDrop+Filtering in action

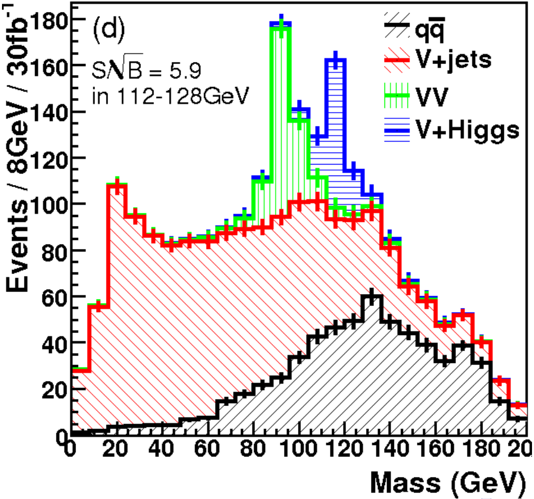
And keep only the 3 hardest



MassDrop for $H \to b\bar{b}$ searches

[J.Buterworth,A.Davison,M.Rubin,G.Salam,08]

This is the kind of Higgs reconstruction one would get



Constraining radiation

N-subjettiness

Given N directions in a jet (axes) [$\neq$ options, e.g. k_t subjets or minimal]

$$\tau_N^{(\beta)} = \frac{1}{p_T R^\beta} \sum_{i \in \text{jet}} p_{t,i} \min{}^{\beta}(\theta_{i,a_1}, \dots, \theta_{i,a_n})$$

Constraining radiation

N-subjettiness

Given N directions in a jet (axes) [$\neq$ options, e.g. k_t subjets or minimal]

$$\tau_N^{(\beta)} = \frac{1}{p_T R^\beta} \sum_{i\in\mathrm{jet}} p_{t,i} \min{}^\beta(\theta_{i,a_1},\dots,\theta_{i,a_n})$$

- Measure of the radiation from N prongs

Constraining radiation

N-subjettiness

Given N directions in a jet (axes) [$\neq$ options, e.g. k_t subjets or minimal]

$$\tau_N^{(\beta)} = \frac{1}{p_T R^\beta} \sum_{i\in\text{jet}} p_{t,i} \min{}^\beta(\theta_{i,a_1}, \dots, \theta_{i,a_n})$$

- Measure of the radiation from N prongs
- $\tau_{N,N-1} = \tau_N/\tau_{N-1}$ is a good variable for N-prong v. QCD

Constraining radiation

N-subjettiness

Given N directions in a jet (axes) [$\neq$ options, e.g. k_t subjets or minimal]

$$\tau_N^{(\beta)} = \frac{1}{p_T R^\beta} \sum_{i\in\text{jet}} p_{t,i} \min{}^\beta(\theta_{i,a_1},\dots,\theta_{i,a_n})$$

- Measure of the radiation from N prongs
- $\tau_{N,N-1} = \tau_N/\tau_{N-1}$ is a good variable for N-prong v. QCD

Planar flow

$$I_{ab} = \frac{1}{m} \sum_{i\in\text{jet}} p_{t,i} \frac{p_{a,i}}{p_{t,i}} \frac{p_{b,i}}{p_{t,i}} \qquad P_f = \frac{4\det(I)}{\text{tr}^2(I)}$$

vanishes for “linear” configurations ⇒ measures planar configurations

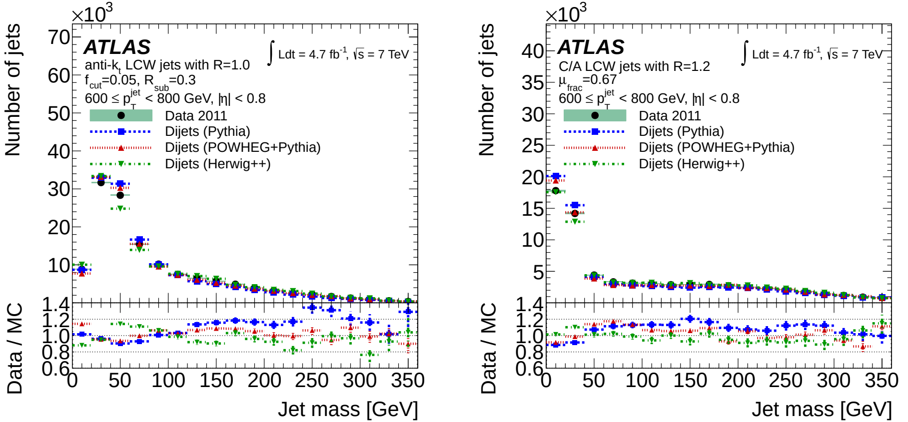
Jet substructure

A few practical examples

Example 1: Monte Carlo v. data

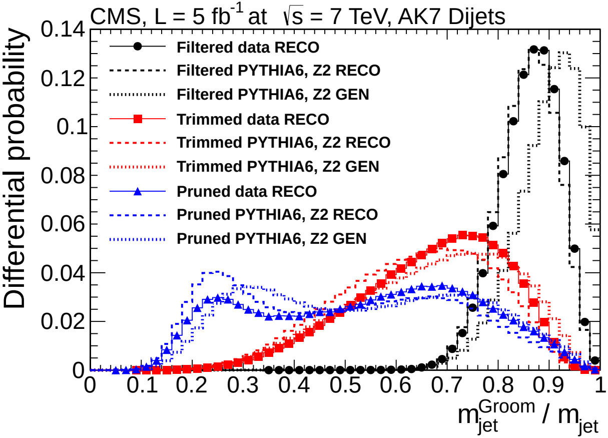
Trimming

Mass-drop+filtering



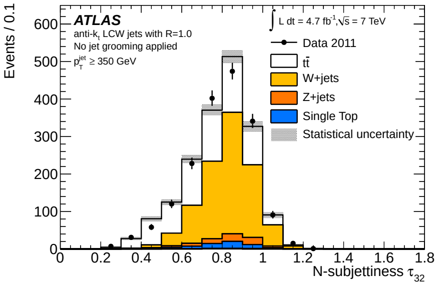
Example 1: Monte Carlo v. data

(“Groomed” mass)/(plain mass)

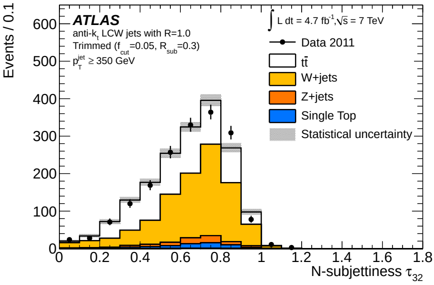


Example 1: Monte Carlo v. data

N-subjettiness τ_{32}

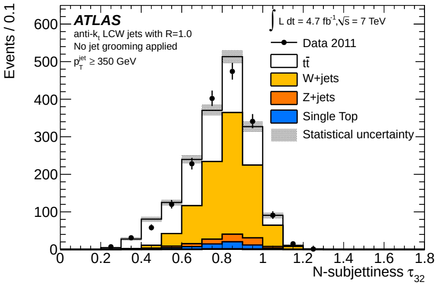


trimming+τ_{32}

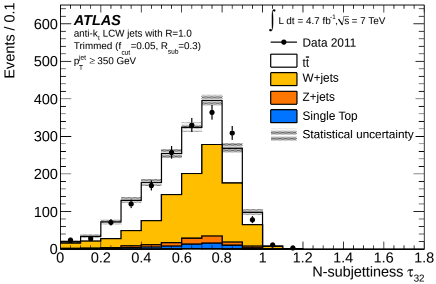


Example 1: Monte Carlo v. data

N-subjettiness τ_{32}



trimming+τ_{32}



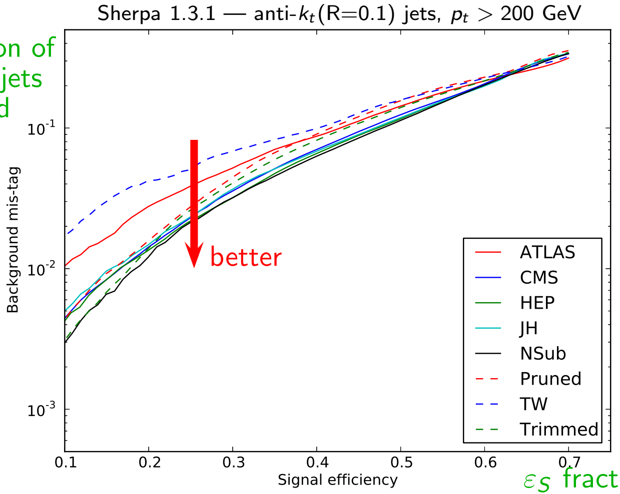
In a nutshell

- decent agreement between data and Monte-Carlo
- but some differences are observed

Example 2: top tagging MC study

[Boost 2011 proceedings]

ε_B fraction of QCD jets tagged



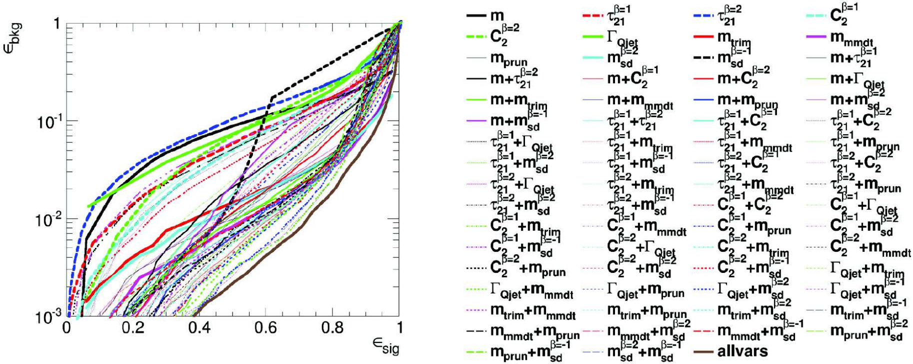
better

ε_S fraction of top jets tagged

Example 3: recent MC study of W tagging

[Boost 2013 WG]

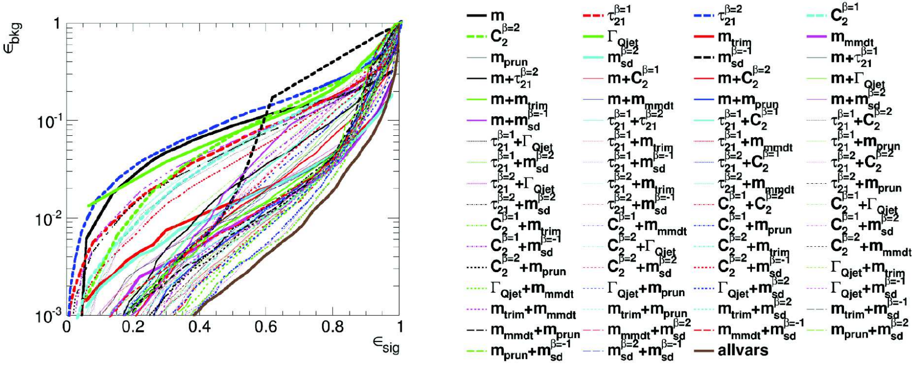
W v. q jets: combination of “2-core finder” + “radiation constraint”



Example 3: recent MC study of *W* tagging

[Boost 2013 WG]

W v. *q* jets: combination of “2-core finder” + “radiation constraint”



- Combination largely helps
- details not so obvious

STOP and think

can we stop blindly running Monte-Carlo and understand things better (from first-principle QCD)?

Example: plain-jet mass and resummation

$$\frac{1}{\sigma}\frac{d\sigma}{dm^2} = \int_0^{R^2} \frac{d\theta^2}{\theta^2} \int_0^1 dz\, P(z)\, \frac{\alpha_s}{2\pi} \delta(m^2 - z(1-z)\theta^2 p_t^2)$$

- We focus on small-R, $p_t R \gg m$

Example: plain-jet mass and resummation

$$\frac{1}{\sigma}\frac{d\sigma}{dm^2} = \int_0^{R^2} \frac{d\theta^2}{\theta^2} \int_0^1 dz\, P(z)\, \frac{\alpha_s}{2\pi} \delta(m^2 - z(1-z)\theta^2 p_t^2)$$

$$\approx \int_0^{R^2} \frac{d\theta^2}{\theta^2} \int_0^1 dz\, \frac{2C_R}{z}\, \frac{\alpha_s}{2\pi} \delta(m^2 - z\theta^2 p_t^2)$$

- We focus on small-R, $p_t R \gg m$
- $P(z) = 2C_R/z$ up to subleading (log) corrections
- $(1-z)$ only need to power (of $m/(p_t R)$) corrections

Example: plain-jet mass and resummation

$$\frac{1}{\sigma}\frac{d\sigma}{dm^2} = \int_0^{R^2}\frac{d\theta^2}{\theta^2}\int_0^1 dz\,P(z)\,\frac{\alpha_s}{2\pi}\delta(m^2 - z(1-z)\theta^2p_t^2)$$

$$\approx \int_0^{R^2}\frac{d\theta^2}{\theta^2}\int_0^1 dz\,\frac{2C_R}{z}\,\frac{\alpha_s}{2\pi}\delta(m^2 - z\theta^2p_t^2)$$

$$\approx \frac{\alpha_s C_R}{\pi}\,\frac{1}{m^2}\log(p_t^2R^2/m^2)$$

- We focus on small-R, $p_tR \gg m$
- $P(z) = 2C_R/z$ up to subleading (log) corrections
- $(1-z)$ only need to power (of $m/(p_tR)$) corrections
- we get a logarithmic enhancement

Example: plain-jet mass and resummation

$$\begin{aligned}\frac{1}{\sigma}\frac{d\sigma}{dm^2} &= \int_0^{R^2}\frac{d\theta^2}{\theta^2}\int_0^1 dz\,P(z)\,\frac{\alpha_s}{2\pi}\delta(m^2-z(1-z)\theta^2p_t^2)\\ &\approx \int_0^{R^2}\frac{d\theta^2}{\theta^2}\int_0^1 dz\,\frac{2C_R}{z}\,\frac{\alpha_s}{2\pi}\delta(m^2-z\theta^2p_t^2)\\ &\approx \frac{\alpha_s C_R}{\pi}\,\frac{1}{m^2}\log(p_t^2R^2/m^2)\end{aligned}$$

- We focus on small-R, $p_tR \gg m$
- $P(z)=2C_R/z$ up to subleading (log) corrections
- $(1-z)$ only need to power (of $m/(p_tR)$) corrections
- we get a logarithmic enhancement
- Or, for the integrated distribution, using $\rho = m^2/(p_t^2R^2)$

$$P_1(>\rho)=\int_\rho^1 dx\,\frac{1}{\sigma}\frac{d\sigma}{dx}=\alpha_s C_R\pi\,\frac{1}{2}\log^2(1/\rho)$$

Example: plain-jet mass and resummation

$$P_1(>\rho) = \alpha_s C_R \pi \frac{1}{2} \log^2(1/\rho)$$

Example: plain-jet mass and resummation

$$P_1(>\rho) = \alpha_s C_R \pi \frac{1}{2} \log^2(1/\rho)$$

For small enough $\rho = m^2/(p_t^2 R^2)$, $\alpha_s \log^2(\rho) \sim 1$: no more perturbative!

Example: plain-jet mass and resummation

$$P_1(>\rho) = \alpha_s C_R \pi \frac{1}{2} \log^2(1/\rho)$$

For small enough $\rho = m^2/(p_t^2 R^2)$, $\alpha_s \log^2(\rho) \sim 1$: no more perturbative!
$\Rightarrow$ resum contributions at all orders

Example: plain-jet mass and resummation

$$P_1(>\rho) = \alpha_s C_R \pi \, \frac{1}{2} \log^2(1/\rho)$$

For small enough $\rho = m^2/(p_t^2 R^2)$, $\alpha_s \log^2(\rho) \sim 1$: no more perturbative!
$\Rightarrow$ resum contributions at all orders

$$P(<\rho) = \sum_{n=0}^{\infty} \frac{1}{n!} \int_0^{R^2} \frac{d\theta_i^2}{\theta_i^2} \int_0^1 dz_i \, P(z_i) \, \left(\frac{\alpha_s}{2\pi}\right)^n \left[\Theta(m_{12\ldots n}^2 < \rho) + \text{virtual}\right]$$

- “virtual” includes any number of the n gluons being virtual

Example: plain-jet mass and resummation

$$P_1(>\rho) = \alpha_s C_R \pi \frac{1}{2} \log^2(1/\rho)$$

For small enough $\rho = m^2/(p_t^2 R^2)$, $\alpha_s \log^2(\rho) \sim 1$: no more perturbative!

$\Rightarrow$ resum contributions at all orders

$$P(<\rho) = \sum_{n=0}^{\infty} \frac{1}{n!} \int_0^{R^2} \frac{d\theta_i^2}{\theta_i^2} \int_0^1 dz_i\, P(z_i) \left(\frac{\alpha_s}{2\pi}\right)^n \left[\Theta(m_{12\dots n}^2 < \rho) + \text{virtual}\right]$$

$$= \sum_{n=0}^{\infty} \frac{1}{n!} \int_0^{R^2} \frac{d\theta_i^2}{\theta_i^2} \int_0^1 dz_i\, P(z_i) \left(\frac{\alpha_s}{2\pi}\right)^n \prod_{i=1}^{n} \left[\Theta(z_i \theta_i^2 < \rho R^2) - 1\right]$$

- “virtual” includes any number of the n gluons being virtual
- Leading term: **independent emissions**

Example: plain-jet mass and resummation

$$P_1(>\rho) = \alpha_s C_R \pi \frac{1}{2} \log^2(1/\rho)$$

For small enough $\rho = m^2/(p_t^2 R^2)$, $\alpha_s \log^2(\rho) \sim 1$: no more perturbative!
$\Rightarrow$ resum contributions at all orders

$$\begin{aligned} P(<\rho) &= \sum_{n=0}^{\infty} \frac{1}{n!} \int_0^{R^2} \frac{d\theta_i^2}{\theta_i^2} \int_0^1 dz_i\, P(z_i) \left(\frac{\alpha_s}{2\pi}\right)^n \left[\Theta(m^2_{12\dots n} < \rho) + \text{virtual}\right] \\ &= \sum_{n=0}^{\infty} \frac{1}{n!} \int_0^{R^2} \frac{d\theta_i^2}{\theta_i^2} \int_0^1 dz_i\, P(z_i) \left(\frac{\alpha_s}{2\pi}\right)^n \prod_{i=1}^{n} \left[\Theta(z_i\theta_i^2 < \rho R^2) - 1\right] \\ &= \exp\left[-P_1(>\rho)\right] \end{aligned}$$

- "virtual" includes any number of the n gluons being virtual
- Leading term: **independent emissions**
- Sudakov exponentiation

Resummation in QCD

A much more general situation

For a jet shape v we will get terms enhanced by $\log^{(2)}(1/v)$ that have to be resummed at all orders

Resummation in QCD

A much more general situation

For a jet shape v we will get terms enhanced by $\log^{(2)}(1/v)$ that have to be resummed at all orders

Leading log (LL)

Resums **double logs** $(\alpha_s \log^2(1/v))^n = (\alpha_s L^2)^n$:

$$P(< v) = \exp\left[-P_1(> \rho)\right]$$

Note: including running-coupling corrections: $P_1 = \sum_{k=1}^{n} (\alpha_s L)^k L$

Resummation in QCD

A much more general situation

For a jet shape v we will get terms enhanced by $\log^{(2)}(1/v)$ that have to be resummed at all orders

Leading log (LL)

Resums **double logs** $(\alpha_s \log^2(1/v))^n = (\alpha_s L^2)^n$:

$$P(< v) = \exp\left[-P_1(> \rho)\right]$$

Note: including running-coupling corrections: $P_1 = \sum_{k=1}^{n} (\alpha_s L)^k L$

Physics idea

- Remember: (i) independent emissions, (ii) real and virtual emissions
- emissions “smaller” than v: do not contribute: real and virtual cancel
- emissions “larger” than v: real are vetoed
  $\Rightarrow$ we are left with virtuals(=-real)

Resummation in QCD

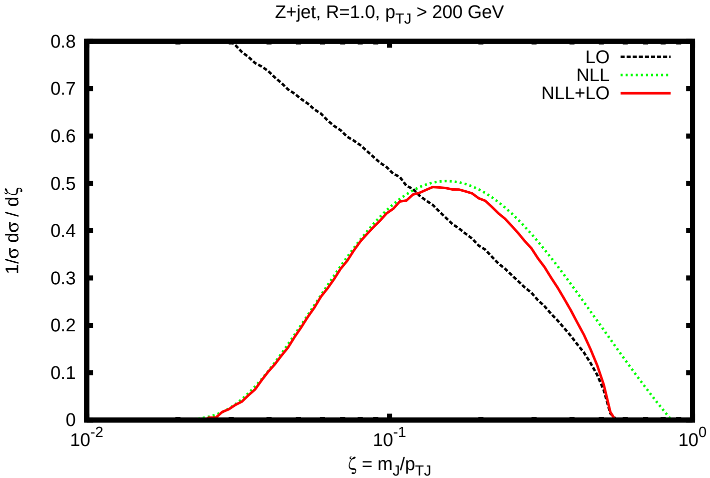
Next-to-leading log (NLL)

$$P(< v) = \exp\left[-g_1(\alpha_s L)L - g_2(\alpha_s L)\right]$$

- g_1 includes double logs (with running coupling)
- g_2 includes **single logs**
    - Finite piece in $P(z)$
    - Multiple (not independent) emissions contributing to v
    - 2-loop running coupling (+ scheme dependence)
    - Nasty non-global logs (out-of-jet emissions emitting back in)
- Can be matched to a fixed-order calculation

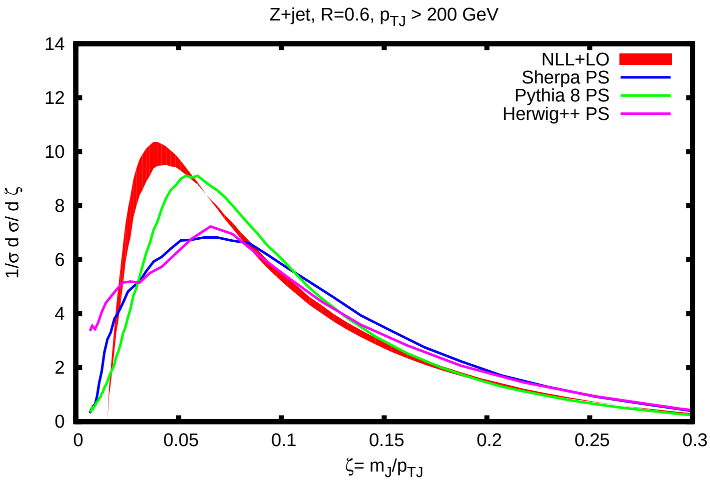
A few plots to illustrate what is going on

matching LO fixed-order with NLL resummation



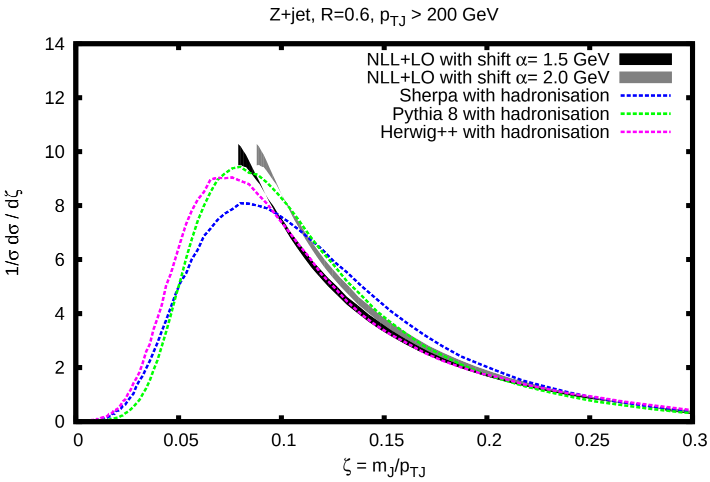
A few plots to illustrate what is going on

Comparison with parton shower



A few plots to illustrate what is going on

Including hadronisation



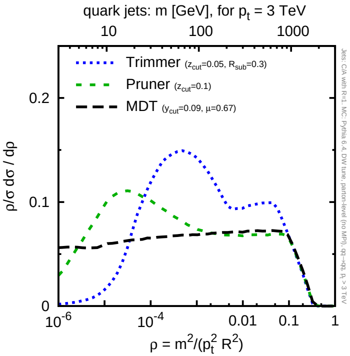
same approach for jet-substructure tools

Monte-Carlo v. analytic

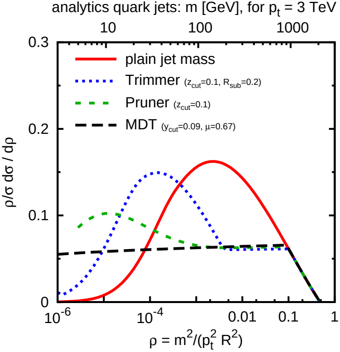
[M.Dasgupta,A.Fregoso,S.Marzani,G.Salam,13]

First analytic understanding of jet substructure:

Monte Carlo



Analytics



- Similar behaviour at large mass/small boost (region tested so far)
- Significant differences at larger boost

Analytic example: mass drop

- Boosted limit: $p_t \gg m$ or $\rho = m^2/(p_t R)^2 \ll 1$
- Emission of one gluon:

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \int \frac{d\theta^2}{\theta^2} dz\, P_{gq}(z)\, \underbrace{\Theta(z > z_{\rm cut})}_{\text{sym. cut}} \underbrace{\Theta(z(1-z)\theta^2 > \rho R^2)}_{\text{mass}}$$

Analytic example: mass drop

- Boosted limit: $p_t \gg m$ or $\rho = m^2/(p_t R)^2 \ll 1$
- Emission of one gluon:

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \int \frac{d\theta^2}{\theta^2} dz\, P_{gq}(z)\, \underbrace{\Theta(z > z_{\rm cut})}_{\text{sym. cut}} \underbrace{\Theta(z(1-z)\theta^2 > \rho R^2)}_{\text{mass}}$$

- Focus on logarithmically enhanced terms

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \left[\log(1/\rho)\log(1/z_{\rm cut}) - \frac{3}{4}\log(1/\rho) - \frac{1}{2}\log^2(1/z_{\rm cut})\right]$$

Analytic example: mass drop

- Boosted limit: $p_t \gg m$ or $\rho = m^2/(p_t R)^2 \ll 1$
- Emission of one gluon:

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \int \frac{d\theta^2}{\theta^2} dz\, P_{gq}(z)\, \underbrace{\Theta(z > z_{\rm cut})}_{\text{sym. cut}} \underbrace{\Theta(z(1-z)\theta^2 > \rho R^2)}_{\text{mass}}$$

- Focus on logarithmically enhanced terms

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \left[\log(1/\rho)\log(1/z_{\rm cut}) - \frac{3}{4}\log(1/\rho) - \frac{1}{2}\log^2(1/z_{\rm cut})\right]$$

- All-order resummation: exponentiation!

$$P_{\text{all orders}}(<\rho) = \exp\left[-P_1(>\rho)\right]$$

Analytic example: mass drop

- Boosted limit: $p_t \gg m$ or $\rho = m^2/(p_t R)^2 \ll 1$
- Emission of one gluon:

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \int \frac{d\theta^2}{\theta^2} dz\, P_{gq}(z)\, \underbrace{\Theta(z > z_{\text{cut}})}_{\text{sym. cut}} \underbrace{\Theta(z(1-z)\theta^2 > \rho R^2)}_{\text{mass}}$$

- Focus on logarithmically enhanced terms

$$P_1(>\rho) = \frac{\alpha_s C_F}{\pi} \left[\log(1/\rho)\log(1/z_{\text{cut}}) - \frac{3}{4}\log(1/\rho) - \frac{1}{2}\log^2(1/z_{\text{cut}})\right]$$

- All-order resummation: exponentiation!

$$P_{\text{all orders}}(<\rho) = \exp\left[-P_1(>\rho)\right]$$

- single log in ρ!

Analytic example: extra notes

Analytic control teaches many lessons:

- Original mass-drop tagger had an extra “mass-drop” condition: no contribution at this order (+work in progress)
- Original mass-drop tagger had an extra “filtering” step: no contribution at this order

Analytic example: extra notes

Analytic control teaches many lessons:

- Original mass-drop tagger had an extra “mass-drop” condition:
  no contribution at this order (+work in progress)
- Original mass-drop tagger had an extra “filtering” step:
  no contribution at this order
- Original mass-drop tagger recursed into most massive branch:
  looses direct exponentiation!

Analytic example: extra notes

Analytic control teaches many lessons:

- Original mass-drop tagger had an extra “mass-drop” condition: no contribution at this order (+work in progress)
- Original mass-drop tagger had an extra “filtering” step: no contribution at this order
- Original mass-drop tagger recursed into most massive branch: looses direct exponentiation!
- Absence of problematic non-global logs

Analytic example: extra notes

Analytic control teaches many lessons:

- Original mass-drop tagger had an extra “mass-drop” condition: no contribution at this order (+work in progress)
- Original mass-drop tagger had an extra “filtering” step: no contribution at this order
- Original mass-drop tagger recursed into most massive branch: looses direct exponentiation!
- Absence of problematic non-global logs
- Non-perturbative corrections using similar techniques than previously

Analytic example: extra notes

- Trimming:
  - Same as mass-drop for $\rho \geq f_{\rm filt}(R_{\rm filt}/R)^2$
  - double log behaviour ($\log^2(1/\rho)$) of plain jet mass for $\rho < f_{\rm filt}(R_{\rm filt}/R)^2$

Analytic example: extra notes

- Trimming:
    - Same as mass-drop for $\rho \geq f_{\rm filt}(R_{\rm filt}/R)^2$
    - double log behaviour ($\log^2(1/\rho)$) of plain jet mass for $\rho < f_{\rm filt}(R_{\rm filt}/R)^2$
- SoftDrop: essentially the same as mMDT but with double logs

Analytic example: extra notes

- Trimming:
  - Same as mass-drop for $\rho \geq f_{\rm filt}(R_{\rm filt}/R)^2$
  - double log behaviour ($\log^2(1/\rho)$) of plain jet mass for $\rho < f_{\rm filt}(R_{\rm filt}/R)^2$
- SoftDrop: essentially the same as mMDT but with double logs

Stay tuned

First-principle understanding of jet substructure

- is still a young field but looks promising
- allows to understand what is going on
- allows control over th. uncertainties
- allows to introduce new, better, tools

Summary

Jets are everywhere

hard quarks/gluons in a collider event come out as jets

Summary

Jets are everywhere

hard quarks/gluons in a collider event come out as jets

Beware of IR divergences

- Use IRC-safe observables (insensitive to coll. and soft em.)
- Often give you logs (sometimes to be resummed)
- Specify your objects clearly (e.g. jet R and $p_{t,min}$

Summary

Jets are everywhere

hard quarks/gluons in a collider event come out as jets

Beware of IR divergences

- Use IRC-safe observables (insensitive to coll. and soft em.)
- Often give you logs (sometimes to be resummed)
- Specify your objects clearly (e.g. jet R and $p_{t,min}$

Boosted jets

- Other objects can give you jets
- Increasing importance in the future
- room for both QCD & important particle-physics measurements