Jet substructure

LECTURE PLAN

1. COLLIDER PHENOMENOLOGY

- COLLIDING PARTICLES
- PARTON-MODEL FOR THE DRELL-YAN PROCESS
- BREIT-WIGNER & NWA

2. QUANTUM CHROMO DYNAMICS

- A REVIEW OF QCD
- RADIATIVE CORRECTIONS to DY
- DGLAP EVOLUTION

3. RESUMMATION

- SOFT-COLLINEAR FACTORISATION, IRC SAFETY
- THE TRANSVERSE MOMENTUM OF THE Z BOSON

4. JET PHYSICS

- WHY JETS?
- JET DEFINITIONS

5. JET SUBSTRUCTURE

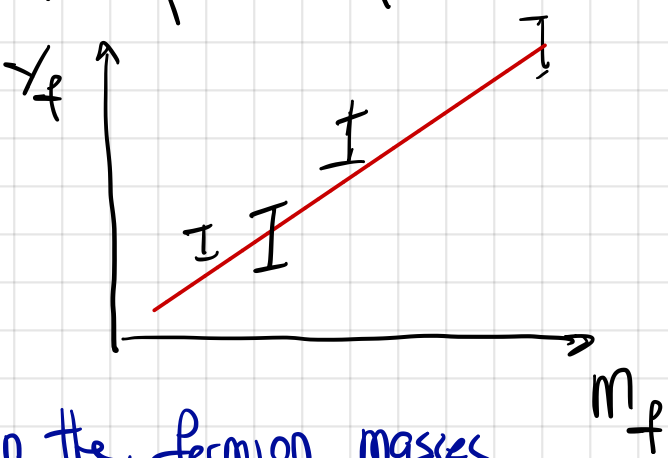
- GROOMING and TAGGING
- MACHINE LEARNING (briefly)

AN INTRODUCTION to JET SUBSTRUCTURE

- We've seen how jets are a useful tool to describe hadronic final-state.
- We can compute and measure jet properties
- Before doing so, let's take a quick detour to motivate these studies
- This actually follows the historic development... but it's still very much relevant.

- the LHC was built to discover and study the Higgs boson (more appropriately to understand EWSB.

→ The Higgs mechanism relates the coupling of each SM with the Higgs to the particle's mass.
- this also happens for the fermions via the Yukawa couplings.



→ hierarchy in the fermion masses translates into hierarchy in the couplings

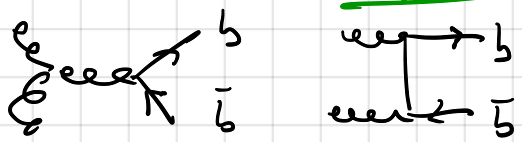
$Y_{top} \sim 1$
$Y_{el.} \sim 10^{-6}$

so we want to study $H \to f\bar{f}$ decays to shed light on this matter.

- $m_H = 125$ GeV, $m_t = 173$ GeV, so no on-shell decay
- the second lightest fermion is b-quark $m_b = 4.2$ GeV
  ($y_b \sim 3 \cdot 10^{-2}$)

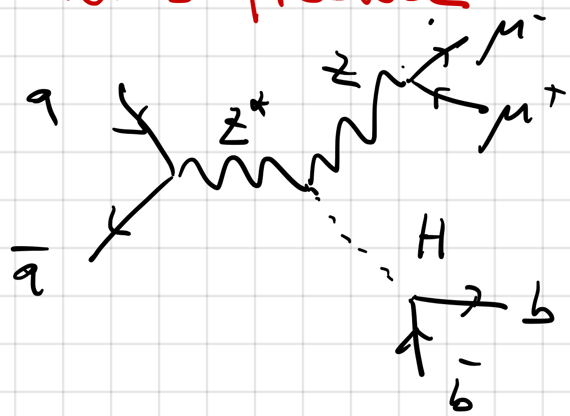
GREAT! let's study $H \to b\bar{b}$ at the LHC!

HUGE QCD backgrounds!



OUR Z boson comes to rescue us:

→ let us produce ZH final states: we take a hit in x-sec, but the Z boson allows us to cut down the bkg.



We can "trigger" on $\mu^+\mu^-$

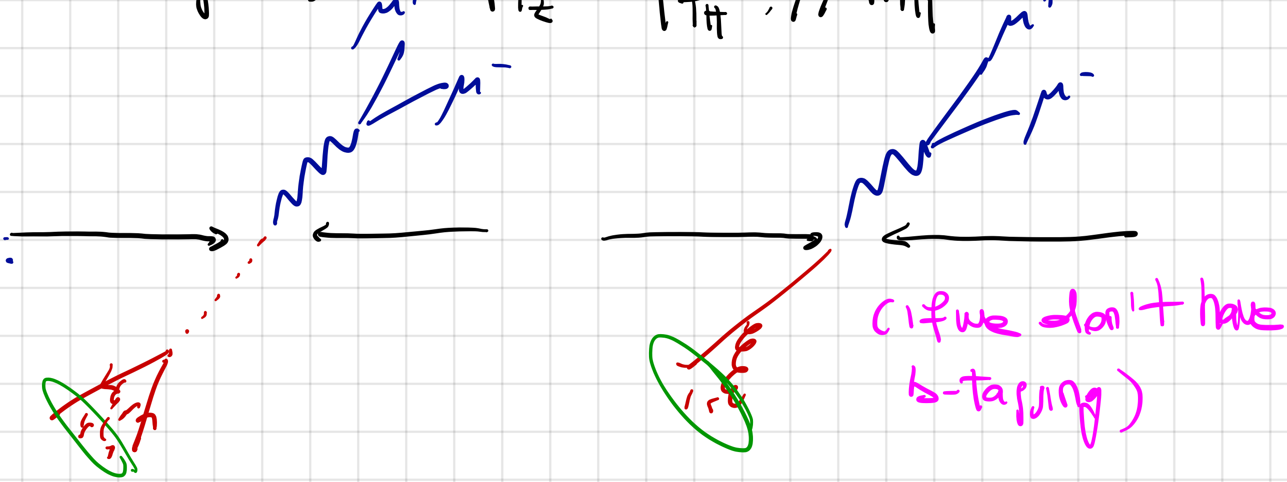
What is the main bkg to this signal process? Z+jets

(actually we can restrict this to b-jets, but we won't discuss b-tagging here).

The JET SUBSTRUCTURE REVOLUTION was sparked by the BDRS paper (2008)

PhD students

in order to suppress combinatoric bkg we should at the "boosted" regime $p_{T_Z} \sim p_{T_H} \gg m_H$



if the Higgs is boosted, its decay products are collimated and reconstructed in one jet:

$$\text{LO:} \quad m_H^2 = (p_b + p_{\bar b})^2 \simeq 2 p_b \cdot p_{\bar b} =$$

$$\simeq z(1-z)\, p_{T_H}^2\, \theta_{b\bar b}^2 \overset{\text{if } z = 1/2}{=} \frac{1}{4} p_{T_H}^2 \theta_{b\bar b}^2$$

$$\text{so} \quad \theta_{b\bar b} < R \iff \frac{4 m_H^2}{p_{T_H}^2} < R^2 \quad \text{i.e.} \quad \boxed{p_{T_H} > \frac{2 m_H}{R}}$$

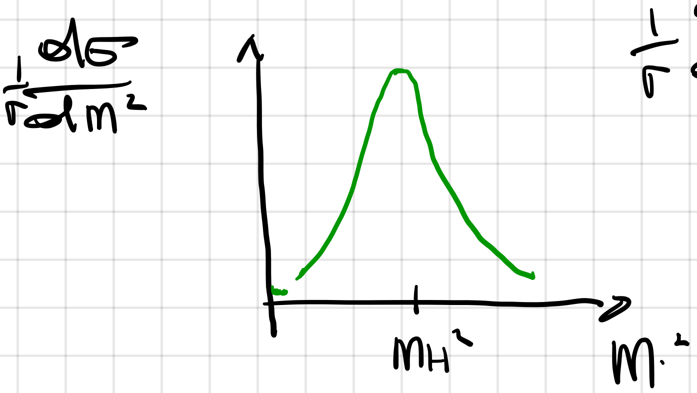
- SIMILAR for Z, W, top boosted decays.
- THE GAME WE PLAY: we look at a jet properties to try and distinguish signal jets for bkg (QCD) jets

the JET MASS

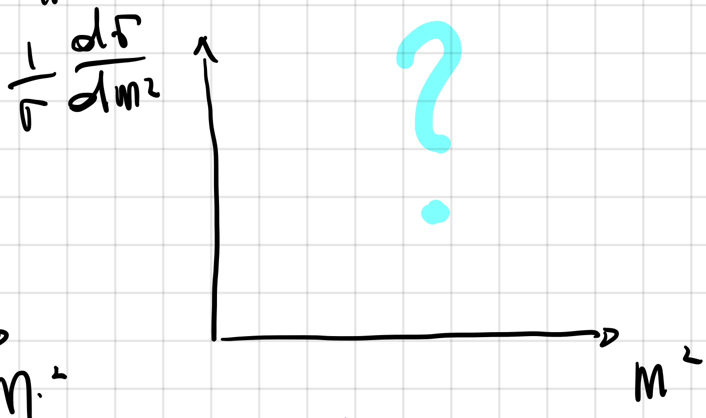
- If we are able to collect all the Higgs decay products (typically large-R), in the NWA we have

$$\left(\sum_{i \in jet} p_i\right)^2 = p_H^2 = m_H^2$$

- So at parton-level the signal jet invariant mass distribution is peaked around m_H:



SIGNAL JET



BKG (QCD) JET

- What does the m^2-distr. look like for a QCD jet?
- the only scale is p_T so $m^2 \sim p_T^2$
- Let's do a $O(\alpha_s)$ calculation in the collinear limit

e.g.

$$\frac{1}{\sigma_0}\frac{d\sigma}{dp_T\, dm^2} \simeq \frac{\alpha_s}{2\pi} C_F \int_0^{R^2} \frac{d\vartheta^2}{\vartheta^2} \int_0^1 dz\, P_{gq}(z)\, \delta\left(m^2 - z(1-\cancel{z})\vartheta^2 p_T^2\right)$$

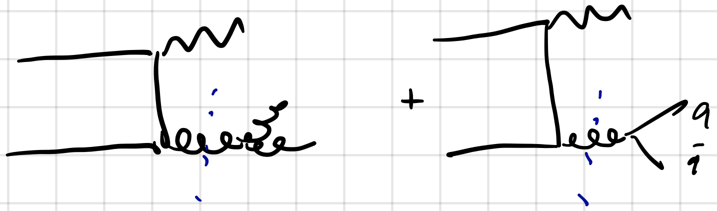
$$= \frac{\alpha_s C_F}{2\pi} \frac{1}{m^2} \int_0^1 dz\, \frac{1+(1-z)^2}{z}\, \Theta\left(\frac{m^2}{z p_T^2} < R^2\right)$$

so
$$\frac{1}{\sigma_0}\frac{d\sigma}{dp_T^2\, dm^2} \simeq \frac{\alpha_s C_F}{\pi}\frac{1}{m^2}\left[\int_{\frac{m^2}{p_T^2R^2}}^{1}\frac{dz}{z} + \int_0^1 dz\left(-1+\frac{z}{2}\right)\right] + O\left(\frac{m^2}{p_T^2R^2}\right)$$

$$= \frac{\alpha_s C_F}{\pi}\frac{1}{m^2}\left[\ln\left(\frac{p_T^2R^2}{m^2}\right) - \frac{3}{4}\right]$$

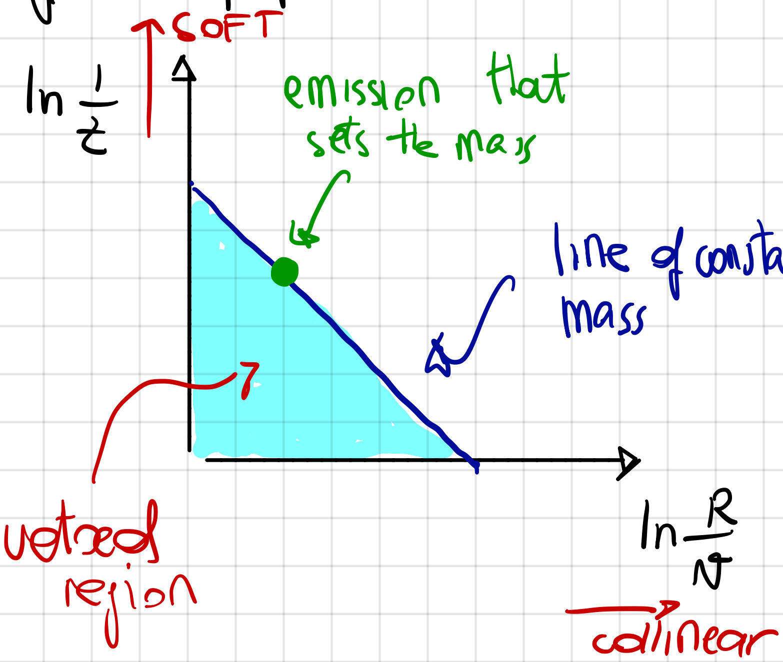
$\frac{p_T^2R^2}{m^2} = \frac{1}{\rho}$; $\rho = \frac{m^2}{p_T^2R^2}$

- **EXERCISE** Perform the same calculation but for:



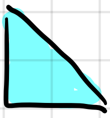
- Here we stick to quark jets.
- Large logarithms in the regime we are interested, we $p_T^2 \gg m^2/R^2$ need to resum.

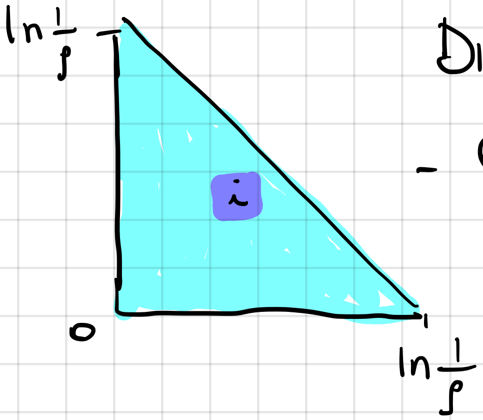
- Instead of doing the calculation as we did for q_T, let's try a "graphical" approach using the Lund plane



$$m^2 = z\theta^2 p_T^2$$
$$\ln m^2 = \ln z + \ln\frac{\theta^2}{R^2} + \ln p_T^2R^2$$
$$\ln\frac{1}{z} = -\ln\frac{R^2}{\theta^2} + \ln\frac{1}{\rho}$$

the emission • sets the mass, emissions above the are much softer / more collinear and give vanishing contributions

· emissions in  would alter the jet mass: we need to veto them.



Divide the area into n squares

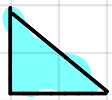
- emission probability in each square is $\propto A_i$

$$P_i = \frac{\alpha_s C_F}{\pi} A_i = \frac{\alpha_s}{\pi} C_F \frac{1}{n} \frac{1}{2} \ln^2\frac{1}{\rho}$$

- no-emission prob. in each square: $1 - P_i$

· Total no-emission probability in the blue area:

$$\lim_{n\to+\infty} \left(1 - \frac{1}{n} \frac{\alpha_s C_F}{2\pi} \ln^2\frac{1}{\rho}\right)^n = e^{-\frac{\alpha_s}{2\pi} C_F \ln^2\rho}$$

$= e^{-}$ 

- this is the leading-logarithmic, fixed-coupling approximation of the Sudakov form factor.

- So we get

$$\frac{1}{\sigma} \frac{d\sigma}{dp_T^2\, dm^2} \simeq \left(\frac{\alpha_s C_F}{\pi} \ln\frac{1}{\rho} - \frac{3}{4}\right) e^{-\frac{\alpha_s}{2\pi} C_F \ln^2\rho}$$

- VERY CRUDE, BUT PHYSICALLY MOTIVATED PICTURE of THE RESUMMATION.

- Can we do better? Can we reach NLL resummation?

JET MASS @ NLL

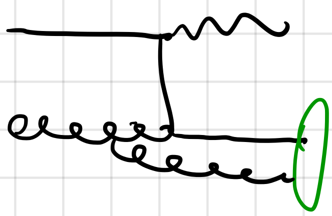
① EASY THINGS

(same ingredients as for Z q_T)

- running coupling at 2-loops
- full splitting functions
- CMW scheme

② MORE DIFFICULT THINGS

- soft gluons at large angles: they don't fully factorise and give rise to color-correlations (non trivial colour factor)



- these are single-log contributions to the radiator of the form

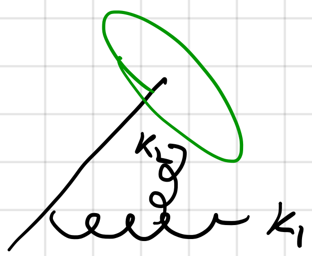
$$C \; f(R^2) \; \alpha_s^n \ln^n \frac{1}{\rho}$$

complicated colour factor (could be a matrix) → C

$$f(R) \overset{R\to 0}{=} aR^2 + bR^4 + \dots$$

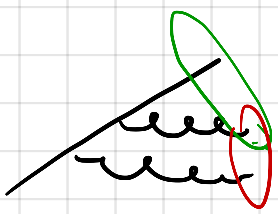
③ VERY DIFFICULT THINGS

① NON-GLOBAL LOGs

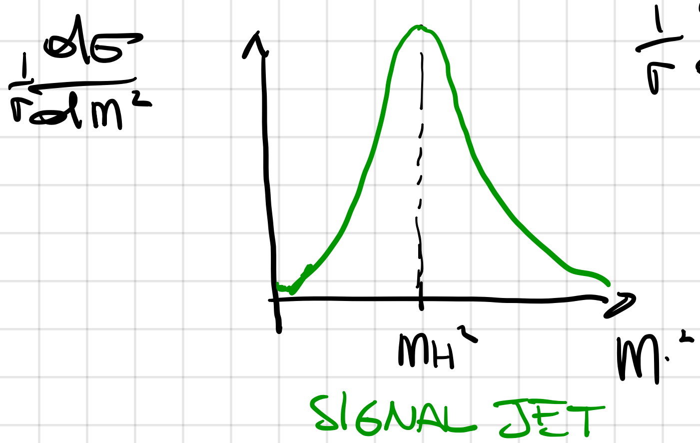


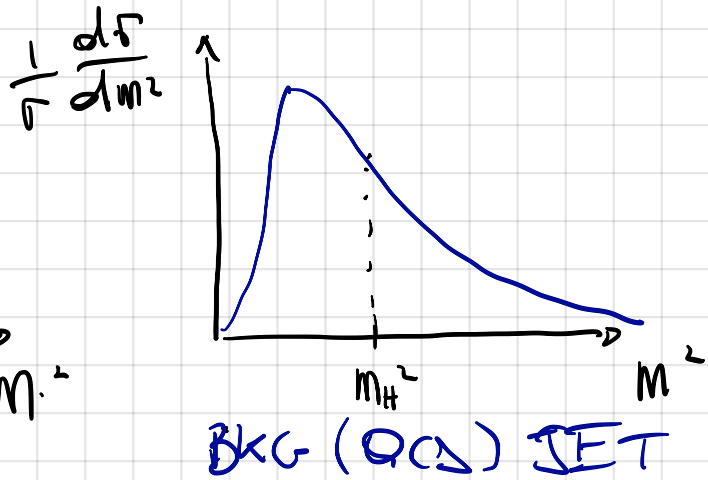
they don't exponentiate, usually treated numerically (large N_c)

② CLUSTERING LOGs (jet algorithm dependence)



Let's go back to our signal vs bkg





so, in principle, they peak at different values and can be separated.

However: the busy environment of the LHC pollutes this picture

UE, pile-up, FSR, broaden and shift the distributions.

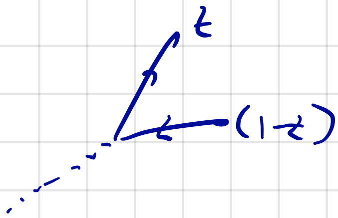
- SIGNAL and BKG end up to look very similar.
- We have to dig deeper in the jet structure and exploit more information.

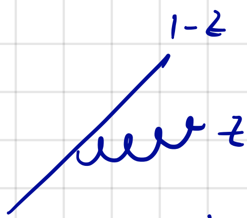
KEY CONCEPTS IN JSS

① **GROOMING**: we want to go back as much as possible to a partonic picture (in a IRC safe way!): resolve the jet at a smaller (angular) scale and remove what is soft and large angle.

② **TAGGING**: once you have cleaned up your jet, find a kinematic feature that distinguishes signal and bkg and cut on it:

E.G.





$P_{h\to b\bar{b}} \sim 1$ $\qquad$ $P_{gq} \sim \frac{1}{z}$

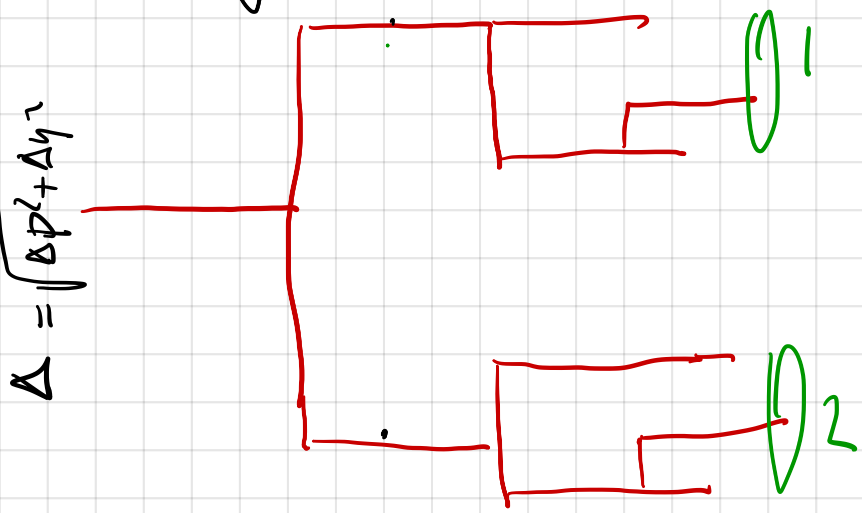
SYMMETRIC vs ASYMMETRIC SPLITTINGS

so $\quad \min(z, 1-z) > z_c$

SOFT DROP

- a popular grooming algorithm is SOFT DROP

START with anti-k_T jet and re-cluster it with C/A in order to have a QCD-motivated angular-ordered clustering tree



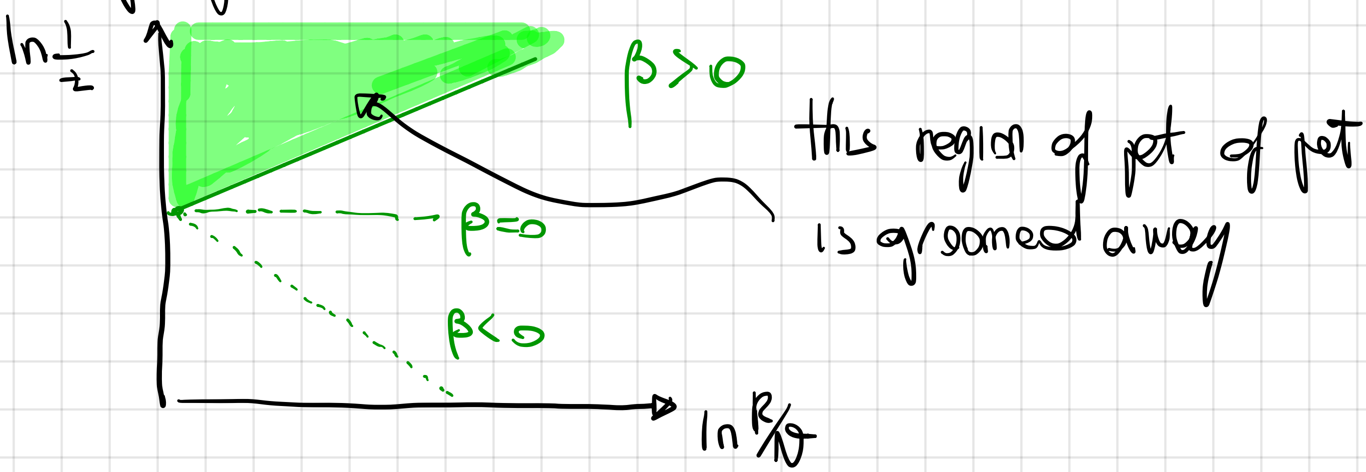
① undo the last step of the clustering

② if $\frac{\min(p_{T_1}, p_{T_2})}{p_{T_1} + p_{T_2}} > z_c \left(\frac{\Delta}{R}\right)^\beta$

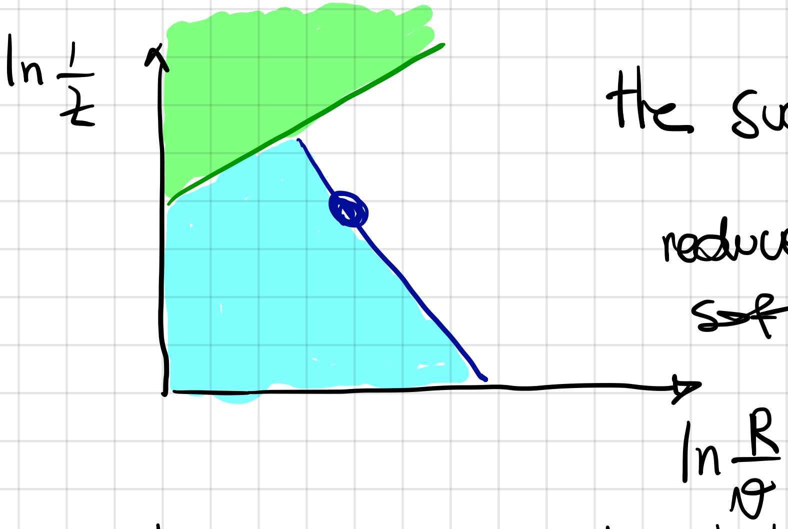
deem the jet to be the SD-jet

③ define j to be the hardest of j_1 and j_2 and iterate.

- Among many groomer, SD has become popular because of its intriguing properties both theoretical and exp.



SOFT-DROP JET MASS DISTRIBUTION



the Sudakov exponent has a reduced sensitivity to the soft region!

ⓐ SD jets receive small contributions from UE

ⓑ SD jets often have reduced hadronisation corrections

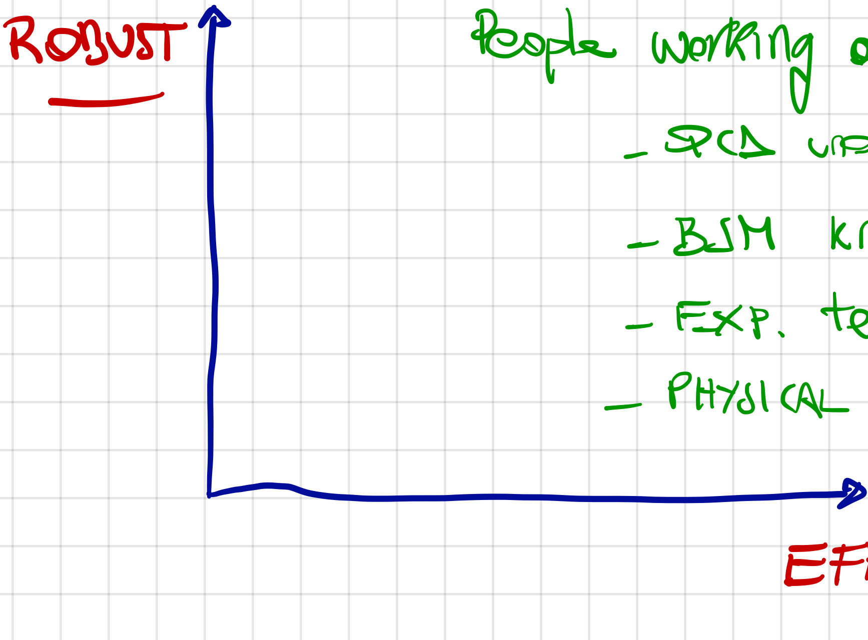
ⓐ + ⓑ : perturbative description of SD jets is more reliable than standard jets (with caveats)

ⓒ SD jets have reduced sensitivity to soft wide angle emissions: no NGLs and no colour correlations

ⓐ + ⓑ + ⓒ : PT theory is more reliable and easier!

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{SD}}$$ known at N^3LL !!!

- SOFT-DROP is an example of a JSS tool which is efficient and robust.
- used in searches and SM measurements.

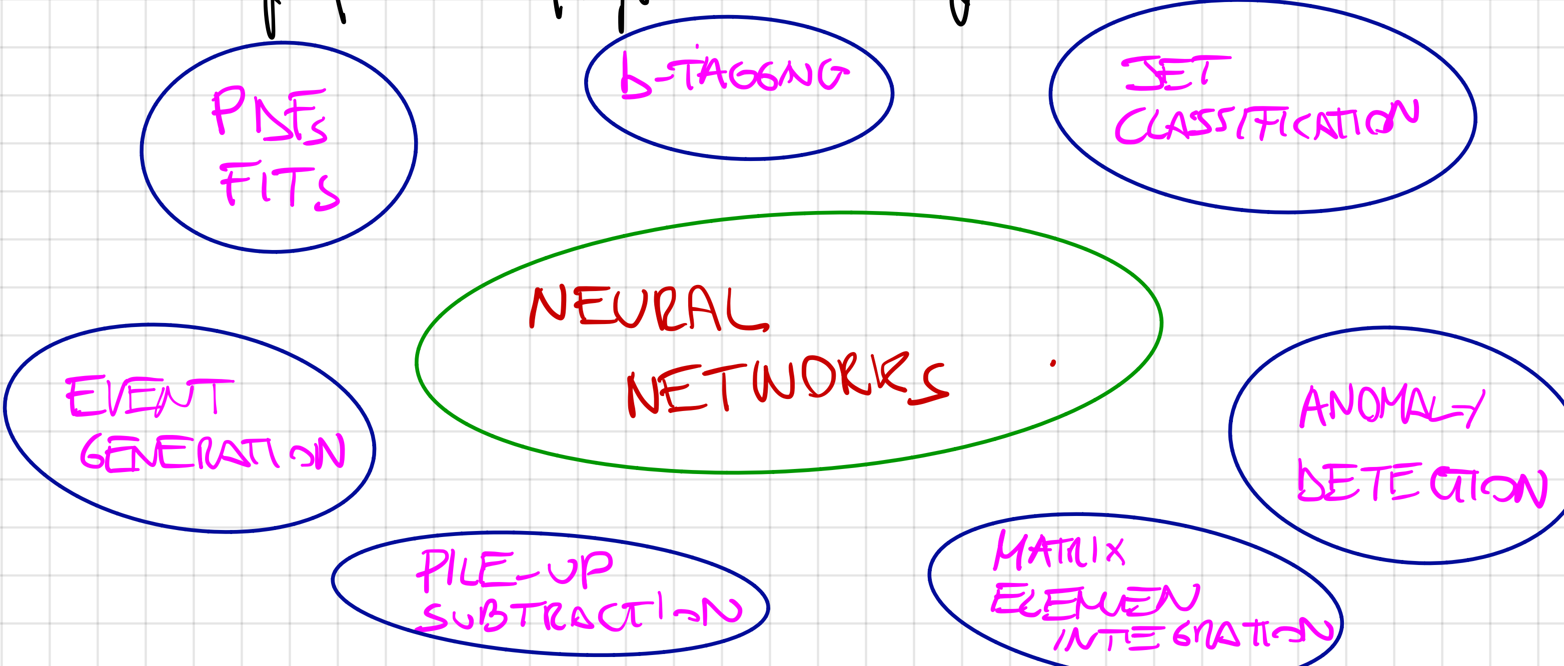


People working on JSS exploited
- QCD understanding
- BSM knowledge
- Exp. techniques
- PHYSICAL INTUITION AND IMMAGINATION

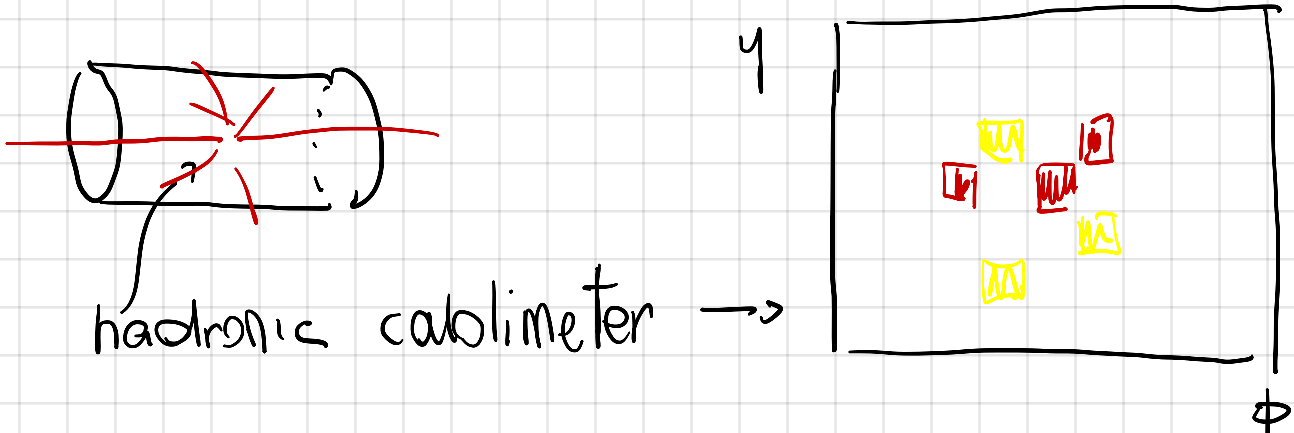
Hundreds ideas, tens of algorithms publicly available (FASTJET contrib) and used by the experiments

DEEP LEARNING REVOULTION

Past 5 years have seen an explosion of application and development of AI algorithms.
Jet physics has been a lively playground, but many areas of particle physics now rely on them:



AN EXAMPLE : JET IMAGES



HITS ON CELLS of THE HADRONIC CALORIMETER LOOK LIKE PIXELS ON A IMAGE.

If we can train a (convolutional) NN to distinguish between pictures of dogs and cats, can we train it to distinguish jets from $H \to b\bar{b}$ from QCD jets?

There are many caveats: jet images are sparse, we need pre-processing to avoid washing out when considering many images

BUT RESULTS ARE SPECTACULAR!

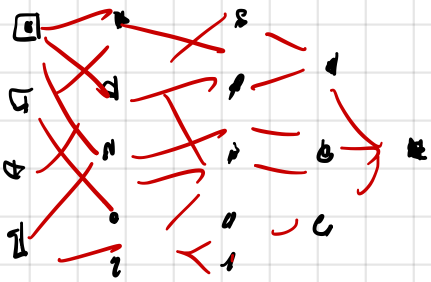
ML classification algorithms outperform (by far!) cleverly designed JSS algorithms.

Should I be happy or sad?

ASIDE: training process

starts with labelled training samples < S, B

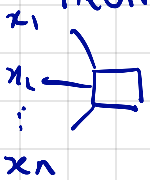
INPUTS



adjust the network parameters to minimise the cost function

$C_{\{\vec{a}_i, b_i\}}(y_{out} - y_{true})$

neutron



neurons

$f(\vec{a}_i \cdot \vec{x} + b_i)$

where f is a non-linear function eg sigmoid $f(x) = \frac{1}{1+e^{-x}}$.

$\vec{x}$ are the input to the NN. In the jet image case above the pixels.

INPUTS can be "LOW LEVEL" calo entries, particle 4-momenta

but we can also exploit our EXPERT KNOWLEDGE and use "HIGH LEVEL" theory-inspired variables

QFTs provides us with a good understanding of the underlying processes and symmetries

DEEP LEARNING MEETS DEEP THINKING (Jesse Thaler)

risks of bias?

opportunity to find out what the network is learning?

a final example: the LUND JET PLANE

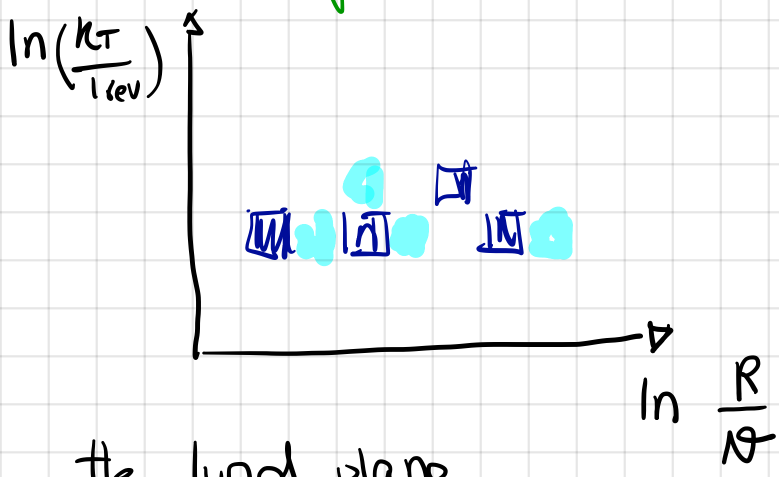
can be turned into an actual observable:

① recluster the jet with C/A

② step back through the clustering history (as for SD)

and at each step record the kinematics of the splitting, eg opening angle, relative transverse momentum

If you always follow the hardest branch, you build the "primary Lund jet plane" (Dryer, Salam, Soyez)



(just a coordinate transf from $\left(\ln \frac{R}{\vartheta}, \ln \frac{1}{z}\right)$)

- the lund plane density can be computed in PT!
- it's been measured at the LHC!
- can be used to construct jet images that can be fed to a NN!
- IT'S NOT A CALO IMAGE BUT A QCD motivated one!