Jet physics

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

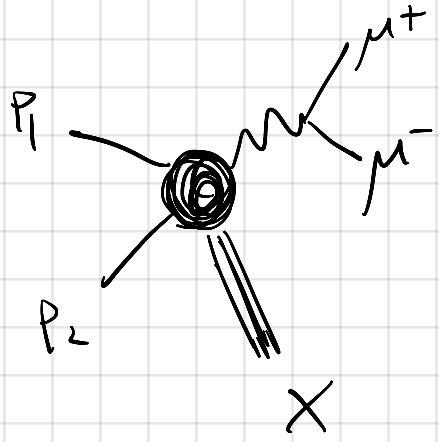
- WHY JETS?
- JET DEFINITIONS

⑤ JET SUBSTRUCTURE

- GROOMING and TAGGING
- MACHINE LEARNING (briefly)

AN INTRODUCTION TO JETS

- In the past lecture we've seen that we can study QCD radiation by looking at Z q_T

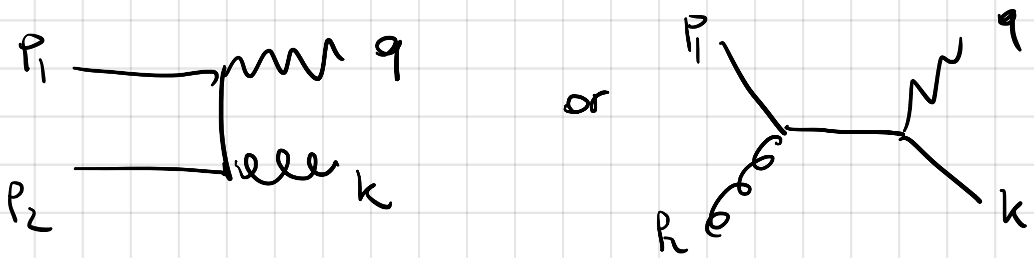


- we would like to study X more directly.

We expect X to be at high energy a collection of partons; that fragment into hadrons (mostly pions)

- What is the perturbative description of X?
- Does it make sense? ie Can we take $O(\text{partons}) \simeq O(\text{hadrons})$

- Let's try. At $O(\alpha_s)$ this is pretty straightforward:

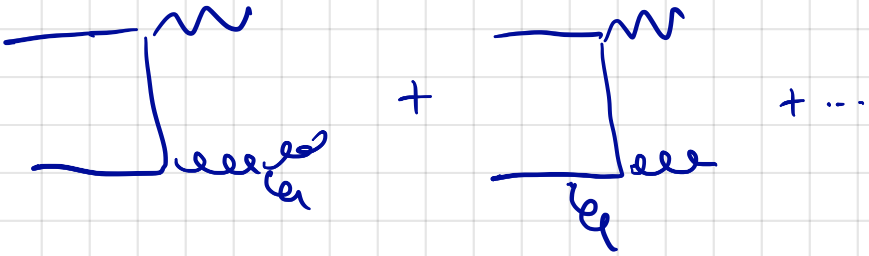


- X is either a quark or a gluon.
- its kinematic distributions are strictly related to the ones of the Z boson.

- At $\mathcal{O}(\alpha_s^2)$ we have
  - real emissions : 2 partons
  - virtual corrections: 1 parton + 1 loop

- Can we compute the x-section for $Z+2$ partons?
(yes, I know we cannot measure partons, if we can compute it, we could relate it to a hadron-level obs.)

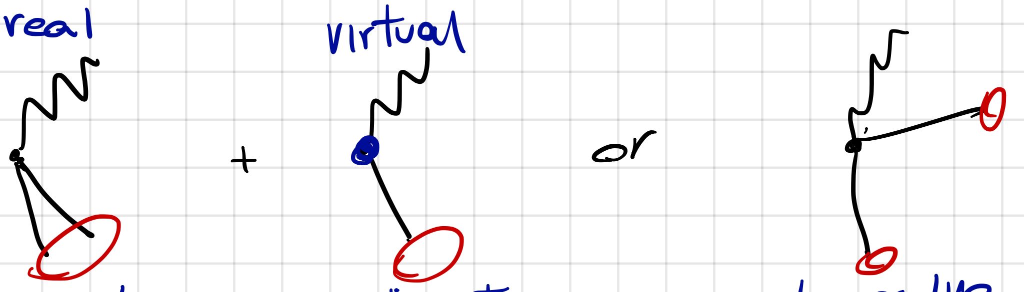
e.g. $Z+g+g$



- we expect ISR coll. sing to be absorbed by PDFs and FSR to cancel against ... VIRTUAL corrections. but these do not contribute to $Z+g+g$.

SO, WE CANNOT compute the cross-section to produce $Z+2$ partons in pert. theory: it diverges!

- We need to be a little more inclusive.



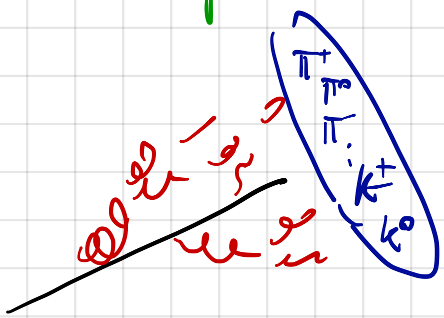
I resolve one object   I resolve two objects

- If I have two hard emissions away from sing. limits, I resolve <u>two</u> objects

- If the two emissions are near a sing conf., I treat them as one object, together with the virtual corrections and I resolve <u>one</u> object.

. These "objects" are called JETs and are the closest thing to the concept of partons ... but useful!

. Why are they called jets?
remember that in <u>QCD</u> emissions are enhanced at small angles: $\alpha_s \frac{d\vartheta^2}{\vartheta^2} P(z)$



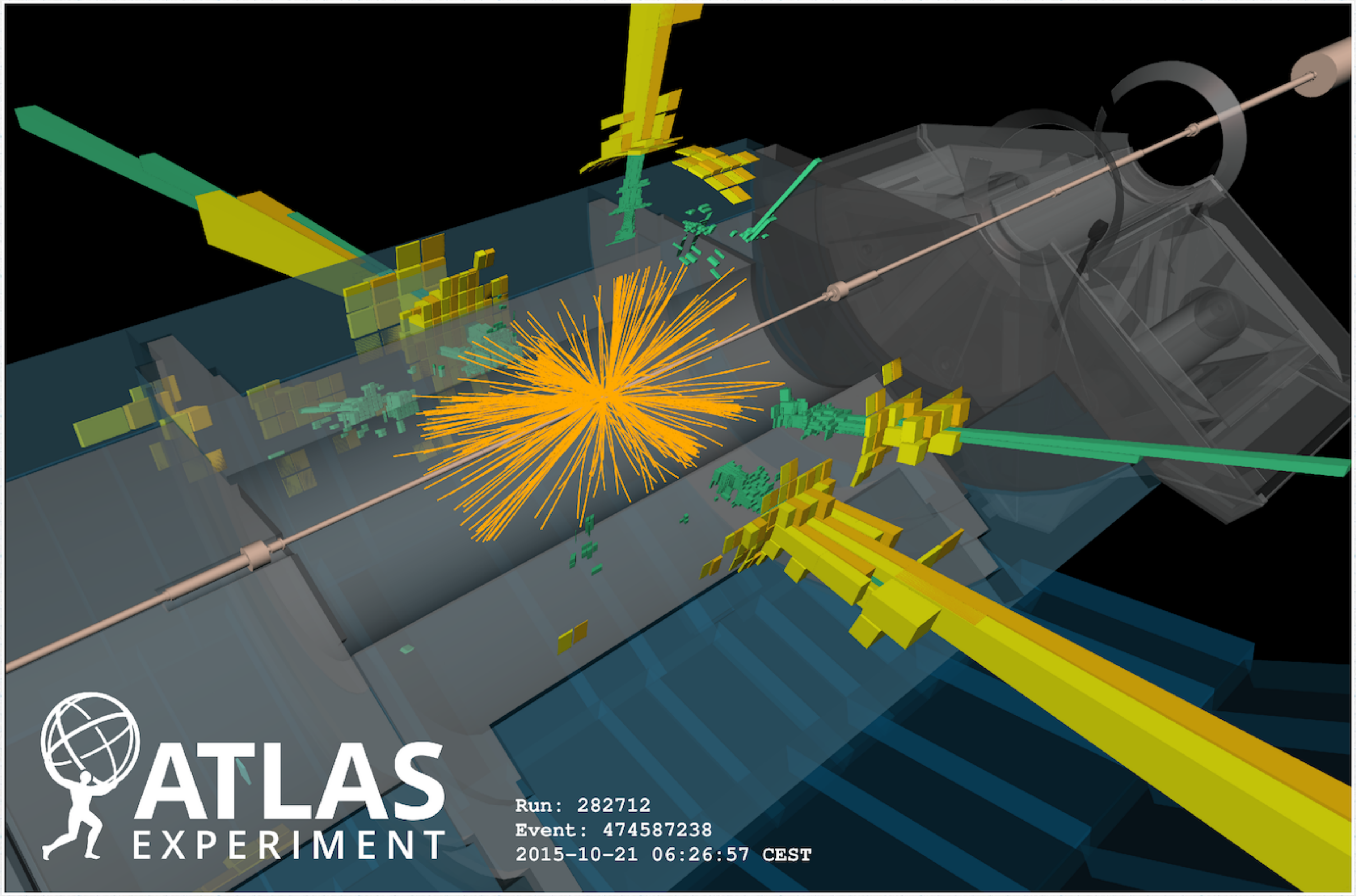
→ radiation is collimated along hard directions

→ partons eventually hadronize but we can still talk about jets.

→ jet formation is an experimental evidence of QCD!

→ jets are at the very boundary between theory and experiment.

jets for experimentalists



* high-energy collisions ofter results into collimated sprays of particles

JET DEFINITION

- **algorithm** → how do I decide whether two objects are nearby?
  eg anti-k_T
- **parameters** → what is my resolution?
  eg jet radius
- **recombination scheme** → how do I combine objects?
  eg E-scheme

object = a particle or something built from particles
sometimes called pseudo jet.

JET DEFINITIONS SHOULD make sense for both theorists and exp.

- We should be able to run it on a few partons or $O(10^3)$ particles, ... or on calo cells!

EXP: fast and easy to calibrate

THEO: guess what? IRC safety!

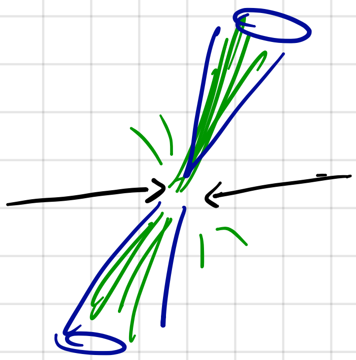
SNOWMASS accord (1990s)

1. simple to implement in exp. analysis
2. simple to implement in th. analysis
3. defined at any order in PT
4. yield finite x-sec at any order in PT
5. yield x-sec ~ insensitive to hadronisation

Jets used at the Tevatron in the 1990s early 2000s were not safe beyond NLO.

FIRST DEFINITION OF A JET Sterman-Weinberg (1977)

$e^+e^- \to 2$ jets : all but a fraction ε of the energy is within two cones of opening angle δ.



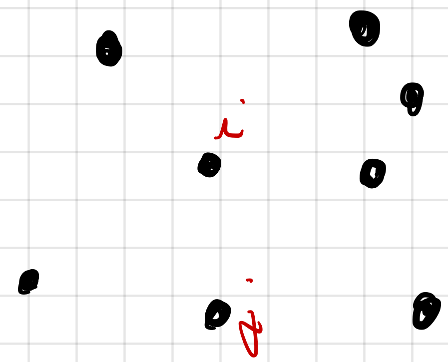
- IRC safe $\to$ can be computed as a function of the two resolution parameters δ, ε.

it's an example of a cone algorithm.

Nowadays, CLUSTERING ALGORITHMS are MORE POPULAR

· **BOTTOM-UP approach:**

① - start with a list of particles



② compute all mutual distances d_{ij} and distances from the beam d_{Bi} (can be an external parameter)

③ find the minimum of all $\{d_{ij}\}$ an $\{d_{iB}\}$

- if the min is d_{ij} → recombine $i+j$
- if the min is d_{iB} → call i a jet and remove it

④ GO TO ①

{list of particles} → {list of jets}.

every jet has
- 4-momentum
- axis
- list of constituents
- clustering tree

valuable information about jet formation and QCD dynamics.

A popular family of jet clustering algorithm is the generalised k_T family

$$d_{ij} = \min\left(k_{T_i}^{2p}, k_{T_j}^{2p}\right) \frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{R^2}$$

$p=0$ C/A algorithm: purely geometric

$p=1$ k_T (Durham) algorithm: faithful to QCD sing. structure

$p=-1$ anti-k_T algorithm: grows jets around hard lines.

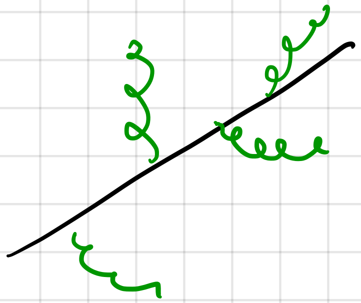
Ex Show that for a jet of just 2 particles, any of the above algorithms clusters the two particles together if $\Delta_{ij} = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2} < R$ ⤳ jet radius.

for $n \geq 3$ particles, the algorithms behave very differently

C/A: purely geometric, particles at small angles are clustered first, the clustering tree is angular-ordered.

k_T : $\frac{k_T^2 \Delta^2}{R^2} \simeq \frac{(k_T \vartheta)^2}{R^2}$ particles at small relative trans. momentum are cluster first

C/A & k_T "invert" the QCD fragmentation process.



anti-k_T is counter-intuitive: two soft particles are always very far apart: jets grow around hard seeds.

Anti-k_T is the STANDARD for LHC physics

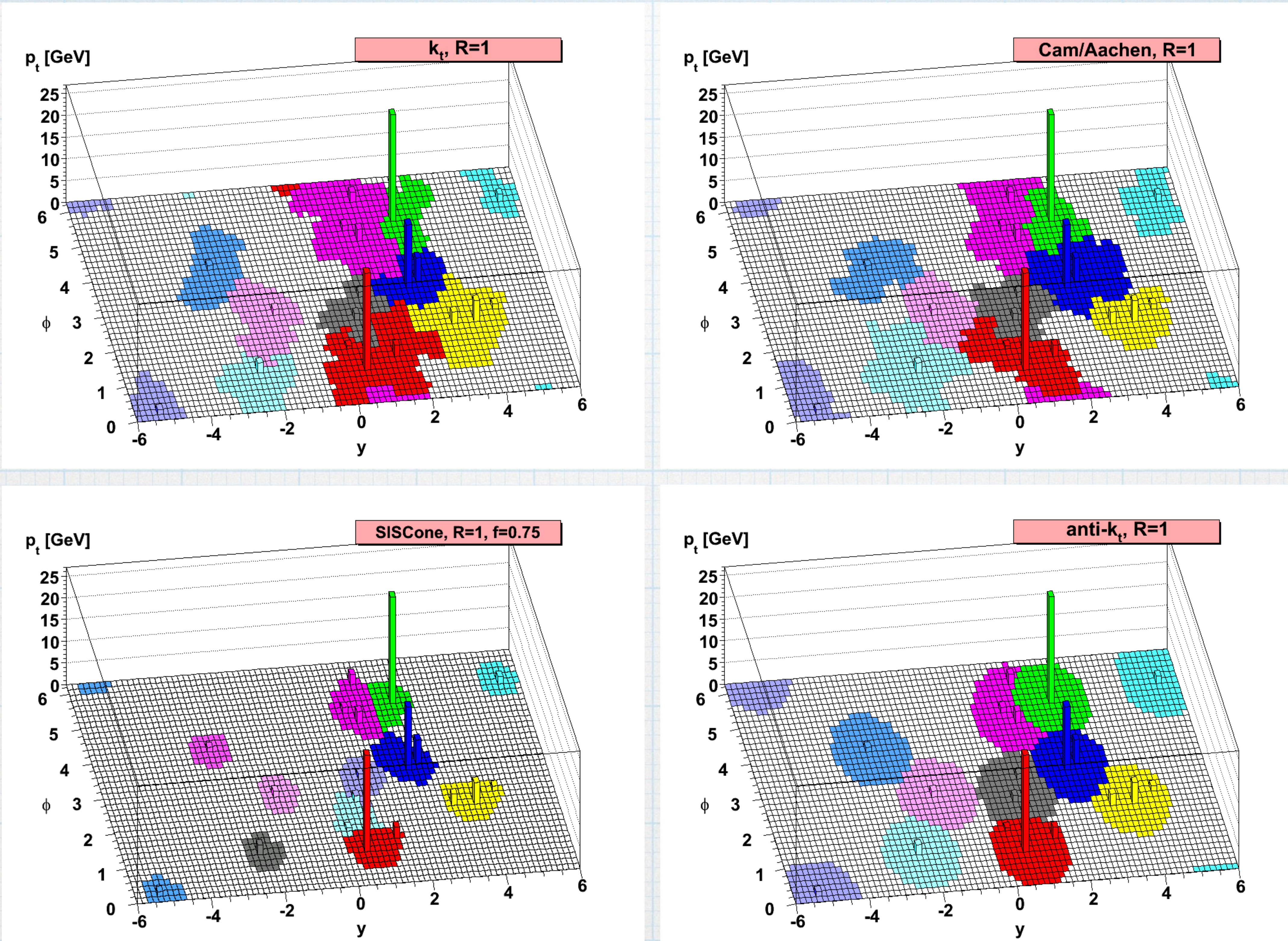
BUT WHY?

- We've seen that hadron colliders are messy environment.
- Effects that we have neglected because "suppressed" eg $\left(\frac{\Lambda_{QCD}}{Q}\right)^2$ in collinear factorisation, can give non-negligible corrections

- MULTIPLE-PARTON-INTERACTIONS

- PILE-UP (remember 25 collisions per bunch crossing + out of time pile-up)

comparing them all



- So now back to our DY process.

- We can now talk about cross-sections and distributions for $Z+1$ jet, which are finite order by order in α_s.

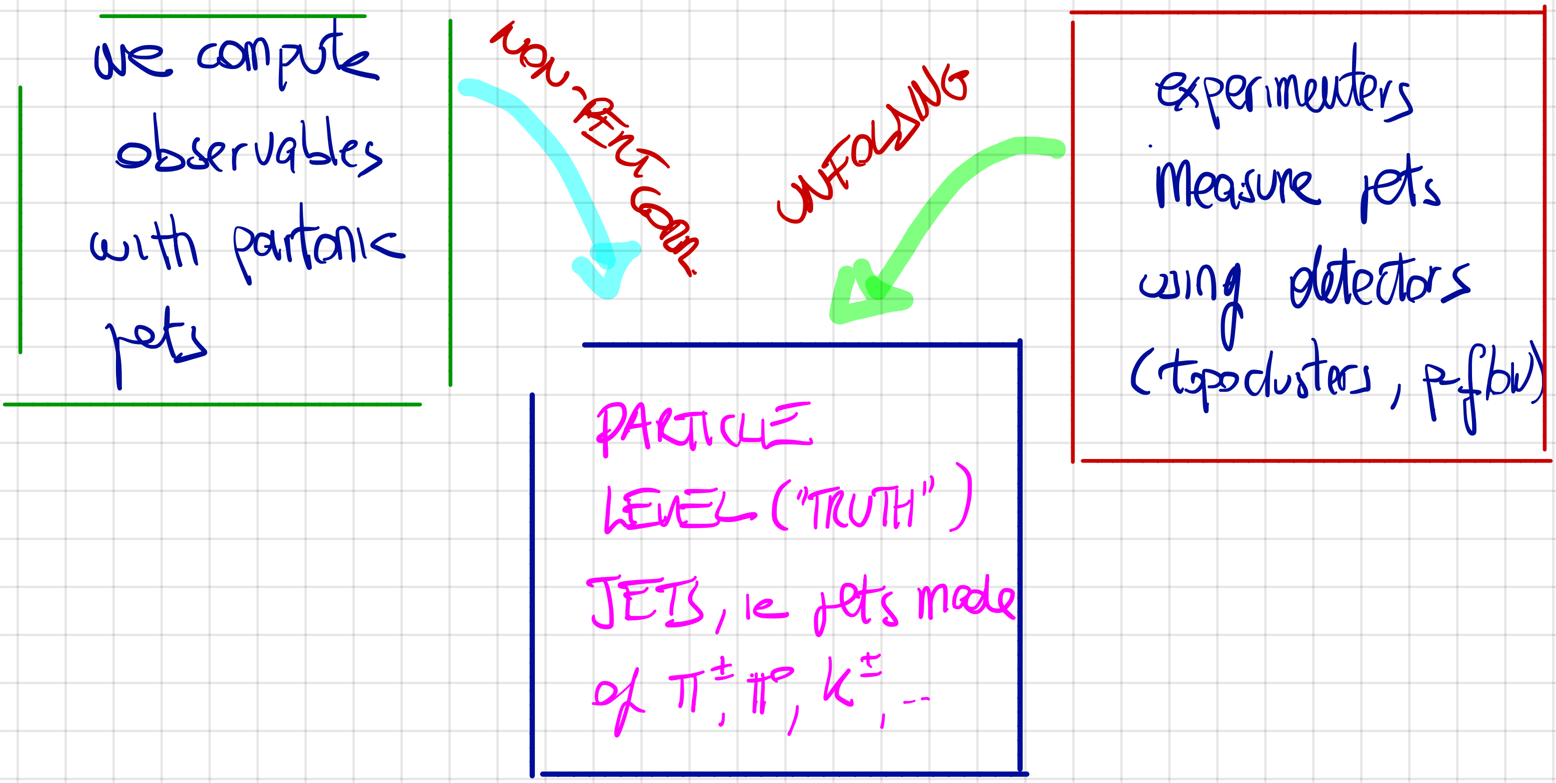
- We can also ask for more jets:

$Z + 2$ jets (at least two, or just two) starts at $O(\alpha_s \cdot \alpha_s) = O(\alpha_s^2)$

$Z+3$ jets starts at $O(\alpha_s^3)$

- Thus, we can explore processes which are rarer and rarer, going down the staircase plot.

BUT, HOW IS THIS DONE IN PRACTICE?



MEANINGFUL COMPARISONS