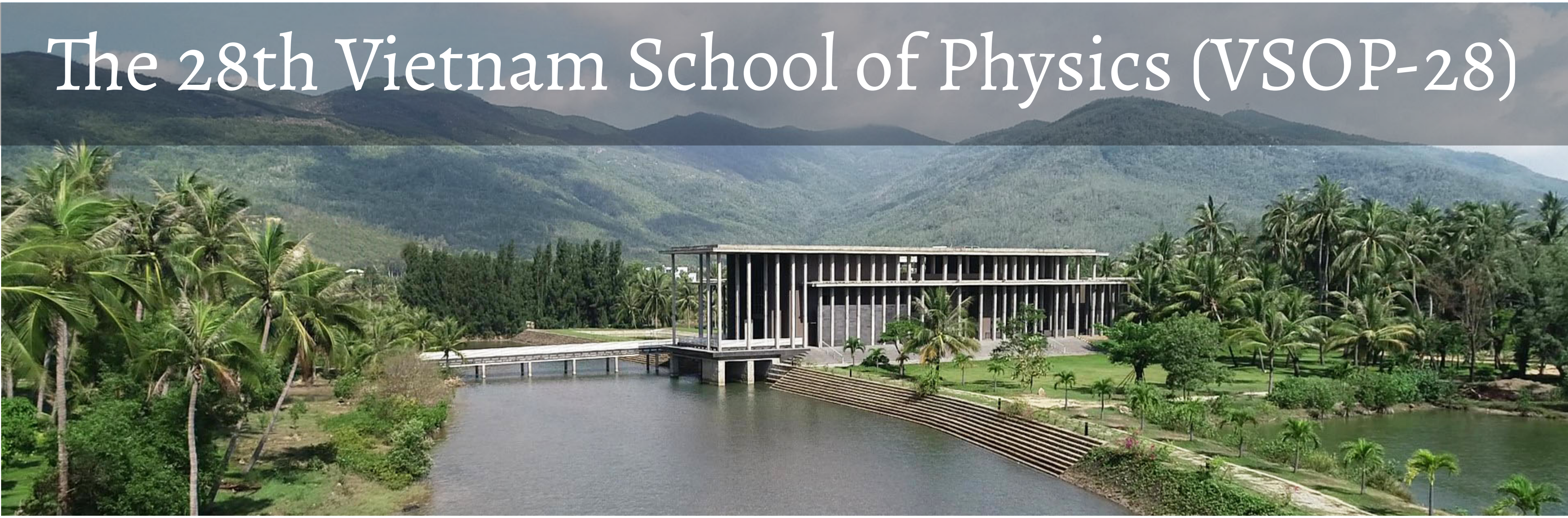


Experimental methods for physics at the LHC

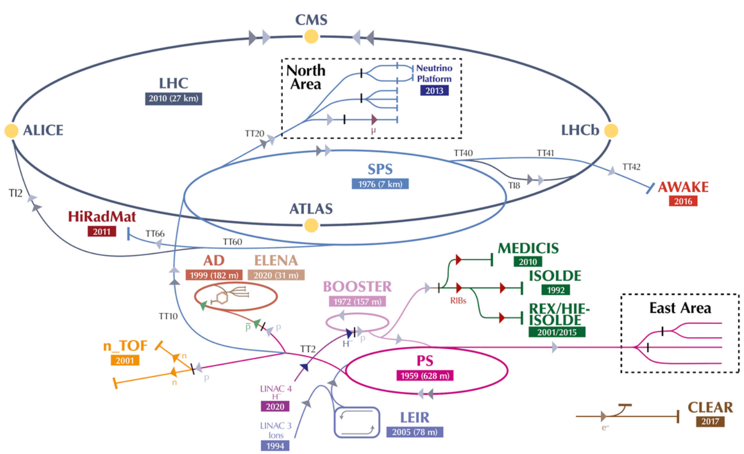
Sourabh Dube

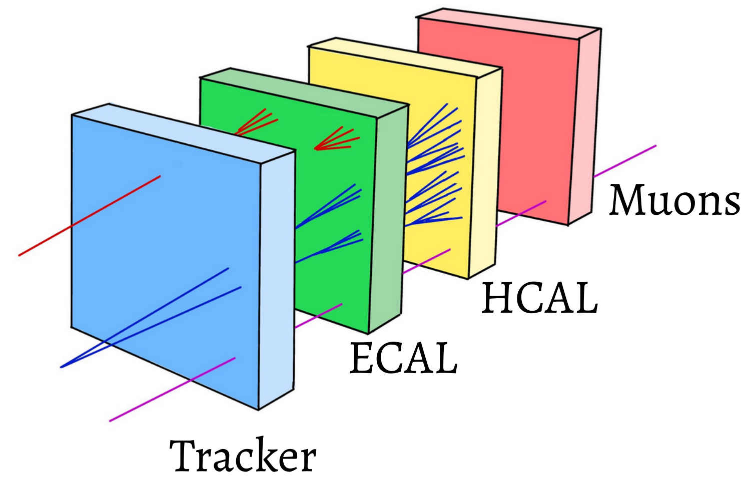
IISER PUNE

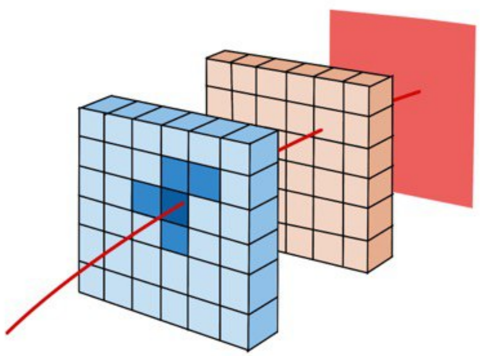
July 24, 2022 to
August 5, 2022

Lecture 3: Object Reconstruction

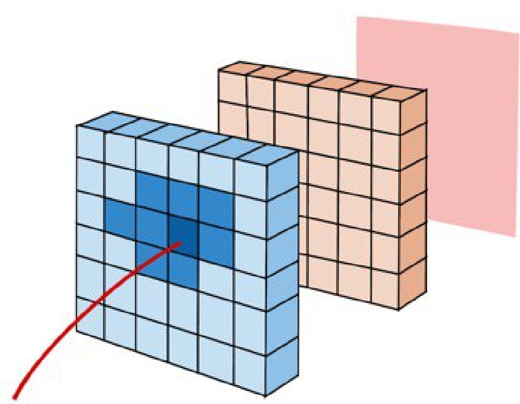
Summary so far…



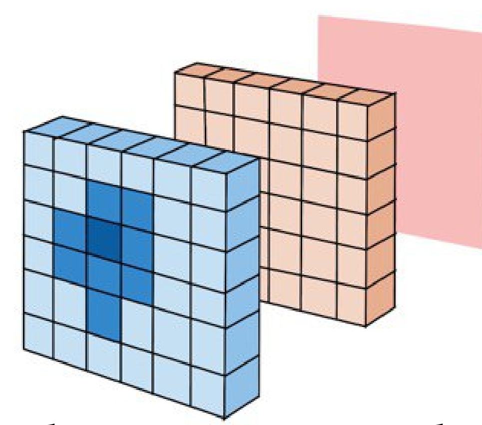




Muon: match inner track to outer track



Electron: match inner track to ECAL energy cluster

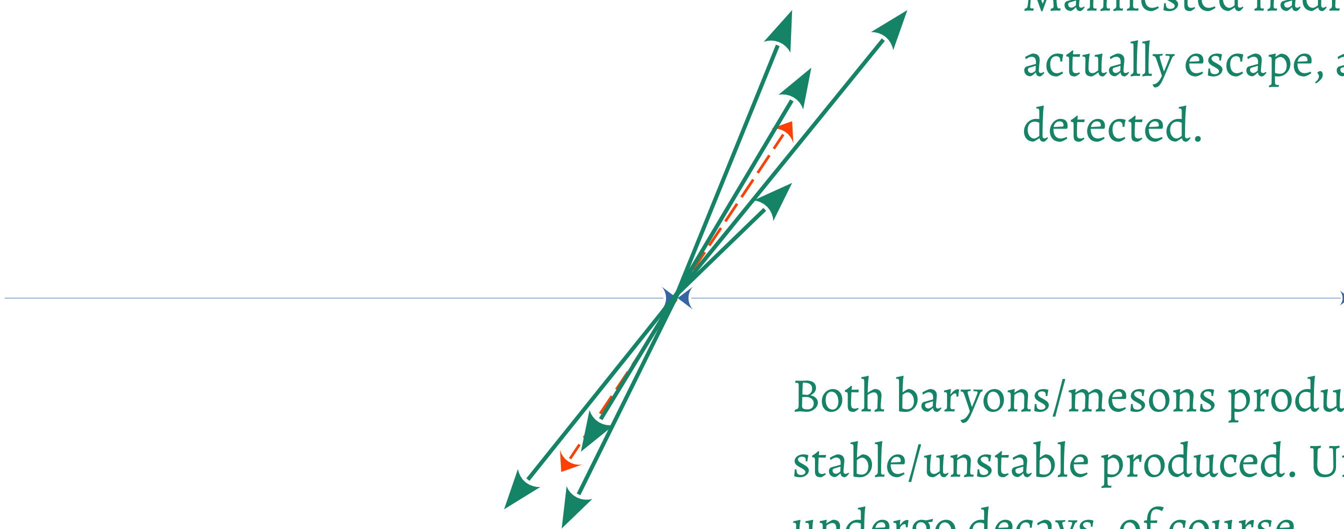


Photon: <u>no</u> inner track, just ECAL energy cluster

Jets

Manifested hadrons are what actually escape, and will be detected.

Proton-proton collision

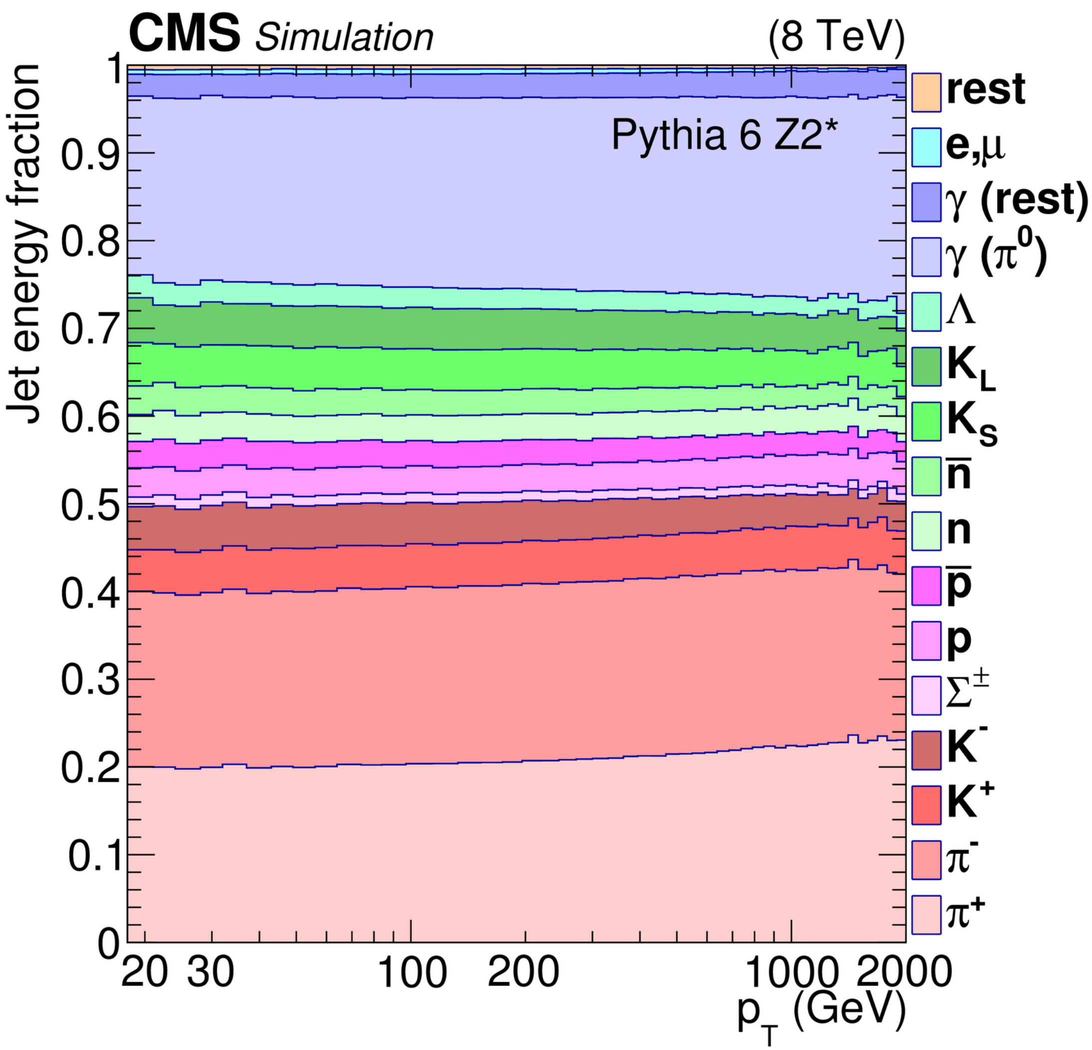


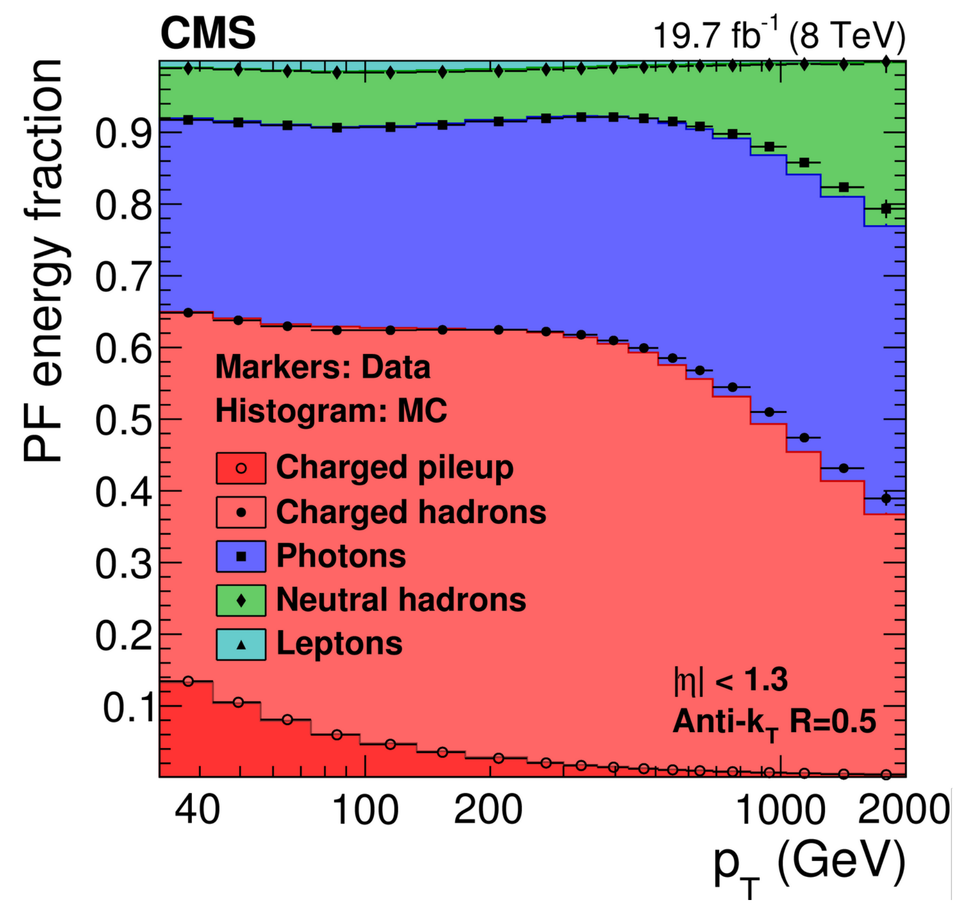
Both baryons/mesons produced, both stable/unstable produced. Unstable hadrons undergo decays, of course.
(Different ways to hadronize 'same' initial state)

Recall that 'colored' particles produce hadrons.
These hadrons will travel together, and we would like to combine them into a single unit, called a jet.

We want the jet properties (4-vector) to correlate well with the properties of the initial colored particle that gave rise to the jet.

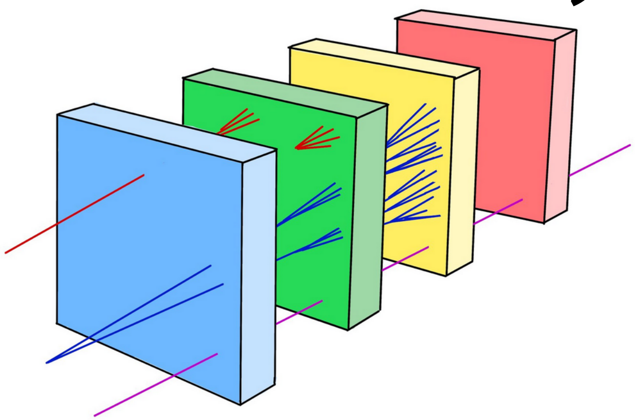
What are jets made of?

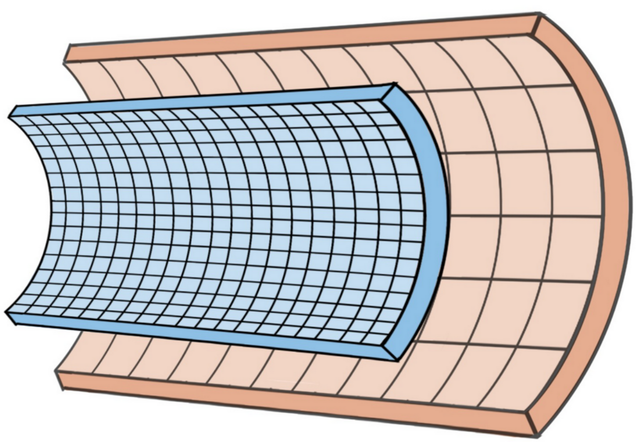




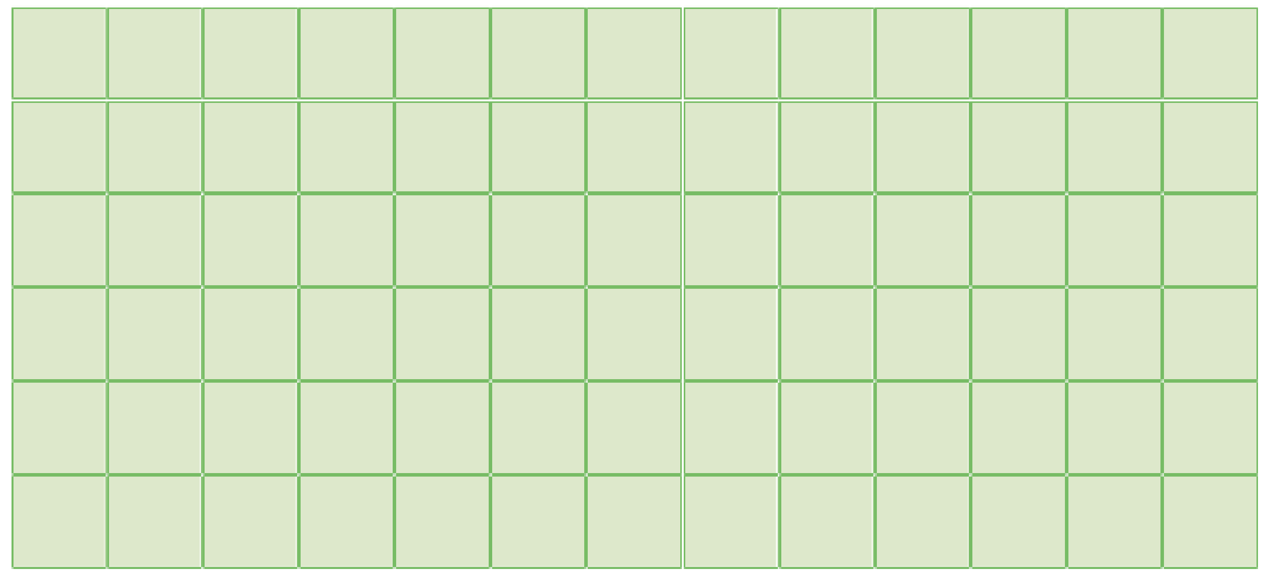
JINST 12 (2017) P02014

Jet clustering

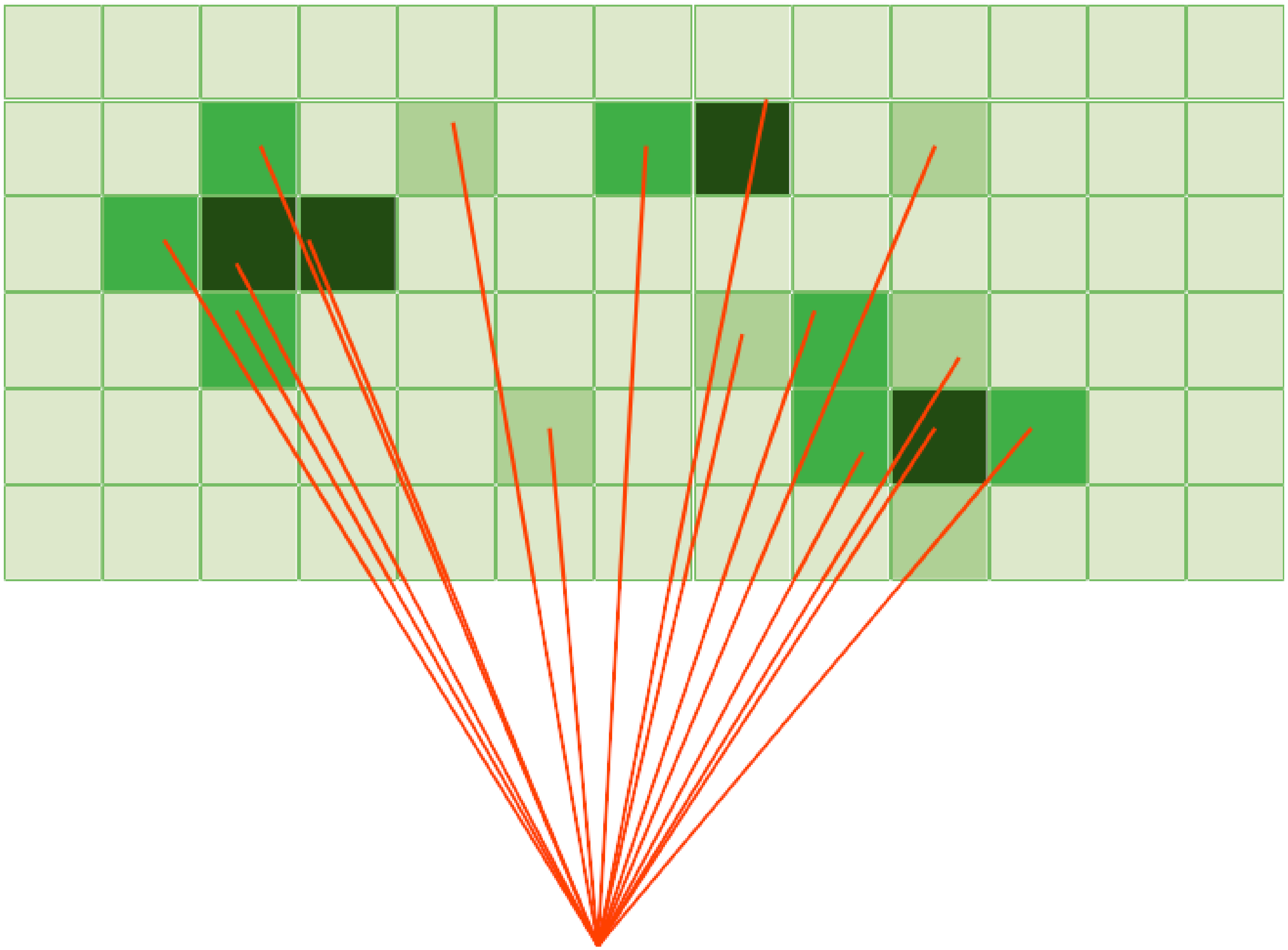




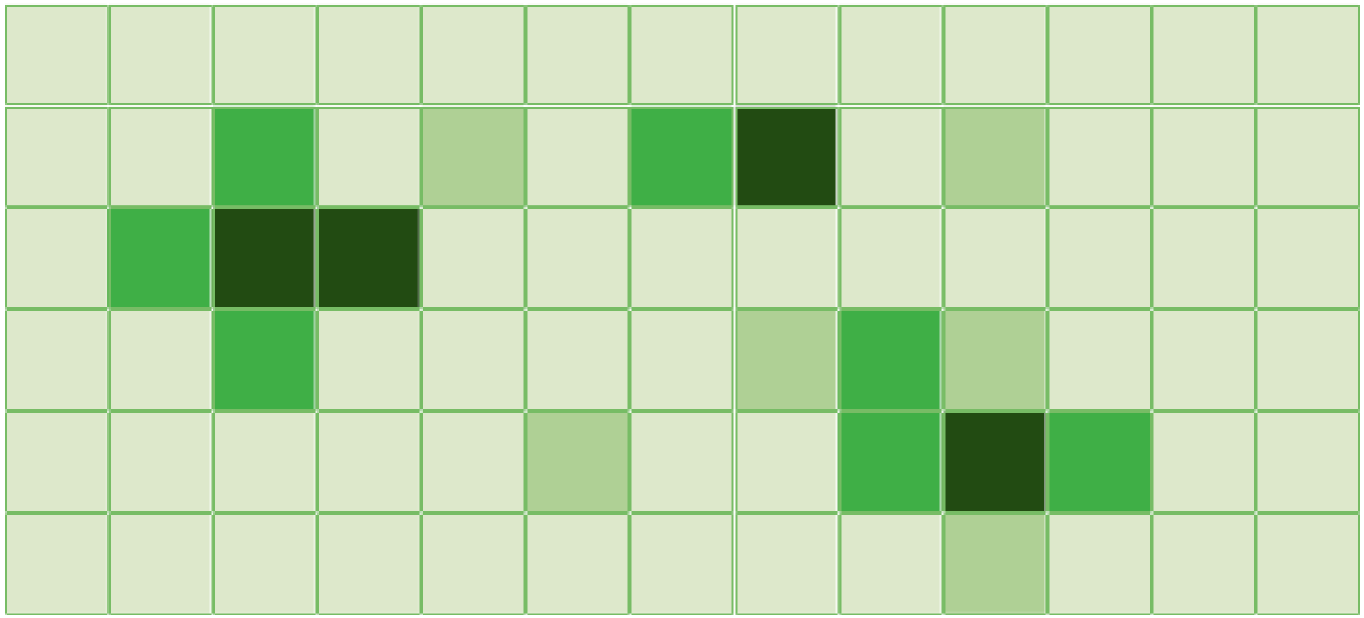
Calorimeter towers



Jet clustering

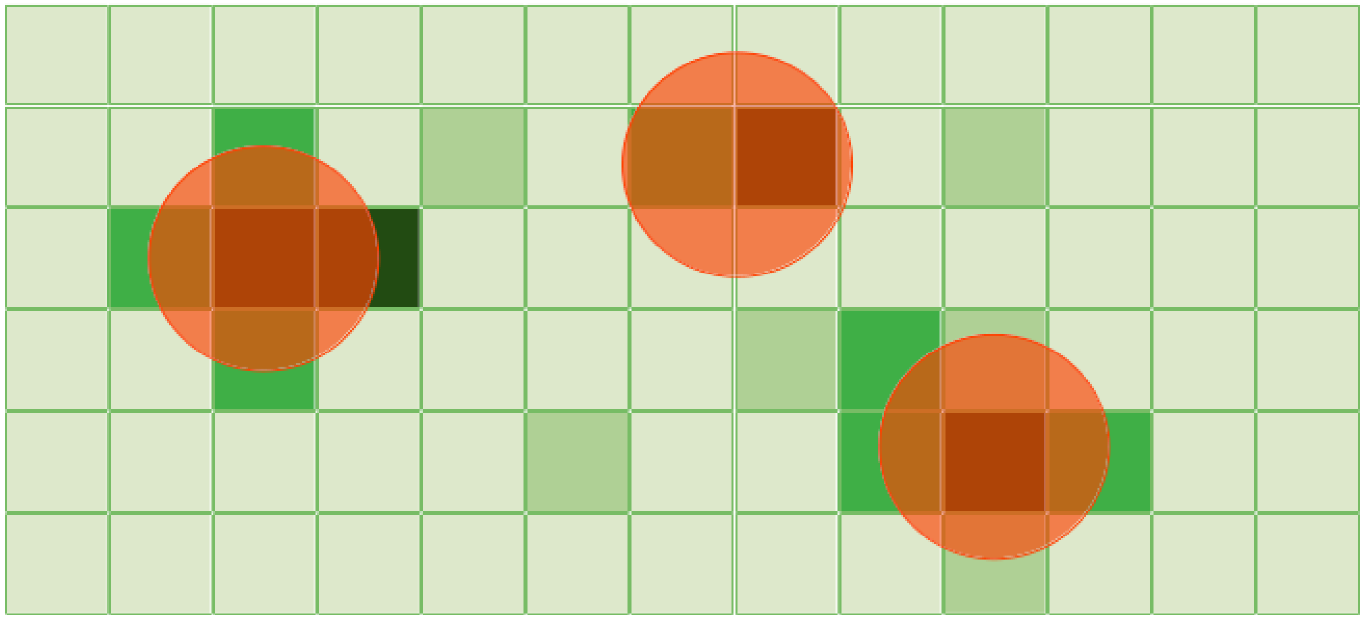


Jet clustering



The Jet clustering algorithm runs on the objects we give it (such as calorimeter towers).
It merges objects together, until we end up with one logical objects (i.e. a single 4-vector)

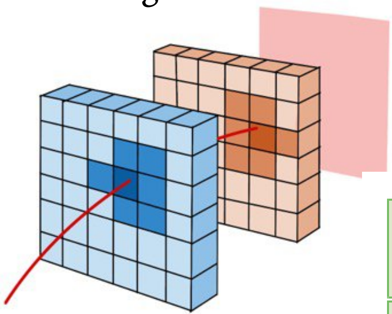
Jet clustering



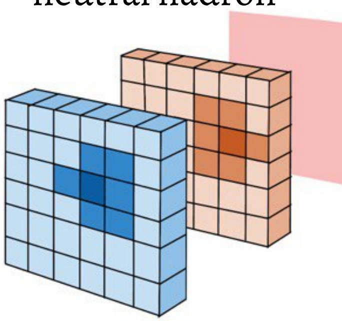
Objects can be list of calorimeter towers,
list of charged/neutral hadrons, list of truth/generator particles
It merges objects together, until we end up with one logical objects
(i.e. a single 4-vector)

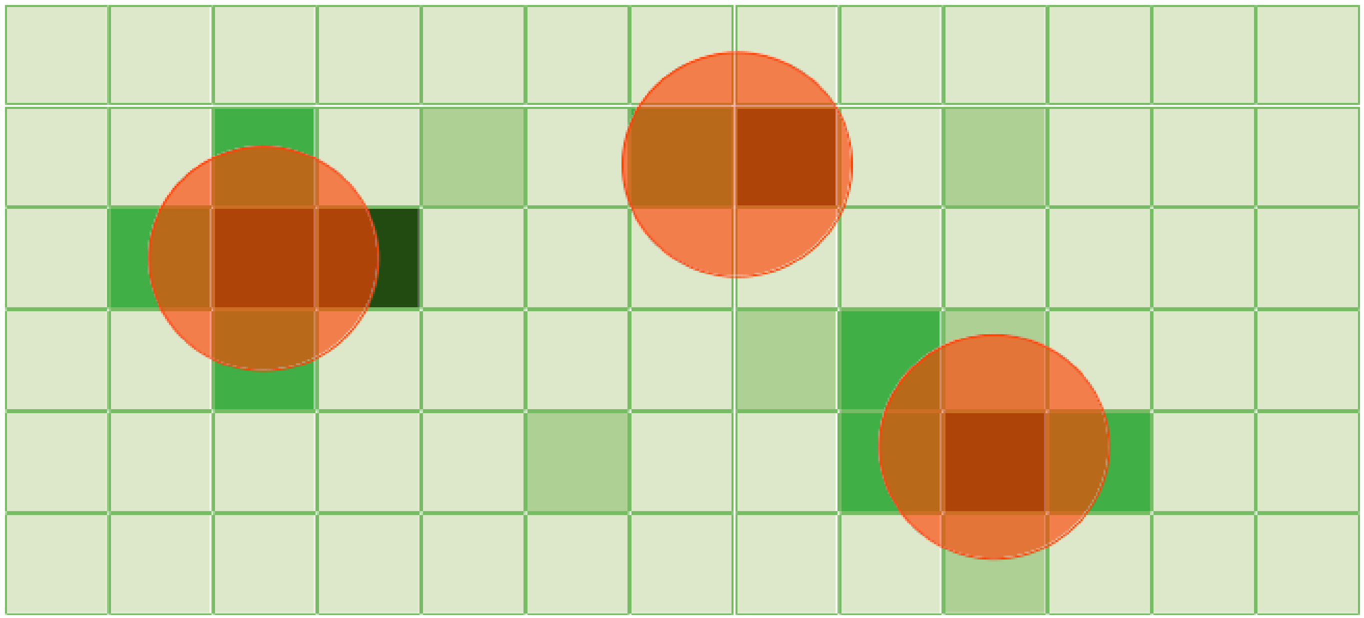
Jet clustering

Charged hadron



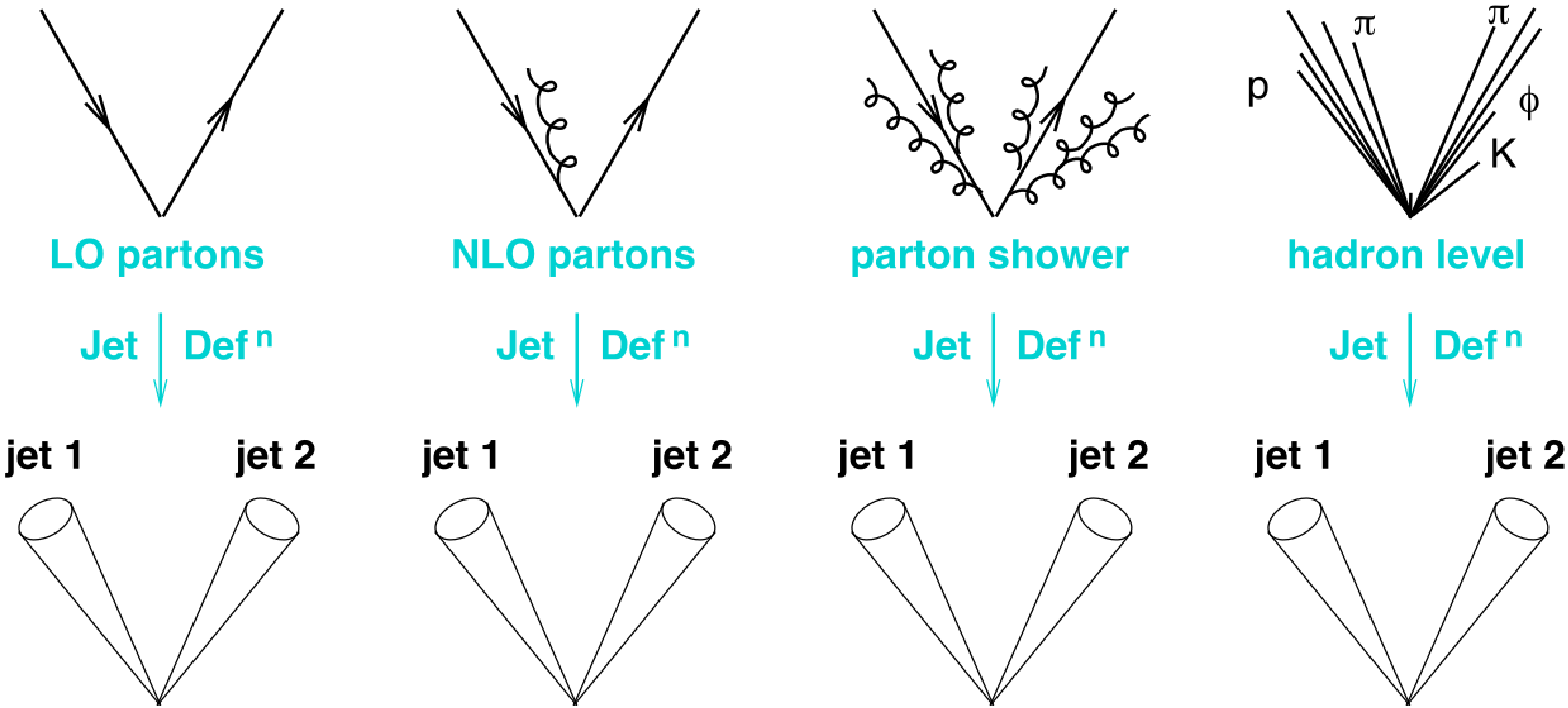
neutral hadron





Objects can be list of calorimeter towers,
list of charged/neutral hadrons, list of truth/generator particles
It merges objects together, until we end up with one logical objects
(i.e. a single 4-vector)

What do we need to worry about?



Projection to jets should be resilient to QCD effects

IRC safety

Jet clustering algorithm

Sequential combination algorithms

Two parameters: R and p

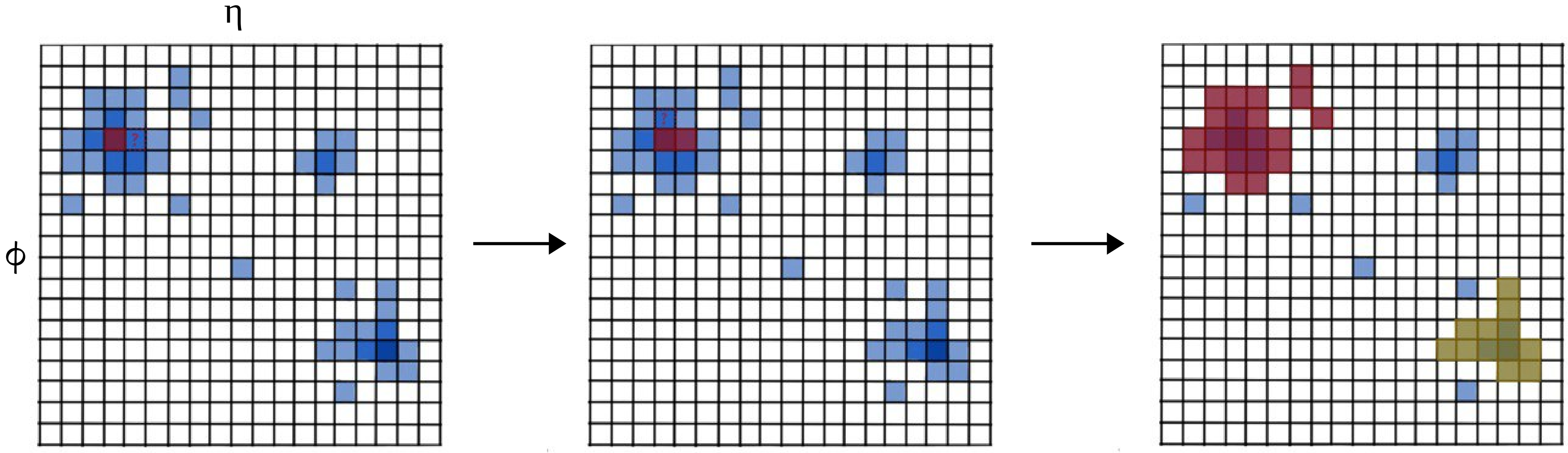
Consider two objects *i* and *j* with
k_T = transverse momentum,
y = rapidity, ϕ = azimuthal angle
B = beam, R = 'radius' parameter

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$\Delta_{ij}^2 = (\Delta y)^2 + (\Delta \phi)^2$$

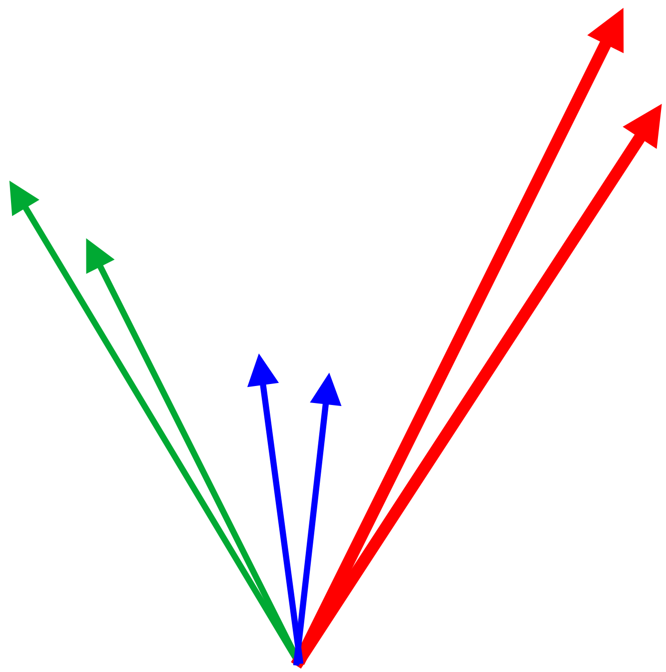
$$d_{iB} = k_{ti}^{2p}$$

If $d_{ij} < d_{iB}$, then merge *i* and *j* (new *i*)
If $d_{iB} < d_{ij}$, then *i* is a jet.
Repeat till all *i* are exhausted.



Jet clustering algorithms

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$



p = 1 : k_T algorithm

Start small

p = 0 : Cambridge-Aachen algorithm

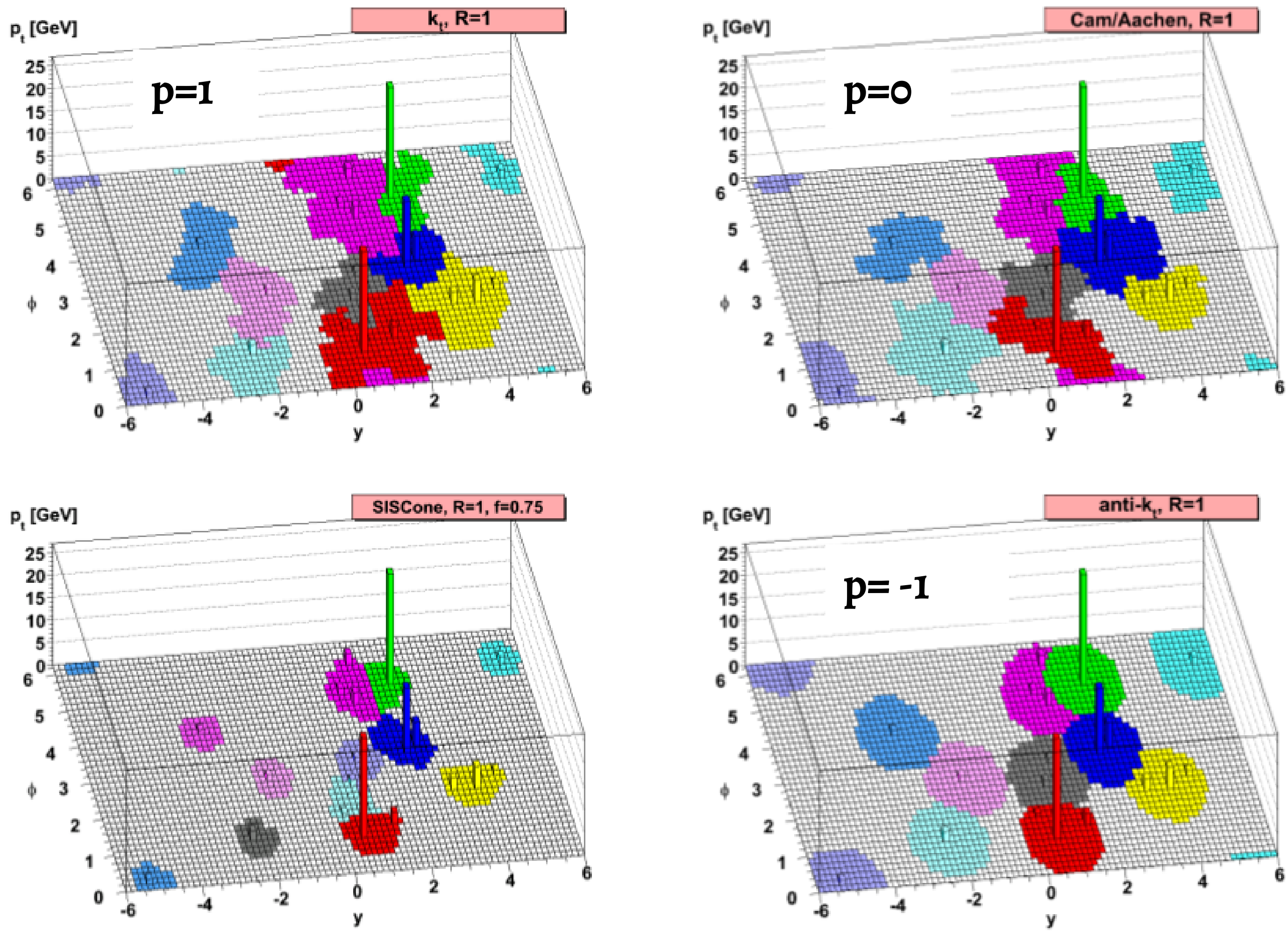
Start closest

p = -1: anti-k_T algorithm

Start big

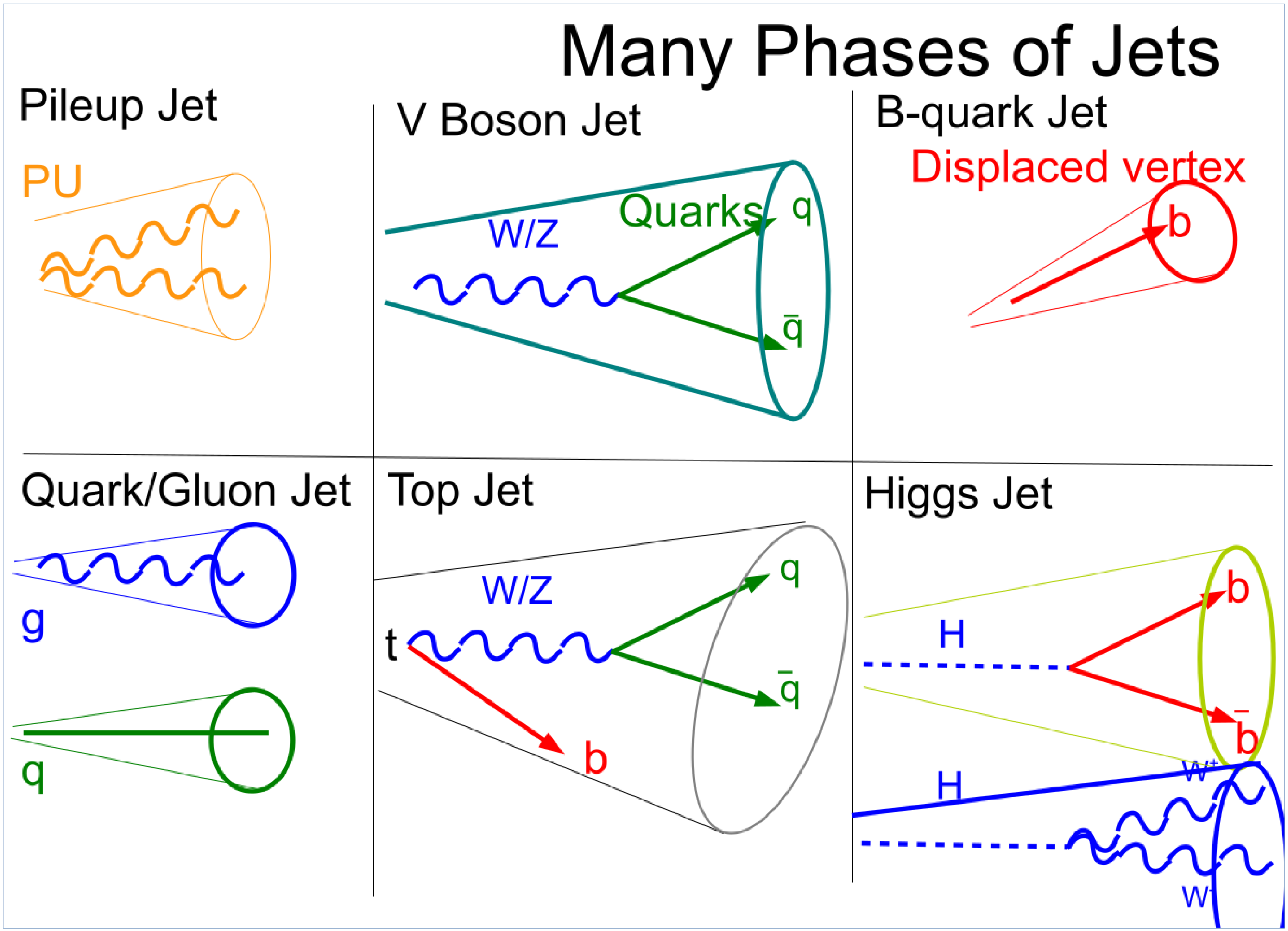
Jet clustering algorithm

$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$



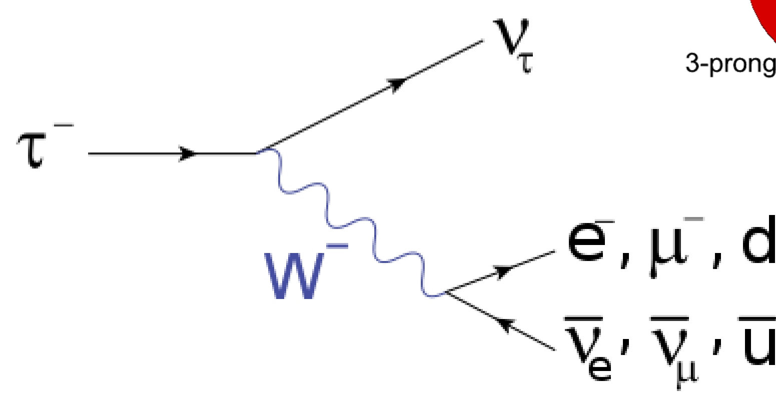
JHEP 0804:063,2008

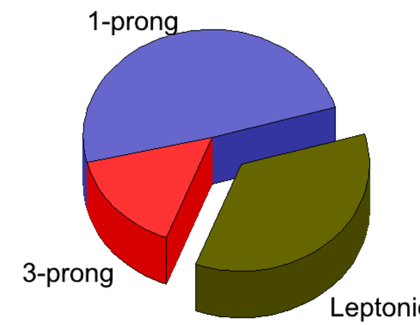
Not just hadronized quarks/gluons



Taus

τ^- DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Modes with one charged particle			
particle$^-$ ≥ 0 neutrals $\geq 0K^0\nu_\tau$ ("1-prong")		(85.24 ± 0.06) %	
particle$^-$ ≥ 0 neutrals $\geq 0K^0_L\nu_\tau$		(84.58 ± 0.06) %	
$\mu^-\overline{\nu}_\mu\nu_\tau$	[g]	(17.39 ± 0.04) %	
$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[e]	$(3.67 \pm 0.08) \times 10^{-3}$	
$e^-\overline{\nu}_e\nu_\tau$	[g]	(17.82 ± 0.04) %	
$e^-\overline{\nu}_e\nu_\tau\gamma$	[e]	(1.83 ± 0.05) %	
$h^- \geq 0K^0_L\ \nu_\tau$		(12.03 ± 0.05) %	
$h^-\nu_\tau$		(11.51 ± 0.05) %	
$\pi^-\nu_\tau$	[g]	(10.82 ± 0.05) %	
$K^-\nu_\tau$	[g]	$(6.96 \pm 0.10) \times 10^{-3}$	
$h^- \geq 1$ neutrals ν_τ		(37.01 ± 0.09) %	
$h^- \geq 1\pi^0\nu_\tau$ (ex. K^0)		(36.51 ± 0.09) %	
$h^-\pi^0\nu_\tau$		(25.93 ± 0.09) %	
$\pi^-\pi^0\nu_\tau$	[g]	(25.49 ± 0.09) %	
$\pi^-\pi^0$ non-$\rho(770)\nu_\tau$		$(3.0 \pm 3.2) \times 10^{-3}$	
$K^-\pi^0\nu_\tau$	[g]	$(4.33 \pm 0.15) \times 10^{-3}$	
$h^- \geq 2\pi^0\nu_\tau$		(10.81 ± 0.09) %	
$h^-2\pi^0\nu_\tau$		(9.48 ± 0.10) %	
$h^-2\pi^0\nu_\tau$ (ex. K^0)		(9.32 ± 0.10) %	
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	[g]	(9.26 ± 0.10) %	
$\pi^-2\pi^0\nu_\tau$ (ex. K^0), scalar		$< 9 \times 10^{-3}$	CL=95
$\pi^-2\pi^0\nu_\tau$ (ex. K^0), vector		$< 7 \times 10^{-3}$	CL=95
$K^-2\pi^0\nu_\tau$ (ex. K^0)	[g]	$(6.5 \pm 2.2) \times 10^{-4}$	



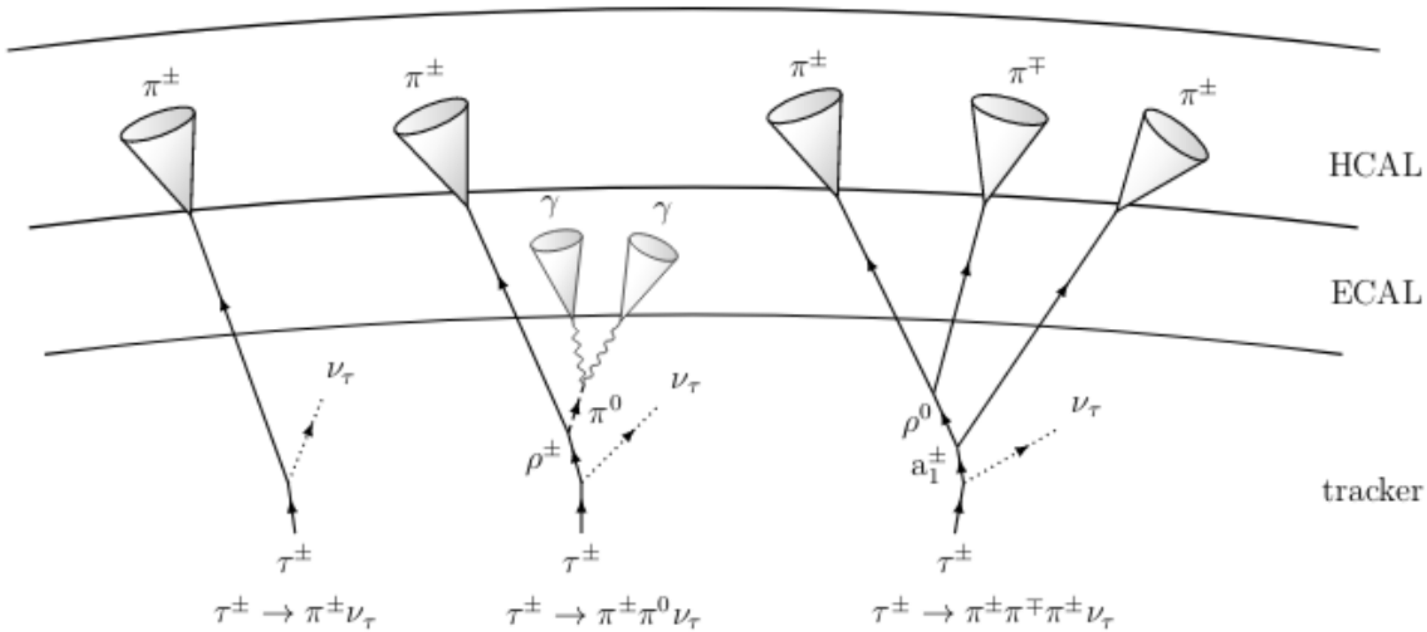


If a tau decays to an electron or muon, we already detected it.

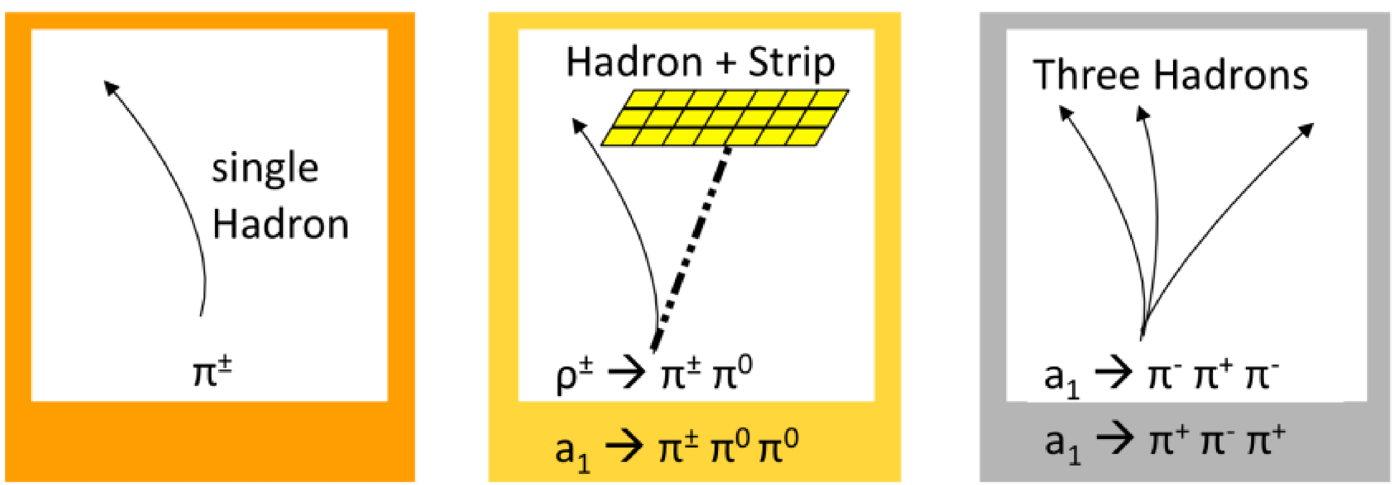
So our goal is to detect the **hadronic decays of the tau**.

Trouble is, if it decays to hadrons… then how is the end-result different from just quarks/gluons that produce hadrons (a jet) ?

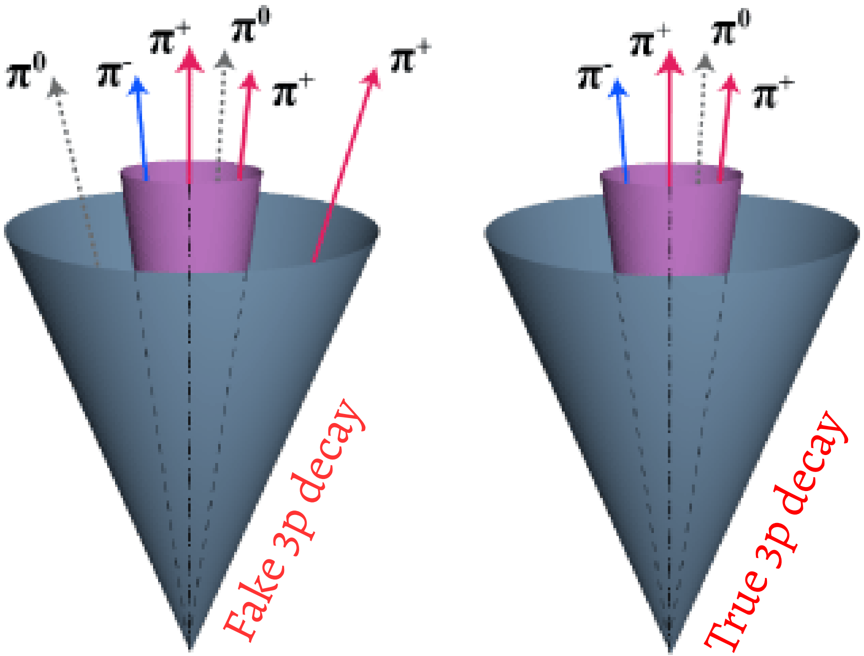
Tau reconstruction

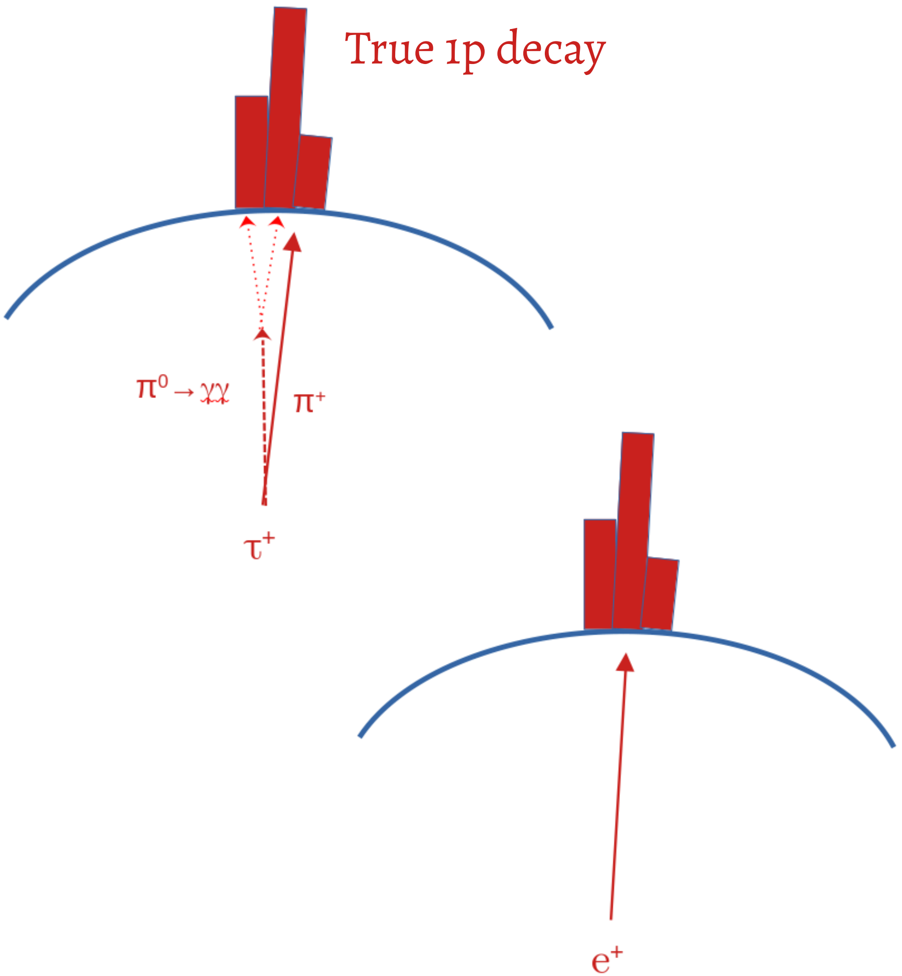


Izaak W. Neutelings



Taus are tough….

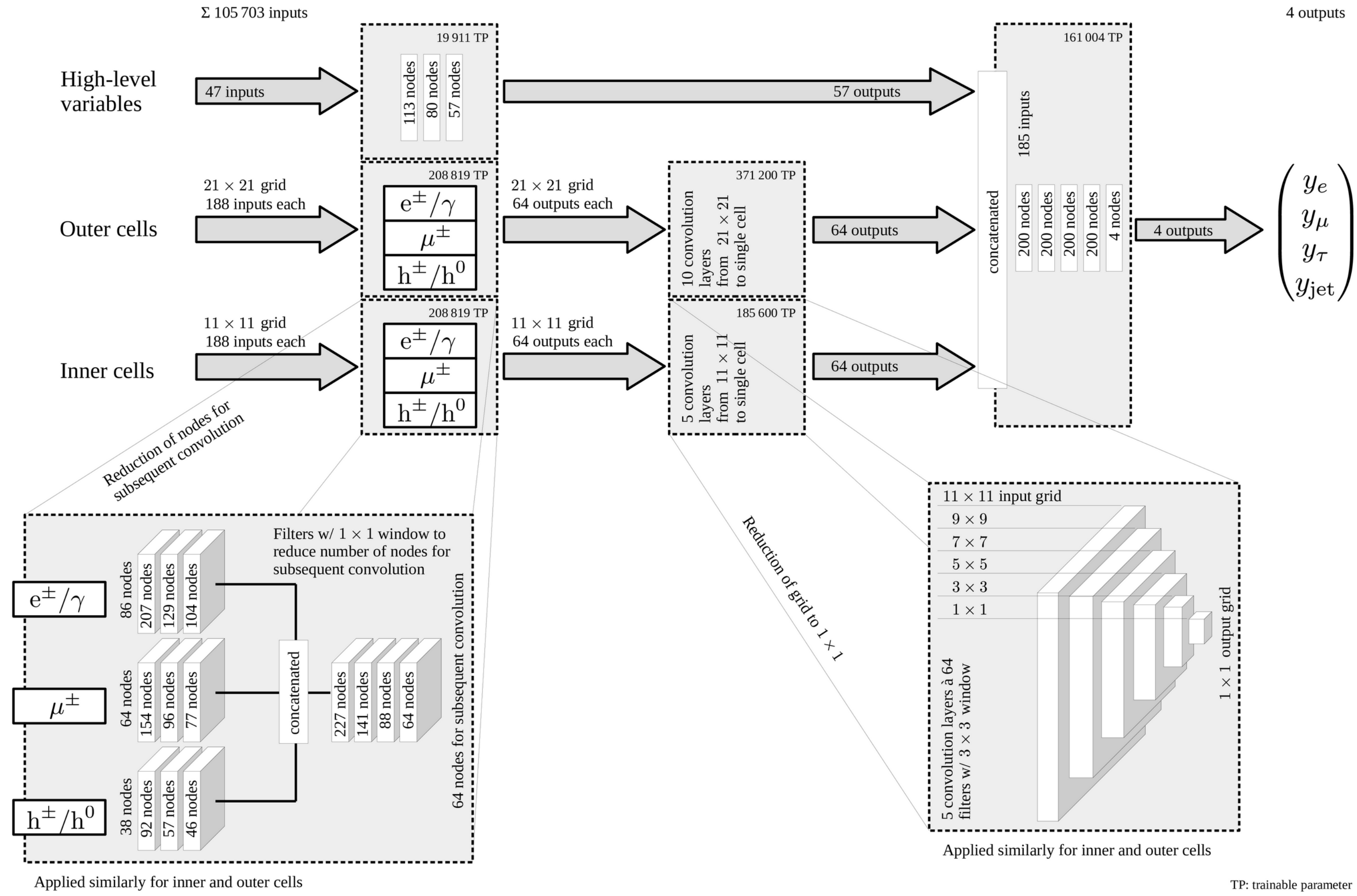




Pick some properties and set requirements such that we end up selecting more τ and less of the background

Can you think of some properties?

CMS Tau identification

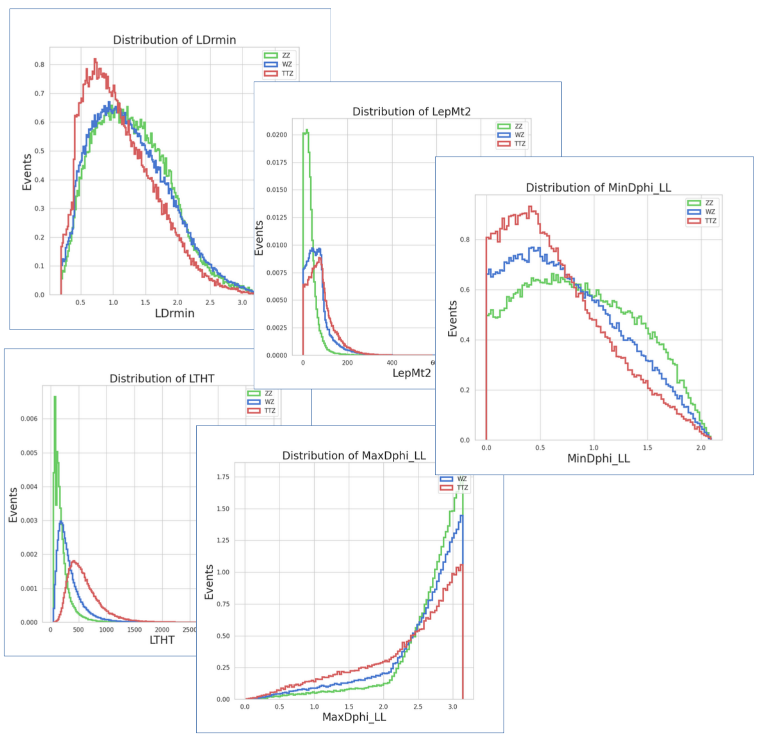


Architecture of a deep neural network (a multiclassifier) to identify hadronically decaying τ leptons.

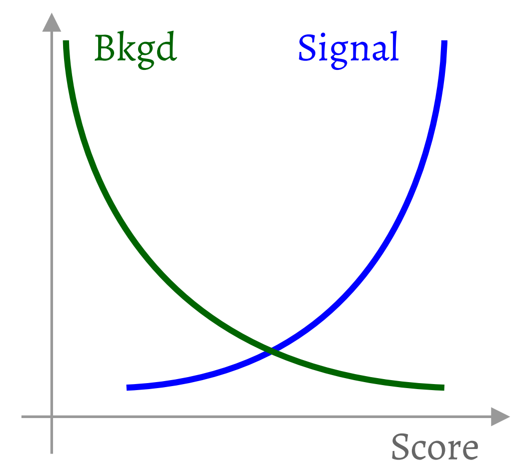
arXiv:2201.08458 [hep-ex]

Machine Learning *for now*

You will get a full set of lectures later in the school.



A box which takes inputs (object/event properties) and gives an output **f** such that **f** is distributed as

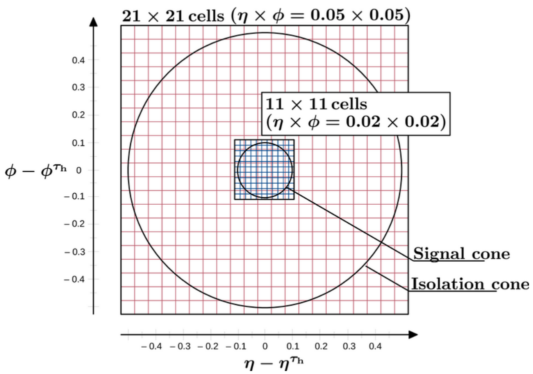


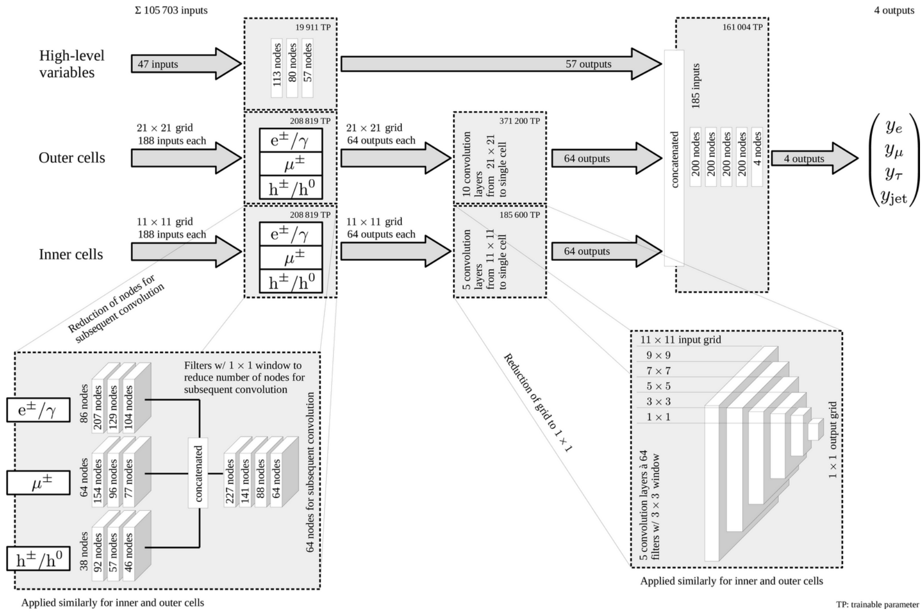
An MVA will take in several inputs and give an output that aims to “classify” the inputs into two or more categories.

This description will suffice us for now, and we will of course revisit it as needed.

CMS Tau identification

Inputs:
Many many high level and low-level variables





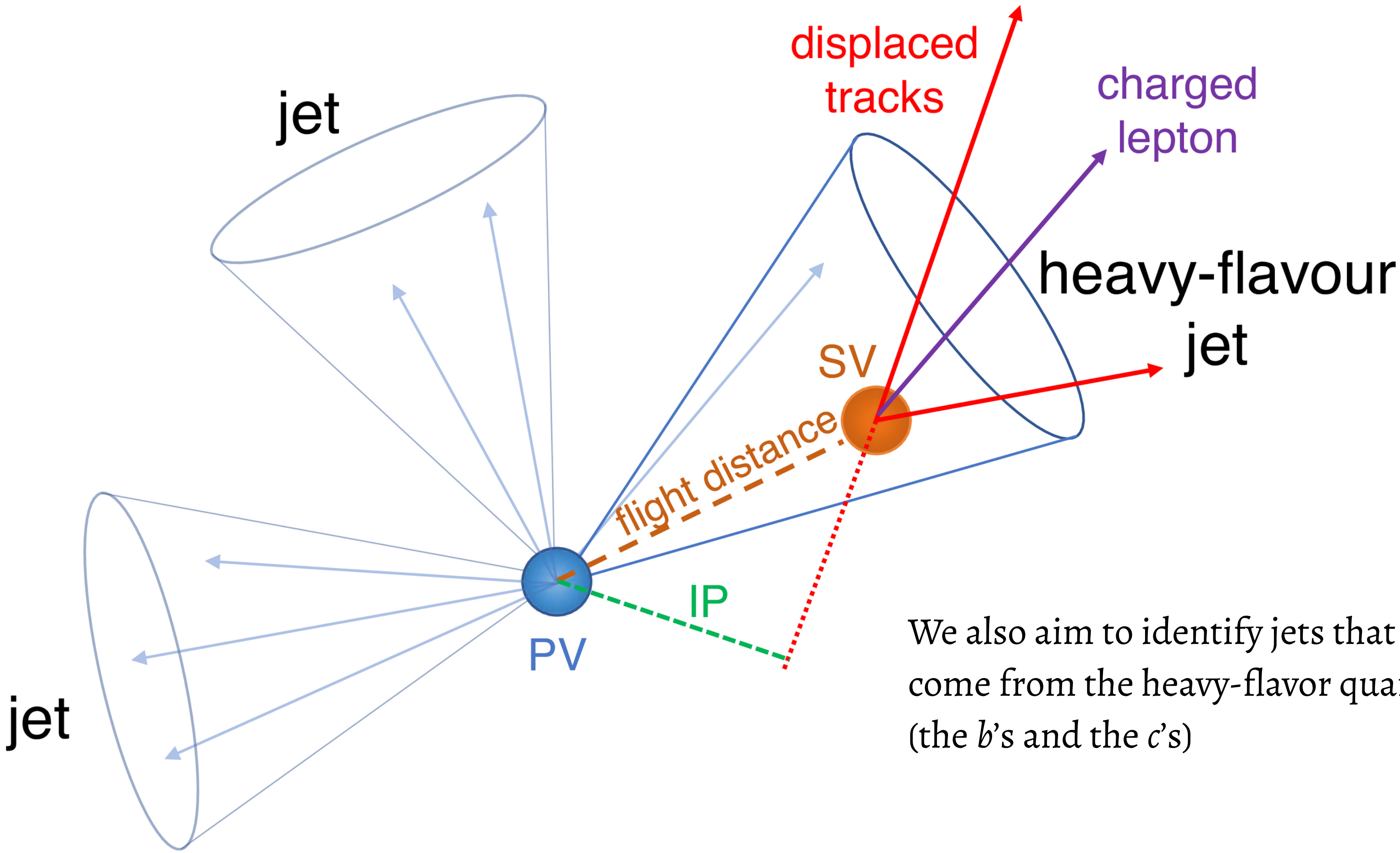
Output:
"Probability" that object is electron, muon, usual jet or hadronically decaying tau.

Particle	N_{var}	Inputs
PF charged hadron	27	Track PV/SV/quality, PUPPI, HCAL energy fraction
PF neutral hadron	7	PUPPI, HCAL energy fraction
Electron	37	Electron track quality, track/cluster matching, cluster shape
PF electron	22	Track PV/SV/quality, PUPPI
PF photon	23	Track PV/SV/quality, PUPPI
Muon	37	Track quality, muon station hits, ECAL deposits
PF muon	23	Track PV/SV/quality, PUPPI

Architecture of a deep neural network (a multiclassifier) to identify hadronically decaying τ leptons.

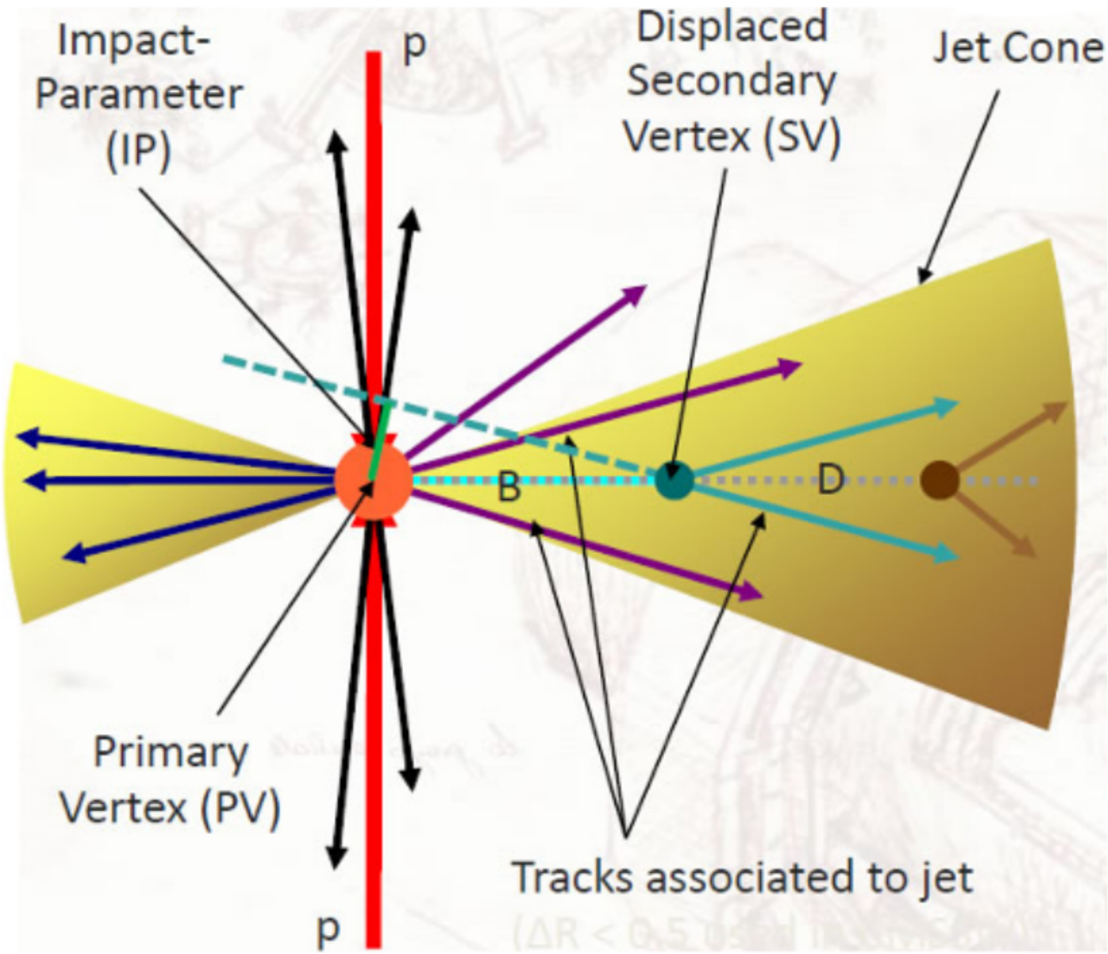
arXiv:2201.08458 [hep-ex]

b-jets and *c*-jets



We also aim to identify jets that come from the heavy-flavor quarks (the *b*'s and the *c*'s)

Special properties of the heavy quarks



High masses

- 4.2 GeV for b quark

-1.3 GeV for c quark

(Strange quark mass 93 MeV)

Long lifetimes

- cτ ~450 μm for b quark

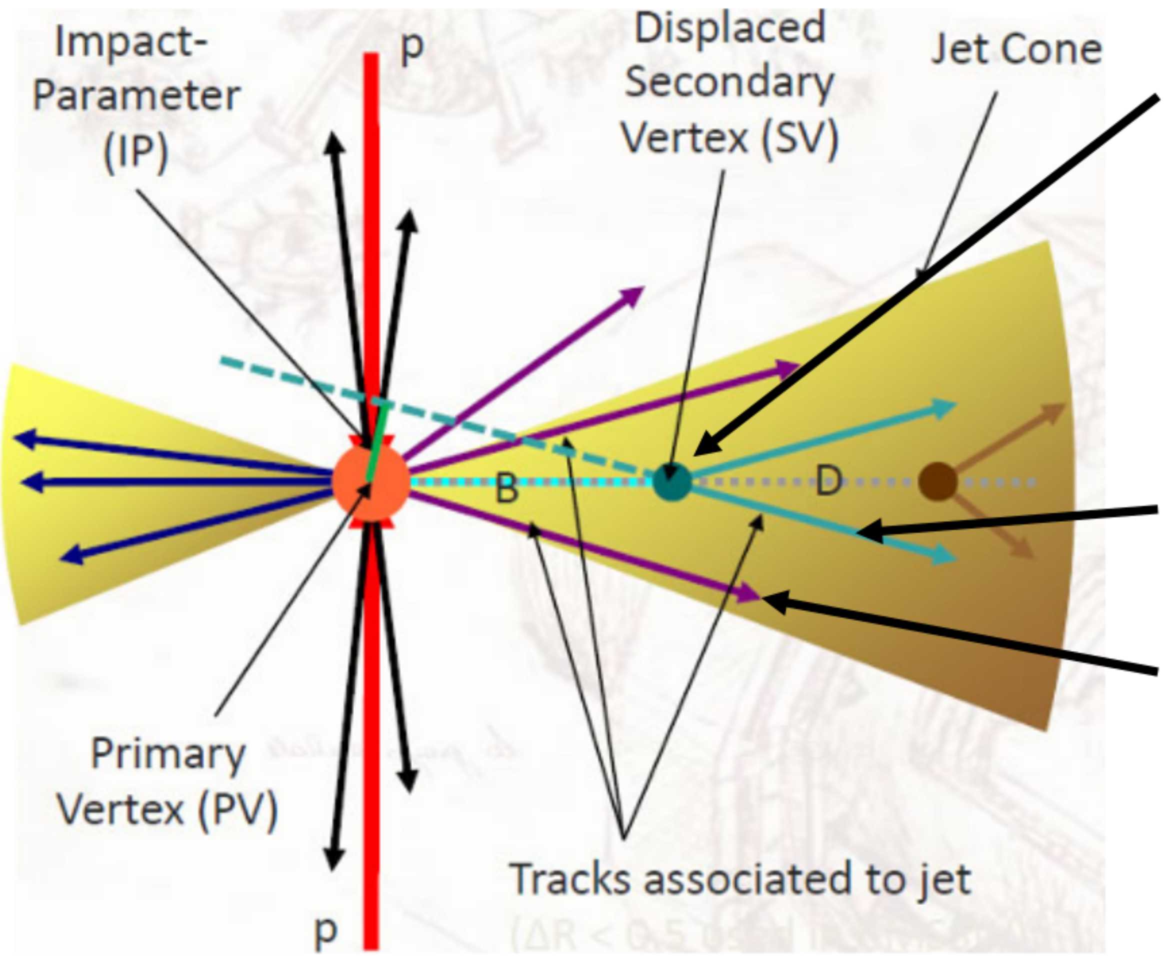
  Or ~5 mm at 50 GeV p_T

- cτ ~100–300 μm for c quark

  Or ~1–3 mm at 50 GeV p_T

High number of tracks associated to the jet on average

Special properties of the heavy quarks



High masses
-Look for SV with high mass

Long lifetimes
Look for tracks with high impact parameters

High number of tracks associated to the jet on average

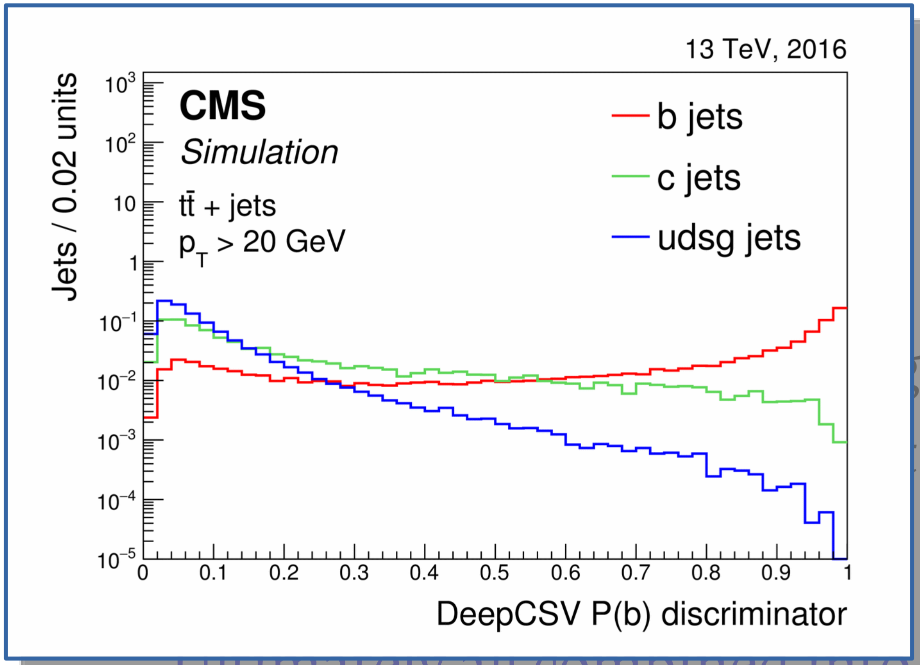
b-tagging, *c*-tagging

Algorithms based on
track properties,
or holistic properties (charged/neutral hadrons, leptons),
or secondary vertex properties.

Ultimately all combined into a multivariate (NN) based approach.

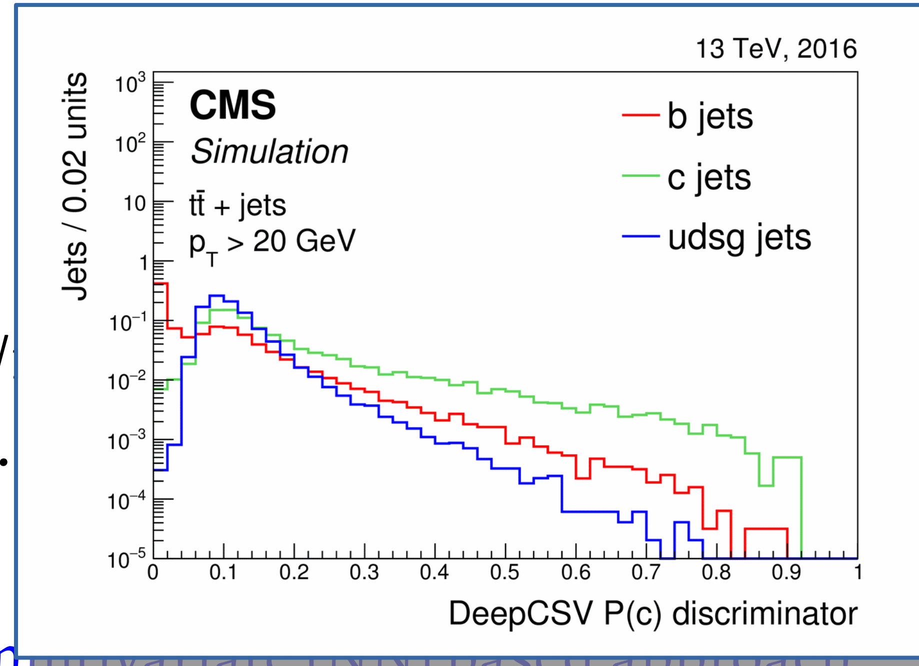
Also then discriminating quark jets from gluon jets….

b-tagging, *c*-tagging

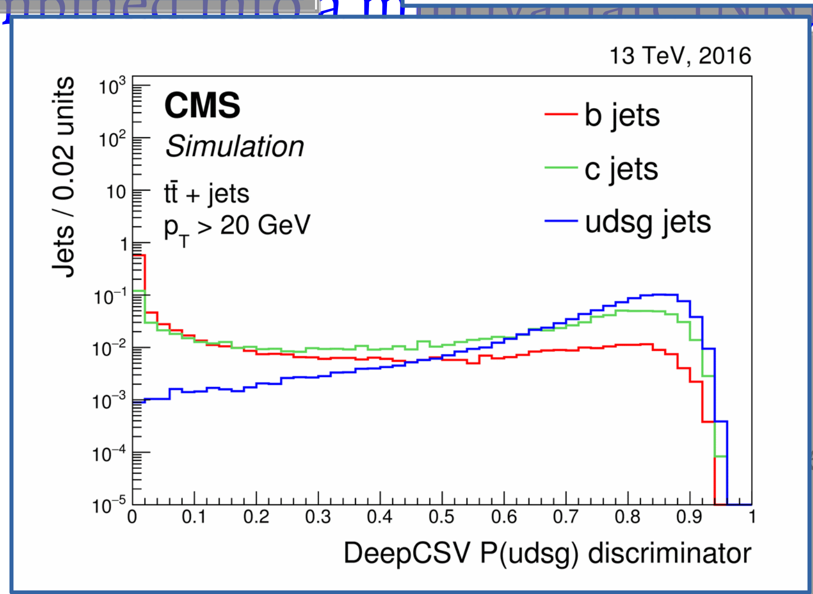


ged/

ies.



Ultimately all com... a m... based approach.



JINST 13 (2018) P05011

ets from gluon jets....

Particle Identification

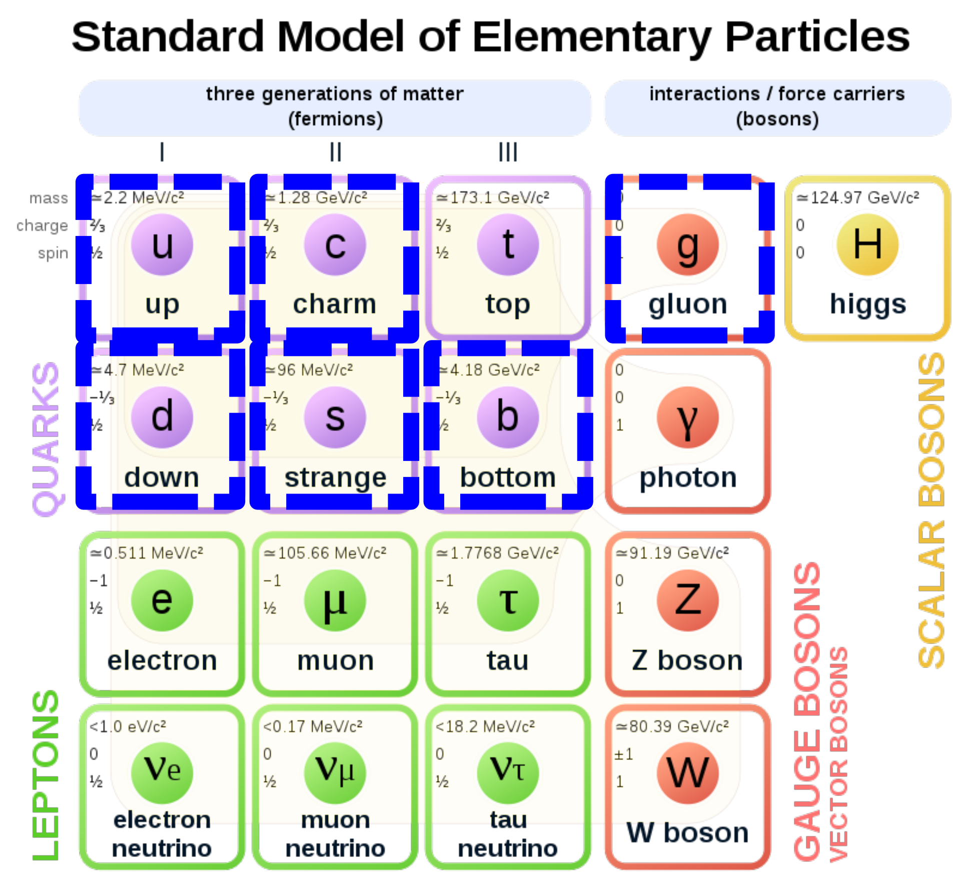
Which particles can we detect directly?

Electrons, Muons, Taus, Photons,

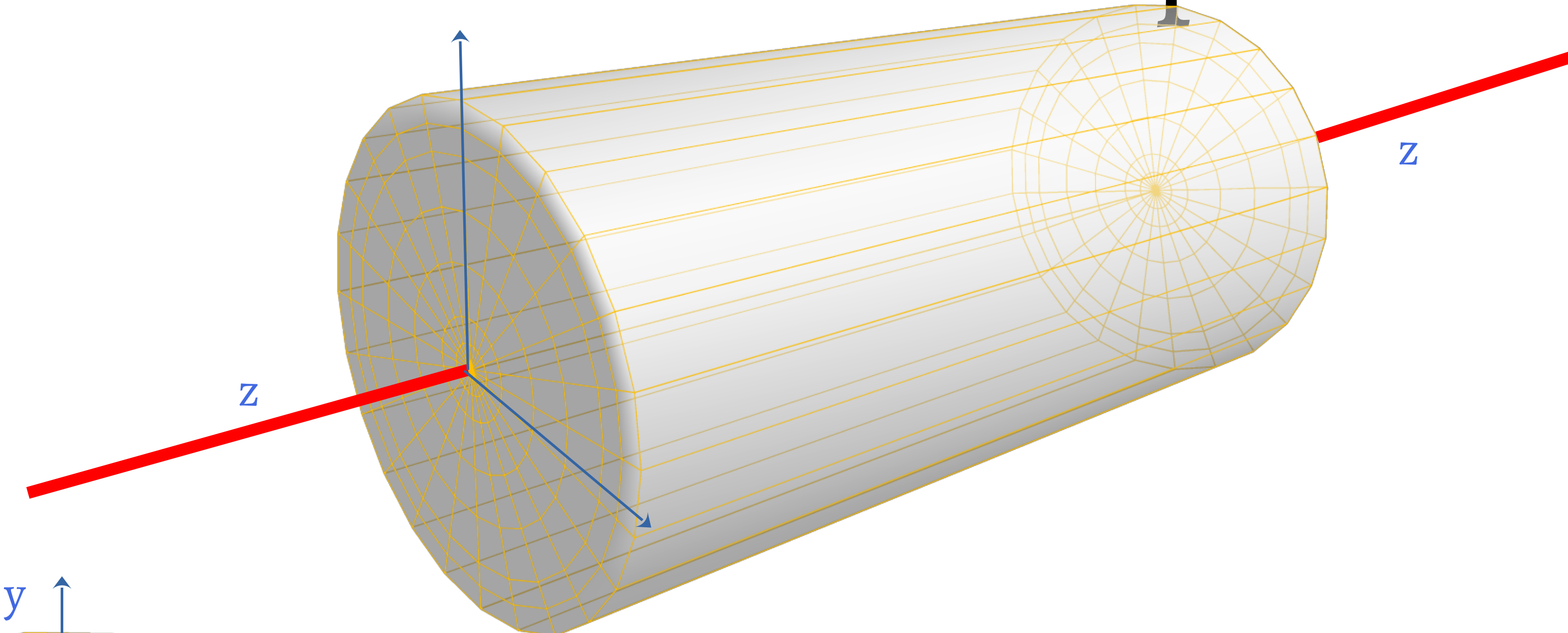
Quarks, gluons manifest as jets (of hadrons)

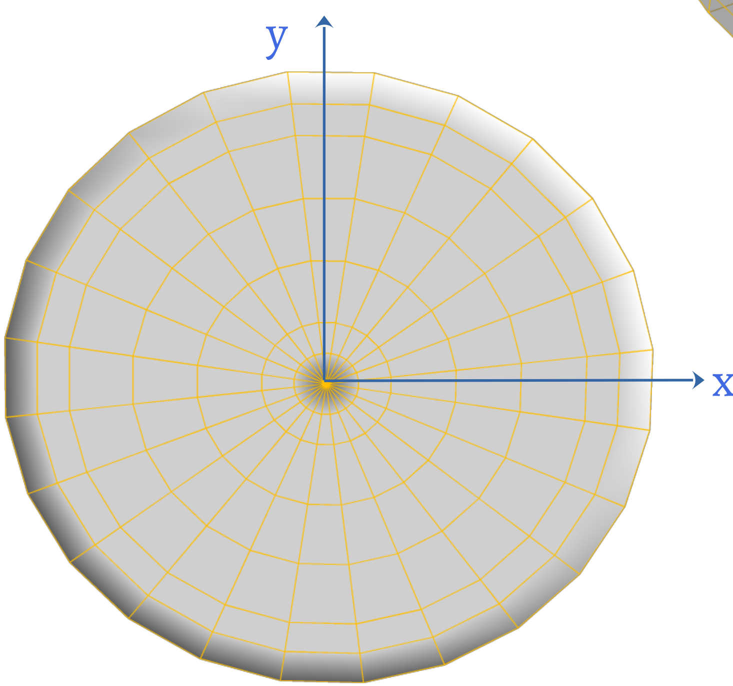
(*b*-jet, *c*-jet, q-g discrimination)

These hadronize, producing hadrons such as pions, kaons, neutrons etc.

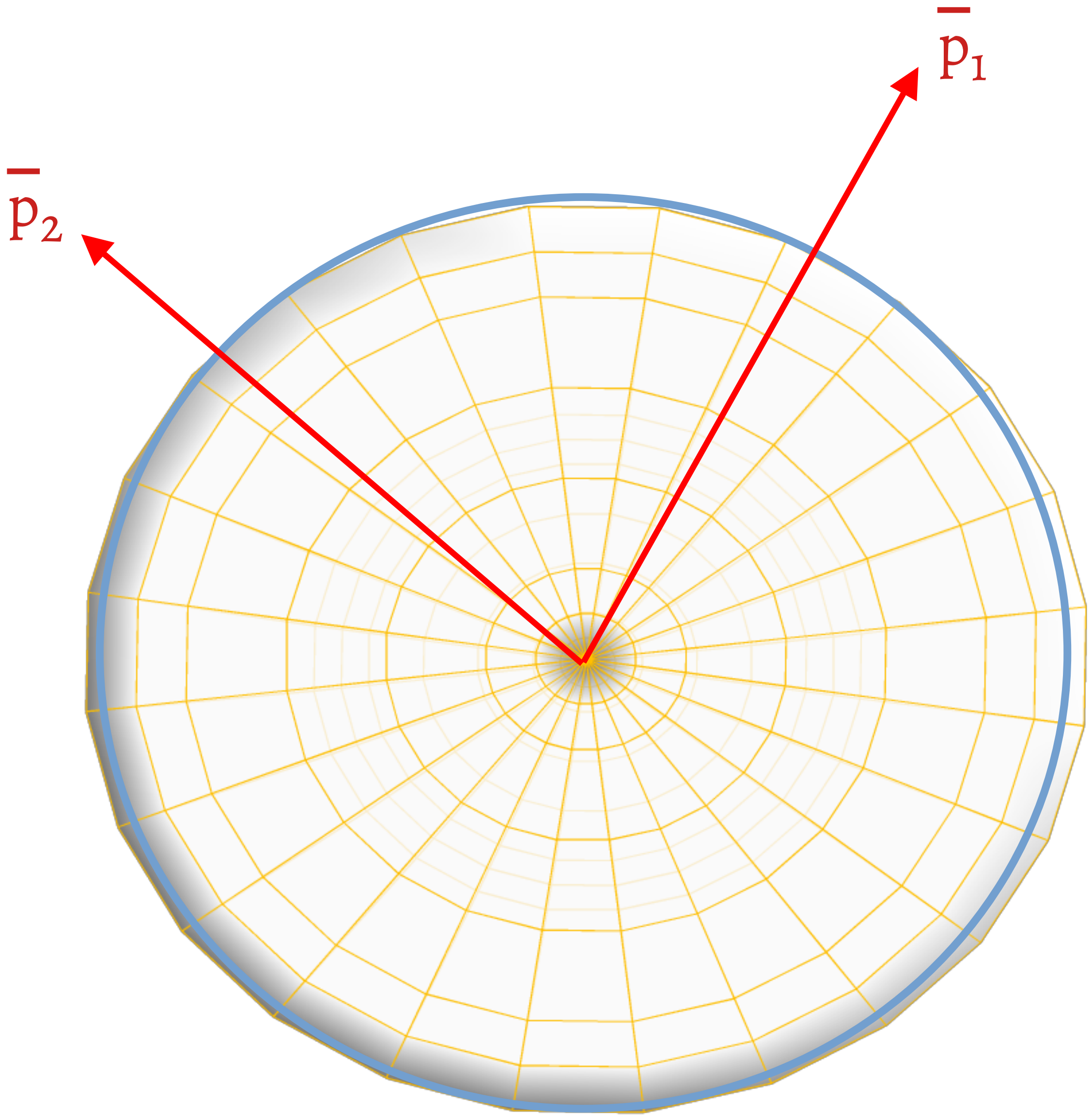


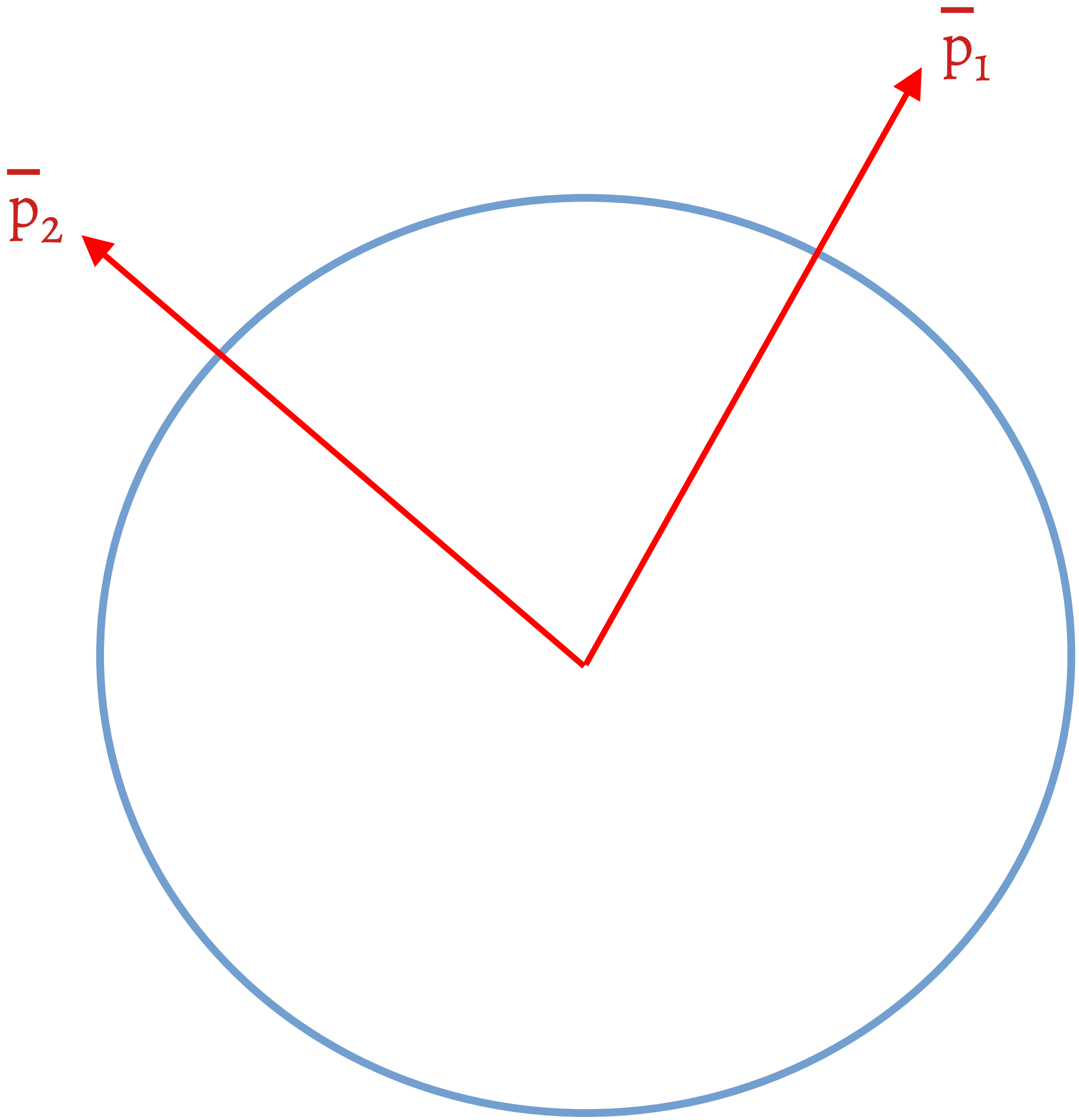
Consider the transverse plane

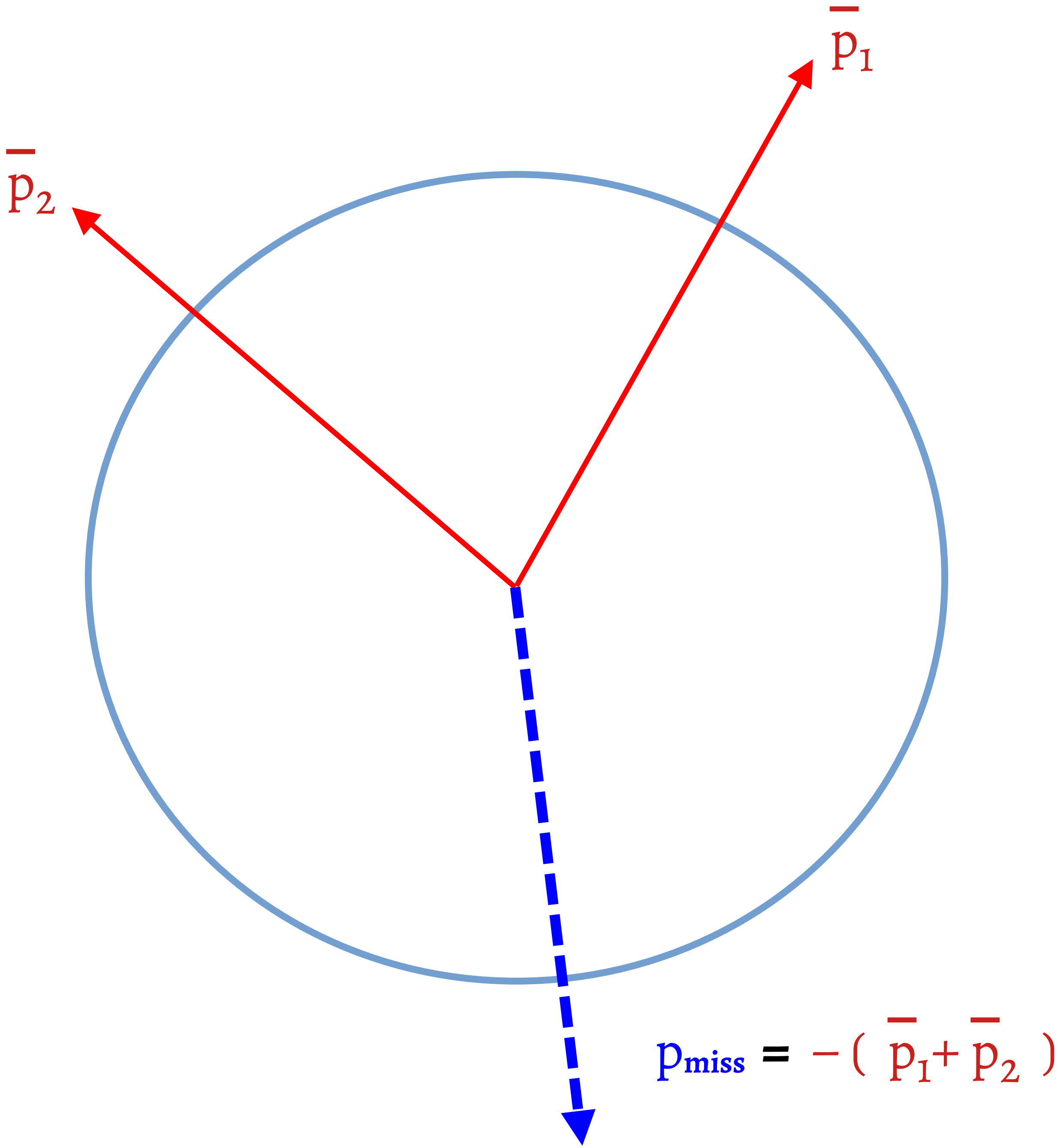




The beam is in & out of page at the center.


$\bar{p}_1$
$\bar{p}_2$


$\bar{p}_1$
$\bar{p}_2$

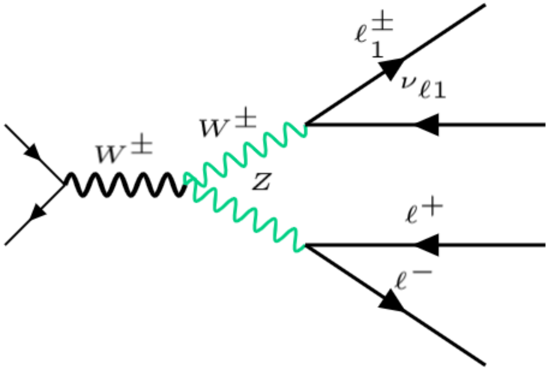

$\bar{p}_1$
$\bar{p}_2$
$p_{miss} = -(\bar{p}_1 + \bar{p}_2)$

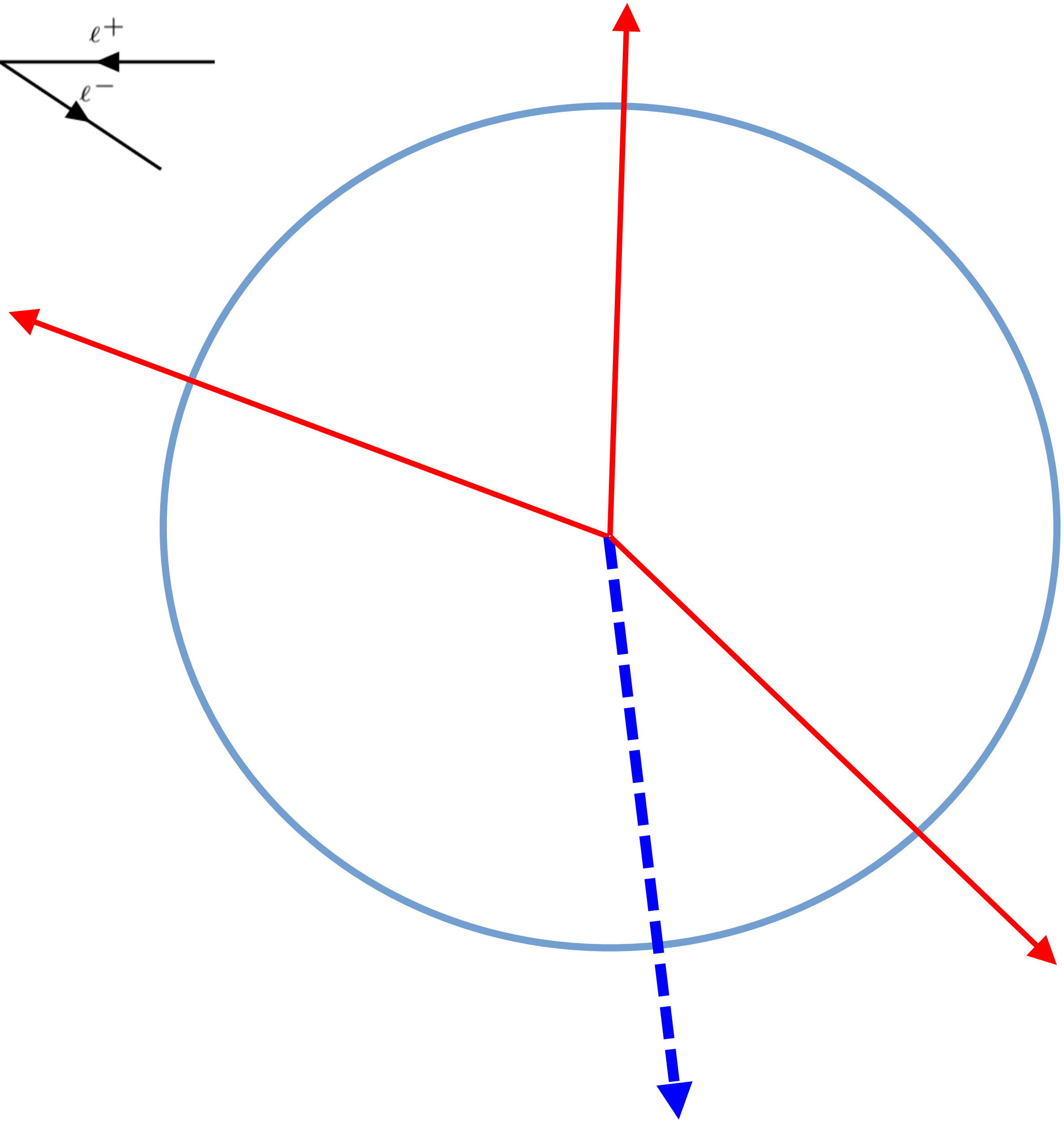
Missing momentum

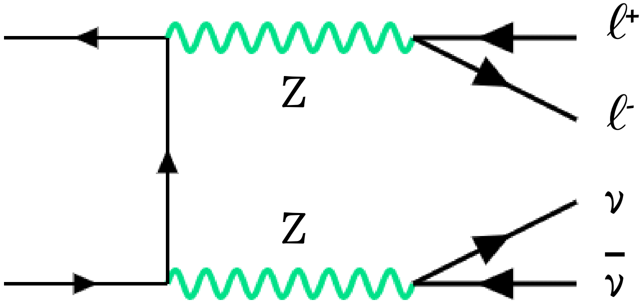
Defined as the negative of the vector sum of p_T of all observed particles.

This means one has to understand all the observed particles well.

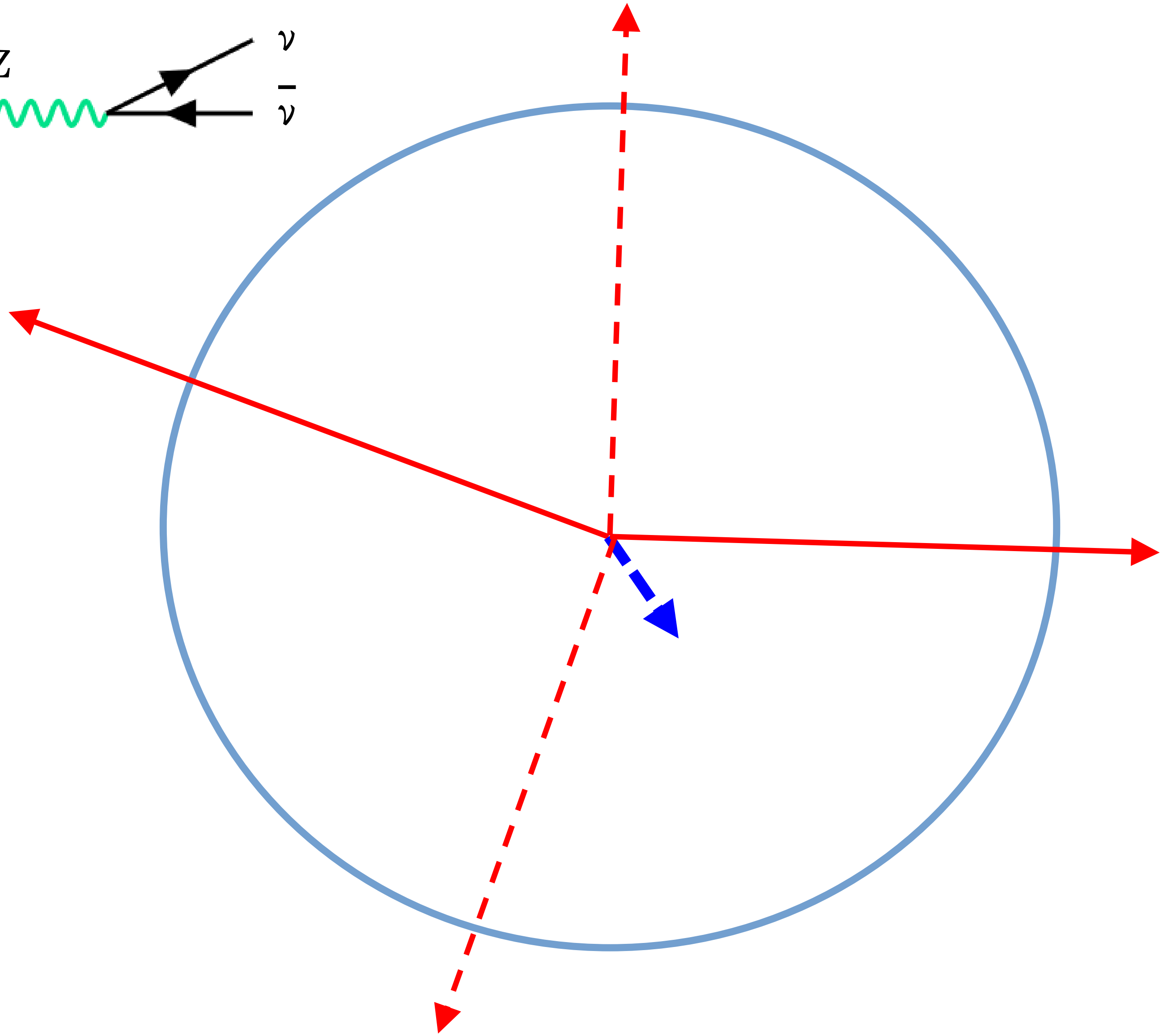
Mismeasurements in measuring existing particle 4-vectors will impact missing momentum.


$W^{\pm}$
$W^{\pm}$
Z
$\ell_1^{\pm}$
$\nu_{\ell 1}$
ℓ^{+}
ℓ^{-}



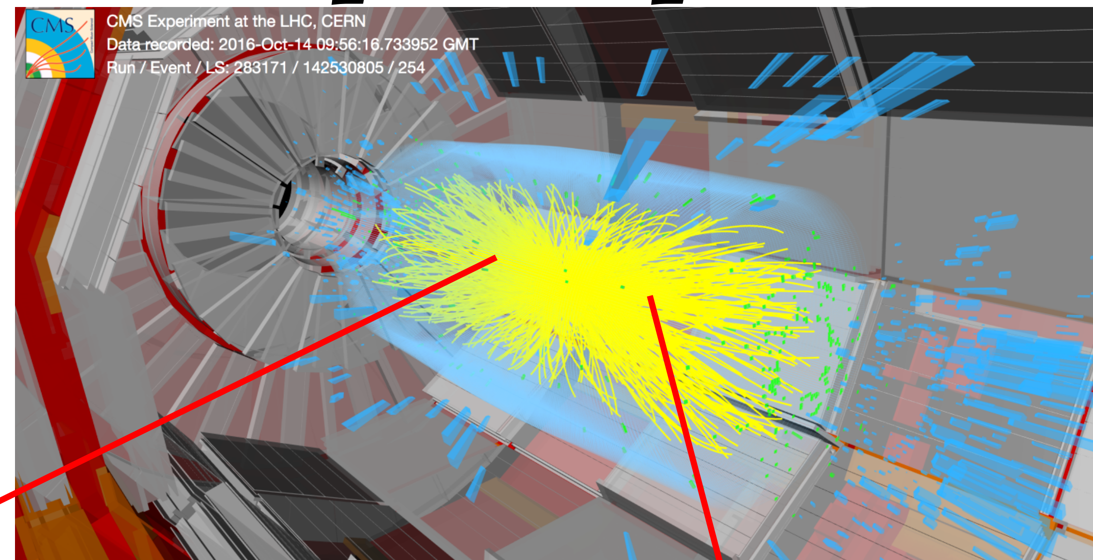


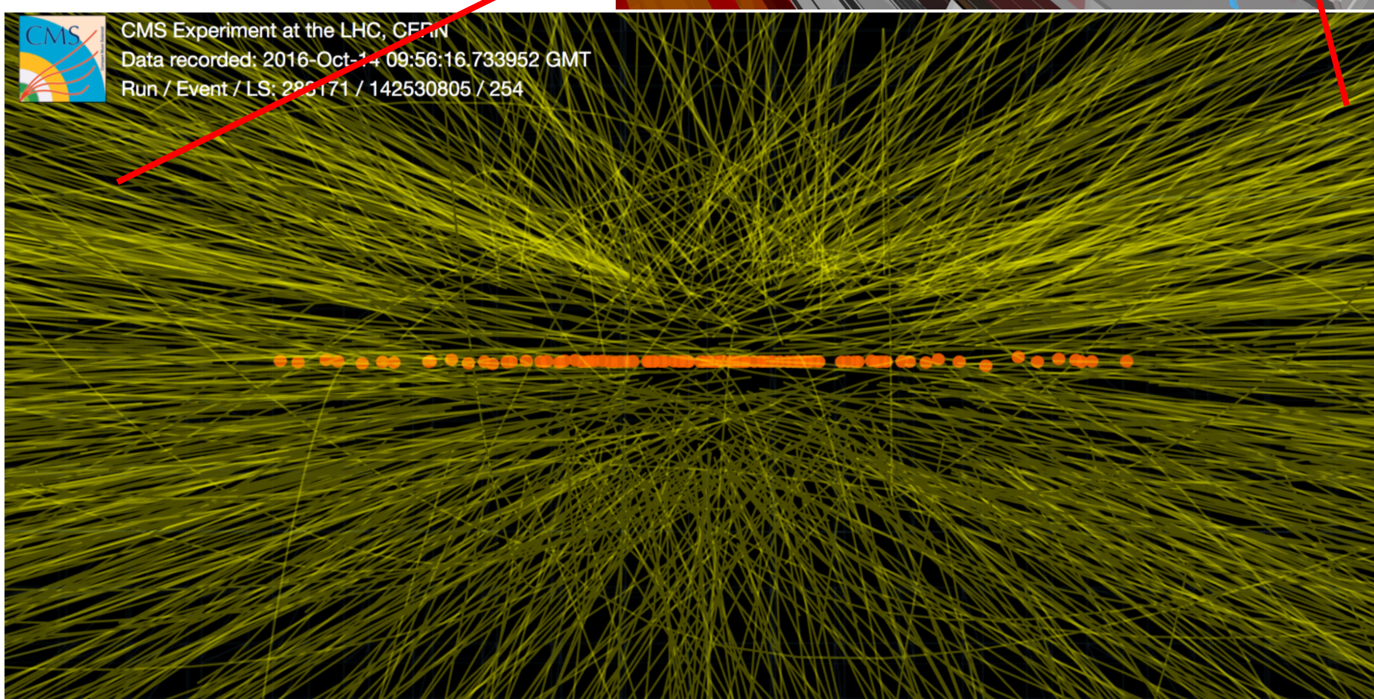
ℓ+
ℓ-
Z
Z
ν
ν̄

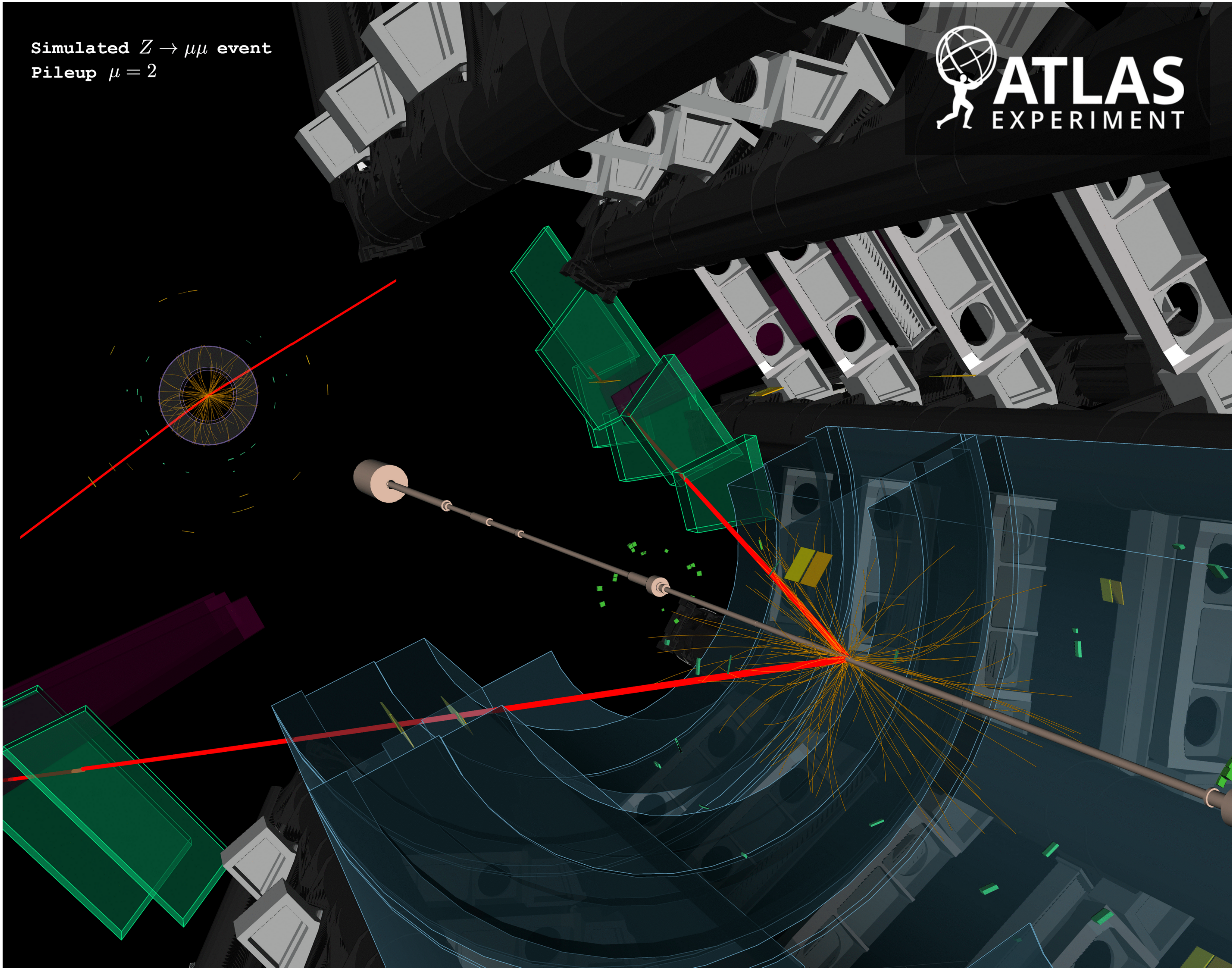


Reality check: pileup

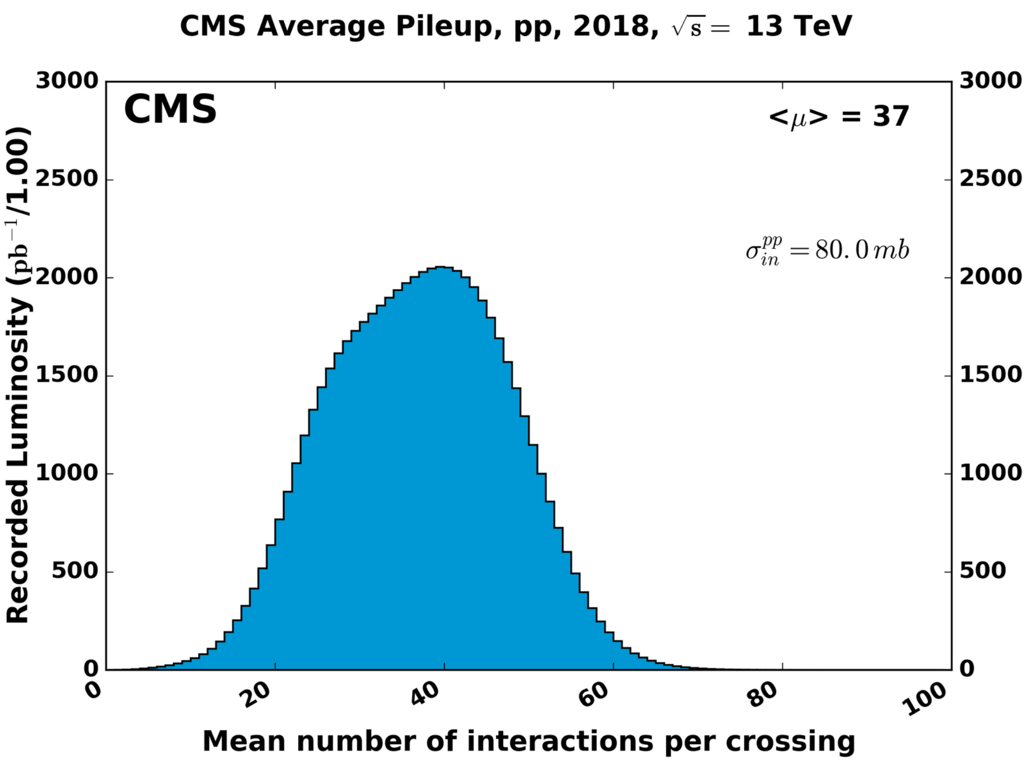
Pileup: Multiple proton-proton interactions in the same bunch crossing

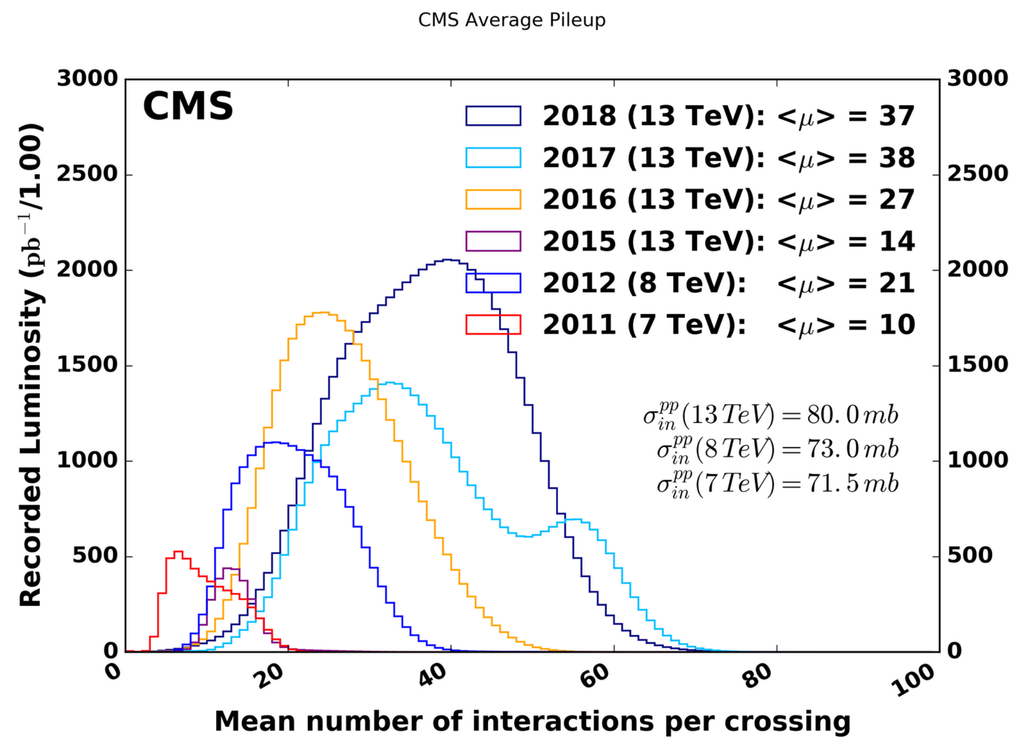




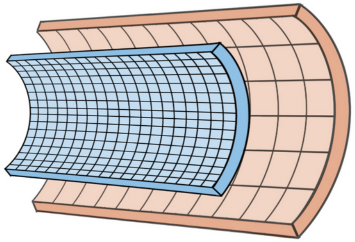

Simulated $Z \to \mu\mu$ event
Pileup $\mu = 2$
ATLAS
EXPERIMENT

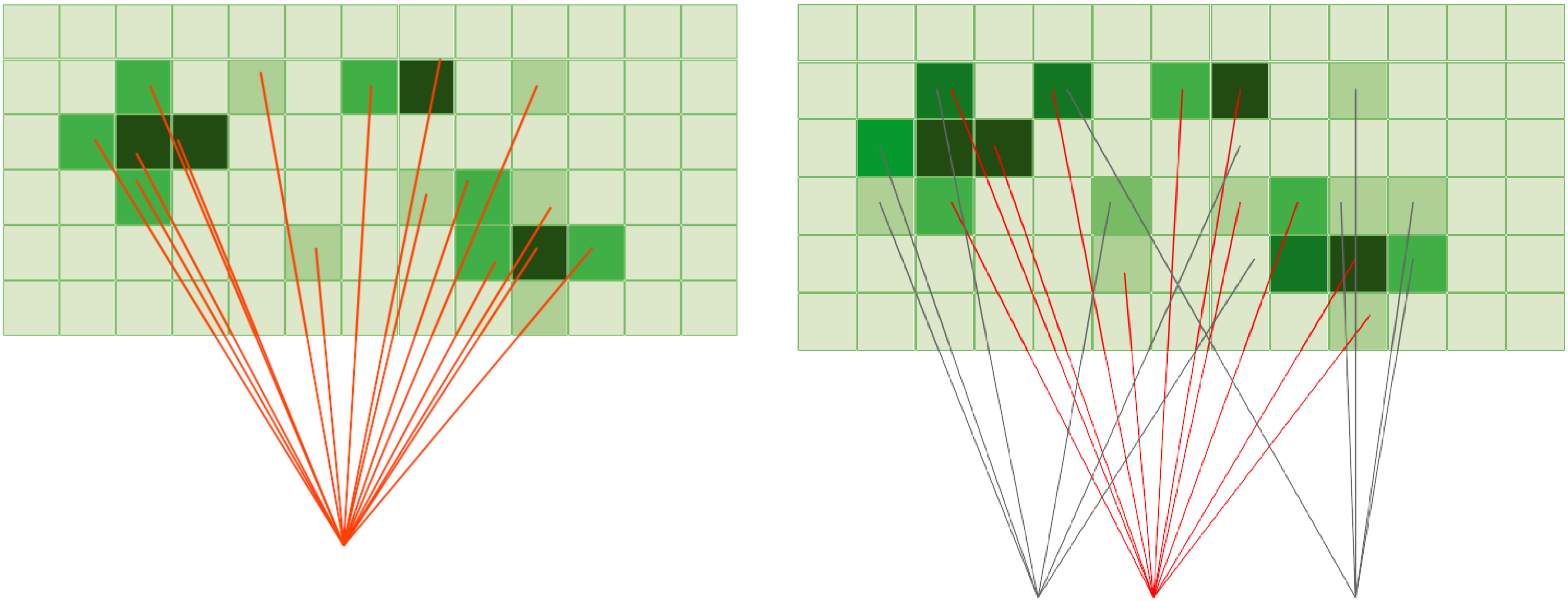
Mean number of interactions





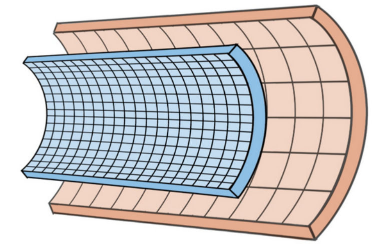
Impact of pileup

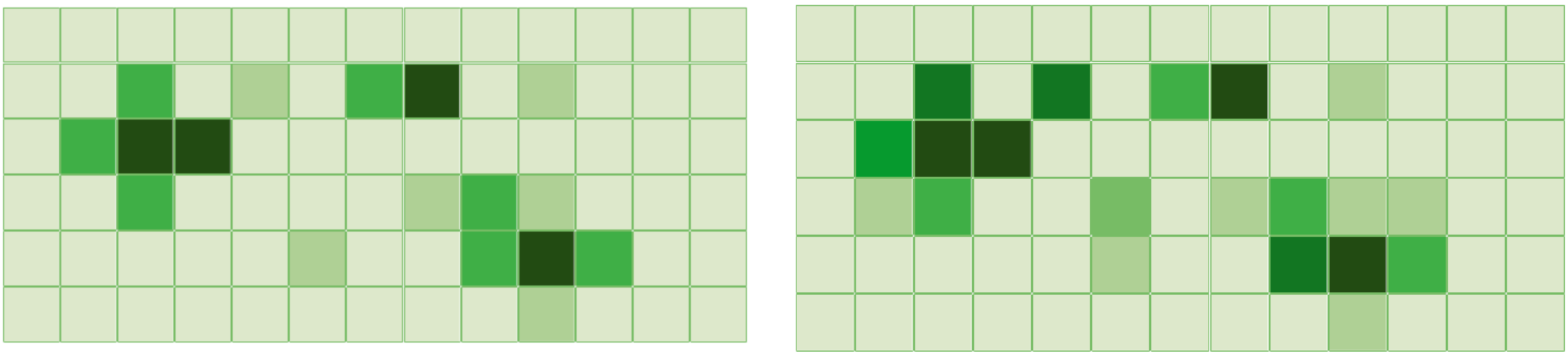




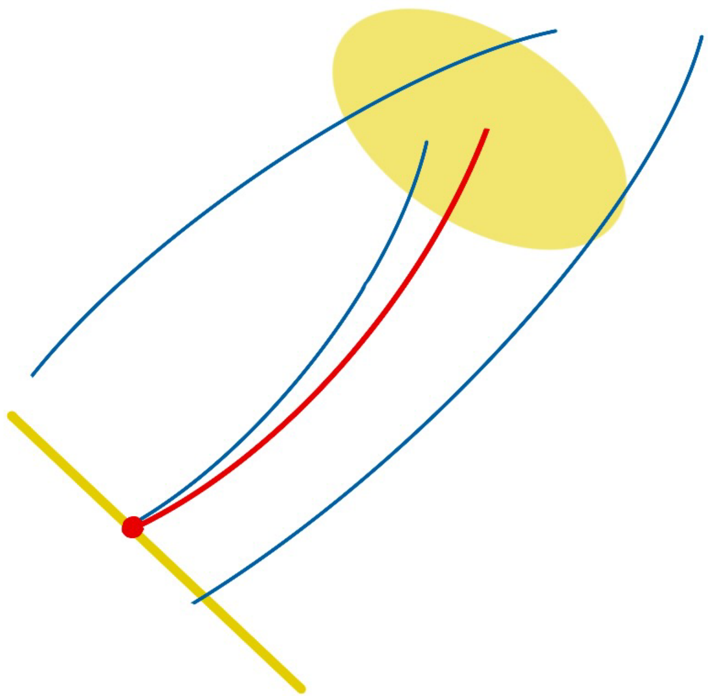
Additional pileup interactions also deposit energy in the calorimeters.

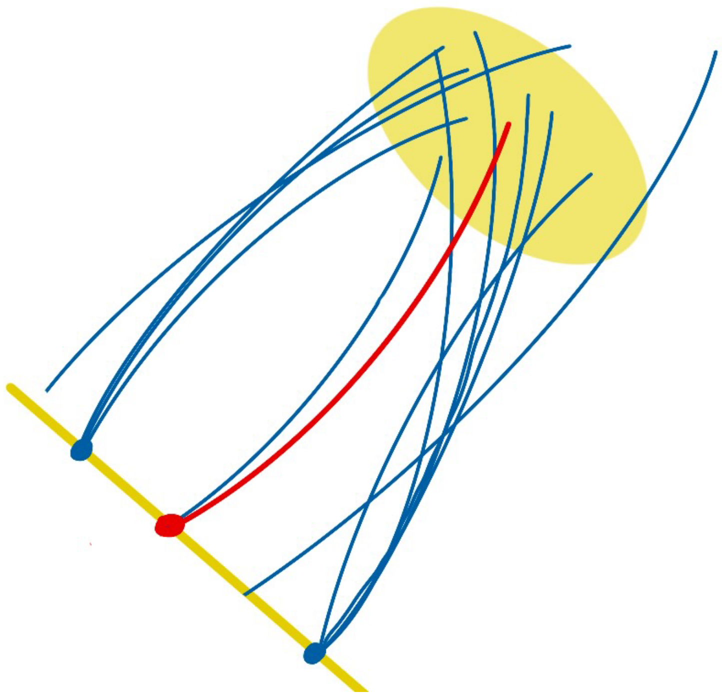
Impact of pileup





Impact of pileup



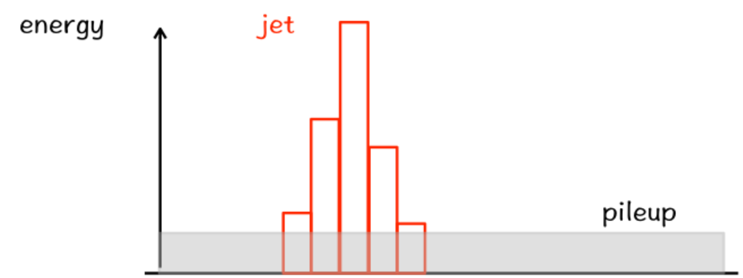


Additional pileup interactions also impact lepton isolation.

Accounting for pileup

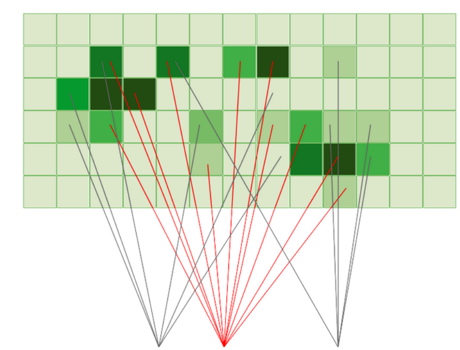
There are several different ways in which the effect of pileup is corrected for.

Corrections based on overall energy deposits



Jet grooming *(later...)* aims to locally correct effect

Use estimates of charged hadrons and vertices to subtract



PileUp Per Particle Identification (**PUPPI**):

Use all of these to give a weight to how likely a particle is from primary vertex (or from pileup) – then use this weight downstream.

Acquiring the data

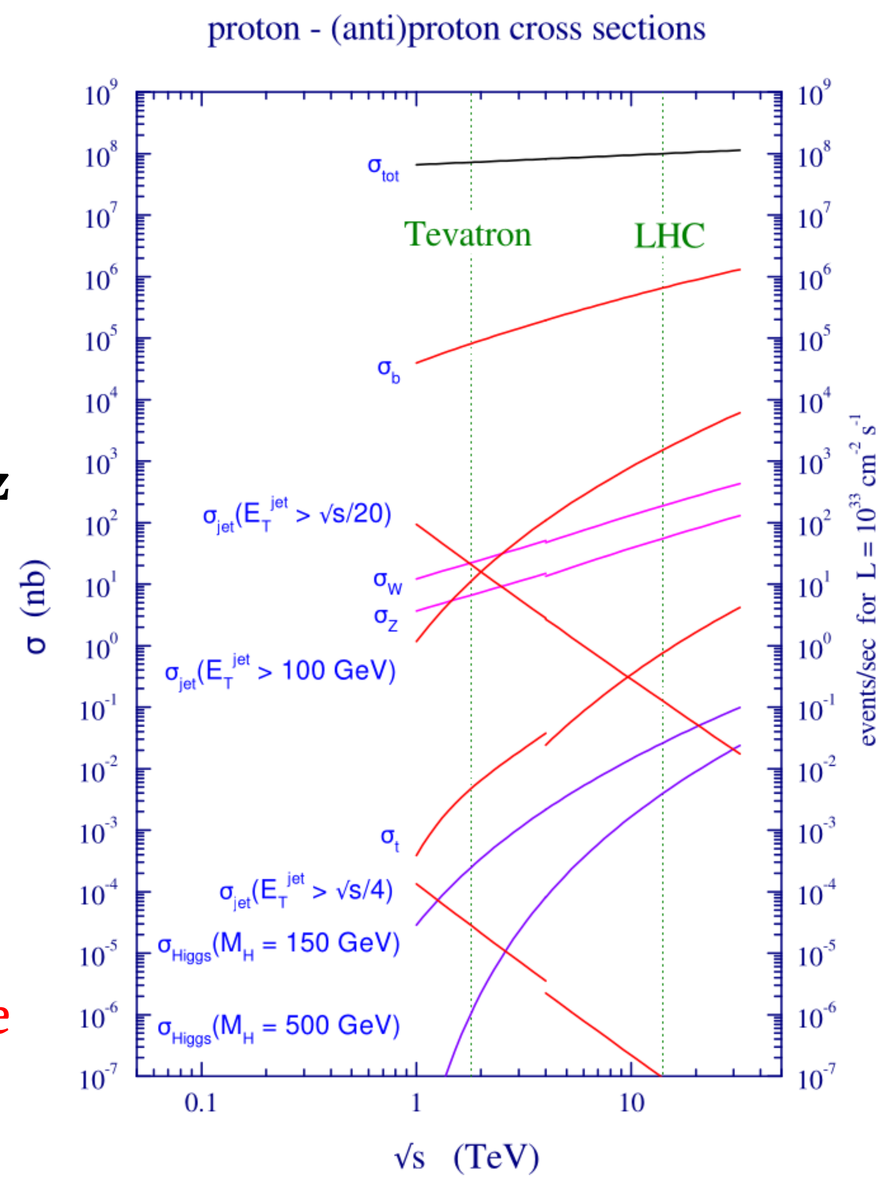
Triggers

$$N = \mathcal{L}\,\sigma$$

Collisions (i.e. bunch crossings) happen at **40 MHz**
This rate (given the event size [~1 MB]) is too large for us to write everything to storage (~ 40 TB/s)

Technology limits us to writing output at about **1 kHz**

How to pick which 1000 events/s to keep out of the 40 million collisions/s ?



Rept.Prog.Phys.70:89,2007
arXiv:hep-ph/0611148

Trigger

Our goal is to capture all events of ‘interest’

We can only analyse events that the trigger keeps, we wish to be as inclusive as possible.

A trigger works online, i.e. it has to decide as the data is coming in.

It is a fast filter that decides rapidly whether to keep the data from an event or not.

Trigger

Our goal is to capture all events of 'interest'

We select **'interesting'** events:
<u>Anything that passes some predecided conditions</u>
(a) Single muon with pT>40 GeV
(b) Two electrons with pT> 25, 15 GeV
(c) MET > 400 GeV
Etc.

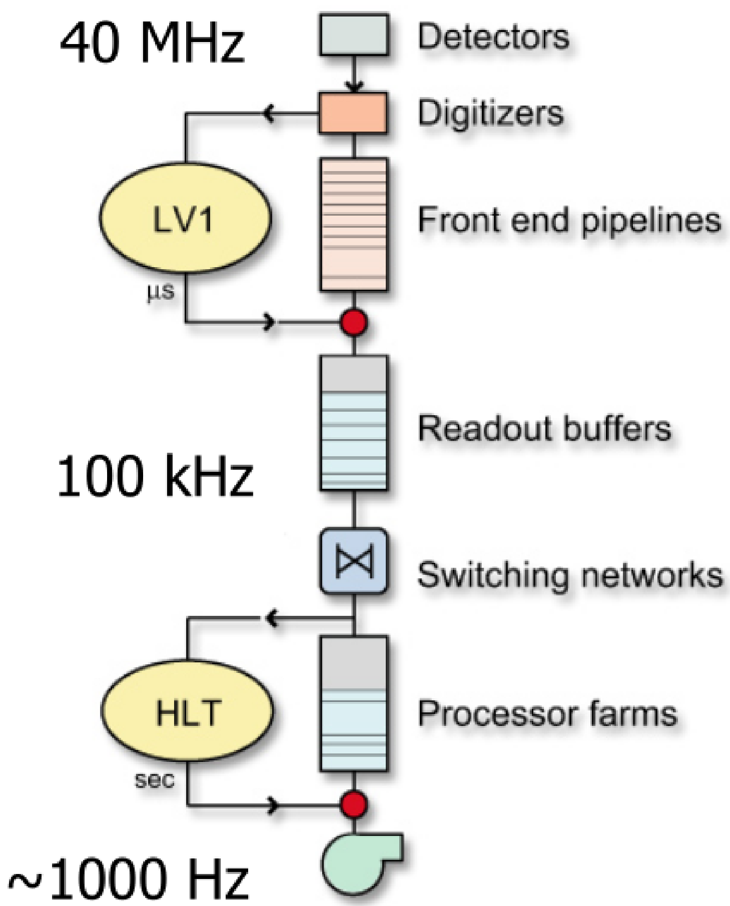
Each of these is a path, and the final decision to keep event is a logical OR of each condition.
All together called as a trigger table.

Trigger deadtime : Trigger is not live for some reason so we cannot collect data

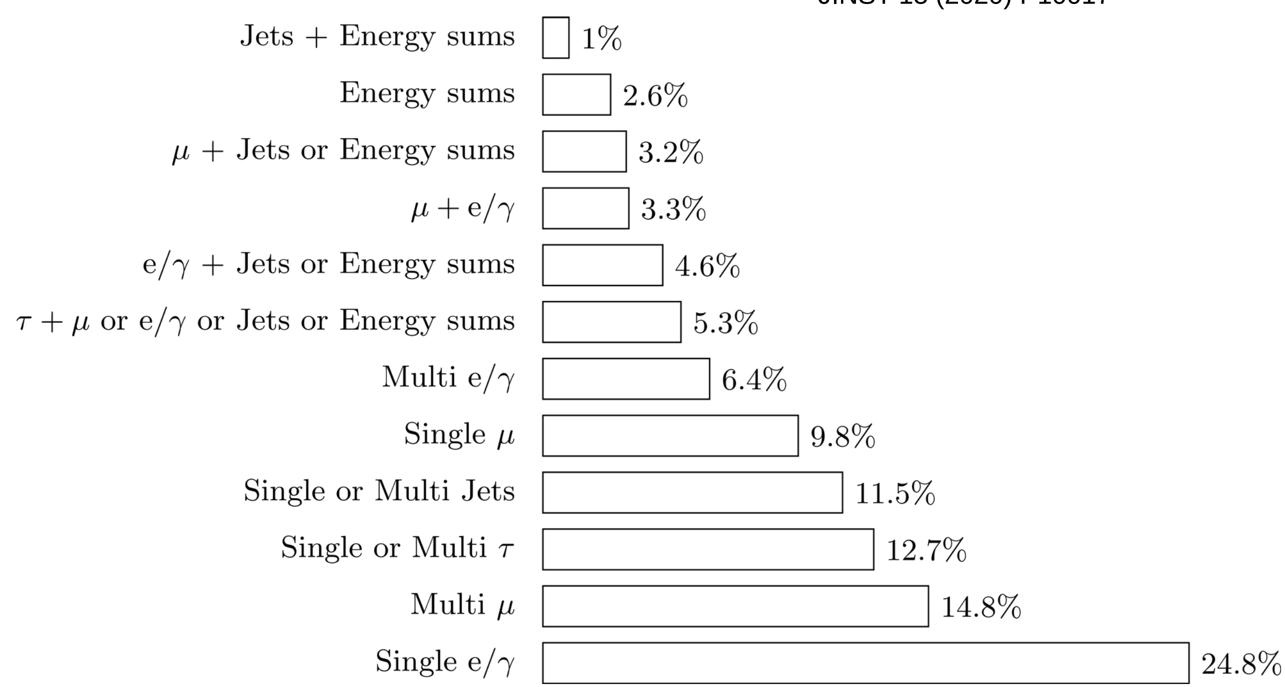
Trigger prescale : Keep every n^{th} event that fires the trigger, adjusting n to allowed bandwidth

CMS trigger design

P. Bortignon



JINST 15 (2020) P10017



Fractions of the 100 kHz rate allocation for single- and multi-object triggers and cross triggers in a typical CMS physics menu during Run 2.

LV1 is hardware based

HLT is software based