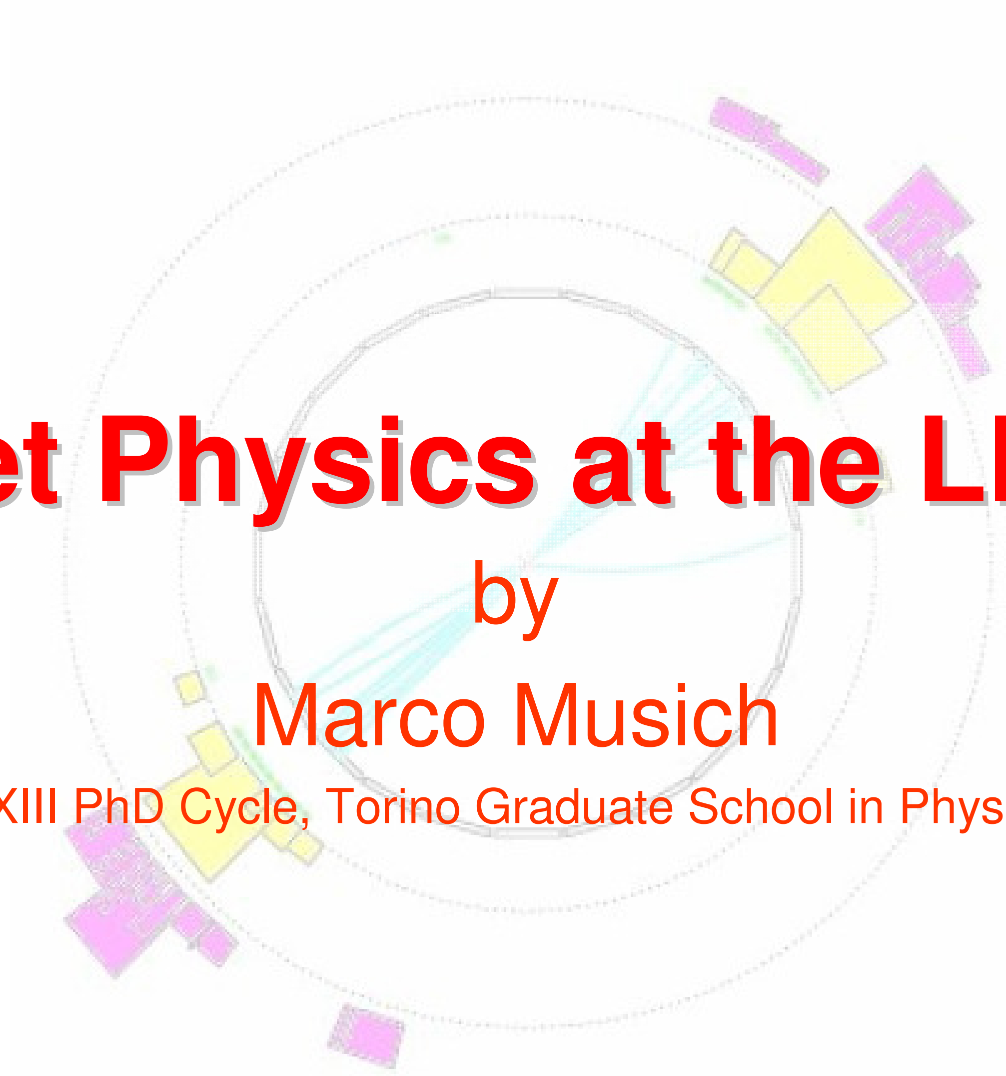


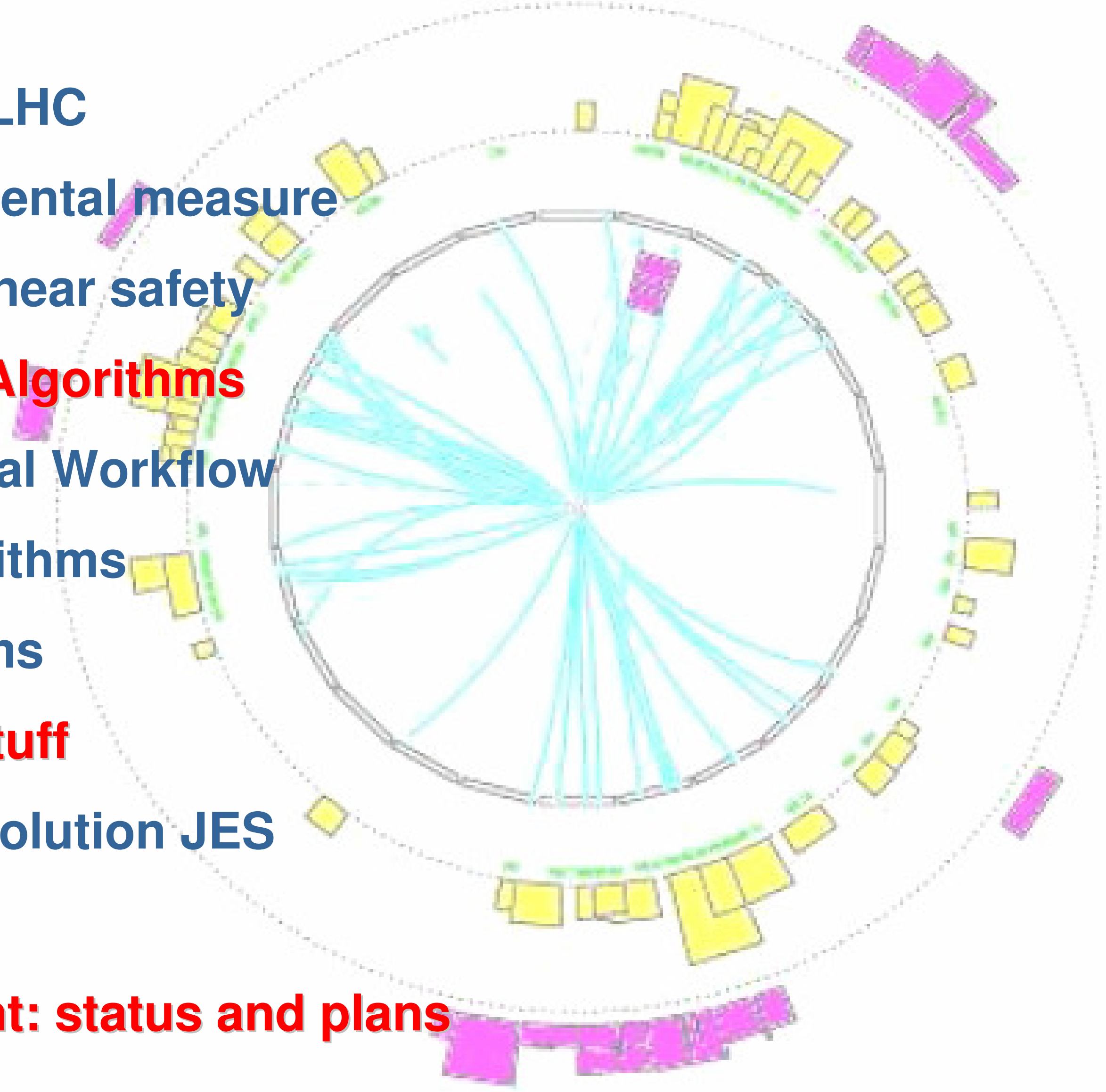
Jet Physics at the LHC

by

Marco Musich

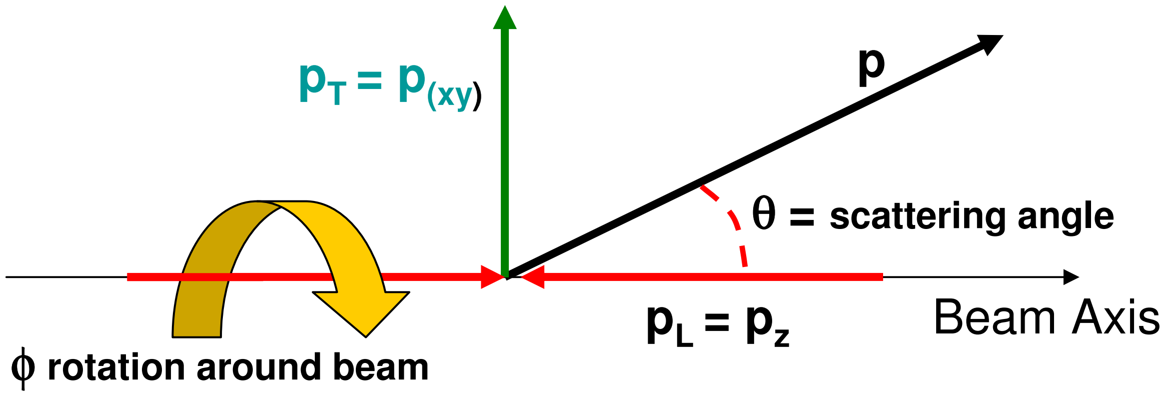
(XXIII PhD Cycle, Torino Graduate School in Physics)

Outline



- **Jet Definition**
  - Jets at the LHC
  - Jet experimental measure
  - IR and collinear safety
- **Jet Clustering Algorithms**
  - Experimental Workflow
  - Cone Algorithms
  - k_T Algorithms
- **Experimental stuff**
  - Energy Resolution JES
  - Triggers
- **α_S measurement: status and plans**

Hadron collider glossary



Coordinates chosen to describe geometry:

Pseudorapidity: η(θ)

Azimuth: ϕ

Rapidity y is invariant under Lorentz Boost:

$$y = \frac{1}{2}\ln\left(\frac{E+p_L}{E-p_L}\right) \quad \text{At high energy} \rightarrow \quad y \approx \frac{1}{2}\ln\left(\frac{|\vec{p}|+p_L}{|\vec{p}|-p_L}\right) = -\ln\left(\tan\frac{\theta}{2}\right)\boxed{=\eta}$$

Since: $p_{beam} = (E_{beam}, 0, 0, \pm E_{beam}) \rightarrow p^T_{beam} = 0$

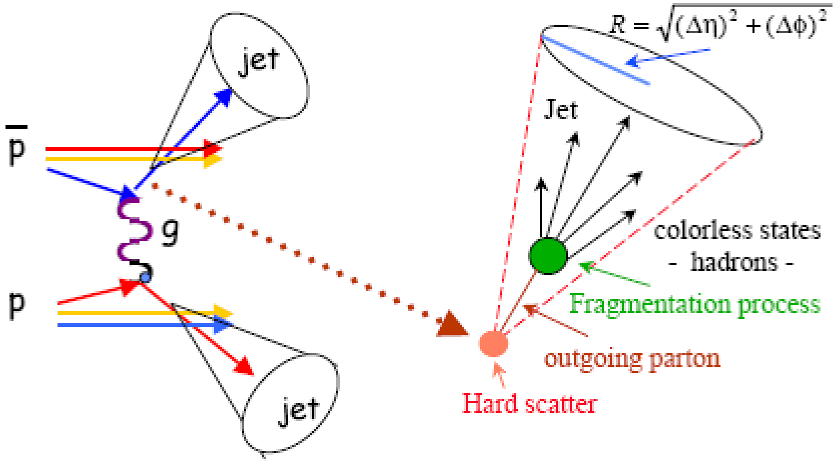
$$\boxed{\sum p_T = \sum E_T = 0}$$

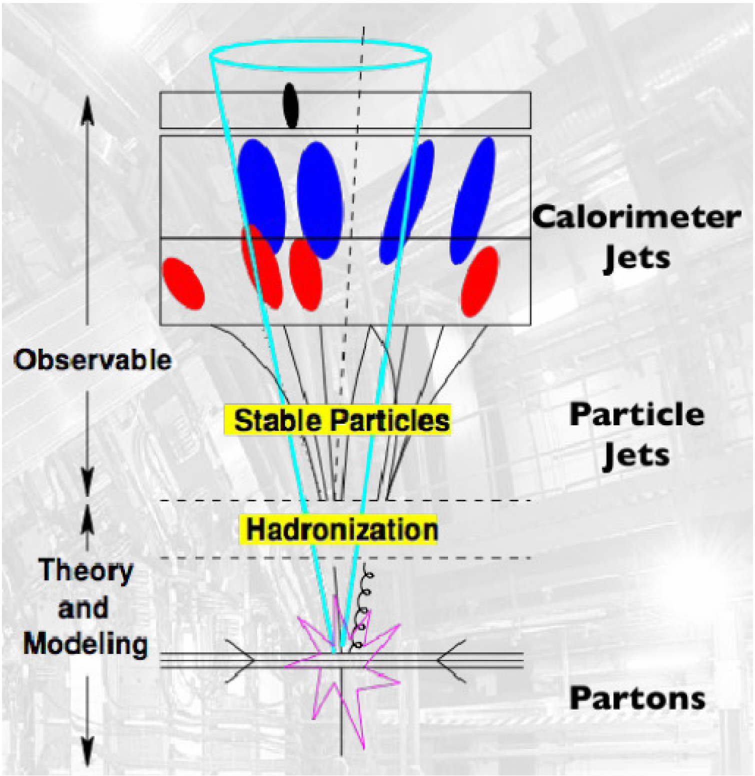
Transverse kinematical quantities are the best measured, since they are constrained and generally high p_T yields interesting physics

What is a Jet?

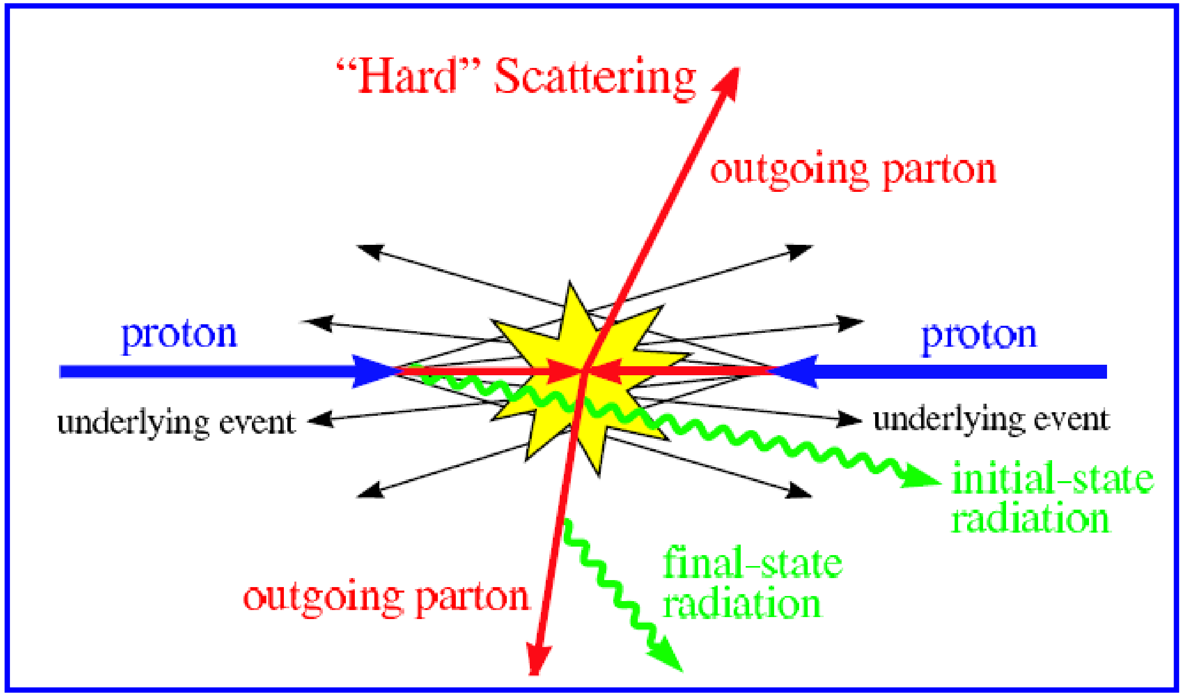
What is a Jet?

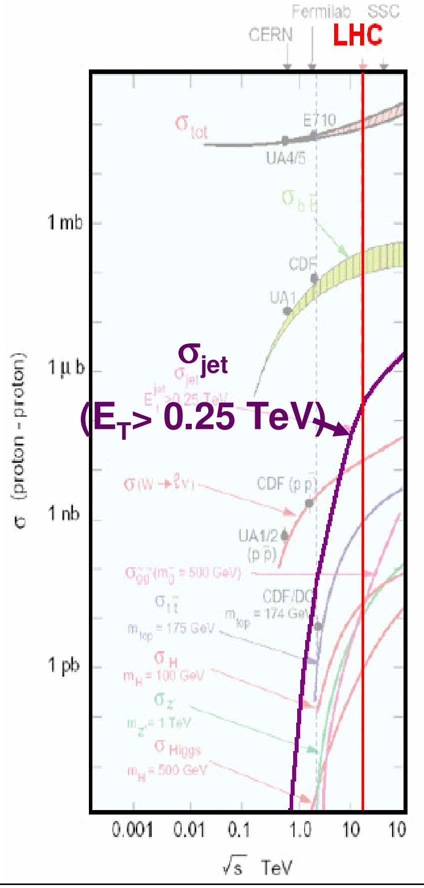
- A jet is a **collimated spray of hadrons** produced by the soft quark/gluon radiation and hadronization in a hard scattering process
- By studying their properties we can determine the properties of the original partons (***quarks and gluons***)
- Almost **every process of interest** at LHC contains jets in the final state





Jets at LHC





Environment of an hadron-hadron collider as the LHC is such that in every final state jets will be involved

Jets can come from:

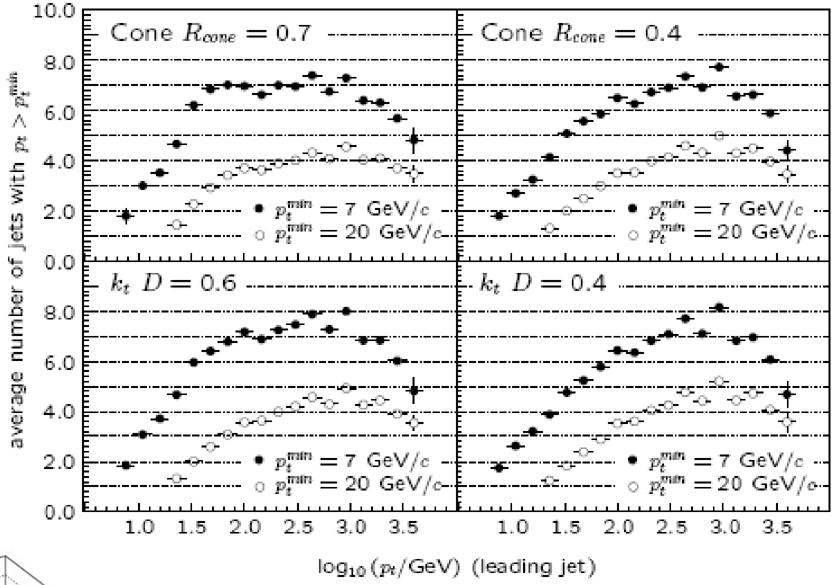
- **Hard Scattering (high p_T jets)**
- **ISR and FSR (softer p_T spectrum, from splitting)**
- **Underlying Event (UE) (even softer spectrum)**

p_T^{min} (TeV/c)	σ (nb)	Events/year
0.2	100	$\approx 10^9$
1.0	0.1	$\approx 10^6$
2.0	1.0×10^{-4}	$\approx 10^3$
3.0	1.3×10^{-6}	≈ 10

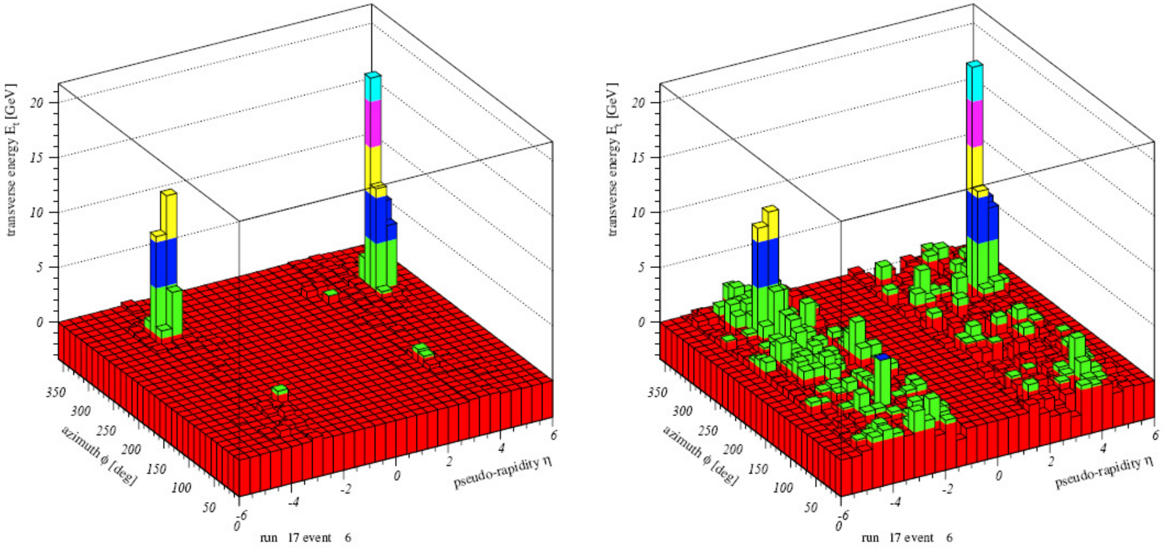
Jets at LHC (Pile-up)

The huge hadronic background of LHC, has the additional problem of **Pile-Up.**

At design luminosity ($\mathcal{L}=10^{34}$ cm^{-2}s^{-1}) the LHC will deliver an average rate of $\langle N \rangle$ = **20 piled-up** hard scattering interactions per bunch crossing.



Need to separate hard scattering jets from huge soft spectra from **UE, MB** (minimum bias) and **pile-up**

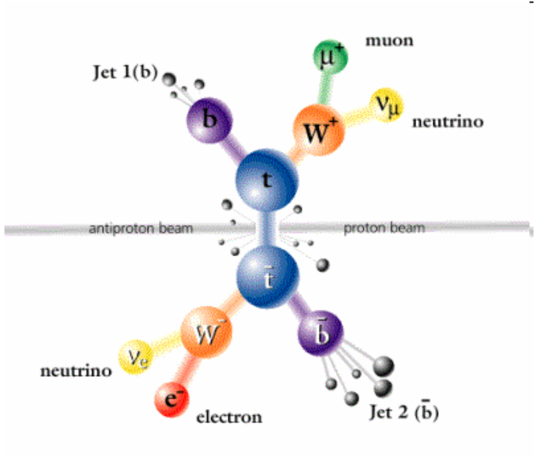


A di-jet event, with and without **pile-up**

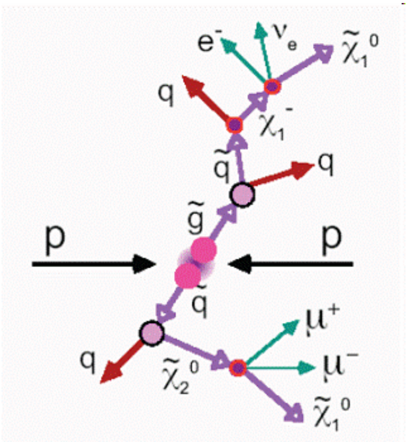
Interesting Jet events

Will be jet physics interesting at the LHC?

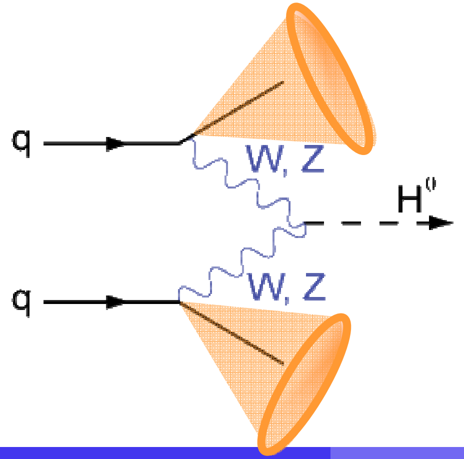
- The QCD cross section pp→j +X ensures that jets will dominate LHC pysics
  - Top quark precision measurement



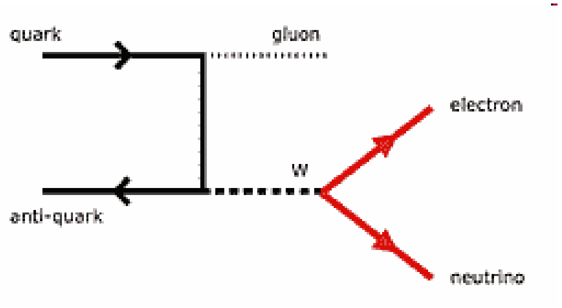
Supersimmetry



  - SM Higgs from VBF (2 forward jets)



Electroweak physics (W,Z +jets)



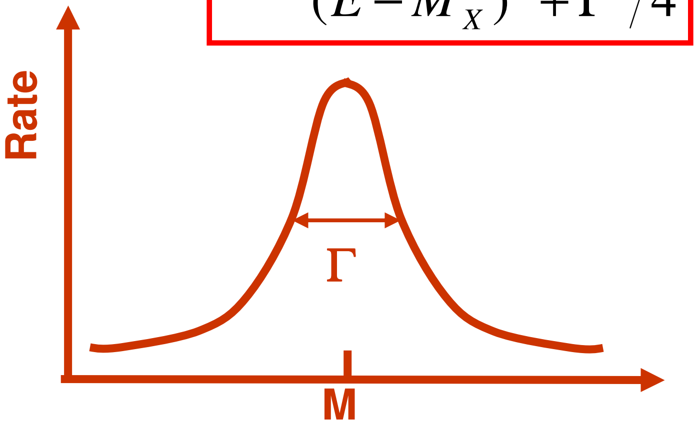
Heavy resonances in di-jets

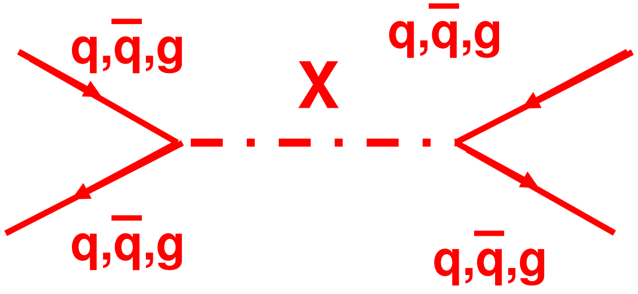
Di-jet production is a process of high interest al LHC:

- **Quark compositeness** by studying angular distribution
- **BSM particles** decaying as a di-jet resonance
- **QCD** at the highest energy

$$\sigma \approx \frac{\Gamma_{X\to f}}{(E-M_X)^2+\Gamma^2/4}$$

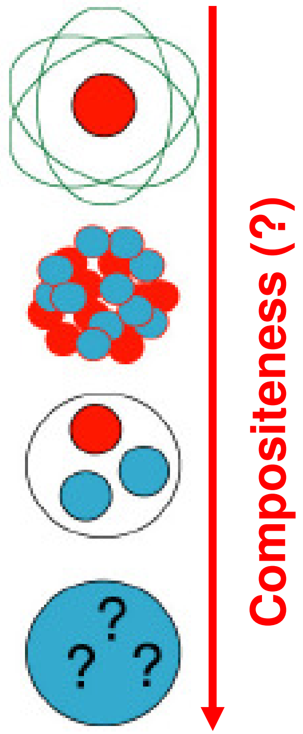
Model Name	X	Color	J^P	Γ / (2M)	Chan
E_6 Diquark	D	Triplet	0^+	0.004	ud
Excited Quark	q*	Triplet	$\frac{1}{2}^+$	0.02	qg
Axigluon	A	Octet	1^+	0.05	$q\bar{q}$
Coloron	C	Octet	1^-	0.05	$q\bar{q}$
Octet Technirho	ρ_{T8}	Octet	1^-	0.01	$q\bar{q}$,gg
R S Graviton	G	Singlet	2^-	0.01	$q\bar{q}$,gg
Heavy W	W '	Singlet	1^-	0.01	$q_1\bar{q}_2$
Heavy Z	Z '	Singlet	1^-	0.01	$q\bar{q}$





Parton - Parton Resonances
Observed as dijet resonances.

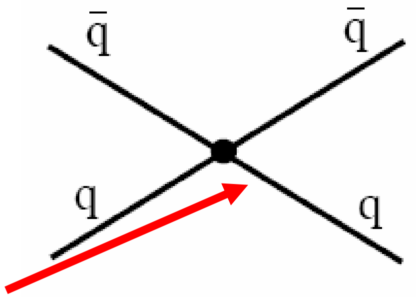
QCD at High Energy



Compositeness scale Λ_C:

- $\Lambda_C = \infty \rightarrow$ point like quarks
- $\Lambda_C =$ finite $\rightarrow$ substructure at mass scale Λ_C

For $\sqrt{s} << \Lambda_C$ composite interaction goes like a contact term



$$\mathcal{L} = \pm \frac{g^2}{2\Lambda_C^2} (\bar{q}_L \gamma^\mu q_L) \cdot (\bar{q}_L \gamma_\mu q_L)$$

hence:

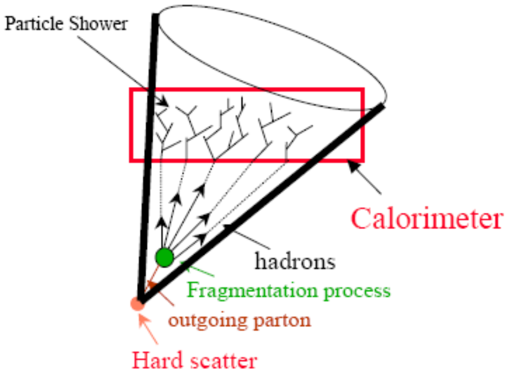
dσ ~ [QCD + interferece + compositeness]

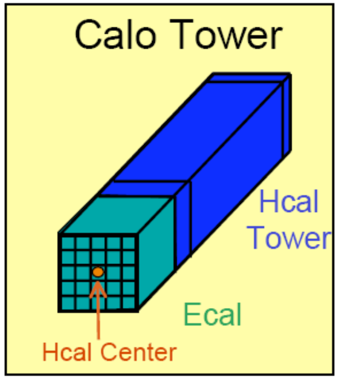
$$d\sigma \sim 1/(1-\cos\theta^*)^2 \qquad d\sigma \sim 1/(1+\cos\theta^*)^2$$

define $\chi = e^{2|\eta|} = \dfrac{1+\cos\theta^*}{1-\cos\theta^*}$ ⇒ And check: $\boxed{dN/d\chi}$

How a jet is measured?

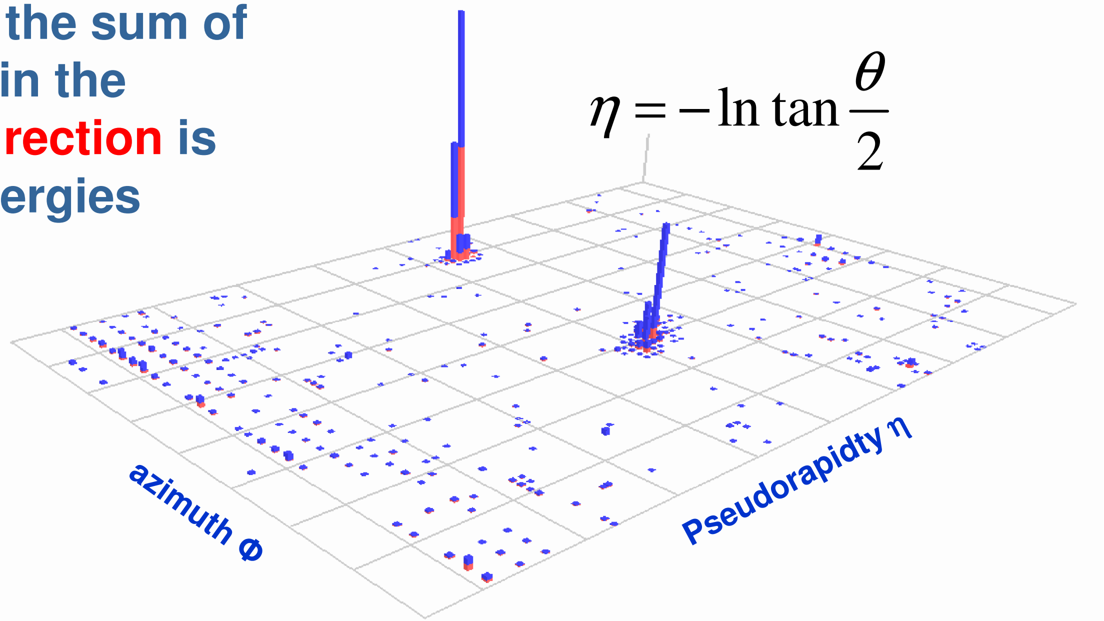
How do we measure a Jet?





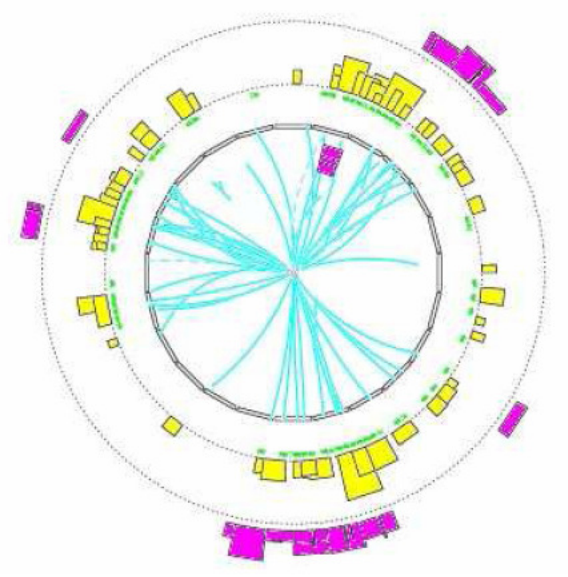
- A jet is measured using tracking devices and calorimeters.
- Calorimeters are generally segmented in subdivisions called **towers**, which map the 4π steradians of calorimeter acceptance into "bins" of azimuth ϕ and pseudorapidity η
  - **Energy** of a Jet is given by the sum of the energies (ΣE_T) measured in the interested towes, while the **direction** is the (η,ϕ) of the centroid of Energies

$$\eta = \frac{\sum \eta_i E_{T,i}}{\sum E_{T,i}} \qquad \phi = \frac{\sum \phi_i E_{T,i}}{\sum E_{T,i}}$$



$$\eta = -\ln \tan \frac{\theta}{2}$$

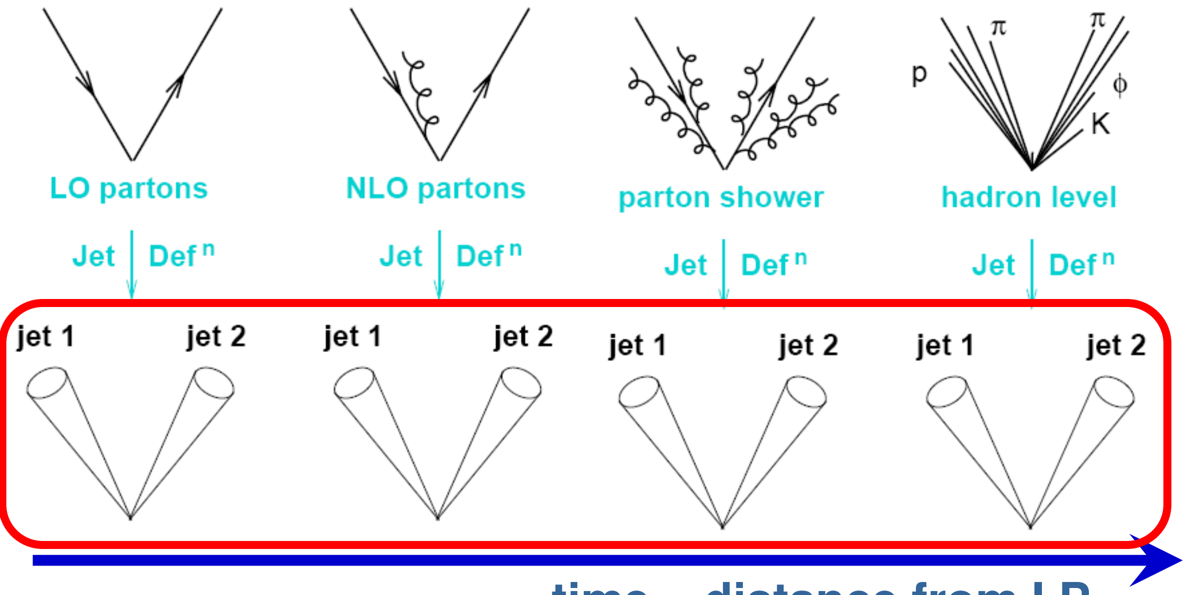
Jet Clustering



How do we define a Jet?

- A jet is a spray of hadrons (~O(10)),and in the most interesting events at LHC there will be many jets/event.

- Underlying physics lies on *quarks and gluons,* how to project reliably O(100) hadrons onto a handful of *partons*?



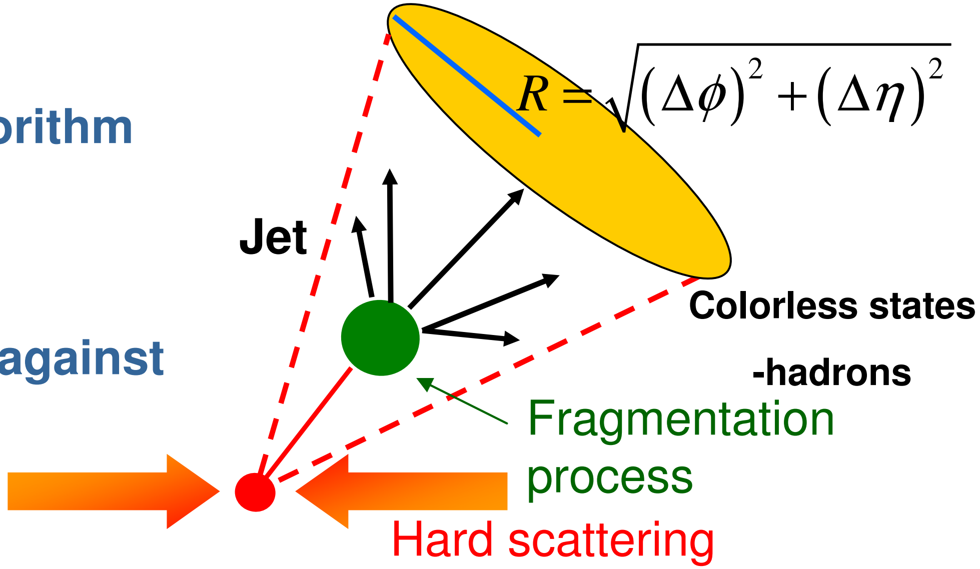
time – distance from I.P.

- Jet definitions should be resilient of QCD effects (e.g.: soft gluon radiation, parton shower, hadronization)

Infrared and collinear safety

How do we define a Jet?

- A jet is a whatever a clustering algorithm finds as a jet in a event
- Desired properties:
  - ***Infrared Safety*** – Same energy against addition of **soft particles** or low energetic tower
  - ***Collinear Safety*** – Same output against distribution of energy in adjacent towers



Unfortunately:

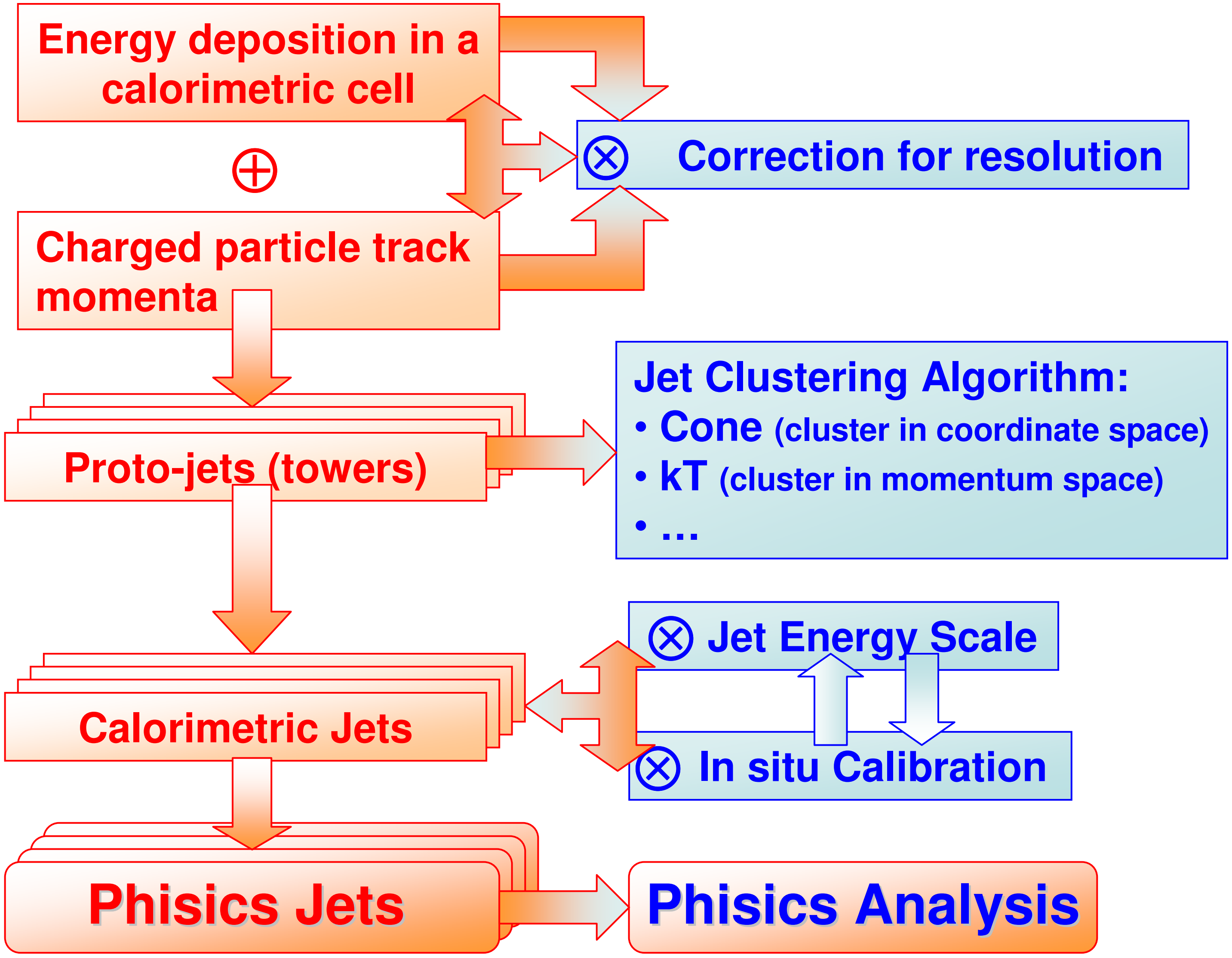
Majority of QCD branching are indeed soft and collinear!

$$M^2{}_{g\to g_i g_j}(k_j)[dk_j]\cong\frac{2\alpha_s C_A}{\pi}\frac{dE_j}{\min(E_i,E_j)}\frac{d\theta_{ij}}{\theta_{ij}}\Rightarrow$$

Logarithmically divergent for:

$$E_j << E_i \qquad \theta_{ij}<<1$$

Experimental workflow



Energy deposition in a calorimetric cell

⊕

Charged particle track momenta

⊗ **Correction for resolution**

Proto-jets (towers)

Jet Clustering Algorithm:
- **Cone** (cluster in coordinate space)
- **kT** (cluster in momentum space)
- …

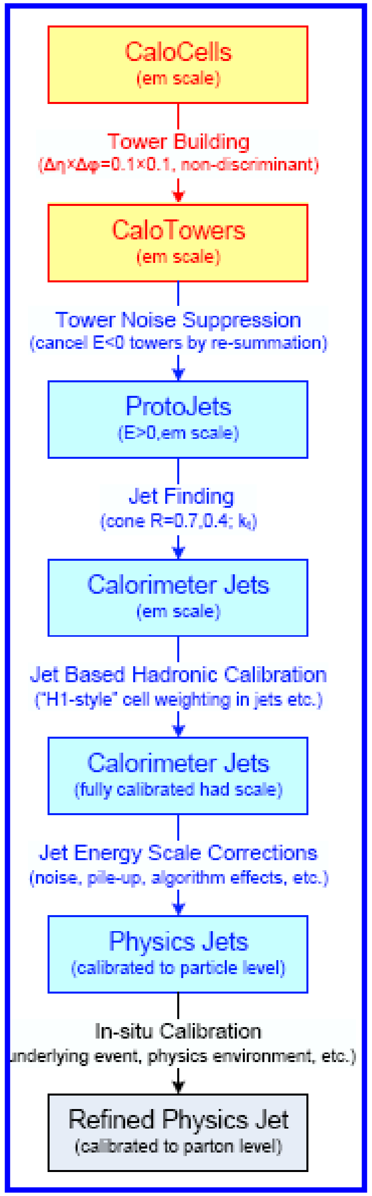
Calorimetric Jets

⊗ **Jet Energy Scale**

⊗ **In situ Calibration**

Phisics Jets

Phisics Analysis



CaloCells
(em scale)

Tower Building
($\Delta\eta\times\Delta\varphi=0.1\times0.1$, non-discriminant)

CaloTowers
(em scale)

Tower Noise Suppression
(cancel E<0 towers by re-summation)

ProtoJets
(E>0,em scale)

Jet Finding
(cone R=0.7,0.4; k_t)

Calorimeter Jets
(em scale)

Jet Based Hadronic Calibration
("H1-style" cell weighting in jets etc.)

Calorimeter Jets
(fully calibrated had scale)

Jet Energy Scale Corrections
(noise, pile-up, algorithm effects, etc.)

Physics Jets
(calibrated to particle level)

In-situ Calibration
nderlying event, physics environment, etc.)

Refined Physics Jet
(calibrated to parton level)

Iterative Cone

Some useful variables

- **Cone center:** (η^C,ϕ^C) → jet direction
- **Particle in the cone:** $i \subset C$ iff

$$\Delta R_{iC} = \sqrt{(\eta^i - \eta^C)^2 + (\phi^i - \phi^C)^2} < R$$

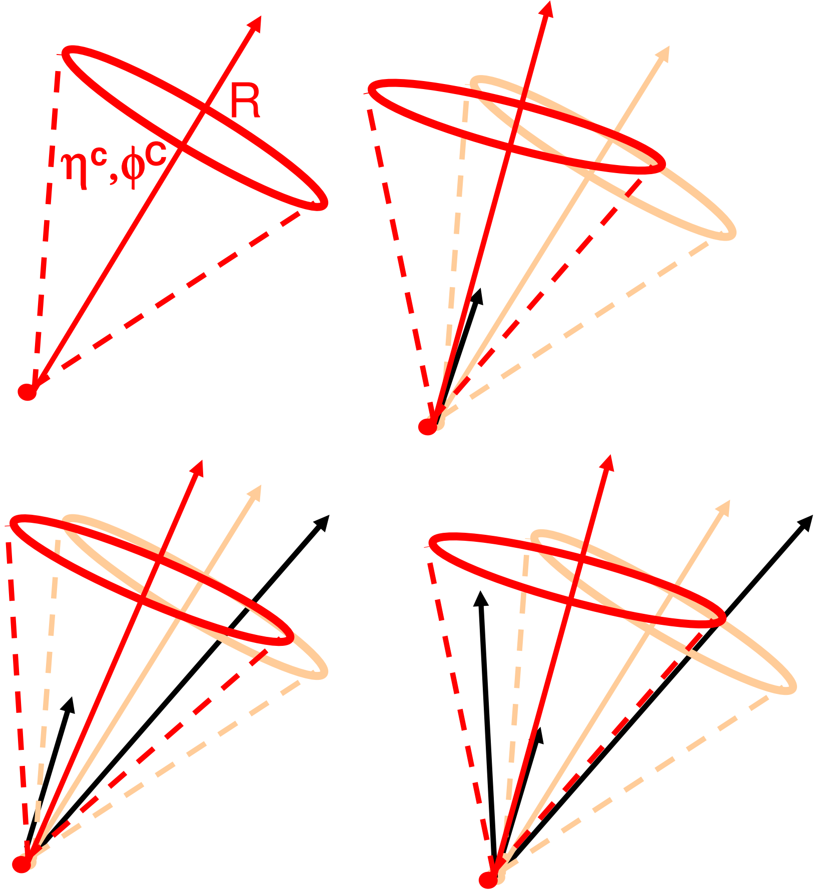
- **Transverse Energy:**

$$E_T^{\,C} = \sum_{i \subset C} E_T^i \qquad \left[E_T^i \cong p_T^i \right]$$

- **Centroid:**

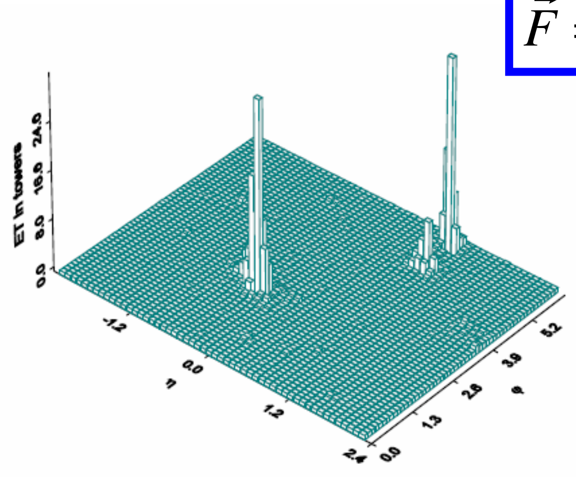
$$\overline{\eta}^C = \sum_{i \subset C} E_T^i * \eta^i / E_T^{\,C} \quad ; \quad \overline{\phi}^C = \sum_{i \subset C} E_T^i * \phi^i / E_T$$

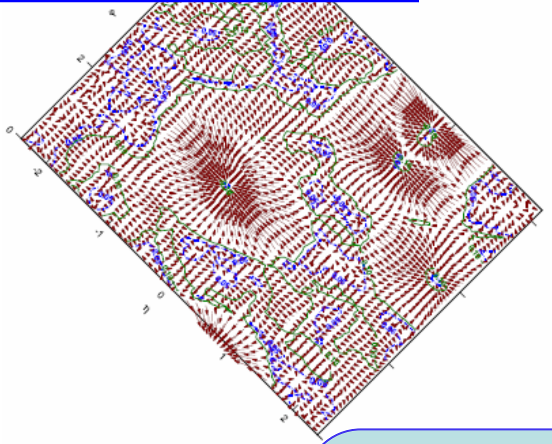
- **Iterate on** $i \subset C$ **until Flow vector** $\vec{F} = (\eta^C - \overline{\eta}^C, \phi^C - \overline{\phi}^C)$ **vanishes.**



Iterative cone

$$\vec{F} = (\eta^C - \overline{\eta}^C, \phi^C - \overline{\phi}^C)$$





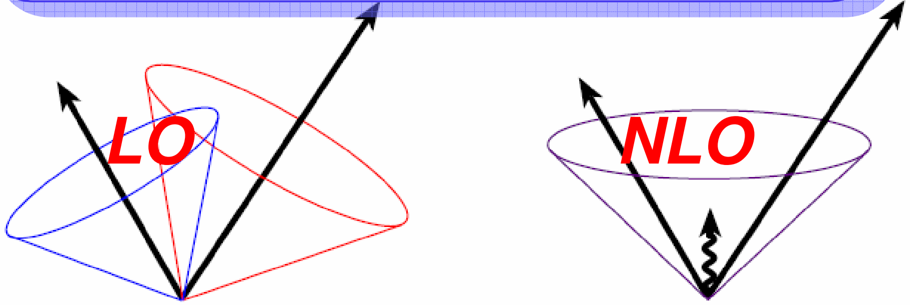
Example of a **Flow vector** map obtained using the iterative cone algorithm

Cone Algorithm Pros ☺

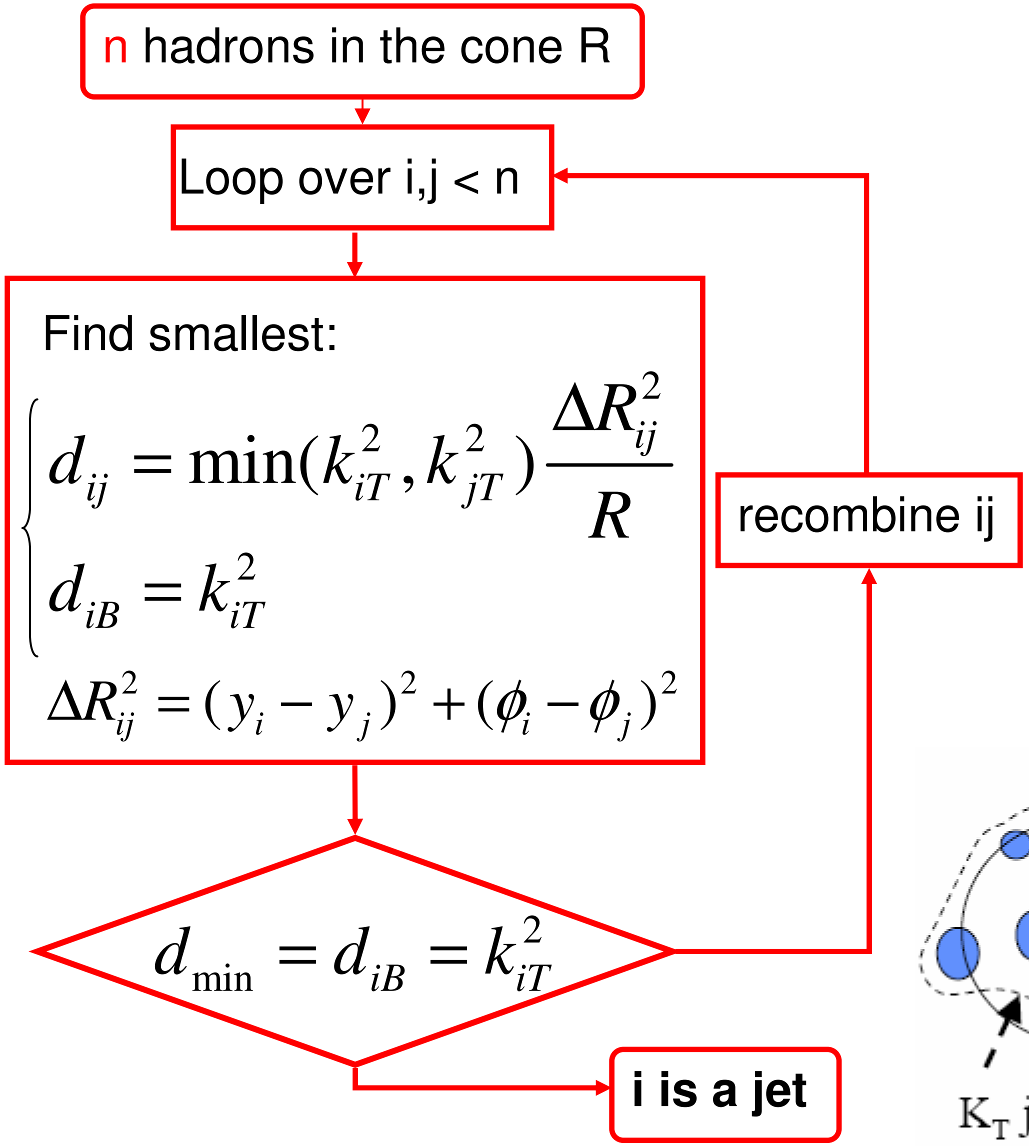
- Unique discrete jets, with a single parameter (R)
- Easy to implement
- Easy to correct pile-up

Cone Algorithm Contras ☹

- Overlaps → need **split/merge**
- need seeds (**Infrared sensitive, Unsafe (?) At NLO**)



k_T algorithm



n hadrons in the cone R

Loop over i,j < n

Find smallest:

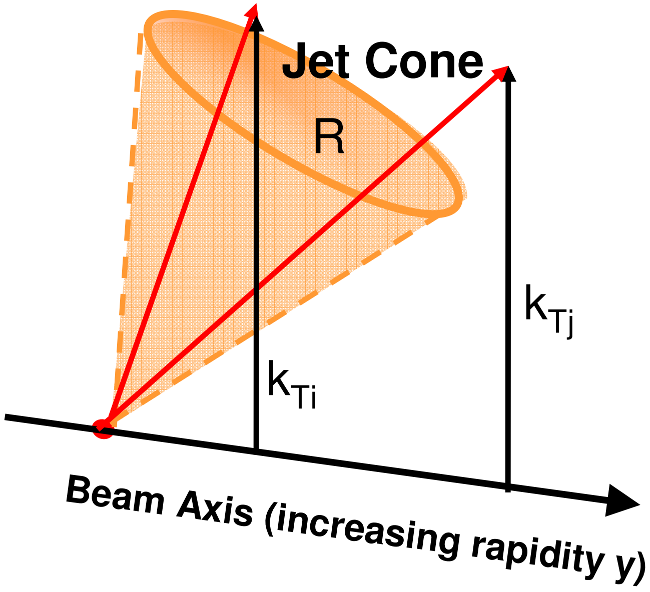
$$\begin{cases} d_{ij} = \min(k_{iT}^2, k_{jT}^2)\dfrac{\Delta R_{ij}^2}{R} \\ d_{iB} = k_{iT}^2 \end{cases}$$

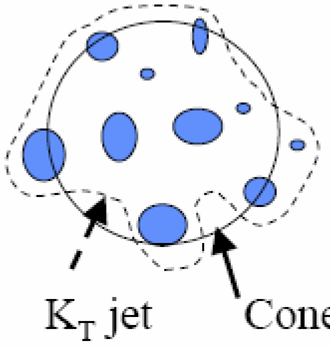
$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

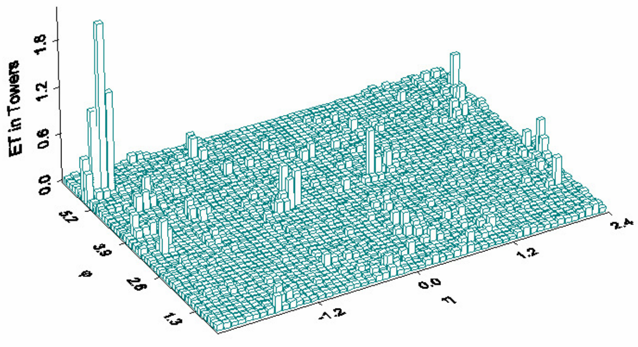
$$d_{\min} = d_{iB} = k_{iT}^2$$

recombine ij

i is a jet







Jet Algorihms

Cone algorithms:

- Seed towers
  - Only iterate over towers above certain threshold

JETCLU: Snowmass (E_T) - scheme

$$E_T^{jet} = \sum_k E_T^K,$$

$$\eta^{\mathrm{jet}} = \frac{\sum_k E_T^k \cdot \eta_k}{E_T^{jet}}, \ \phi^{\mathrm{jet}} = \frac{\sum_k E_T^k \cdot \phi_k}{E_T^{jet}}$$

MIDPOINT: E - scheme

$$E^{jet} = \sum_k E^K, \ P_i^{jet} = \sum_k P_i^K$$

$$(\mathrm{massive\ \ jets: P_T^{jet}}, Y^{jet})$$

  - MidPoint adds extra seed in centre of each pair of seeds → Infrared and collinear safe
- Ratcheting (JetClu only)
  - All towers initially inside a cone must stay in a cone
- Jet merging/splitting is an issue:
  - Need to define a F_{merge} parameter

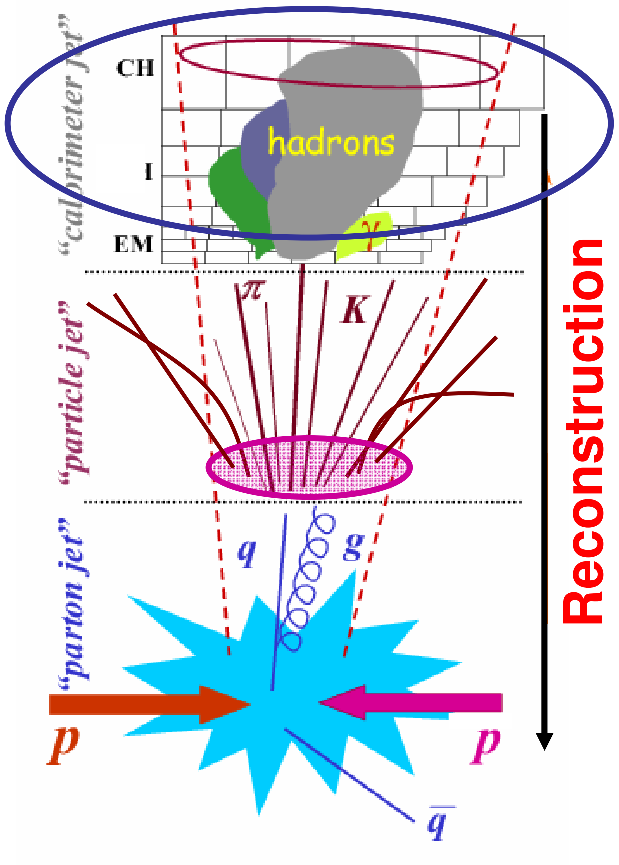
K_T algorithm:

- Preferred by theory
  - Partons are separated into jets according to their transverse momentum
- Compute for each pair (i,j) and for each particle (i) the quantities

$$d_{ij} = \min(P^2{}_{T,i}, P^2{}_{T,j}) \frac{\Delta R^2}{D^2} \qquad d_i = (P_{T,i})^2$$

  - Iteration until find stable jets
  - Use E-scheme
  - Infrared and collinear safe
- No merging/splitting parameter needed
- successfully used at LEP and HERA → relatively new in hadron colliders
- More sensitive to Underlying event and multiple interactions

Jet Energy Scale



- A calorimeter/particle jet is defined by an algorithm.
- Jet kinematics and corrections depend on the reconstruction algorithm and parameters.

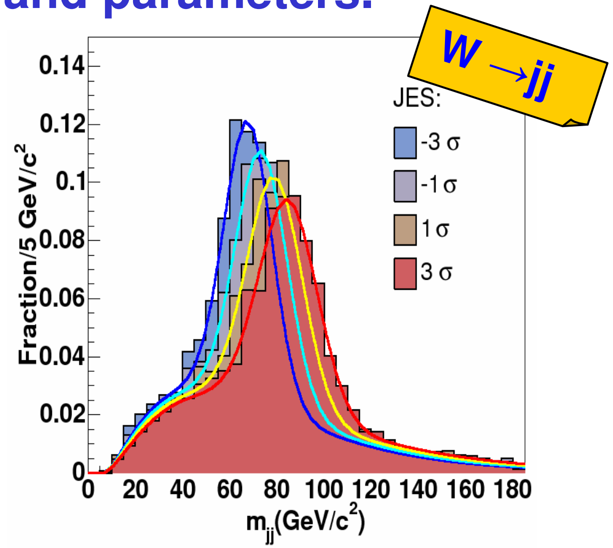
Calorimeter jets

↓

Particle-level jets

↓

Parent Parton



- Measured jet Energy is biased, due to experimental resolution and systematic errors.

$$\boxed{E_{jet} = \alpha E_{jet}^{RAW} - O}$$

E^{raw} = measured energy

O = systematic offset

α = correction factor

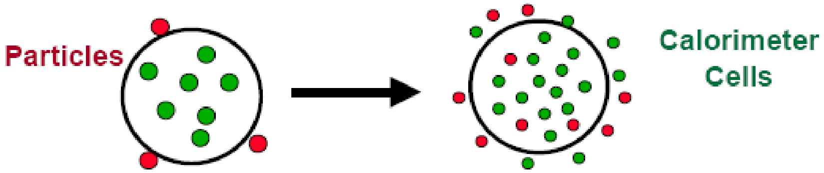
Jet Energy Scale

$$\begin{cases} E_{jet} = \alpha E_{jet}^{RAW} - O \\ E_{jet} = \dfrac{E_{jet}^{RAW} - O}{R(\sum E_i) \otimes F(\eta) \otimes S} \end{cases}$$

Correction Factors:

- **R(E) absolute response function**
- **F(η) relative response correction**
- **S showering correction**

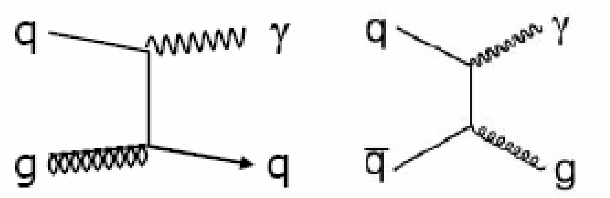
- **Jet energy scale correction is carried out by steps**
  - **O Background subtraction (electronic noise + pile-up)**
    <O> estimate from MC. Offset correction
  - **F(η) Relative response calibration (inter-calibration) in function of pseudorapidity**
  - **R(E) Absolute response calibration (Energy loss, leakage…)**
  - **S Shower Correction (energy lost OOC, efficiency loss)**
  - **OOC: *out of the cone* correction**

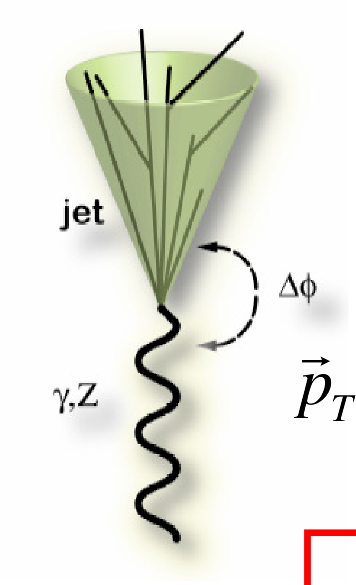


Calibration Techniques

- **Missing E_T Projection Fraction Method**

γ,Z + Jet





Particle Level:

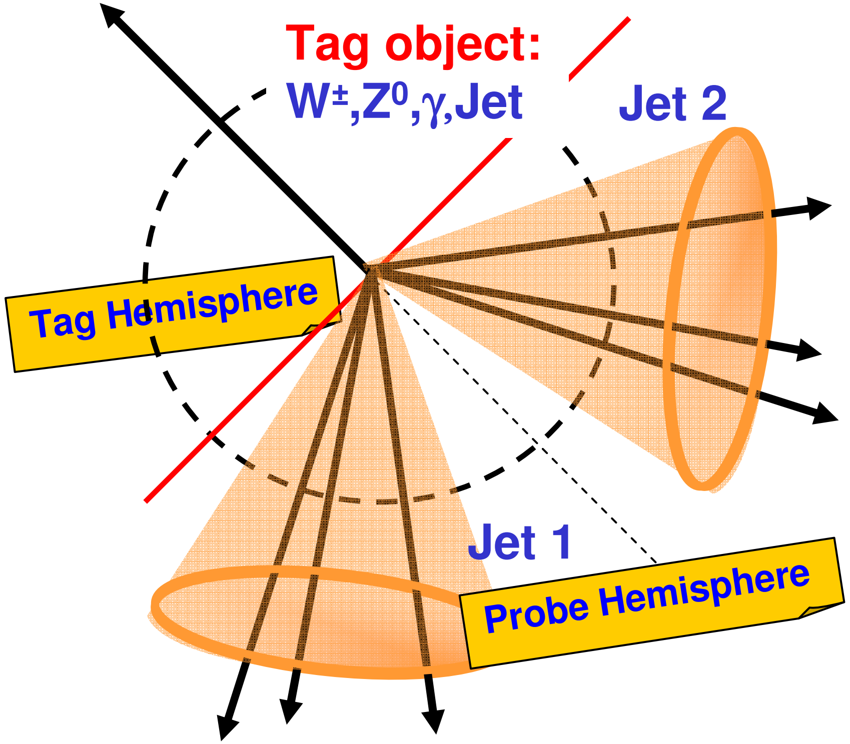
$$\vec{p}_{T,\gamma} + \sum \vec{p}_T^{\,had} = 0$$

Detector Level:

$$\vec{p}_{T,\gamma} + R_{had} \sum \vec{p}_T^{\,had} = -\vec{\not{E}}_T$$

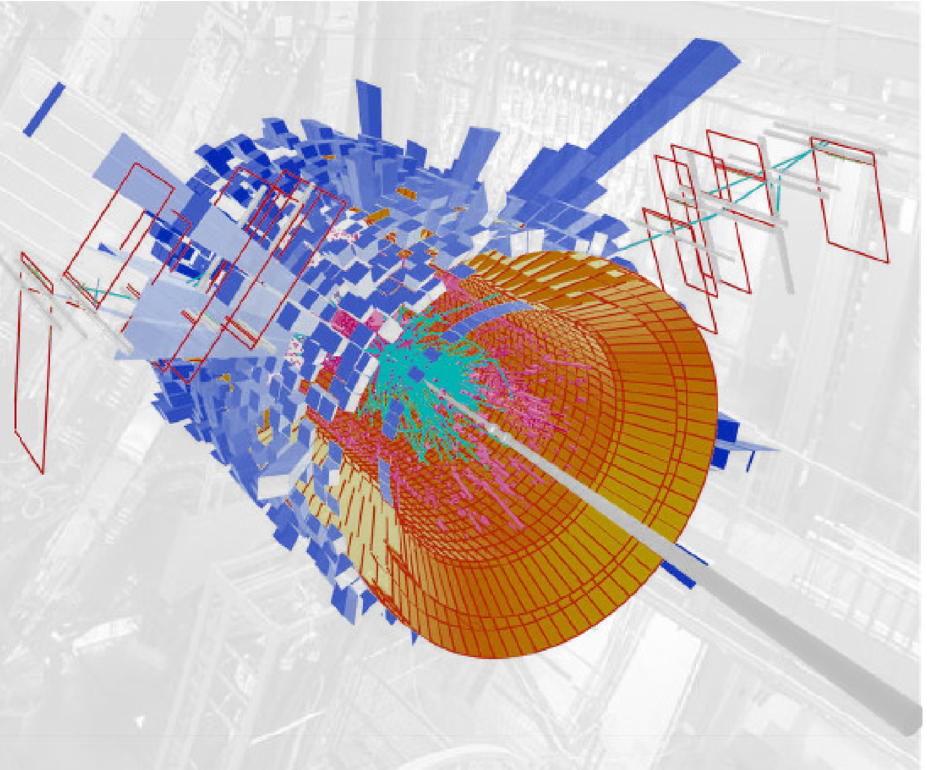
$$\boxed{R_{had} = 1 + \frac{\vec{\not{E}}_T \cdot \vec{p}_{T,\gamma}}{\vec{p}_{T,\gamma}^{\,2}}}$$

- **Hemisphere Method**



$$\boxed{H = \frac{\sum_{probeH} \left|\vec{p}_T \cdot \hat{n}_{tag}\right|}{\sum_{tagH} \left|\vec{p}_T \cdot \hat{n}_{tag}\right|} \approx \frac{k_T^{jet}}{p_{T,\gamma}}}$$

Jet Triggers

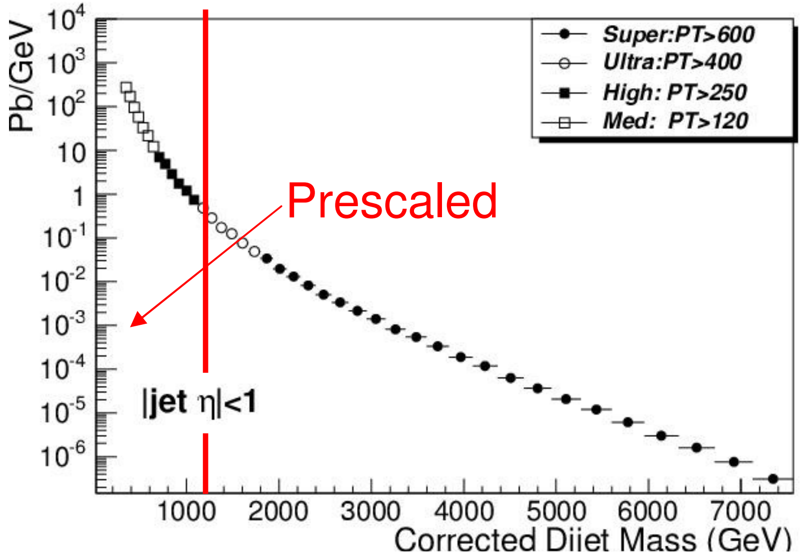


- Collision rate at LHC is expected to be 40 MHz

- 40 million events every second ! Experiments cannot read out and save that many.

Two levels of trigger are used

- Level 1 (L1) is fast custom built hardware Reduces rate to ~ 100 KHz:
- High Level Trigger (HLT) is a PC farm Reduces rate to ~ 150 Hz:

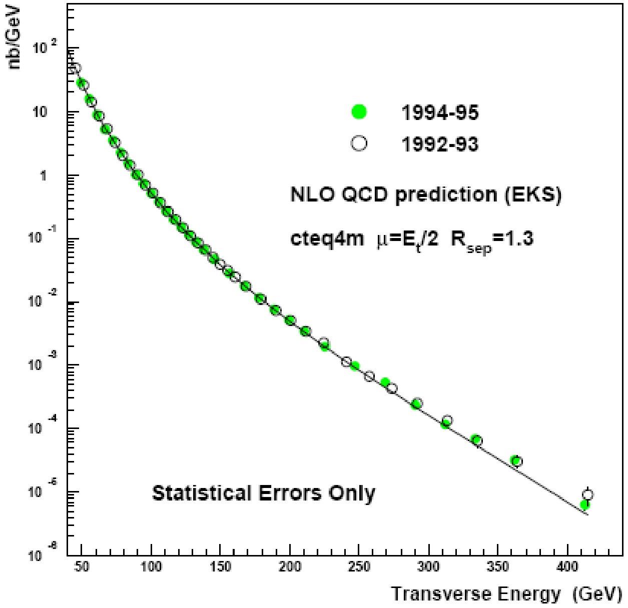


- Jet trigger at L1 uses energy in a square $\Delta\eta \times \Delta\phi$ = 1 cell x 1cell **($E_T^{cell} > E_{T,cut}$)**
- Jet trigger at HLT uses same jet algorithm as analysis and rejects if**:**

$$\sum_{TT\subset\Delta R} E_T^i = E_T^{recojet} > E_{T,cut}$$

Strong coupling measure

Extraction of the strong coupling constant α_S from inclusive jet production cross section



$$\frac{d\sigma}{dE_T}\left(pp\rightarrow j+X\right)=\alpha_S^2(\mu_R)X(\mu_F,E_T)\left[1+\alpha_S^2(\mu_R)k_1(\mu_R,\mu_F)\right]$$

NLO inclusive jet production cross section

- μ_R = renormalization scale
- μ_F = renormalization scale
- LO contribution: $\alpha_S^2\left(\mu_R\right)X^0\left(\mu_{F,}E_T\right)$
- NLO contribution: $\alpha_S^3\left(\mu_R\right)X^0\left(\mu_{F,}E_T\right)k_1\left(\mu_R,\mu_{F,}E_T\right)$

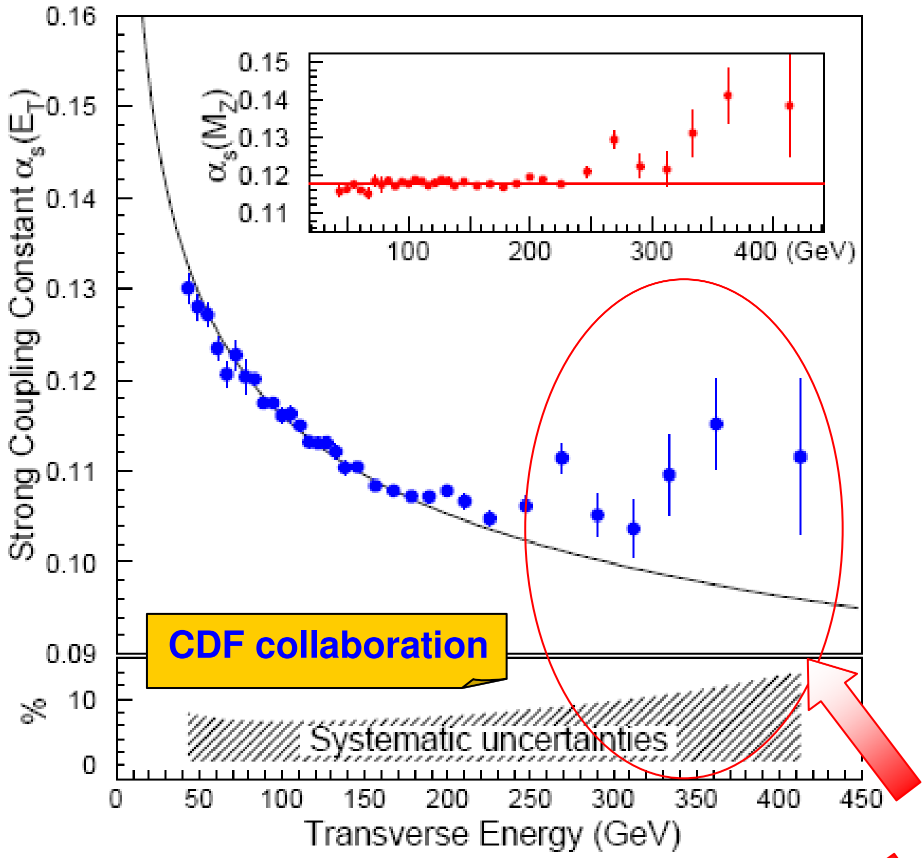
Procedure:

- Calculate via MC X^0,k_1 (μ_R,μ_F=E_T)
- Measure $d\sigma/dE_T$ and extract α_S
- Evolve α_S at M_Z scale via:

$$\boxed{\alpha_S(M_Z)=\frac{\alpha_S(\mu_R)}{1-\alpha_S(\mu_R)(b_0+b_1\alpha_S(\mu_R))\ln(\mu_R/M_Z)}}$$

Strong coupling measure

Then one can subdivide the jet sample in ET bins :



Repeat the whole procedure for each bin:

- **$\alpha_S(\mu_R = E_T)$ for each bin**
- **evolve to M_Z scale**
- **linear fit for α_S (M_Z) vs E_T**

➢**If perturbative QCD holds, α_S (M_Z) should be a constant (within the errors)**

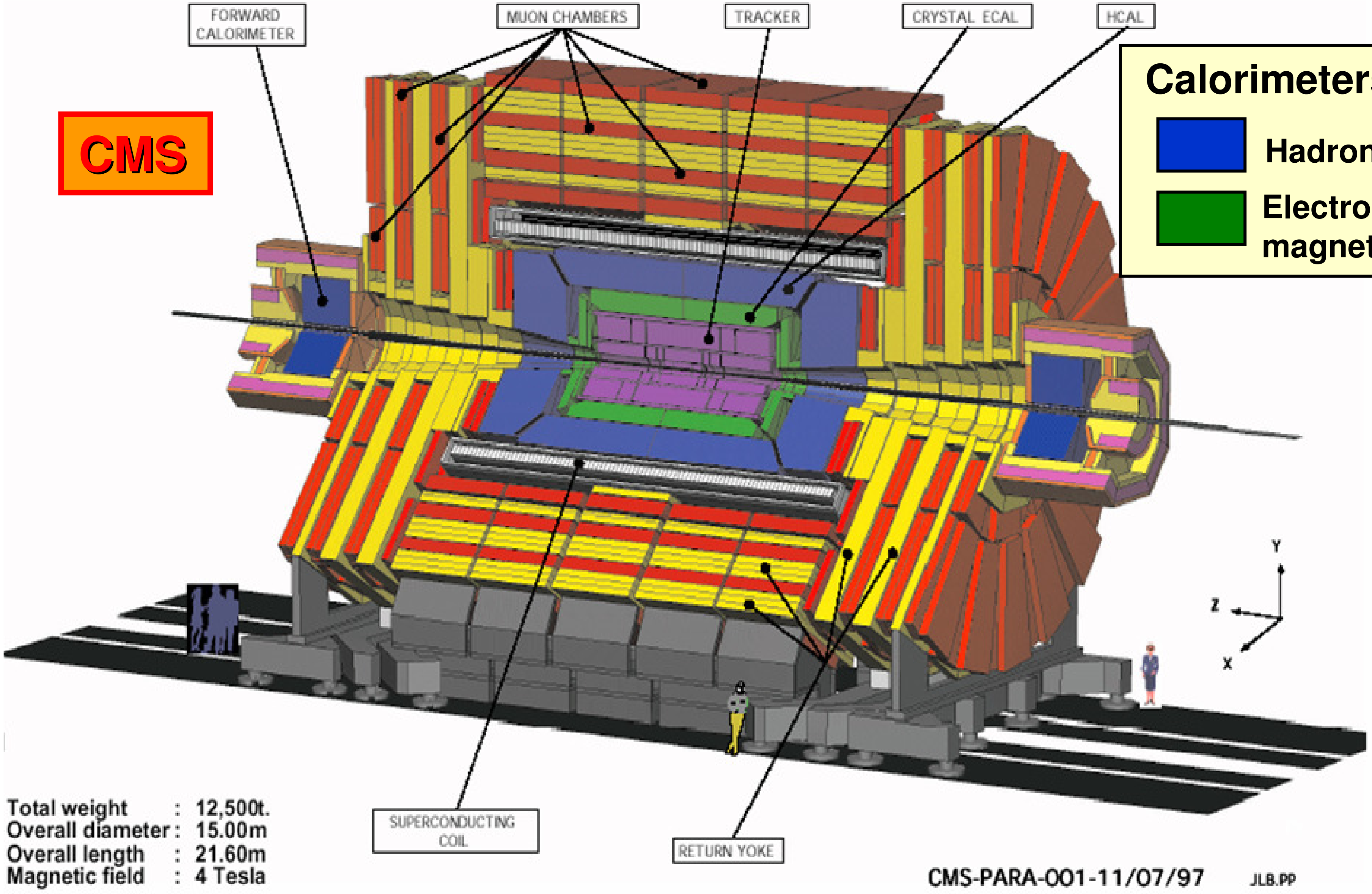
➢**Tevatron already did the measure and found α_S(M_Z) constant within 1σ**

Measure biased by the **exclusion of most energetic bins (E_T>250 GeV)** since the scarce knowledge of **high x gluon pdf** plays as a fundamental systematical error

See Daniele's talk…

Experimental Apparatus

CMS



Calorimeters

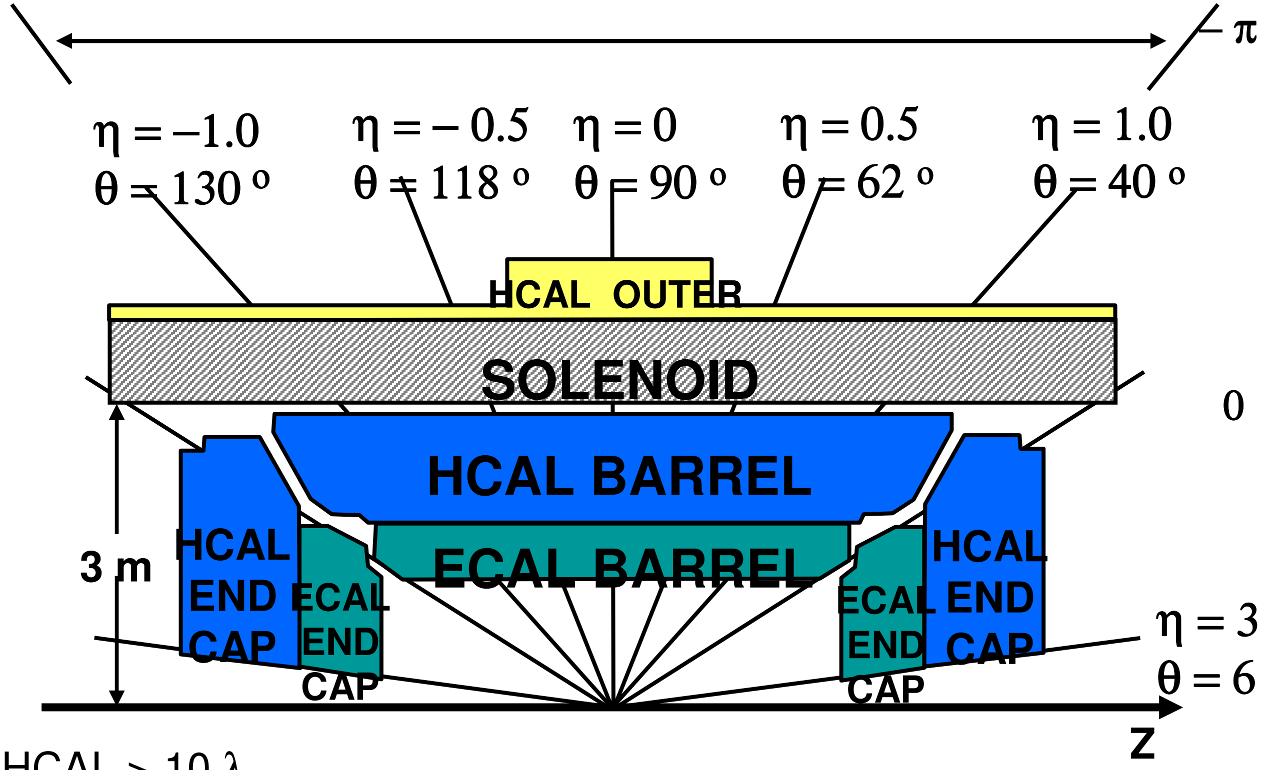
🟦 **Hadronic**

🟩 **Electro-magnetic**

Total weight : 12,500t.
Overall diameter : 15.00m
Overall length : 21.60m
Magnetic field : 4 Tesla

Experimental Apparatus

- **THE CMS CALORIMETRICAL APPARATUS**



HCAL > 10 λ_I
ECAL > 26 λ_0