Proposed exercise

We want to set-up a trigger to detect $Z \to \mu^+\mu^-$ decays in pp collisions at LHC. We have a low threshold (LT, p_T >4 GeV) and a high threshold (HT, $p_T >$ 20 GeV) single muon triggers. The efficiencies of the two triggers for the muons coming from Z decays are ϵ(LT)=89.2%, ϵ(HT)=62.1%. Determine the efficiencies for triggering on Z decays in the two configurations: (1) LT1 AND LT2, (2) HT1 OR HT2 .

Proposed exercises

In DAFNE operations for KLOE-2 experiment:

Top-up injection
2 mA injections at a rate of 2 Hz with 60% duty cycle
Veto of KLOE-2 DAQ for 50ms at each single injection
Dead time DAQ 4 μs
Trigger rate ~ 8 kHz

Determine DAQ inefficiency

Proposed exercise

The values of the parameter $\mu = \sigma/\sigma_{SM}$ for the Higgs boson for the three main decay channels measured in 2014 by ATLAS were:

$$\mu_{\gamma\gamma} = 1.55 \pm 0.30$$

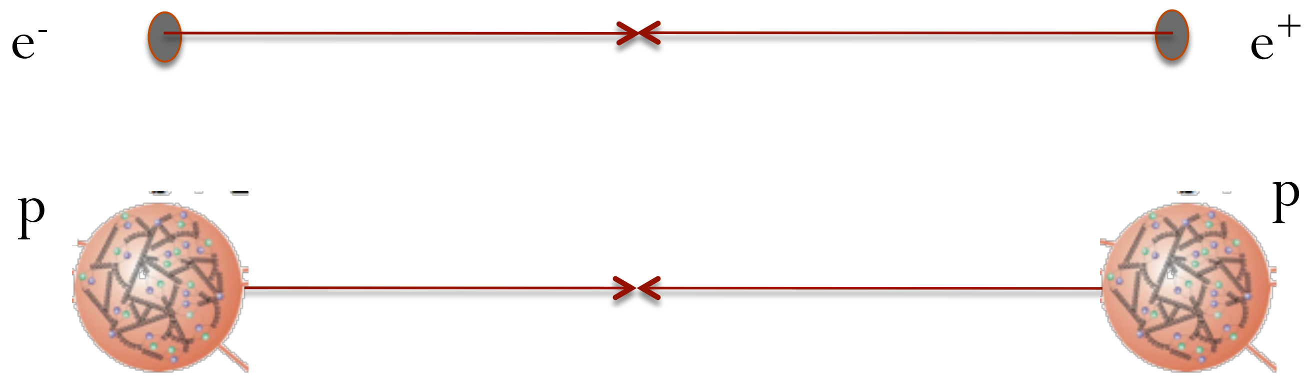
$$\mu_{ZZ} = 1.43 \pm 0.37$$

$$\mu_{WW} = 0.99 \pm 0.29$$

Evaluate the compatibility among the three independent ATLAS results and calculate the best overall estimate of μ from ATLAS. Then evaluate the compatibility with the SM expectation (μ=1).

Proposed exercise

Consider the Higgs production (M_H =125 GeV) at a pp collider at $\sqrt{s} = 14$ TeV. Evaluate the interval in rapidity y and the minimum value of x for direct Higgs production.



The proton is a complex object done by "partons":

valence quarks / *sea quarks* / *gluons*

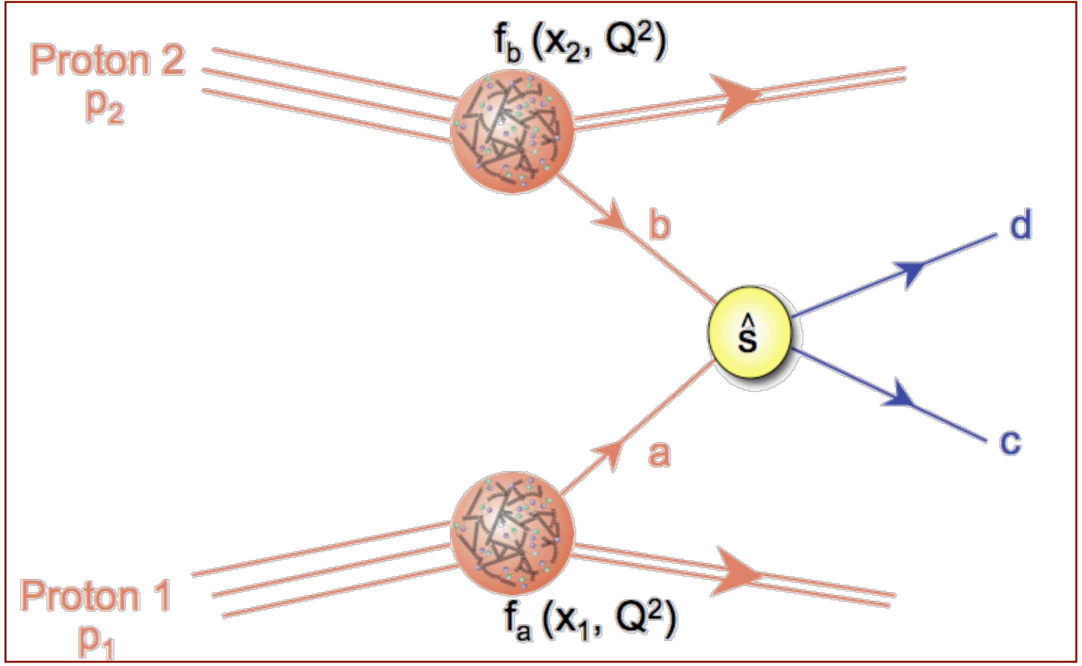
s = (center of mass energy of interaction)^2

$\hat{s}$ = (center of mass energy of *elementary* interaction)^2

e^+e^-: interactions btw point-like particles with $\sqrt{\hat{s}} \approx \sqrt{s}$

pp: interactions btw point-like partons with $\sqrt{\hat{s}} << \sqrt{s}$

Parton-parton collision: a+b → d+c.



a,b = quarks or gluons;
d,c = quarks, gluons, or leptons, vector bosons,…;
x = fraction of proton momentum carried by each parton;
$\hat{s}$ = parton-parton c.o.m. energy = x_1x_2s (see later);

Theoretical method: the ***factorization theorem***

$$d\sigma(pp \to cd) = \int_0^1 dx_1 dx_2 \sum_{a,b} f_a(x_1,Q^2) f_b(x_2,Q^2) d\hat{\sigma}(ab \to cd)$$

Two ingredients to predict pp cross-sections:

→ proton pdfs (f_a and f_b)

→ $\hat{\sigma}$ "fundamental process" cross-section

parton-parton collisions – let's define the relevant variables

- Parton momentum fractions: x_1 and x_2
  - Assume no transverse momentum
  - Assume proton mass negligible

$$p_1 = x_1 P_1 = x_1 \frac{\sqrt{s}}{2}(1,0,0,1)$$

$$p_2 = x_2 P_2 = x_2 \frac{\sqrt{s}}{2}(1,0,0,-1)$$

$$\hat{s} = (p_1 + p_2)^2 = x_1 x_2 s$$

- Rapidity: I evaluate the "velocity" of the parton system in the Lab frame:
  - It measures how fast the parton c.o.m. frame moves along z

$$\beta = \frac{p_z}{E} = \frac{(p_1 + p_2)_z}{(p_1 + p_2)_E} = \frac{x_1 - x_2}{x_1 + x_2}$$

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z} = \frac{1}{2}\ln\frac{1+\beta}{1-\beta} = \frac{1}{2}\ln\frac{x_1}{x_2}$$

- Relation between parton rapidity and each single x:

$$x_1 = \sqrt{\frac{\hat{s}}{s}}e^{y}$$

$$x_2 = \sqrt{\frac{\hat{s}}{s}}e^{-y}$$

Rapidity limit for a resonance of mass M

- Suppose that we want to produce in a partonic interaction a resonance of mass M then decaying to a given final state (e.g. pp→Z+X with Z→μμ. Limits in x and y of the collision ?
  - Completely symmetric case: $x_1=x_2=x$

$$x^2 = \frac{M^2}{s}; x = \sqrt{\frac{M^2}{s}}; e^y = 1; y = 0$$

  - Maximally asymmetric case: $x_1=1$, $x_2=x_{min}$

$$x_1 = 1; x_2 = x_{\min} = \frac{M^2}{s}; y_{\max} = \frac{1}{2}\ln\frac{s}{M^2}$$

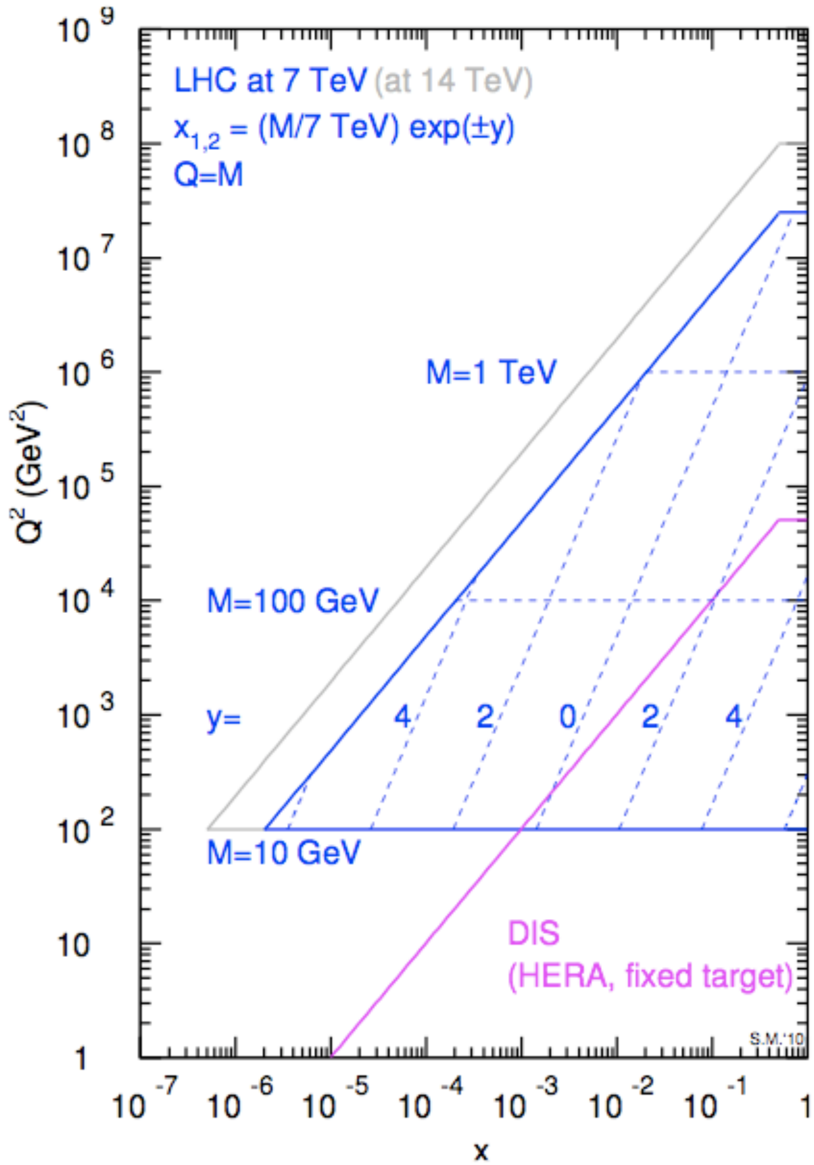
- Z production at LHC, Tevatron and SpS

	LHC (14 TeV)	**Tevatron (1.96 TeV)**	**SpS (560 GeV)**
x_{min}	4.2×10^{-5}	2.1×10^{-3}	0.026
y_{max}	5.03	3.07	1.82

The x-Q^2 plane

→ x – Q^2 plane ($Q^2=M^2=\hat{s}$) c.o.m. energy of parton interaction. LHC vs. previous experiments showing where PDF are needed to interpret LHC results.

→ NB pp vs. ppbar
ppbar ≈ qqbar collider
pp ≈ gluon collider



Variables for particles emerging from the collision

- Rapidity y can be defined for any particle emerging from the collision. Let's consider a particle of mass m, energy-momentum E, p and define the rapidity

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

- Pseudorapidity η: it is the rapidity of a particle of 0 mass:

$$\eta = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta} \rightarrow \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\tan\frac{\theta}{2}$$

- Transverse energy and momentum:

$$E_T^2 = p_x^2 + p_y^2 + m^2 = E^2 - p_z^2 = \frac{E^2}{\cosh^2 y}; p_T^2 = p_x^2 + p_y^2 = p^2\sin^2\theta$$

- General consideration: Energy and momentum conservation are expected to hold "roughly" in the transverse plane. This gives rise to the concept of missing E_T
- We do not expect momentum conservation on the longitudinal direction.

Properties of the rapidity

- Rapidity y can be defined for any particle emerging from the collision. Let's consider a particle of mass m, energy-momentum E, p and define the rapidity

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\beta\cos\theta}{1-\beta\cos\theta}$$

- Properties
  - If we operate a Lorentz boost along z, y is changed additively (so that Δy the "rapidity gap" is a relativistically invariant quantity):

$$y' = y + y_b$$

$$y_b = \ln\left[\gamma_b\left(1+\beta_b\right)\right]$$

(only for the restricted class of Lorentz transformations corresponding to a boost along the longitudinal z axis)

  - If expressed in terms of (p_T, y, ϕ, m) rather than (p_x,p_y,p_z,E) the invariant phase-space volume gets a simpler form:

$$d\tau = \frac{1}{2}dp_T^2 dy d\phi$$

  - so that in case of matrix element uniform over the phase-space, you expect a uniform particle distribution in y and p_T^2.

Invariant mass and missing energy

- The invariant mass of 2 particles emerging from the IP can be written in terms of the above defined variables

$$M^2 = m_1^2 + m_2^2 + 2[E_T(1)E_T(2)\cosh\Delta y - \boldsymbol{p}_T(1)\cdot\boldsymbol{p}_T(2)]$$

$$E_T(i) = \sqrt{|\boldsymbol{p}_T(i)|^2 + m_i^2}$$

Invariant mass and missing energy

- The invariant mass of 2 particles emerging from the IP can be written in terms of the above defined variables

$$M^2 = m_1^2 + m_2^2 + 2[E_T(1)E_T(2)\cosh\Delta y - \boldsymbol{p}_T(1)\cdot\boldsymbol{p}_T(2)] \qquad E_T(i) = \sqrt{|\boldsymbol{p}_T(i)|^2 + m_i^2}$$

At hadron colliders, a significant and unknown proportion of the energy of the incoming hadrons in each event escapes down the beam-pipe. Consequently if invisible particles are created in the final state, their net momentum can only be constrained in the plane transverse to the beam direction. Defining the z-axis as the beam direction, this net momentum is equal to the missing transverse energy vector

$$\boldsymbol{E}_T^{\text{miss}} = -\sum_i \boldsymbol{p}_T(i) \ , \tag{47.49}$$

where the sum runs over the transverse momenta of all visible final state particles.

Invariant mass and missing energy

- The invariant mass of 2 particles emerging from the IP can be written in terms of the above defined variables

$$M_W^2 = 2E_{T1}E_{T2}(\cosh\delta\eta - \cos\delta\phi).$$

- Non-interacting particles such as neutrinos can be detected via a momentum imbalance in the event. But since most of the longitudinal momentum is "lost", the balance is reliable only in the transverse direction. ➔ Missing Transverse Energy $\vec{\not{E}}_T$

$$\vec{\not{E}}_T = -\sum_{k=1}^{Ncl} \vec{E}_{Tk} - \sum_{i=1}^{Nm} \vec{p}_{Ti}$$

$$\vec{E}_{Tk} = \frac{E_k \cos\varphi_k}{\sinh\eta_k}\hat{x} + \frac{E_k \sin\varphi_k}{\sinh\eta_k}\hat{y}$$

Example: W mass constraint: evaluation of neutrino direction

Lastly, since the mass of the W particle is well known [5], we can constrain the invariant mass of the e, ν pair, and solve for the longitudinal momentum of the neutrino. To do this, we can use Eq. (17):

$$M_W^2 = 2E_{T1}E_{T2}(\cosh\delta\eta - \cos\delta\phi).$$

Rewriting this expression, we get

$$\cosh\delta\eta = \frac{M_W^2}{2E_{T1}E_{T2}} + \cos\delta\phi. \tag{21}$$

Solving for $\delta\eta$ gives

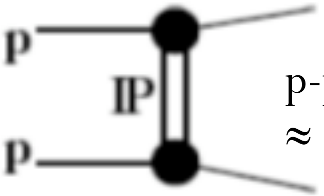
$$\delta\eta = ln\frac{r + \sqrt{r^2 - 1}}{2}, \tag{22}$$

where r is the right-hand side of Eq. (21). Because $\delta\eta$ is the difference in pseudorapidity between the electron and the neutrino, there are two solutions to the problem. That is, there is no way of resolving the ambiguity of whether the neutrino is at a lower or higher rapidity relative to the electron as seen from the fact that the hyperbolic cosine $\cosh\delta\eta$ is even in $\delta\eta$. Both solutions are possible, at least in principle.

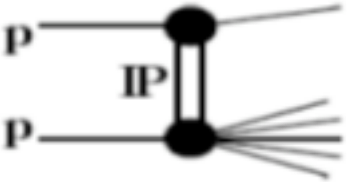
http://vsharma.ucsd.edu/lhc/Baden-Jets-Kinematics-Writeup.pdf

A detailed look at a p-p collision. What really happens ?

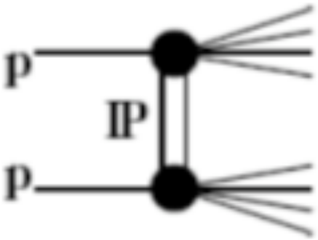
(A) "Real" proton-proton collision (*pomeron exchange*): 40% of the times



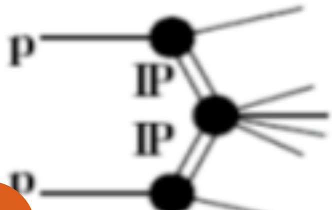
p-p elastic scattering
≈ 25%



Single diffraction
≈ 10%

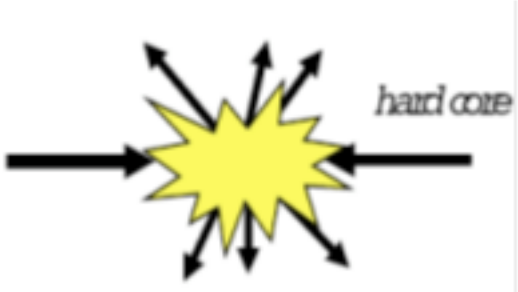


Double diffraction
≈ 1%



Central diffraction
≈ 1%

(B) Inelastic non-diffractive: 60% of the times



Where is the *fundamental physics* in this picture ?
Among non-diffractive collisions **parton-parton collisions**.
Signatures:

proton-proton collision
➔ "forward"

parton-parton collision
➔ "transverse"

Jets - I

Starting from the '70s observation of jet production in e^+e^-, pp and ep collisions. QCD explanation (for e^+e^-):

$e^+e^- \rightarrow$ qqbar $\rightarrow$ hadronisation results in

two jets of hadrons if q (qbar) momenta >> O(100MeV)

NB: in low energy e^+e^- you see multi-hadrons not jets…

2-jet events: qqbar or gg final state that hadronise in 2 jets
in back-to-back configuration;

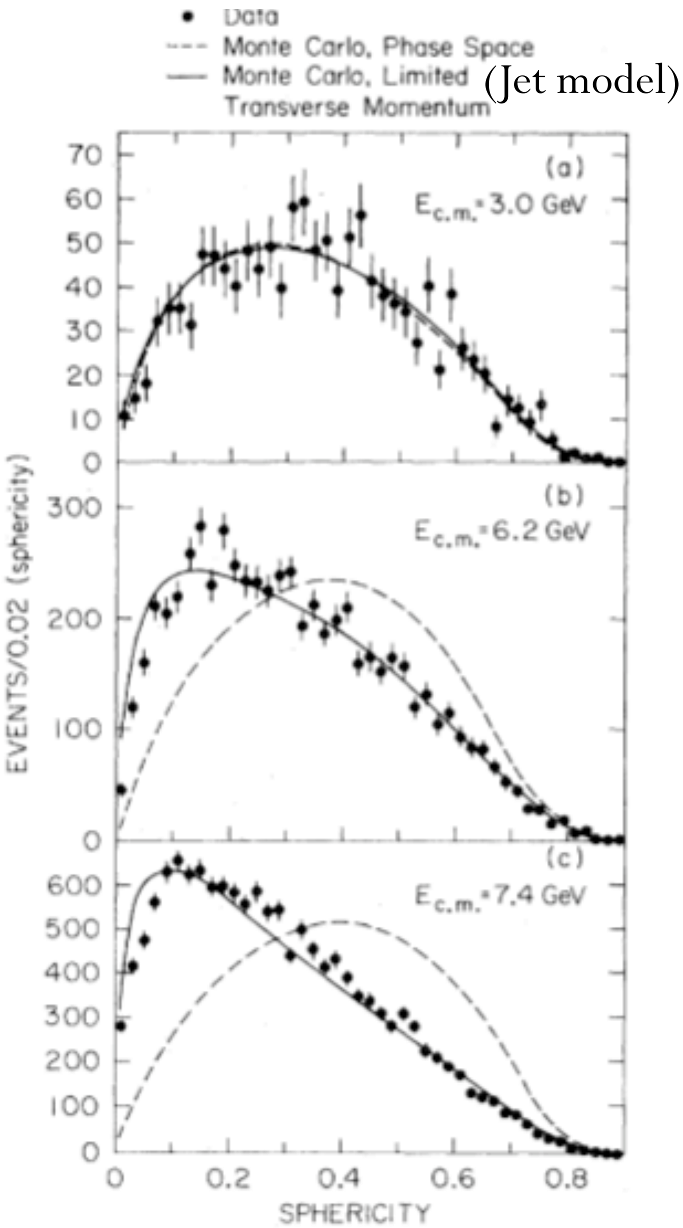
3-jet events: one hard gluon irradiation gives rise to an
additional jet (3jet/2jet is a prediction of pQCD)

Several variables can be defined to discriminate "2-jet-like" behaviour wrt isotropic behaviour:

sphericity S 0<S<1

Here, p_{ti} are the transverse momenta of all hadrons in the final state relative to an axis chosen such that the numerator is minimised. (S=0 back-to-back, S=1 isotropic)

$$S = \frac{3\sum_{k=1}^{N} p_{ti}^2}{2\sum_{k=1}^{N} p_i^2}$$



Several variables have been introduced to specify the jet-like nature of an event. For example:

$$\text{Sphericity} \equiv S' = \frac{3}{2}\min_{\boldsymbol{n}}\left(\frac{\sum_i \boldsymbol{p}_{Ti}^2}{\sum_i \boldsymbol{p}_i^2}\right), \tag{25.2.1}$$

where $\boldsymbol{n}$ is an arbitrary unit vector relative to which $\boldsymbol{p}_{Ti}$ is measured;

$$\text{Thrust} \equiv T = \max_{\boldsymbol{n}}\left(\frac{\sum_i |\boldsymbol{p}_i \cdot \boldsymbol{n}|}{\sum_i |\boldsymbol{p}_i|}\right) \tag{25.2.2}$$

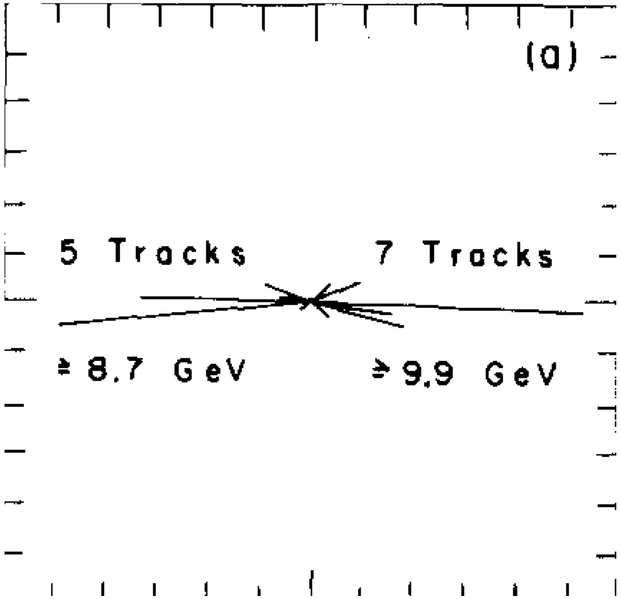
$$\text{Spherocity} \equiv S = \left(\frac{4}{\pi}\right)\min_{\boldsymbol{n}}\left(\frac{\sum_i |\boldsymbol{p}_{\mathrm{T}i}|}{\sum_i |\boldsymbol{p}_i|}\right)^2 \tag{25.2.3}$$

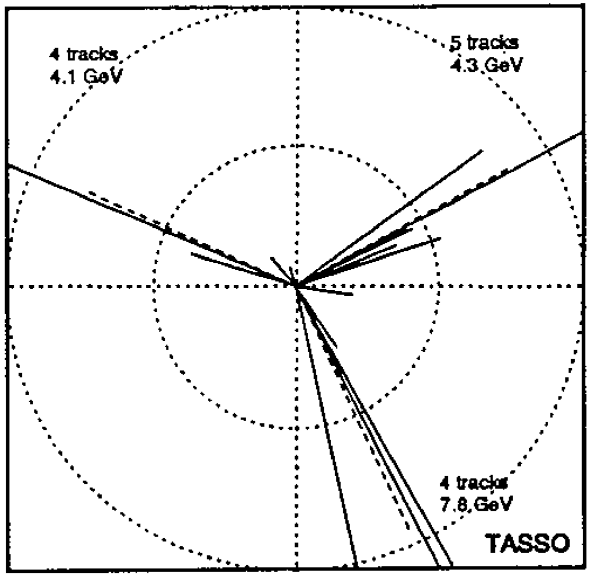
$$\text{Acoplanarity} \equiv A = 4\min_{\boldsymbol{n}}\left(\frac{\sum_i |\boldsymbol{p}_{\mathrm{out}i}|}{\sum_i |\boldsymbol{p}_i|}\right)^2, \tag{25.2.4}$$

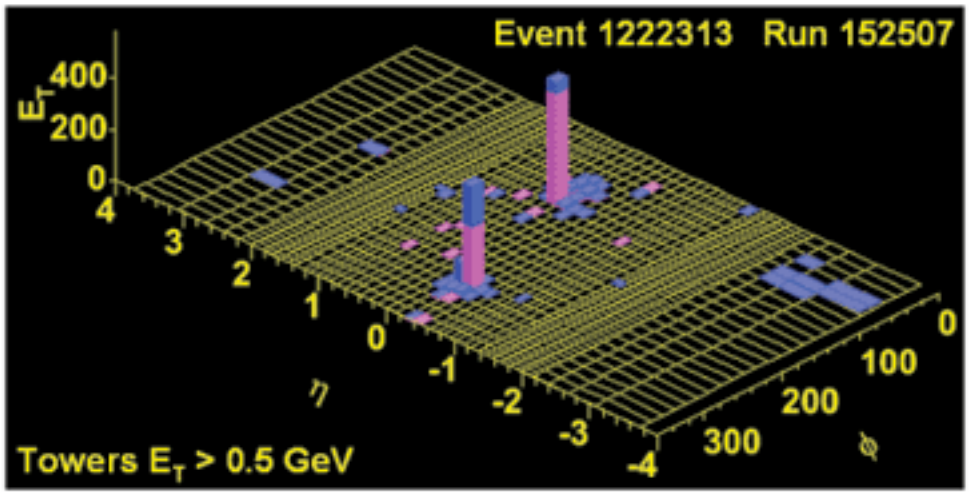
where $\boldsymbol{p}_{\mathrm{out}i}$ is measured transverse to a plane with normal $\boldsymbol{n}$. In these the sum is over all detected particles, and $\boldsymbol{n}$ is varied until the desired maximum or minimum is found.

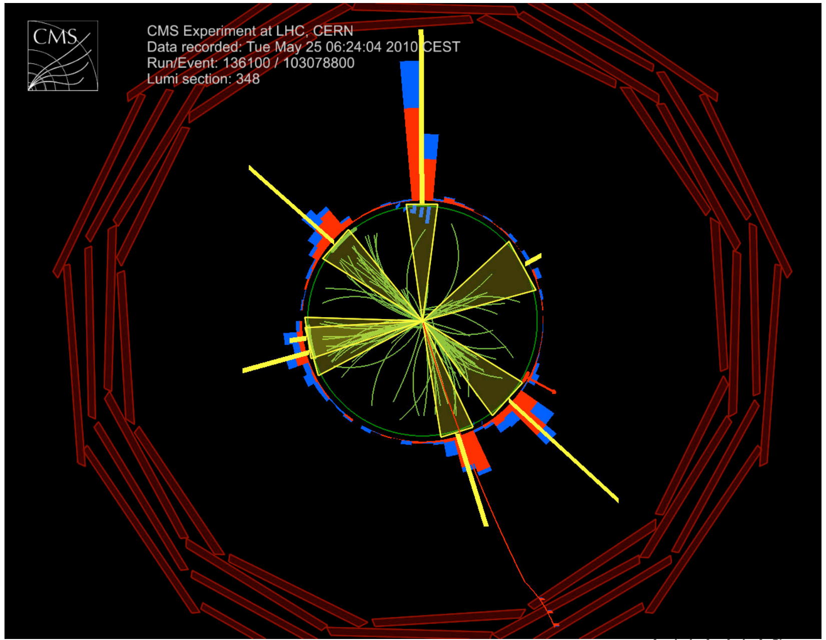
For an ideal two-jet event one would have $S' = 0$, $T = 1$, $S = 0$ and $A = 0$, whereas an isotropic distribution has $S' = 1$, $T = \frac{1}{2}$, $S = 1$ and $A = 1$.

Jets - II

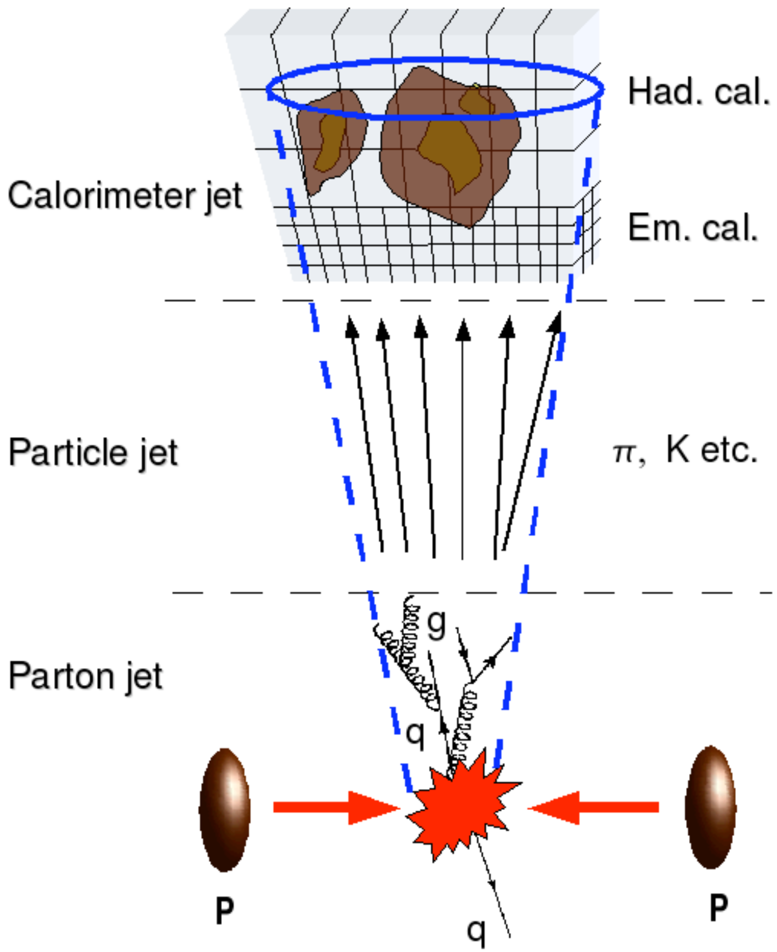

(a)
5 Tracks
7 Tracks
≥ 8.7 GeV
≥ 9.9 GeV


4 tracks
4.1 GeV
5 tracks
4.3 GeV
4 tracks
7.8 GeV
TASSO


Event 1222313 Run 152507
E_T
400
200
0
4
3
2
1
0
-1
-2
-3
-4
η
0
100
200
300
φ
Towers E_T > 0.5 GeV


CMS
CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

Jets - III



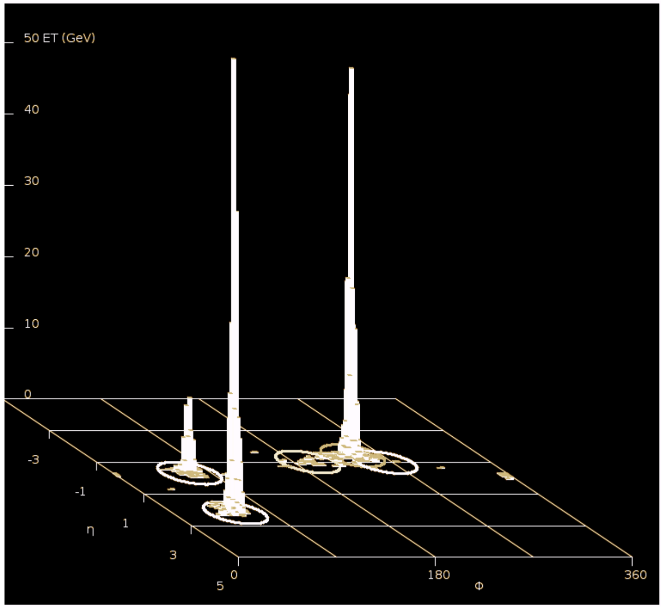
Jet experimental definition:

- based on calorimeter cells
- based on tracks
- → quadri-momentum evaluated (E,p)

Jet algorithms:

- sequential recombination
- cone algorithms
- kT algorithms (against infrared divergences)

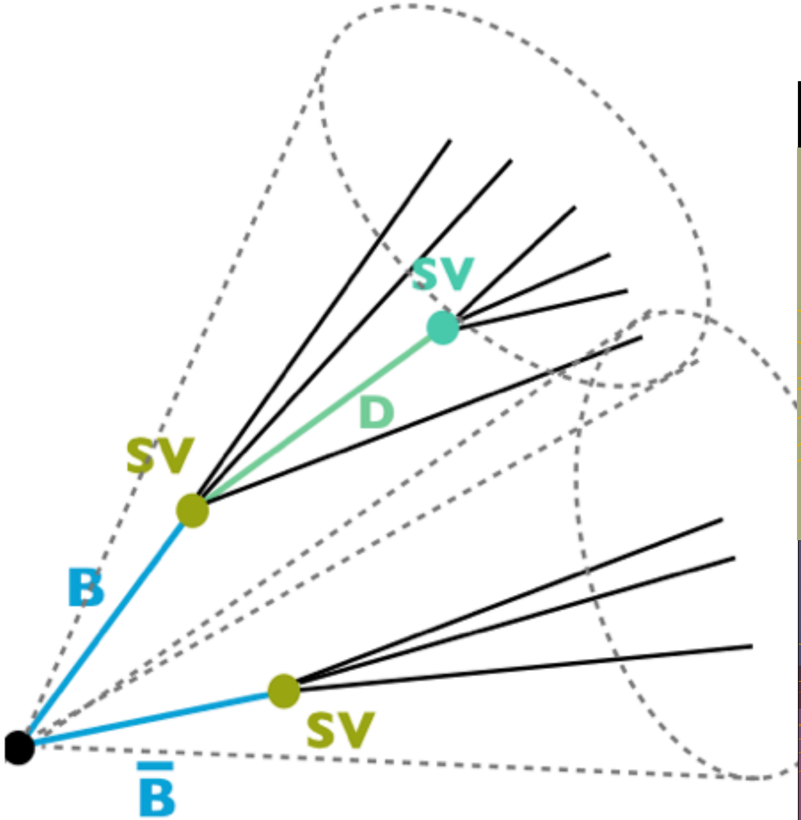
$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

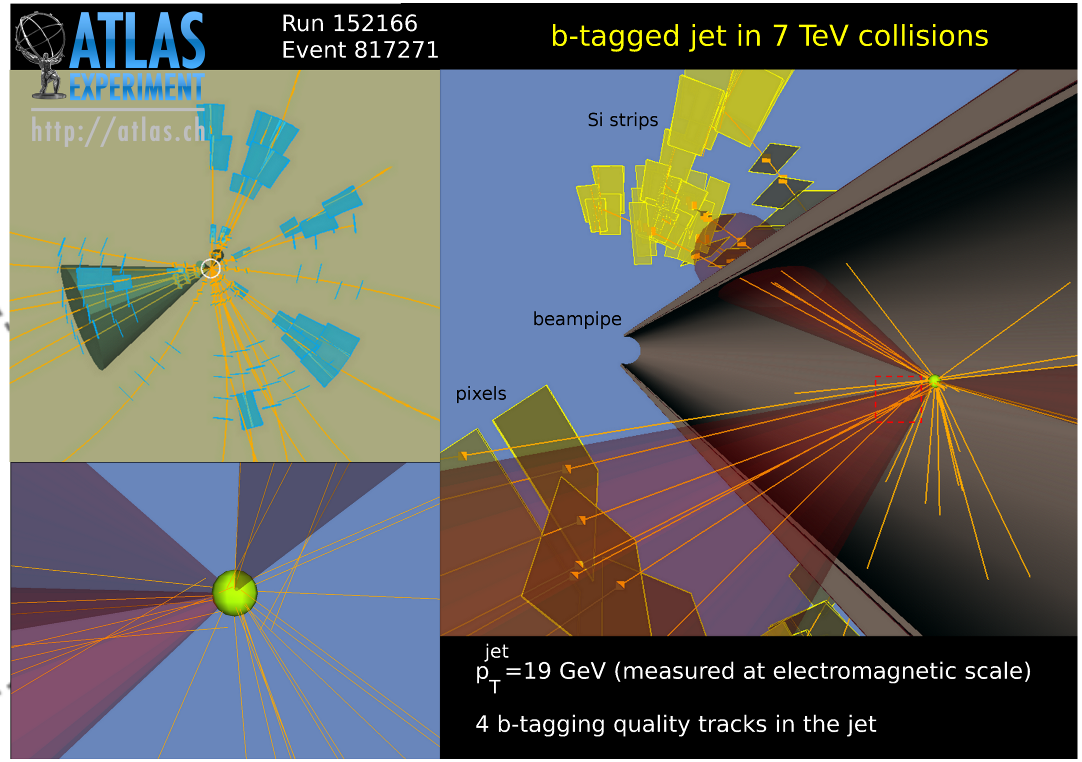


b-Jets

Two main methods to "tag" B-jets:

1) Displaced vertices
2) One or more leptons from semi-leptonic decays. Leptons are not isolated.





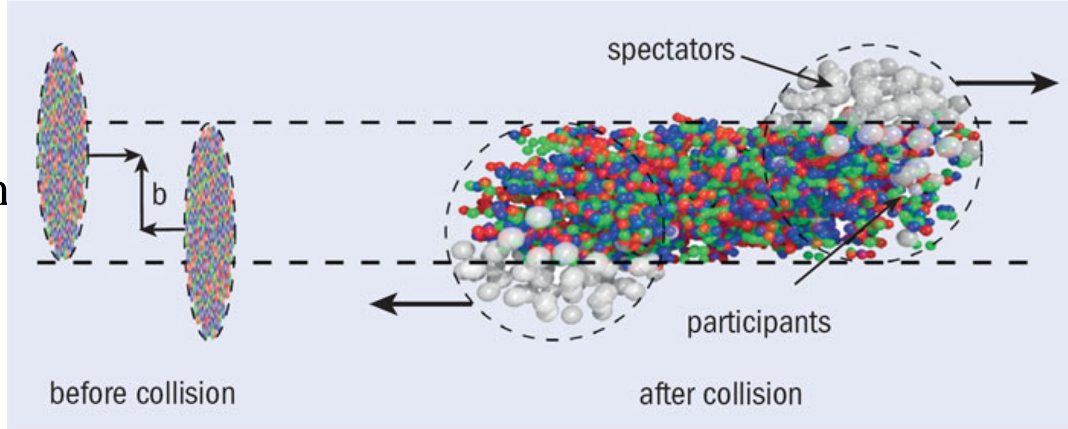
Heavy Ion collisions: the centrality

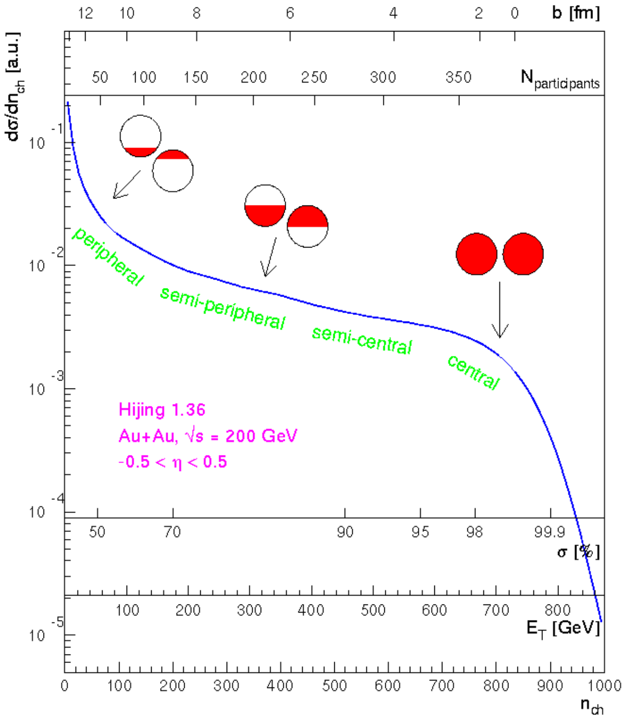
In heavy ion collisions we define the impact parameter ***b***.

b=0 or small ➔ "central" collision

b large ➔ "peripheral" collision

The "***centrality***" is a measure of ***b***





How can we experimentally measure the centrality of each event ?

In a heavy ion collision many particles are produced, mostly in the forward region.

➔ Total energy measured in the Forward detectors

➔ Divide in "percentile" of centralities

Centrality definition

The centrality is usually expressed as a percentage of the total nuclear interaction cross section σ [2]. The centrality percentile c of an A–A collision with an impact parameter b is defined by integrating the impact parameter distribution $\mathrm{d}\sigma/\mathrm{d}b'$ as

$$c = \frac{\int_0^b \mathrm{d}\sigma/\mathrm{d}b'\,\mathrm{d}b'}{\int_0^\infty \mathrm{d}\sigma/\mathrm{d}b'\,\mathrm{d}b'} = \frac{1}{\sigma_{AA}} \int_0^b \frac{\mathrm{d}\sigma}{\mathrm{d}b'}\,\mathrm{d}b'. \quad (1)$$

Centrality definition

Events were sorted into different centrality classes. The centrality of heavy-ion interactions is related to the number of participating nucleons and hence to the energy released in the collisions. In CMS, the centrality is defined as percentiles of the energy deposited in the HF. The most central/peripheral event class, i.e. (0–2.5)%/(70–80)% in this analysis, has a large/small number of participants and a large/small energy deposit in HF. In order to estimate the mean number of participating nucleons ($\langle N_{\text{part}} \rangle$) and its systematic uncertainty for each centrality class, a Glauber model of the nuclear collision was used [16–18].

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the central field volume are the silicon pixel and strip trackers, lead-tungstate crystal electromagnetic calorimeter (ECAL) and the brass-scintillator hadron calorimeter (HCAL). These calorimeters are physically divided into the barrel and endcap regions covering together the region of $|\eta| < 3.0$. The Hadronic Forward (HF) calorimeters cover $|\eta|$ from 2.9 to 5.2. The HF calorimeters use quartz fibers embedded within a steel absorber. The CMS tracking system, located inside the calorimeter, consists of pixel and silicon-strip layers covering $|\eta| < 2.5$. A set of scintillator tiles, the Beam Scintillator Counters (BSC), are mounted on the inner side of the HF calorimeters to trigger on heavy-ion collisions and reject beam-halo interactions. In addition, two Zero Degree Calorimeters (ZDC) are used for systematic checks. For more details on CMS see [14].

Centrality definition

Method: assign to each event a centrality given by the percentile region where the event goes.