Introduction to Hadron Collider Physics

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INTRODUCTION

Ingredients of the Standard Model

Length, energy...

$$\text{Energy, } E \quad \xleftrightarrow[E=\hbar\omega]{\hbar} \quad \text{Pulsation, } \omega \sim \frac{1}{T}$$

$$c \quad \updownarrow \quad E = pc \qquad\qquad c \quad \updownarrow \quad \lambda = \frac{c}{\omega}$$

$$\text{Momentum, } p \quad \xleftrightarrow[p=\frac{\hbar}{\lambda}]{\hbar} \quad \text{Wave length, } \lambda$$

Quantum mechanics : Energy and 1/Time are equivalent

Special relativity : Time and space are equivalent

c and ħ are only conversion factor due to our definition of units in the international system (Joule, meter, second,…)

ħ = c = 1, dimensionless

… and elementarity

Compton wavelength : $$E = \frac{hc}{\lambda}$$

Length scale ↔ Energy scale

To probe a system a size L,

if $\lambda \gg L$: system looks punctual = elementary particle

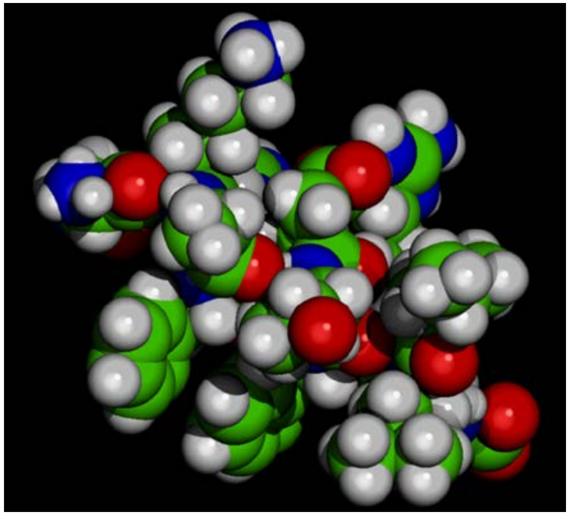
if $\lambda \ll L$: may be sensitive to substructure

Smaller scales ↔ Greater energies

Nucleon size : $\lambda \sim$ fm (10^{-15}m) → E ~100 MeV (QCD scale)

Tevatron/LHC : E~1-10 TeV → $\lambda \sim 10^{-18}$ -10^{-19} m

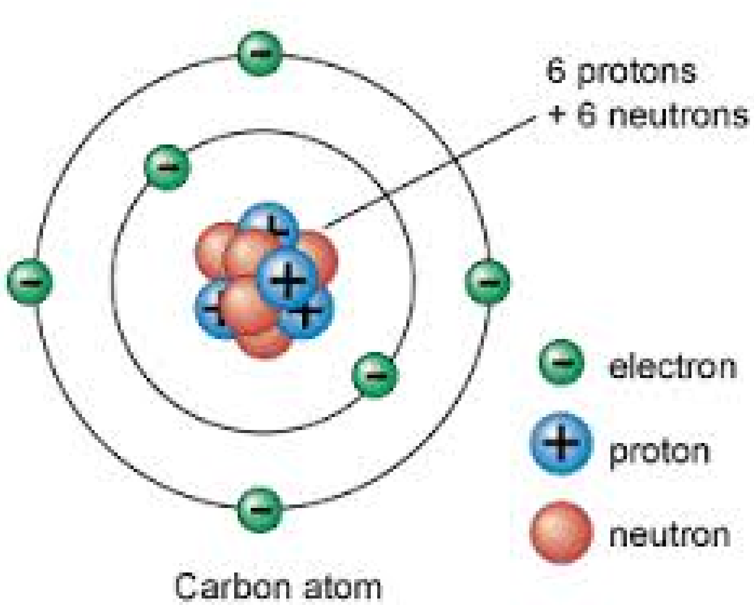
Ordinary matter



Electron

Nucleus

Electromagnetism : photons



Condensed matter physics, statistical physics and thermodynamics, chemistry

Nuclear forces

Nucleus is composed of

protons (EM charge +1)

neutrons (neutral)

Unstable under electrostatic interaction (Coulomb repulsion)

Need an extra interaction to glue the nucleons together

Strong interaction

Nucleons can change into one another : beta decay

$n \rightarrow p\, e^- \nu_e$ and $p \rightarrow n\, e^+ \nu_e$

This require an additional fermion : neutrino

Weak interaction

NO LARGE SCALE EFFECTS : SHORT RANGE INTERACTION

Relativistic equation

Classical quantum equation ("Schrödinger equation"):

$$E = \frac{p^2}{2m} \xleftrightarrow[E\to i\hbar\frac{\partial}{\partial t},\ \vec{p}\to i\hbar\vec{\nabla}]{\text{quantization}} i\hbar\frac{\partial}{\partial t}\varphi = -\frac{\hbar^2}{2m}\vec{\nabla}^2\varphi$$

Relativistic quantum equation ("Klein-Gordon equation"):

$$E^2 = p^2c^2 + m^2c^4 \xleftrightarrow[E\to i\hbar\frac{\partial}{\partial t},\ \vec{p}\to i\hbar\vec{\nabla}]{} \Box\psi + \frac{m^2c^2}{\hbar^2}\psi = 0$$

For a static charge :

$$\vec{\nabla}^2\psi + \frac{m^2c^2}{\hbar^2}\psi = 0$$

Yukawa potential

$$\vec{\nabla}^2\psi + \frac{m^2c^2}{\hbar^2}\psi = 0$$

Massless particle : Laplace equation

In electrostatic as the equation for the potential

$$\vec{\nabla}^2 V = 0 \Longrightarrow \boxed{V = \frac{g}{r}}$$

The photon is massless : infinite range

If massive vector :

$$\vec{\nabla}^2 U = \frac{mc^2}{\hbar} U \Longrightarrow \frac{1}{r^2}\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right) = \frac{mc^2}{\hbar} U \Longrightarrow \boxed{U(r) = \frac{g}{r}e^{-r/R}}$$

Yukawa potential : finite range $R = \dfrac{\hbar}{mc}$

Interactions

energy/momentum exchange via a mediator particle

Electromagnetism :

infinite range, massless particle : the PHOTON

Weak interaction :

finite range << nuclear radius, massive vectors

W^+, W^-, Z masses ~ 100 GeV, range ~ 10^{-18}m

typical interaction times : 10^{-12}s

Strong interaction (nuclear)

finite range ~ fm (nucleus size) : massive pions (140 MeV)

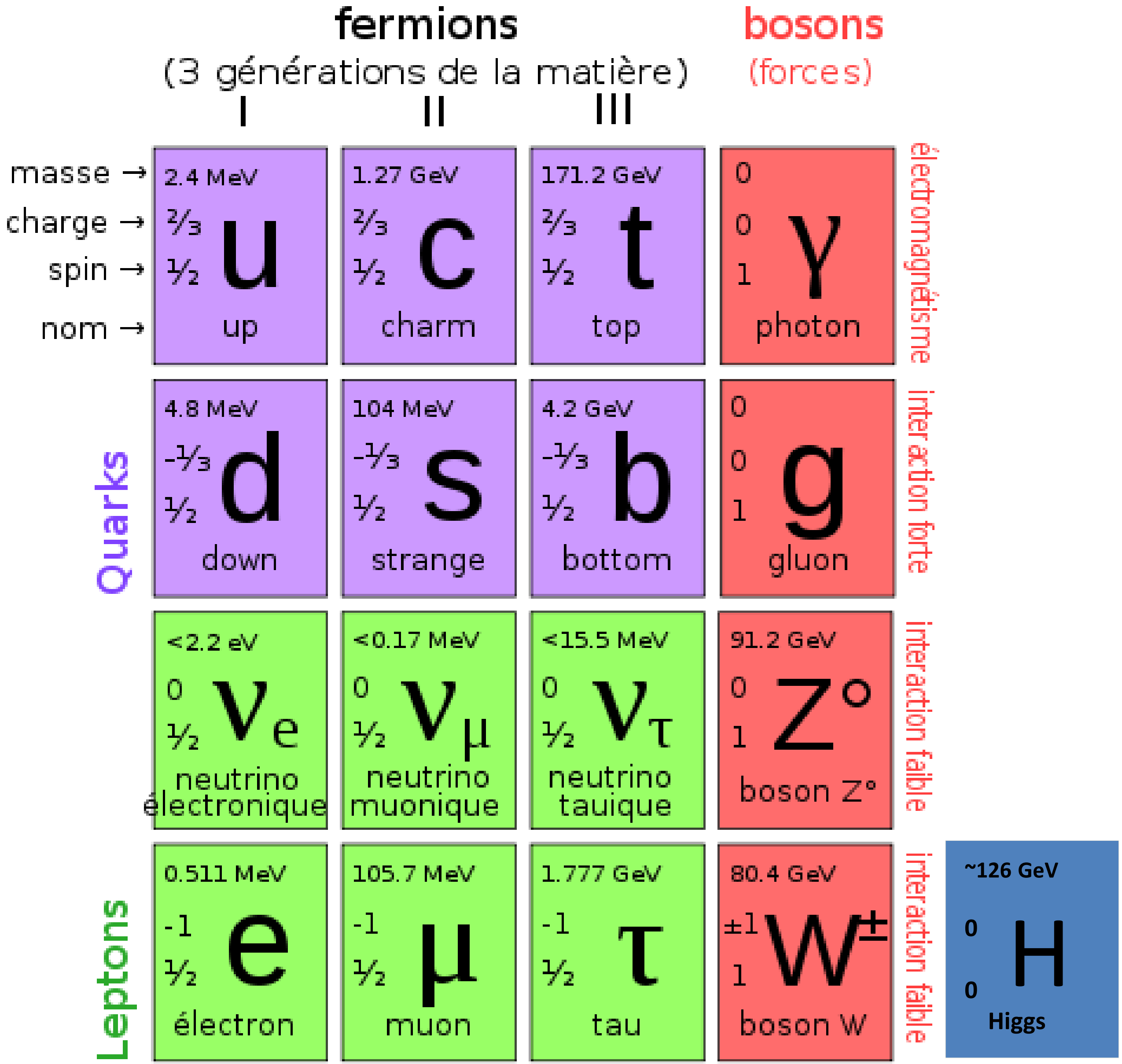
Rem : nuclear interactions are only an effective interaction resulting from strong interaction between quarks

Standard model particles

Model interaction between fermions
- **quarks**
- **leptons**

Through boson exchange
- **EM : γ**
- **weak : W^+, W^- , Z**
- **strong : gluons**

Extra stuff :
- **Higgs boson**



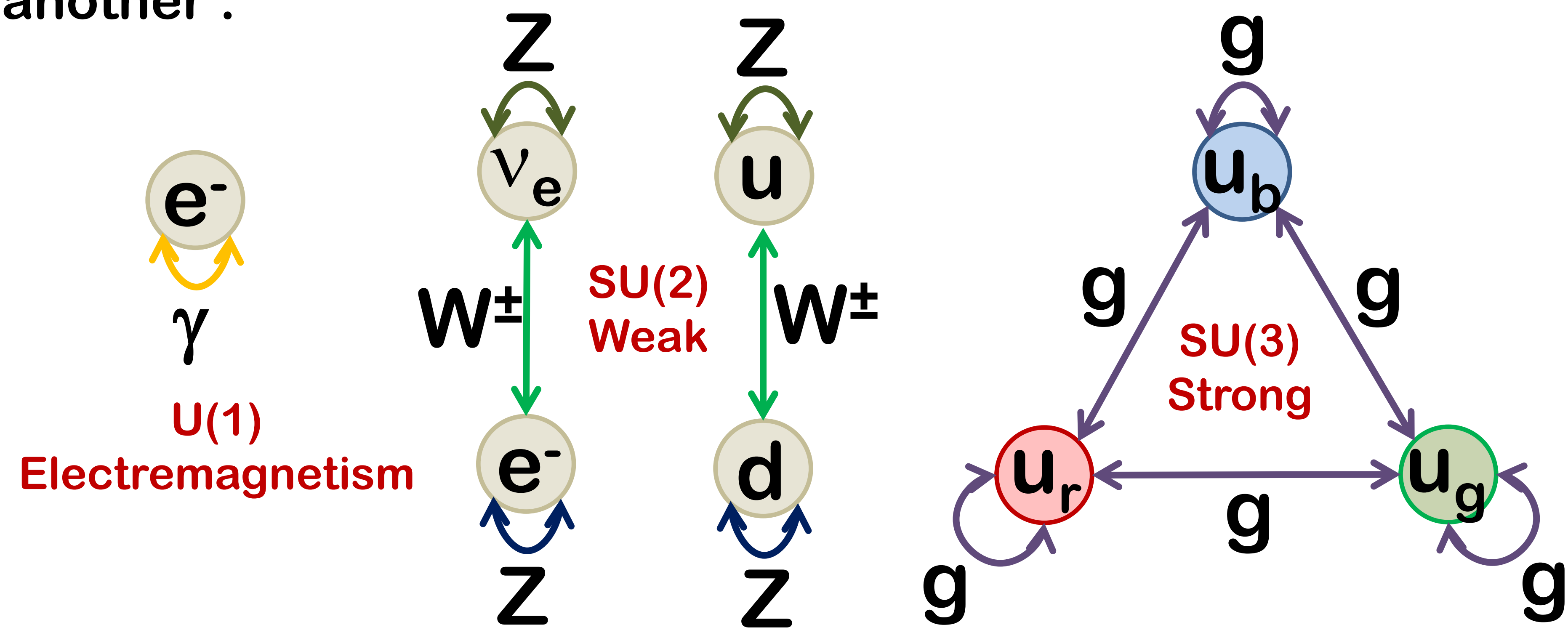
Gauge theories

Regroup particles into multiplets

Particle from a same multiplet behave identically with respect of an interaction :

different states of a same object

Interaction modify objects within the multiplet into one another :



Hidden behind this : Lie group theory and representations

The strong interaction

Main differences with respect to electromagnetism

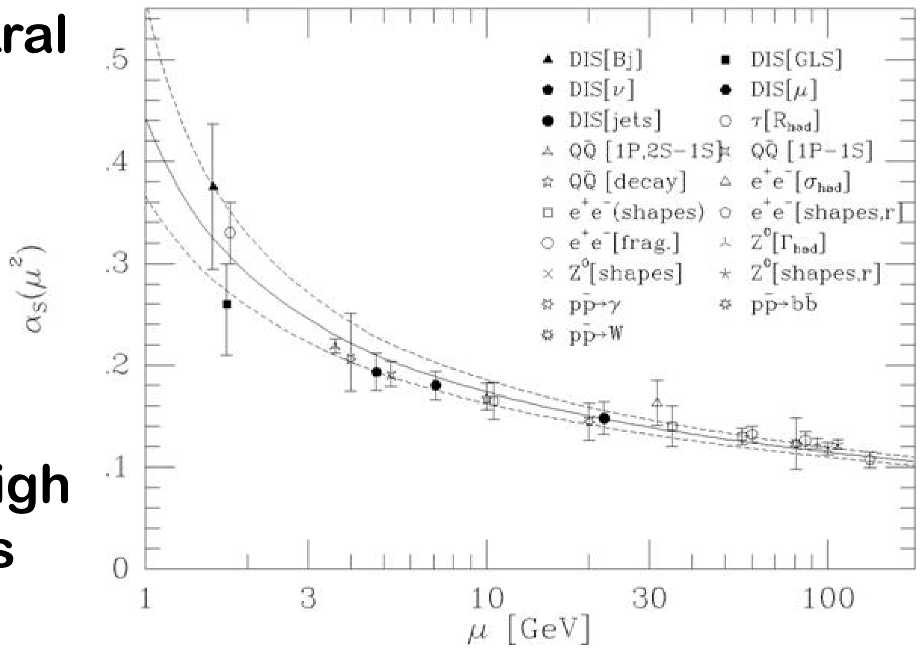
- * **3 charges** (red, blue, green) instead of 1
- * **8 bosons** (gluons) instead of 1
- * **gluons carry color charge** : self interactions

Coupling goes up at low energy

→ **Confinement** : only (color)neutral bound states can exist the hadrons

Baryons : 3 quarks (all 3 colors)
neutron, proton,…

Mesons : quark-antiquark
pions, kaons…



→ **Asymptotic freedom** : at very high energy, quarks behaves as electrons

→ **Perturbative calculation** possible only at high energies

The weak interaction

Electroweak interaction : (formal) unification of electromagnetic and weak interactions

Neutral currents : Z boson exchange

Charged currents : W^+ / W^- exchange

only SM interaction that can change flavour

within SU(2) multiplets : $e \leftrightarrow \nu_e$, $\mu \leftrightarrow \nu_\mu$, $\tau \leftrightarrow \nu_\tau$

$d \leftrightarrow u$, $s \leftrightarrow c$, $b \leftrightarrow t$

between families of quarks (flavour mixing)

Broken symmetry : particles in the multiplets are clearly not the same (different masses !)

Solved by Higgs mechanism

19 Free parameters

Model parameters : unpredicted by theory, need measure

Gauge theory (interactions)

Interaction intensity or couplling : 3 interactions

α_{Strong}, α_{EM}, α_{Weak}

Masses of the fermions :

Yukawa couplings to the Higgs dield : 9(+3) massive fermions

m_u, m_d, m_s, m_c, m_b, m_t, m_e, m_μ , m_τ , ($m_{\nu e}$, $m_{\nu\mu}$, $m_{\nu\tau}$)

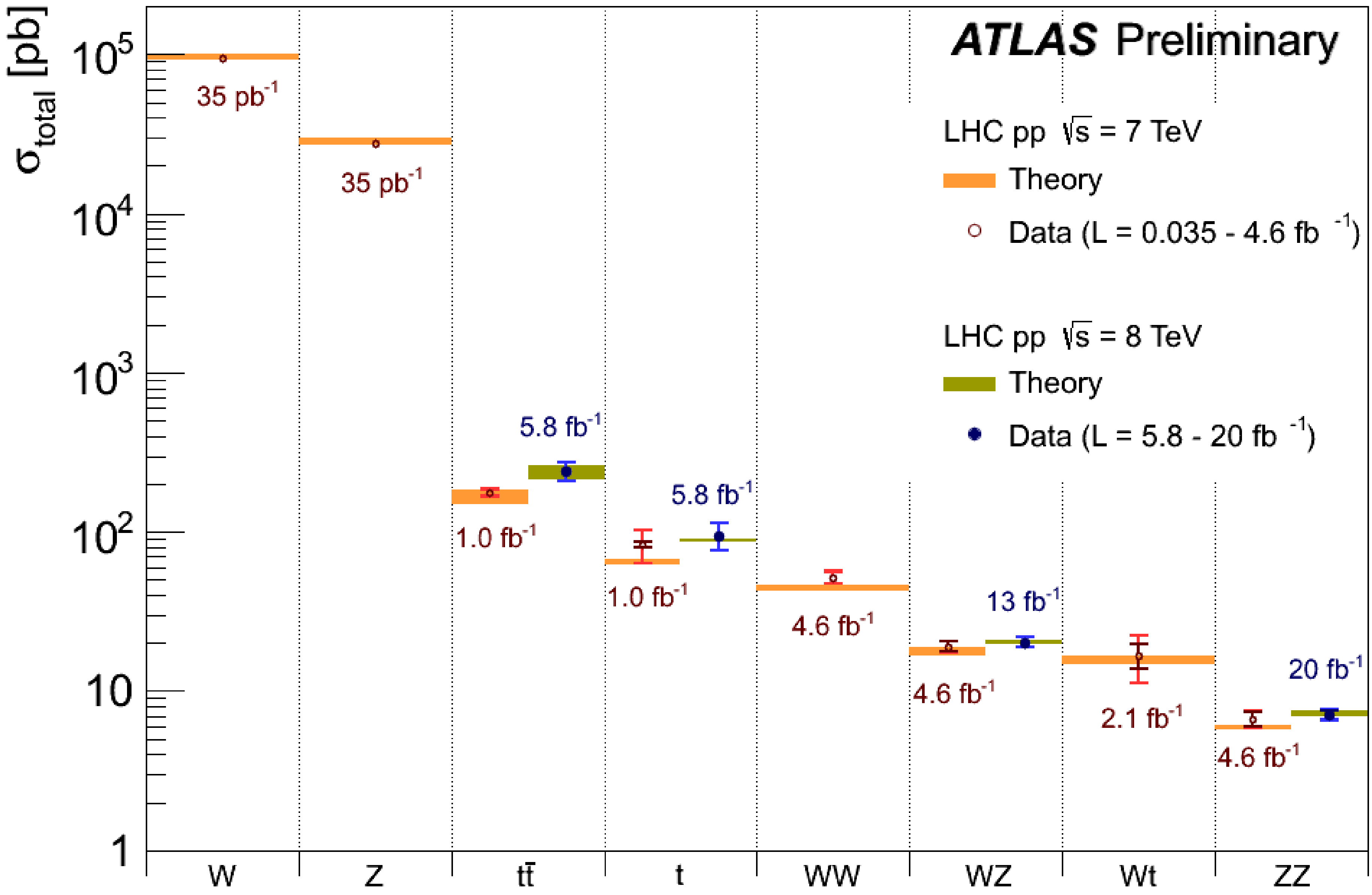
Masses of weak bosons and Higgs mechnism :

2 paramers : Higgs mass m_H and self-coupling λ

Quarks flavour mixing : 3 angles +1 phase

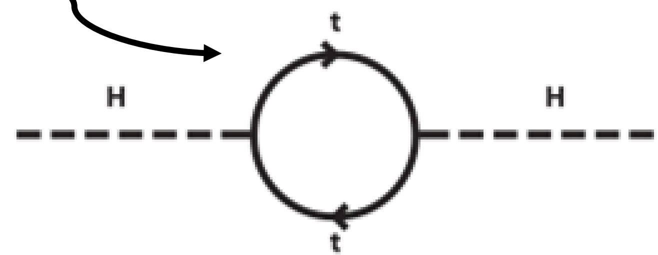
Strong CP violation : 1 phase (=0 ?)

Standard model observables



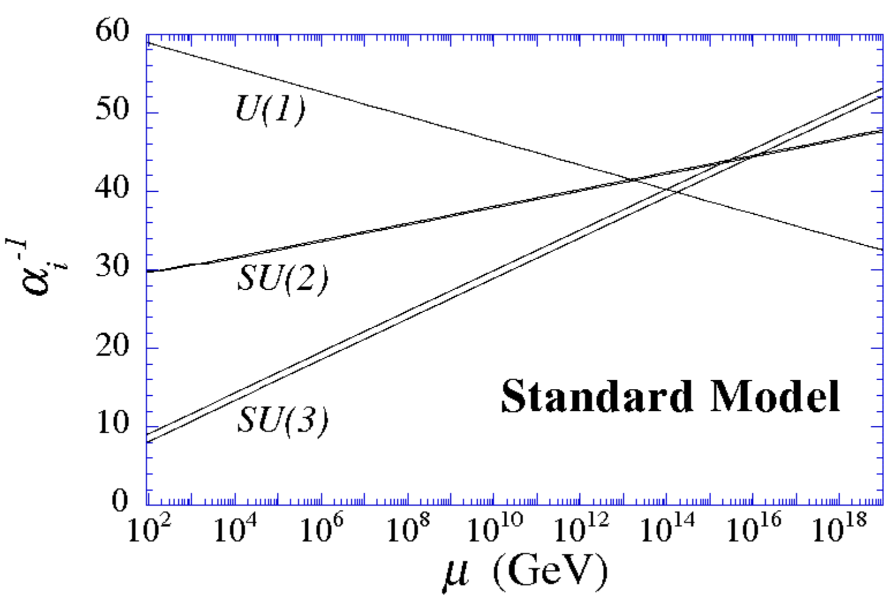
SM limitations

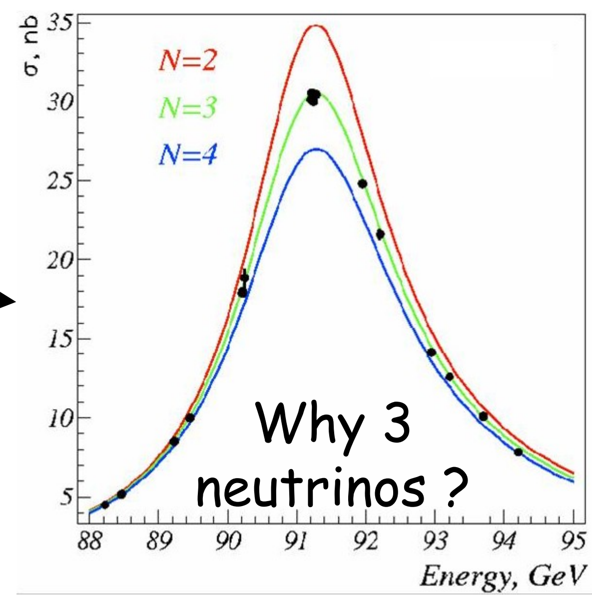
- Too many unpredicted quantities (masses...)
- No neutrino masses $\rightarrow$ needed to explain neutrino oscillations
- Quadratic divergences to loop corrections to the Higgs mass : hierachy problem : $\rightarrow$ need some fine tuning to cancell huge quantities



- Why only 3 families ?
- No coupling unification
- No gravitation

...





Effective model up to the TeV scale

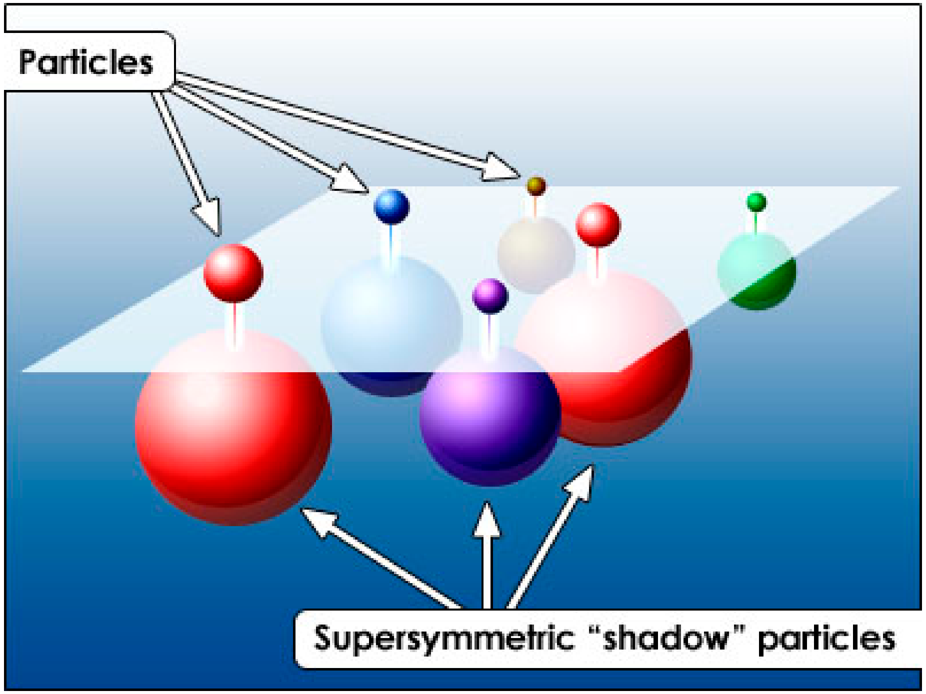
Supersymmetry

New symmetry ($\neq$ gauge symmetries) :

Boson $\leftrightarrow$ Fermion

Each SM particle get a supersymmetric partner :

Quarks, leptons : fermions (s=½) $\rightarrow$ Squarks, Slepton : bosons (s=0)
Gauge bosons : bosons (s=1) $\rightarrow$ Jauginos : fermions (s=½)
Higgs bosons : bosons (s=0) $\rightarrow$ **Higgsinos** : fermions (s=½)



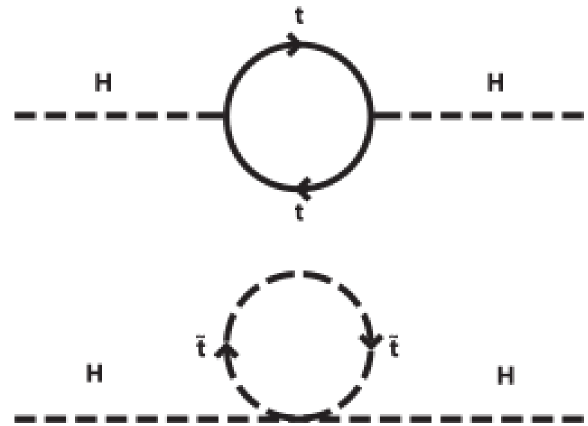
Higgs sector

5 physical states instead of 1 h^0, H^0, A^0, H^+, H^-

Higgsinos/ EW Jauginos mixing (Photino, Wino, Zino)

$\rightarrow$ 4 charginos $\tilde{\chi}^{\pm}_{1,2}$
$\rightarrow$ 4 neutralinos : $\tilde{\chi}^0_{1,2,3,4}$

Supersymmetry



Cancel (mostly) quadratic divergences

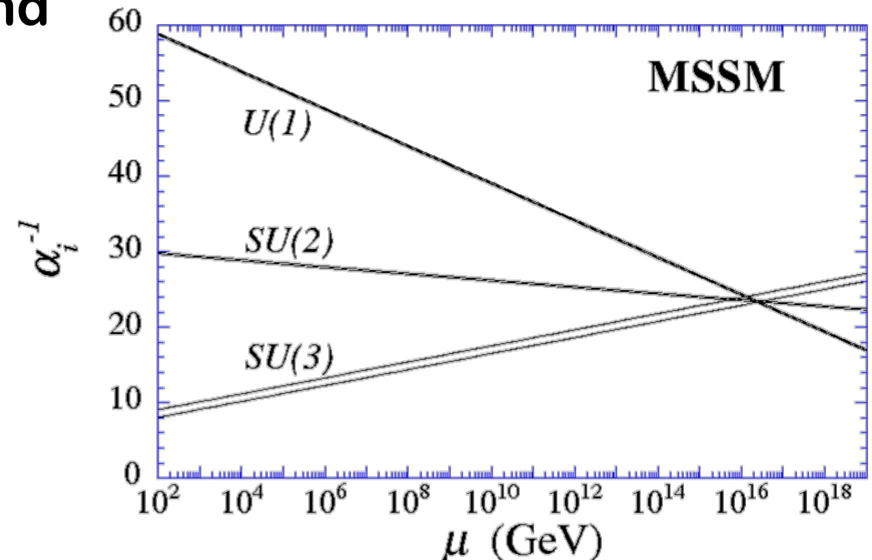
Boson loops cancel fermion loops

Unification at high energy

Only one interaction ?

Dark matter candidate

Depending on model and parameters the lightest SUSY particle (LSP) is stable (and neutral and weakly interacting…)



Broken symmetry

no SUSY particles observed yet :

$$m_{SUSY} \neq m_{MS}$$

Breaking mecanism ???

+more 120 free parameters

Reduced to 5 to 20 depending on several hypotheses : MSSM, NMSSM, MFV, GMSB…

GUT : Grand Unified Theories

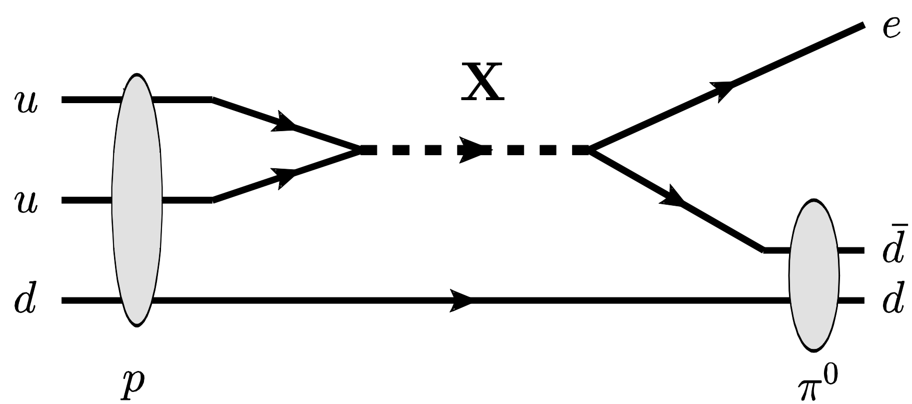
Try to include the SM gauge symmetry into a larger group

$$U(3)_C x SU(2)_L x U(1)_Y \subset G_{GUT}$$

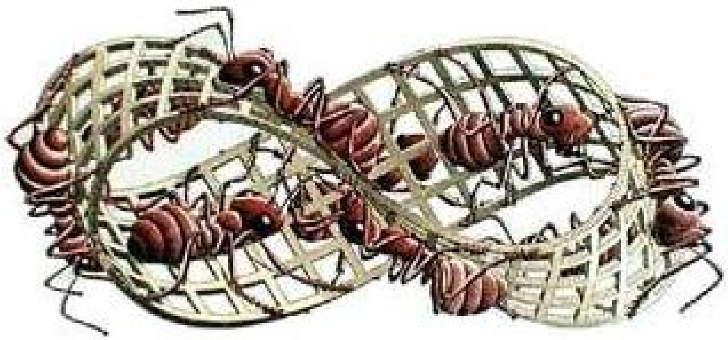
- One single coupling constant
- Induce couplings between quarks and fermions : proton becomes unstable constrains the mass of the new gauge bosons to be really heavy (10^{14-15}GeV).

Broken symmetry

- Extra « Higgs-like » bosons
- New massive gauge bosons similar to EW : Z', W'
- New type of gauge bosons coupling quarks and leptons : LeptoQuark



Extra dimensions

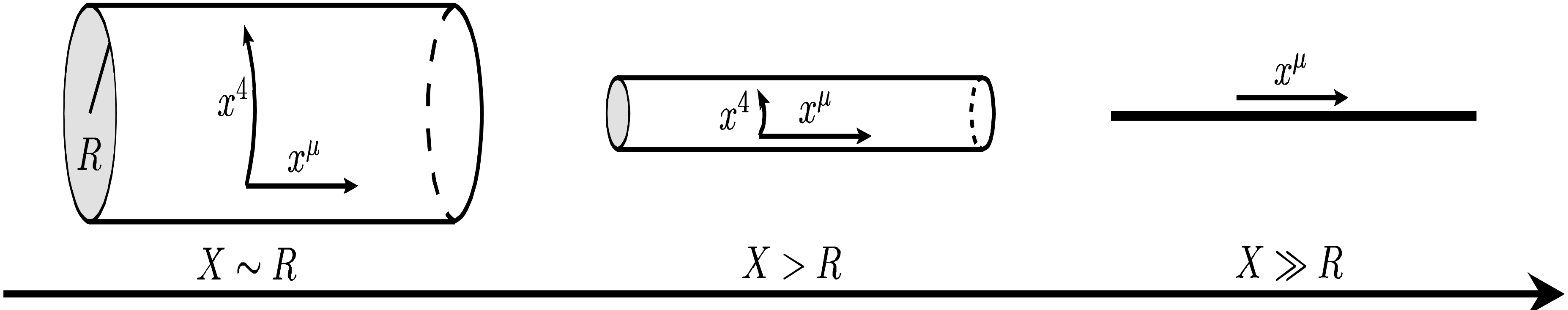


Add extra space-like dimensions

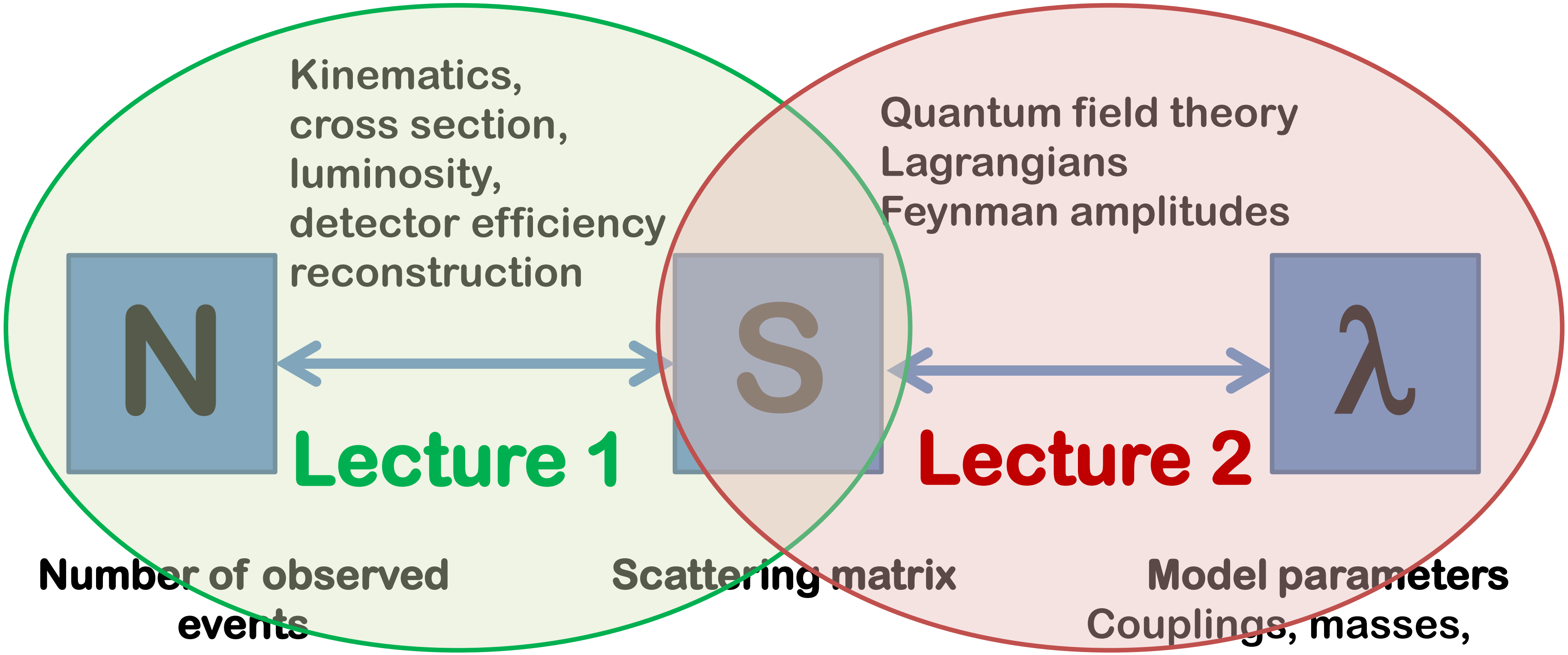
- compactified dimensions : no macroscopic effects

- depending on model only some particles can propagate into these dimensions (for exemple, for the graviton it will « dilute » the gravitationnal constant)

- predicts new resonnances/particles (Kaluza-Klein towers)



General overview



Number of observed events

Number of reconstructed top quark pairs

Experimental observable

Scattering matrix

|<i|S|f>|² = probability of changing an initial state |i> to a final state |j>

Eg : |i> = pp
|f>=top pairs (+X)

Model parameters

Couplings, masses, mixing angles…

Number and nature of particles in SM

19 parameters,
12 fermions,
3 gauge interaction +SSB

Much more in SUSY…

PART I

From event counting to cross-section

Allowed processes

Is it kinematically allowed ?

E/P conservation : $p_{tot} = \sum p_i = \sum p_f$

Lorentz invariance $|p_{tot}|^2 = s$, same in all referentials

in system restrframe : $s = |p_{tot}|^2 = |E_{tot}|^2$

$\sqrt{s}$ is the center of mass energy

in final state restframe,

if all aprticles are at rest $s = |\sum p_f|^2 = |\sum m_f|^2$ $\sqrt{s} = \sum m_f$

in general $\sqrt{s} > \sum m_f$

Is it dynamically allowed ? (does the interaction exist)

Lagrangian and Feynman diagrams

Quantum number conservations (spin, charges, ...)

eg : electron can change into a neutrino, with a W boson emission

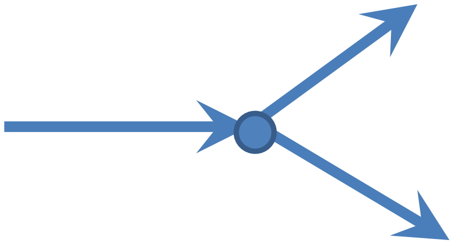
Kinematics

Focus on 2 kind of processes :

1 → N : Decay of one particle into many

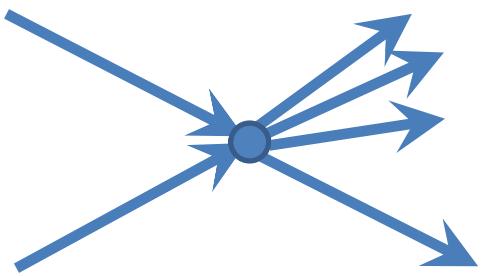
$$\sqrt{s} = M > \sum m_k$$ **heavy → light**

Lighter particles are stable



2 → N : Scattering of 2 particles

$$\sqrt{s} = p + \sqrt{p^2 + m_1^2 + m_2^2} > m_1 + m_2$$

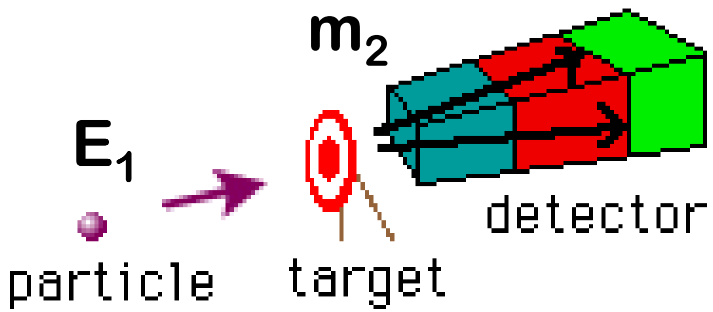


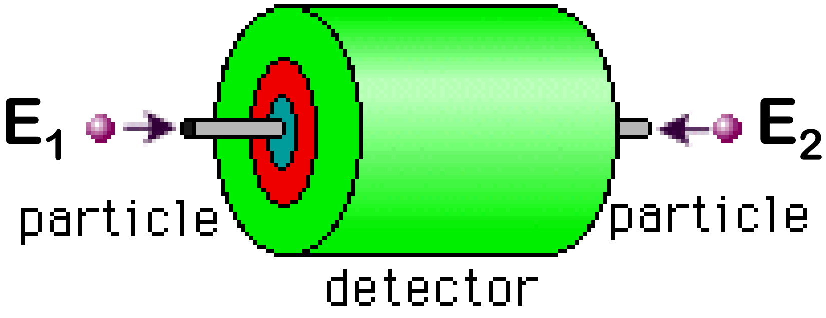
Can convert kinetic energy into mass

Produce high mass particles from high energy low mass particles

That's why we build colliders

Why colliding hadrons





$$\sqrt{s} \approx \sqrt{2\, E_1\, m_2}$$

$$\sqrt{s} = \sqrt{4\, E_1\, E_2} = 2\, E_{beam}$$

(if $E_1 = E_2$)

c.m. frame = lab frame

⇨ If E>m : Much more efficient to collide to attain higher energy in c.m. with same beam energy

⇨ But less matter density, less collisions, more difficult to study rare processes

Why colliding hadrons

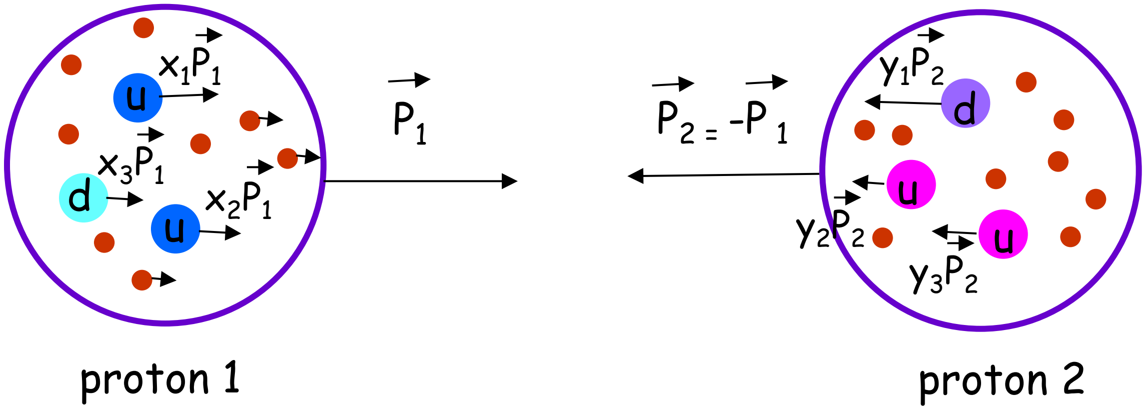
For large energies (Tevatron, LHC), collisions happen between the substructure of the hadrons : partons

- Valence quarks (u,d)
- Sea quarks (u,d,s,c,b,t) (QCD quantum fluctuations)
- Gluons (QCD quantum fluctuations)

Each parton carries a fraction x of the proton momentum

☺ Covers a wide range of center of mass energy : good to look at new particles through resonnances.

☹ Total energy collision and partons energies remains unknown



From partons to hadrons

Factorisation theorem : decouple pertubative and non perturbative effect

$$\sigma_{p\bar{p}\to X} = \sum_{\text{partons}: i,j} \int_0^1 \int_0^1 f_i^p(x_1) f_j^{\bar{p}}(x_2)\, \hat{\sigma}_{ij\to X}\, dx_1 dx_2$$

Parton density function

Non pertubative QCD : can only be measured

$f_p(x,Q^2)$ = Prob to find a given parton p (u,d,s,c,b,t or gluon) with momentum fraction x, at energy (or length) scale Q in a proton.

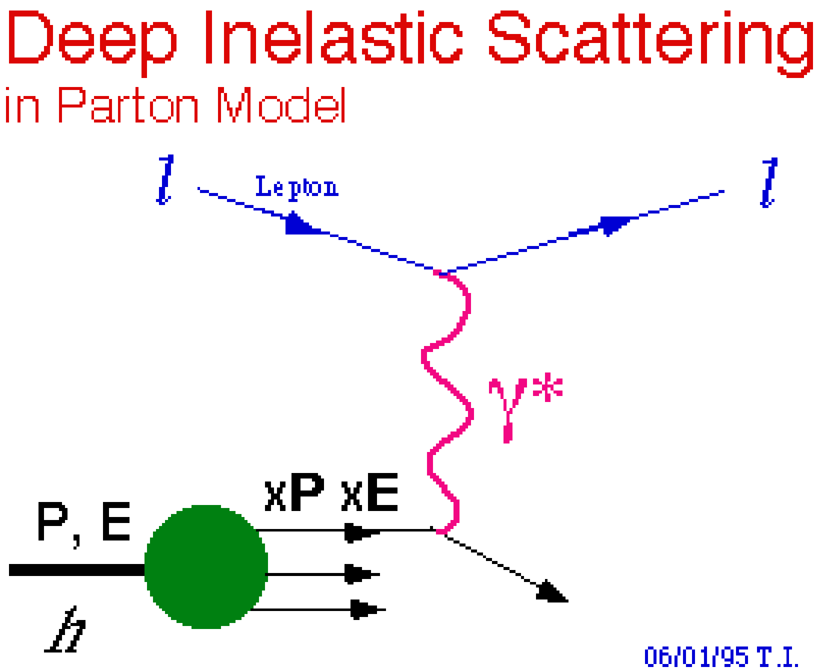
Partonic cross-sections

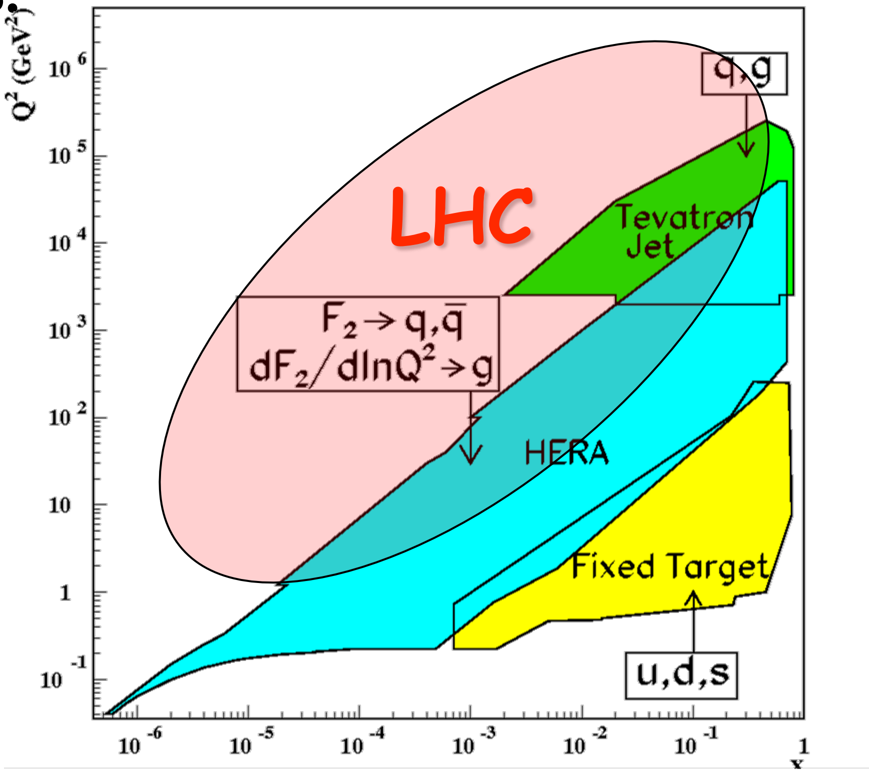
Hard scattering between two partons

Pertubative QCD : can be computed through Feynman diagrams

PDFs : Parton density function

Measured in Deep Inelastic Scattering of electron (punctual probe of fixed energy) on protons.

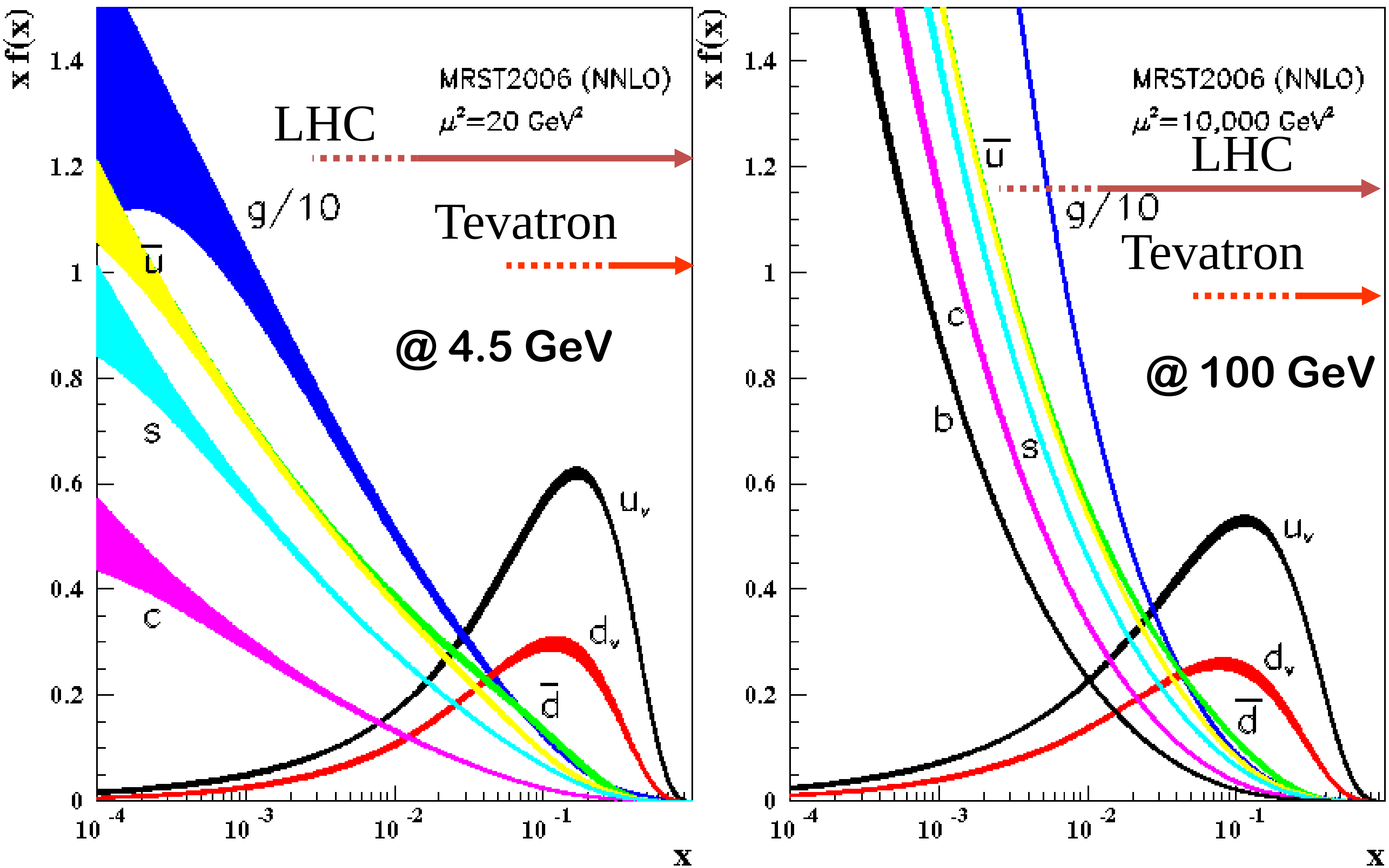




Collider experiments : HERA (Desy, Hamburg) + Fixed targets

- **Measured at "low" Q^2**
- **Evolution as function of Q^2 theoretically known :**
  DGLAP equations.

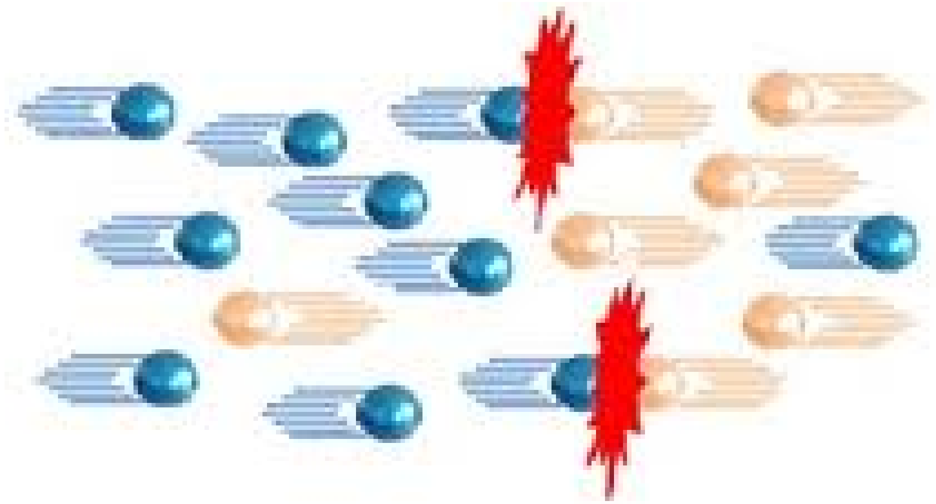
PDFs : Parton density function



Colliding protons : an event

In a collider hadrons ares grouped by bunches :

10^{12-13} for protons, 10^{9-11} for antiprotons



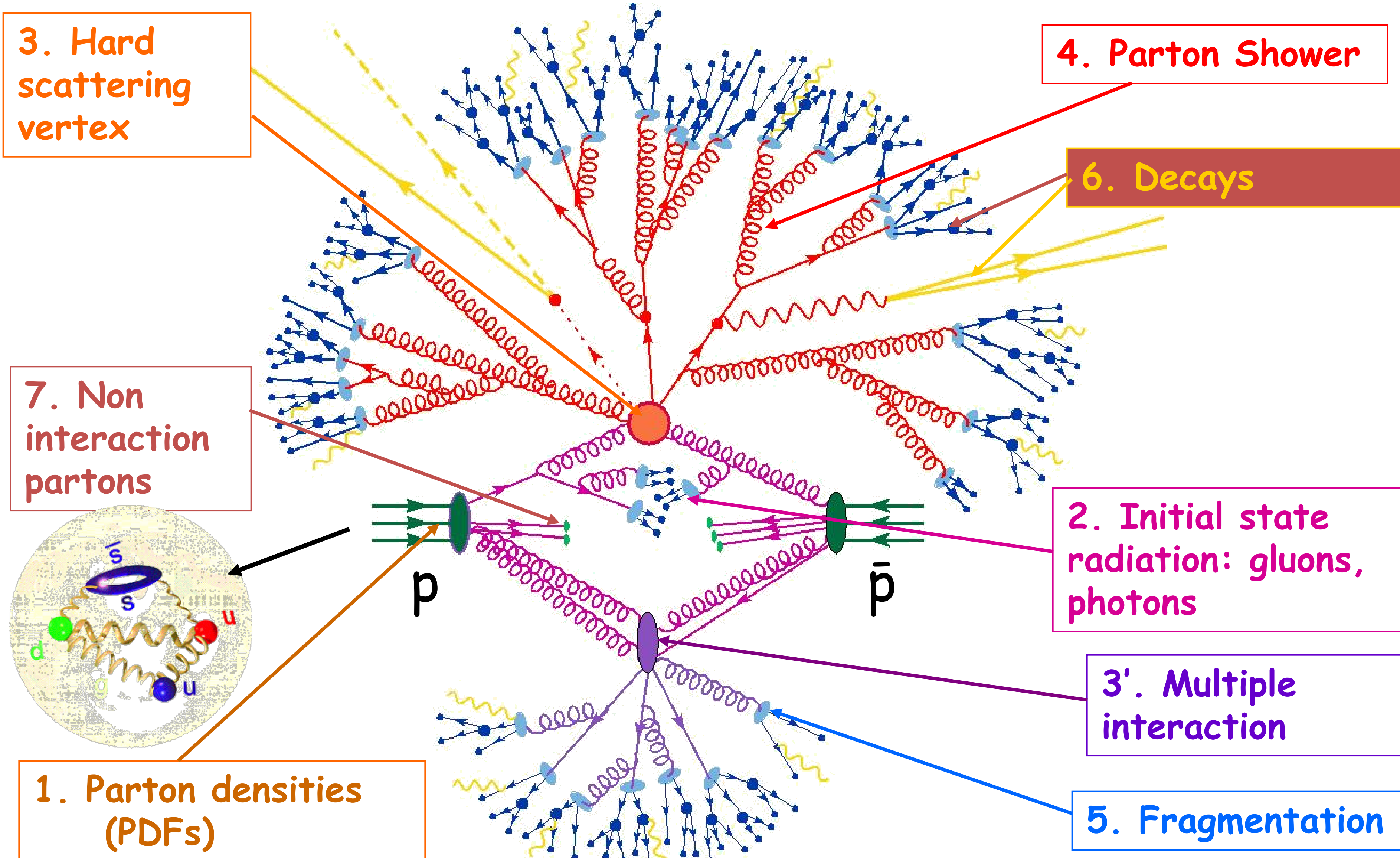
When 2 bunches collide, this makes an EVENT

bunch crossing time :

@ LCH : 50/25 ns   event rate : 20-40 MHz

@ Tevatron : 496 ns   event rate : 2 MHz

(simplified) Hadronic collision



What to detect (1)

Particle lifetime τ_0 : number of surviving particles at time t

$$N(t) = N_0 \exp(-t / \tau_0)$$

With time measured in the particle restframe.

In another frame, apply Lorentz boost :
$\rightarrow$ time dilatation, longer apparent lifetime

$\tau = \gamma \tau_0$ **with** $\gamma = (1 - v^2/c^2)^{-1/2}$ **(Lorentz factor)**

Average flight length in the detector:

$$L = v\,t = \beta c\,t = \beta \gamma c \tau_0 = p c \tau_0 / m$$

Only particles with L>detector size can be directly detected.

Other particles will decay before entering the detector

What to detect (2)

Stable particles

electrons

protons

photons

neutrinos (but don't interact)

Unstable particles

muons $\mu^{\pm}$, $c\tau$ = 6.59 x 10^4 cm

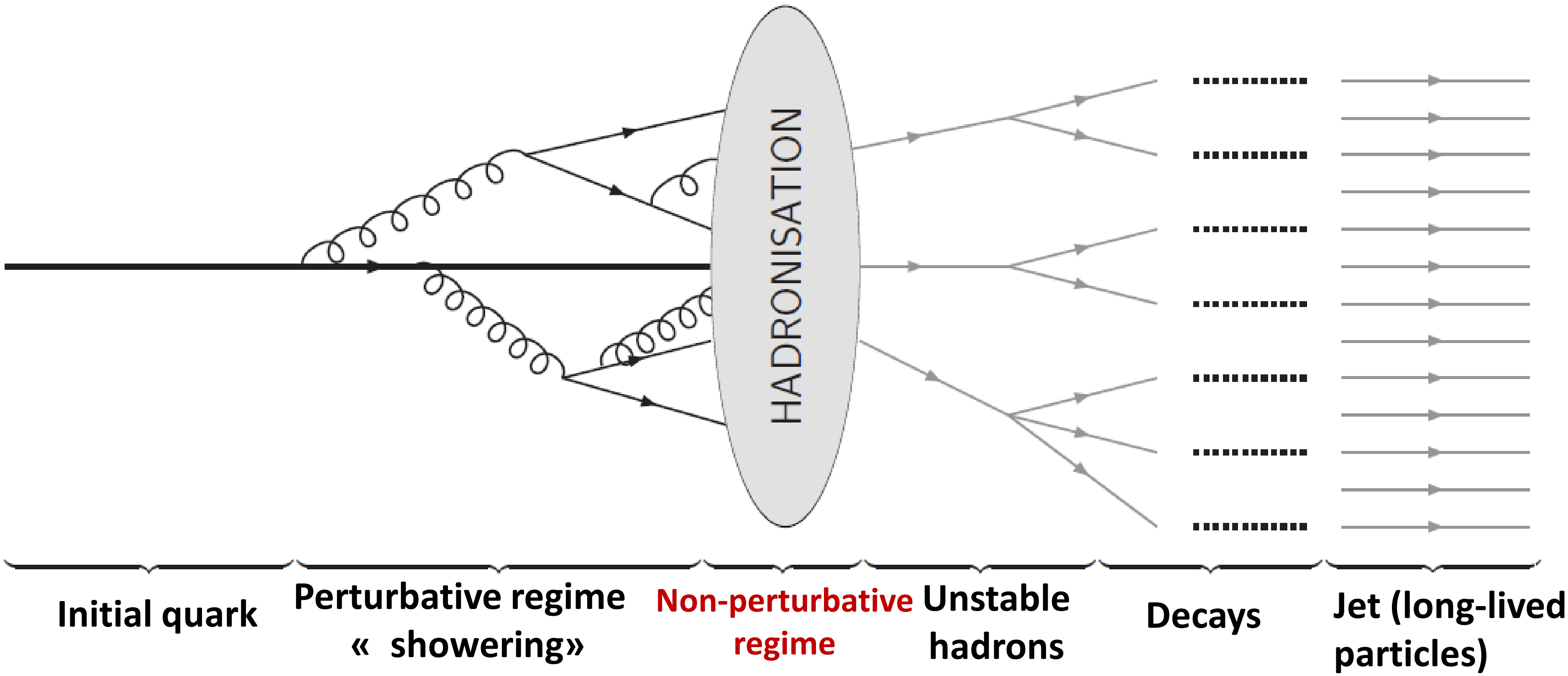
charge pions $\pi^{\pm}$, $c\tau$ = 780.4 cm

charged kaons $K^{\pm}$ $c\tau$ = 370.9 cm

neutral kaons K^0 $c\tau$ = 1554 cm

neutrons $c\tau$ = 2.7 x 10^{13} cm

Jets



Final states quarks and gluons are colored particles
High energy : gluon radiation (brehmstrallung)
until reach non perturbative regime : confinement kicks in

Jet : bunch of collimated particles (mostly hadrons), sharing the momentum of the initial parton

Typical SM signature

Neutral pion

$\pi^0 \rightarrow \gamma\gamma$ **Two, highly collimated photons**

τ lepton

$\tau \rightarrow e\,\nu, \mu\,\nu$: 1 electron/muon, $p_T \sim 0.5\, p_{T\tau}$

$\tau \rightarrow$ pions ($\pi^\pm, \pi^0$): small jet (a few pions)

W boson

$W^+ \rightarrow e^+\nu, \mu^+\nu$: 1 electron/muon ($p_T \sim$ 40 GeV), missing energy

$W^+ \rightarrow q\bar{q}$: 2 jets ($p_T \sim$ 40 GeV), invariant mass ~80 GeV

Z boson

$Z \rightarrow ee, \mu^+\mu^-, q\bar{q}$: 2 electrons/muon/jets

$p_T \sim$ 40 GeV, invariant mass ~91 GeV

Top quark

$t \rightarrow bW$: 1 b-jet ($p_T \sim$ 70 GeV), 1 W boson (see above)

Luminosity and Cross section

The number of events is given by a simple formula

$$N = L.\sigma$$

collider

physics

L = Luminosity

Describe the number of effective pp collisions

σ : cross section
-> related to the physics parameter

Describe the processes $pp \rightarrow X$

Luminosity

Instantaneous luminosity : $dN/dt = \Lambda(t)$

Number of collisions :

proportional to

number of particles per bunch : n_1, n_2

frequency of collisions : f

inversely proportional to the beam size : $\sigma_x . \sigma_y$

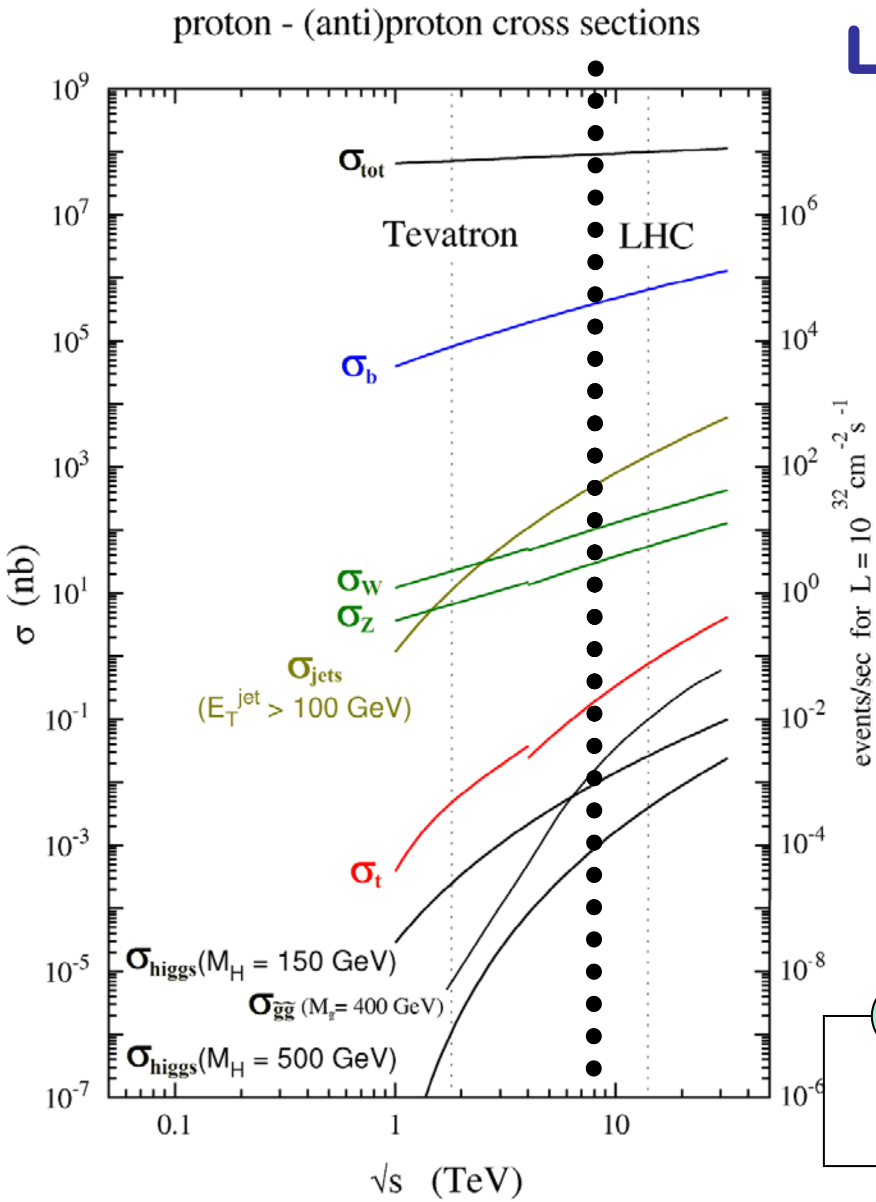
σ_x and σ_y are the transverse dispersion of the beam

$$\Lambda = \frac{f.n_1.n_2}{4\pi.\,\sigma_x\,\sigma_y}$$

Instantaneous luminosity: in $cm^{-2}.s^{-1}$

Integrated luminosity : $L = \int \Lambda(t)$ in pb^{-1} or fb^{-1}

Triggering



$L = 5.10^{33}\ cm^{-2}s^{-1}$ @ LHC 8TeV

~ 500.10^6 events / s

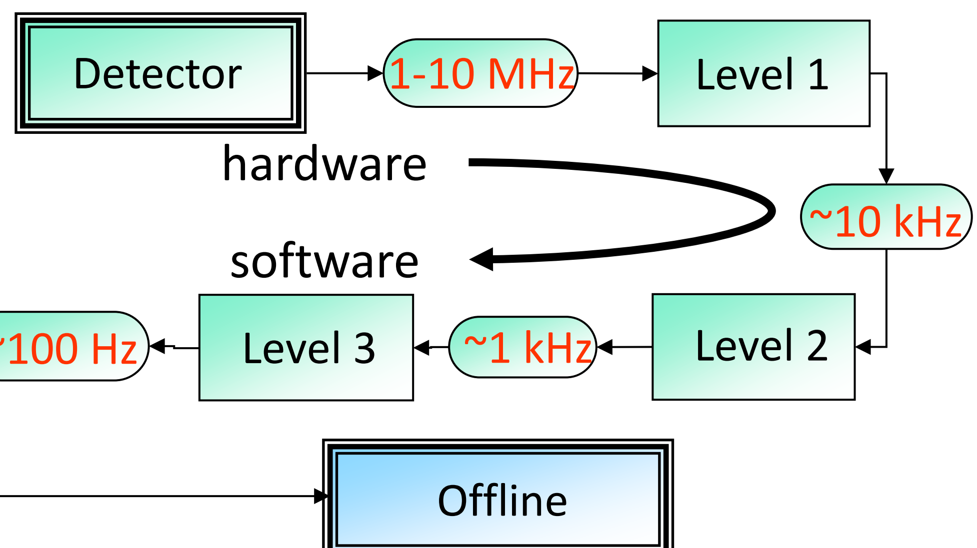
~ 2.10^6 $b\bar{b}$ pairs / s

~ 500 W bosons / s

~ 50 Z bosons / s

~ 2 $t\bar{t}$ pairs / s

~ 0.2 Higgs bosons / s



Number of detected events

$$N = L.\varepsilon.\sigma + b$$

ε : Efficiency

Trigger efficiency

Detector geometric acceptance

Reconstruction efficiency

Selection efficiency

b : Backgrounds

Misidentified objects

Miscalibrated objects

Geometry and kinematics

3 coordinates systems are used (and mixed !!!)

- cartésian : **P** = (P_x, P_y, P_z)
- sphérical: **P** = (P, θ, φ)
- modified spherical : **P** = (P_T, η, φ)

z = beam axis (x,y) = transverse plane

θ = azimuthal angle (relative to z) $\rightarrow [0,\pi[$

φ = polar angle (in transverse plane) $\rightarrow [0,2\pi[$

P = momentum ($P^2 = P_x^2 + P_y^2 + P_z^2$)

P_T = transverse momentum ($P_T^2 = P_x^2 + P_y^2$)

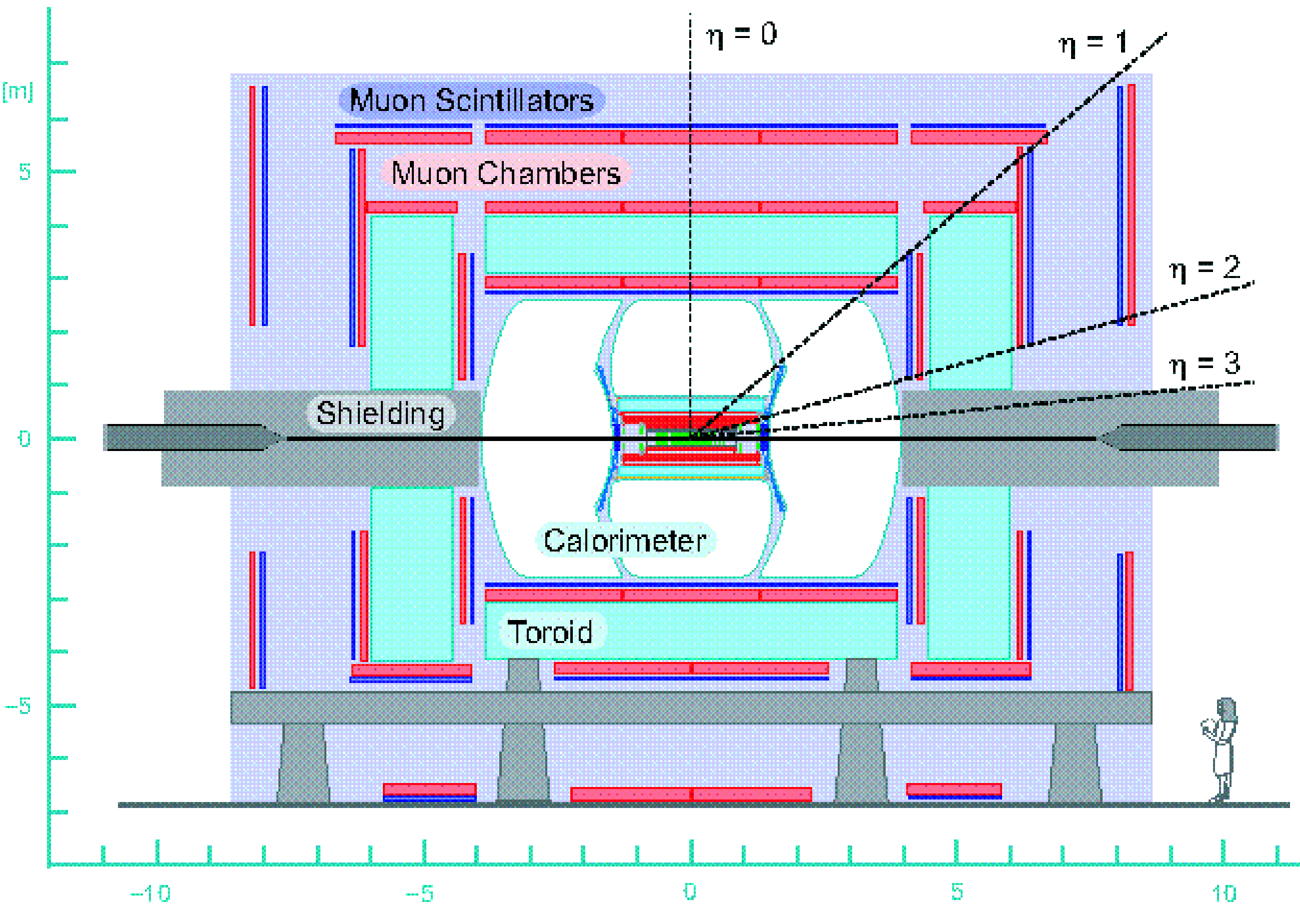
η = pseudorapidity $\eta = -\ln\left(\tan\frac{\theta}{2}\right) = \frac{1}{2}\ln\left(\frac{P+P_z}{P-P_z}\right)$ $\rightarrow$ **geometry**

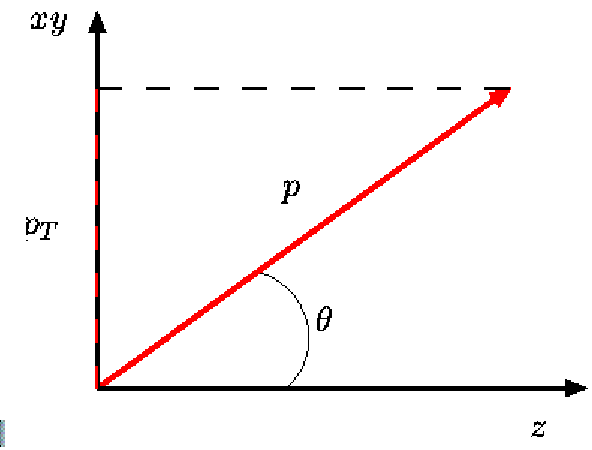
Massless/relativistic particle :

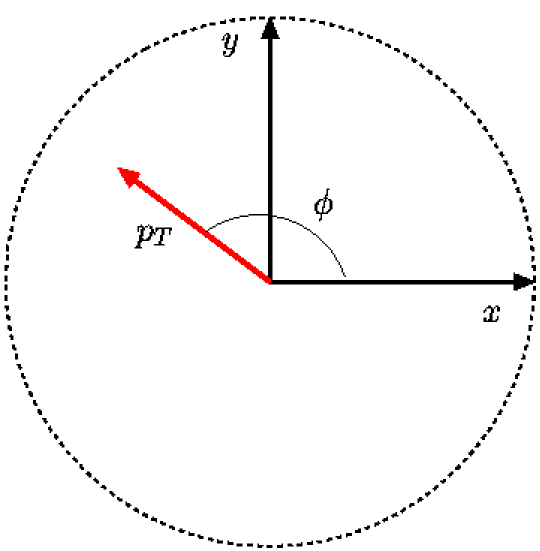
P = E and η = y (rapidity) $\eta = \frac{1}{2}\ln\left(\frac{E+P_z}{E-P_z}\right) = y$

Rapidity intervals are Lorentz invariant

Detector geometry



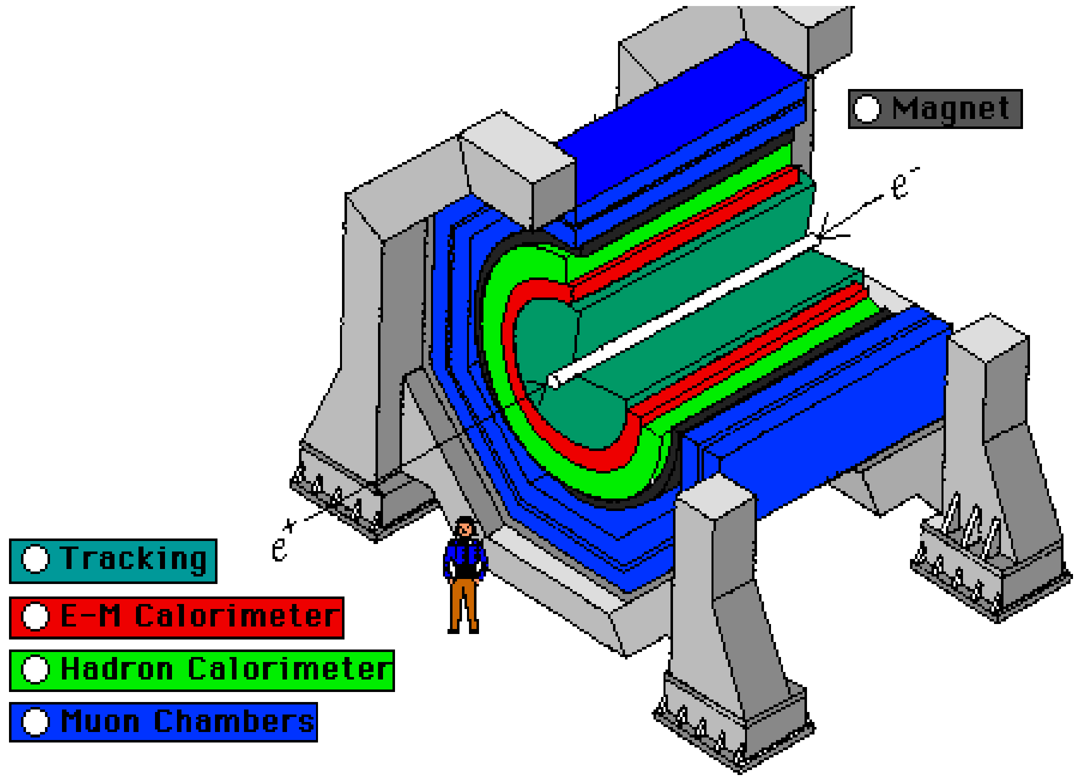




η=0 : transverse plane $P_z=0$

η=∞ : beam axis $P_x=P_y=0$

Generic detector



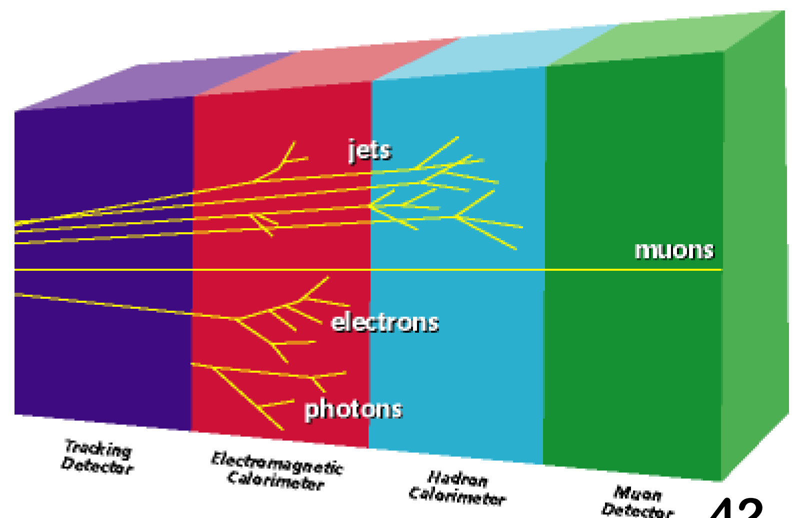
Subdetectors

Tracker : charged particles

EM Calorimeter: electrons, photons, jets

HAD Calorimeter : jets

Muon system : muons



Reconstruction

Two kind of detectors

- **Trakers :**
  trajectory of charged particles, very low energy deposit
  use B field to determine momentum
- **Calorimeters :**
  destructive measurment : particles are stopped
  energy measurement
  segmented detectors : momentum direction

Detector output

- **hits in tracker : points along trajectory**
- **energy deposit in calorimeters cells**

Physical objects to identify

- **tracks**
- **electrons and photons**
- **hadronic jets**
- **tau leptons**
- **vertices (interaction points)**
- **muons**
- **b-quark jets**
- **missing energy**

Reconstruction = determine the 4-momentum of each particles.

4 or 3 parameters per object (at high energy $m \approx 0$, $E=p$)

Reconstruction

Reconstruction algorithms:

- Clustering hits / cells from a same object.
- Detemine the 4-momentum of the object
- Many events, many read-out channels : fast algorithms

Caracterising the algorithm

- Algorithm efficiency: How many objects are missed ?
- Misidentification : How many object are wrongly identified?

Compromise to find :

- very good identification but low efficiency
- very good efficieny but low purity

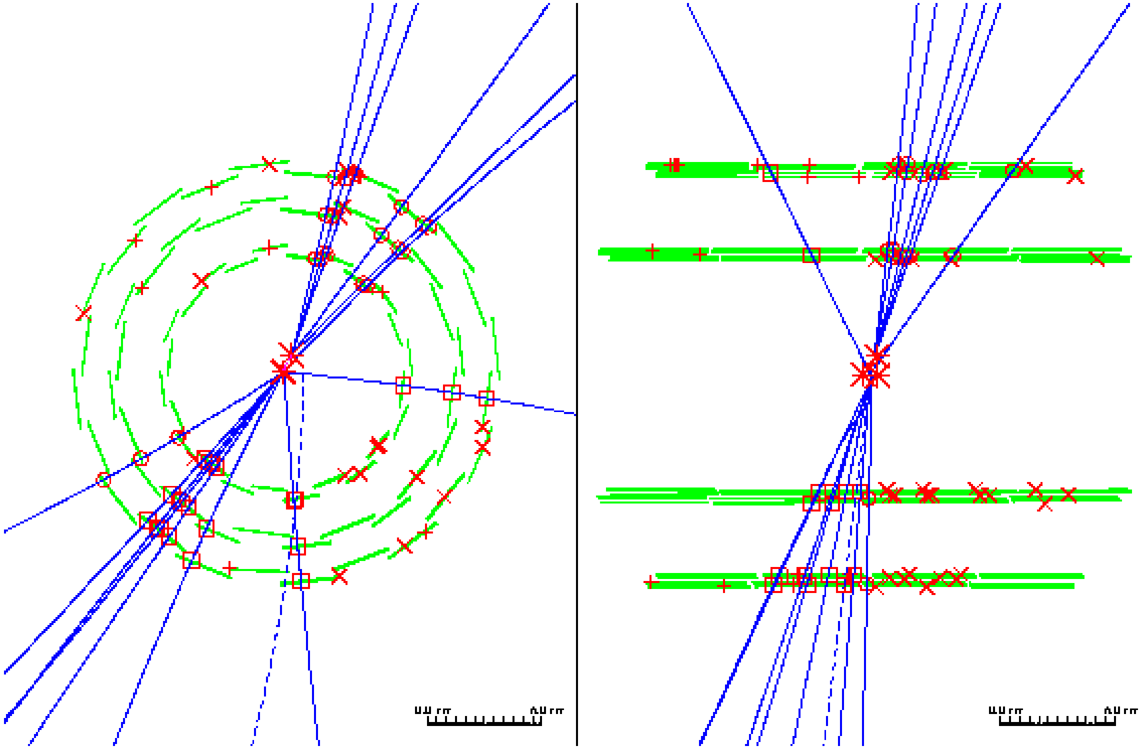
Calibration of algorithms:

- Correct from measured value to true value
- Estimation of the precision/resolution on energy/momentum

Tracking and vertexing

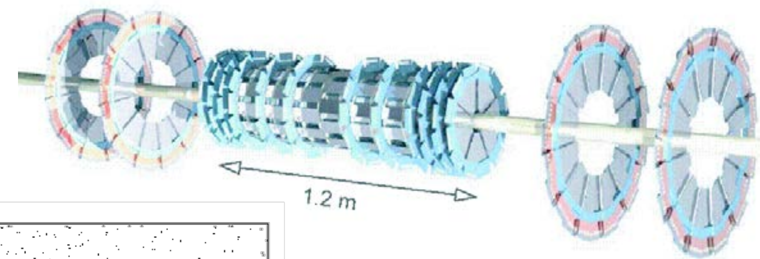
Heavy Khi-square fits : Kalman filters
- **fit helicoidal trajectory to hits : track**
- **fit convergence of tracks : vertex**

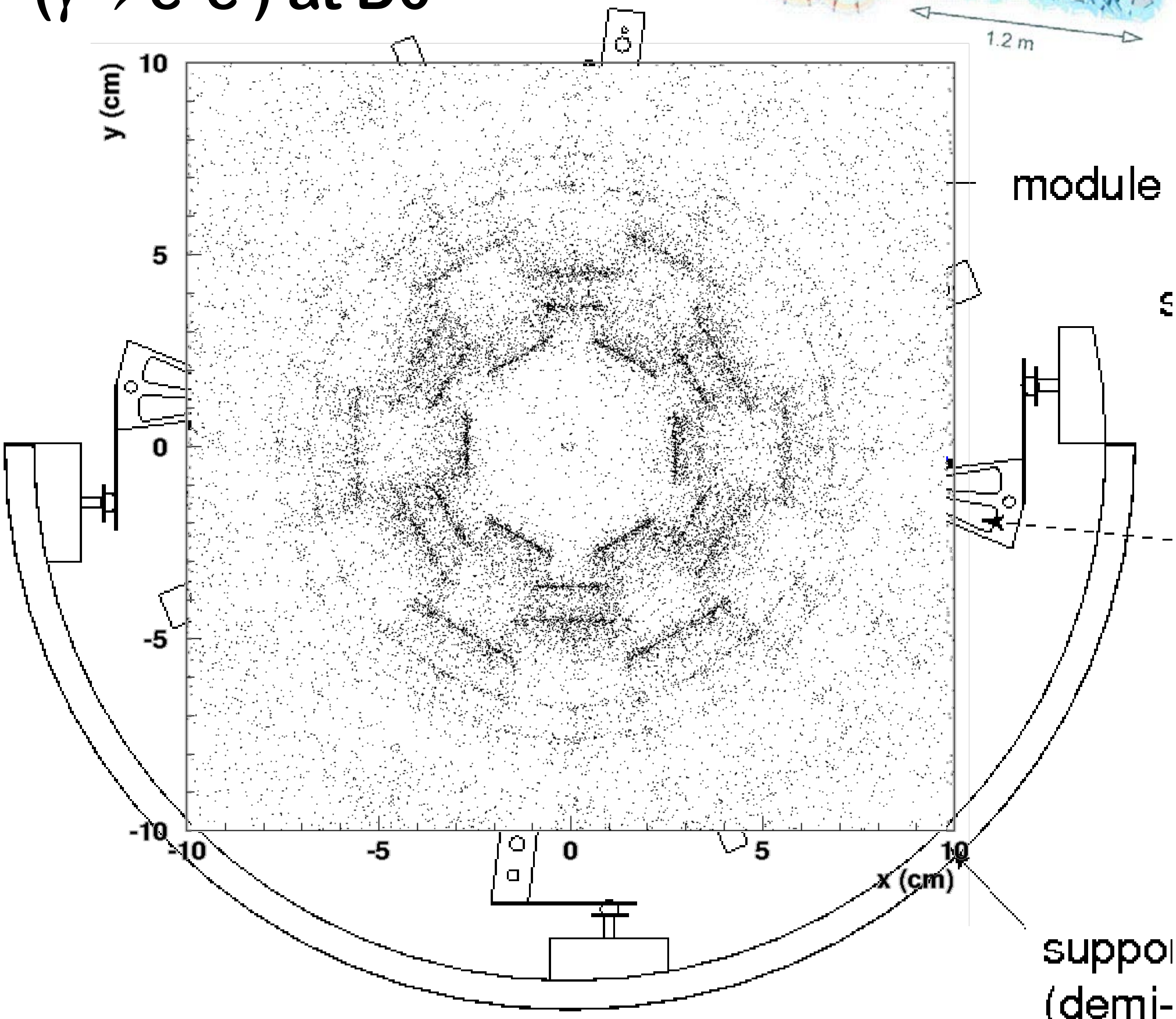
Main collision vertex : primary vertex
Long lived particles (B hadrons) : secondary vertices



Check of the reconstruction

Pair creation in tracker matter
($\gamma \rightarrow e^+e^-$) at D0





Showers

Electromagnetic : photon/electrons

High energy particles

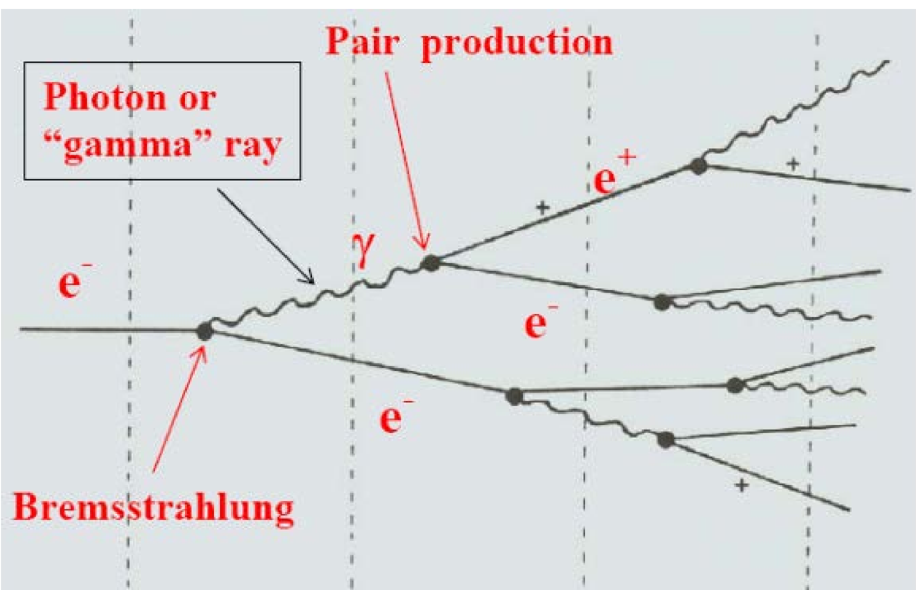
$e \to e\gamma$ Brehmstrallung

$\gamma \to e^+e^-$ Pair creation

$\to$ Shower

Low energy : compton, photoelectric, positron annihilation, ionisation…

$\to$ Particles are stopped/absorbed



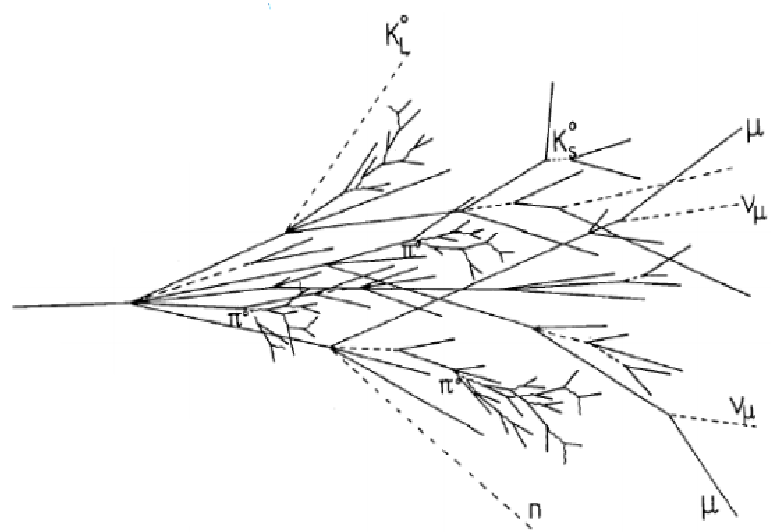
Hadronic

Inelastic collisions induce fission

Produciton of secondary hadrons

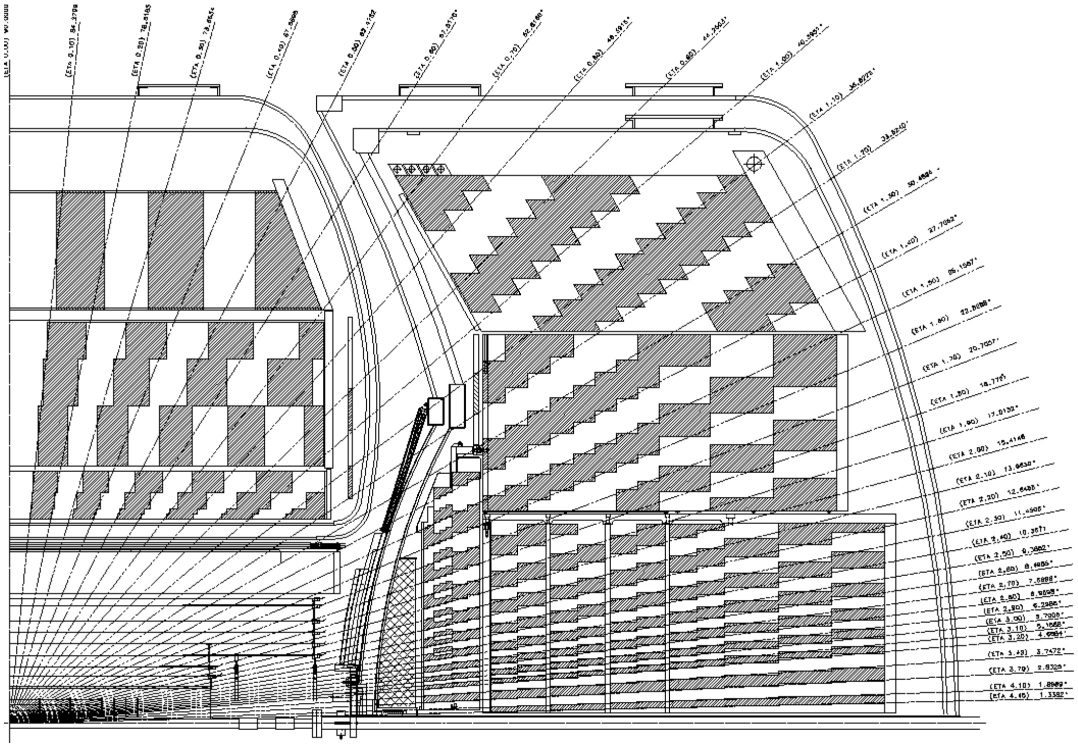
Jet : many hadrons, suppoerposition of shower

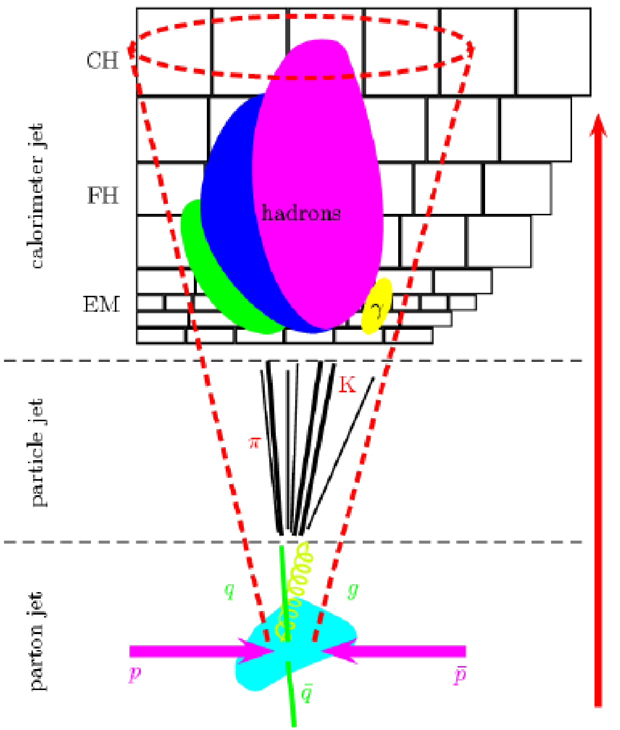
Wider than EM showers



Calorimetry : jets, electrons, photons

Calorimeter structure : pseudoprojective towers of cells (η, φ constant)





Jets and electrons are build clustering neighbouring cells and towers

- start point : towers with high energy deposit (several GeV)

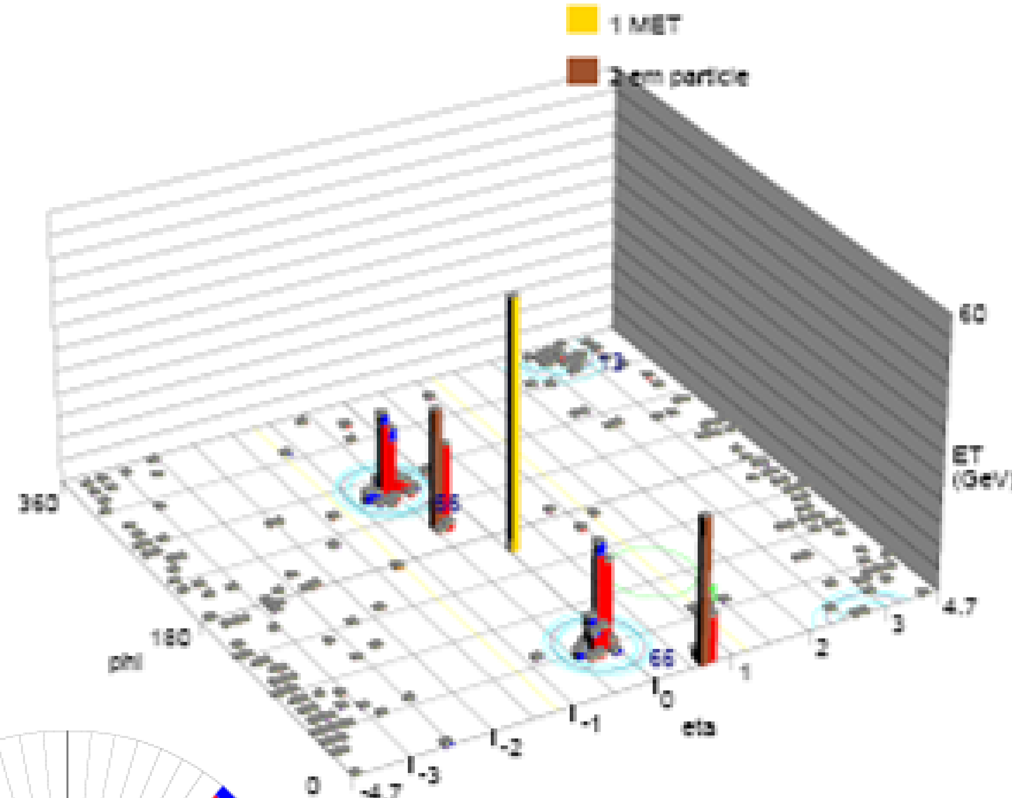
- add closest towers withi na given range : need to define distance

p.e (η, φ) space distance $\Delta R^2 = \Delta\eta^2 + \Delta\varphi^2$

$\Delta R < r_0$: circle in (η, φ) space , « cone » in physical space

Fixed cone algorithm (simplest one, many others : seedless cone, kT…)

Calorimetry : jets, electrons, photons



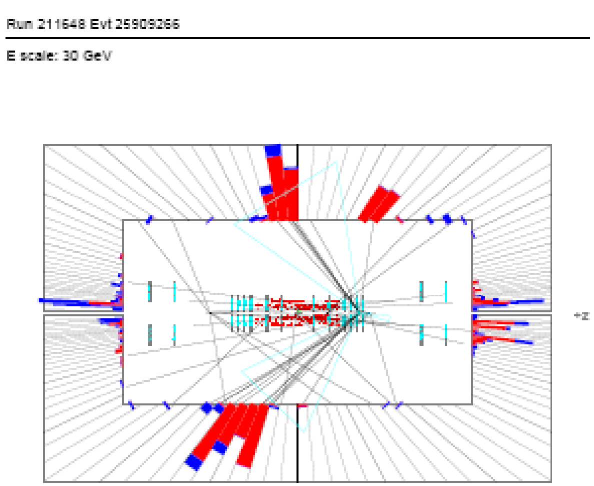
Electron/jet separation

Shower shape

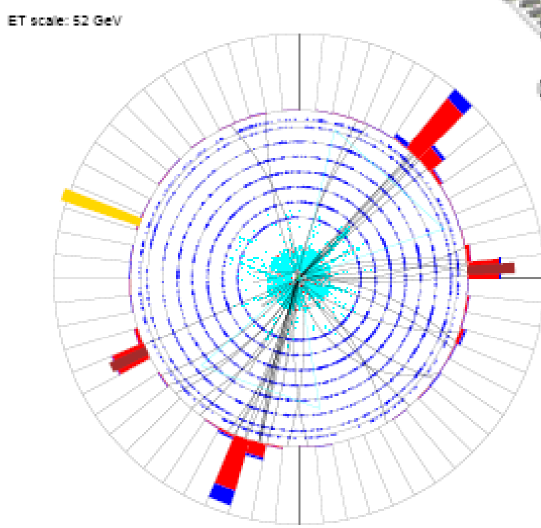
Calorimeter structure (EM/Had)

Electron/photon separation

Match to charge particle track



(a) Vue en coupe RZ.



(b) Vue en projection XY.

Blue : Hadronic calorimeter energy

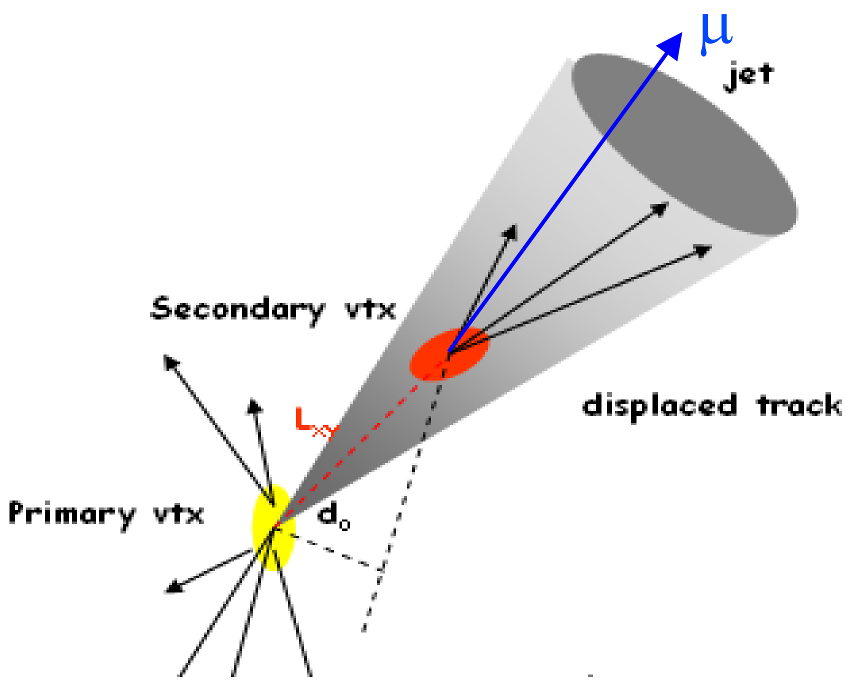
Red : Electromagnetic calorimeter energy

Jets from b quarks

B-quark hadrons decays

Weak interaction : large lifetime ($\sim 10^{-12}$s) : displaced secondary vertex

Large fraction of semi-leptonic decays (~20%) : muons or electrons within th jet cone



Identification techniques

match tracks to calorimeter jets

look for secondary vertices build upon those track

muon / jet matching

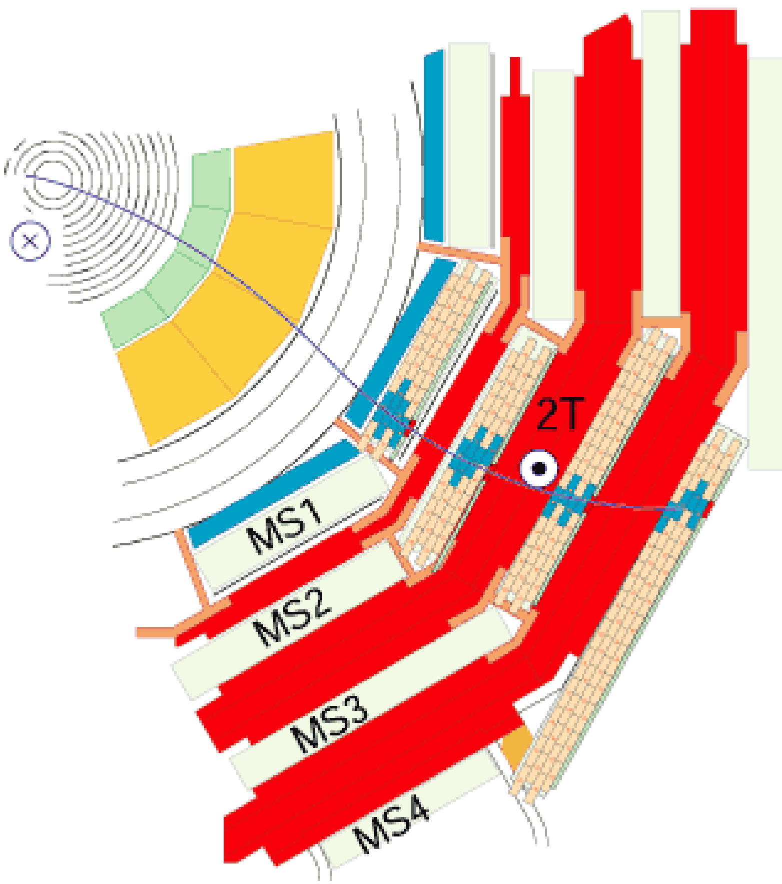
Complex identification : efficiency = 50% , mistag=0.1%

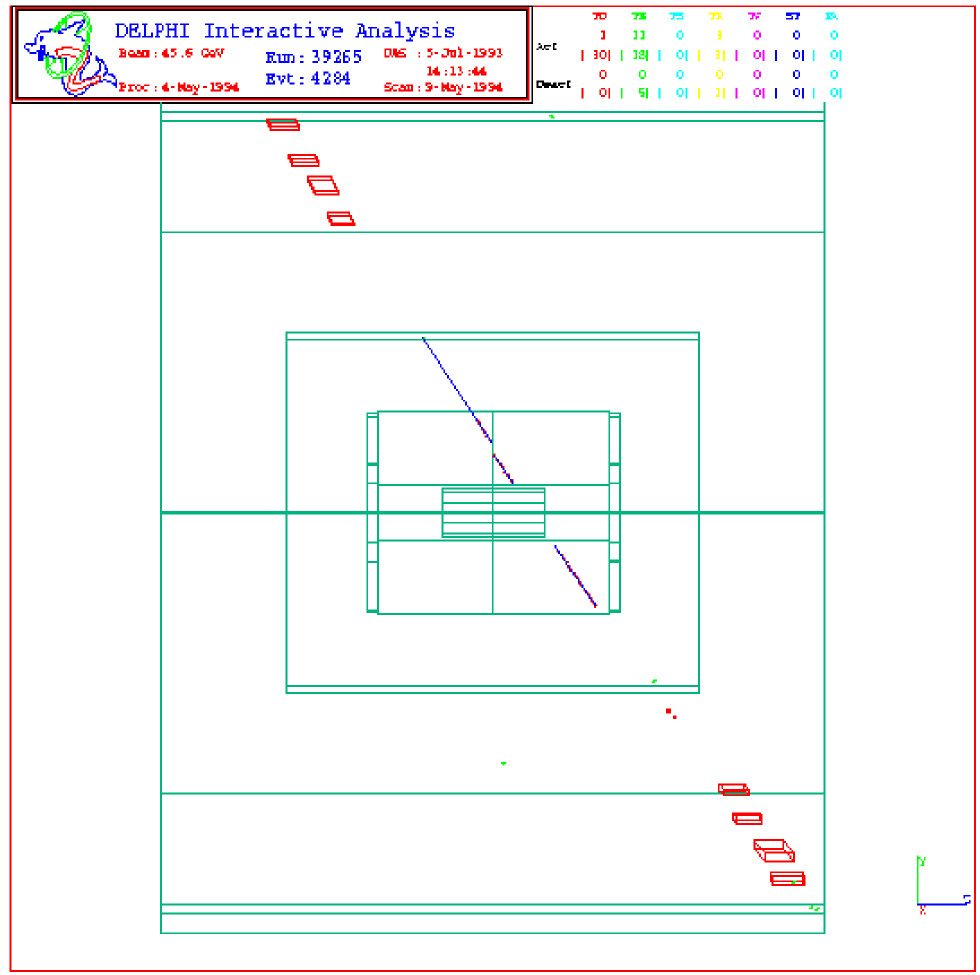
Muons

Muons are the only particles that go out of the calorimeter

External tracking system with independent B field

Match to internal tracker for better momentum resolution





Missing transverse energy

Momentum conservation

$\sum p_x^{final} = \sum p_x^{init} = 0$ $\sum p_y^{final} = \sum p_y^{init} = 0$

$\sum p_z^{final} = \sum p_z^{init} = ???$ Because of parton density

If one measure all transverse momenta of final particles

$0 = \sum p_x^{final} = \sum p_x^{detected} + \sum p_x^{undetected}$ $\sum p_x^{undetected} = \not{E}_{Tx}$

Same for y axis. Finally $\not{E}_T : \sqrt{\not{E}_{Tx} + \not{E}_{Ty}}$

Interpretation of the imbalance :

neutrino, if only one $\not{E}_{T} = p_T$

neutralino, other new physics with no interaction

instrumental noise, miscalibration : sensitive to all resolution effects on all objects (jets, electron, muons...)

Physics analysis

Search for new particle

Cross-section measurment

Particle property (mass, spin…) measurement

Step 1 : process and signature

identify pertinent process(es) (Feynman diagrams)

determine final state(s) (eg: 2 electrons, 1 muon, 3 jet and missing energy…)

identify processes with similar signatures (backgrounds)

In hadron collisions, many jets are produced

one will always try to find non fully hadronic final states

- containing leptons (e ou mu)
- containing photons
- containing high-p_T jets

Physics analysis

Step 2 : event selection

apply selection cuts to isolate the wanted signature.

estimate the signal selection efficiency

estimate the background contributions

- Monte Carlo simulations
- theoretical calculation of cross-section.
- data-driven methods

Step 3 : extract final result from selected data

It is never possible to identify the process creating an event

Only **statistical analysis** :

- compute average number of expected events
- use Poisson statistic

Monte Carlo simulation

Use MC Simulation to mimic the physical processes

❶ Hard scatter process : use differentation cross section as pdf
softwares : ALPGEN, MadEvent, MC@NLO, POWHEG

❷ Showering, Hadronization;, Multiple interaction : empirical models (non perturbative QCD)
softwares : Pythia, Herwig/Jimmy

❸ Detector material : energy deposit in matter (Bethe-Bloch,…)
software : GEANT 4

❹ Detector response (electronics) : digitization

At the end simulated data have the same format as raw data out of the detector.
One can use the same reconstruction and analysis cuts

Exemple : Higgs search

Main production mode: gluon fusion gg $\rightarrow$ H

- need leptons/photons in final states

  H $\rightarrow$ WW, H $\rightarrow$ ZZ : at least one W/Z $\rightarrow$ leptons

  H $\rightarrow$ $\tau\tau$ (need tau-id ?)

  H $\rightarrow$ $\gamma\gamma$ (very clean but low BR)

Other modes : WH, ZH, ttH(->WbWbH) (10 to 100 times less)

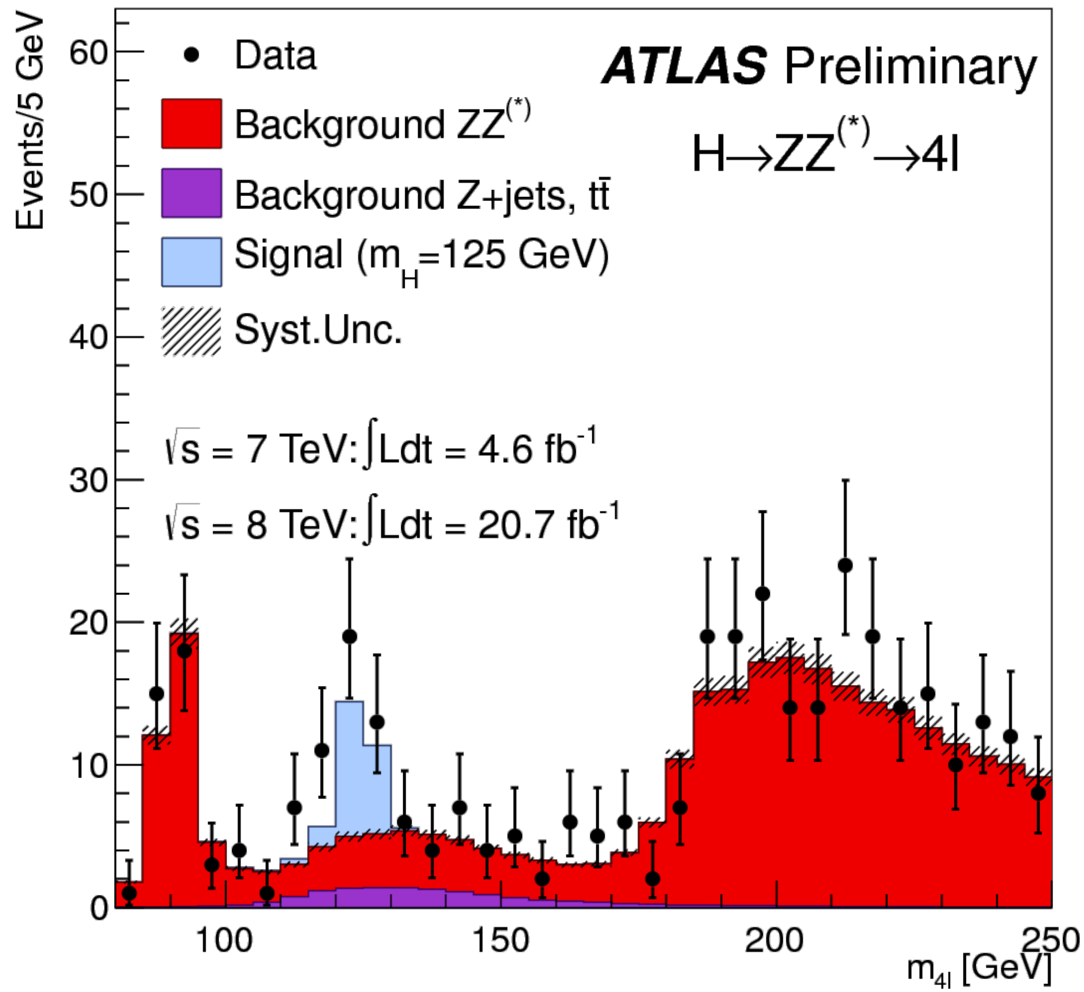
- leptonic decay of Z/W .
- H $\rightarrow$ bb needs b-tagging.

Exemple : H → ZZ* → 4 leptons

Selection :

4 muons, 4 electrons or 2 muons and 2 electrons with high p_T (> 25 GeV)

Invariant mass of 2 identical leptons compatible with m_Z



Main backgrounds :

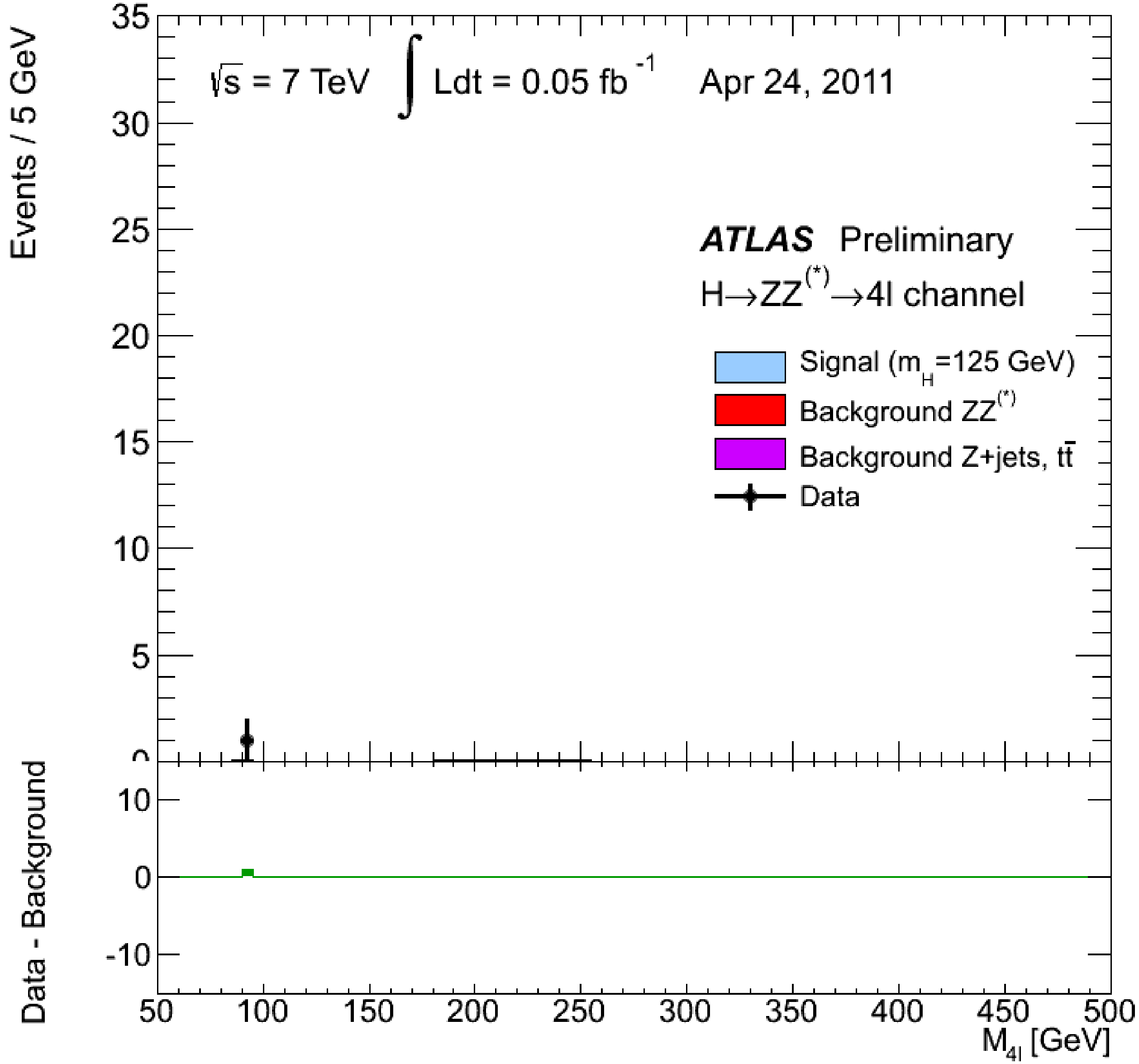
- Physical : ZZ, ZZ*

$q\bar{q}$ -> ZZ* -> 4 leptons

- Intrumantal : Z+jets

Use the invariant mass of the 4 lepton as discriminating variable.

Exemple : H → ZZ* → 4 leptons



Exemple : H → γγ

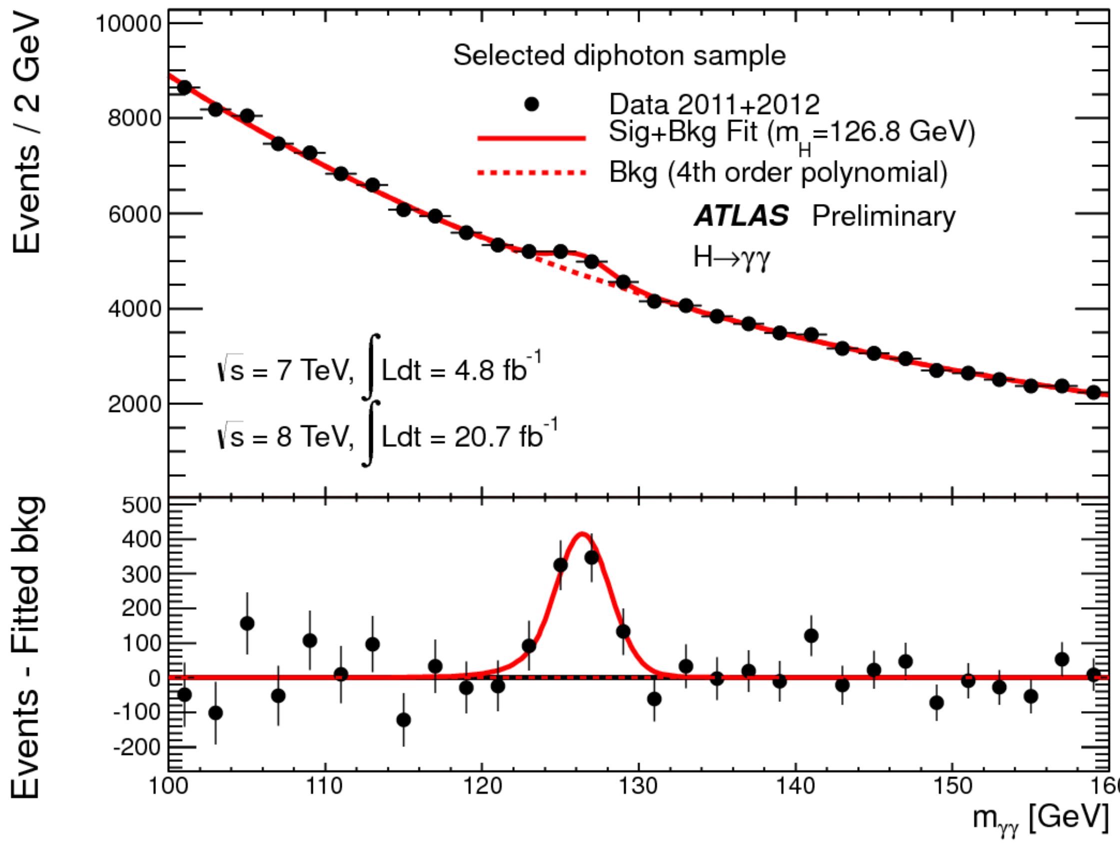
Selection: **2 clearly identified photons with high p_T (> 25 GeV)**

Main backgrounds :

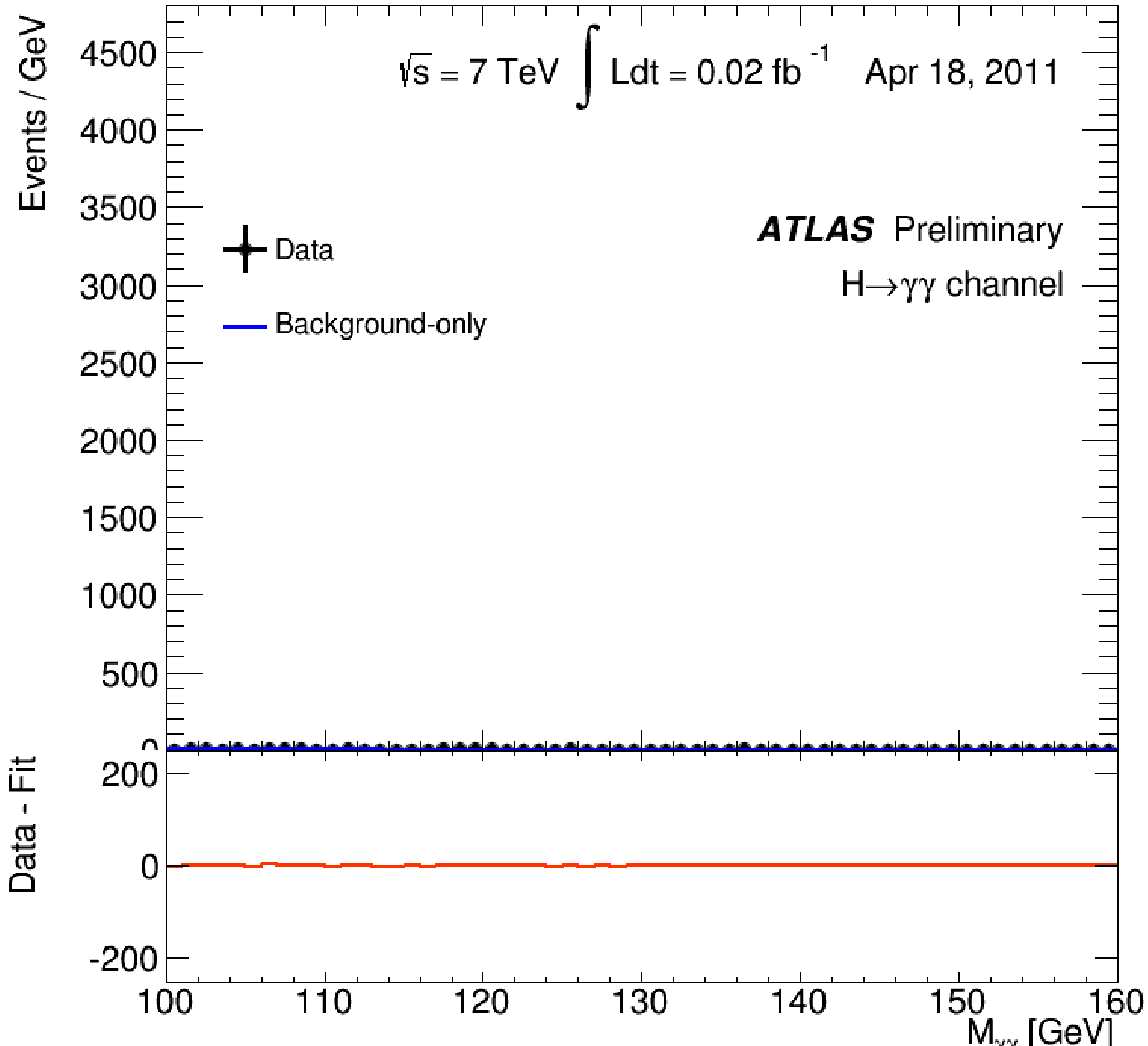
- **physical di-photon : $q\bar{q} \to \gamma\gamma$**
- **di-electron (Z) and di-jets ($q\bar{q}$, gg) events with 2 mis-identifications**

Discriminating variables:
Invariant mass of the photons system

Required good resolution on 4-momenta : E, η, φ



Exemple : H → γγ



Events / GeV
$\sqrt{s}$ = 7 TeV $\int$ Ldt = 0.02 fb^{-1} Apr 18, 2011
ATLAS Preliminary
H→γγ channel
Data
Background-only
Data - Fit
$M_{\gamma\gamma}$ [GeV]