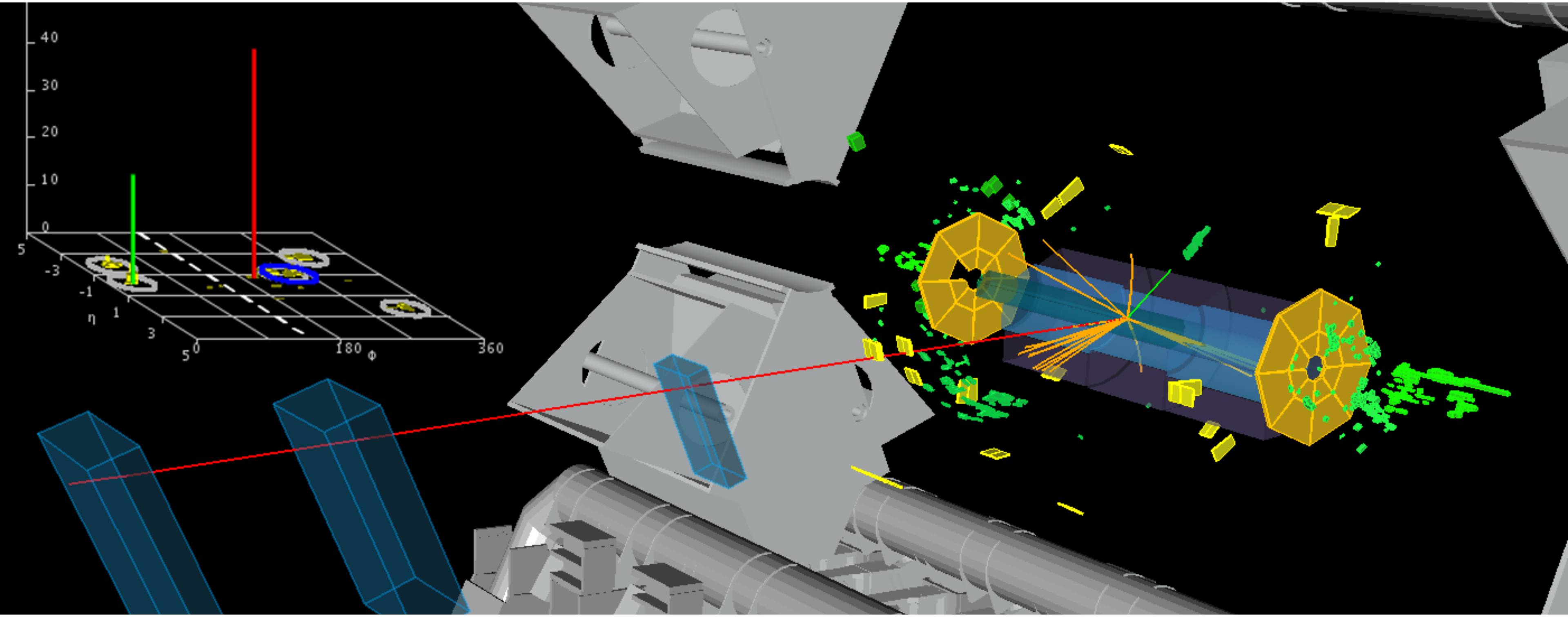
Collider Physics

Lecture 1- *Fundamentals* CHIPP 2017



eμ event *(type of events of historical relevance)*

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Disclaimer and Practical Informations

These lectures will cover mostly LHC pp-collisions physics.

- Heavy ions collisions is an important part of the LHC physics program but for lack of time will not be covered in these lectures
- Heavy Flavor physics will be covered in Gudrun Hiller's lectures
- Future collider physics will be covered in Alain Blondel's lectures
- Detectors will be covered in Frank Hartmann's lectures

Apologies for a slight bias (in terms of results and plots) towards ATLAS

- Please do not hesitate to contact me should you have any further questions:
  kado@lal.in2p3.fr

- At CERN: 40-1-D028 (Phone 16 49 57 and office 7 11 43)

Bilbliography

Exhaustive, detailed and excellent reference with detailed and up-to-date reviews PDG:

http://www-pdg.lbl.gov

Historical review of the Standard Model with references

Collider physics lectures:

- Maxim Perelstein TASI 2009
- Giulia Zanderighi European School of High Energy Physics 2016
- Guillaume Unal Ecole de GIF 2004
- Daniel Treille Ecole de GIF 2004

Outline

Lecture 1 – Fundamentals of the Standard Model, Particle colliders and the LHC

Lecture 2 – LHC Standard Model physics and the discovery of the Higgs boson

Lecture 3 – Higgs physics at LHC

Lecture 4 – Direct searches for new Physics at LHC

Lecture 1 - Fundamentals

Introduction – Historical perspective

Standard Model – Fundamental aspects of the Standard Model

Precision EW data and fit – Higgs physics at LHC

« Cahier des charges » of the LHC – Motivations and goals

Fundamentals of colliders

Fundamentals of the LHC

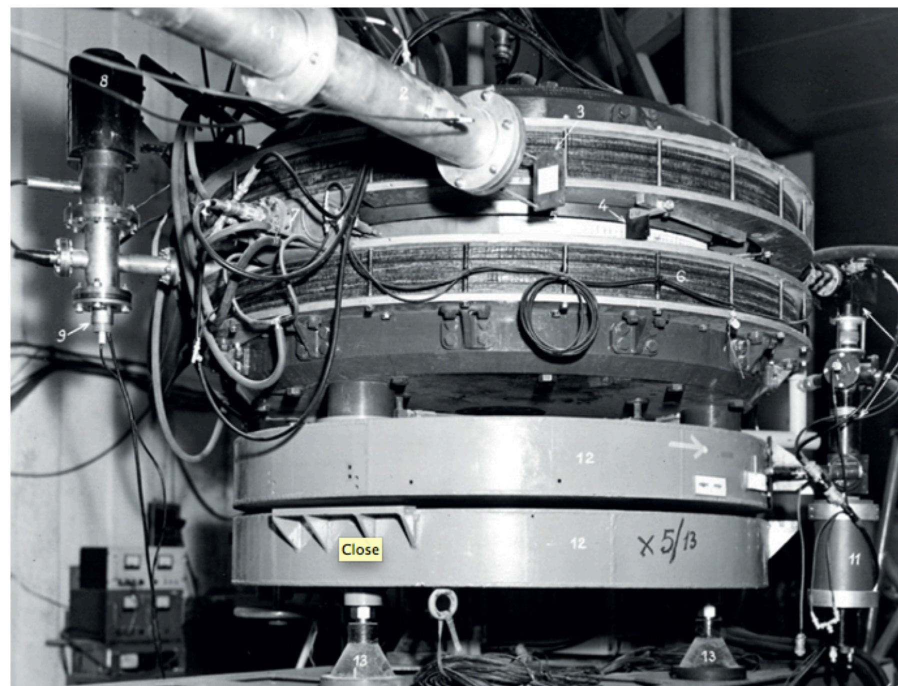
Historical Perspective

Our **direct** knowledge of nature at the smallest scales (smaller than 10^{-16} m) relies mostly on colliders.

The Standard Model of particle physics and colliders started approximately at the same time.

The birth of the Standard model can be roughly dated in 1957-1959, and required 5 decades to be really completed.

The first collider (AdA – Anello di Accumulazione) was built in 1961 in Frascati (then at LAL), had a radius of 3 meters and collided electrons and posirons at a centre-of-mass energy of 500 MeV.



Colliders have grown in complexity and on their two main FOM i.e. Centre-of-Mass energy and luminosity.

However the basic principles are the same!

(Selected) TH Foundations of the Standard Model

1954 - Yang-Mills theories for gauge interactions…

1958 – Feynman,Tomonaga, and Schwinger – QED

$$SU(2)_L \otimes U(1)_Y$$

1957-59 – Schwinger, Bludman and Glashow introduce W bosons for the weak charged currents

1961 – Goldstone theorem

1964 – Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

1967 – Weinberg “A model of leptons”

1971 – Renormalization of the SM – t’Hooft and Veltman

$$SU(3)_c$$

1964 – Gell-Man and Zweig the Quark model

1965 – Han, Nambu and Greenbberg the color charge

1973 – Gross, Wilcek, Politzer – Asymptotic freedom (observed earlier by t’Hooft and others) – b function now computed at up to 5 loops!

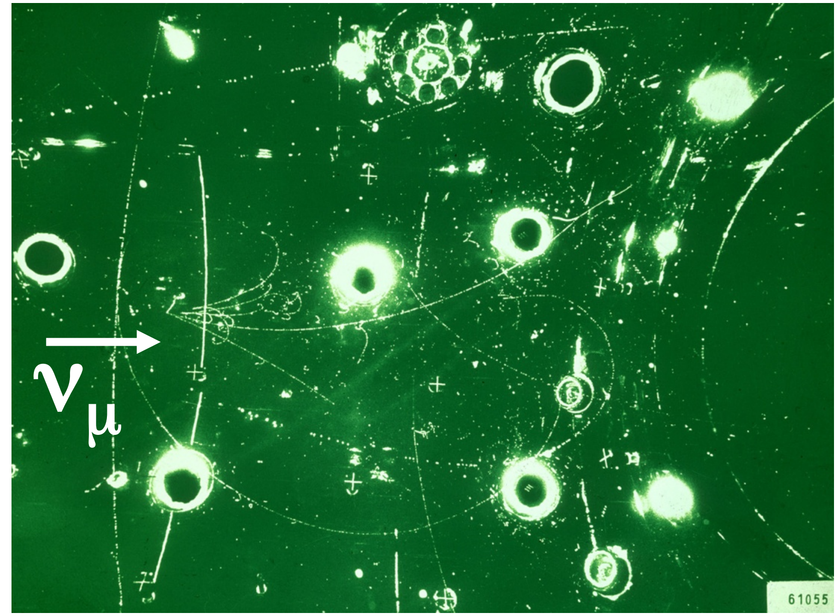
(Selected) Founding Landmark Results (I)

1973: neutral current discovery
(Gargamelle experiment, CERN)

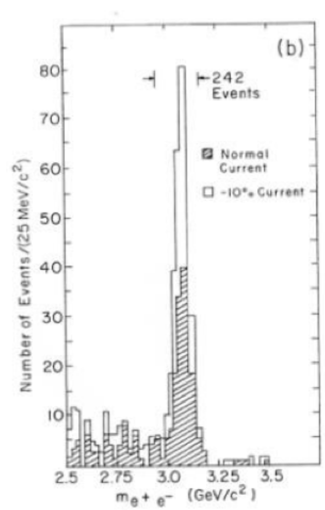
Evidence for neutral current events $\nu + N \rightarrow \nu + X$ in ν-nucleon deep inelastic scattering

1973-1982: $\sin^2\theta_W$ Measurements in deep inelastic neutrino scattering experiments (NC vs CC rates of νN events)

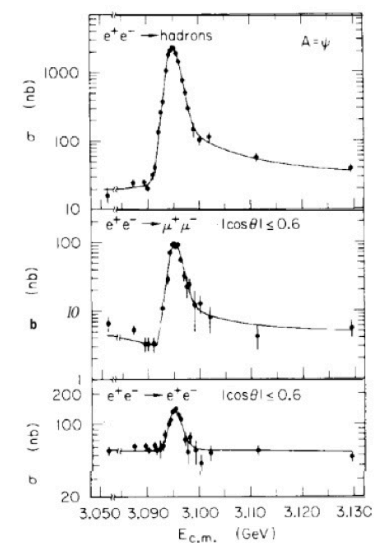
1974 Discovery of the J/Psi at SLAC and at Brookhaven



AGS - Brookhaven



SPEAR – SLAC



(Selected) Founding Landmark Results (II)

1974 - Discovery of the J/Psi - c quark	SPEAR - AGS
1975 - Discovery of the tau lepton	SPEAR
1977 - Discovery of the Upsilon - b quark	Fermilab
1979 - Discovery of the gluon	PETRA
1983 - Discovery of the W and Z bosons	SppS
1990 - Number of light neutrino families	LEP - SLC
1993 - Top quark discovery	Tevatron
1991 – Precision EW results	LEP – SLC - Tevatron
2000 – Tau neutrino	DONUT

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu}$$

$$\theta < 10^{-10}$$

From neutron electric dipole moment measurements

The strong CP problem

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

The less elegant Higgs sector:

- Carries the largest number of parameters of the theory
- Not governed by symmetries
- Gauge Hierarchy (and Naturalness)
- Flavor hierarchy
- Neutrino masses

QCD Unbroken "simplicity"

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \psi + h.c.$$

$SU(3)$ Color is an exact symmetry

Unbroken: gluons are massless

Simplicity: Only one free parameter g_s

QCD is flavor blind

The QCD Lagrangian:

$$\mathcal{L} = -\frac{1}{4} \sum_i F^i_{\mu\nu} F^{i\mu\nu} + \sum_r \bar{q}_{r\alpha} (i\not{D}^\alpha_\beta - m_r) q^\beta_r$$

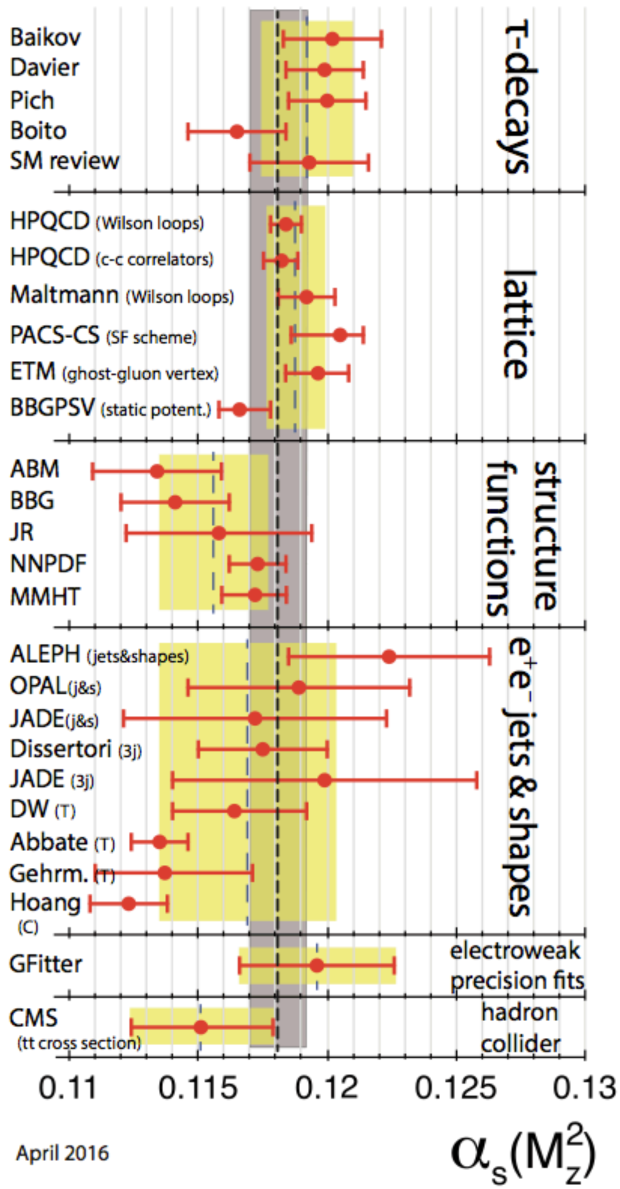
Field strength (including gluon self interaction):

$$F^i_{\mu\nu} = \partial_\mu G^i_\nu - \partial_\nu G^i_\mu - g_s f_{ijk} G^j_\mu G^k_\nu$$

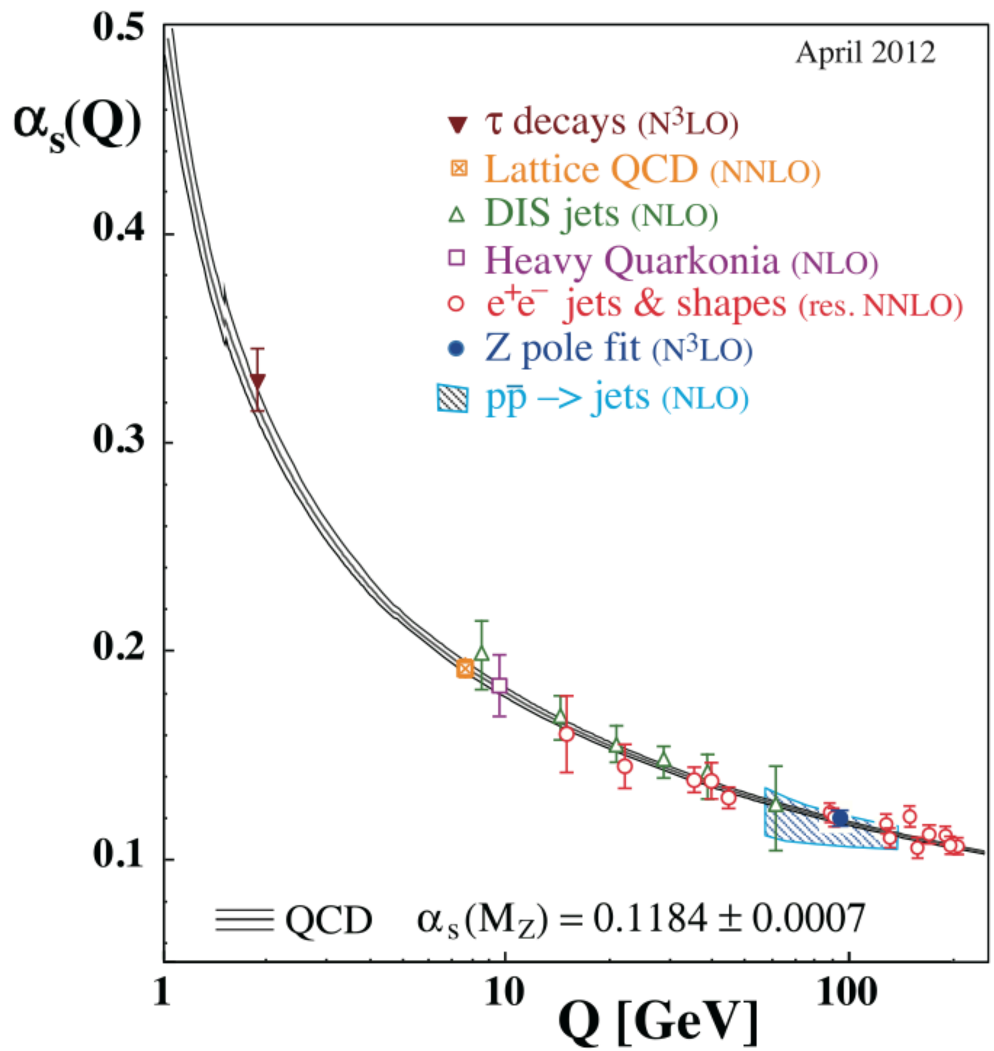
Covariant derivative – interaction with quarks (t^a_{ij} color matrices)

$$\not{D}^\mu_{ij} = \partial^\mu \delta_{ij} + i g_s t^a_{ij} G^\mu_a$$

Landmark Results (at Colliders)



- One coupling constant known at ~1%
- Its running precisely measured



From SC to SSB in Particle Physics

SC (BCS) Theory

1950 – Landau and Ginzburg
JETP 20 (1950) 1064

1957 – Bardeen, Cooper and Schrieffer Phys. Rev. 108 (1957) 1175

1958 – P. W. Anderson
Phys. Rev. 112 (1958) 1900
SC and gauge invariance

1963 – P. W. Anderson
Phys. Rev. 130 (1963) 439
Gauge field with mass (non relativistic)

Particle Theory

1954 - Yang-Mills theories for non abelian gauge interactions

1957-59 – Schwinger, Bludman and Glashow introduce W bosons for the weak charged currents…

… but local gauge symmetry forbids gauge bosons masses.

1962 – J. Schwinger
Phys. Rev. 125 (1962) 397
Gauge invariance and mass

1964 – W. Gilbert Phs. Rev. Lett 12 (1964) 713
Thought to be impossible in relativistic theories !

Spontaneous Symmetry Breaking (SSB)

Nambu (1960) and Goldstone (1961)

Massless scalars occur in a theory with SSB… but not only

The symmetry is not apparent (hidden) in the ground state

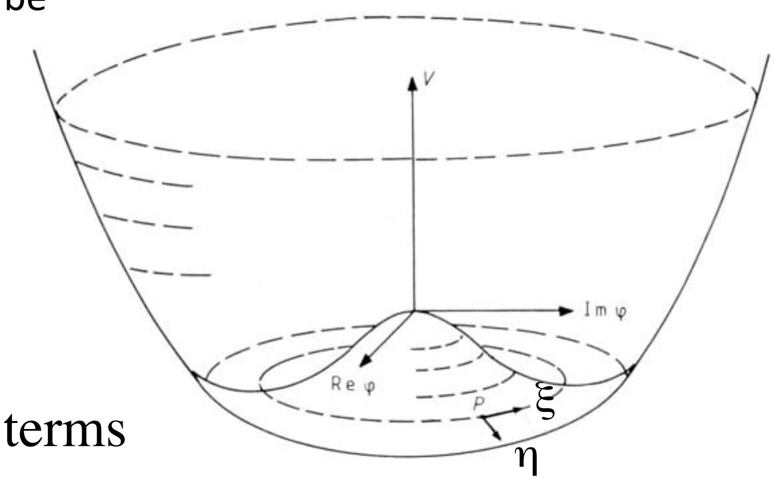
From a simple (complex) scalar theory with a U(1) symmetry

$$\varphi = \frac{\phi_1 + i\phi_2}{\sqrt{2}} \qquad L = \partial_\nu \varphi^* \partial^\nu \varphi - V(\varphi) \qquad V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$$

The Lagrangian is invariant under : $\varphi \rightarrow e^{i\alpha}\varphi$

$$v = -\frac{\mu^2}{\lambda}$$

Shape of the potential if $\mu^2<0$ and $\lambda>0$ necessary for SSB and be bounded from below.



Change frame to local minimum frame :

$$\varphi = \frac{v + \eta + i\xi}{\sqrt{2}}$$

No loss in generality.

$$L = \frac{1}{2}\underbrace{\partial_\nu \xi \partial^\nu \xi}_{} + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \underbrace{\mu^2 \eta^2}_{} + \text{interaction terms}$$

Massless scalar **Massive scalar**

Digression on Chiral Symmetry

In the massless quarks approximation : $SU(2)_L x SU(2)_R$ the chiral symmetry is an (approximate) global symmetry of QCD

The chiral symmetry is broken by means of coherent states of quarks (which play a role similar to the cooper pairs in the BCS superconductivity theory)

It is a Dynamical Symmetry Breaking where the pseudo-goldstone bosons are the π^+,π^0,π^- mesons

And the massive scalar is also there : the sigma!

This is the basis of the construction of an effective field theory ChPT allowing for strong interaction calculations at rather low energy

Spontaneous Local Symmetry Breaking (SSB)

Let the aforementioned continuous symmetry U(1) be local :

α(x) now depends on the space-time x.

$$\varphi \to e^{i\alpha(x)}\varphi$$

The Lagrangian can now be written : $$L = (D_\nu \varphi)^* D^\nu \varphi - V(\varphi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

In terms of the covariant derivative : $D_\nu = \partial_\nu - ieA_\nu$

The gauge invariant field strength tensor : $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$

And the Higgs potential : $V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$

Here the gauge field transforms as : $$A_\mu \to A_\mu + \frac{1}{e}\partial_\mu \alpha$$

Again translate to local minimum frame : $$\varphi = \frac{v + \eta + i\xi}{\sqrt{2}}$$

$$L = \frac{1}{2}\partial_\nu \xi \partial^\nu \xi + \frac{1}{2}\partial_\nu \eta \partial^\nu \eta + \mu^2 \eta^2 - v^2 \lambda \eta^2 + \frac{1}{2}\underbrace{e^2 v^2 A_\mu A^\mu} - evA_\mu \partial^\mu \xi - F^{\mu\nu} F_{\mu\nu} + \text{ITs}$$

Mass term for the gauge field! But…

What about the field content?

A massless Goldstone boson ξ a massive scalar η and a massive gauge boson!

Number of d.o.f. : 1 1 1

Number of initial d.o.f. : 2 Does not match!

But wait! The term $evA_\mu \partial^\mu \xi$ is unphysical

The Lagrangian should be re-written using a more appropriate expression of the translated scalar field choosing a particular gauge where h(x) is real :

$$\varphi = (v + h(x))e^{i\frac{\theta(x)}{v}}$$

Gauge fixed to absorb θ

Then the gauge transformations are : $\varphi \rightarrow e^{-i\frac{\theta(x)}{v}}\varphi \qquad A_\mu \rightarrow A_\mu + \frac{1}{ev}\partial_\mu \theta$

$$L = \frac{1}{2}\partial_\nu h \partial^\nu h - \lambda v^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$ Massive scalar : The Higgs boson

$$+(1/2)e^2 v^2 A_\mu A^\mu - F^{\mu\nu}F_{\mu\nu}$$ Massive gauge boson

$$+(1/2)e^2 A_\mu A^\mu h^2 + ve^2 A_\mu A^\mu h$$ Gauge-Higgs interaction

The Goldstone boson does not appear anymore in the Lagrangian

$|D_\mu \phi|^2$

EW Spontaneous Symmetry Breaking

$$SU(2)_L \times U(1)_Y$$

Introducing a double of complex scalar fields (4 d.o.f.) : $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ \\ \phi^o \end{pmatrix}$

Setting aside the gauge kinematic terms the Lagrangian can be written :

$$\mathcal{L} = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) \qquad \begin{cases} D_\mu = \partial_\mu - ig\vec{W}_\mu . \vec{\sigma} - ig' \frac{Y}{2} B_\mu \\ V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \end{cases}$$

The next step is to develop the Lagrangian near : $< \phi >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

Choosing the specific real direction of charge 0 of the doublet is not fortuitous :

$$\phi = e^{-i\vec{\sigma}.\vec{\xi}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ H + v \end{pmatrix}$$

Non electrically charged vacuum

Again choosing the gauge that will absorb the Goldstone bosons ξ...

Then developing the covariant derivative for the Higgs field :

Just replacing the Pauli matrices :

$$D_\mu \varphi = \partial_\mu \varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g'B_\mu & g(W_\mu^1 - iW_\mu^2) \\ g(W_\mu^1 + iW_\mu^2) & -gW_\mu^3 + g'B_\mu \end{pmatrix}\varphi$$

Then using : $W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}$

$$D_\mu \varphi = \partial_\mu \varphi - \frac{i}{2}\begin{pmatrix} gW_\mu^3 + g'B_\mu & \sqrt{2}gW_\mu^+ \\ \sqrt{2}gW_\mu^- & -gW_\mu^3 + g'B_\mu \end{pmatrix}\varphi = \begin{pmatrix} 0 \\ \partial_\mu h \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \sqrt{2}gvW_\mu^+ + \sqrt{2}ghW_\mu^+ \\ -gvW_\mu^3 + g'vB_\mu - ghW_\mu^3 + g'hB_\mu \end{pmatrix}$$

For the mass terms only :

$$(D_\mu \varphi)^+ D^\mu \varphi = \partial_\mu h \partial^\mu h + \frac{1}{4}g^2 v^2 W_\mu^+ W^{-\mu} + \frac{1}{8}\begin{pmatrix} W_\mu^3 & B_\mu \end{pmatrix}\begin{pmatrix} g^2v^2 & -gg'v^2 \\ -gg'v^2 & g'^2v^2 \end{pmatrix}\begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix}$$

Explicit mixing of W^3 and B.

The Lagrangian can then be written :

$$\mathcal{L} = \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4$$

Massive scalar : The Higgs boson

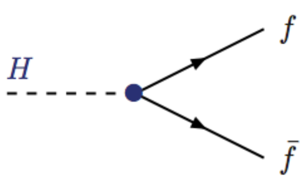
$$+ \frac{1}{2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu - \frac{g g' v^2}{2} W^3_\mu B^\mu + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu\right]$$

Massive gauge bosons

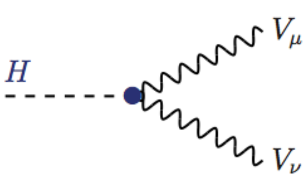
$$+ \frac{1}{v}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H - \frac{g g' v^2}{2} W^3_\mu B^\mu H + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu H\right]$$

$$+ \frac{1}{2v^2}\left[\frac{g'^2 v^2}{4} B_\mu B^\mu H^2 - \frac{g g' v^2}{2} W^3_\mu B^\mu H^2 + \frac{g^2 v^2}{4} \vec{W}_\mu . \vec{W}^\mu H^2\right]$$

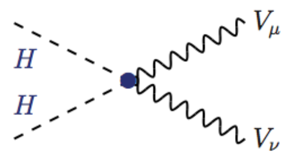
Gauge-Higgs interaction



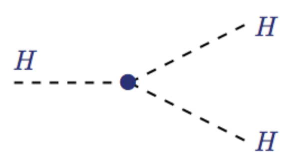
$g_{Hff} = m_f/v$



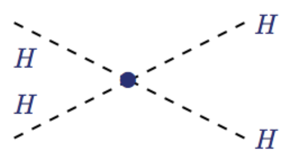
$g_{HVV} = 2M_V^2/v$



$g_{HHVV} = 2M_V^2/v^2$



$g_{HHH} = 3M_H^2/v$



$g_{HHHH} = 3M_H^2/v^2$

Keep this in mind for the next lectures…

Consequences of the mechanism :

1.- Two massive charged vector bosons *(charged currents)* :

$$m_W^2 = \frac{g^2 v^2}{4}$$

Thus v = 246 GeV

The theory (and gauge group) was chosen to describe charged current interactions

2.- One massless vector boson : $m_\gamma = 0$

The photon corresponding to the unbroken $U(1)_{EM}$

Consequence of developing the Higgs field along the neutral and real part of the doublet

Predictions :

1.- One massive neutral vector boson Z: *(Neutral currents not discovered at the time)*

$$m_Z^2 = (g^2 + g'^2)v^2/4$$

2.- One massive scalar particle: **The Higgs boson**

Higgs mass is an unknown parameter of the theory or equivalently the quartic coupling λ

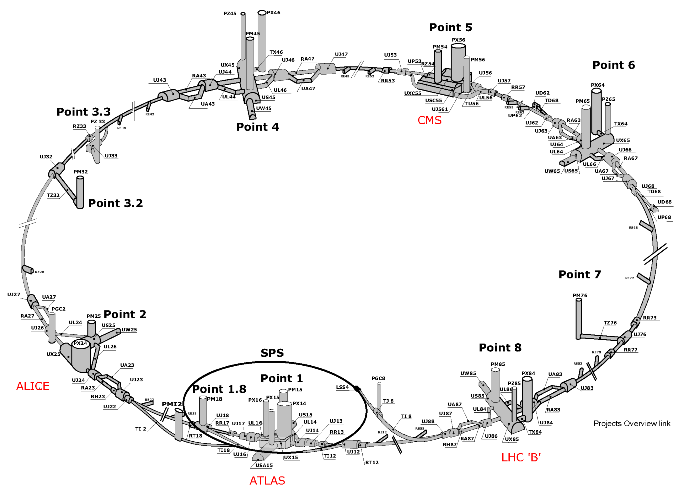
$$m_H^2 = \frac{4\lambda(v) m_W^2}{g^2}$$

3.- Gauge couplings and masses (at tree level): $\rho = 1$ $\quad \frac{M_W}{M_Z} = \rho \frac{g^2}{g^2 + g'^2} = \rho \cos^2\theta_W$

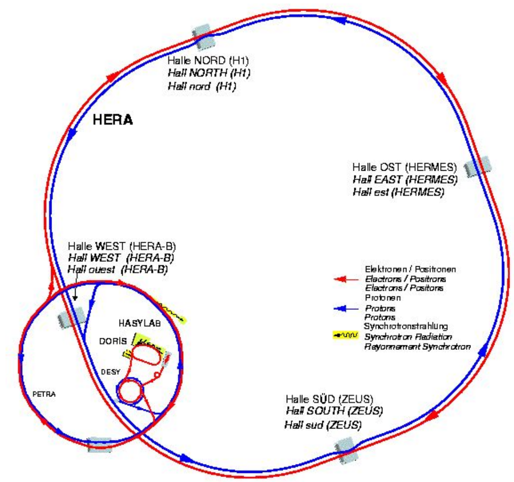
Protected by cutsodial symmetry at higher orders

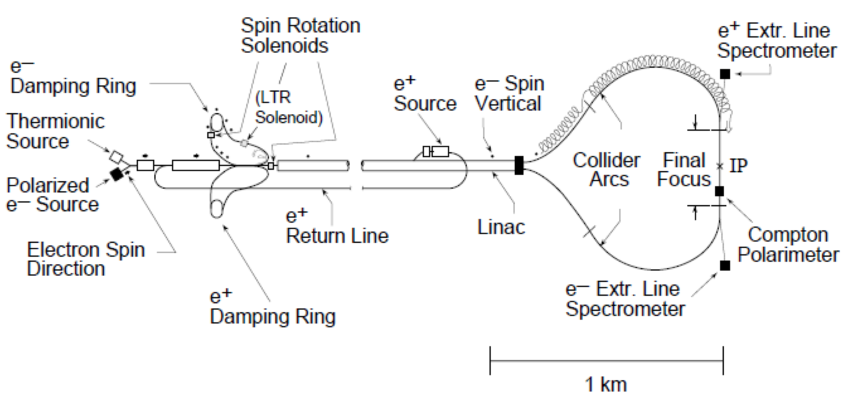
Main (non B factories) colliders before the LHC

LEP 1989-2000 e^+e^- 91Gev,130-208GeV

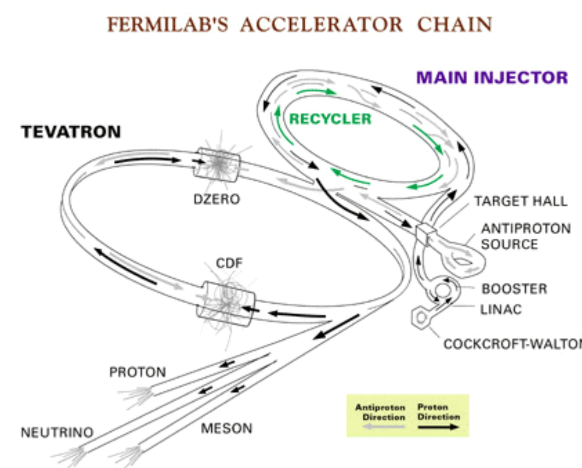


HERA 1992-2007 ep 27.5 Gev - 920 GeV





SLC 1988-1998 e^+e^- 91GeV



Tevatron 1987-2011 pp ~2TeV

Electroweak Precision Data Before the LHC

- The EW sector of the Standard Model (excluding the Yukawa sector and the Higgs potential) has only 3 parameters. The complete set of SM parameters include the Higgs mass the fermion masses and mixing and α_s.

- A useful (for precision) set of these 3 parameters are

- The fine structure constant : $\alpha = 1/137.035999679(94)$ — 10^{-9}

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

- The Fermi constant : $G_F = 1.166367(5) \times 10^{-5}\,\mathrm{GeV}^{-2}$ — 10^{-5}

Determined from muon lifetime

- The Z mass : $M_Z = 91.1876(21)\,\mathrm{GeV}$ — 10^{-5}

Measured from the Z lineshape scan at LEP

- At three level other parameters such as M_W are fully determined by the relation

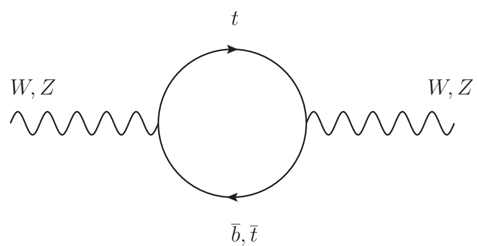
$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2(1 - \frac{M_W^2}{M_Z^2})}$$

- At loop level all parameters matter mix through (small) corrections, these corrections are parameterized by form factors e.g.:

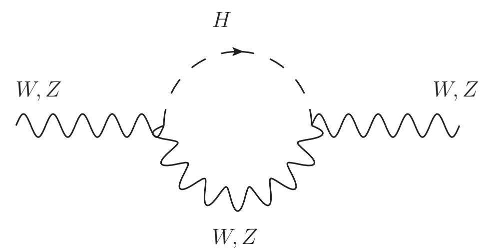
$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2(1-\frac{M_W^2}{M_Z^2})}(1+\Delta r)$$

- These form factors are computed at a very high level of precision (at two loops).

- In the Eq. above Δr also depends on M_W which requires an iterative method to solve. M_W has been computed including 3-loop QCD corrections.



$$\propto m_t^2$$



$$\propto \log\frac{M_H}{M_Z}$$

- Then use the SM quantum corrections to fit the model parameters in order to:
    - Improved determination of the model parameters
    - Probe the consistency of the Standard Model

Main EW collider results before the LHC

Observables

- Z-pole observables: LEP/SLD results
- MW and ΓW: LEP/Tevatron
- mt :Tevatron
- $\Delta\alpha_{had}(5)$
- mc, mb: world averages

Comments

- Numerous observables O(40)
- Numerous experiments/analyses (with different systematics)
- Numerous TH inputs

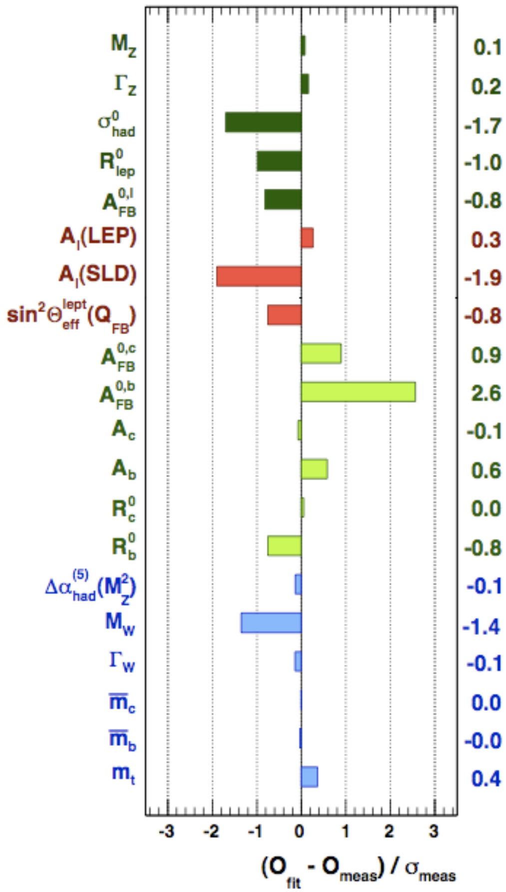
Fit Parameters

M_Z, M_H, $\Delta\alpha_{had}(5)$, α_s, m_c, m_b, m_t (and TH uncertainties)

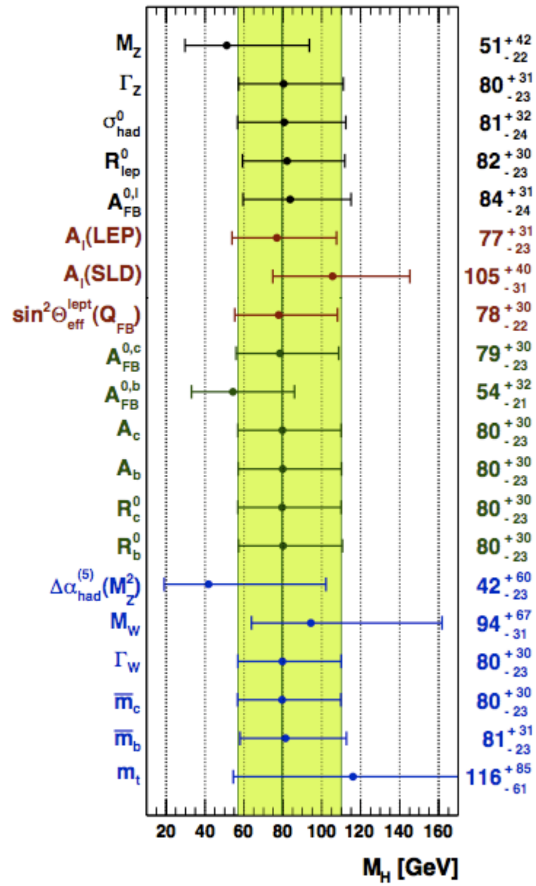
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	
R^0_b	0.21629 ± 0.00066	
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	
m_t [GeV]	173.20 ± 0.87	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2757 ± 10	

From R. Kogler (Gfitter coll.)

Fit Results

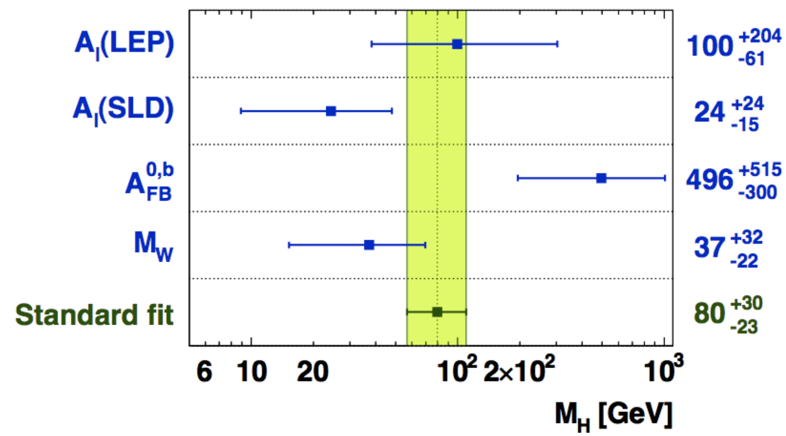


Comparing fit results to the measured values



MH fit excluding specific observables

$$\mathrm{Prob}(\chi^2, 13) = 0.23$$

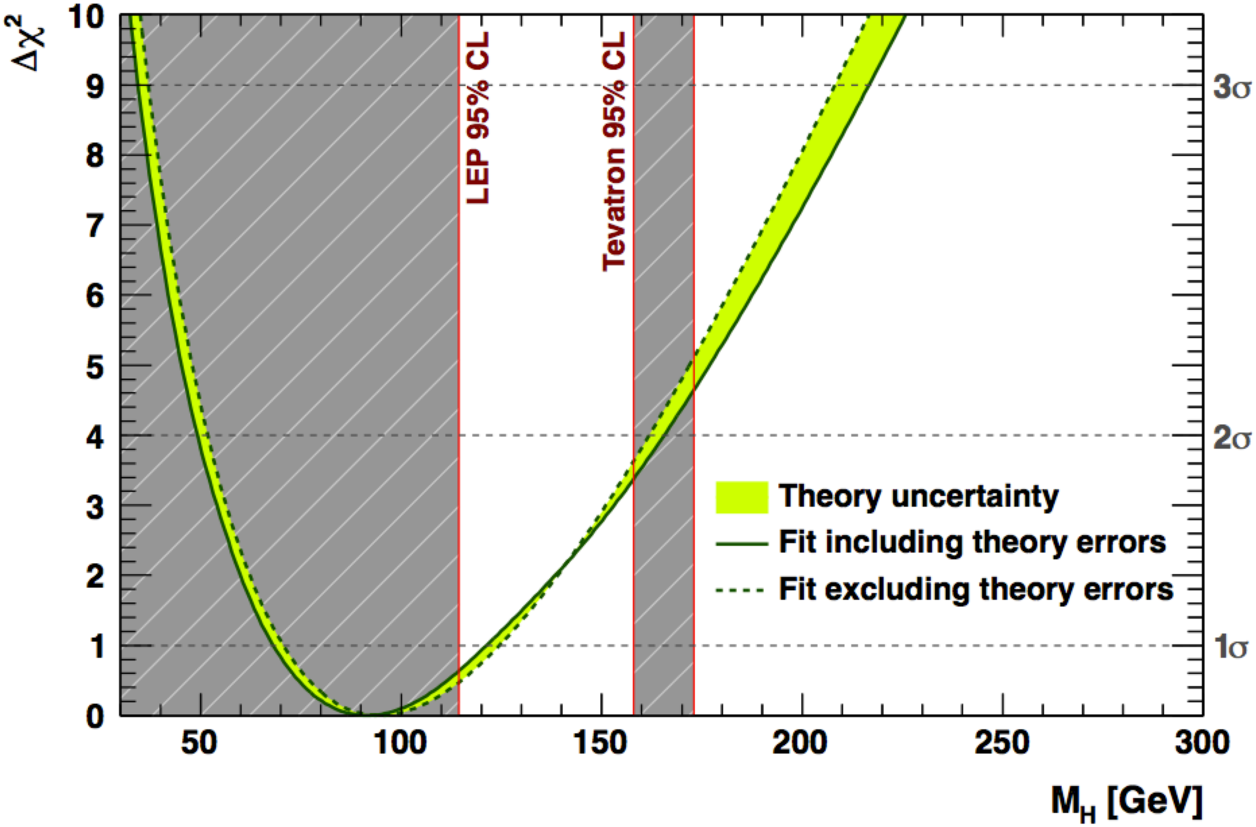


MH from specific observables

Fit Results (partial)

Parameter	Input value	Free in fit	Results from global EW fits: Standard fit	Complete fit	Complete fit w/o exp. input in line
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1874 ± 0.0021	91.1877 ± 0.0021	$91.2001\,^{+0.0174}_{-0.0178}$
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4959 ± 0.0015	2.4955 ± 0.0015	2.4950 ± 0.0017
σ^0_{had} [nb]	41.540 ± 0.037	–	41.477 ± 0.014	41.477 ± 0.014	41.468 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.018	20.742 ± 0.018	$20.717\,^{+0.029}_{-0.025}$
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	–	0.01638 ± 0.0002	0.01610 ± 0.9839	0.01616 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1478\,^{+0.0011}_{-0.0010}$	$0.1471\,^{+0.0008}_{-0.0009}$	–
A_c	0.670 ± 0.027	–	$0.6682\,^{+0.00046}_{-0.00045}$	$0.6680\,^{+0.00032}_{-0.00046}$	$0.6680\,^{+0.00032}_{-0.00047}$
A_b	0.923 ± 0.020	–	$0.93470\,^{+0.00011}_{-0.00012}$	$0.93464\,^{+0.00008}_{-0.00013}$	$0.93464\,^{+0.00008}_{-0.00011}$
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035	–	0.0741 ± 0.0006	$0.0737\,^{+0.0004}_{-0.0005}$	$0.0737\,^{+0.0004}_{-0.0005}$
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	–	0.1036 ± 0.0007	$0.1031\,^{+0.0007}_{-0.0006}$	0.1036 ± 0.0005
R^0_c	0.1721 ± 0.0030	–	0.17224 ± 0.00006	0.17224 ± 0.00006	0.17225 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	$0.21581\,^{+0.00005}_{-0.00007}$	0.21580 ± 0.00006	0.21580 ± 0.00006
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012	–	0.23143 ± 0.00013	$0.23151\,^{+0.00012}_{-0.00010}$	$0.23149\,^{+0.00013}_{-0.00009}$
M_H [GeV] $^{(\circ)}$	Likelihood ratios	yes	$80\,^{+30[+75]}_{-23[-41]}$	$116.4\,^{+18.3[+28.4]}_{-\ 1.3[-\ 2.2]}$	$80\,^{+30[+75]}_{-23[-41]}$
M_W [GeV]	80.399 ± 0.025	–	$80.382\,^{+0.014}_{-0.016}$	80.364 ± 0.010	$80.359\,^{+0.010}_{-0.021}$
Γ_W [GeV]	2.098 ± 0.048	–	$2.092\,^{+0.001}_{-0.002}$	2.091 ± 0.001	$2.091\,^{+0.001}_{-0.002}$
m_t [GeV]	172.4 ± 1.2	yes	172.5 ± 1.2	172.9 ± 1.2	$178.2\,^{+9.8}_{-4.2}$
$\Delta\alpha^{(5)}_{\mathrm{had}}(M^2_Z)$ $^{(\dagger\triangle)}$	2768 ± 22	yes	2772 ± 22	$2767\,^{+19}_{-24}$	$2722\,^{+62}_{-53}$
$\alpha_s(M^2_Z)$	–	yes	$0.1192\,^{+0.0028}_{-0.0027}$	$0.1193\,^{+0.0028}_{-0.0027}$	$0.1193\,^{+0.0028}_{-0.0027}$

The Standard Blue Band Plot

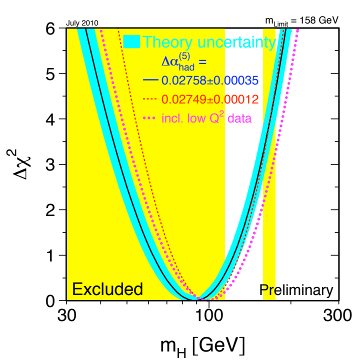


- The fit yielded :

$$91^{+30}_{-23}\ \mathrm{GeV}$$

- The 95% limit :

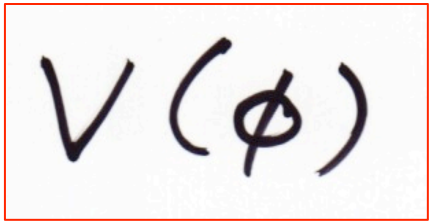
$$163\ \mathrm{GeV}$$



$$\alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha_\ell(m_Z^2) - \Delta\alpha_{had}(m_Z^2) - \Delta\alpha_{top}(m_Z^2)}$$

As mentioned above α(0) measured with ~10^{-9} precision

The difficulty is how to evaluate : $\Delta\alpha_{had}(m_Z^2)$



Running Quartic Coupling

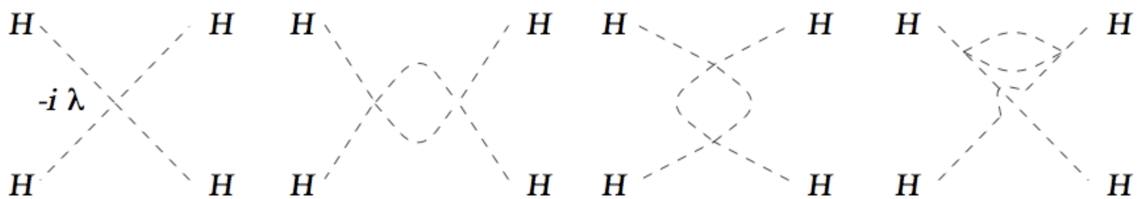
Triviality

The (non exhaustive though rather complete) evolution of the quartic coupling :

$$32\pi^2 \frac{d\lambda}{dt} = \boxed{24\lambda^2} - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

If the Higgs mass had been large (large λ) :

The first term of the equation would have been dominant due to diagrams such as :



$$\frac{d\lambda(Q^2)}{dt} = \frac{3}{4\pi^2}\lambda^2(Q^2) \longrightarrow \frac{1}{\lambda(Q^2)} = \frac{1}{\lambda(Q_0^2)} - \frac{3}{4\pi^2}\ln\left(\frac{Q^2}{Q_0^2}\right)$$

$$M_H^2 = 2\lambda v^2$$

If Q can be high at will eventually lead to Landau pole

Triviality condition to avoid such pole : $1/\lambda(Q) > 0$

$$\boxed{M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}}$$

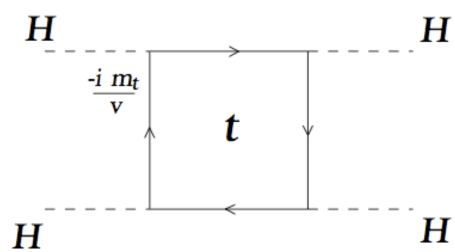
$V(\phi)$

Running Quartic Coupling
Vacuum stability

Looking closer into the limit where the Higgs boson mass is small (which is the case) :

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - \boxed{24y_t^4} + \cdots$$

The last term of the equation is dominant and due to diagrams such as :



$$\sim \frac{m_t^4}{v^4}$$

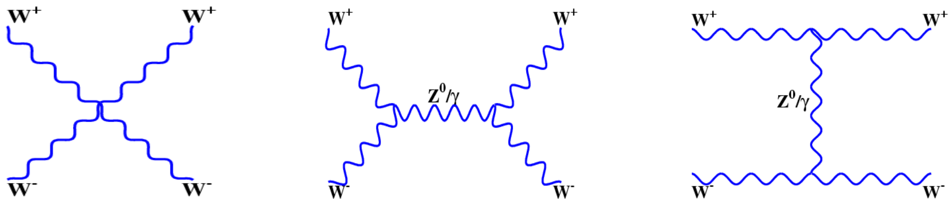
The equation is then very simply solved : $\lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$

Requiring that the solutions are stable (non-negative quartic coupling) :

$\lambda(\Lambda) > 0$ then $\boxed{M_H^2 > \frac{3v^2}{2\pi^2} y_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)}$

The No-Loose Theorem at the LHC

$$W_L^+ W_L^- \to W_L^+ W_L^-$$



Without the Higgs boson the scattering amplitude is:

$$\mathcal{A} \sim \sqrt{2} G_F (s + t)$$

Where s and t are the Mandelstam variables: $1 + 2 \to 3 + 4$

$$s = (p_1 + p_2)^2$$
$$t = (p_1 - p_3)^2$$

The amplitude does therefore not preserve pertubative unitarity.

Introducing a Higgs boson modifies the amplitude as follows:

$$\mathcal{A} \sim -\sqrt{2} G_F m_H^2 \left(\frac{s}{s - m_H^2} + \frac{t}{t - m_H^2} \right)$$

To preserve perturbative unitarity the amplitude should not exceed O(1) for any large s and therefore :

$$G_F m_H^2 < \mathcal{O}(1) \qquad m_H < \mathcal{O}(1 TeV)$$

The origin of the No Loose theorem* at the LHC

Approximate

The Mission of the LHC

- **The no-loose theorem**: Discover the Higgs boson or reveal strong dynamics in vector boson scattering

- **Probe the electroweak scale**: with direct searches for new phenomena beyond the Standard Model.

- **Probe the Standard model and higher scales indirectly**: Through CP-violation in Heavy Flavors, rare B decays, etc… Through precision measurements of Higgs couplings, standard EW parameters, anomalous couplings, etc…

- **Study strongly interacting matter at extreme energy densities**.

In all these areas the LHC is already an immense success

Basics of Particle Colliders

Types of particles collided ee, ep, pp, ppbar and to some extent photons, gluons and quarks (perhaps in the future muons).

The centre-of-mass energy E_{CM} (at beam energies for which the mass of the particle is negligible), the centre of mass energies of two particles colliding « head on »:

$$p_A = (E_A, 0, 0, +E_A) \quad p_B = (E_B, 0, 0, +E_B)$$

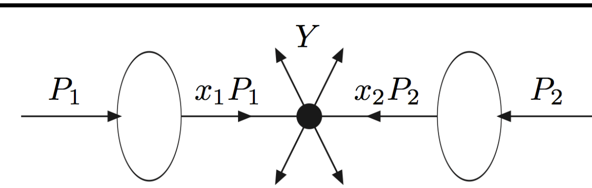
$$\sqrt{s} = 2\sqrt{E_A E_B}$$

For beams with same energy: $\sqrt{s} = 2E$

Comparison with fixed target (on a Hydrogen) with « stationnary » protons:

$$\sqrt{s} = \sqrt{2Em_p}$$

In High energy proton collisions only a fraction of the pp Centre-of-Mass energy is carried by the partons in collision $\hat{s} = x_1 x_2 s$



Basics of Particle Colliders

Scattering cross section

In head-on collisions of beams containing large number of particles the number of collisions leading to an event should be proportional to the number of particles in each beam, NA and NB, and inversely proportional to the beams cross-sectional area A. The coefficient of proportionality is the scattering cross section for this particular final state:

$$\sigma = \frac{N_{evts} \times \mathcal{S}}{N_A N_B}$$

The instantaneous Luminosity L is defined using the rate of events

$$R = \sigma \mathcal{L}$$

When beam collide with a ferquency f, then the rate of

$$\mathcal{L} = \frac{f N_A N_B}{\mathcal{S}}$$

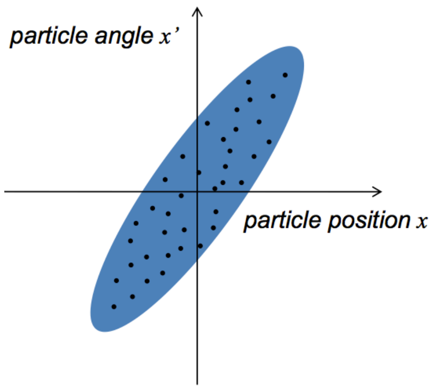
σ_x and σ_y are the transverse dimensions ogf the beam at the interaction point.

$$\mathcal{L} = \frac{f N_A N_B}{4\pi\sigma_x\sigma_y}$$

At the LHC the beams are symetric with a size of 16 μm

Basics of Particle Colliders

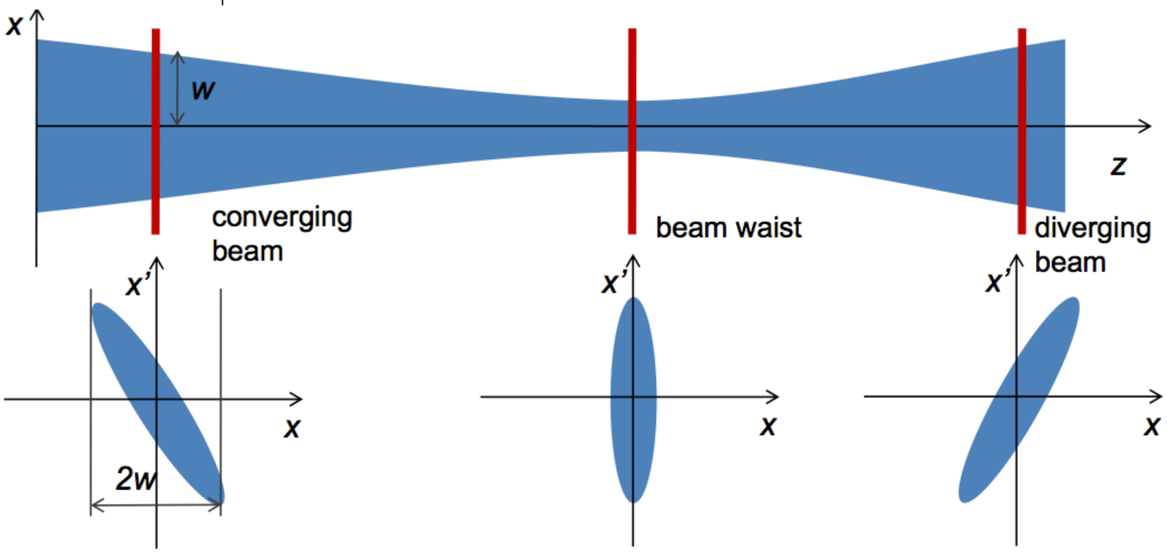
From V. Shiltsev



The emittance of the beam ε in a given direction x is the area of the beam in the (x, x') plane where: $x' = p_x/p_z$

$$\varepsilon = \pi\sigma\sigma'$$

The emittance remains constant along the beamline, but not the aspect ratio.



The amplitude function β gives the aspect ratio of the beam in the phase space

$$\beta = \sigma/\sigma'$$

The amplitude function at the interaction point is denoted β^*

$$\varepsilon\beta^* = \pi\sigma^2$$

The beam enveloppe is parabolic

In this lecture only simplified facts and corrections are given, beam dynamics are complex and in particular, non linear effects from beam-beam interactions are important (beams seeing the field of the other beam).

$$\mathcal{L} = \frac{f N_A N_B}{4\beta^*\varepsilon}$$

List of e^+e^- Colliders (I)

Accelerator	Location	Operations	Characteristics	E (e^-)	E (e^+)	Highlight discovery
AdA	Frascati, Italy; Orsay, France	1961–1964	Circular, 3 meters	250 MeV	250 MeV	Touschek effect (1963); first e+e− interactions recorded (1964)
Princeton-Stanford	Stanford, California	1962–1967	Two-ring, 12 m	300 MeV	300 MeV	e−e− interactions
VEP-1	INP, Novosibirsk, Soviet Union	1964–1968	Two-ring, 2.70 m	130 MeV	130 MeV	e−e− scattering; QED radiative effects confirmed
VEPP-2	INP, Novosibirsk, Soviet Union	1965–1974	Circular, 11.5 m	700 MeV	700 MeV	multihadron production (1966), e+e−→ϕ (1966), e+e−→γγ (1971)
ACO	LAL, Orsay, France	1965–1975	Circular, 22 m	550 MeV	550 MeV	Vector meson studies; then ACO was used as synchrotron light source until 1988
SPEAR	SLAC	1972-1990	80m Rings	4 GeV	4 GeV	Discovery of Charmonium states Discovery of the tau
VEPP-2M	BINP, Novosibirsk	1974–2000	Circular, 17.88 m	700 MeV	700 MeV	e+e− cross sections, radiative decays of ρ, ω, and ϕ mesons
DORIS	DESY	1974–1993	Circular, 300m	5 GeV	5 GeV	Oscillation in neutral B mesons
PETRA	DESY	1978–1986	Circular, 2 km	20 GeV	20 GeV	Discovery of the gluon in three jet events
CESR	Cornell University	1979–2002	Circular, 768m	6 GeV	6 GeV	First observation of B decay, charmless and "radiative penguin" B decays
PEP	SLAC	1980-1990	Circular 2.2km	15 GeV	15 GeV	
SLC	SLAC	1988-1998	Linear 2 miles	45 GeV	45 GeV	First linear collider
BEPC	China	1989–2004	Circular, 240m	2.2 GeV	2.2 GeV	

List of e^+e^- Colliders (II)

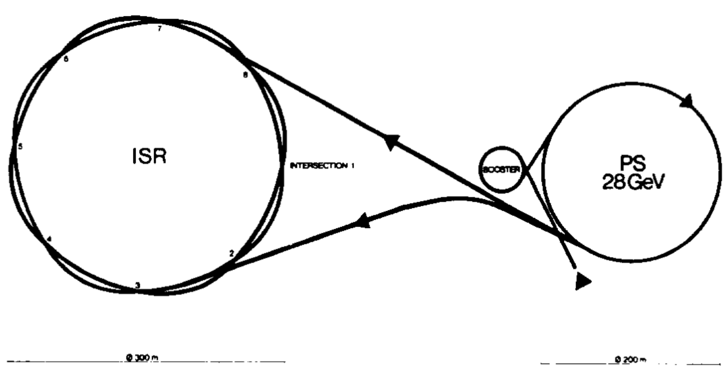
Accelerator	Location	Operations	Characteristics	Energy (e^-)	Energy (e^+)	Highlight/discoveries
LEP	CERN	1989–2000	Circular, 27 km	104 GeV	104 GeV	EW precision and 3 families
VEPP-4M	BINP, Novosibirsk	1994	Circular, 366m	6.0 GeV	6.0 GeV	Precise measurement of psi-meson masses, two-photon physics
Tristan	KEK	1995	Circular, 3km	30 GeV	30 GeV	
PEP-II	SLAC	1998–2008	Circular, 2.2 km	9 GeV	3.1 GeV	Discovery of CP violation in B meson system
KEKB	KEK	1999–2009	Circular, 3 km	8.0 GeV	3.5 GeV	Discovery of CP violation in B meson system
DAΦNE	Frascati, Italy	1999-	Circular, 98m	0.7 GeV	0.7 GeV	Crab-waist collisions (2007)
CESR-c	Cornell University	2002–2008	Circular, 768m	6 GeV	6 GeV	
VEPP-2000	BINP, Novosibirsk	2006-	Circular, 24.4m	1.0 GeV	1.0 GeV	Round beams (2007)
BEPC II	China	2008-	Circular, 240m	3.7 GeV	3.7 GeV	

List of ep Colliders

Accelerator	Location	Operations	Characteristics	Energy (e)	Energy (p)	Highlights/discoveries
HERA	DESY	1992-2007	Ciruclar ring 6.3km	27.5 GeV	930 GeV	PDFs

List of Hadron Colliders

Accelerator	Location	Operations	Characteristics	Beam E	Highlights/discoveries
ISR	CERN	1971-1984	Circular rings 948m	31.5 GeV	Sufficient COM but not sufficient EXP coverage to observe J/Psi and Upsilon (unfortunately)
SPS-SppS	CERN	1981-1984	Circular 6.9km proton/anti-proton	270-315 GeV	W and Z bosons (1981)
TeVatron	Fermilab	1992-2011	Circular 6.3km proton/anti-proton	900-980 GeV	Top quark (1994)
RHIC	Brookhaven NY	Since 2001	Hexagonal rings 3.8km	Polarized protons, Heavy Ions	Probing QGP
LHC	CERN	Since 2008	LEP Tunnel	3.5 – 6.5 TeV	Higgs boson 2012



Observation by S. Van der Meer, that the cross section can be measured using a specific monitor cross section and the rate of measured events when displacing the beams from their center.

S. Van der Meer, ISR-PO/68-31 note

Electron vs. Hadron Colliders

Beamstrahlung energy loss: $$\Delta E \propto \frac{E^4}{m^4 R}$$

LEP Energy reached 209 GeV (3.5 GeV loss per turn), with the same accelerating gradient doubling the energy requires an accelerator 16 times larger!

In comparison at LHC the energy loss per turn is 7 keV $$\frac{\Delta E_p}{\Delta E_e} \propto \frac{m_e^4}{m_p^4} \sim 10^{-13}$$

In e+e- machines the gradient is an essential component, but not only, to reach a decent luminosity requires power, at high energy and high luminosities a substantial amount of power.

The limitation at a hadron collider is the bending power: $$p(TeV) = 0.3B(T)\rho(km)$$

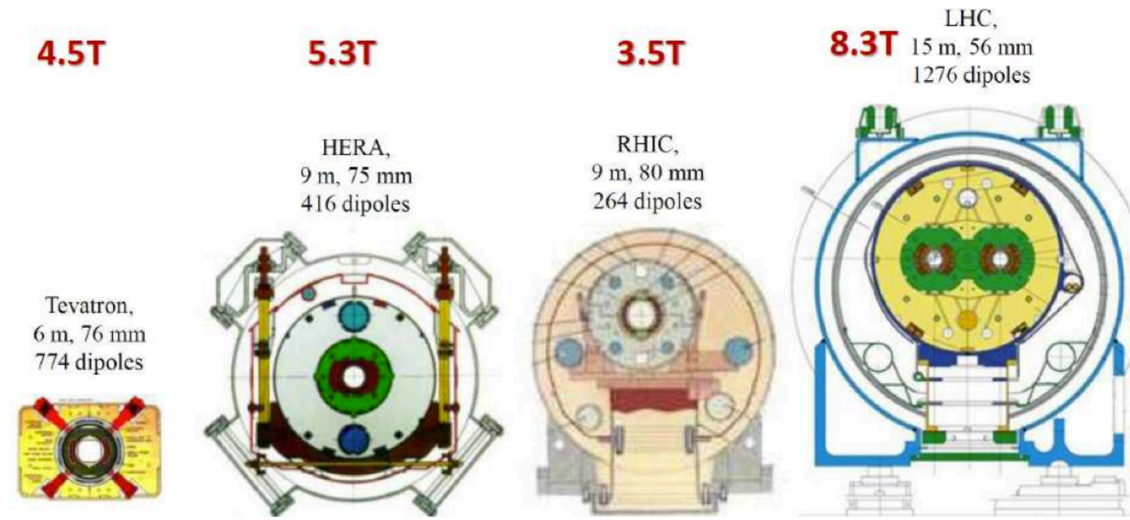
- The effective bending radius is not ~4.3km but rather 2.7km, the nominal LHC requires a magentic field of 8.5T

- The magnetic field at LEP for a COM of 209 GeV required approximately ~1kG

A word about the Technology… towards the LHC

Superconducting magnet are necessary for protons, remarkable technologies.

All use NbTi (critical temperature is about 10K) at different temperatures

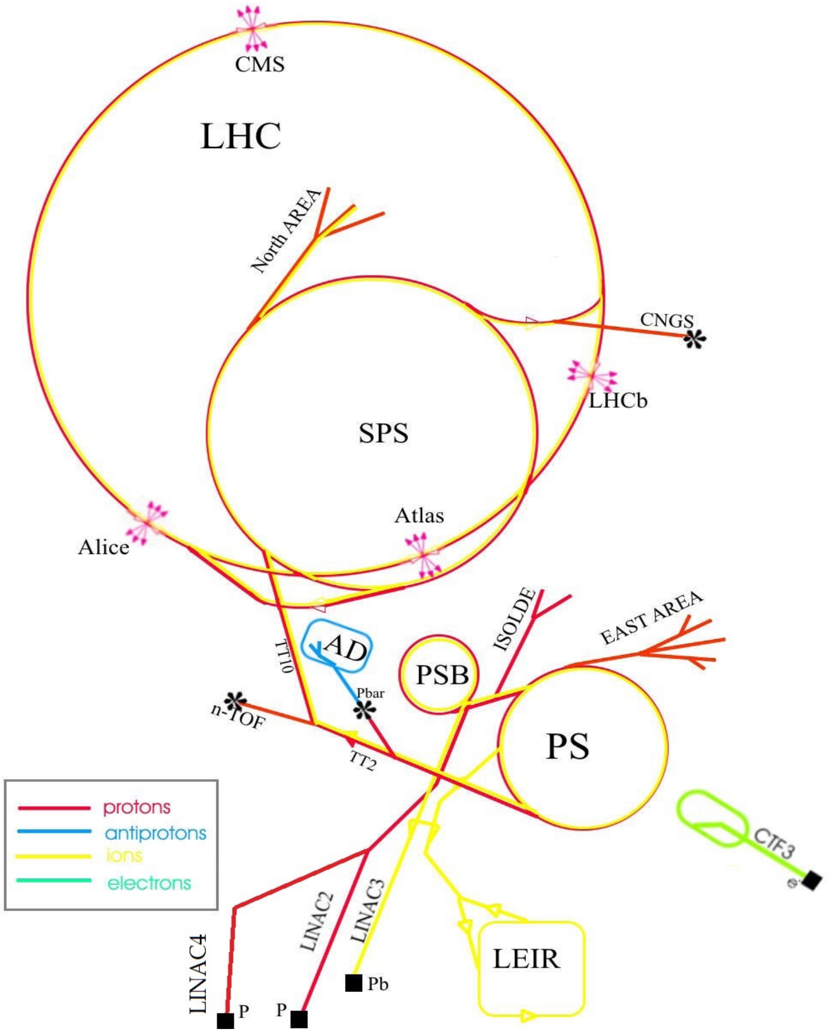


From V. Shiltsev

At the LHC proton-proton (as opposed to proton-anti-proton) allows to reach high luminosities (at the Tevatron Run II approximately 50 000 less anti-protons than protons), however this requires two separate beam pipes.

At high energies of pp collisions the difference in production cross sections typically become very small.

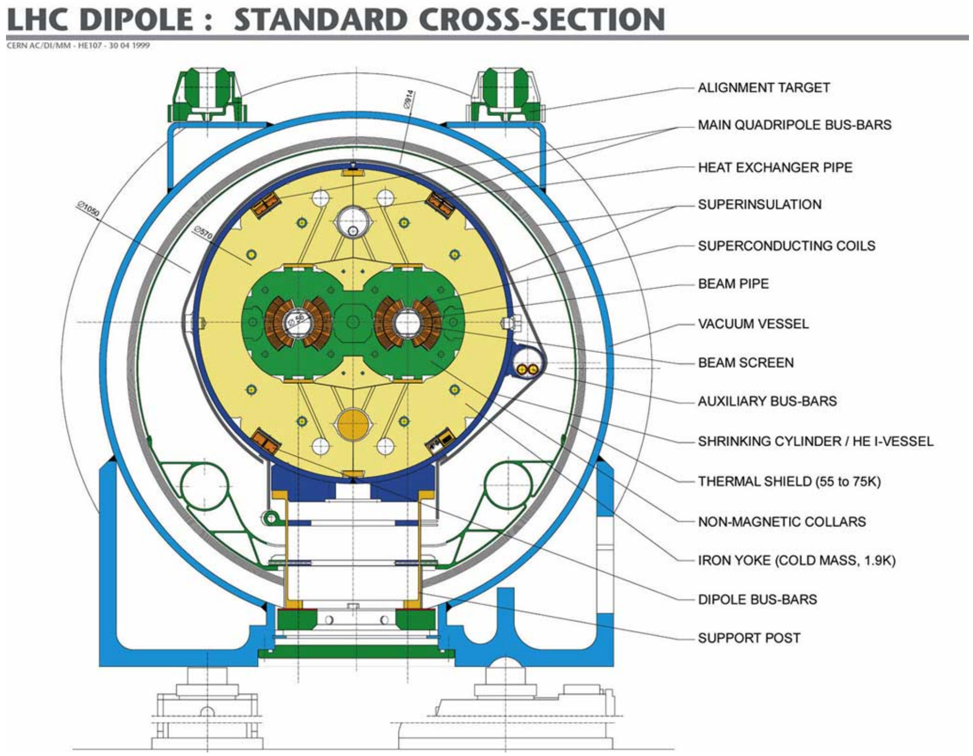
The LHC



- Hydrogen (gas) is ionized in a duoplasmotron.
- First accelerated with a RF quadrupole at 750 keV.
- Acelerated at 50 MeV in a LINAC
- The booster accelerates protons at 1.4 GeV.
- PS brings them to 26 GeV, it is in the PS that bunches are formed with a 25ns spacing.
- SPS accelerates protons to 450 GeV, bunches before injection in the LHC.

The maximum number of bunches (2808) not reached at Run 2 is limited by the injection kickers (~1 μs) and by the beam dump extraction (~3 μs)

The LHC

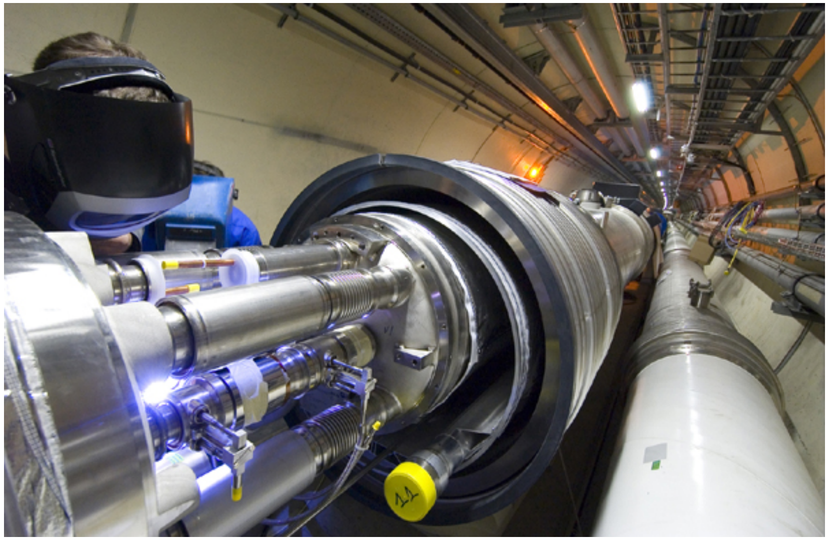


9300 Magnets (among which 1232 bending dipoles) reaching 8.3T with current of 11,400 A.

Beams are made of trains with a total nominal number of bunches of 2808 each containing approximately 100 Bilion protons. Bunches are separated within trains by 25ns (approximately 7m).

Each proton has the kinetic energy of a mosquito and the total energy of the beams is 350 MJ ~ 1 TGV à 150 km/h.

Design, Construction and Commissioning of the LHC



Operation challenge: Unprecedented beam energy and luminosities (for a hadron machine)

- Main challenge : Stored beam energy 2 orders of magnitude higher than existing machines… 350 MJ
- Total stored energy in the magnets (11 GJ, enough to melt 15 tons of copper)

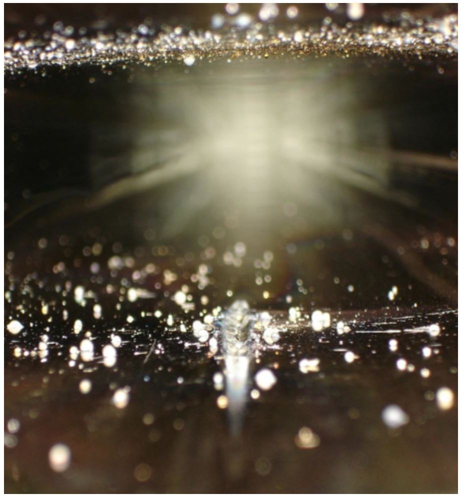
Risk of damage is the main concern :

- From the stored beam energy

(few cm groove in an SPS vacuum chamber from a beam 1% of nominal LHC beam, vacuum chamber ripped open)

- From the stored energy in the magnets

The November 19 2008 incident… (700 m damage area with 39 dipoles and 14 quadrupoles and beam vacuum affected over 2.7 km, 1 year repair)



LHC Luminosity

- Using the normalized emittance (Lorentz invariant, conserved during acceleration phase)

$$\varepsilon_N = \gamma\varepsilon$$

- Beams made of trains of k_b bunches
- With a revolution frequency of f_{rev} (11 kHz)

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi\beta^* \varepsilon_N} F$$

Parameter	2010	2011	2012	2016	Nominal
C.O.M Energy	7 TeV	7 TeV	8 TeV	13 TeV	14 TeV
N_p	1.1 10^{11}	1.4 10^{11}	1.6 10^{11}	1.2 10^{11}	1.15 10^{11}
Bunch spacing / k	150 ns / 368	50 ns / 1380	50 ns /1380	25ns /2300	25 ns /2808
ε (mm rad)	2.4-4	1.9-2.3	2.5	2.6	3.75
β* (m)	3.5	1.5-1	0.6	0.4	0.55
L ($cm^{-2}s^{-1}$)	2x10^{32}	3.3x10^{33}	~7x10^{33}	1.5x10^{33}	10^{34}
PU	~2	~10	~30	~30	~25

Limitations in the Luminosity

- Electron cloud: one of the major intensity limiting factor! Photons from synchotron radiation off protons hit the beam pipe inducing the emission of photo-electrons. The electrons are then accelerated by the subsequent bunches and will hit the beam pipe generating secondary electron, and so on. This will generate a cloud of electrons (an issue seen at other colliders with bunches and small bunch spacing), inducing:

  - Beam instabilities
  - Increase in the pressure
  - Heat in the vacuum pipes
  - kept under control.

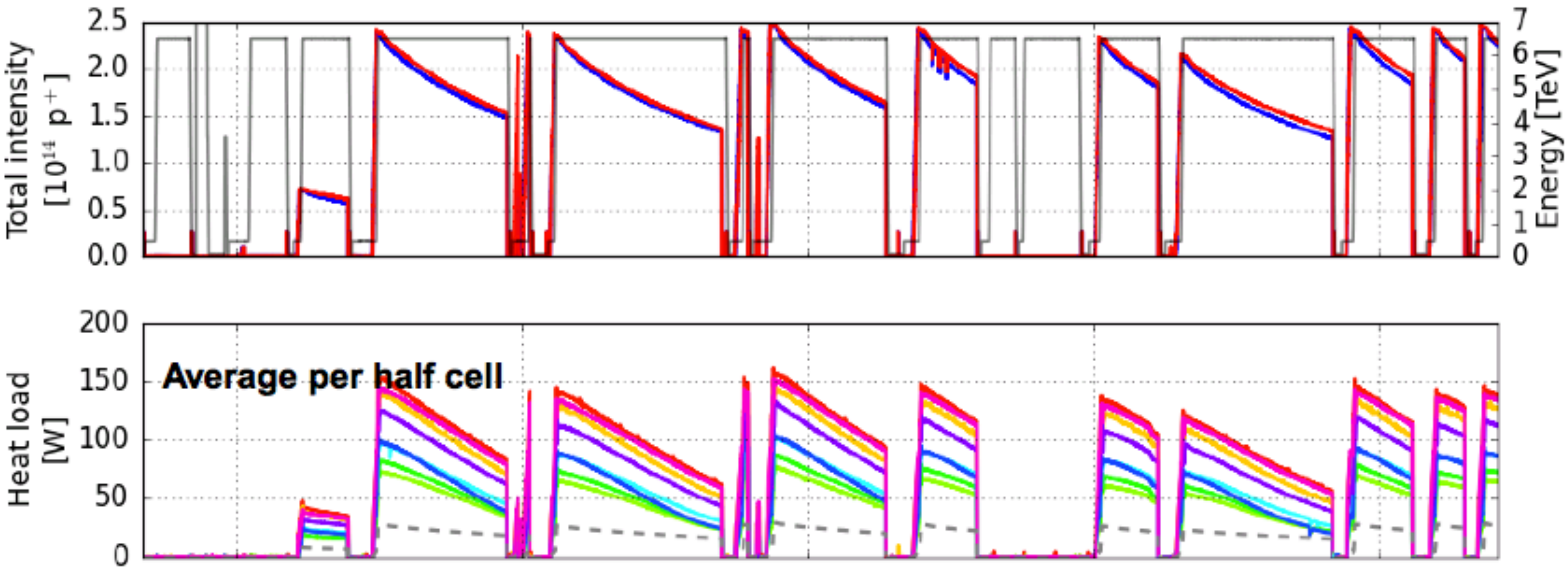
- At LHC beam screen primarily in place to remove heat from synchotron radiation also help to remove heat originating from EC.

- Effect increases with the bunch frequency.

- Scrapping necessary to reach stable beam conditions. At 50ns scrapping at 25ns was efficient, recent operations were uncertain at 25ns, heat load kept under control.

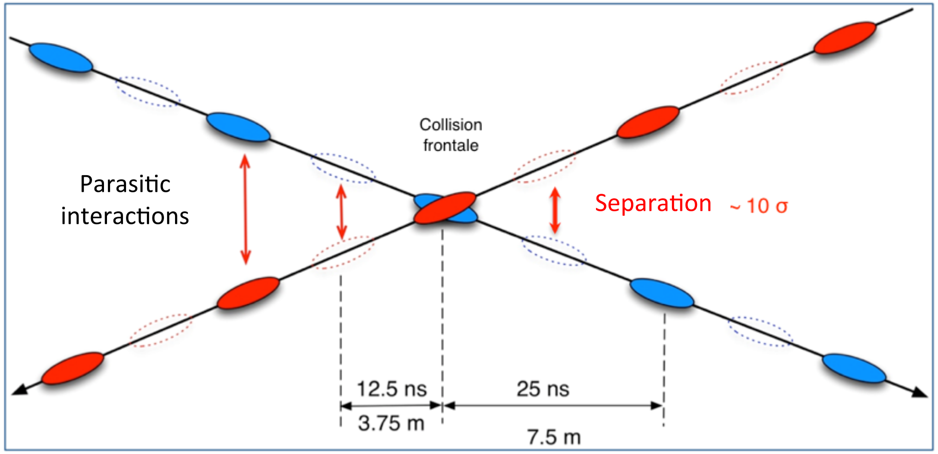
Limitations in the Luminosity

Monitoring of the Heat Load during typical excellent Run 2 week at high intensity



Limitations in the Luminosity

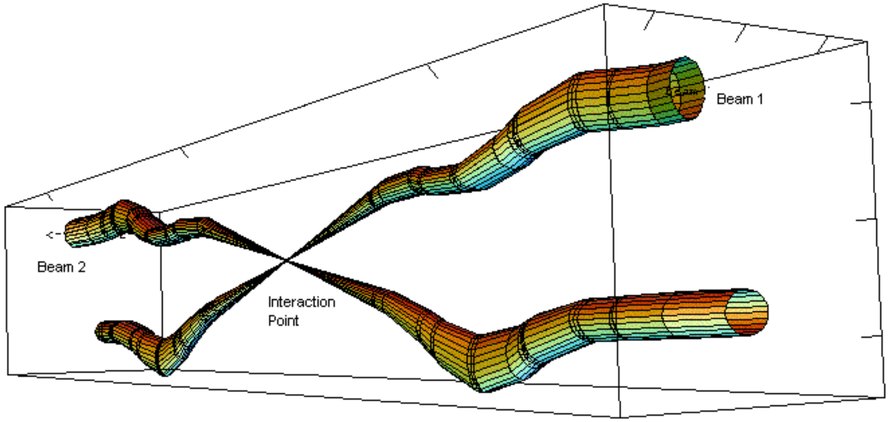
Beams are circulating for ~120m in the same vacuum pipe around Ips, to minimize long distance beam-beam effects beams cross with an angle.



- Crossing angle affects the luminosity by a factor of:

$$F = \frac{1}{\sqrt{1 + (\frac{\theta\sigma_z}{2\sigma_x})}} \sim 0.8$$

$$\theta = 285\mu\text{rad}$$

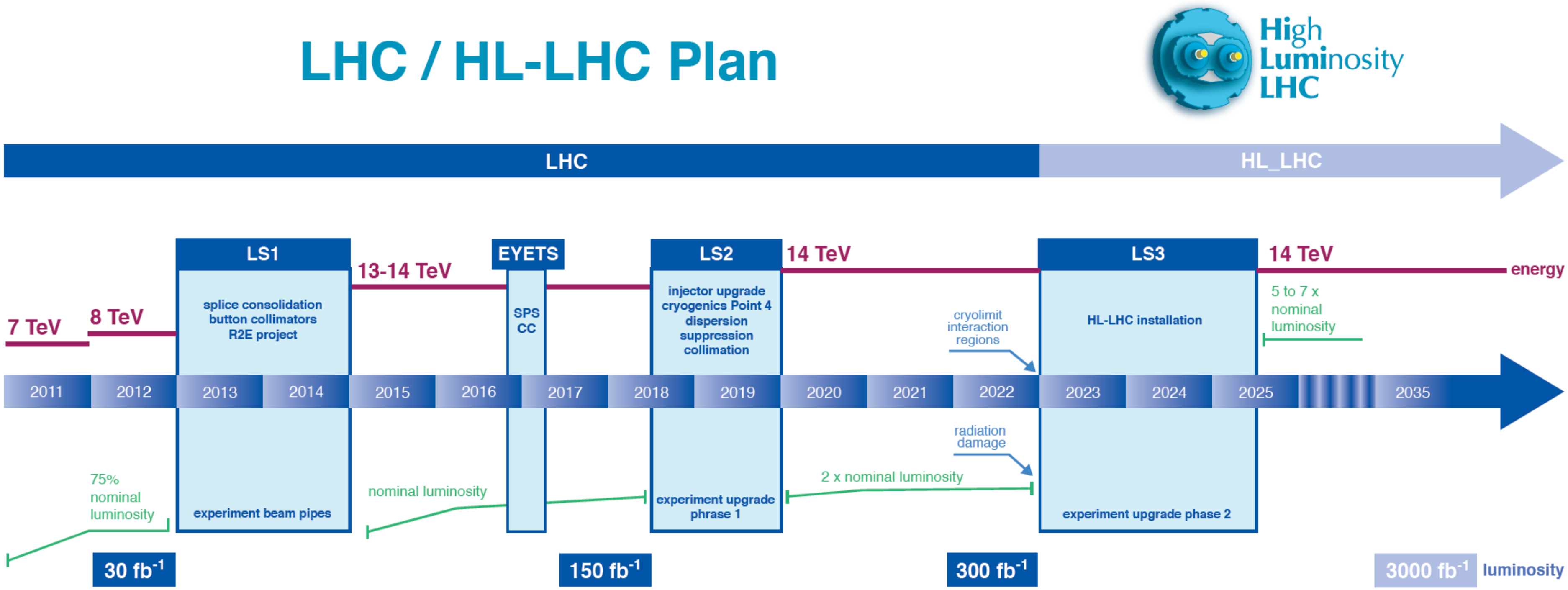


Relative beam sizes around IP1 (Atlas) in collision

- Beam-beam effects still at IPs, where beams are see the effect of the presence of the crossing beam. A limitation for the emittance.

- Another limiting factorQuadrupole aperture at lowest b*

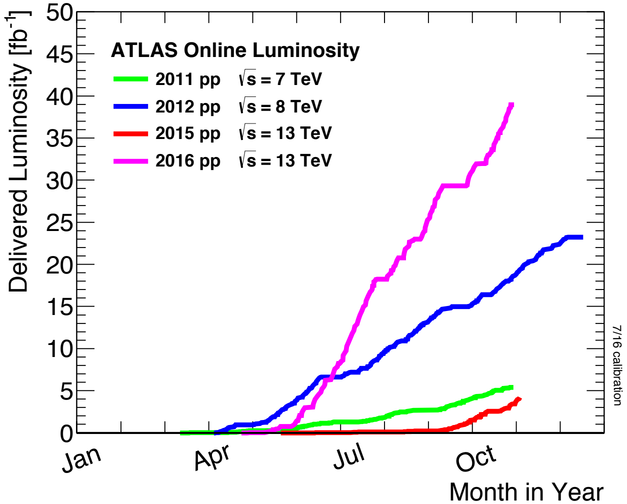
LHC Complete (Latest) Overview

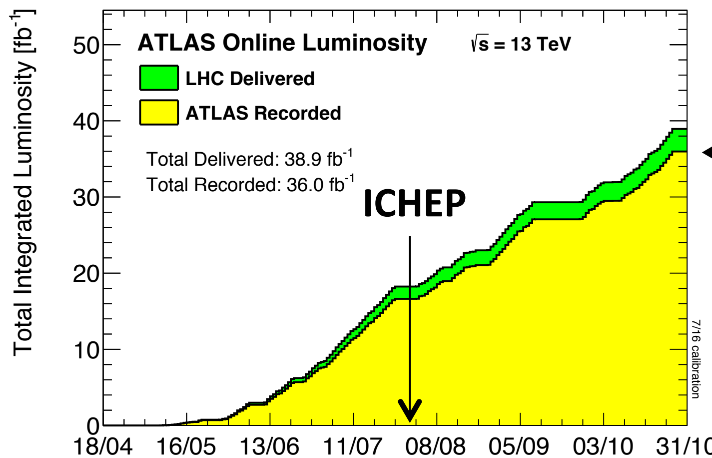


Where do we stand?

- 8th year of the (25 year) program. Reaching almost nominal centre-of-mass energy and surpassed nominal luminosity estimates.
- At the start of an Extended YETS: in particular to replace CMS inner pixel detector.

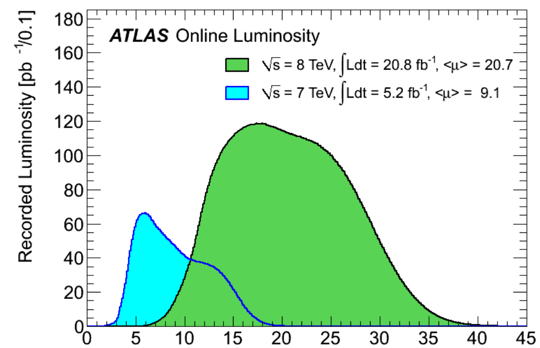
The Run 2 Dataset

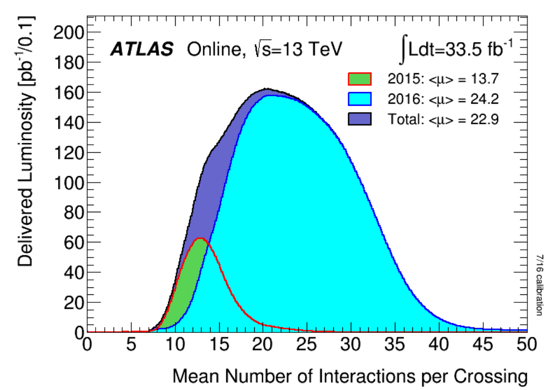




What we currently have

Current dataset ~ 3 x ICHEP 2016 No updates with full dataset yet





Outstanding year for the LHC:

- Peak luminosity from 1.5 10^{34} $cm^{-2}s^{-1}$
- Integrated delivered luminosity of 40 fb^{-1}

Excellent performance of ATLAS:

- In 2016 25 ns inter bunch spacing impact on Pile-up conditions
- ATLAS has recorded 36.0 fb^{-1}
- (with DT efficiency of ~94% and a DQ eff. of 93-95%).

For the physics:

- ICHEP dataset 10 - 12 fb^{-1} : Important threshold in luminosity where most searches reach well beyond Run 1 sensitivity (Higgs measurements as well).

Doubling time of luminosity is now O(1 year)

Machine Status (in a nutshell)

2016 was declared a production year… and the operation team delivered!

With immediate noticeable changes in 2016:

- A lower β^* of 40cm instead of 80cm in 2015.
- A smaller bunch spacing of 25ns

(Some of) **the reasons behind the outstanding luminosity reach in 2016**:

- High machine availability (less UFOs, many fixes and tunings)
- High luminosity lifetime (tunes, couplings and bunch length)
- High peak luminosity (low emittance with BCMS, low beta*, and crossing angle)

For more details see talk by B. Salvant at the LHCC (December 2016)

Such a complex project encountered various issues, very prompt solutions were found: **Congratulations to the Machine operations and coordination teams!**

Possible goals for next year

- Peak luminosity from 1.4 - 2 10^{34} $cm^{-2}s^{-1}$ (depending on BCMS scheme).
- Peak PU from 37 to 56.
- Integrated luminosity between 45 and 60 fb^{-1}.

Pushing LHC Limits

HL-LHC

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \varepsilon_N} F$$

- **Filling at the beam-beam effects limit** Increasing the number of protons per bunch by a factor of 2 to 3.
- **Going to smaller β*** Going to 15cm - will require larger quadrupole aperture.
- **Luminosity leveling** To mitigate the highest peak instantaneous luminosity level luminosity to minimize loss in integrated luminosity.
- **Crossing angle** To mitigate the long range beam-beam effect 285 μrad to 590 μrad.

Goal is a leveled luminosity of ~5 10^{34} $cm^{-2}s^{-1}$

HE-LHC

Doubling the energy will require new magnets e.g. Nb3Sn to reach ~15 T

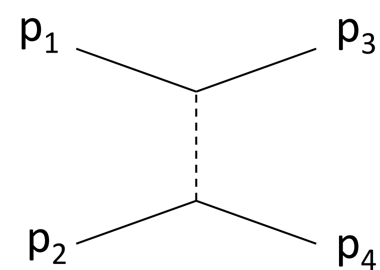
Measurement of the Luminosity

- From beam parameters: beam profiles are measured far from the IPs. The measurement is limited to ~10% precision.

- **Optical theorem**: relates the forward cross section (scattering at 0-angle) and the total cross section.

$$\left(\frac{1}{\mathcal{L}}\frac{dN_{el}}{dt}\right)_{t=0} = (1+\rho^2)\frac{\sigma_{tot}^2}{16\pi}$$

$$\rho = \mathrm{Re}[f_{el}(0)]/\mathrm{Im}[f_{el}(0)]$$



$$t = (p_1 - p_3)^2$$

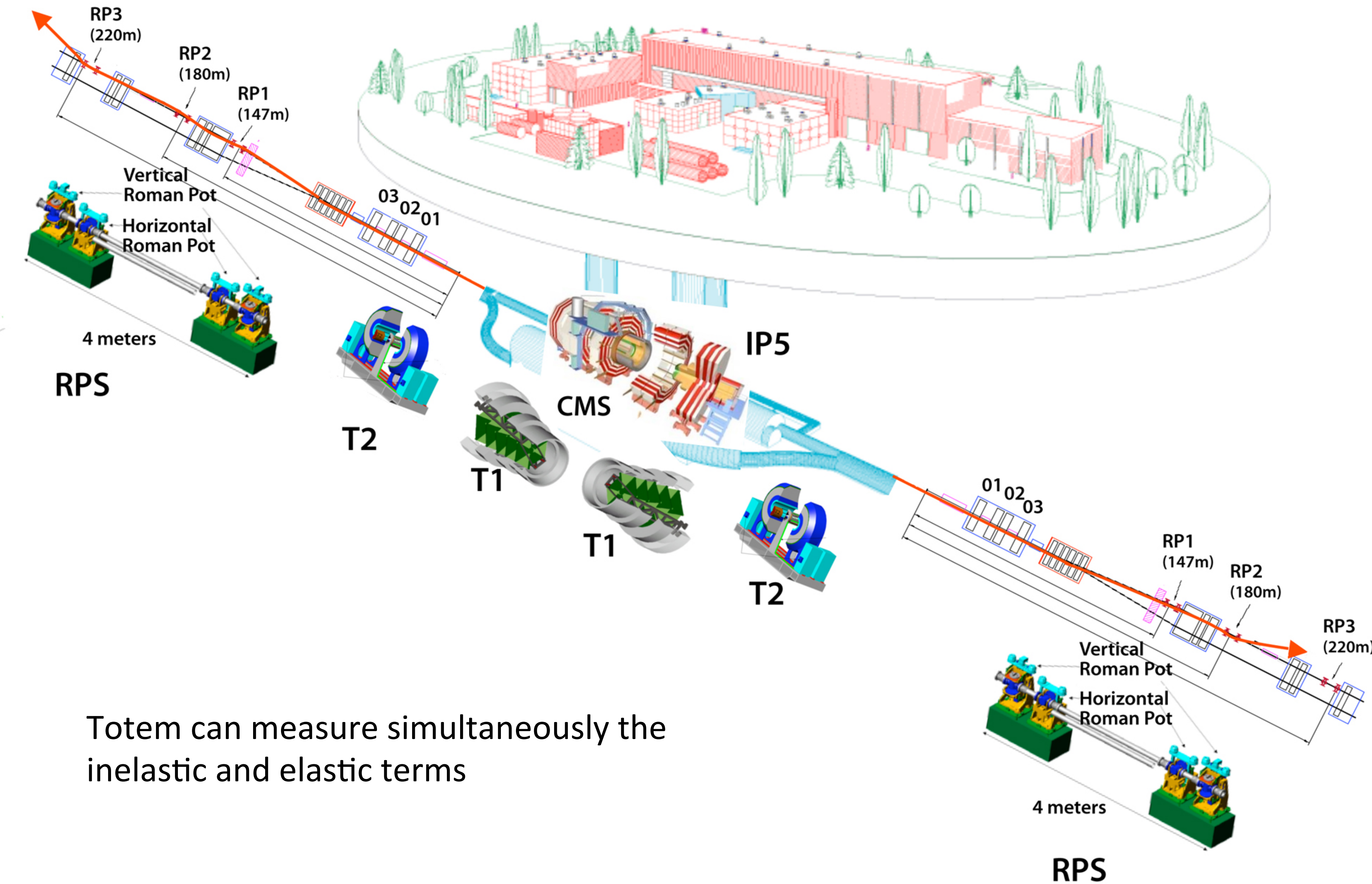
ρ~0.14 is taken from TH predictions, its impact is small, where f_{el} is the forward scattering amplitude.

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2}\frac{(dN_{el}/dt)_{t=0}}{N_{el}+N_{inel}}$$

$$\sigma_{tot} = \frac{N_{el}+N_{inel}}{\mathcal{L}}$$

$$\mathcal{L} = \frac{1+\rho^2}{16\pi}\frac{(N_{el}+N_{inel})^2}{(dN_{el}/dt)_{t=0}}$$

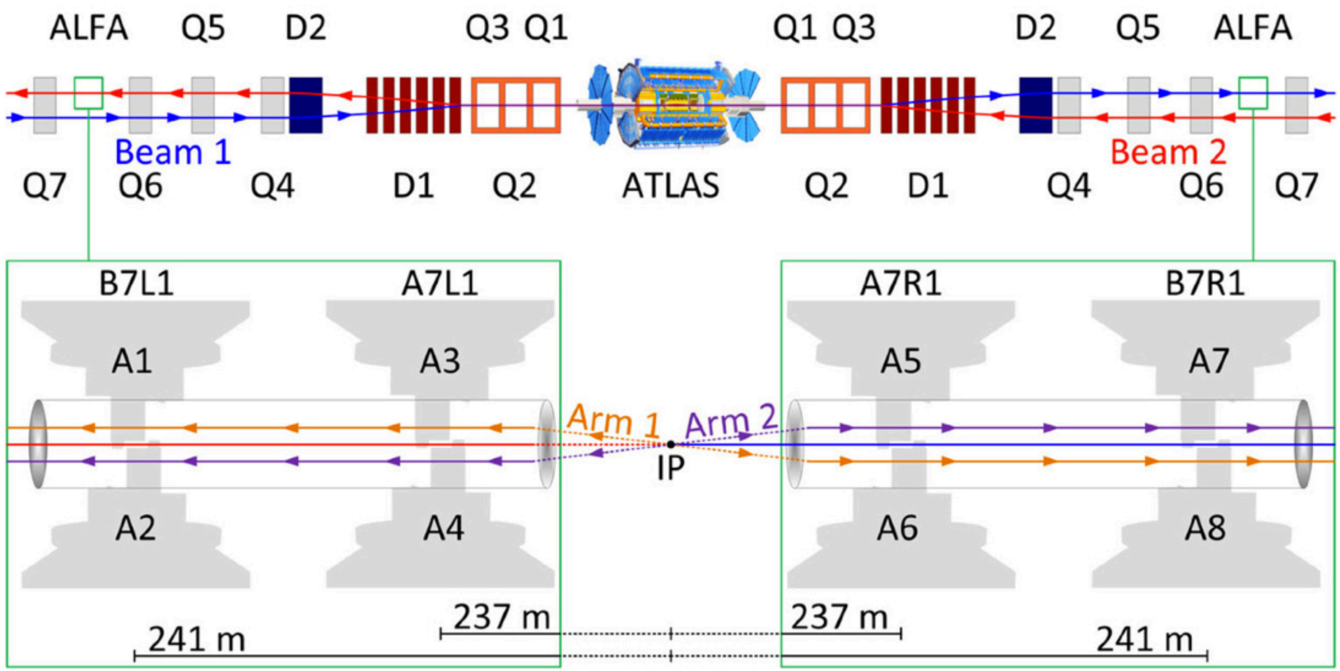
TOTEM Experiment



Totem can measure simultaneously the inelastic and elastic terms

The ALFA Experiment

The Coulomb and Nuclear Interaction region



At very low momentum transfer (t ~ 6 10^{-4} GeV^2) transition from Nuclear to Coulomb scattering with an interference between the two

$$\left(\frac{dN_{el}}{dt}\right)_{t=0} = \mathcal{L}\pi\left(\frac{-2\alpha_{\mathrm{QED}}}{|t|} + \frac{\sigma_{tot}}{4\pi}(i+\rho)e^{-b|t|/2}\right)^2$$

The parameters can be fit to the measured differential cross section and the luminosity determined. Requires very special beam optics with a β* of 2.6 km.

Not achieved yet, only total cross section measurements done using « standard » Luminosity and the optical theorem.

Measurement of the Luminosity

- Luminosiy measurement from relatively precisely known (percent level) processes as for instance γγ interactions such as

$$pp \to p(\ell^+\ell^-)p$$

- Van der Meer Method (from ISRs), back to the very initial formula of the luminosity

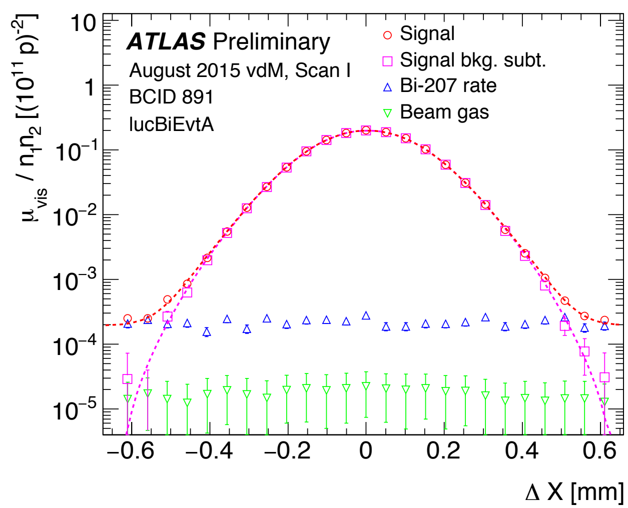
$$\mathcal{L} = \frac{f N_A N_B}{\mathcal{S}}$$

- The revolution frequency is precisely known.
- The number of protons per bunches is monitored through beam current measurements
- The unknown is the area.

VdM observed that the Event Counts in any given process is proportional to the luminosity, so scanning beam separations δ would allow to estimate the the effective area in the luminosity formula:

$$R(\delta x, \delta y) = R_x(\delta x) R_y(\delta y)$$

$$\mathcal{S} = \frac{\int R_x d\delta x}{R_x(0)} \frac{\int R_y d\delta x}{R_y(0)}$$



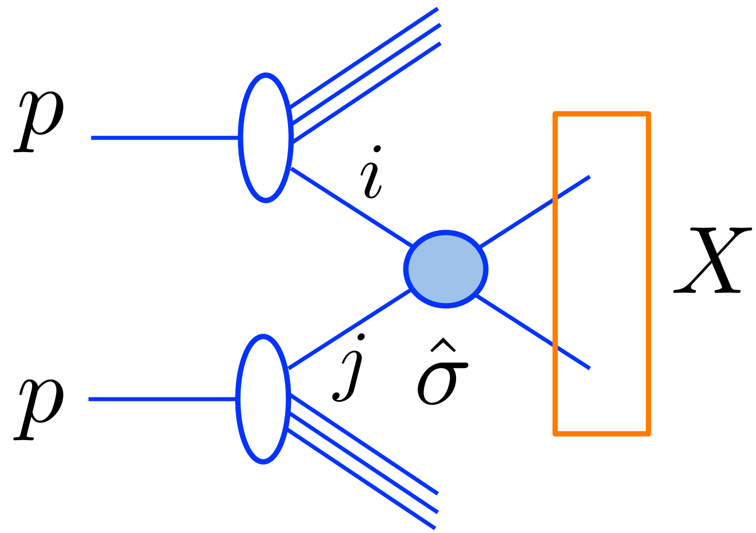
Factorization assumed, but (small) non-factorization observed unambiguously by LHCb SMOG

Precision with VdM for ATLAS 2012 is 1.9%, precision ading beam gas LHCb Run 1 is 1.16%

Factorized Cross Section Formula

In pp collisions

$$\sigma(pp \rightarrow X)$$

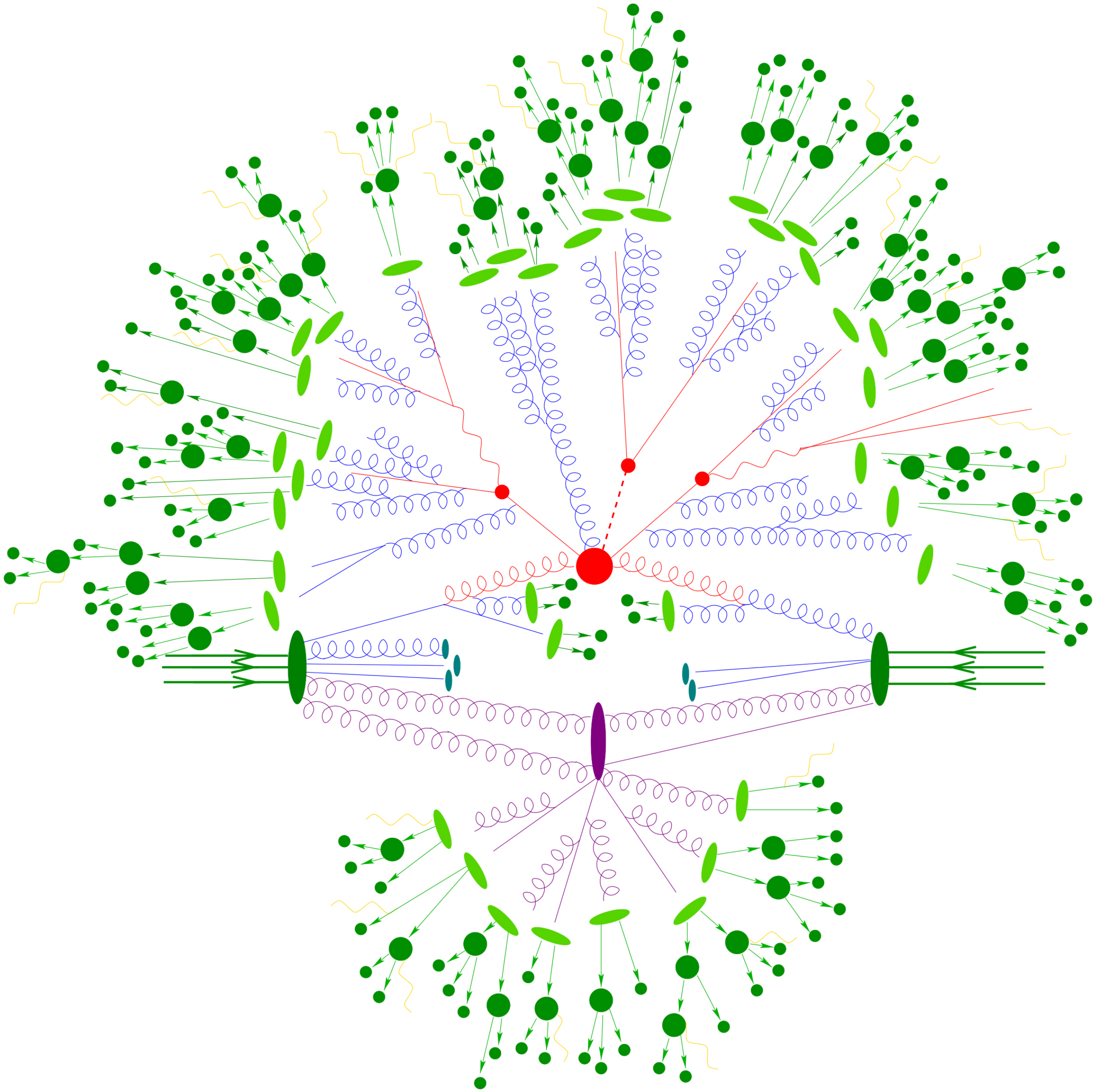


$$\sum_{i,j} \int_0^1 dx_i dx_j f_i(x_i, Q^2) f_j(x_j, Q^2) d\hat{\sigma}(q_i q_j \rightarrow X, \hat{s}, Q^2)$$

Where:

- Q^2 is the energy scale of the process (scale appears when the perturbation serie is not complete)
- q_1 and q_2 are the initial partons
- X_1 and x_2 are the momentum fraction of each parton.

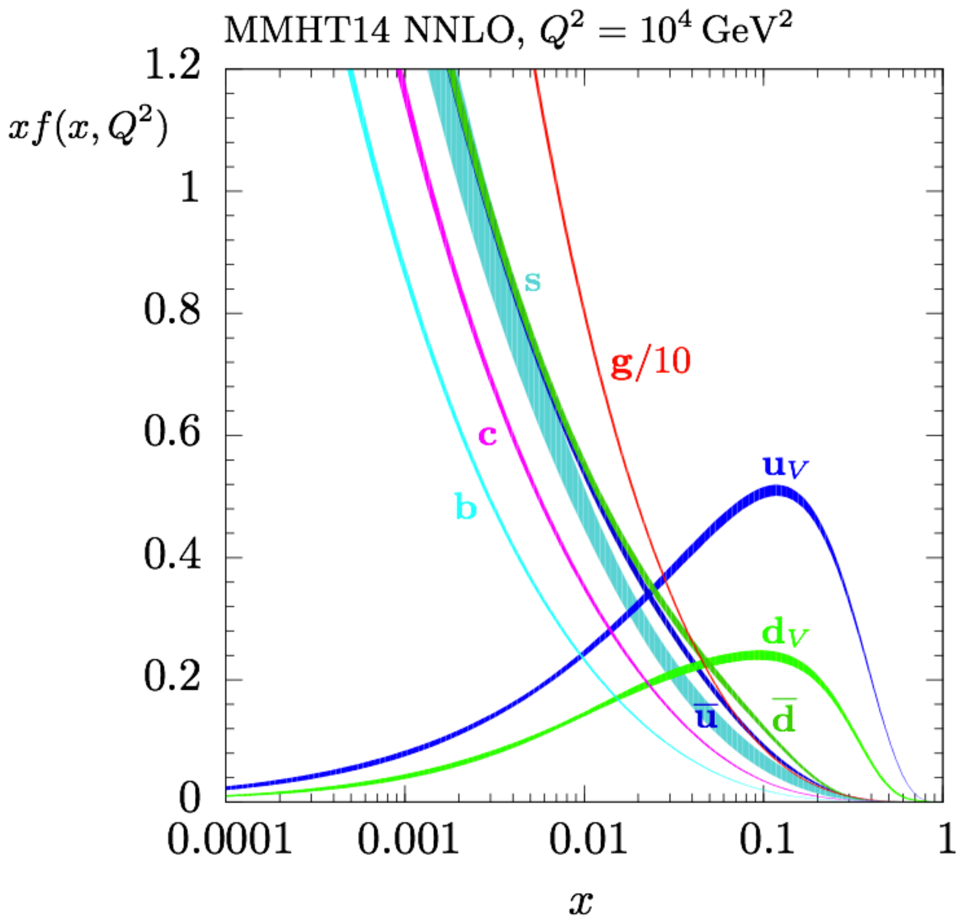
Phenomenology of a pp collision

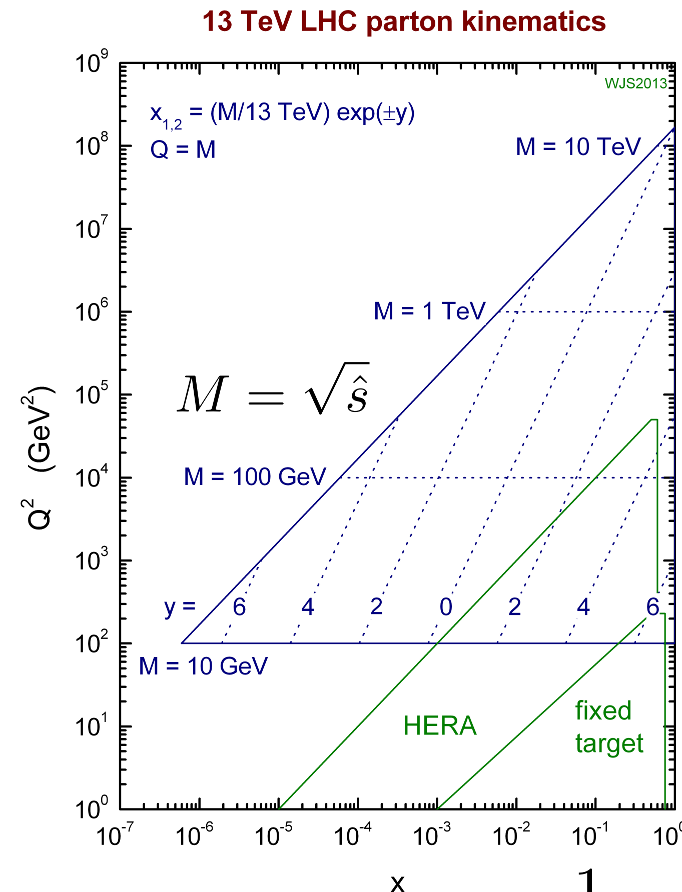


- Hard scattering
- Underlying event (MPI)
- Parton shower
- Hadronization with subsequent decays

Image from F. Krauss

Parton Distribution Functions





$$y = \frac{1}{2} \ln \frac{x_1}{x_2}$$

PDFs are the probability to find a parton with a momentum fraction of x

PDFs are not calculable, but measured inDIS experiments (fixed target and HERA)

PDFs evolution in Q^2 given by Altarelli-Parisi equations

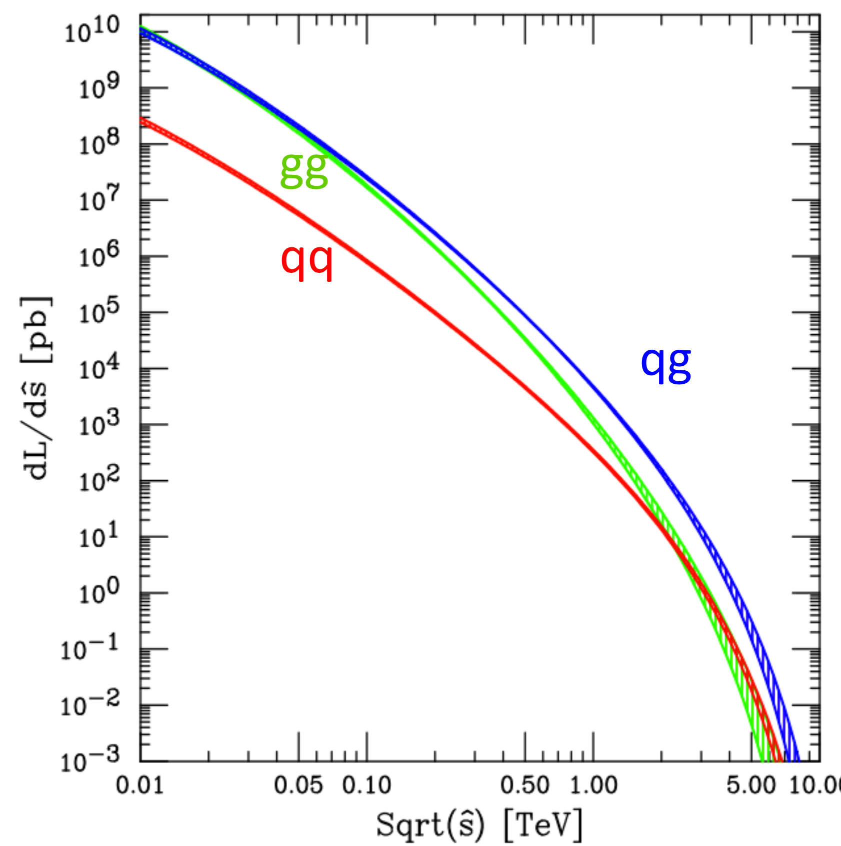
Parton-Parton Luminosities

$$\frac{d\mathcal{L}}{d\hat{s}dy} = \frac{1}{s}\frac{1}{1+\delta_{ij}}[f_i(x_1,Q^2)f_j(x_2,Q^2)+f_i(x_2,Q^2)f_j(x_1,Q^2)]$$

A more usefull definition: $\tau = \hat{s}/s$

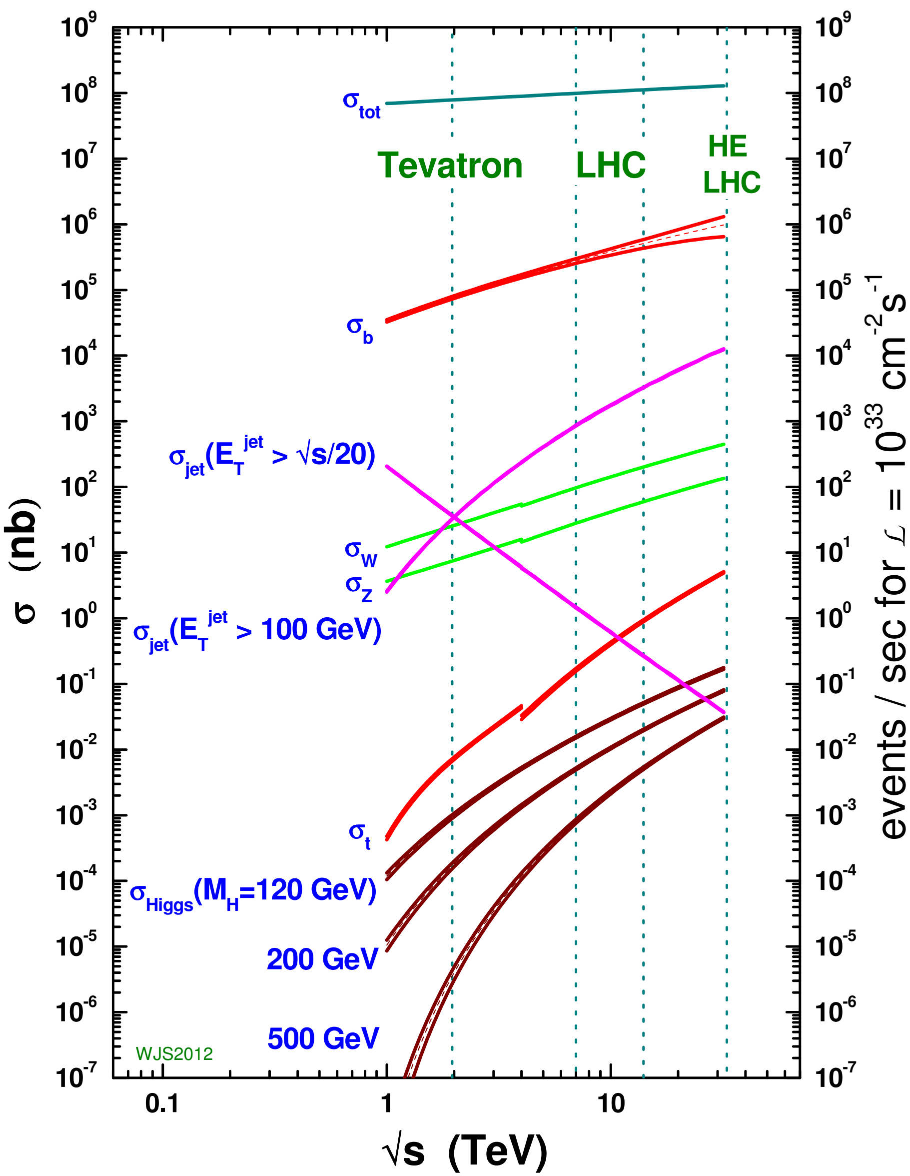
$$\mathcal{L}_{ij} = \tau\frac{d\mathcal{L}}{d\tau} = \frac{\tau}{1+\delta_{ij}}\int_\tau^1 dx[f_i(x)f_j(\tau/x)+f_j(x)f_i(\tau/x)]/x$$

$$\frac{d\sigma}{d\tau} = \sum_{i,j}\mathcal{L}_{ij}\hat{\sigma}(q_i q_j \to X)$$



- gg and qg initiated processes are dominant w.r.t qq
- Parton luminosities will be very interesting to have a guideline on the cross sectoin ratio between different pp centre-of-mass energies

Proton-(anti)-proton Cross Sections



In 2016 with the Luminosity reach the LHC produced a total of ~10^9 interactions per second (in total).

Processes of interest are with much lower production rates: Challenge for the analyses, but even more so for the Trigger!

Detector challenge (in particular robustness to radiation) at the LHC Frank Hartmann's lectures.

Typicaly 3 trigger levels:

- First hardware trigger from 40 MHz to ~100kHz
- Second software level (based on ROI) from 100 kHz to few kHz (partial reconstruction)
- Third level with full software reconstruction of the event down to 1 kHz.

Fundamental LHC Kinematics

In pp collisions the longitudinal momentum of the system is not known a priori (for certain fully reconstructed processes it can be measured), however the transverse momentum is precisely known to nearly vanish (modulo the beam crossing angle which yields - small).

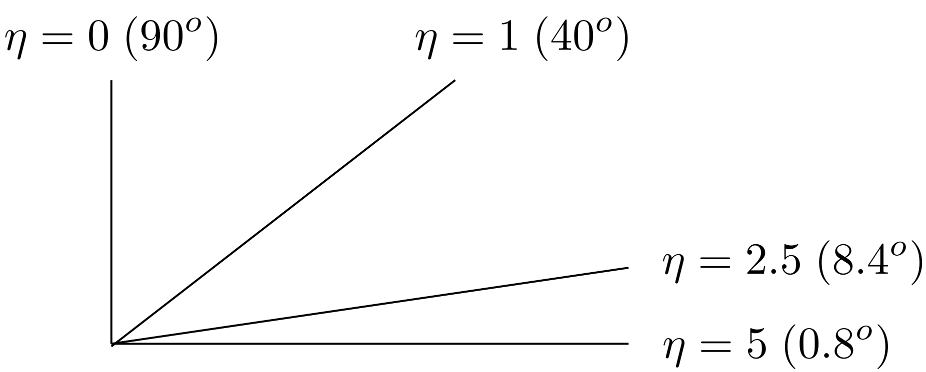
Typical choice of variables which are invariant under a boost along the z-axis.

- Transverse energy: The transverse momentum in the transverse (x,y) plane.
- Rapidity and pseudo rapidity:

Identical if E>>m

$$\begin{cases} y = \ln \dfrac{E + p_z}{E - p_z} \\ \eta = -\ln \tan \dfrac{\theta}{2} \end{cases}$$

Where q is the polar angle w.r.t. to the z-axis.



Soft processes typically have a flat dN/dh distribution and the dN/dP_T distribution is approximately constant as a function of h.

Hard processes have larger $P_{T\ in}$ the central region.