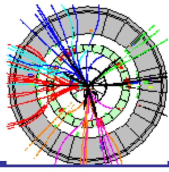


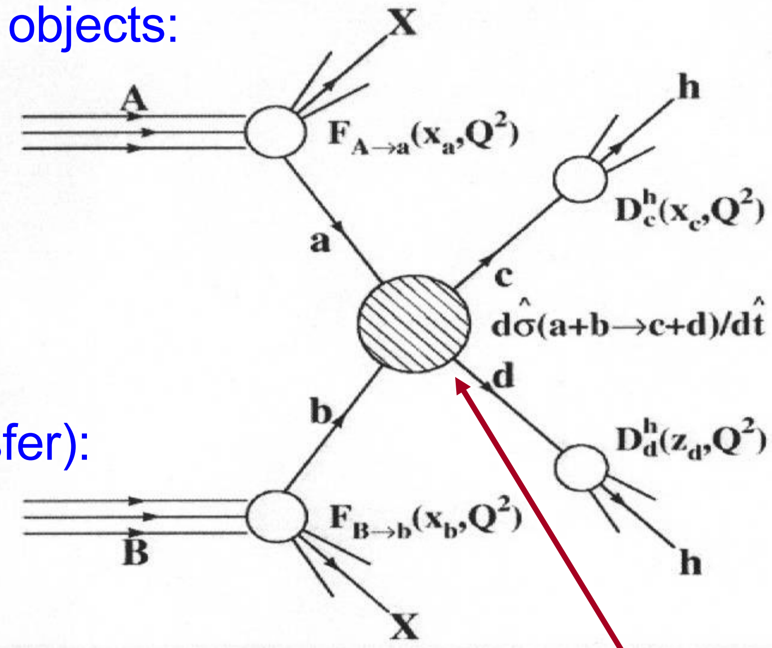
Physics at hadron colliders

- Hadron-hadron interactions
- Higgs
- Future colliders

Hadron-hadron interactions

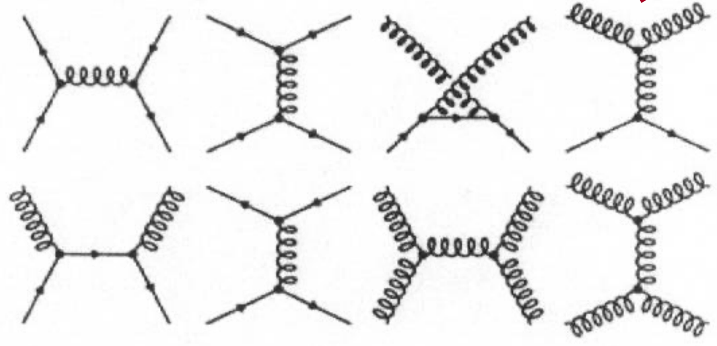
protons complex objects:
partonic substructure: quarks & gluons

hard scattering processes (large momentum transfer):



quark-quark
quark-gluon
gluon-gluon

scattering or annihilation



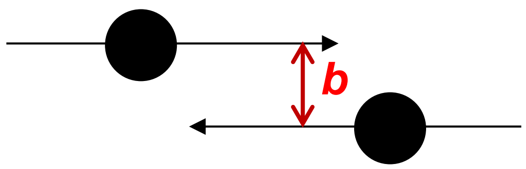
at parton level

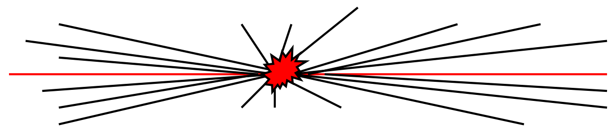
however: hard scattering (high p_T processes) represent only a tiny fraction of the total inelastic pp cross section. e.g. total inelastic cross section ~80 mb at $\sqrt{s}$ = 13 TeV.

Dominated by events with small momentum transfer, in particular by two event types: diffractive (colourless exchange with the quantum numbers of vacuum between the two protons) & minimum-bias (exchange of colour).

Inelastic low p_T hadron-hadron collisions

Most interactions due to interactions at <u>large distance</u> between incoming protons where protons interact as "a whole" $\rightarrow$ small momentum transfer ($\Delta p \approx \hbar / \Delta x$)/ large impact parameter b $\rightarrow$ particles in final state have large (small) longitudinal (transverse) momentum.





$< p_T > \approx 500$ MeV (of charged particles in final state)

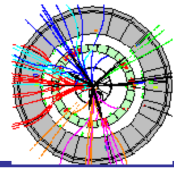
$$\frac{dN}{d\eta} \approx 6$$

~6 charged particles per pseudorapidity unit in central region of experiment (uniform distribution in azimuthal angle)

(LHC numbers)

most energy escapes down the beam pipe.

Called minimum-bias events ("soft" events) & constitute a large fraction of the total cross section e.g. ~ 60 mb of ~ 110 mb at $\sqrt{s}$ = 13 TeV. Perhaps not very interesting in themselves but needs to be understood. Cross section large that they occur multiple times per bunch crossing (e.g. 2023: ~ 50 times) $\Rightarrow$ overlap interesting collisions ("pile-up") & change the measured event quantities.



Diffractive processes

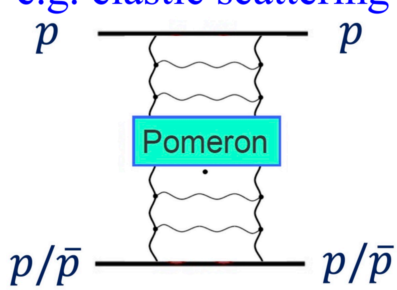
another large part of the total cross section are diffractive processes, where non-colored object(s) are exchanged refered to as ”Pomeron(s)”. Pomeron is described by a system of two (or even number) of gluons or gluon ladder

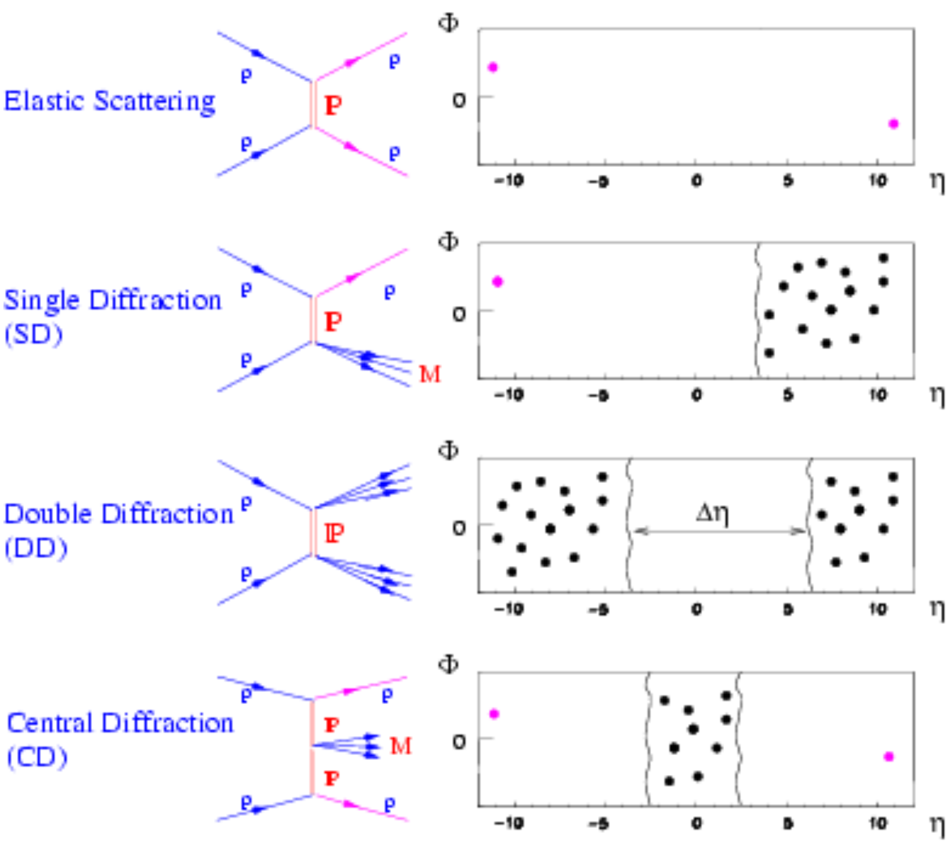
diffractive events characterized by ”rapidity gaps”
(= regions of pseudorapidity without primary particle production)

elastic scattering	~ 30 mb
single diffraction	10 – 16 mb
double diffraction	5 – 10 mb
central diffraction	~ 1 mb

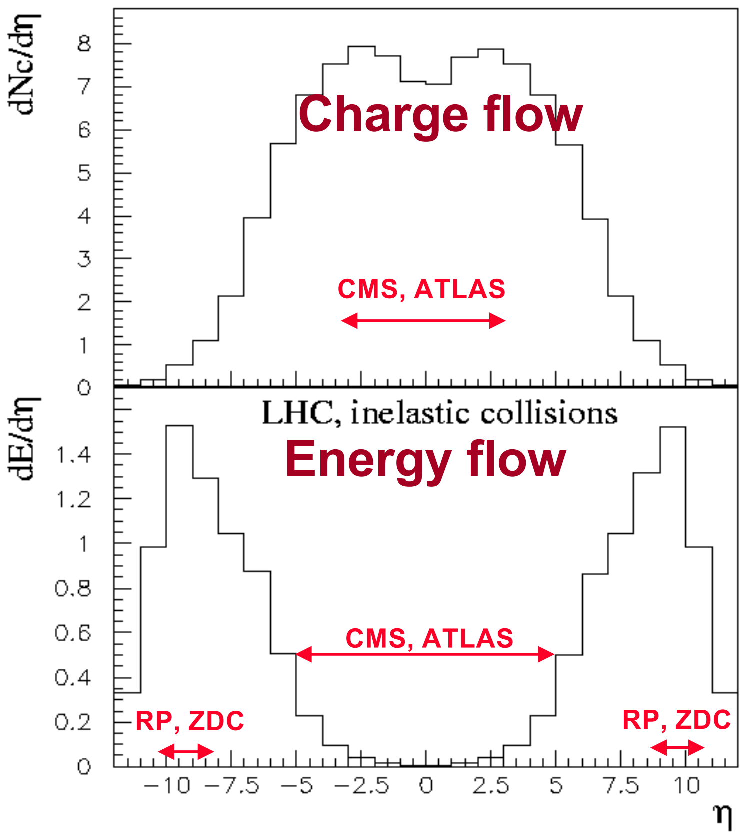
in total ~ 50 mb @ √s = 13 TeV.

e.g. elastic scattering





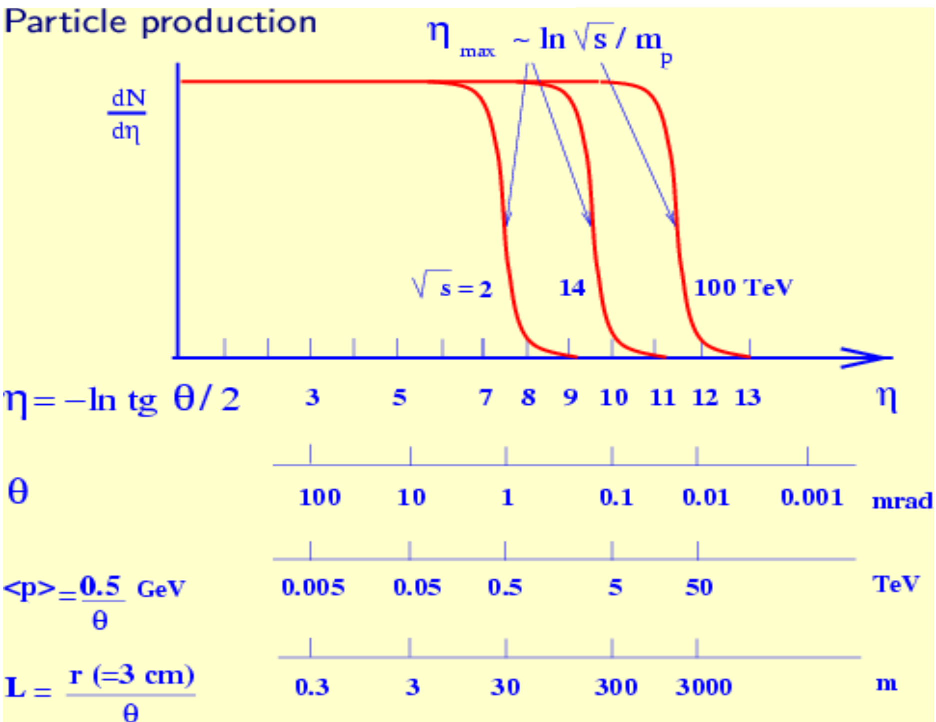
	σ (1.8 TeV)	(13 TeV)
Elastic Scattering	17.8+–0.6 mb	~ 30 mb
Single Diffraction (SD)	9.46+–0.44 mb	10 -16 mb
Double Diffraction (DD)	6.3+–1.7 mb (for Δη > 3)	5 -10 mb
Central Diffraction (CD)		~ 1 mb



charged particle & energy flow in an average proton-proton collision at LHC.

The acceptancies of baseline ATLAS & CMS experiments are also indicated

RP = Roman Pots (detect protons)
ZDC = Zero Degree Calorimeters (detect neutral particles)



pseudorapidity

polar angle

average particle momentum

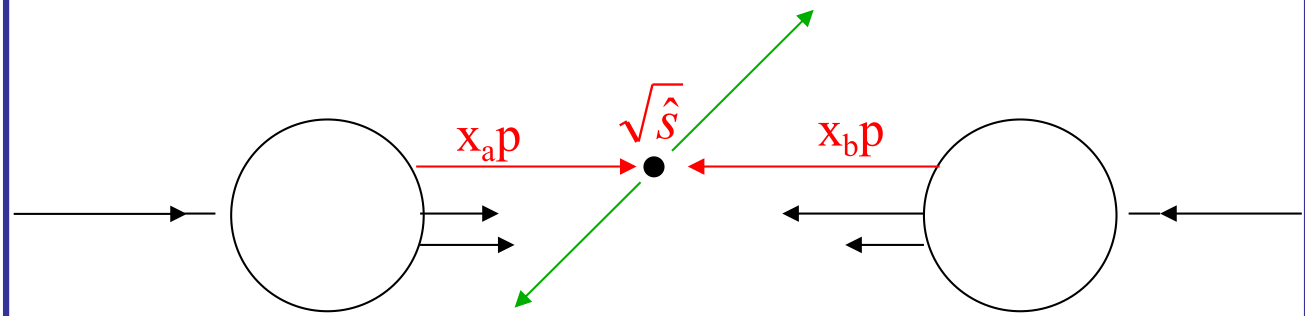
distance to IP @ LHC vacuum chamber radius

IP = interaction point

Inelastic high p_T hadron-hadron collisions

proton beam can be seen as a beam of quarks & gluons with a wide band of energies. occasionally occurs hard scattering between constituents of incoming hadrons.

constituents carry only a fraction 0 < x < 1 of proton momentum.



p ≡ momentum of incoming hadron

- effective centre-of-mass energy $\sqrt{\hat{s}}$ smaller than $\sqrt{s}$ of colliding beams:

if $x_a \approx x_b$

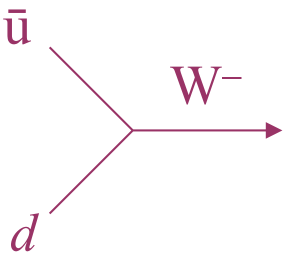
$$\sqrt{\hat{s}} = \sqrt{x_a x_b s} \approx x\sqrt{s}$$

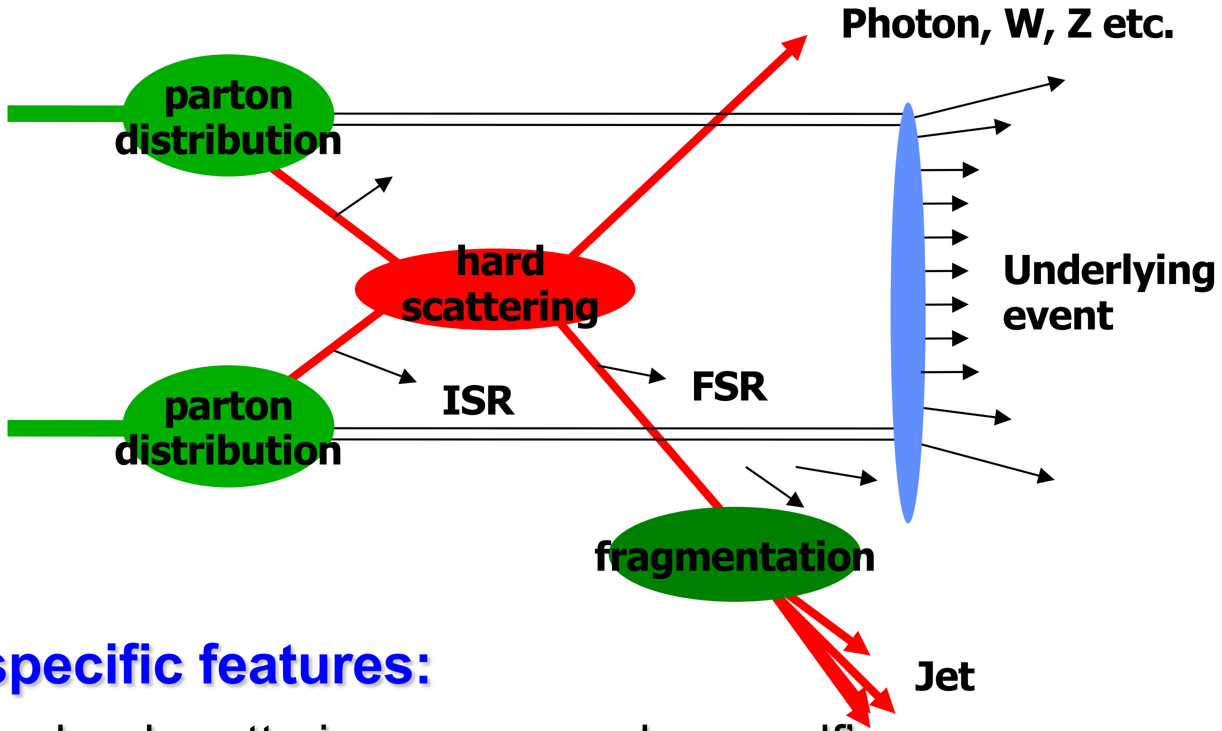
to produce at LHC a mass of:
100 GeV: x ~ 0.007
1 TeV: x ~ 0.07
5 TeV: x ~ 0.36

these are interesting physics events but they are rare.

e.g. $\bar{u} + d \rightarrow W^-$

$$\sigma\,(pp \rightarrow W) \approx 150 \text{ nb} \approx \mathbf{10^{-6}}\,\sigma_{tot}\,(pp)$$





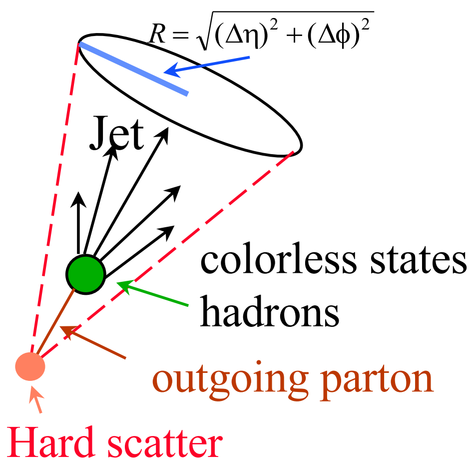
specific features:

- hard scattering σ averaged over pdf's
- initial and final states can emit gluons
- colored final states fragment to form "jets"
- underlying event from proton remnants

fragmentation (hadronization):

- quarks/gluons produced give raise to lots of radiation (α_S is large!) & recombine to form colorless spray of almost collinear hadrons: a jet
- jets = experimental signature of quarks/gluons & observed as localized energy deposits in calorimeters.
- jet energy ≠ parton energy due to calorimeter response, missing (ν's, low p_T & out of cone) particles & overlapping particles (from min. bias events). average corrections applied.

at hadron colliders jets usually formed using simple cone algorithms ($R \approx 0.7$)



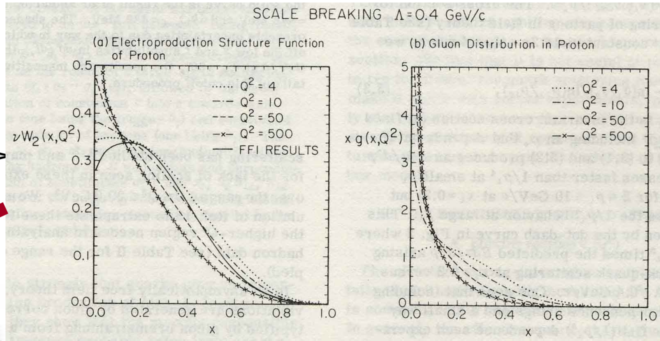
- cross-section :

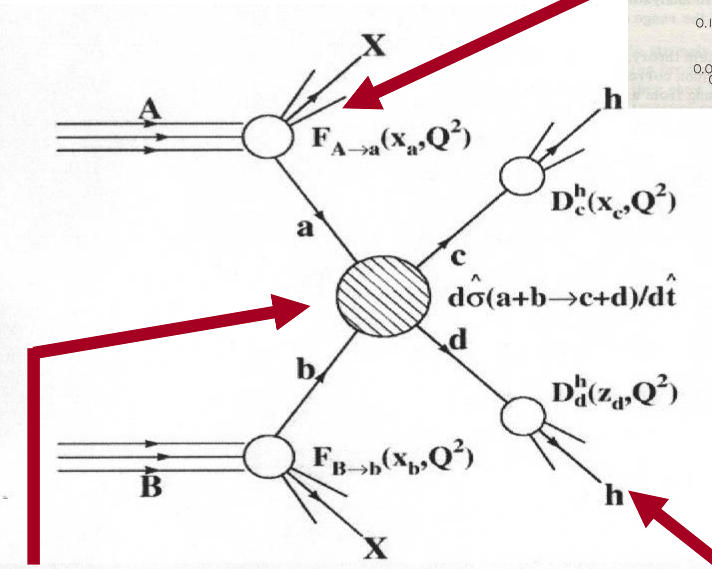
$$\sigma = \sum_{a,b} \int dx_a\, dx_b\, f_a(x_a, Q^2)\, f_b(x_b, Q^2)\, \hat{\sigma}_{ab}(x_a, x_b)$$

$\hat{\sigma}_{ab}$ $\equiv$ hard scattering cross-section

$f_i(x, Q^2) \equiv$ parton distribution function

parton distribution functions
measured in DIS & hadron-hadron collisions





quark & gluon fragmentation functions
measured mostly in e⁺e⁻ collisions; modeled by fragmentation MC

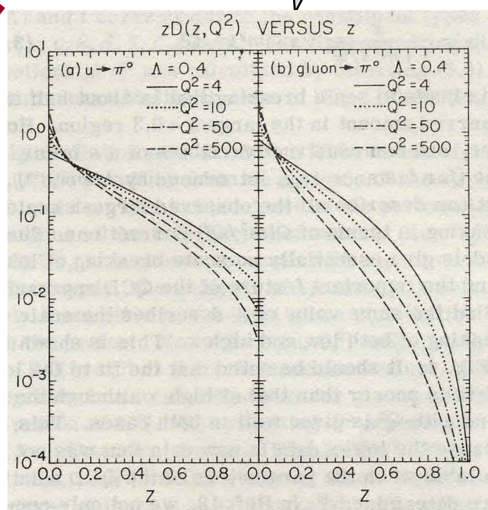


TABLE I. Cross sections for the various constituent quark-quark, quark-gluon, and gluon-gluon subprocesses.[a] The differential cross section is given by $d\hat{\sigma}/d\hat{t} = \pi\alpha_s^2(Q^2)|A|^2/\hat{s}^2$, where $\alpha_s(Q^2)$ is the effective coupling given by Eq. (3.1).

	Subprocess	$\lvert A\rvert^2$
1.	$q_iq_j \to q_iq_j$, $q_i\bar{q}_j \to q_i\bar{q}_j$ $(i\neq j)$	$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
2.	$q_iq_i \to q_iq_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right)-\frac{8}{27}\frac{\hat{s}^2}{\hat{u}\hat{t}}$
3.	$q_i\bar{q}_i \to q_i\bar{q}_i$	$\frac{4}{9}\left(\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right)-\frac{8}{27}\frac{\hat{u}^2}{\hat{s}\hat{t}}$
4.	$q_i\bar{q}_i \to gg$	$\frac{32}{27}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{8}{3}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
5.	$gg \to q_i\bar{q}_i$	$\frac{1}{6}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{u}\hat{t}}\right)-\frac{3}{8}\left(\frac{\hat{u}^2+\hat{t}^2}{\hat{s}^2}\right)$
6.	$q_ig \to q_ig$	$-\frac{4}{9}\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{u}\hat{s}}\right)+\left(\frac{\hat{u}^2+\hat{s}^2}{\hat{t}^2}\right)$
7.	$gg \to gg$	$\frac{9}{2}\left(3-\frac{\hat{u}\hat{t}}{\hat{s}^2}-\frac{\hat{u}\hat{s}}{\hat{t}^2}-\frac{\hat{s}\hat{t}}{\hat{u}^2}\right)$

quark & gluon cross-sections
calculable in QCD

Parton fragmentation function $D_i^h(x, Q^2)$ describes probability to produce certain hadron h from parton i (= $\bar{q}$, q ... g). Analogous to pdf's obtain from DIS.

In fragmentation function, x represents fraction of partons momentum carried by produced hadron $h \leftrightarrow$ In pdf, x represents fraction of momentum of original hadron carried by interacting parton. Q^2 describes here the energy (scale) of the original parton when produced instead of the momentum transfer as for pdf's in DIS.

Fragmentation functions $D_i^h(x, Q^2)$ exhibit similar scaling violations as pdf's $f_i(x, Q^2)$ from DIS. The Q^2 evolution described by similar "DGLAP"–equations:

$$\frac{\partial D_i(x,Q^2)}{\partial \ln Q^2} = \sum_j \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P_{ji}(z,\alpha_s) D_j(\frac{x}{z},Q^2),$$

$$\text{where} \quad P_{ji}(z,\alpha_s) = P_{ji}^{(0)}(z,\alpha_s) + \frac{\alpha_s}{2\pi} P_{ji}^{(1)}(z,\alpha_s) + \ldots$$

Lowest–order functions $P_{ji}^{(0)}(z)$ same as those for pdf's in DIS but higher–order terms different. NB! Splitting function P_{ji} (& not P_{ij}) since D_j describes fragmentation of final parton. P_{ji} = probability for parton i to transfer into parton j.

Effect of Q^2 evolution same as for DIS pdf's: x–distribution shifted towards lower values for larger Q^2's. P_{ji}'s contain singularities at z = 0 & z =1, which have important effects on fragmentation at small & large x, for details see
O. Biebel, P. Nason & B.R. Webber, hep-ph/0109282.

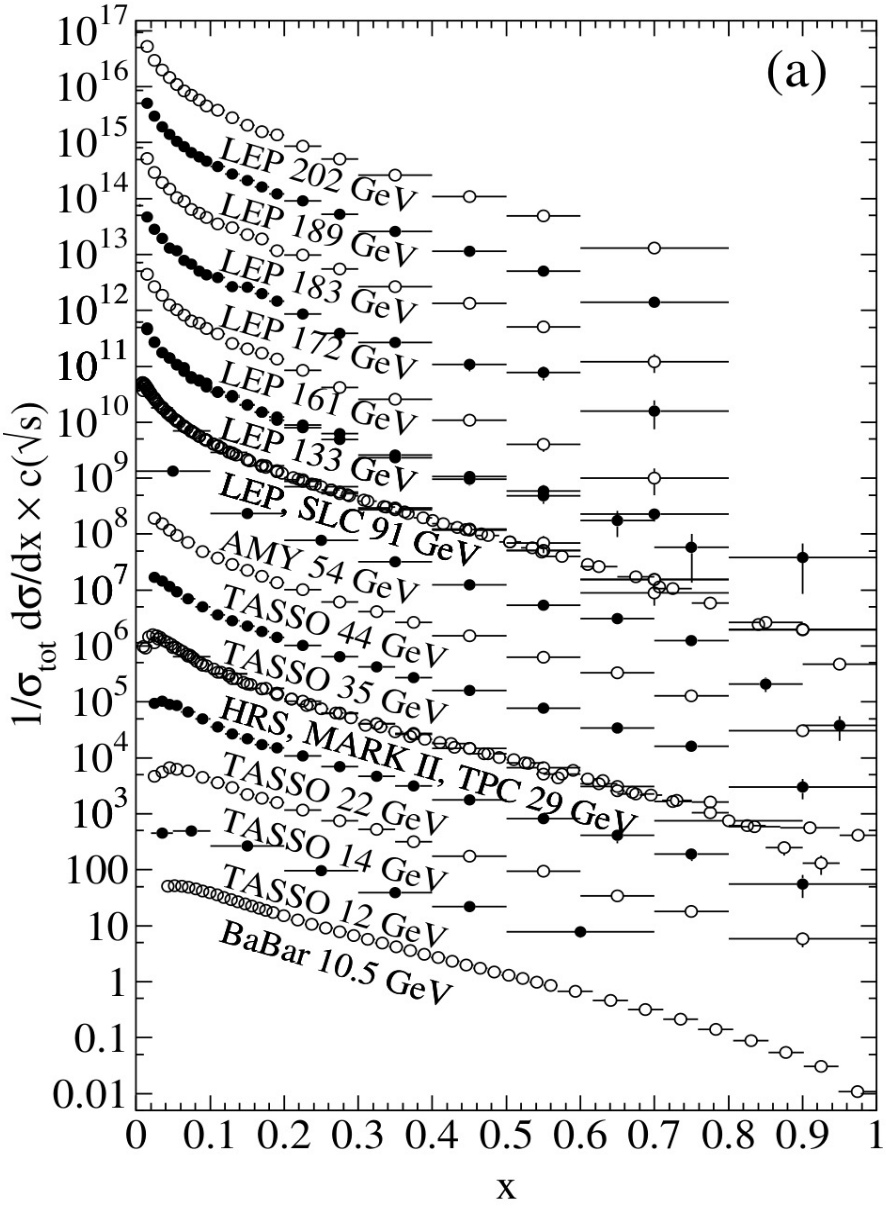
Parton fragmentation function $D_i^h(x,s)$ usually determined from e^+e^- fragmentation functions $F^h(x,s)$.

$$F^h(x,s) = \frac{1}{\sigma_{\text{tot}}}\frac{d\sigma}{dx}(e^+e^- \to hX) = \sum_i \int_x^1 \frac{dz}{z} C_i(s;z,\alpha_s) D_i^h\left(\frac{x}{z},s\right),$$

$$C_q(s;z,\alpha_s) = g_q(s)\delta(1-z) + O(\alpha_s) \;\; \& \;\; C_g(s;z,\alpha_s) = O(\alpha_s)$$

& $g_i(s)$ appropriate (e.g. q) electroweak coupling.

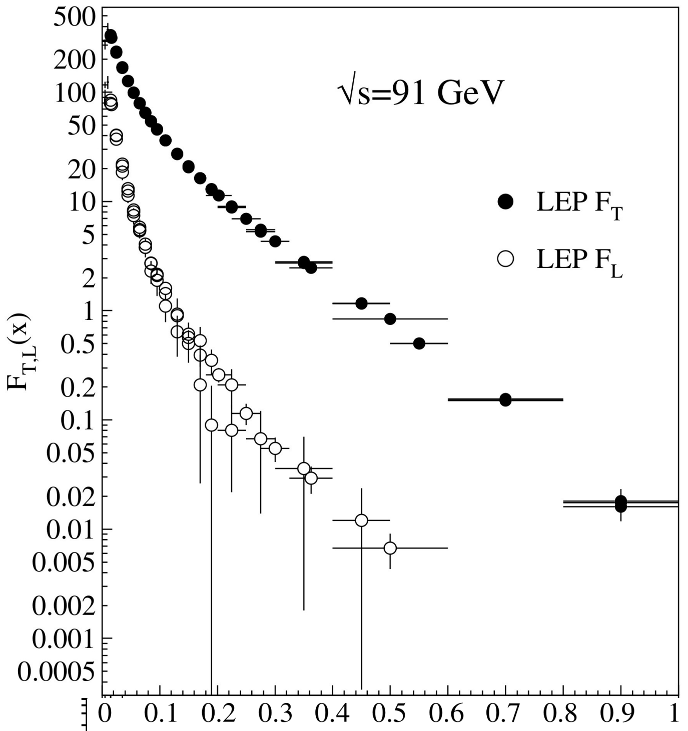
The e^+e^- fragmentation functions for all charged particles for different $\sqrt{s}$. The influence of scaling violations can be seen. Larger $\sqrt{s}$ shifts the x–distribution towards smaller x's.

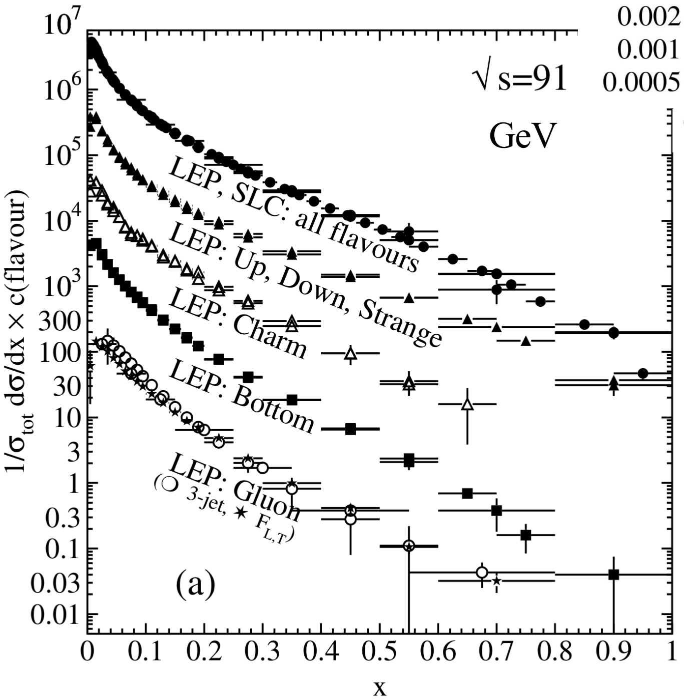


In $e^+e^- \to \gamma/Z^0 \to hX$, differential distribution w.r.t. to x & angle θ between hadron h and incoming e^+:

$$\frac{1}{\sigma_{\rm tot}}\frac{d^2\sigma}{dx\,d\cos\theta}(e^+e^-\to hX)=\frac{3}{8}(1+\cos^2\theta)\,F_T(x,s)+\frac{3}{4}\sin^2\theta\,F_L(x,s),$$

where $F_L(x,s)$ & $F_T(x,s)$ longitudinal & transverse fragmentation functions representing contributions from virtual bosons having longitudinal or transversal polarization (w.r.t. direction of motion of hadron).



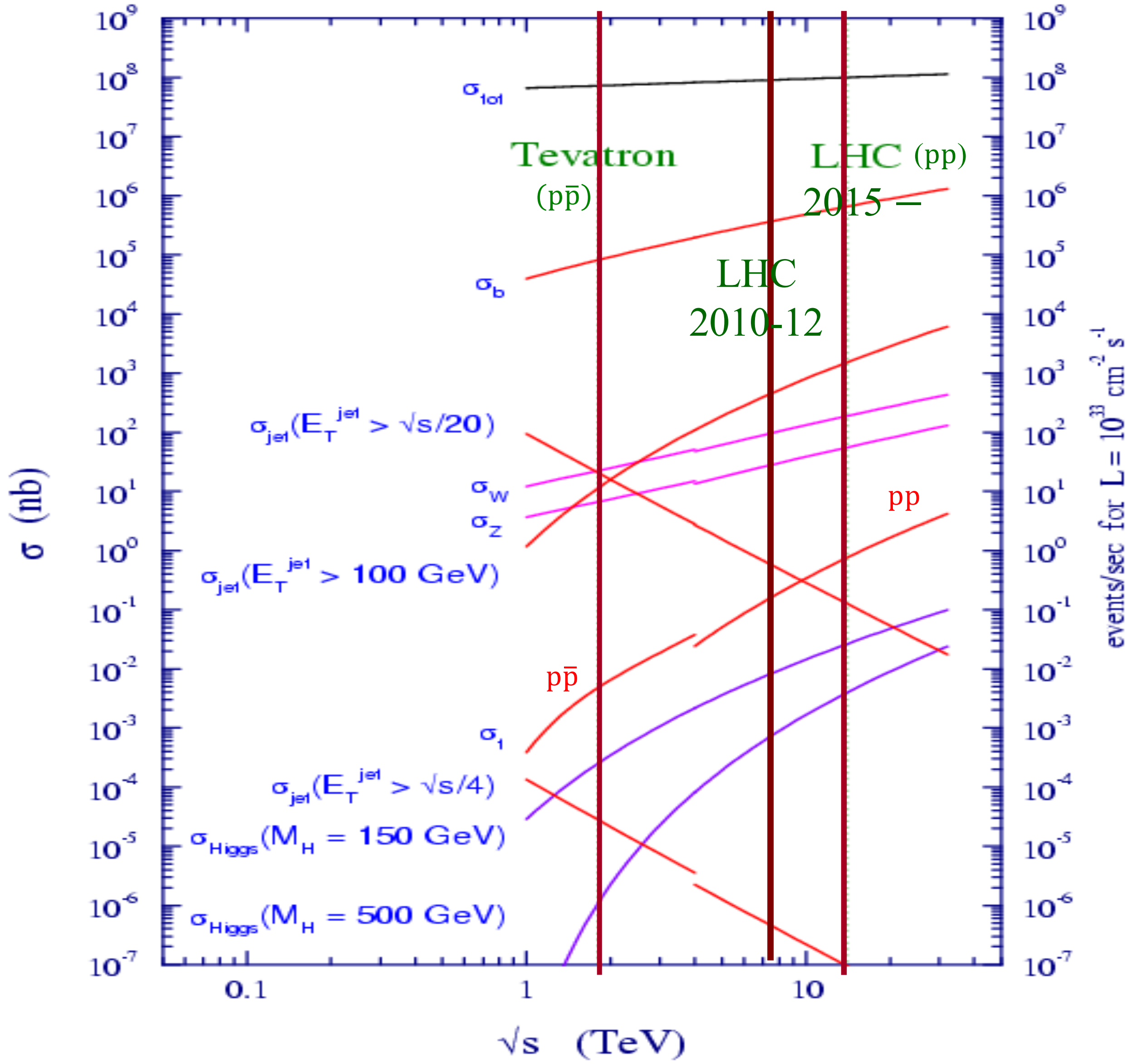


Gluon fragmentation function $D_g(x)$ can be extracted from measured $F_T(x)$ & $F_L(x)$. Coefficient functions C_i's of q & g comparable at $O(\alpha_s)$.

$$F_L(x,s)=C_F\frac{\alpha_s}{2\pi}\int_x^1\frac{dz}{z}\left[F_T(z,s)+4\left(\frac{z}{x}-1\right)D_g(z,s)\right]+O(\alpha_s^2)\quad \& \; C_F=\frac{4}{3}$$

Most interesting processes are **rare processes**:

- involve **heavy particles**
- have **small cross-sections** (e.g. W production)



main background: QCD jets → lepton & photon signatures
important trigger signatures: a) μ (charged particle beyond cal.), b) γ/*e* (em. shower) & c) neutrinos (missing transverse energy).
note: pay a prize for branching ratio i.e. BR(W → lν) ≈ 30%

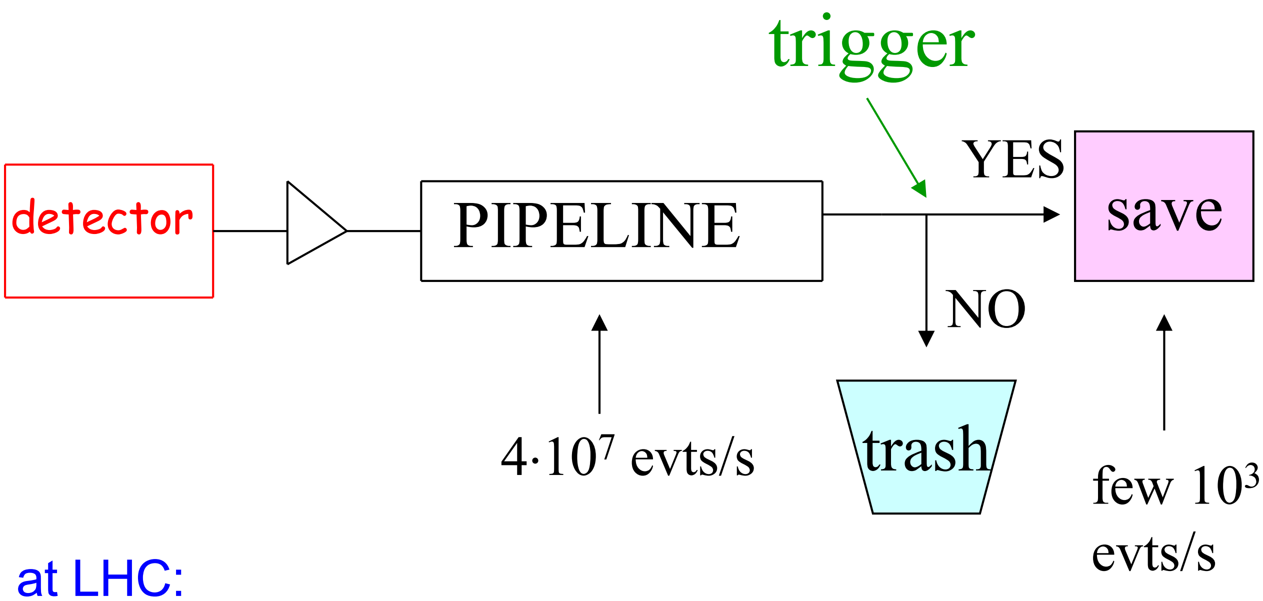
- trigger: much more difficult than in e^+e^- collisions (LHC numbers given)

bunch crossing rate: ~ $4 \cdot 10^7$ events/second
can record ~ few kHz (event size ~1 MB)

⇒ **trigger rejection ~ 10^4**

trigger decision ≈ μs ⟶ > interaction rate (of 25 ns)

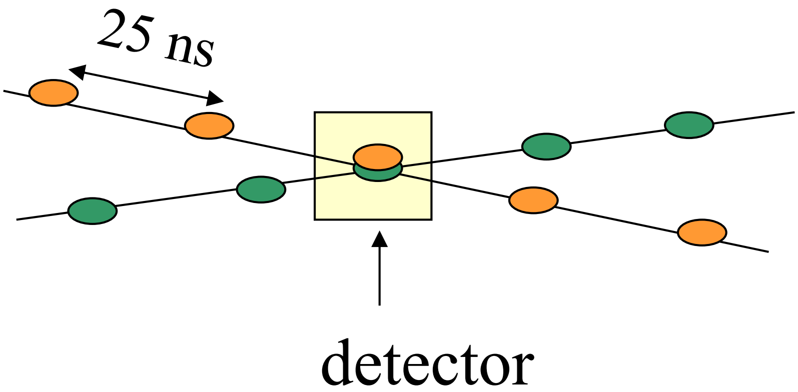
store massive amount of data in pipelines while special trigger processors performs calculations



at LHC:

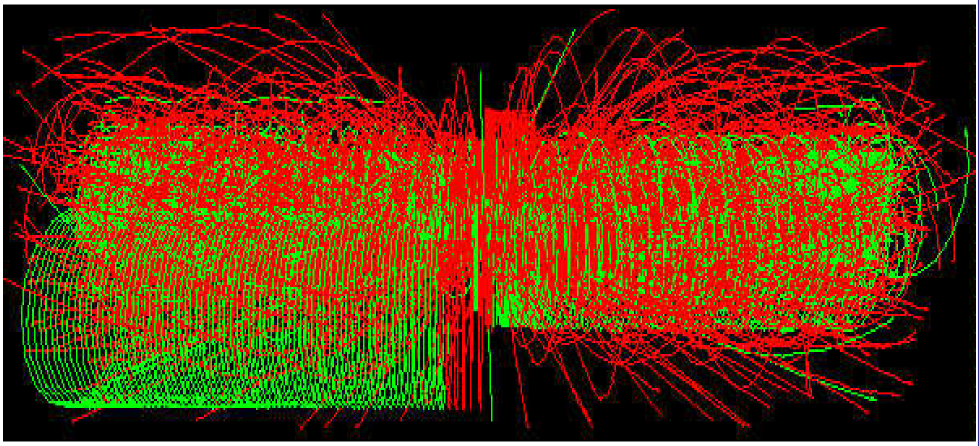
- low level (1^{st}) trigger based (mostly) on calorimetry & muons chamber info ⇒ change for high lumi LHC
- high level trigger (HLT) software based using cruder event reconstruction.
- exceptions: LHCb triggerless (online analysis)

Typical of LHC:
protons grouped in bunches (of ~ few 10^{11} protons) crossing each other at the interaction points every 25 ns



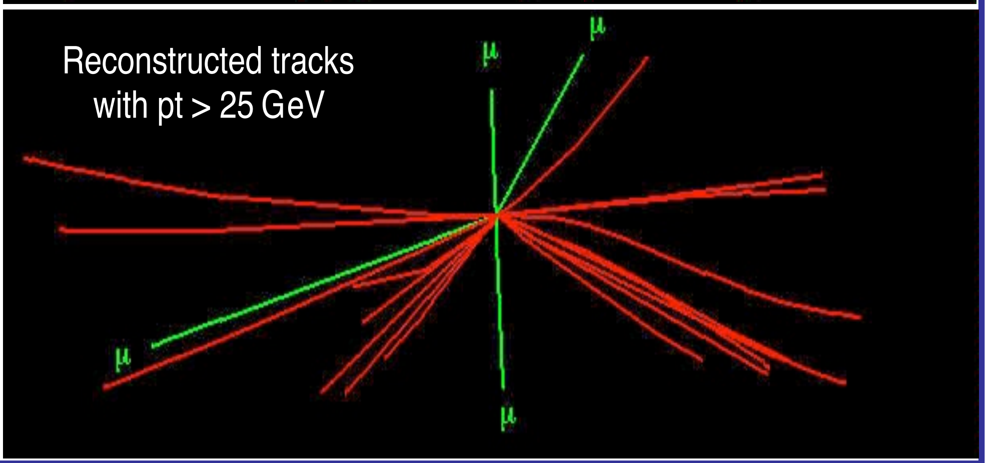
⇒ at each beam crossing ~ 50-60 minimum-bias events are produced at $L \approx$ few 10^{34} cm^{-2}s^{-1}. these overlap with high p_T physics events, giving rise to so-called pile-up

~ 1600 charged particles in the detectors however most particles have low p_T



example: a $H \rightarrow ZZ$; $Z \rightarrow \mu^+\mu^-$ at $L = 10^{+34}$ cm^{-2}s^{-1}

trick: focus on high p_T particles



Pile-up, a very serious experimental difficulty at LHC

Large impact on detector design:

- LHC detectors must have fast response, otherwise integrate over many bunch crossings → too large pile-up

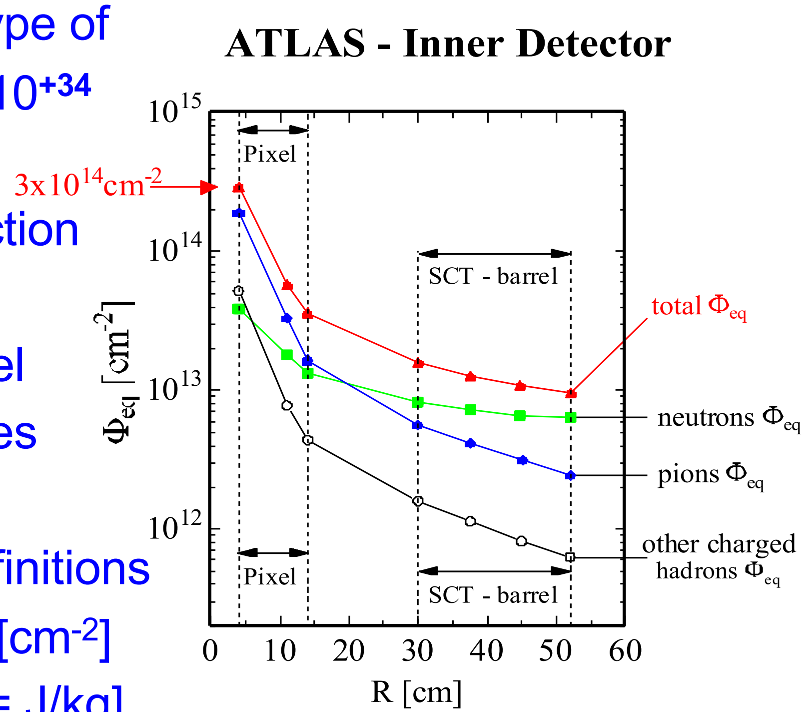
Typical response time : 15-50 ns → integrate over 1-2 bunch crossings → pile-up of ~ 50-60 minimum bias ⇒ very challenging readout electronics

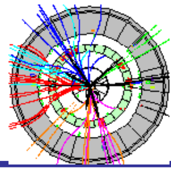
- LHC detectors must be highly granular to minimize probability that pile-up particles are in the same sensitive detector element as interesting object (e.g. γ from $H \to \gamma\gamma$) → large number of electronic channels ⇒ high cost

- LHC detectors must be radiation resistant: high flux of particles from pp collisions → high radiation environment

Fluence of different type of particles in 1 year at 10^{+34} cm^{-2} s^{-1} in ATLAS silicon tracker as function of distance to collsion vertex. Innermost pixel layer (at 4 cm) survives ~3 years with current technology. Some definitions

- fluence: $\Phi = N_{part}/A$ [cm^{-2}]
- dose: $D = E/m$ [Gy = J/kg]





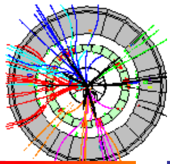
Keyword: large event statistics

Expected event rates in ATLAS & CMS for representative (both known & new) physics processes at current high luminosity running ($\mathcal{L} \approx 2 \cdot 10^{34}$ cm^{-2} s^{-1})

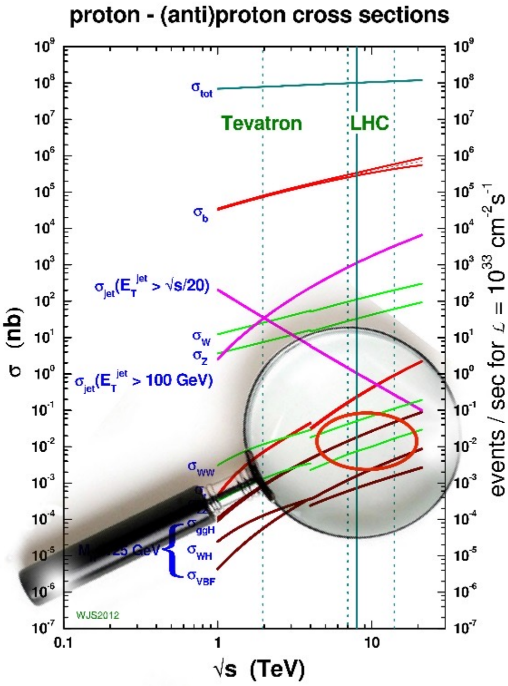
Process	Events/s	Events/year	Other machines (total statistics)
$W \to e\nu$	300	10^9	10^4 LEP / 10^7 Tev.
$Z \to ee$	30	10^8	10^7 LEP
$t\bar{t}$	16	$5 \cdot 10^7$	10^4 Tevatron
$b\bar{b}$	10^6	few 10^{12}	10^8 B-factories
$\tilde{g}\tilde{g}$ ($m_{\mathrm{gluino}} = 1$ TeV)	0.02	$5 \cdot 10^4$	—
H ($m_{\mathrm{H}} = 125$ GeV)	~ 1	few 10^6	10^4 Tevatron
QCD jets $p_T > 200$ GeV	10^3	few 10^9	10^7 Tevatron

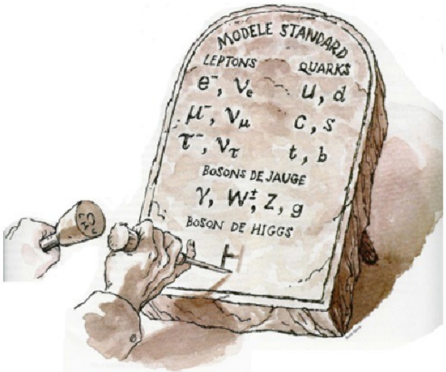
High lumi LHC ($\sim 5 \cdot 10^{35}$ cm^{-2}s^{-1}): statistics 2.5 times larger

$\rightarrow$ LHC is a B-factory, top factory, W/Z factory, Higgs factory, etc…. (the difficult challenge is to extract the signal)

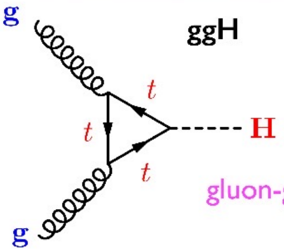


Higgs Physics





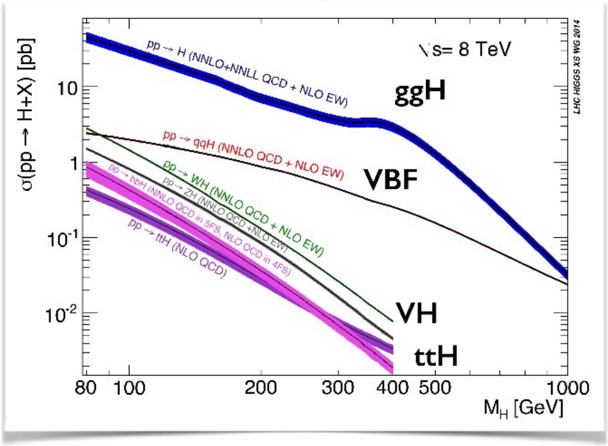
Production of the Higgs Boson

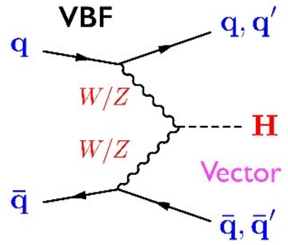


ggH

86%

gluon-gluon Fusion

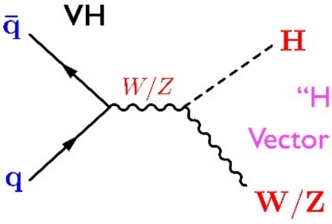




VBF

7%

Vector Boson Fusion

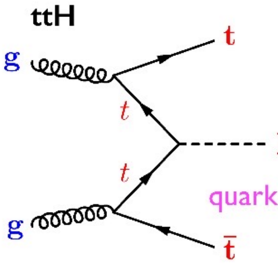


VH

5%

"Higgsstrahlung"

Vector Boson associated



ttH

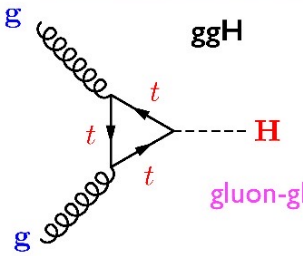
<2%

quark pair associated

18

Production of the Higgs Boson

ggH



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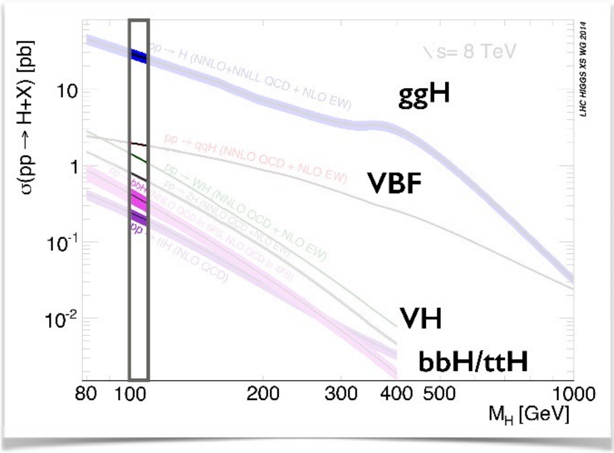
gluon-gluon Fusion



Cross sections (m_H = 125 GeV)

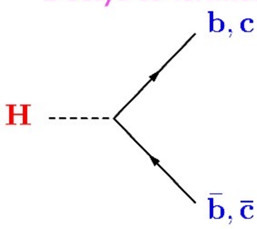
- Tevatron 1.96 TeV
  1.2 pb
  ggH=78% VH=17% VBF=5%
- LHC 8 TeV
  23 pb
  ggH=86% VBF=7% VH=5% ttH<1%
- LHC 13 TeV
  51 pb
  ggH=86% VBF=7% VH=4% ttH=1%

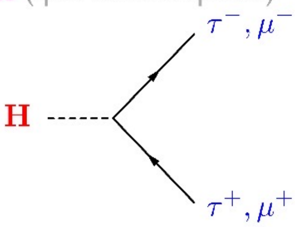
Typical theory uncertainties

- ggH 15% NNnLO
- VBF 5% NLO
- VH 5% NNLO
- ttH 15% LO

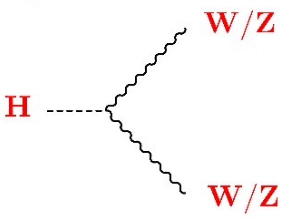
Decays of the Higgs Boson

Decays to fermions (quarks and leptons)

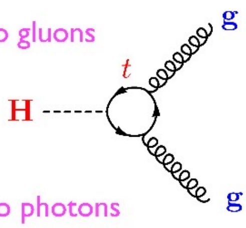




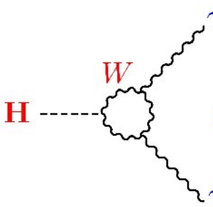
Decays to EW vector bosons

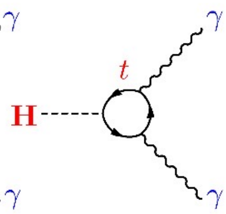


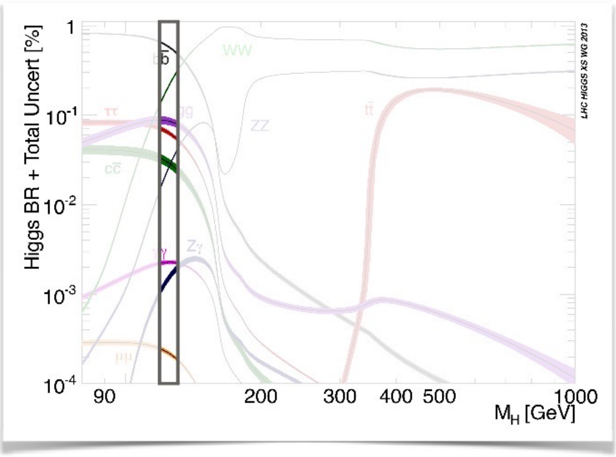
Decay to gluons



Decay to photons







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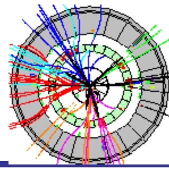
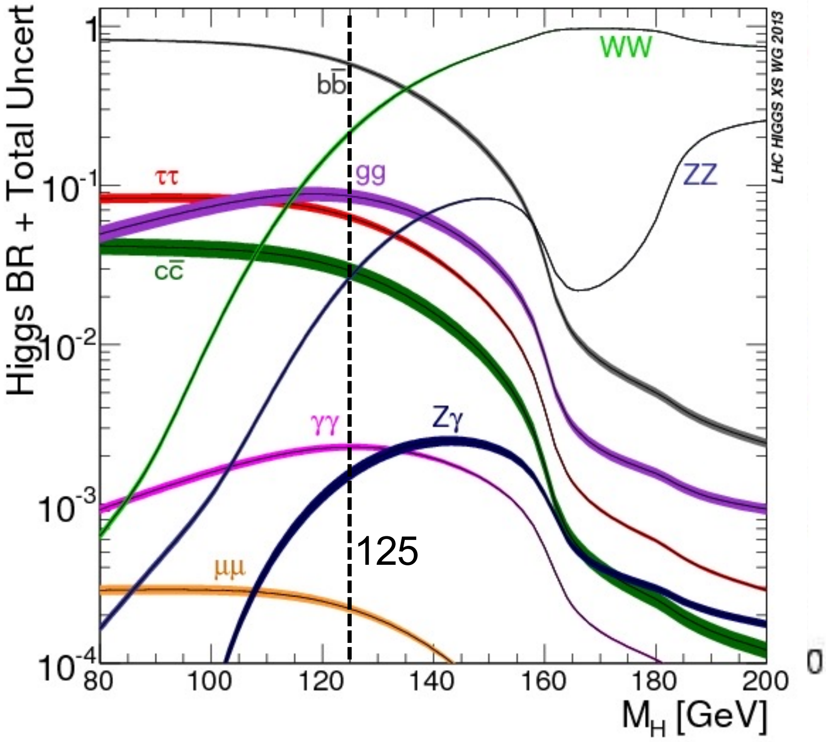


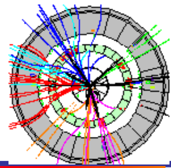
Higgs decay branching ratios

"Higgs couples to mass"



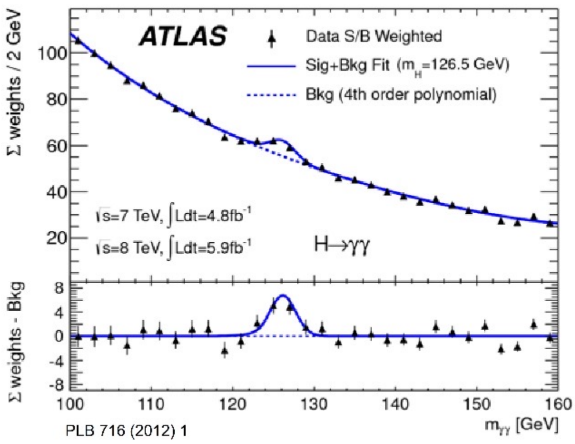
BR(%)	Higgs 125 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	58	15
$c\bar{c}$	3	12
gg	8	0
$\ell^+\ell^-$	0.02 (μ)	10
$\tau^+\tau^-$	6.4	3
γγ	0.2	
W^*W^*	22	
Z^*Z^*	2.7	

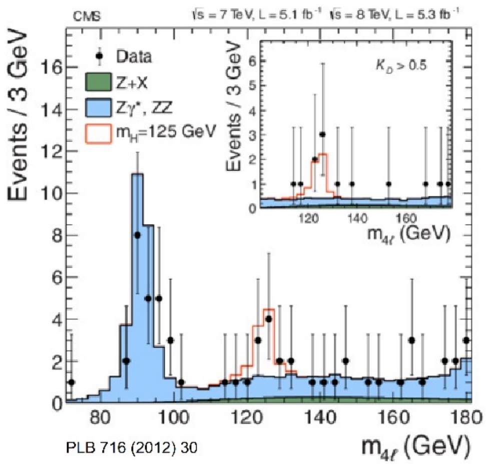
at 1st order: $$\Gamma(H \to f\bar{f}) = \frac{N_C^f G_F m_f^2}{4\sqrt{2}\pi} m_H \beta_f ,$$ where β_f is the fermion velocity in the decay.



CERN 4 July 2012

The Discovery





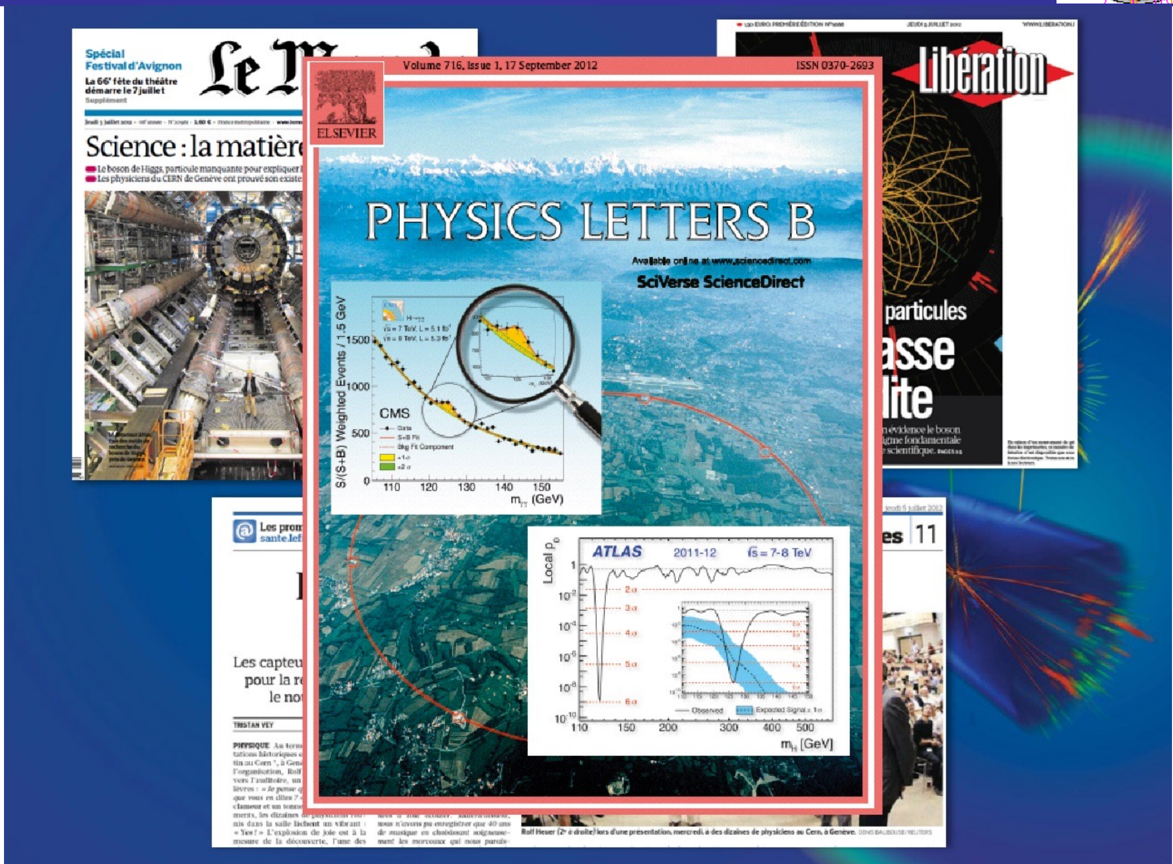
m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV
Combined significance: 5.9σ

m_H = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV
Combined significance: 5.0σ

Three decay mode WW, ZZ and γγ

Five decay modes analysed but no significance signal in H → ττ and bb

Higgs discovery



LHC: Production and Decay

Not an exhaustive table!

★ "seen" ☆ "tried"	H→bb	H→ττ	H→WW	H→ZZ	H→γγ	H→inv.	H→μμ	Σ H→xx
ggH		★	★	★	★		☆	
VBF	☆	★	★	☆	★	☆	☆	
VH	★	☆	☆	☆	☆	☆		
ttH	☆	☆	☆		☆			★
	$\sigma(m_{bb})$ ~20%	$\sigma(m_{\tau\tau})$ 10-20%	$\sigma(m_{WW})$ ~16%	$\sigma(m_{ZZ})$ 1-2%	$\sigma(m_{\gamma\gamma})$ 1-2%			

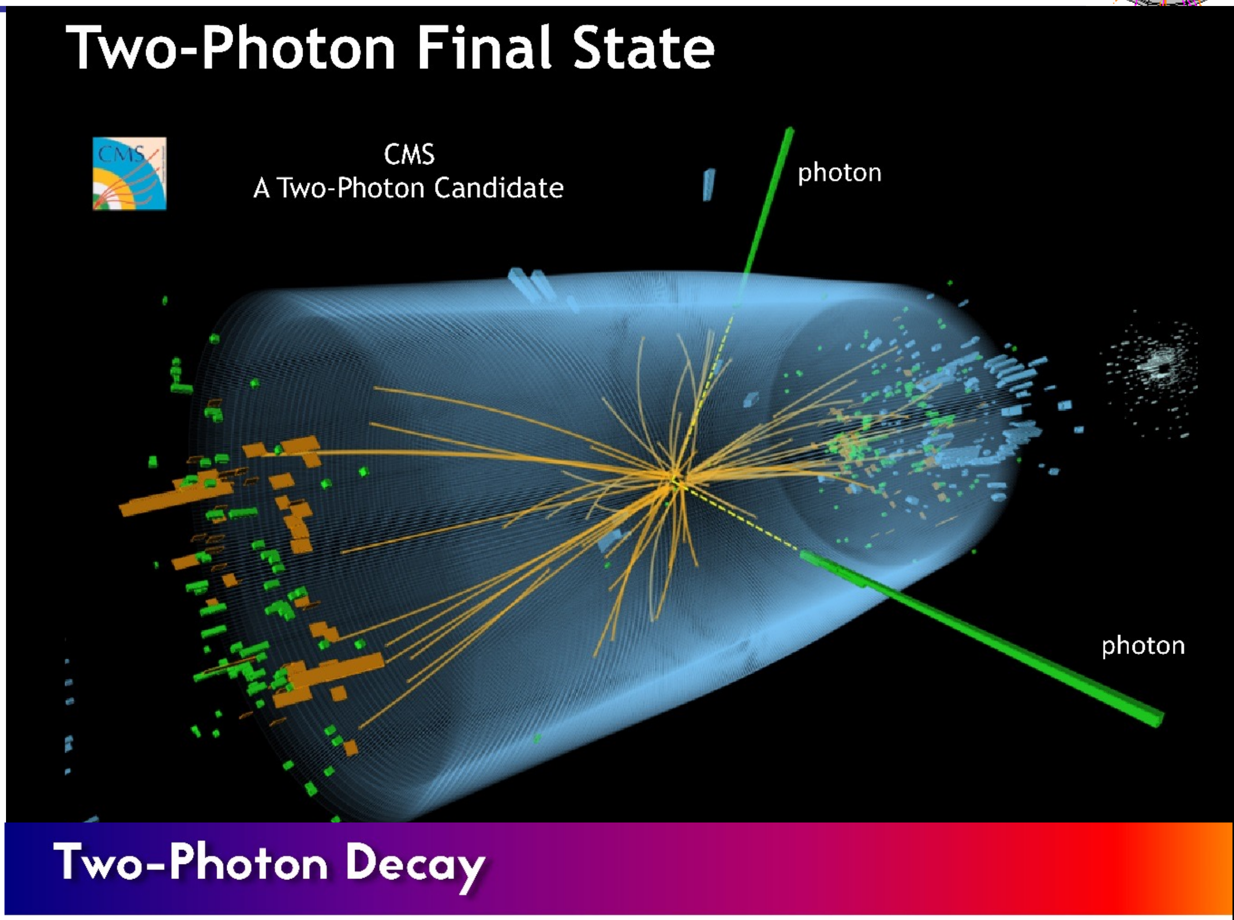
courtesy André David

Run-I (25 fb^{-1} at 7 and 8 TeV):
Approximate number of Higgs boson decays before selection cuts (m_H = 125 GeV)

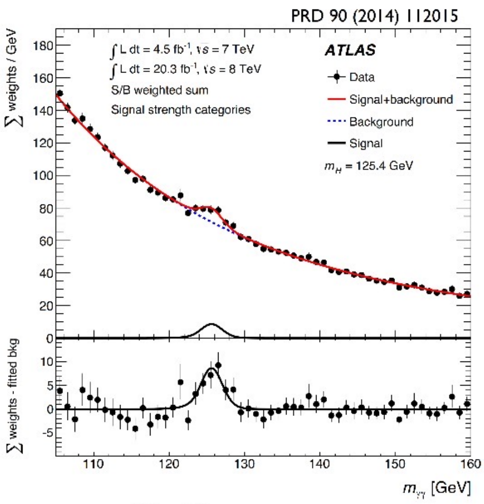
- 9,000 H → WW* → $\ell\nu\ell\nu$
- 900 H → γγ
- 60 H → ZZ* → 4ℓ

27

$H \to \gamma\gamma$



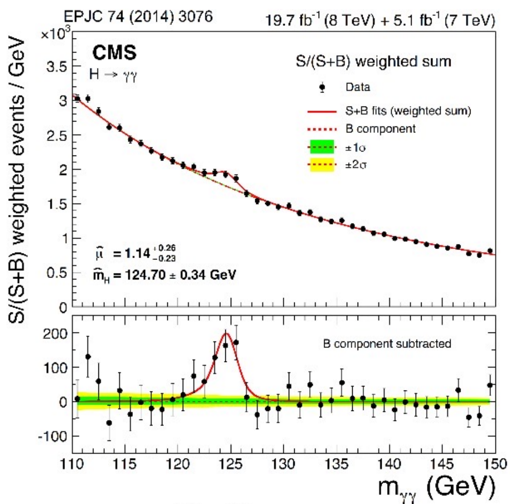
ATLAS



Significance
- observed : 5.2 σ
- expected: 4.6σ

m_H = 126.02 ± 0.43 (stat) ± 0.27 (syst) GeV

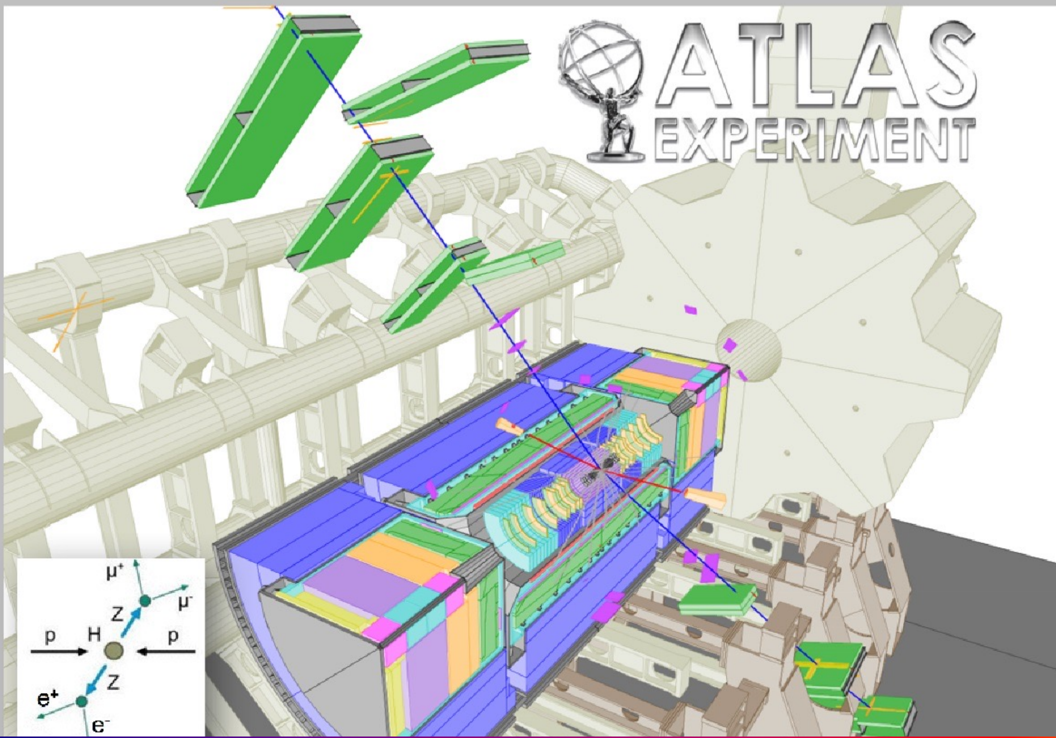
CMS



Significance
- observed : 5.7 σ
- expected: 5.2σ

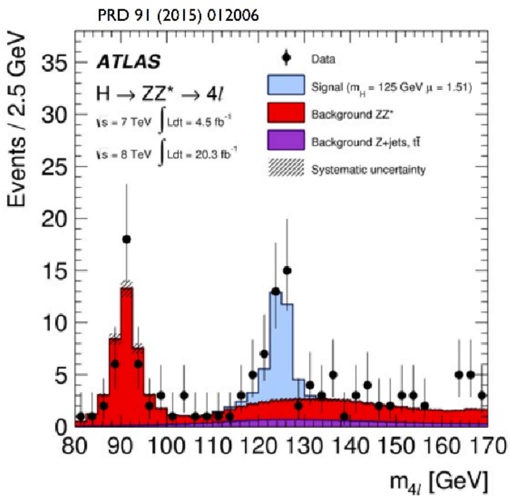
m_H = 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV

Four-Lepton Mode



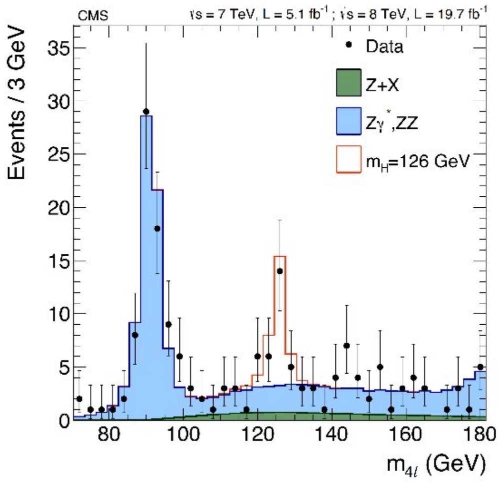
Four-Lepton Decay

ATLAS



m_H = 124.51 ± 0.52 (stat) ± 0.04 (syst) GeV

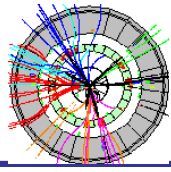
CMS



m_H = 125.59 ± 0.45 (stat) ± 0.17 (syst) GeV

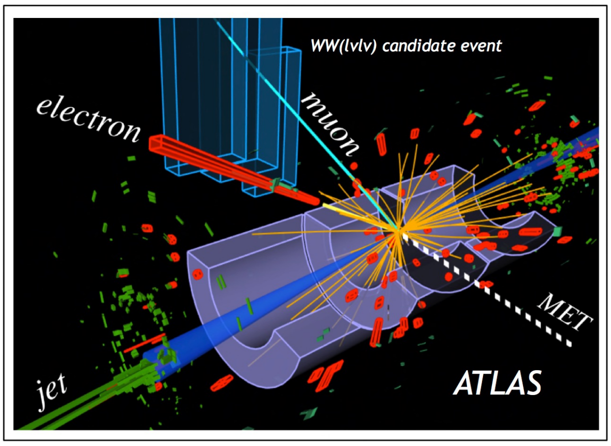
Both experiments observe signals with > 6σ

33



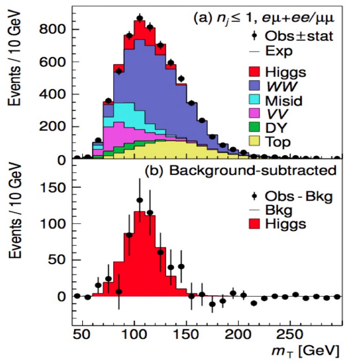
The Discovery Channels

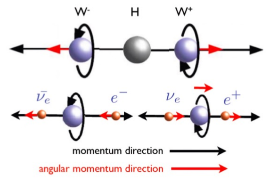
A discovery channel of a different kind: the WW

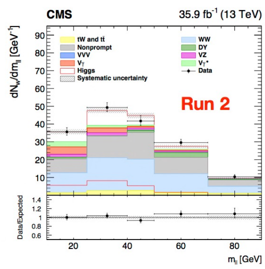


Requires good simulation of backgrounds and control regions in the data.

Uses the V-A nature of the W coupling that transfers the W spin correlation to the electrons.







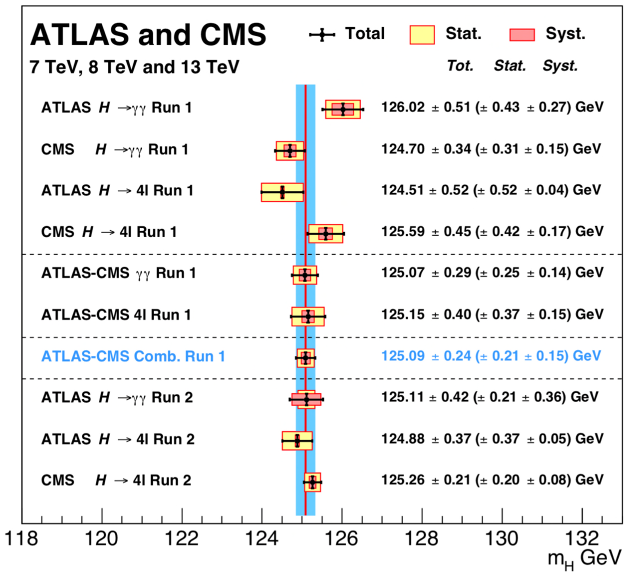
Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

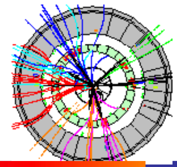
Large event rate, but also large backgrounds from the WW and top production.

First Precision Measurement at the LHC?

Higgs boson mass measurement

- Measurement done exclusively in the diphoton and 4-leptons channel.
- Optimizing the analysis in categories with best mass resolution (photon, electron and muons energy response).
- Reached at Run 1 a precision of 0.2%.
- Among (if not the) most precise measurement done at the LHC in 2013.



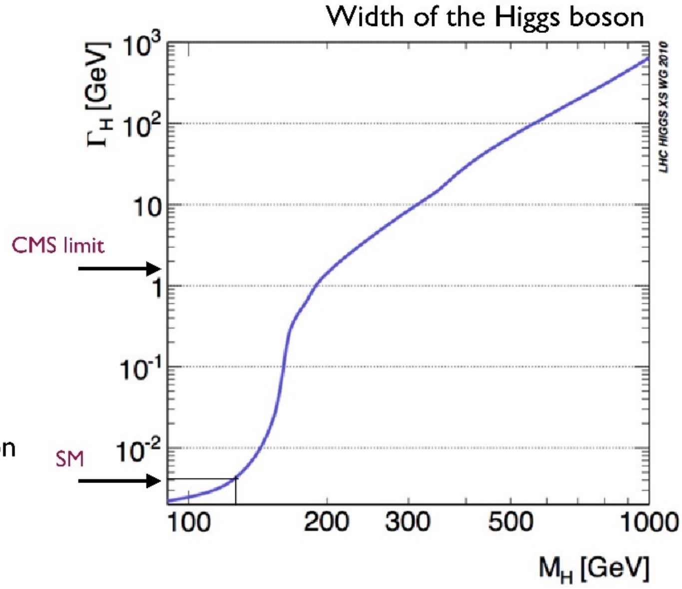


Width of the Higgs Boson

Upper limits on the width can be obtained from the mass peaks (at the level of the experimental resolution)

Γ_H < 1.7 GeV (95%CL)

The width of the SM Higgs boson is of the order of 4MeV



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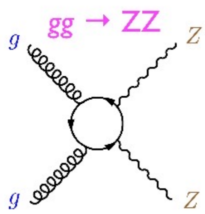
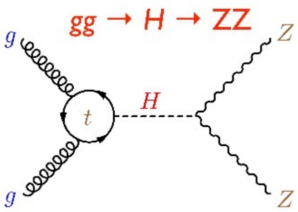
Off-Shell Higgs Boson

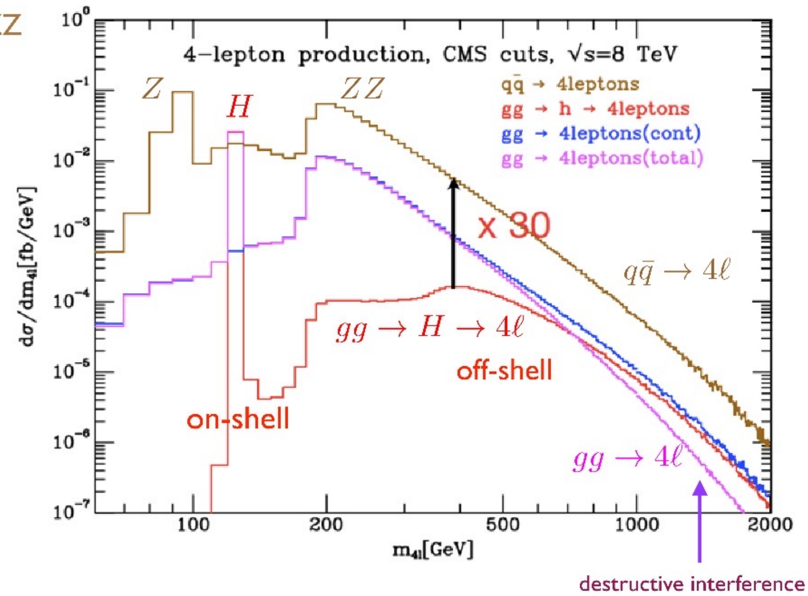
ZZ production = $qq \to ZZ$

but also



and





$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$

CMS: $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

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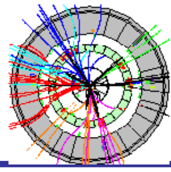


Run 2 Higgs Headlines

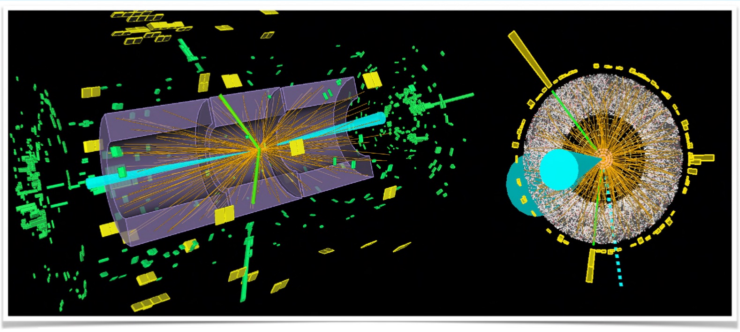
Run 2 Higgs Physics **major milestones** reached: **Third Generation (Charged) Observation Completed!**

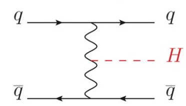
Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 $\pm$ 0.35	1.01 $\pm$ 0.20	1.34 $\pm$ 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 $\pm$ 0.27 *	1.04 $\pm$ 0.20	1.26 $\pm$ 0.26 **

* 13 TeV only derived from cross section measurements
** Lower uncertainty (upper uncertainty 31)

+ evidence for coupling to second generation: $H \rightarrow \mu^+\mu^-$

Higgs boson decays to Taus & Muons

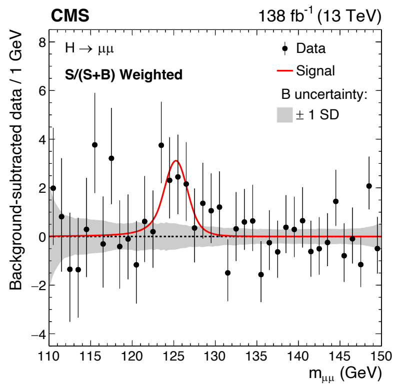


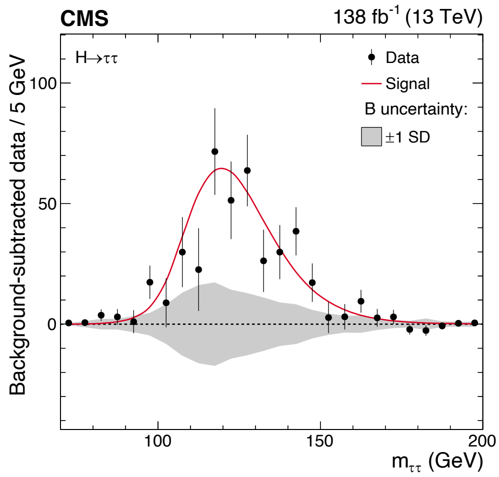


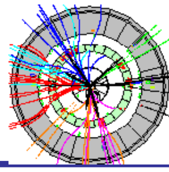
Special VBF process

With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

Background is Z production with two jets, in this region of phase space it is difficult to predict!

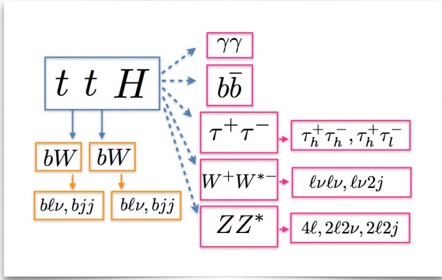




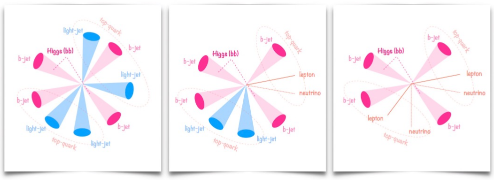


Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



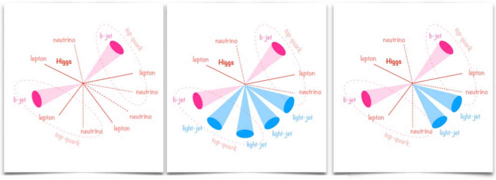
- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)
- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!
- With the new Run at close to double centre-of-mass energy and increased statistics, changes in leading channels.



ttH(bb)

Very large backgrounds of top pair production associated with b jets

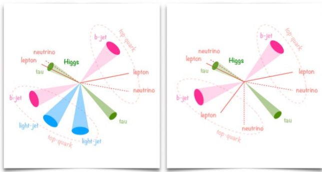
Dominated by background modelling uncertainties

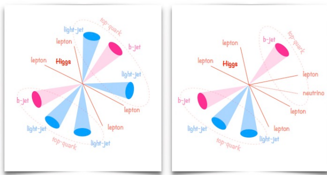


ttH(WW, ZZ and tau tau)

So-called multi-lepton channel

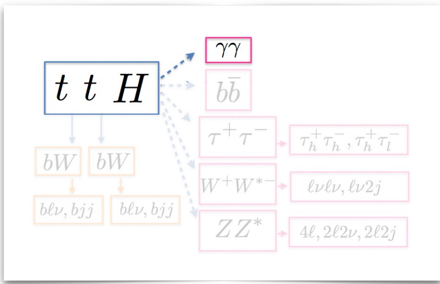
Large number of topologies intricate reducible backgrounds of jets faking leptons.



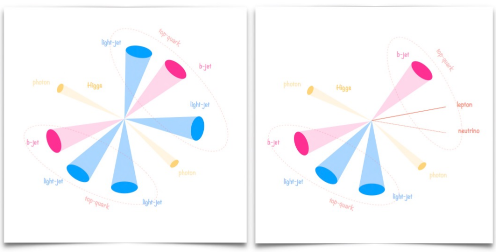


Direct probe of the top Yukawa coupling

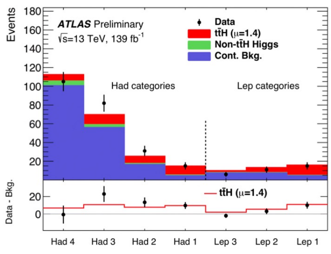
ttH Analyses at LHC: Massively Complex!

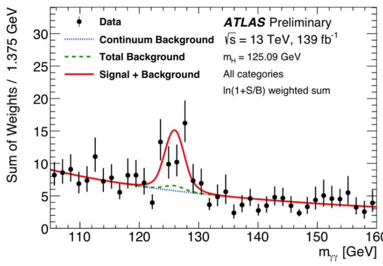


Currently most sensitive channel



Background and signal modelled using analytic functions.





Cross section dominated by statistical uncertainties:

$$1.59\boxed{^{+0.38}_{-0.36}\ \text{(stat.)}}\ ^{+0.15}_{-0.12}\ \text{(exp.)}\ ^{+0.15}_{-0.11}\ \text{(theo.) fb}$$

Expected (4.2σ)

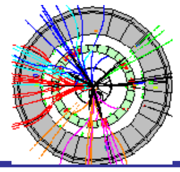
Observed 4.9σ

In combination with the other channels:

Expected 5.1σ

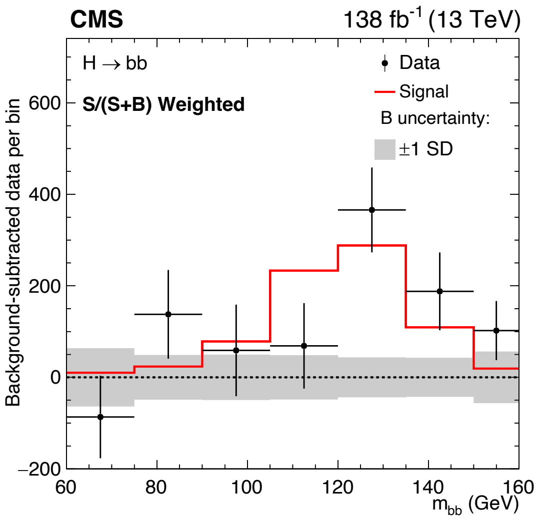
Observed 6.3σ

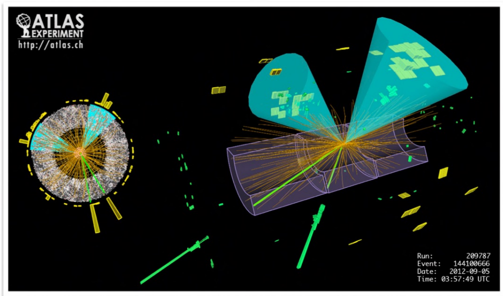
Observation!!



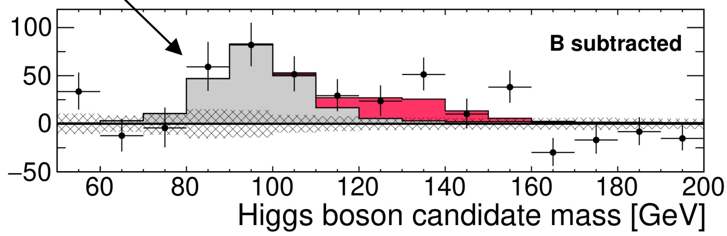
Higgs boson decays to b-quarks & c-quarks

b-quark decay channel of Higgs solidly confirmed





…but c-quark decay channel of Higgs still elude searches



Combination Procedure and Master Formula

What is done in Higgs boson couplings analyses is to count number of signal events in specific production and decay channels.

$$n_s^c = \mu \sum_{i \subset \{\text{prod}\}} \sum_{f \subset \{\text{decay}\}} \mu^i \sigma^i_{SM} \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Same formula as the total cross section measurement formula

These « mu » or signal strength factors cannot be fitted simultaneously, typical fit models include:

μ	$\mu_{if} = \mu_i \mu_f$	$\mu_i \ (\mu_f = 1)$	$\mu_f \ (\mu_i = 1)$
Extrapolated total cross section	Cross section times branching	Cross sections	Branching fractions

Manifest in this formula why absolute couplings cannot be measured with this procedure: μ_i, μ_f cannot be fitted simultaneously.

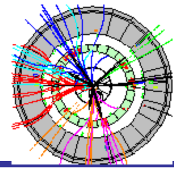
Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian.

$$\boxed{\mathcal{L} \supset \kappa_Z \frac{\mathrm{m}_\mathrm{Z}^2}{v} Z_\mu Z^\mu + \kappa_W \frac{\mathrm{m}_\mathrm{W}^2}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{\mathrm{m}_f}{v} f\bar{f}}$$

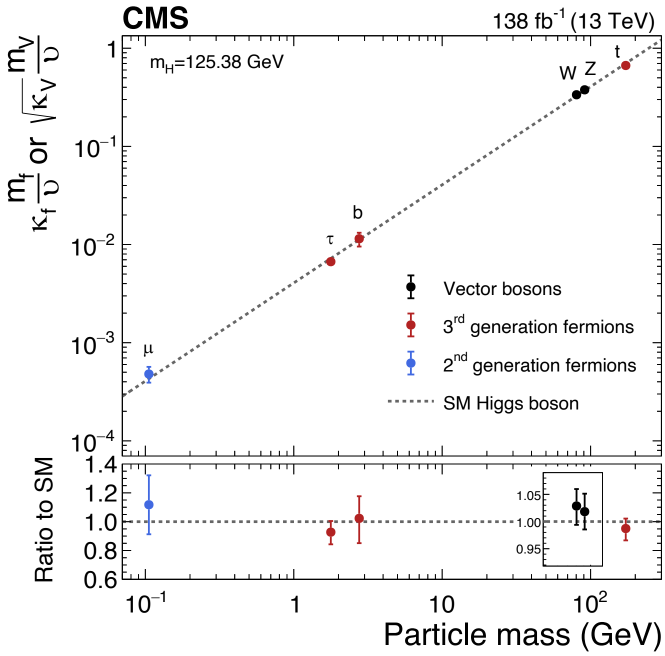
Simply reparametrise the mu values using the kappas!

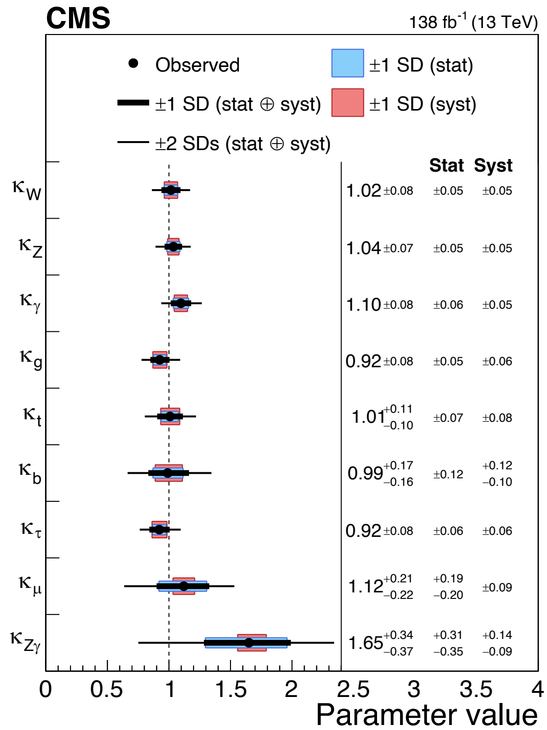
For a complete description see (link) - Chapter 10

Higgs couplings



Run 2 Couplings Measurements

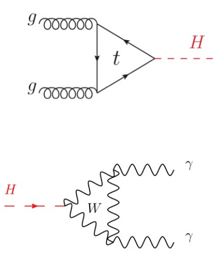




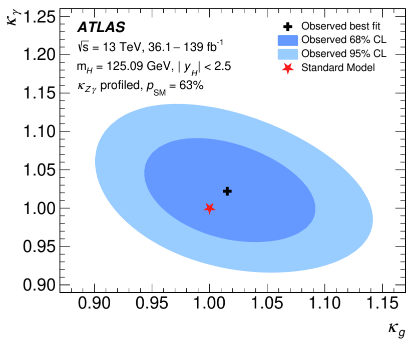
Higgs boson is Standard Model like !

Run 2 Couplings Measurements

Choosing suitable assumptions to probe interesting new physics scenarios scenarios

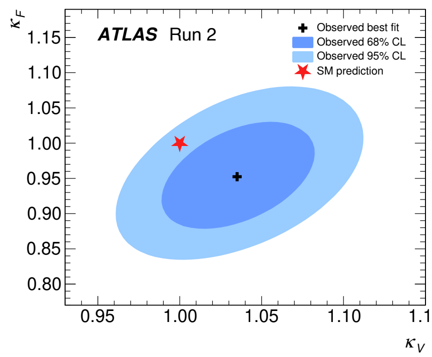


Probing new particles in the loops

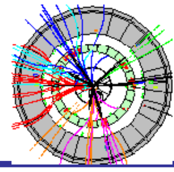


All couplings are set to their Standard Model value except the effective couplings to the photon and the gluon (probing new physics in the loops).

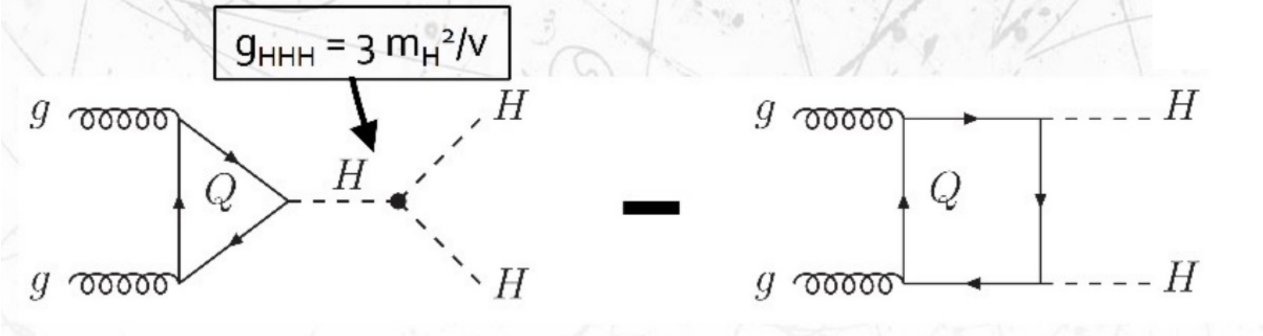
Probing the Gauge bosons vs fermions



All fermion couplings are fixed to one parameter and similarly for all boson, the couplings to the gluons and the photons are resolved.



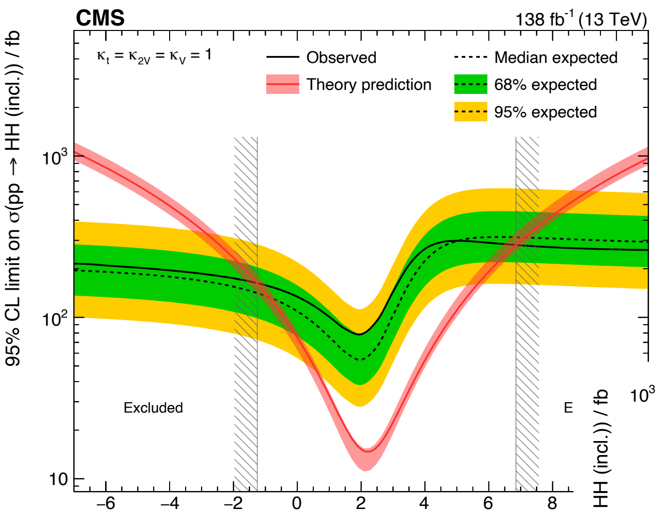
- **Higgs self coupling**
  - **Measurable through double Higgs production**



(accidental) negative interference between the two diagrams reduces cross section and hence sensitivity to g_{HHH} coupling

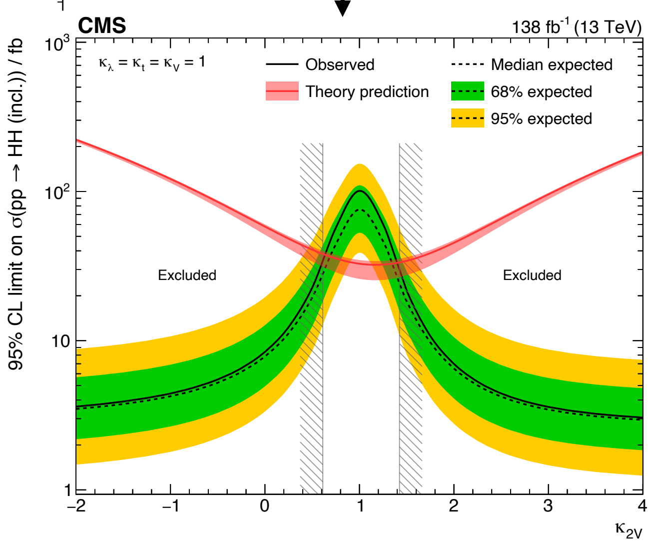
Rule of thumb: event yield ~ 1000 smaller than for single H

Most sensitive channels: $H\,(\rightarrow b\bar{b}) + H\,(\rightarrow \tau^+\tau^-|b\bar{b}|\gamma\gamma)$



Limits on self-coupling

Limits on quartic coupling

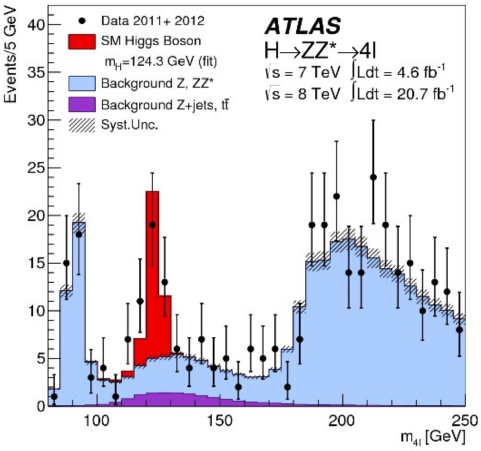


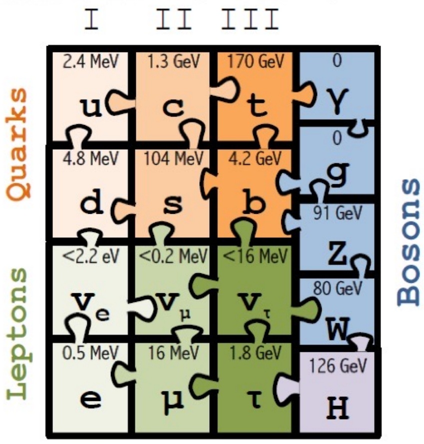
Not yet enough sensitivity!

Most likely need high luminosity LHC to discover double Higgs production

2012-24: The SM becomes the Standard Theory

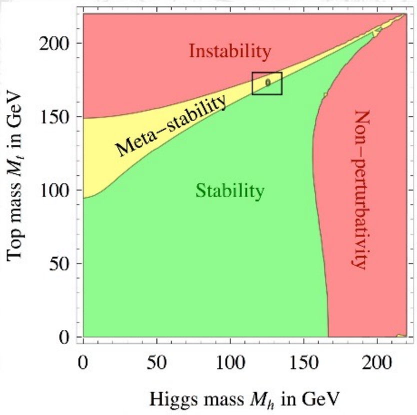
- **2012-24: The Higgs boson era**
  - 2012: Discovery of the standard model Higgs boson at the LHC (ATLAS, CMS)
    - m_H = 125.4 ± 0.5 GeV (ATLAS), 125.0 ± 0.3 GeV (CMS)
    - Mass, couplings, spin, width in agreement with Standard Theory predictions
  - 2012-24: No new physics found at the LHC Run1 at the TeV scale
  - 2014: Nobel Prize to Englert and Higgs





And now, what ?

- **The Standard Model has become the Standard Theory**
  - It explains/describes all observations and measurements from high-energy colliders
    - It is also able, in principle, to predict all measurements at future colliders
      - As well as the fate of the Universe …



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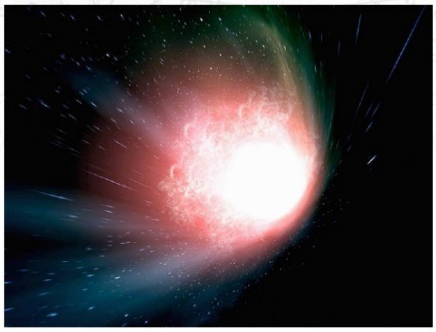
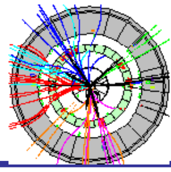


  - On the theory side, no new physics is needed beyond this Standard Theory
- **Is this the end ?**



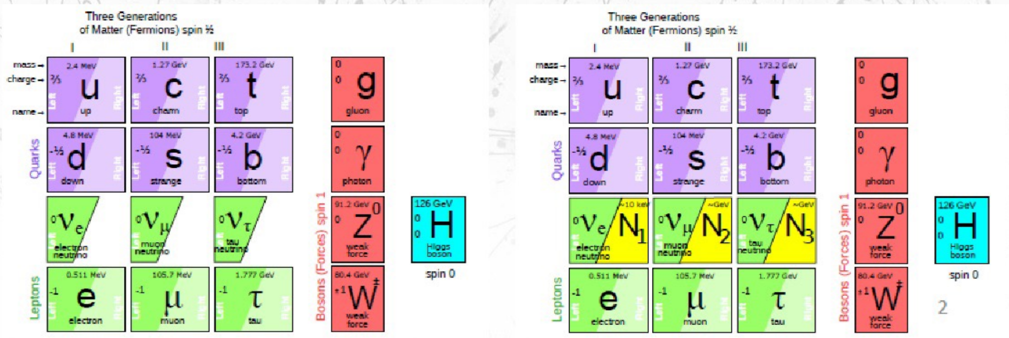
It is (most likely) not the end …

- There seems to be something beyond the Standard Theory
  - Many unanswered fundamental questions all based on experimental observations, e.g.
    - Why 3 generations of fermions ?
    - Why is the Higgs boson so light (so-called “naturalness” or “hierarchy” problem) ?
    - What is the origin of neutrino masses and oscillations ?
    - What is the composition of dark matter (5 times the mass of baryonic matter) ?
    - Why is gravity so weak ?
    - What is the origin of the matter-antimatter asymmetry in the Universe [BAU] ?
    - What is the origin of the Universe’s accelerated expansion ?
- New Physics?
  - Many diverse theoretical ideas…

  - Is new physics at larger masses ? Or at smaller couplings ? Or both ?
    - Only way to find out: *go look*, following the historical approach:
      - Direct searches for new heavy particles
        - ⇒ Need colliders with *larger energies*
      - Searches for the imprint of new physics on W, Z, top, and Higgs properties
        - ⇒ Need colliders / measurements with *unprecedented accuracy*

Precision vs Energy (1)

- The Standard Theory is complete ? Obviously three pieces missing !



  - Three right-handed neutrinos ?
    - Extremely small couplings, nearly impossible to find but could explain quite a bit !
      - Small m_ν (see-saw), DM (light N_1), and BAU (leptogenesis)
    - Need very-high-precision experiments to unveil
      - Could cause a slight reduction (increase) in the Z (H) invisible decay width
      - Could open exotic Z and Higgs decays: Z, H → $\nu_i N_i$
        - Possibly measurable / detectable in precision e^+e^- collisions
        - Most likely out of reach for hadron colliders (small couplings)

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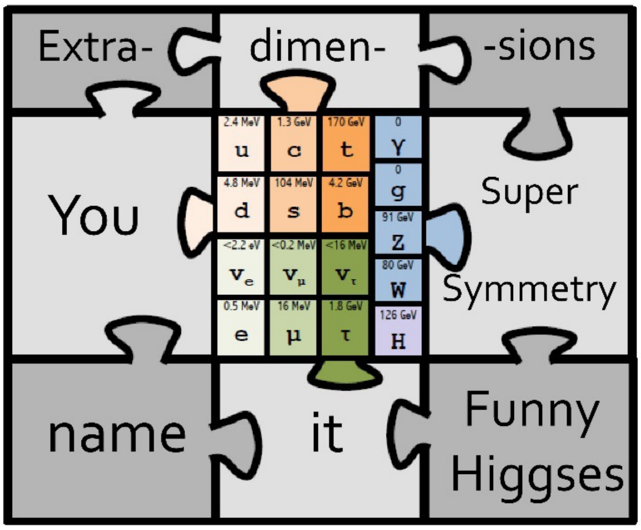
Precision vs Energy (2)

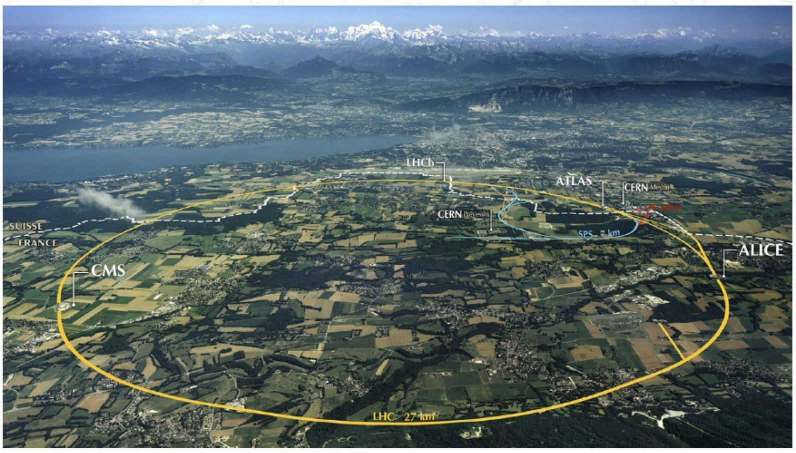
- Others lean towards higher-energy replicas of the standard theory



- Direct searches at larger energies may be the key – but how much larger ?
  - Rare decays and precise measurements may also unveil these extension's imprints

Short-term perspectives (2025-2040)

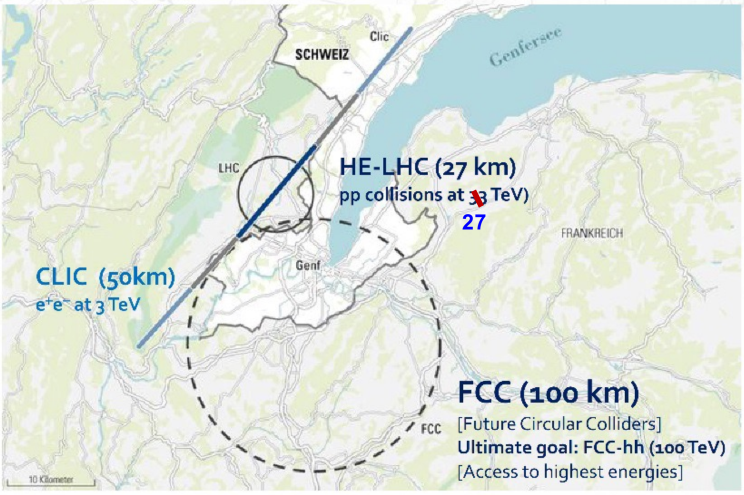
- In 2020, European Strategy said (very similar statements from US)
  - Exploit the full potential of the LHC until ~2040 as the highest priority
    - Get 75-100 fb^{-1} at 13 TeV by 2018 (LHC Run2: completed)
    - Get ~300 fb^{-1} at 13.6 TeV by 2025 (LHC Run 3: on-going)
    - Upgrade machine and detectors to get 3 ab^{-1} at 14 TeV by ~2040 (HL-LHC: Approved)
      - A first step towards both energy and precision frontier



Future colliders

Long-term perspectives (2045-2080)

- In 2020 European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines *at CERN*
    - HE-LHC, a programme for an energy increase to ~~28~~ 27 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 100 TeV   favoured!
    - CLIC, an e^+e^- collider project with $\sqrt{s}$ from 0.3 to 3 TeV



Similar circular projects
(50, 70, or 100 km) in China
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV

Mid-term perspectives (2030-2045)

- In 2020 European Strategy said (very similar statements from US)
  - Acknowledge the strong scientific case of e^+e^- colliders with intermediate $\sqrt{s}$
    - Participate in ILC if Japan government moves forward with the project
    - In the context of the FCC, perform accelerator R&D and design studies
      - In view of a high-luminosity, high-energy, circular e^+e^- collider as a first step

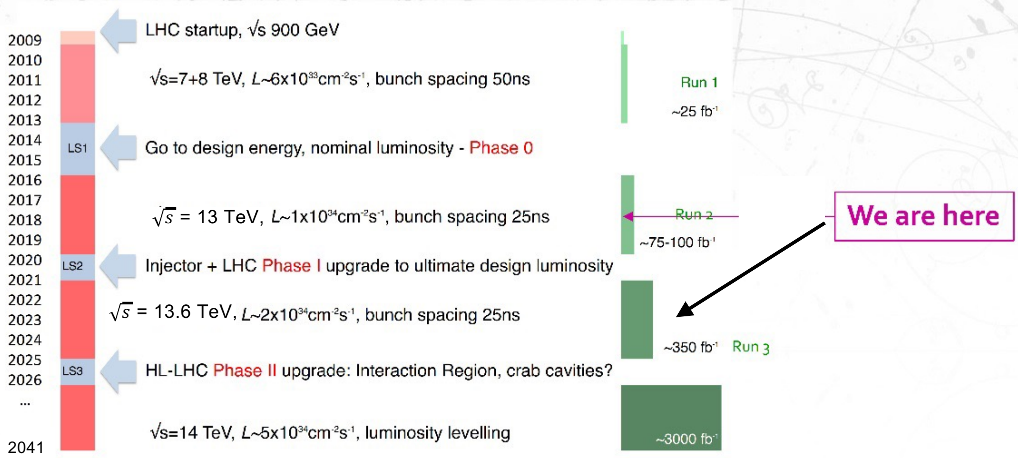
FCC (100 km)
First step: FCC-ee (91-400 GeV)
[Use the tunnel ultimately aimed at FCC-hh]

Note: CLIC can also run at $\sqrt{s}$ ~380 GeV in ~2035-2040

Future colliders

Can / should we do everything ? (1)

- The cost (10's B$) and challenges of these projects are paramount
  - A choice will have to be made at one point, but it would be too early to make it now
    - The LHC, indeed, is still rather in its infancy

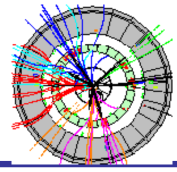


  - The 13.6 TeV Run3 is under way: new data might bring a whole new light on the process
    - Next check point after LHC Run2 for the next European strategy update in 2025-26

Can / should we do everything ? (2)

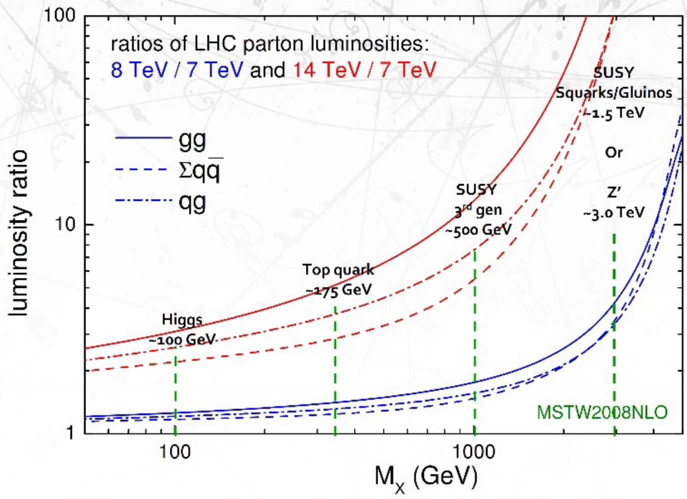
- Hand-waving anticipation: With the 13.6 TeV Run3 data, we may
  - Find a new heavy particle (or new heavy particles)
    - The (HL-) LHC will study this (these) particles to some extent
    - If m < 3 TeV, CLIC becomes interesting (if copiously produced in e^+e^- collisions)
    - Larger energies might be needed to find & study the whole new spectrum (FCC-hh)
    - An e^+e^- Z factory (FCC-ee) might be useful to study the underlying quantum structure
      - Note: m_H and m_{top} were predicted *correctly* with no new physics
        - New physics will probably be very difficult to find anyway
  - Find no new particle, but find a hint for non-standard Higgs properties
    - The (HL-) LHC will improve the precision on these measurements to some extent
    - e^+e^- factories for Higgs (ILC, FCC-ee) become very interesting machines
    - Push the energy frontier to its limits (CLIC, FCC-hh)
  - Find no new particle, and standard Higgs properties
    - Push precision measurements to their limits (FCC-ee)
    - Possibly push energy frontier to its limits (CLIC, FCC-hh)
- Let's now try to quantify the respective merits of all options

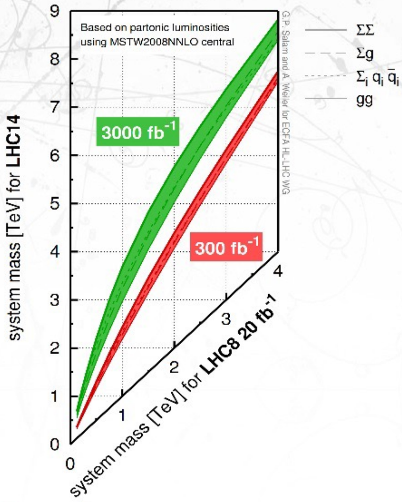
HL-LHC



Physics prospects with HL-LHC (3)

- **Physics programme at the LHC in a nutshell (cont'd)**
  - **The energy increase from Run1 (7/8 TeV) to Run2 (13/14 TeV) is very exciting**





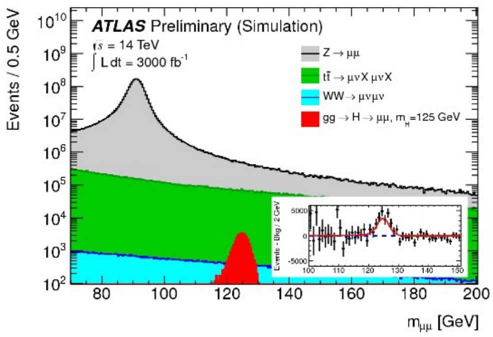
  - **More energy buys a lot, both for precision and new physics reach**
    - **Cross sections multiplied by 3, 5, 10, 100 at m = 0.1, 0.35, 1 and 3 TeV**
    - **Mass reach for new physics roughly doubled**

Precision Higgs physics (3)

- **Higgs couplings projections (cont'd)**

Coupling	LHC Run1	LHC (300 fb^{-1})	HL-LHC (3000 fb^{-1})
κ_W	12%	4-6%	2-5%
κ_Z	15%	4-6%	2-4%
κ_t	30%	14-15%	7-10%
κ_b	30%	10-13%	4-7%
κ_τ	16%	6-8%	2-5%

  - **HL-LHC would bring a factor 1.5 to 2 on top of 300 fb^{-1}**
    - **Limited by systematic uncertainties**
  - **Becomes sensitive to, e.g., $H \to \mu\mu$**
    - **Expect 35K signal events with 3 ab^{-1}**
      - **S/B ~ 0.3% → 10σ significance**
    - **Coupling measured to ~ 10%**
      - **20-30% with 300 fb^{-1}**

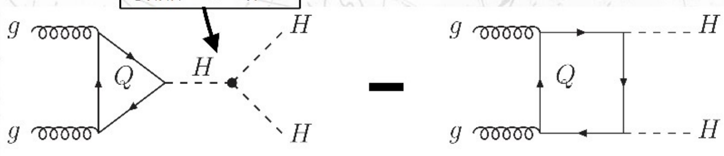


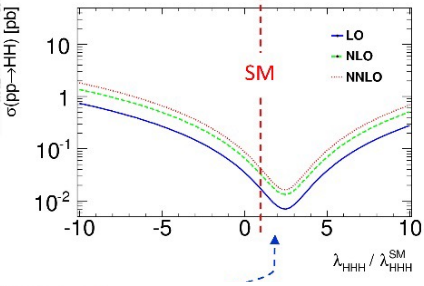
HL-LHC

Precision Higgs physics (5)

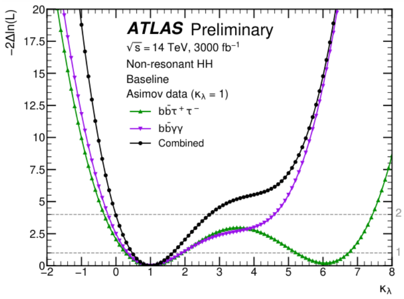
- **Higgs self coupling**
  - Measurable through double Higgs production

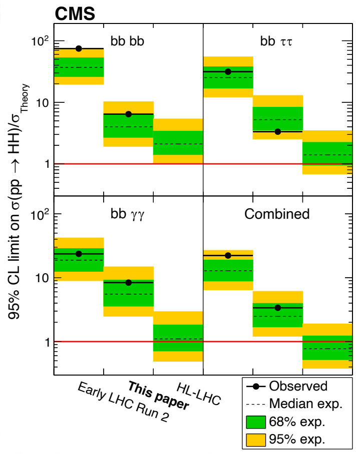
$g_{HHH} = 3\,m_H^2/v$





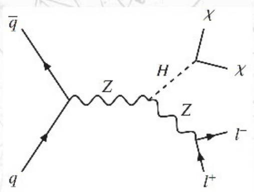
Double Higgs boson production discovery seems to be within HL-LHC reach (especially if ATLAS & CMS data combined)

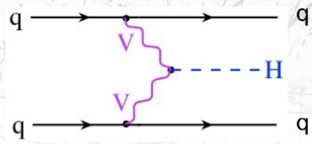


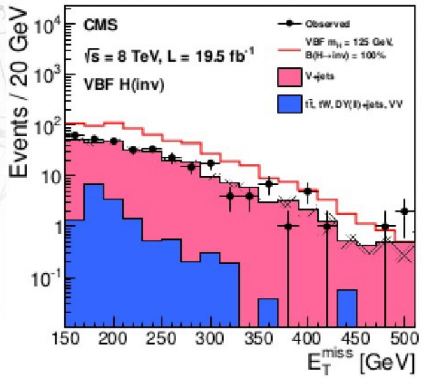


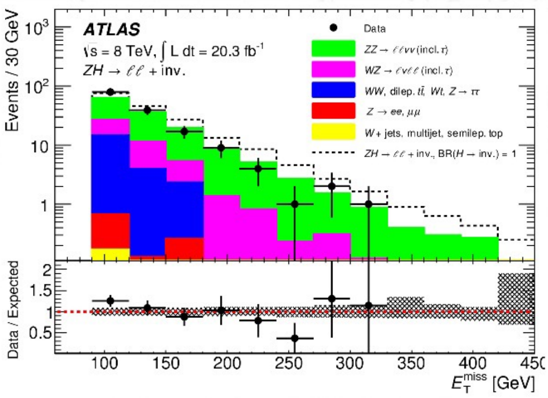
Precision Higgs physics (6)

- **Invisible Higgs decays**







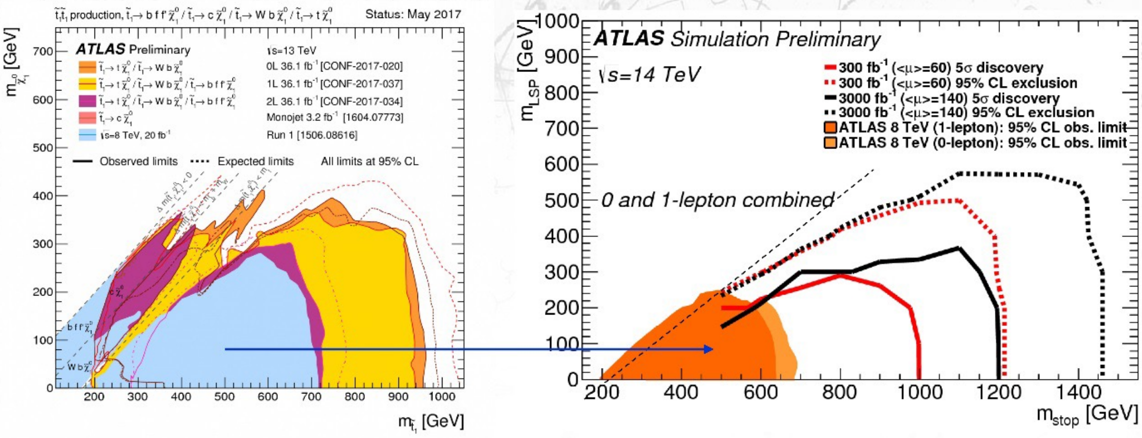


	BR_{inv} (95% CL)
LHC Run1	40-50%
LHC 300 fb^{-1}	20-30%
HL-LHC	10-15%

- Improves DM search at low mass

Supersymmetry (2)

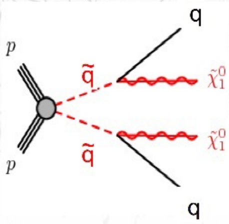
- **Search for third generation squark (cont'd)**
  - **Today :** **Projections with 300 and 3000 fb^{-1}**

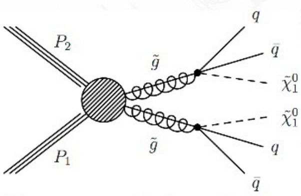


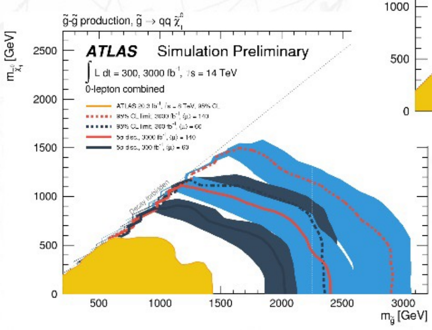
- **Mass reach extended by a factor 2 with LHC at 14 TeV (300 fb^{-1}): covers the 1 TeV region**
  - **Further 20% extension with HL-LHC**
- **If no excess is seen with 300 fb^{-1}**
  - **The HL-LHC discovery potential vanishes entirely**

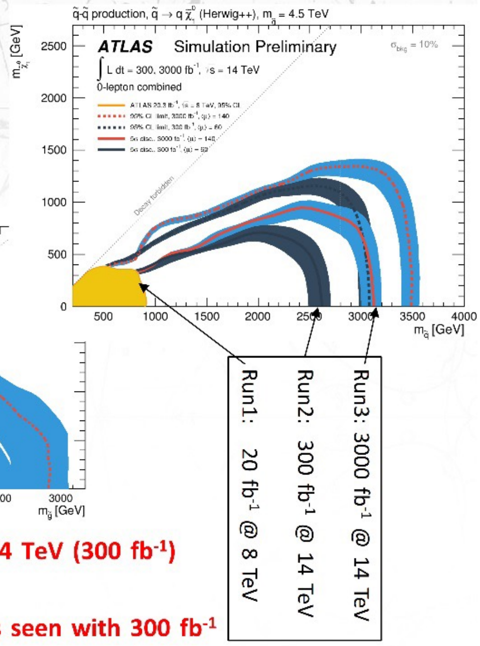
Supersymmetry (3)

- **Search for other squarks and gluinos**
  - **Can be heavier than the lighter stop – already excluded up to 1 TeV in Run1**









- **Mass reach extended by a factor 2 – 3 with LHC at 14 TeV (300 fb^{-1})**
  - **Further extended by 20% with HL-LHC**
- **Discovery potential of HL-LHC vanishes if no excess is seen with 300 fb^{-1}**

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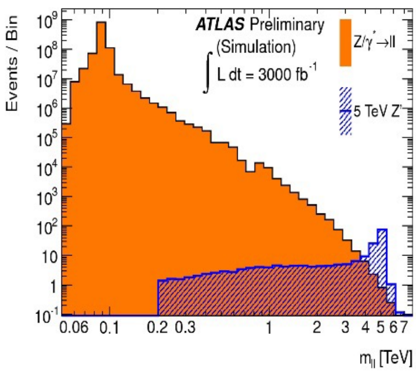
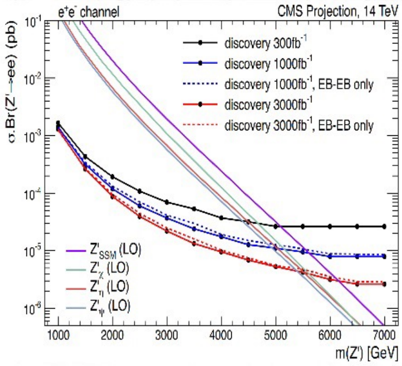
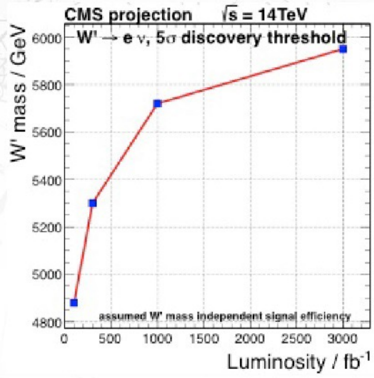
New gauge bosons: W', Z'

- Look for heavy di-lepton resonance: $Z' \rightarrow e^+e^-$, $\mu^+\mu^-$, or $W'^+ \rightarrow e^+\nu_e$, $\mu^+\nu_\mu$
  - Z' and W' masses up to 2-3 TeV excluded at LHC Run1





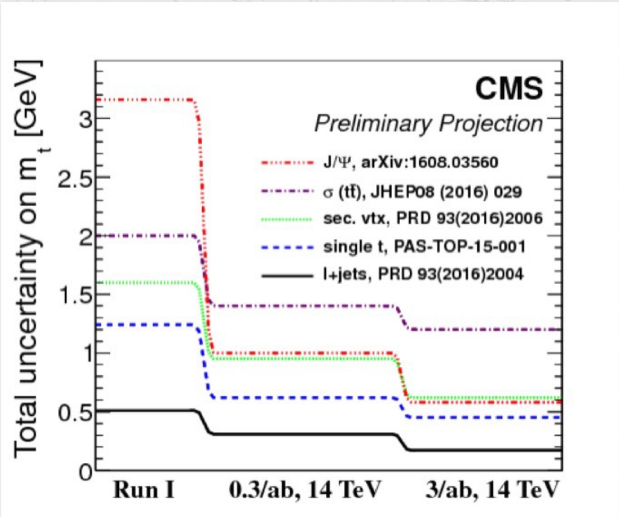


- Mass reach extended by a factor 2 with LHC at 14 TeV (300 fb^{-1})
  - Further extended by 20% with HL-LHC
- Discovery potential of HL-LHC vanishes if no excess is seen with 300 fb^{-1}
  - (Not visible in the graphs above)

Top quark mass (2)

- The top quark mass at HL-LHC
  - There is still much more to come: systematic uncertainties are statistically limited
    - And there are more methods out there to try

Today: $\delta m_{top} \simeq 0.5$ GeV



- Projected uncertainties
  - Reduction by a factor 2
    - After 300 fb^{-1}
    - Again after 3000 fb^{-1} @ HL-LHC
- Ultimate reach: ~ 200 MeV (exp.)
  - Theory uncertainty: ~ 500 MeV
    - What is the quantity that is being measured? "MC top mass"
  - Must answer this very question
    - Otherwise 3000 fb^{-1} won't do much better then 300 fb^{-1}