Introduction to Particle Physics
- Chapter 13 -

Higgs boson discovery

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Chapter summary:

- Higgs coupling with fermions and gauge bosons
- Branching ratios
- Higgs search at LEP
- Higgs search at LHC
- Higgs discovery at LHC
- Higgs properties
- A few words about Supersymmetry
- A few words about Dark Matter

Higgs couplings with W and Z

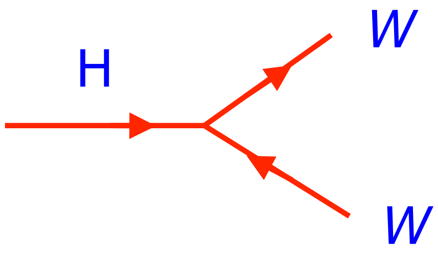
- Electroweak Lagrangian that is invariant for a local gauge transformation:

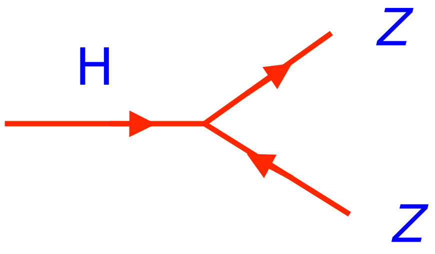
$$\mathcal{L} = \bar{\Psi}_L \gamma^\mu \left[i\partial_\mu - g\vec{I} \cdot \vec{W}_\mu(x) - \frac{g'}{2} Y \cdot B_\mu \right] \Psi_L + \bar{\Psi}_R \gamma^\mu \left[i\partial_\mu - \frac{g'}{2} Y \cdot B_\mu \right] \Psi_R + \mathcal{L}_{free}(\vec{W}, B)$$

- Replacing in the Lagrangian the field φ obtained after the spontaneous symmetry breaking

$$\varphi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

we get the Higgs couplings with the gauge bosons:





$$\frac{m_W}{m_Z} = \cos\theta_W$$

$$g_{HWW} = \frac{g^2 v}{2} = \frac{2m_W^2}{v}$$

$$m_W = \frac{1}{2} g v$$

$$g_{HZZ} = \frac{g^2 v}{4\cos^2\theta_W} = \frac{m_Z^2}{v}$$

$$v = \frac{1}{\sqrt{\left(G\sqrt{2}\right)}} \approx 246\ GeV$$

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Higgs couplings with the fermions

- After the spontaneous symmetry breaking we insert in the Lagrangian the field

$$\boxed{\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}}$$

and we get:

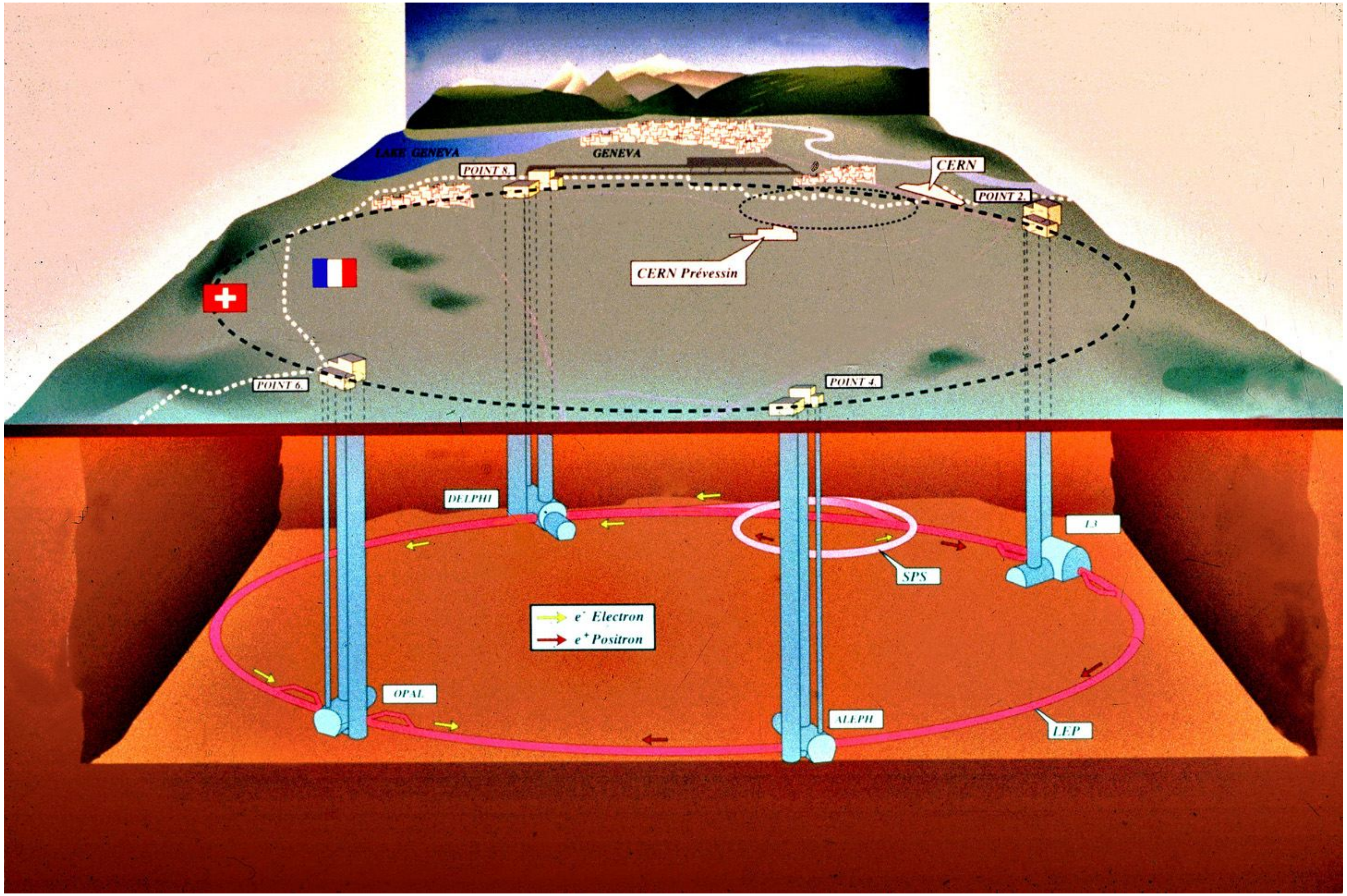
$$\boxed{L = -\underbrace{\frac{g_e v}{\sqrt{2}}\left[\bar{e}_R e_L + \bar{e}_L e_R\right]}_{\text{Mass term}} - \underbrace{\frac{g_e}{\sqrt{2}}\left[\bar{e}_R e_L + \bar{e}_L e_R\right]H}_{\text{Higgs coupling with the electron}}}$$

$$\boxed{m_e = \frac{g_e \cdot v}{\sqrt{2}}}$$

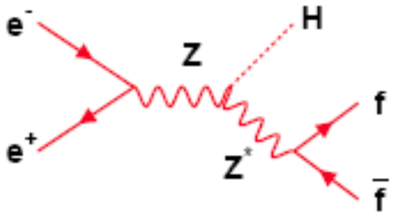
$$\Rightarrow \quad \boxed{L = -m_e \bar{e}e - \left(\frac{m_e}{v}\right)\bar{e}eH}$$

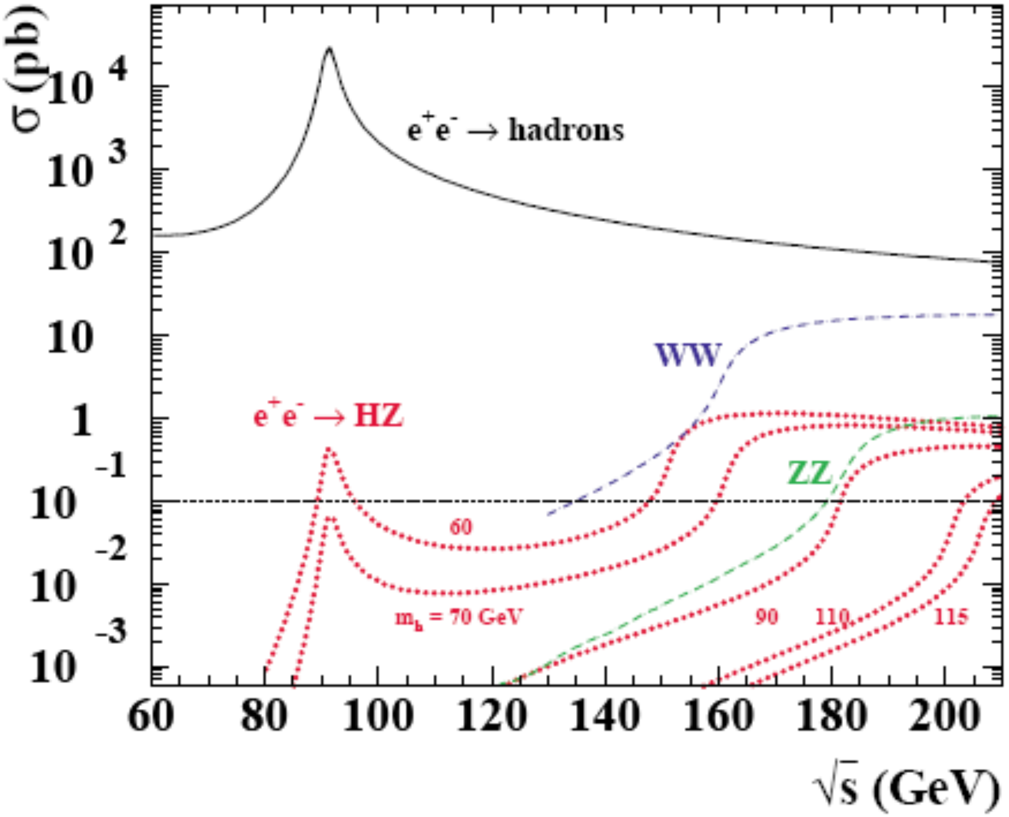
N.B. the coupling constant is proportional to the fermion mass

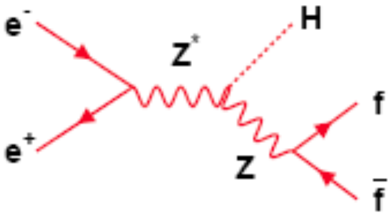
Higgs boson search at LEP



Higgs production cross-section at LEP





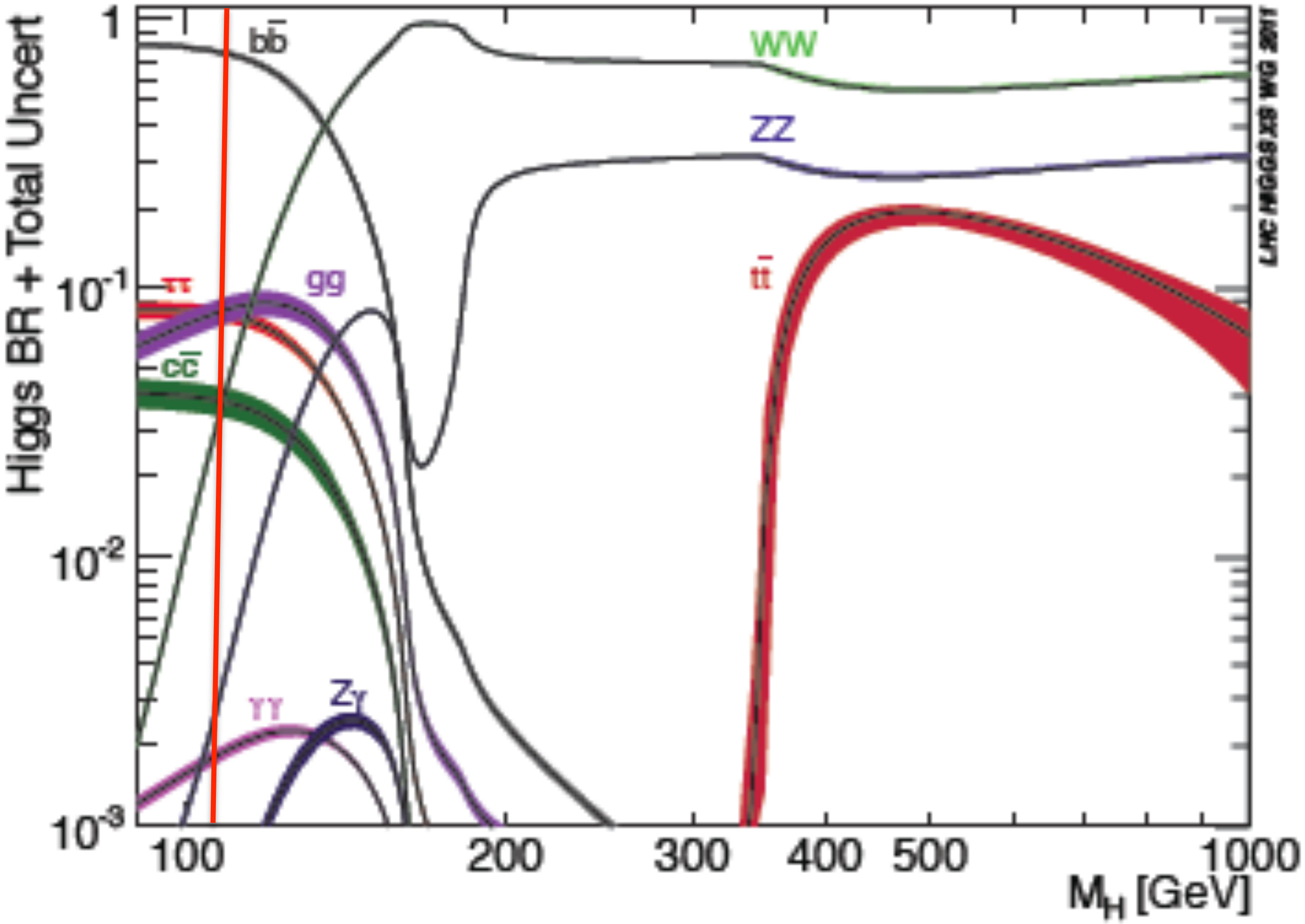


With a luminosity of about 100pb^{-1} and reasonable detection efficiency, sensitive to a cross section of $O(0.1)$ pb.

Need LEP2 to produce $m_H \gtrsim 65$ GeV. Reach $m_H \lesssim \sqrt{s} - M_Z$

Must take into account many background processes

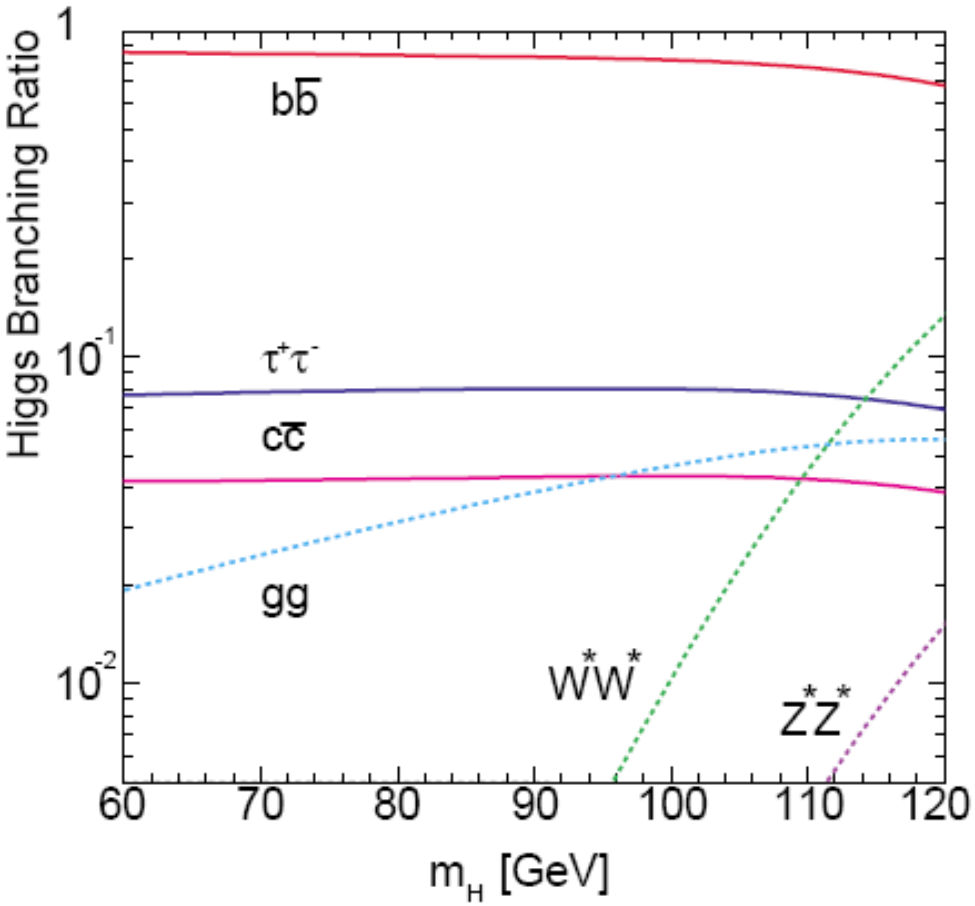
Higgs Branching Ratios



The dominant decay channel is H→bb up M_H≈ 120 GeV

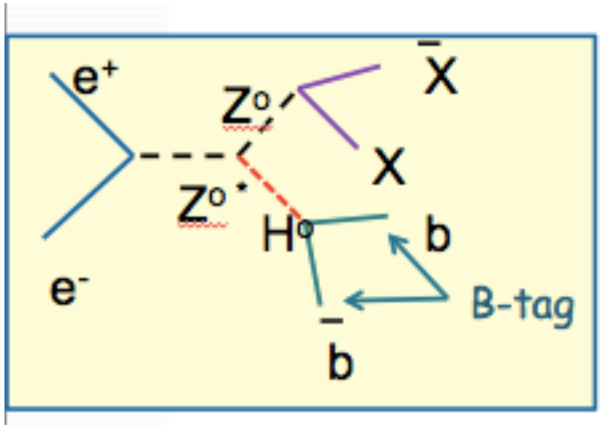
Higgs decays Branching Ratios

"Higgs couples to mass"



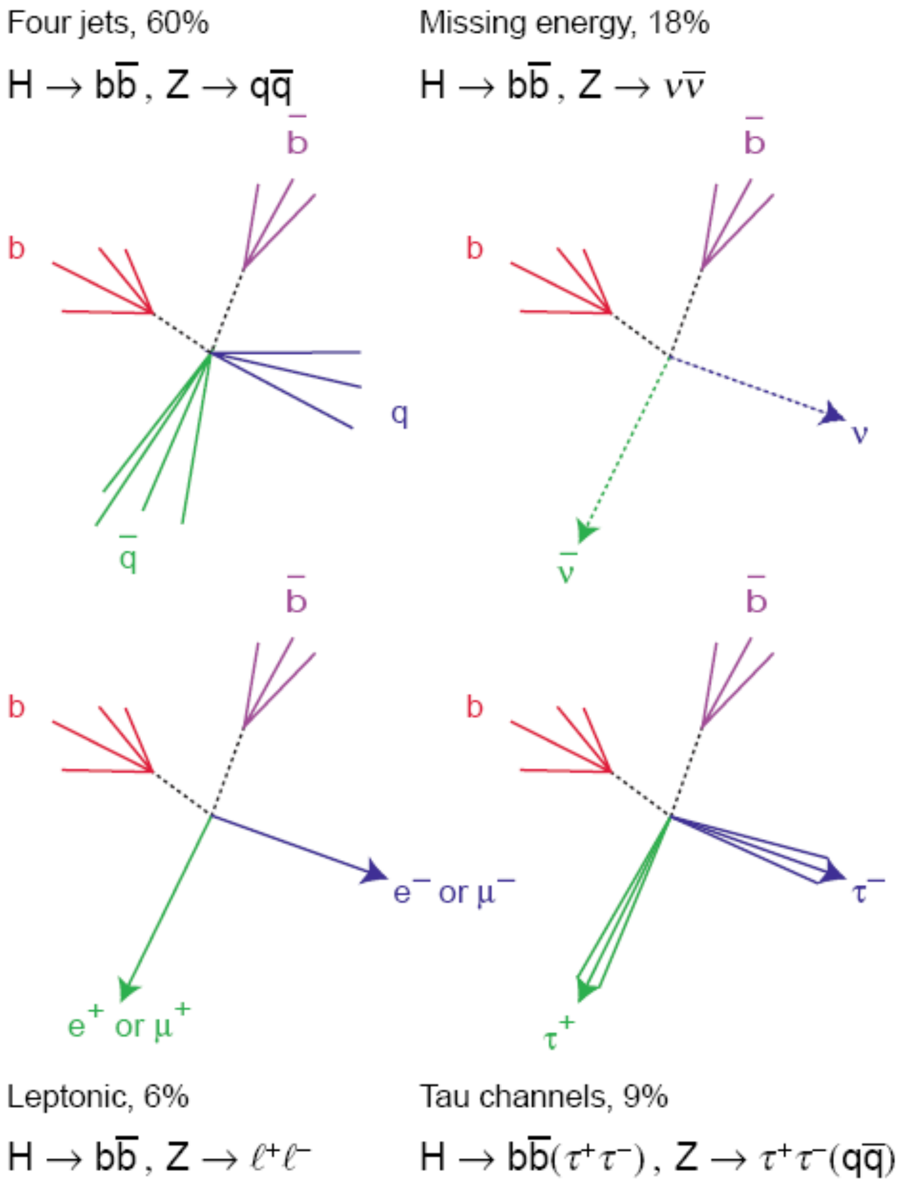
BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	

HZ decays



- Higgs boson decays into a b quark pair
- According to the Z decays we have different event topologies:
  - Z → e^+e^- ; $\mu^+\mu^-$ (small B.R. but very little background, it was the golden channel)
  - Z → $\nu\bar{\nu}$ (good compromise between B.R. and background)
  - Z → $q\bar{q}$ (High QCD background)

NO HIGGS FOUND AT LEP


Four jets, 60%

$H \rightarrow b\bar{b}\,,\ Z \rightarrow q\bar{q}$

Missing energy, 18%

$H \rightarrow b\bar{b}\,,\ Z \rightarrow \nu\bar{\nu}$

Leptonic, 6%

$H \rightarrow b\bar{b}\,,\ Z \rightarrow \ell^+\ell^-$

Tau channels, 9%

$H \rightarrow b\bar{b}(\tau^+\tau^-)\,,\ Z \rightarrow \tau^+\tau^-(q\bar{q})$

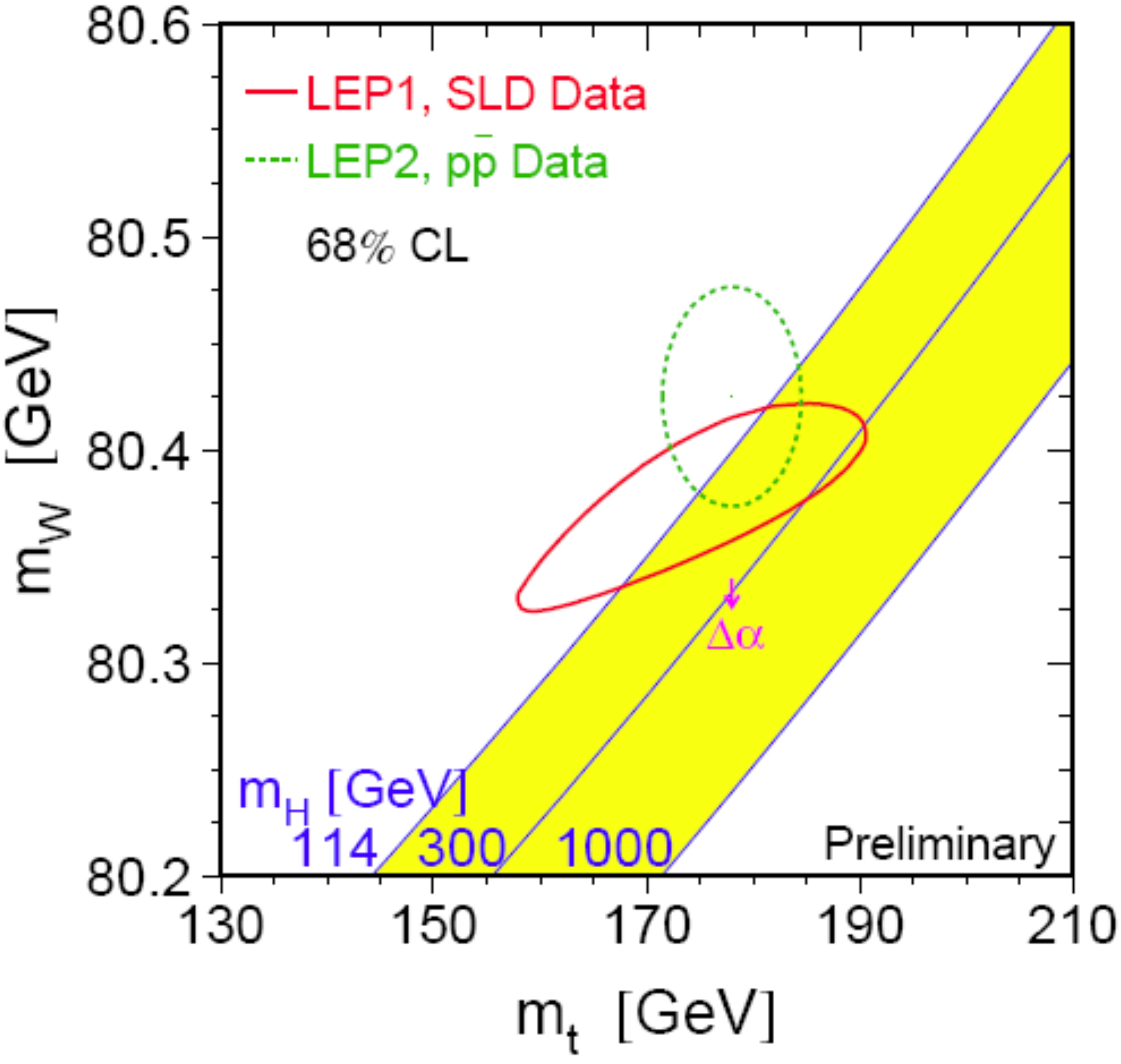
Global electroweak fit and Higgs mass

Fit to data from LEP, SLD, Tevatron...

Electroweak variables depend on m_t^2 and $\log m_H$ through radiative corrections

Consistency between predicted top and W mass (Z pole) and direct measurements

Preference for low Higgs mass.



Constraints on Higgs mass

Electroweak fits

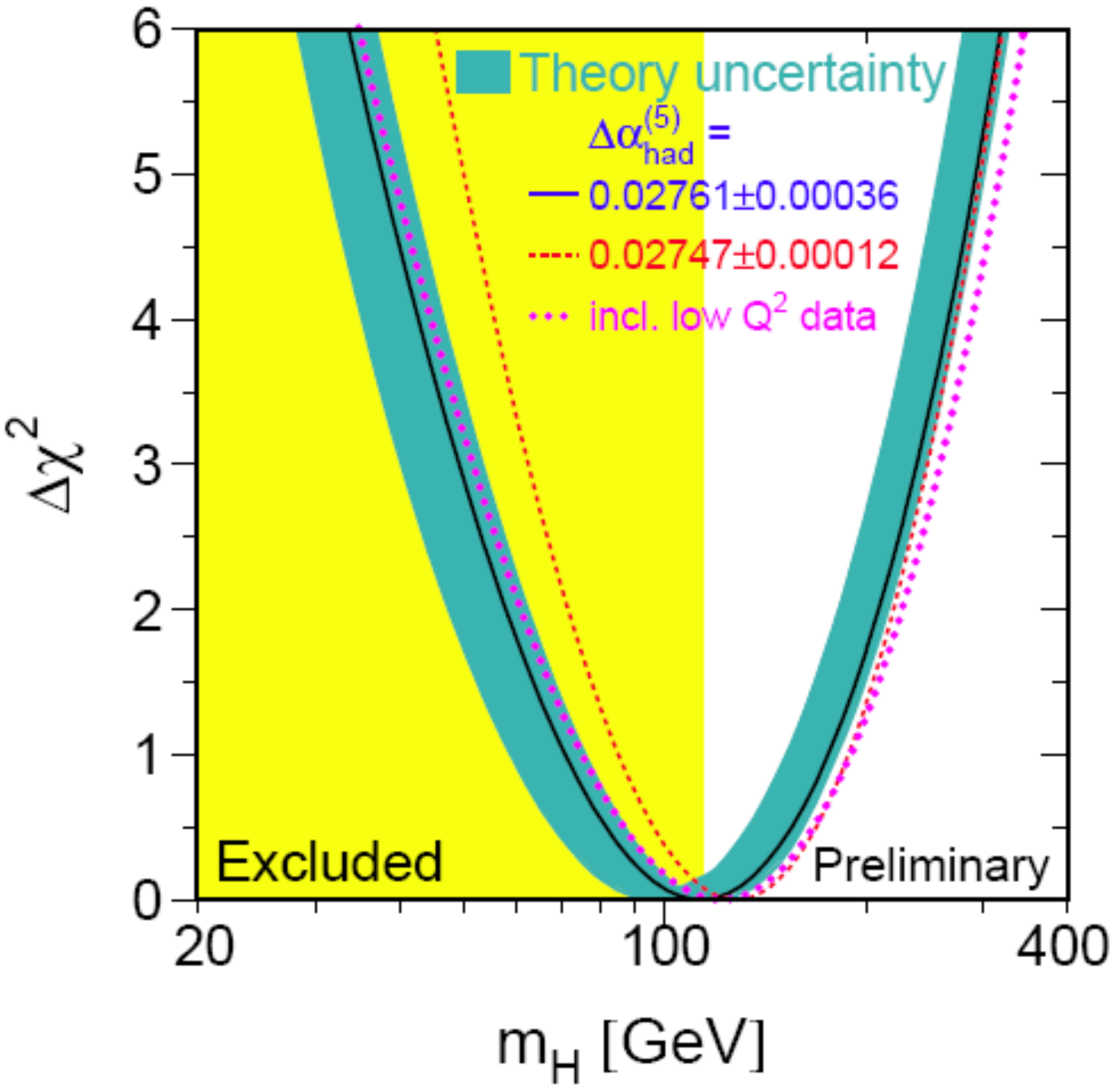
$m_H < 237$ GeV (95% CL)

Theory: self consistency of SM to GUT scale $\approx 10^{16}$ GeV

$130 < m_H < 190$ GeV.

m_H higher - theory non-perturbative,

m_H lower - vacuum unstable.



The Large Hadron Collider LHC

Installed in 26.7 km LEP tunnel

Depth of 70-140 m

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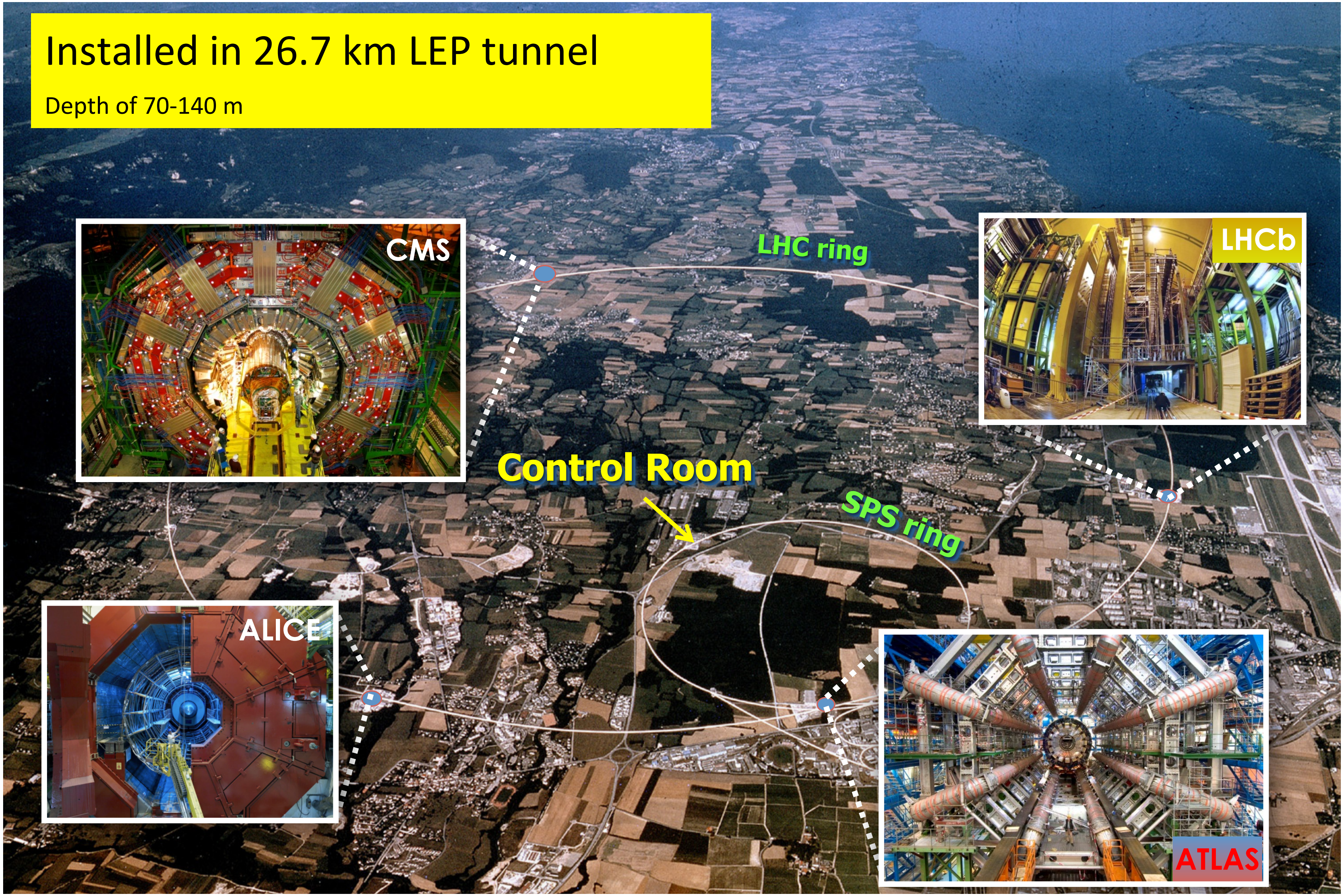
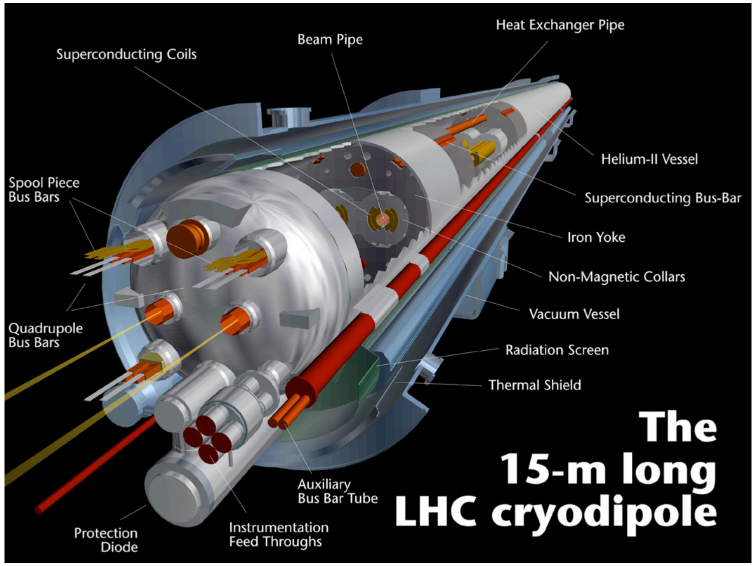


LHC ring layout

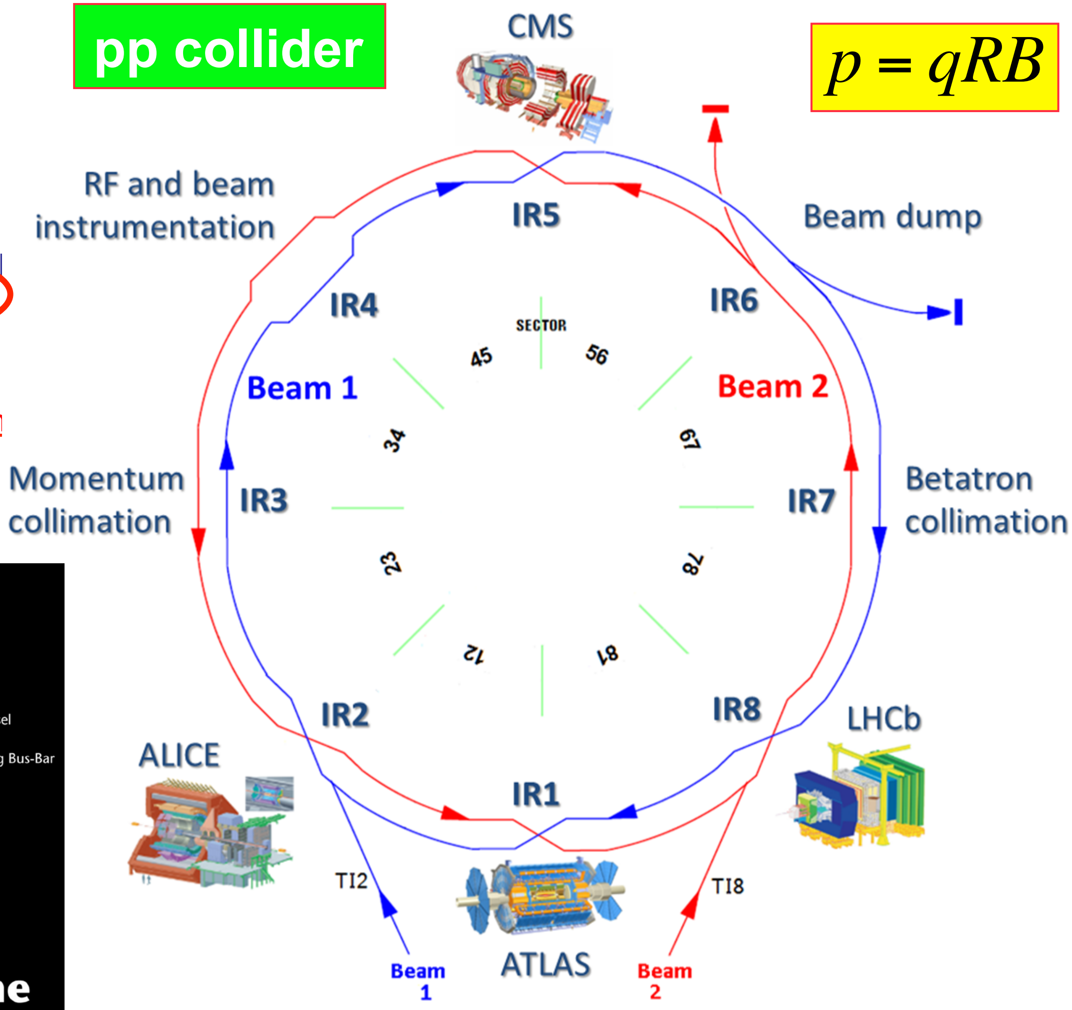
- ❑ Total length 26.66 km, in the former LEP tunnel.
- ❑ 8 arcs (sectors), ~3 km each.
- ❑ 8 straight sections of 700 m.
- ❑ Beams cross in 4 points.
- ❑ Design energy 7 TeV obtained with superconducting magnets operating at 8.3 T.
- ❑ 2-in-1 magnet design with separate vacuum chambers.
- ❑ **2 COUPLED rings**.



The 15-m long LHC cryodipole

pp collider

$p = qRB$



Design √s=14 TeV

Production cross-section at LHC

proton - (anti-)proton cross sections

$$dN/dt = L\sigma$$

1 b=10^{-24} cm^2 →

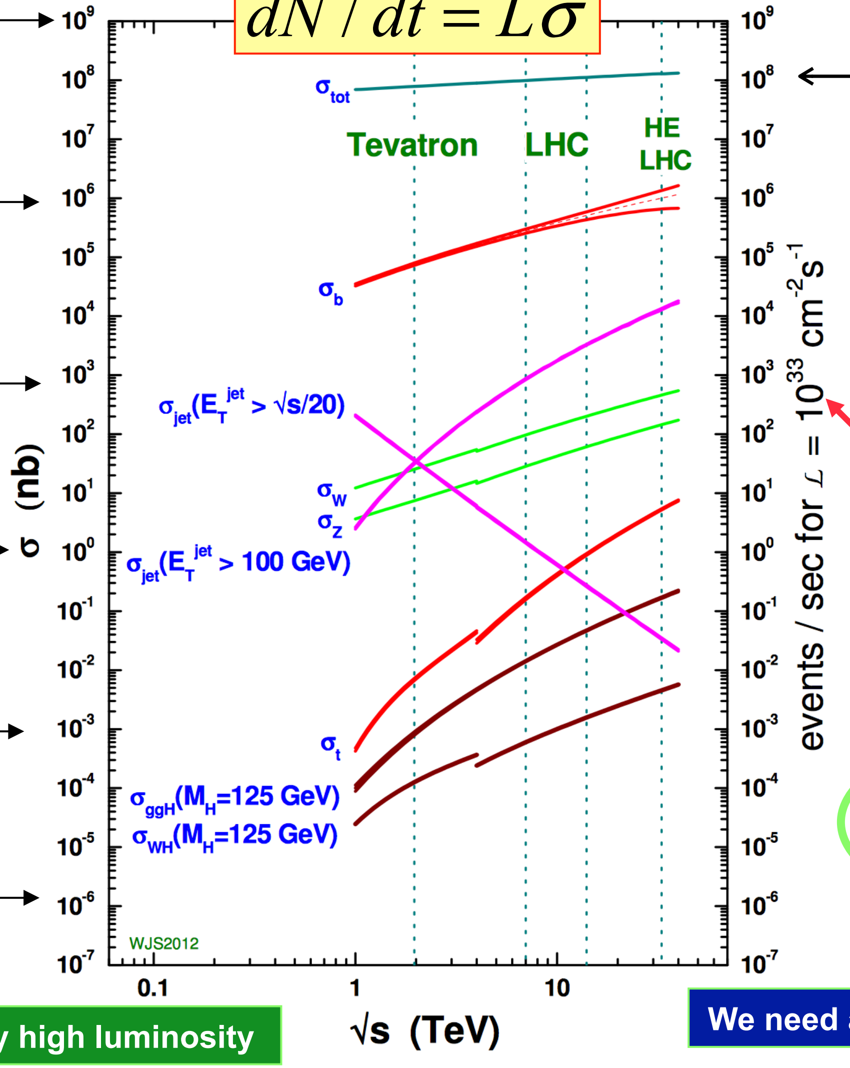
1 mb ↔

1 μb ↔

1 nb ↔

1 pb ↔

1 fb ↔



↔ total cross section: 10^8 evts/s (dominated by strong interaction)

Background is around here

(QCD bg)

↔ max. read-out: ~ 10^3 evts/sec

$\mathcal{L}$(2016)=10^{34} cm^{-2}s^{-1} ➔ x 10 the ev/s

↔ O(1) top-event/sec

↔ O(1) Higgs/min

Rare events/interesting events are around here

We need a very high luminosity

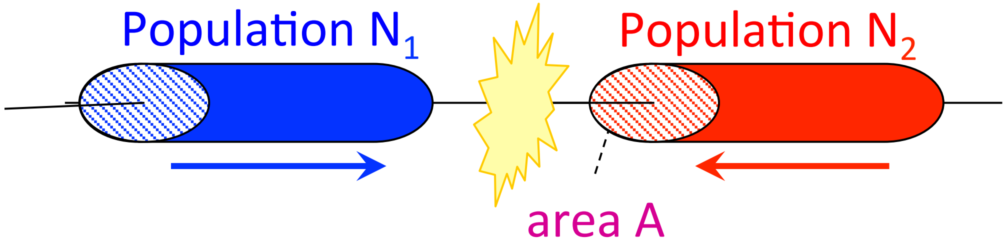
We need a very high background rejection capability

Collider Luminosity

The key parameter for the experiments is the event rate dN/dt. For a physics process with *cross-section σ* it is proprotional to the collider **Luminosity *L***:

$$dN/dt = L\sigma$$

unit of L : (surface × time)$^{-1}$



$$dN/dt = \sigma \times \underbrace{k\,\frac{N1 \bullet N2}{A} \times \frac{\text{encounters}}{\text{second}}}_{L}$$

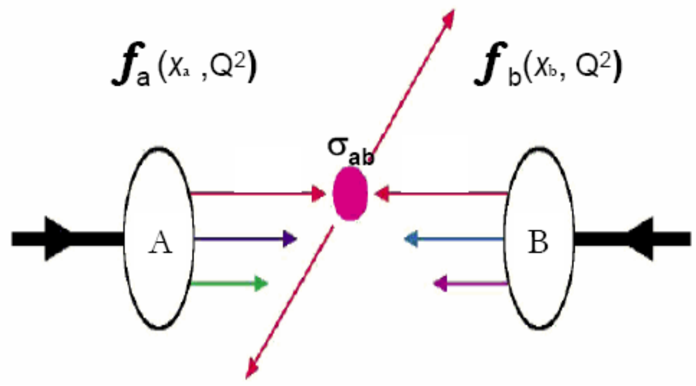
To maximize L we have to squeeze as many particles as possible into the smallest possible volume !

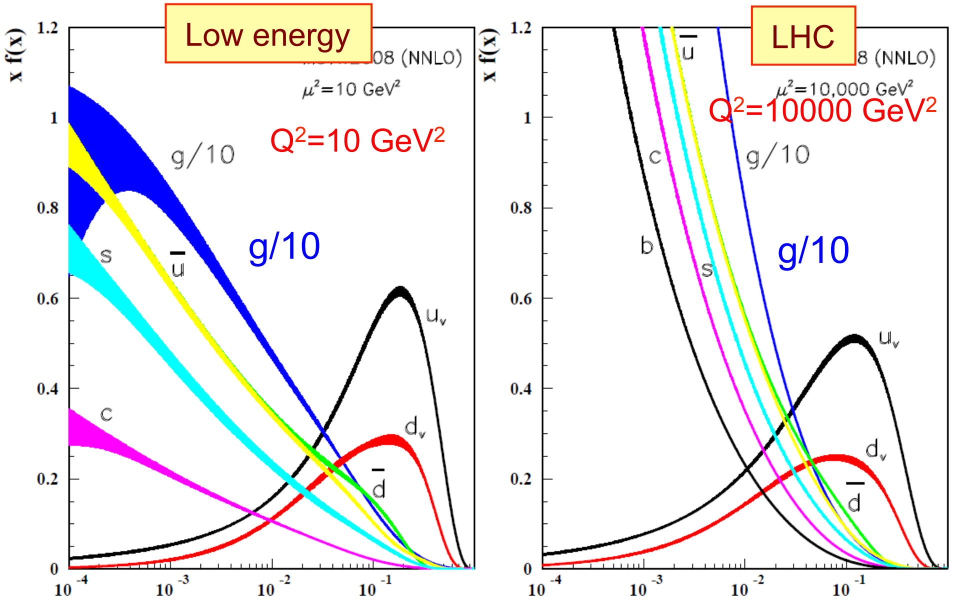
$$L = \frac{kN^2 f}{4\pi\sigma_x\sigma_y}$$

LHC Design

$k = 2808$
$N = 1.15\times10^{11}$
$s^*_x = s^*_y = 16$ mm
$L \sim 10^{34}$ cm^{-2}s^{-1}

LHC: parton-parton interactions





LHC is a gluon machine

Interaction between the partons which constitute the hadrons:

not well defined parton energy but energy distribution → pdf

PDFs are parameterizations of the partonic content of the proton:

at Hadron Colliders cross-section calculations are a convolution of the cross-section at parton level and PDFs

$$\sigma_X = \boxed{\sum_{a,b}} \int_0^1 dx_a dx_b \boxed{f(x_a, flav_a, Q^2) f(x_b, flav_b, Q^2)} \cdot \boxed{\sigma_{ab\to X}(x_a, x_b, Q^2)}$$

Sum over initial partonic states a,b

Parton Density Function

hard scattering cross-section

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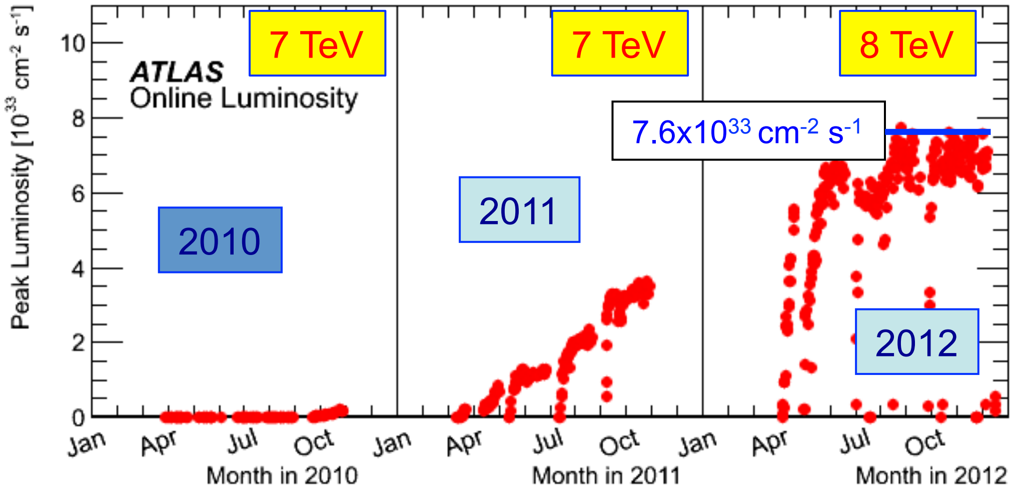
Luminosity: 2011, 2012, 2015 and 2016



7 TeV

7 TeV

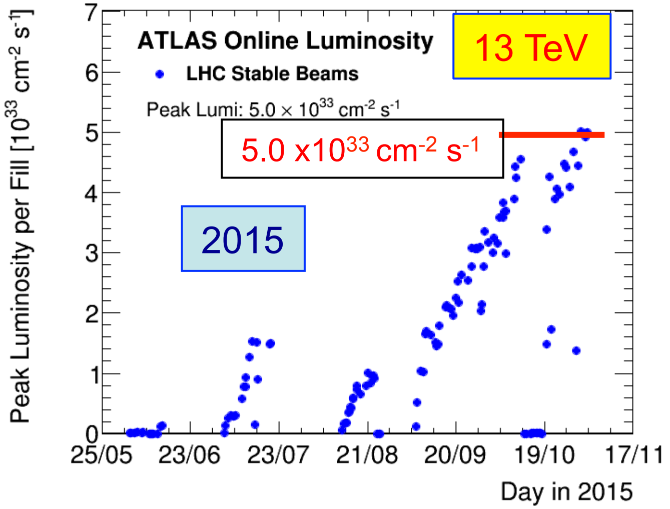
8 TeV

7.6×10^{33} cm^{-2} s^{-1}

2010

2011

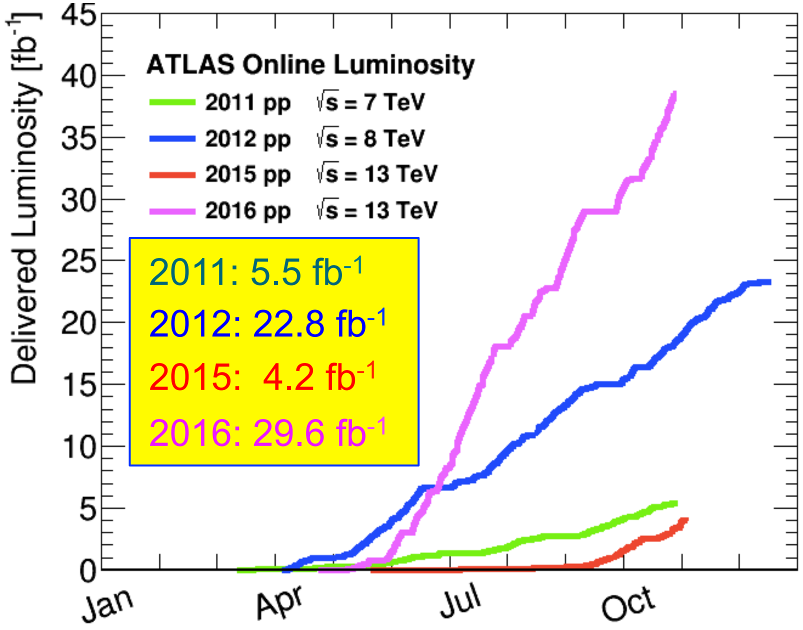
2012



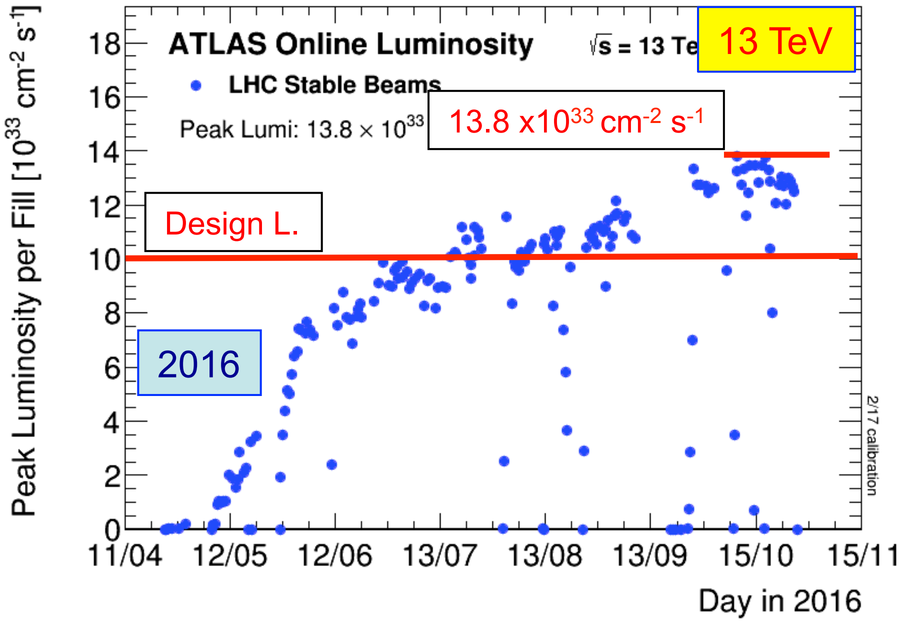
13 TeV

5.0 $\times 10^{33}$ cm^{-2} s^{-1}

2015



2011: 5.5 fb^{-1}
2012: 22.8 fb^{-1}
2015: 4.2 fb^{-1}
2016: 29.6 fb^{-1}



13 TeV

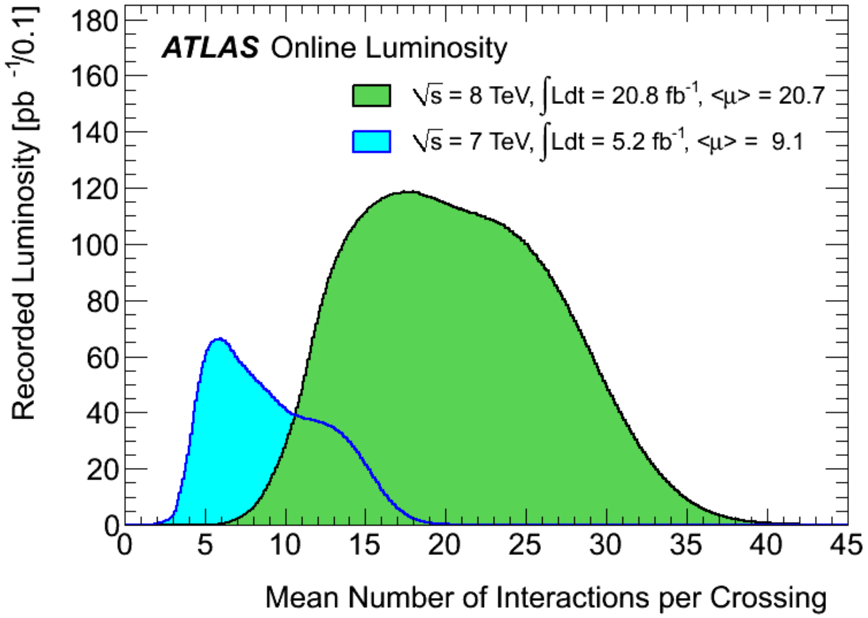
13.8 $\times 10^{33}$ cm^{-2} s^{-1}

Design L.

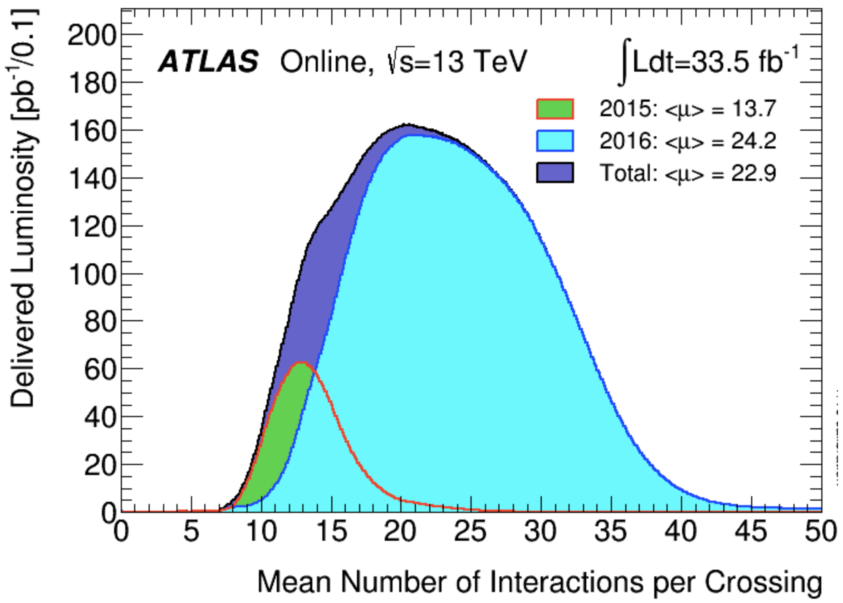
2016

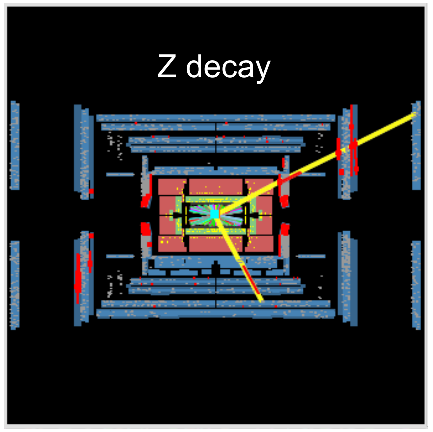
Pile-up

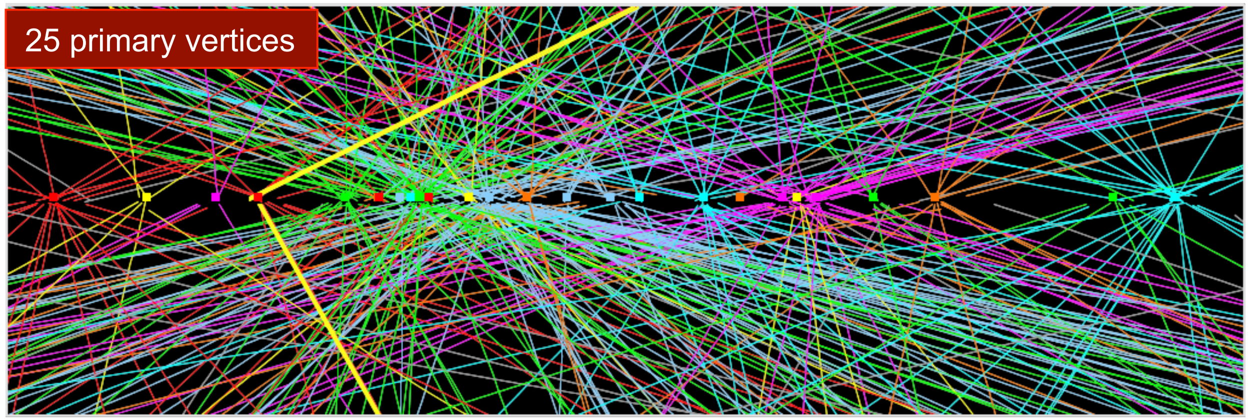
2011/12: 50 ns bunch spacing



2015/16: 25 ns bunch spacing







The ATLAS detector

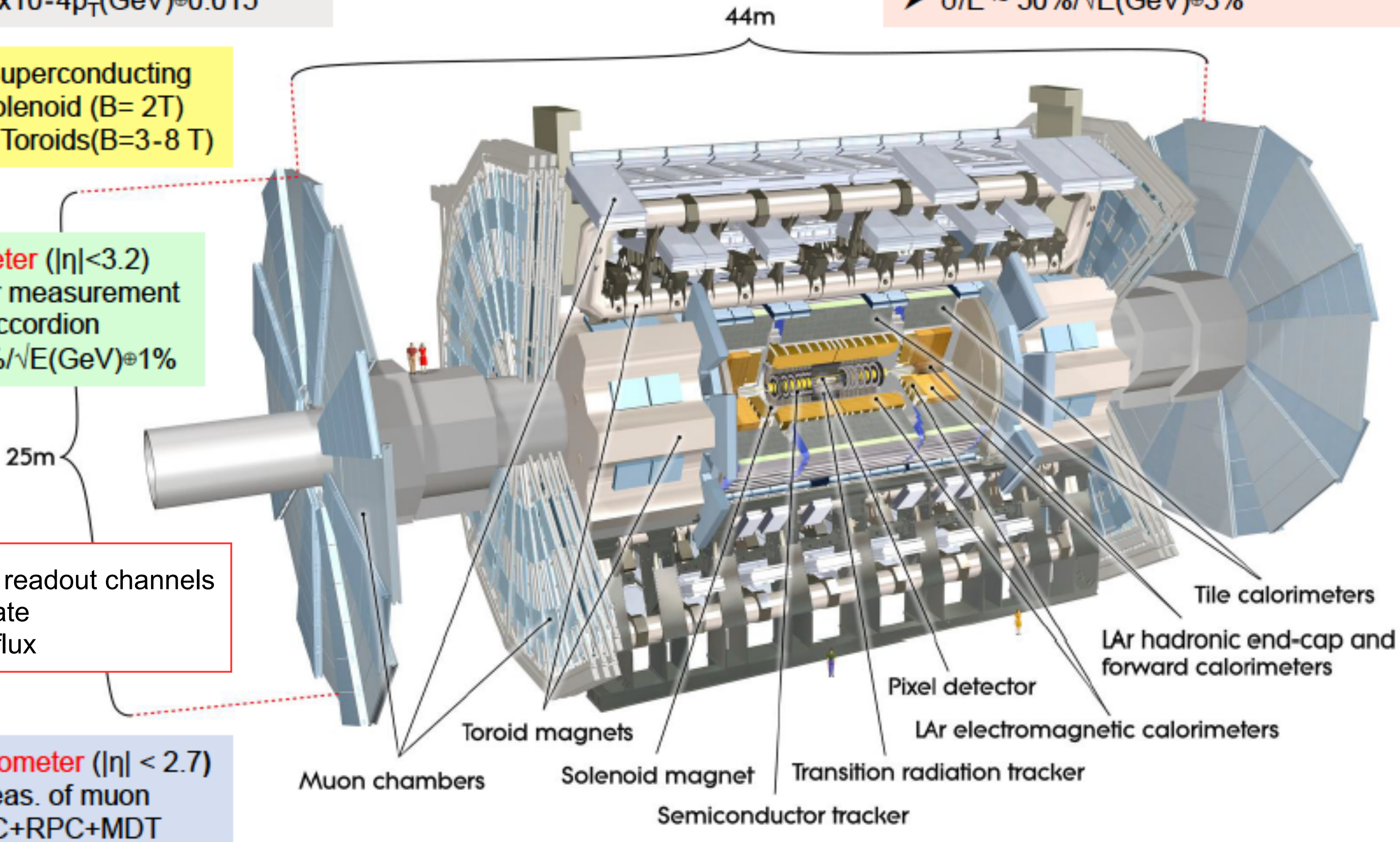
Inner detector ($|\eta|< 2.5$, B=2T)
Tracking, vertexing, dE/dx, e/π ID
- Si pixels, Si strips, Trans. Rad. det.
- $\sigma/p_T \sim 3.8\text{x}10\text{-}4 p_T(\text{GeV}) \oplus 0.015$

Length: 44 m
Height: 25 m
Weight: 7000 t

Hadron Calorimeter ($|\eta|<5$)
Trigger and meas. of jet/Emiss
- Fe/scintillator (central), Cu/W-LAr (fwd)
- $\sigma/E \sim 50\%/\sqrt{E(\text{GeV})} \oplus 3\%$

Magnets 4 Superconducting
- Central Solenoid (B= 2T)
- 3 Air core Toroids(B=3-8 T)

EM Calorimeter ($|\eta|<3.2$)
e/γ ID trigger measurement
- Pb-Lar accordion
- $\sigma/E \sim 10\%/\sqrt{E(\text{GeV})} \oplus 1\%$

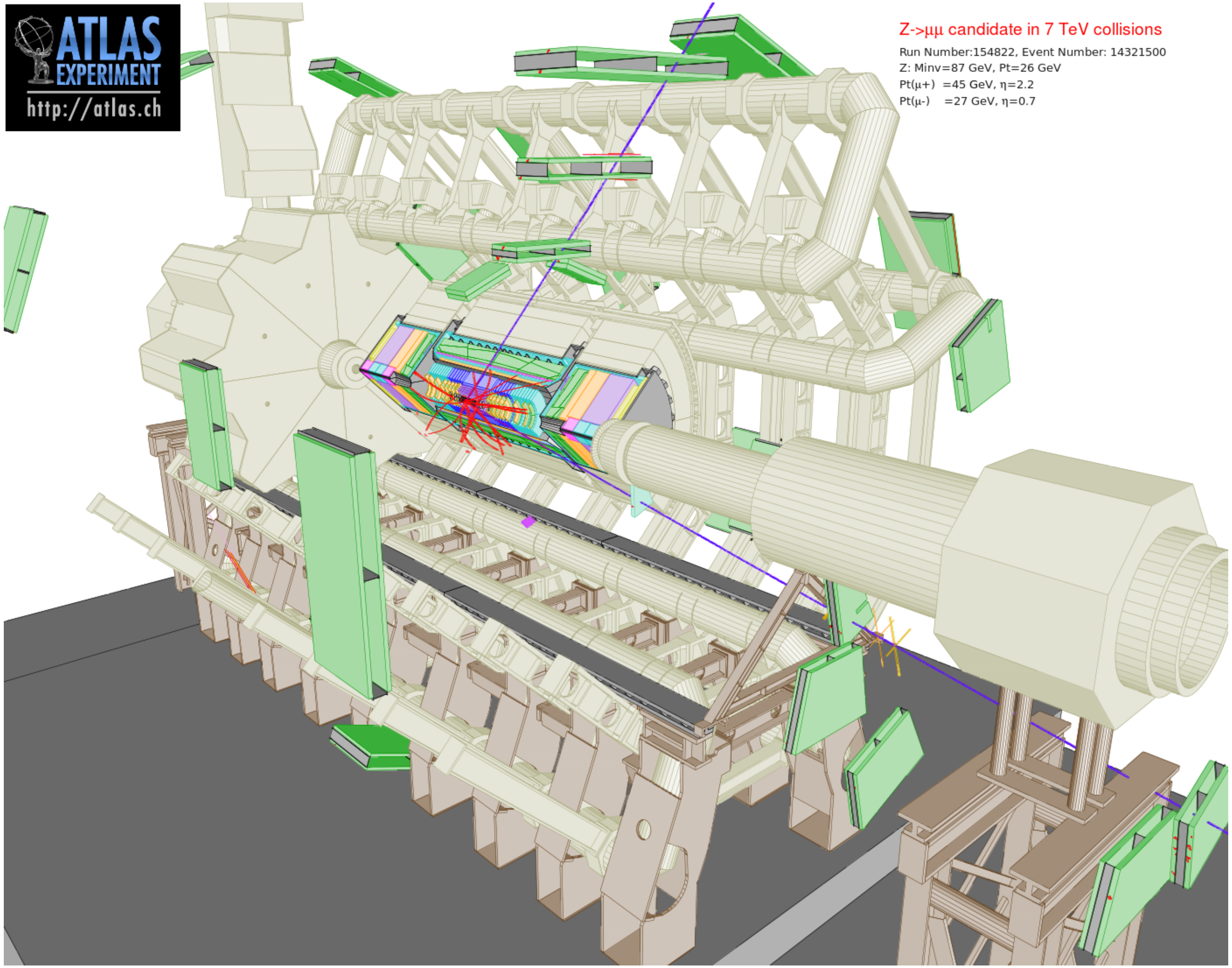


$150 \cdot 10^6$ electronic readout channels
40 MHz collision rate
10^{14} B/s raw data flux

Muon spectrometer ($|\eta| < 2.7$)
Trigger & meas. of muon
- CSC+TGC+RPC+MDT
- σ/p_T <10 % up to 1 TeV

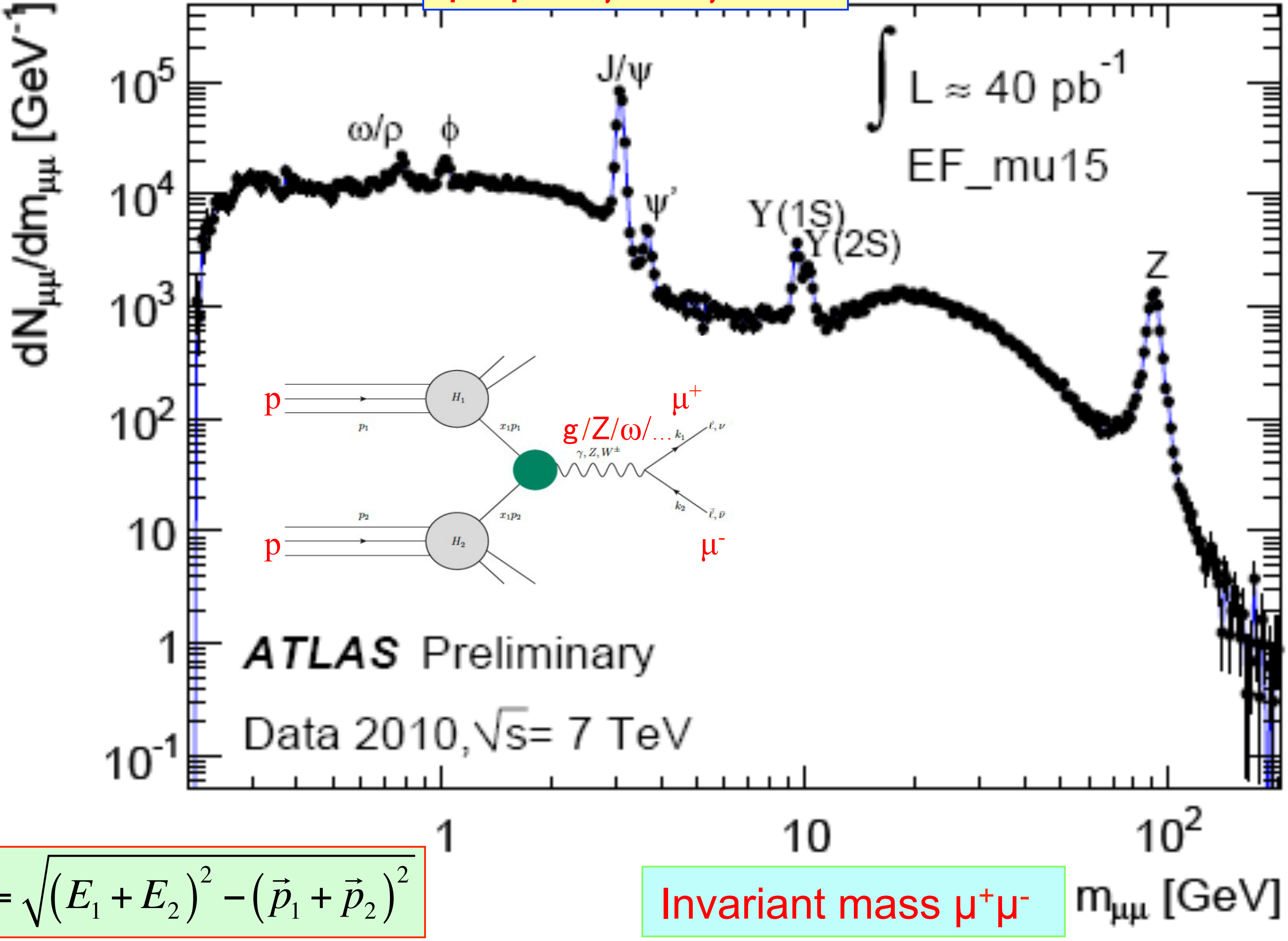
Planning & construction 1990 to 2007; operation from 2009 to ~2035

ATLAS: Z→$\mu^+\mu^-$ candidate



ATLAS: 50 years in one slide

$p+p \rightarrow \mu^+ + \mu^- + X$

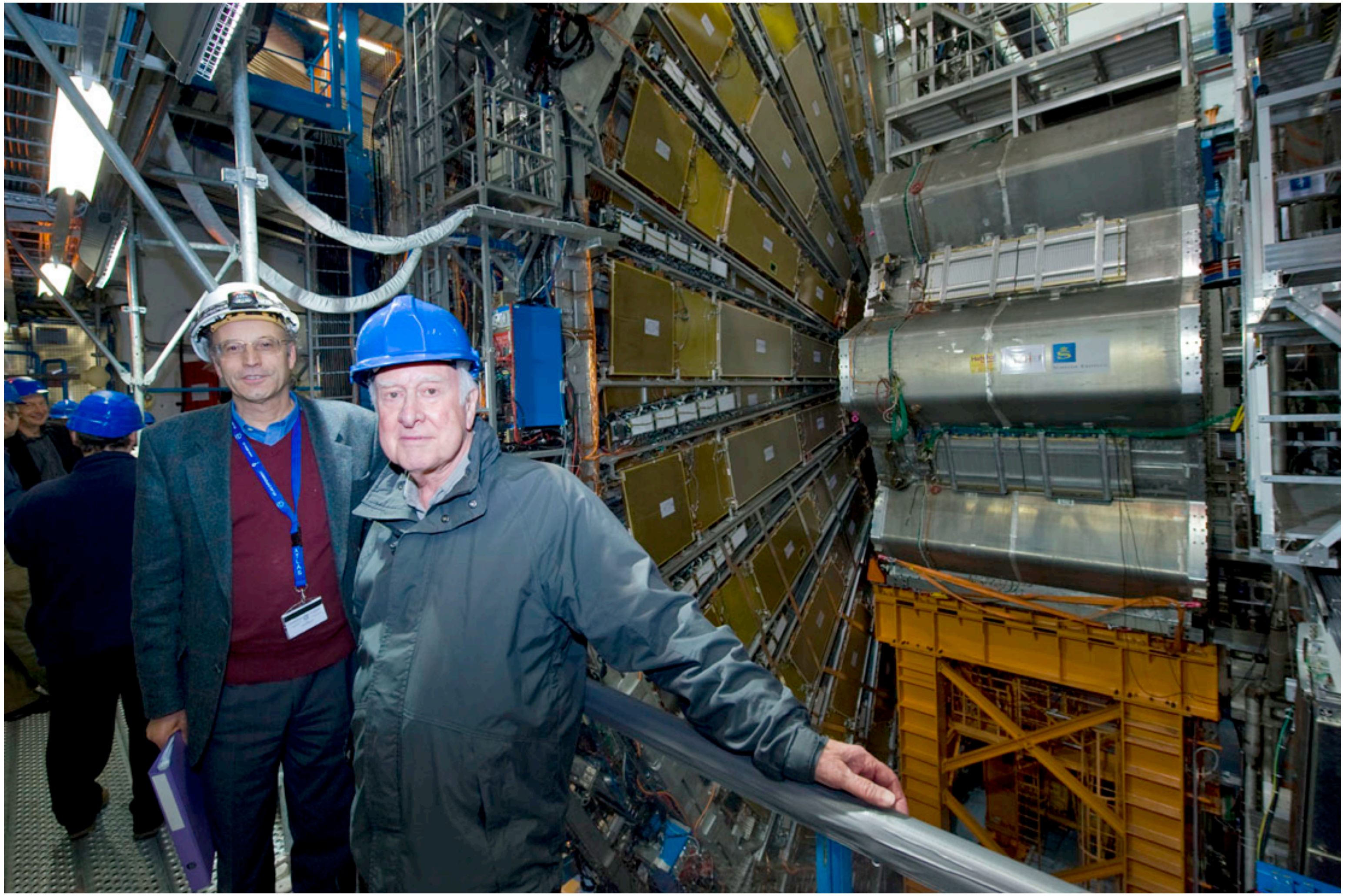


Peak positions are used to check scale momentum calibration

$$m_{\mu\mu} = \sqrt{\left(E_1 + E_2\right)^2 - \left(\vec{p}_1 + \vec{p}_2\right)^2}$$

Invariant mass $\mu^+\mu^-$

The Higgs boson



The first Higgs seen in the ATLAS Experiment

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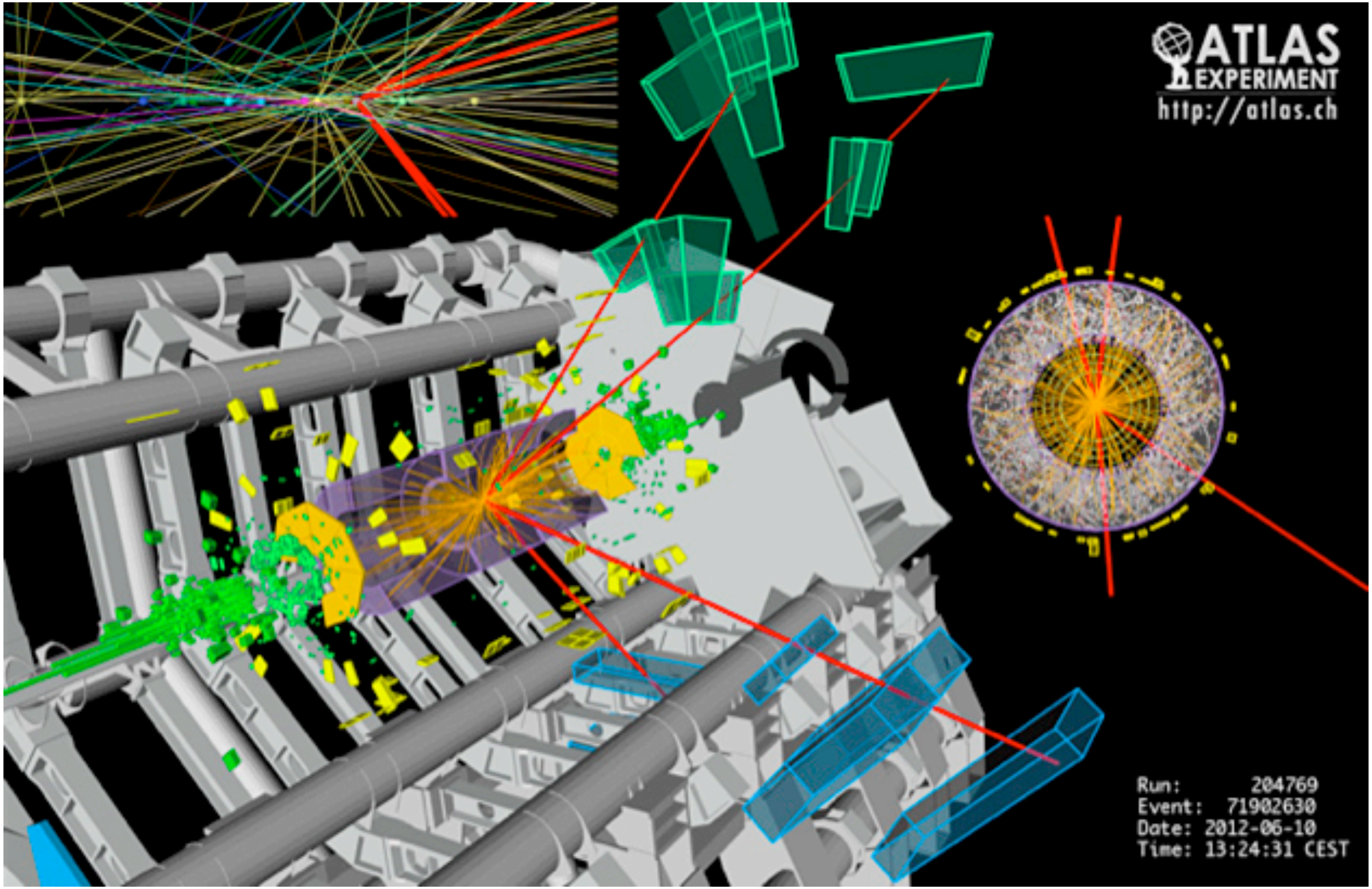
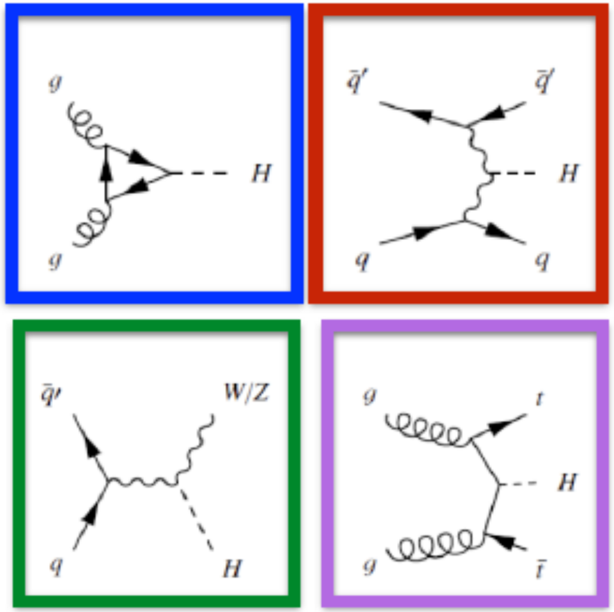
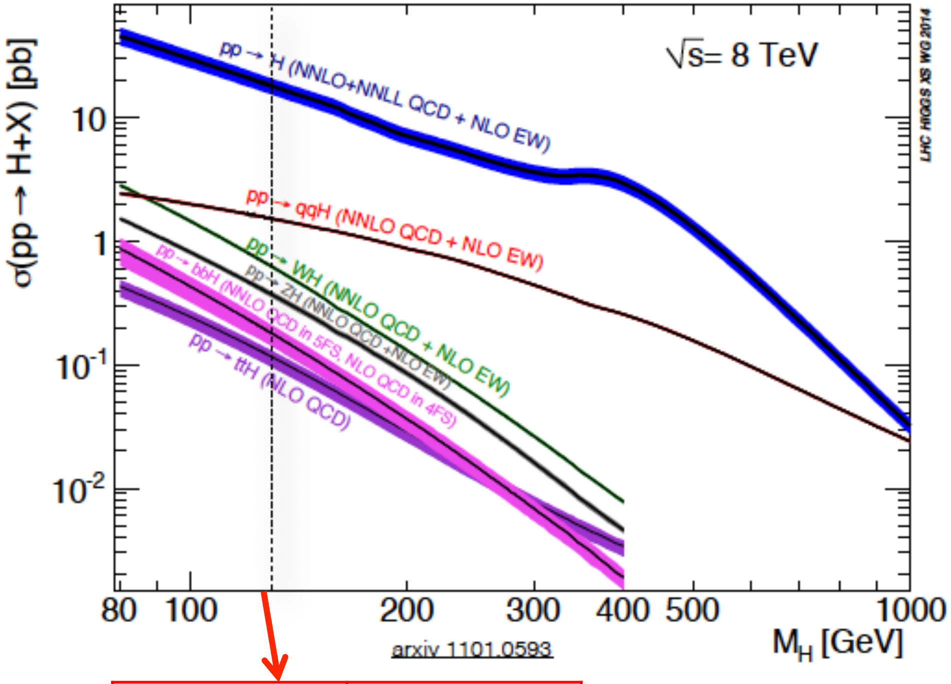
$H \rightarrow ZZ^* \rightarrow \mu^+\mu^-\mu^+\mu^-$



SM Higgs Boson Production



Production process	Cross section [pb]	
	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.57 ± 0.04
WH	0.573 ± 0.016	0.698 ± 0.018
ZH	0.332 ± 0.013	0.412 ± 0.013
bbH	0.155 ± 0.021	0.202 ± 0.028
ttH	0.086 ± 0.009	0.128 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001
Total	17.4 ± 1.6	22.3 ± 2.0

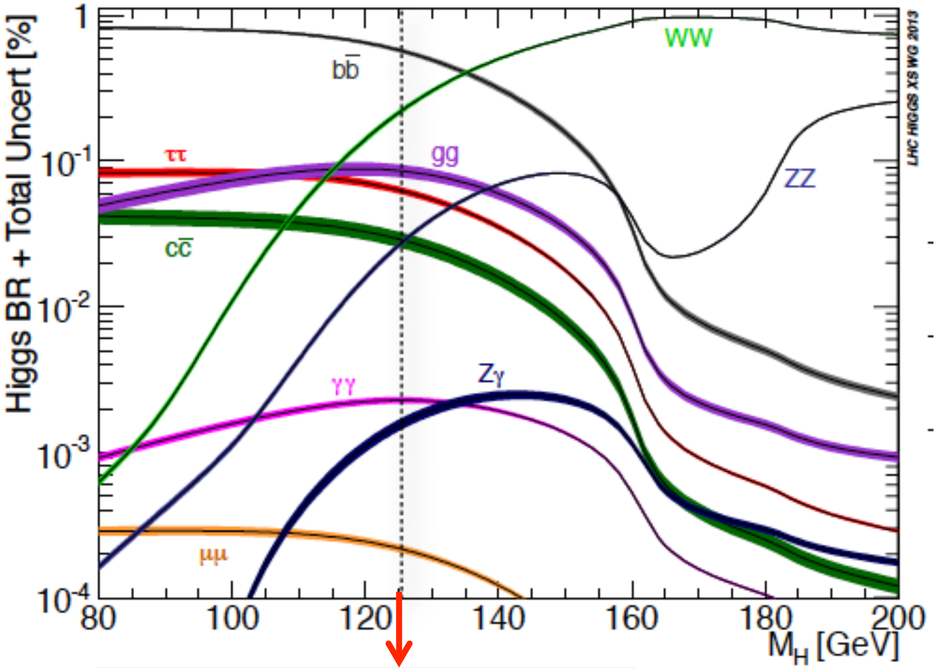


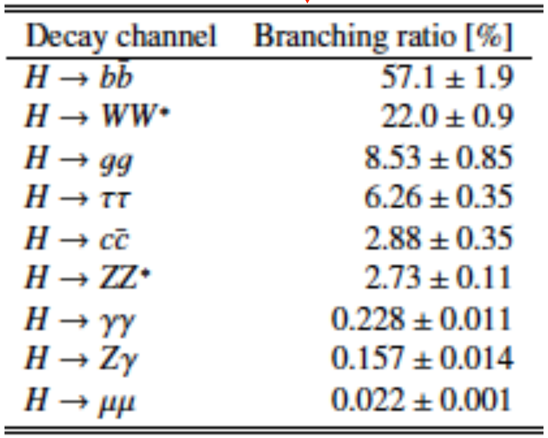
arxiv 1101.0593

ggF	**~86%**	Gluon Fusion
VBF	**~7%**	Vector Boson Fusion
VH	**~5%**	Higgs-strahlung
bbH/ttH	**~1.5%**	ttbar associated production

$\sigma_{tot}(13\ \text{TeV}) = \sim 2\sigma_{tot}(8\ \text{TeV})$

Higgs Boson decay modes





Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.1 ± 1.9
$H \to WW^*$	22.0 ± 0.9
$H \to gg$	8.53 ± 0.85
$H \to \tau\tau$	6.26 ± 0.35
$H \to c\bar{c}$	2.88 ± 0.35
$H \to ZZ^*$	2.73 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.157 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

Higgs couplings (tree level)

$$g_{HWW} = g m_W$$

$$g_{HZZ} = g \frac{m_Z}{2\cos\ \theta_W}$$

$$g_{Hee} = g \frac{m_e}{2m_W}$$

They are proportional to the mass

Most used decay modes are built using isolated leptons (e,μ), photons and missing energy

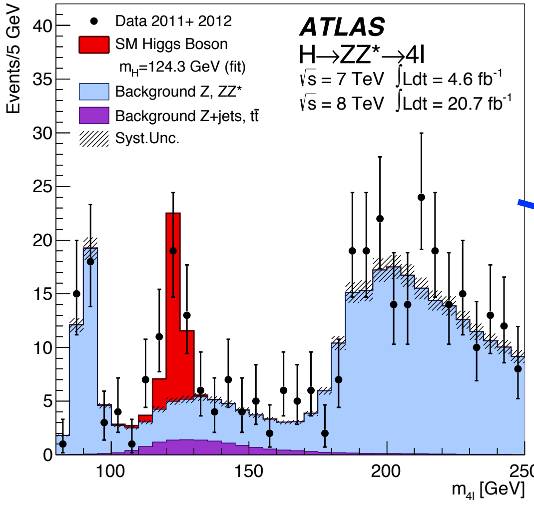
H→ZZ*→4l(e,μ)	~0.013%
H→γγ	~0.23%
H→ττ	~6.3%
H→WW→lνlν	~1.1%

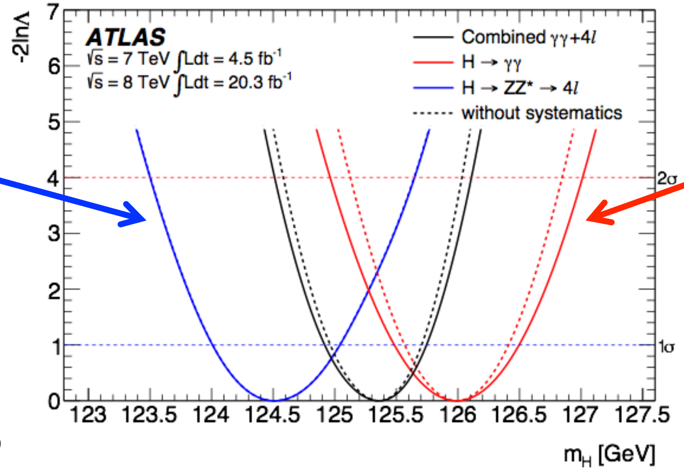
Higgs Boson Mass Measurement

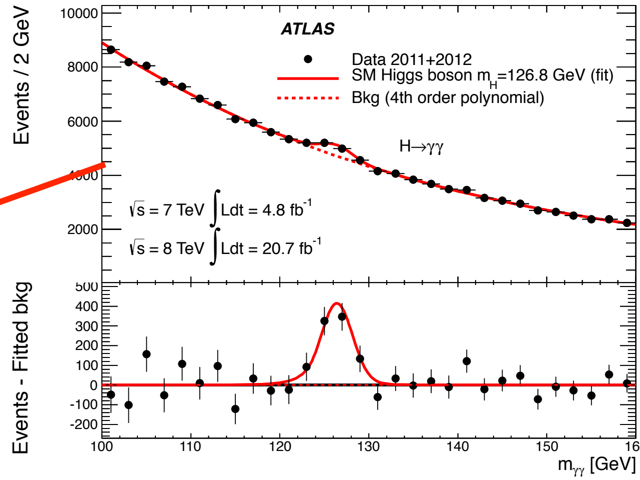
- Precise measurement of m_H from channels with the best mass resolution: H→γγ and H→ZZ*→4l (e,μ) (but B.R.≈0.25% only)
- Dominant uncertainties:
  photon energy scale (H→γγ), statistics (H→4l)

H → ZZ* → 4l (e,μ)

H → γγ



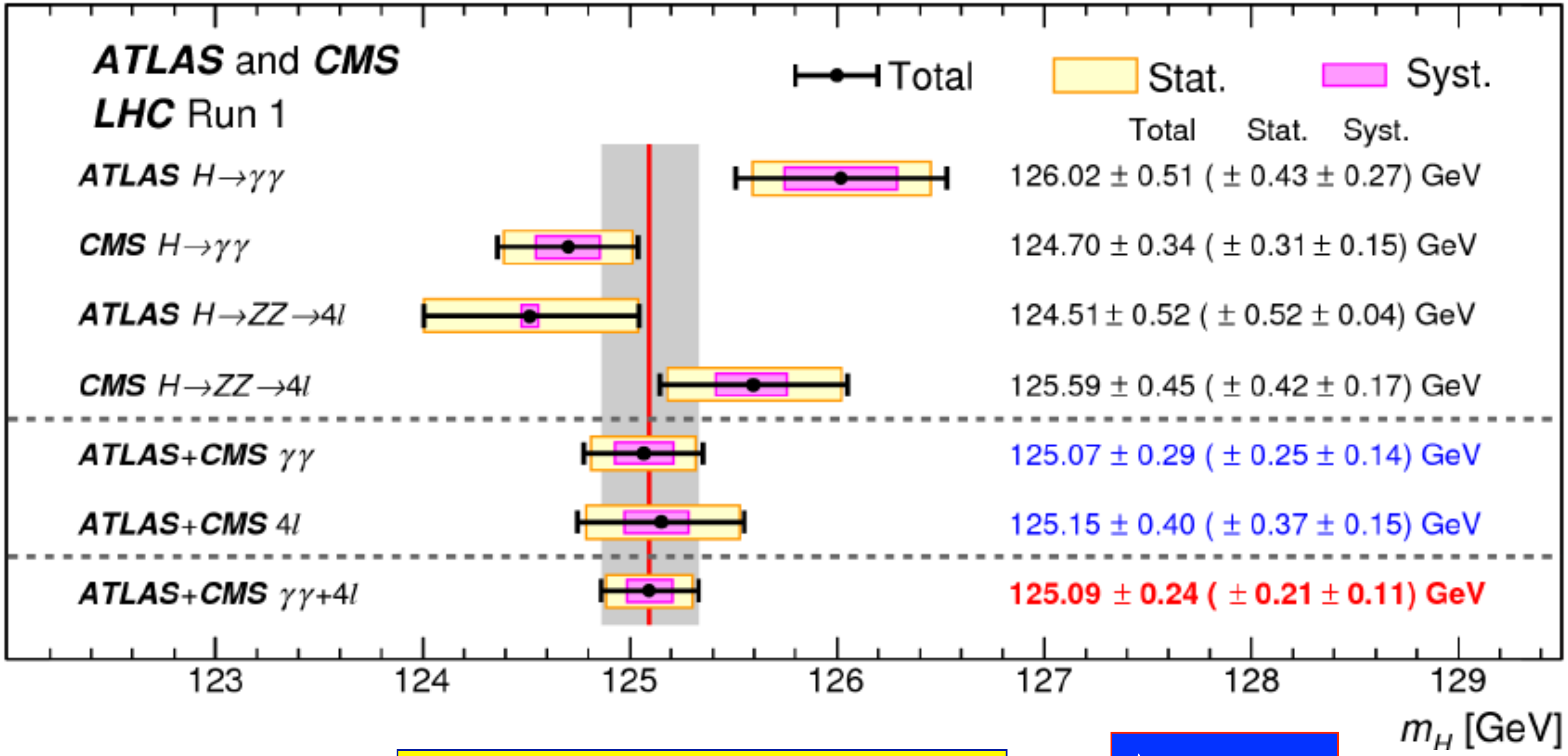




Combined mass: m_H=125.36±0.37 (stat) ±0.18 (syst) GeV

Combined Higgs Boson Mass

ATLAS-CMS PRL 114 (2015) 191803



m_H=125.09±0.24 GeV

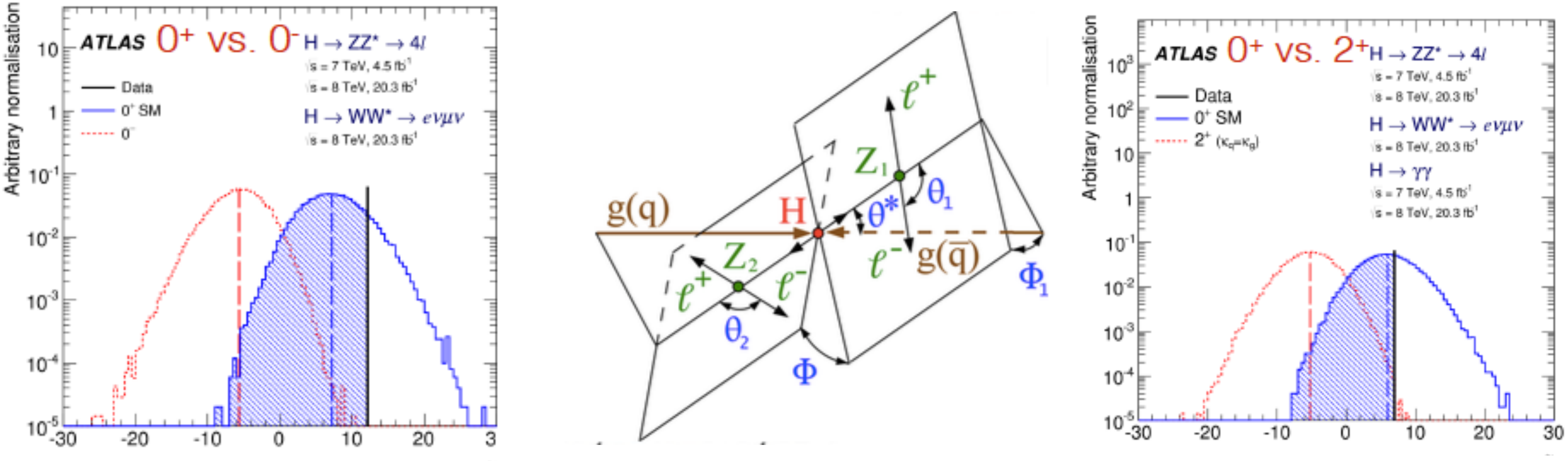
$$\frac{\Delta m}{m} = 0.2\%$$

Higgs Boson Spin Measurement

- Test SM (0+) against various models

  - Spin-2 Higgs
  - Spin-0 odd (BSM Higgs)
  - (Spin-1 ruled out by observation of H→ γγ decays)

- In all tested cases non-SM models rejected at >99% CL

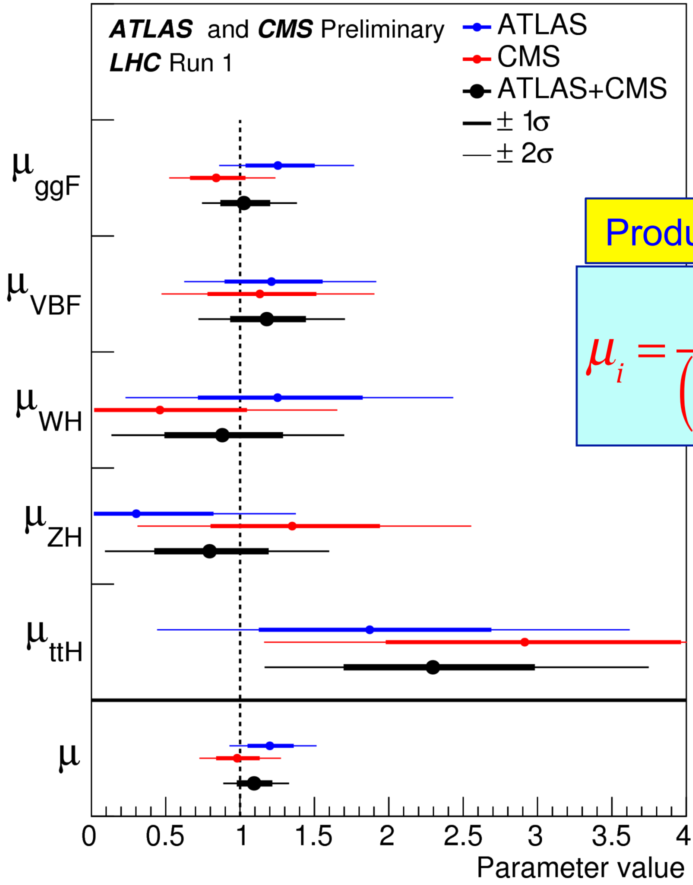


(Multivariate analysis (MVA) based on angular variables)

1/3

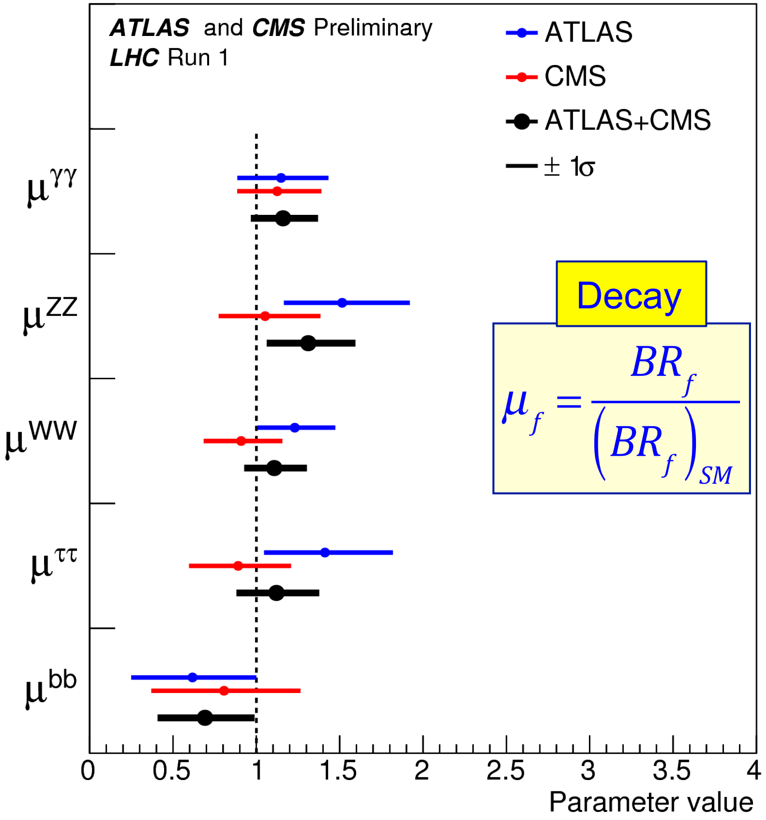
Comparison with SM expectations

Measure the ratio between observed rate and SM Higgs boson expectation



Production

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$$



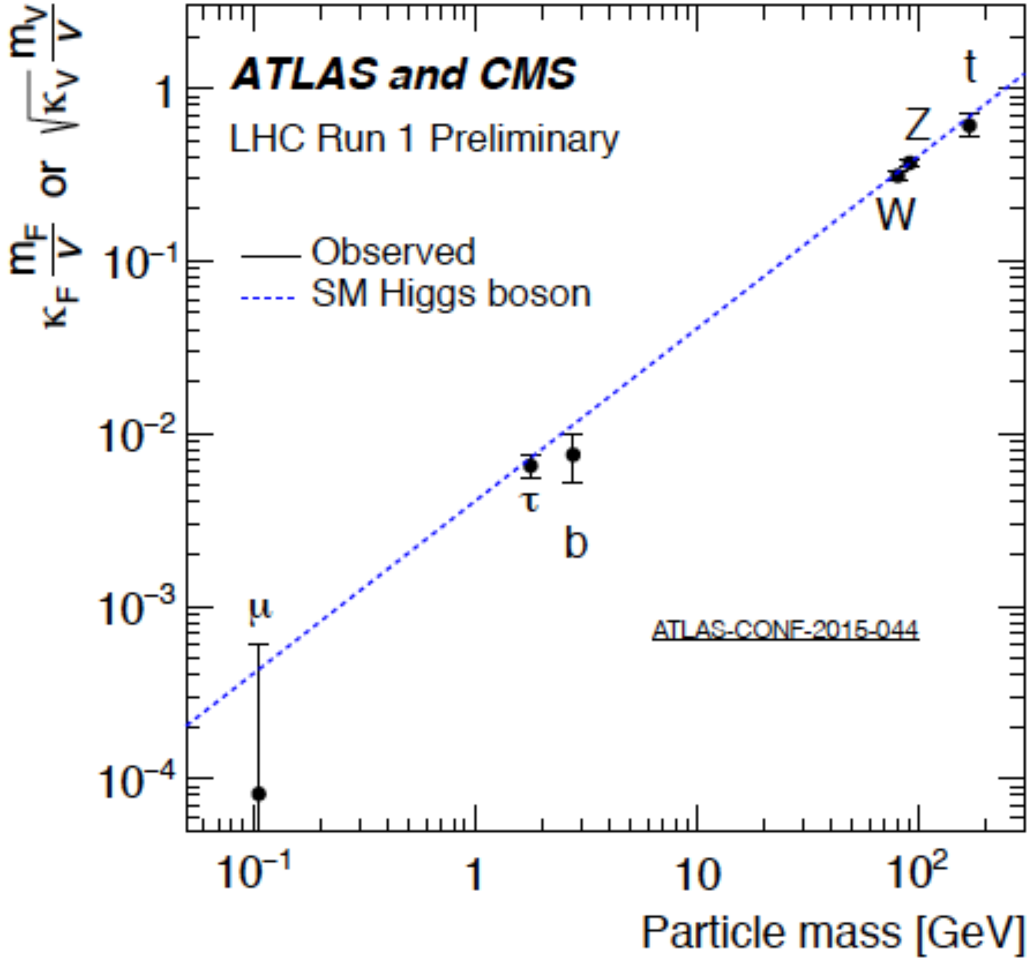
Decay

$$\mu_f = \frac{BR_f}{(BR_f)_{SM}}$$

(μ on production modes have been combined assuming SM BR for the decay)

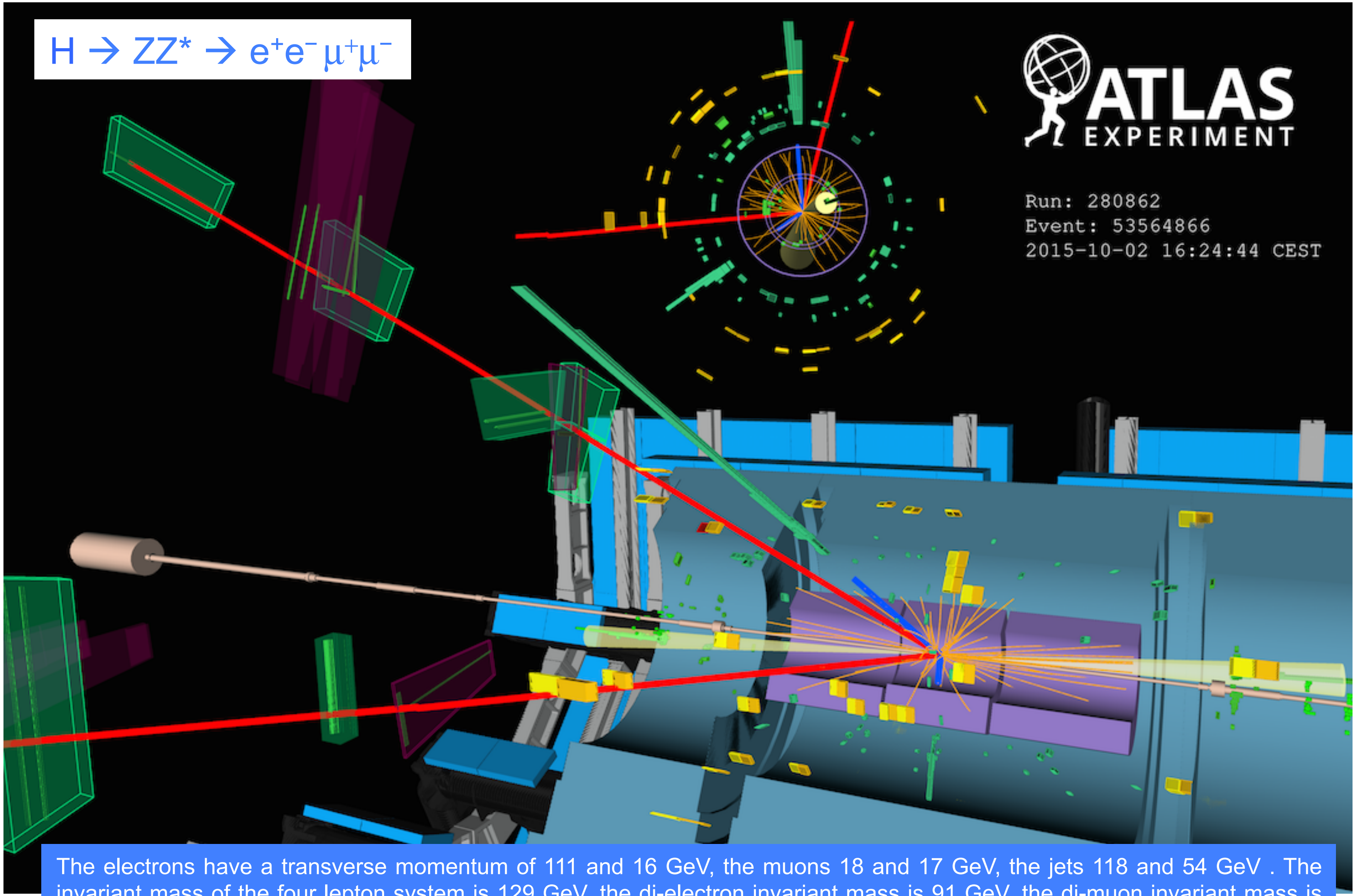
Results are SM like (all $\mu_s \sim 1$)

Higgs Boson Couplings



Coupling strengths scale with mass just as predicted by the SM

First look at 13 TeV data for H(125)

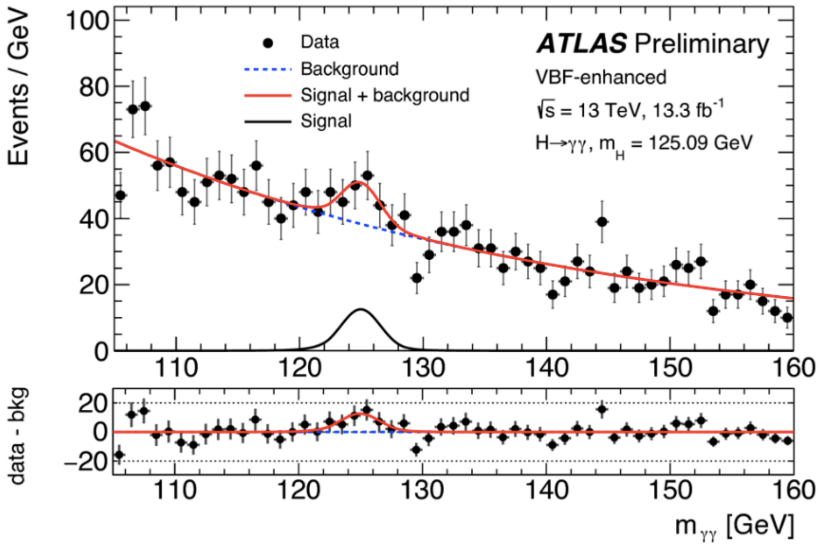


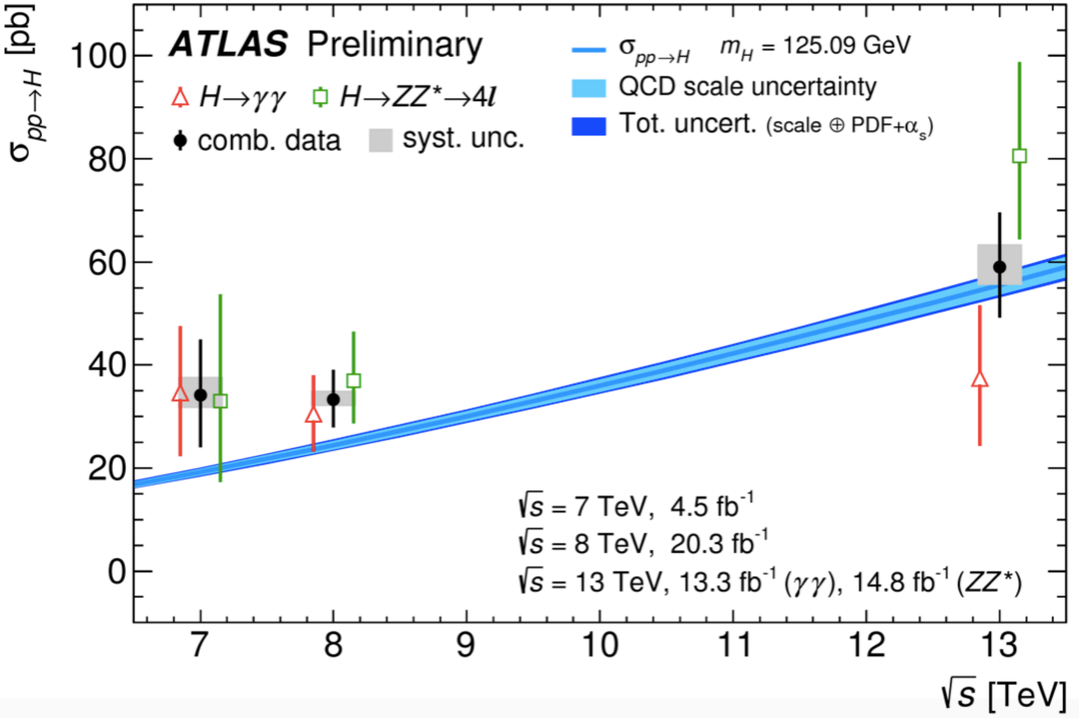
$H \rightarrow ZZ^{*} \rightarrow e^{+}e^{-}\mu^{+}\mu^{-}$

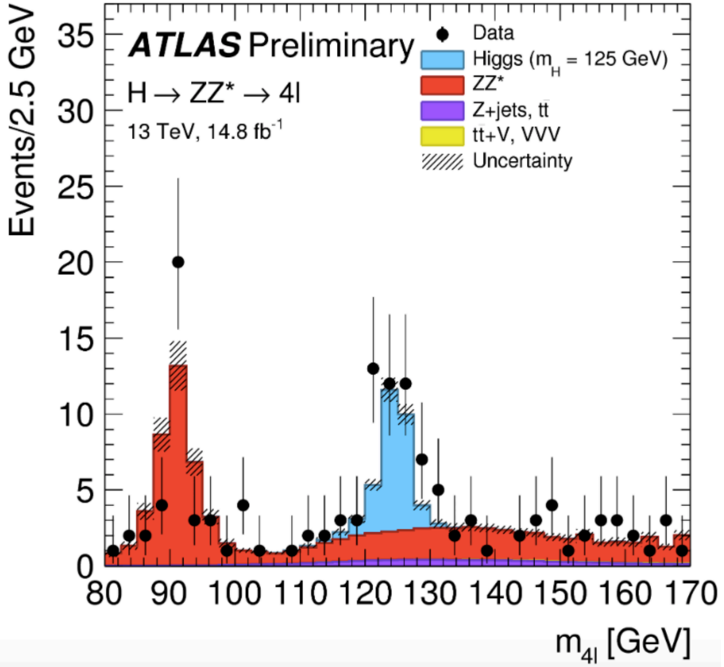
The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, the jets 118 and 54 GeV . The invariant mass of the four lepton system is 129 GeV, the di-electron invariant mass is 91 GeV, the di-muon invariant mass is 29 GeV, The di-jet invariant mass is 2 TeV.

First look at 13 TeV data for H(125)

The Higgs signal is "still" present in the 13 TeV data.







A brief introduction to SuperSymmetry

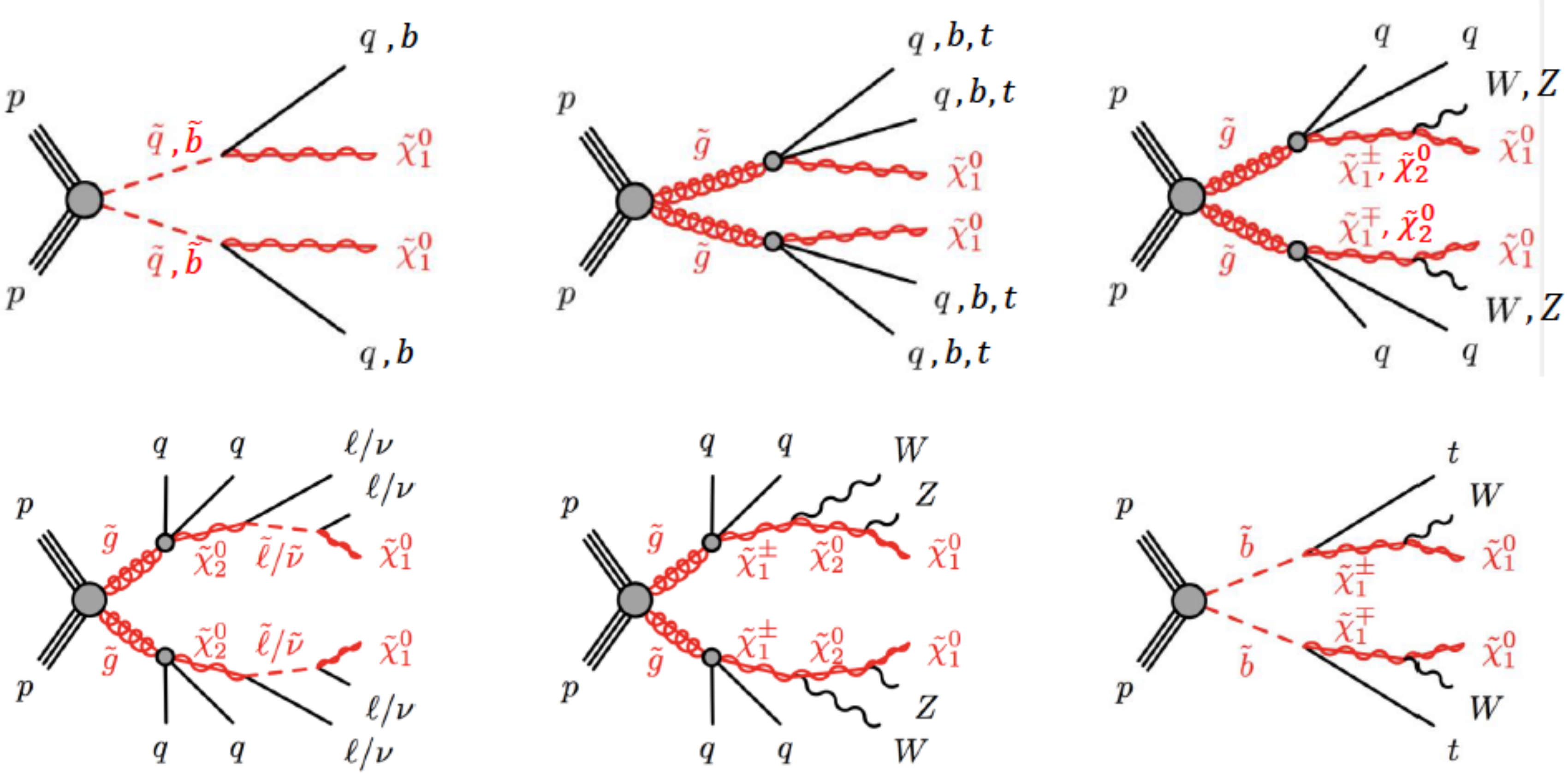
- **SuSy is a generalization of the SM: symmetry between fermions and bosons**
  - Introduces sfermions and gauginos
    → doubles particles content with respect to SM
  - Extended Higgs sector: h, H, A, H^+, H^-
- PRO:
  - Alleviates hierarchy problem ($m_h << m_P$)
  - has a good Dark Matter candidate (neutralino)
  - Allows for gauge coupling unification
- CONS:
  - Over 100 free parameters (although with some ad hoc assumptions we can reduce the number of parameters)
  - wide range of possible experimental signatures

It was expected ''something'' at the TeV scale

1/3

Search for susy particles

a few diagrams with susy particles in the final state, with the decay chain

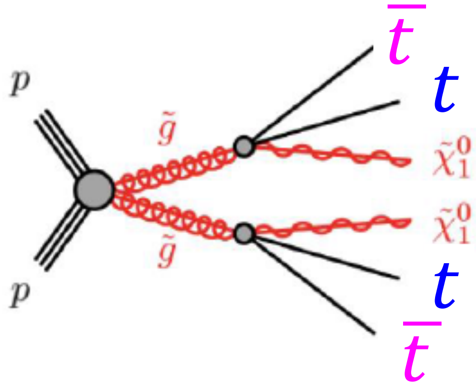


- **Lightest susy particle ($\tilde{\chi}_1^0$) escapes detection → Missing Transverse Momentum and Missing Energy**

- **Different analysis strategies according to many different final states**

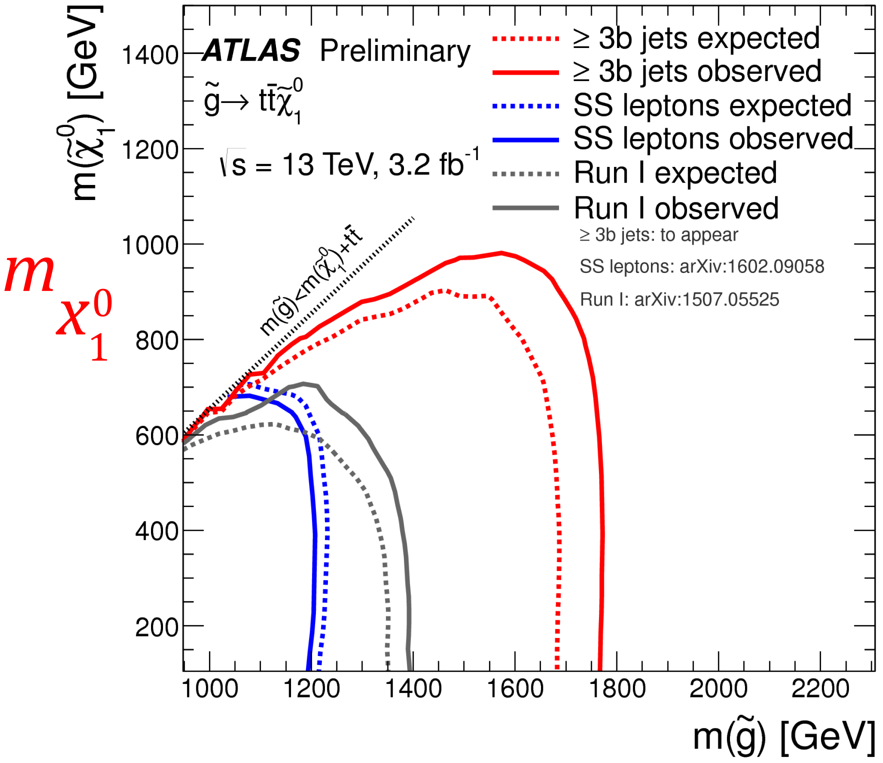
1/3

example: gaugino and neutralino mass limits



No signal has been found (yet)!

exclusion plot



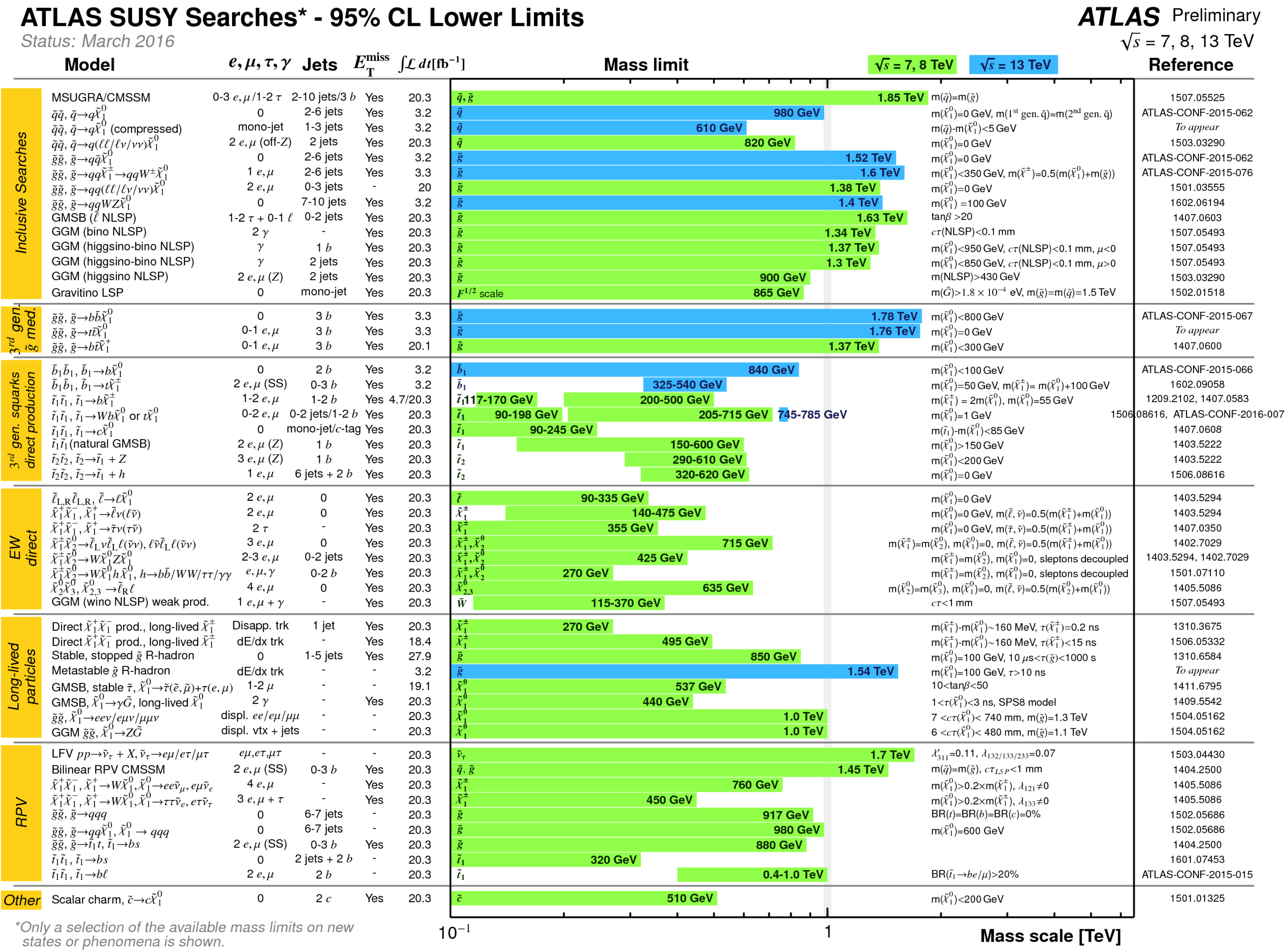
From other susy searches many exclusions limits on the parameters phase space

now there is less and less room to “manouver”.

Particles masses higher and higher; cross-sections lower and lower

1/3

ATLAS susy particles: Run2 results



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

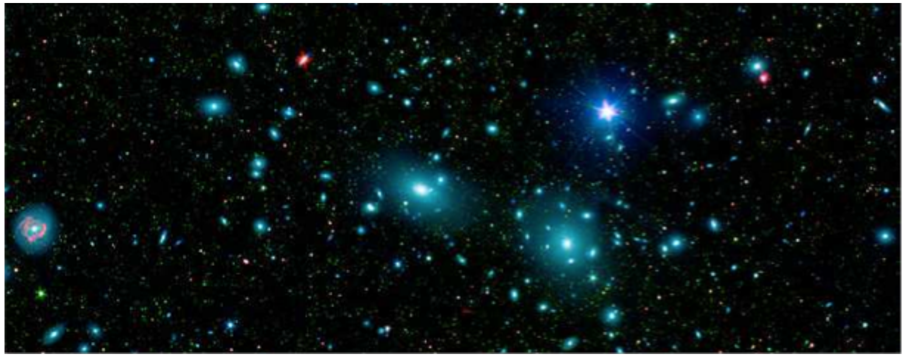
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV   🟦 $\sqrt{s}$ = 13 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$	🟩 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	$\tilde{q}$	🟦 980 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2015-062
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$	🟦 610 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<5 GeV	*To appear*
	$\tilde{q}\tilde{q}$, $\tilde{q}\rightarrow q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$	🟩 820 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	$\tilde{g}$	🟦 1.52 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2015-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^{\pm}\rightarrow qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	2-6 jets	Yes	3.3	$\tilde{g}$	🟦 1.6 TeV	m($\tilde{\chi}_1^0$)<350 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2015-076
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	🟩 1.38 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqWZ\tilde{\chi}_1^0$	0	7-10 jets	Yes	3.2	$\tilde{g}$	🟦 1.4 TeV	m($\tilde{\chi}_1^0$) =100 GeV	1602.06194
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	🟩 1.63 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	🟩 1.34 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}_1^0$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	🟩 1.3 TeV	m($\tilde{\chi}_1^0$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	🟩 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	🟩 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	3.3	$\tilde{g}$	🟦 1.78 TeV	m($\tilde{\chi}_1^0$)<800 GeV	ATLAS-CONF-2015-067
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	3.3	$\tilde{g}$	🟦 1.76 TeV	m($\tilde{\chi}_1^0$)=0 GeV	*To appear*
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	🟩 1.37 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$	🟦 840 GeV	m($\tilde{\chi}_1^0$)<100 GeV	ATLAS-CONF-2015-066
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\rightarrow t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	3.2	$\tilde{b}_1$	🟦 325-540 GeV	m($\tilde{\chi}_1^0$)=50 GeV, m($\tilde{\chi}_1^{\pm}$)= m($\tilde{\chi}_1^0$)+100 GeV	1602.09058
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	🟩 117-170 GeV 🟩 200-500 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	🟩 90-198 GeV 🟩 205-715 GeV 🟦 745-785 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616, ATLAS-CONF-2016-007
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	🟩 90-245 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	🟩 150-600 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	🟩 290-610 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\rightarrow\tilde{t}_1+h$	1 e,μ	6 jets + 2 b	Yes	20.3	$\tilde{t}_2$	🟩 320-620 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\rightarrow\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	🟩 90-335 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	🟩 140-475 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	🟩 355 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^0$	🟩 715 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^0$	🟩 425 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\rightarrow W\tilde{\chi}_1^0h\tilde{\chi}_1^0$, $h\rightarrow b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^0$	🟩 270 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\rightarrow\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	🟩 635 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$	🟩 115-370 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	🟩 270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	🟩 495 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	🟩 850 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	$\tilde{g}$	🟦 1.54 TeV	m($\tilde{\chi}_1^0$)=100 GeV, τ>10 ns	*To appear*
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\rightarrow\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\rightarrow\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	🟩 440 GeV	1<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\rightarrow ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\rightarrow Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	🟩 1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\rightarrow\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\rightarrow e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	🟩 1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}$, $\tilde{g}$	🟩 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	🟩 760 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\rightarrow W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	🟩 450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	🟩 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	🟩 980 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow\tilde{t}_1t$, $\tilde{t}_1\rightarrow bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	🟩 880 GeV		1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$	🟩 320 GeV		1601.07453
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\rightarrow b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	🟩 0.4-1.0 TeV	BR($\tilde{t}_1\rightarrow be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\rightarrow c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	🟩 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

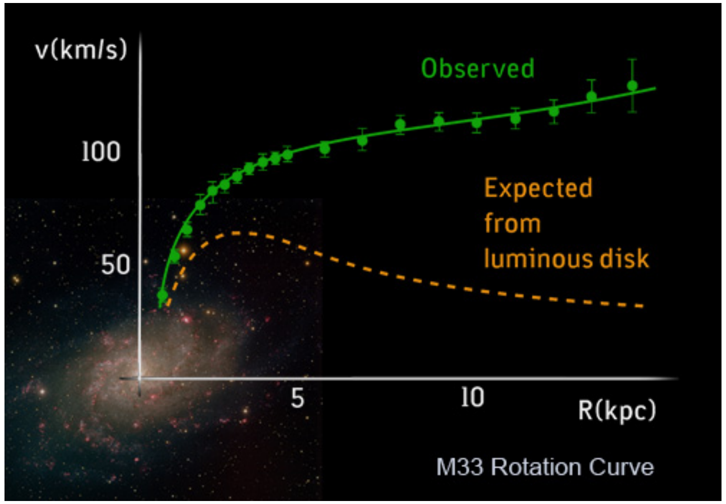
*Only a selection of the available mass limits on new states or phenomena is shown.

Evidence for Dark Matter



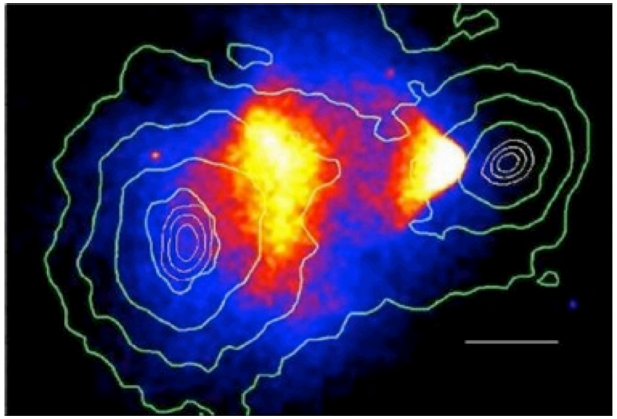
*Comprises **majority** of **mass** in Galaxies*

Missing mass on Galaxy Cluster scale Zwicky (1937)



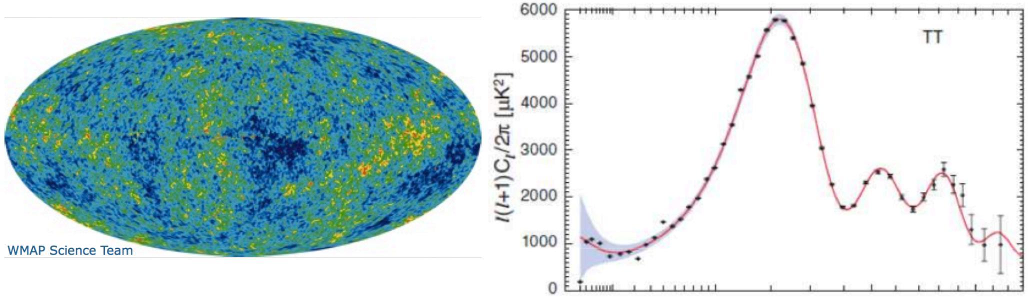
*Large **halos** around Galaxies*

Rotation Curves Rubin+(1980)



*Almost **collisionless***

Bullet Cluster Clowe+(2006)



WMAP Science Team

Non-Baryonic Big-Bang Nucleosynthesis,

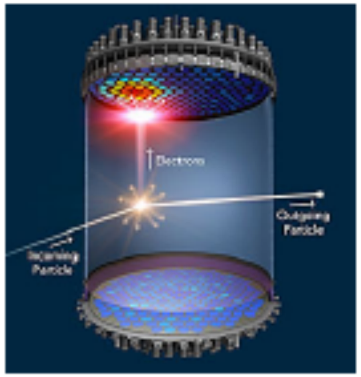
CMB Acoustic Oscillations

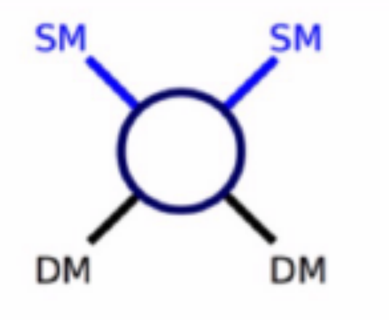
WMAP(2010),*Planck*(2015)

Detecting Dark Matter

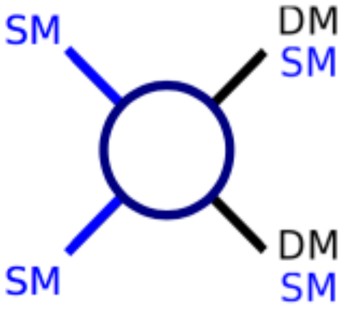
Assumption: non-gravitational interaction with ordinary matter

Indirect Detection



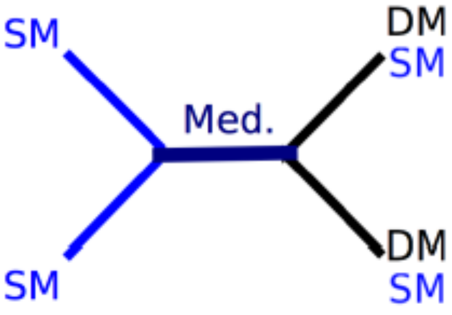


Direct Detection



Colliders
(Contact interaction)

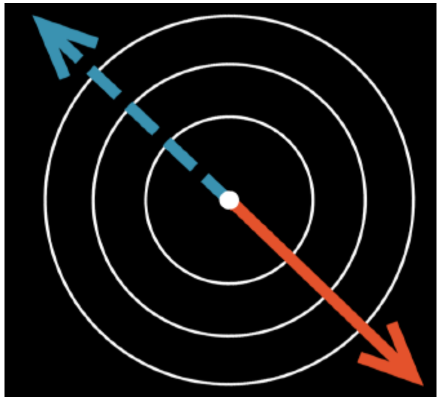
Contact interaction (EFT)
"works" if the scale $\Lambda >> Q^2$ (like Fermi theory).
otherwise we need a Simplified Model with (at least) a Mediator



Colliders
(Simplified Models)

Detecting Dark Matter at LHC

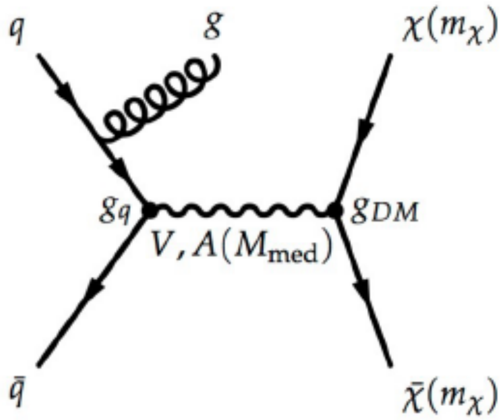
Non-interacting DM particles
→ Missing transverse energy (MET)



X (jet, photon, etc..)

General analysis strategy

- Require MET
- Select for X
- Veto other objects
- Additional cuts to suppress background
- Data-driven techniques to estimate background → invert vetoes



Results are interpreted in the Simplified Model framework to allow comparison with Direct Detection

- Mediator particle connects the SM quarks to DM particles:
  - Axial Vector, Pseudoscalar, etc…
- Model depends on four parameters:
  - DM mass, Mediator mass, SM-mediator coupling, DM-mediator coupling

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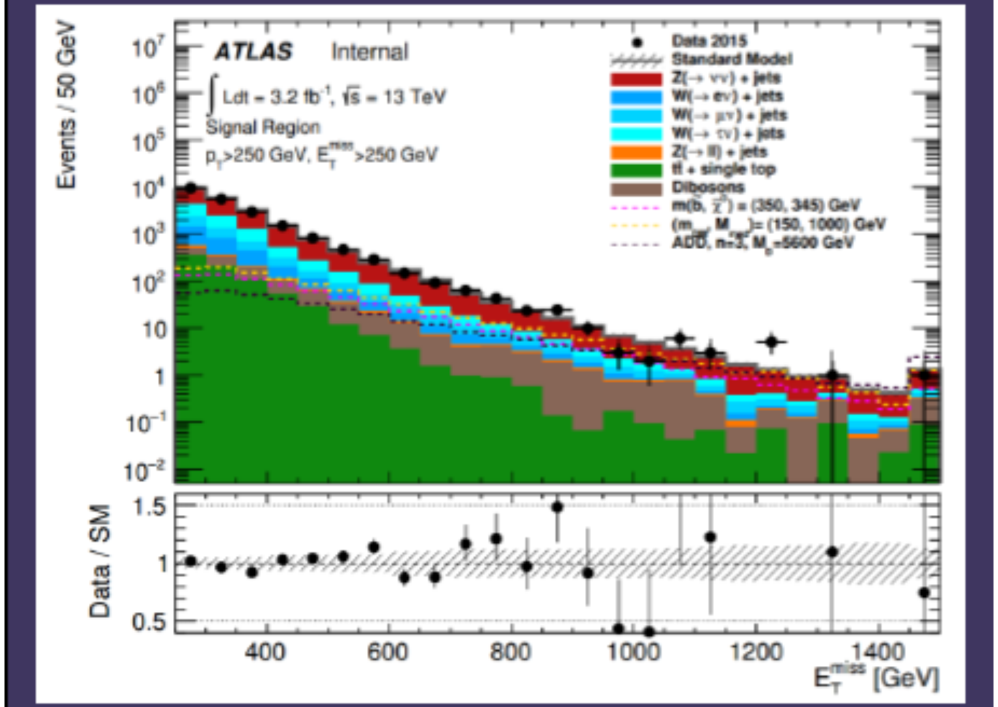
DM at ATLAS; one example: monojet

Backgrounds

- ☐ Main backgrounds are EW processes with intrinsic E_T^{miss} , accompanied by jets:
  - ➢ Z(νν)+jets: irreducible background
  - ➢ W(lν)+jets: with unrecostructed or misidentified lepton
- ☐ Both estimated from data using leptonic Z or W control regions
- ☐ **Other backgrounds:**
  - ➢ Non-collision background (data)
  - ➢ Multijet background (data)
  - ➢ Z→ee, top, diboson (MC)

Signal Region MET



↪ No excess observed

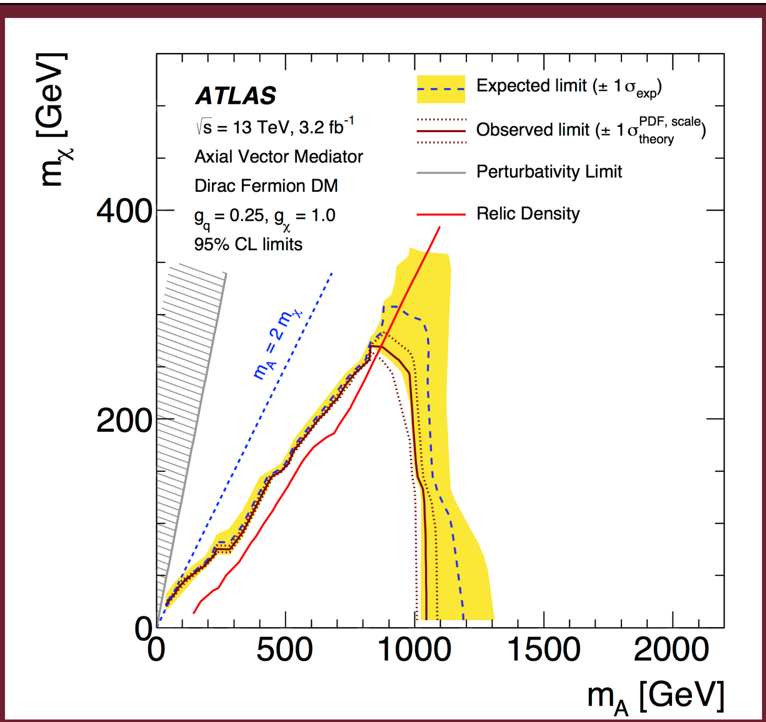
Dominant uncertainties:

Statistical (3-10%), top (~3%), boson+jet modeling (2-4%)

1/3

DM at ATLAS; one example: monojet

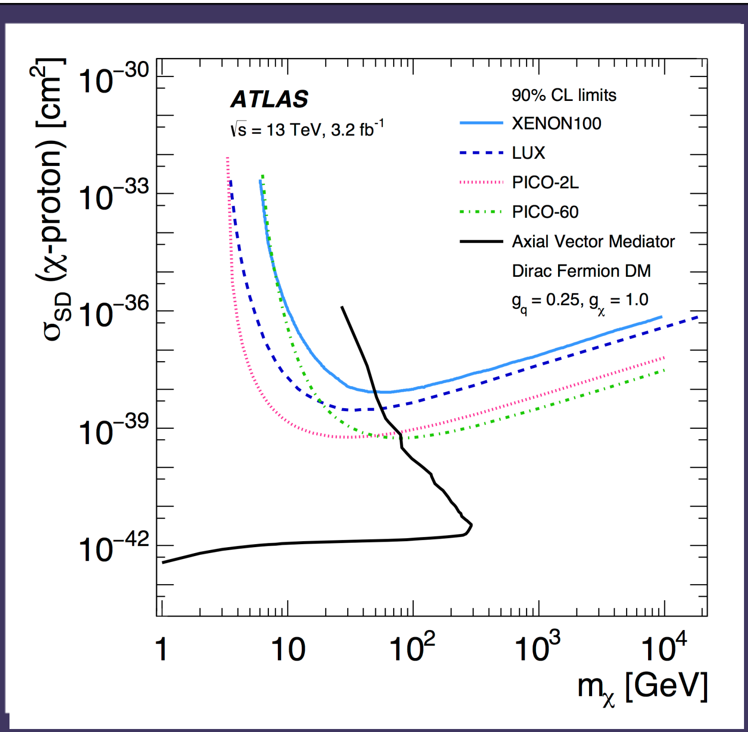
Results



Limits as a function of DM & mediator mass

➡ Axial vector mediator, fixed values of g_{DM} & g_{SM}

DM excluded up to 250GeV for 1 TeV mediator



LHC limits reinterpreted as limit on DM-proton scattering cross-section

➡ LHC complementary at low m_{DM}

Parameter values & limit interpretation as recommended by the LHC Dark Matter Working Group [ArXiv:1603.04156]

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End of chapter 13