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

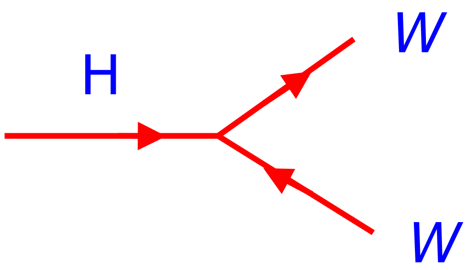
- Electroweak Lagrangian that is invariant for a local gauge transformation:

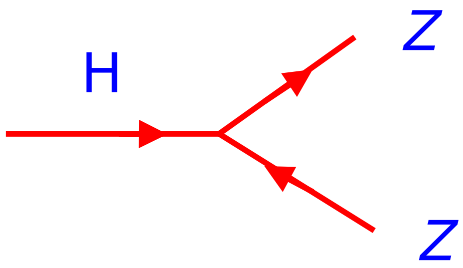
$$L = \bar{\Psi}_L \gamma^\mu \left[i\partial_\mu - g\vec{I} \cdot \vec{W}_\mu(x) - \frac{g'}{2} Y \cdot B_\mu \right] \Psi_L + \bar{\Psi}_R \gamma^\mu \left[i\partial_\mu - \frac{g'}{2} Y \cdot B_\mu \right] \Psi_R + L_{free}(\vec{W}, B)$$

- 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:





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

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

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

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

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

Higgs couplings with the fermions

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

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

and we get:

$$\mathcal{L} = -\frac{g_e v}{\sqrt{2}}\left[\bar{e}_R e_L + \bar{e}_L e_R\right] - \frac{g_e}{\sqrt{2}}\left[\bar{e}_R e_L + \bar{e}_L e_R\right] H$$

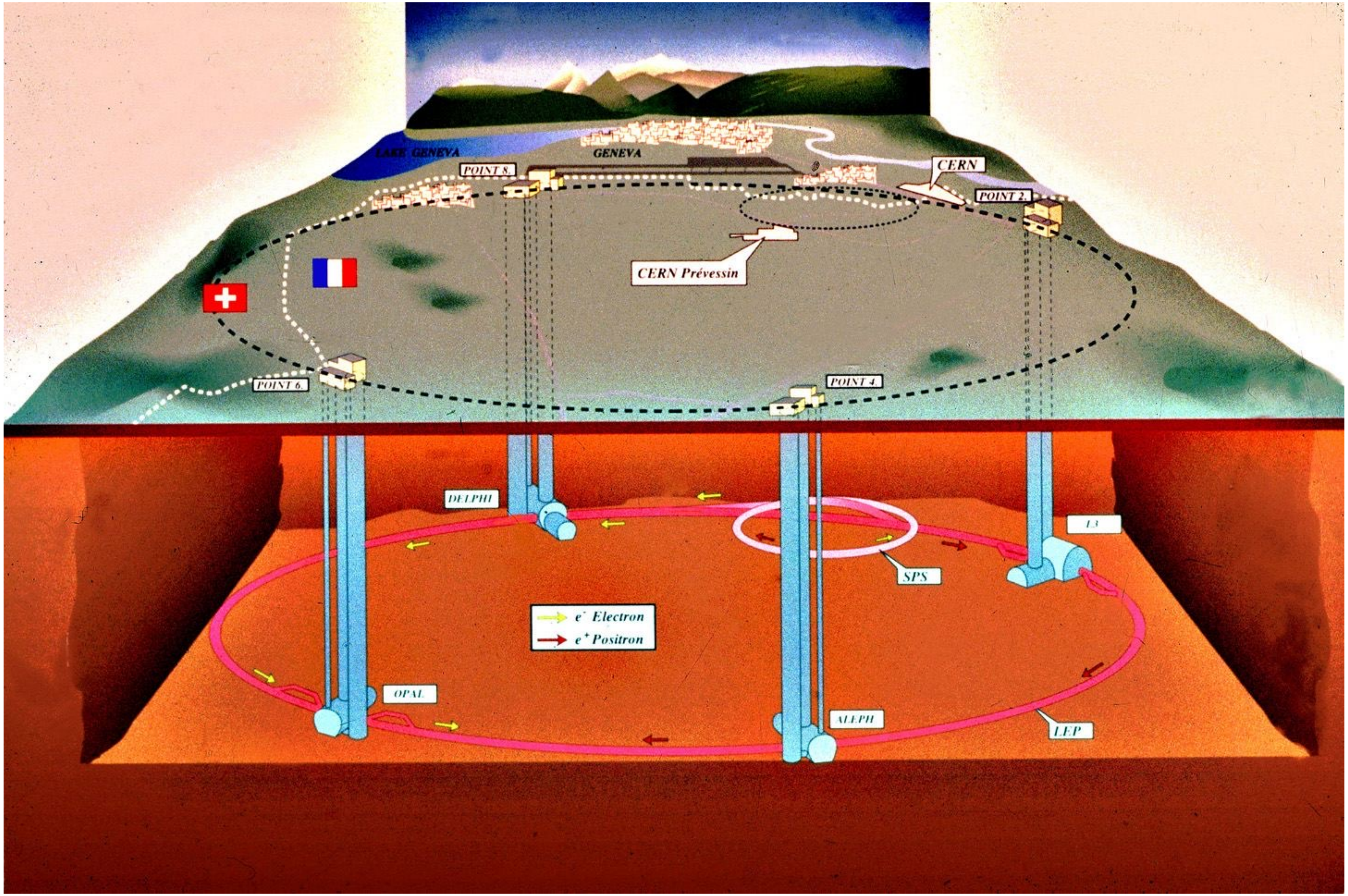
↑ Mass term ↑ Higgs coupling with the electron

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

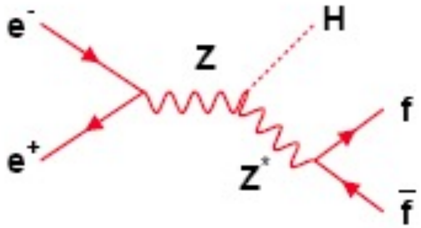
$$\Rightarrow \quad \mathcal{L} = -m_e \bar{e} e - \left(\frac{m_e}{v}\right) \bar{e} e H$$

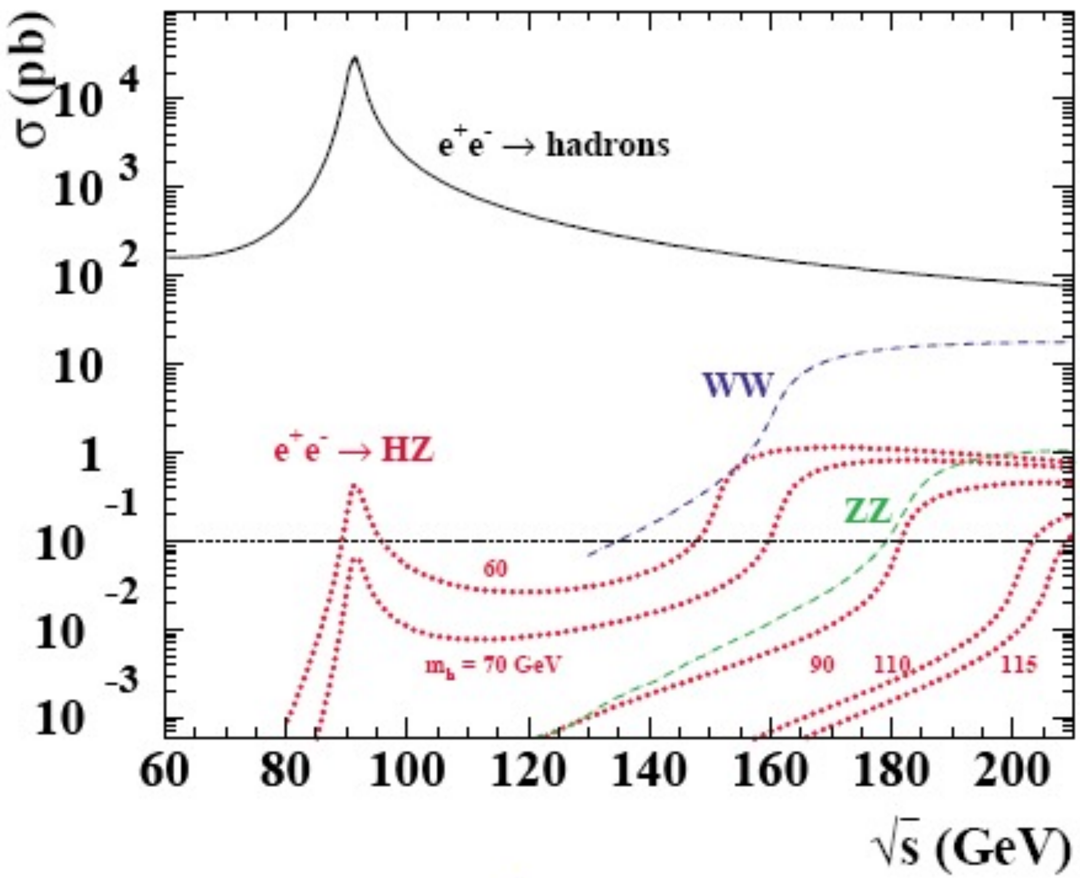
N.B. the coupling constant is proportional to the fermion mass

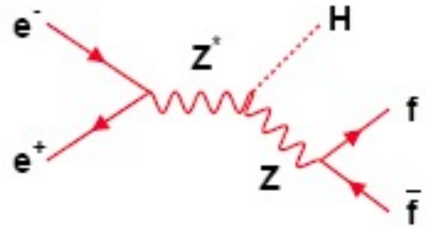
Higgs boson search at LEP



Higgs production cross-section at LEP





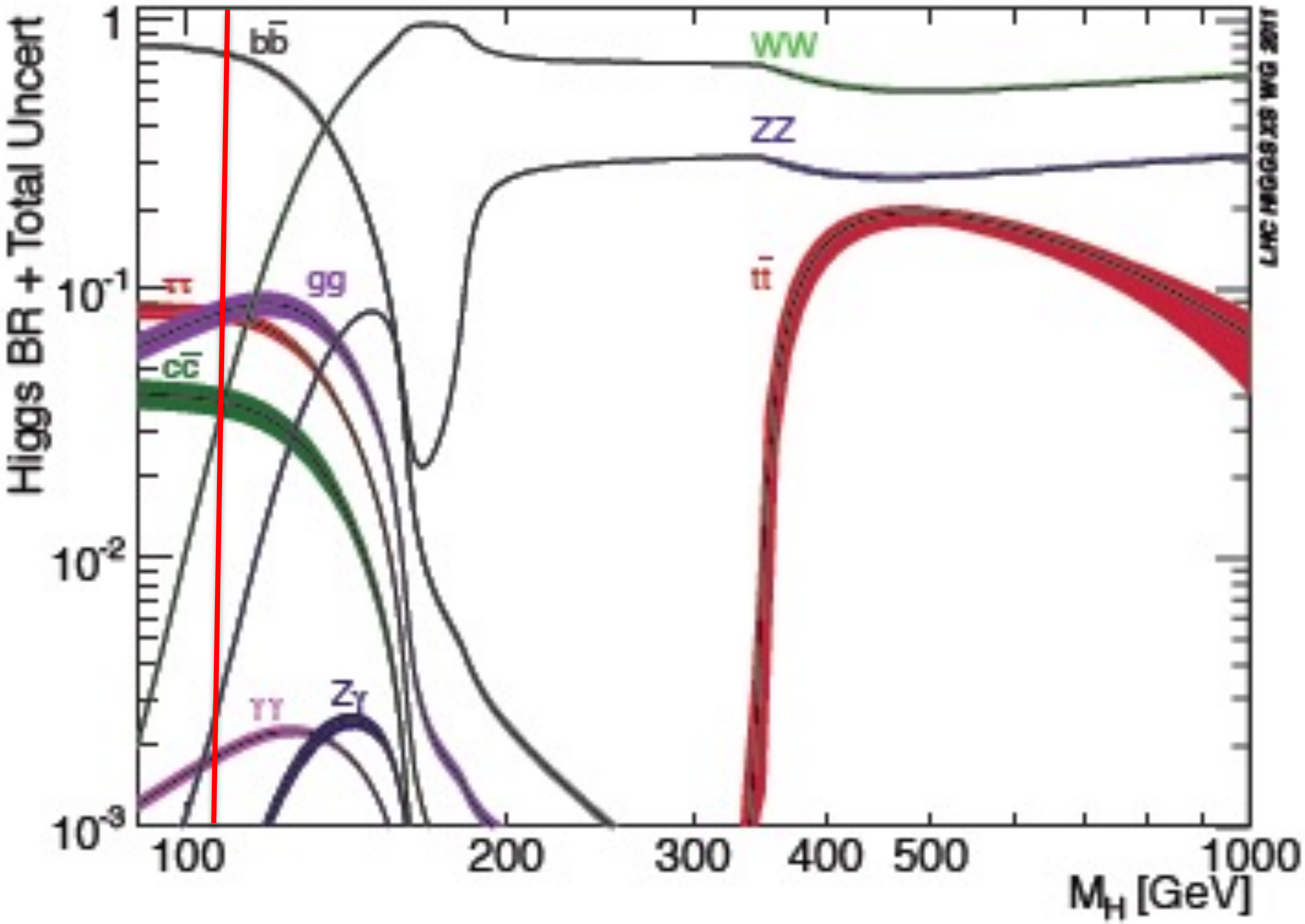


With a luminosity of about 100pb^{-1} and reasonable detection efficiency, sensitive to a cross section of $O(0.1)$ pb.

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

Must take into account many background processes

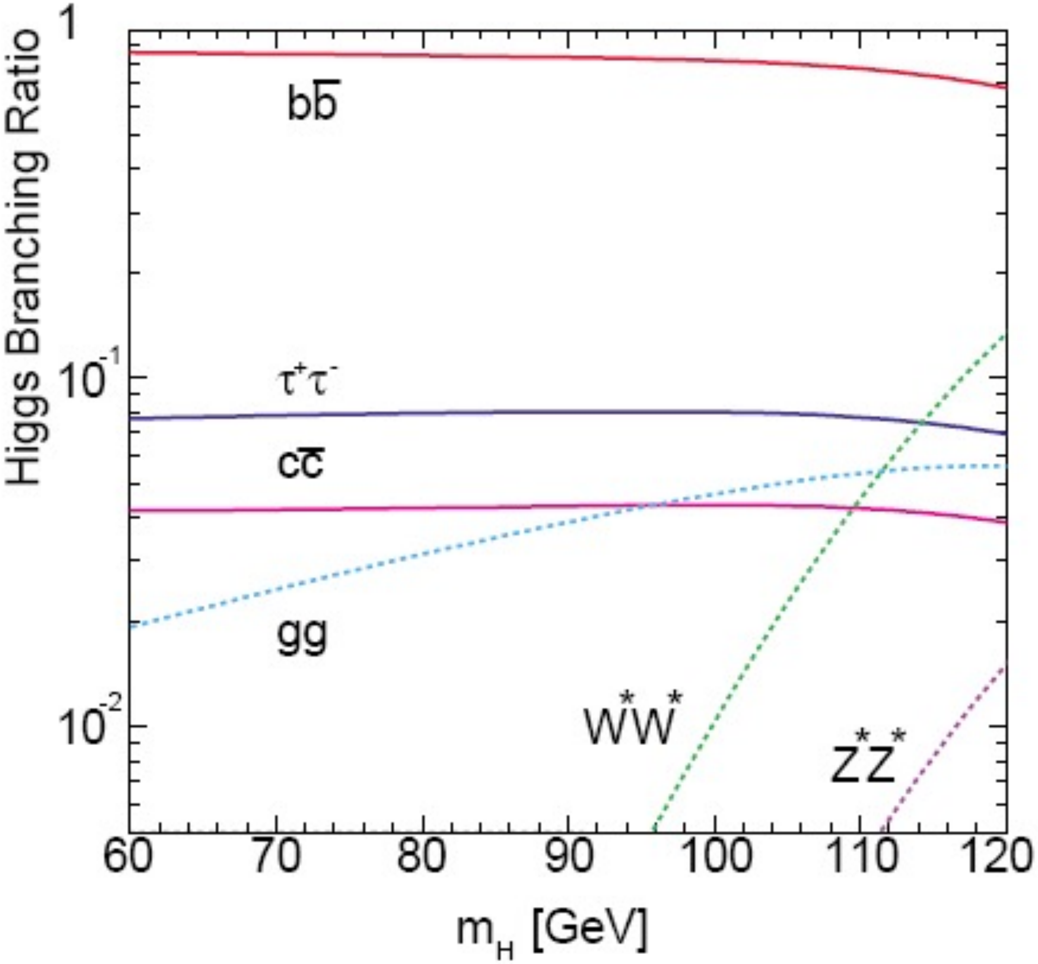
Higgs Branching Ratios



The dominant decay channel is H→bb up $M_H \approx 120$ GeV

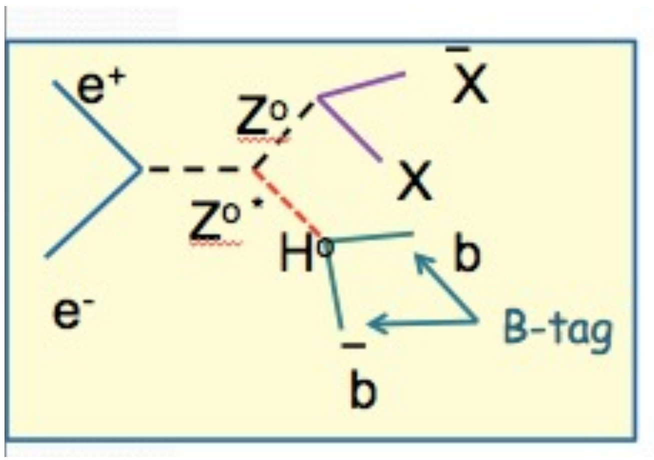
Higgs decays Branching Ratios

"Higgs couples to mass"



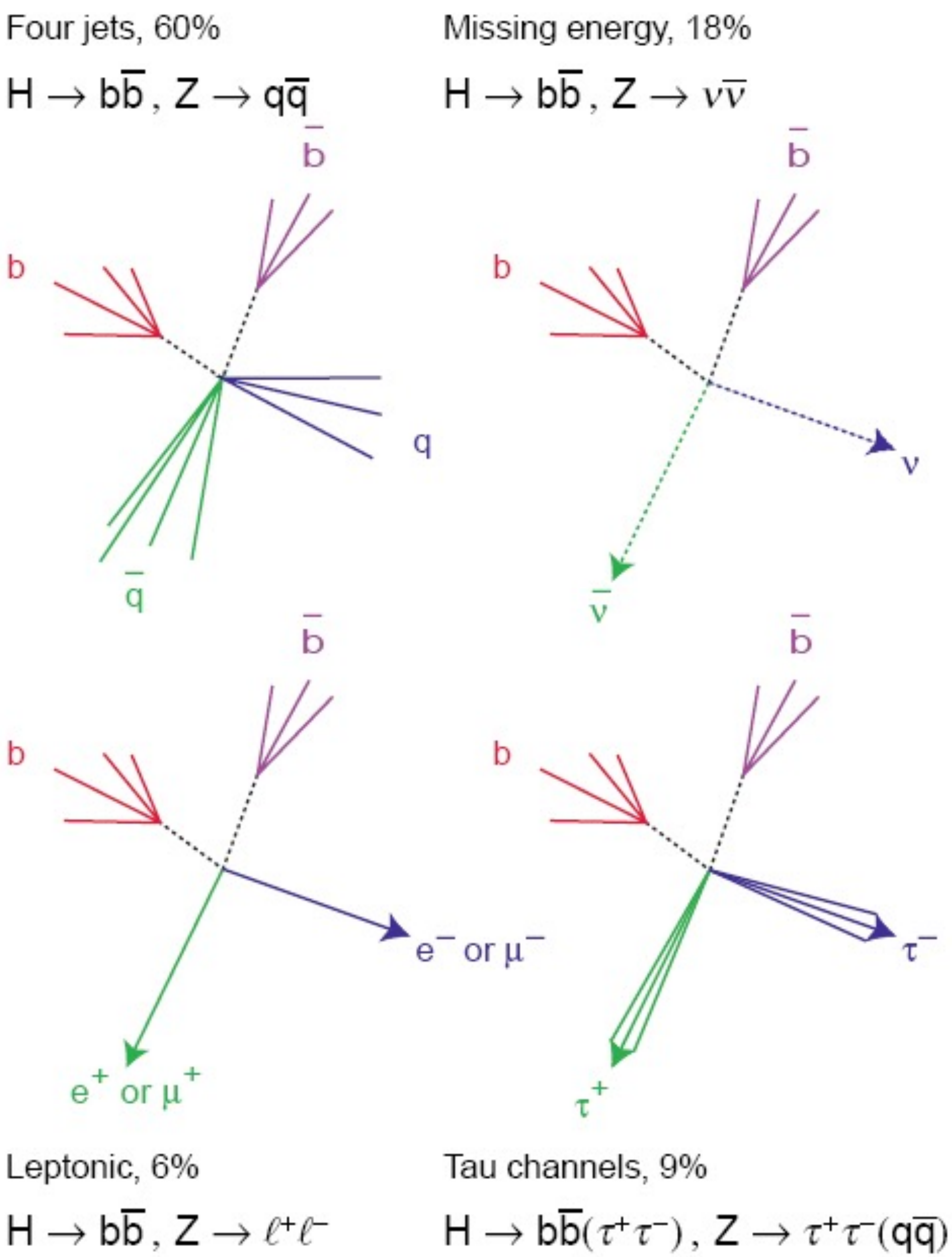
BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	

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



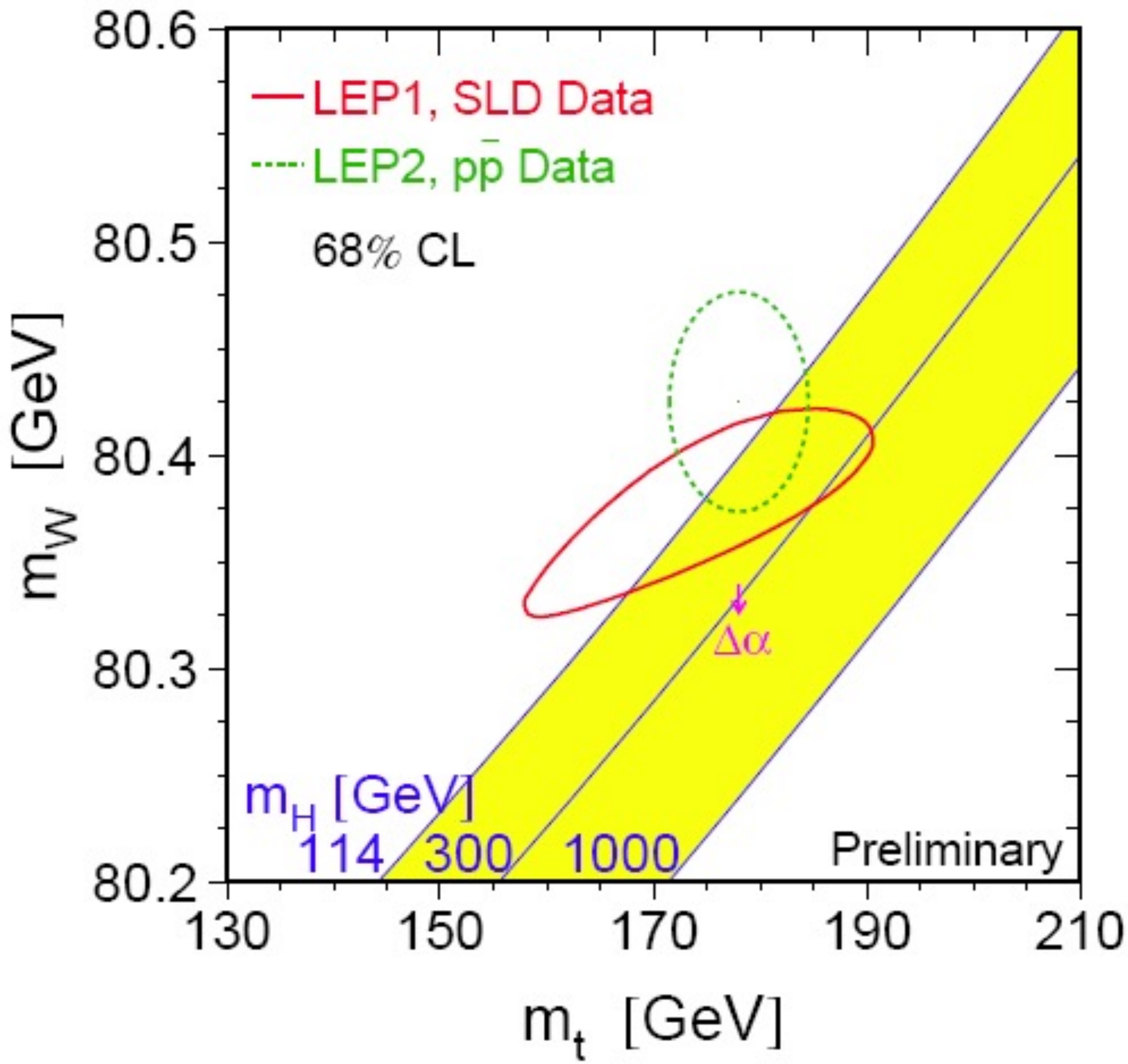
Global electroweak fit and Higgs mass

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

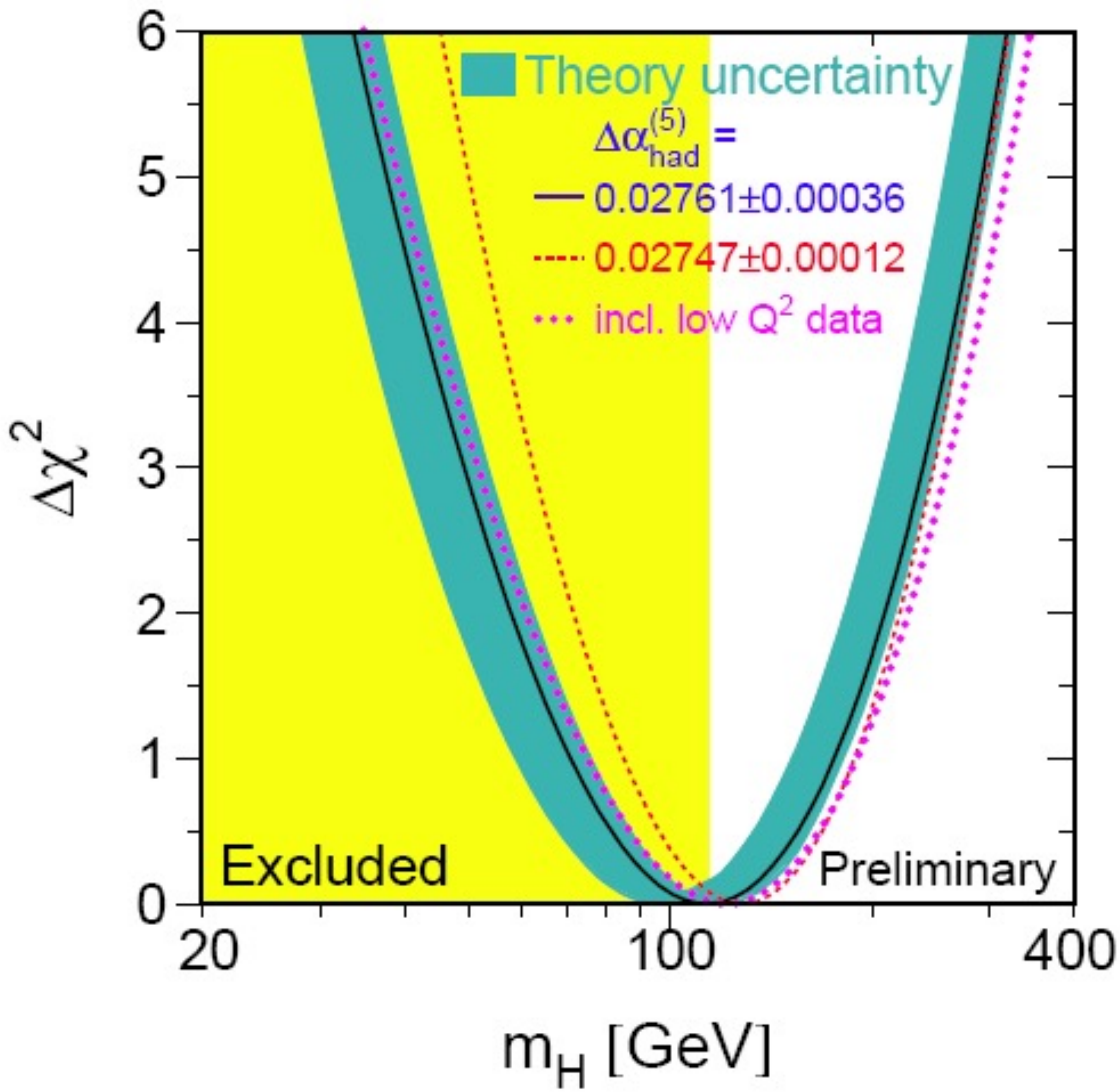
$m_H < 237$ GeV (95% CL)

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

$130 < m_H < 190$ GeV.

m_H higher - theory non-perturbative,

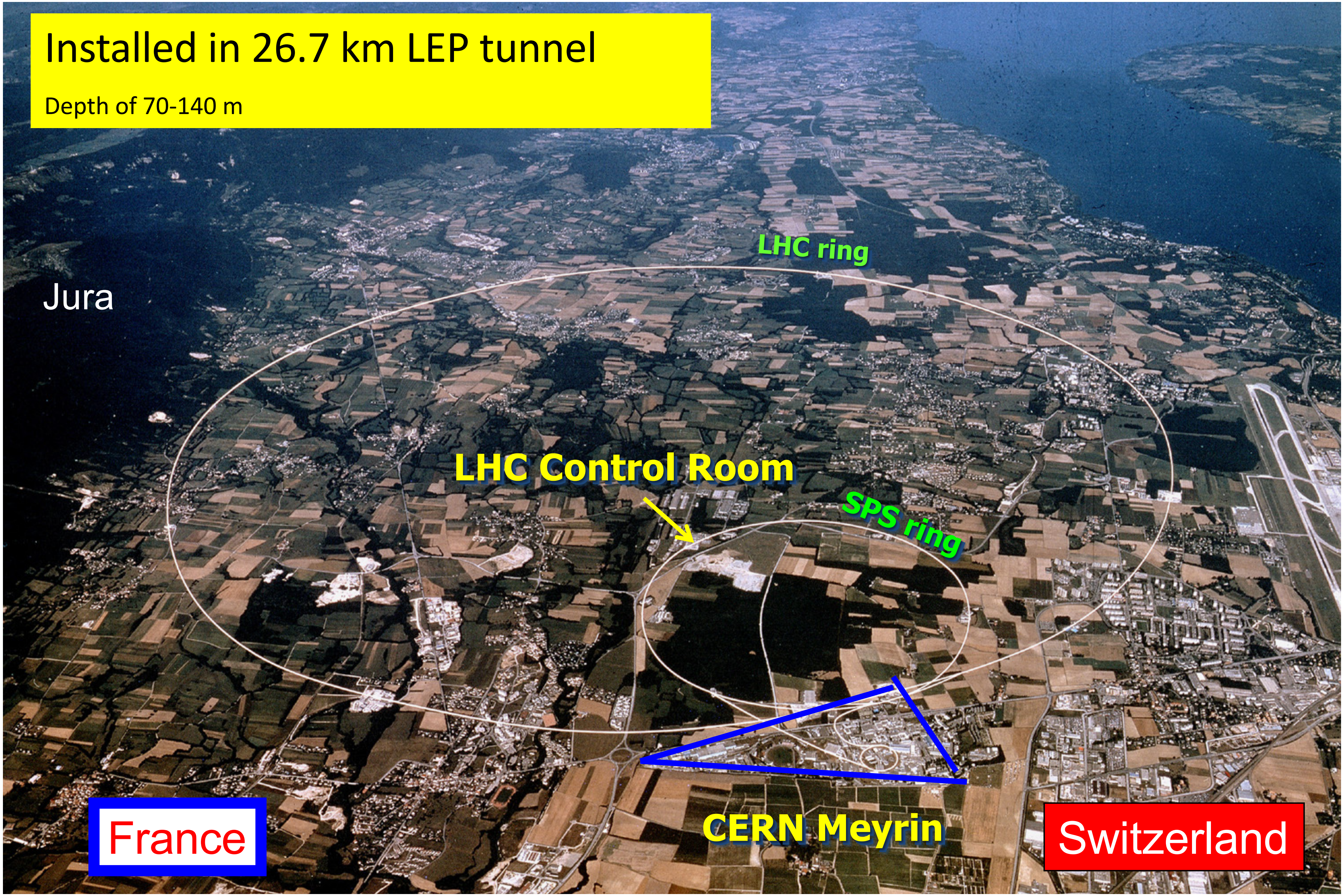
m_H lower - vacuum unstable.



The Large Hadron Collider LHC

Installed in 26.7 km LEP tunnel

Depth of 70-140 m



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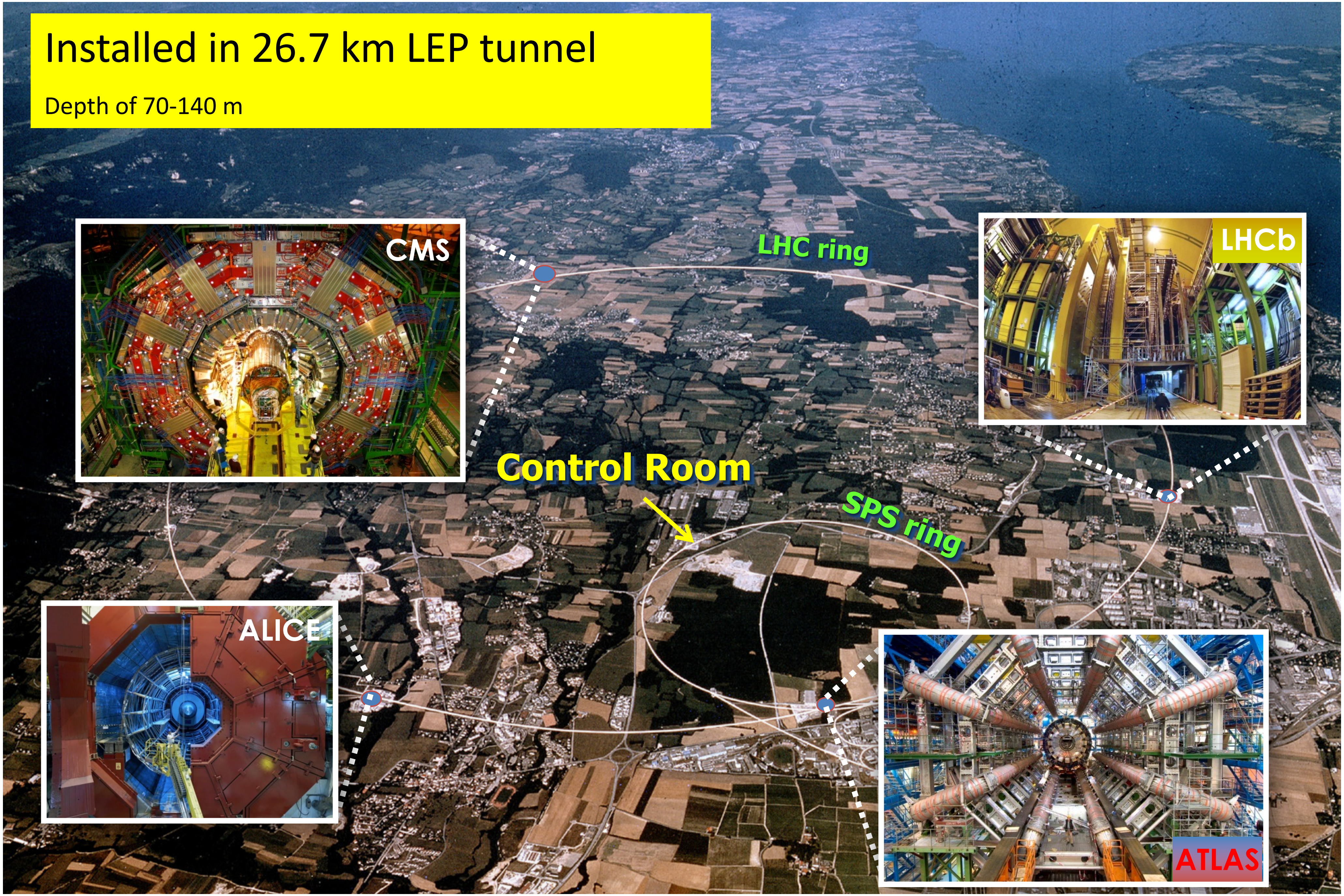
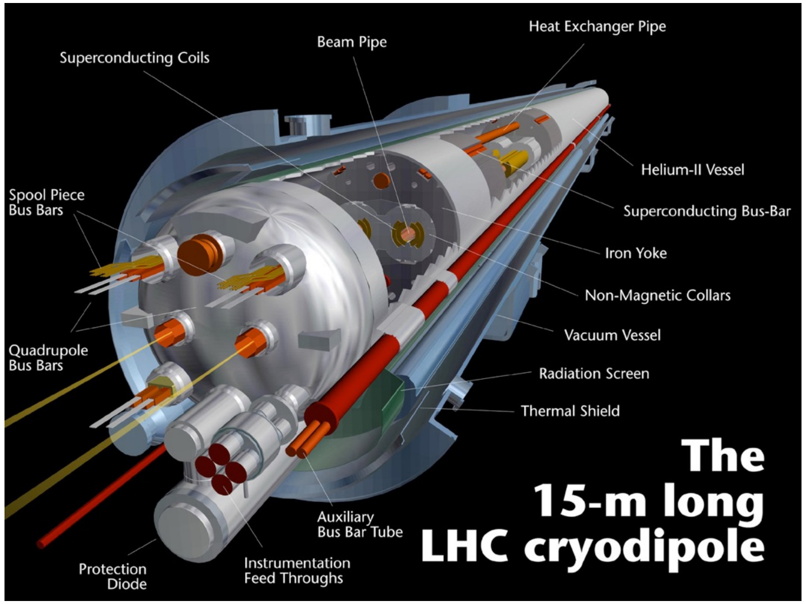


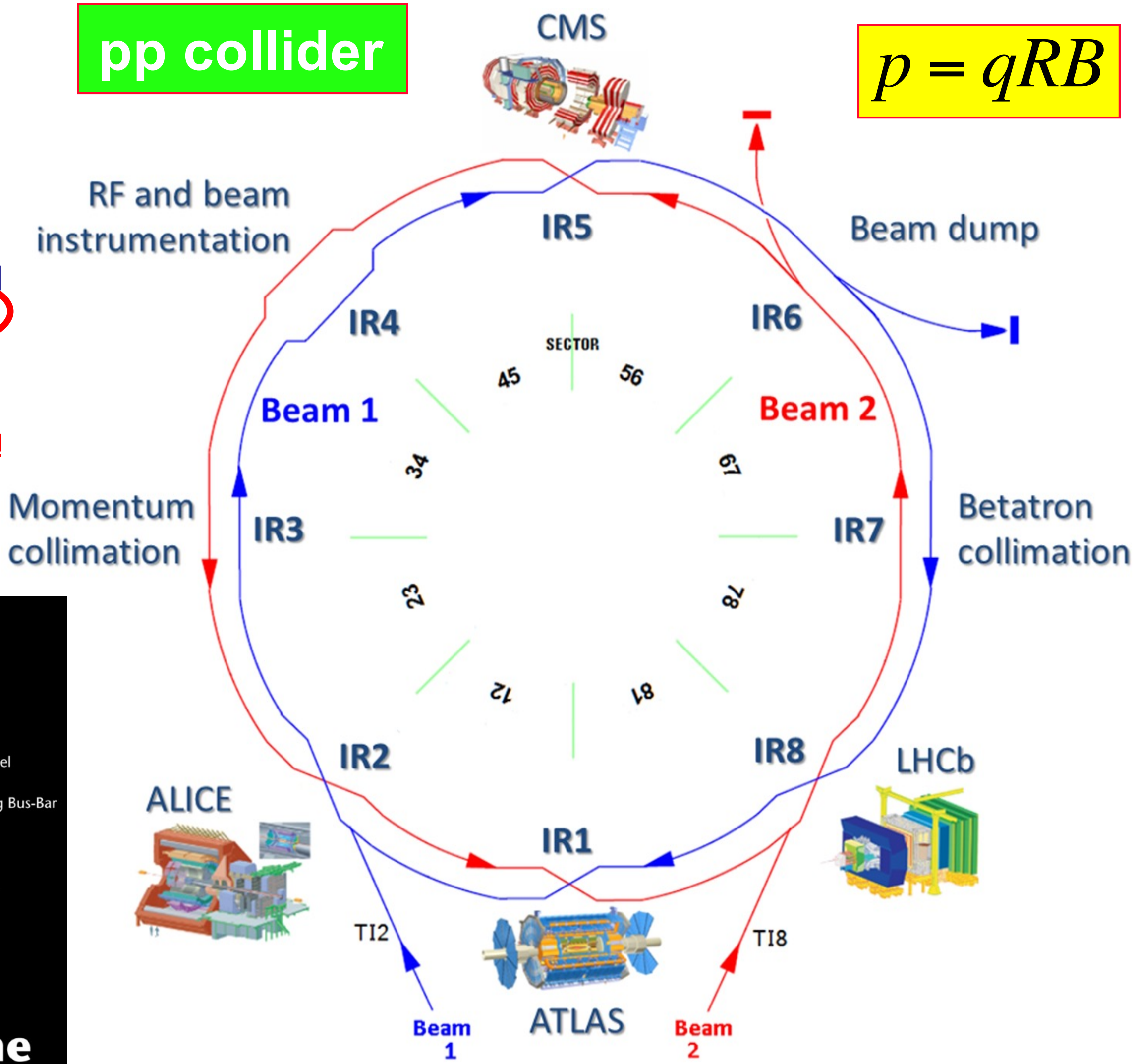
LHC ring layout

- 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**.

pp collider

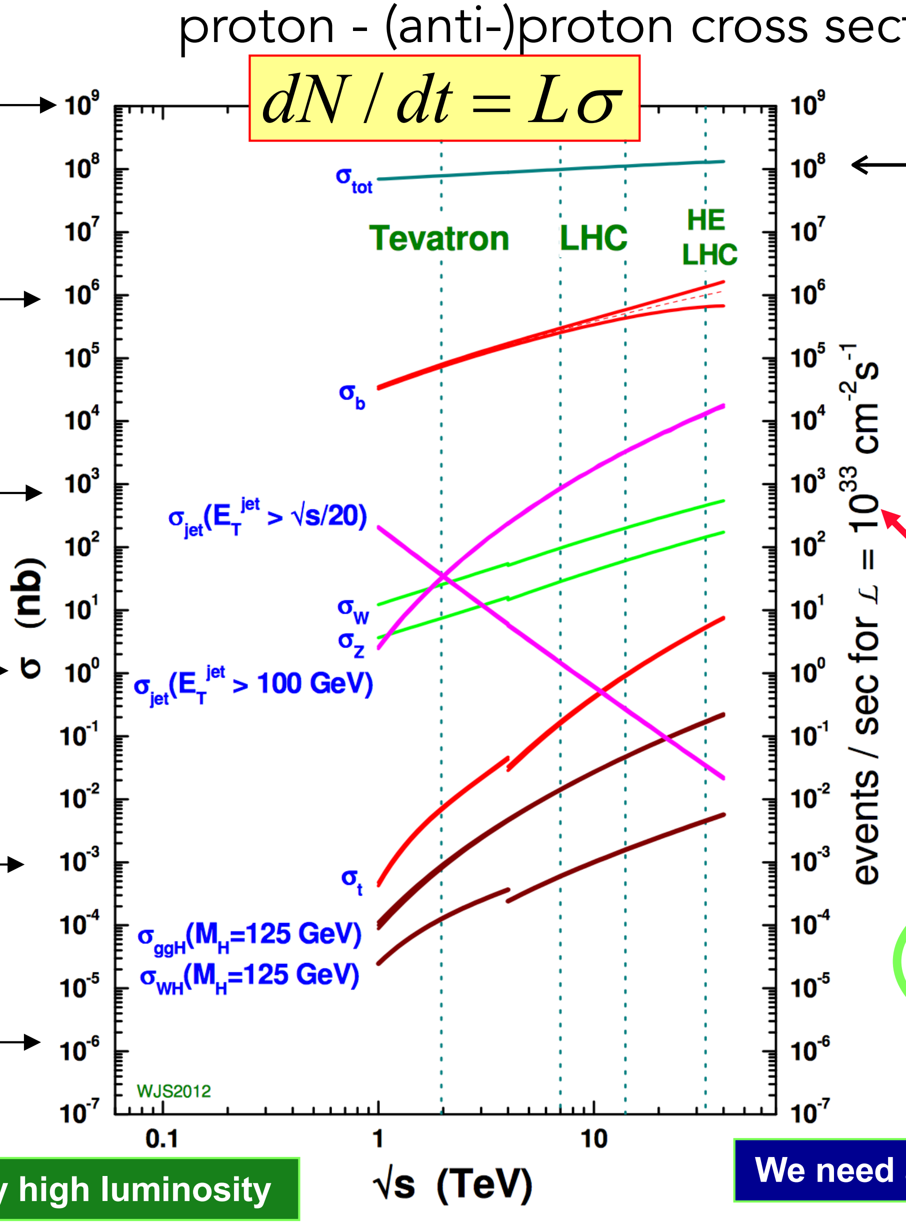
$p = qRB$





Design $\sqrt{s}$=14 TeV

Production cross-section at LHC



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

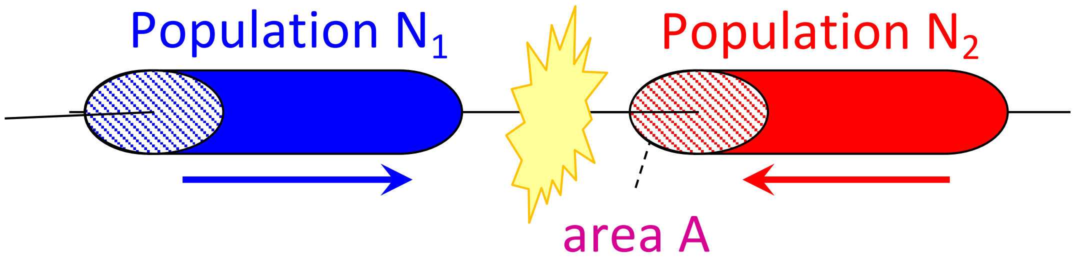
We need a very high background rejection capability

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)$^{-1}$



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

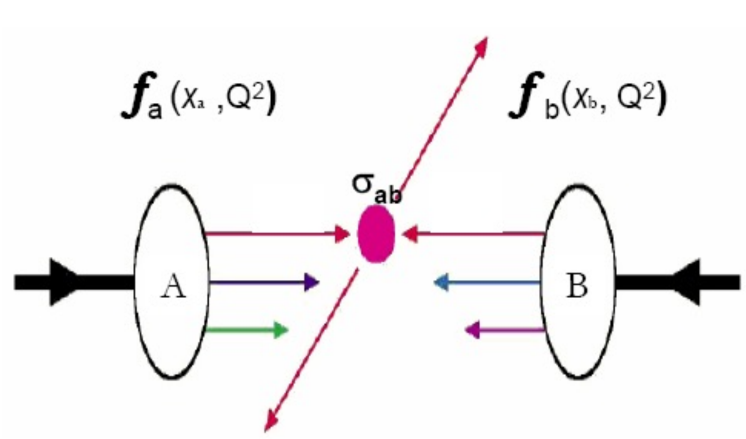
To maximize L we have to squeeze as many particles as possible into the smallest possible volume !

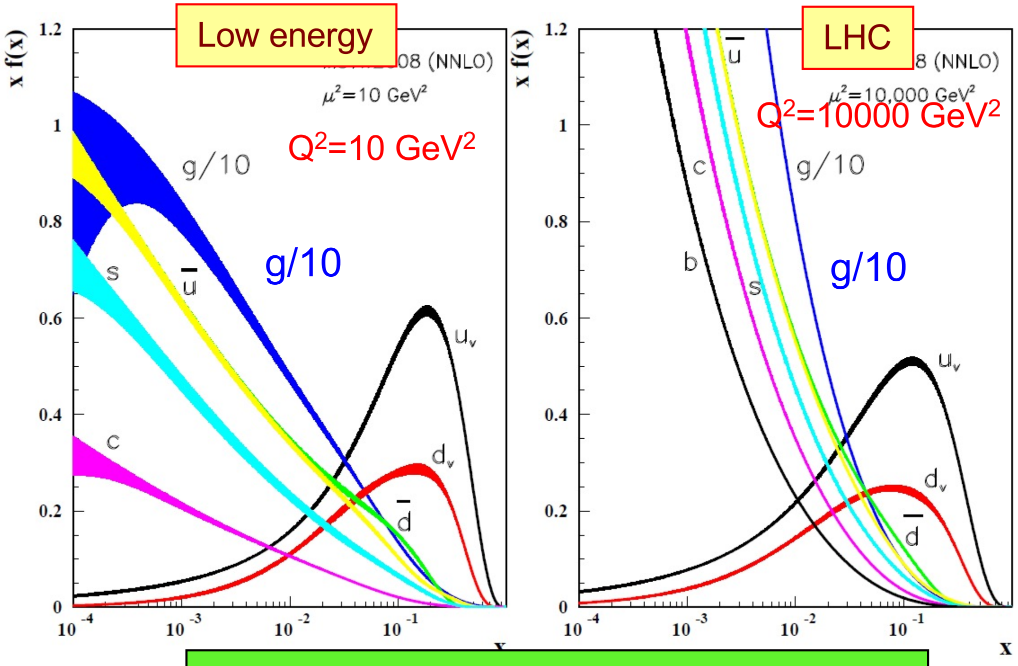
$$L = \frac{kN^2 f}{4\pi\sigma_x\sigma_y}$$

LHC Design

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

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

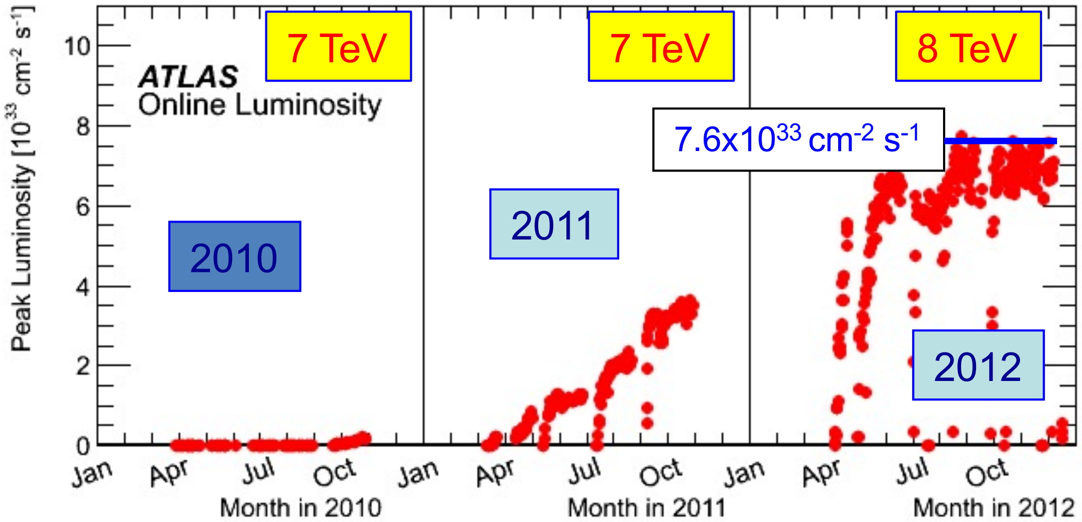
$$\sigma_X = \sum_{a,b} \int_0^1 dx_a dx_b\, f(x_a, flav_a, Q^2) f(x_b, flav_b, Q^2) \cdot \sigma_{ab \to X}(x_a, x_b, Q^2)$$

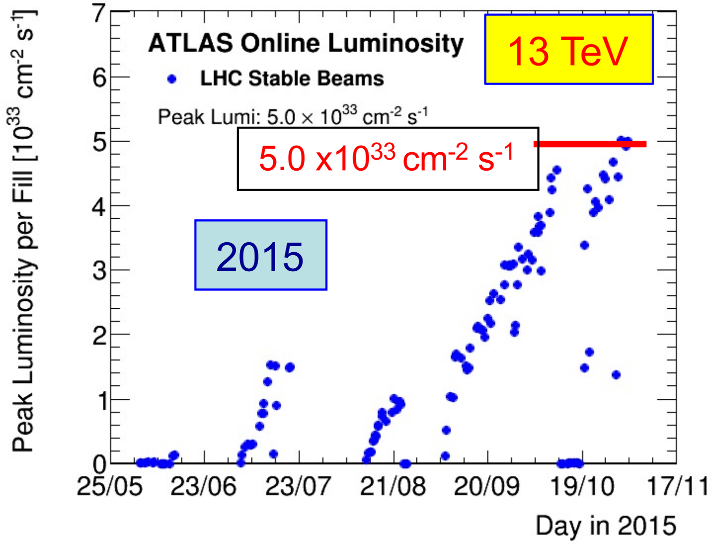
Sum over initial partonic states a,b

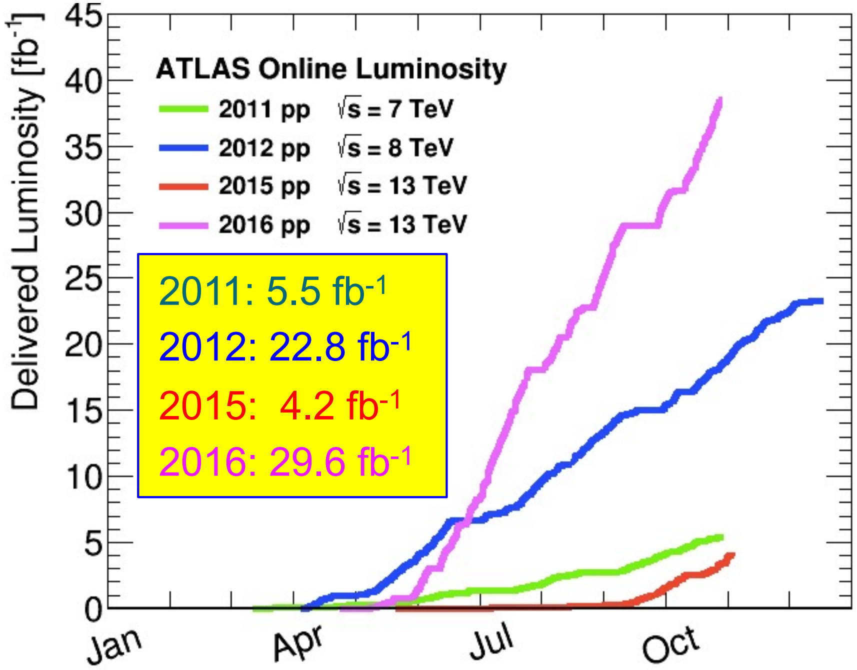
Parton Density Function

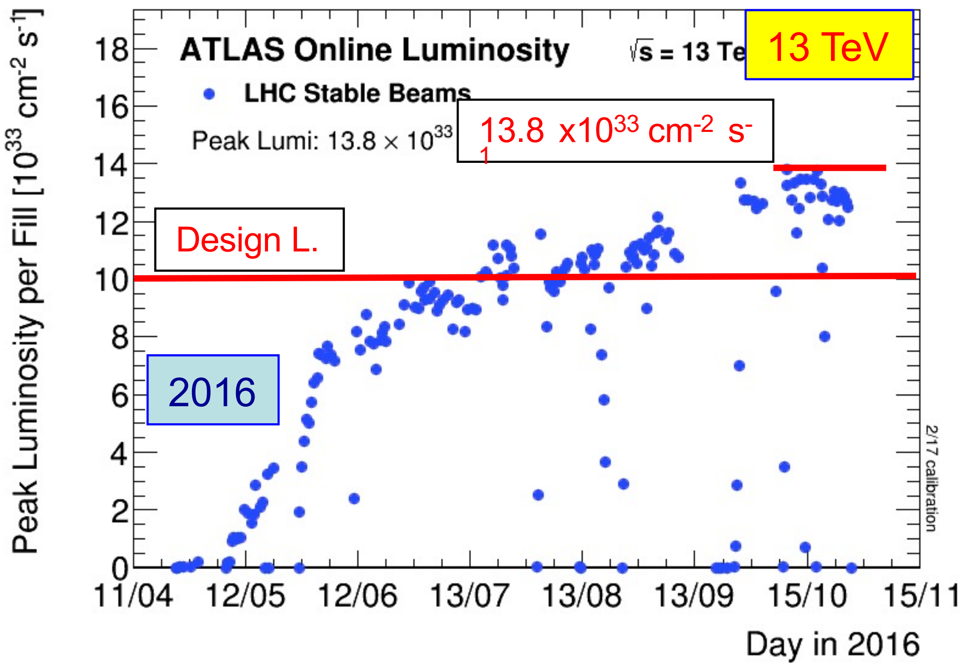
hard scattering cross-section

Luminosity: 2011, 2012, 2015 and 2016



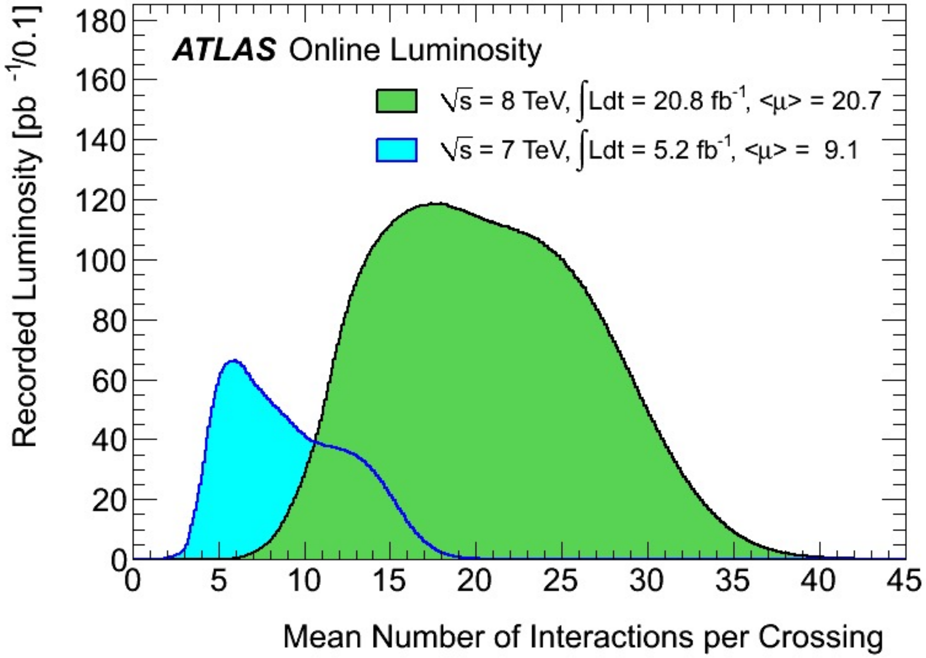




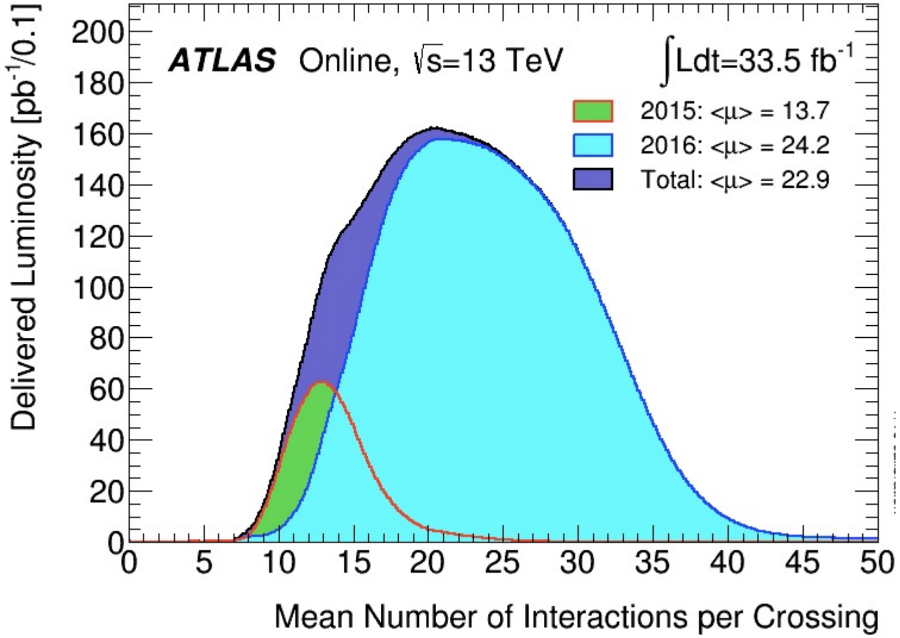


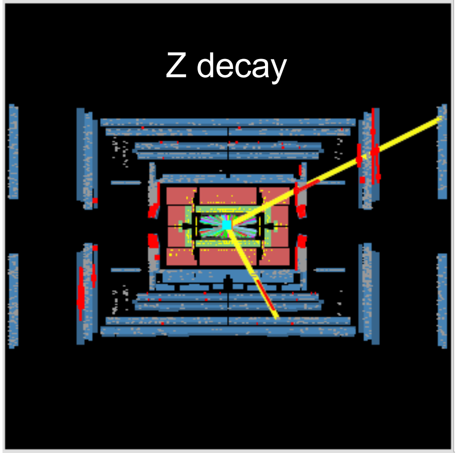
Pile-up

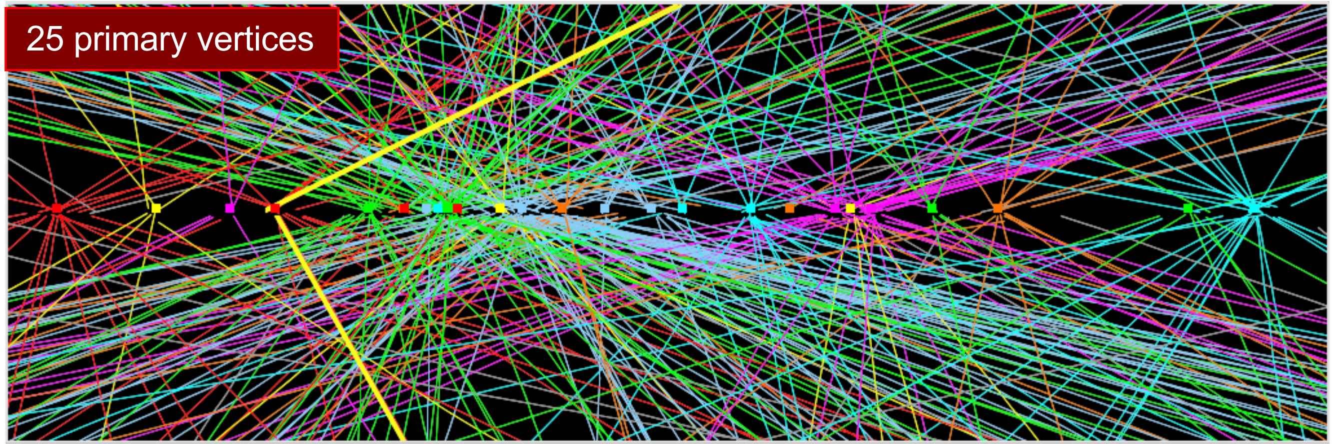
2011/12: 50 ns bunch spacing



2015/16: 25 ns bunch spacing







The ATLAS detector

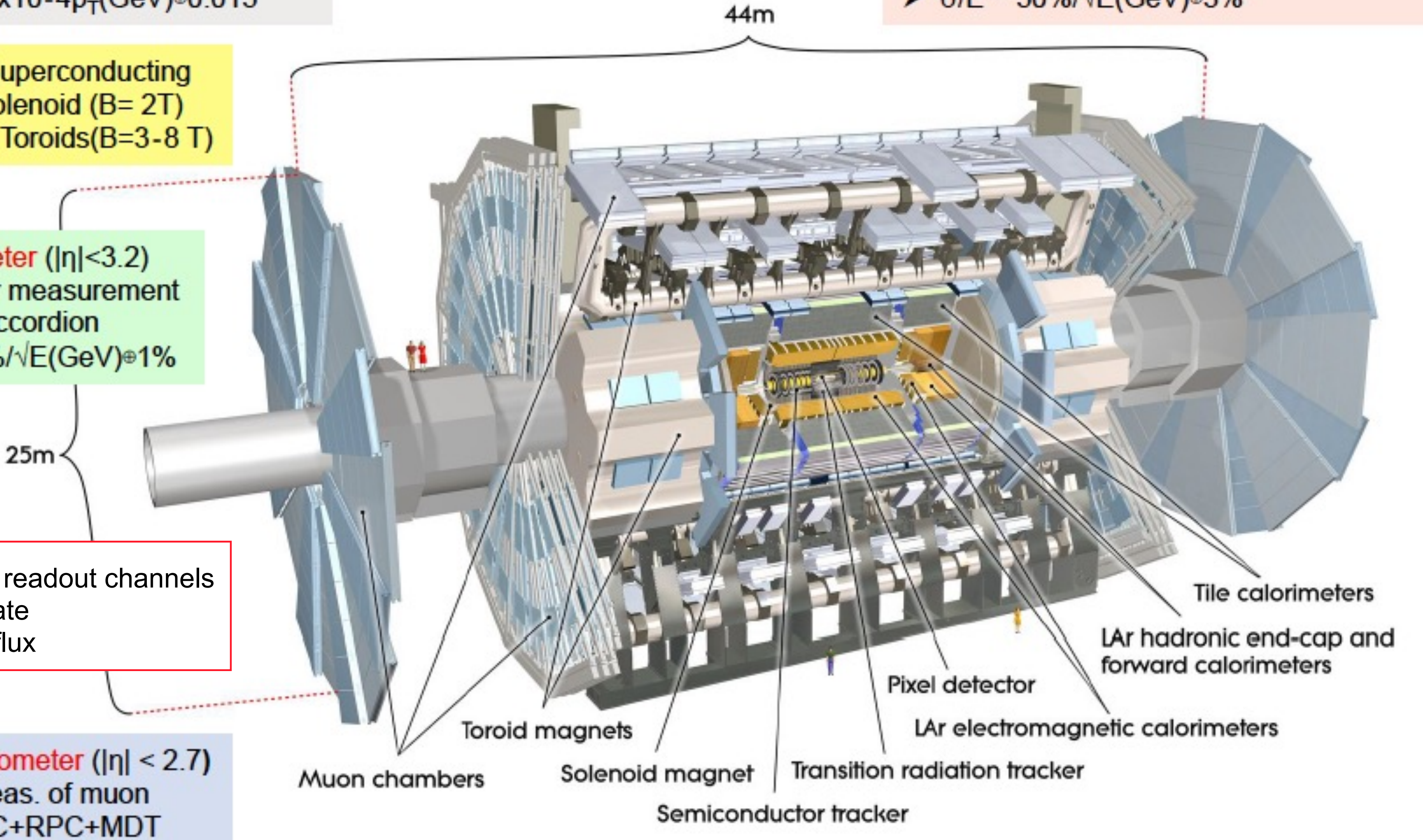
Inner detector (|η|< 2.5, B=2T)
Tracking, vertexing, dE/dx, e/π ID
- Si pixels, Si strips, Trans. Rad. det.
- σ/p_T ~3.8x10-4p_T(GeV)⊕0.015

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

Hadron Calorimeter (|η|<5)
Trigger and meas. of jet/Emiss
- Fe/scintillator (central), Cu/W-LAr (fwd)
- σ/E ~ 50%/√E(GeV)⊕3%

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

EM Calorimeter (|η|<3.2)
e/γ ID trigger measurement
- Pb-Lar accordion
- σ/E ~ 10%/√E(GeV)⊕1%

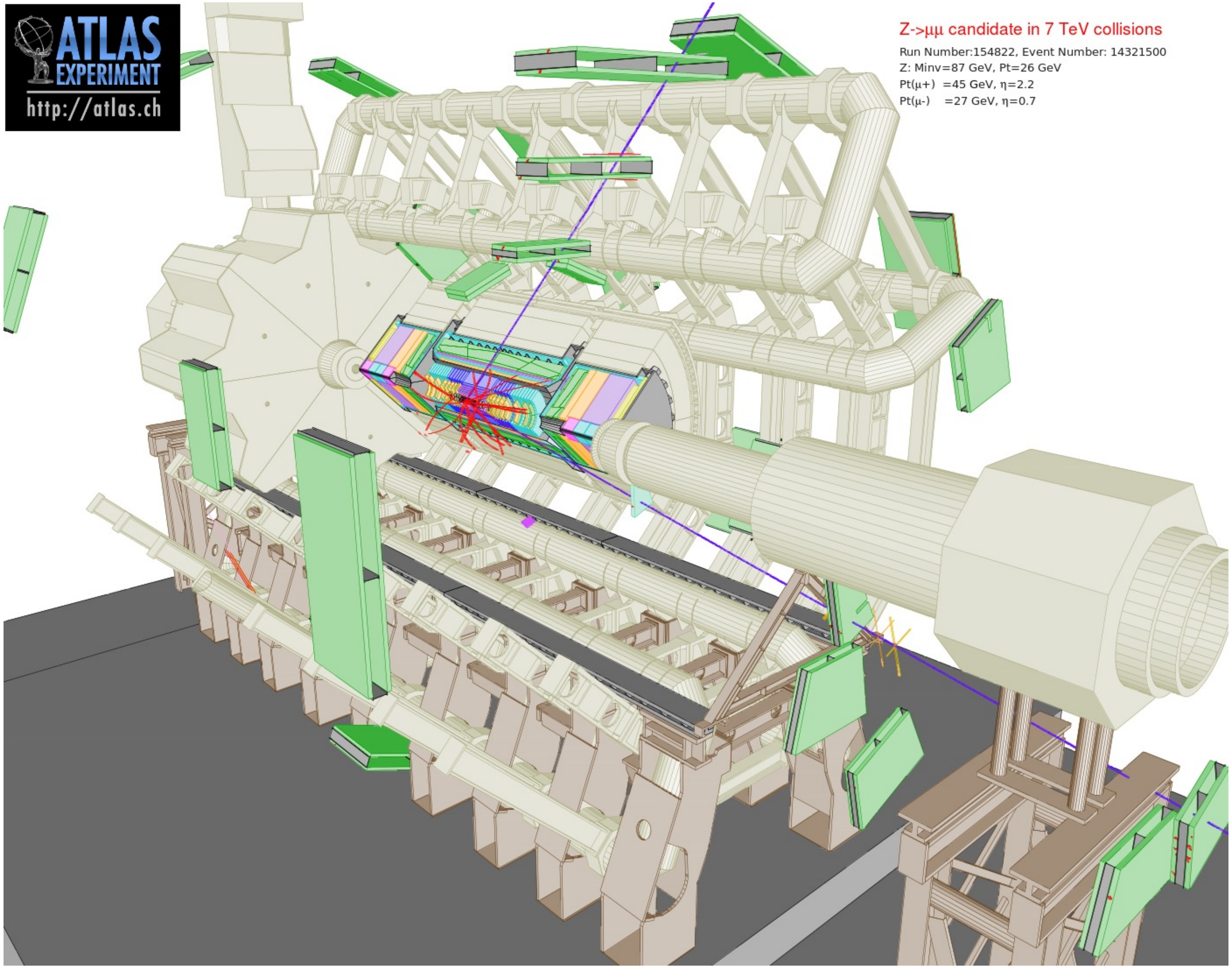


$150 \cdot 10^6$	electronic readout channels
40 MHz	collision rate
10^{14} B/s	raw data flux

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

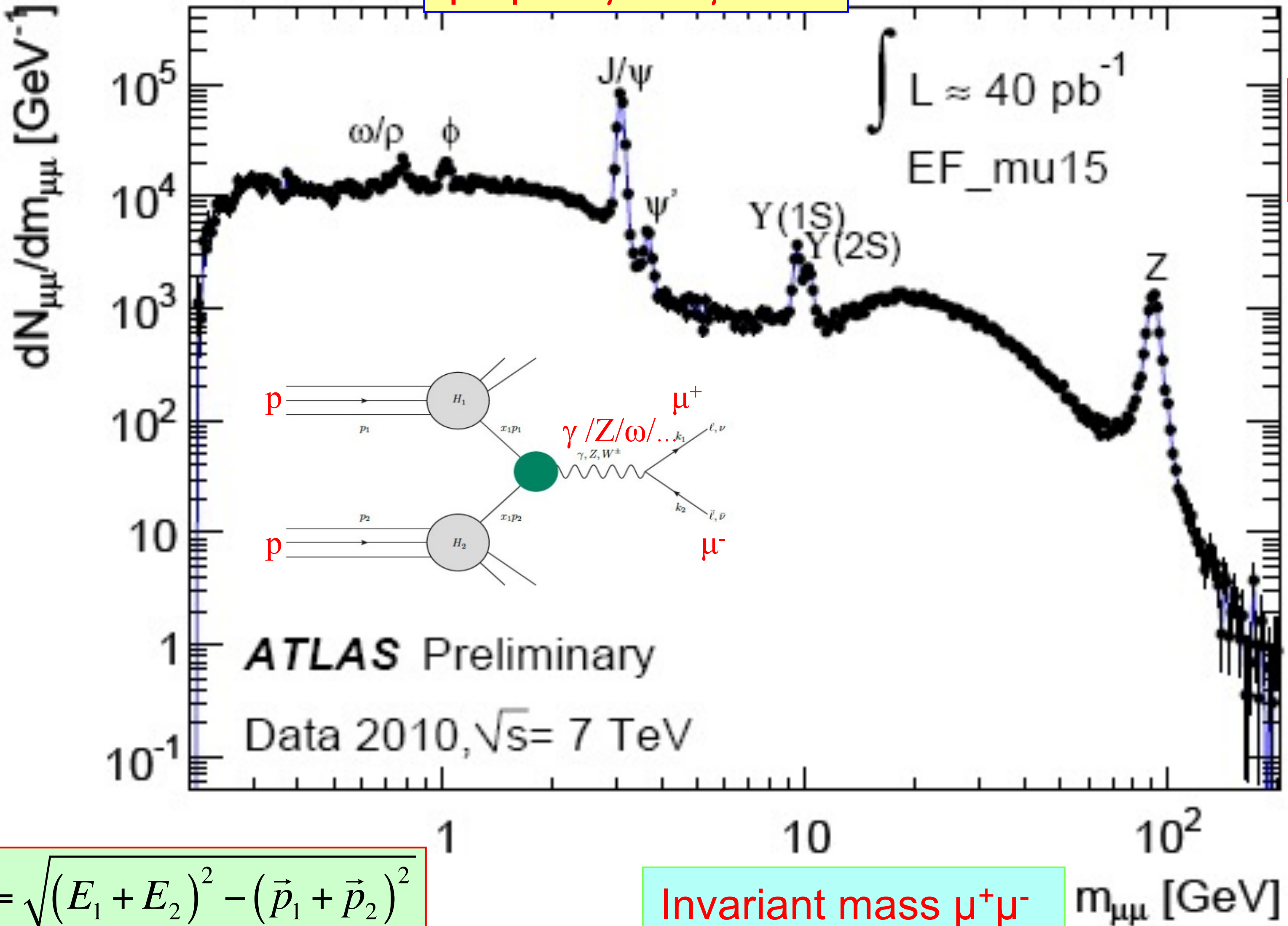
Planning & construction 1990 to 2007; operation from 2009 to ~2035

ATLAS: Z→$\mu^+\mu^-$ candidate



ATLAS: 50 years in one slide

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

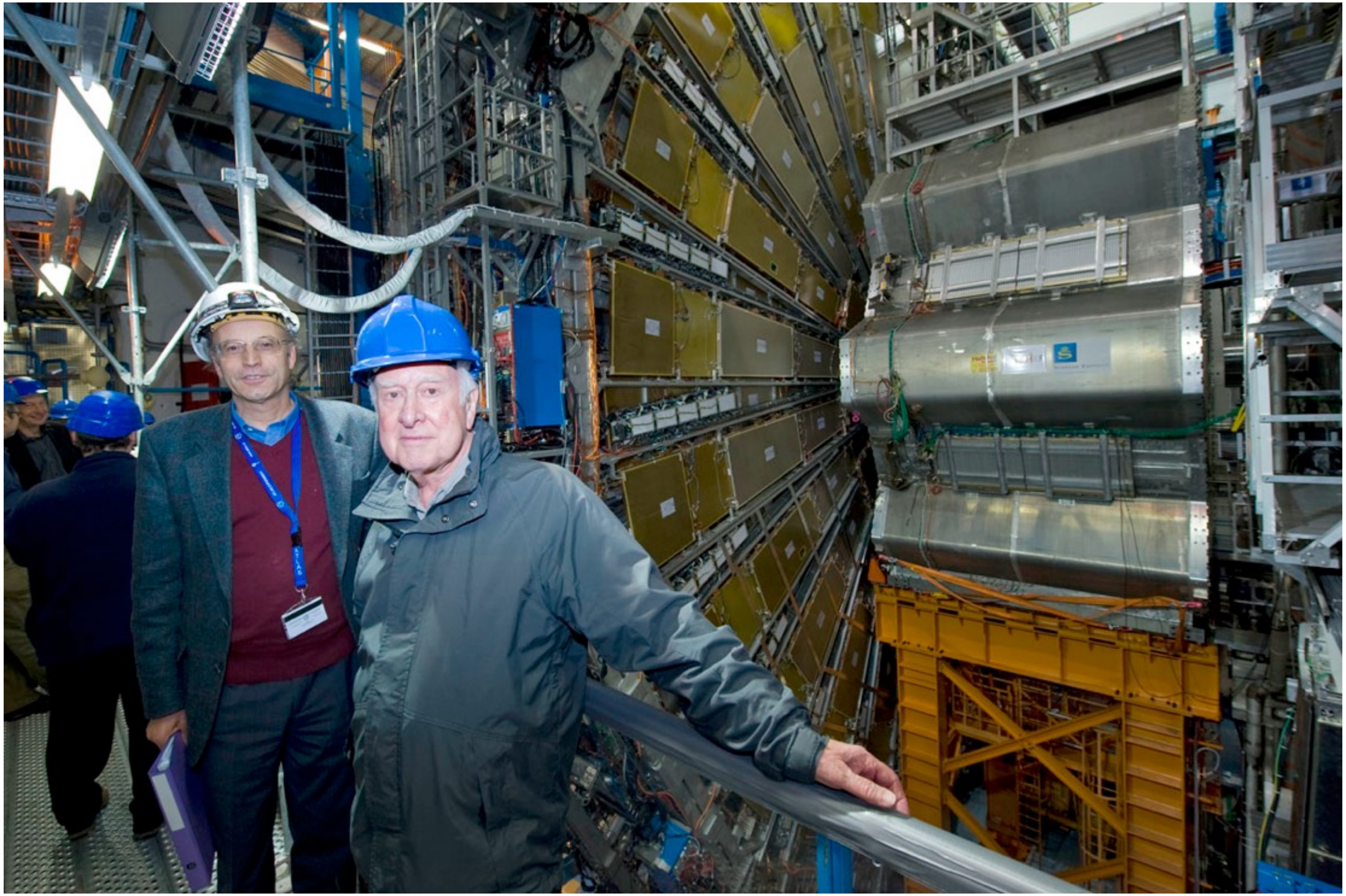


Peak positions are used to check scale momentum calibration

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

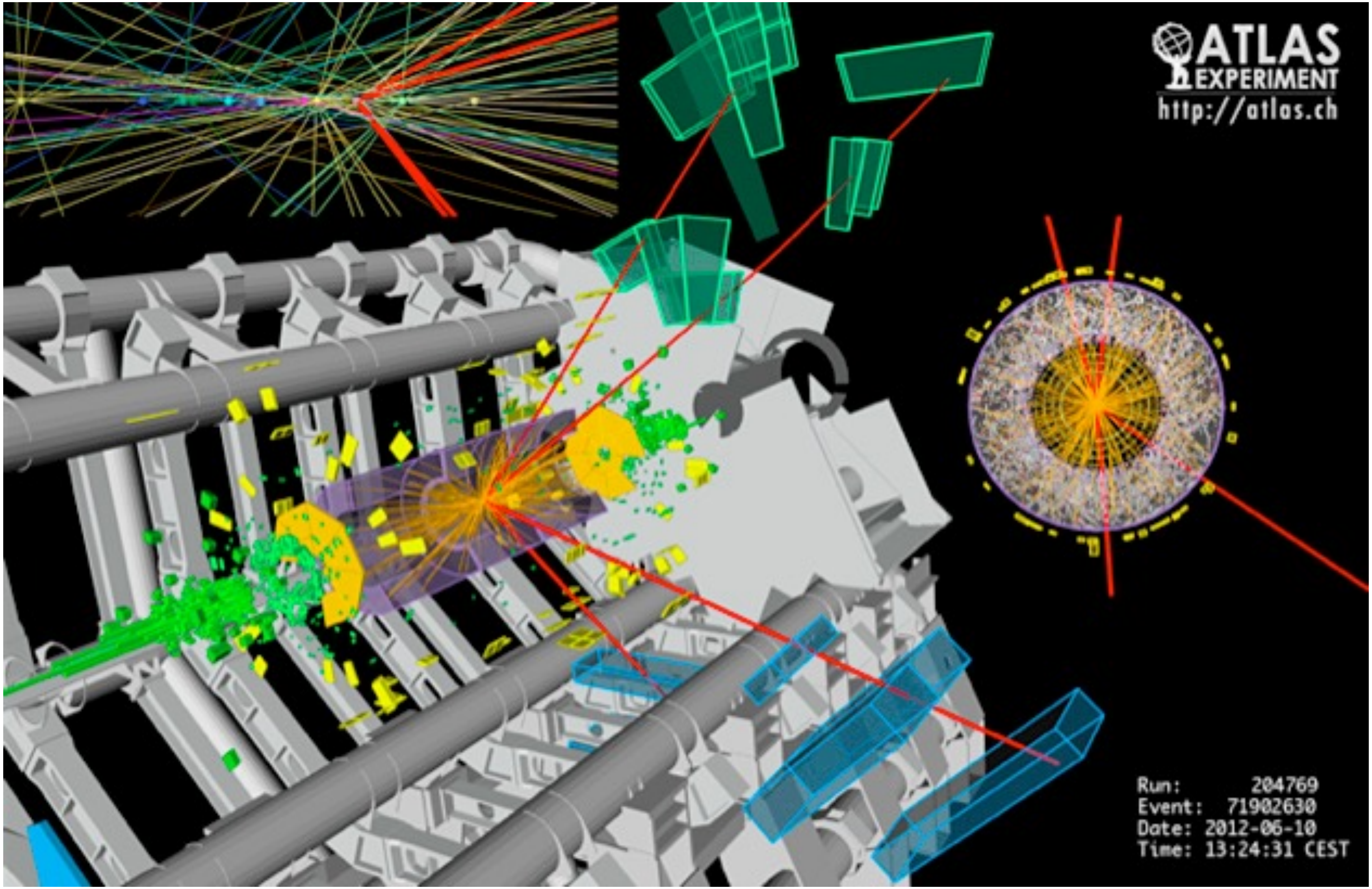
Invariant mass $\mu^+\mu^-$

The Higgs boson

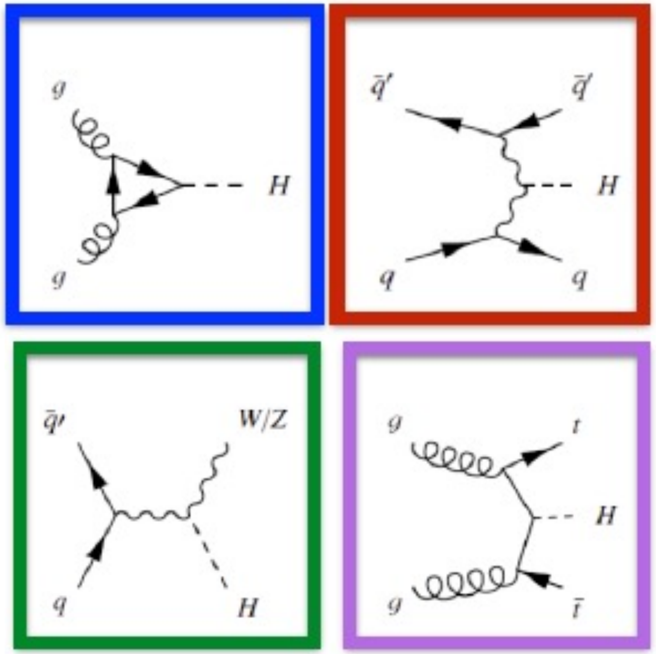


The first Higgs seen in the ATLAS Experiment

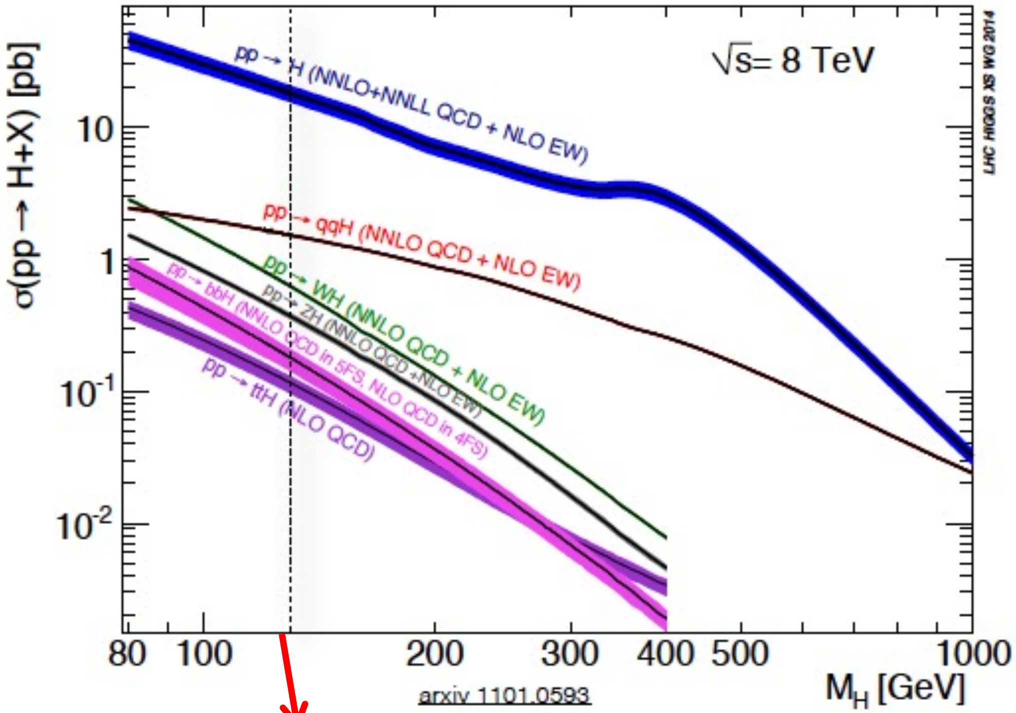
$H \rightarrow ZZ^* \rightarrow \mu^+\mu^-\ \mu^+\mu^-$



SM Higgs Boson Production



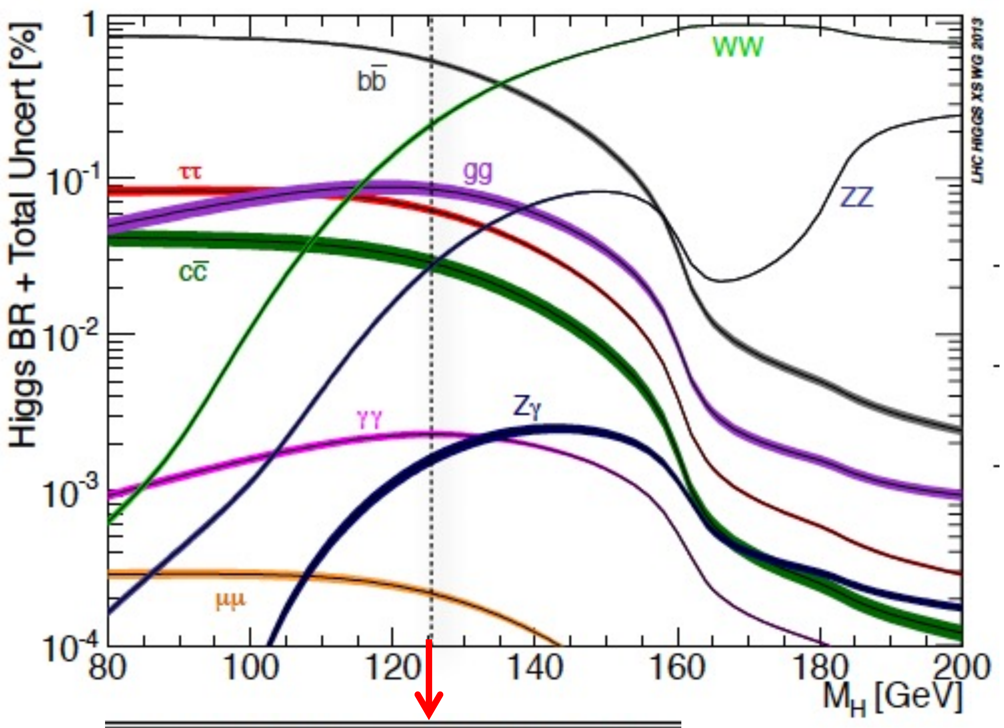
Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV
ggF	15.0 ± 1.6	19.2 ± 2.0
VBF	1.22 ± 0.03	1.57 ± 0.04
WH	0.573 ± 0.016	0.698 ± 0.018
ZH	0.332 ± 0.013	0.412 ± 0.013
bbH	0.155 ± 0.021	0.202 ± 0.028
ttH	0.086 ± 0.009	0.128 ± 0.014
tH	0.012 ± 0.001	0.018 ± 0.001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



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

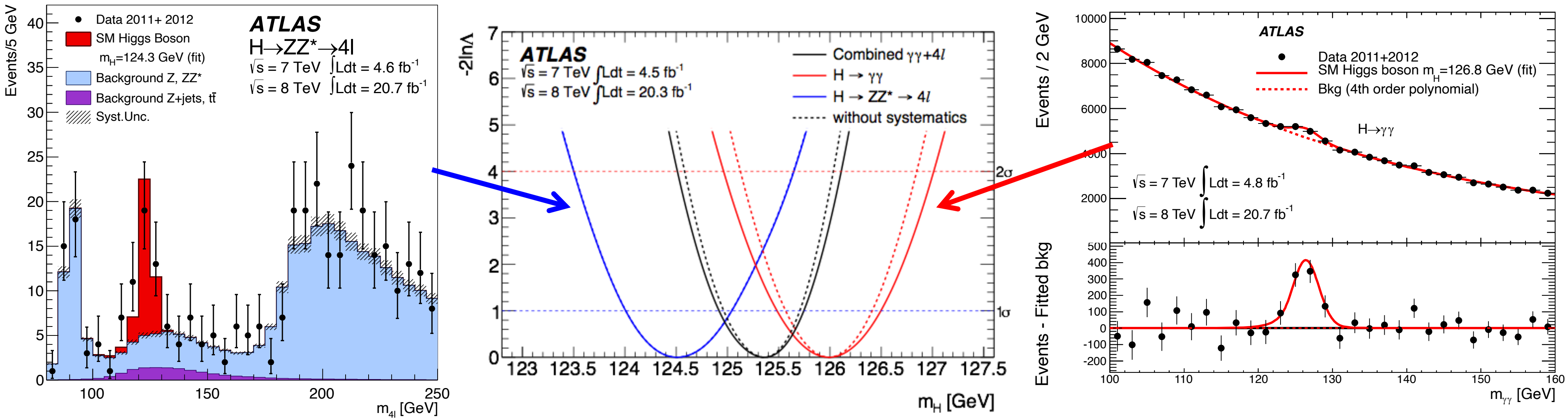
H→ZZ*→4l(e,μ)	**~0.013%**
H→νν	**~0.23%**
H→ττ	**~6.3%**
H→WW→lνlν	**~1.1%**

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)

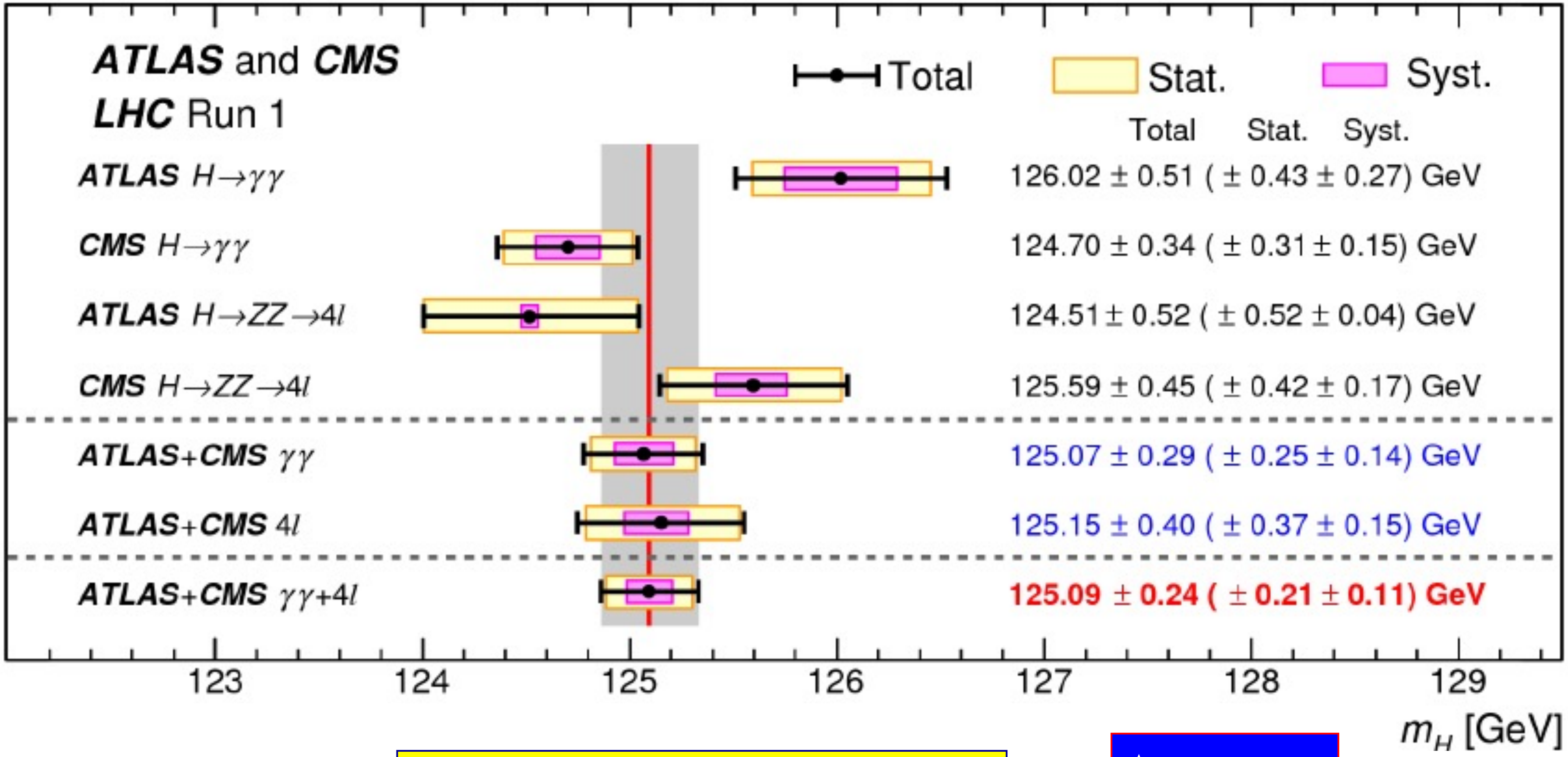
H → γγ



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

Combined Higgs Boson Mass

ATLAS-CMS PRL 114 (2015) 191803



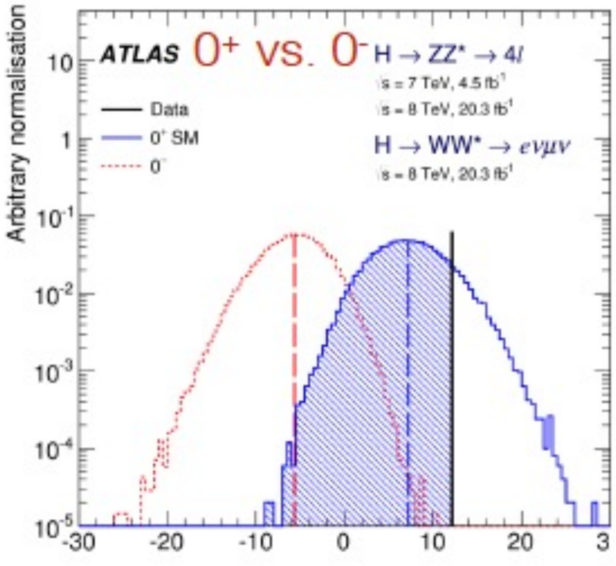
$m_H = 125.09 \pm 0.24$ GeV

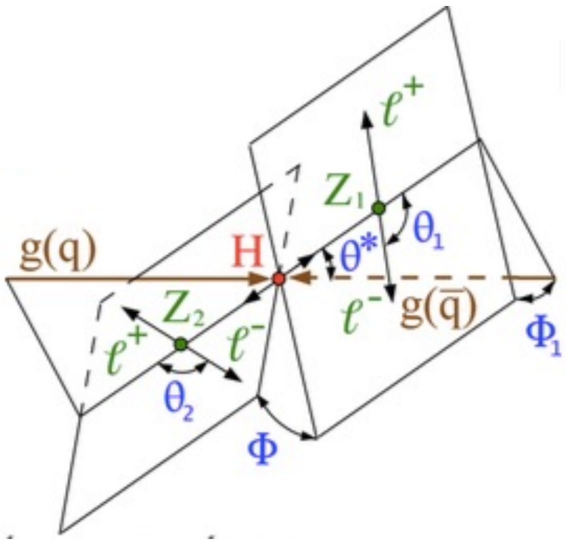
$$\frac{\Delta m}{m} = 0.2\%$$

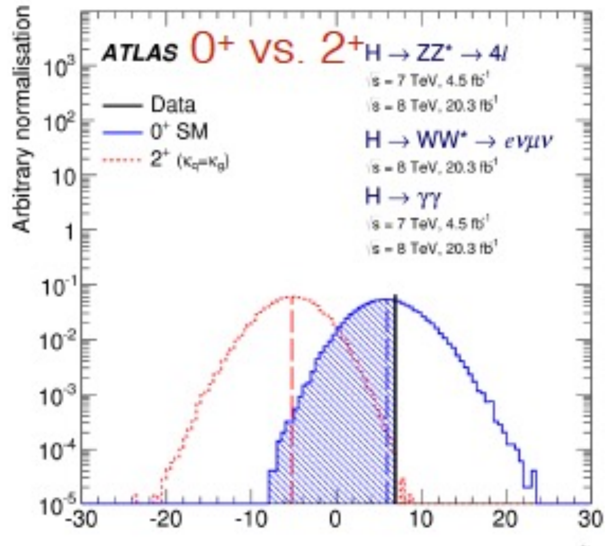
Higgs Boson Spin Measurement

- 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



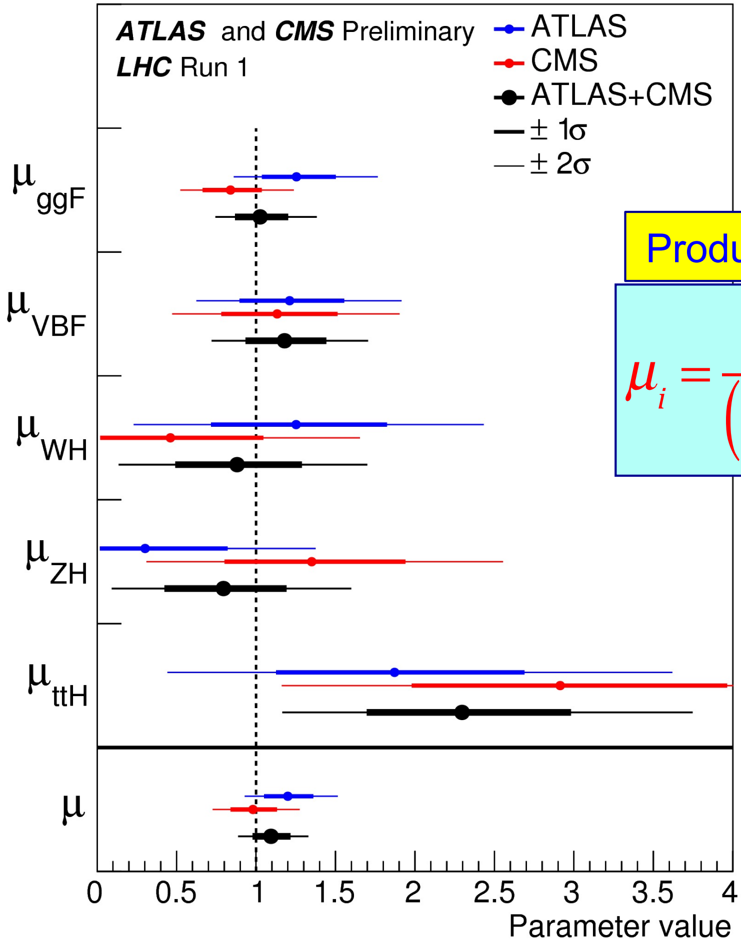




(Multivariate analysis (MVA) based on angular variables)

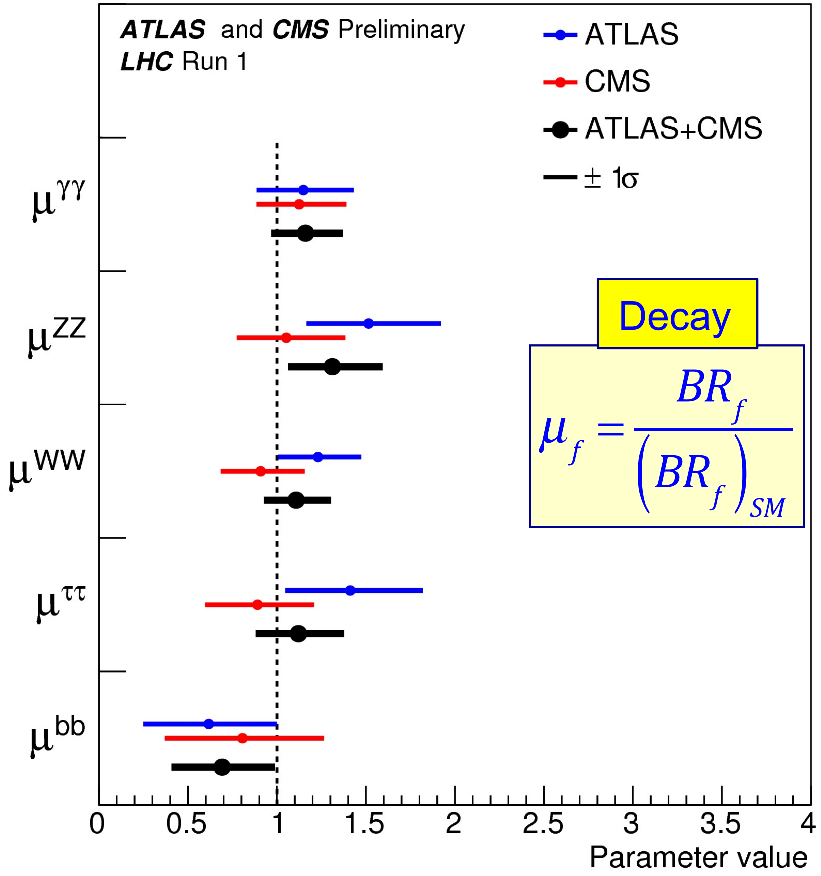
Comparison with SM expectations

Measure the ratio between observed rate and SM Higgs boson expectation



Production

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



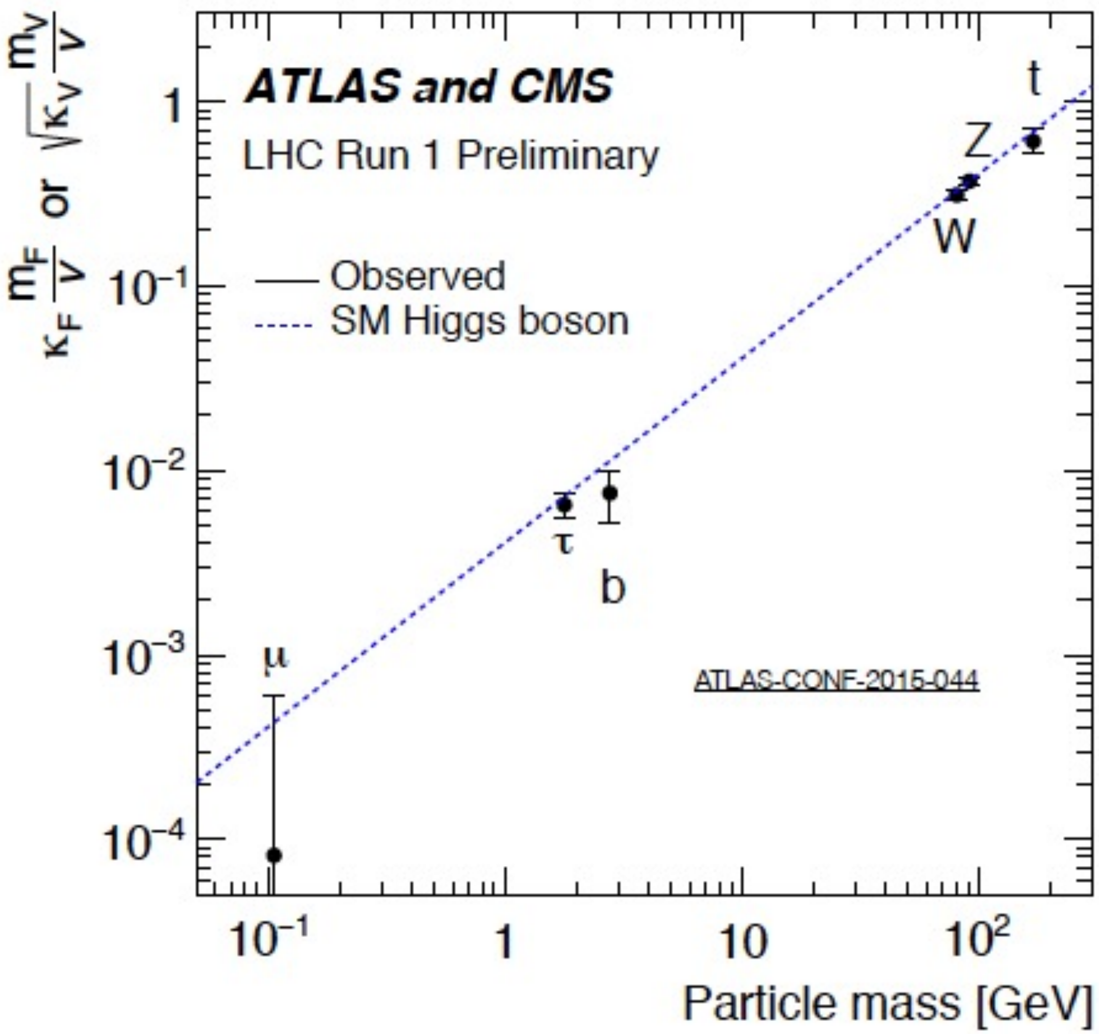
Decay

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

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

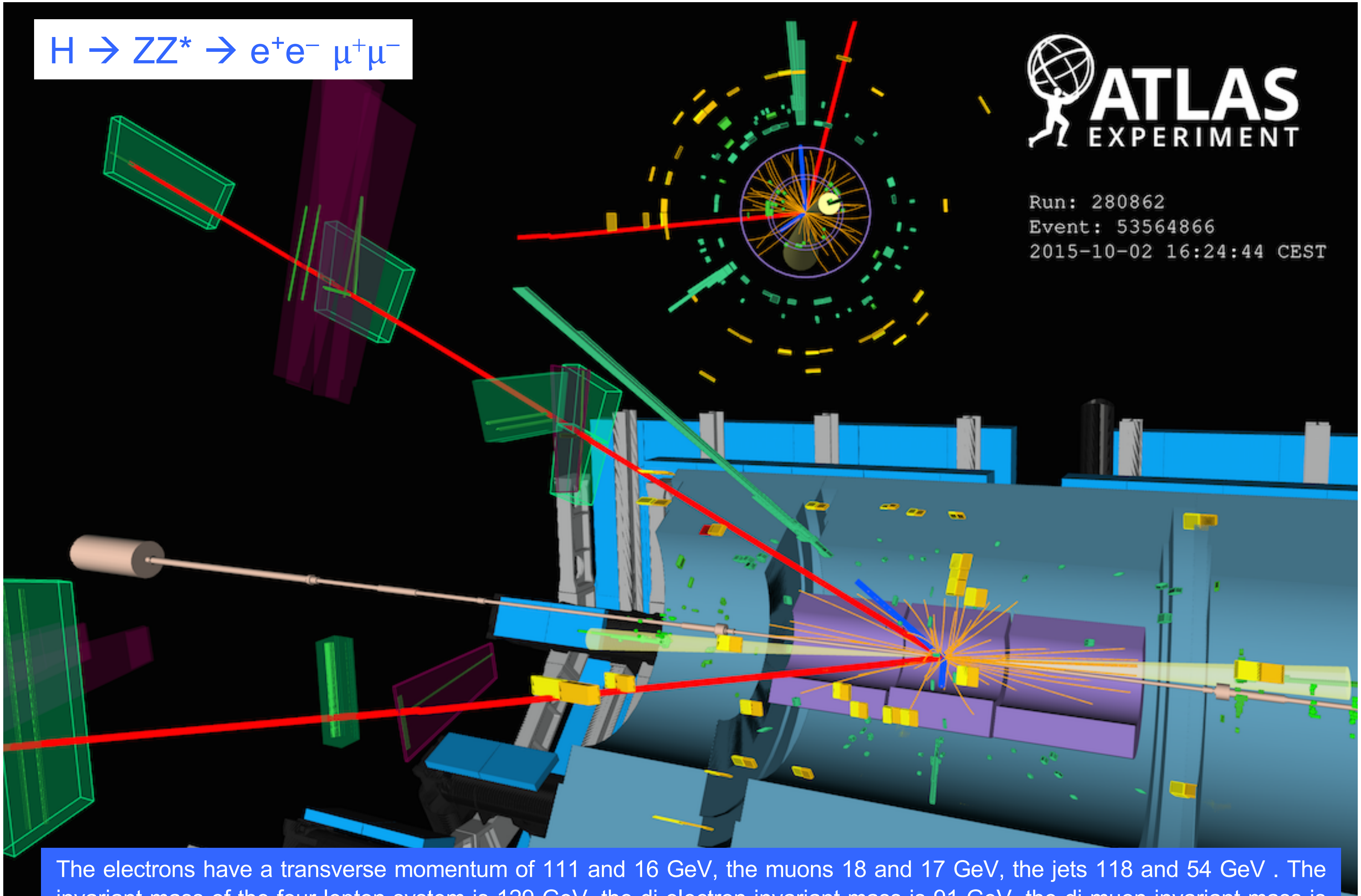
Results are SM like (all $\mu_s \sim 1$)

Higgs Boson Couplings



Coupling strengths scale with mass just as predicted by the SM

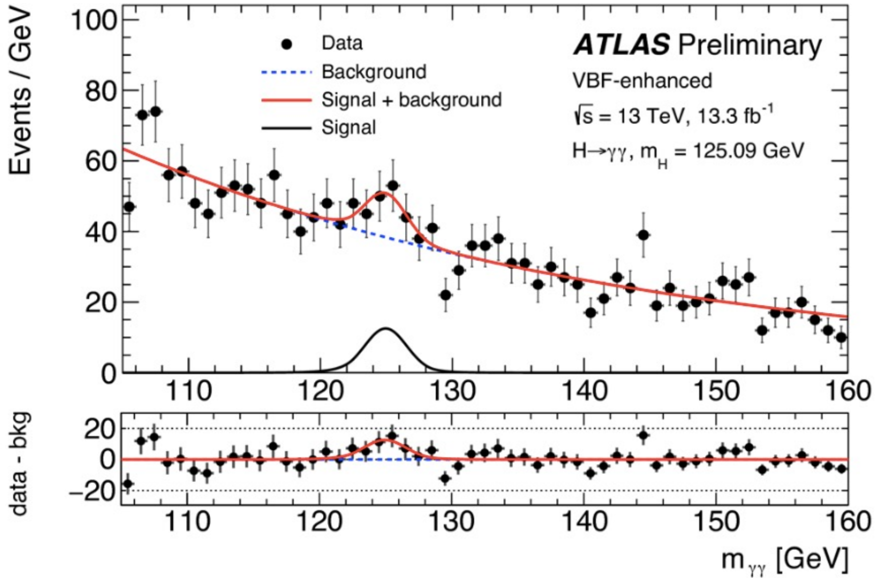
First look at 13 TeV data for H(125)

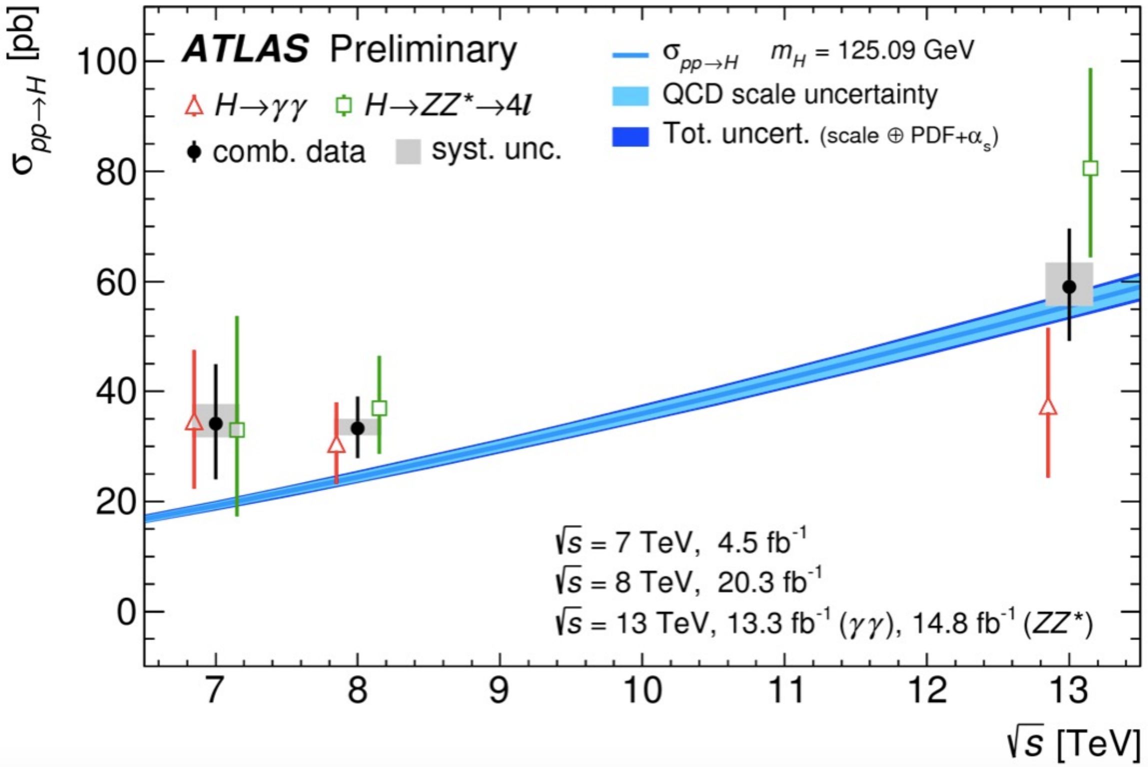


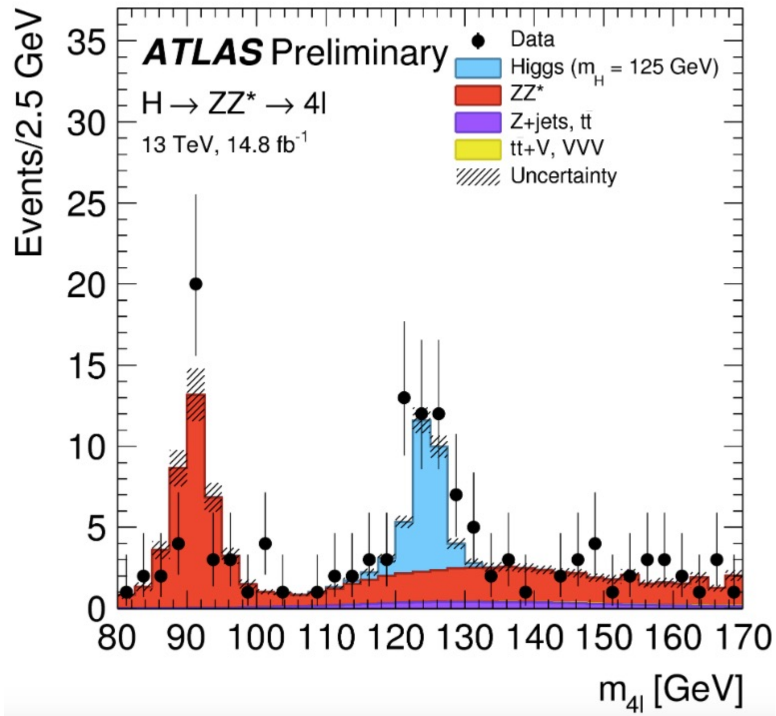
The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, the jets 118 and 54 GeV . The invariant mass of the four lepton system is 129 GeV, the di-electron invariant mass is 91 GeV, the di-muon invariant mass is 29 GeV, The di-jet invariant mass is 2 TeV.

First look at 13 TeV data for H(125)

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







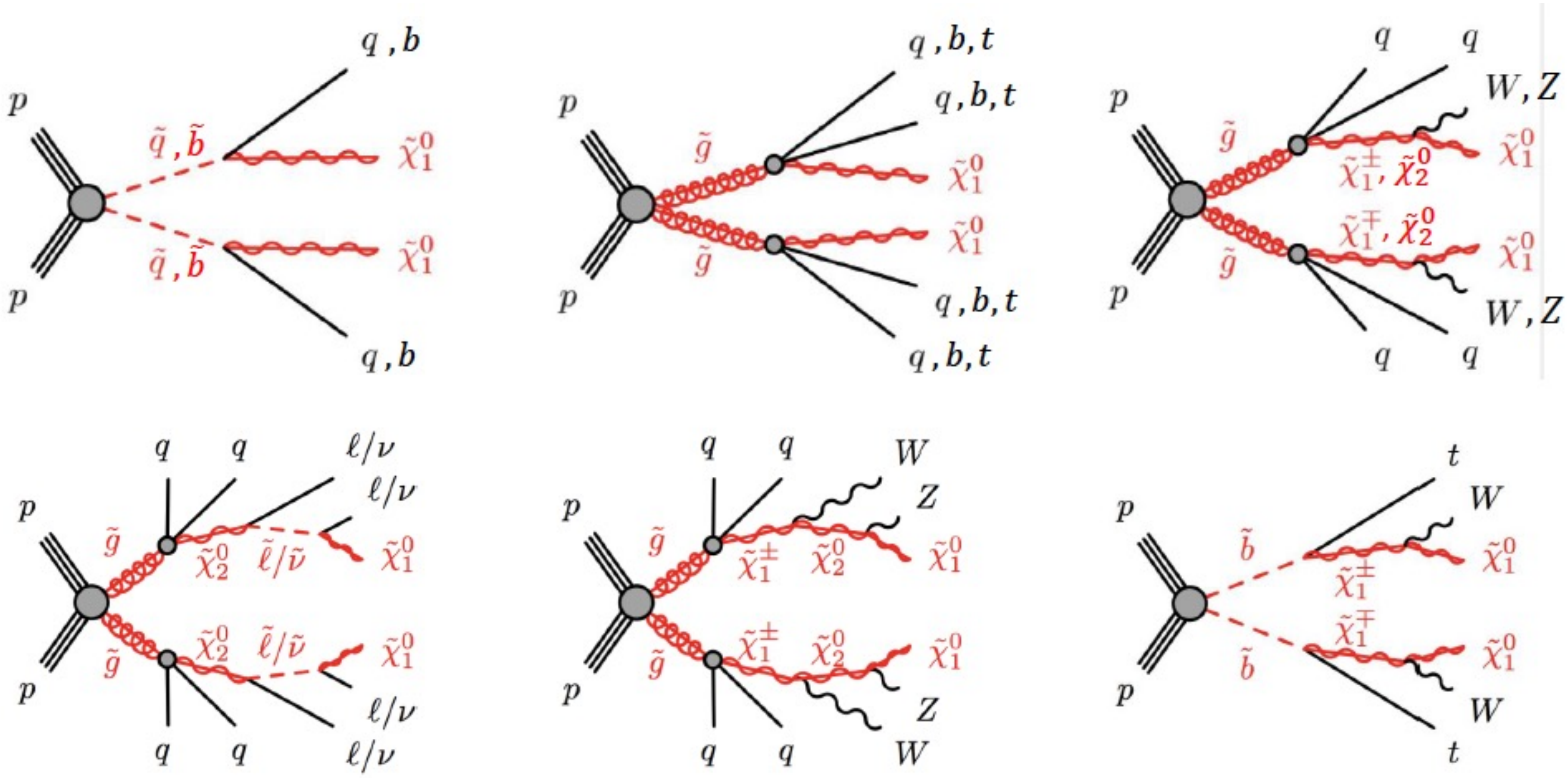
A brief introduction to SuperSymmetry

- **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

Search for susy particles

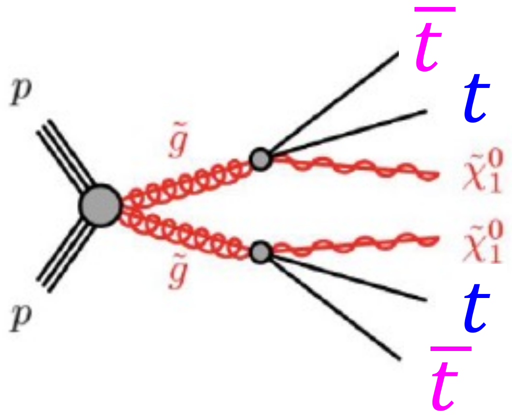
a few diagrams with susy particles in the final state, with the decay chain



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

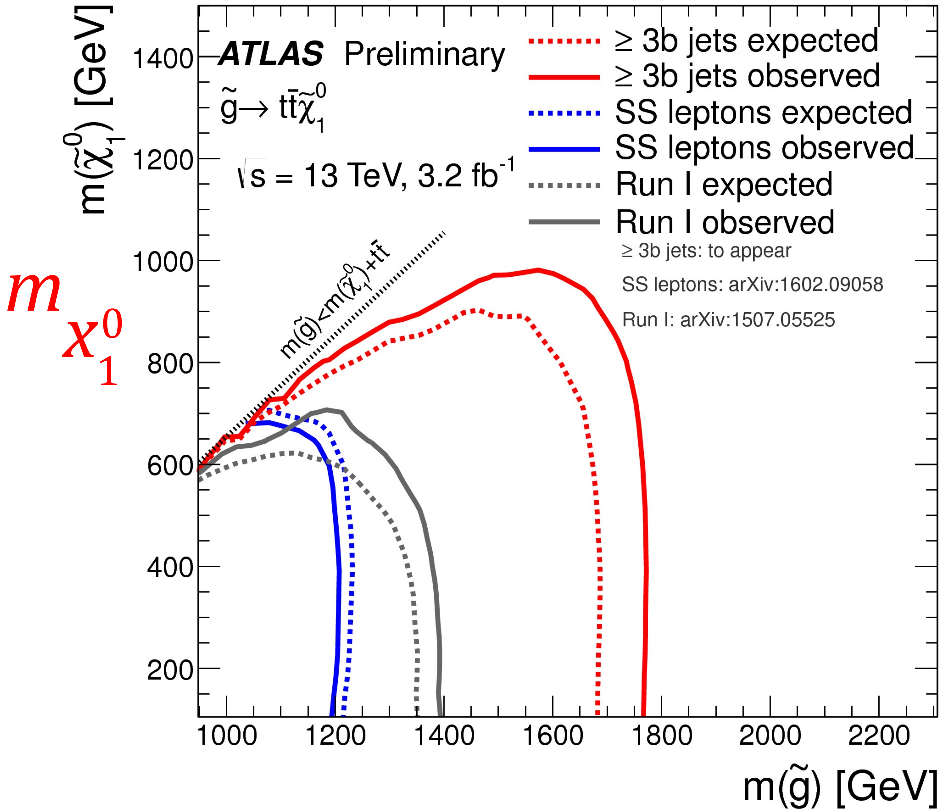
- **Different analysis strategies according to many different final states**

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

ATLAS susy particles: Run2 results

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2016

ATLAS Preliminary

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

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

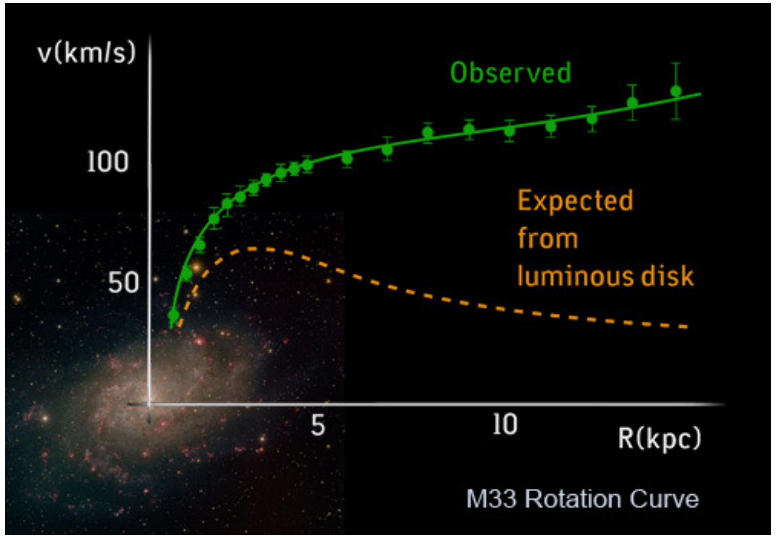
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e, μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	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
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ (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
	$\tilde{q}\tilde{q}, \tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 820 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	3.2	$\tilde{g}$ 1.52 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2015-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	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
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20	$\tilde{g}$ 1.38 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$	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.	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	3.3	$\tilde{g}$ 1.78 TeV	m($\tilde{\chi}_1^0$)<800 GeV	ATLAS-CONF-2015-067
	$\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	3.3	$\tilde{g}$ 1.76 TeV	m($\tilde{\chi}_1^0$)=0 GeV	To appear
	$\tilde{g}\tilde{g}, \tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	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	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	3.2	$\tilde{b}_1$ 840 GeV	m($\tilde{\chi}_1^0$)<100 GeV	ATLAS-CONF-2015-066
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	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
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	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
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ 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
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	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
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-610 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$	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	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$ 90-335 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0, h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	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
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	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 $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, 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
	$\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$	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 $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to Z\tilde{G}$	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 $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	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
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	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
	$\tilde{g}\tilde{g}, \tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 980 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}, \tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 880 GeV		1404.2500
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$ 320 GeV		1601.07453
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$	2 e, μ	2 b	-	20.3	$\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$ 510 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

Mass scale [TeV] (10^{-1} … 1)

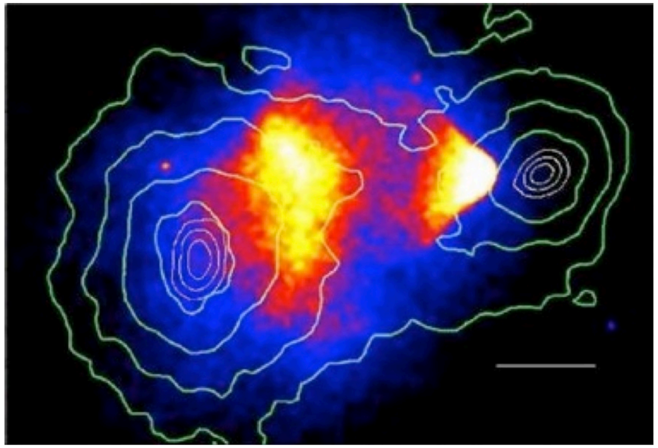
*Only a selection of the available mass limits on new states or phenomena is shown.

Evidence for Dark Matter

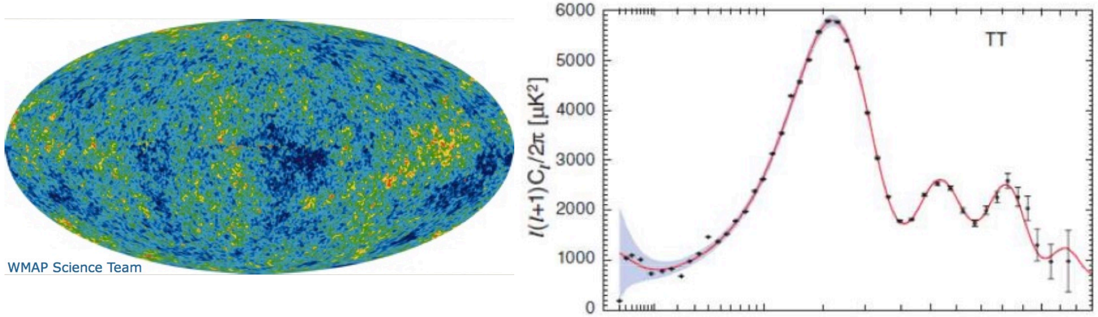
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale Zwicky (1937)



*Large **halos** around Galaxies*
Rotation Curves Rubin+(1980)



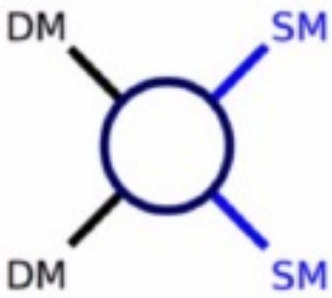
*Almost **collisionless***
Bullet Cluster Clowe+(2006)



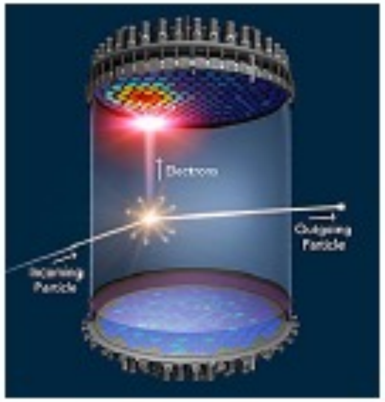
Non-Baryonic Big-Bang Nucleosynthesis, CMB Acoustic Oscillations *WMAP*(2010),*Planck*(2015)

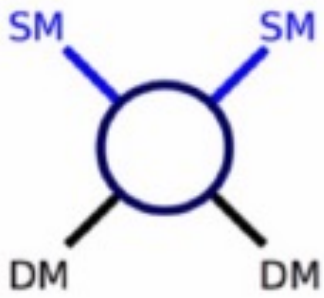
Detecting Dark Matter

Assumption: non-gravitational interaction with ordinary matter

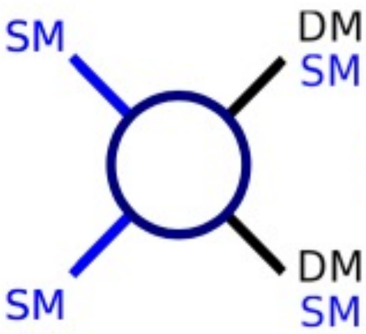


Indirect Detection



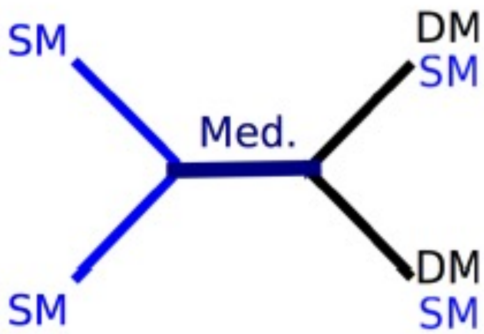


Direct Detection



Colliders
(Contact interaction)

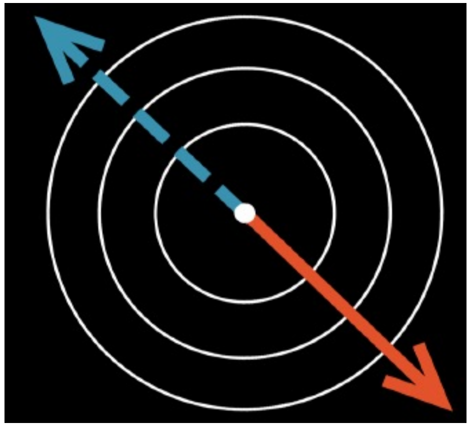
Contact interaction (EFT)
"works" if the scale $\Lambda >> Q^2$
(like Fermi theory).
otherwise we need a Simplified Model with (at least) a Mediator



Colliders
(Simplified Models)

Detecting Dark Matter at LHC

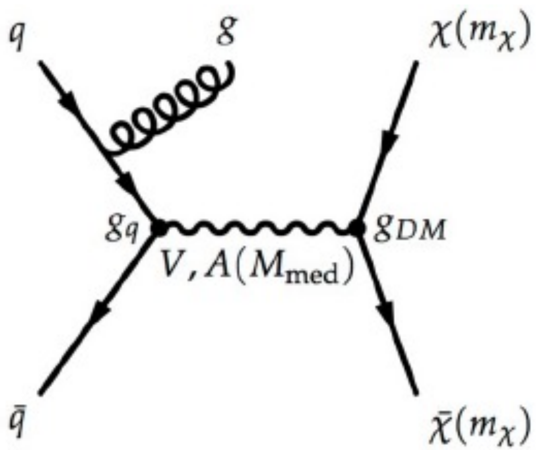
Non-interacting DM particles
→ Missing transverse energy (MET)



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

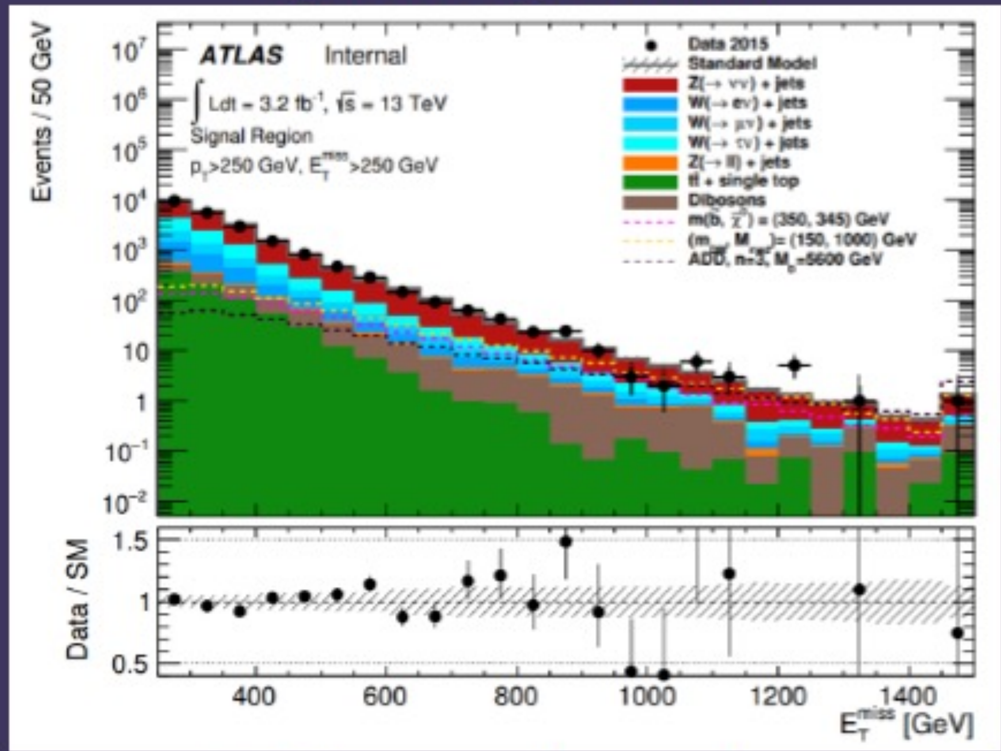
DM at ATLAS; one example: monojet

Backgrounds

- Main backgrounds are EW processes with intrinsic E_T^{miss}, accompanied by jets:
  - $Z(\nu\nu)$+jets: irreducible background
  - $W(l\nu)$+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



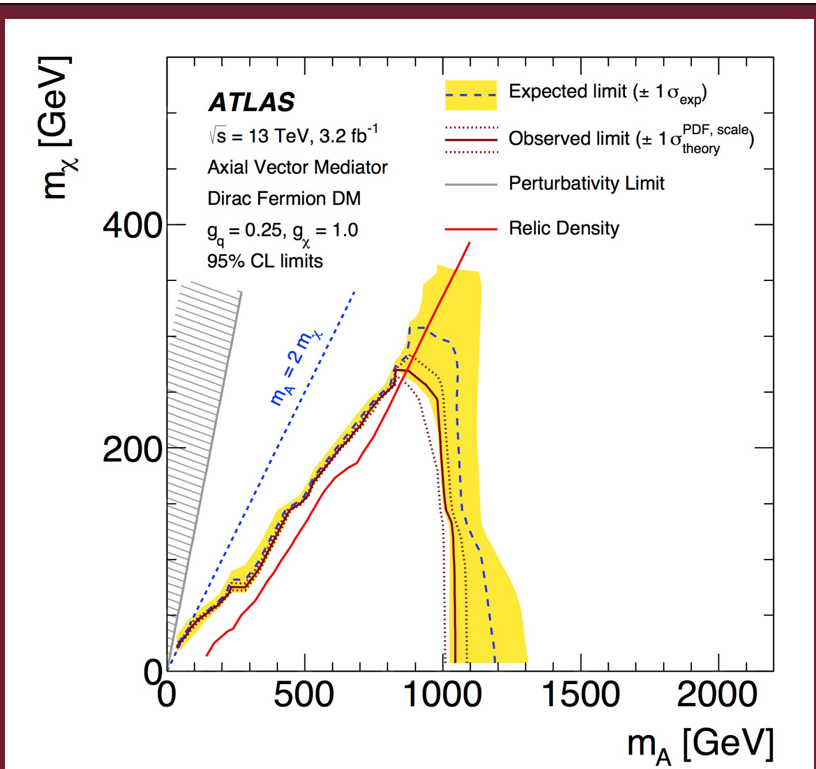
➥ No excess observed

Dominant uncertainties:

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

DM at ATLAS; one example: monojet

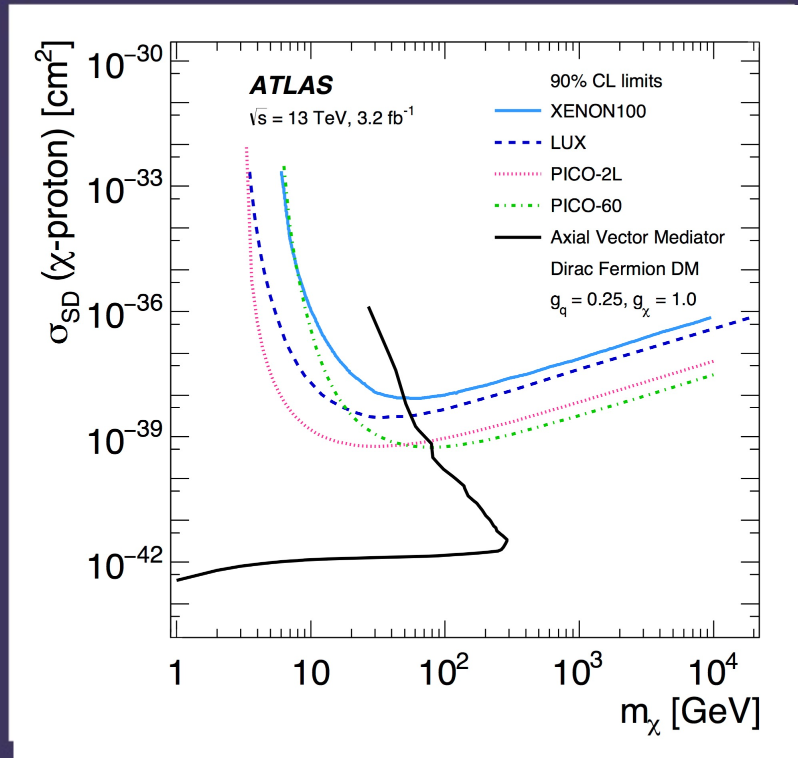
Results



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]

SAPIENZA
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End of chapter 13