Facts and Phantoms at the High Energy Frontier

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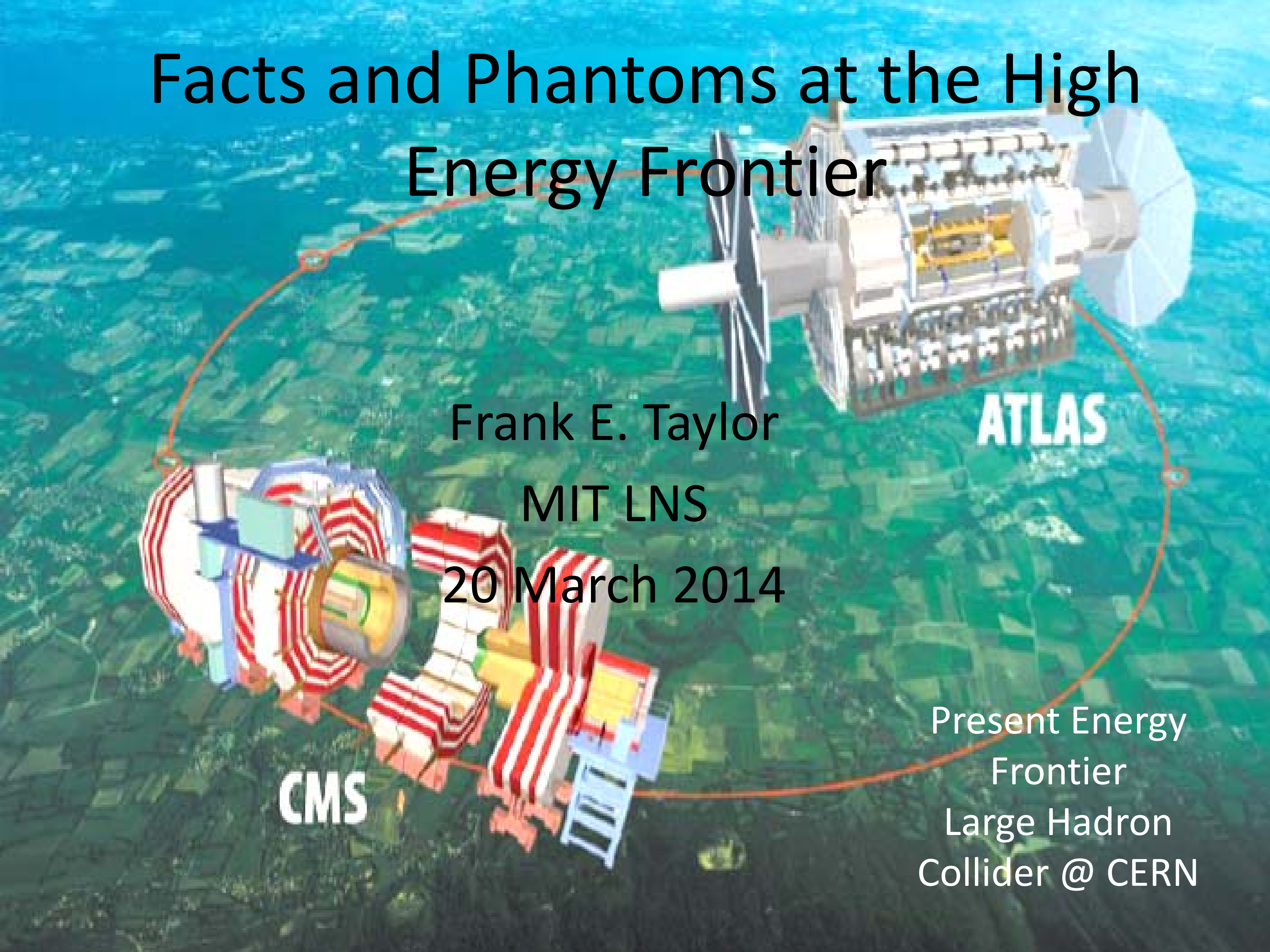


Present Energy Frontier
Large Hadron Collider @ CERN

Situation

- The structure of the Standard Model (SM) was sufficient to define experimental stepping stones leading to the recent discovery of the Higgs scalar boson (July 2012), considered to be the 'last' SM particle
  - This is a stunning success!
- A number of questions are left unanswered:
  - Is the particle discovered really the SM Higgs or does it have other scalar partners ?
  - Can the SM really describe all high energy phenomena up to the Planck scale ?
  - What about SUSY ? Hidden Sectors ? U(1) A' ?
  - Where do the fermion mixing (CKM) and CP parameters come from?
  - What constitutes Dark Matter and Dark Energy ?

The Standard Model of EW Interactions

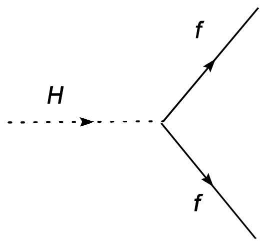
- $SU(2)_L \times U(1)_Y$ Gauge Group + Higgs Mechanism

  - EM **$e = (4\pi\alpha)^{1/2}$**
  - CC **$g = 2(\sqrt{2}Gf)^{1/2}$ Mw**
  - NC **$g' = g \tan\theta w$**

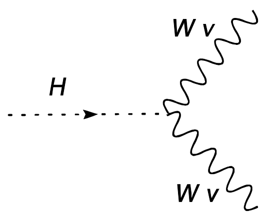
$$\tan\theta_w = \frac{g'}{g} \text{ and } e = \frac{g'\,g}{\sqrt{g'^2 + g^2}}$$

Higgs Particle & Couplings

$$\langle v \rangle = \left(G_\mu \sqrt{2}\right)^{-1/2} \approx 246 \text{ GeV}$$

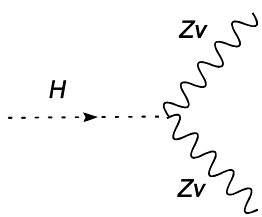


$$-im_f \left(G_F \sqrt{2}\right)^{1/2}$$

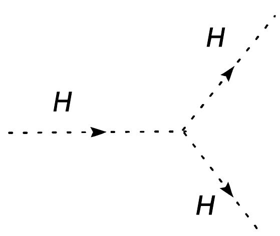


$$-igM_W g_{\mu\nu}$$

Couplings depends on Mass by design



$$\frac{-igM_Z}{\cos\theta_W} g_{\mu\nu}$$



$$-6i|\lambda|\, v = -3i\, M_H^2 \left(G_F \sqrt{2}\right)^{1/2}$$

SM with Radiative Corrections

- Running $\alpha(0) \dashrightarrow \alpha(M_Z^2)$ by QED & $\langle v \rangle = \left(G_\mu \sqrt{2}\right)^{-1/2} \approx 246\ \mathrm{GeV}$
  - Contributions to γ self energy term

$$\frac{1}{\alpha(0)} - \frac{1}{\alpha(M_Z^2)} = \sum_f Q_f^2 \ln\left(\frac{m_f^2}{M_Z^2}\right)$$

- Vector gauge boson mass relations

$$M_Z^2 = \frac{\pi\, \alpha_{em}}{\sqrt{2}\, G_\mu \sin^2\theta_W \cos^2\theta_W\, \zeta_Z}$$

$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\, \alpha_{em}}{\sqrt{2}\, G_F\, \zeta_W\, M_Z^2}}\right)$$

- Vector gauge boson partial widths

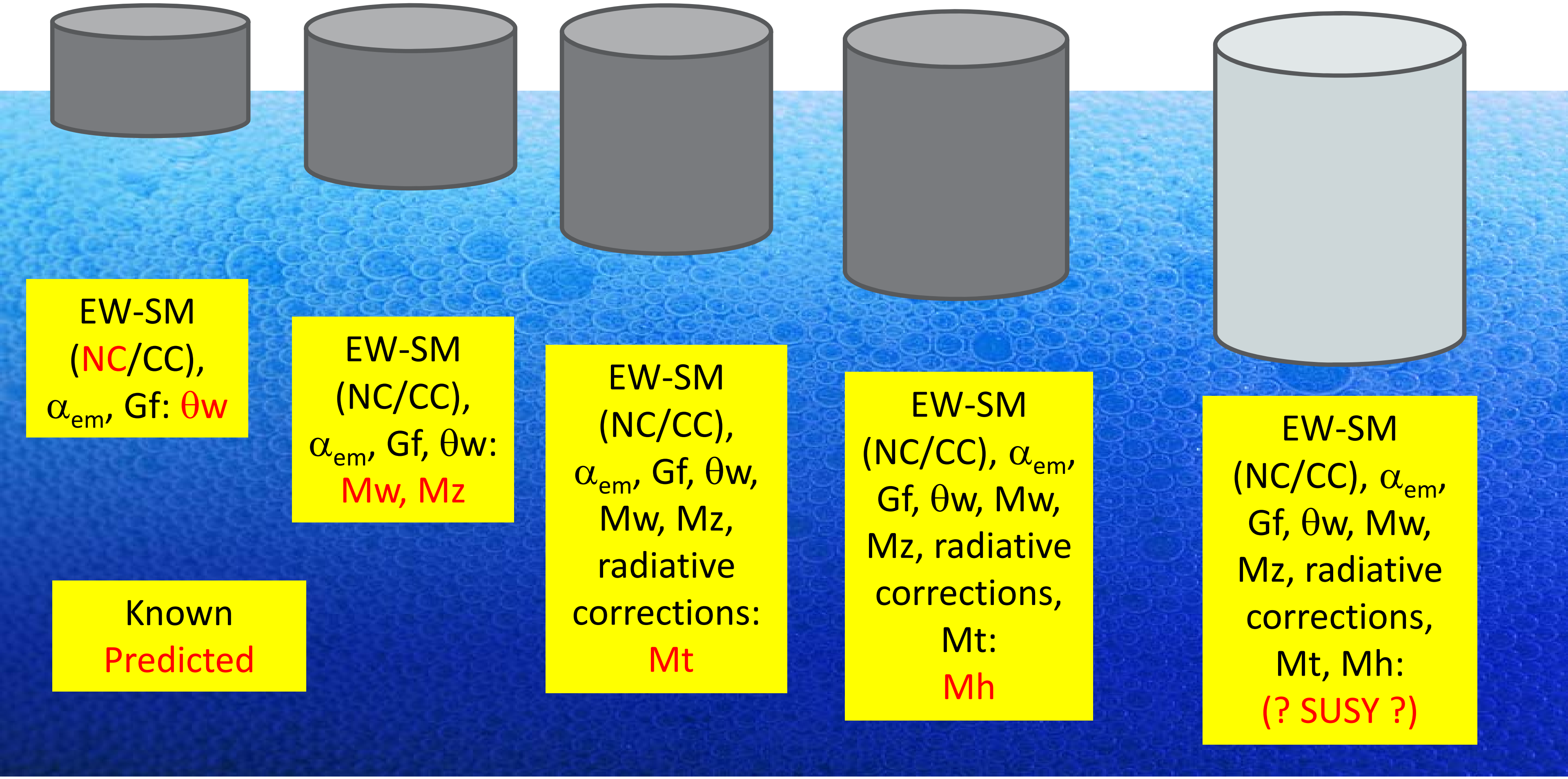
$$\Gamma_{\bar{f}f} = \frac{\sqrt{2}\, G_m M_Z^3}{12\pi} N_c \left(g_{Vf}^2 + g_{Af}^2\right) \zeta_{ff}$$

Correction Terms

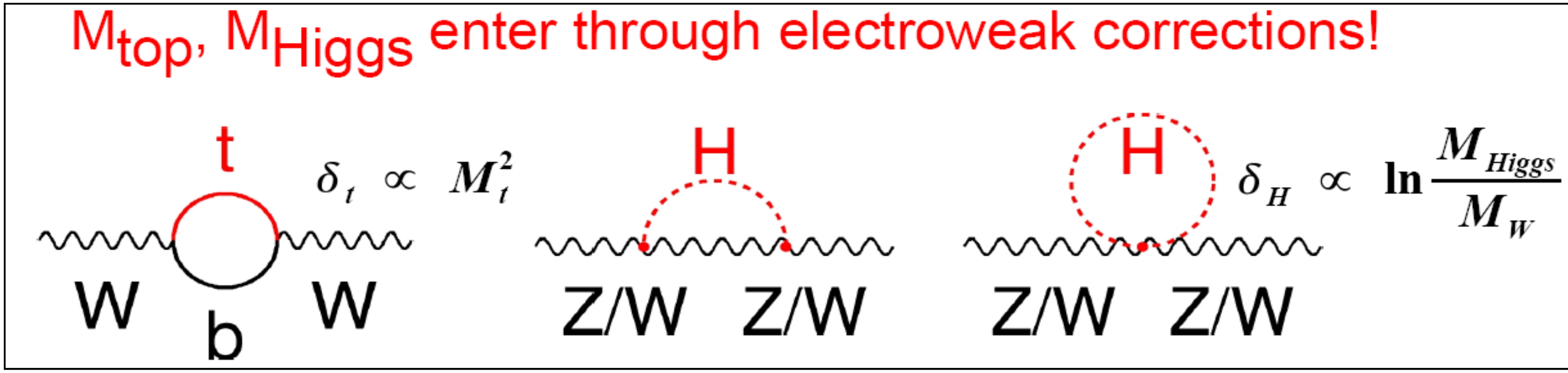
$\sim M_{top}^2$

$\sim \ln(M_{higgs})$

Standard Model Stepping Stones



Radiative Terms



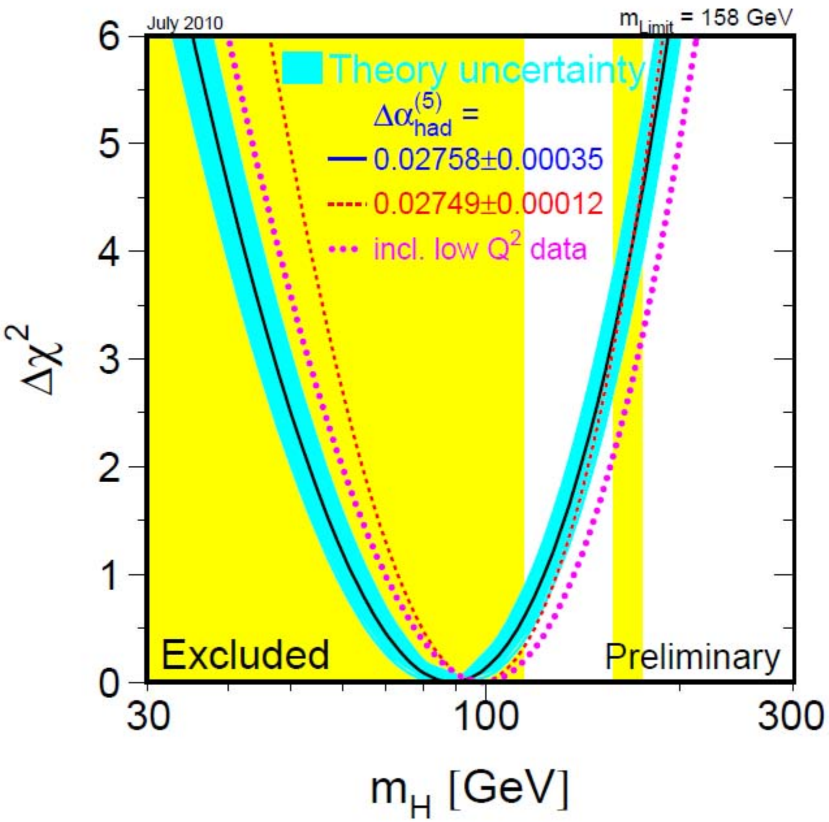
The large value of M_T makes it play a big role. M_H plays a smaller role.

$$\delta_H \approx g^2[\ln(M_H/M_w) + g^2 (M_H/M_W)^2] \approx g^2 \ln(M_H/M_w)$$

"The Screening Theorem and Higgs System": Veltman XXXIV Cracow School of Theoretical Physics, Zakopane, Poland, June 1-10, 1994

The next to the last stepping Stone

- Summer 2010 EW Working Group before LHC data



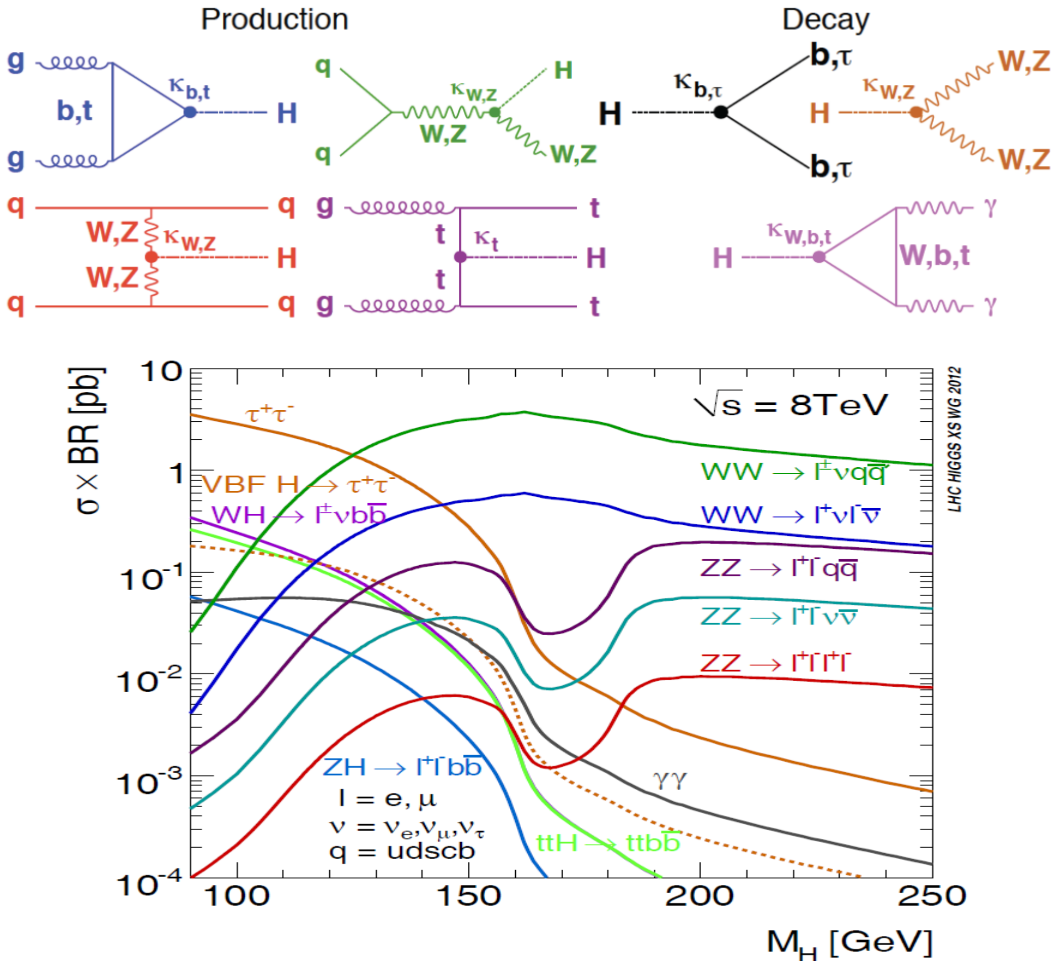
$$\Delta r \sim \ln\left[\frac{M_{Higgs}}{M_W}\right]$$

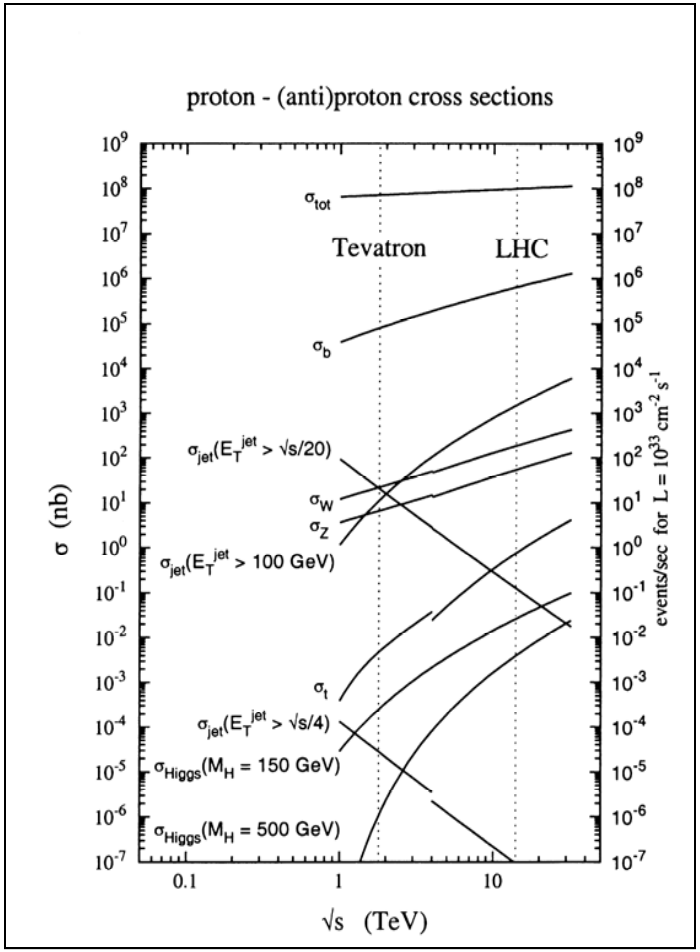
CERN-PH-EP-2010-095

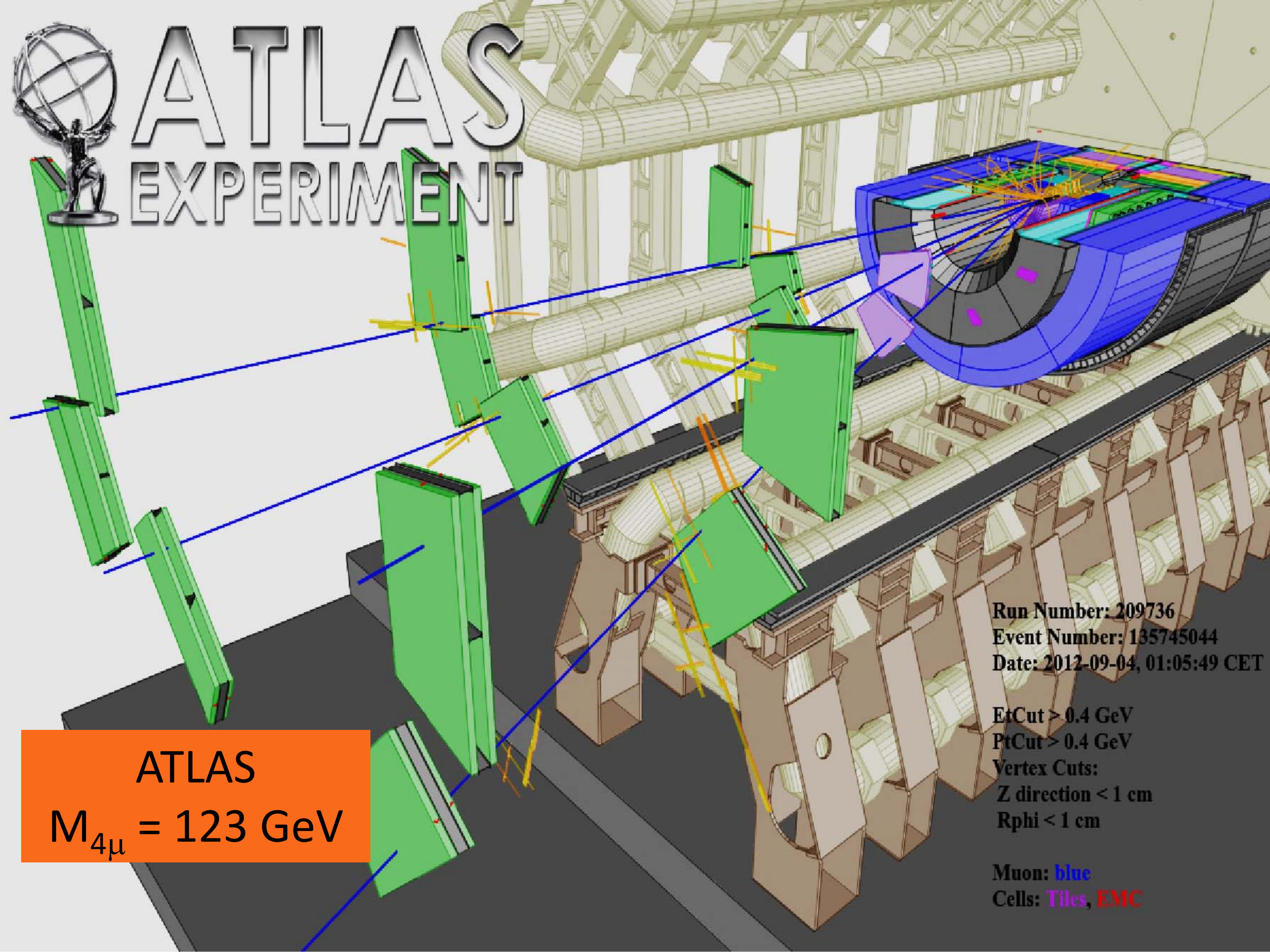
Mh = 89 +35/−26 GeV EW precision
Mh > 114 GeV LEPII
Mh < 158 GeV Tevatron
Mh > 175 GeV Tevatron

We had a pretty good idea on where to look for the Higgs!

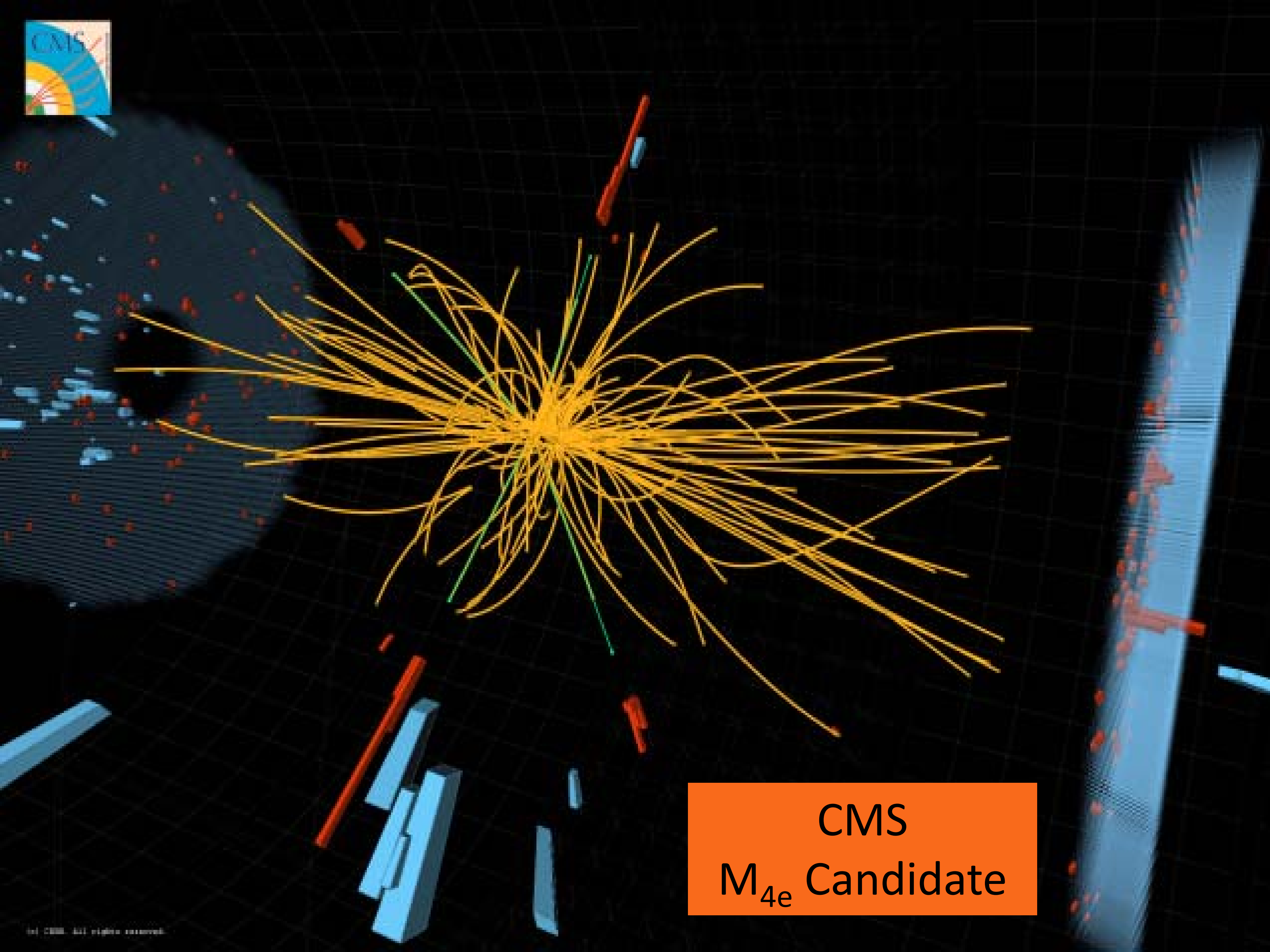
SM Higgs Cross Sections & Branching Ratios



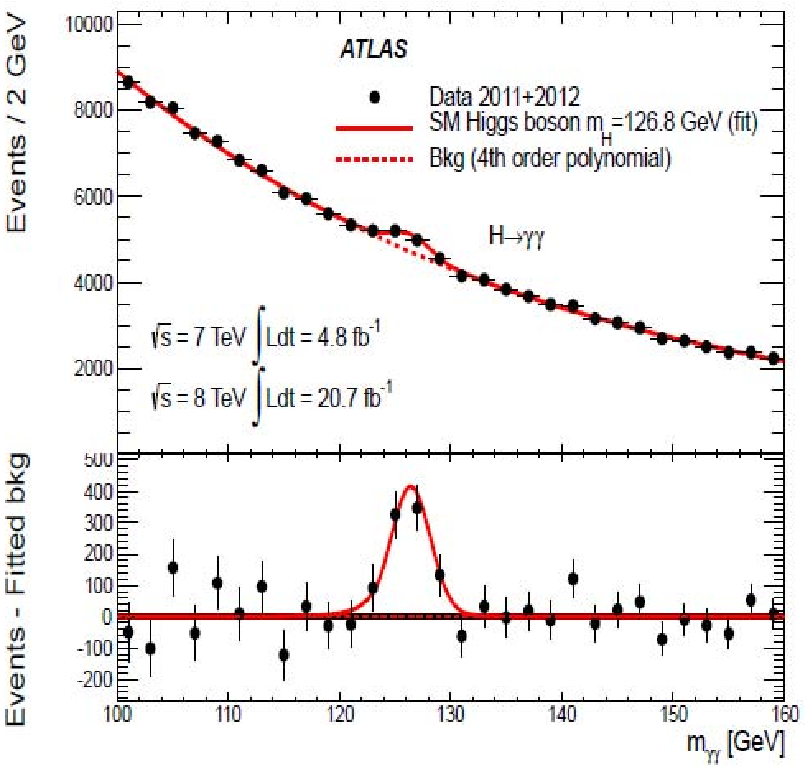


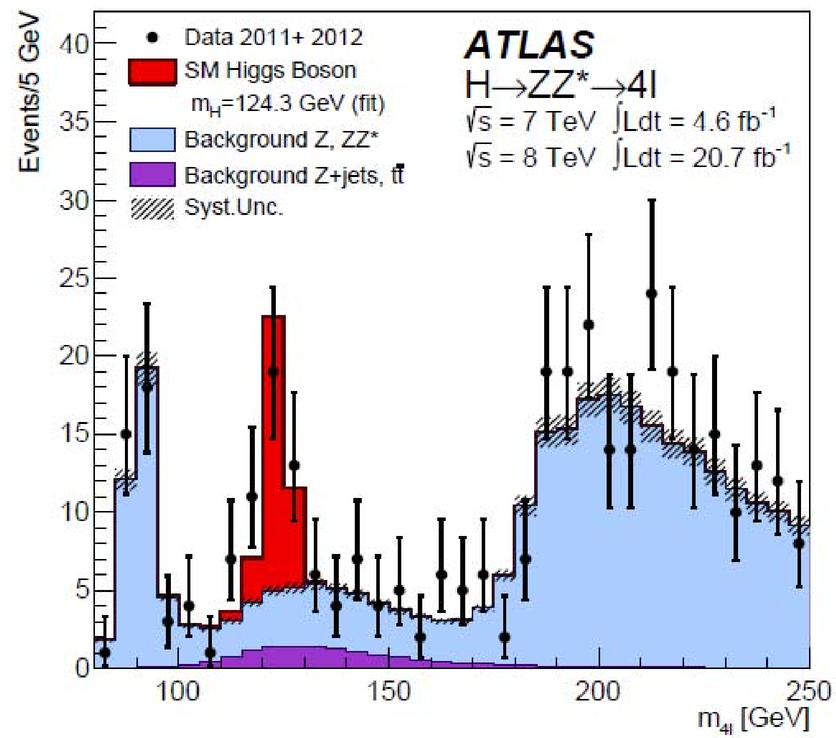


ATLAS
EXPERIMENT
Run Number: 209736
Event Number: 135745044
Date: 2012-09-04, 01:05:49 CET
EtCut > 0.4 GeV
PtCut > 0.4 GeV
Vertex Cuts:
Z direction < 1 cm
Rphi < 1 cm
Muon: blue
Cells: Tiles, EMC
ATLAS
M4μ = 123 GeV

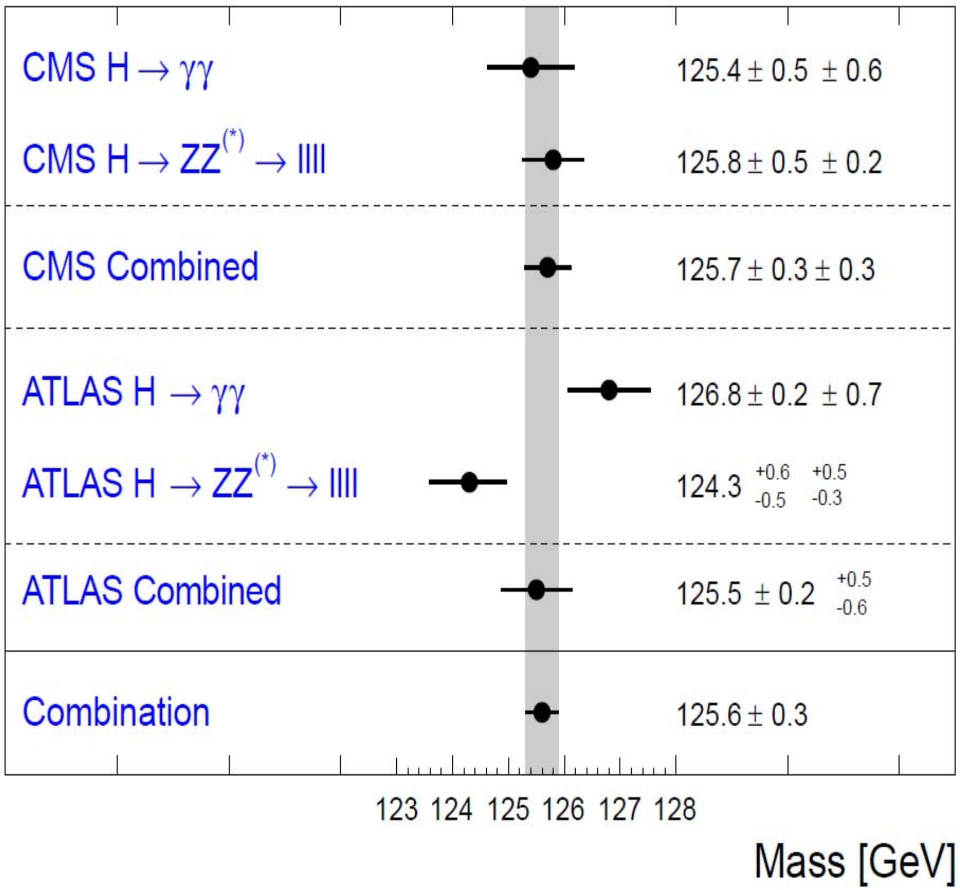

CMS
M_{4e} Candidate

M_{Higgs} Detection @ LHC - ATLAS

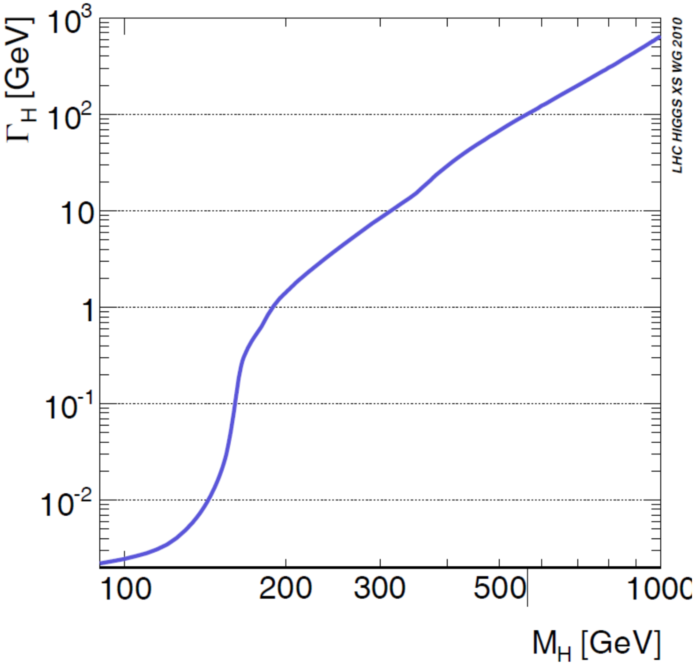




SM-Like Higgs Properties

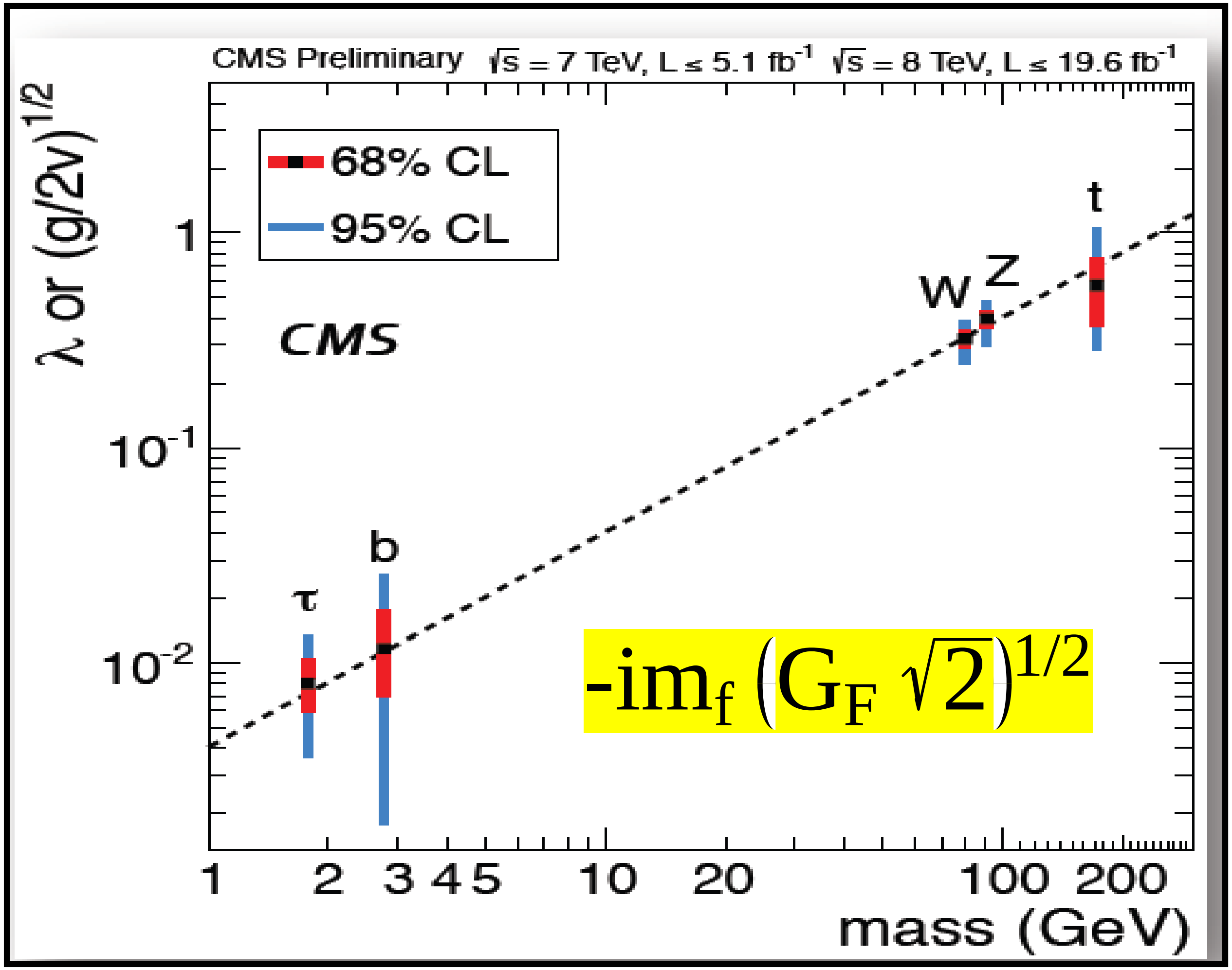


Width ~ 4.2 MeV (Theory)

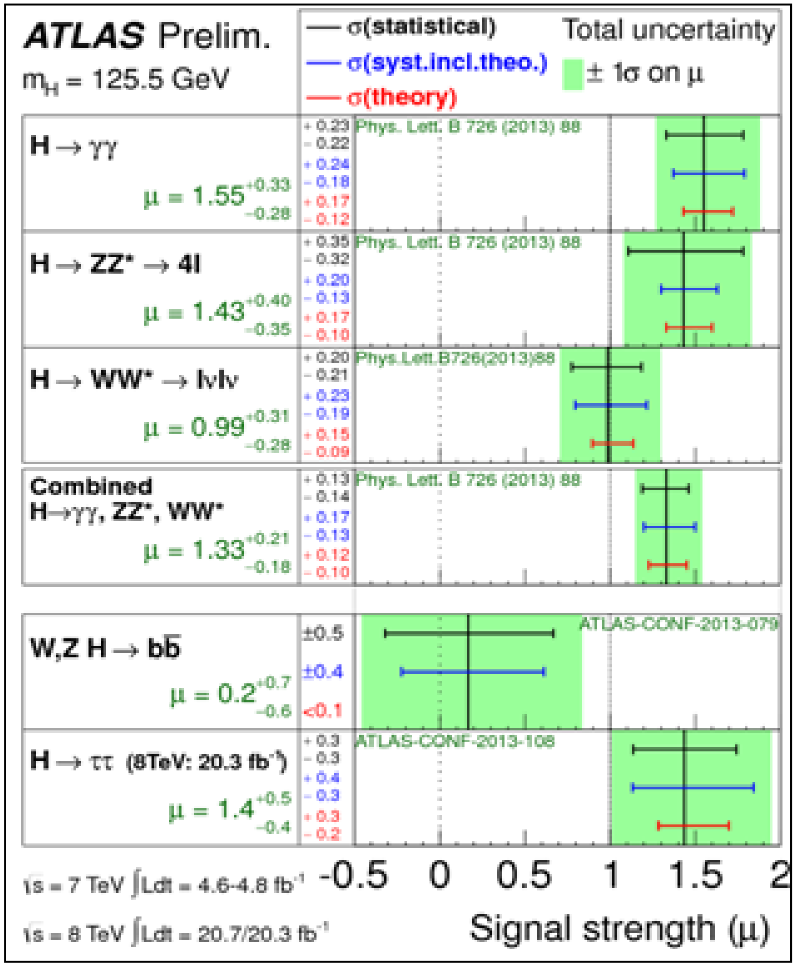


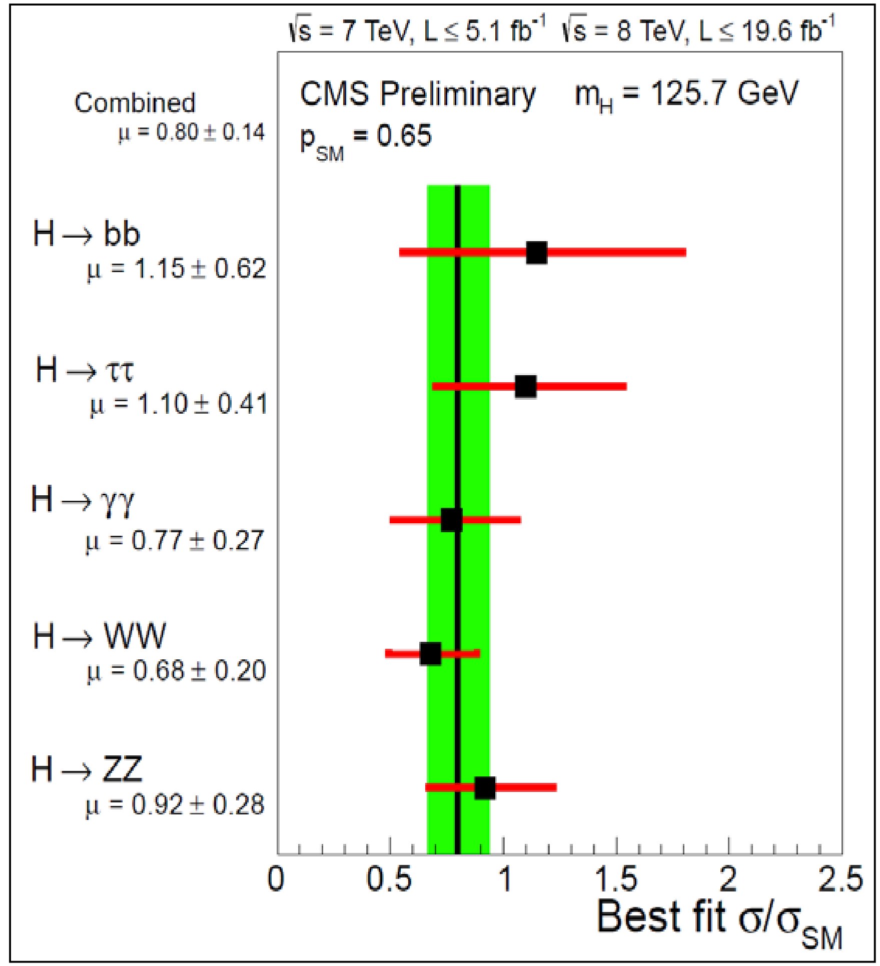
CMS measurement
$\Gamma/\Gamma_{SM} < 4.2$ @ 95% CL
Updated Today at La Thuille

Higgs Couplings ≈ F(mass)

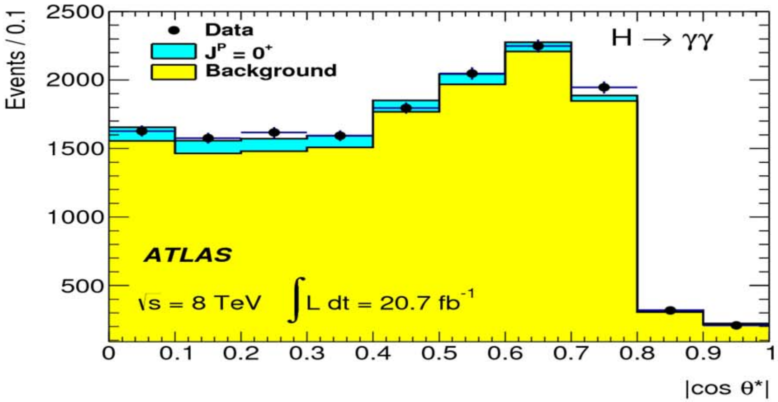


Higgs Signal Strength vs. Theory

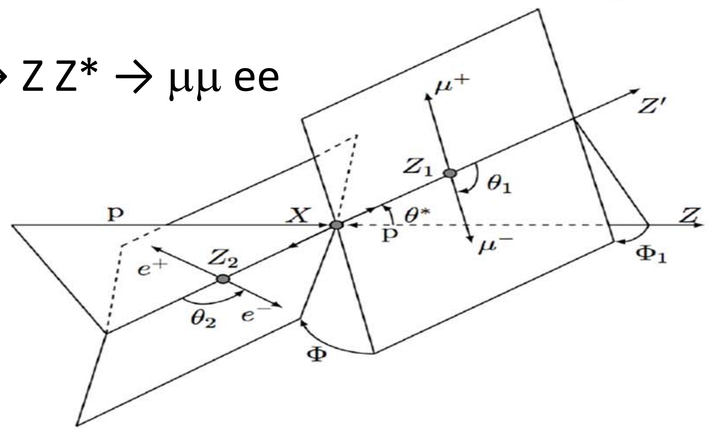


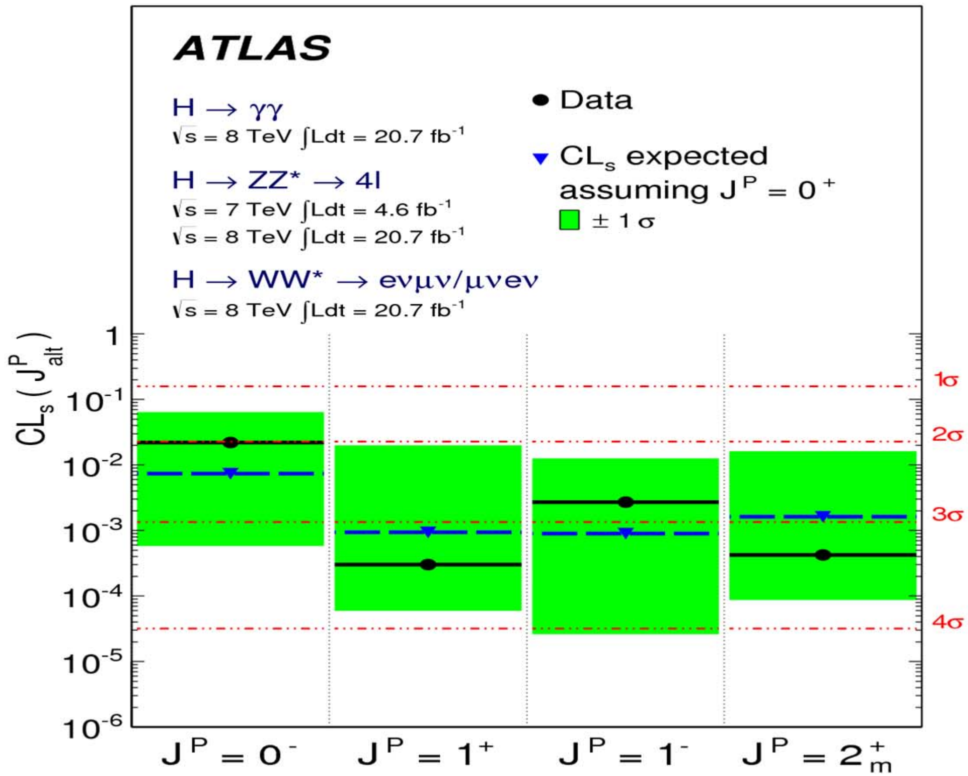


Higgs Spin Determination



H → Z Z* → μμ ee

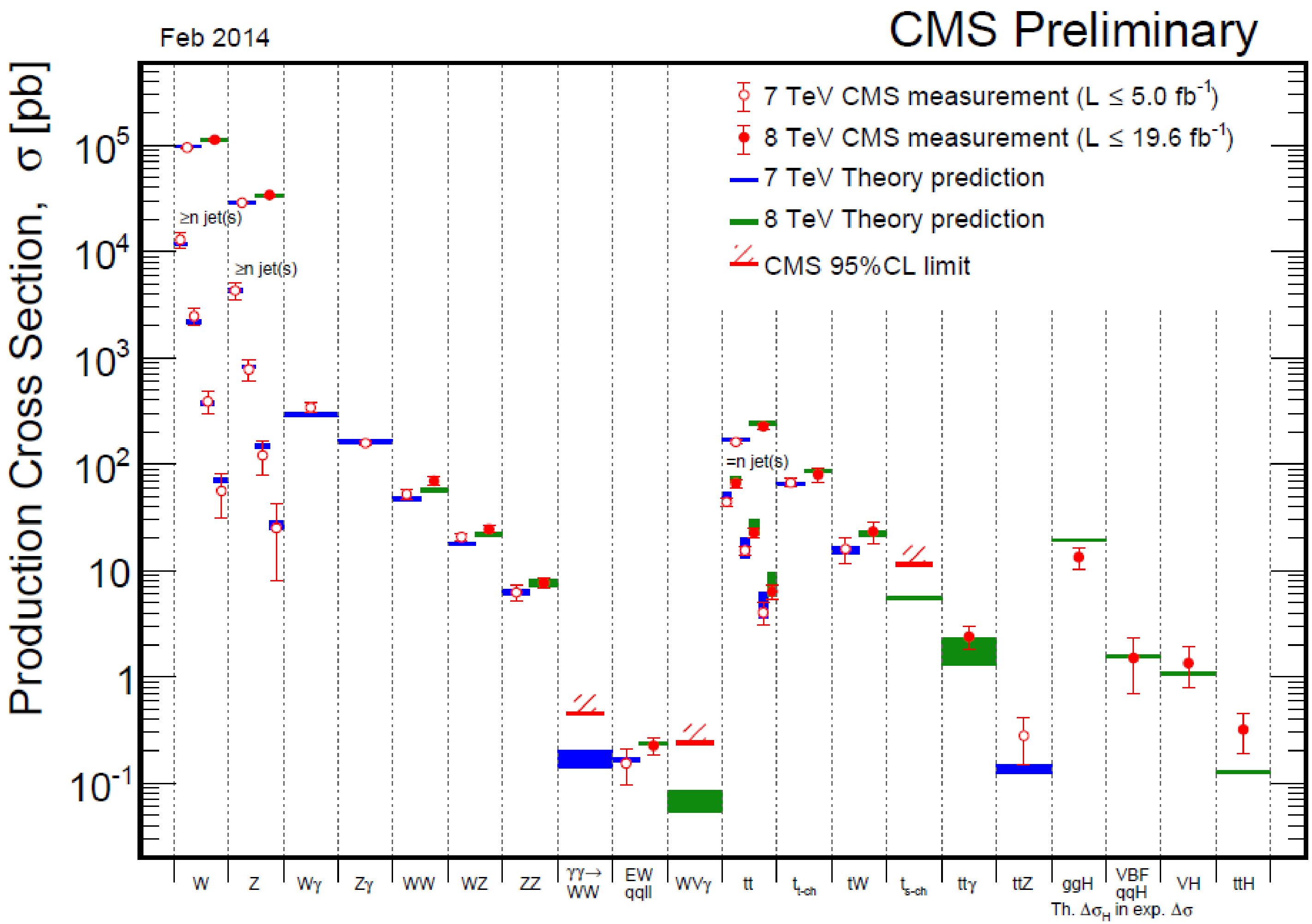




Data are compatible with $J^P = 0^+$
$J^P = 0^-, 1^+, 1^-, 2^+_m$ excluded at CL = 98%
Phys. Lett. B 726 (2013) 120-144

Mass, Spin, CP, Branching Ratios, Production Cross Section are all consistent with the SM Higgs

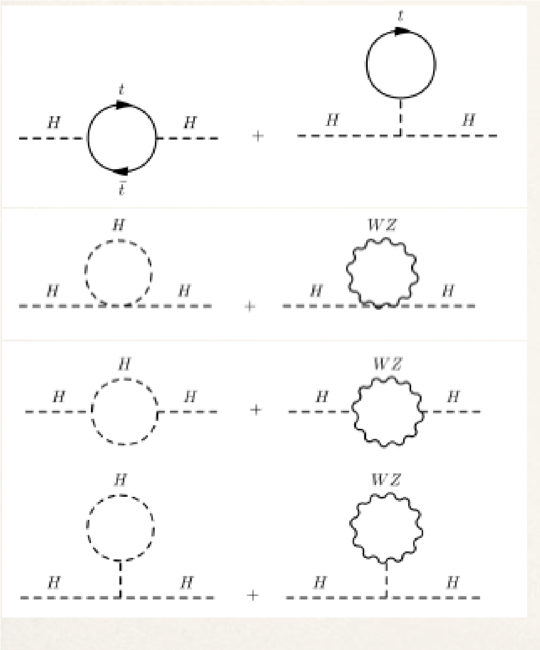
Tests of the SM @ LHC



Theoretical Problem – Experimental Opportunity

Radiative corrections to the Higgs mass as a function of energy scale Λ:

$$M_H^2 = M_0^2 + \frac{3\Lambda_C^2}{8\pi^2 v^2}\left[\underbrace{M_H^2 + 2M_W^2 + M_Z^2}_{B} - \underbrace{4m_t^2}_{F}\right] + \ldots$$



Note that Bosons enter the series with opposite sign of the Fermions. It would seem that a fine tuning (cancelation of terms) is needed to keep the Higgs mass finite up to the Planck scale.

Supersymmetry provides a natural solution – for every fermion there is a corresponding supersymmetric boson partner & vice versa.

Supersymmetry is a candidate theory to solve this dilemma

To paraphrase George Santayana: "Those who fail to confirm or reject the theories of the past are condemned to repeat the search"

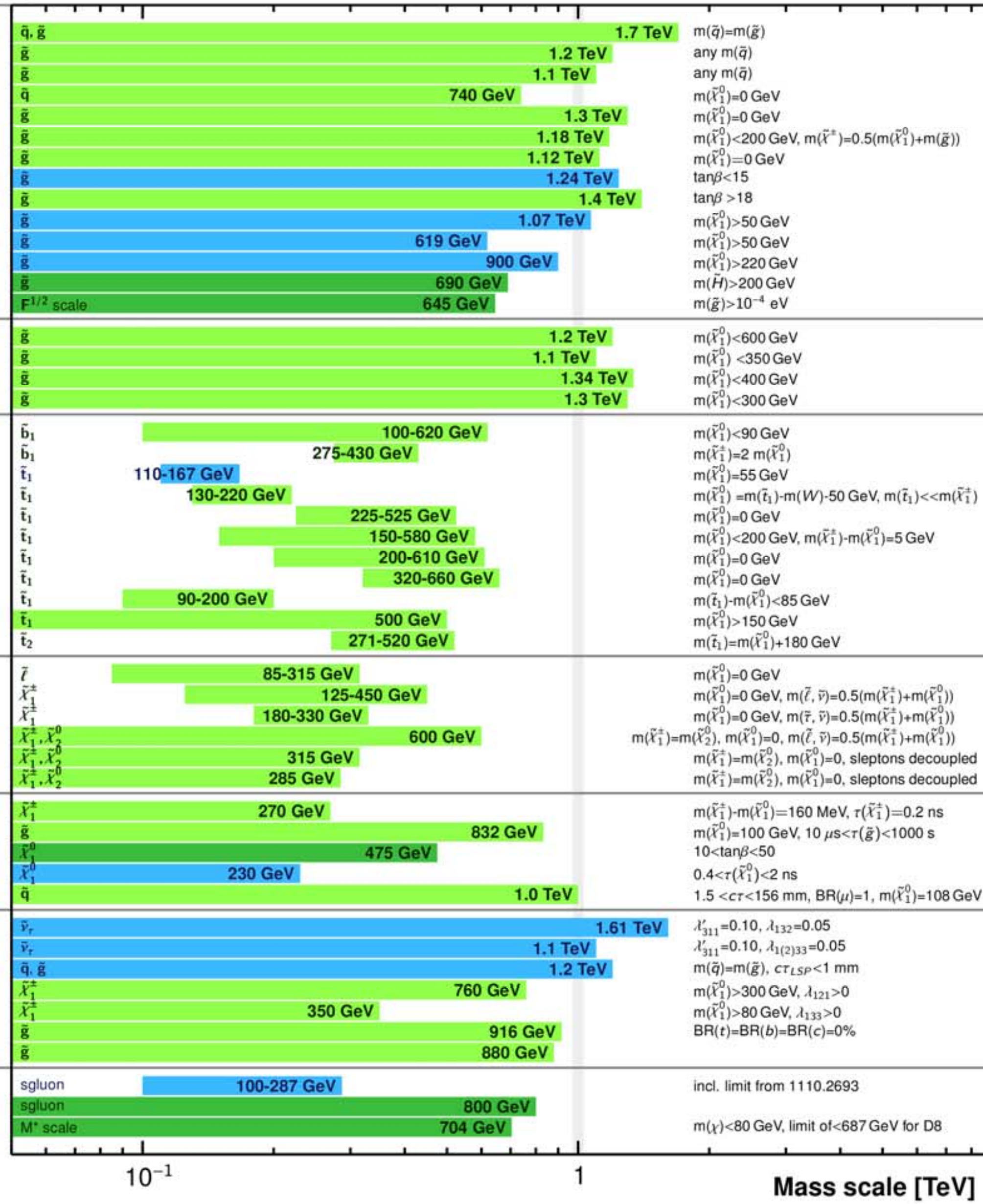
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: SUSY 2013

ATLAS Preliminary

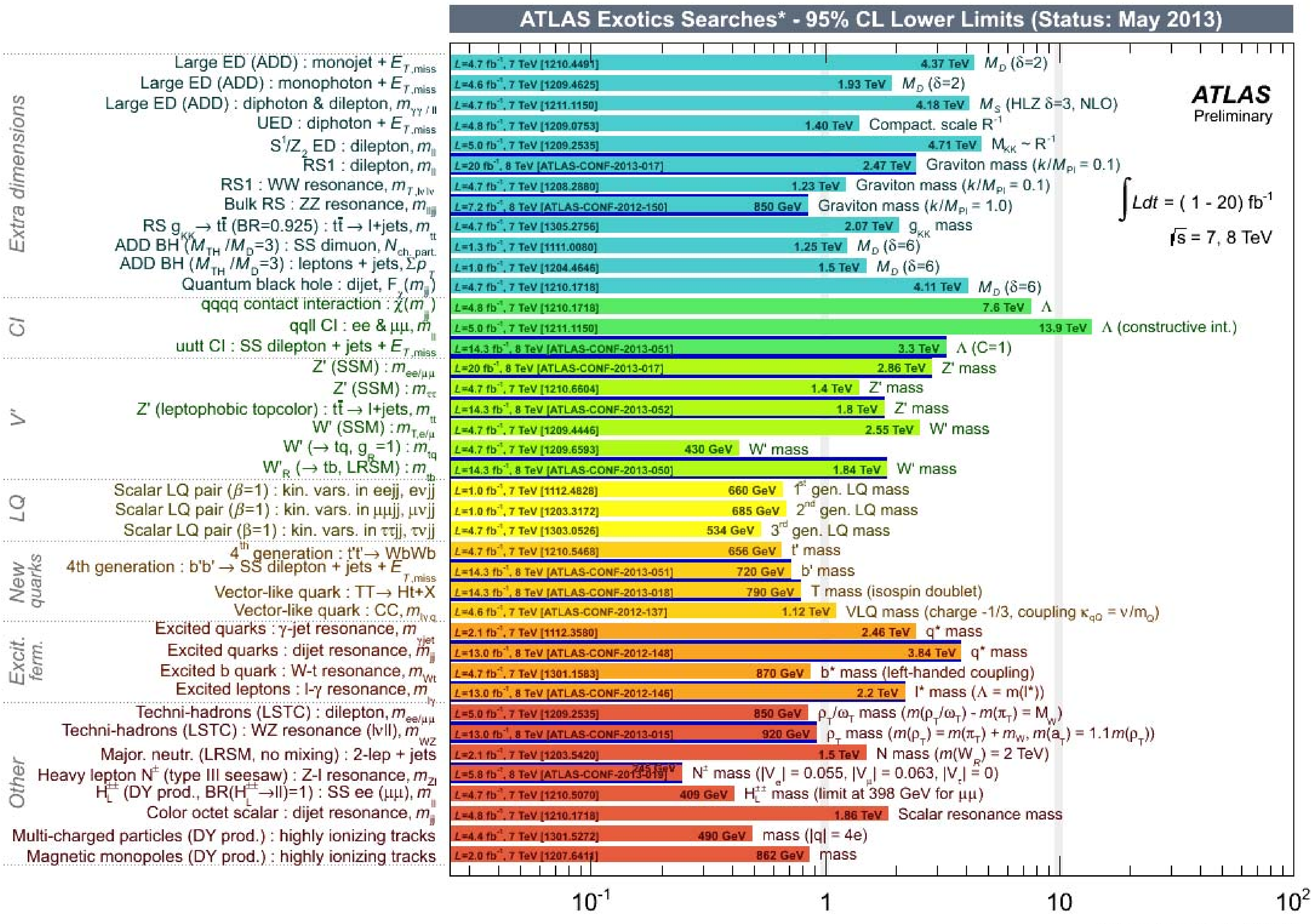
$\int \mathcal{L}\, dt = (4.6 - 22.9)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^\pm\to qqW^\pm\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta$ >18	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	-	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	1209.0753
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H})$>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}_1^0)$<600 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	ATLAS-CONF-2013-061
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	ATLAS-CONF-2013-061
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	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^\pm$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 275-430 GeV	$m(\tilde{\chi}_1^\pm)=2\, m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-220 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^\pm)$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 225-525 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-065
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^\pm$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^\pm)-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-200 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	ATLAS-CONF-2013-068
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 271-520 GeV	$m(\tilde{t}_1)=m(\tilde{\chi}_1^0)$+180 GeV	ATLAS-CONF-2013-025
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	$\tilde{\ell}$ 85-315 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^\pm$ 125-450 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 180-330 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^\pm)+m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	3 e,μ	0	Yes	20.7	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^\pm)=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
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, $\tau(\tilde{\chi}_1^\pm)$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	22.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	ATLAS-CONF-2013-057
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	1 e,μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 760 GeV	$m(\tilde{\chi}_1^0)$>300 GeV, λ_{121}>0	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.7	$\tilde{\chi}_1^\pm$ 350 GeV	$m(\tilde{\chi}_1^0)$>80 GeV, λ_{133}>0	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	1 b	Yes	14.3	sgluon 800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147



$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.



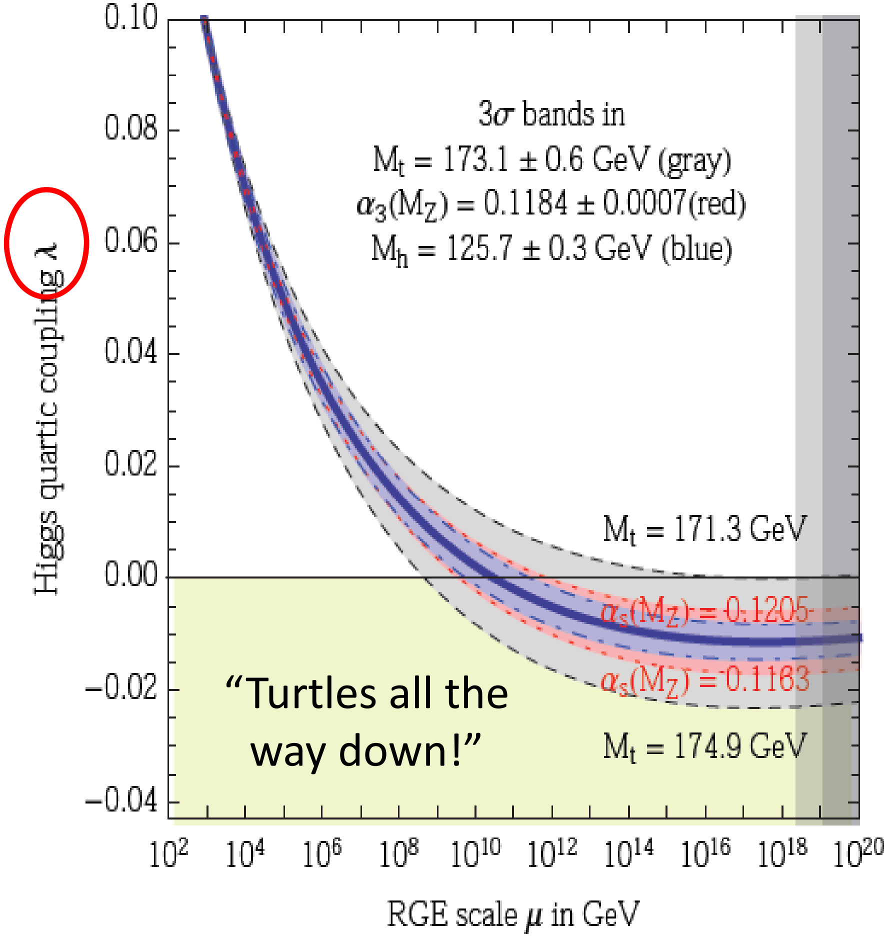
*Only a selection of the available mass limits on new states or phenomena shown

The SM Higgs Potential

- M_H is light - therefore there is the possibility that its potential could be finite up to the Planck scale
  - Examine the Higgs potential quartic coupling, λ, as a function of energy scale

$$V = -m^2|H|^2 + \lambda|H|^4$$

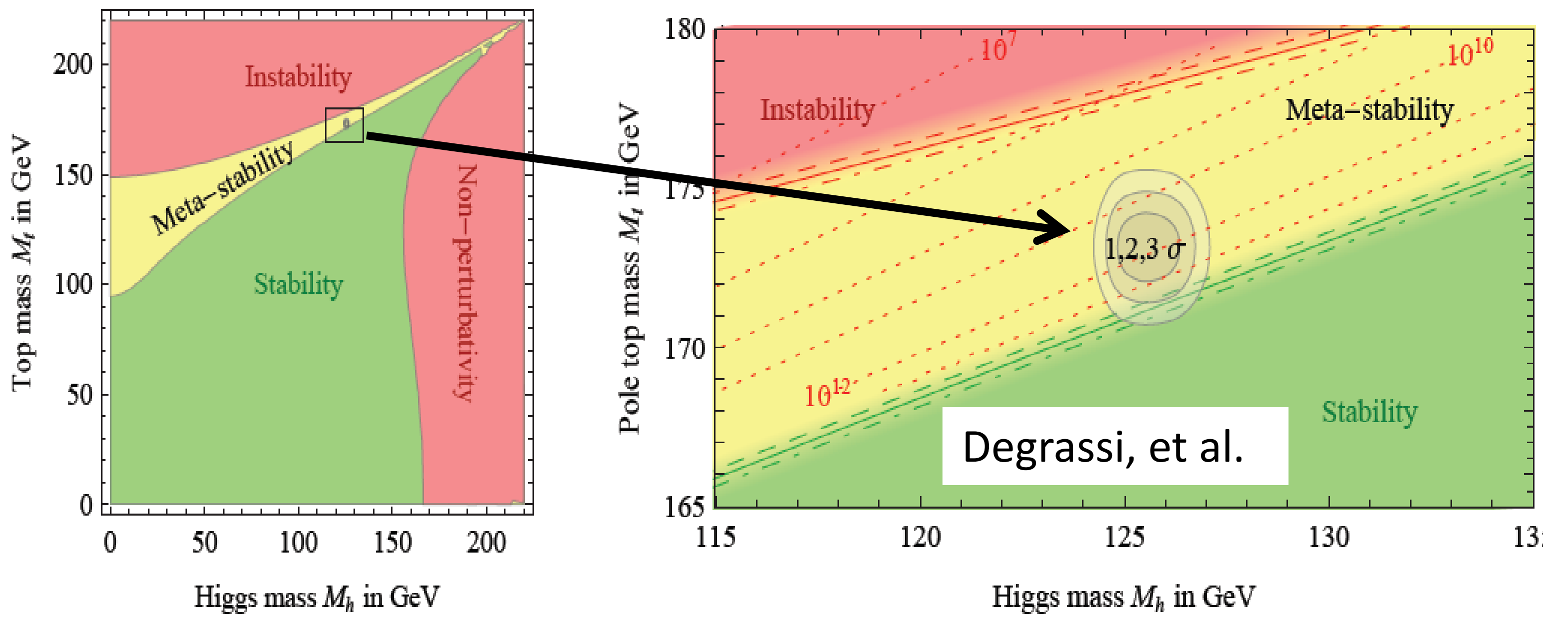
  - Find that λ goes negative (meta-stable) but with some spread in parameters within errors goes to 0 at Planck scale (extrapolation only 16 orders of magnitude !)



Degrassi, et al. , arXiv:1205.6497v2

Stability of SM Vacuum

The minimum M_H value that ensures vacuum stability is where the Higgs potential quartic coupling goes to 0. Note that this point is only a few orders of magnitude away from the Planck scale given experimental errors.



$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\,.$$

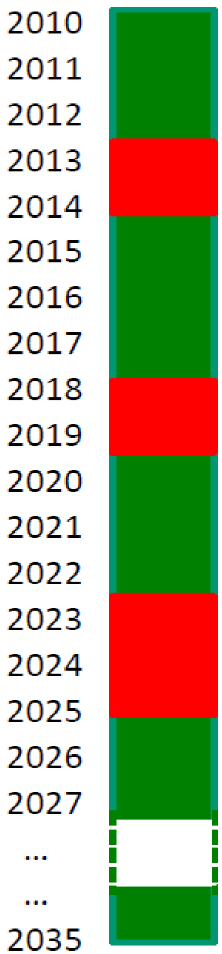
for stability

Near Term Physics Program

- More precise measurements of the Higgs properties
  - Better mass and BR determinations
  - Width (?) by interference with $\gamma\gamma$ background
  - Search for multi-Higgs production
- Search for violations of the SM
  - A cross section that does not agree, for example
- Search for physics beyond the standard model
  - Z', SUSY, Extra dimensions, Black holes, Dark Matter
- Detector upgrades are underway to better trigger and withstand the expected pileup at high L

LHC Luminosity Projections to 2027

updated by CERN
Dec. 2, 2013



Run 1: √s=7-8 TeV, ∫Ldt=25 fb-1, pileup **μ≈20**

$L^{peak}=0.7\times10^{34}\ cm^{-2}s^{-1}$

LS1: **phase 0** upgrade

Run 2: √s≈13-14 TeV, ∫Ldt≈120 fb-1, pileup **μ≈43**

$L^{peak}=1.6\times10^{34}\ cm^{-2}s^{-1}$

LS2: **phase 1** upgrade

Run 3: √s≈14 TeV, ∫Ldt≈350 fb-1, pileup **μ=50-80**

$L^{peak}\approx2\text{-}3\times10^{34}\ cm^{-2}s^{-1}$

LS3: **phase 2** upgrade

HL-LHC: √s≈14 TeV, ∫Ldt≈3000 fb^{-1}, pileup **μ≈140-200**

$L^{peak}=20\times10^{34}\ cm^{-2}s^{-1}$ leveled to $L^{peak}=(5\text{-}7.5)\times10^{34}\ cm^{-2}s^{-1}$

*LS="long shutdown"

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

Complete reconstruction of 1500 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines

18 000 electrical Quality Assurance tests

10170 leak tightness tests

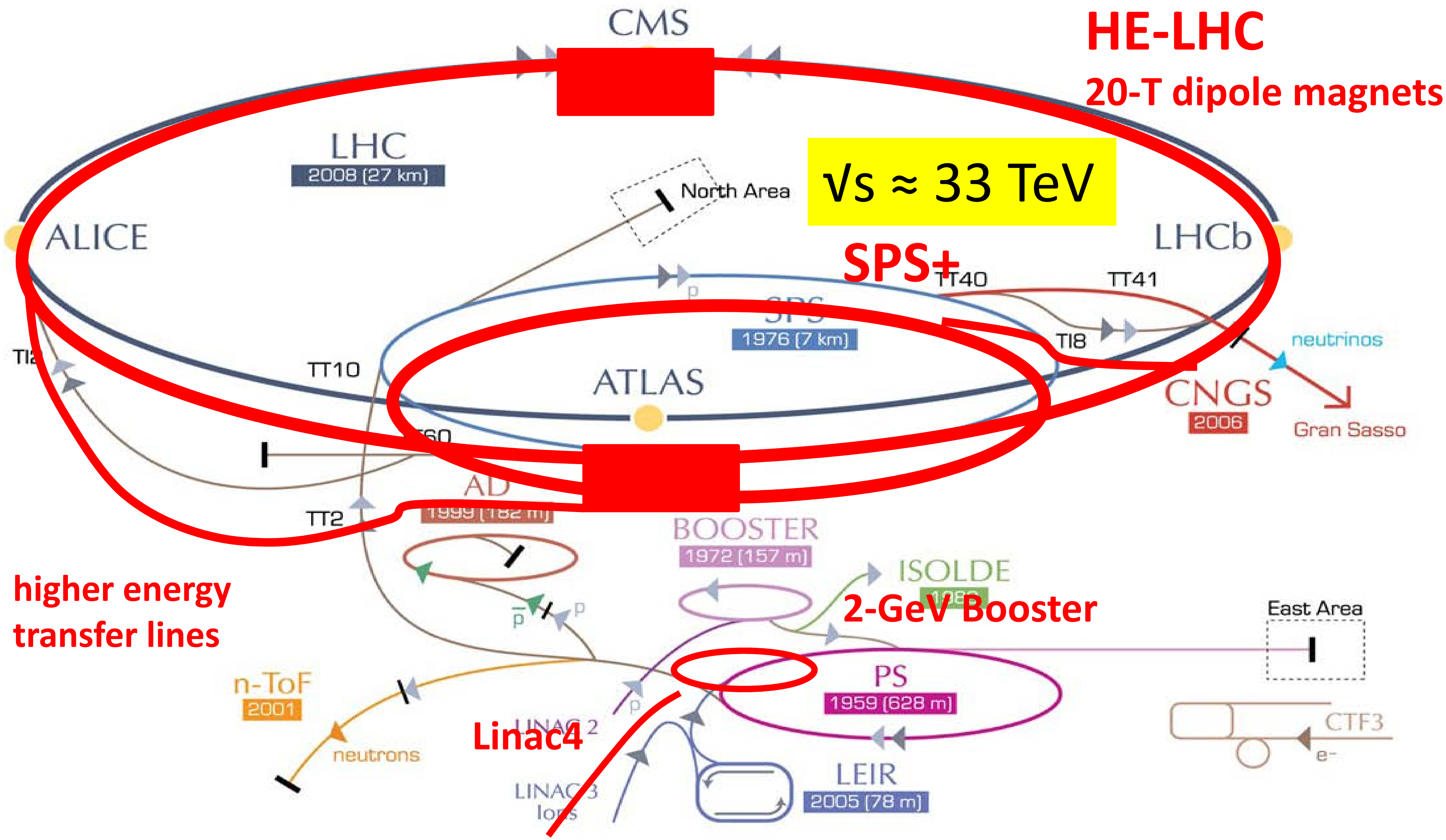
4 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

Longer Term Upgrade: High Energy-LHC



LHC Results

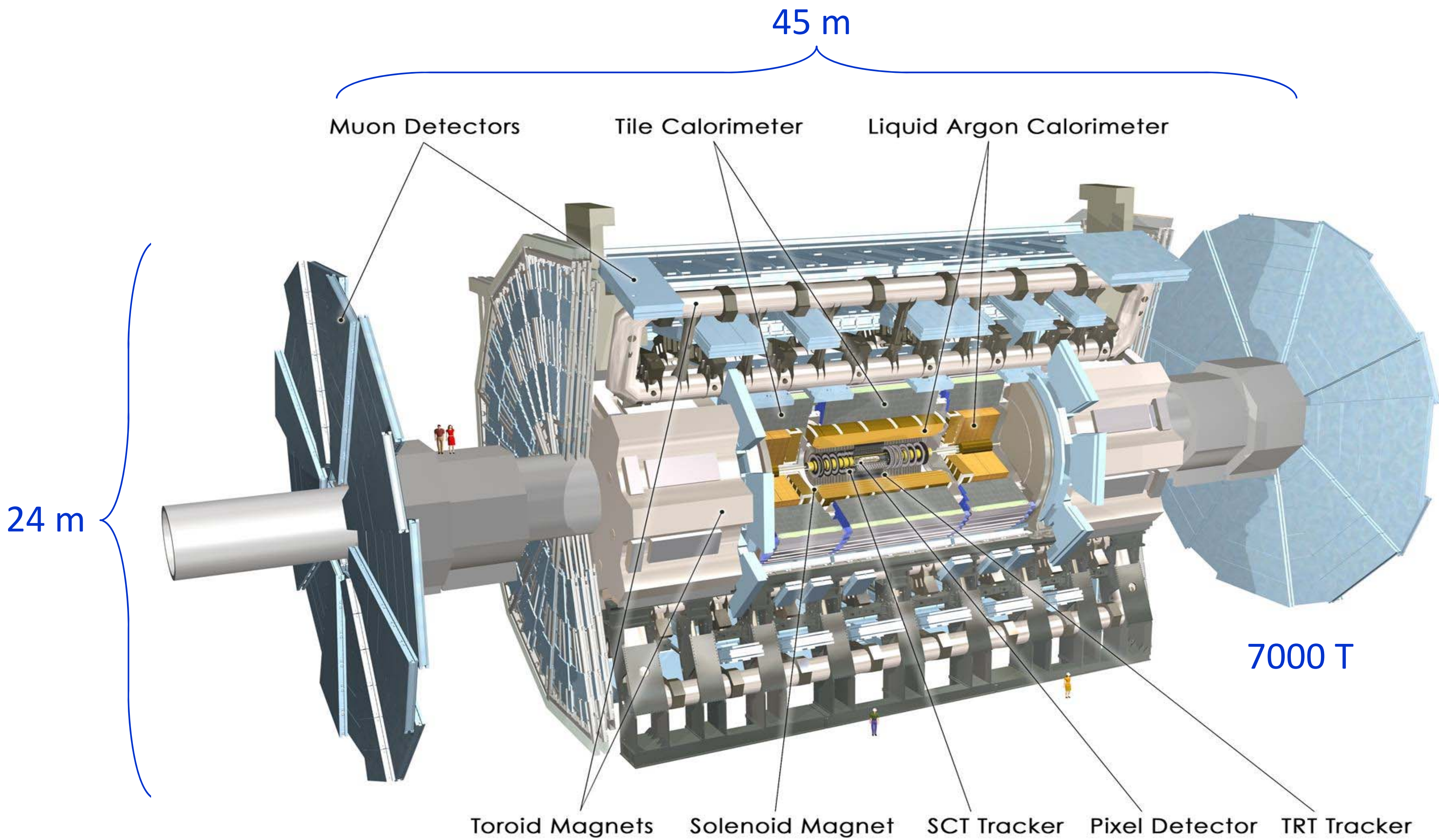
- So far the LHC physics program has beautifully confirmed the predictions of the SM!
  - The Higgs is consistent with a single scalar particle of mass 126 GeV
  - Branching ratios agree with the predictions of the SM
  - Data in the future will refine these results
- What about the phantoms?
  - SUSY and Extra Dimensions and Black Holes and Dark Matter not yet observed
  - Given the (near) meta-stability of the vacuum SUSY really needed (?) (Bardeen, Lykken, Iso, …)
- LHC running in 2015 will have $\sqrt{s} \approx 13$ TeV and that factor of 1.6 increase in energy may (?) uncover another energy threshold.
  - At $\sqrt{s} = 8$ TeV no new energy thresholds have been observed

Summary

- We high energy physicists have been very privileged to work in the era of the SM of the EW sector during the last 40 years. We had guidance of the energy required for the next machine
  - In a sense all the energy scales were derived from theory, prior discovery and the values of G_f, θ_w & α_{em} - the stepping stones
  - This is a remarkable achievement!
- The future is not so certain but if history is any guide probing the highest energies will uncover new phenomena
  - There are many possibilities but no clear theoretical guidance
  - There are examples of physics proposed where the energy scale was not known but eventually discovered - example
    - Neutrino oscillations discovered long after paper by B. Pontecorvo
  - What about SUSY – forever a phantom or to become a fact?

Backup Slides

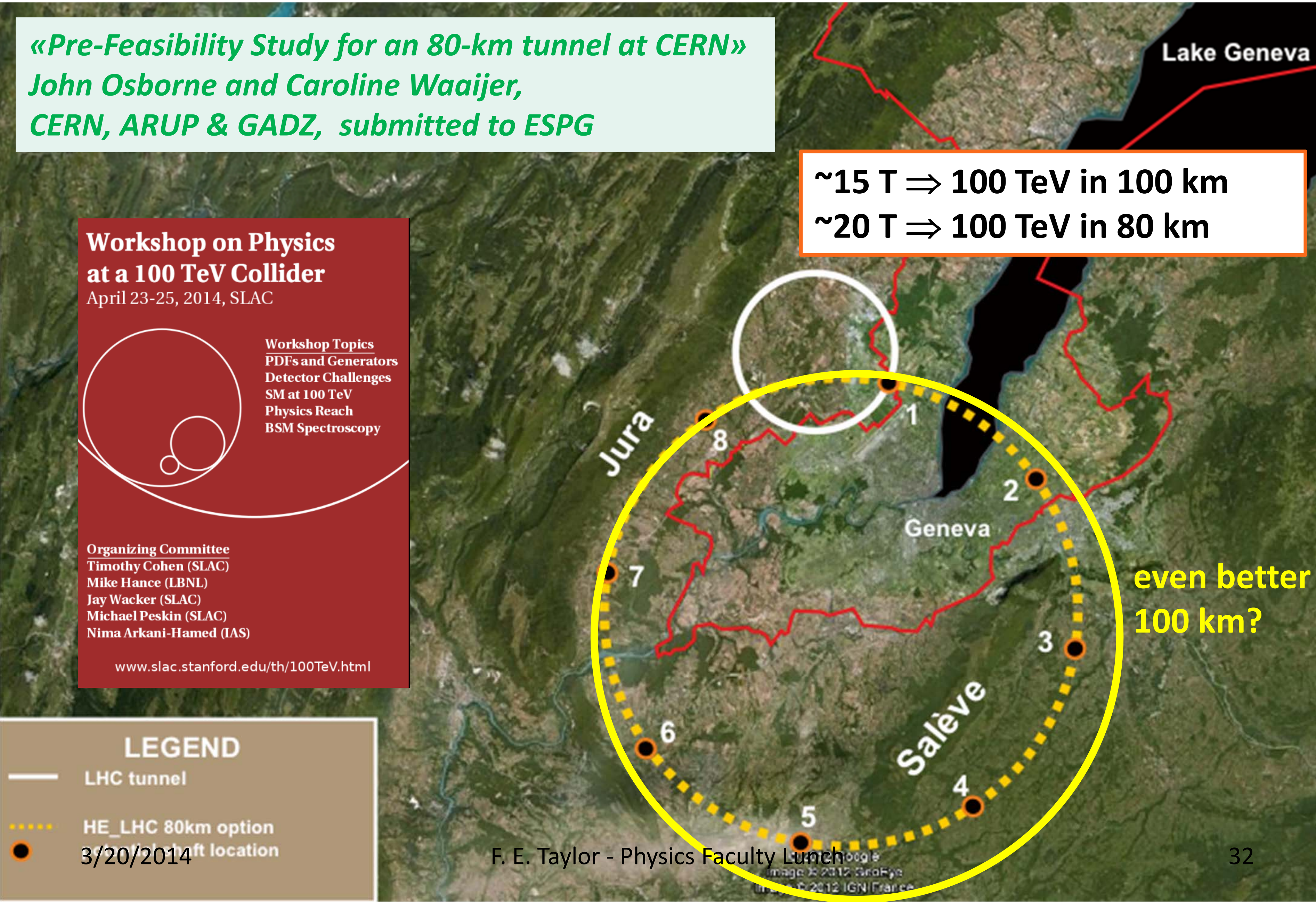
ATLAS Detector



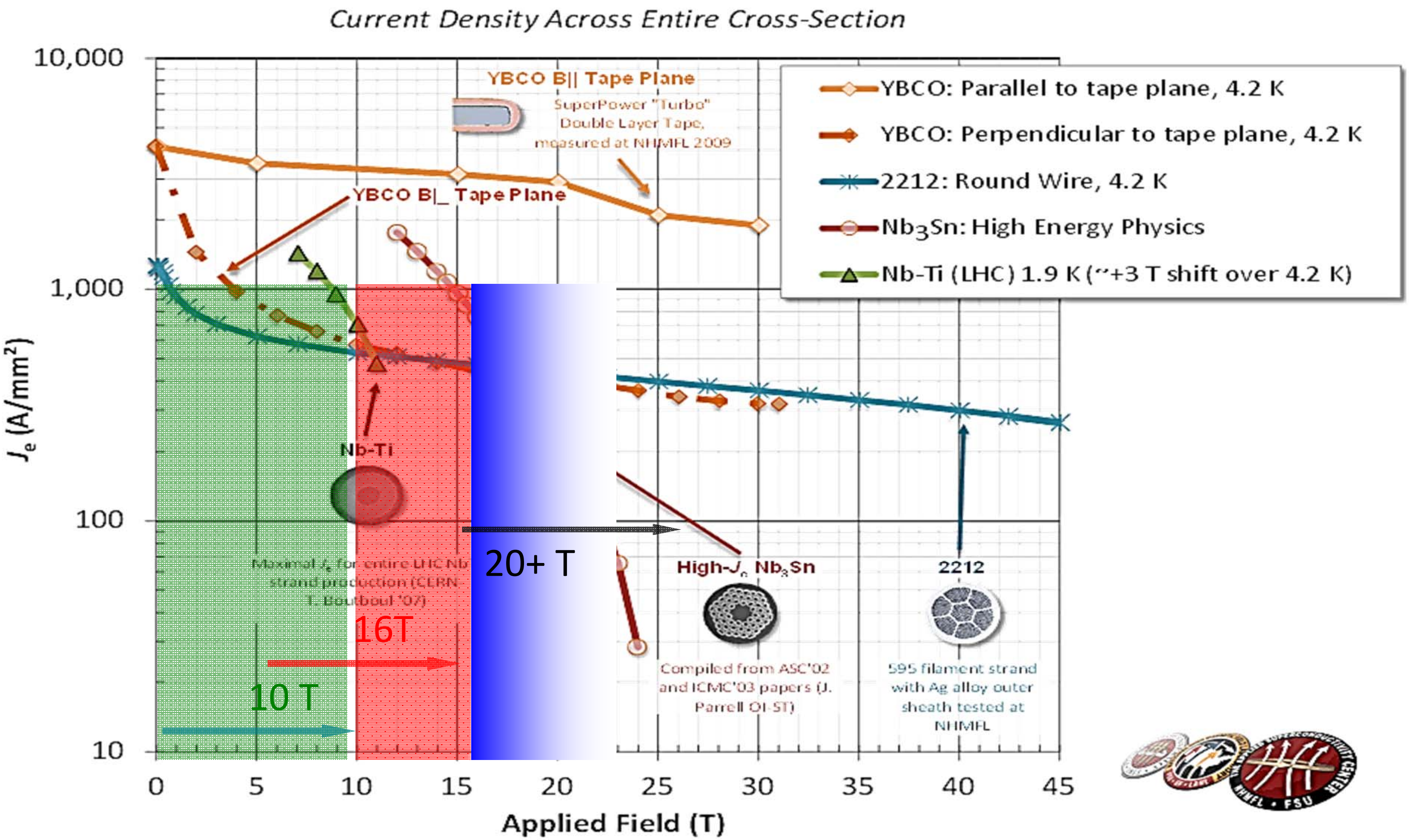
100 TeV FCC 80-100 km tunnel: Geneva option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG

~15 T ⇒ 100 TeV in 100 km
~20 T ⇒ 100 TeV in 80 km



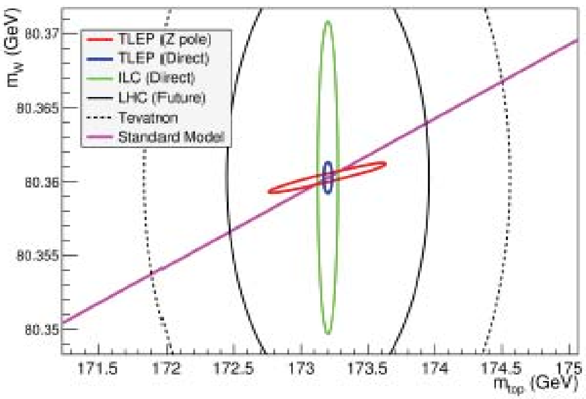
Superconductors



Physics Prospectus @ 100 TeV

FCC/TLEP Physics in a Nutshell

- 10^{12} Z, 10^{8} WW, 2 x 10^{6} ZH, 10^{6} tt
- Sensitivity to BSM physics through precision Z, W, H, t processes
  - Higgs invisible width to .16%, $g_{H\gamma\gamma}$ to 1.4%, g_{HZZ} to .05%, $g_{H\tau\tau}$ to .49%
  - ΔM_W = <.5 MeV, ΔM_Z < 100 KeV
- Search for rare processes



Sally Dawson, BNL Dec-2013

[TLEP physics, arXiv:1308.6176]