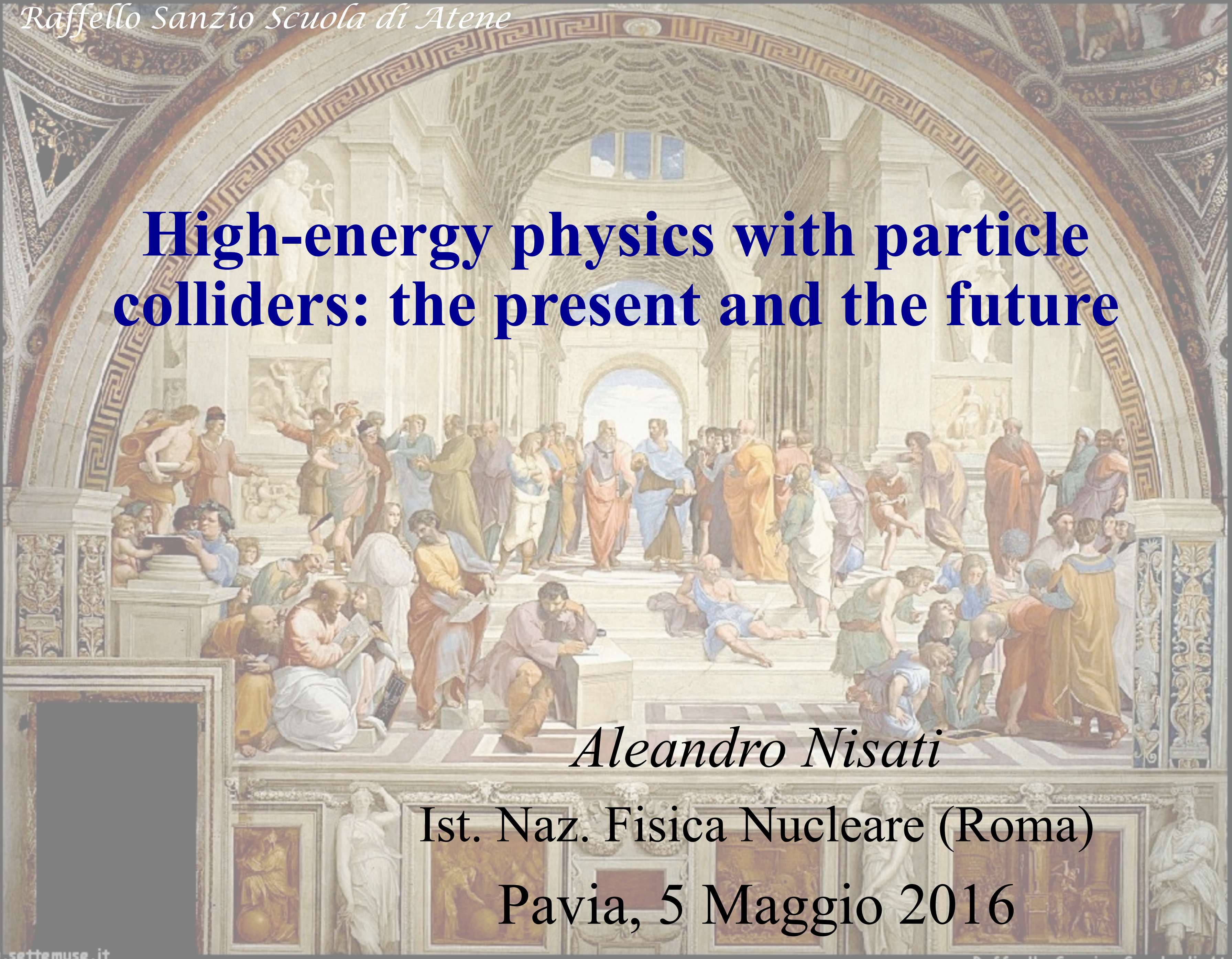


Raffello Sanzio Scuola di Atene

High-energy physics with particle colliders: the present and the future

Aleandro Nisati

Ist. Naz. Fisica Nucleare (Roma)

Pavia, 5 Maggio 2016

Index

Where are we today?

- *July 2012*: ATLAS and CMS announce the observation of a new, neutral particle with mass near 125 GeV, compatible with the Higgs boson predicted by the Standard Model
- The discovery is made searching for the Standard Model *bosonic* decays:
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ^* \rightarrow 4l$ ($l=e,\mu$)
  - $H \rightarrow WW^* \rightarrow l\nu l\nu$ ($l=e,\mu$)
  - Recently, preliminary results from the $\sqrt{s}=7,8$ TeV run (*Run1*) based on the ATLAS and CMS combination have provided the observation of the $H \rightarrow \tau\tau$ decay mode as well. First observation of a *fermionic* Higgs boson decay: see:

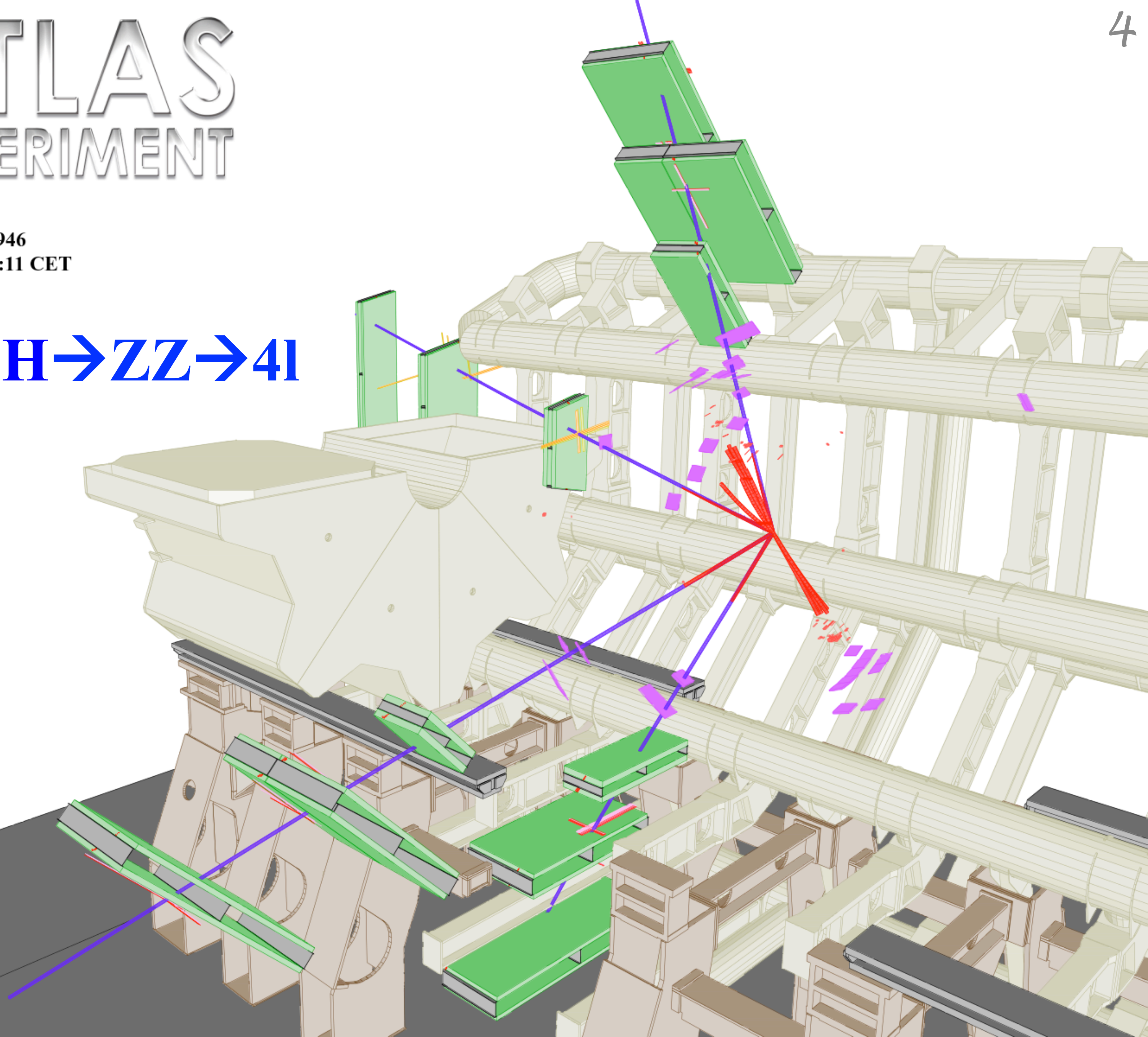
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-044/

Run Number: 189280,
Event Number: 143576946
Date: 2011-09-14, 11:37:11 CET

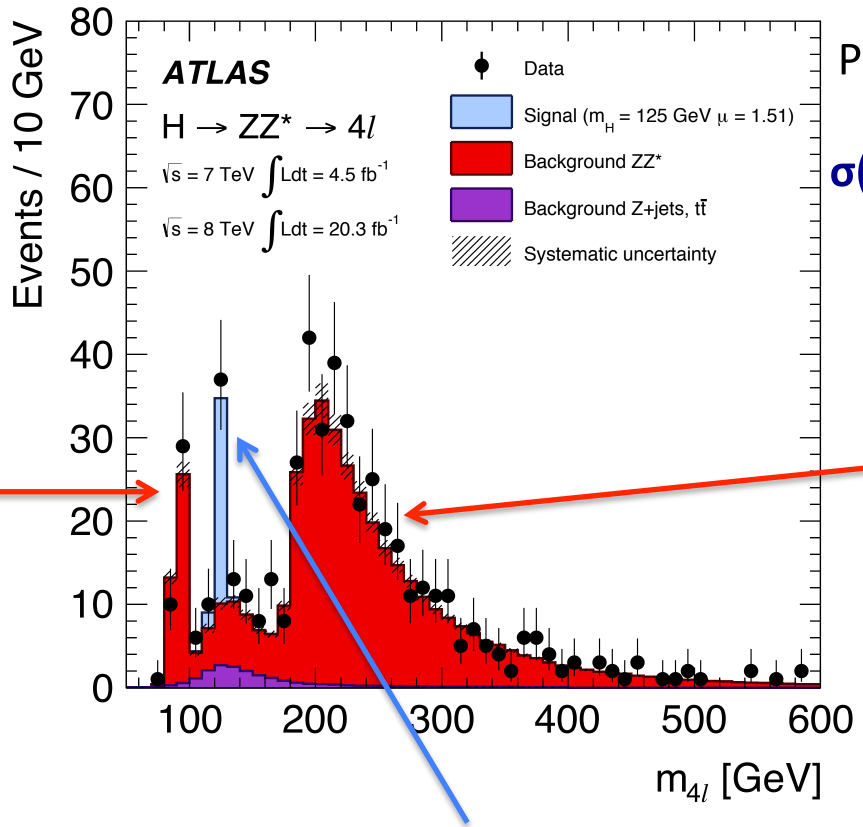
EtCut>0.3 GeV
PtCut>3.0 GeV
Vertex Cuts:
Z direction <1cm
Rphi <1cm

Muon: blue
Cells:Tiles, EMC

H→ZZ→4l



$H \rightarrow ZZ^* \rightarrow 4l$



Phys. Rev. D 91, 012006

$\sigma(m_H=125$ GeV$) \cong 1.6\text{-}2.2$ GeV

$Z \rightarrow 4l$

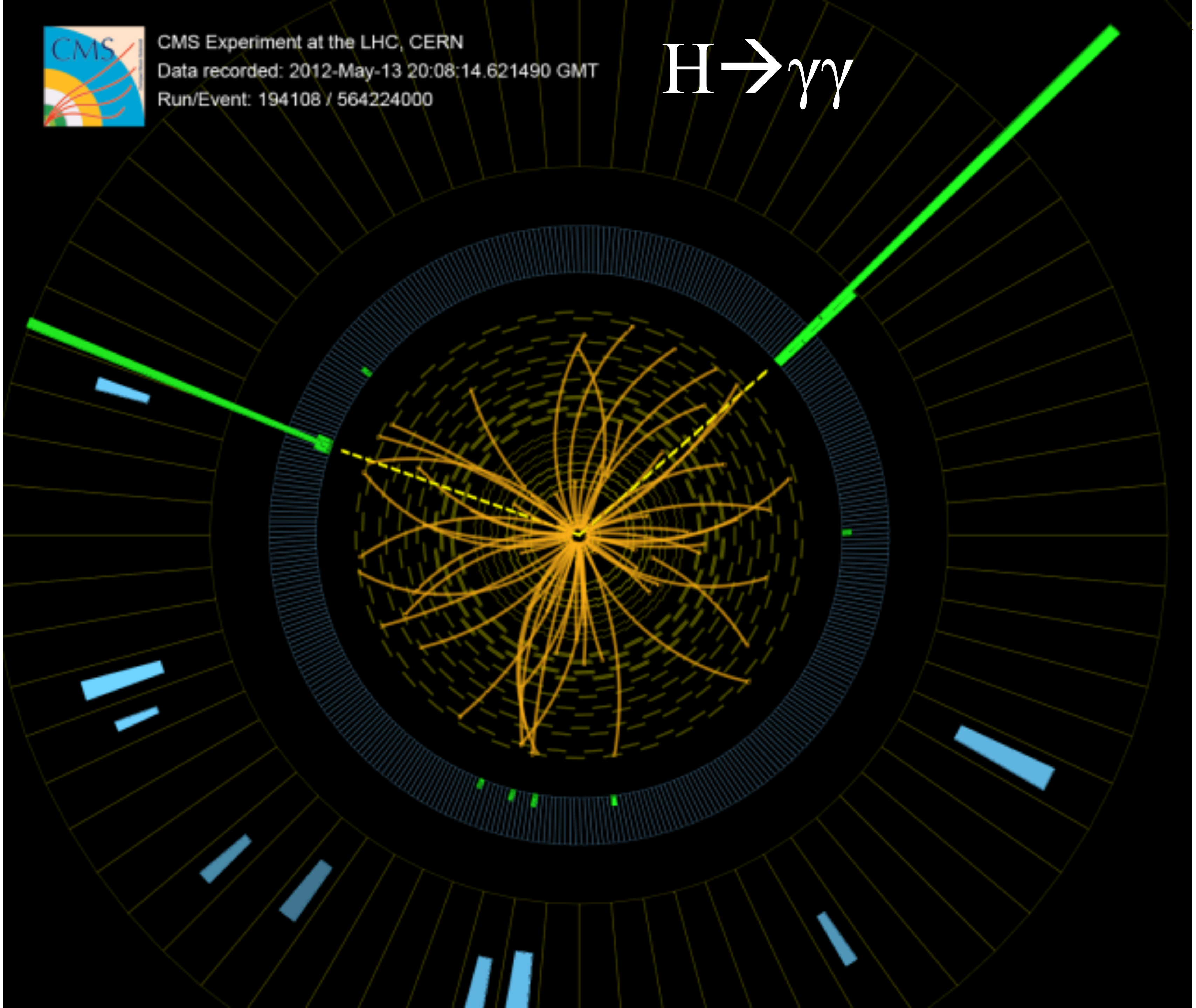
$ZZ \rightarrow 4l$ (continuum)

$H \rightarrow ZZ^* \rightarrow 4l$

$$\mu = \sigma_{\text{observed}} / \sigma_{\text{SM}}$$
$$\mu_{H(SM)} = 1$$
$$\mu_{\text{backg}} = 0$$

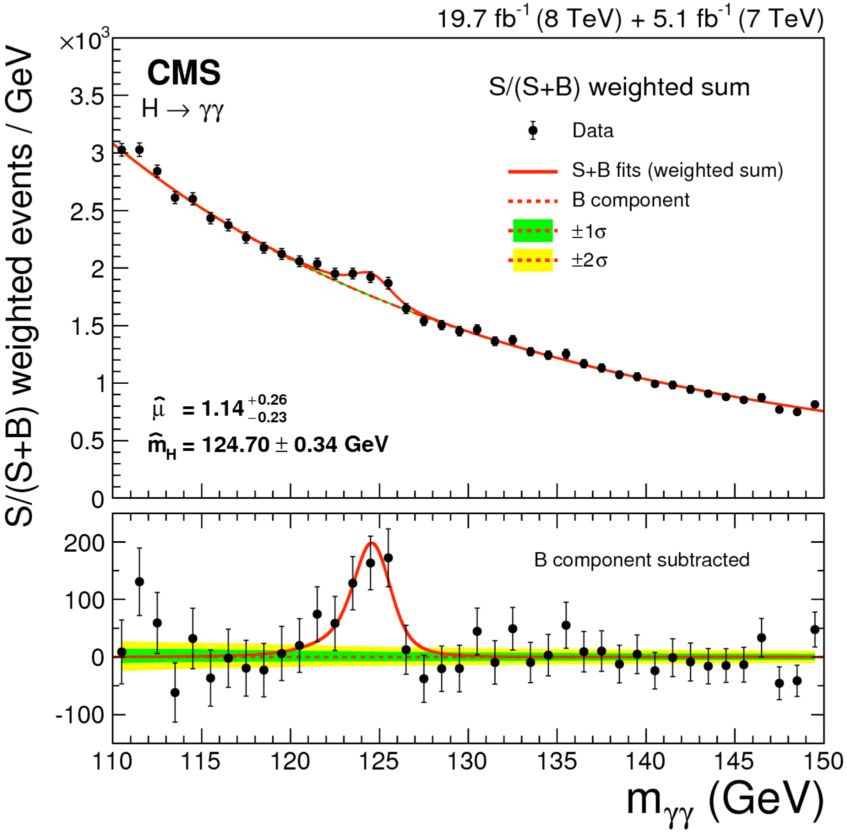
The distribution of the four-lepton invariant mass, $m_{4\ell}$. The signal expectation shown is for a mass hypothesis of m_H=125 GeV

H→γγ


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
CMS

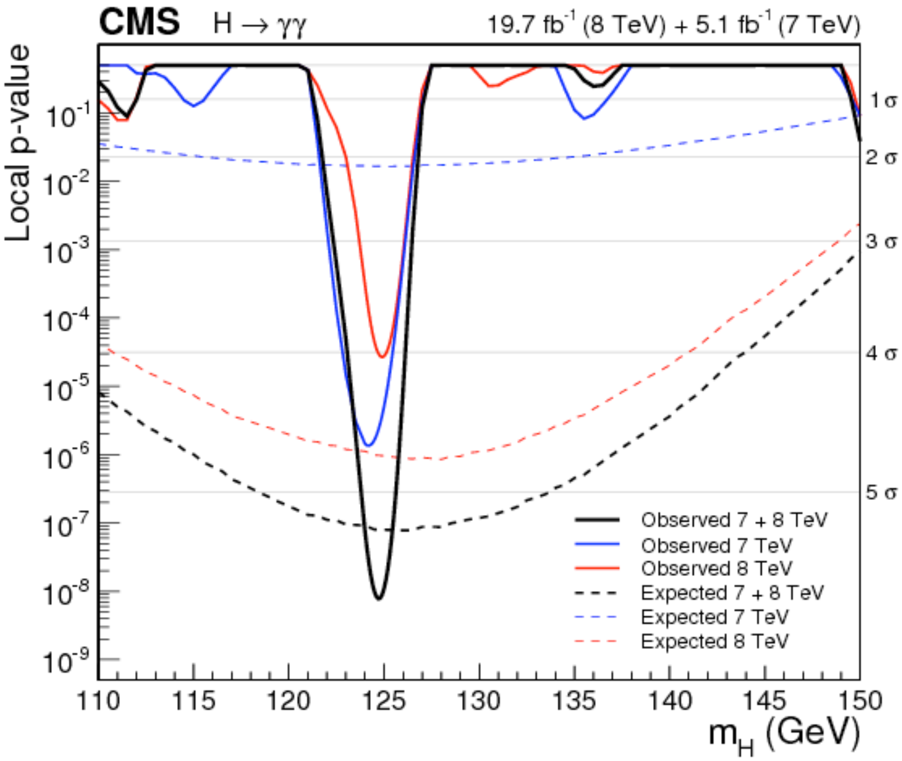
H→γγ

10.1140/epjc/s10052-014-3076-z



Background + Signal fit Sum of the $m_{\gamma\gamma}$ distribution from the 7 and 8 TeV datasets, together with the data binned.

The European Physical Journal C
10.1140/epjc/s10052-014-3076-z



Best-fit signal strength, μˆ
Signal significance = 5.7 σ (5.7 expected)

ATLAS-CONF-2015-044

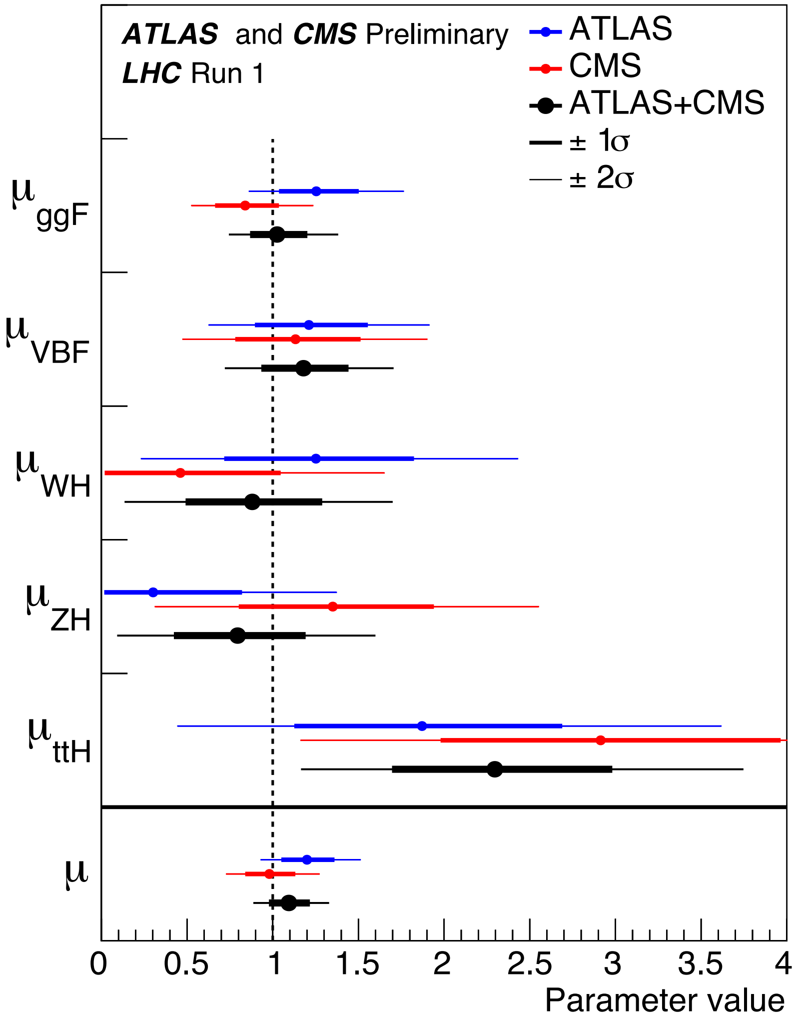
125 GeV Higgs boson signal strength

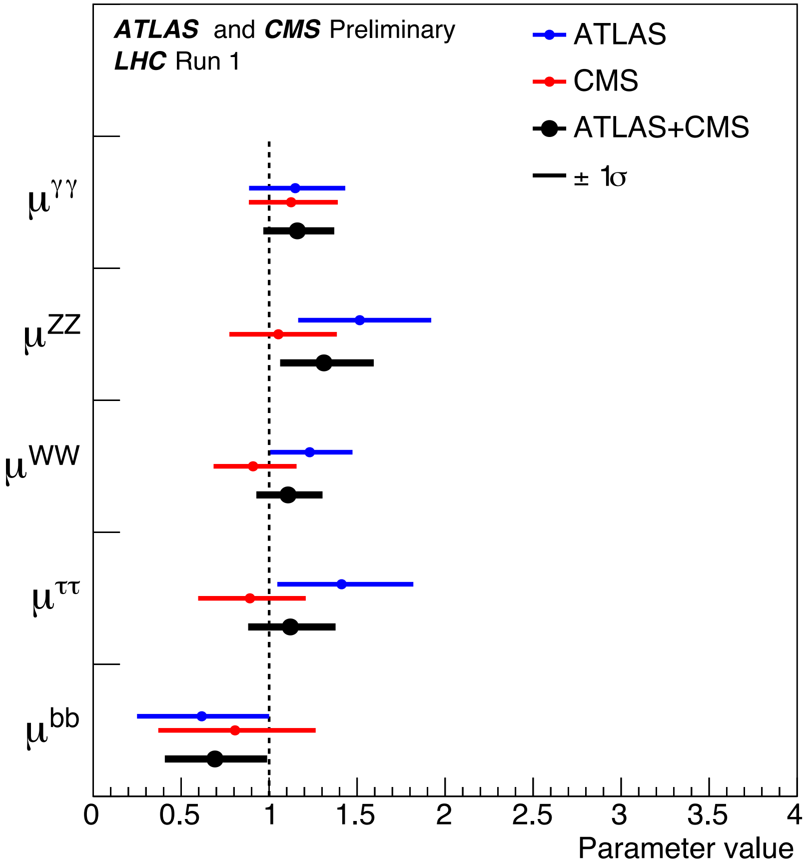
Production

$\mu = \sigma_{observed}/\sigma_{SM}$

Decay

$\mu_{H(SM)} = 1$
$\mu_{backg} = 0$



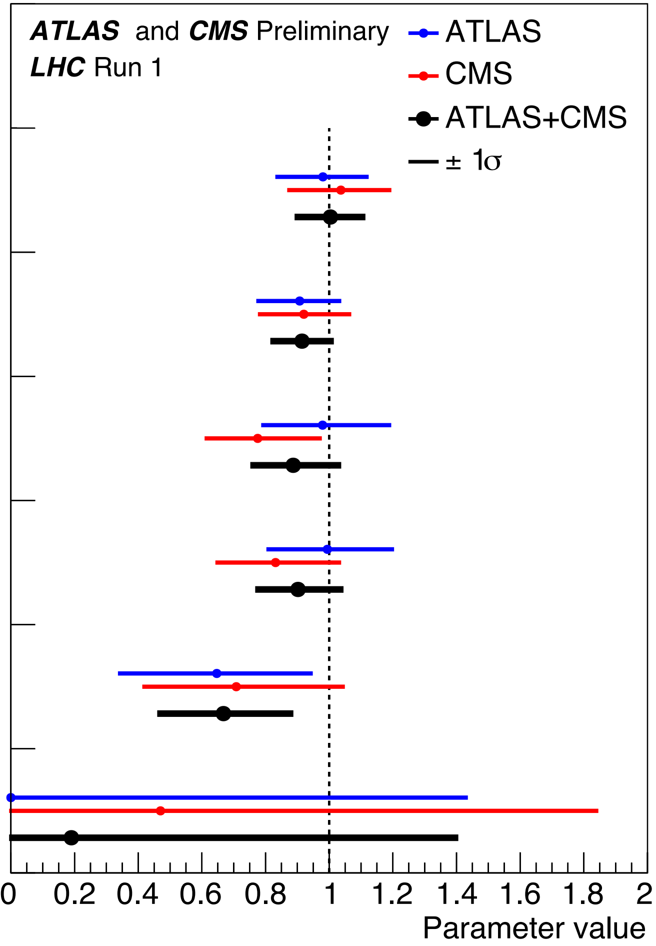


Production and decay signal strengths for the combination of ATLAS and CMS.

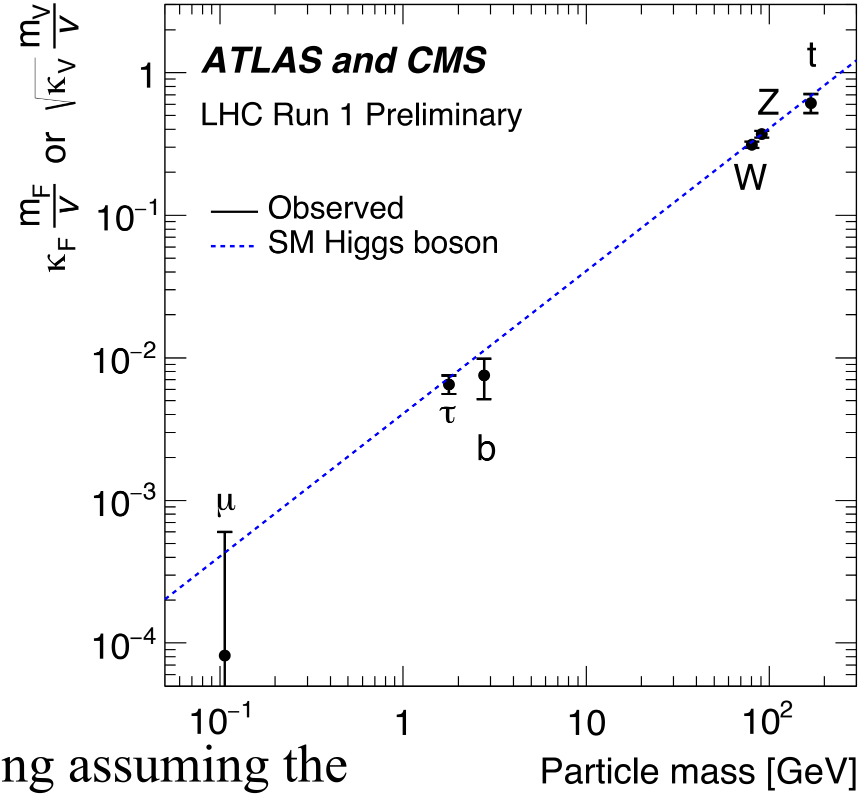
125 GeV Higgs boson couplings

$$k = g_{observed}/g_{SM}$$

ATLAS-CONF-2015-044



Fit results for the combination of ATLAS and CMS in the case of the parametrisation with reduced coupling modifiers

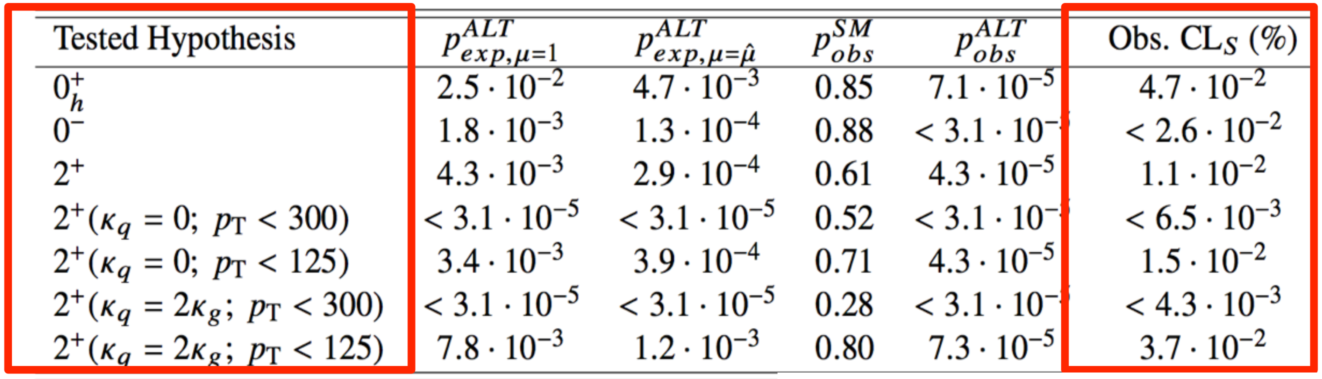


ATLAS and CMS combination of coupling assuming the absence of BSM particles in the loops, $BR_{BSM}=0$, and $\kappa_j \geq 0$.

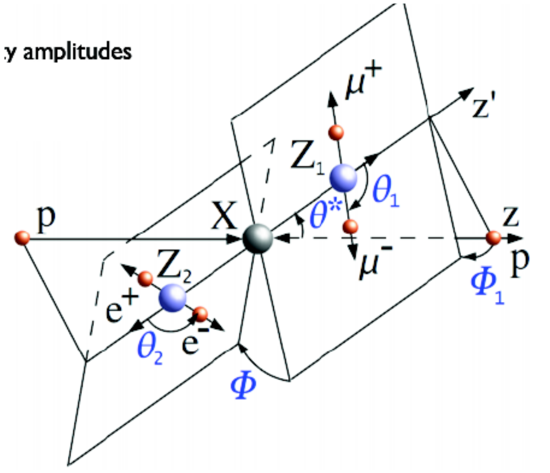
Spin/CP properties

- Study Higgs boson decay kinematic to extract spin/CP properties
- Spin 1 and 2 hypotheses (in many variants) are excluded at >95% C.L.

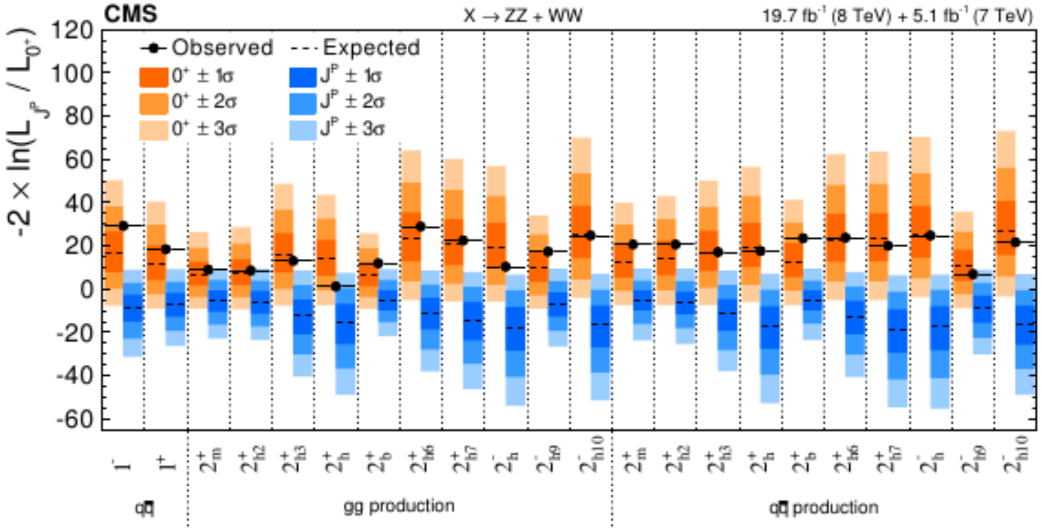
ATLAS



Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL$_S$ (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$



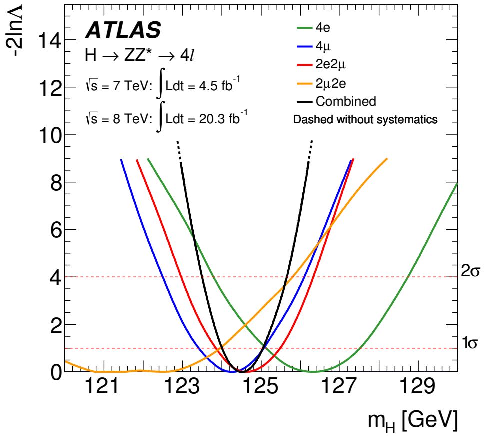
CMS



Higgs boson mass

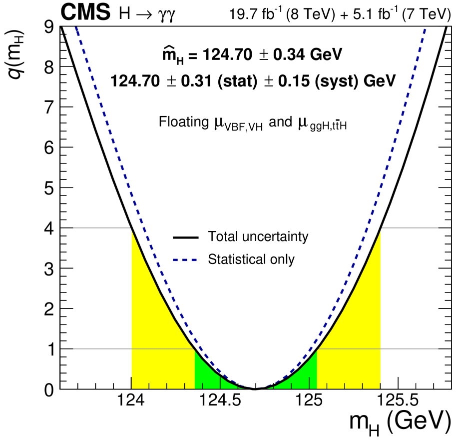
- Combined mass through simultaneous fit to H→4l and H→γγ datasets
  - **Scale accuracy at the level of 0.1%! ← spectrometer & calorimeter calibration important**

H→4l



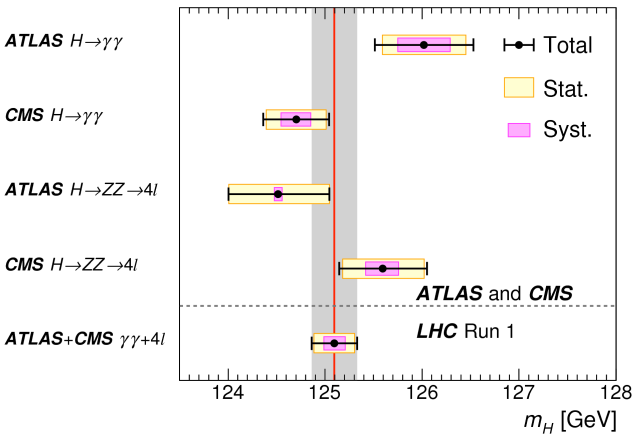
PHYSICAL REVIEW D 90, 052004 (2014)

H→γγ



EPJC 75:212

combination



Phys. Rev. Lett. 114, 191803

	ATLAS	CMS
H→4l	124.51 ± 0.52 ± 0.06	125.6 ± 0.4 ± 0.2
H→γγ	125.98 ± 0.42 ± 0.28	124.70 ± 0.31 ± 0.15
Combination	**125.36 ± 0.37 ± 0.18**	**125.02 $^{+0.26}_{-0.27}$ $^{+0.14}_{-0.15}$**
ATLAS + CMS	**125.09 ± 0.21 (stat) ± 0.11(scale)** ± 0.02 (other) ± 0.01(theory)	

Uncertainty dominated by statistics, it will improve with more data from Run2

Higgs boson mass

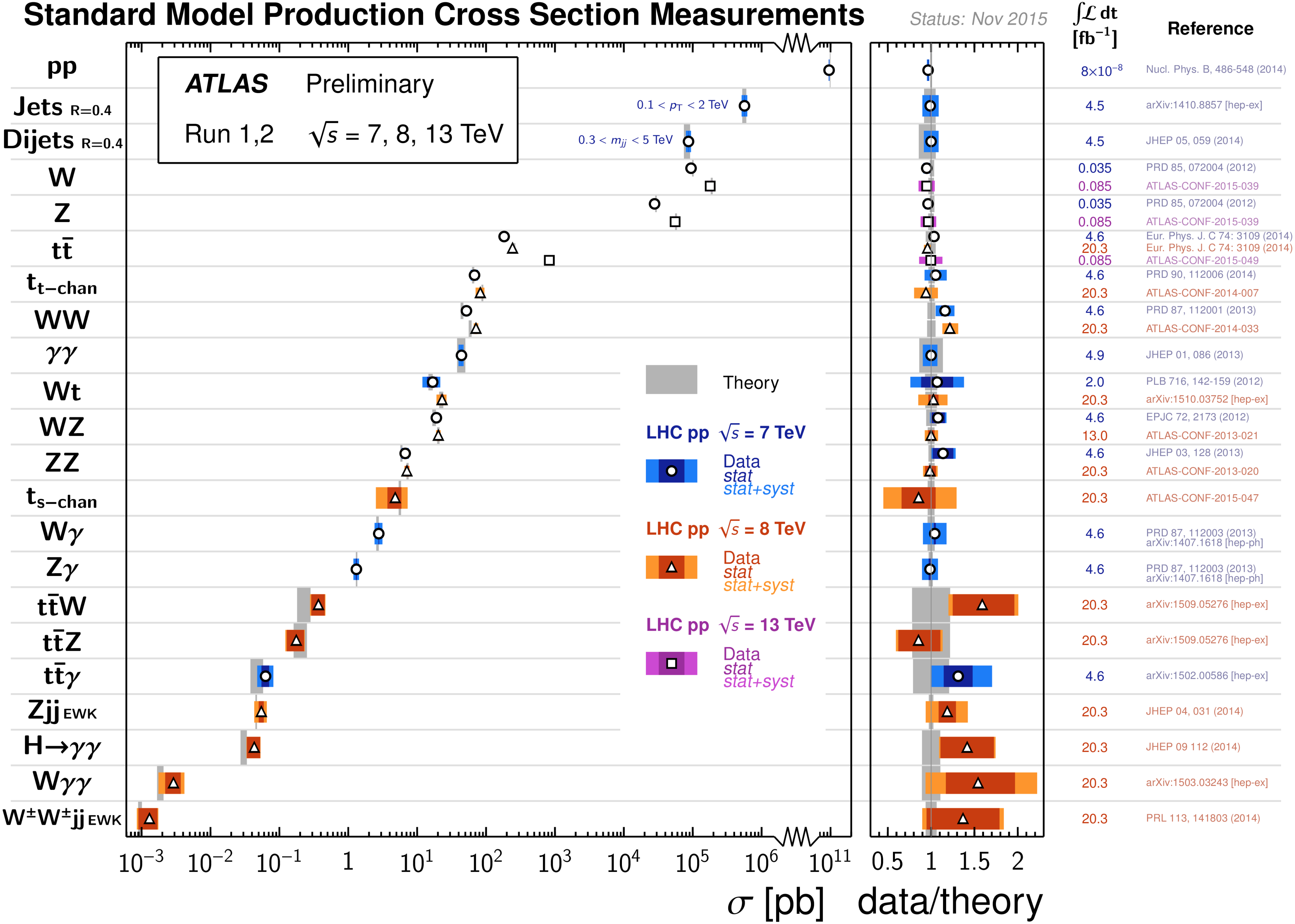
- Combined mass through simultaneous fit to H→4l and H→γγ datasets
  - **Scale accuracy at the level of 0.1%! ← spectrometer & calorimeter**

- ***m_H was the only fundamental parameter missing to completely set the SM structure***
- ***We just entered a new era: precision tests are now needed in order to "discover" possible deviations from SM***

	ATLAS	CMS
H→4l	124.51 ± 0.52 ± 0.06	125.6 ± 0.4 ± 0.2
H→γγ	125.98 ± 0.42 ± 0.28	124.70 ± 0.31 ± 0.15
Combination	**125.36 ± 0.37 ± 0.18**	**$125.02\ ^{+0.26}_{-0.27}\ ^{+0.14}_{-0.15}$**
ATLAS + CMS	**125.09 ± 0.21 (stat) ± 0.11(scale)** ± 0.02 (other) ± 0.01(theory)	

Uncertainty dominated by statistics, it will improve with more data from Run2

Standard Model Production Cross Section Measurements



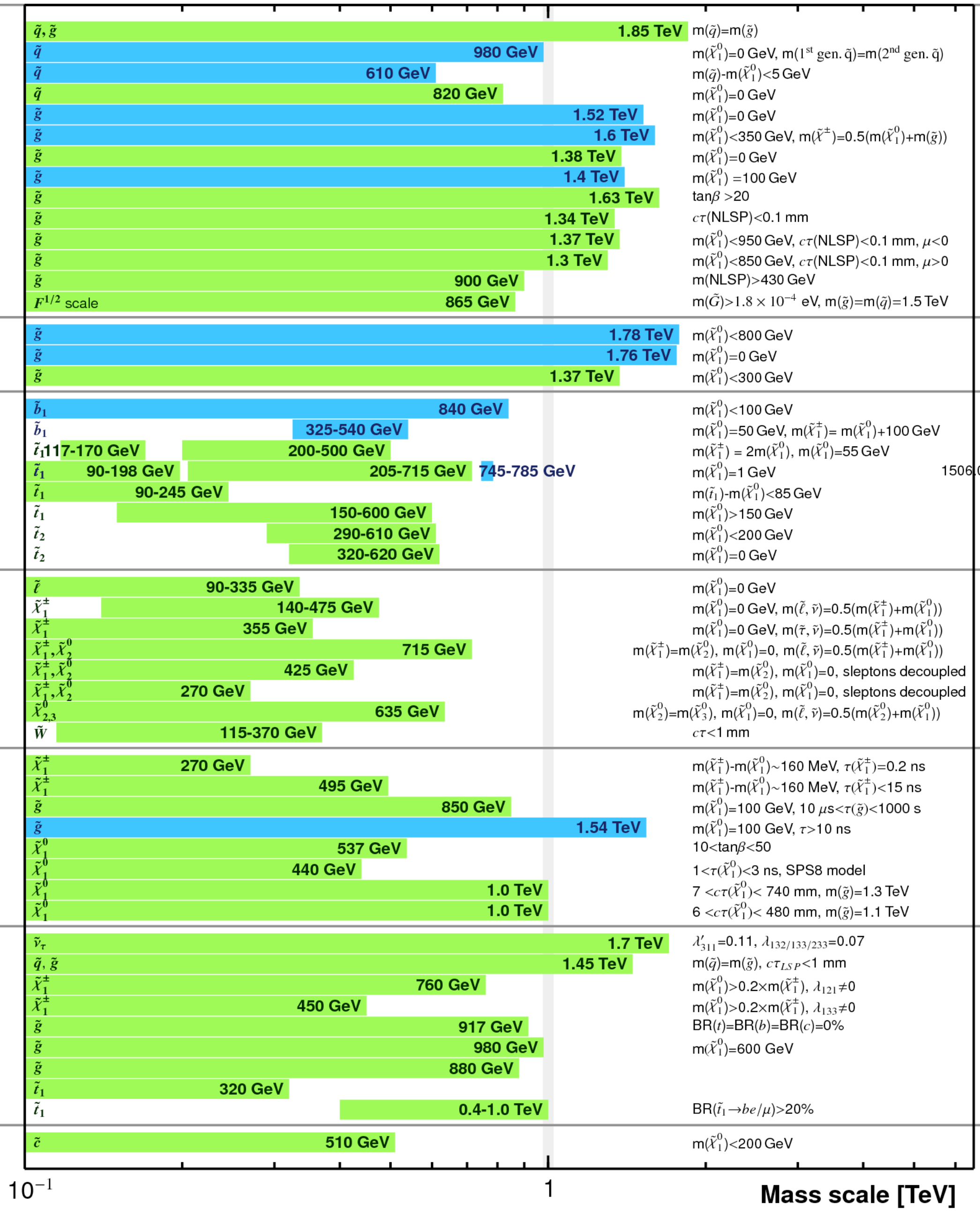
ATLAS SUSY Searches* - 95% CL Lower Limits

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
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	3.2	$\tilde{q}$ 🟦 980 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m(1^{st} gen. $\tilde{q}$)=m(2^{nd} gen. $\tilde{q}$)	ATLAS-CONF-2015-062
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	$\tilde{q}$ 🟦 610 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	*To appear*
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$ 🟩 820 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	3.2	$\tilde{g}$ 🟦 1.52 TeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2015-062
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^{\pm}_1\to qqW^{\pm}\tilde{\chi}^0_1$	1 e,μ	2-6 jets	Yes	3.3	$\tilde{g}$ 🟦 1.6 TeV	m($\tilde{\chi}^0_1$)<350 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2015-076
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 🟩 1.38 TeV	m($\tilde{\chi}^0_1$)=0 GeV	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	0	7-10 jets	Yes	3.2	$\tilde{g}$ 🟦 1.4 TeV	m($\tilde{\chi}^0_1$) =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($\tilde{\chi}^0_1$)<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($\tilde{\chi}^0_1$)<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.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	3.3	$\tilde{g}$ 🟦 1.78 TeV	m($\tilde{\chi}^0_1$)<800 GeV	ATLAS-CONF-2015-067
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	3.3	$\tilde{g}$ 🟦 1.76 TeV	m($\tilde{\chi}^0_1$)=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($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	3.2	$\tilde{b}_1$ 🟦 840 GeV	m($\tilde{\chi}^0_1$)<100 GeV	ATLAS-CONF-2015-066
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^{\pm}_1$	2 e,μ (SS)	0-3 b	Yes	3.2	$\tilde{b}_1$ 🟦 325-540 GeV	m($\tilde{\chi}^0_1$)=50 GeV, m($\tilde{\chi}^{\pm}_1$)= m($\tilde{\chi}^0_1$)+100 GeV	1602.09058
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^{\pm}_1$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟩 200-500 GeV	m($\tilde{\chi}^{\pm}_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	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($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2016-007
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 🟩 90-245 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)<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($\tilde{\chi}^0_1$)>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($\tilde{\chi}^0_1$)<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($\tilde{\chi}^0_1$)=0 GeV	1506.08616
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 🟩 90-335 GeV	m($\tilde{\chi}^0_1$)=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	$\tilde{\chi}^{\pm}_1$ 🟩 140-475 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}^{\pm}_1$ 🟩 355 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1407.0350
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 🟩 715 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^{\pm}_1$)+m($\tilde{\chi}^0_1$))	1402.7029
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 🟩 425 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^{\pm}_1,\tilde{\chi}^0_2$ 🟩 270 GeV	m($\tilde{\chi}^{\pm}_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$ 🟩 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	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 $\tilde{\chi}^{\pm}_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^{\pm}_1$ 🟩 270 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^{\pm}_1$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}^{\pm}_1$ 🟩 495 GeV	m($\tilde{\chi}^{\pm}_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^{\pm}_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 🟩 850 GeV	m($\tilde{\chi}^0_1$)=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($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	*To appear*
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 🟩 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 🟩 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}^0_1$ 🟩 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}^0_1$ 🟩 1.0 TeV	6 <$c\tau$($\tilde{\chi}^0_1$)< 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
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}^{\pm}_1$ 🟩 760 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^{\pm}_1$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu + \tau$	-	Yes	20.3	$\tilde{\chi}^{\pm}_1$ 🟩 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^{\pm}_1$), $\lambda_{133}\neq0$	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
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 🟩 980 GeV	m($\tilde{\chi}^0_1$)=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, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 🟩 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

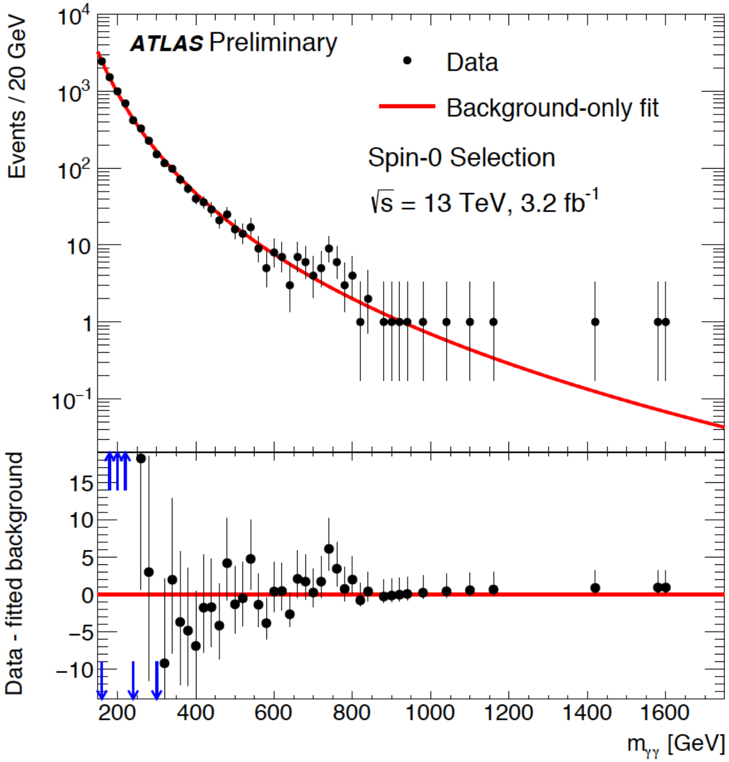
*Only a selection of the available mass limits on new states or phenomena is shown.

Searches for γγ resonances

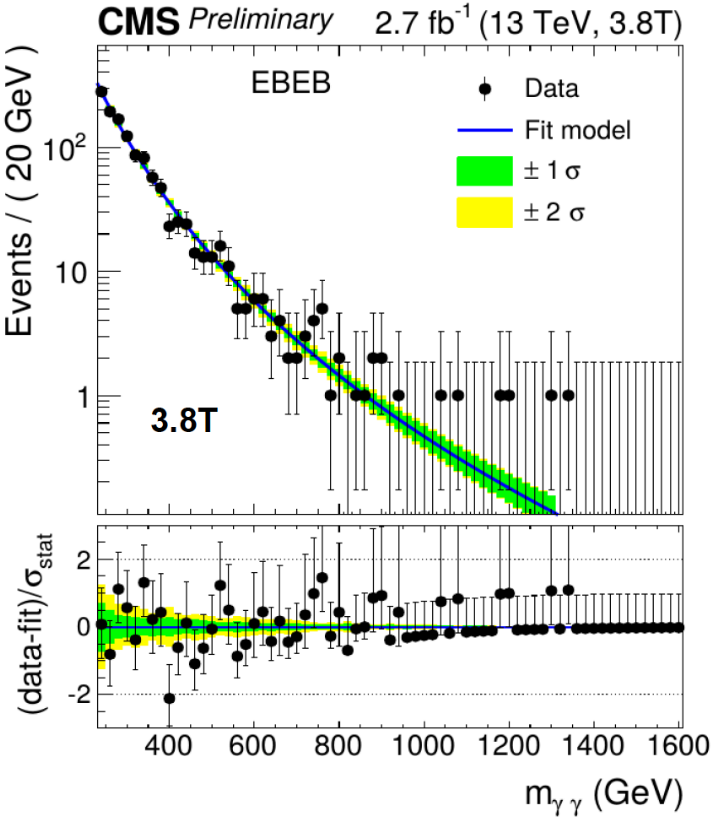
- Select events with two high-p_T isolated photons – plot the γγ invariant mass, $m_{\gamma\gamma}$

SPIN-0 ANALYSIS

background-only fit



2878 events ($m_{\gamma\gamma}$ > 200 GeV)



Searches for high-mass γγ resonances

ATLAS

- Largest deviation from B-only hypothesis m_X ~750 GeV, Γ_X ~45GeV(6%)
- Local significance=3.9σ
- Global significance=2.0σ

CMS

- Largest excess observed for m_X = 760 GeV and Γ/m = $1.4x10^{-2}$
- Similar significance for narrow-width hypothesis.
- "Global" significance < 1σ.

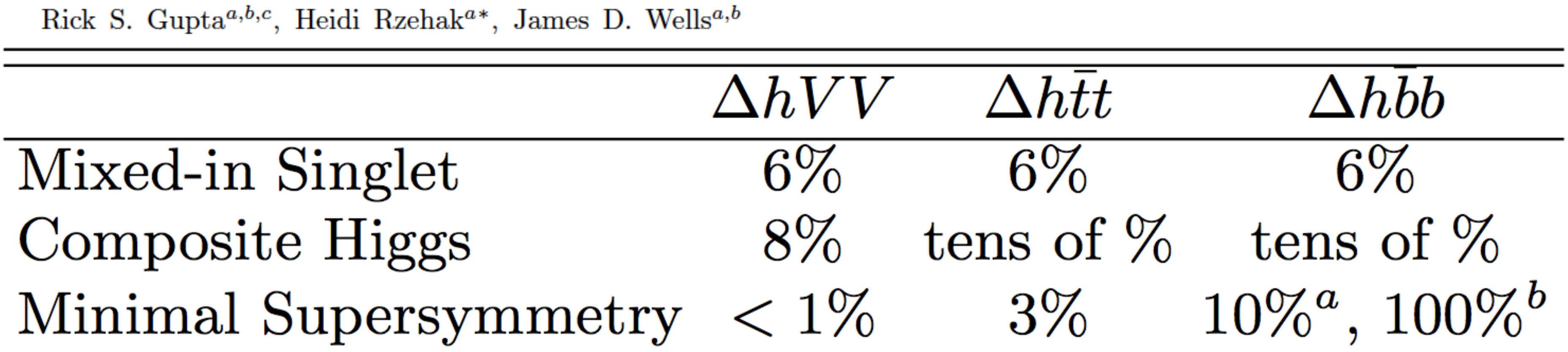
What Next?

What Next?

- Many open points in high-energy physics, still. Among these:
  - Is the **Standard Model** an ***effective theory*** of more general fundamental theory, or is it rather a ***sector of the final fundamental theory***?
  - Is the 125 GeV Higgs boson **the fundamental scalar** predicted by SM, or is it explained by an extend theory?
  - What's the nature and the origin of **Dark Matter**?
  - ***Hierarchy***, problem (aka *fine-tuning* or *naturalness*), calling for new particles to stabilize quantum corrections to the Higgs boson mass (but it is a real problem??)
  - ***Flavour problem***: what's the explanation of the large matter over antimatter dominance in the universe?
  - ***Neutrino masses***
  - … (many others, not listed here)

What's Next – an example

arXiv:1206.3560v3



Rick S. Gupta[a,b,c], Heidi Rzehak[a*], James D. Wells[a,b]

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC Run1 experiment	**~15%**	**~40%**	**~30%**
LHC 14 TeV 300 fb^{-1} (1 exp.)	**~6%**	**~15%**	**~12%**

- 14 TeV & 300 fb^{-1} projections based on what we learnt from early 2012 analyses
  - Since then, more channels have been included in the 125 GeV Higgs boson data analyses

Which tools?

- **LHC** – real: present and near future
- The LHC Luminosity Upgrade, **HL-LHC** – the concrete *mid-term future*

… and then the *far future* open options:

- The LHC energy upgrade, **HE-LHC**
- Linear e^+e^- colliders
- Circular e^+e^- colliders
- Photon colliders
- Very high-energy hadron colliders
- Muon collider(s)
- …

Next steps -1-

- LHC is the only high-energy particle collider in operation today at it will be the only one for many years to come!
- All future projects in HEP should be based on the outcome from LHC ($\sqrt{s} \cong 14$ TeV; $L \cong 300$ fb^{-1})
- We have two possible situations after LHC (300 fb^{-1})
  1. LHC will not provide direct observation of New Physics at O(1 TeV) scale, or
  2. New Physics will be observed at LHC

Next steps -2-

- In **both cases** the luminosity upgrade of LHC, **HL-LHC**, is the most realistic and sensible project to perform in the short term:

1. **We do not find New Physics at the LHC ➔**
    a. **Precision studies of the *125 GeV Higgs boson sector***
    b. **Precision Measurements of Standard Model in general**
    c. **Continue the search for New Physics,** in particular for **rare processes**. Deviations from SM will indicate presence of New Physics not too far away from the energy scale of the LHC

– ***All of this represents essential input for future collider experiments!***

Next steps -3-

- Need to change mentality in HEP:
  it is not true that

New Physics =(only) discovery of new particles!

- ➔ New Physics is in the observation of New Phenomena
- LHC has delivered the (first?) new phenomenon: a neutral scalar of 125 GeV mass
  - **If elementary, it would be the first point-like scalar ever seen in nature!**
  - Must look at it **closely**, it represents a portal to a completely unknown new territory

Next steps -4-

2. **We find new physics at the LHC** ➔ it will redesign the priorities of HEP.

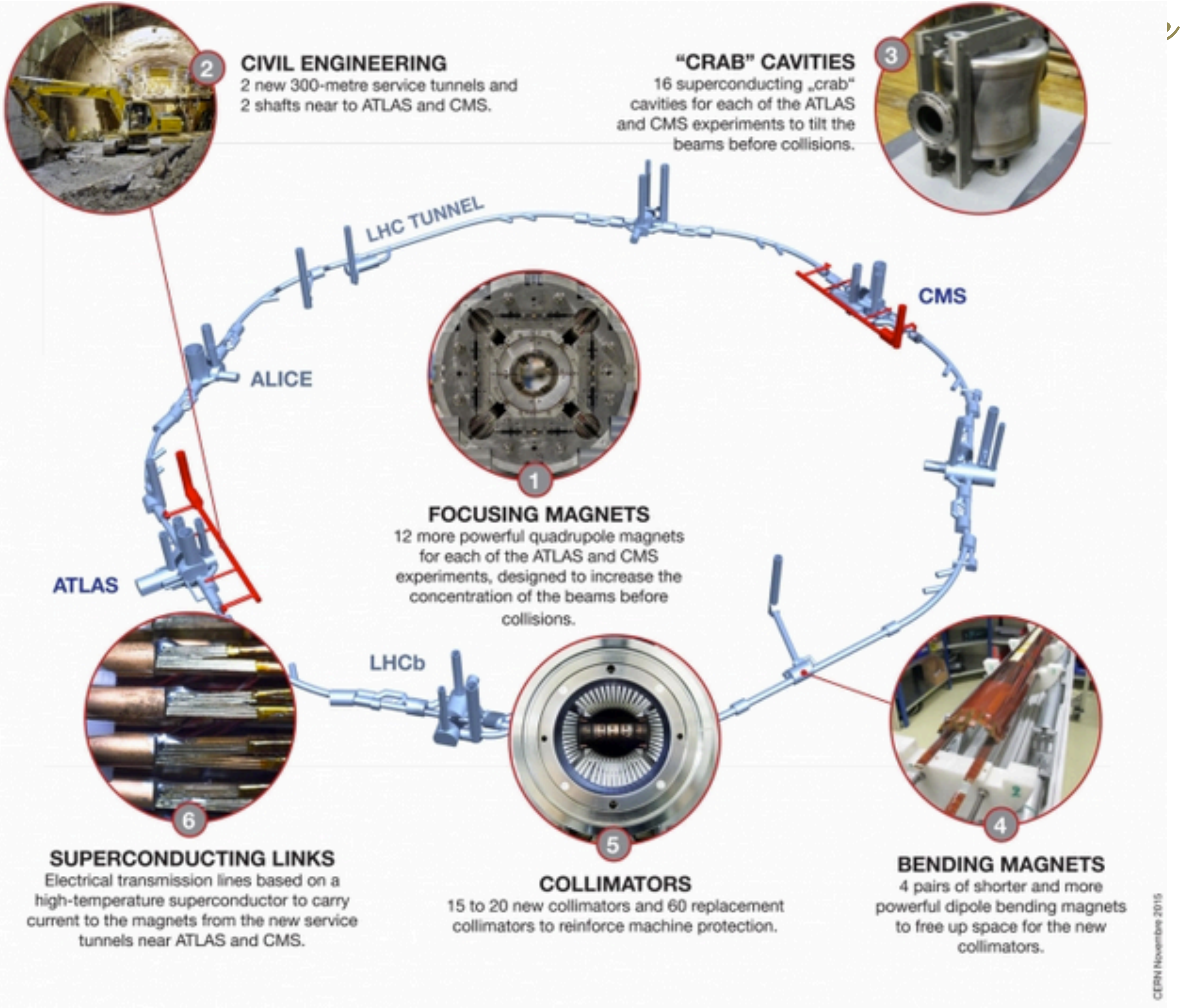
   Need to understand what this new phenomena would be, and with more data from LHC/HL-LHC would be important to a) to validate with statistics the nature of the effects seen, and b) to study the associated properties

   In addition perform the Precision Measurements already mentioned

   – Example (from these days…): the 750 GeV γγ excess, if confirmed to be of physics nature by the data we're collecting this year

- **All of this represents essential input for future collider experiments**

The High-Luminosity LHC



CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

"CRAB" CAVITIES
16 superconducting „crab" cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

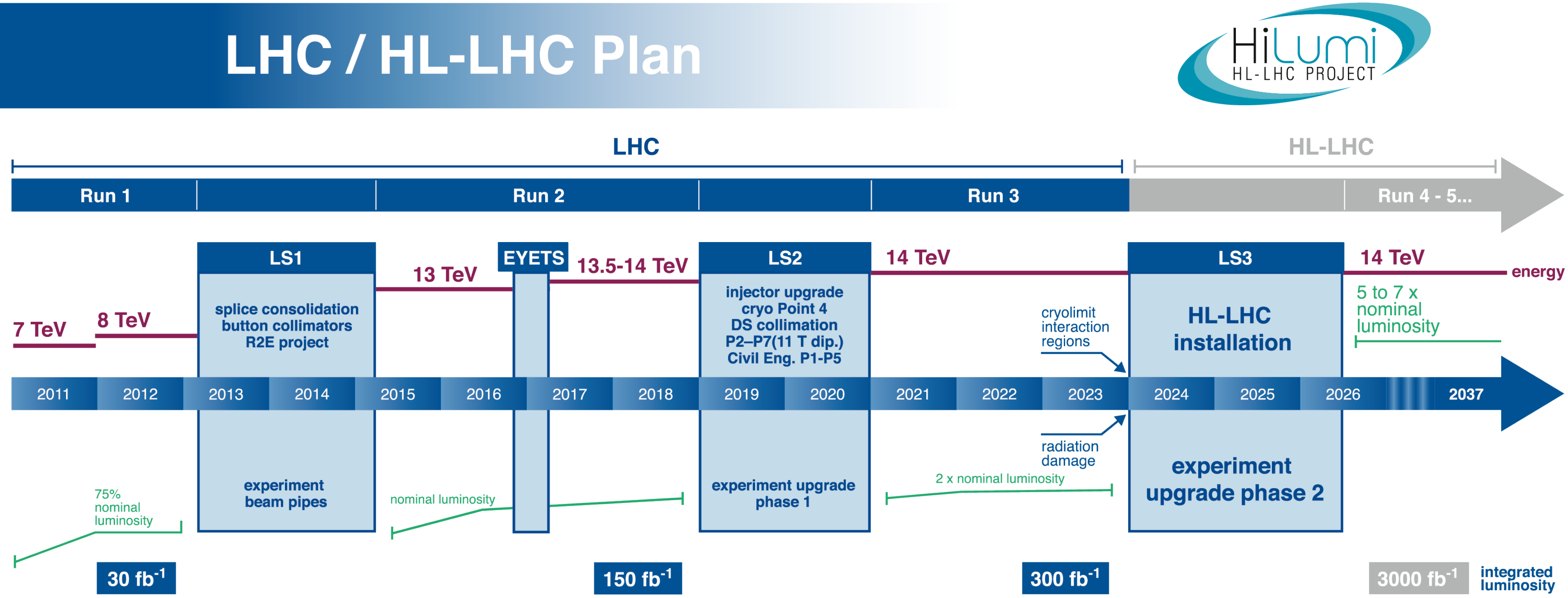
FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.

The High Luminosity LHC



Run 1

Magnet splice update

Run 2 at ~full design energy

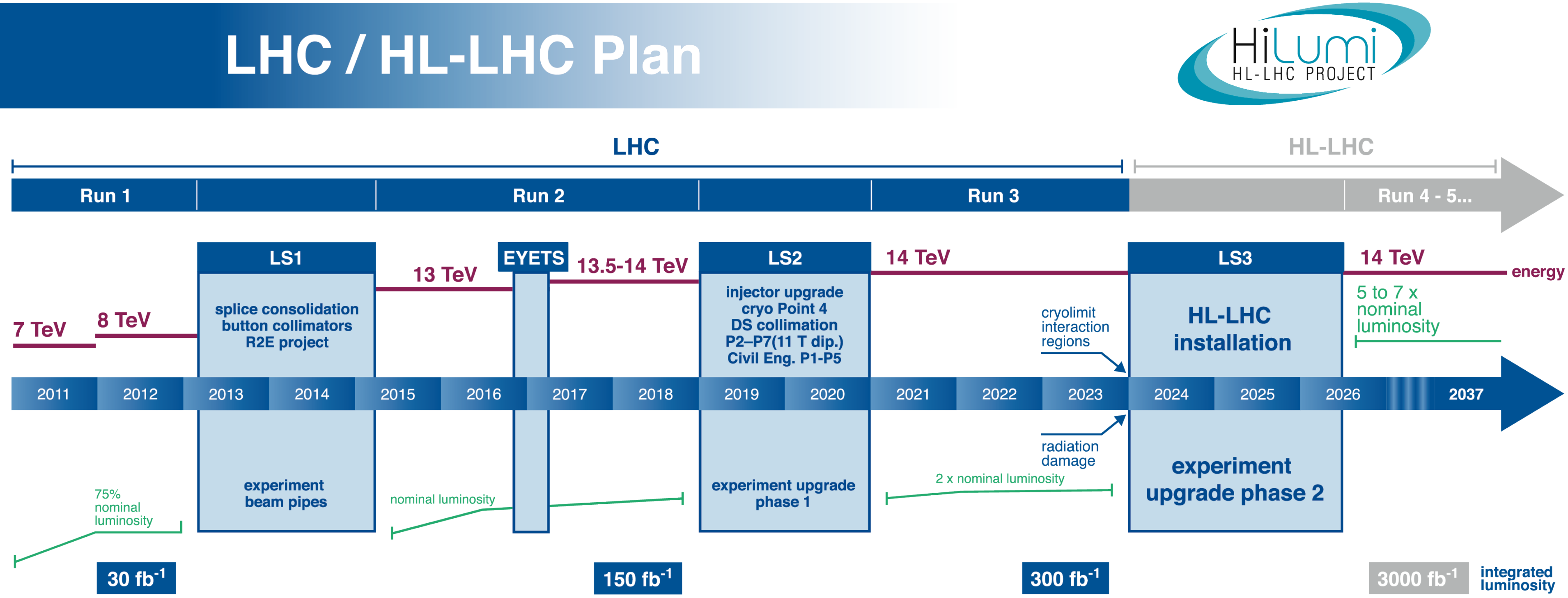
Phase I upgrades (injectors)

Run 3 → original design lumi

Phase II upgrades (final focus)

HL-LHC: ten times design lumi

The High Luminosity LHC



LHC / HL-LHC Plan

HiLumi HL-LHC PROJECT

LHC

HL-LHC

Run 1

Run 2

Run 3

Run 4 - 5...

7 TeV

8 TeV

LS1

splice consolidation
button collimators
R2E project

experiment
beam pipes

13 TeV

EYETS

13.5-14 TeV

LS2

injector upgrade
cryo Point 4
DS collimation
P2–P7(11 T dip.)
Civil Eng. P1-P5

experiment upgrade
phase 1

14 TeV

cryolimit
interaction
regions

radiation
damage

LS3

HL-LHC
installation

experiment
upgrade phase 2

14 TeV

energy

5 to 7 x
nominal
luminosity

2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2037

75%
nominal
luminosity

nominal luminosity

2 x nominal luminosity

30 fb^{-1}

150 fb^{-1}

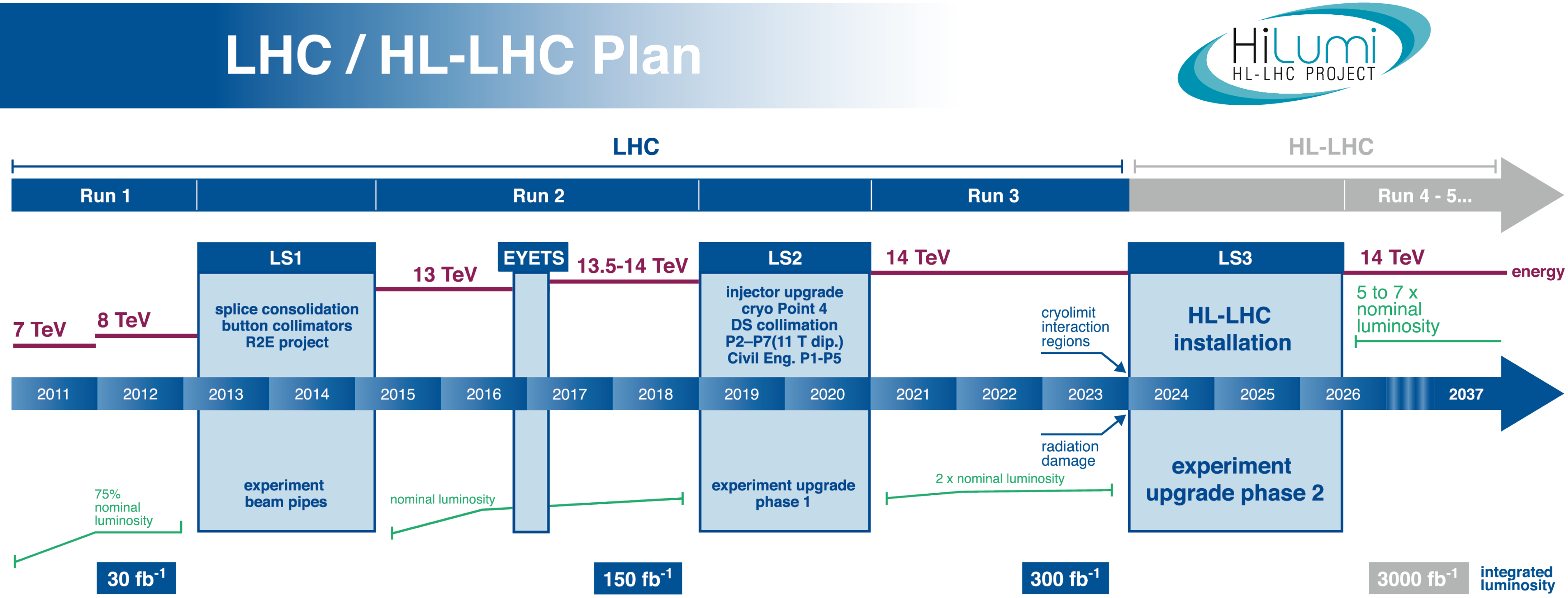
300 fb^{-1}

3000 fb^{-1}

integrated
luminosity

the CERN Council adopted the European Strategy for Particle Physics in Brussels on 30 May 2013, its first priority was agreed to be *“[…] Europe’s top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030 […]”.*

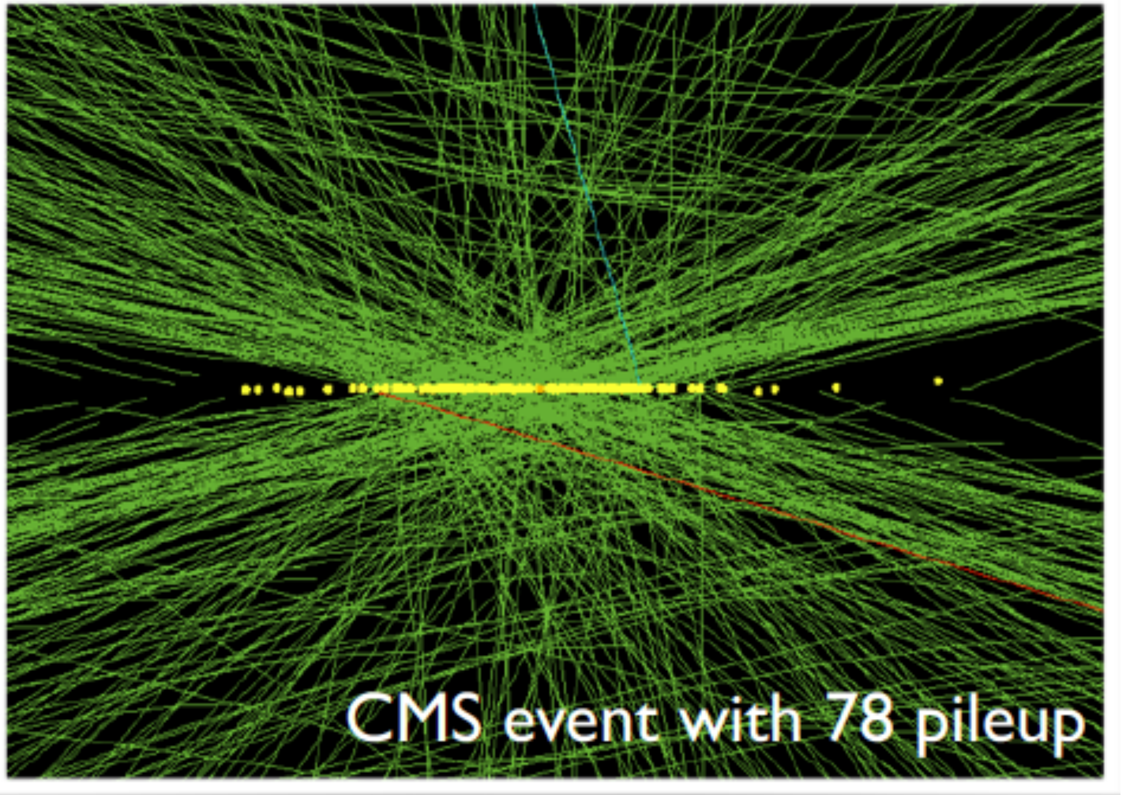
The High Luminosity LHC



- Full exploitation of LHC is top priority in Europe & US for high energy physics
- Operate HL-LHC with 5 (nominal) to 7.5 (ultimate) $\times 10^{34}$ cm^{-2}s^{-1} to collect 3000 fb^{-1} in ~ ten years.

The challenge of HL-LHC

- The challenge of HL-LHC, both for detectors and physics, is the **event pile-up**
  - ***$n = (\sigma L)/(n_B f_r)$*** with $\sigma \sim 81$ mb, $L=7.5\ 10^{34}$ cm^{-2} s^{-1}, $n_B = 2808$ and $f_r= 11450$ Hz ➔ $n \sim 200$ events per bunch crossing



Detector Upgrade

- Some of present the sub-systems will either not survive the high luminosity environment (radiation damage) or not function efficiently because of the increased data rates (detector occupancy and event pile-up).
- ➔ important to upgrade the present ATLAS and CMS detectors to cope with the HL-LHC environment!
  - Entirely **new inner tracking systems** to measure charged particles will be required, and
  - the energy-measuring **calorimeters** will also need partial replacement, in the endcap region for CMS and possibly in the more forward region for ATLAS

Physics at HL-LHC

Physics at HL-LHC

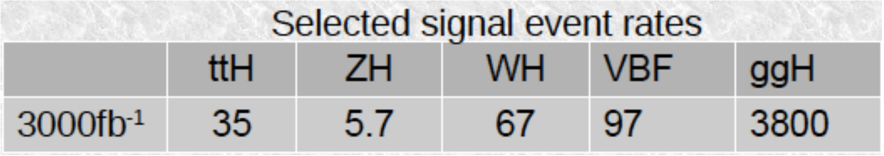
- Lots of physics simulation performed since 2012 (Euopean Strategy, Cracow), and revisited afterwards. These includes:
- **125 GeV Higgs boson rates & couplings**
  - **ttH production**, rare decays such as **H→μμ**, Zγ, J/ψγ, …
- 125 GeV Higgs boson 2HDM interpretation assuming SM production and decays
- 125 GeV Higgs width, CP property studies
- 125 GeV Higgs *Invisible* decays and portal to Dark Matter
- BSM Higgses decays to bosons
- **Double Higgs production and self-coupling**
- Vector Boson Scattering
- **New Physics: SUSY** process: electroweak production studies, **third generation searches**
- New Physics: mono-Higgs, dilepton resonances, di-top resonances, top quark FCNC
- …

Higgs boson sector

- Many aspects must be studied in detail:
  - – Production/decay rates and rare modes, in particular
    - **the Yukawa coupling with the top quark, ttH**
    - **the H→$\mu^+\mu^-$ and other rare decays**
    - **the Higgs boson couplings in general**
    - **the natural width Γ_H (SM: ~ 4.2 MeV)**
  - – Differential distributions: $d\sigma/dp_T$, $d\sigma/d\eta$, …
  - – Spin/CP properties
  - – Higgs selfcoupling
  - – Search for partners of the 125 GeV Higgs boson

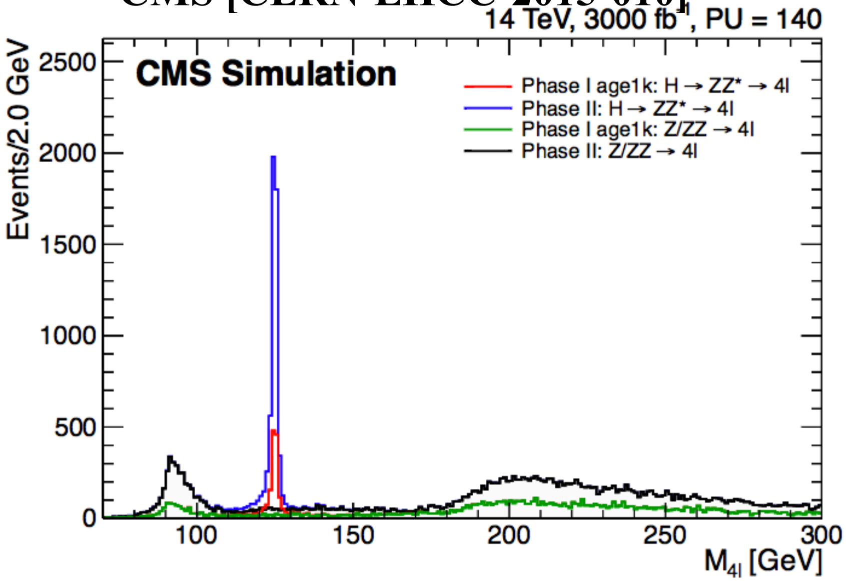
H→ZZ*→4l

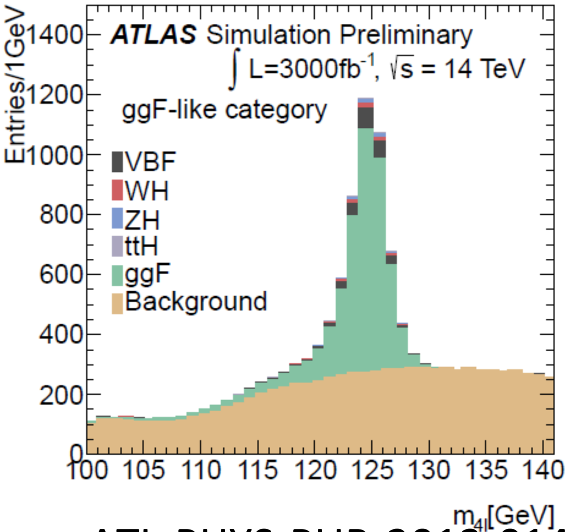
The large event yield of high mass resolution processes H→γγ and H→ZZ*→4l will provide large statistics and high-purity samples for precision property and differential distribution measurements



Selected signal event rates					
	ttH	ZH	WH	VBF	ggH
$3000fb^{-1}$	35	5.7	67	97	3800

CMS [CERN-LHCC-2015-010]



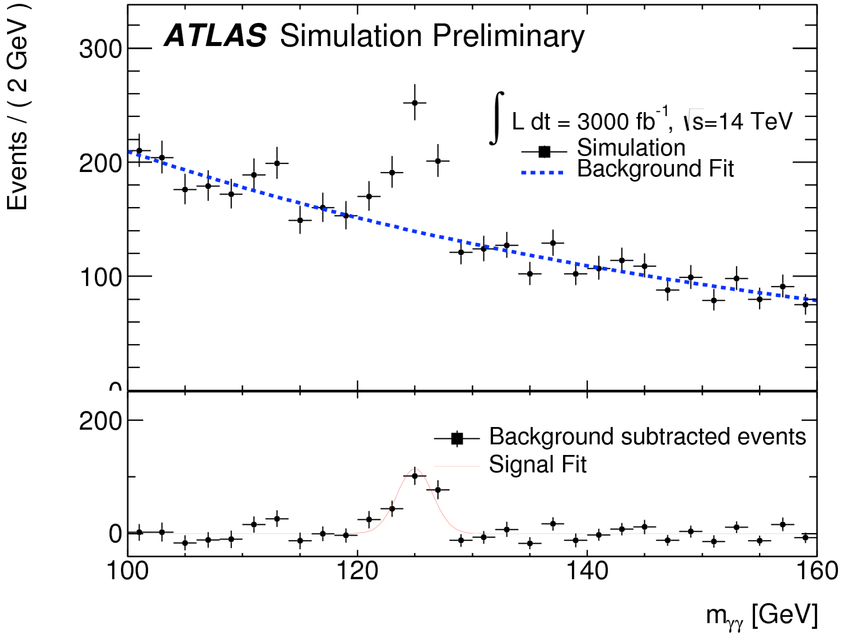


ATL-PHYS-PUB-2013-014

Four lepton mass distributions for the full Phase-II luminosity of 3000 fb^{-1} for the signal, $H \to ZZ \to 4l$, and for the irreducible $ZZ \to 4l$ background.

ttH, H→γγ

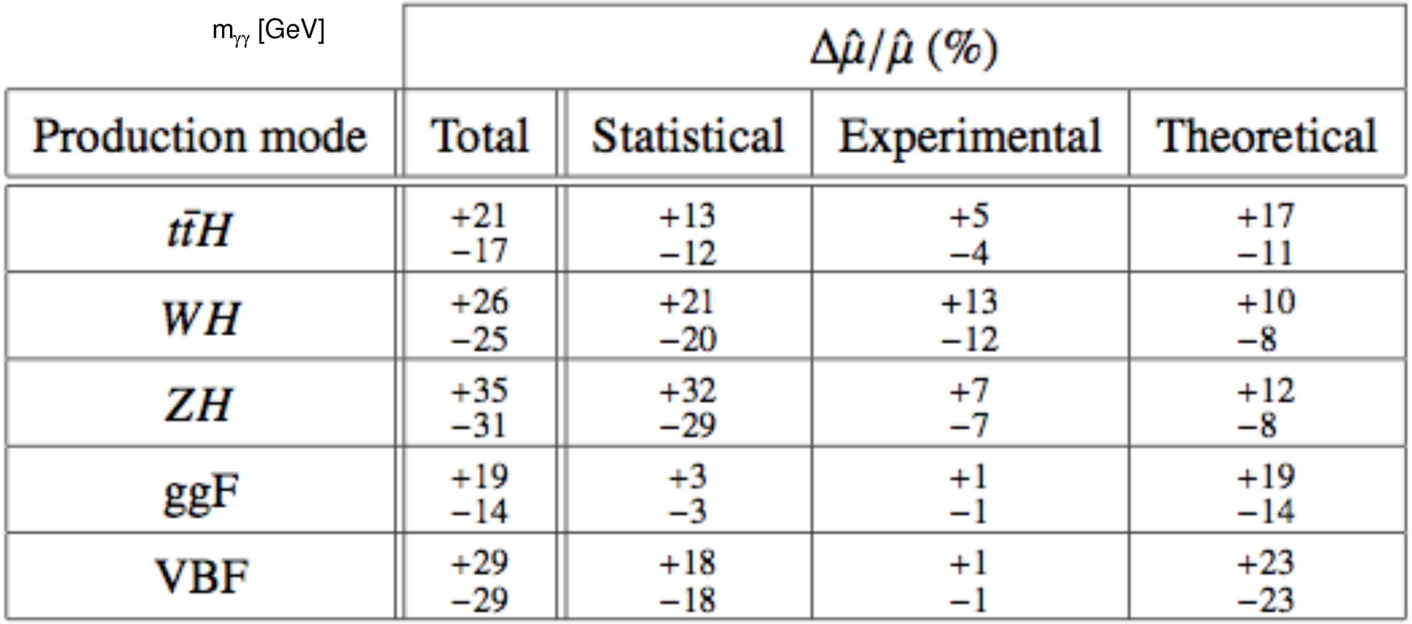
ATL-PHYS-PUB-2013-014



- Sensitive to top in both production and decay
- Yields top Yukawa coupling
- ttH not possible at lepton colliders (1st-generation)

Experimental uncertainty on ttH signal strength: **~12%**

ATL-PHYS-PUB-2014-012



	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
Production mode	Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$
WH	$^{+26}_{-25}$	$^{+21}_{-20}$	$^{+13}_{-12}$	$^{+10}_{-8}$
ZH	$^{+35}_{-31}$	$^{+32}_{-29}$	$^{+7}_{-7}$	$^{+12}_{-8}$
ggF	$^{+19}_{-14}$	$^{+3}_{-3}$	$^{+1}_{-1}$	$^{+19}_{-14}$
VBF	$^{+29}_{-29}$	$^{+18}_{-18}$	$^{+1}_{-1}$	$^{+23}_{-23}$

Rare decays

H→μμ

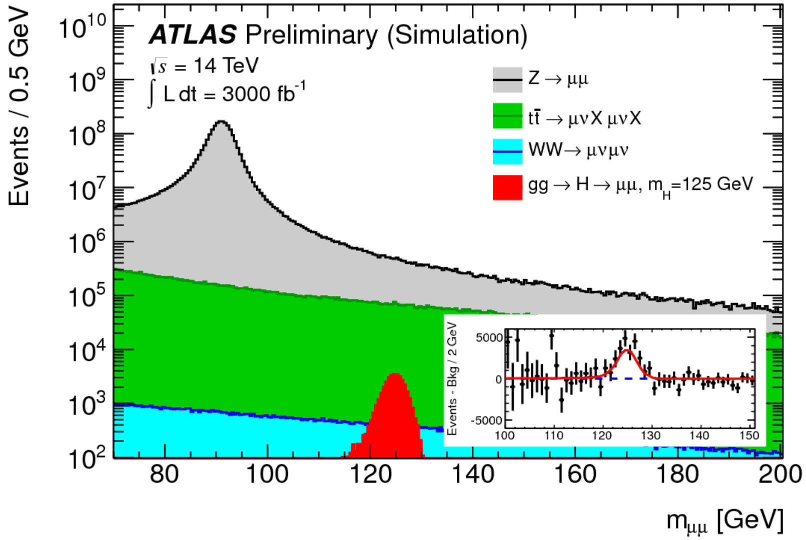
- Allows direct study of coupling to two different leptons
- Signal significance > 7σ

ATL-PHYS-PUB-2013-014

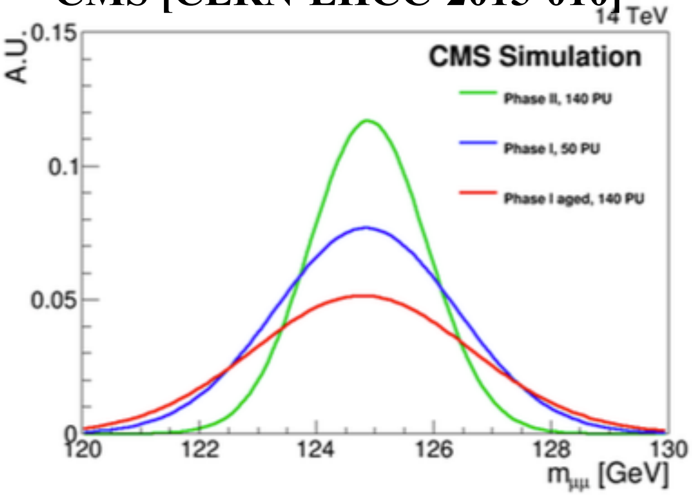
$\mathcal{L}$ [fb^{-1}]	300	3000
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%

- ***CMS: revised projection, expect 5% on coupling measurement at HL-LHC***

ATL-PHYS-PUB-2013-007



CMS [CERN-LHCC-2015-010]



CMS H→μμ coupling precision improves from 8% to 5% with Phase II upgrade

ATL-PHYS-PUB-2014-006

H→Zγ

- In Standard Model, this decay proceeds entirely via loops predominantly involving heavy charged particles
- ➔ sensitive to possible new physics
- ~4σ evidence of the SM decay is possible at HL-LHC

LHCP2015

Precision on signal strength

channel	Prec. (%) 100 fb^{-1}	Prec. (%) 300 fb^{-1}		Prec. (%) 3000 fb^{-1}	
ttH $H\to\gamma\gamma$	~65	38	36	17	12
ttH $H\to ZZ^*\to 4l$	~85	49	48	20	16
VBF $H\to\gamma\gamma$	~80	47	43	22	15
VBF $H\to ZZ^*\to 4l$	~60	36	33	21	16
$H\to\mu\mu$	~70	39	38	16	12
$H\to\tau\tau$	~18	14	8	8	5
$H\to bb$	~20	14	11	7	5
$H\to\gamma\gamma$	~15	12	6	8	4
$H\to 4l$	~15	11	7	9	4
$H\to 4l$	~15	11	7	7	4

My personal estimates

ATLAS: experimental & theory uncertianties; only exp. uncertainty

CMS: current exp.l & theory uncertianties; exp. uncertainty $\propto 1/\sqrt{L}$ and ½ theory unc.

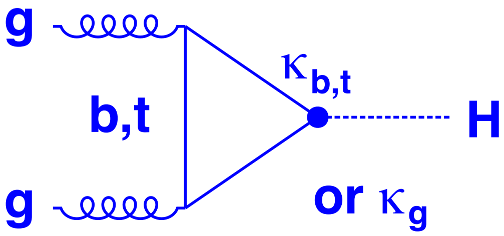
ATLAS assumed luminosity uncertainty: 3%

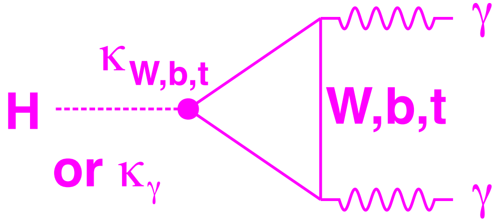
From signal rates to Higgs couplings

- The cross section times branching ratio for initial state *i* and final state *f* is given by

$$\sigma \cdot Br(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- **The total width Γ_H is too narrow to measure at LHC**
  - Assume it is the sum of the visible partial widths – no additional invisible modes
- **Cross sections and branching ratios scale with κ^2** ($\rightarrow \Delta\kappa \sim 0.5\ \Delta\mu$)
- Gluon and photon couplings can be assumed to depend on other SM couplings, or to be independent to allow for new particles in the loop





Higgs Couplings

- VH->bb included in ATLAS, updates for H->Zγ, VH/ttH->γγ (*)
- No BSM Higgs decay modes assumed

–Comparable numbers for κ_W,$\kappa_{Z,}$ $\kappa_{t,}$ and κ_γ between the two experiments

–Couplings can be determined with 2-10% precision at 3000fb^{-1} (for CMS Scenario 2)

CMS: http://arxiv.org/abs/1307.7135

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300fb^{-1}	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000fb^{-1}	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

–ATLAS: [no theory uncert., full theory uncert.]

–CMS: [Scenario 2, Scenario1]

(*) ATLAS documents:
ATL-PHYS-PUB-2014-011
ATL-PHYS-PUB-2014-006
ATL-PHYS-PUB-2014-012
ATL-PHYS-PUB-2014-016

Coupling fit with L=300 and 3000 fb^{-1}

Measurement accuracy per experiment! **(model dependent)**

Coupling modifier	300 fb^{-1}	3000 fb^{-1}	
$k_{W,Z}$, $k_{\gamma,}$	6%	3%	
k_b	12%	5%	down-quark type
k_t	15%	7%	Top Yukawa coup.
k_τ	10%	5%	lepton coupling
k_μ	22%	7%	2nd generation

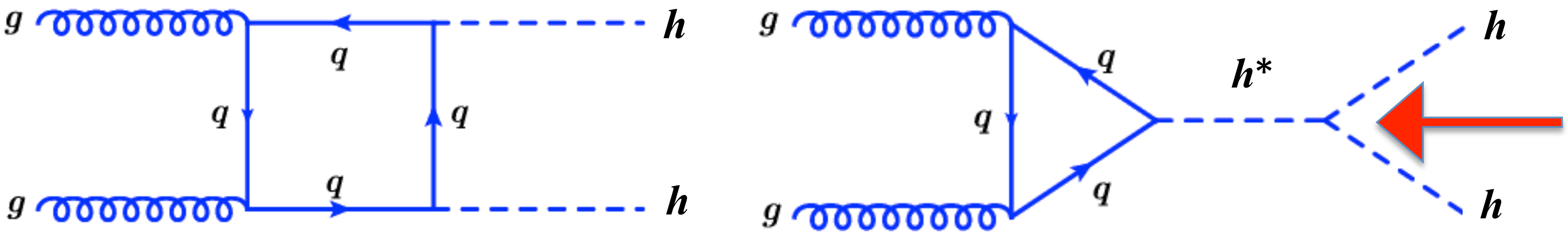
based on the results presented in this talk

CMS: http://arxiv.org/abs/1307.7135
ATLAS: ATL-PHYS-PUB-2014-016

Model independent scenario: ➔ based on coupling ratio measurements, in backup

Higgs self-coupling -1-

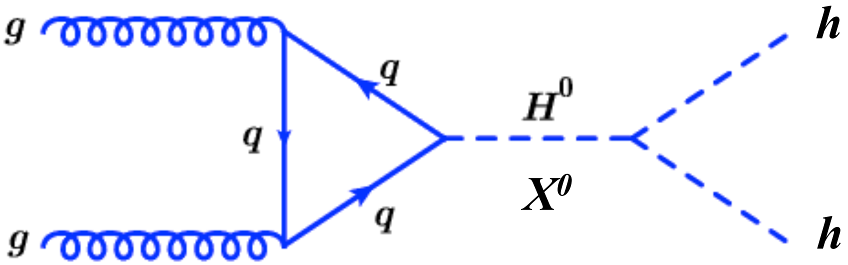
- Never seen self-interacting fundamental particles!
- Is the Higgs potential so "simple" as the one described by the Standard Model?
  - $V(\phi) = \mu^2(\phi^+\phi) + \lambda(\phi^+\phi)^2$ $\lambda = m_H/v^2$; $\mu^2 = (1/2)m^2{}_H$
  - This is not the case in several BSM implementations ➔ experimental verification is essential, e.g. measuring HH production
  - ➔Any deviation will reveal New Physics!
- The parameter λ can be probed studying the production of HH from the self-coupling process



Higgs self-coupling -1con't-

- Never seen self-interacting fundamental particles!
- Is the Higgs potential so "simple" as the one described by the Standard Model?
  - – $V(\phi) = \mu^2(\phi^+\phi) + \lambda(\phi^+\phi)^2$ $\lambda = m_H/v^2$; $\mu^2 = (1/2)m^2{}_H$
  - – This is not the case in several BSM implementations ➔ experimental verification is essential, e.g. measuring HH production
  - – ➔Any deviation will reveal New Physics!
- Example of New Physics processes:

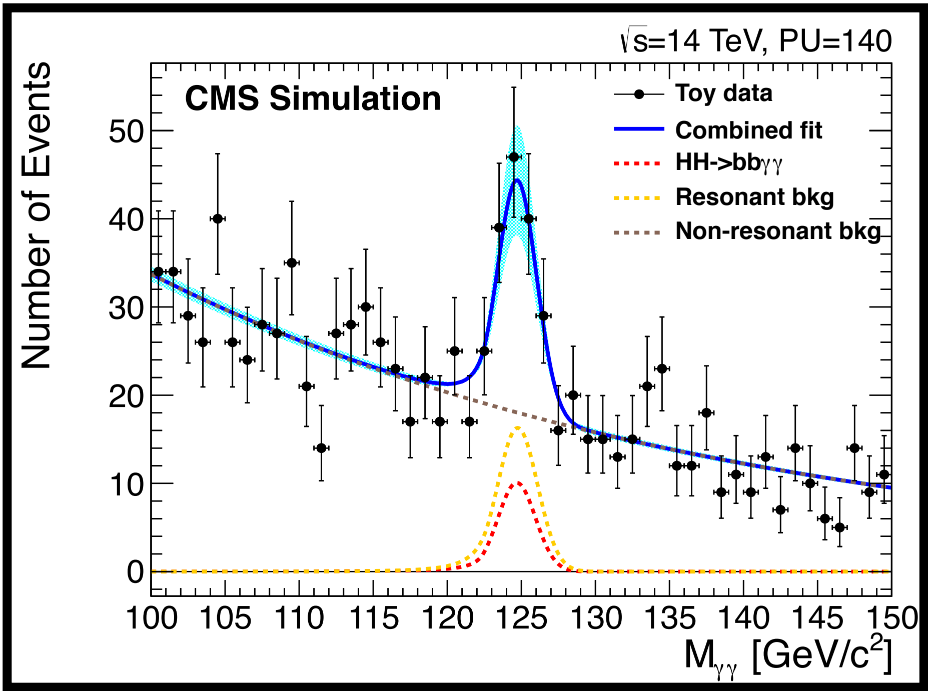
2HDM Models: 5 Higgs bosons:
h^0, H^0 (CP-even); A^0 (CP-odd)
$H^\pm$



Higgs self-coupling -2-

- For LHC, HL-LHC, several hh final states are already under study:
  - hh→ bbγγ
  - hh→ bbττ
  - hh→ bbWW
  - hh→ γγWW
  - …

hh→bbγγ



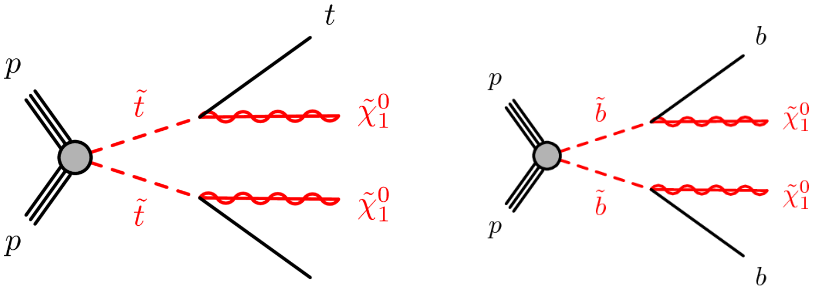
hh→bbγγ

process ATLAS	Expected events in 3000 fb^{-1}
SM HH→bbγγ	8.4± 0.1
bbγγ	9.7 ± 1.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2
top background	3.4 ± 2.2
ttH(γγ)	6.1 ± 0.5
Z(bb)H(γγ)	2.7 ± 0.1
bbH(γγ)	1.2 ± 0.1
Total background	47.1 ± 3.5
S/√B (barrel+endcap)	1.2

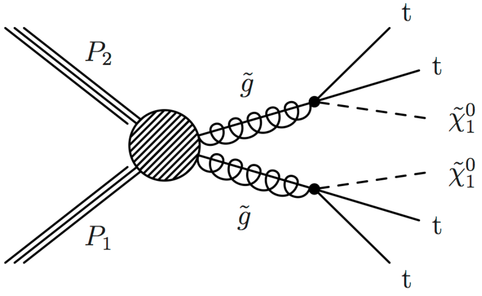
- Combination of HH→bbττ and HH→bbγγ yields a significance of 1.9 standard deviations; measurement accuracy: 54% (per experiment)
- Measurement of HH production at the HL-LHC at the level of 30% should be possible

Search for New Physics; an example: SUSY: stop and sbottom

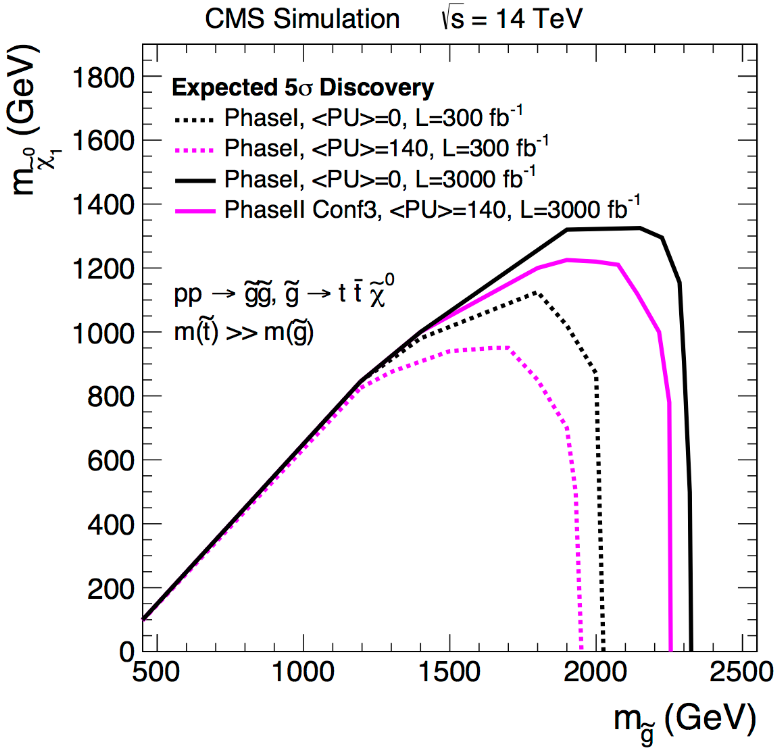
- Naturalness motivates stop/sbottom searches where the third family squarks are lightest



ATLAS stop a
sbottom pair
production



CMS gluino pair productio
with decay
via stop to ttχ

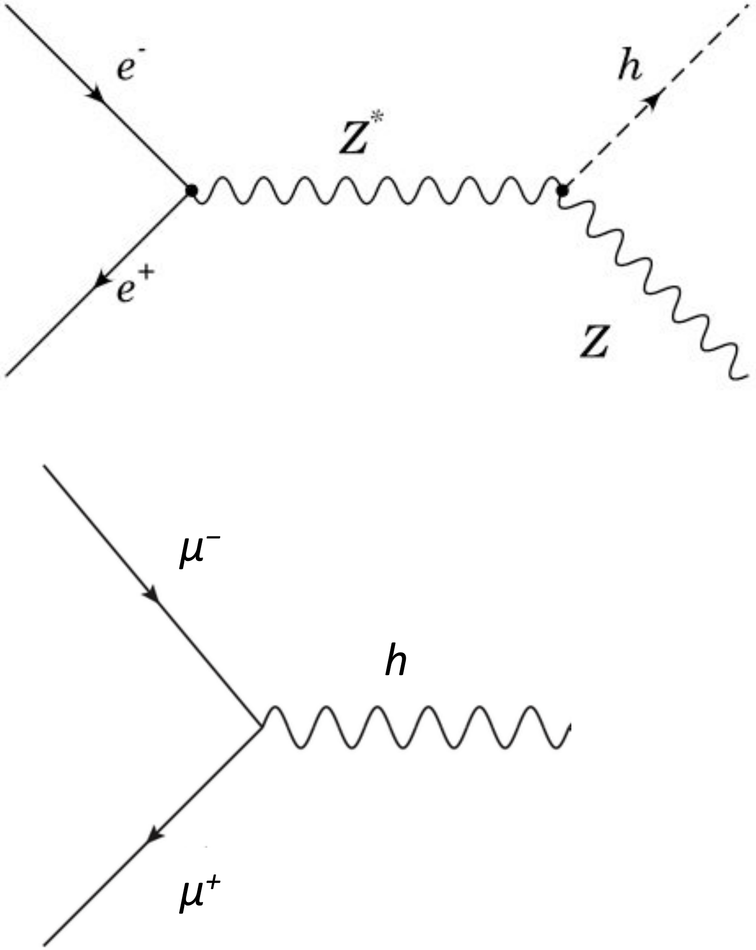


5σ discovery, simplified model	300 fb^{-1}	3000 fb^{-1}
stop mass from direct production [ATLAS]	Up to 1.0 TeV	Up to 1.2 TeV
gluino mass with decay to stop [CMS]	Up to 1.9 TeV	Up to 2.2 TeV
sbottom mass from direct production [ATLAS]	Up to 1.1 TeV	Up to 1.3 TeV

The post-LHC era

- Many ideas on the table – two main groups:
  - **Higgs Factories**:
    - Electron-Positron colliders
      - Circular: FCC-ee, CepC
      - Linear: ILC, CLIC
    - Photon collider: SAPPHiRE
    - Muon collider
  - **Very High Energy hadron colliders**
    - Circular proton collider: HE-LHC, FCC-hh, CppC

Higgs boson production at lepton colliders

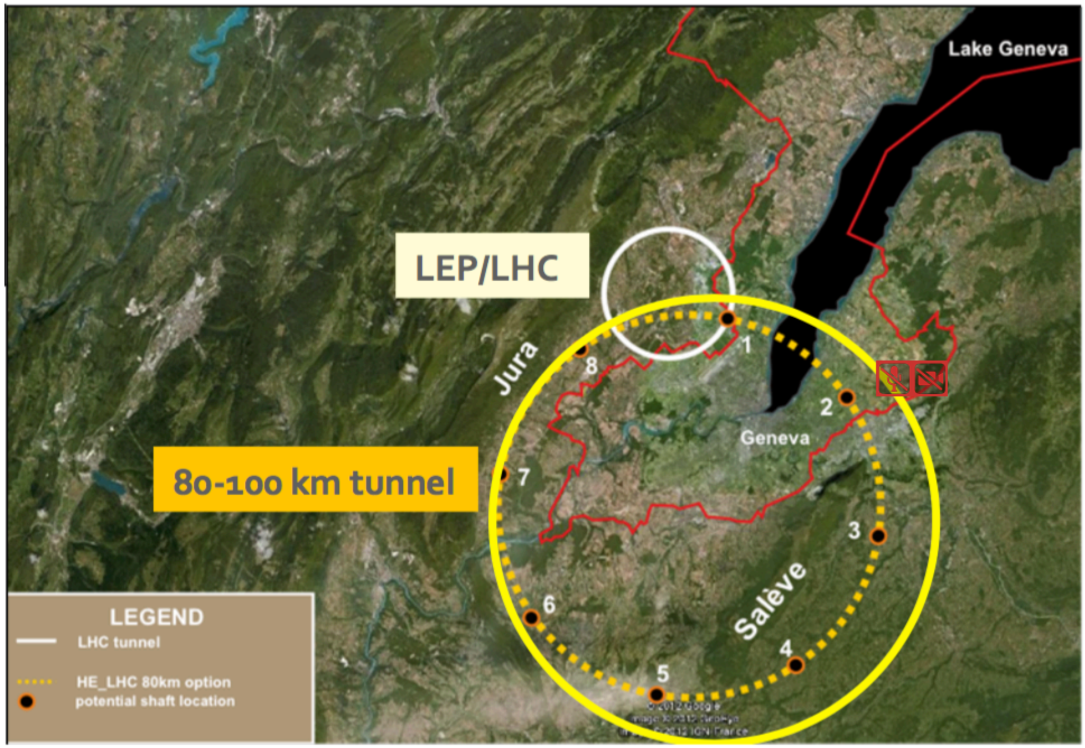


- **In e+e- colliders**, the dominant H production goes with **the associated production channel e+e_ → ZH**
  - **It does require $E_{CM} > m_Z + m_H = 216$ GeV**
- **The s-channel** allows direct lineshape scan, but the production rate is **too small** because the too small Yukawa coupling of H to electrons

- **In μ+μ- colliders**, the H production in the s-channel is significant
  - muon collider can produce in the s-channel $(m_\mu/m_e)^2 = 4.3\times10^4$ more Higgs bosons
  - **It does require $E_{CM} \sim m_H = 125$ GeV**
  - The only way for direct Γ_H measurement

FCC-ee/hh/eh

Description	**value**
Circumference [km]	**(80) 100**
centre-of-mass energy e+e– [GeV]	**91, 160, 240, 350**
Luminosity [10^{34} cm^{-2} s^{-1}]	**5.1 @ 240 GeV**
Synchrotron radiation loss [GeV/turn]	**1.67 @ 240 (→ 50 MW/ beam)**



- Circular collider at CERN to collide
  - electron-positron
  - proton-proton (see later)
  - electron-proton (not discussed in this seminar)

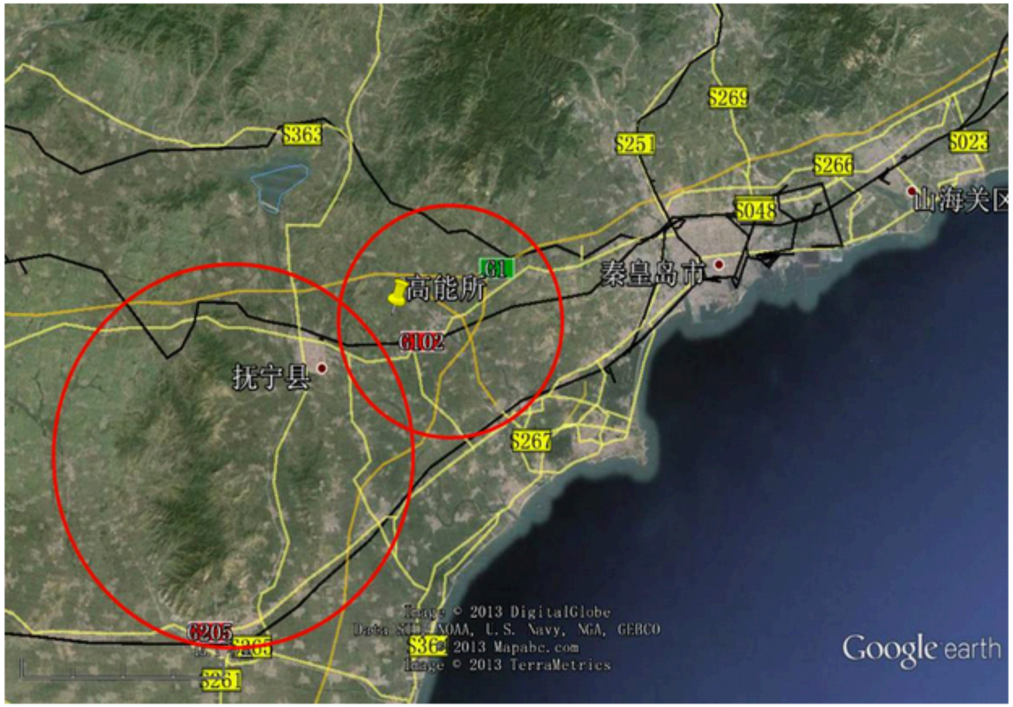
  beams

CEPC

- electron-positron circular collider in China

http://cepc.ihep.ac.cn/intro.html updated on 3 August 2014

Description	value
Circumference [km]	53.6
Centre-of-mass energy [GeV]	240
Luminosity [10^{34} cm^{-2} s^{-1}]	1.80
Synchrotron radiation loss [GeV/turn]	3.01 (→ 50 MW/ beam)



Schematic of 50 or 100 km tunnel f or a Chinese electron-positron Collider (CEPC) and Super proton-proton Collider in Qinhuangdao (秦皇岛), with great geological conditions and strong support from the local municipal government, could be the potential site.

CLIC

CDR in: https://edms.cern.ch/ui/file/1234244/7/CERN-2012-007.pdf

Description	500 GeV	3 TeV
Centre-of-mass energy [TeV]	0.5	3
Luminosity [10^{34} cm^{-2} s^{-1}]	2.3	5.9
Accelerator gradient [MV/m]	80	100
Total Length [km]	13.0	48.4

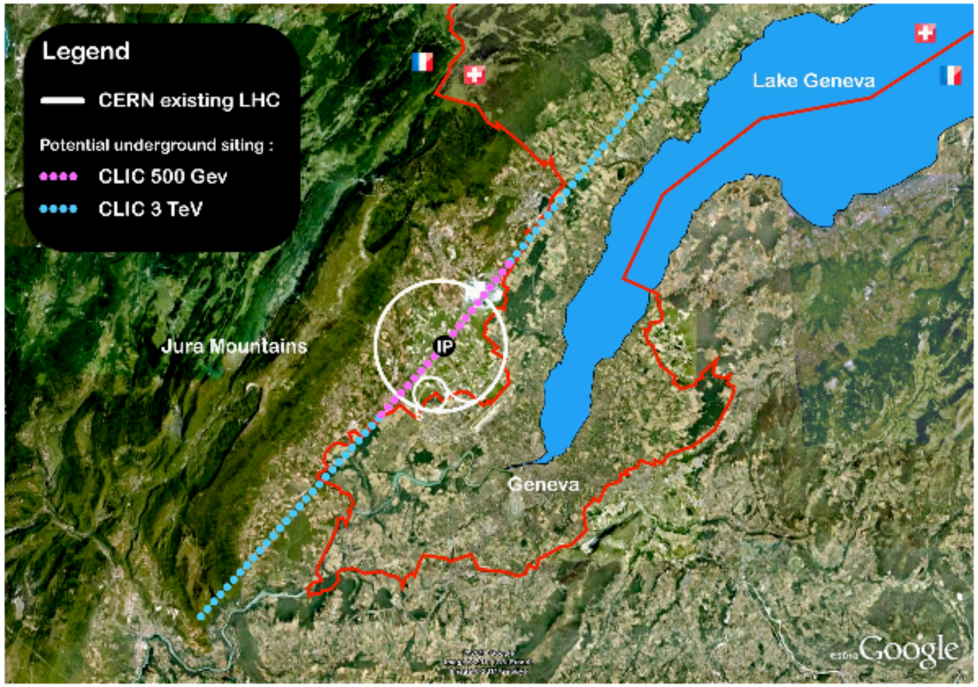


Fig. 2.2: Map showing a potential location for the CLIC accelerator complex

ILC Facility Design (Technical Design Report 2014)

Ring to Main Linac
(including bunch compressors
→ reduce σz to eliminate
hourglass effect at IP)

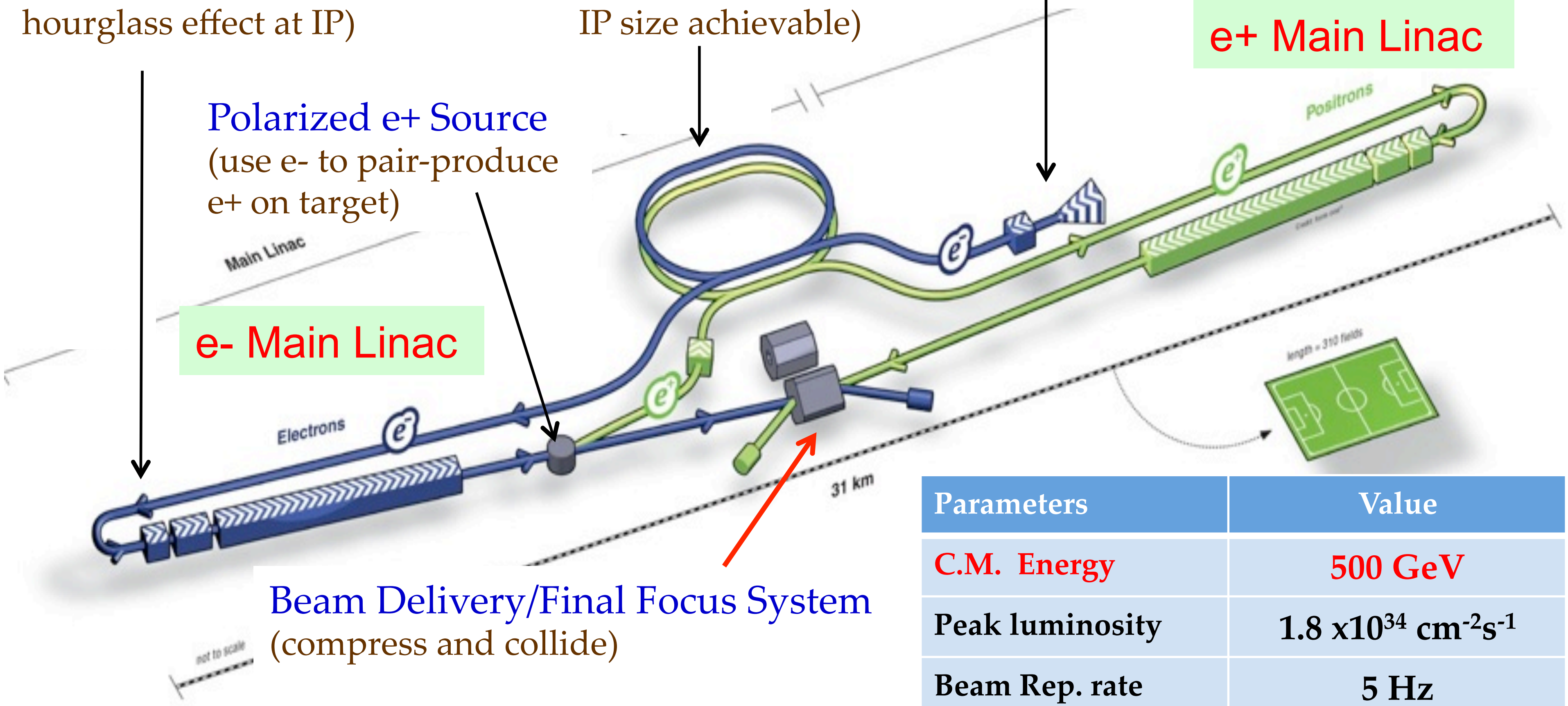
Damping Rings
(reduce emittance
→ smaller transverse
IP size achievable)

Polarised Electron Source
(deliver stable beam current)

e+ Main Linac

Polarized e+ Source
(use e- to pair-produce
e+ on target)

e- Main Linac



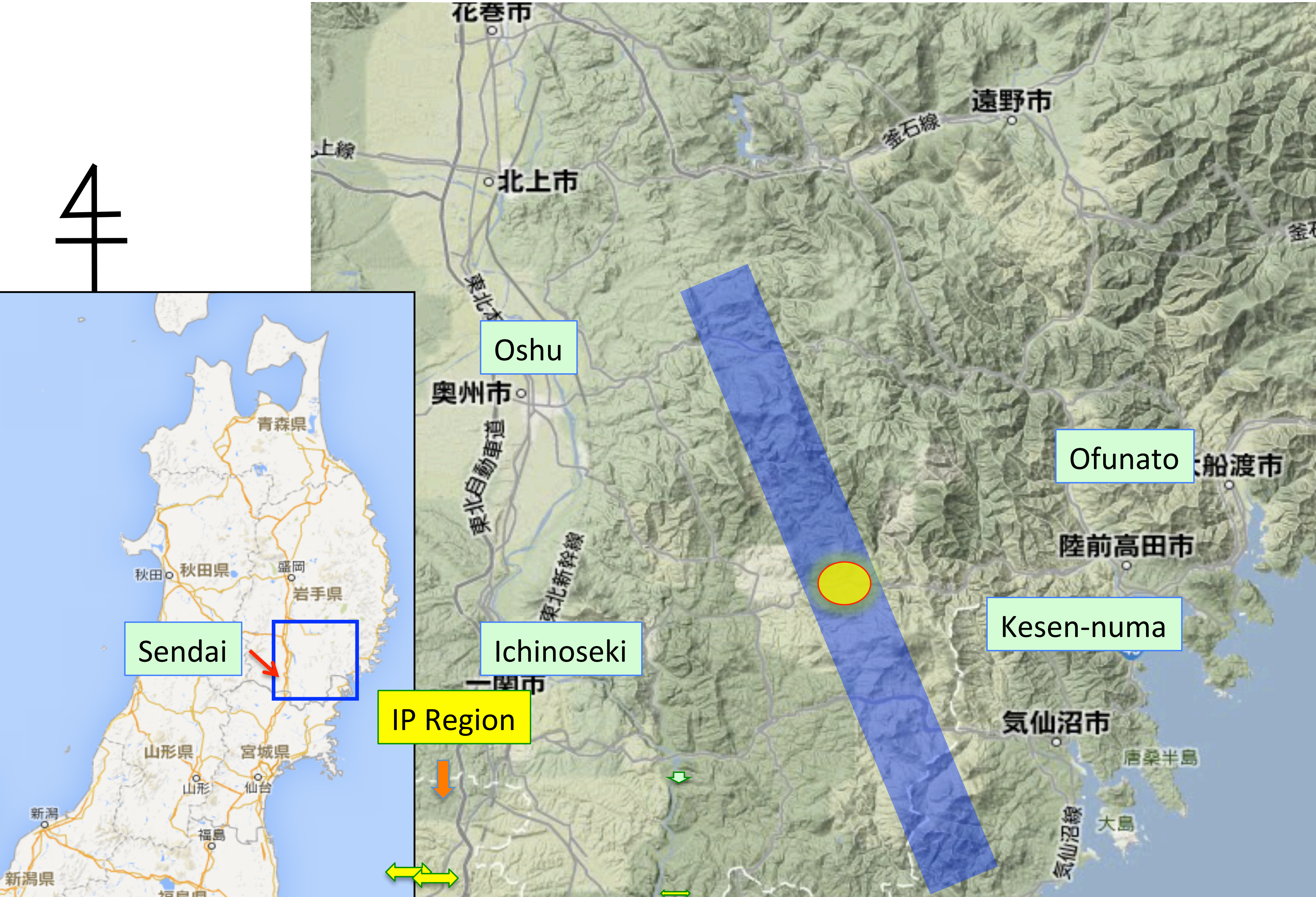
Beam Delivery/Final Focus System
(compress and collide)

Two detectors ("Push-Pull" option)

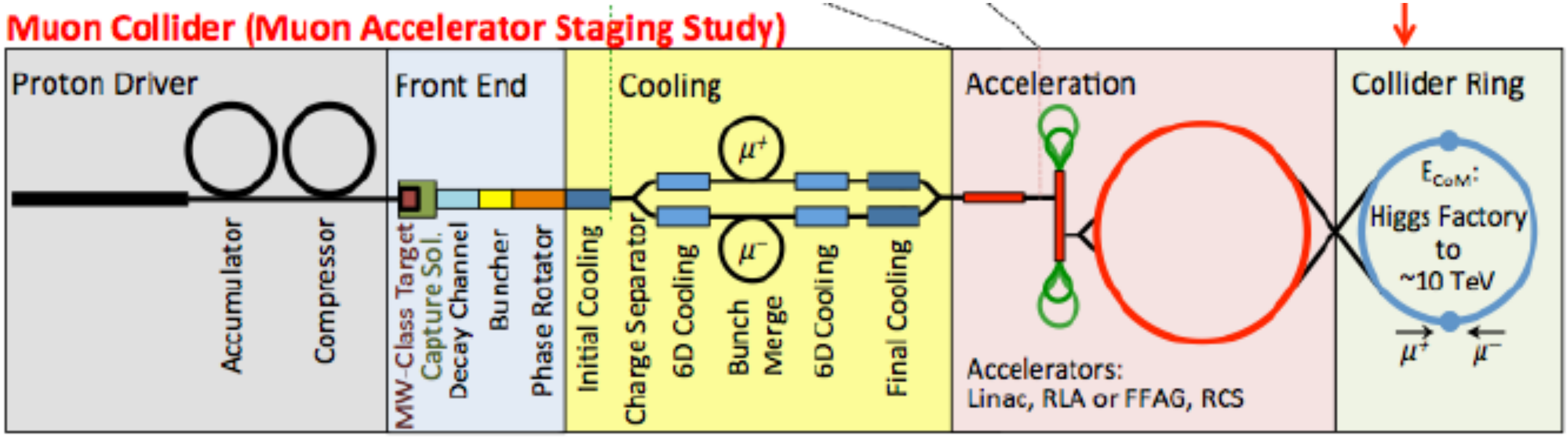
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

ILC Scheme | © www.form-one.de

Site Specific design: the “preferred” site

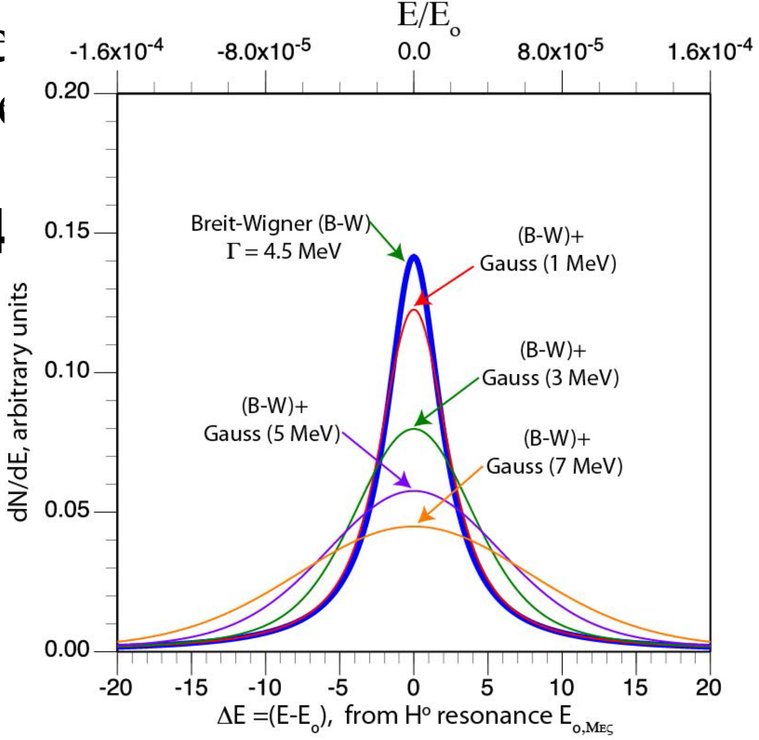


Muon collider



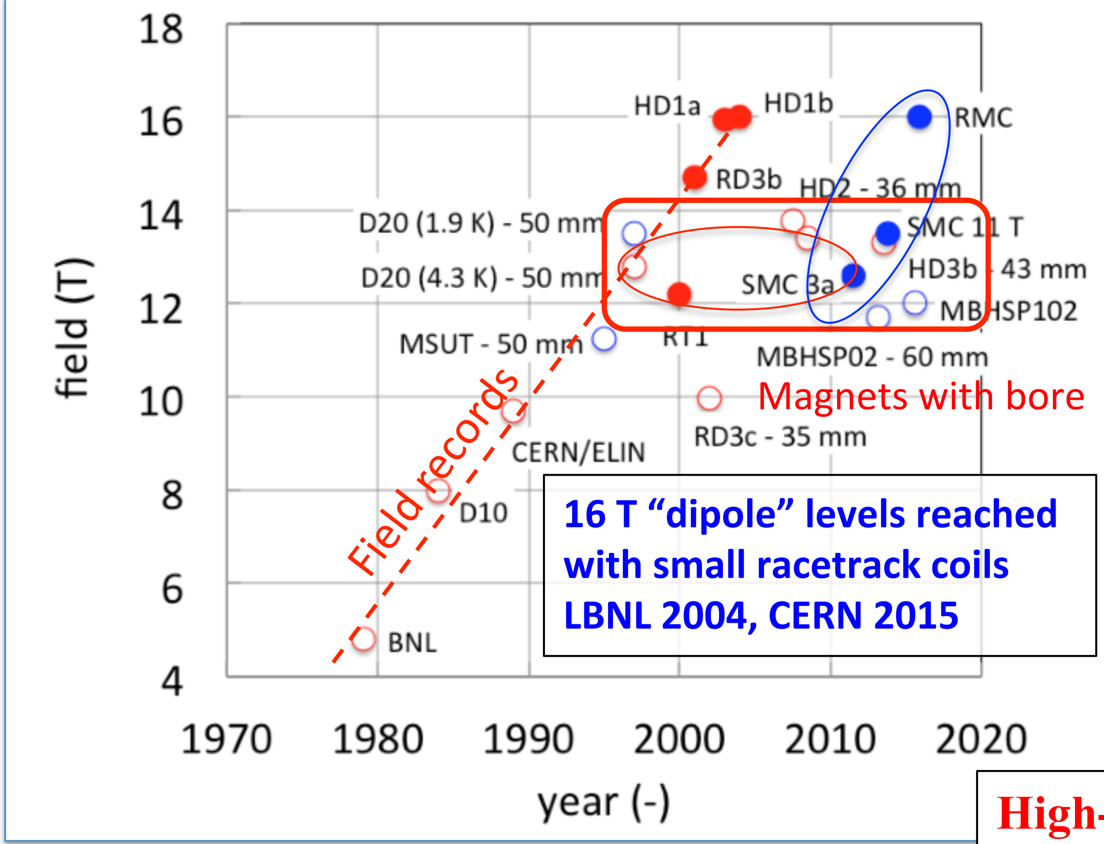
C. Rubbia, Venice_March2013

- The determination of the **width Γ_H** is be crucial in the determination of the natur of the particle and the underlying physics. **The SM prediction is only ~ 4 MeV, a formidable task!**
- Assuming an instantaneous luminosity of 0.6×10^{32} cm^{-2}s^{-1}, ~ 4400 (SM) Higgs bosons /year are produced (per experiment)



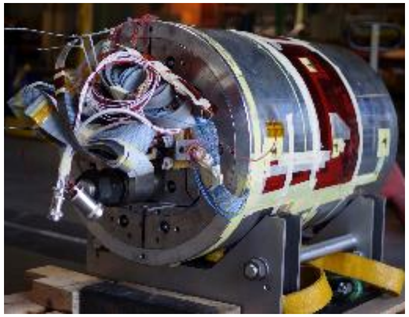
FCC-hh / HE-LHC

- **FCC-hh: hadron collider in the FCC-ee/TLEP tunnel**
  - **√s ~ 100 TeV using 16T Nb_3Sn magnets**
  - √s ~ 50 TeV using 8.4T NbTi magnets (LHC dipoles)
- **HE-LHC: new hadron collider in the LHC tunnel**
  - Needs new dipoles to increase the collision energy
  - **For a 16T Nb_3Sn magnet we would get ~30 TeV**



16 T "dipole" levels reached with small racetrack coils LBNL 2004, CERN 2015

LBNL HD1



CERN RMC

High-Temperature Superconducting (HTS) magnets also under study and development

Example: Higgs boson couplings

Uncertainties	HL-LHC	μ Collider	CLIC 350 ~.5 ab^{-1}	ILC 250 ~1.1 ab^{-1}	CEPC 240 ~2 ab^{-1}	FCC-ee 10 ab^{-1} 240 2.6 ab^{-1} 350
m_H [MeV]	40?	0.06	40	30	5.5	8
Γ_H [%]	[indirect]	4.0	5.0	5.4	4.4	1.0
g_{HZZ} [%]	2	-	0.8	0.6	0.40	0.15
g_{HWW} [%]	2	2.2	1.8	2.3	1.9	0.2
g_{Hbb} [%]	4	2.3	2.0	2.5	2.1	0.4
$g_{H\tau\tau}$ [%]	4	5	3.7	2.7	2.3	0.5
g_{Hcc} [%]	-	-	3.2	3.2	2.7	0.7
$g_{H\gamma\gamma}$ [%]	2	10	-	8.2	7.4	1.5
g_{Hgg} [%]	3	-	3.6	3	2.4	0.8
g_{Htt} [%]	5	-	-	-	-	-
$g_{H\mu\mu}$ [%]	5	2.1	-	-	14	6.2
g_{HHH} [%]	30 →	-	-	-	-	-
	ATLAS+CMS combination (my estimate)	Taken from M. Klute LCWS 2015	M. Pandurovic, Gomel School 2015	J. Tian, ICHEP2014	main_preCDR.	arXiv:1308.6176v3

Conclusions

- With the discovery of the 125 GeV Higgs boson, a new era in high-energy physics is just opened!
- The Standard Model is a complete theory now:
  - test its validity at the highest possible theoretical and experimental precision
  - It does not explain all observations in nature: new physics must exist at some energy scale
  - The Higgs sector is experimentally completely new and its investigation may reveal precious information on where new physics could be
- Direct searches for new objects and new phenomena are essential
- LHC and its luminosity upgrade, HL-LHC, can shed light on the nature of the 125 Higgs boson at the level of O(few %) on couplings, and search for new particles at the O(few TeV) scale
- Decision on the next future collider(s) cannot be taken until we'll not first see what the outcome from LHC
  - Appointment with the European Strategy (symposium in 2018/19)

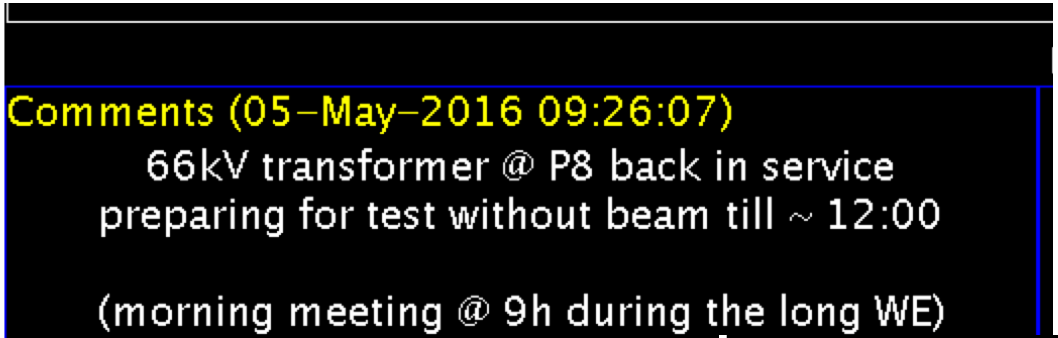
GRAZIE!!

The LHC is almost back! ☺

5:30 am on Friday 29 April

Electrical perturbation

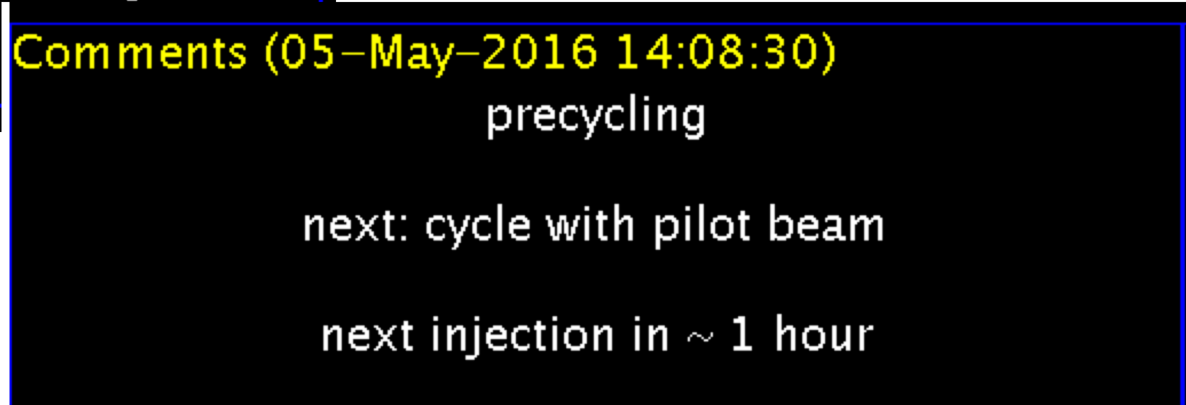
- Cause: short circuit caused by *fouine* on 66kV transformer in point 8
- Transformer connections damaged



Comments (05–May–2016 09:26:07)

66kV transformer @ P8 back in service
preparing for test without beam till ~ 12:00

(morning meeting @ 9h during the long WE)



Comments (05–May–2016 14:08:30)

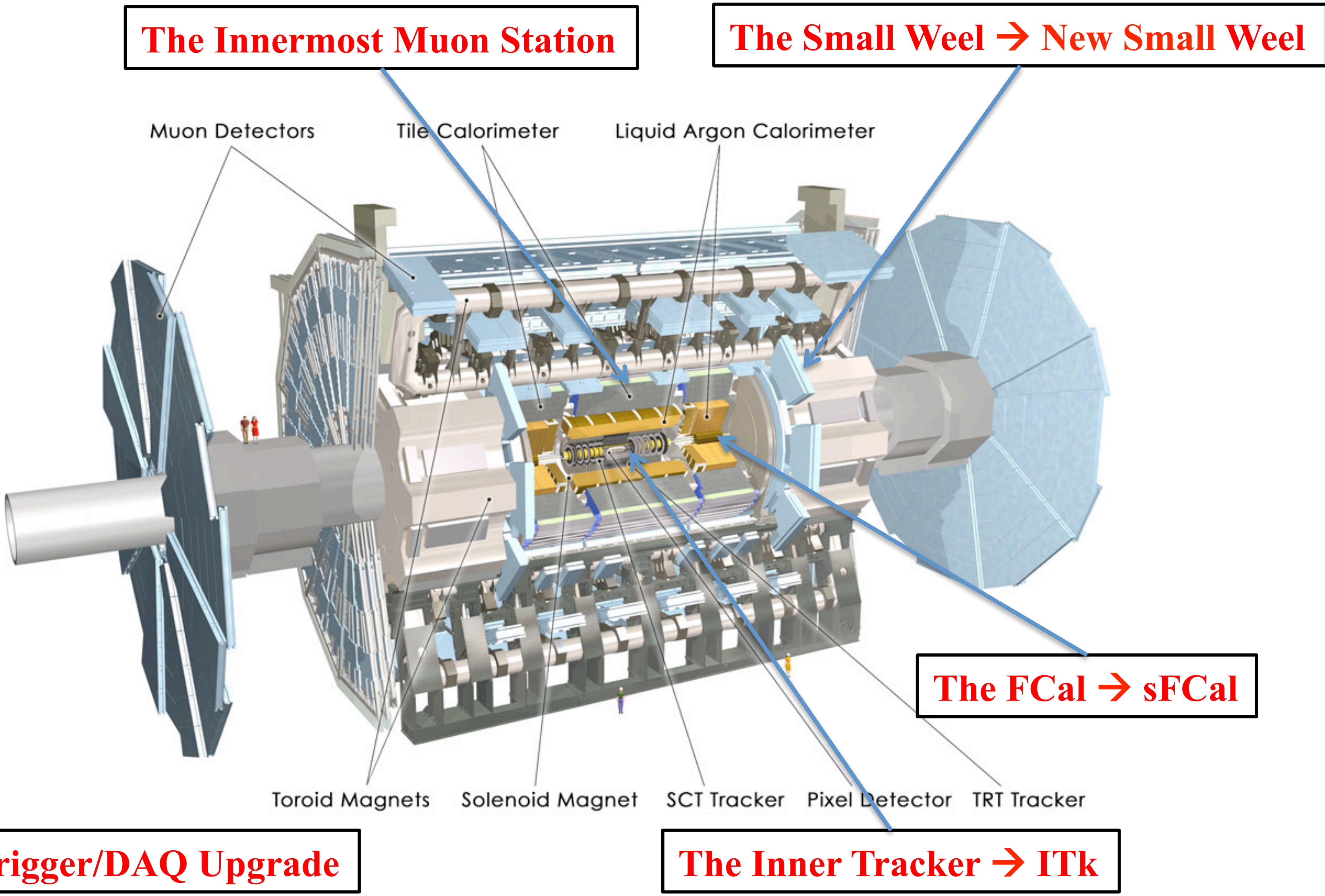
precycling

next: cycle with pilot beam

next injection in ~ 1 hour

backup

The ATLAS detector upgrade



The Innermost Muon Station

The Small Weel → New Small Weel

The FCal → sFCal

also Trigger/DAQ Upgrade

The Inner Tracker → ITk

ATLAS & CMS Upgrade

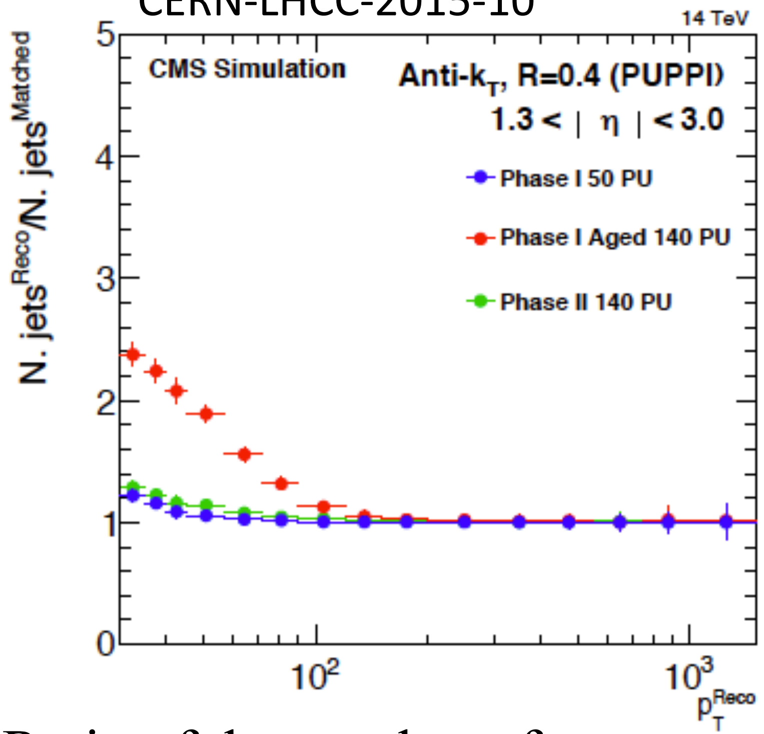
- Pileup mitigation is a critical element of the design
- More details on:
  - ATLAS [CERN-LHCC-2015-020]
  - & CMS [CERN-LHCC-2015-019]

  "Scoping Documents" showing impact of different cost scenarios on physics performance,

  and on:
  - ATLAS Phase II LoI [CERN-LHCC-2012-022],
  - CMS Technical Proposal [CERN-LHCC-2015-010]

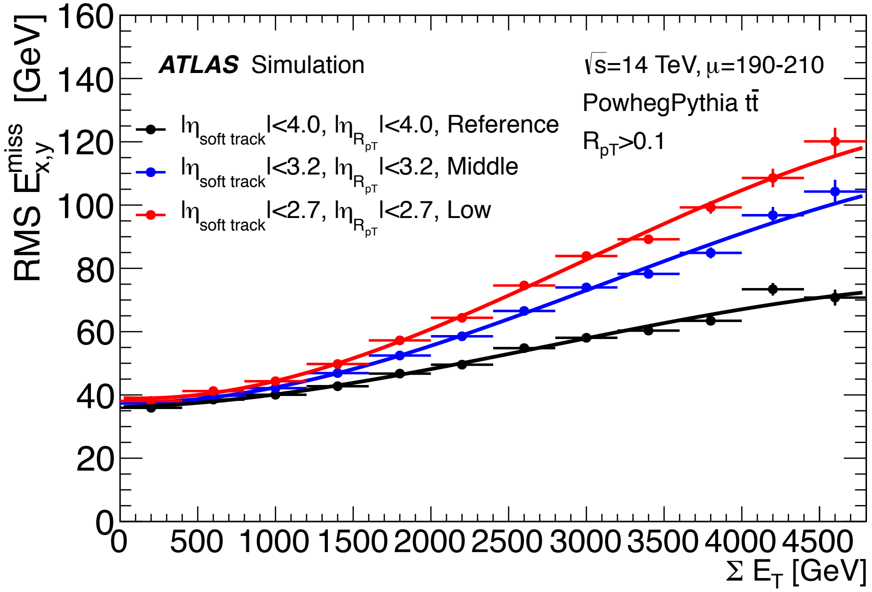
Example of pileup mitigation

CERN-LHCC-2015-10



Ratio of the number of reconstructed jets with the *PUPPI*[1] algorithm to the number of reconstructed jets matched to particle level jets for different p_T bins.

CERN-LHCC-2015-020



The resolutions of the x and y components of E_T^{miss} in the three scoping scenarios for samples of $t\bar{t}$ events with μ=200. The resolutions are shown as a function of the scalar sum of total transverse energy in the event, with MC statistical uncertainties.

---

1. [http://arxiv.org/pdf/1407.6013v2.pdf]

k-framework:
determination of coupling deviations

Coupling to fermions: $g_F = \kappa_F \frac{\sqrt{2} m_F}{v}$ Coupling to bosons: $g_V = \kappa_V \frac{2 m_V^2}{v}$

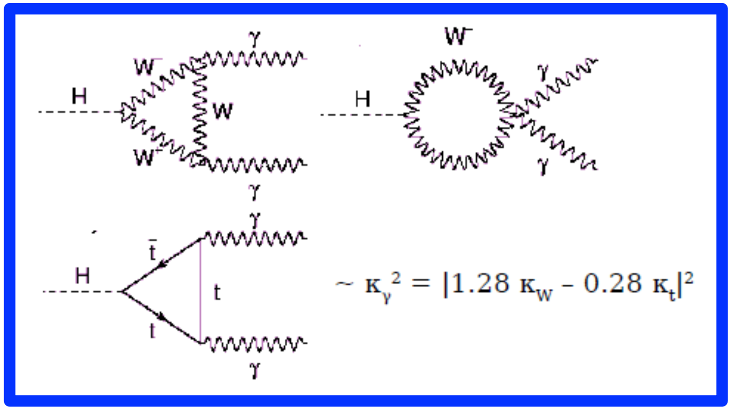
Write rates in terms of k_i parameters

The index *i* is related to each individual elementary particle

- Production: $\sigma_i \sim \kappa_i^2 \, \sigma_i^{SM}$
- Decay: $\Gamma_i \sim \kappa_i^2 \, \Gamma_i^{SM}$
- Total Width: $\Gamma_H = \Sigma_i \, \kappa_i^2 \, \Gamma_i^{SM}$

Example:

$$\frac{\sigma \cdot \mathrm{B}\,(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$



$$\sim \kappa_\gamma^2 = |1.28\ \kappa_W - 0.28\ \kappa_t|^2$$

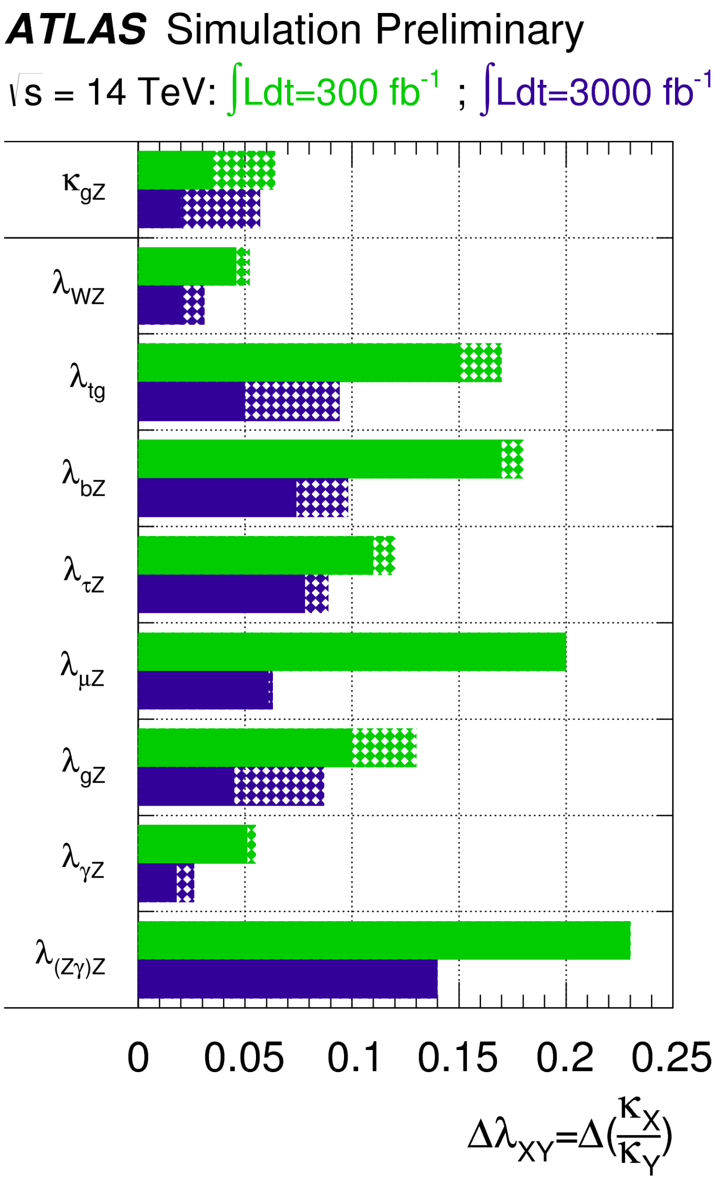
Total width not measured at LHC (upper limits can be derived from off-shell production studies)

Assumptions:

- ***Only one Higgs boson***
- ***Only scalar modifications of the coupling strength: kinematics as in SM***
- ***$J^P = 0^+$***

Interference in H→γγ, gg→H, ...:
→ some relative sign-ambiguities solved

Higgs Couplings



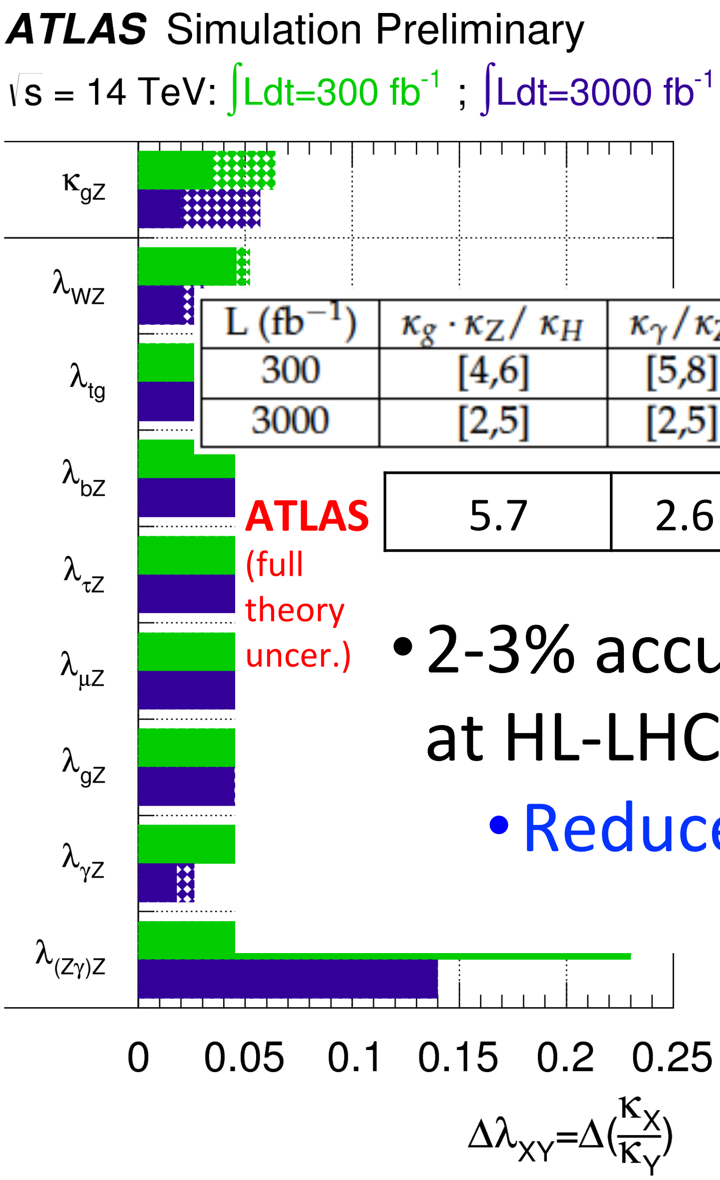
- Most generic model: remove the assumption on the total width
  - – Only ratios of the coupling scale factors can be determined at LHC
  - – Use given process as a reference

ATL-PHYS-PUB-2015-024

- Total Higgs boson width can be probed at LHC studying the comparison of on-shell and off-shell Higgs boson production
- Recent study by ATLAS indicates that, under a number of assumptions, the (SM) Higgs boson width can be estimated with a **systematic uncertainty of ~ 2 MeV:**

$$\Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1}\ \text{MeV (stat+sys)}.$$

Higgs Couplings

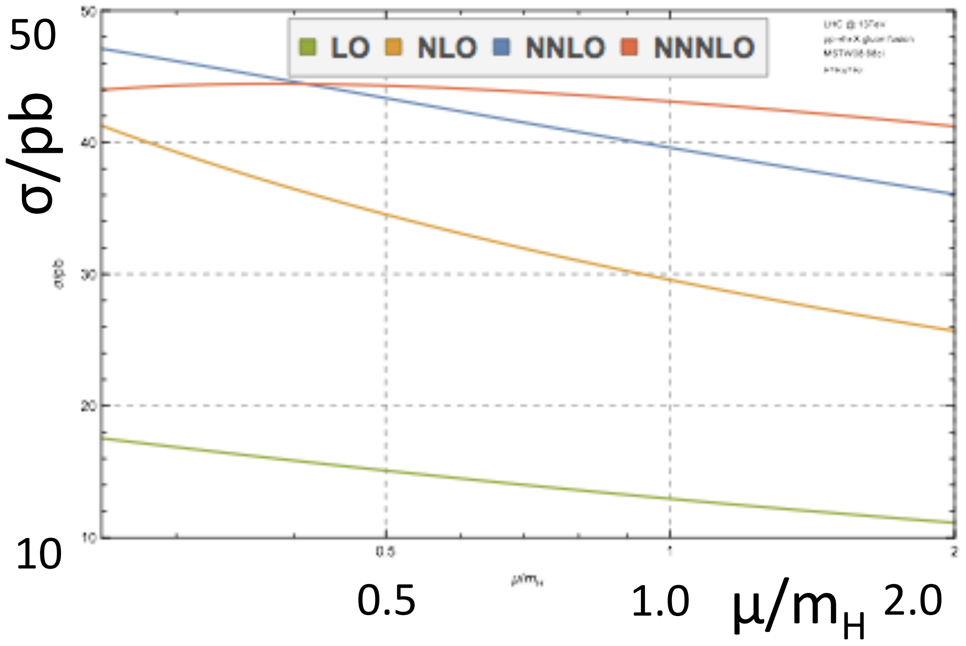


CMS [Scenario2,Scenario1]

L (fb^{-1})	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ/κ_Z	κ_W/κ_Z	κ_b/κ_Z	κ_τ/κ_Z	κ_Z/κ_g	κ_t/κ_g	κ_μ/κ_Z	$\kappa_{Z\gamma}/\kappa_Z$
300	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]
ATLAS (full theory uncer.)	5.7	2.6	3.1	9.8	8.9	8.7	9.4	6.3	14

- 2-3% accuracy on a few coupling constants at HL-LHC
  - Reduced theoretical uncertainties needed

N^3LO ggF production cross section



C. Anastasiou et al.:
http://arxiv.org/abs/1107.0683 ,
http://arxiv.org/abs/1403.4616 ,
http://arxiv.org/abs/1411.3584 ,
http://arxiv.org/abs/1503.06056

FIG. 2: Scale variation of the gluon fusion cross-section at all perturbative orders through N^3LO.

- For renormalisation and factorisation scales equal to half the Higgs mass, the N^3LO corrections are of the order of +2.2%. The total scale variation at N^3LO is 3%, reducing the uncertainty due to missing higher order QCD corrections by a factor of three.
- However the procedure to transfer the scale variations to theory uncertainty on the cross section is not firmly established (why considering a factor 2 and ½, for example?)

[1] http://arxiv.org/abs/1409.5036
[2] http://arxiv.org/abs/1307.1843

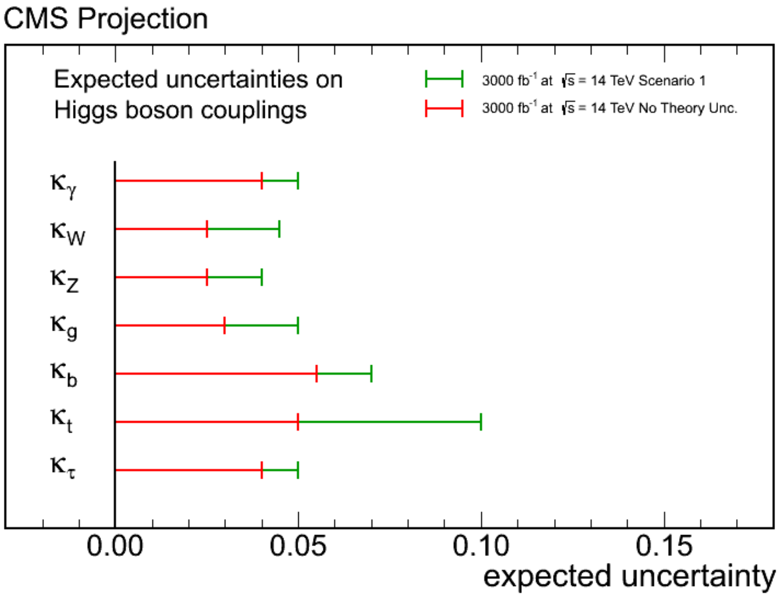
Effects of theory uncertainties

- Theoretical uncertainties limit the achieved precision
- Reducing the theoretical uncertainties is a worthwhile endeavor

CMS:

Scenario 1

No theory uncertainty



ATLAS: Deduced size of theory uncertainty to increase total uncertainty by <10% for 3000 fb^{-1}

Scenario	Status	by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	2014 [10–12]	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$						
PDF	8	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	6–19	-
$q\bar{q}H$						
PDF	3.3	-	-	2.8	-	-
$t\bar{t}H$						
PDF	9	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	2

See also talk from W. Verkerke, this conference

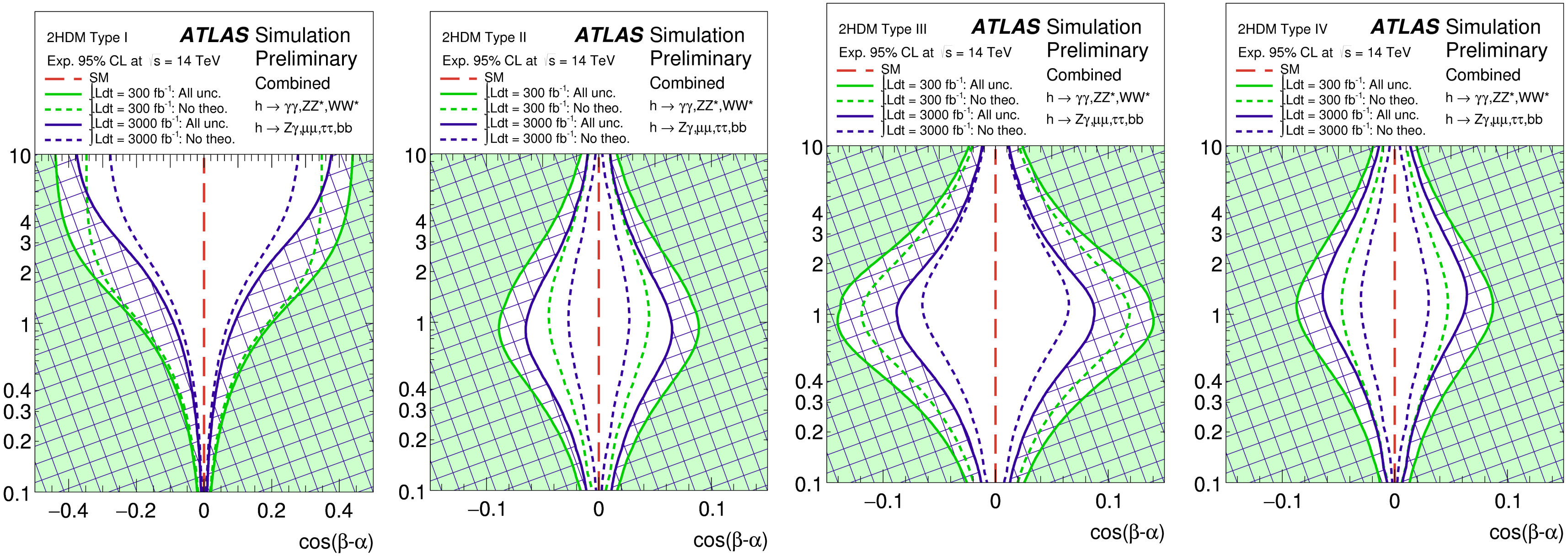
Interpretation for BSM Higgs sector

- Use expected accuracy in the couplings k_i of the 125 GeV Higgs boson
- Same decays as in the SM are assumed (b-associated production included as a correction)

h(125) is the light scalar of the 2HDM

ATL-PHYS-PUB-2014-017

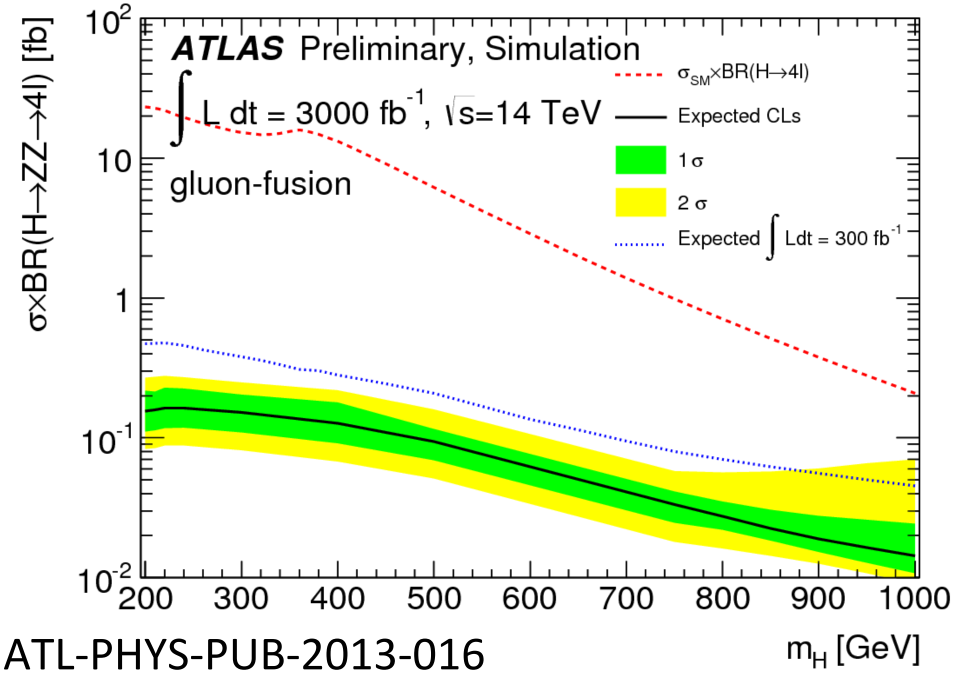
Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$



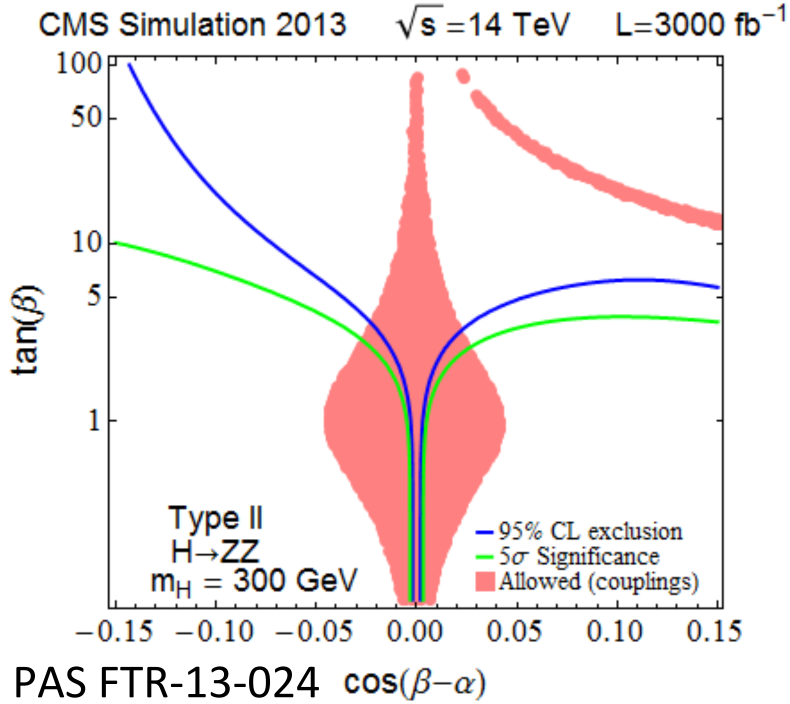
ATL-PHYS-PUB-2014-017

Direct BSM Higgs searches: example H→ZZ→4l

- The 4l final state has small cross section but is clean and well reconstructed
- A heavy SM-like Higgs boson decaying to 4l occurs in several extensions of the scalar sector (2HDM,EWK singlet)
- Limits improve by a factor ~3 with 3000 fb^{-1} wrt 300 fb^{-1}
- Similar sensitivity for ATLAS and CMS (~0.01-0.1 fb)



ATL-PHYS-PUB-2013-016



CMS PAS FTR-13-024

CLIC

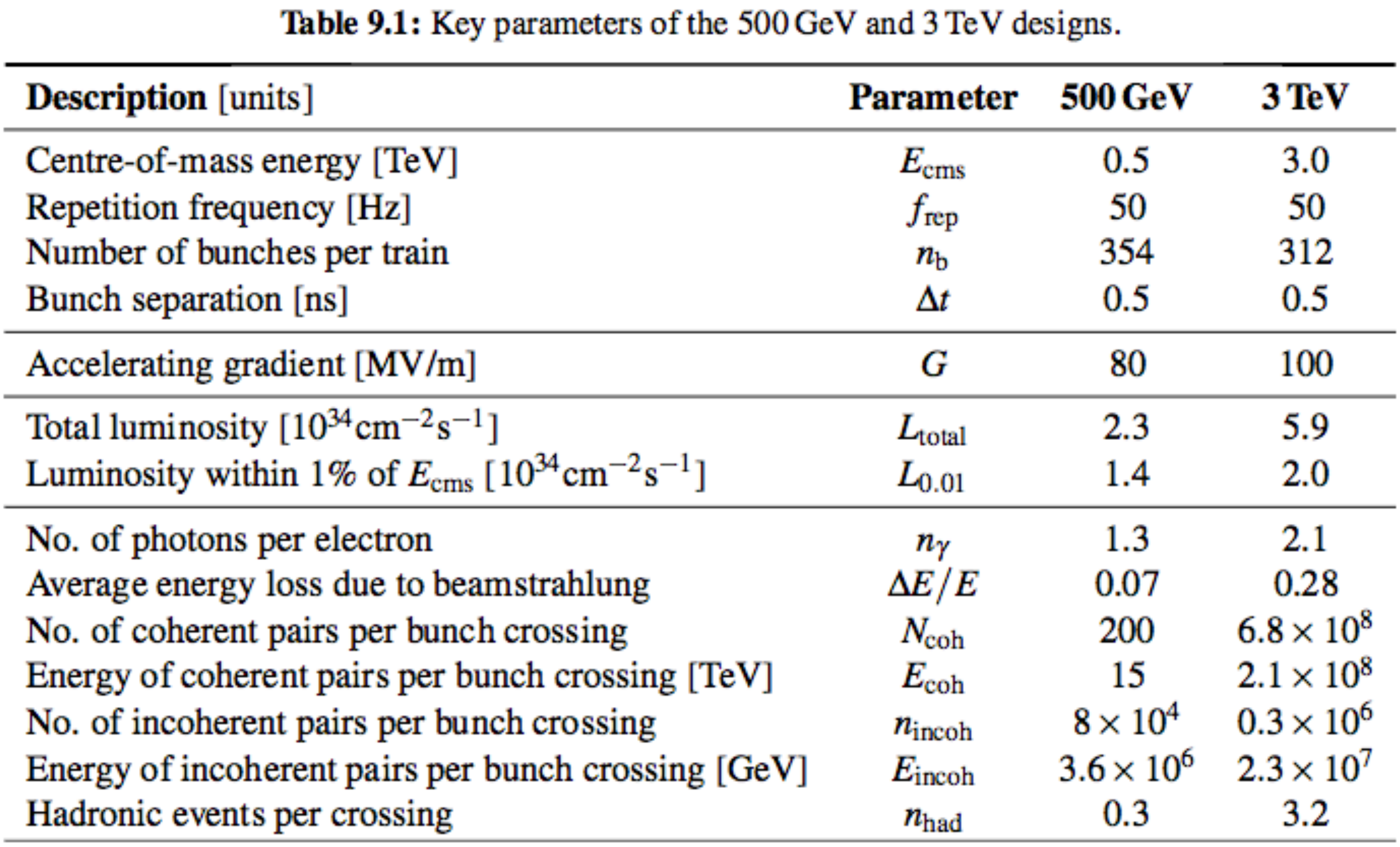


Table 9.1: Key parameters of the 500 GeV and 3 TeV designs.

Description [units]	**Parameter**	**500 GeV**	**3 TeV**
Centre-of-mass energy [TeV]	E_{cms}	0.5	3.0
Repetition frequency [Hz]	f_{rep}	50	50
Number of bunches per train	n_{b}	354	312
Bunch separation [ns]	Δt	0.5	0.5
Accelerating gradient [MV/m]	G	80	100
Total luminosity [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	L_{total}	2.3	5.9
Luminosity within 1% of E_{cms} [$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	$L_{0.01}$	1.4	2.0
No. of photons per electron	n_{γ}	1.3	2.1
Average energy loss due to beamstrahlung	$\Delta E/E$	0.07	0.28
No. of coherent pairs per bunch crossing	N_{coh}	200	6.8×10^{8}
Energy of coherent pairs per bunch crossing [TeV]	E_{coh}	15	2.1×10^{8}
No. of incoherent pairs per bunch crossing	n_{incoh}	8×10^{4}	0.3×10^{6}
Energy of incoherent pairs per bunch crossing [GeV]	E_{incoh}	3.6×10^{6}	2.3×10^{7}
Hadronic events per crossing	n_{had}	0.3	3.2

- p