CERN Status and Future Plans

Arcetri, May 17th 2016

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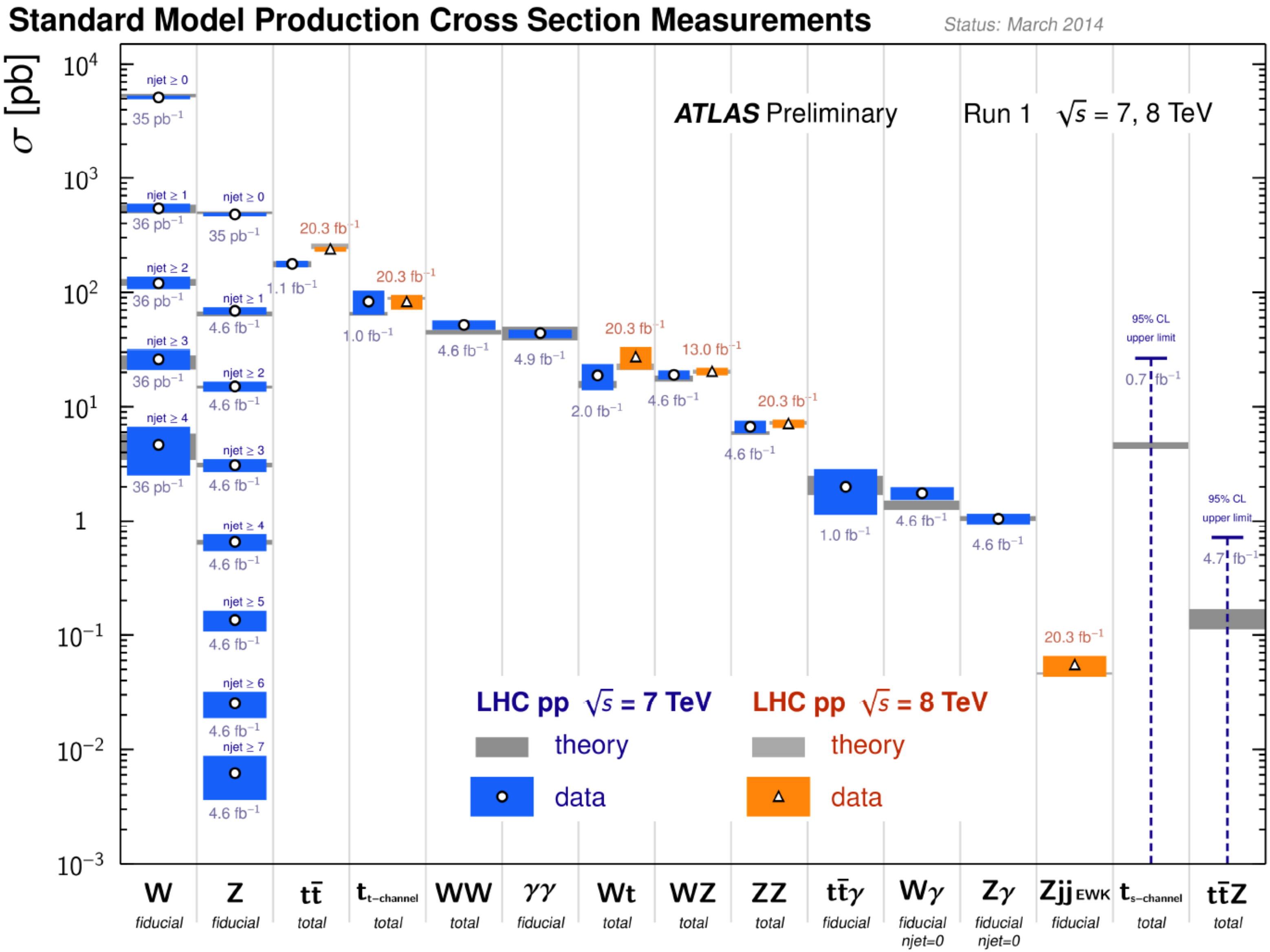
INFN

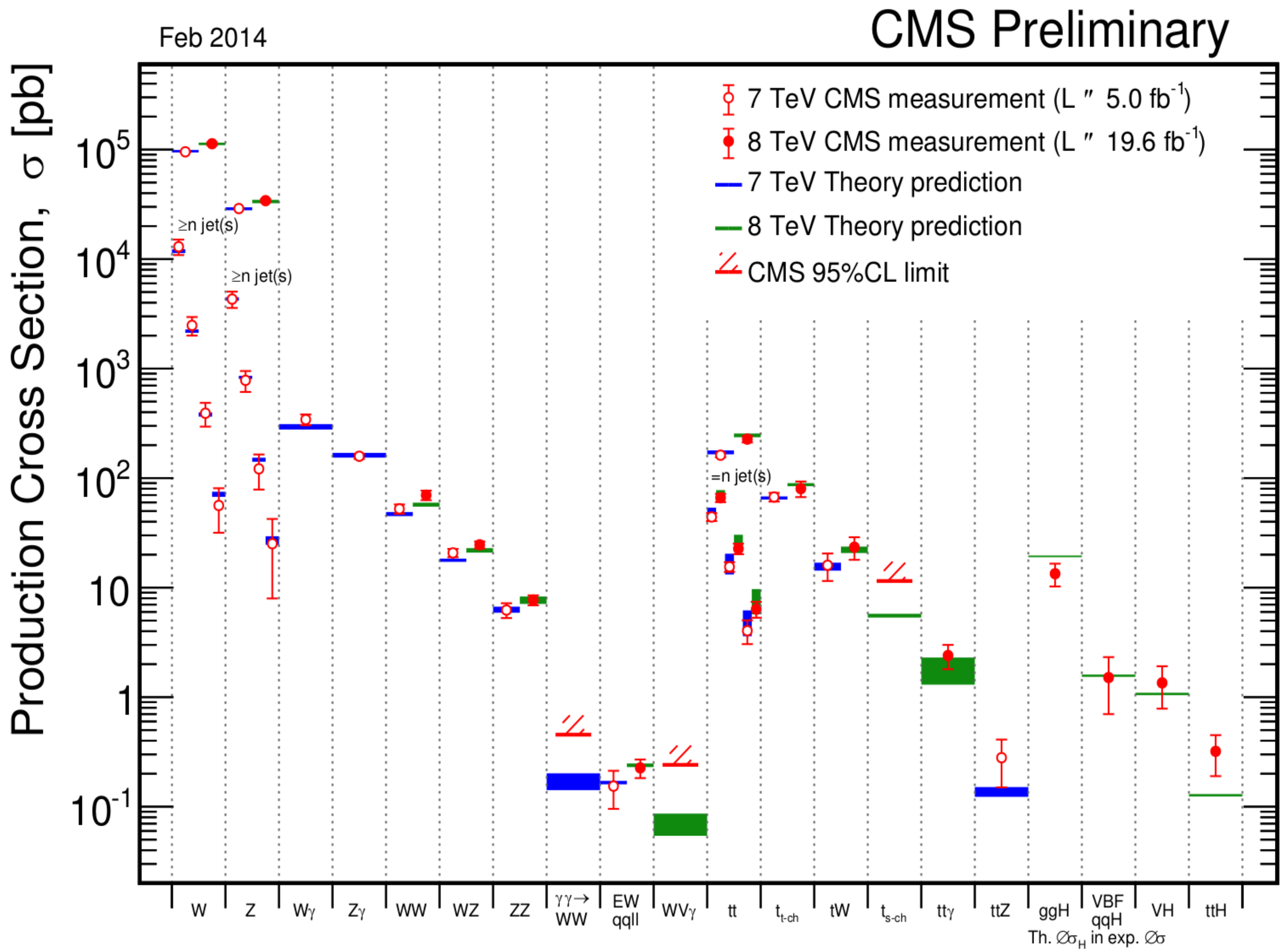
After LHC Run 1 (2010-2012):

- We have consolidated the Standard Model
  (a wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics, $B_s \rightarrow \mu\mu$ decay)
- We have completed the Standard Model: discovery of the messenger of the BEH-field, the Higgs boson discovery
- We have found interesting properties of the hot dense matter
- **We have NO evidence of New Physics, although tantalizing hints have survived scrutiny**

SM@LHC


Standard Model Production Cross Section Measurements
Status: March 2014
σ [pb]
10^4
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
ATLAS Preliminary
Run 1 $\sqrt{s}$ = 7, 8 TeV
njet ≥ 0
35 pb^{-1}
njet ≥ 1
36 pb^{-1}
njet ≥ 2
36 pb^{-1}
njet ≥ 3
36 pb^{-1}
njet ≥ 4
36 pb^{-1}
njet ≥ 0
35 pb^{-1}
njet ≥ 1
4.6 fb^{-1}
njet ≥ 2
4.6 fb^{-1}
njet ≥ 3
4.6 fb^{-1}
njet ≥ 4
4.6 fb^{-1}
njet ≥ 5
4.6 fb^{-1}
njet ≥ 6
4.6 fb^{-1}
njet ≥ 7
4.6 fb^{-1}
20.3 fb^{-1}
1.1 fb^{-1}
20.3 fb^{-1}
1.0 fb^{-1}
4.6 fb^{-1}
4.9 fb^{-1}
20.3 fb^{-1}
2.0 fb^{-1}
13.0 fb^{-1}
4.6 fb^{-1}
20.3 fb^{-1}
4.6 fb^{-1}
1.0 fb^{-1}
4.6 fb^{-1}
4.6 fb^{-1}
20.3 fb^{-1}
95% CL
upper limit
0.7 fb^{-1}
95% CL
upper limit
4.7 fb^{-1}
LHC pp $\sqrt{s}$ = 7 TeV
theory
data
LHC pp $\sqrt{s}$ = 8 TeV
theory
data
W
fiducial
Z
fiducial
$t\bar{t}$
total
$t_{t\text{-channel}}$
total
WW
total
γγ
fiducial
Wt
total
WZ
total
ZZ
total
$t\bar{t}\gamma$
fiducial
Wγ
fiducial
njet=0
Zγ
fiducial
njet=0
Zjj EWK
fiducial
$t_{s\text{-channel}}$
total
$t\bar{t}Z$
total

SM@LHC


Feb 2014
CMS Preliminary
Production Cross Section, σ [pb]
10^5
10^4
10^3
10^2
10
1
10^{-1}
7 TeV CMS measurement (L ″ 5.0 fb^{-1})
8 TeV CMS measurement (L ″ 19.6 fb^{-1})
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
γγ→WW
EW qqll
WVγ
tt
t$_{t\text{-ch}}$
tW
t$_{s\text{-ch}}$
ttγ
ttZ
ggH
VBF qqH
VH
ttH
Th. ∅σ$_H$ in exp. ∅σ

HIG-14-009

Higgs Combination

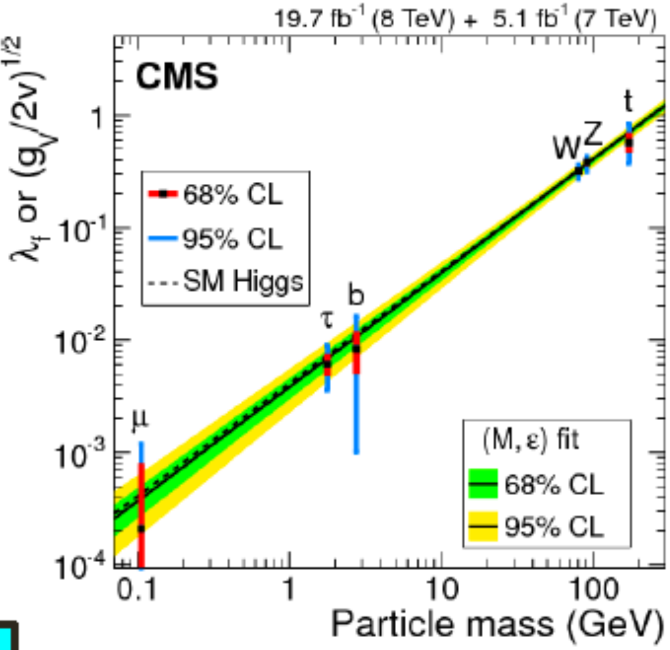
- Five main decay channels all published
- **Combination submitted Dec 30**
- All results consistent with SM Higgs

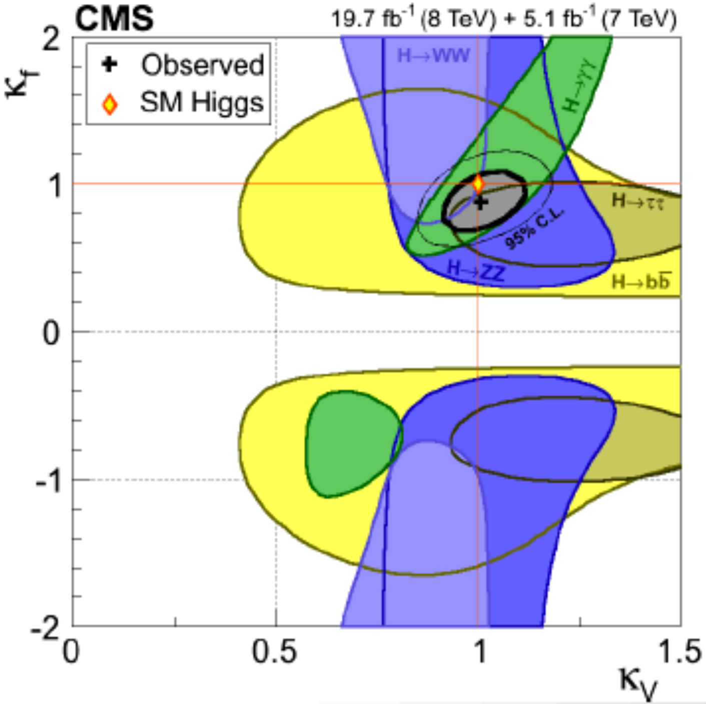
https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig14009PaperTwiki

$$m_{\mathrm{H}} = 125.02\ ^{+0.26}_{-0.27}\ (\mathrm{stat.})\ ^{+0.14}_{-0.15}\ (\mathrm{syst.})\ \mathrm{GeV}$$

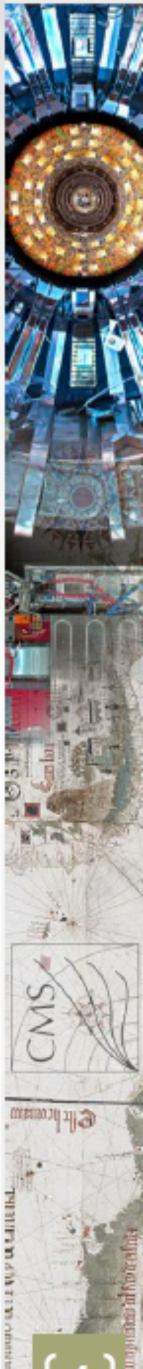
$$\mu = 1.00\ ^{+0.14}_{-0.13}\ [\pm 0.09\ (\mathrm{stat.})\ ^{+0.08}_{-0.07}\ (\mathrm{theo.}) \pm 0.07\ (\mathrm{syst.})]$$

Channel	Obs (σ)	Exp (σ)
H → ZZ	6.5	6.3
H → γγ	5.6	5.3
H → WW	4.7	5.4
H → ττ	3.8	3.9
H → bb	2.0	2.6
H → μμ	< 0.1	0.4





n!

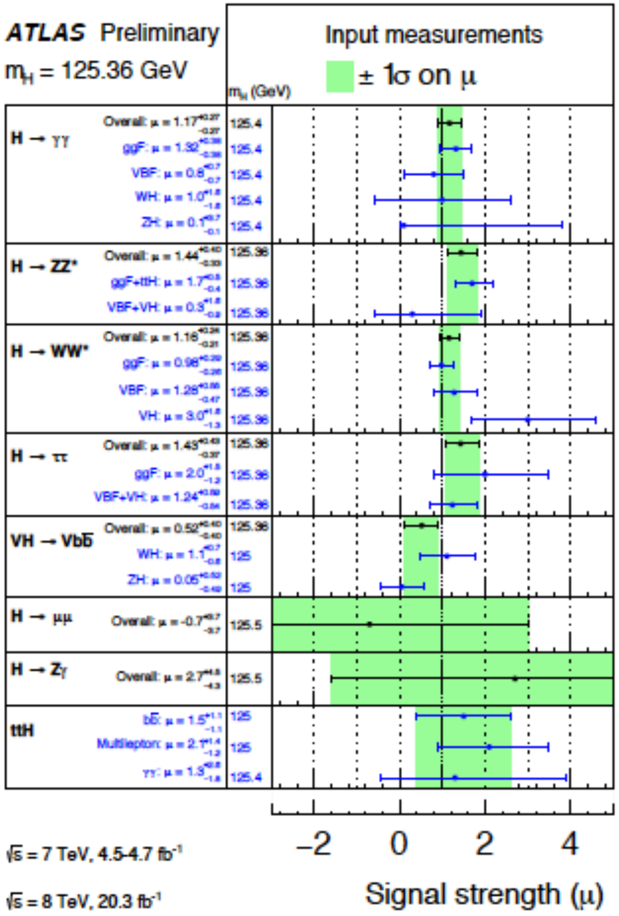


Higgs production, rates, couplings

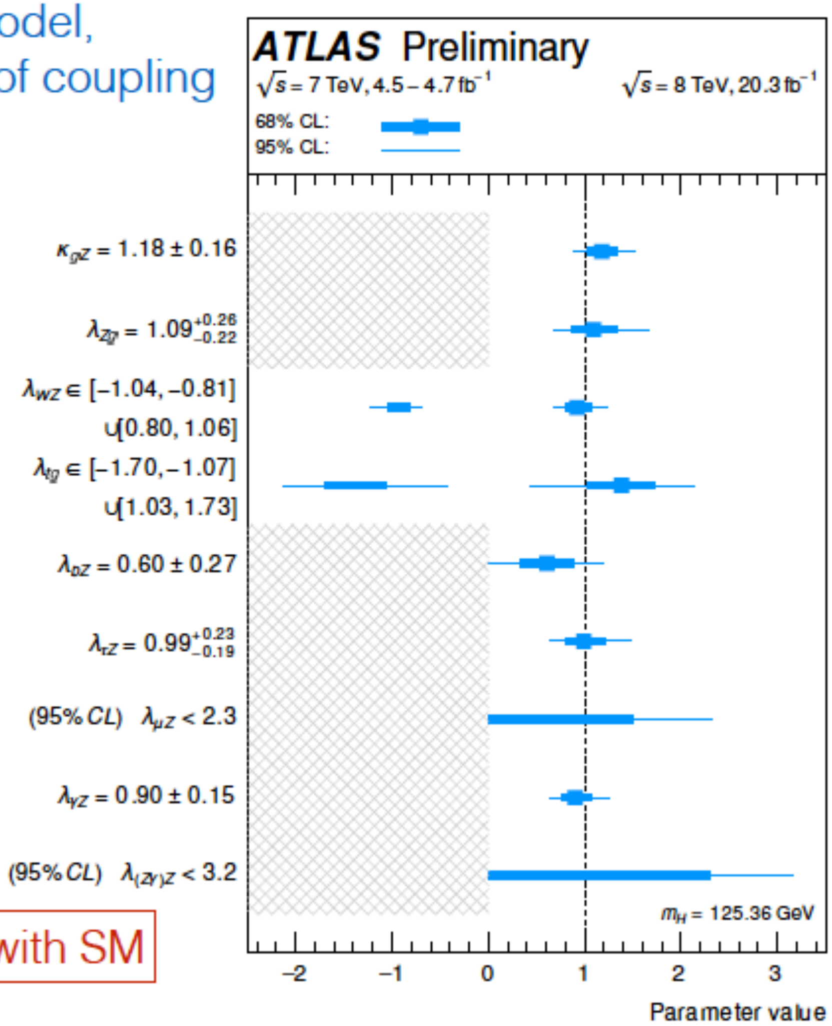
ATLAS-CONF-2015-007

Measurement of coupling strengths in a variety of models, with varying levels of model dependence (assumptions)

Combination of most channels



Most generic model, measure ratios of coupling strengths



→ consistency with SM

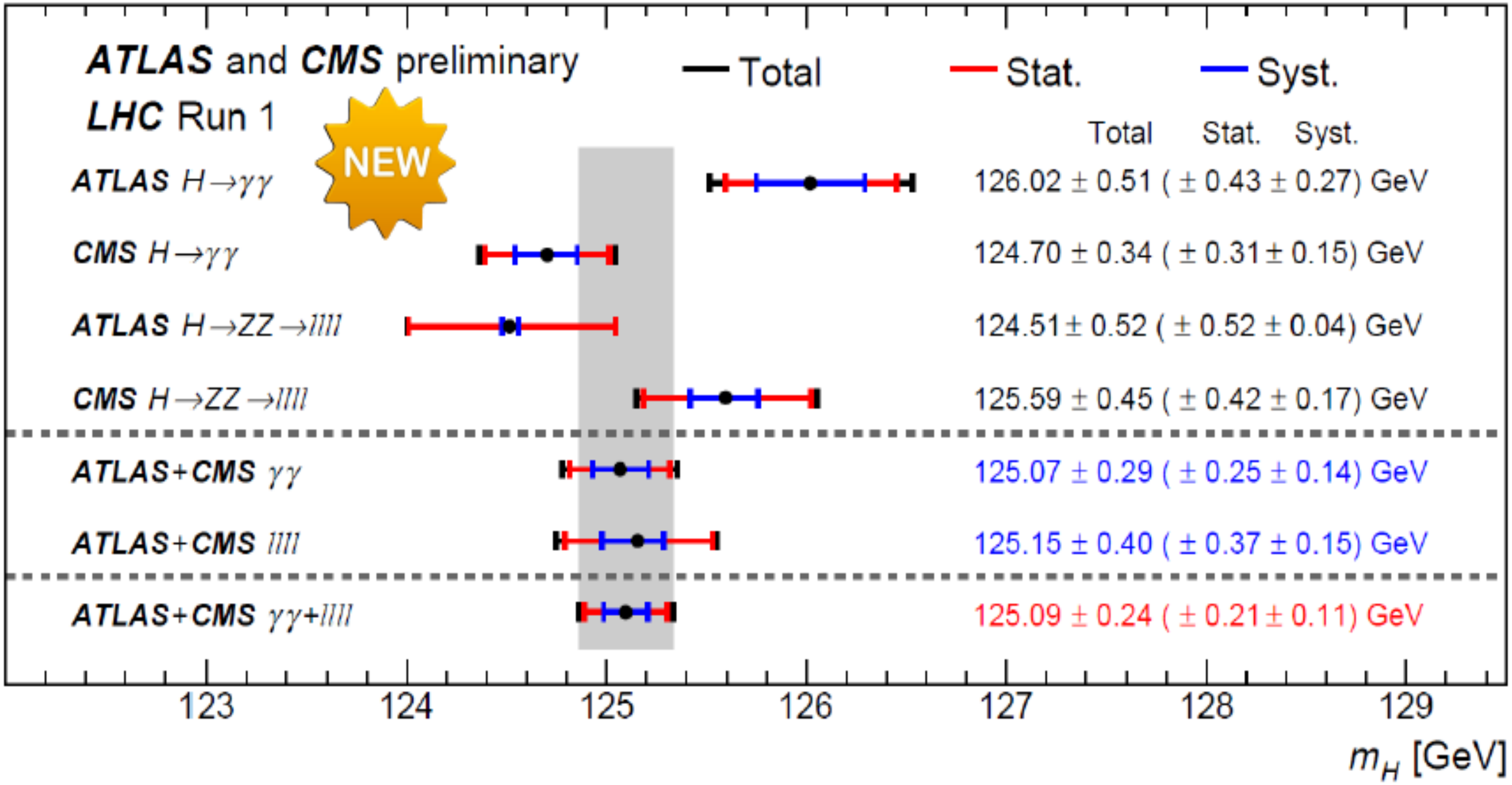
VBF invisible Higgs search (ATLAS-CONF-2015-004):
BR(H→invis.) < 29% (obs.) and < 35% (exp.) at 95% CL.

ATLAS+CMS Higgs mass combination

… and the ATLAS+CMS combined Higgs boson mass is:

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$ **(0.19% precision!)**

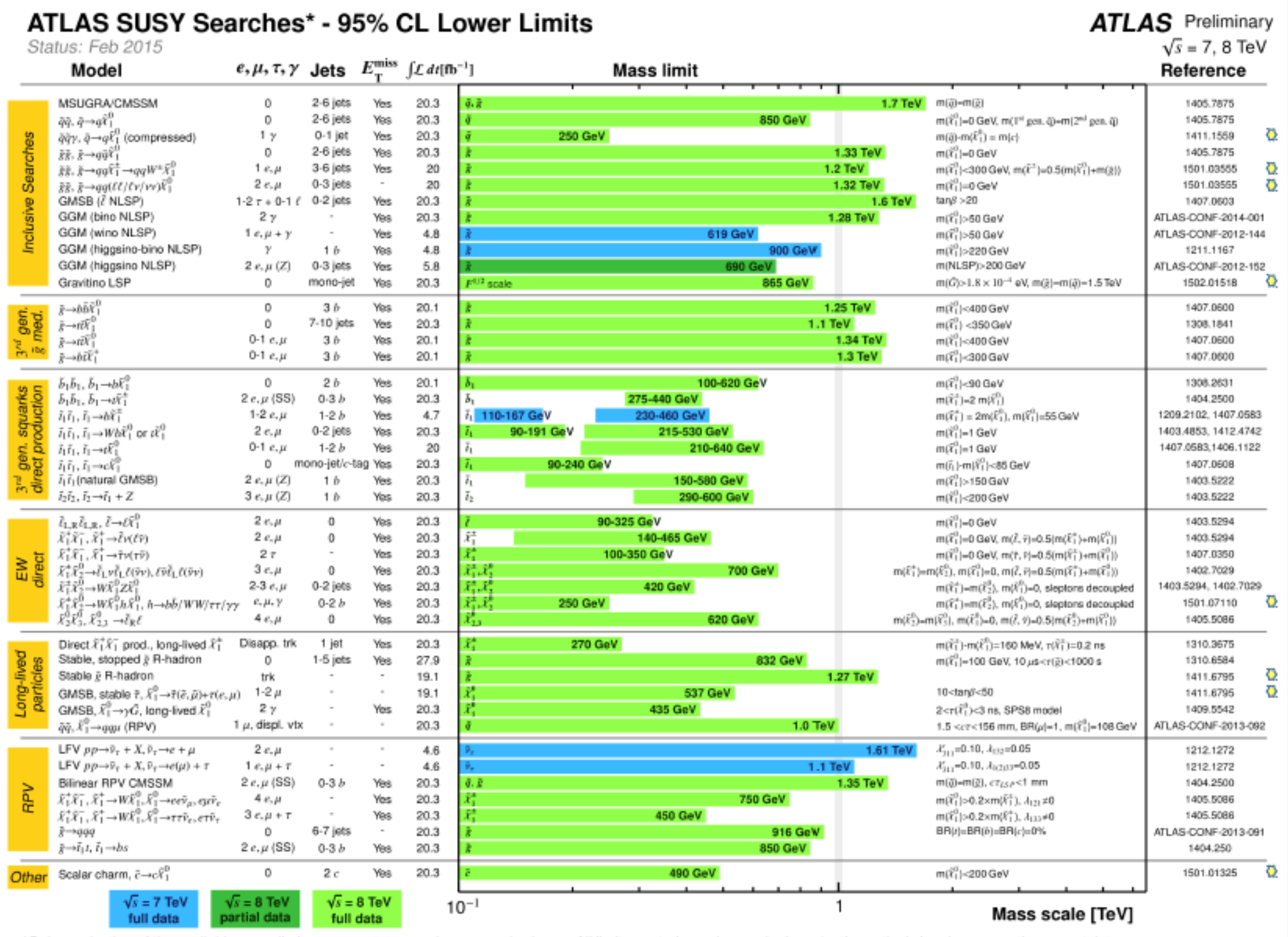
$$= 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$$



	Total	Stat.	Syst.
ATLAS $H\rightarrow\gamma\gamma$	126.02 ± 0.51	(± 0.43	± 0.27) GeV
CMS $H\rightarrow\gamma\gamma$	124.70 ± 0.34	(± 0.31	± 0.15) GeV
ATLAS $H\rightarrow ZZ\rightarrow llll$	124.51 ± 0.52	(± 0.52	± 0.04) GeV
CMS $H\rightarrow ZZ\rightarrow llll$	125.59 ± 0.45	(± 0.42	± 0.17) GeV
ATLAS+CMS $\gamma\gamma$	125.07 ± 0.29	(± 0.25	± 0.14) GeV
ATLAS+CMS $llll$	125.15 ± 0.40	(± 0.37	± 0.15) GeV
ATLAS+CMS $\gamma\gamma$+$llll$	125.09 ± 0.24	(± 0.21	± 0.11) GeV

Run-1 SUSY program completing

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary
$\sqrt{s}$ = 7, 8 TeV

	Model	e,μ,τ,γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})-m(\tilde{\chi}^0_1) = m(c)$	1411.1559 ★
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}^0_1)$<300 GeV, $m(\tilde{\chi}^\pm)=0.5(m(\tilde{\chi}^0_1)+m(\tilde{g}))$	1501.03555 ★
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1501.03555 ★
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}^0_1)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}^0_1)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}^0_1)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518 ★
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}^0_1)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}^0_1)$<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	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}^0_1)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}^\pm_1)=2\,m(\tilde{\chi}^0_1)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV 230-460 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 $t\tilde{\chi}^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV 215-530 GeV	$m(\tilde{\chi}^0_1)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}^0_1)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 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	$\tilde{t}_1$ 150-580 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	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1403.5222
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	$\tilde{\ell}$ 90-325 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	$\tilde{\chi}^\pm_1$ 140-465 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	$\tilde{\chi}^\pm_1$ 100-350 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	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 700 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	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 420 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	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 250 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	$\tilde{\chi}^0_{2,3}$ 620 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
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, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795 ★
	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<$\tan\beta$<50	1411.6795 ★
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 435 GeV	2<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}^0_1\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}^0_1)$=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	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 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	$\tilde{\chi}^\pm_1$ 750 GeV	$m(\tilde{\chi}^0_1)>0.2\times m(\tilde{\chi}^\pm_1)$, $\lambda_{121}\neq0$	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	$m(\tilde{\chi}^0_1)>0.2\times m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	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	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1501.01325 ★

🟦 $\sqrt{s}$ = 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.

CMS and LHCb $B^0_{s,d} \to \mu\,\mu$ combination

Fit to full run I data sets of both experiments, sharing parameters

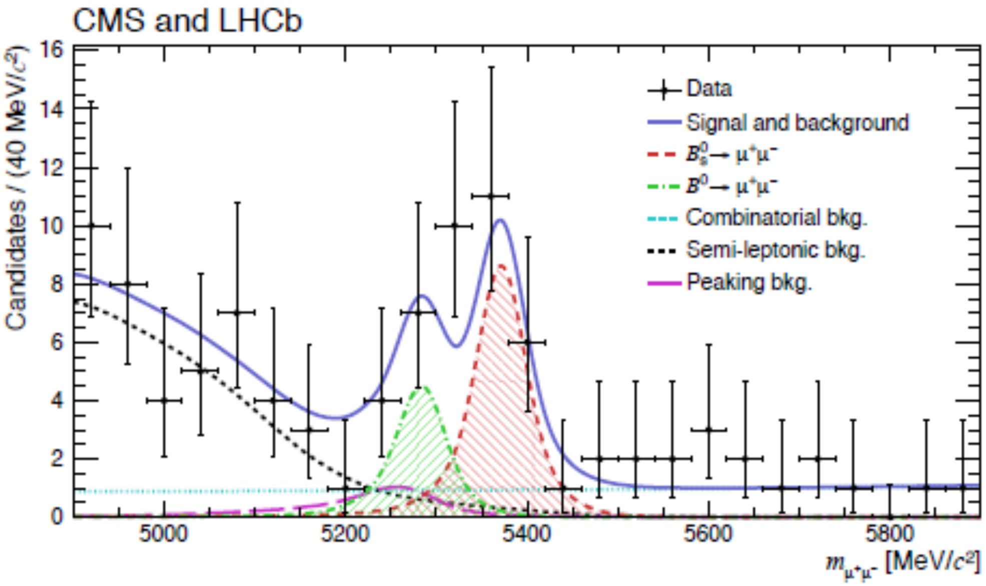
Result demonstrates power of combing data from >1 experiment (an LHC first!)

$$\mathcal{B}(B^0_s \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

6.2 σ for the $B^0{}_s \to \mu^+\mu^-$

(Expected SM 7.6 σ)

✦ First **observation**



projection of invariant mass in most sensitive bins

Where we stand

- We have exhausted the number of “known unknowns” within the current paradigm.

- Although the SM enjoys an enviable state of health, we know it is incomplete, because it cannot explain several outstanding questions, supported in most cases by experimental observations.

Looking for “unknown unknowns”

Needs a synergic use of:

- High-Energy colliders
- neutrino experiments (solar, short/long baseline, reactors, $0\nu\beta\beta$ decays),
- cosmic surveys (CMB, Supernovae, BAO, Dark E)
- gravitational waves
- dark matter direct and indirect detection
- precision measurements of rare decays and phenomena
- dedicated searches (WIMPS, axions, dark-sector particles)
- …..

From the Update of the European Strategy for Particle Physics

The success of the LHC is proof of the effectiveness of the European organizational model for particle physics, founded on the sustained long-term commitment of the CERN Member States and of the national institutes, laboratories and universities closely collaborating with CERN.

Europe should preserve this model in order to keep its leading role, sustaining the success of particle physics and the benefits it brings to the wider society.

The scale of the facilities required by particle physics is **resulting in the globalization of the field**. The European Strategy takes into account the worldwide particle physics landscape and developments in related fields and should continue to do so.

From the P5 report

Particle physics is global.

The United States and major players in other regions can together address the full breadth of the field's most urgent scientific questions **if each hosts a unique world-class facility at home and partners in high-priority facilities hosted elsewhere**.

Strong foundations of international cooperation exist, with the Large Hadron Collider (LHC) at CERN serving as an example of a successful large international science project.

Reliable partnerships are essential for the success of international projects. Building further international cooperation is an important theme of this report, and this perspective is finding worldwide resonance in an intensely competitive field.

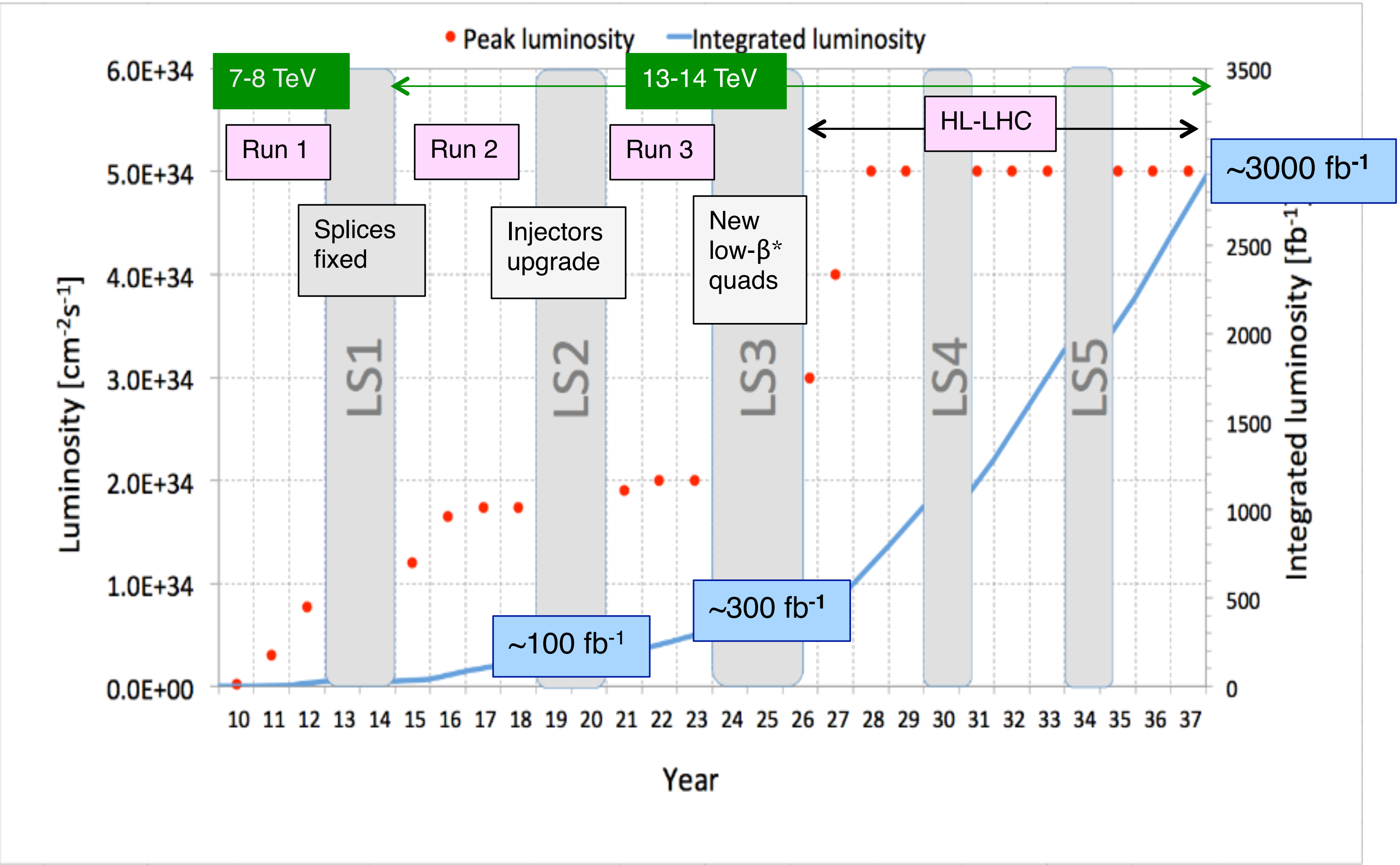
From Japan HEP Community

The committee makes the following recommendations concerning large-scale projects, which comprise the core of future high energy physics research in Japan.

Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, **Japan should take the leadership role in an early realization of an e+e- linear collider**. In particular, if the particle is light, experiments at low collision energy should be started at the earliest possible time. In parallel, continuous studies on new physics should be pursued for both LHC and the upgraded LHC version. Should the energy scale of new particles/physics be higher, accelerator R&D should be strengthened in order to realize the necessary collision energy.

Should the neutrino mixing angle $\boldsymbol{\theta}_{13}$ be confirmed as large, **Japan should aim to realize a large-scale neutrino detector through international cooperation**, accompanied by the necessary reinforcement of accelerator intensity, so allowing studies on CP symmetry through neutrino oscillations.
This new large-scale neutrino detector should have sufficient sensitivity to allow the search for proton decays, which would be direct evidence of Grand Unified Theories.

The LHC timeline



Where is New Physics?

The question

- Is the mass scale beyond the LHC reach ?
- Is the mass scale within LHC's reach, but final states are elusive ?

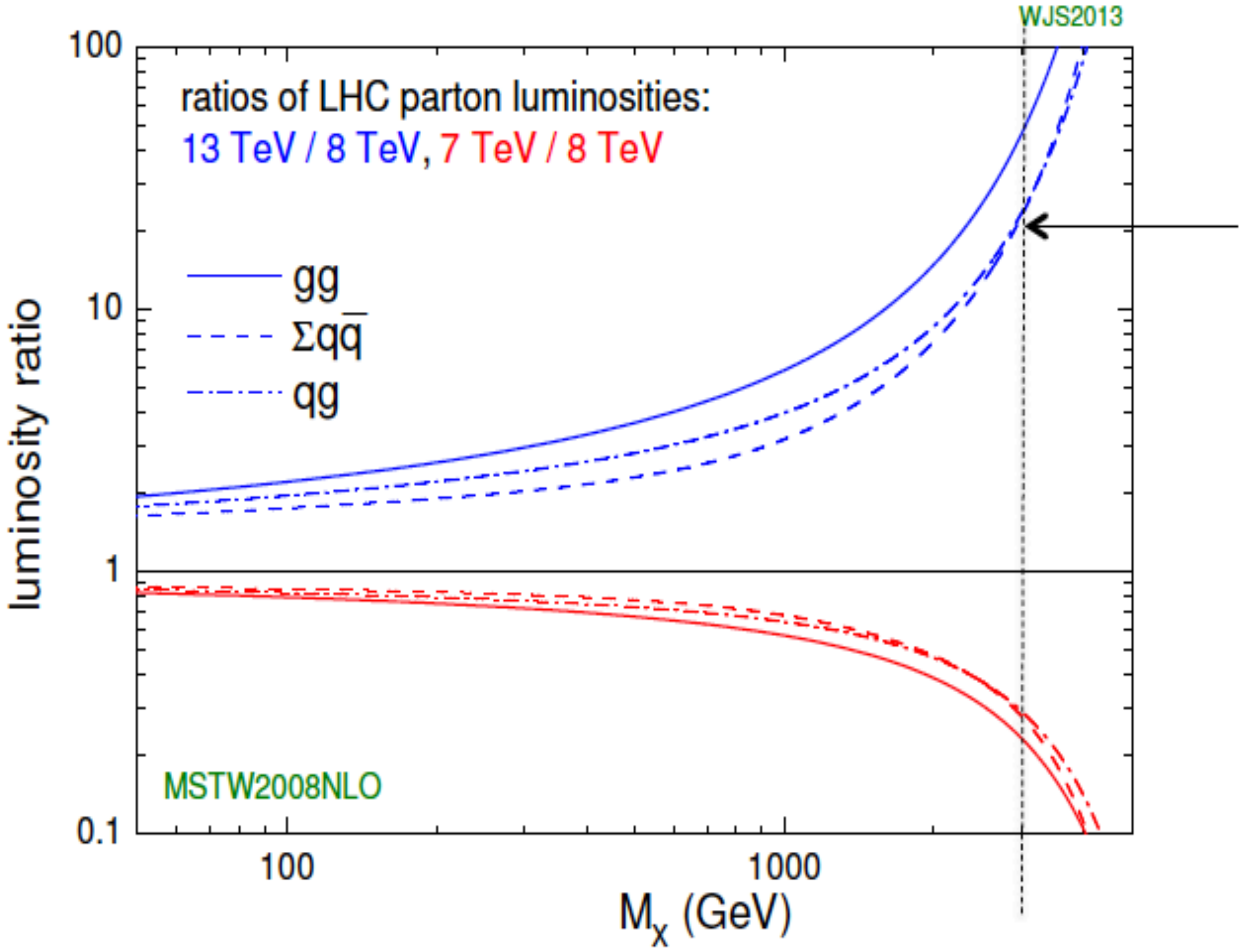
We should be prepared to exploit both scenarios, through:

- Precision
- Sensitivity (to elusive signatures)
- Extended energy/mass reach

Extending the reach…

- Weak boson scattering
- Higgs properties
- Supersymmetry searches and measurements
- Exotics
- t properties
- Rare decays
- CPV
- ..etc

13 TeV vs 8 TeV

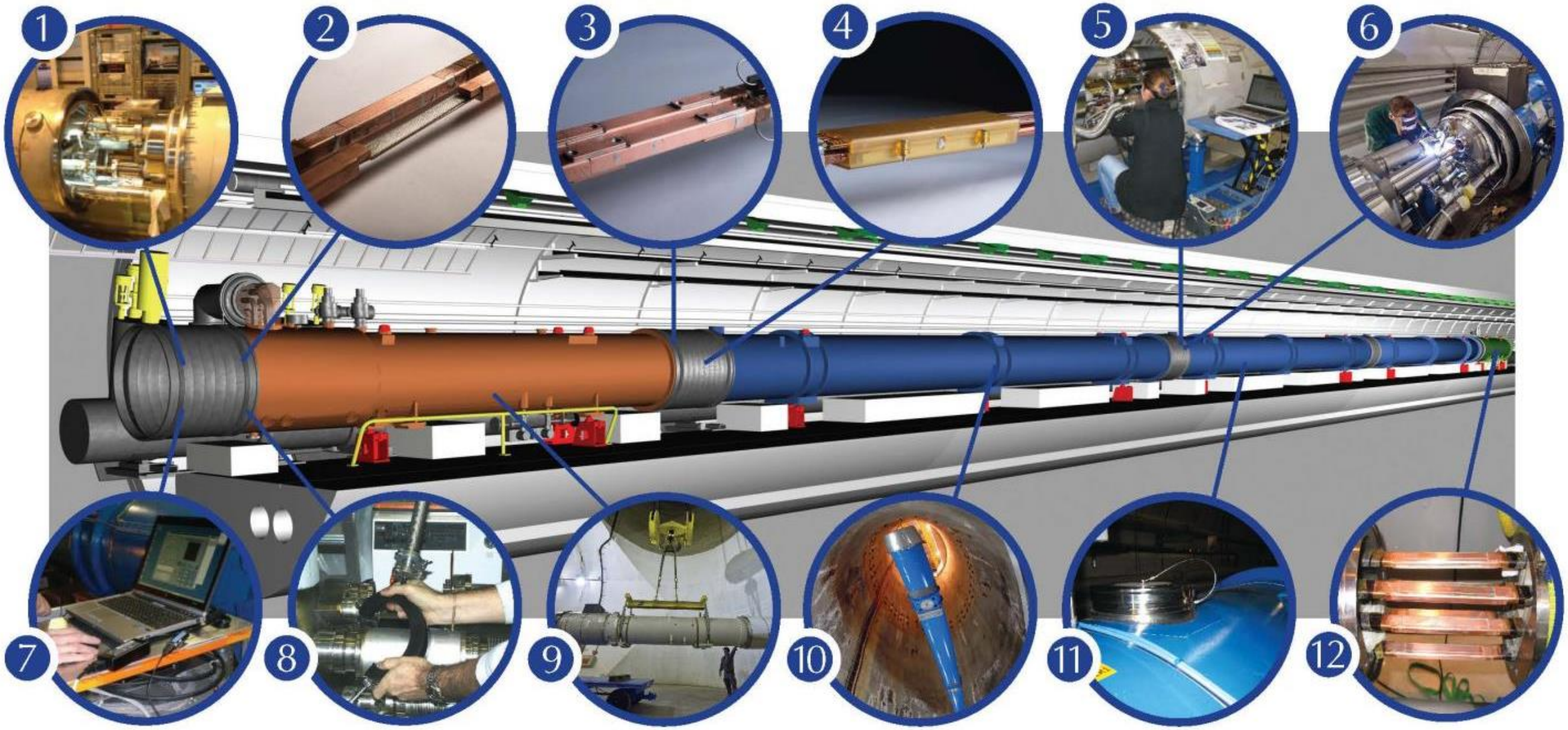


Ratio of 13 TeV / 8 TeV

Cross sections:

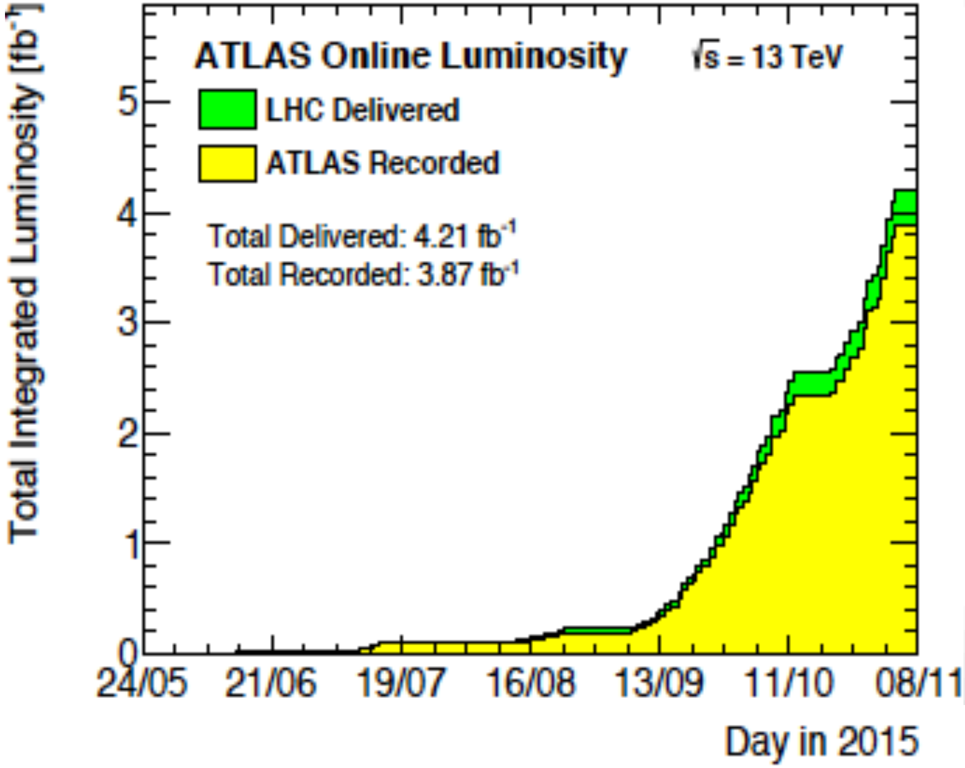
- Z′ at 3 TeV: **20**
- q* at 4 TeV: **56**
- QBH at 5 TeV: **370**
- QBH at 6 TeV: **9000**

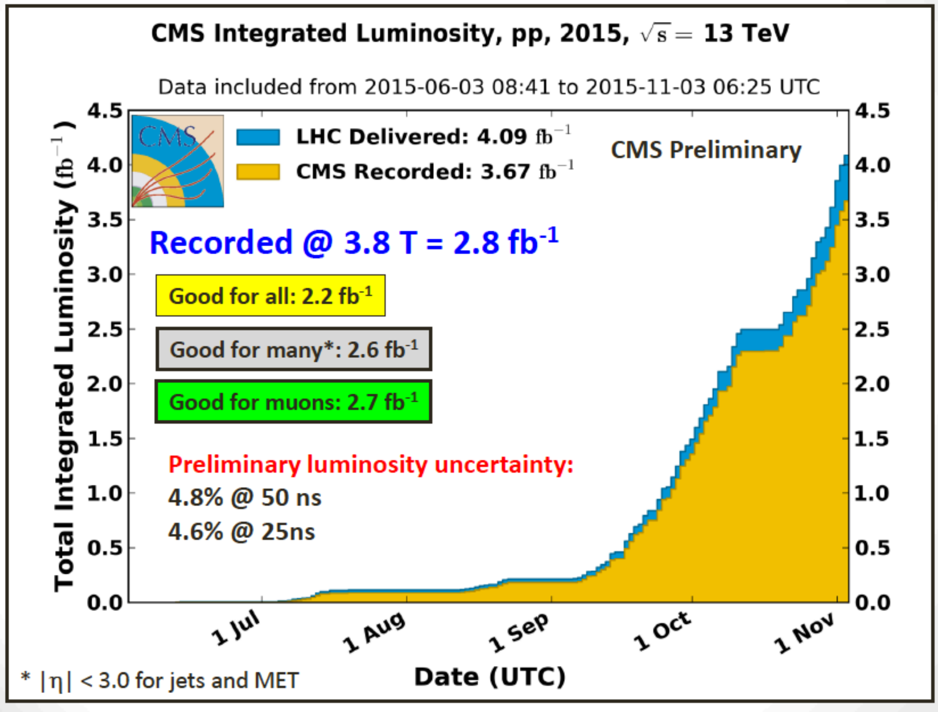
The main 2013-14 LHC consolidations



1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines
7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 3 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

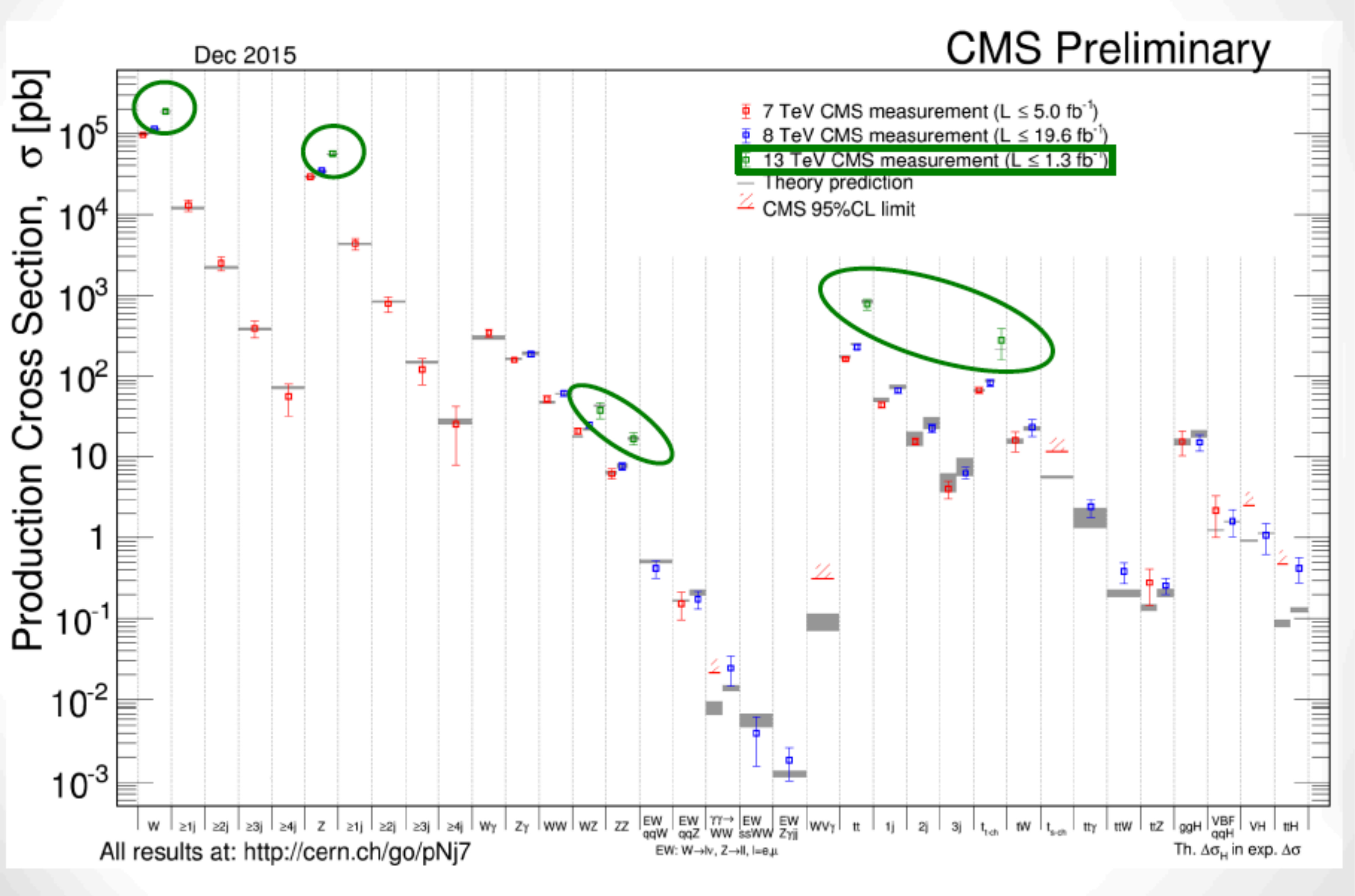
Run2 @13 Tev in 2015



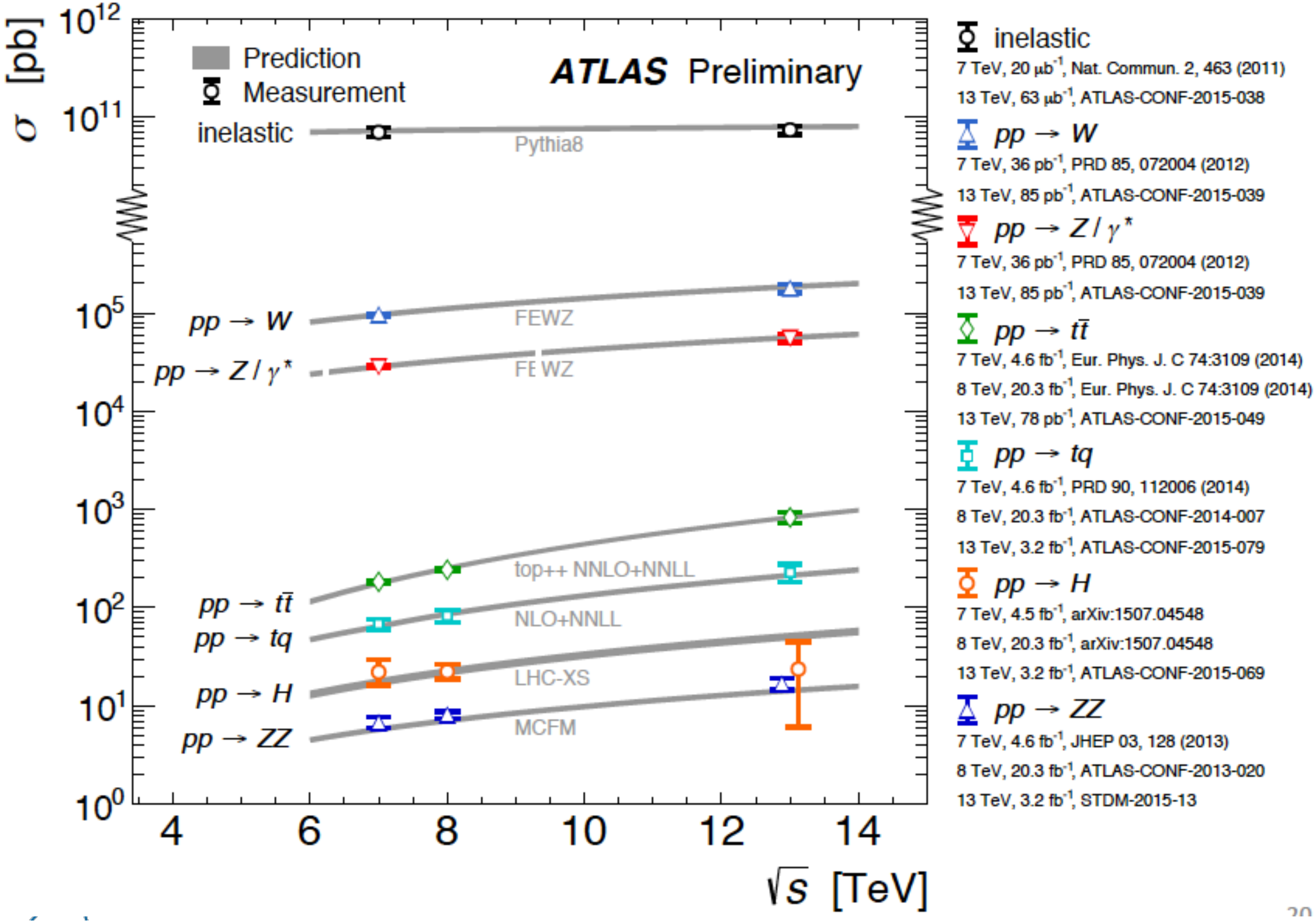


- Experiments in good shape (except for cryo problem with CMS solenoid)
- ~4 pb^{-1} collected

SM Physics at 13 TeV



SM Physics at 13 TeV



The tantalizing diphotons: ATLAS

Search for a **Two Photons Resonance** (I)

ATLAS-CONF-2015-081

Inclusive search for two photon resonance
(optimized for a scalar resonance)

- Selection of two photons with pT/m thresholds of 0.3 and 0.4 and pT dependent calorimeter and track isolation criteria
- Typical prompt photon purity 90%

Background from a functional

Similar to the dijet search but chosen using the Fisher F-test and the spurious signal method measured in events from Sherpa, Diphox and Jetphox:

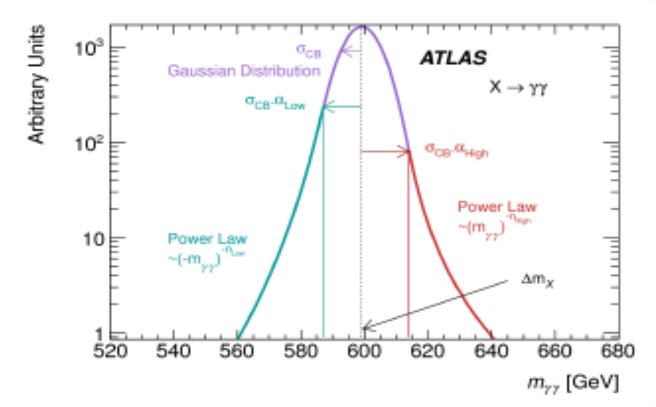
$$f_{bkg}(x; b, \{a_k\}) = (1 - x^{1/3})^b \, x^{\sum_{j=0}^{k} a_j \log(x)^j}$$

$$x \equiv \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

Here a simple form with k=0 is used

Signal Model

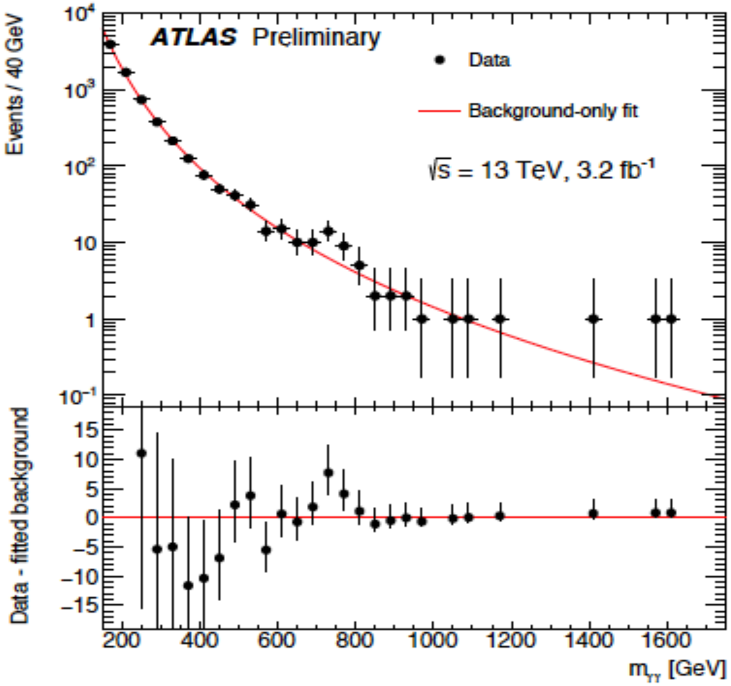
- **NWA**: Use Double Sided Crystal Ball function
- **LW**: Use DSCB fitted from simulated samples with different widths with up to 25% of the resonance mass



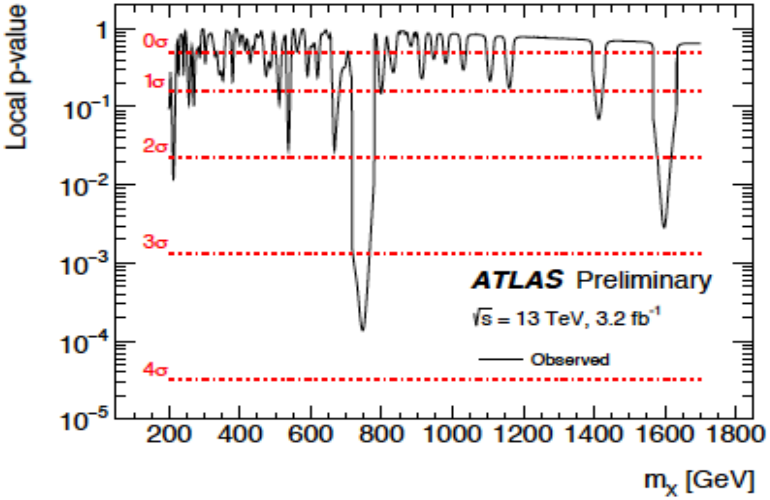
The tantalizing diphotons: ATLAS

Search for a **Two Photons Resonance** (II)

Results: Events with mass in excess of 200 GeV are included in **unbinned fit**



- **In the NWA search, an excess of 3.6σ** (local) is **observed at a mass hypothesis of minimal p_0 of 750 GeV**
- **Taking a LEE in a mass range** (fixed before unblinding) **of 200 GeV to 2.0 TeV the** global significance **of the excess is** **2.0σ**

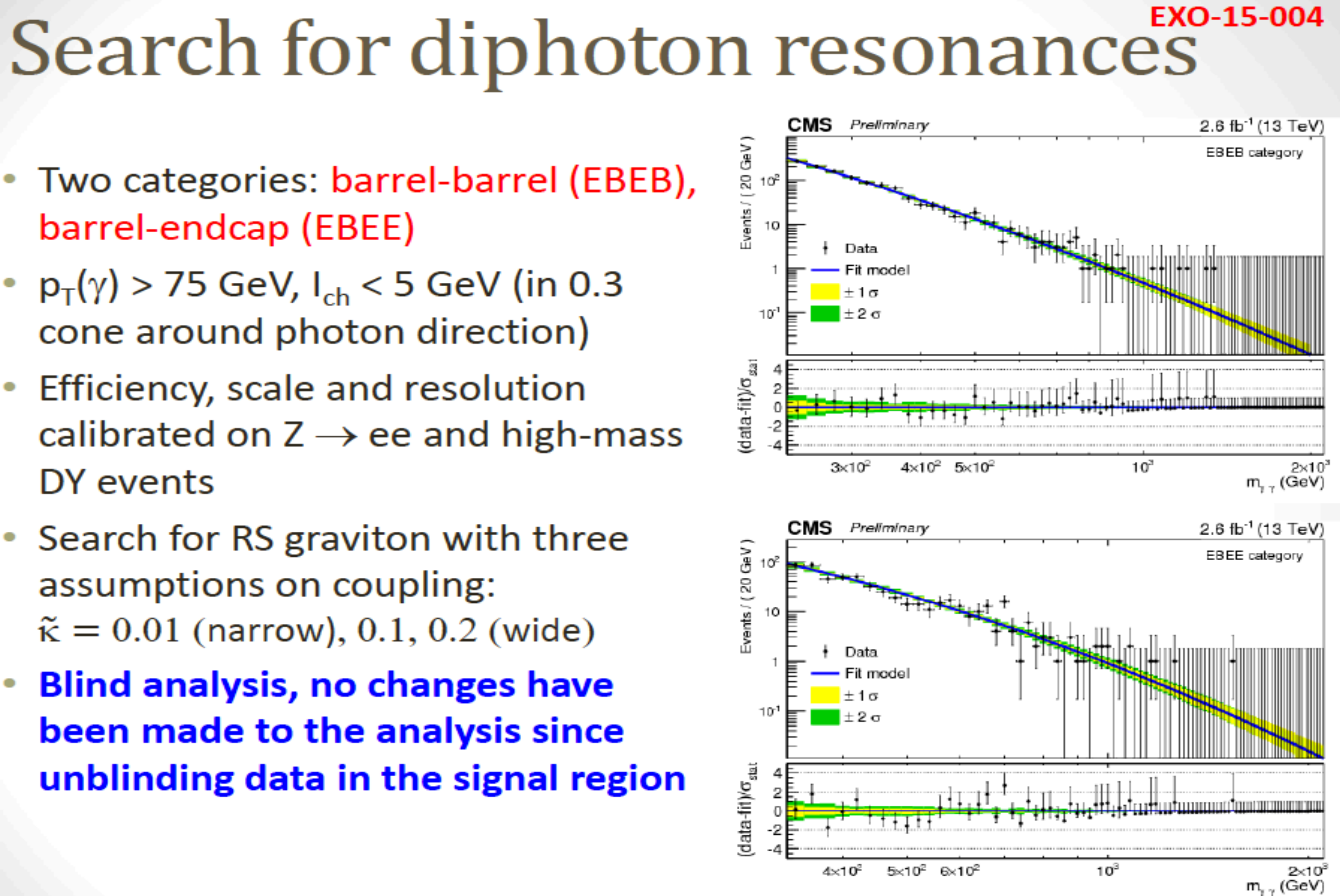


In the NWA fit the resolution uncertainty is profiled in the NWA fit and is pulled by 1.5σ

The data was then fit under a **LW hypothesis** yielding a width of approximately 45 GeV
(Approx. 6% of the best fit mass of approximately 750 GeV)

- As expected the local significance increases to **3.9σ**
- Taking into account a LEE in mass and width of up to **10%** of the mass hypothesis of **2.3σ** (Note: upper range in resolution fixed after unblinding)

…and CMS

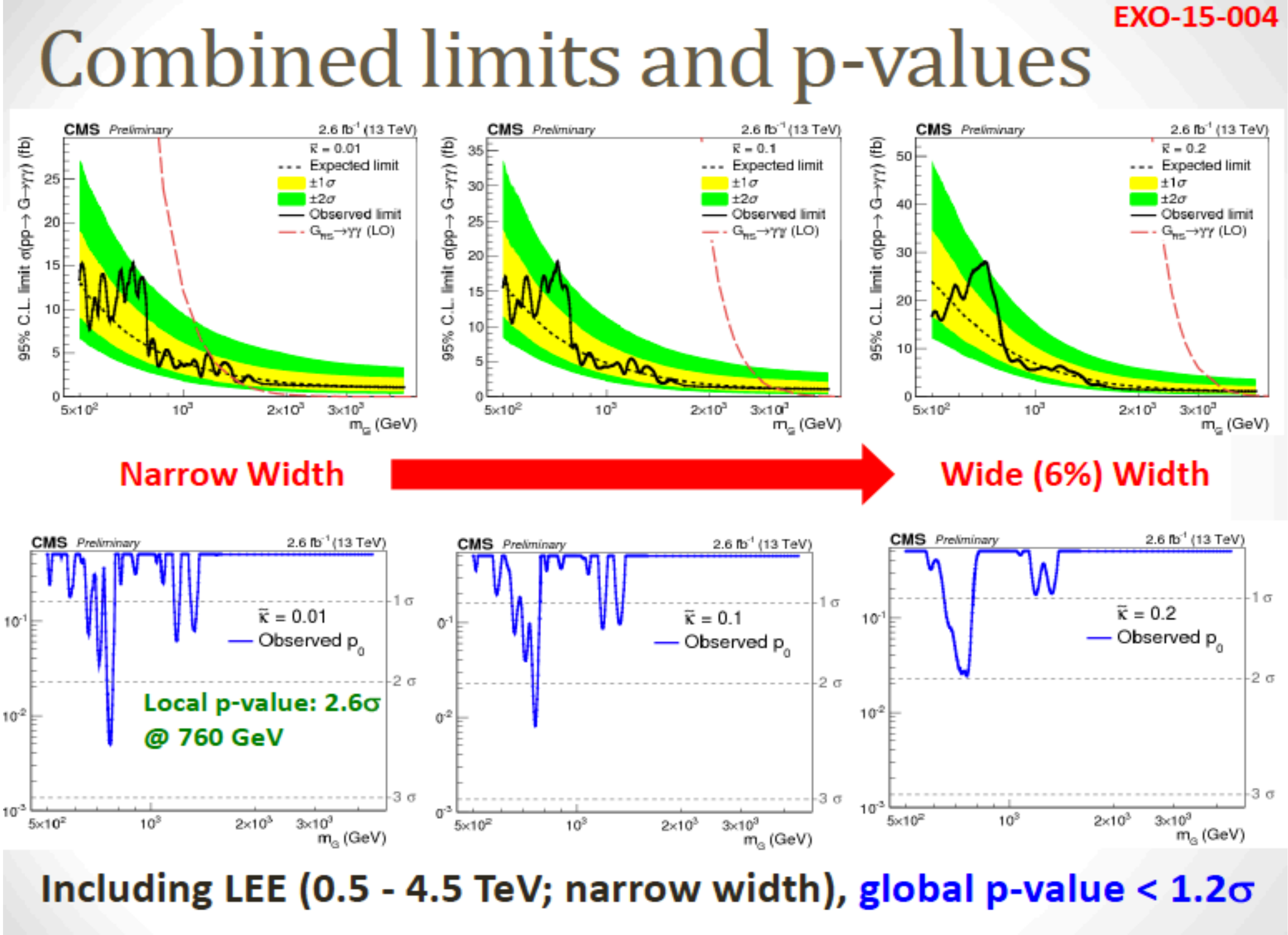


EXO-15-004

Search for diphoton resonances

- Two categories: barrel-barrel (EBEB), barrel-endcap (EBEE)
- $p_T(\gamma) > 75$ GeV, $I_{ch} < 5$ GeV (in 0.3 cone around photon direction)
- Efficiency, scale and resolution calibrated on $Z \rightarrow ee$ and high-mass DY events
- Search for RS graviton with three assumptions on coupling: $\tilde{\kappa} = 0.01$ (narrow), 0.1, 0.2 (wide)
- **Blind analysis, no changes have been made to the analysis since unblinding data in the signal region**

…and CMS



EXO-15-004

Combined limits and p-values

Narrow Width → Wide (6%) Width

Local p-value: 2.6σ @ 760 GeV

Including LEE (0.5 - 4.5 TeV; narrow width), global p-value < 1.2σ

Only time will tell…

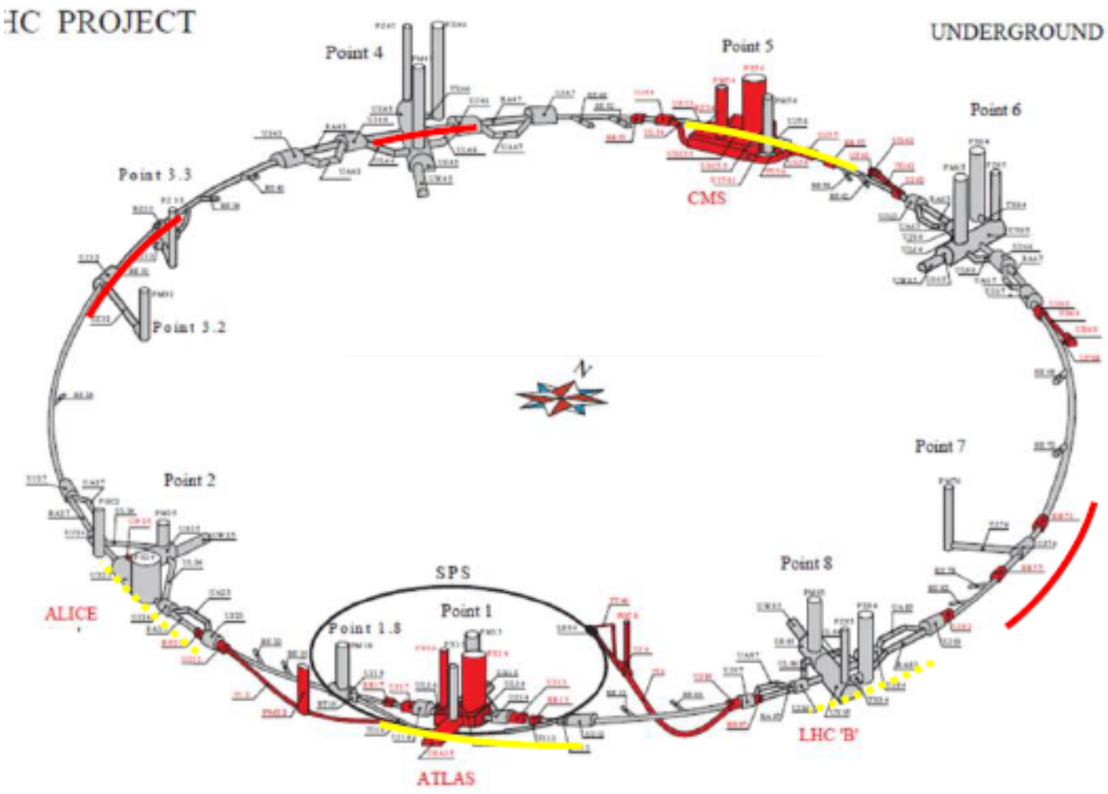
LHC FILL NUMBER: 4935 STABLE BEAMS SINCE 09h 03m	Beam	Intensity	Stored E	Particle	Bunches	Beam Energy	17-05-2016 07:02:28
PROTON PHYSICS	1	7.01E+13	73.0 MJ	Proton	889	6.50 TeV	
Inj. scheme: 25ns_889b_877_810_828_72bpi_15inj_950ns	2	7.22E+13	75.1	Proton	889		

2016-05-17 08:52:10 Programmed dump between 8:30 and 9:00 Next: luminosity calibration fill with IP2 & 8 fill with 889 bunches Roman pots in

Luminosity [E30 s-1 cm-2] [pb-1] [(mb)^-1]

	ATLAS	ALICE	CMS	LHCb
	PHYSICS	PHYSICS	PHYSICS	PHYSICS
Instantaneous	1811.1	1.4	1776.1	150.7
Integrated fill	84.8	47.2	83.3	4.8
Integrated/h	6.5	5.1	6.4	0.5
beta * [m]	0.4	10.0	0.4	3.0

The HL-LHC Project



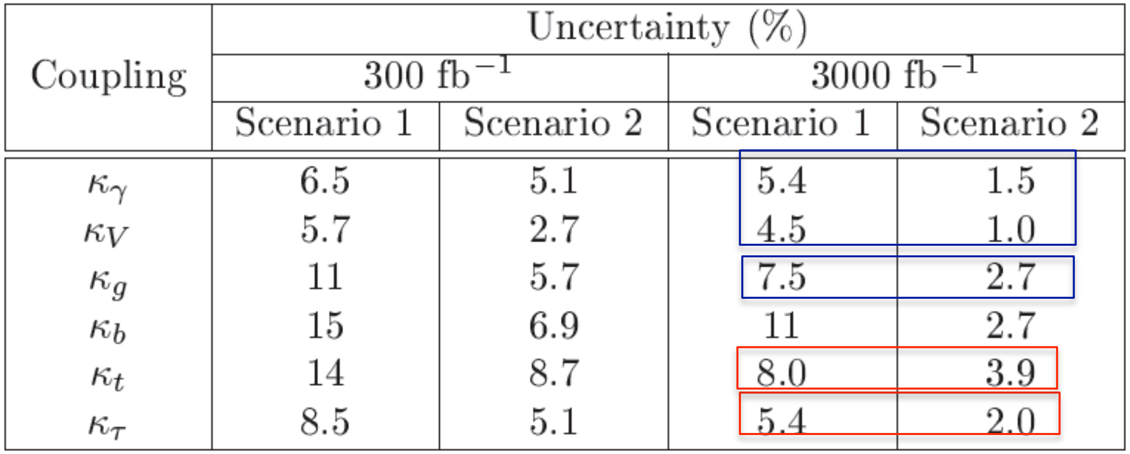
- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

Project leadership: L. Rossi and O. Brüning

Higgs couplings fit at HL-LHC

CMS



Coupling	Uncertainty (%)			
	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

CMS Projection

Assumption NO invisible/undetectable contribution to Γ_H:

- Scenario 1: system./Theory err. unchanged w.r.t. current analysis
- Scenario 2: systematics scaled by 1/sqrt(L), theory errors scaled by ½

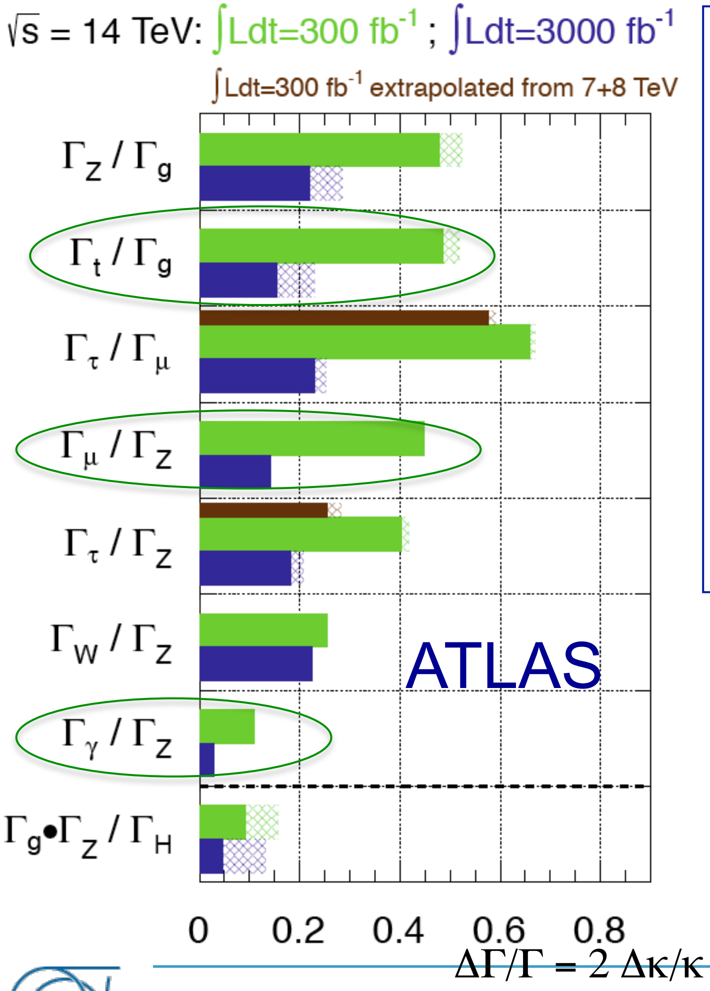
✓ γγ loop at 2-5% level

✓ down-type fermion couplings at 2-10% level

✓ direct top coupling at 4-8% level

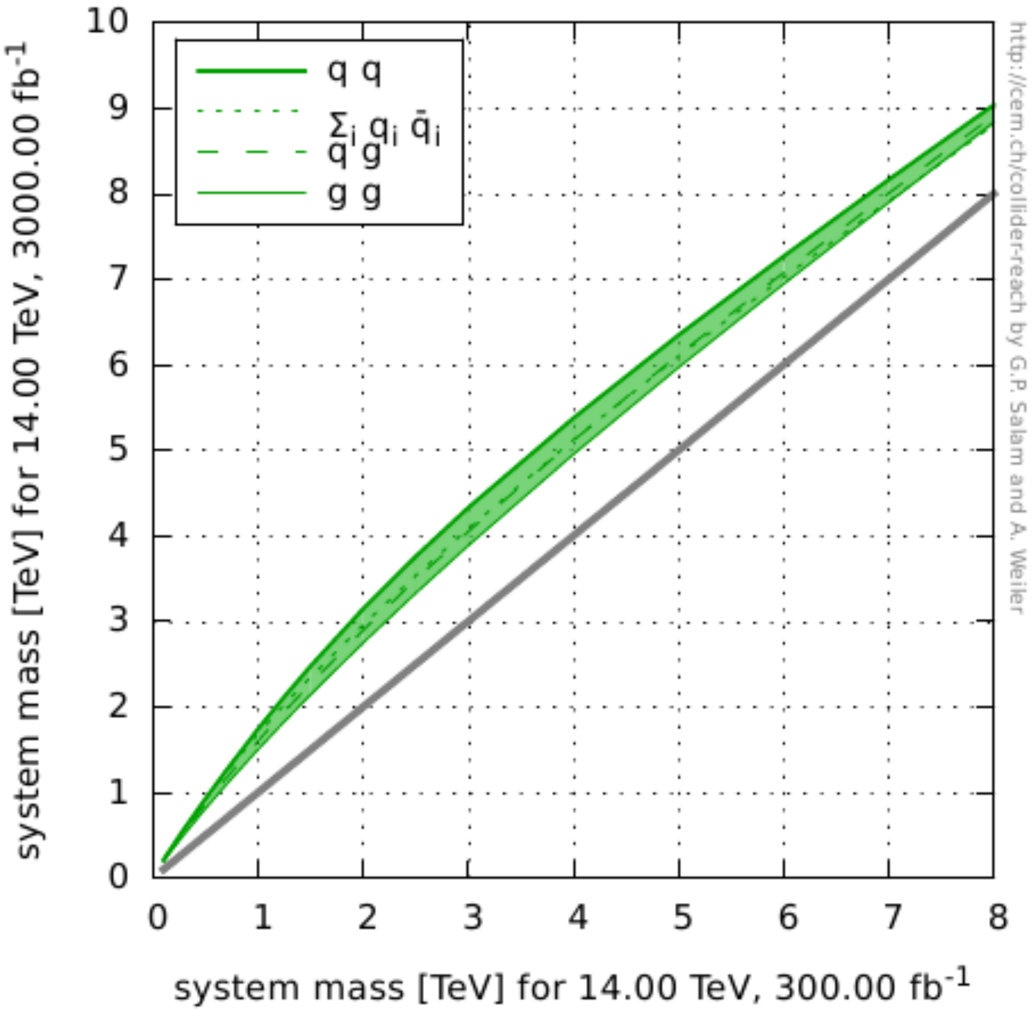
✓ gg loop at 3-8% level

Coupling Ratios Fit at HL-LHC

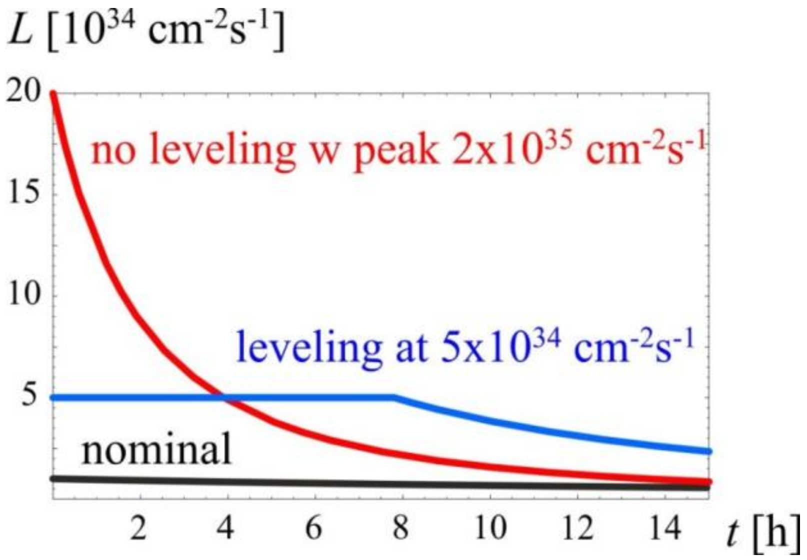


- Fit to coupling ratios:
  - No assumption BSM contributions to Γ_H
  - Some theory systematics cancels in the ratios
- Loop-induced Couplings γγ and gg treated as independent parameter
  - κ_γ/κ_Z tested at 2%
  - gg loop (BSM) κ_t/κ_g at 7-12%
  - 2nd generation ferm. κ_μ/κ_Z at 8%

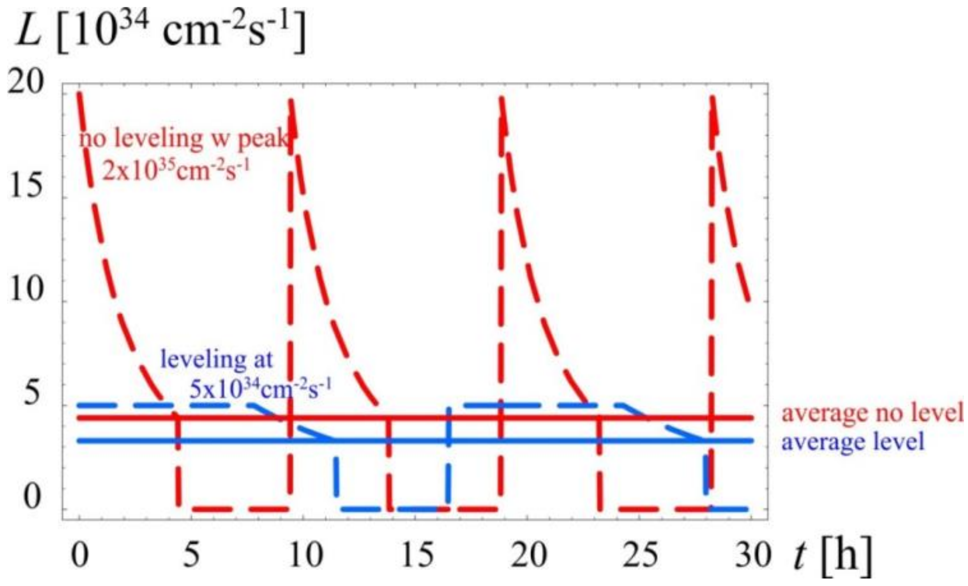
Extending the reach….



Luminosity Levelling, a key to success



- High peak luminosity
- Minimize pile-up in experiments and provide "constant" luminosity



- Obtain about 3 - 4 fb^{-1}/day (40% stable beams)
- About 250 to 300 fb^{-1}/year

Baseline parameters of HL for reaching 250 -300 fb^{-1}/year

25 ns is the option

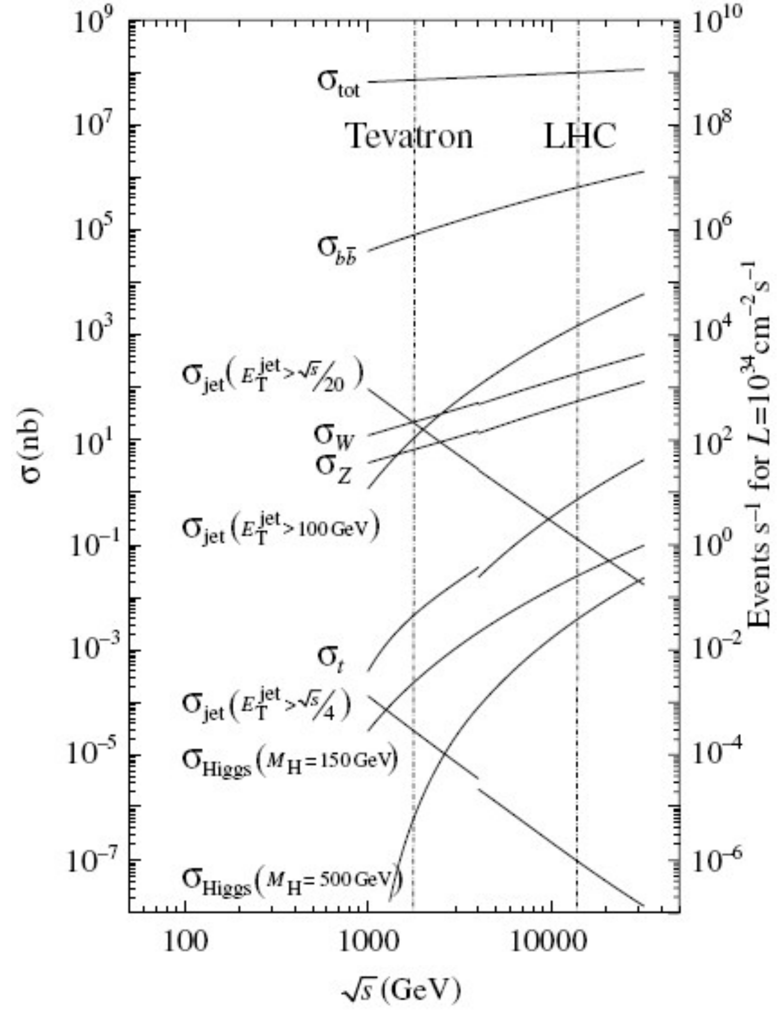
However:

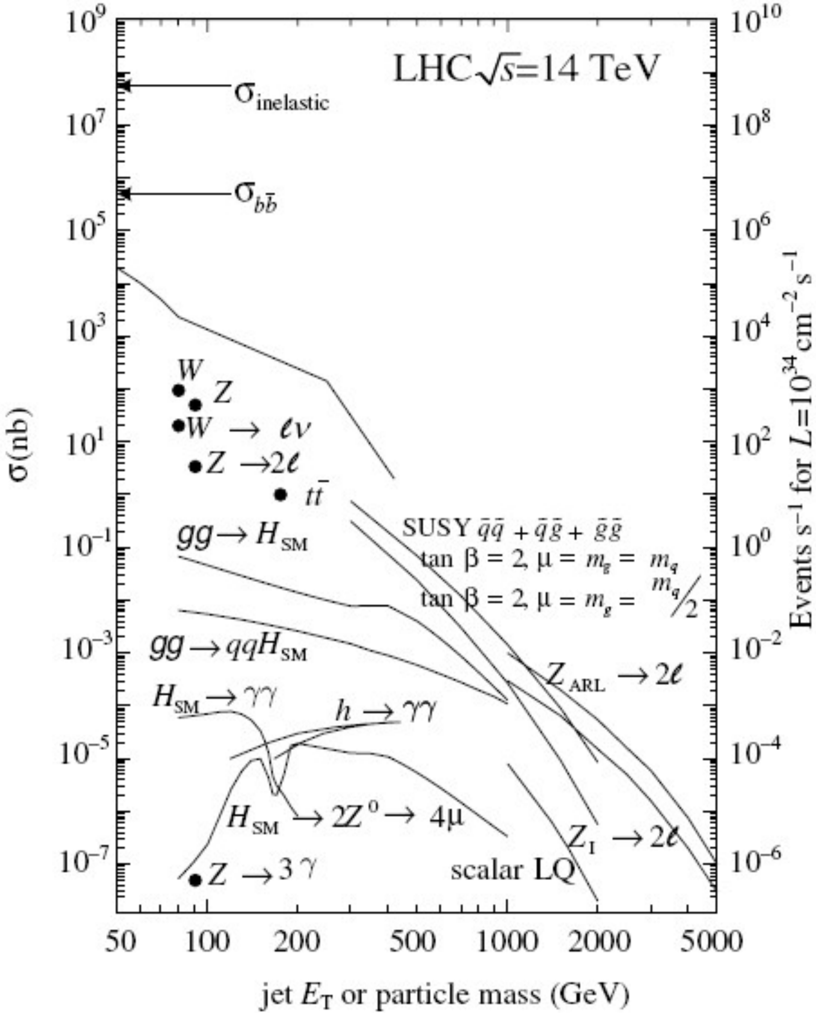
50 ns should be kept as alive and possible because we DO NOT have enough experience on the actual limit *(e-clouds, I_{beam})*

	25 ns	50 ns
# Bunches	2808	1404
p/bunch [10^{11}]	**2.0 (1.01 A)**	**3.3 (0.83 A)**
ε_L [eV.s]	2.5	2.5
σ_z [cm]	7.5	7.5
$\sigma_{\delta p/p}$ [10^{-3}]	0.1	0.1
$\gamma\varepsilon_{x,y}$ [μm]	**2.5**	**3.0**
β^* [cm] (baseline)	15	15
X-angle [μrad]	**590 (12.5 σ)**	**590 (11.4 σ)**
Loss factor	0.30	0.33
Peak lumi [10^{34}]	6.0	7.4
Virtual lumi [10^{34}]	20.0	22.7
$T_{leveling}$ [h] @ 5E34	**7.8**	**6.8**
#Pile up @5E34	123	247

Continuous global optimisation with LIU

The detectors challenge





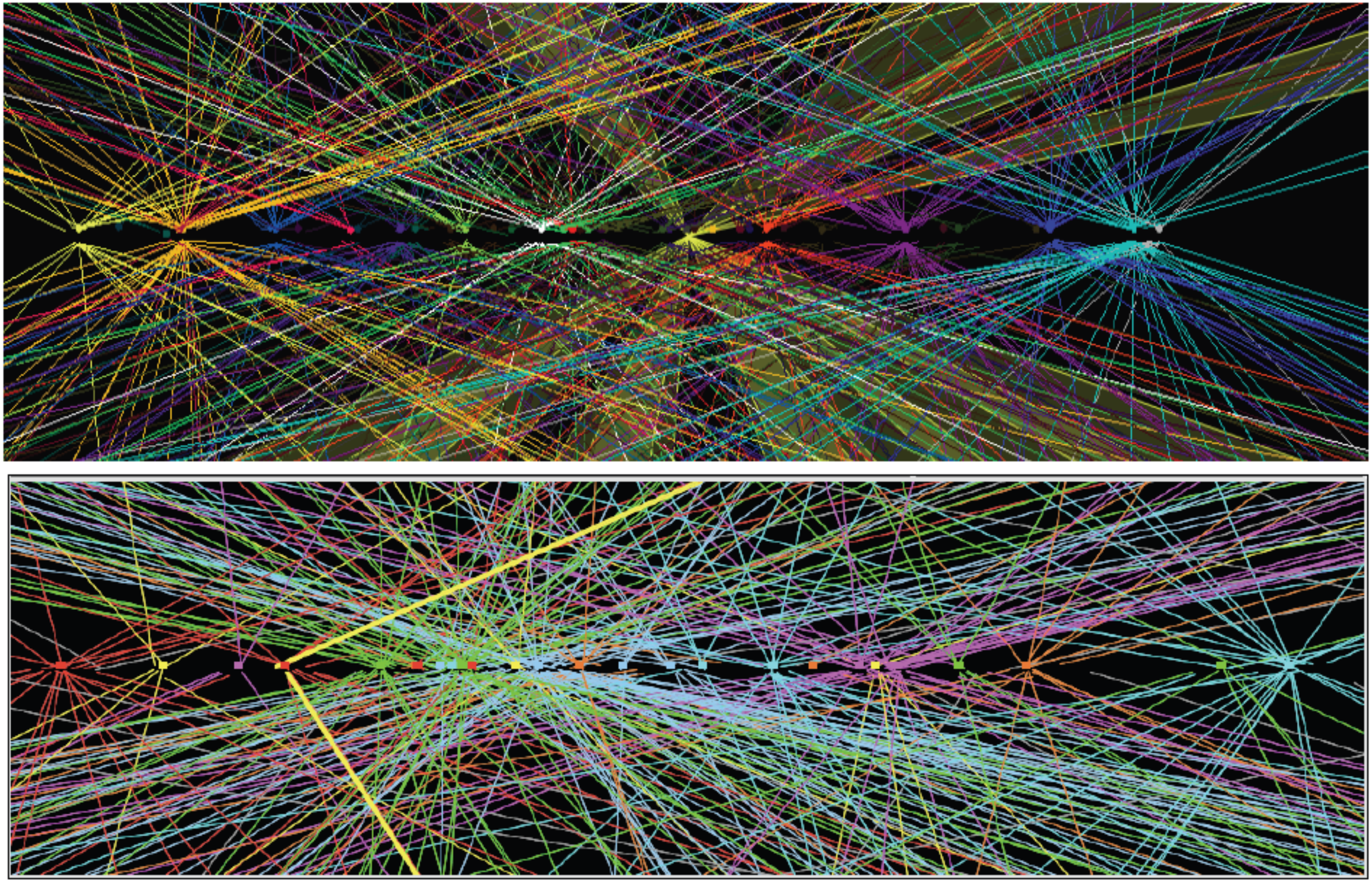
7 – 11 orders of magnitude between inelastic and “interesting” - “discovery” physics event rate

The detectors challenge

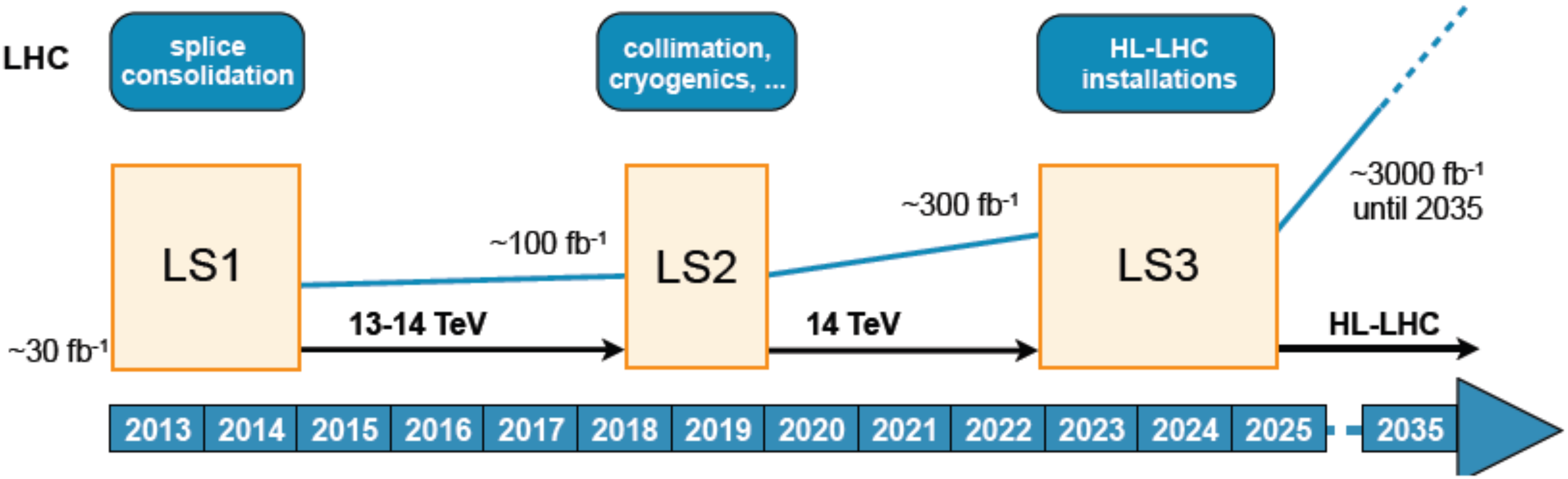
In order to exploit the LHC potential, experiments have to maintain full sensitivity for discovery, while keeping their capabilities to perform precision measurements at low p_T, in the presence of:

- Pileup
  - <PU> ≈ 50 events per crossing by LS2
  - <PU> ≈ 60 events per crossing by LS3
  - <PU> ≈ 140 events per crossing by HL-LHC
- Radiation damage
  - Requires work to maintain calibration
  - Limits performance-lifetime of the detectors
    - Light loss (calorimeters)
    - Increased leakage current (silicon detectors)

Try to visualize x5!



ATLAS Upgrade Roadmap



ATLAS Phase-0

New inner pixel layer
Detector consolidation
2015: FTK deployment

ATLAS Phase-1

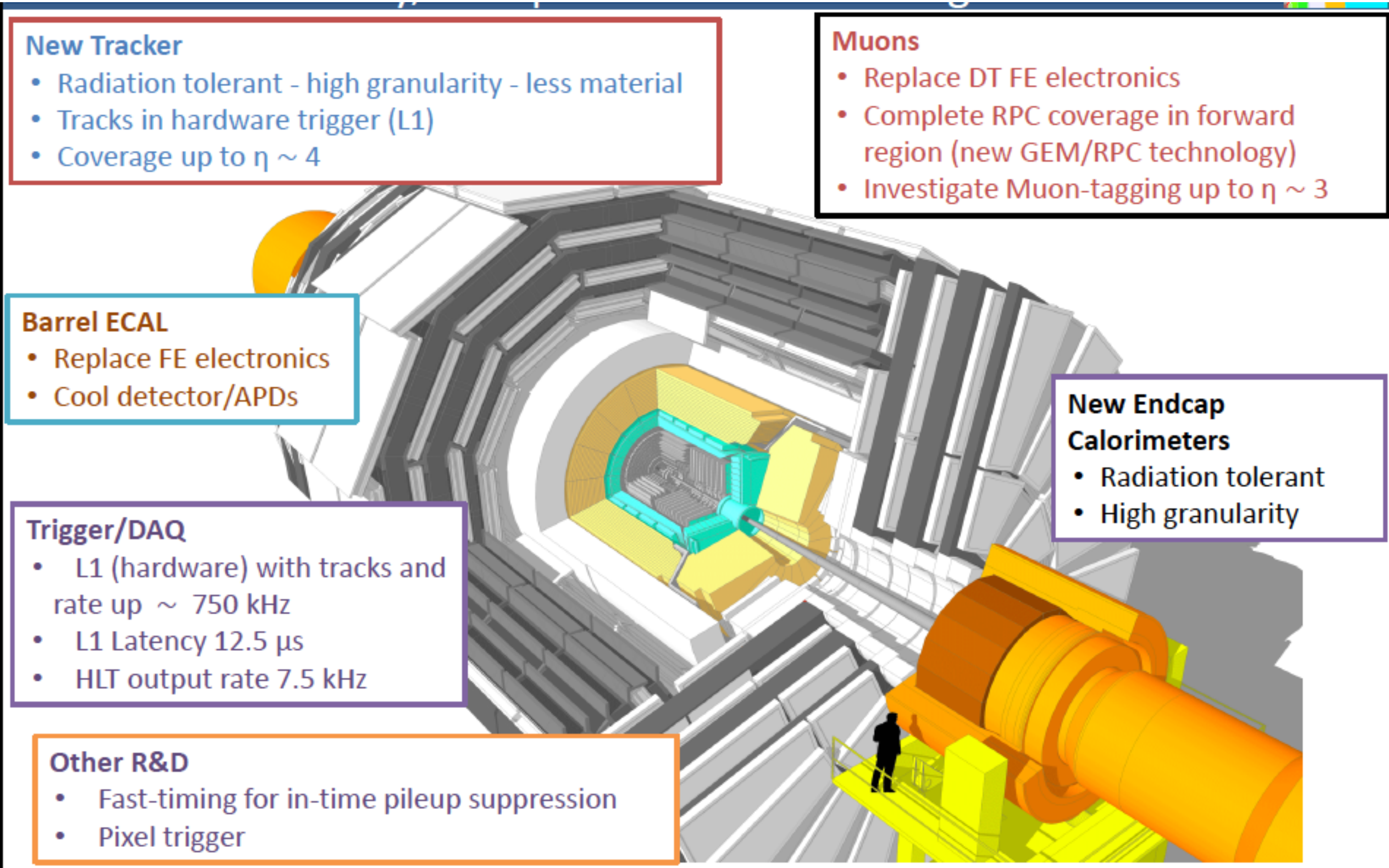
Improve L1 Trigger, NSW and LAr electronics to cope with higher rates

ATLAS Phase-2

Prepare for 140-200 pile-up events
Replace Inner Tracker
New L0/L1 trigger scheme
Upgrade muon/calorimeter electronics
Upgrade of DAQ detector readout

A long and exciting road ahead !

CMS Phase II Upgrade



New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 3

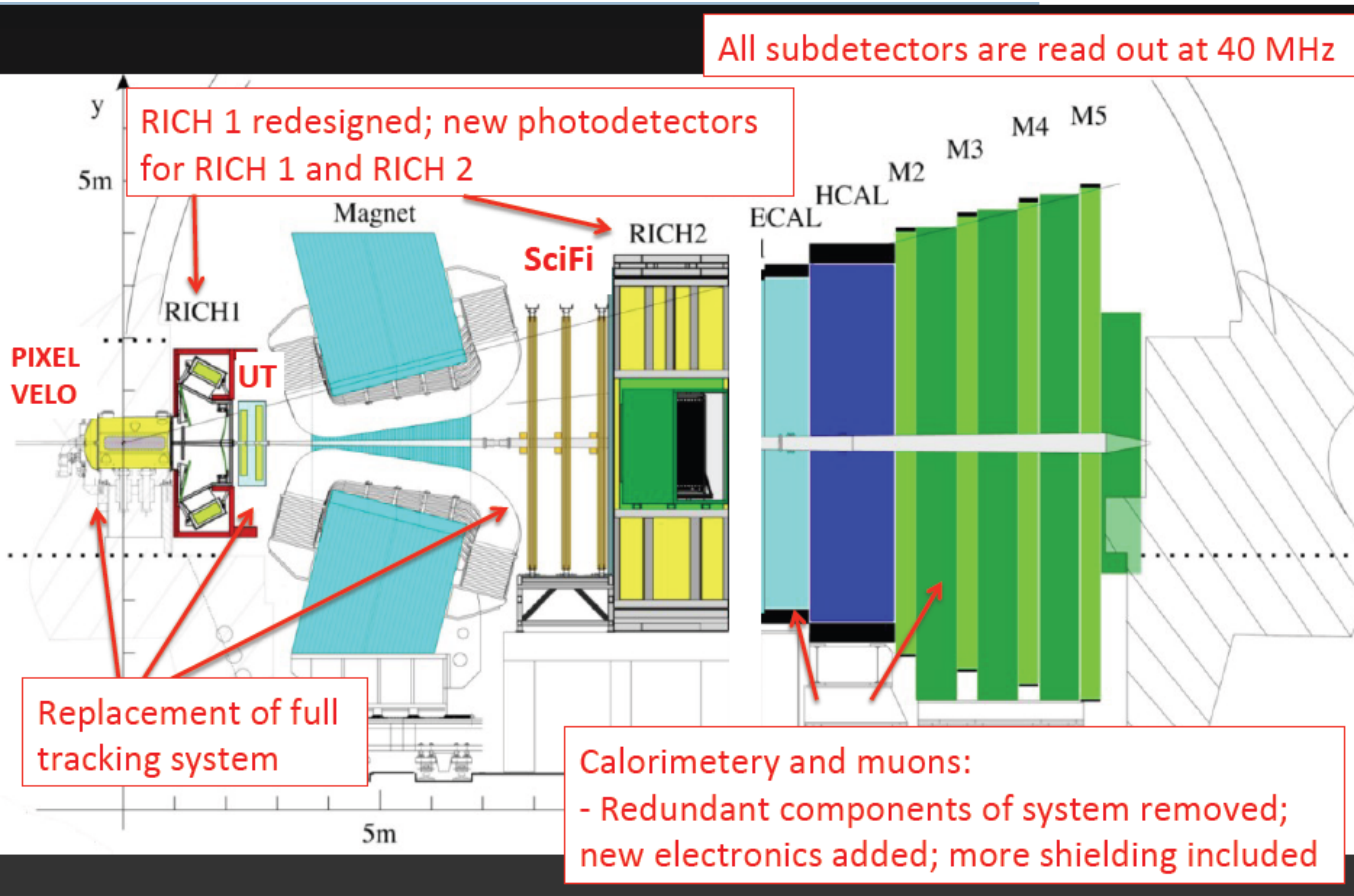
Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

New Endcap Calorimeters
- Radiation tolerant
- High granularity

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 750 kHz
- L1 Latency 12.5 μs
- HLT output rate 7.5 kHz

Other R&D
- Fast-timing for in-time pileup suppression
- Pixel trigger

LHCb Upgrade



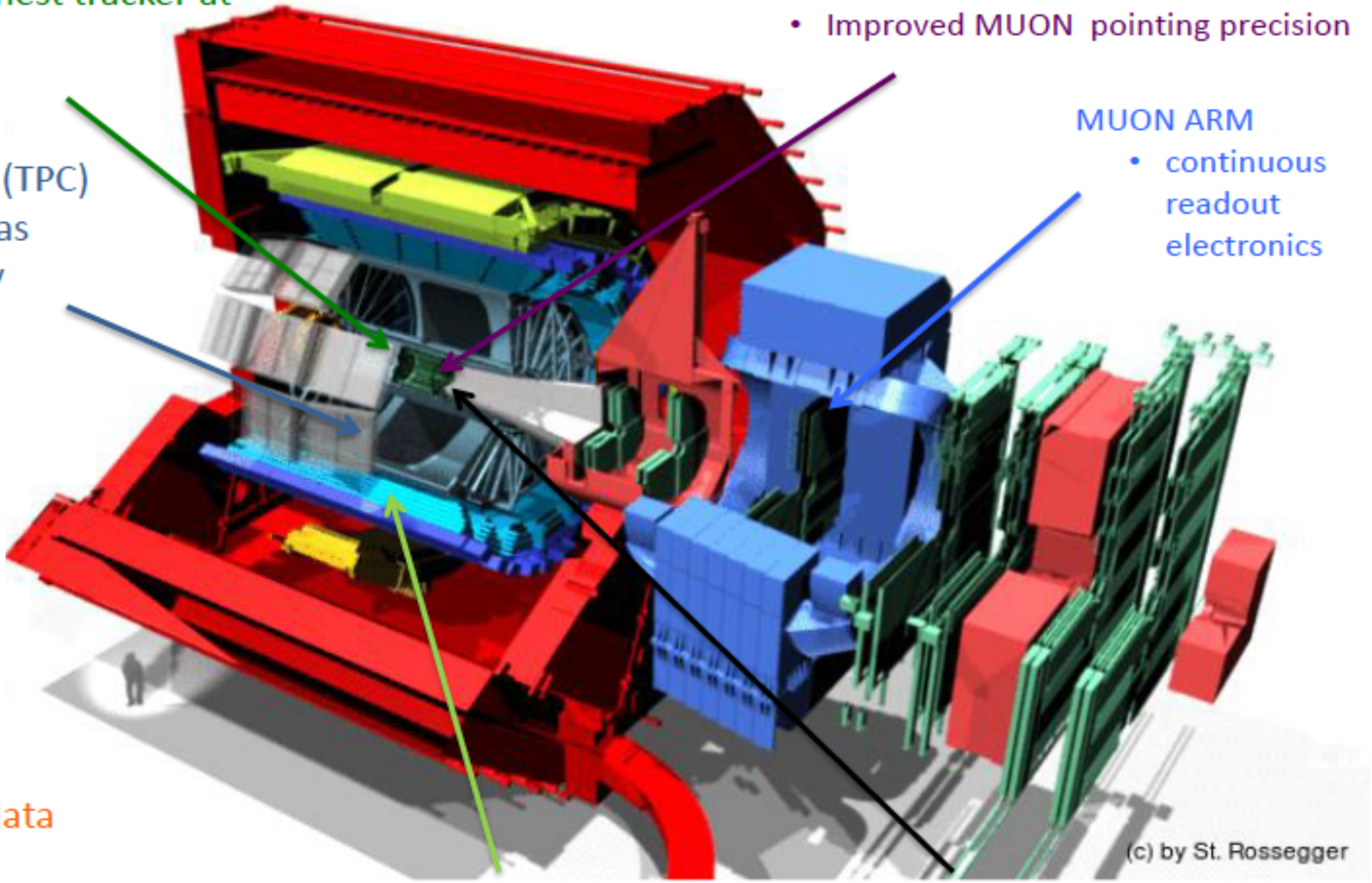
All subdetectors are read out at 40 MHz

RICH 1 redesigned; new photodetectors for RICH 1 and RICH 2

Replacement of full tracking system

Calorimetery and muons:
- Redundant components of system removed; new electronics added; more shielding included

ALICE Upgrade



New Inner Tracking System (ITS)

- improved pointing precision
- less material -> thinnest tracker at the LHC

Muon Forward Tracker (MFT)

- new Si tracker
- Improved MUON pointing precision

MUON ARM

- continuous readout electronics

Time Projection Chamber (TPC)

- New Micropattern gas detector technology
- continuous readout

New Central Trigger Processor (CTP)

Data Acquisition (DAQ)/ High Level Trigger (HLT)

- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

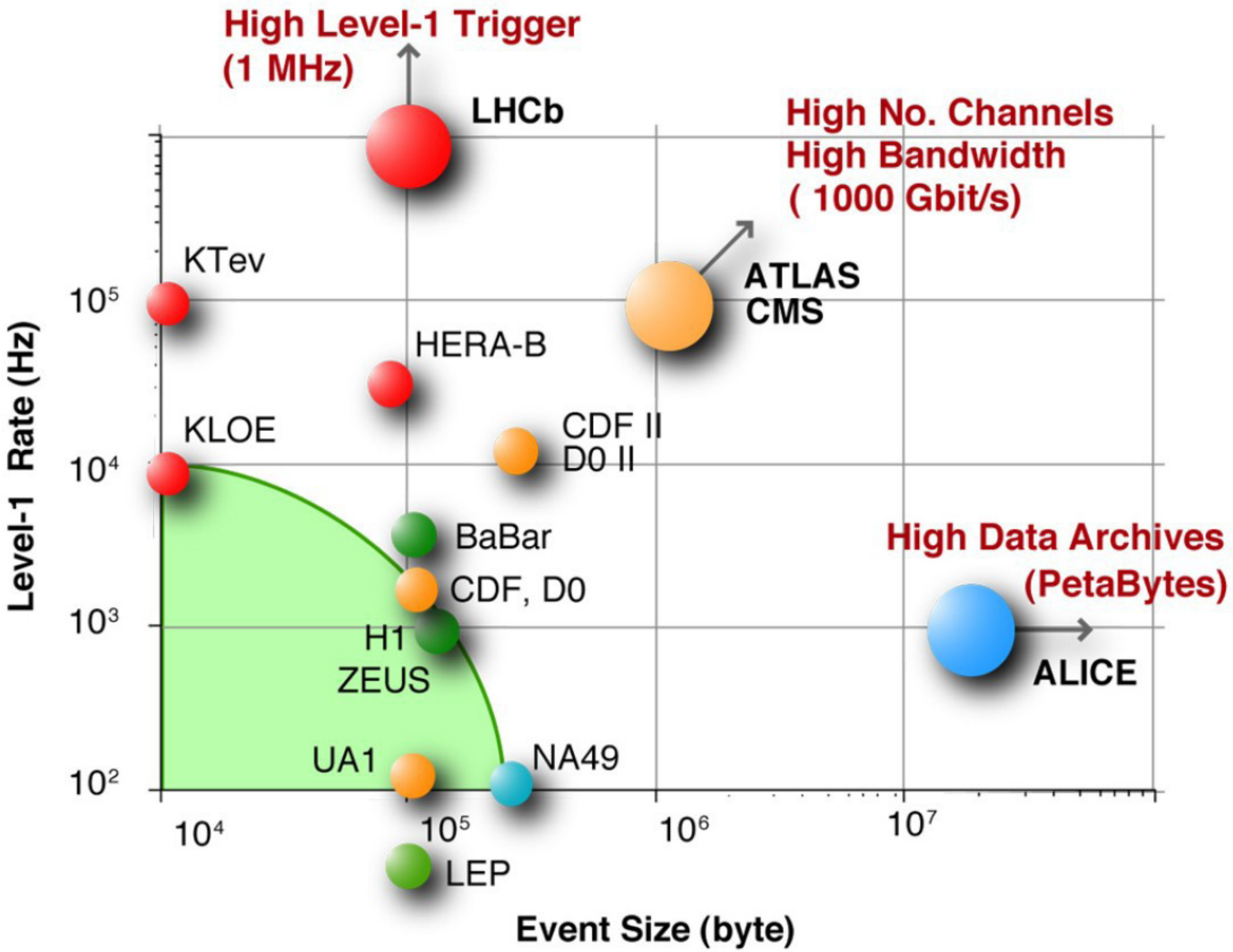
(c) by St. Rossegger

TOF, TRD

- Faster readout

New Trigger Detectors (FIT)

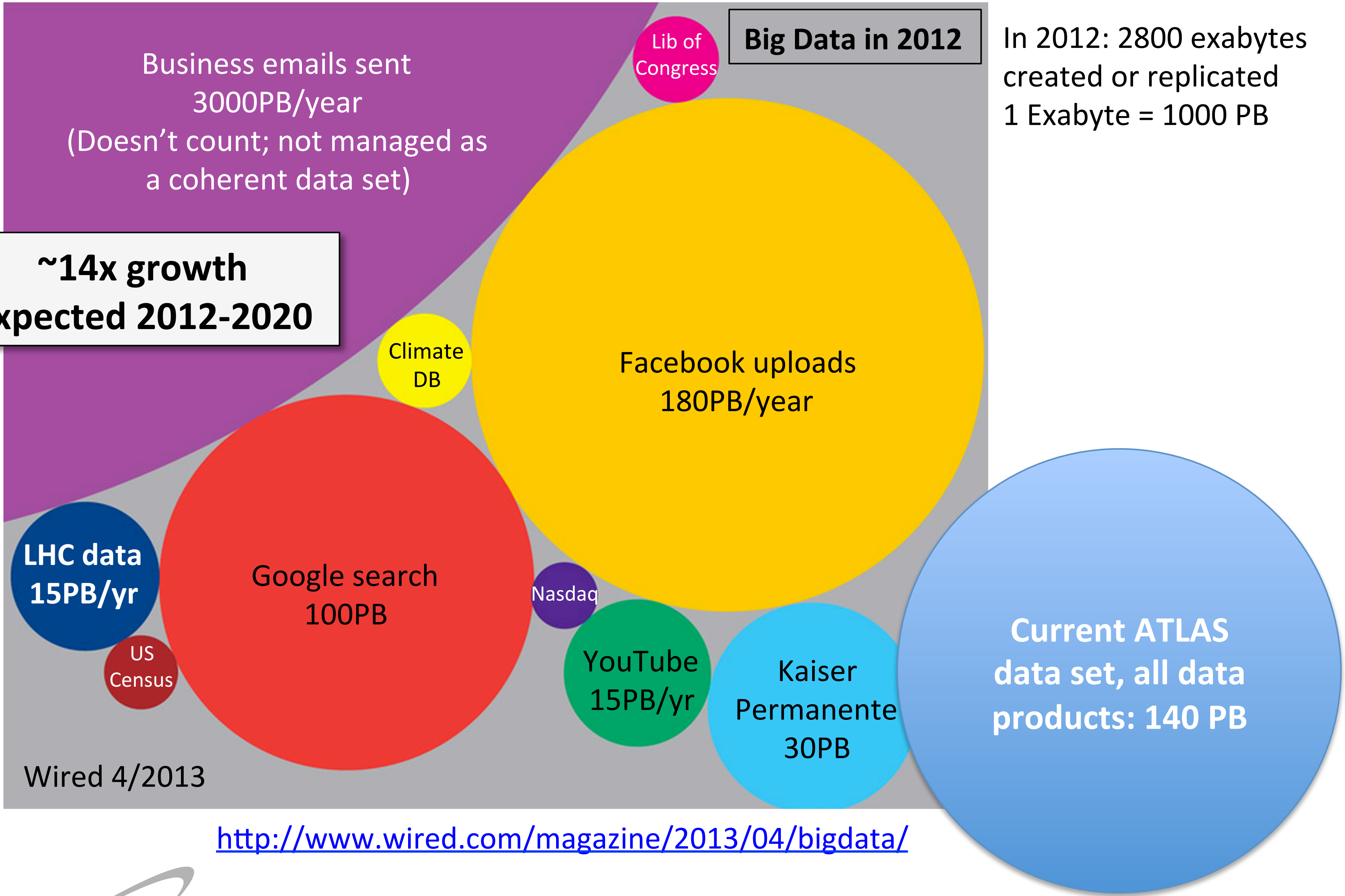
The data challenge



From: Torre Wenaus, CHEP 2013

Data Management

Where is LHC in Big Data Terms?



~14x growth expected 2012-2020

In 2012: 2800 exabytes created or replicated
1 Exabyte = 1000 PB

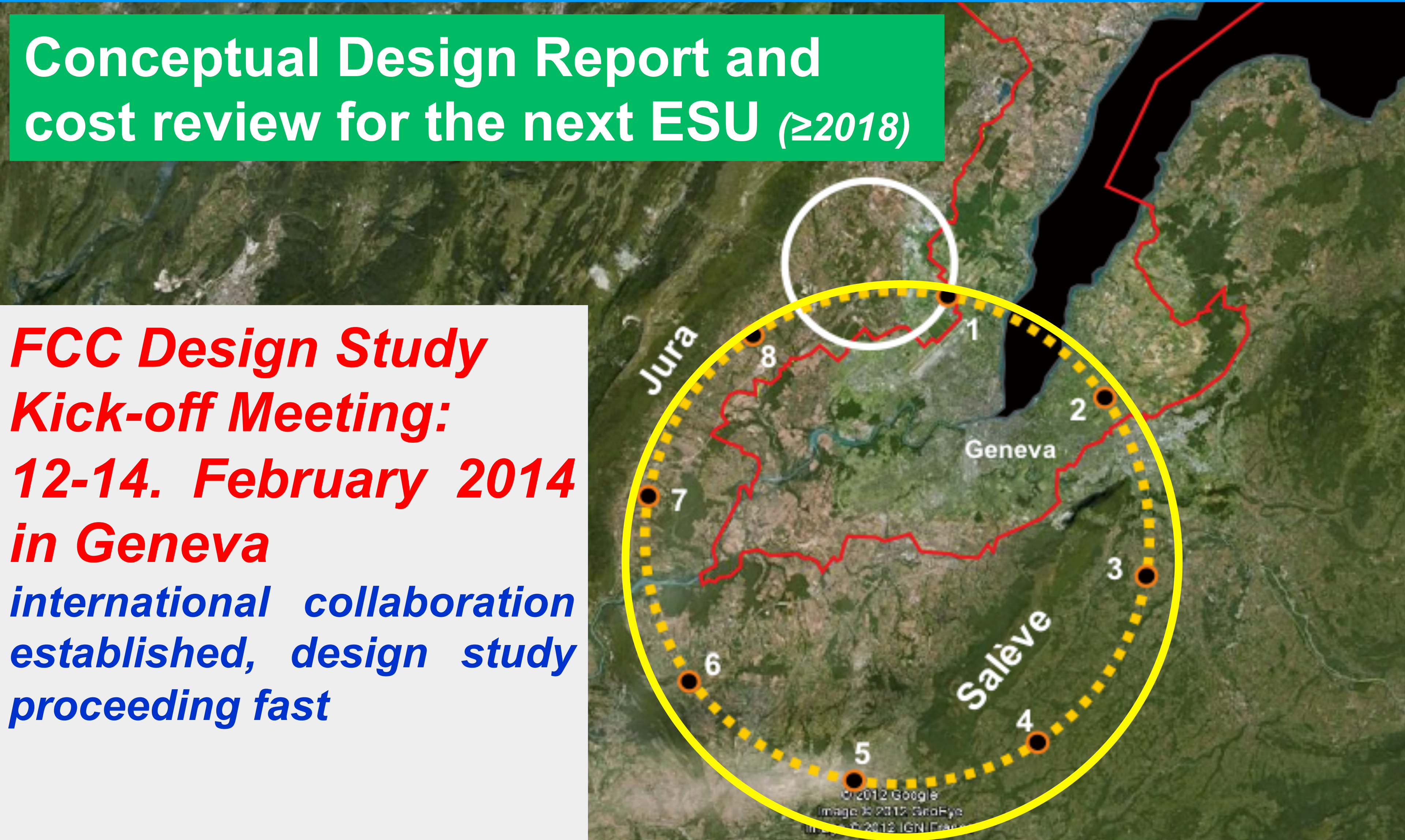
http://www.wired.com/magazine/2013/04/bigdata/

100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements
with possibility of e+-e- (TLEP) and p-e (VLHeC)

Conceptual Design Report and cost review for the next ESU *(≥2018)*

FCC Design Study Kick-off Meeting: 12-14. February 2014 in Geneva

international collaboration established, design study proceeding fast



FCC: physics reach in a nutshell

FCC-hh: 100 TeV

- explore directly the 10-50 TeV E-scale
- provide conclusive exploration of EWSB dynamics
- study nature the Higgs potential and EW phase transition
- say final word about heavy WIMP dark matter
- etc.

FCC-ee: 90-350 GeV

- indirect sensitivity to E scales up to O(100 TeV) by measuring most Higgs couplings to O(0.1%), improving the precision of EW parameters measurements by ~20-200, $\Delta M_W < 1$ MeV, $\Delta m_{top} \sim 10$ MeV, etc.
- sensitivity to very-weakly coupled physics (e.g. light, weakly-coupled dark matter)
- etc.

FCC-ep: ~ 3.5 TeV

- unprecedented measurements of PDF and α_s
- new physics: leptoquarks, eeqq contact interactions, etc.
- Higgs couplings (e.g. Hbb to ~ 1%)
- etc.

Machines are complementary and synergetic, e.g. from measurement of ttH/ttZ ratio, and using ttZ coupling and H branching ratio from FCC-ee, FCC-hh can measure ttH to ~ 1%

The challenge is not only the machine…

Detectors R&D :

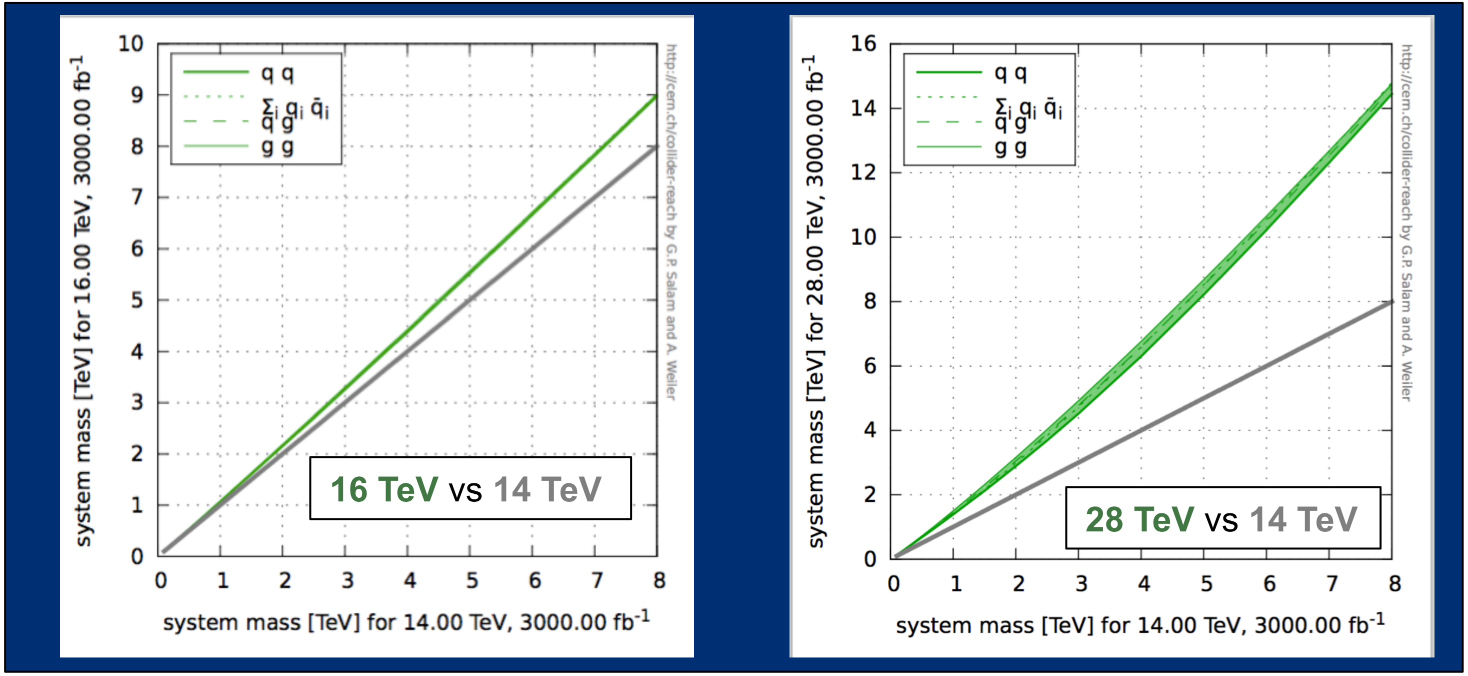
- Ultra-light, ultra-fast, ultra-granular, rad-hard, low-power Si trackers
- 10^8 channel imaging calorimeters (power consumption and cooling at high-rate machines,..)
- big-volume 5-6 T magnets (~2 x magnetic length and bore of ATLAS and CMS, ~50 GJ stored energy) to reach momentum resolutions of ~10% for p~20 TeV muons

Theory:

- improved theoretical calculations (higher-order EW and QCD corrections) needed to match present and future experimental precision on EW observables, Higgs mass and branching ratios.
- Work together with experiments on model-independent analyses in the framework of Effective Field Theory

Higher $\sqrt{s}$ in the LHC tunnel ?

Fabiola Gianotti,
FCC Week 2016

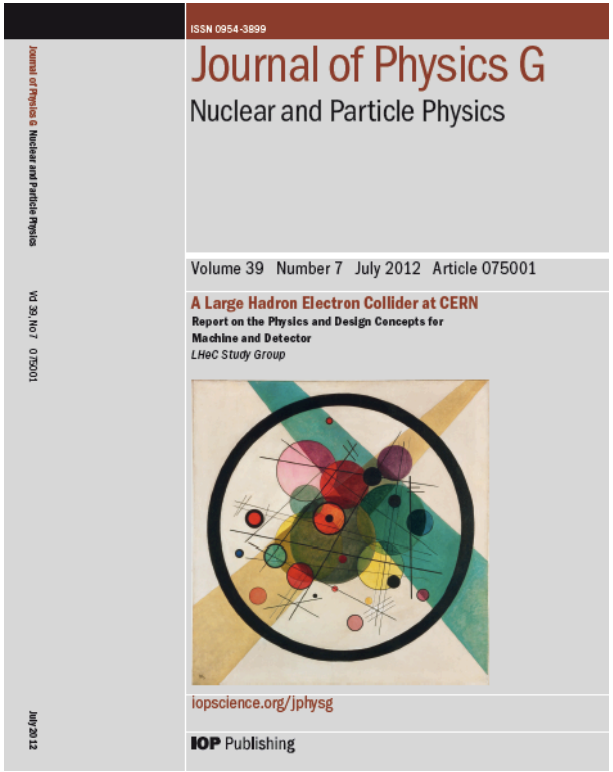


Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb_3Sn magnets)
→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
→ Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ $\sqrt{s}$~ 30 TeV)
☐ uses existing tunnel and infrastructure; can be built at fixed budget
☐ strong physics case if new physics from LHC/HL-LHC
☐ powerful demonstration of the FCC-hh magnet technology

LHeC, not only PDFs



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Nuclear and Particle Physics

Volume 39 Number 7 July 2012 Article 075001

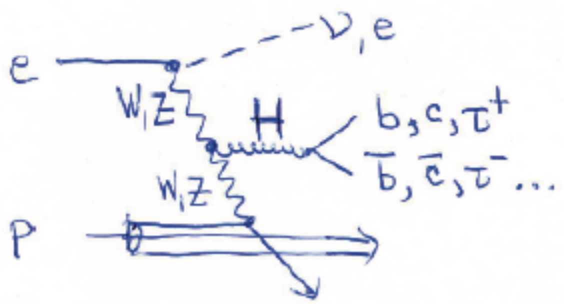
A Large Hadron Electron Collider at CERN

Report on the Physics and Design Concepts for Machine and Detector

LHeC Study Group

iopscience.org/jphysg

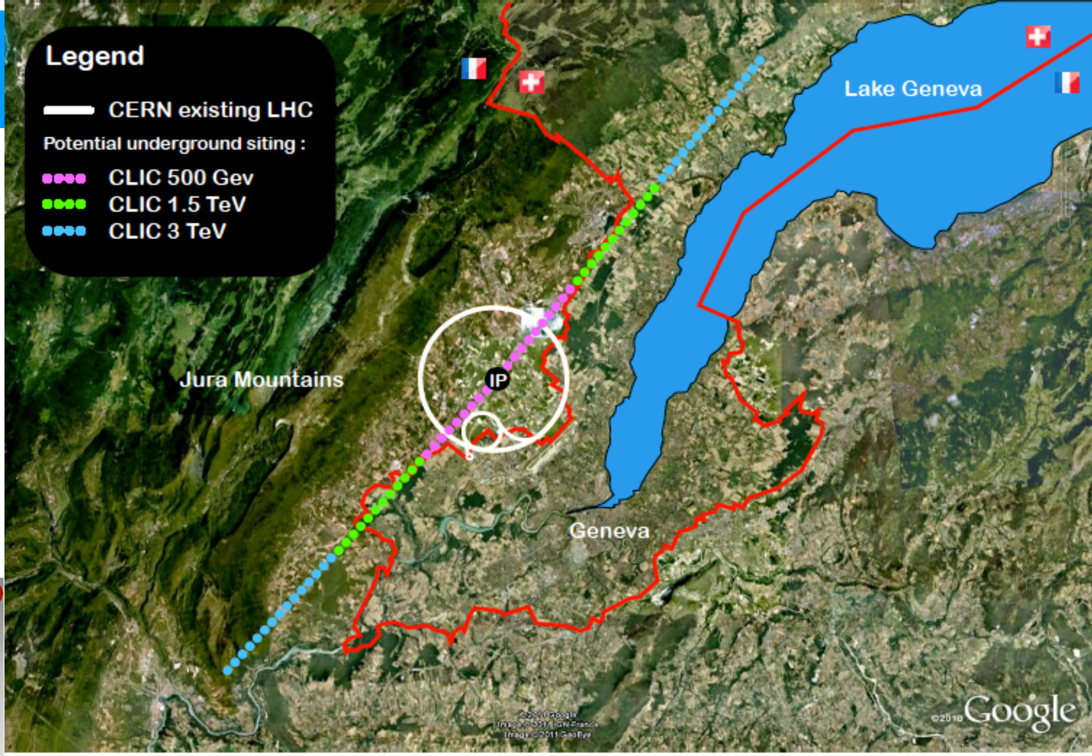
IOP Publishing

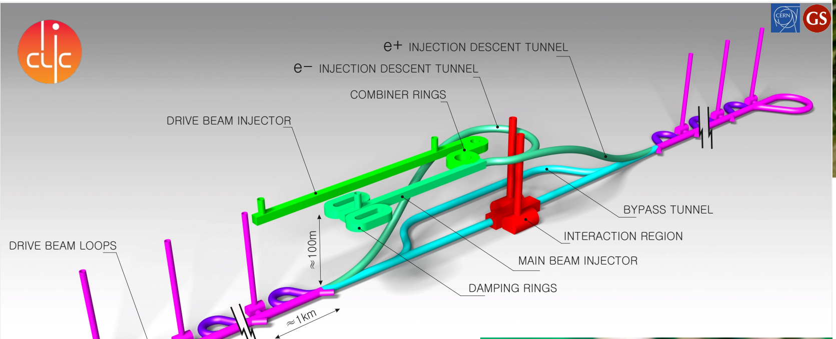


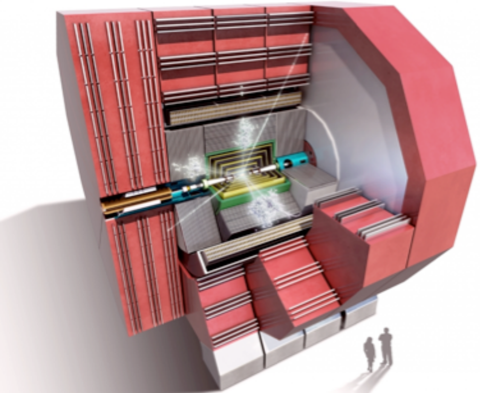
Continuing activity on
Physics
Detector
ERL

Goal: L~10^{34} cm^{-2}s^{-1}

The CLIC project







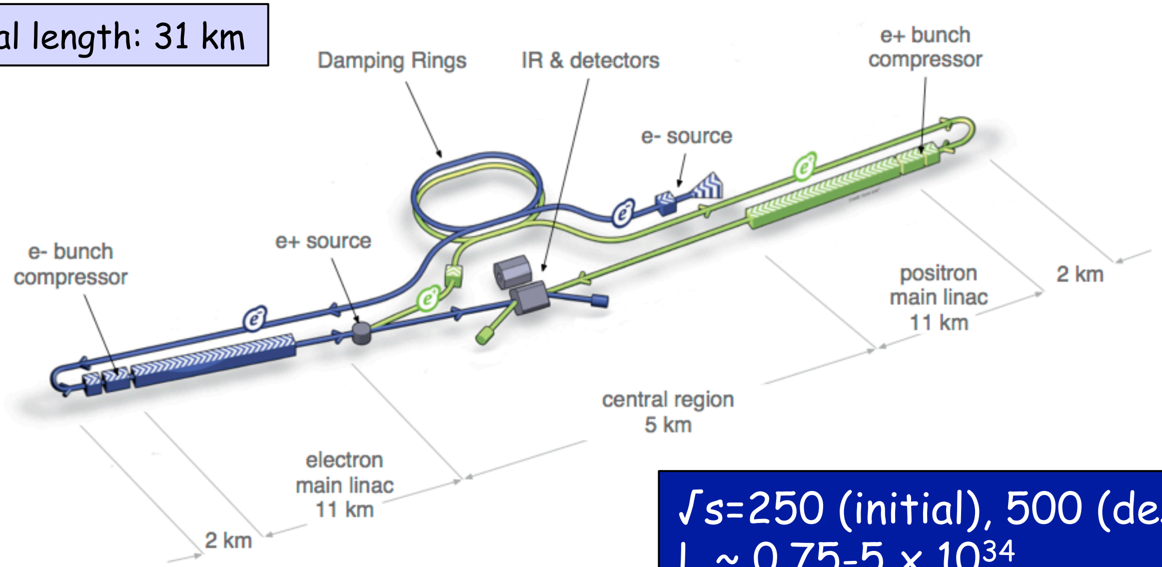

CALICE tungsten-DHCAL


Complete module, PETs (above), Acc. Structure (right)

International Linear Collider (ILC)

Technical Design Report released in June 2013

Total length: 31 km



√s=250 (initial), 500 (design), 1000 (upgrade) GeV
L ~ 0.75-5 x 10^{34}
(running at √s=90, 160, 350 GeV also envisaged)

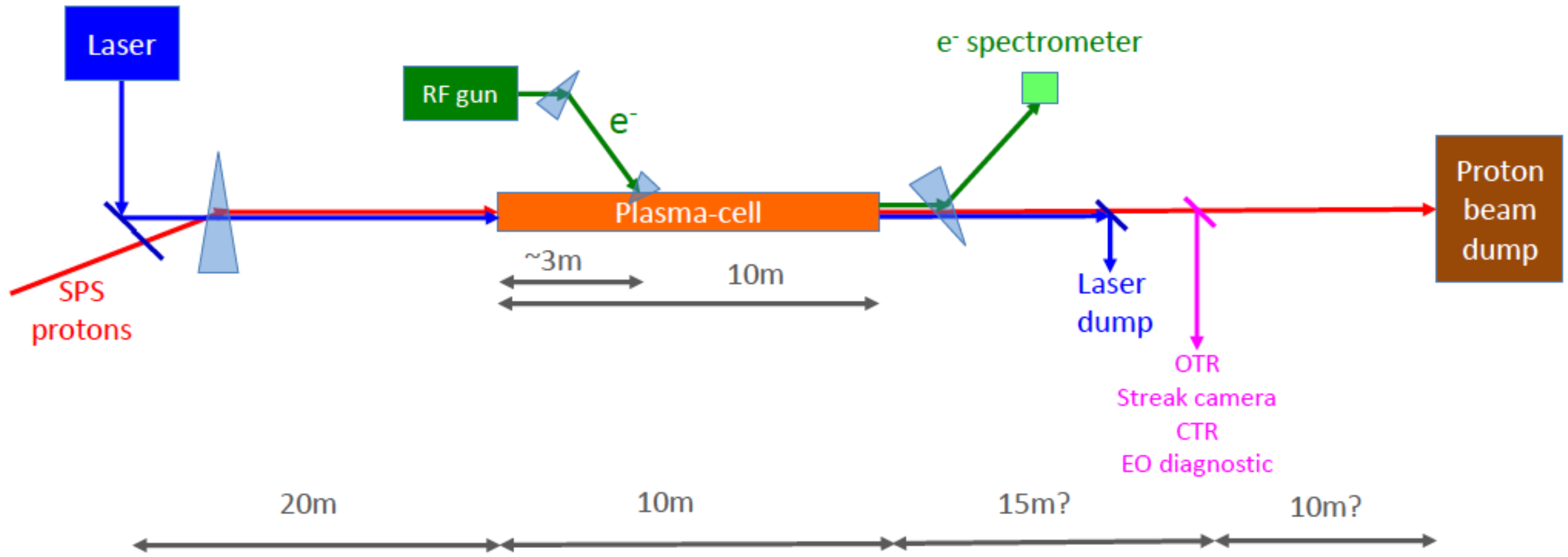
Main challenges:

- ☐ ~ 15000 SCRF cavities (1700 cryomodules), 31.5 MV/m gradient
- ☐ 1 TeV machine requires extension of main Linacs (50 km) and 45 MV/m
- ☐ Positron source; suppression of electron-cloud in positron damping ring
- ☐ Final focus: squeeze and collide nm-size beams

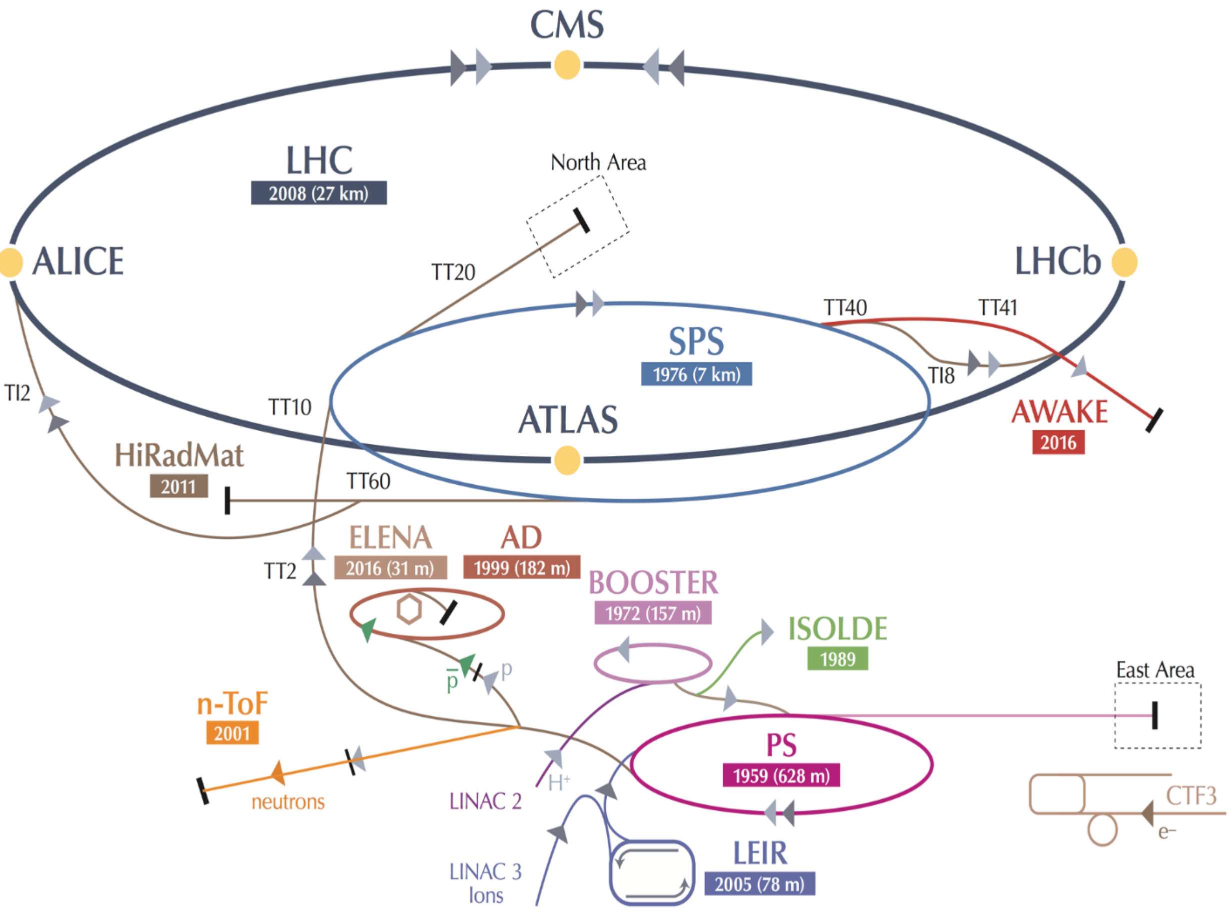
☐ Japan interested to host → decision ~2018 based also on ongoing international discussions
Mature technology: 20 years of R&D experience worldwide
(e.g. European xFEL at DESY is 5% of ILC, gradient 24 MV/m, some cavities achieved 29.6 MV/m)
→ Construction could technically start ~2019, duration ~10 years → physics could start ~2030

Disruptive Technologies: Wakefield Acceleration

Experimental Layout



A compelling scientific programme beyond the LHC



~20 experiments > 1200 physicists

AD: Antiproton Decelerator for antimatter studies

CAST, OSQAR: axions

CLOUD: impact of cosmic rays on aeorosols and clouds → implications on climate

COMPASS: hadron structure and spectroscopy

ISOLDE: radioactive nuclei facility

NA61/Shine: ions and neutrino targets

NA62: rare kaon decays

NA63: radiation processes in strong EM fields

n-TOF: n-induced cross-sections

UA9: crystal collimation

Neutrino Platform: collaborating with experiments in US and Japan → see later

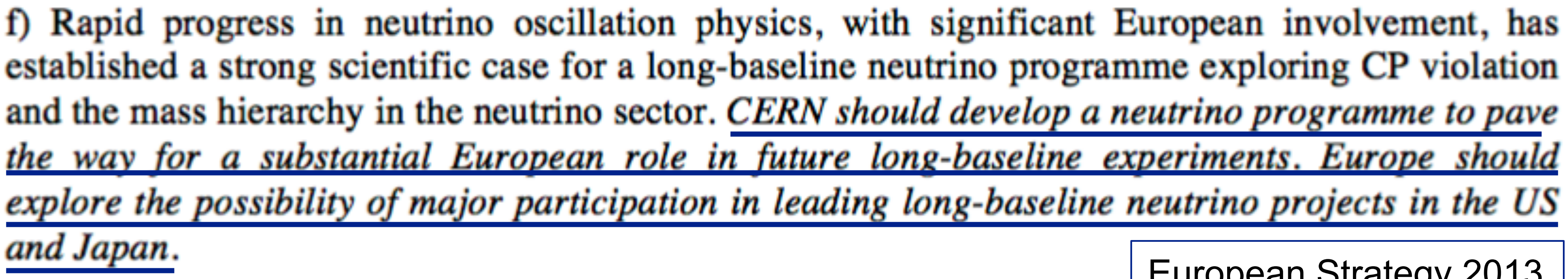
CERN neutrino activities

Neutrino oscillations (e.g. $\nu_\mu \rightarrow \nu_e$) established (since 1998) with solar, atmospheric, reactor and accelerator neutrinos → imply neutrinos have masses and mix
Since then: great progress in understanding ν properties at various facilities all over the world

Nevertheless, several open questions:

- ☐ Origin of ν masses (e.g. why so light compared to other fermions ?)
- ☐ Mass hierarchy: normal (ν_3 is heaviest) or inverted (ν_3 is lightest) ?
- ☐ Why mixing much larger than for quarks ?
- ☐ CP violation (observed in quark sector): do ν and anti-ν behave in the same way?
- ☐ Are there additional (sterile) ν (hints from observed anomalies)?

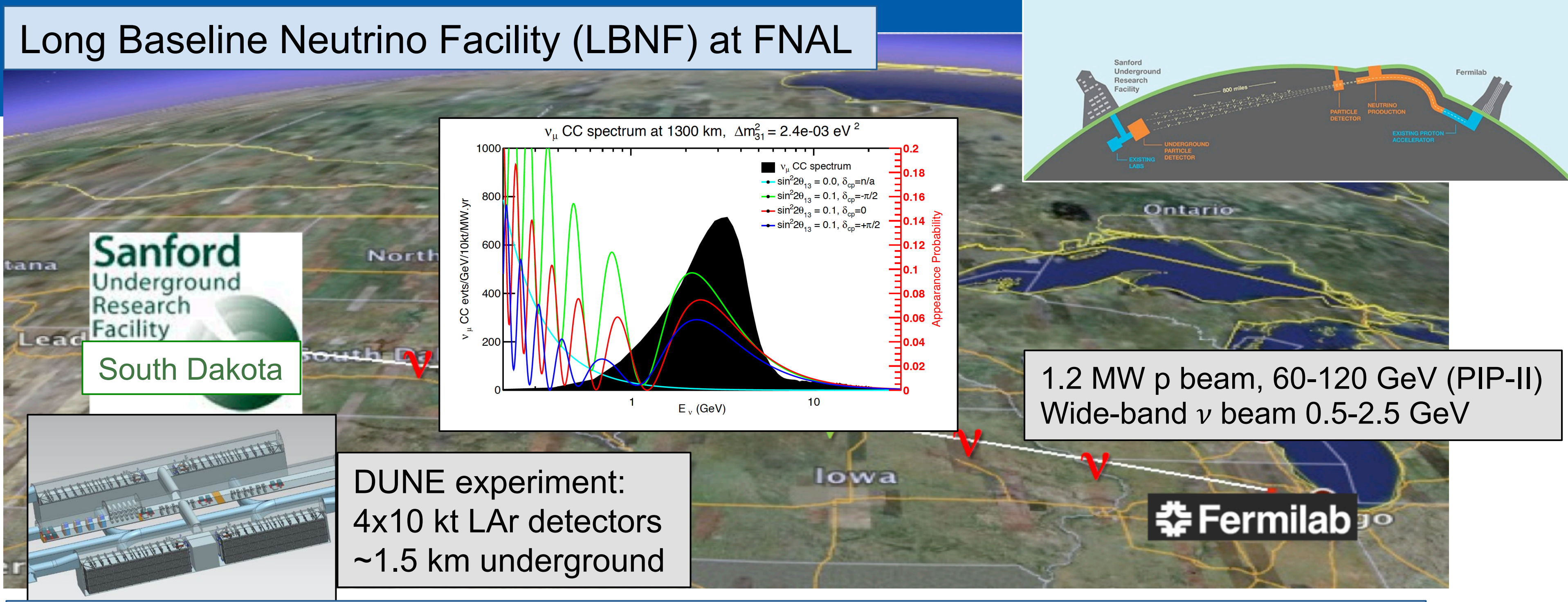
Accelerator experiments can address some of above questions studying $\nu_\mu \rightarrow \nu_e$ oscillations
Need high-intensity p sources (> 1MW) and massive detectors, as ν are elusive particles and the searched-for effects tiny → Next-generation facilities planned in US and Japan.



f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

European Strategy 2013

Long Baseline Neutrino Facility (LBNF) at FNAL



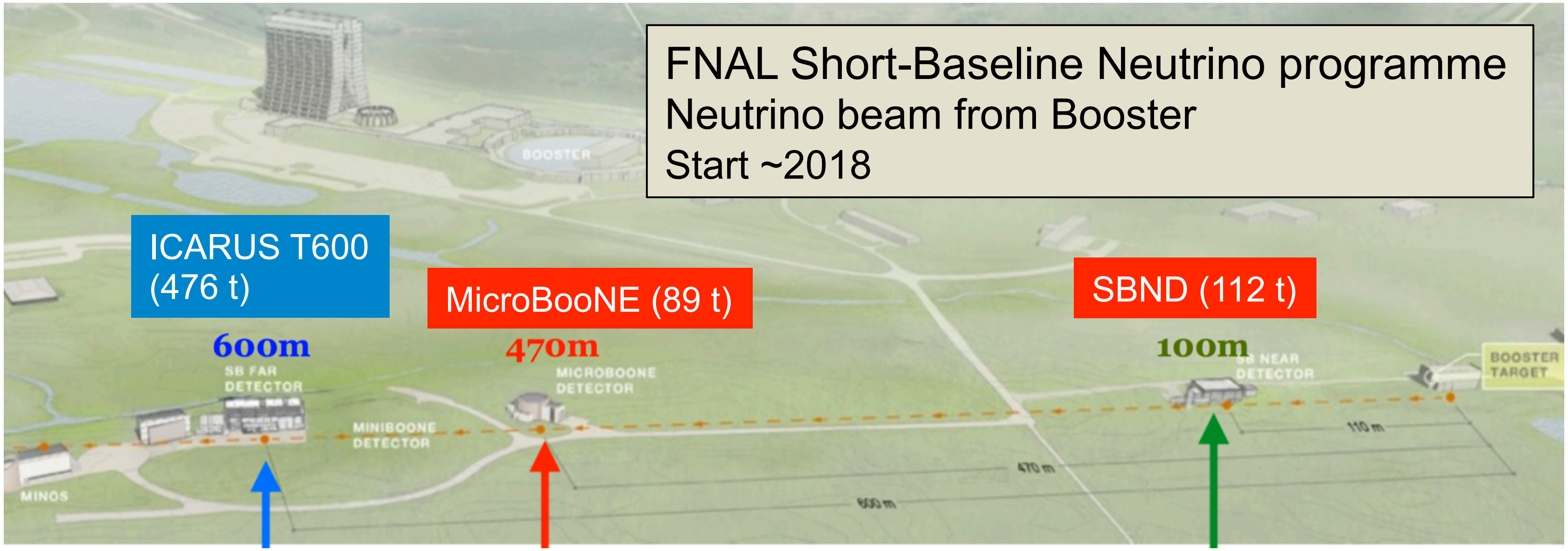
Sanford Underground Research Facility

South Dakota

DUNE experiment:
4x10 kt LAr detectors
~1.5 km underground

1.2 MW p beam, 60-120 GeV (PIP-II)
Wide-band ν beam 0.5-2.5 GeV

Far site construction starts ~2017, 1st detector installed ~2022, beam from FNAL ~ 2026



FNAL Short-Baseline Neutrino programme
Neutrino beam from Booster
Start ~2018

ICARUS T600
(476 t)

600m

MicroBooNE (89 t)

470m

SBND (112 t)

100m

A 25+ years Physics Program

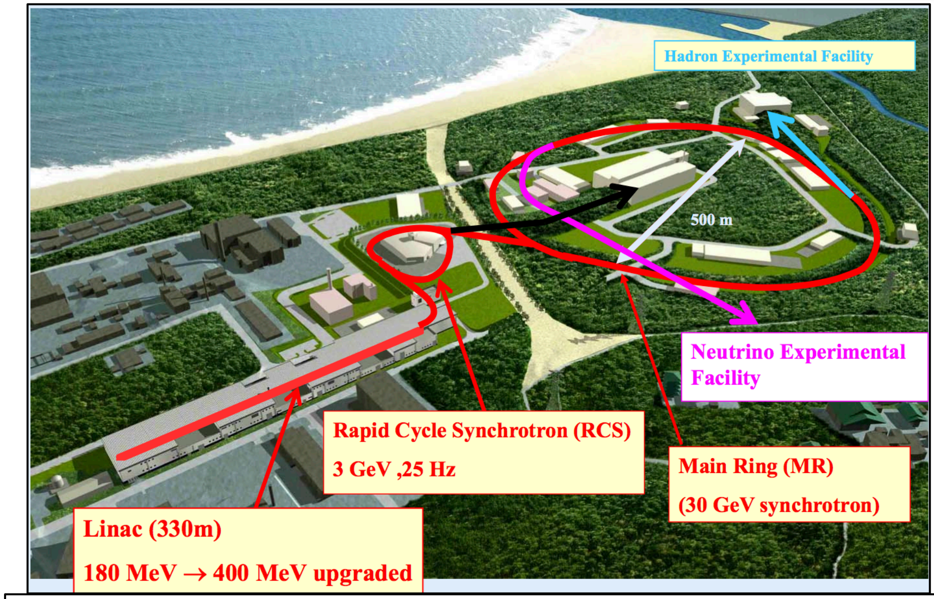
On the beam:

- Perform a comprehensive investigation of neutrino oscillations to:
  - test CP violation in the lepton sector
  - determine the ordering of the neutrino masses
  - test the three-neutrino paradigm
- Perform a broad set of neutrino scattering measurements with the near detector

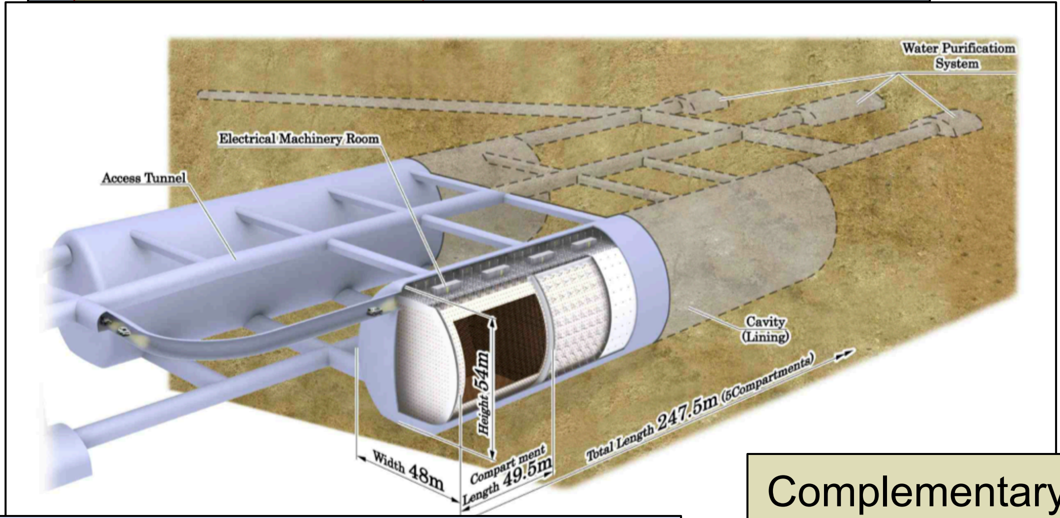
Exploit the large, high-resolution, underground far detector for non-accelerator physics topics:

- atmospheric neutrino measurements
- searches for nucleon decay
- measurement of astrophysical neutrinos (especially those from a core-collapse supernova).

Hyper-Kamiokande, JPARC: construction could start ~2018



0.38 → 0.75 → > 1 MW p source
E_p = 30 GeV → E_ν~ 0.6 GeV
Narrow-band ν beam
→ high intensity at oscillation peak



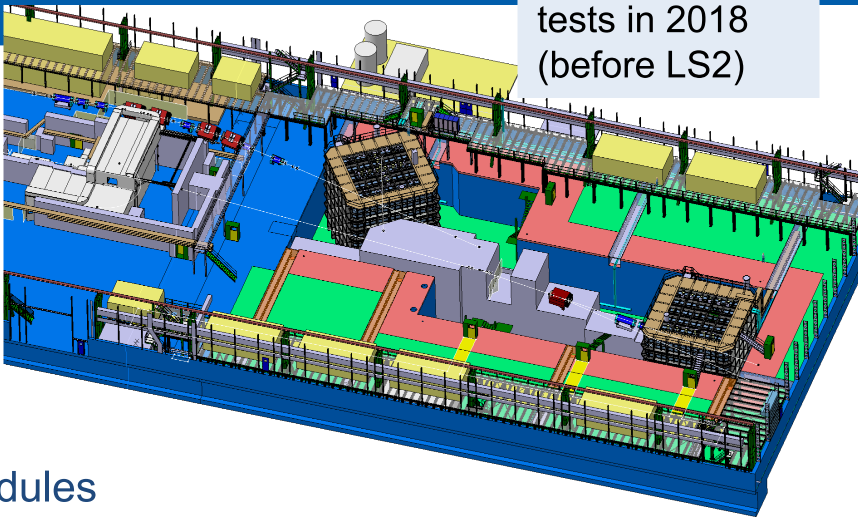
~0.5 Mton Water Cerenkov detector (~20 x Super-K)
~ 1 km underground
~ 2.5^0 off-axis → narrow-band beam

Complementary to LBNE: different detector technology, shorter baseline (→ less sensitive to mass hierarchy), narrow-band beam (→ high statistics of ν/anti-ν at oscillation peak but limited measurement of oscillation spectrum)

CERN Neutrino Platform

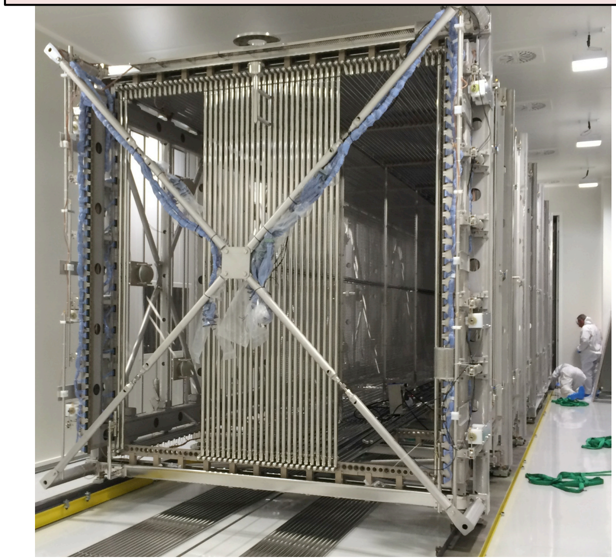
Mission:

- ☐ Provide charged beams and test space to neutrino community → North Area extension
- ☐ Support European participation in accelerator neutrino experiments in US and Japan:
- → R&D to demonstrate large-scale LAr technology (cryostats, cryogenics, detectors)
- → Construction of one cryostat for DUNE detector modules
- → Construction of BabyMIND magnet: muon spectrometer for WAGASCI experiment at JPARC

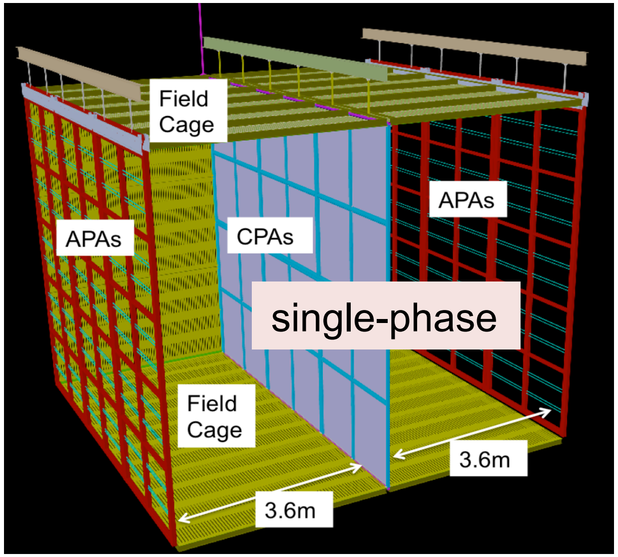


ready for beam tests in 2018 (before LS2)

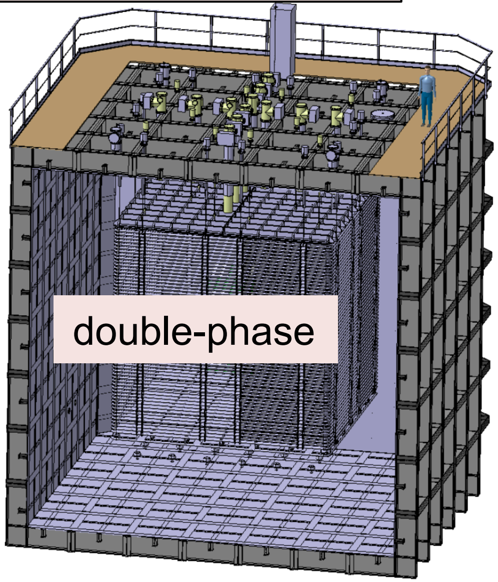
Refurbishment of ICARUS T600 for short baseline programme
→ ship to FNAL beg 2017



Construction and test of “full-scale” prototypes of DUNE drift cells: ~ 6x6x6 m^3, ~ 700 tons



single-phase

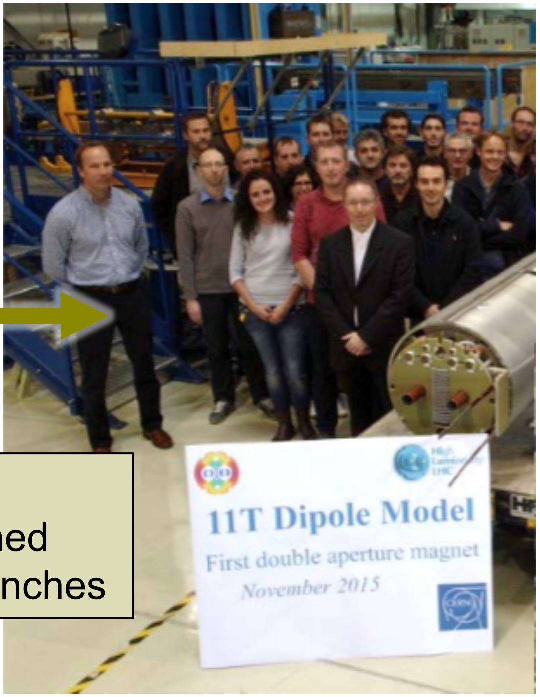


double-phase

FCC magnet technology: learning from LHC/HL-LHC

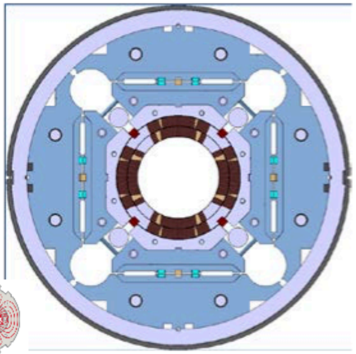
“Natural” continuation of LHC and HL-LHC programmes.
Step-wise approach → each step deployed and operated in a (big) accelerator:

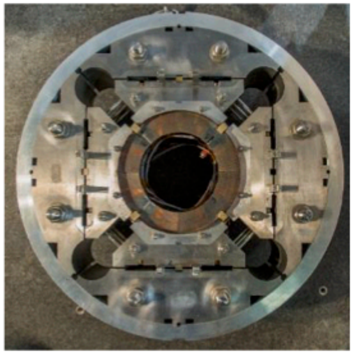
- ☐ LHC: 8.3 T → push to ultimate field of 9 T ?
- ☐ HL-LHC: Nb_3Sn technology:
  - -- 11 T dipoles in dispersion suppression collimators
  - -- 12-13 T peak field low-β quads for ATLAS and CMS IR’s

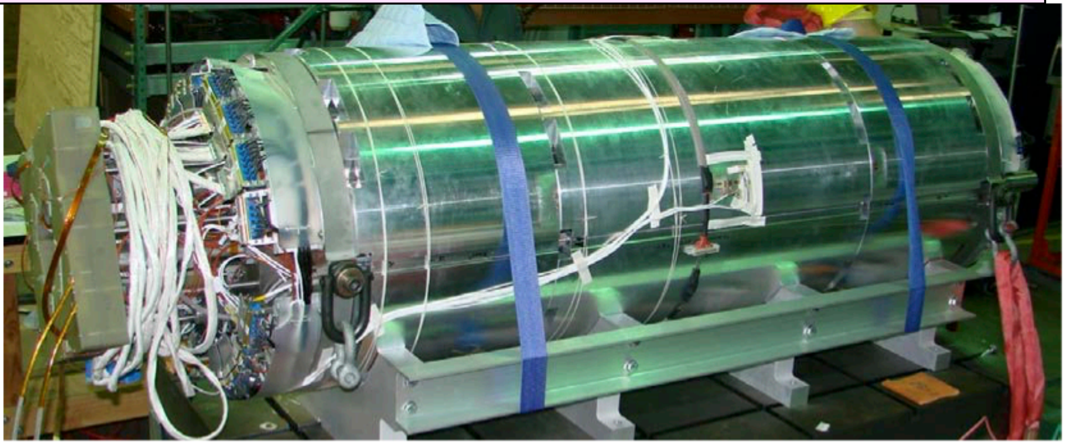


December 2015: short (1.8 m) Nb_3Sn two-in-one dipole reached 11.3 T (> nominal) without quenches

March 2016: short (1.5 m) Nb_3Sn quadrupole model (final aperture =150 mm) reached current 18 kA (nominal: 16.5 kA). CERN-US LARP Collaboration (2 coils from CERN + 2 coils from US)







Future opportunities other than high-energy colliders

A “Physics Beyond Colliders" Study Group has been put in place

Mandate
Explore opportunities offered by CERN accelerator complex and infrastructure to address outstanding questions in particle physics through projects:

☐ complementary to future high-energy colliders (HE-LHC, CLIC, FCC)
☐ exploiting unique capabilities of CERN accelerator complex and infrastructure
☐ complementary to other efforts in the world → optimise resources of the discipline globally
Examples: searches for rare processes and very-weakly interacting particles, electric dipole moments, etc.

→ Enrich and diversify CERN’s future scientific programme

☐ Will bring together accelerator scientists, experimental and theoretical physicists
☐ Kick-off meeting in Summer 2016
☐ Final report end 2018 → in time for European Strategy

One of the goals is to involve interested worldwide community, and to create synergies with other laboratories and institutions in Europe (and beyond)

In summary

An exciting period in front of us:

- We have finished the inventory of the “known unknown”…
- …but we have a vast space to explore (and a few tantalizing hints to probe)
- We have a solid physics program for the next 15 – 20 years
- In this time period we have to prepare for the next steps, setting directions, technologies and political frames.

In summary

Experimental results will be dictating the agenda of the field.

We will need:

- Flexibility
- Preparedness
- Visionary global policies

THANK YOU