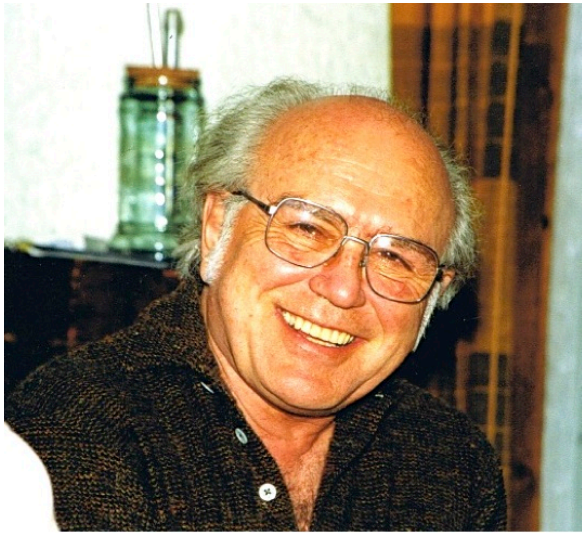
LHC Now and in the Future



Bruno Zumino
Memorial Meeting

April 27, 2015
Sergio Bertolucci
CERN

Where we stand

After LHC Run 1:

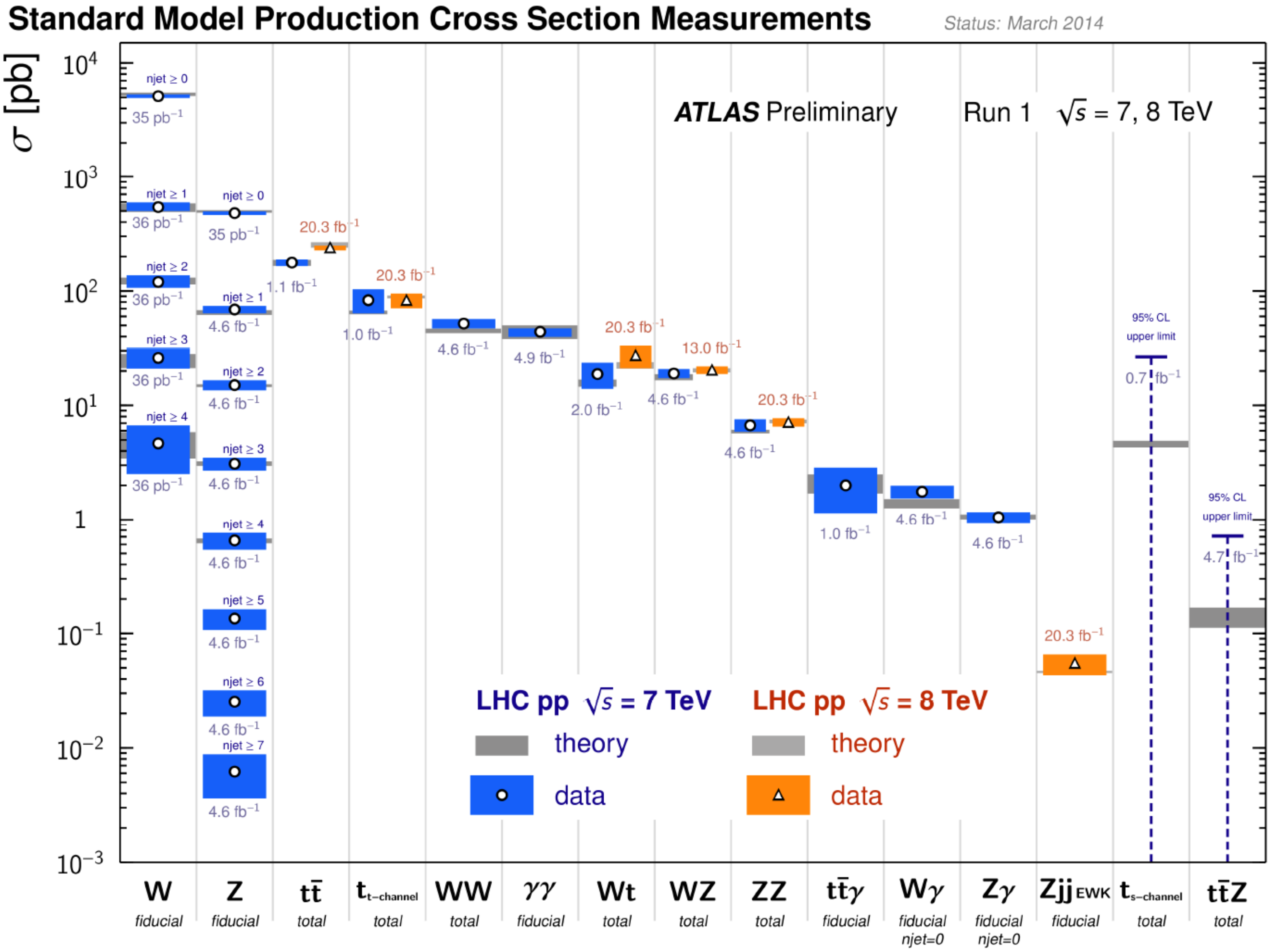
- We have consolidated the Standard Model
  (a wealth of measurements at 7-8 TeV, including the rare, and very sensitive to New Physics, $B_s \rightarrow \mu\mu$ decay)

- We have completed the Standard Model: discovery of the messenger of the BEH-field, the Higgs boson discovery

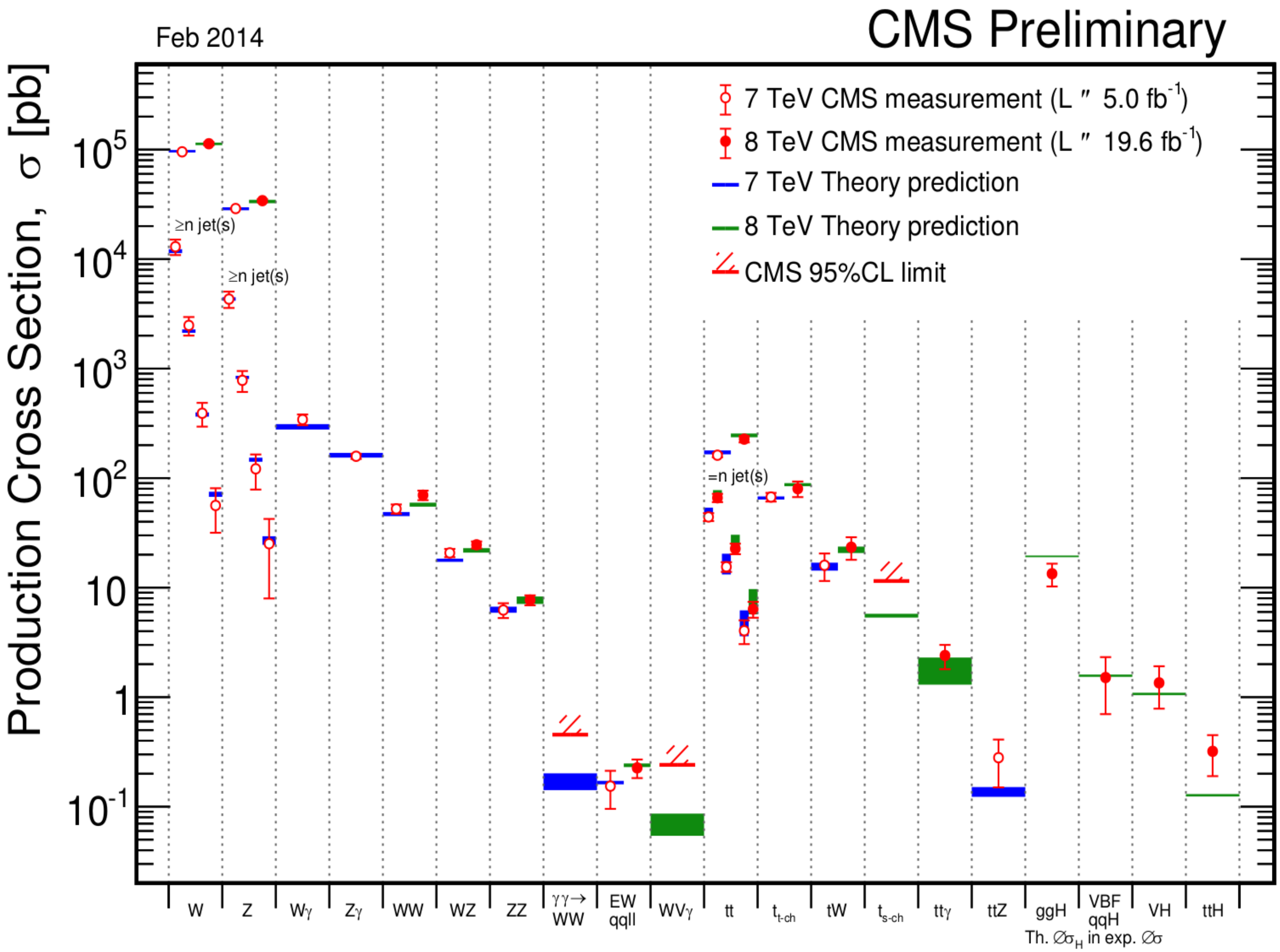
- We found interesting properties of the hot dense matter

- **We have NO evidence of New Physics**

SM@LHC

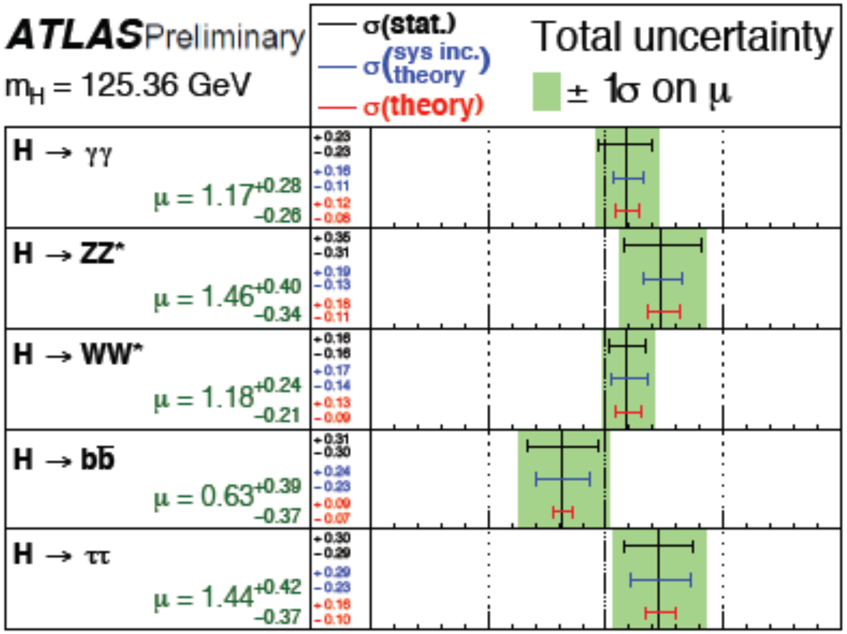

Standard Model Production Cross Section Measurements
Status: March 2014
σ [pb]
10^4
10^3
10^2
10^1
1
10^−1
10^−2
10^−3
ATLAS Preliminary
Run 1 √s = 7, 8 TeV
njet ≥ 0
35 pb^−1
njet ≥ 1
36 pb^−1
njet ≥ 2
36 pb^−1
njet ≥ 3
36 pb^−1
njet ≥ 4
36 pb^−1
njet ≥ 0
35 pb^−1
njet ≥ 1
4.6 fb^−1
njet ≥ 2
4.6 fb^−1
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 √s = 7 TeV
theory
data
LHC pp √s = 8 TeV
theory
data
W
fiducial
Z
fiducial
tt̄
total
t_t−channel
total
WW
total
γγ
fiducial
Wt
total
WZ
total
ZZ
total
tt̄γ
fiducial
Wγ
fiducial
njet=0
Zγ
fiducial
njet=0
Zjj EWK
fiducial
t_s−channel
total
tt̄Z
total

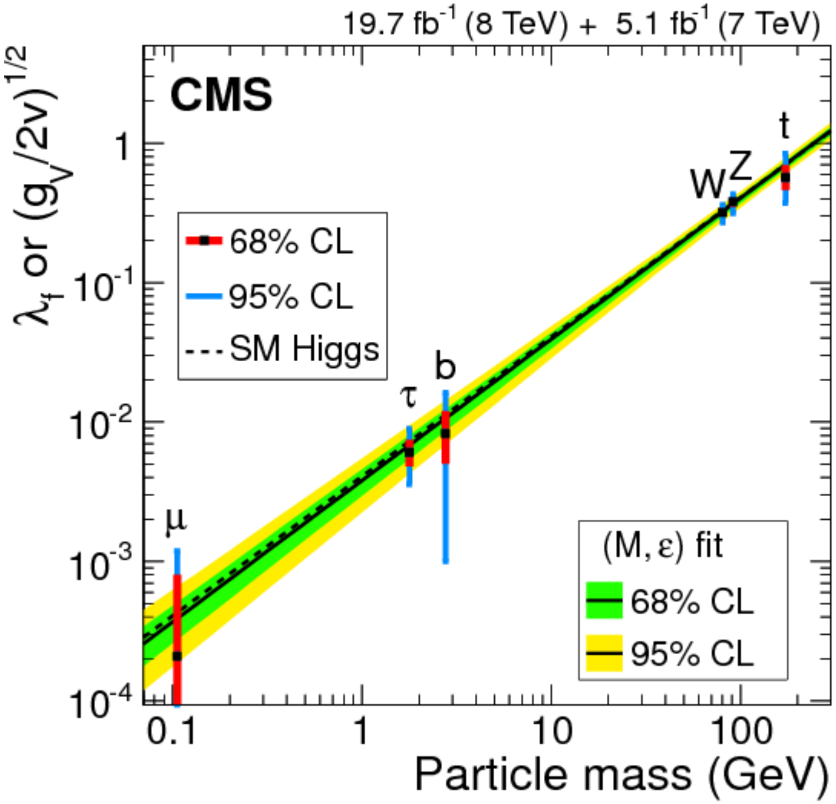
SM@LHC


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-ch
tW
t_s-ch
ttγ
ttZ
ggH
VBF qqH
VH
ttH
Th. ∅σ_H in exp. ∅σ

Higgs@LHC

[ATLAS-CONF-2015-007]





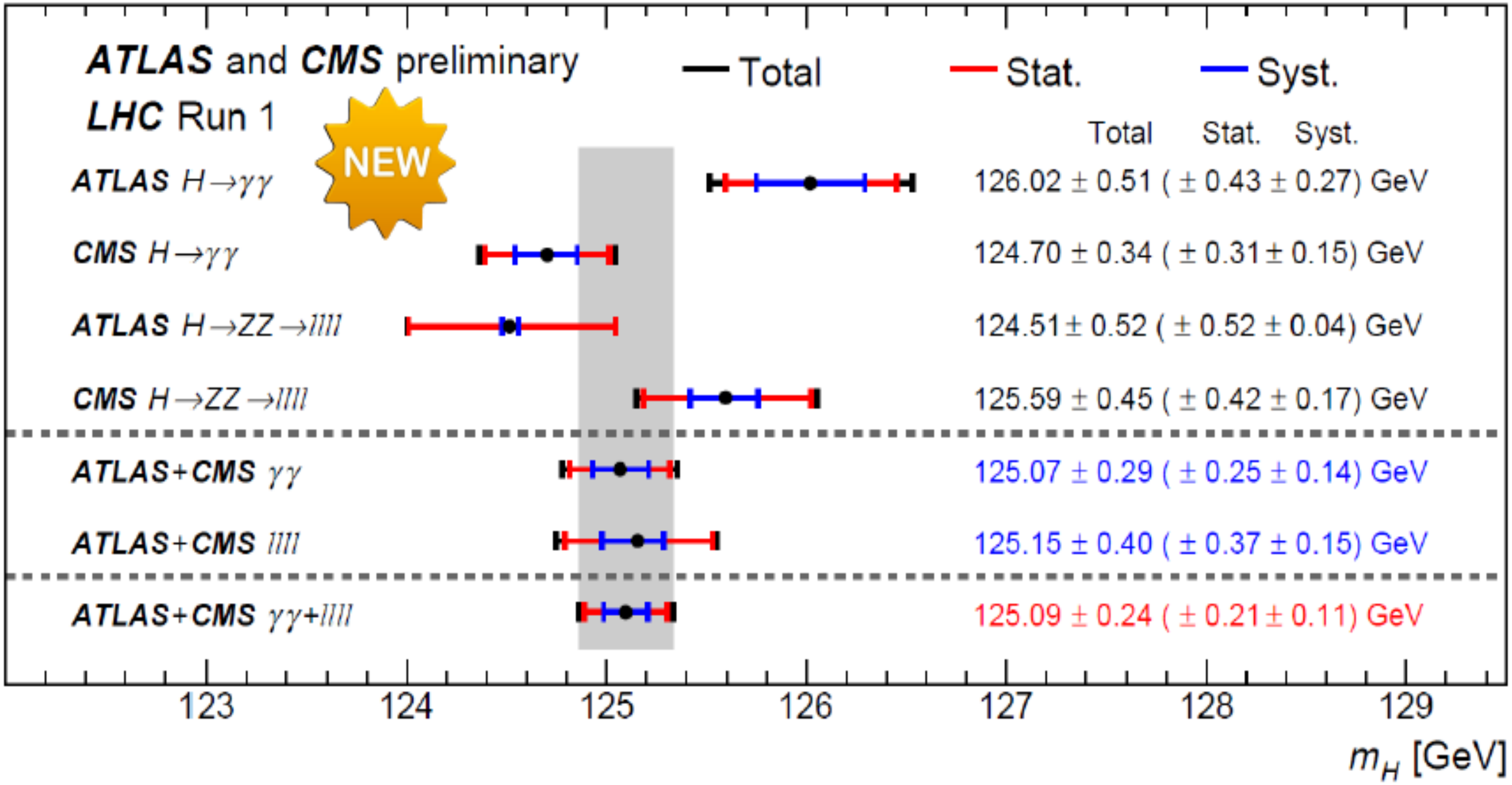
No significant deviation from SM so far

ATLAS+CMS Higgs mass combination

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

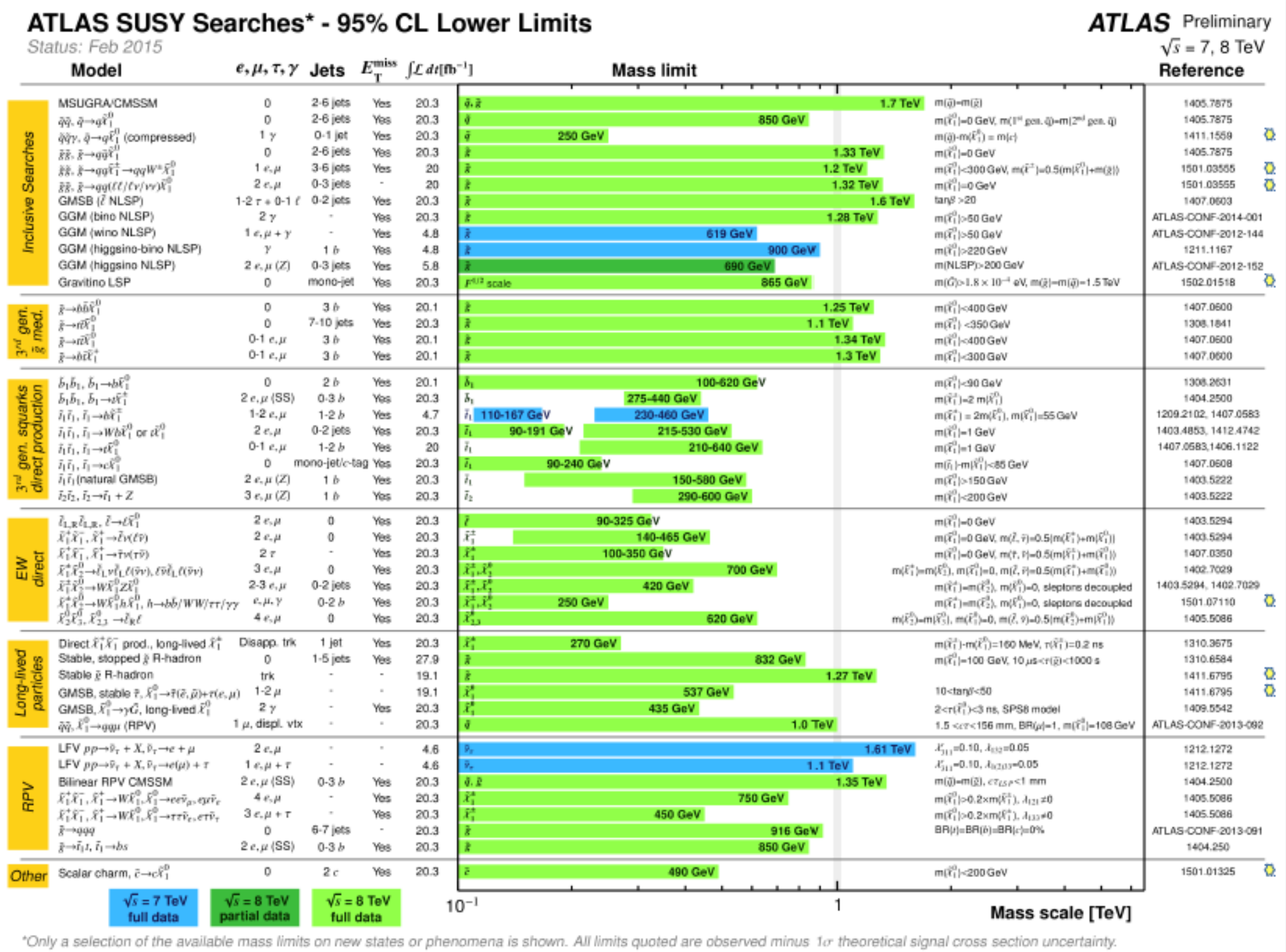
$$m_H = 125.09 \pm 0.24 \text{ GeV}$$ **(0.19% precision!)**

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



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}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q},\tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	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,μ + γ	-	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
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	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
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	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,μ + τ	-	-	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×$m(\tilde{\chi}^\pm_1)$, $\lambda_{121}\neq0$	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,μ + τ	-	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
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	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

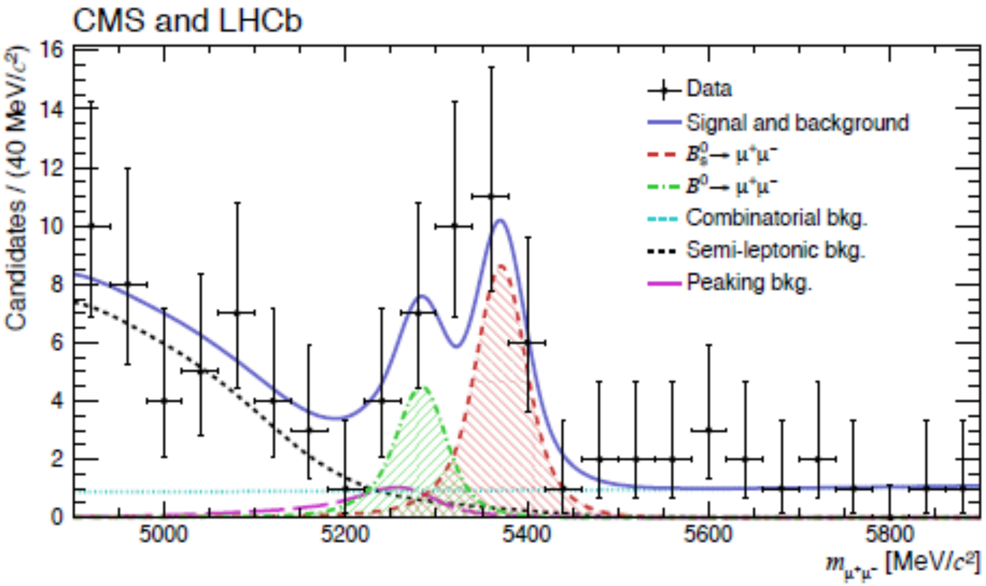
Result demonstrates power of combing data from >1 experiment (an LHC first!)
It was presented at CKM conference in Vienna, & will be submitted to Nature

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

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 many cases by experimental observations.

Main outstanding questions in today's particle physics

Higgs boson and EWSB
- ☐ m_H natural or fine-tuned ?
  → if natural: what new physics/symmetry?
- ☐ does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? Or is there a new dynamics ?
- ☐ elementary or composite Higgs ?
- ☐ is it alone or are there other Higgs bosons ?
- ☐ origin of couplings to fermions
- ☐ coupling to dark matter ?
- ☐ does it violate CP ?
- ☐ cosmological EW phase transition (is it responsible for baryogenesis ?)

Neutrinos:
- ☐ ν masses and and their origin
- ☐ what is the role of H(125) ?
- ☐ Majorana or Dirac ?
- ☐ CP violation
- ☐ additional species → sterile ν ?

Dark matter:
- ☐ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ☐ one type or more ?
- ☐ only gravitational or other interactions ?

The two epochs of Universe's accelerated expansion:
- ☐ primordial: is inflation correct ? which (scalar) fields? role of quantum gravity?
- ☐ today: dark energy (why is Λ so small?) or gravity modification ?

Quarks and leptons:
- ☐ why 3 families ?
- ☐ masses and mixing
- ☐ CP violation in the lepton sector
- ☐ matter and antimatter asymmetry
- ☐ baryon and charged lepton number violation

Physics at the highest E-scales:
- ☐ how is gravity connected with the other forces ?
- ☐ do forces unify at high energy ?

At what E scale(s) are the answers ?

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)
- 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 (USA)

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.

European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

***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. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

Table 1
Summary of Scenarios

Project/Activity	Scenarios			Science Drivers					Technique (Frontier)
	Scenario A	Scenario B	Senario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B.	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

TABLE 1 Summary of Scenarios A, B, and C. Each major project considered by P5 is shown, grouped by project size and listed in time order based on year of peak construction. Project sizes are: Large (>$200M), Medium ($50M-$200M), and Small (<$50M). The science Drivers primarily addressed by each project are also indicated, along with the Frontier technique area (E=Energy, I=Intensity, C=Cosmic) defined in the 2008 P5 report.

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 ?**

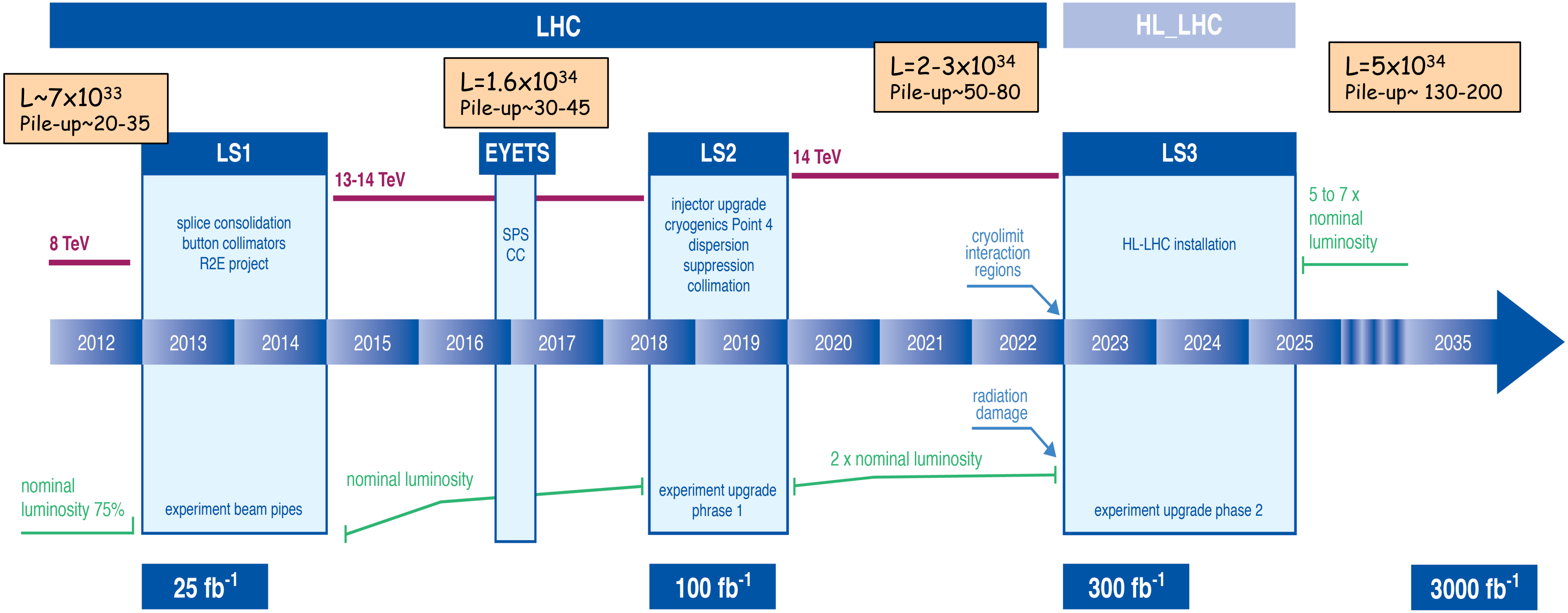
We should be prepared to exploit both scenarios, through:

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

The LHC timeline

L.Rossi

New LHC / HL-LHC Plan



Extending the reach…

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

14 TeV vs 8 TeV – Gain Factors

Use parton luminosities to illustrate the gain of 14 vs 8 TeV

Higgs:

pp → H, H→WW, ZZ and γγ

mainly gg: Factor ~2

SUSY – 3rd Generation:

Mass scale ~ 500 GeV

qq and gg: Factor ~ 8

SUSY – Squarks/Gluino:

Mass scale ~ 2.0 TeV

qq,gg,qg: Factor ~300

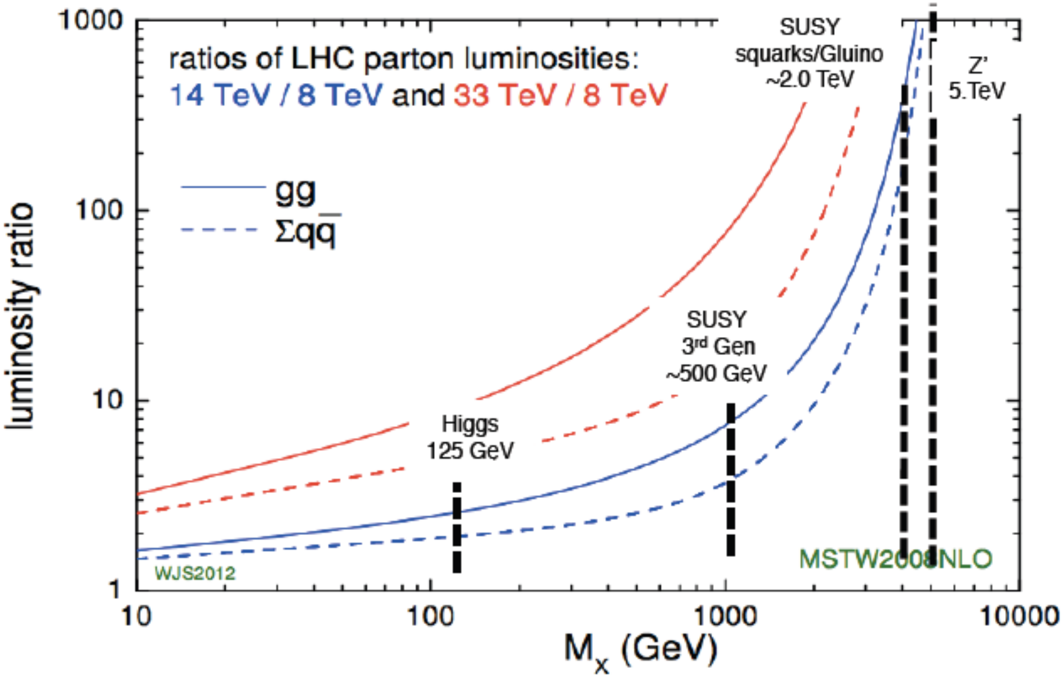
Z' :

Mass scale ~ 5 TeV

qq: Factor ~1000

O. Buchmuller

J. Stirling



For the searches increase in energy will help a lot!

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

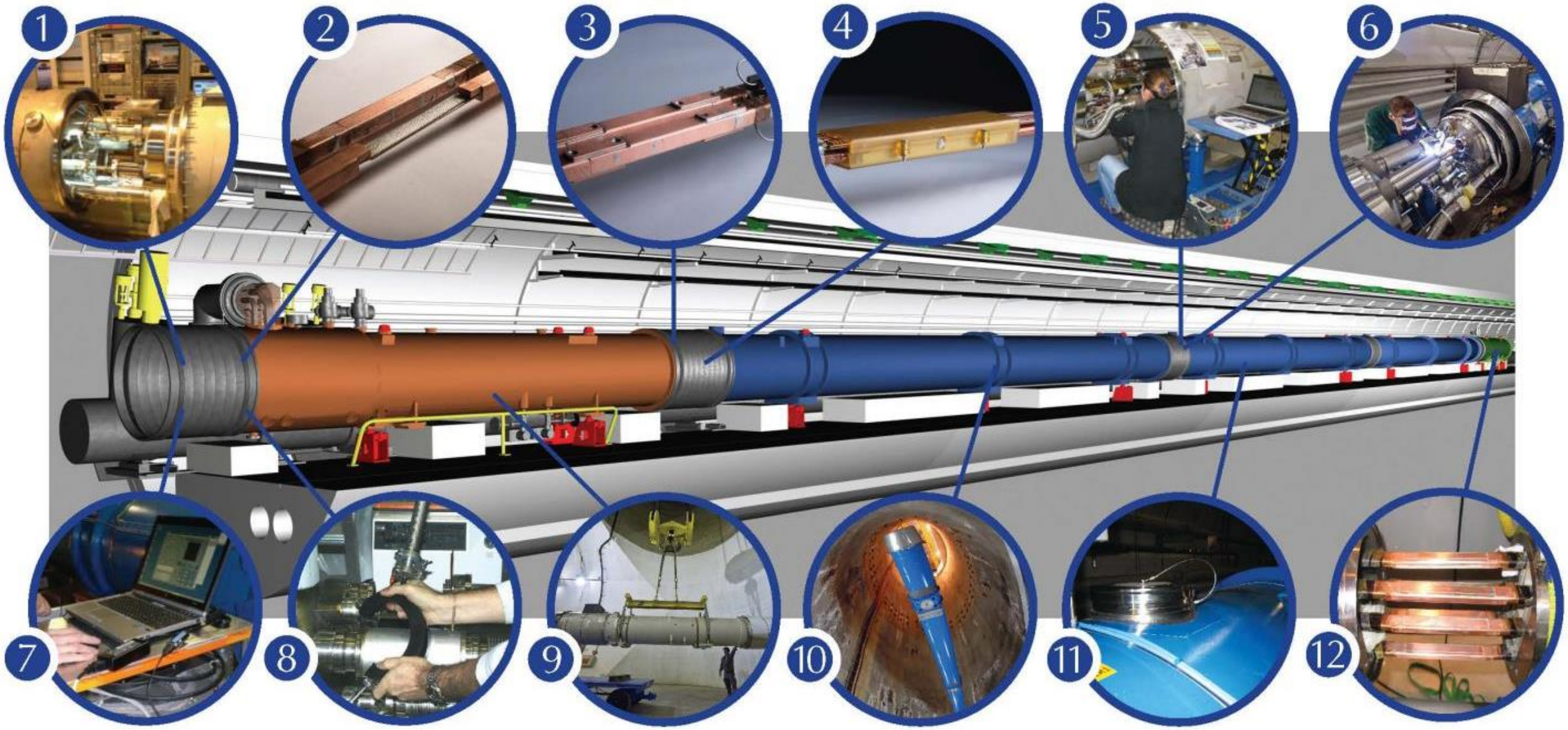
Complete reconstruction of 1500 of these splices

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

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

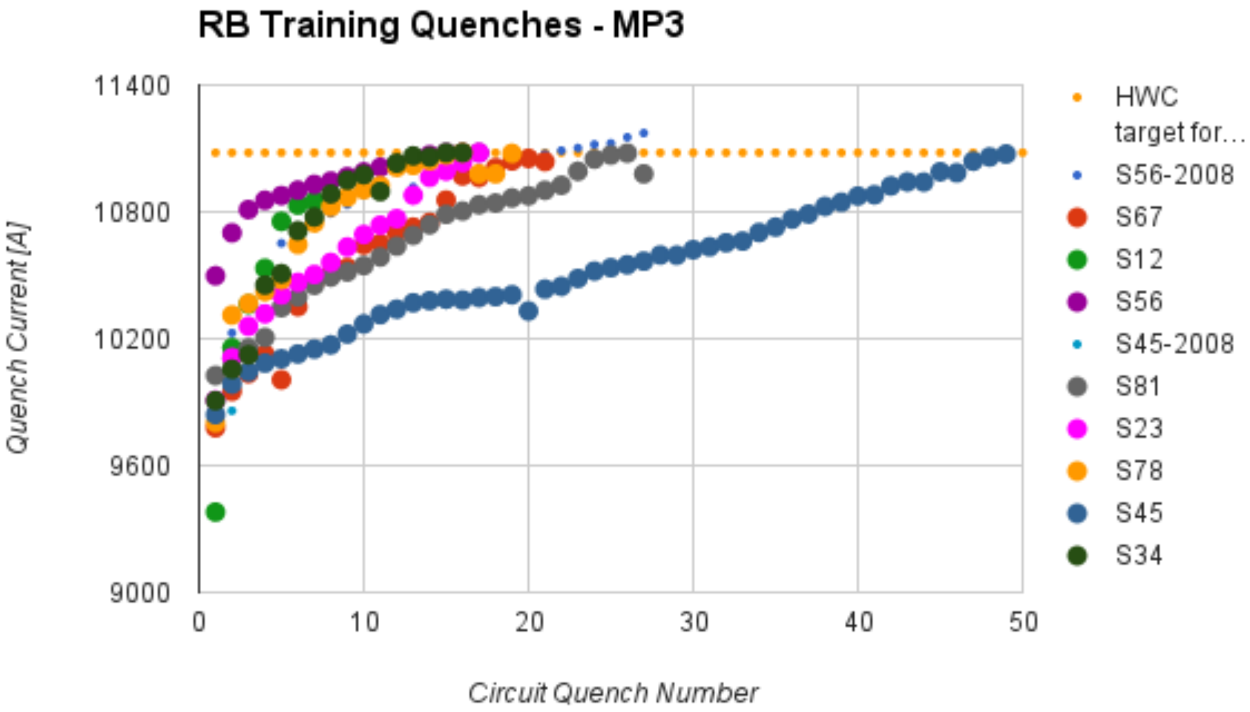
3 quadrupole magnets to be replaced

15 dipole magnets to be replaced

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

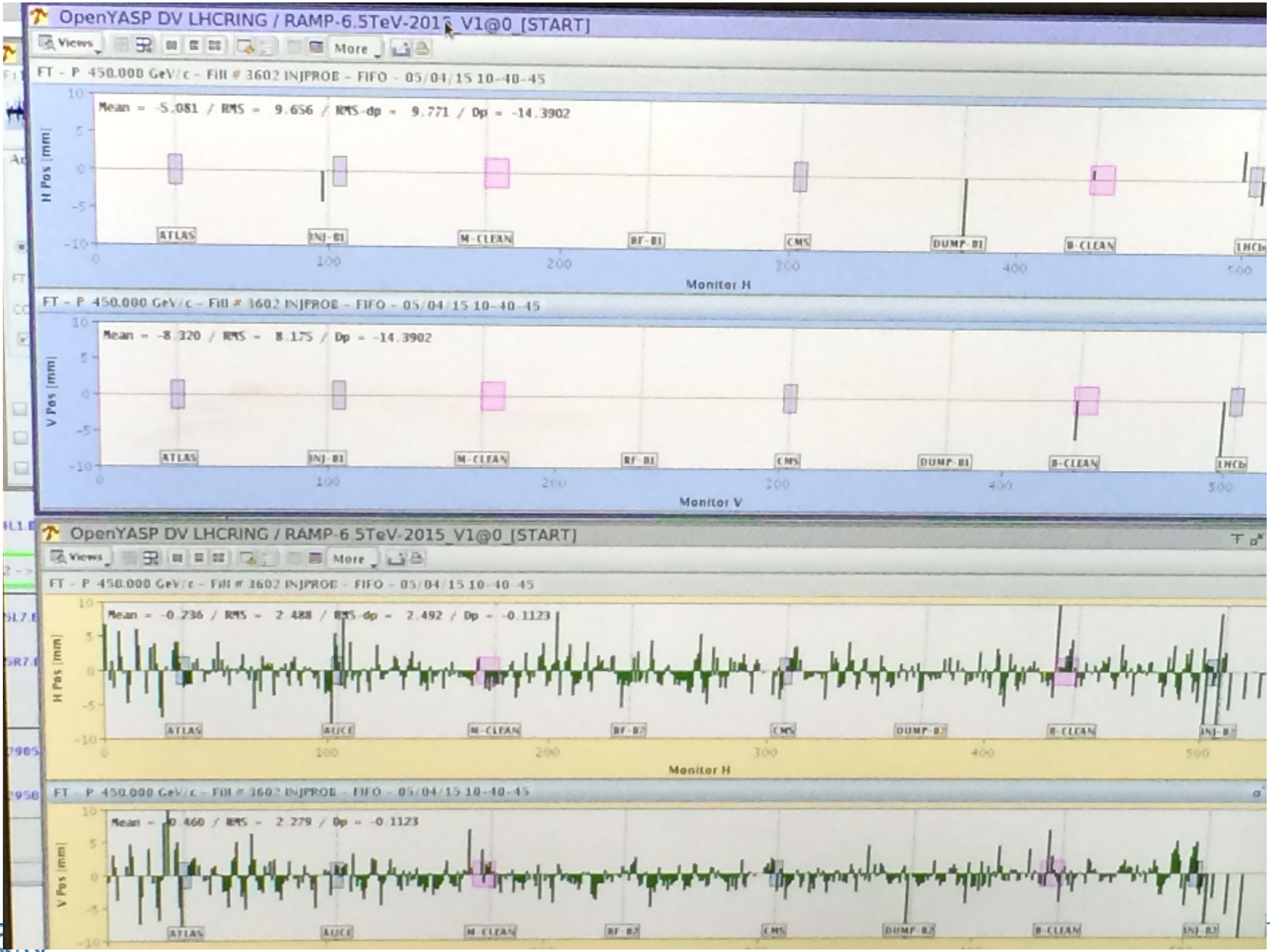
Consolidation of the 13 kA circuits in the 16 main electrical feedboxes

Training quenches



All sectors fully qualified at 6.5 TeV

Easter 2015: beams are back!


OpenYASP DV LHCRING / RAMP-6.5TeV-2015_V1@0 [START]

FT - P 450.000 GeV/c - Fill # 3602 INJPROB - FIFO - 05/04/15 10-40-45

Mean = -5.081 / RMS = 9.656 / RMS-dp = 9.771 / Dp = -14.3902

FT - P 450.000 GeV/c - Fill # 3602 INJPROB - FIFO - 05/04/15 10-40-45

Mean = -8.320 / RMS = 8.175 / Dp = -14.3902

OpenYASP DV LHCRING / RAMP-6.5TeV-2015_V1@0 [START]

FT - P 450.000 GeV/c - Fill # 3602 INJPROB - FIFO - 05/04/15 10-40-45

Mean = -0.236 / RMS = 2.488 / RMS-dp = 2.492 / Dp = -0.1123

FT - P 450.000 GeV/c - Fill # 3602 INJPROB - FIFO - 05/04/15 10-40-45

Mean = 0.460 / RMS = 2.279 / Dp = -0.1123

…and at 6.5 TeV

LHC FILL NUMBER: 3657 FLAT TOP

BEAM SETUP

Inj. scheme: 30 bunches for MUFO spaced

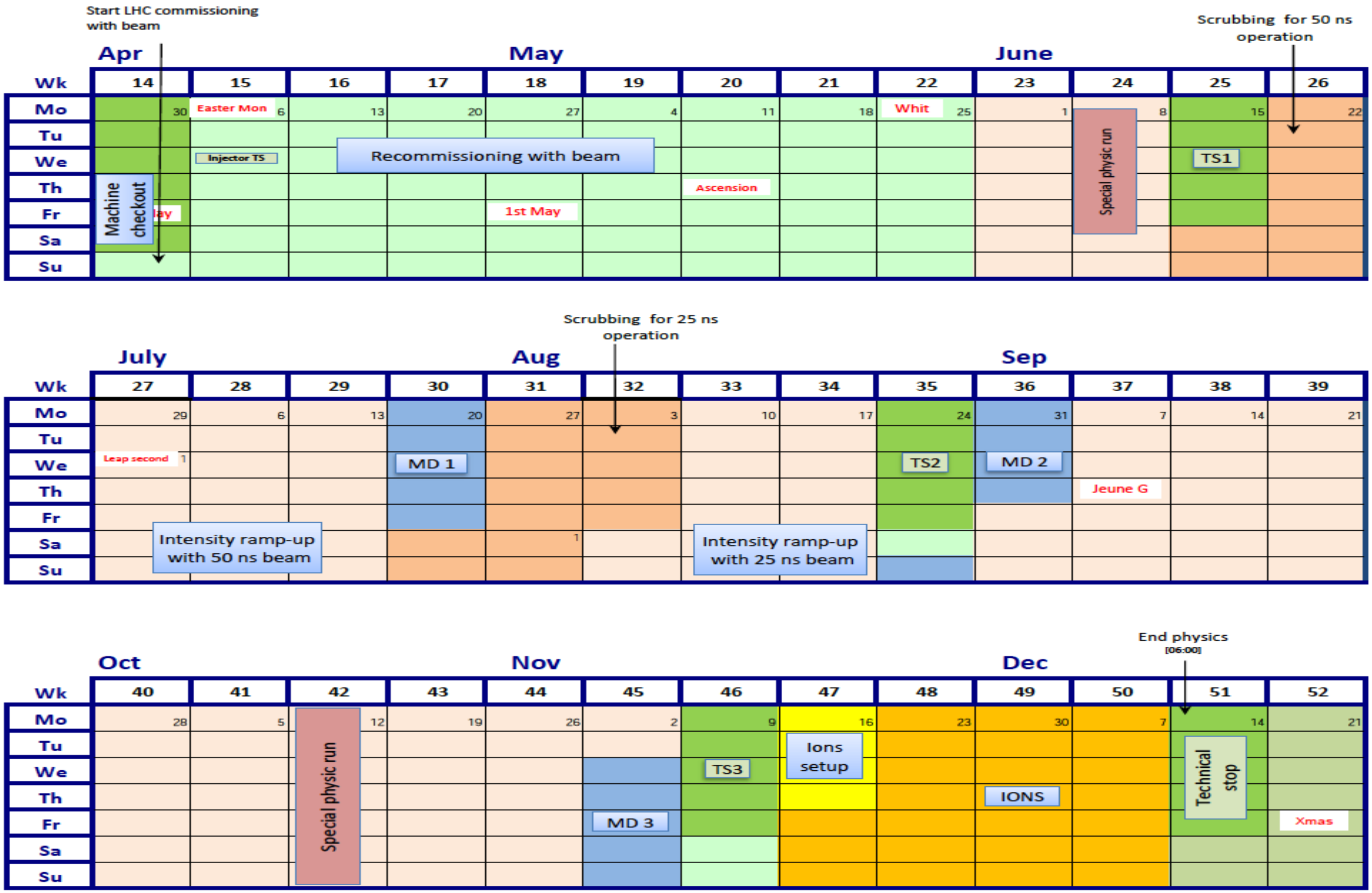
Beam	Intensity	Stored E	Particle	Bunches	Beam Energy
1	8.80E+9	9.16 kJ	Proton	1	6.50 TeV
2	1.03E+10	10.7	Proton	1	

27-04-2015
05:31:51

2015-04-27 03:20:56 ULO monitoring....

	ATLAS	ALICE	CMS	LHCb
	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous	0.0	0.0	0.0	0.0
Integrated fill	0.0	0.0	0.0	0.0
Integrated/h	0.0	0.0	0.0	0.0
beta * [m]	0.0	0.0	0.0	0.0

LHC Schedule 2015



Start LHC commissioning with beam

Scrubbing for 50 ns operation

	Apr				May					June			
Wk	14	15	16	17	18	19	20	21	22	23	24	25	26
Mo	30	Easter Mon 6	13	20	27	4	11	18	Whit 25	1	Special physic run 8	15	22
Tu													
We		Injector TS	Recommissioning with beam									TS1	
Th	Machine checkout						Ascension						
Fr	lay				1st May								
Sa													
Su													

Scrubbing for 25 ns operation

	July				Aug					Sep			
Wk	27	28	29	30	31	32	33	34	35	36	37	38	39
Mo	29	6	13	20	27	3	10	17	24	31	7	14	21
Tu													
We	Leap second 1			MD 1					TS2	MD 2			
Th											Jeune G		
Fr		Intensity ramp-up with 50 ns beam					Intensity ramp-up with 25 ns beam						
Sa					1								
Su													

End physics [06:00]

	Oct				Nov					Dec			
Wk	40	41	42	43	44	45	46	47	48	49	50	51	52
Mo	28	5	Special physical run 12	19	26	2	9	16	23	30	7	14	21
Tu								Ions setup				Technical stop	
We							TS3						
Th										IONS			
Fr						MD 3							Xmas
Sa													
Su													

- 🟩 Technical Stop
- 🟦 Machine development
- 🟩 Recommissoning with beam
- 🟥 Special physics runs (indicative - schedule to be established)
- 🟧 Scrubbing (indicative - dates to be established)

Maximum beam energy : **13 TeV c.m. in 2015**

Decision to run at a **maximum** energy of 6.5 TeV per beam during the powering tests and during 2015.
(10 to 15 training quenches per sector are expected to be needed to reach that energy).

NO change of beam energy in 2015.

A decision regarding the possibility of increasing the energy will be taken later in 2015, based on the experience gained in all eight sectors at 6.5 TeV per beam during powering tests and operation with beams.

LHC goal for **2015 and for Run 2 and 3**

Priorities for the 2015 run :

- **Establish proton-proton collision at 13 TeV with 25ns and *low* β* to prepare production run in 2016.**
  Optimisation of physics-to-physics duration
- **Later in 2015: decision on special runs "when and duration" (90m optics): not in the 1st part of the year. Waiting LHCC recommendation**
- **Pb-Pb run: one month at the end of 2015**

The goal for Run 2 luminosity is 1.3 x 10^{34} cm^{-2} s^{-1} and operation with 25 ns bunch spacing (2800 bunches), giving an estimated pile-up of 40 events per bunch crossing.

"A maximum pileup of ~50 is considered to be acceptable for ATLAS and CMS"

LHC goal for **2015 and for Run 2 and 3**

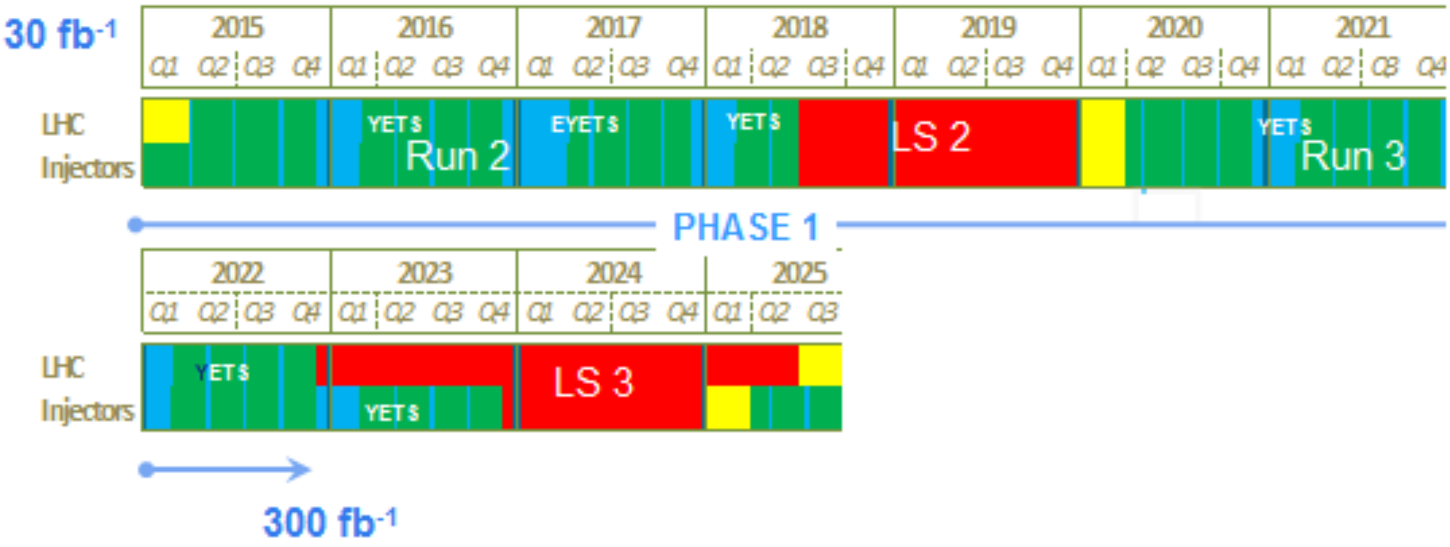
Integrated luminosity goal:

2015 : 10 fb^{-1}

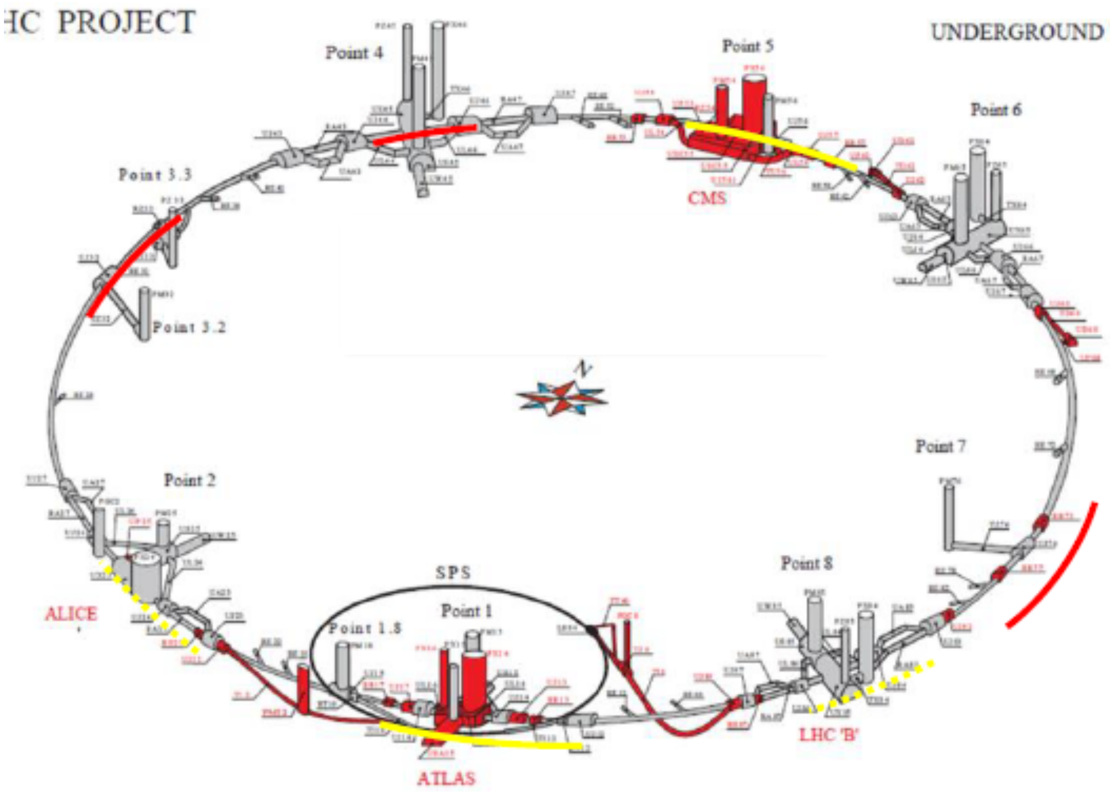
Run2: ~100-120 fb^{-1}

(better estimation by end of 2015)

300 fb^{-1} before LS3



The HL-LHC Project



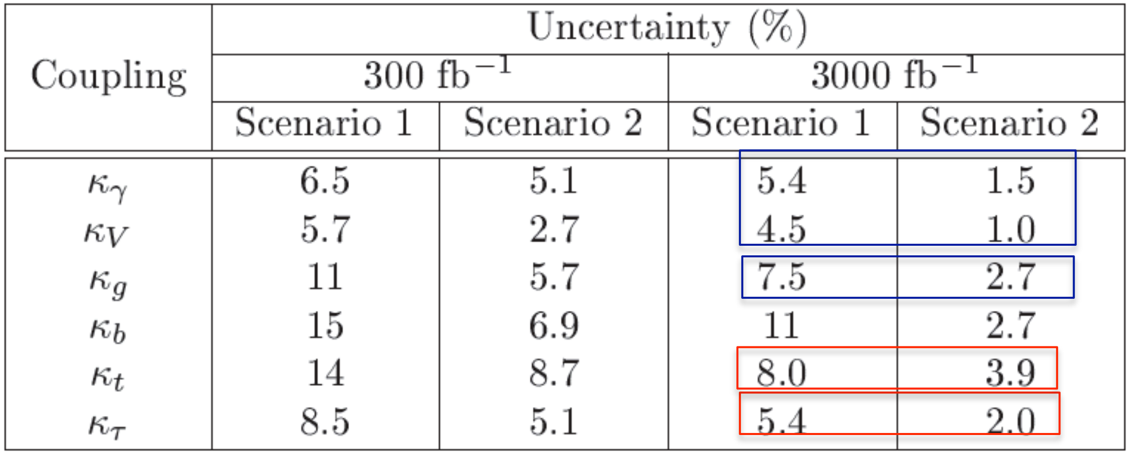
- New IR-quads Nb$_3$Sn (inner triplets)
- New 11 T Nb$_3$Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

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

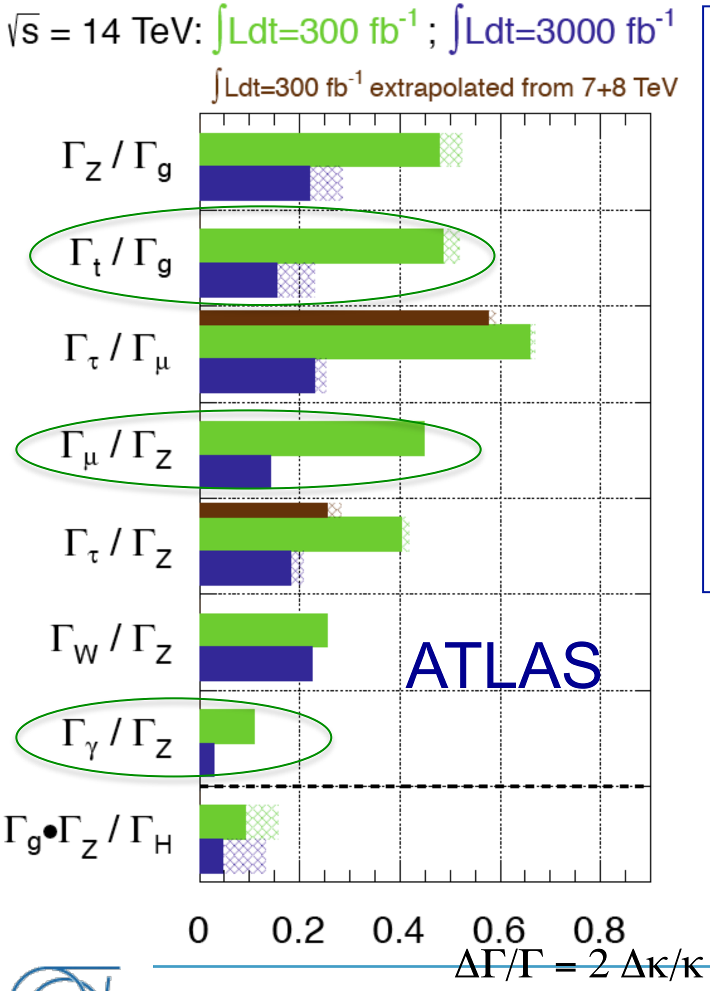
✓ γγ loop at 2-5% level

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

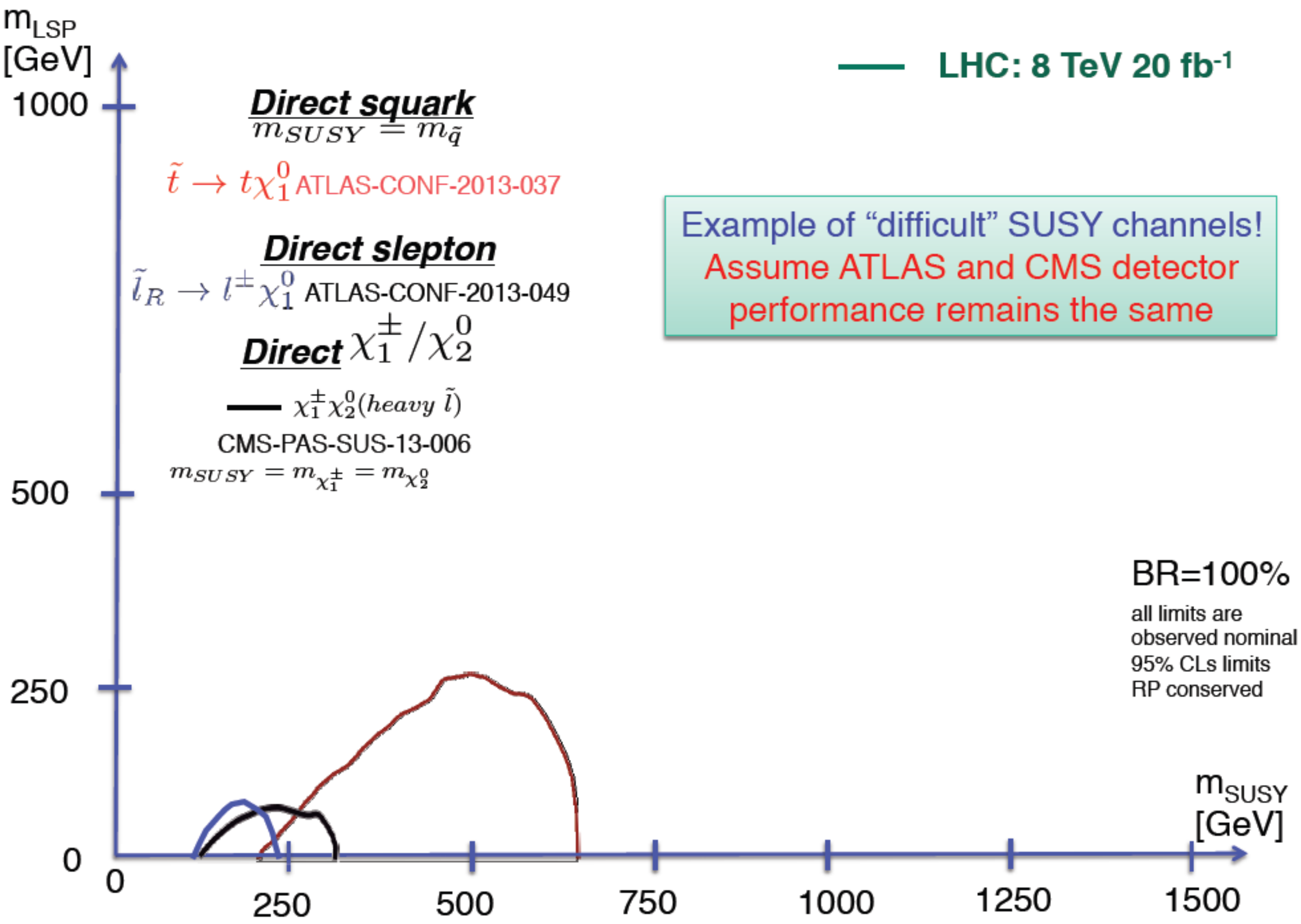
✓ direct top coupling at 4-8% level

✓ gg loop at 3-8% level

Coupling Ratios Fit at HL-LHC



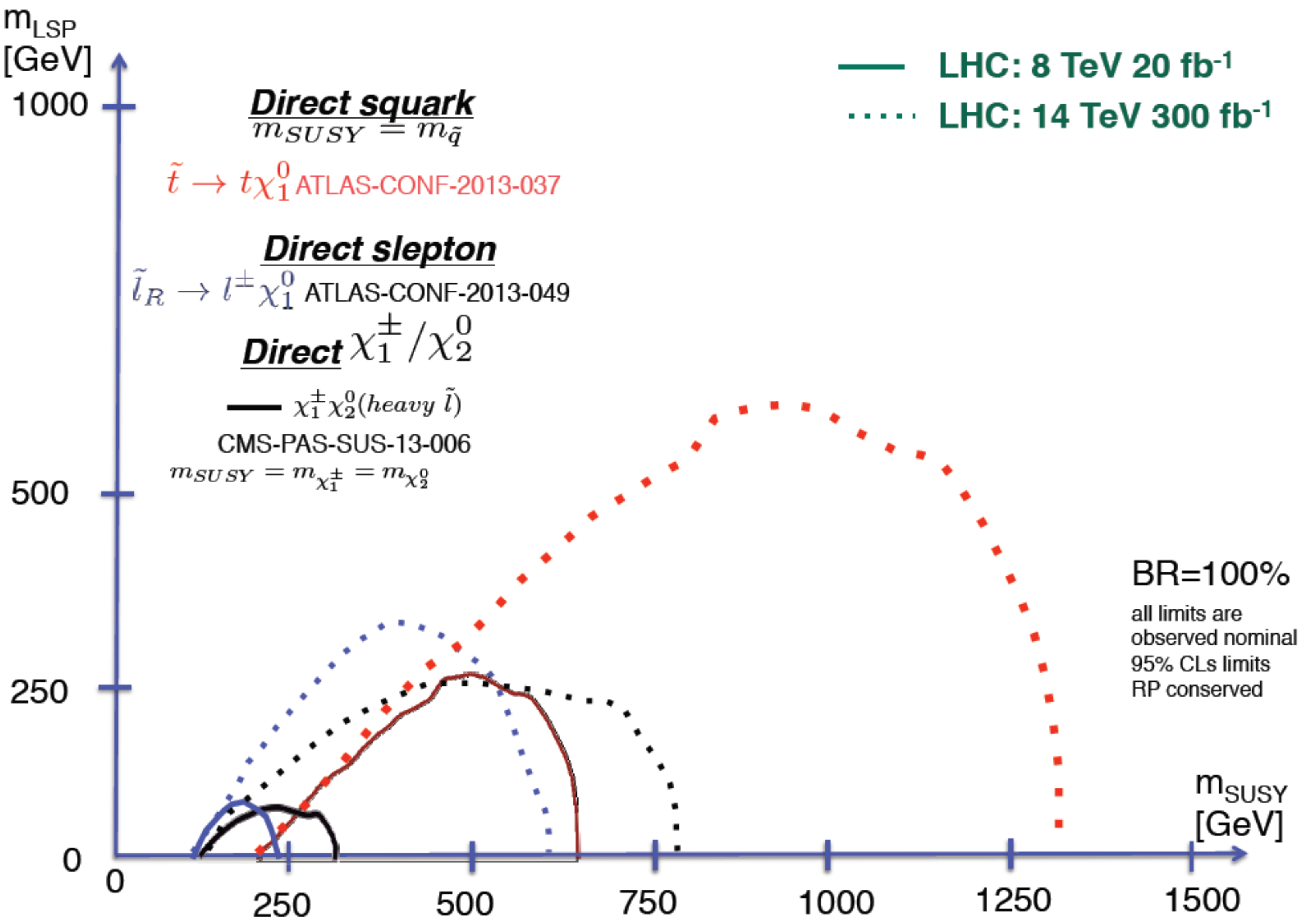
- Fit to coupling ratios:
  - No assumption BSM contributions to Γ_H
  - Some theory systematics cancels in the ratios
- Loop-induced Couplings $\gamma\gamma$ and gg treated as independent parameter
  - κ_γ/κ_Z tested at 2%
  - gg loop (BSM) κ_t/κ_g at 7-12%
  - 2nd generation ferm. κ_μ/κ_Z at 8%

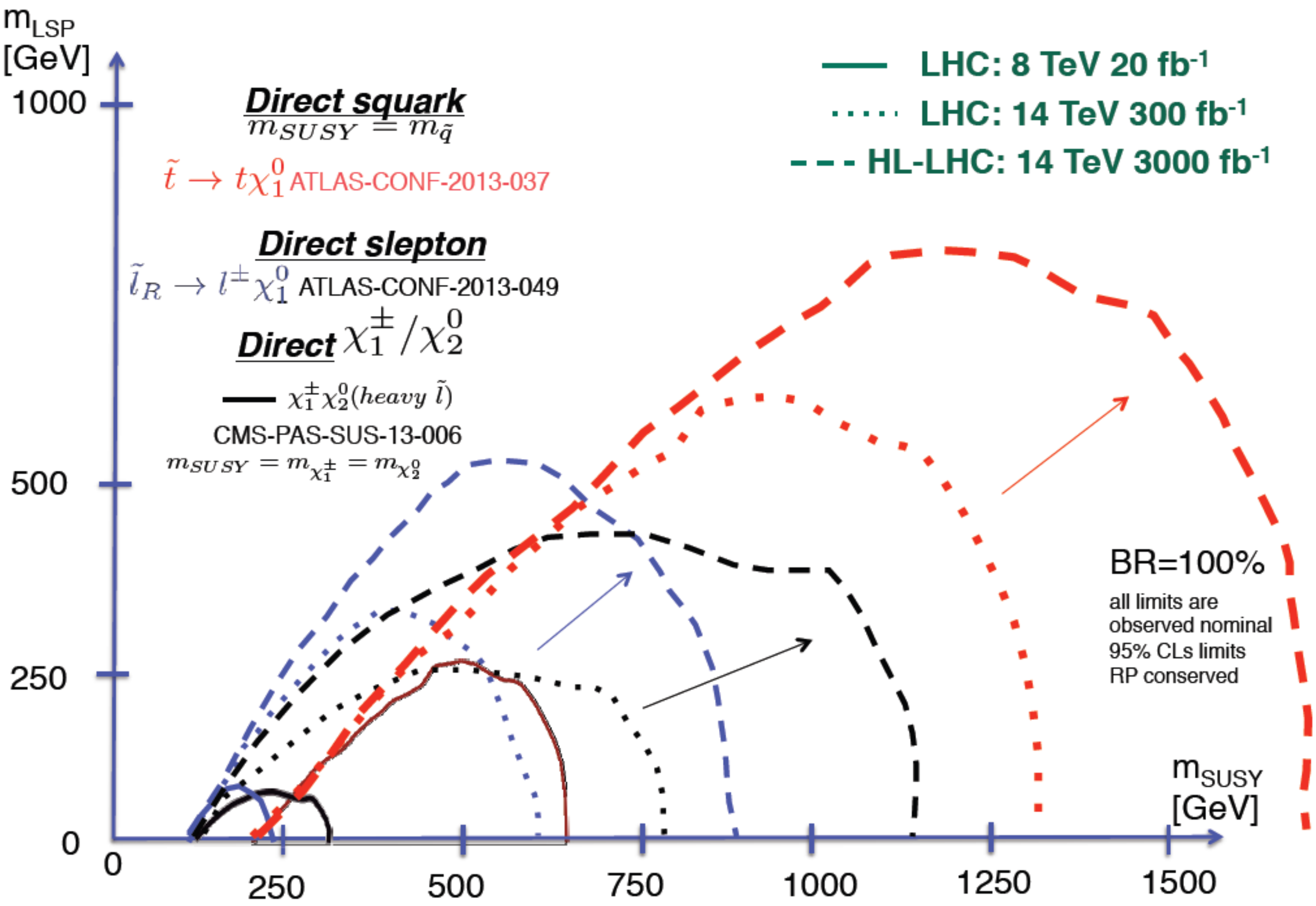


Example of "difficult" SUSY channels!
Assume ATLAS and CMS detector performance remains the same

BR=100%

all limits are
observed nominal
95% CLs limits
RP conserved

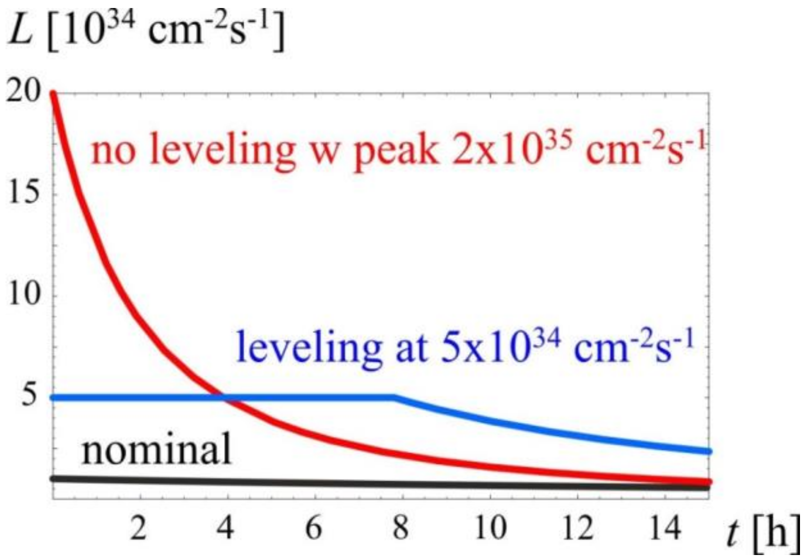

m_{LSP} [GeV]
1000
500
250
0
0
250
500
750
1000
1250
1500
m_{SUSY} [GeV]
LHC: 8 TeV 20 fb^{-1}
LHC: 14 TeV 300 fb^{-1}
Direct squark
$m_{SUSY} = m_{\tilde{q}}$
$\tilde{t} \rightarrow t\chi_1^0$ ATLAS-CONF-2013-037
Direct slepton
$\tilde{l}_R \rightarrow l^{\pm}\chi_1^0$ ATLAS-CONF-2013-049
Direct $\chi_1^{\pm}/\chi_2^0$
$\chi_1^{\pm}\chi_2^0(heavy\ \tilde{l})$
CMS-PAS-SUS-13-006
$m_{SUSY} = m_{\chi_1^{\pm}} = m_{\chi_2^0}$
BR=100%
all limits are observed nominal 95% CLs limits RP conserved



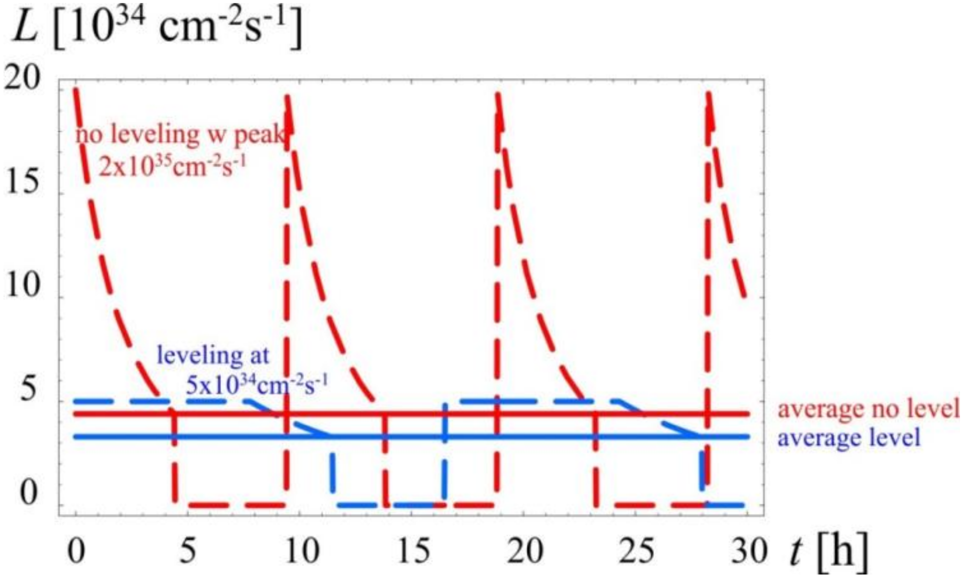
BR=100%

all limits are observed nominal 95% CLs limits RP conserved

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

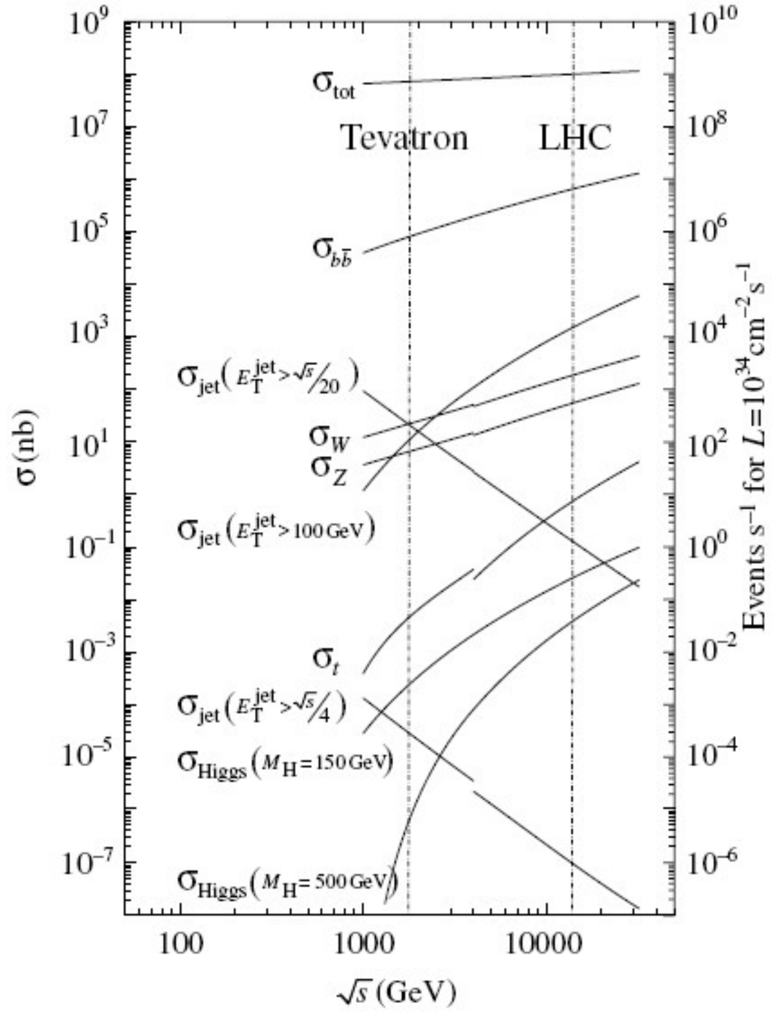
However:

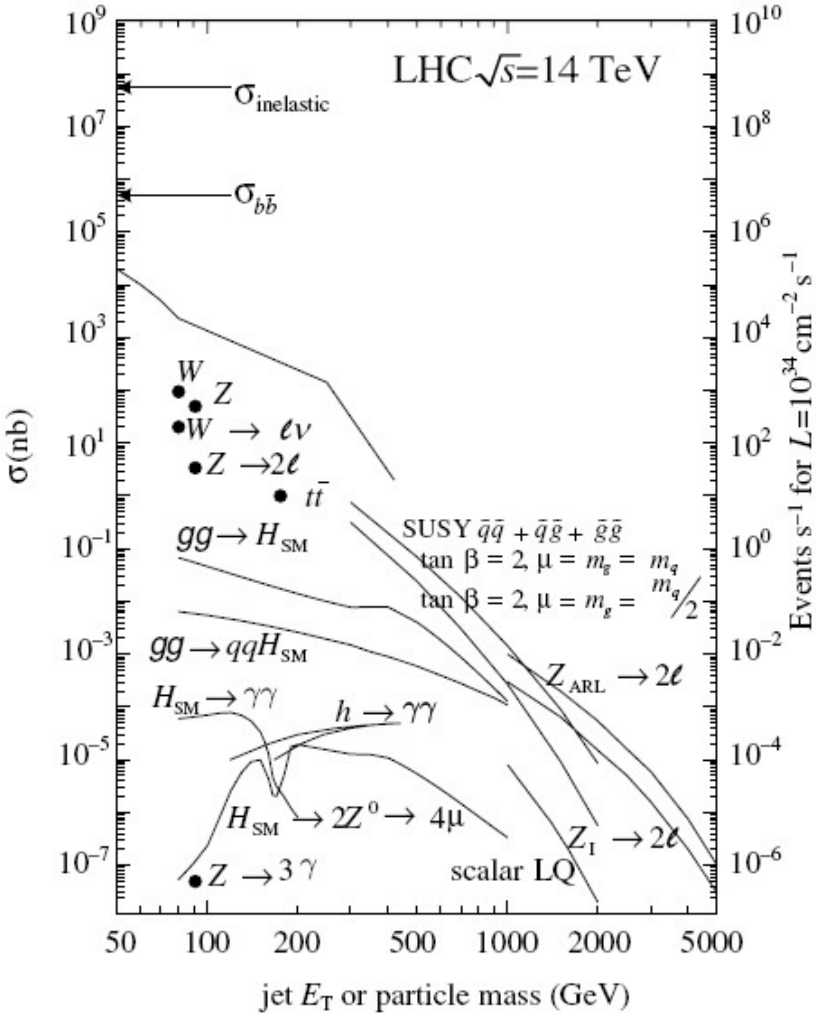
50 ns should be kept as alive and possible because we DO NOT have enough experience on the actual limit *(e-clouds, I_{beam})*

Continuous global optimisation with LIU

	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

The detectors challenge





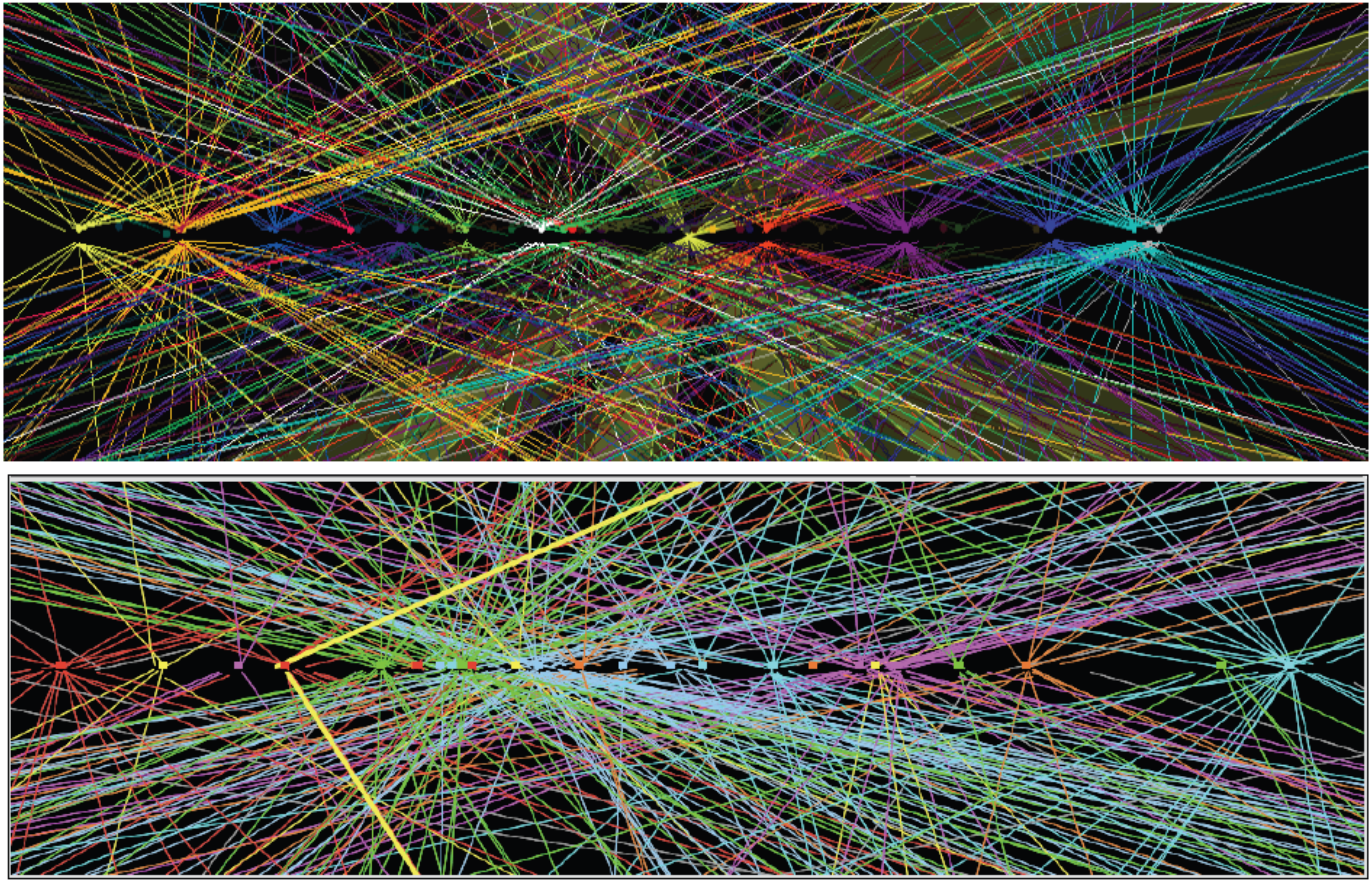
7 – 11 orders of magnitude between inelastic and "interesting" - "discovery" physics event rate

The detectors challenge

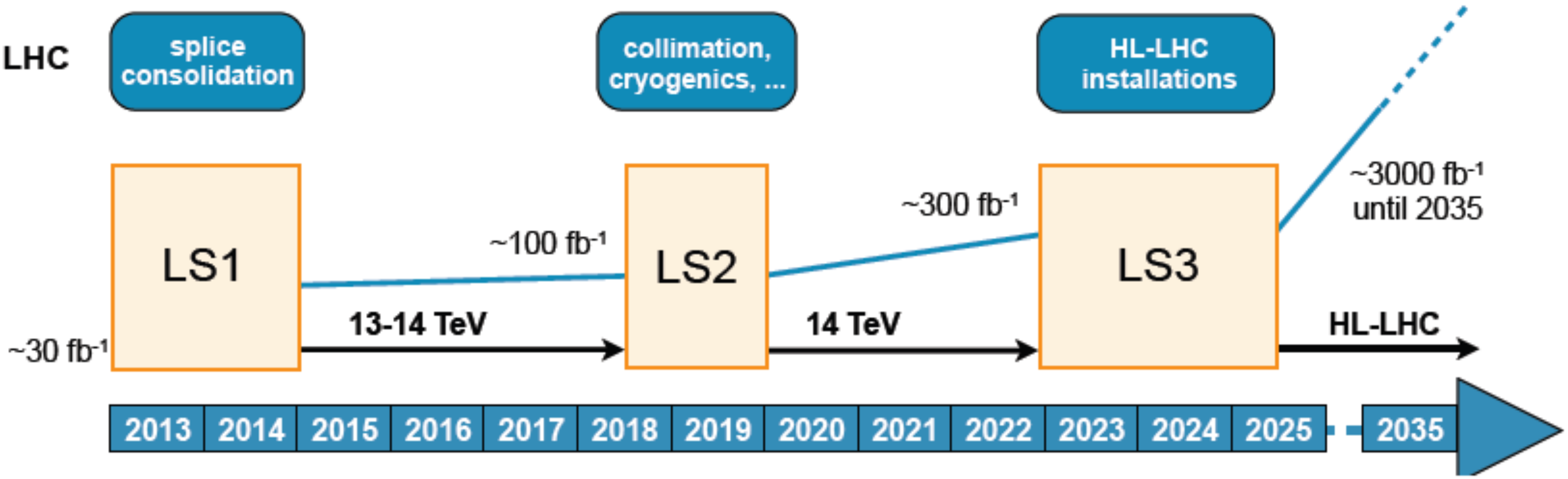
In order to exploit the LHC potential, experiments have to maintain full sensitivity for discovery, while keeping their capabilities to perform precision measurements at low p_T, in the presence of:

- 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



LHC

splice consolidation

collimation, cryogenics, ...

HL-LHC installations

LS1

LS2

LS3

~30 fb^{-1}

~100 fb^{-1}

~300 fb^{-1}

~3000 fb^{-1}
until 2035

13-14 TeV

14 TeV

HL-LHC

2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2035

ATLAS Phase-0

New inner pixel layer
Detector consolidation
2015: FTK deployment

ATLAS Phase-1

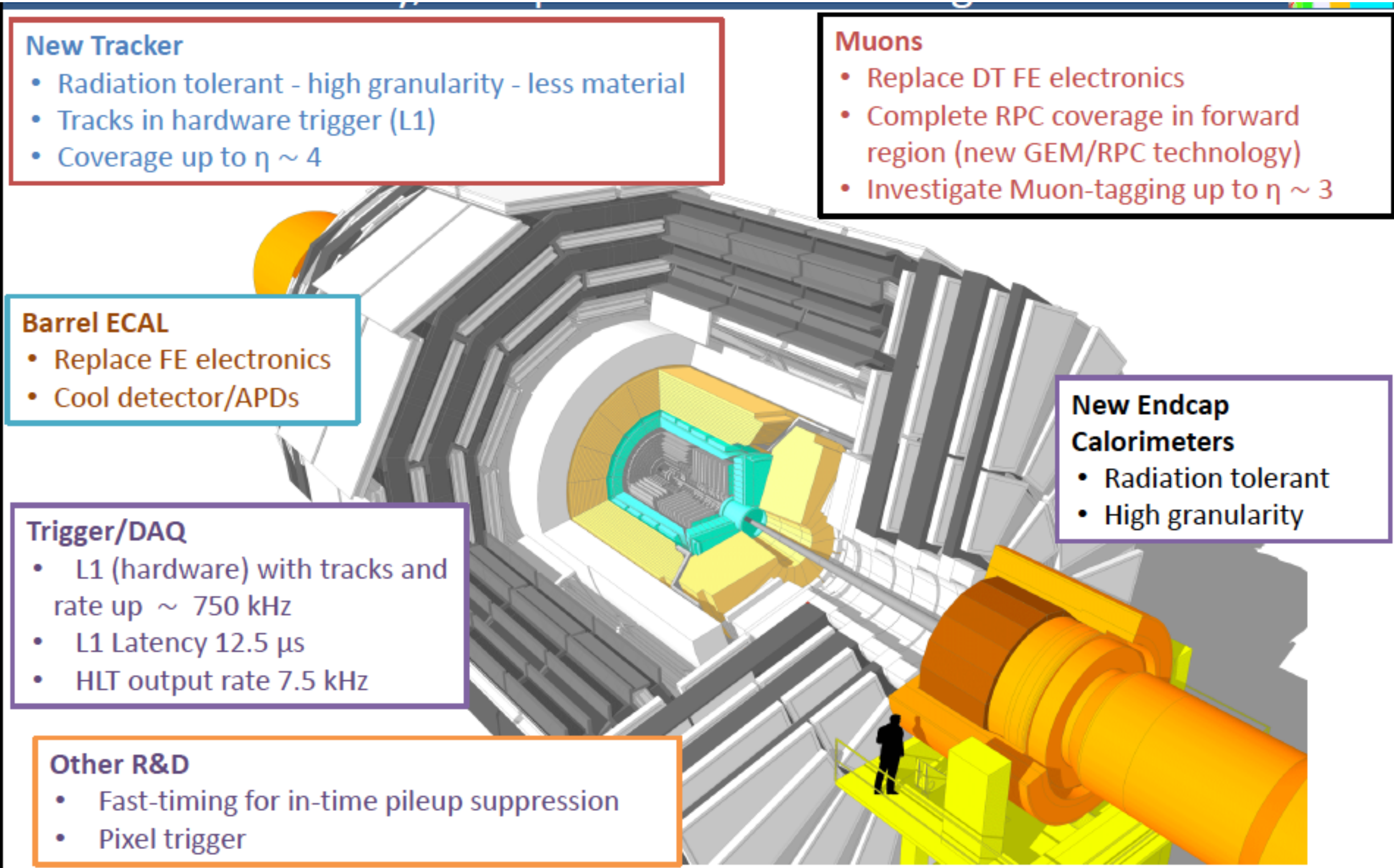
Improve L1 Trigger, NSW and LAr electronics to cope with higher rates

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

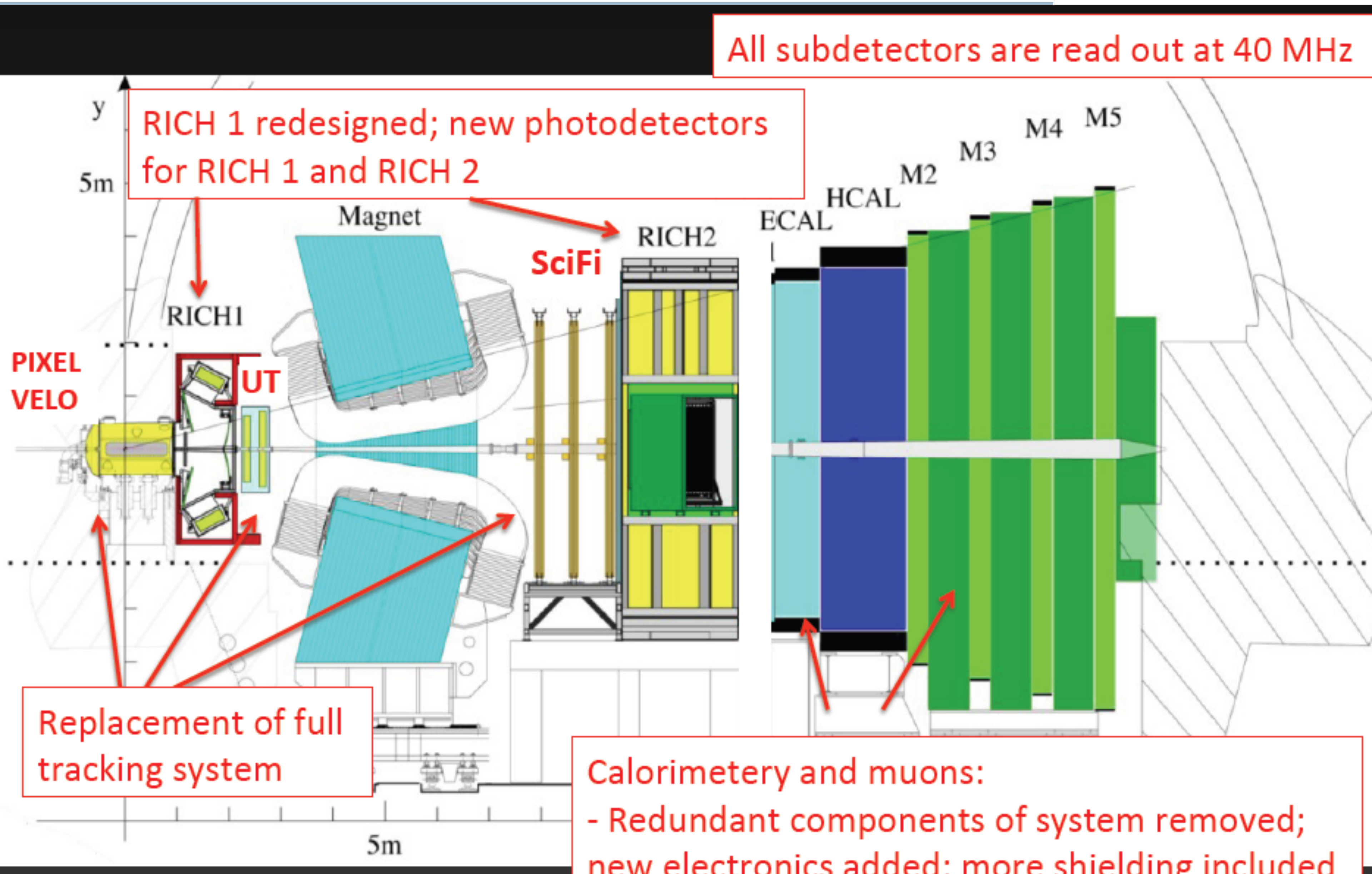
Barrel ECAL
- Replace FE electronics
- Cool detector/APDs

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



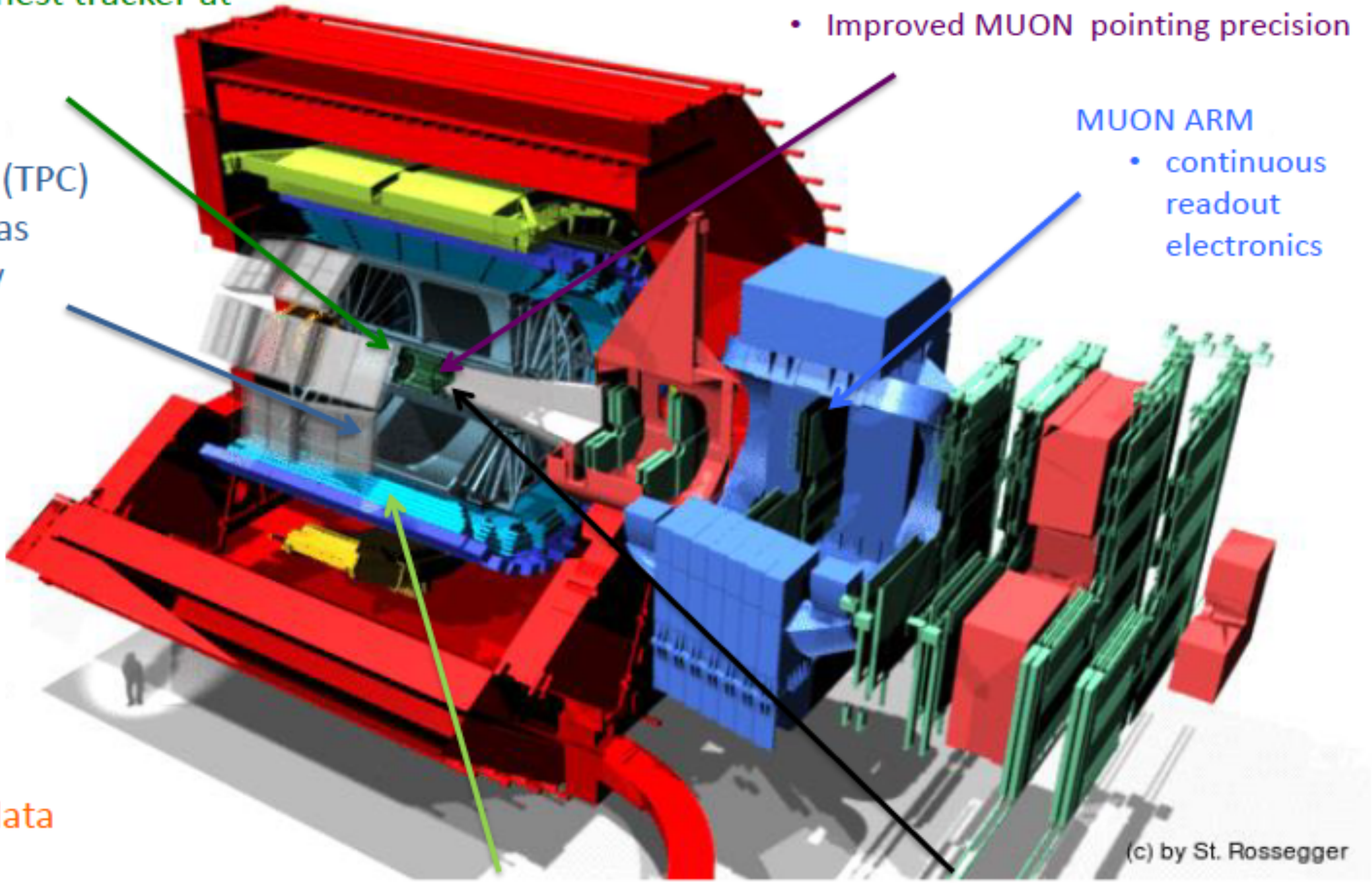
All subdetectors are read out at 40 MHz

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

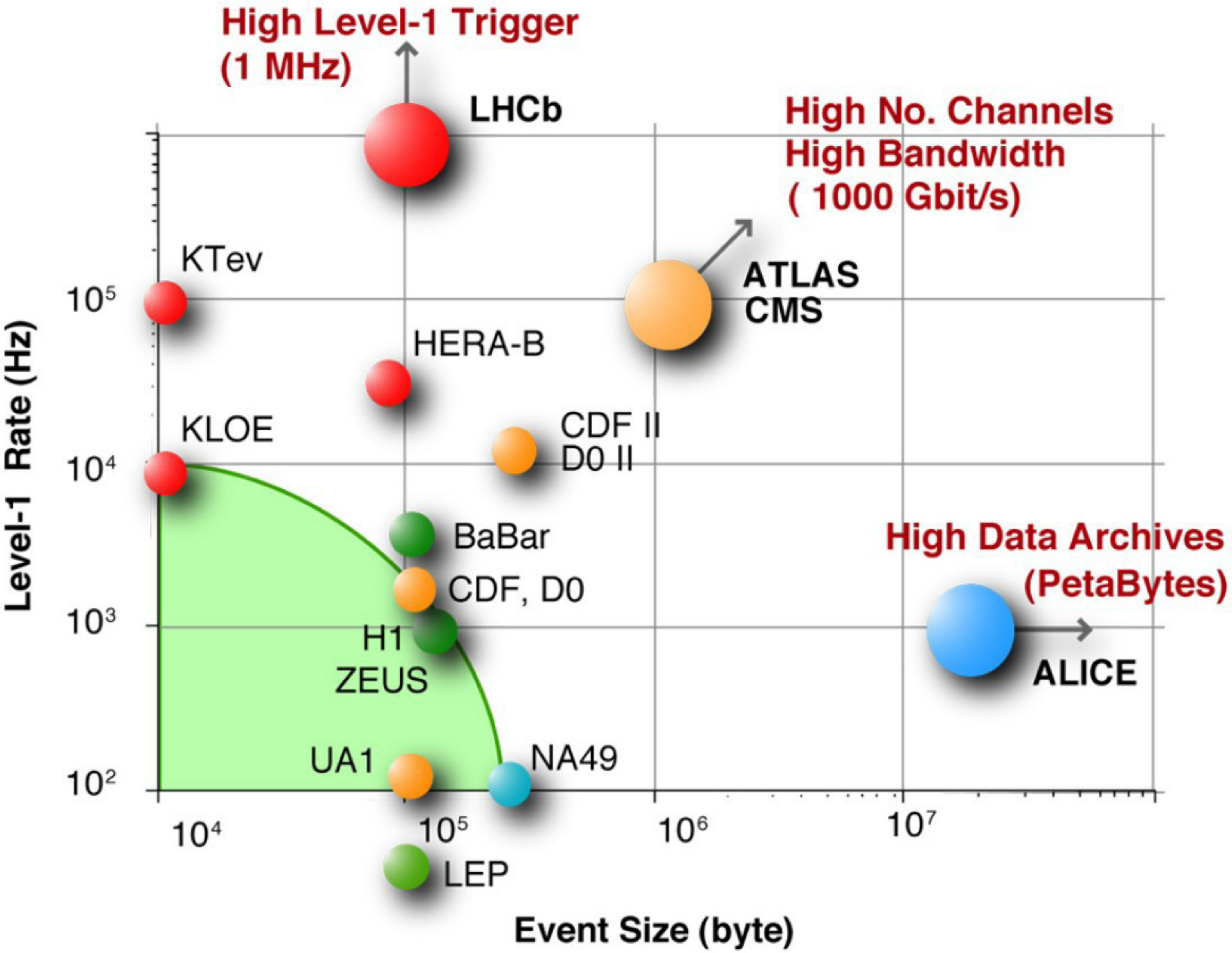
New Central Trigger Processor (CTP)

Data Acquisition (DAQ)/ High Level Trigger (HLT)
- new architecture
- on line tracking & data compression
- 50kHz Pbb event rate

TOF, TRD
- Faster readout

New Trigger Detectors (FIT)

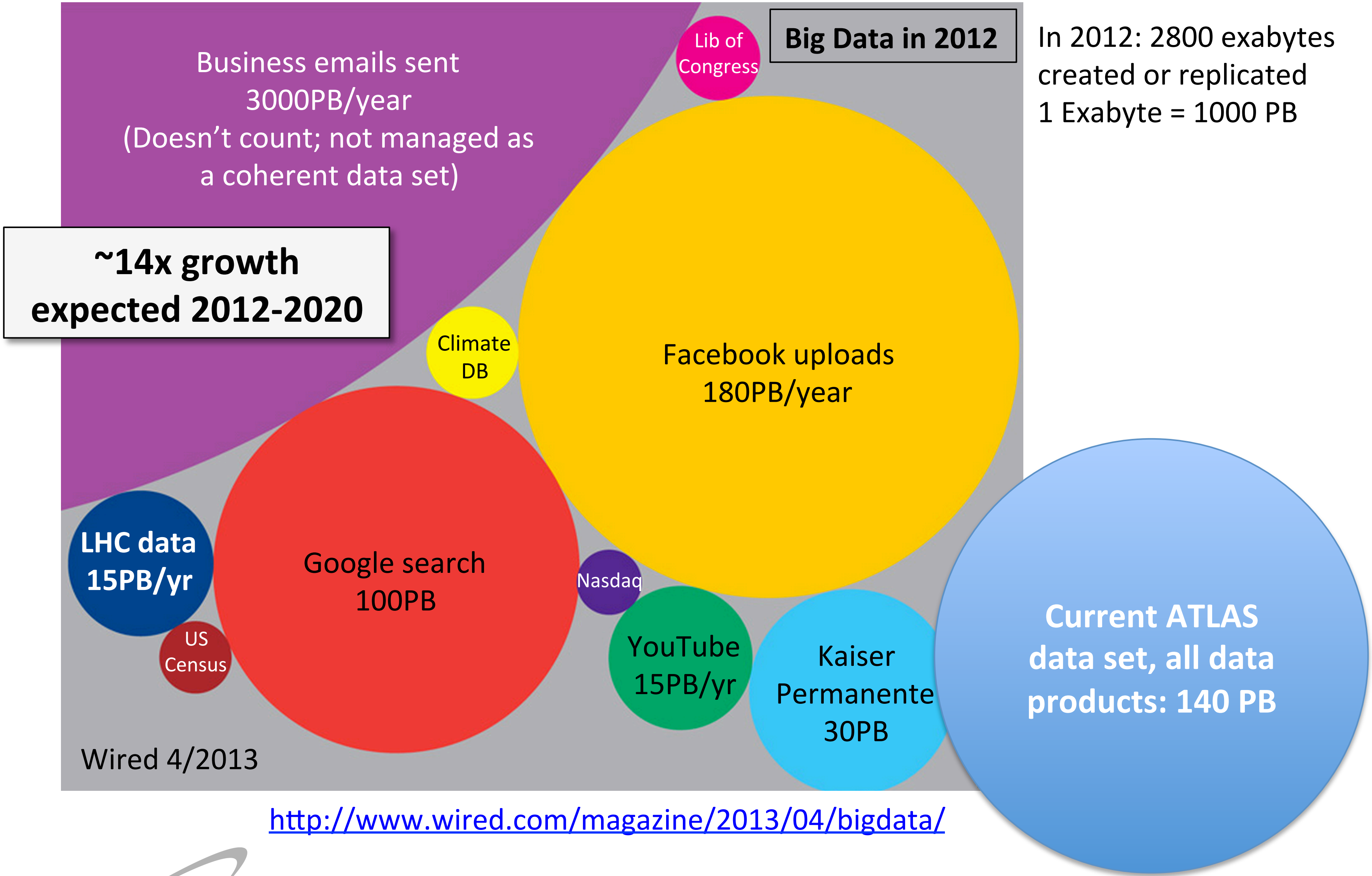
The data challenge



From: Torre Wenaus, CHEP 2013

Data Management

Where is LHC in Big Data Terms?



~14x growth expected 2012-2020

Current ATLAS data set, all data products: 140 PB

Wired 4/2013

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

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

Software

- Moore’s law only helps us if we can make use of the new multi-core CPUs with specialised accelerators etc. (Vectorisation, GPUs, …)
  - No longer benefit from simple increases in clock speed
- Ultimately this requires HEP software to be re-engineered to make use of parallelism at all levels
  - Vectors, instruction pipelining, instruction level pipelining, hardware threading, multi-core, multi-socket.
- Need to focus on commonalities:
  - GEANT, ROOT, build up common libraries
- This requires significant effort and investment in the HEP community
  - Concurrency forum already initiated
  - Ideas to strengthen this as a collaboration to provide roadmap and incorporate & credit additional effort

Ian.Bird@cern.ch

European Strategy for Particle Physics

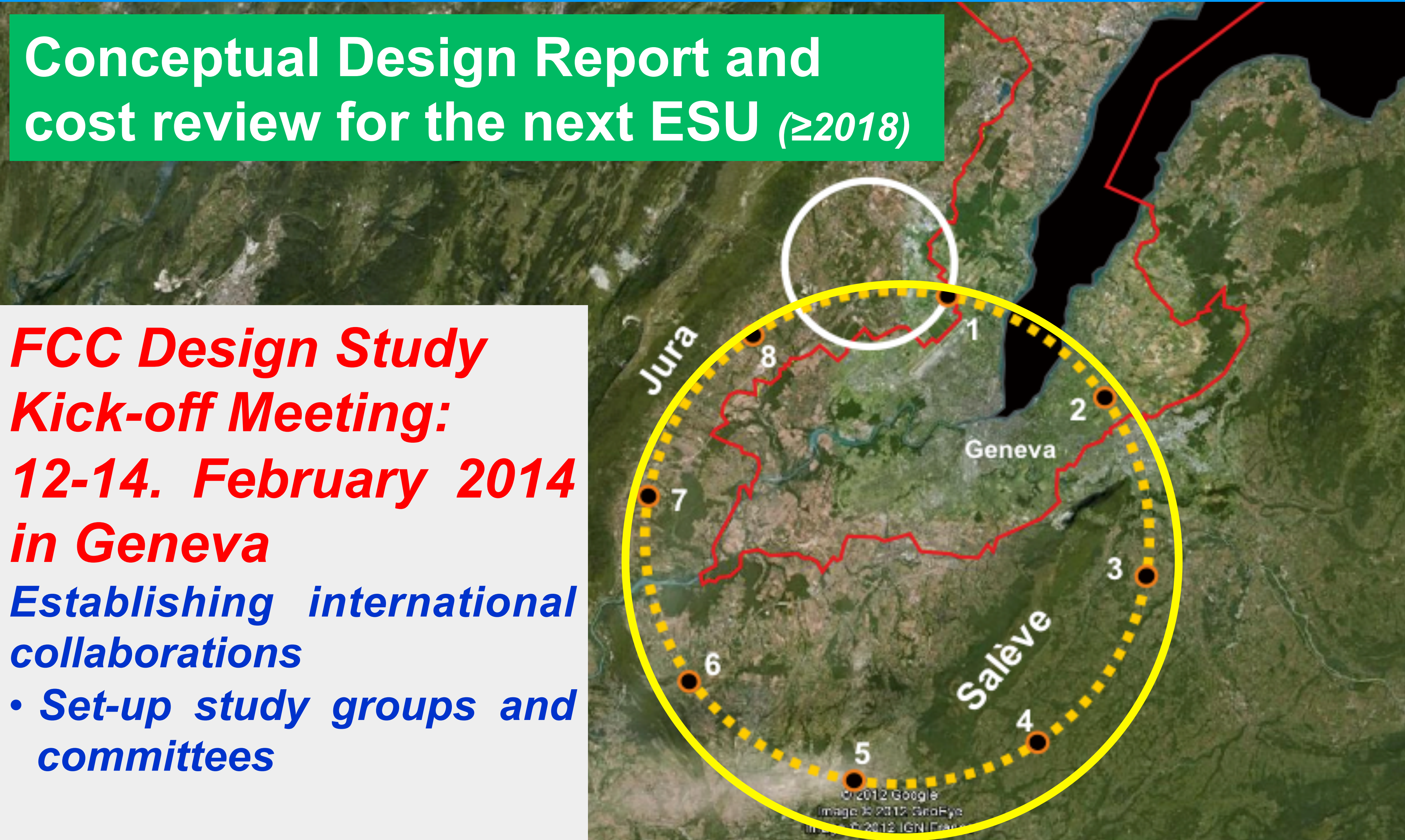
High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. ***CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.***

80-100 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

Establishing international collaborations

- ***Set-up study groups and committees***

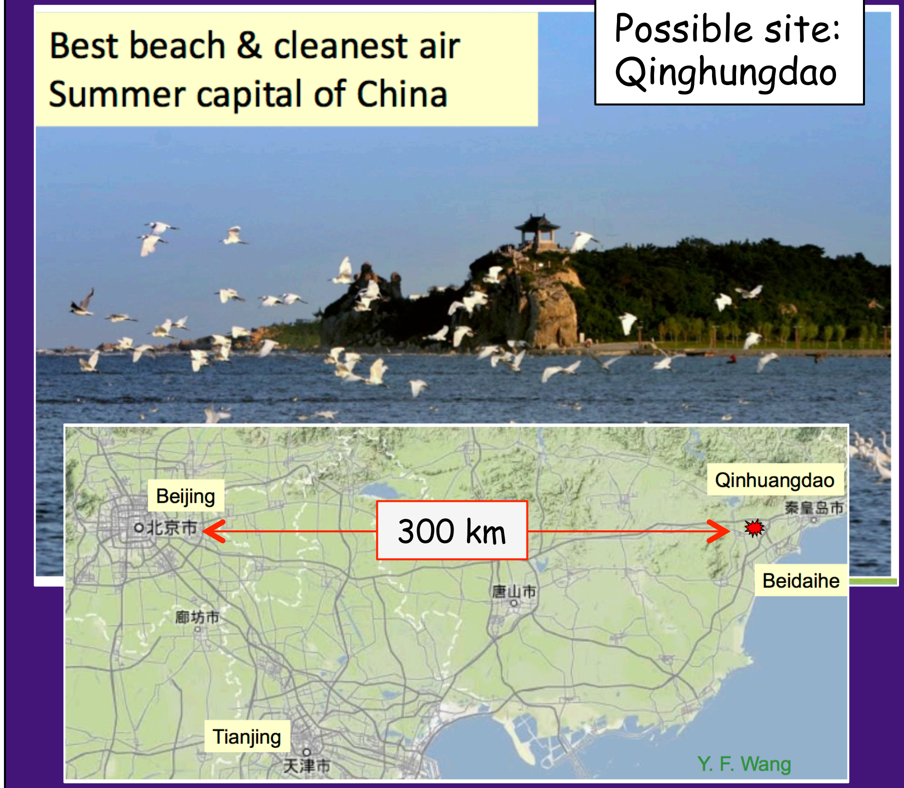
Future high-energy circular colliders

Parameters are indicative and fast evolving, as no CDR yet

China: 50-70 km e^+e^- $\sqrt{s}$=240 GeV (CepC) followed by 50-90 TeV pp collider (SppC) in same tunnel

50 km e^+e^- machine + 2 experiments:

- ☐ pre-CDR: end 2014
- ☐ construction: 2021-2027
- ☐ data-taking: 2028-2035
- ☐ cost (material): ~3 B$



Best beach & cleanest air
Summer capital of China

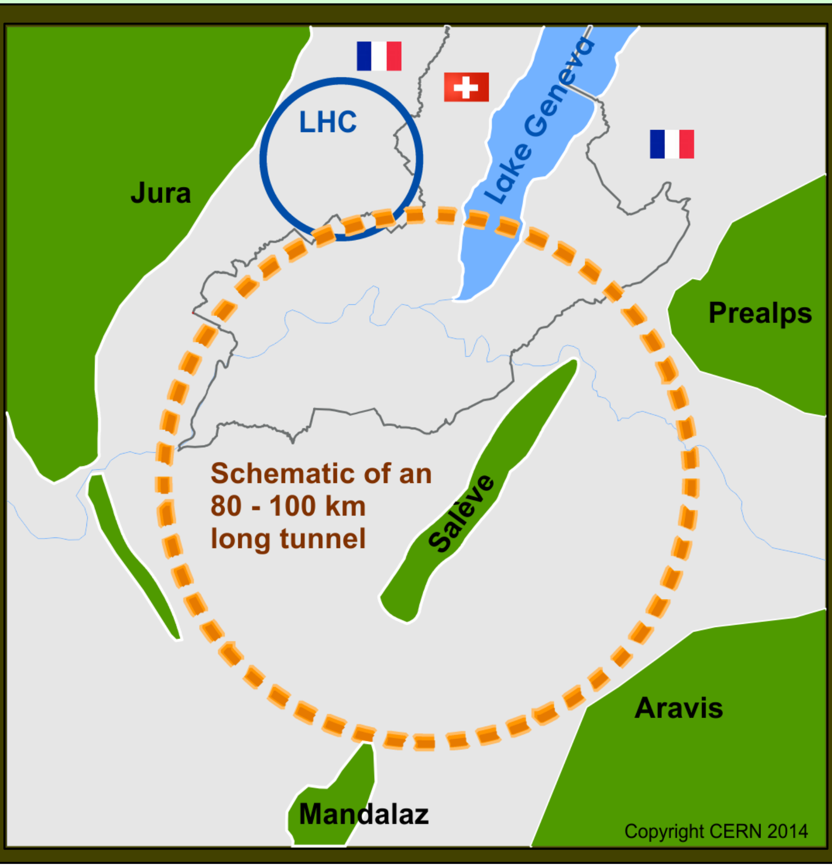
Possible site:
Qinghungdao

Y. F. Wang

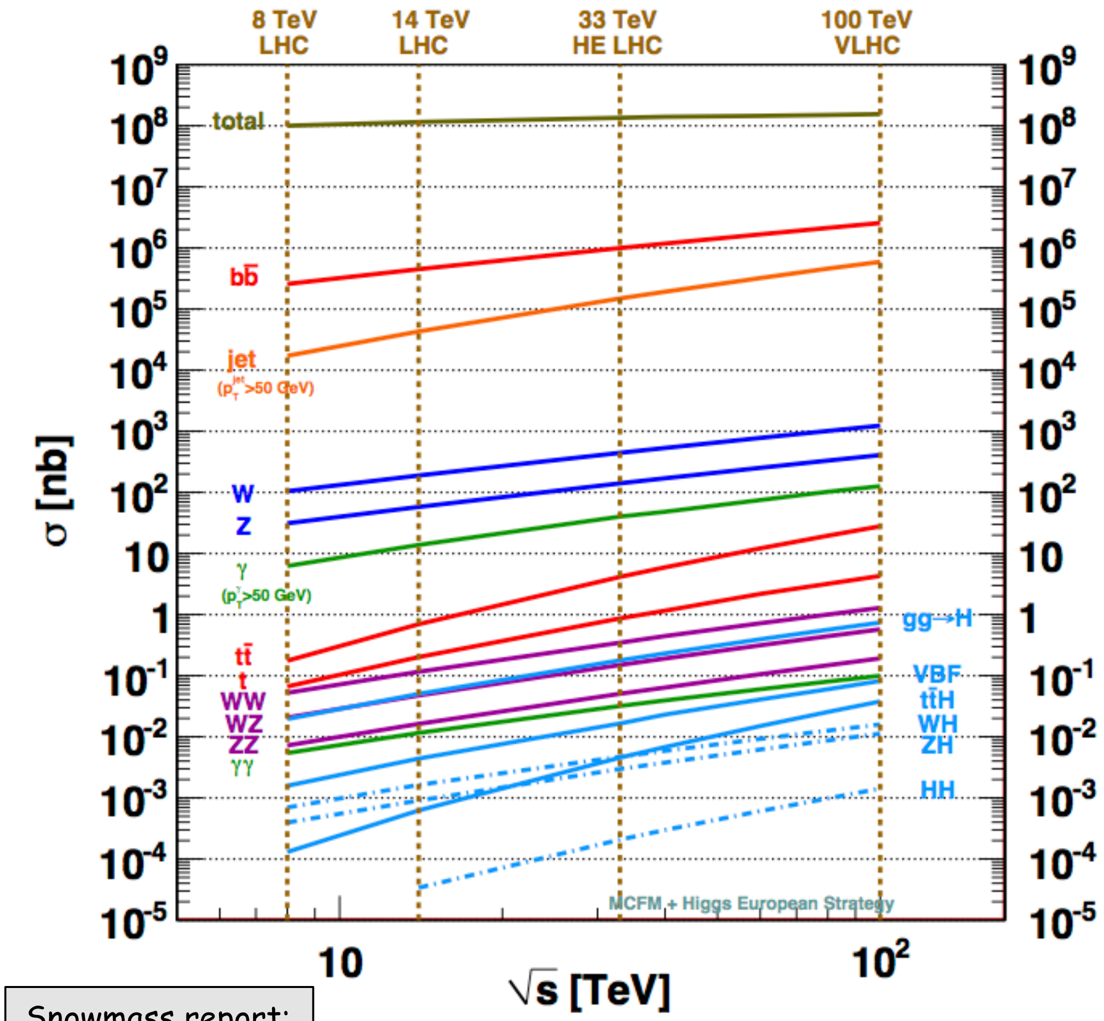
CERN FCC: international design study for Future Circular Colliders in 80-100 km ring:

- ☐ 100 TeV pp: ultimate goal (FCC-hh)
- ☐ 90-350 GeV e^+e^-: possible intermediate step (FCC-ee)
- ☐ $\sqrt{s}$= 3.5-6 TeV ep: option (FCC-eh)

Goal of the study: CDR in ~2018.



Cross sections vs √s



Snowmass report:
arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

→ With 10000/fb at √s=100 TeV expect: 10^{12} top, 10^{10} Higgs bosons, 10^8 m=1 TeV stop pairs, …

No time to idle (exp and theory)

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

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 tools to do it exhaustively.
- 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.

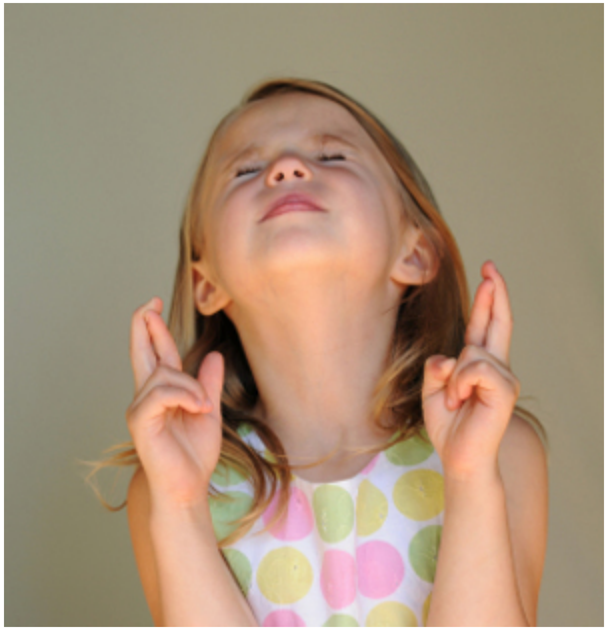
In summary

Experimental results will be dictating the agenda of the field.

We will need:

- Flexibility
- Preparedness
- Visionary global policies

- ...and a bit of luck!



Thank you!