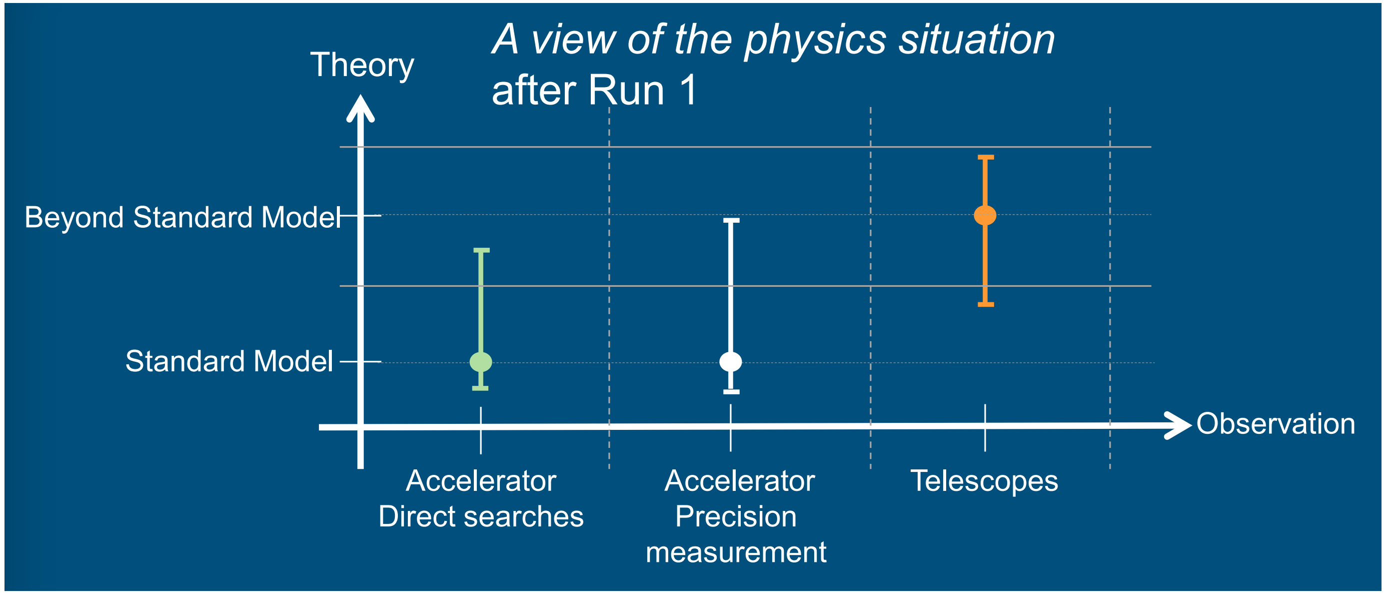
Physics at run 2

The ultimate search engine: LHC

Jorgen Beck Hansen / NBI
On behalf of the LHC experiments

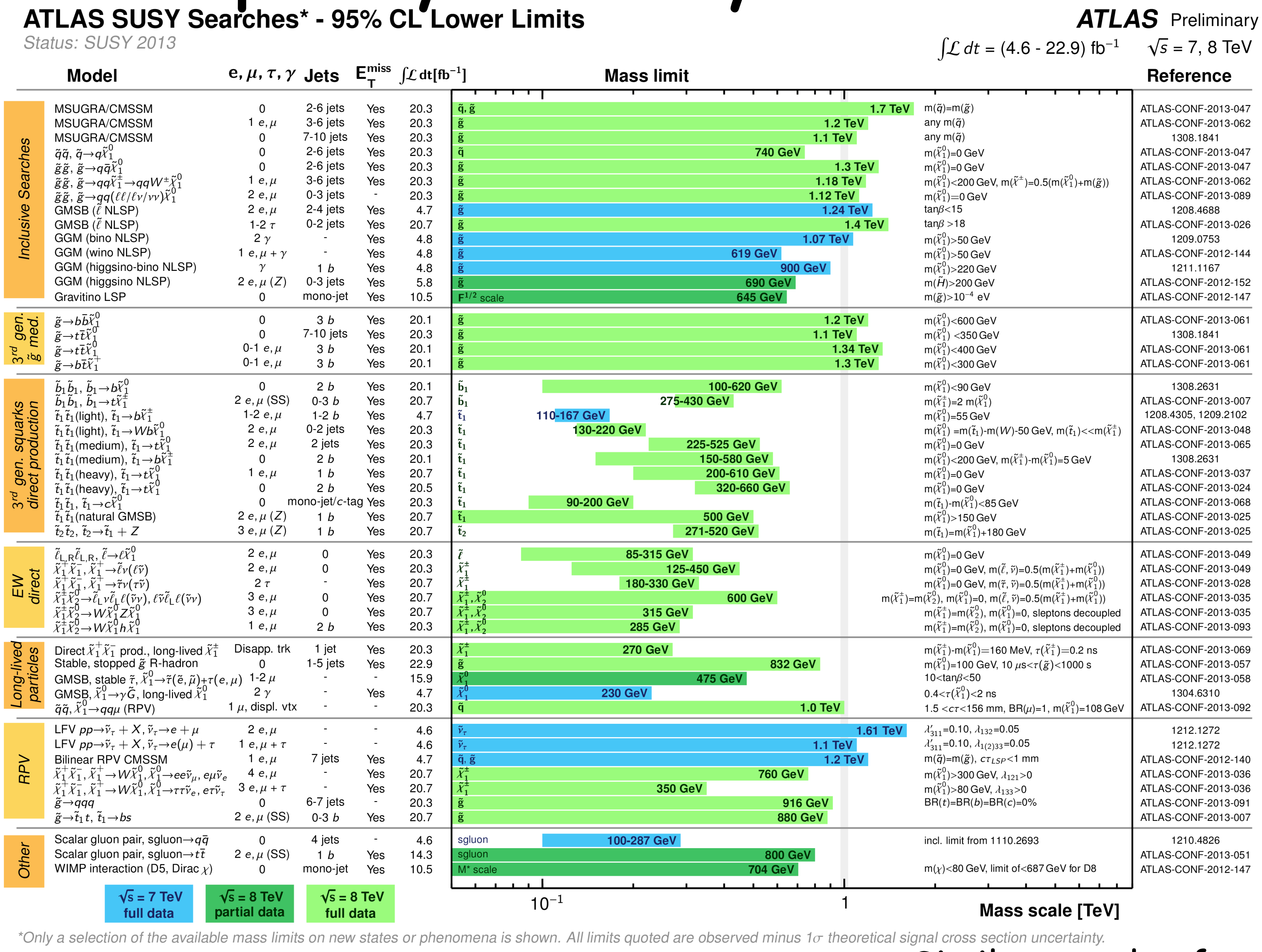
Credits to many colleagues from CMS, ATLAS etc. for the compilation and the many studies as presented in ECFA, Snowmass, RLIUP,…

What Do we know?



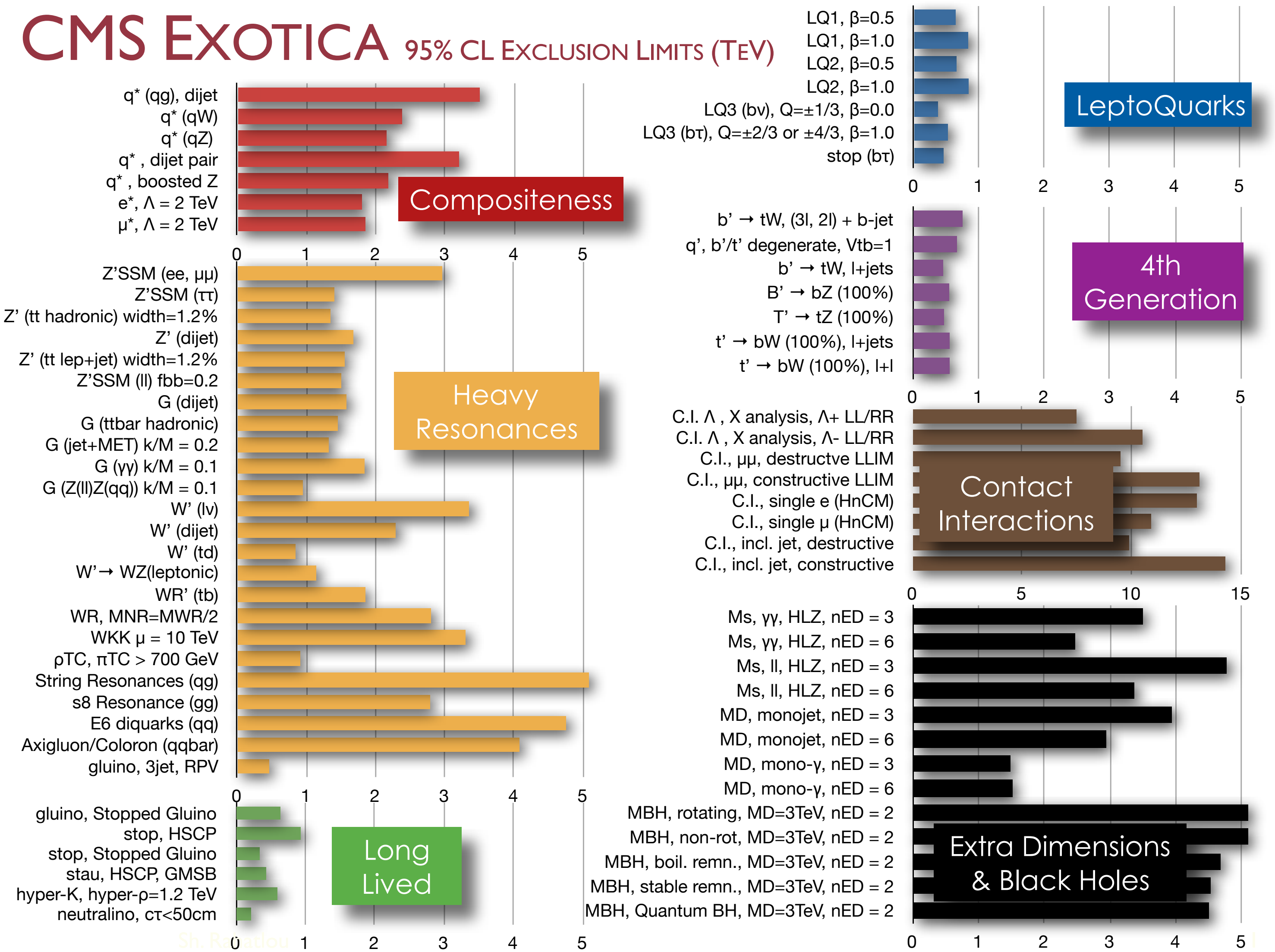
- **Consolidated the Standard Model**
  - Immense set of measurements at 7-8 TeV
    - Precision measurements in EW and QCD
    - Rare processes, very sensitive to New Physics, like $B_s \to \mu\mu$ decay)
- **Completed the Standard Model: Higgs boson discovery**
  - ~5 σ from each of $H \to \gamma\gamma$, $H \to l\nu l\nu$ and $H \to 4l$ per experiment
  - ~3 σ from $H \to \tau\tau$ and ~3 σ from $W/ZH \to W/Zbb$ per experiment
  - Potential separation 0+/2+ and pure O+/O- at 4σ level by combination?
  - Some couplings to 20-30 %

Supersymmetry searches



Similar results from CMS

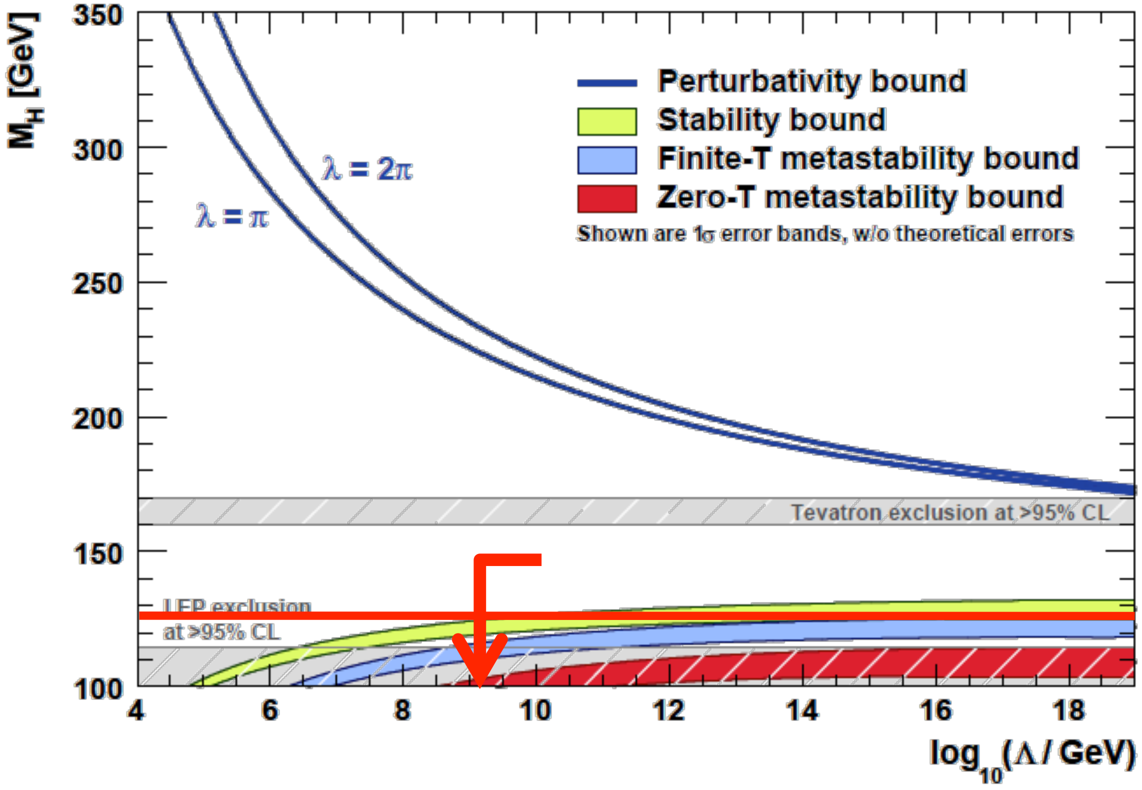
Exotic searches



Similar results from ATLAS

The Standard Model is here to STAY!!!

- NO evidence or minute indication of any new physics (~1++ Tev):



Depending on top mass and α_s

New physics scale required if

$m_H < 129$ (+- 6) GeV

(arxiv 1205.2893)

- A Higgs mass of ~126 GeV indicates a potential **New Physics** scale at 9 TeV
  - Optimistic? It could be higher w/o problems
  - Fine tuning requirements points to 2 TeV (10%) increasing to 9 TeV (1%) (arxiv 0003170v1)

Physics landscape by 2015

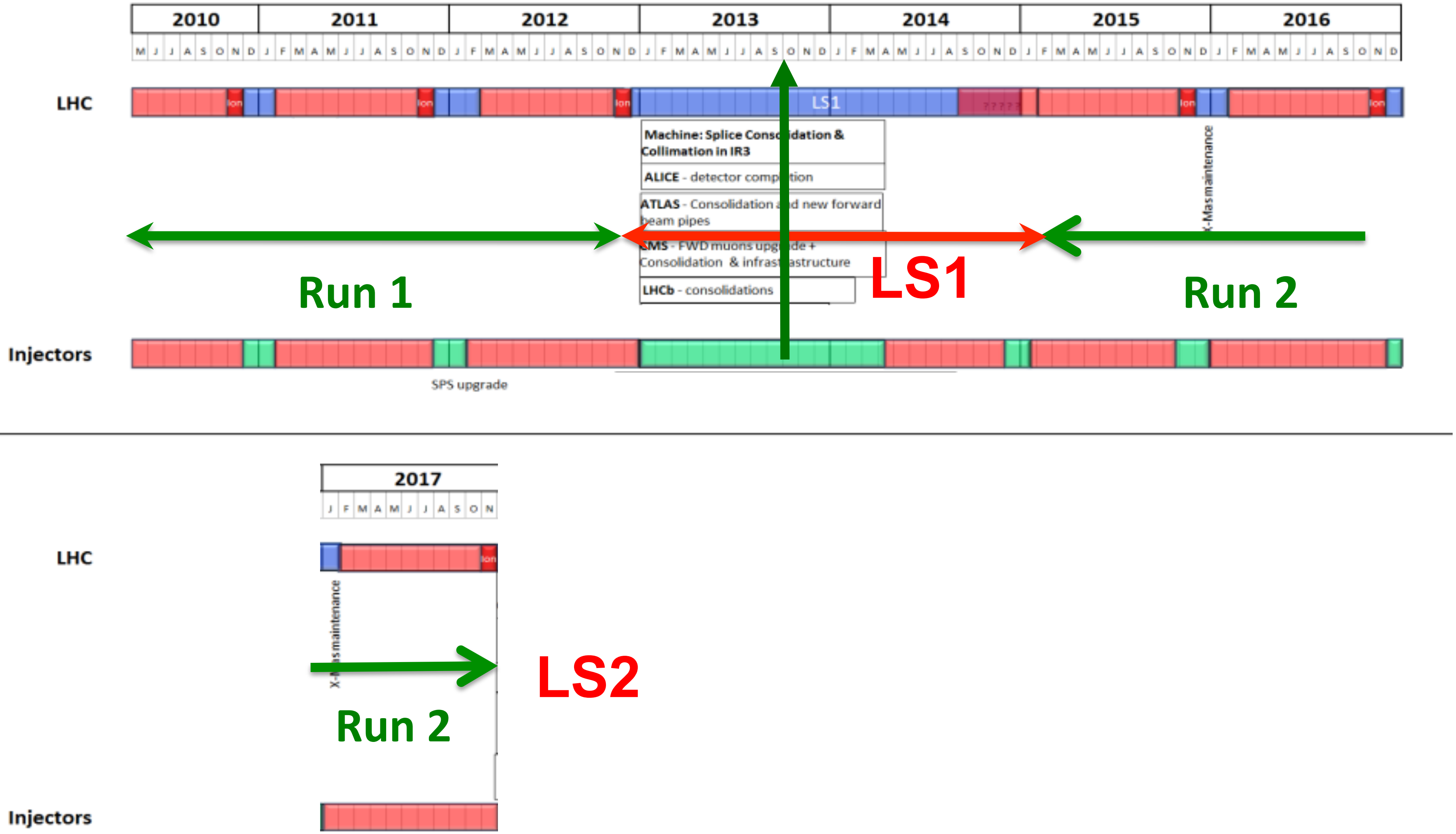
- The Puzzle: The SM is not the ultimate theory of particle physics, because of the many outstanding questions
  - Why is the Higgs boson so light ("naturalness"/fine-tuning/ hierarchy problem) ?
  - What is the the nature of the dark part (96% !) of the universe ?
  - What is the origin of the matter-antimatter asymmetry ?
  - Why is gravity so weak ?

- The expected integrated luminosity of RUN 2 implies
  - If New Physics exists at the TeV scale its discovery at $\sqrt{s}$ ~ 14 TeV happens in 2015++ → it requires **a lot of luminosity**

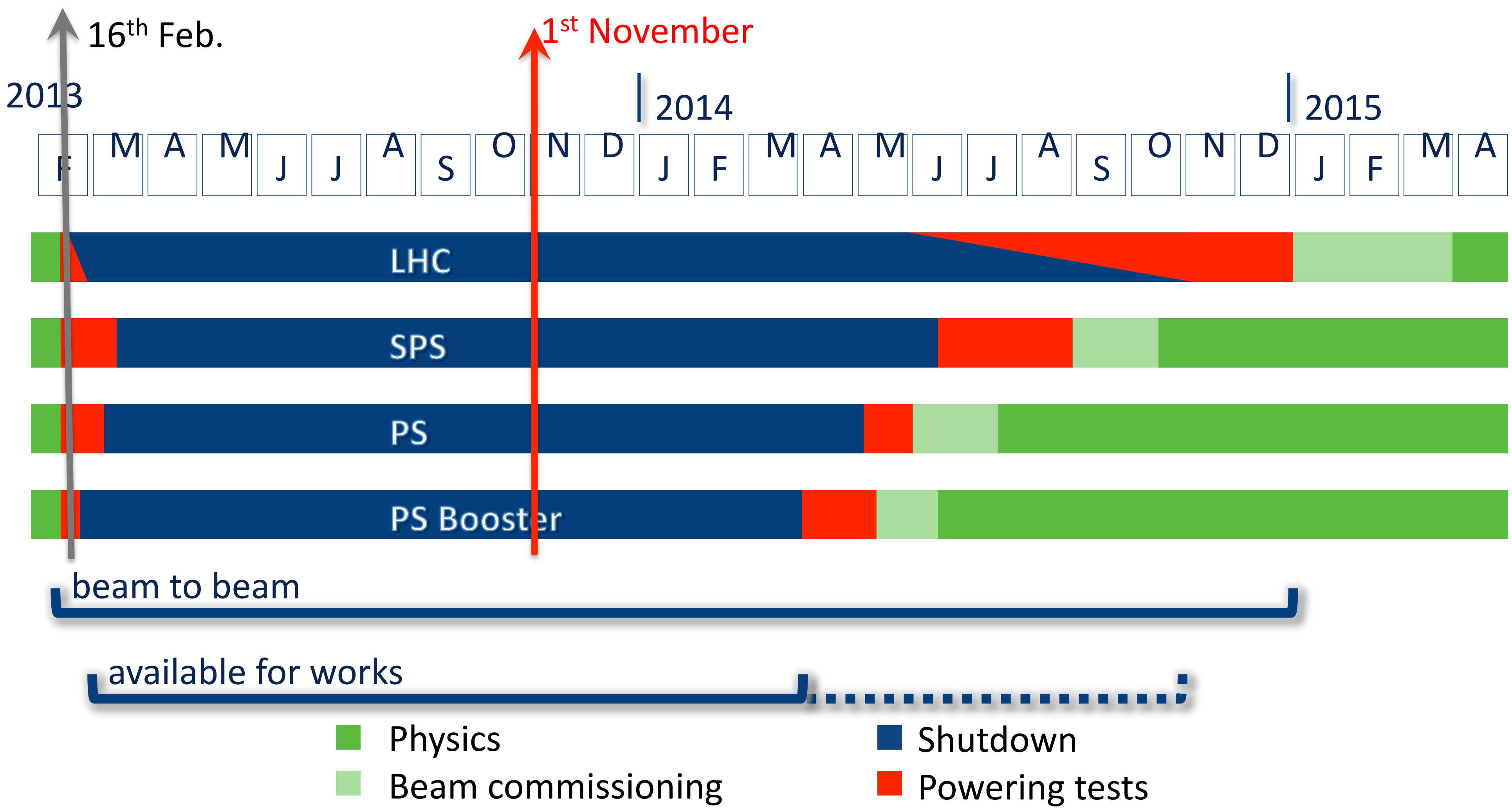
Run 2 of the LHC will be marked by
precision studies and
search for **small signals**

"Prediction is very difficult, especially about the future"

LHC Roadmap Run 2
3 years Operation Run after LS1



LS 1 from 16th Feb. 2013 to Dec. 2014



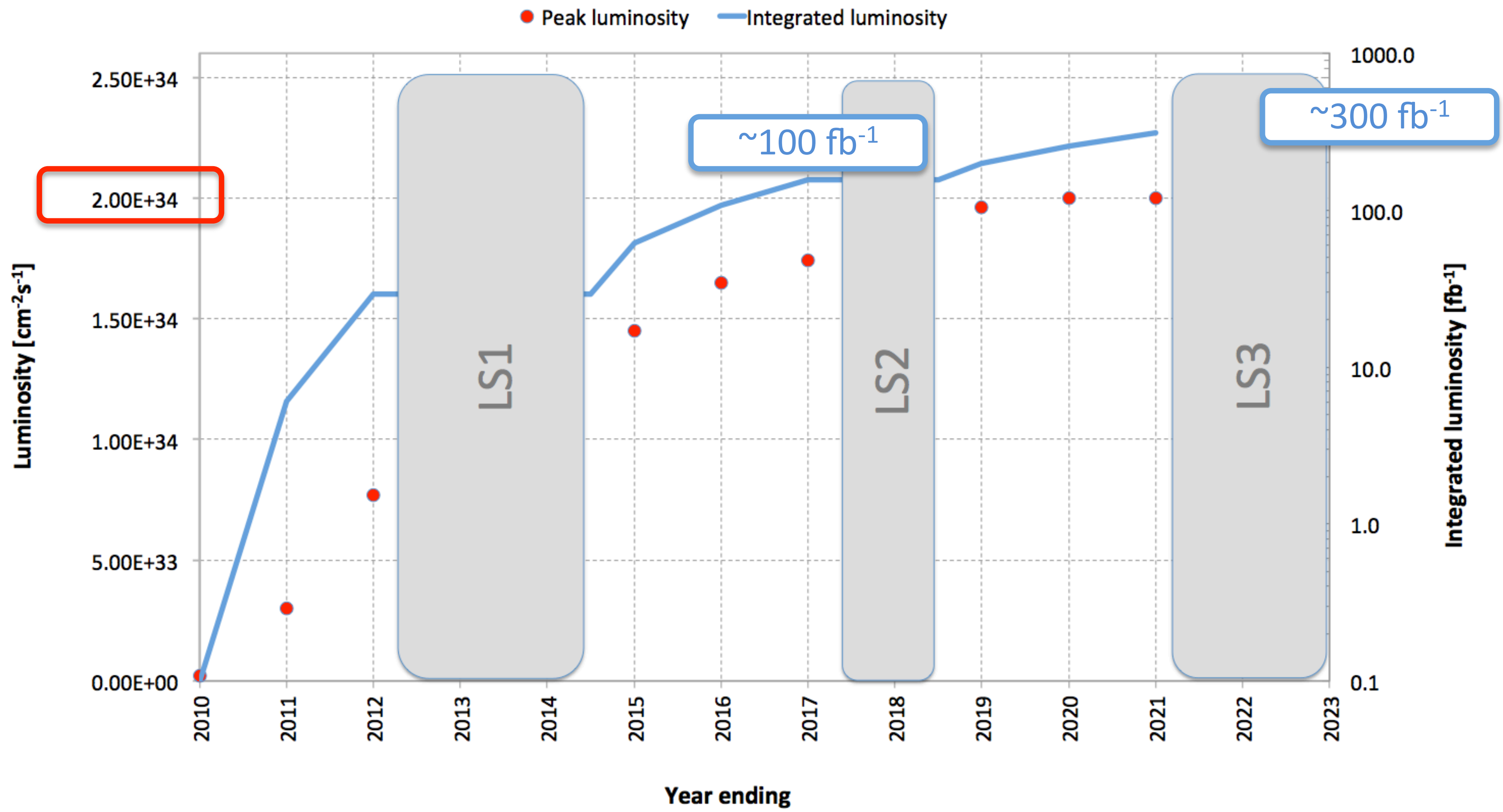
LHC Roadmap Run 2

- Energy: 6.5 TeV
- Bunch spacing: 25 ns
  - pile-up considerations
- Injectors potentially able to offer nominal intensity with even lower emittance

Run 2:
Start with 6.5 TeV and later decision towards 7 TeV according to magnet training

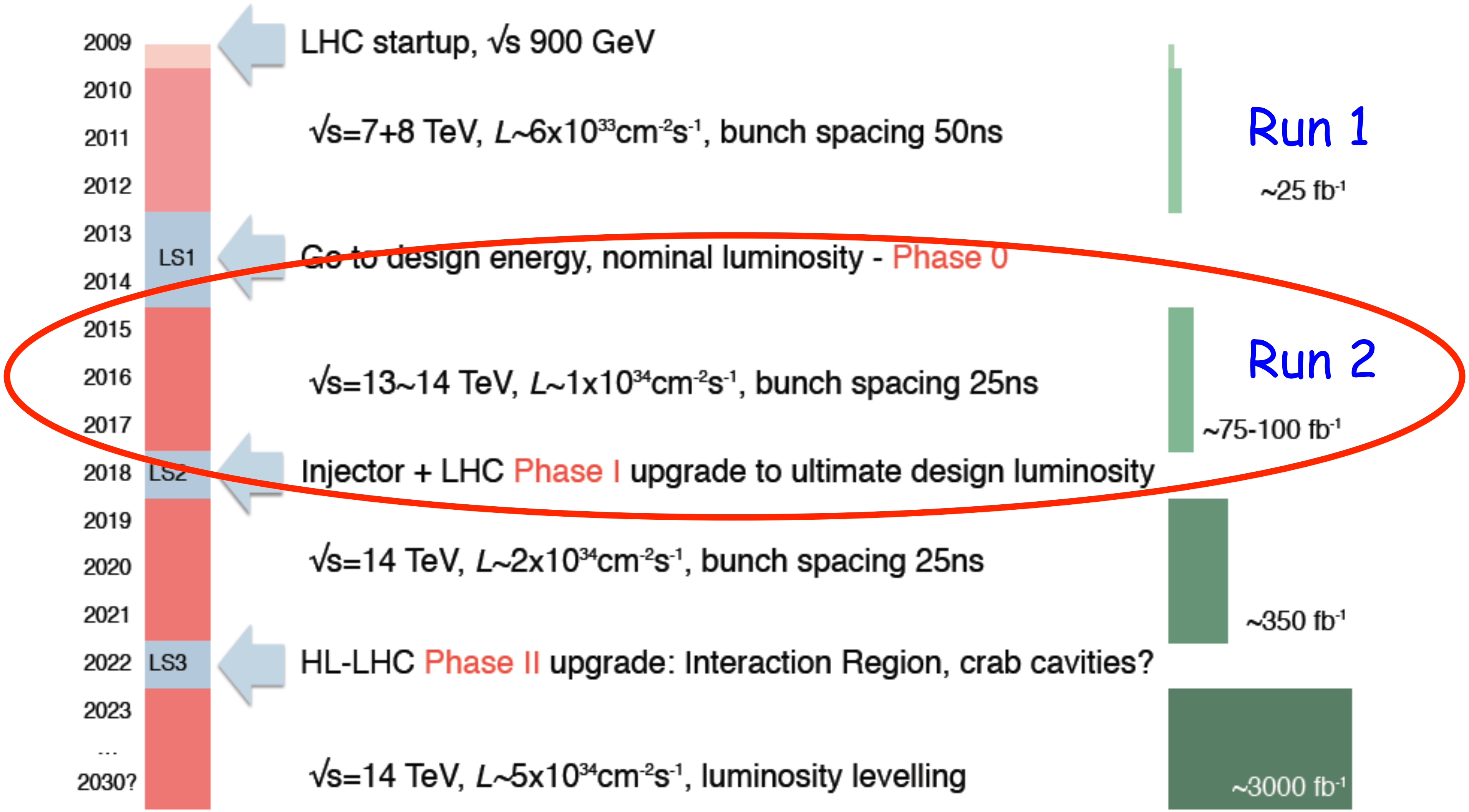
	Number of bunches	Ib LHC FT [1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns BCMS	2590	1.15	1.9	**1.7e34**	49	~45

Luminosity evolution



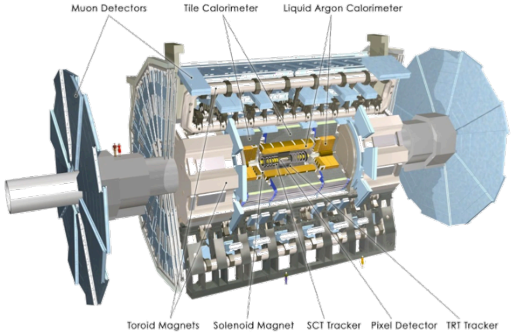
Still uncertainty on length of end-of-year breaks   Usual caveats apply

LHC Roadmap

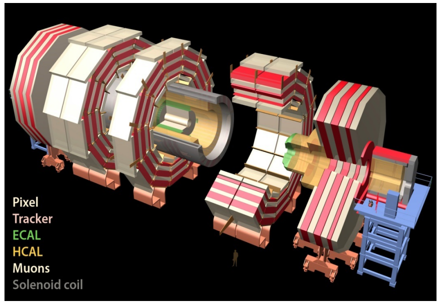

2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
LHC startup, √s 900 GeV
√s=7+8 TeV, L~6x10^33 cm^-2 s^-1, bunch spacing 50ns
Run 1
~25 fb^-1
Go to design energy, nominal luminosity - Phase 0
√s=13~14 TeV, L~1x10^34 cm^-2 s^-1, bunch spacing 25ns
Run 2
~75-100 fb^-1
Injector + LHC Phase I upgrade to ultimate design luminosity
√s=14 TeV, L~2x10^34 cm^-2 s^-1, bunch spacing 25ns
~350 fb^-1
HL-LHC Phase II upgrade: Interaction Region, crab cavities?
√s=14 TeV, L~5x10^34 cm^-2 s^-1, luminosity levelling
~3000 fb^-1

Detector upgrades

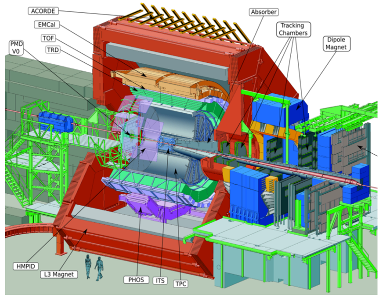
- Detectors will need to be improved to be able to maintain performance at Run 2



•4th Si Pixel layer (IBL)
•Complete muon coverage
•Repairs (TRT, LAr and Tile)
•New beampipe and Infrastructure updates



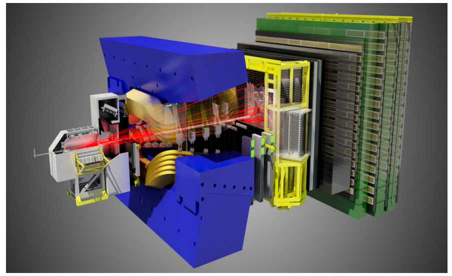
•Complete muon coverage
•Cooler tracker
•Photodetectors in HCAL
•New beampipe and infrastructure updates



High statistics HI measurements using rare probe particles at low pT.

10nb-1, min bias

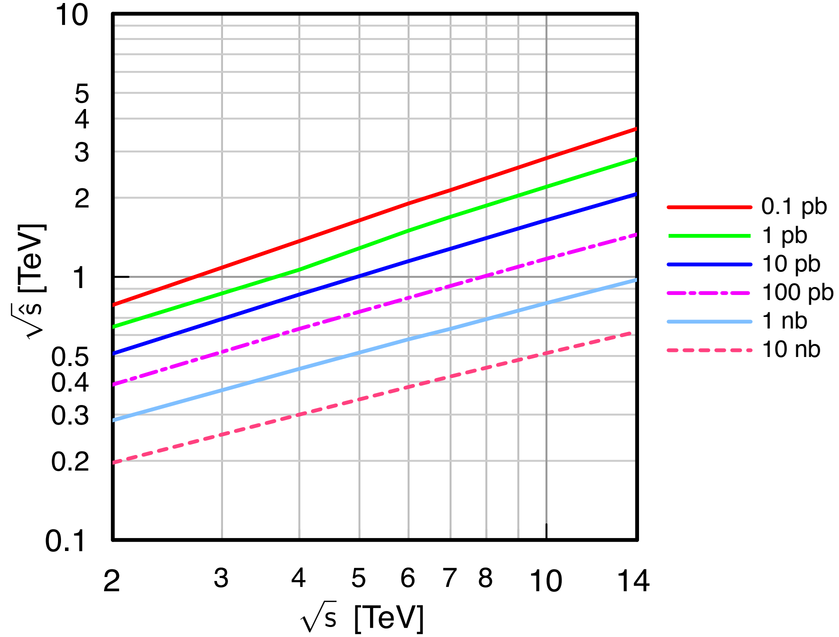
Single phase major upgrade to detector & readout in LS2

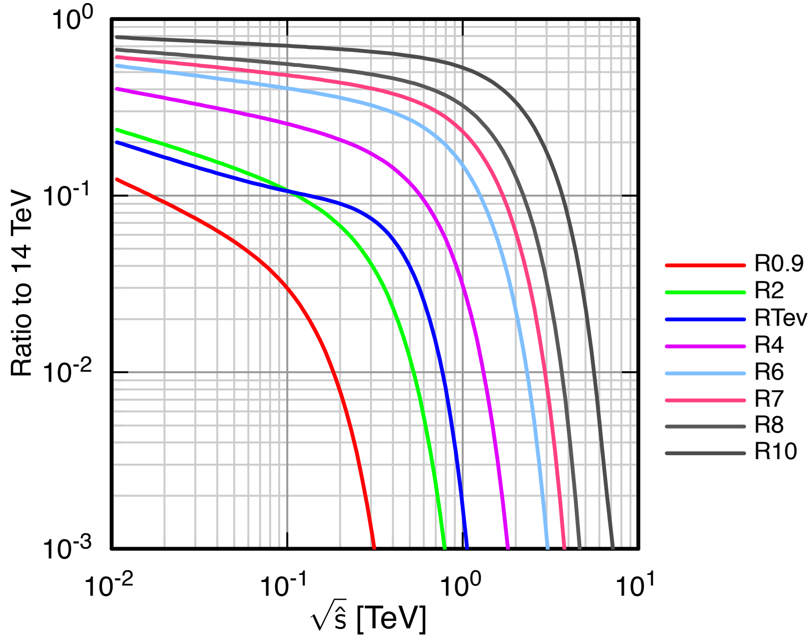


Record very high stats to search for effect of possible new physics on flavour structure. (complementary to ATLAS & CMS progr)
50fb-1 , 40Mz readout

Single phase major upgrade to detector & readout in LS2

Parton luminosities





- Looking at these in detail gives excellent idea about relative power of LHC14 vs LHC8, i.e.
  - How much luminosity is needed for process X at LHC14 to supersede the LHC8?
- **Rule of thumb: x10 in luminosity ~ x2 in energy (process dependent)**
- Plots from C. Quigg: *LHC Physics Potential versus Energy*, arXiv: 1101.3201

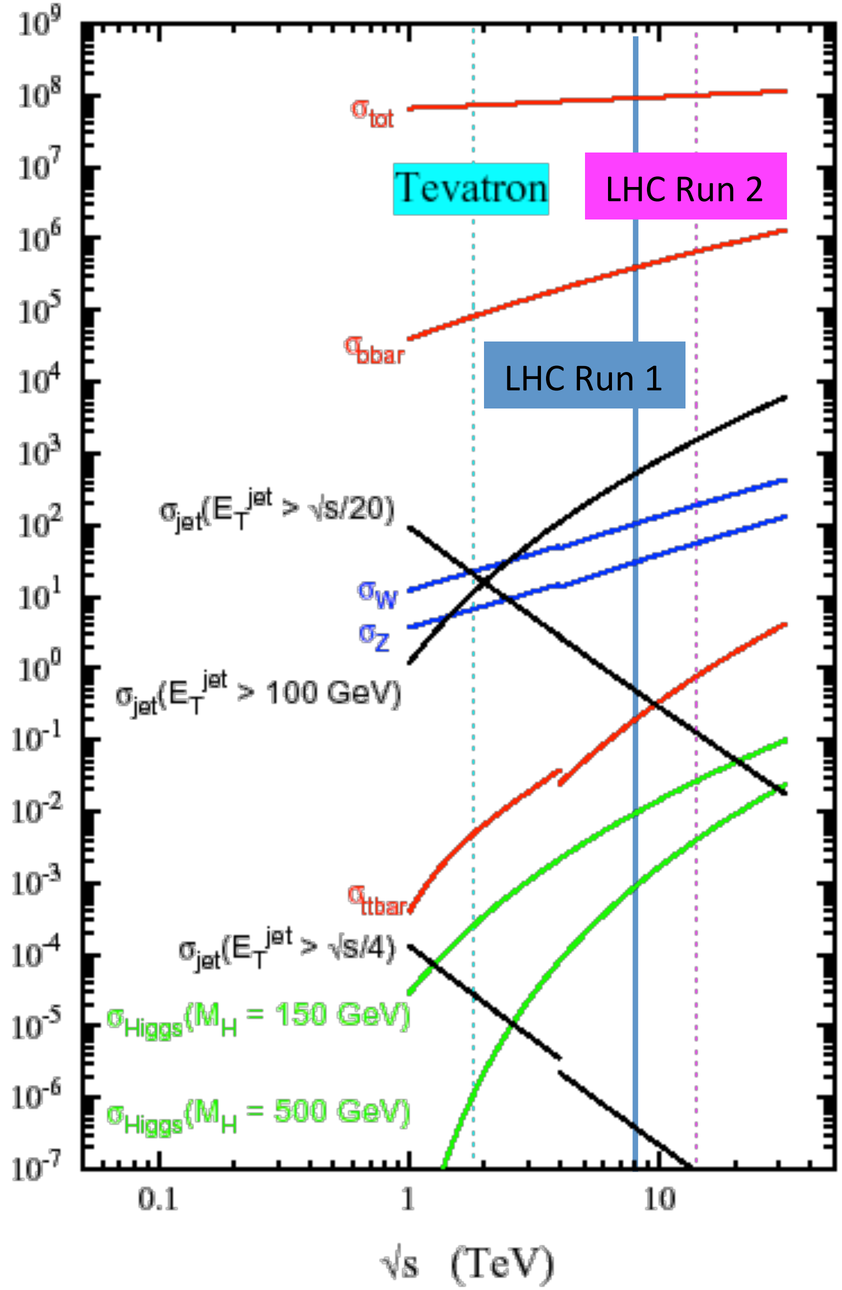
Physics prospects at Run 2

- Increase of cross sections from LHC8 to LHC14
  - Improved discovery potential at LHC
- ***A Higgs factory***:
  - 5.5M Higgs events produced
  - 100K event useful for precision measurements
- Note: today ATLAS+CMS have 1400 Higgs events

Physics subjects

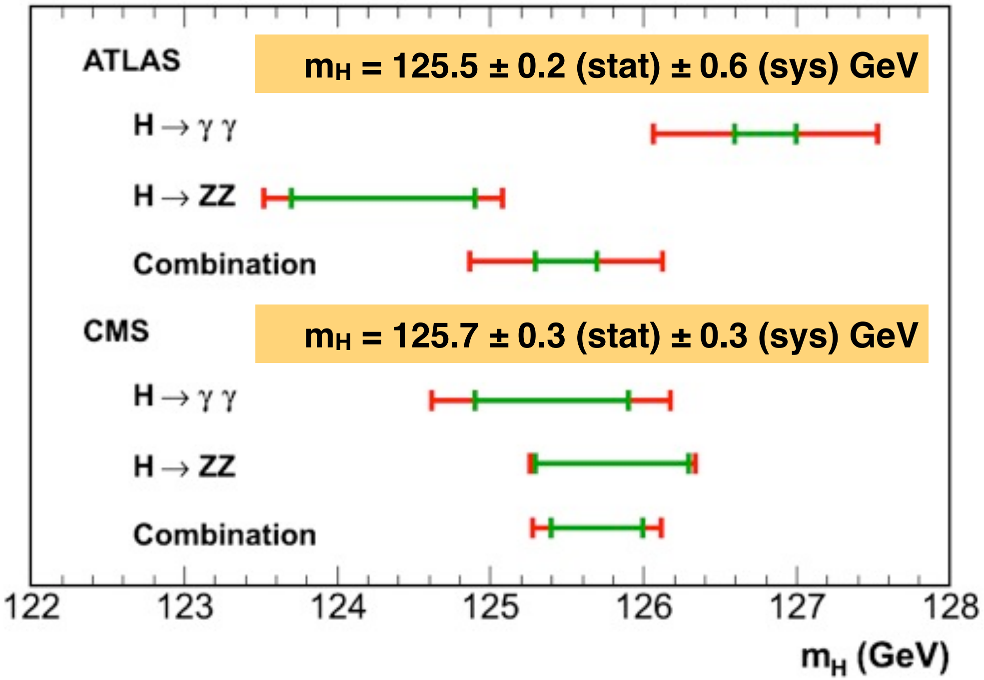
- Higgs precision measurement
  - Mass
  - Cross-sections
- Measure as many Higgs couplings to fermions and bosons as precisely as possible
- Very weak possibility to observe that the Higgs boson fixes the SM problems with $W_L W_L$ scattering at high E
- Extend limits for searches

CMS and ATLAS white papers: arXiv:1307.7135 and 1307.7292



Higgs Physics Potential - Mass

High resolution channel H → γγ and H → ZZ* → 4l



ATLAS 115 GeV < m_{4l} < 125 GeV

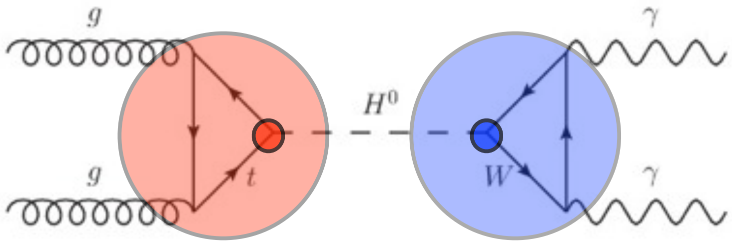
	total signal full mass range	signal	$ZZ^{(*)}$	$Z + \text{jets}, t\bar{t}$	S/B	expected	observed
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	5.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

CMS 110 GeV < m_{4l} < 160 GeV

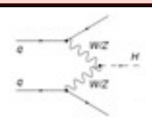
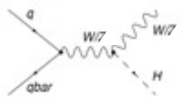
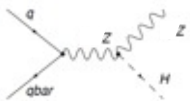
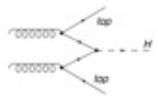
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	38.5 ±1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ±2.7
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	21.1 ±1.5
Observed	16	23	32	71

Δm of 150(100) MeV achievable for 100(300) fb-1

Higgs Precision measurements



m_H = 125 GeV

Process	Diagram	Cross section [fb]	Unc. [%]
gluon-gluon fusion		19520	15
vector boson fusion		1578	3
WH		697	4
ZH		394	5
ttH		130	15

m_H = 125 GeV

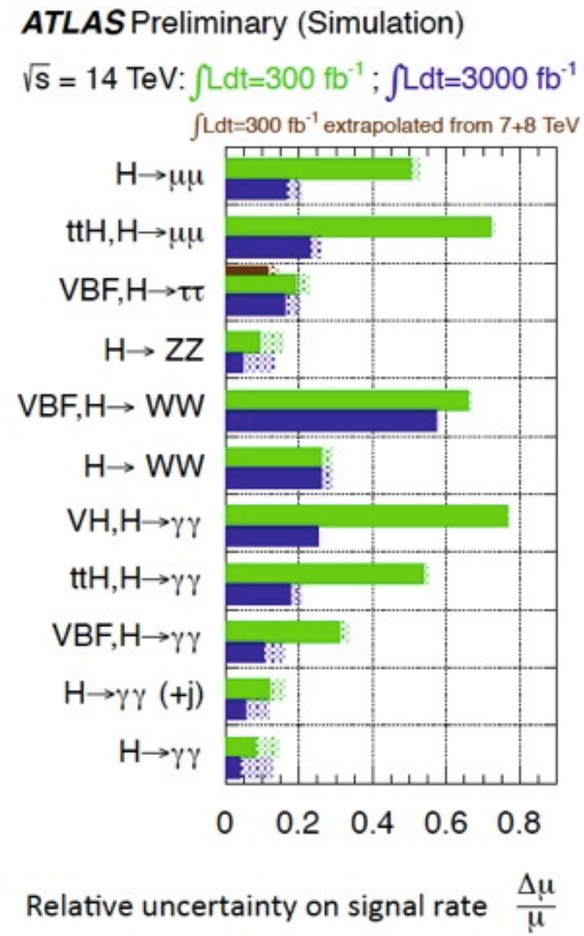
Decay	BR [%]	Unc. [%]
bb	57.7	3.3
ττ	6.32	5.7
cc	2.91	12.2
μμ	0.022	6.0
WW	21.5	4.3
gg	8.57	10.2
ZZ	2.64	4.3
γγ	0.23	5.0
Zγ	0.15	9.0
Γ_H [MeV]	4.07	4.0

* uncertainties need improvements for future precision measurements

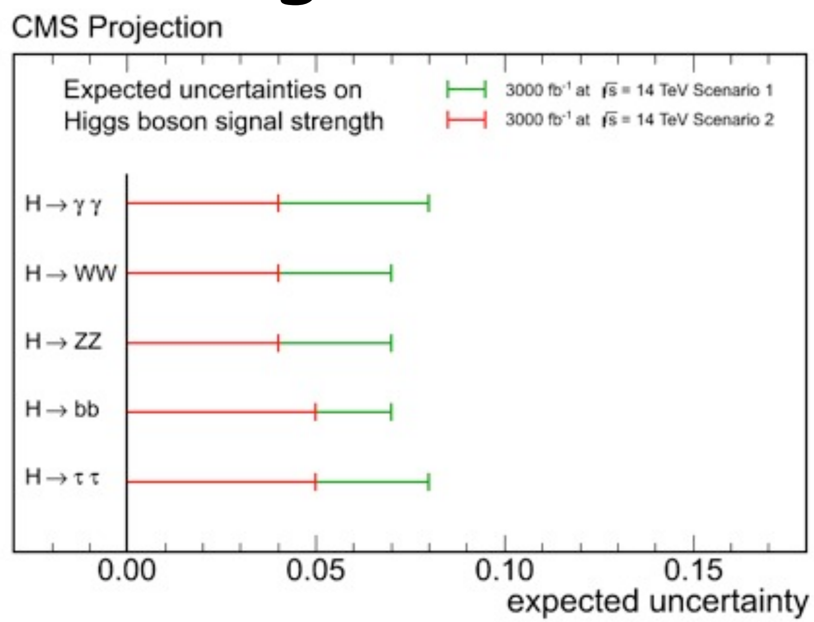
Warning: Numbers are for 3000 fb^{-1} expected to be about x(4-5) worse

Uncertainty on signal strength

- 100 fb-1 is a factor 1.5 larger!



Based on parametric simulation



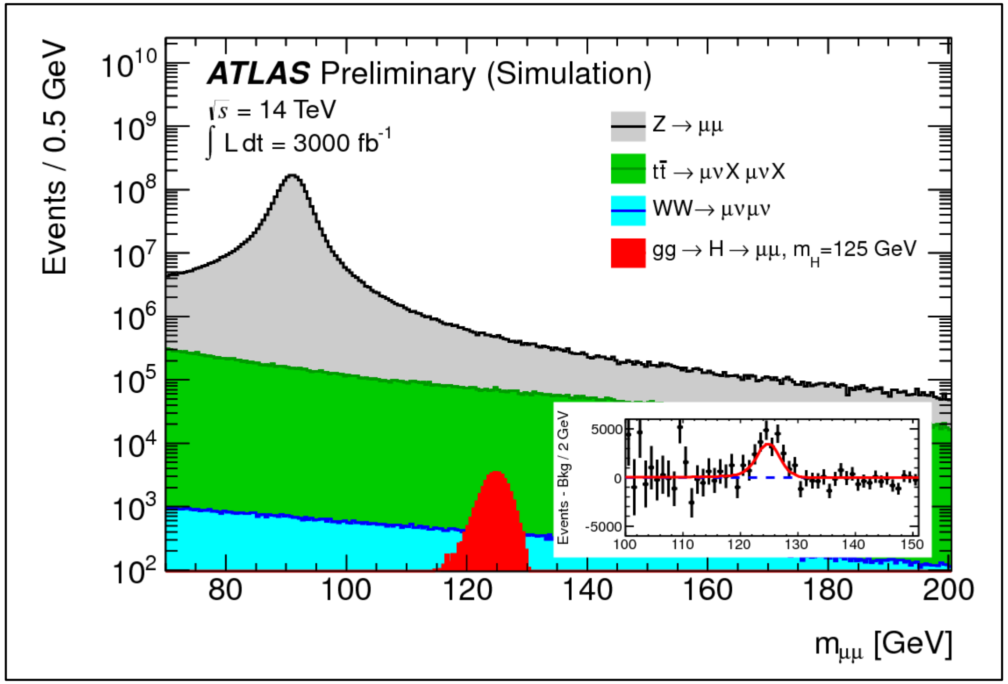
L (fb^{-1})	$H\to\gamma\gamma$	$H\to WW$	$H\to ZZ$	$H\to bb$	$H\to\tau\tau$	$H\to Z\gamma$	$H\to$ inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[6, 17]

Assumptions on systematic uncertainties
Scenario 1: no change
Scenario 2: Δ theory / 2, rest ∝ 1/√L

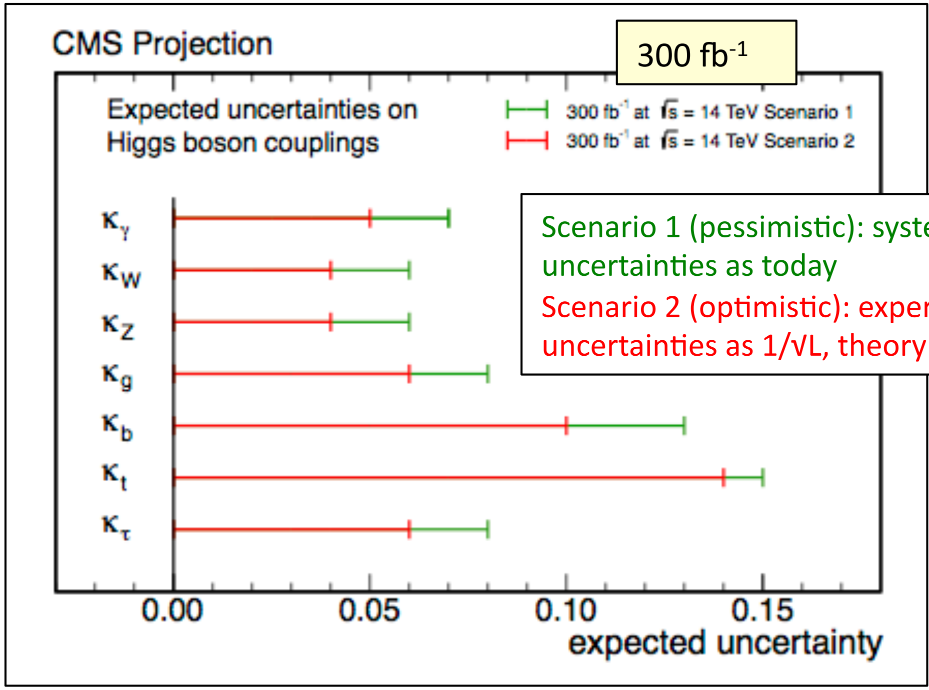
Extrapolated from 2011/12 results

Fermion decays

- Establish observation (5σ) in fermion modes (ττ / bb)
- Some potential for rare decays like H→μμ
  - Gives direct access to Higgs couplings to fermions of the second generation.
  - Today's sensitivity: 8xSM cross-section
  - With 100 fb^{-1} expect 550 signal events (but: S/B ~ 0.3%)
    - Higgs-muon coupling can measured to about >30%

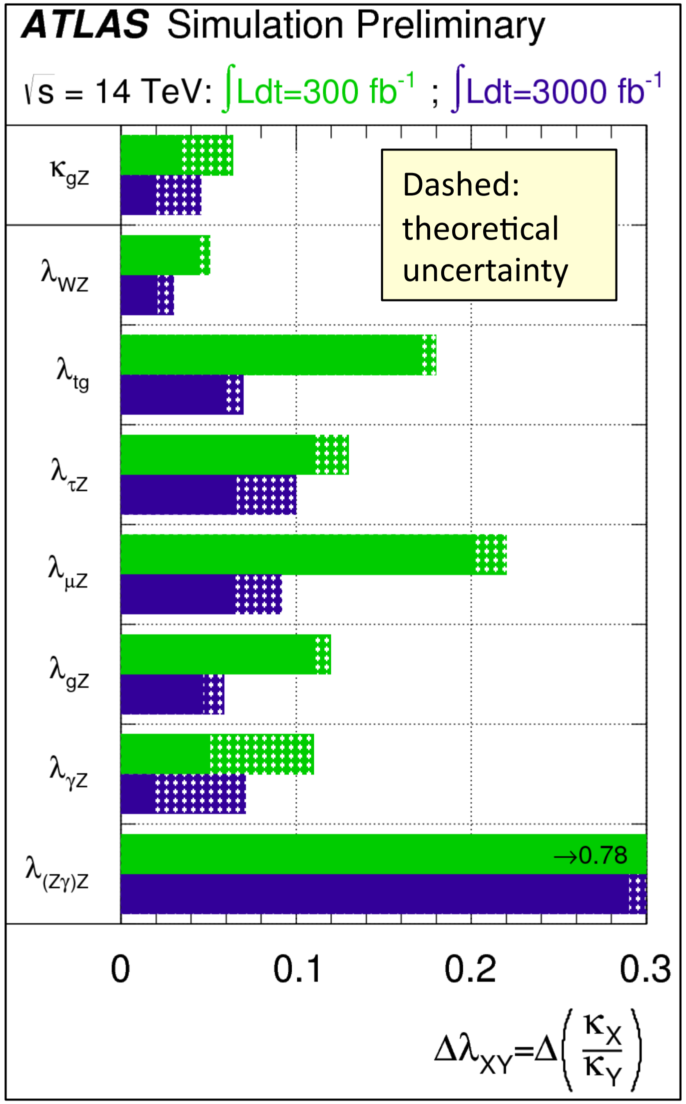


Higgs (anomalous) Couplings



Scenario 1 (pessimistic): systematic uncertainties as today

Scenario 2 (optimistic): experimental uncertainties as 1/√L, theory halved



Dashed: theoretical uncertainty

k_i= measured coupling normalized to SM prediction

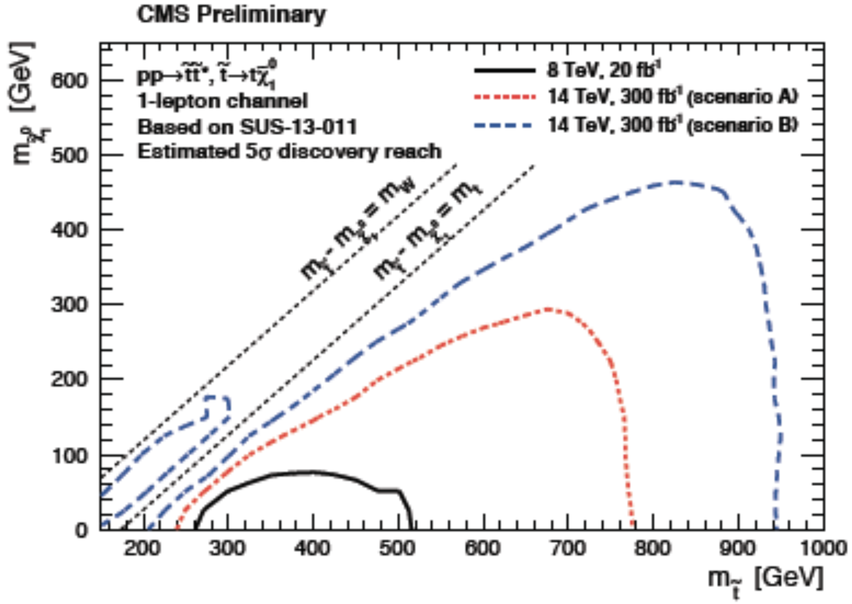
$$\lambda_{ij}=k_i/k_j$$

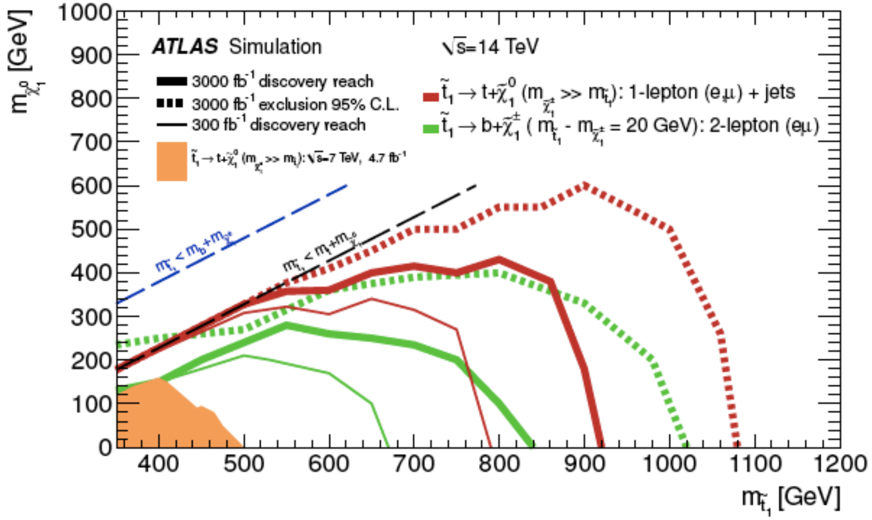
Expected sensitivity with 100 fb-1

7-25%

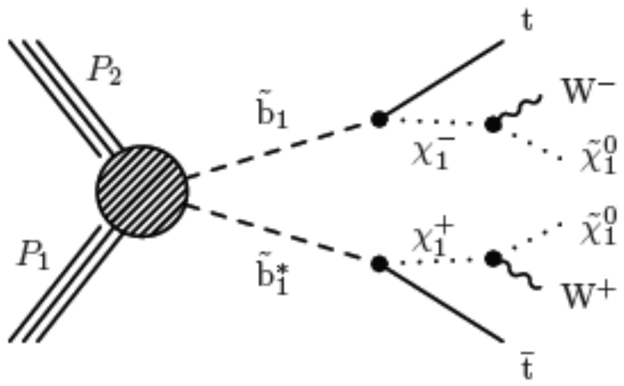
Stop discovery potential

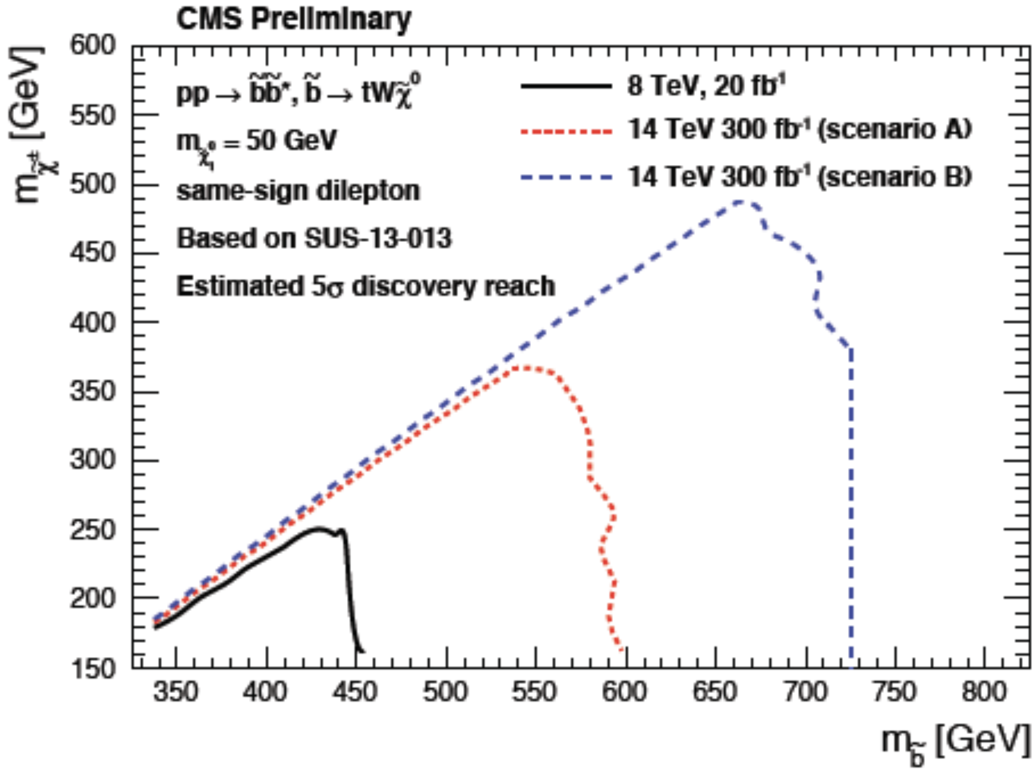
- Challenging analysis due to large top background
- Systematic uncertainties important
- 300 fb^{-1}:
  - Discovery up to 700 GeV in direct production
- Further improvements may be possible with reoptimization





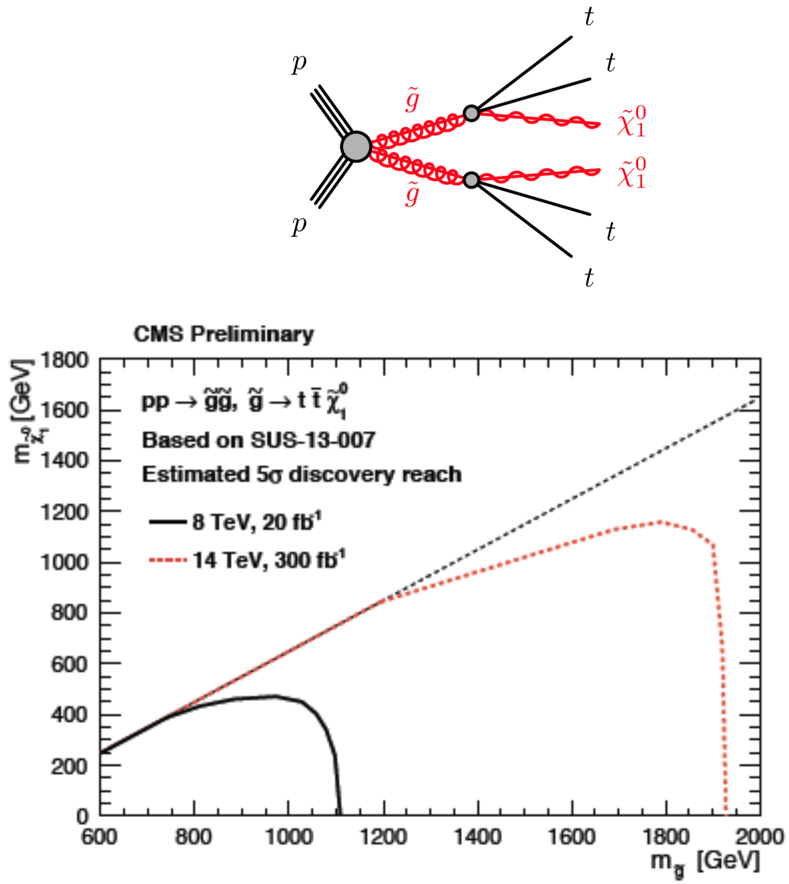
SBottom discovery potential

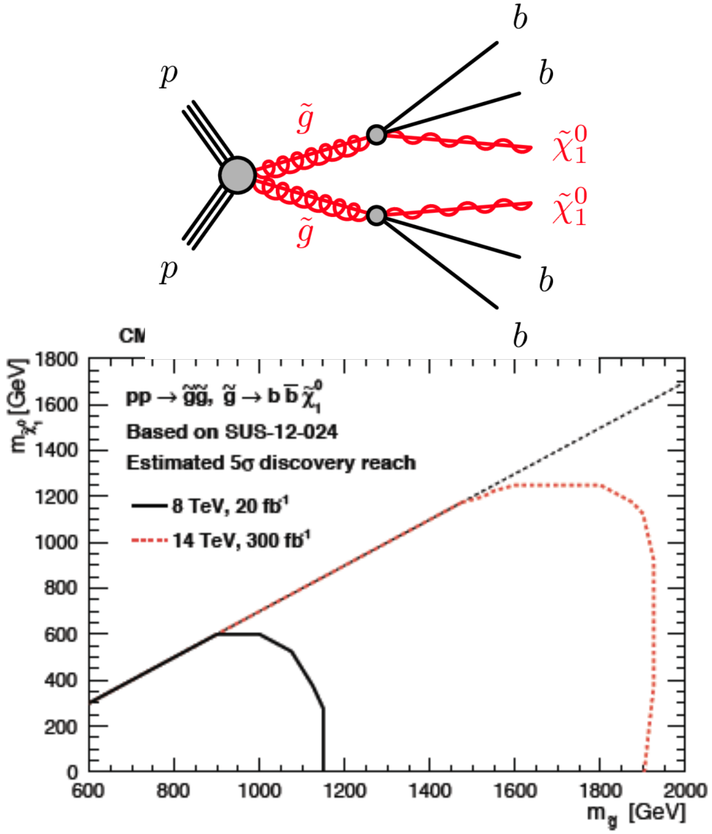




- Sbottom also supposedly light due to mixing with stop
- Discovery with 100 fb-1 for masses up to 500++ GeV
  - Scenario A: syst. errors as today
  - Scenario B: syst. errors scaled with 1/√L **(but at least 10%)**

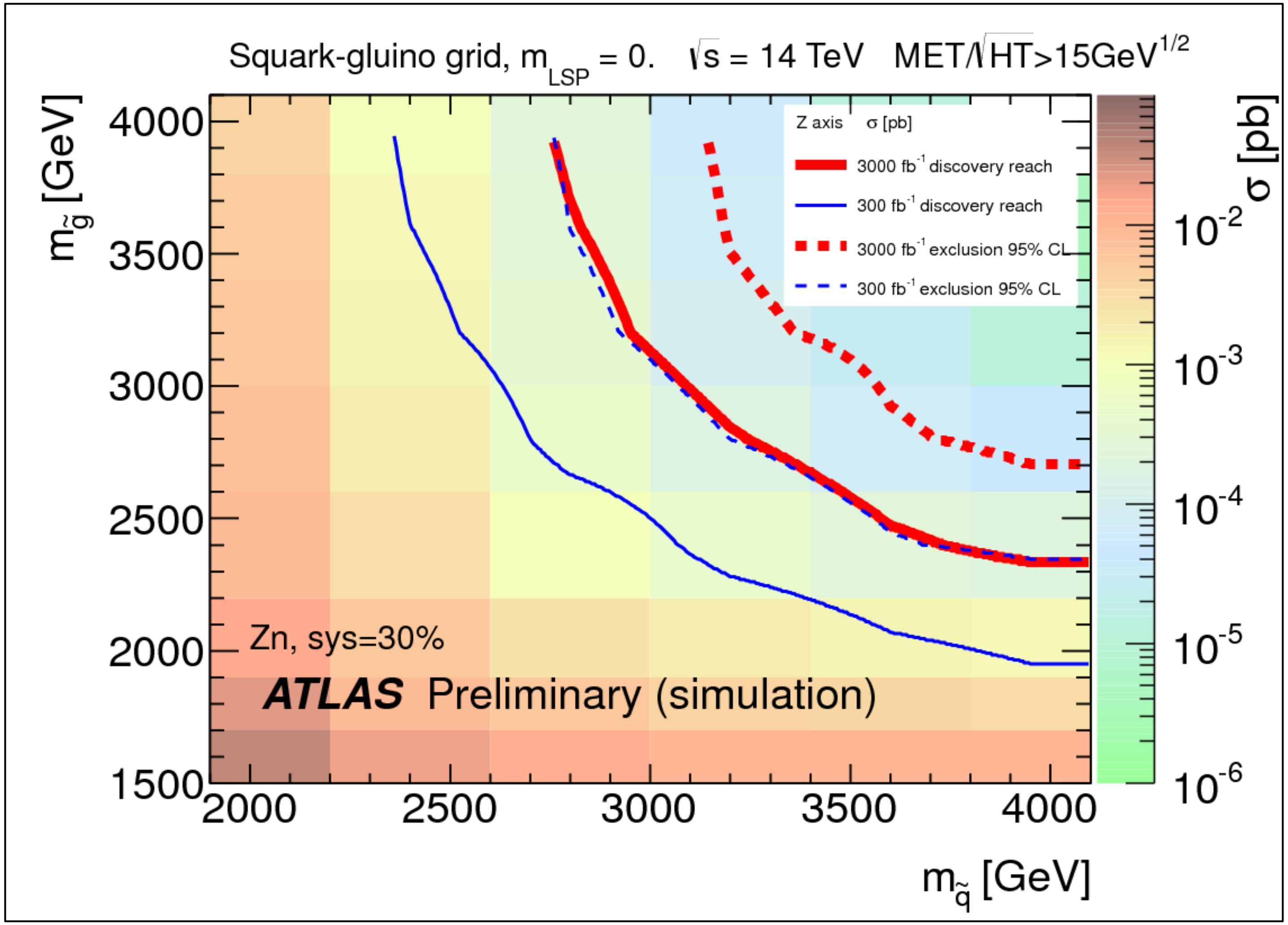
Gluino reach if decay via top/bottom





- With 100 fb-1 will reach about 1.7 TeV in gluino mass both in top- and b-decay signatures

Generic Squarks and Gluinos

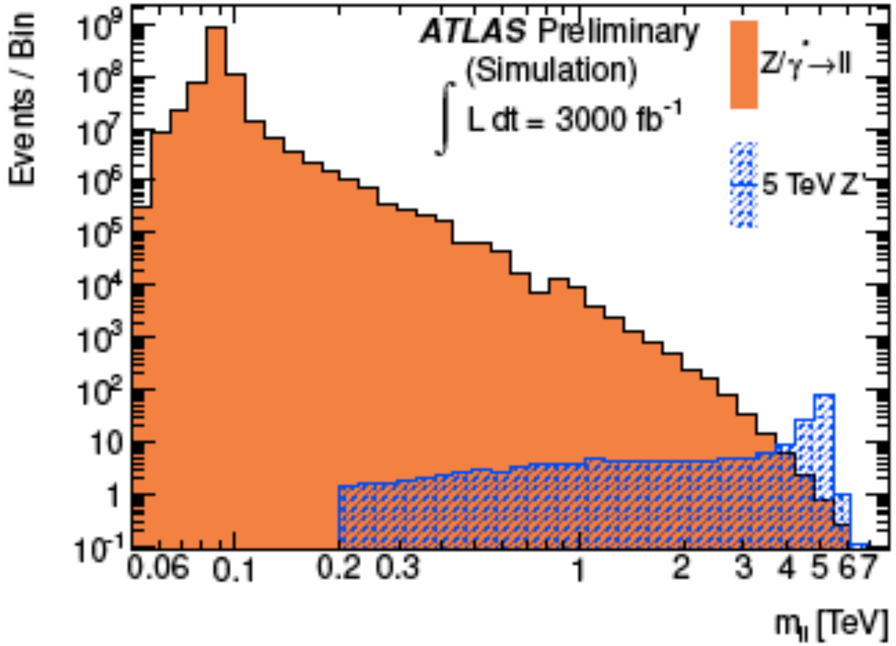


100-200 GeV lower limits at 100 fb^{-1}

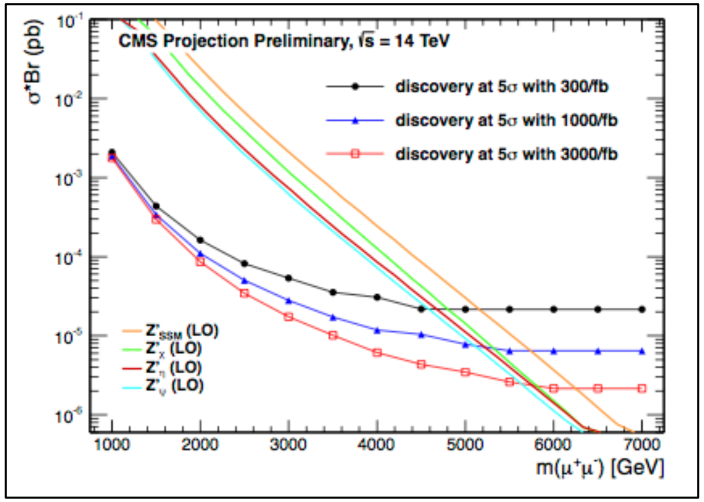
Will be extended to 2.1 TeV

Dilepton resonances: limits

- Current limits are on **σxBR** are ~0.3 fb
- Expect to improve by a factor of ~40 with HL-LHC
- Probe Z' SSM up to masses of 5.5 TeV



95% CL limits on:		
	Z'-> ee (TeV)	**Z'->μμ (TeV)**
Run-1 data	2.79	2.48
300 fb^{-1}	6.5	6.4
3000 fb^{-1}	7.8	7.6



Conclusion

- The discovery of a (the ?) Higgs boson is a giant leap in our understanding of fundamental physics and the structure and evolution of the universe

  So far completing SM

- As no hint of NP is found

Run 2 of the LHC will be marked by
precision studies and
search for **small signals**

- Depending on the type of NP limits may improve well over 1 TeV compared to current limits
- For Supersymmetry limits improve with several 100 GeV