Physics at Future Colliders

- **Lecture 1 (Wednesday 2 August, 10:25)**
  - **An historical perspective (1964-2017): The need for precision and energy**
  - **A strategy for the future: Towards the precision and energy frontier**
  - **The short-term perspectives (2020-2035): The HL-LHC**

- **Lecture 2 (Thursday 3 August, 10:25)**
  - **The quest for precision (2030-2050): Linear or circular?**

- **Lecture 3 (Thursday 3 August, 11:35)**
  - **The energy frontier (2045-2080): Leptons or hadrons?**
  - **Thinking out of the box: Muon collider**
  - **Towards the next European Strategy update (2019-2020)**

The help and inspiration from ***Patrick Janot*** in the preparation for these lectures is warmly acknowledged

"No doubt that future high energy colliders are extremely challenging projects.

However, the correct approach, as scientists, is not to abandon our exploratory spirit, nor give in to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable."

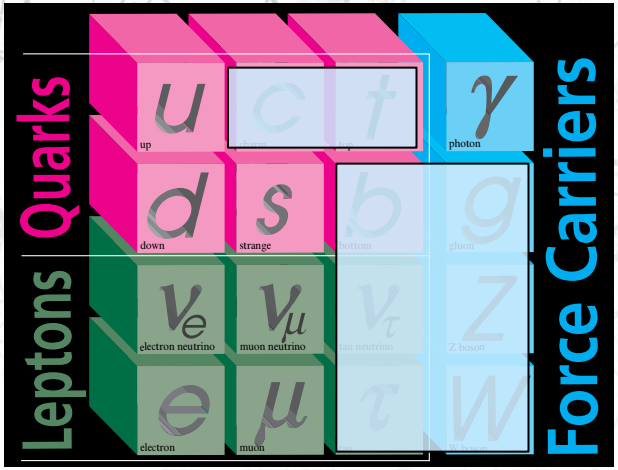
Fabiola Gianotti, DG CERN

Lecture 1

An historical perspective (1964-2017):
The need for precision and energy

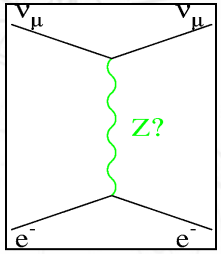
1964-1974: The rise of the Standard Model

- Little was known experimentally



+ Discovery of CP violation in $K^0_L \rightarrow \pi\pi$ decays
(Kronin, Finch: 1964)

+ Discovery of neutral currents $\nu_\mu e \rightarrow \nu_\mu e$
(Gargamelle: 1973)



- Mostly theoretical advances
  - 1964: Spontaneous symmetry breaking mechanism (Brout-Englert, Higgs)
  - 1967: Unification of electroweak interactions (Glashow, Weinberg, Salam)
    - With $m_\gamma = 0$, $m_W = m_Z \cos\theta_W$, and a Higgs boson
  - 1970: Prediction of the c quark (Glashow, Illiopoulos, Maiani)
  - 1971: Elucidate quantum structure of electroweak interactions (t'Hooft, Veltman)
    - Predicts and computes quantum corrections
  - 1973: Six quarks needed for CP violation (Kobayashi, Maskawa)
  - 1974: *Complete formulation of the Standard Model !* (Illiopoulos)

1974-1984: The rise of centre-of-mass energy

- **Collisions at large √s: A-priori obvious way to discover heavier particles**

Year	Discovery	Experiment	√s (GeV)	Observation
1974	**c quark** (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \to J/\Psi)$ $J/\Psi \to \mu^+\mu^-$
1975	**τ lepton** (m=1.777 GeV)	e^+e^- ring (SLAC)	8	$e^+e^- \to \tau^+\tau^-$ $e^+\mu^-$ events
1977	**b quark** (m~4.5 GeV)	Fixed target (FNAL)	25	$\Upsilon \to \mu^+\mu^-$
1979	**gluon** (m = 0)	e^+e^- ring (DESY)	30	$e^+e^- \to q\bar{q}g$ Three-jet events
1983	**W, Z** (m ~ 80, 91 GeV)	$p\bar{p}$ ring (CERN)	900	$W \to l\nu$ $Z \to l^+l^-$

- **Standard model particle spectrum is filling up quickly**
  - **Three families, but top quark missing**
  - **Higgs boson missing but $m_W \sim m_Z \cos\theta_W$: smoking gun for the Higgs mechanism**
- **Quantum structure not tested: requires precision measurements**

1987-2011: The rise of precision (1)

- 1987/1989: Start of SLC (linear e^+e^- collider) and LEP (e^+e^- collider ring)
  - Much larger luminosity at LEP, much faster commissioning
  - 1989@LEP: Only three species of light, active neutrinos – ν_e, ν_μ, and ν_τ
    - $e^+e^- \rightarrow Z \rightarrow$ hadrons at LEP1, measurement of the Z boson line shape

  - After 5 years at LEP1: per-mille precision

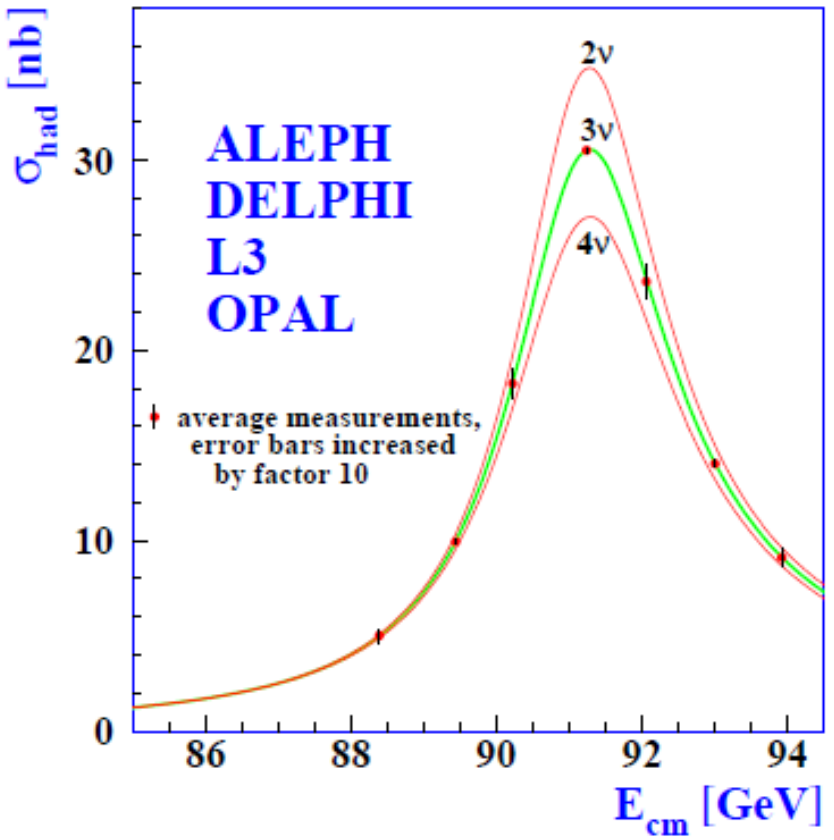
$N_\nu = 2.984 \pm 0.008$

(Note the 2σ deficit)

$\Gamma_Z = 2495.2 \pm 2.3$ MeV

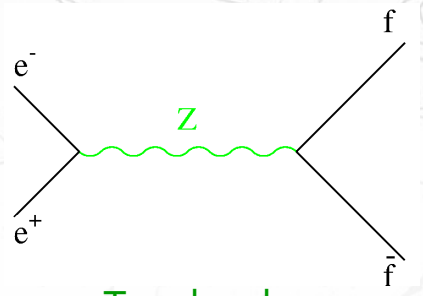
$m_Z = 91187.5 \pm 2.1$ MeV

$\alpha_s = 0.1190 \pm 0.0025$

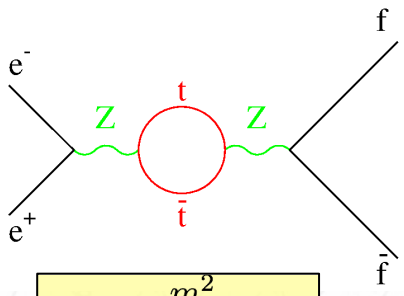


1987-2011: The rise of precision (2)

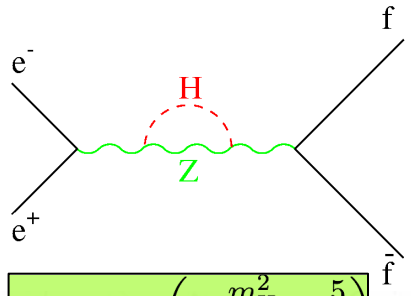
- **What is the use of such precision anyway**
  - **1994 Precision of the top quark mass**
    - **Remember quantum corrections from t'Hooft and Veltman work (1971)**



Tree level



$$0.002 \times \frac{m_t^2}{m_W^2} \simeq 1\%$$



$$-0.0006 \times \left(\ln \frac{m_H^2}{m_W^2} - \frac{5}{6} \right)$$

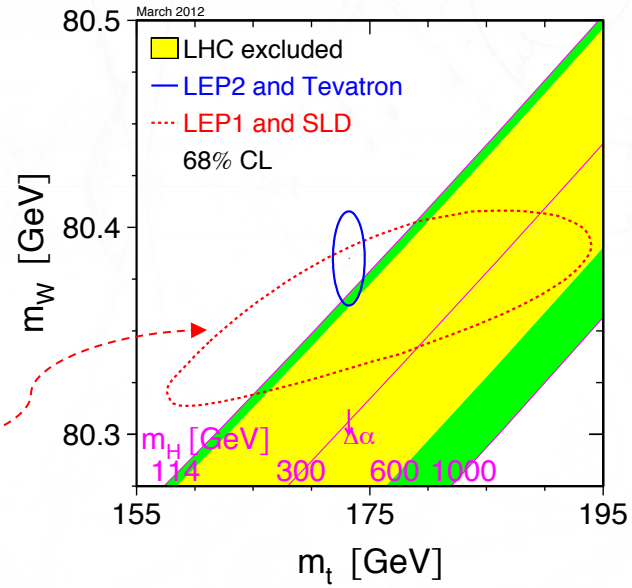
[small correction]

- **Example: $\Gamma_Z \rightarrow \Gamma_Z \times (1+\Delta\rho)$**

$$\Delta\rho = 0.0020 \times \frac{m_t^2}{m_W^2} - 0.0006 \times \left(\ln \frac{m_H^2}{m_W^2} - \frac{5}{6} \right) + \ldots$$

- **Similarly, $m^2_W = m^2_Z \cos^2\theta_W^{eff} (1+\Delta\rho)$**
  ($\sin^2\theta_W^{eff}$ from, e.g., asymmetries)

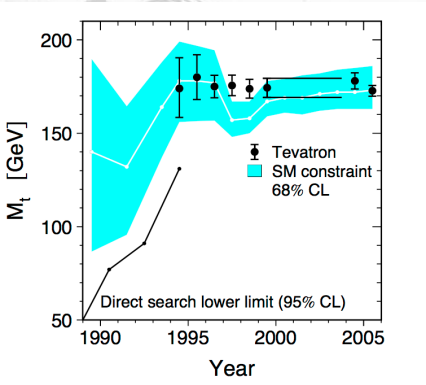
- **Precict m_W and m_{top} from Z measurements**

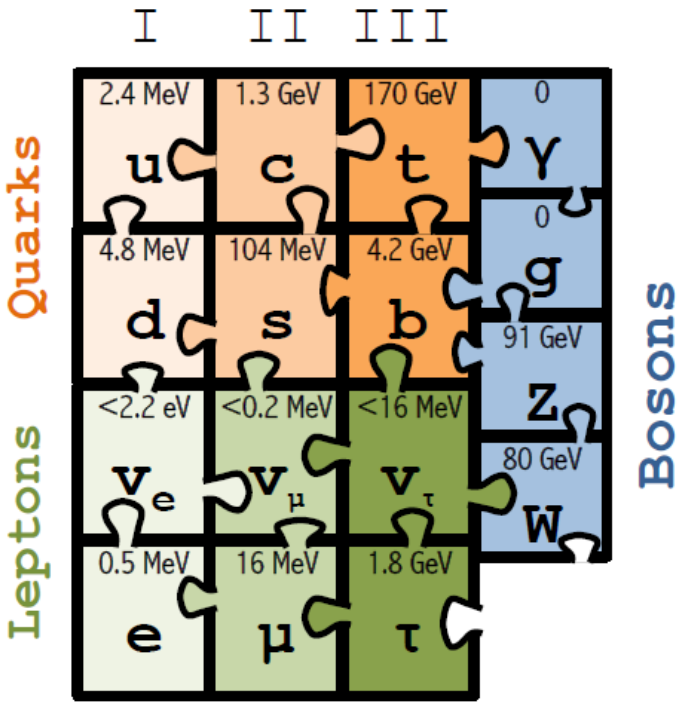


1987-2011: The rise of precision (3)

- **1995-2011: Testing the quantum structure of the standard model**
  - **1995: Discovery of the top quark at the Tevatron (D0, CDF)**
  - **1995-2011: Measurement of m_{top} (Tevatron)**
    - **m_{top}(Obs.) = 173.2 ± 0.9 GeV**
    - **m_{top}(Pred.) = 178.0 ± 4.3 GeV** [LEP/SLD/m_W , for m_H = 150 GeV]
  - **1997-2011: Measurement of m_W (LEP2, Tevatron)**
    - **m_W(Obs.) = 80385 ± 15 MeV**
    - **m_W(Pred.) = 80363 ± 20 MeV** [LEP/SLD/m_{top}]
  - **1999: Nobel Prize for t'Hooft and Veltman**
  - **Standard Model almost complete**
    - **Only the Higgs boson is missing, but …**
    - **Prediction from Higgs mechanism**
      - **$m^2_W = m^2_Z \cos^2\theta_W (1+\Delta\rho)$**

        Verified!





1987-2011: The rise of precision (4)

- **1989-2011: Looking for the Higgs boson's imprint**
  - **1999-2011: The Higgs boson is cornered by all precision measurements**
    - **Remember (for example)**
      - $m^2_W = m^2_Z \cos^2\theta_W (1+\Delta\rho)$

$$\Delta\rho = 0.0020 \times \frac{m_t^2}{m_W^2} - 0.0006 \times \left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots$$

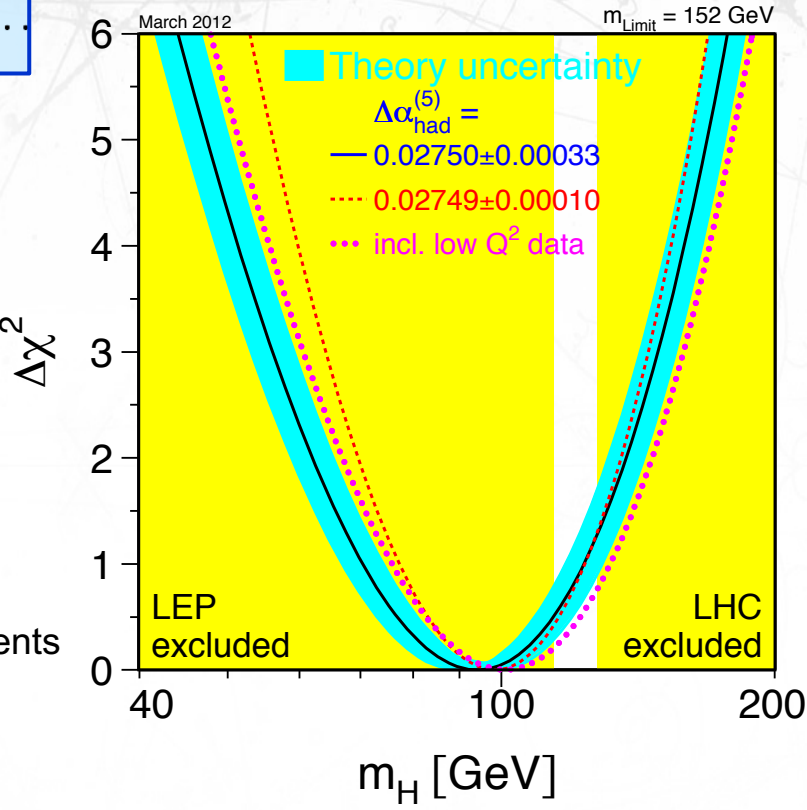
  - **m_Z, m_{top} and m_W are known with precision**
    - **The standard model has nowhere to go !**

114 GeV < m_H < 152 GeV

[LEP/SLD/m_W/m_{top}]
at 95% CL

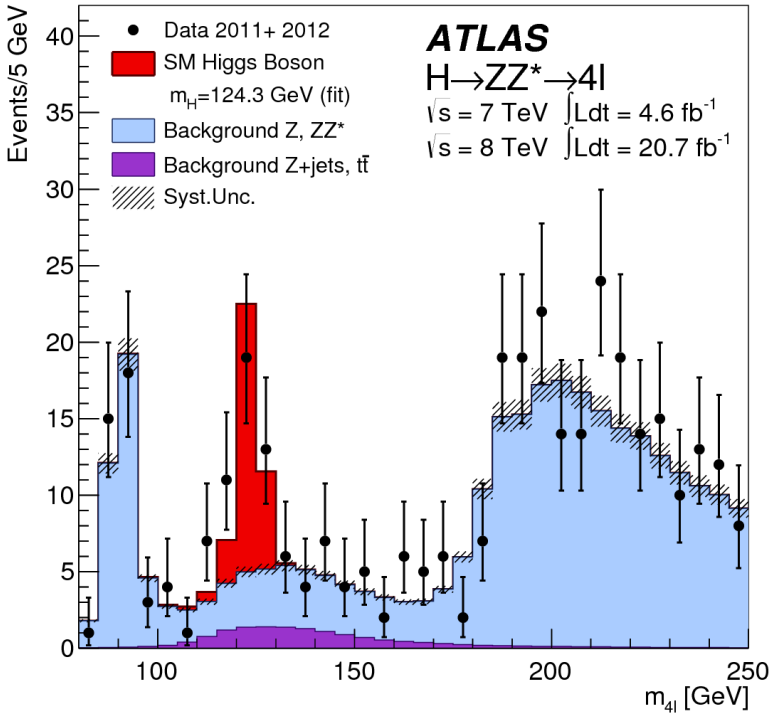
Direct searches @ LEP
Just 10 GeV below the target.
(important for the future!)

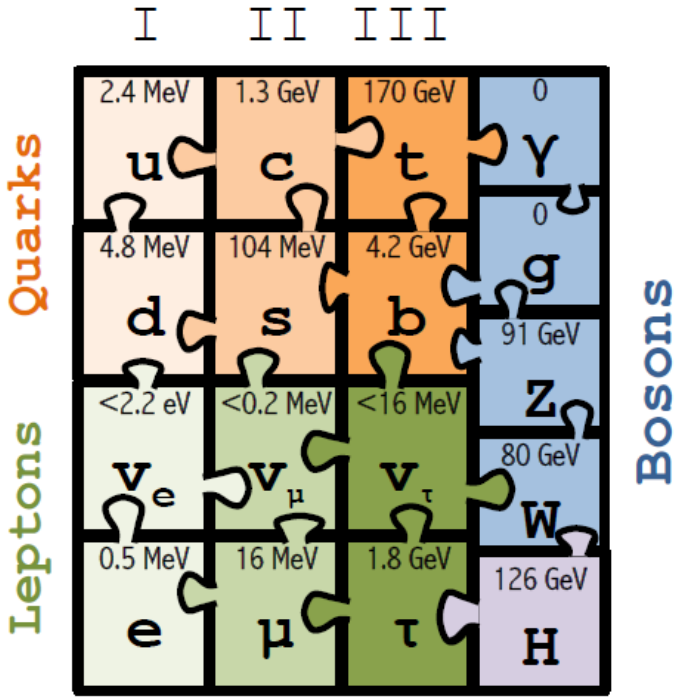
Fit to precision measurements



2012-14: The SM becomes the Standard Theory

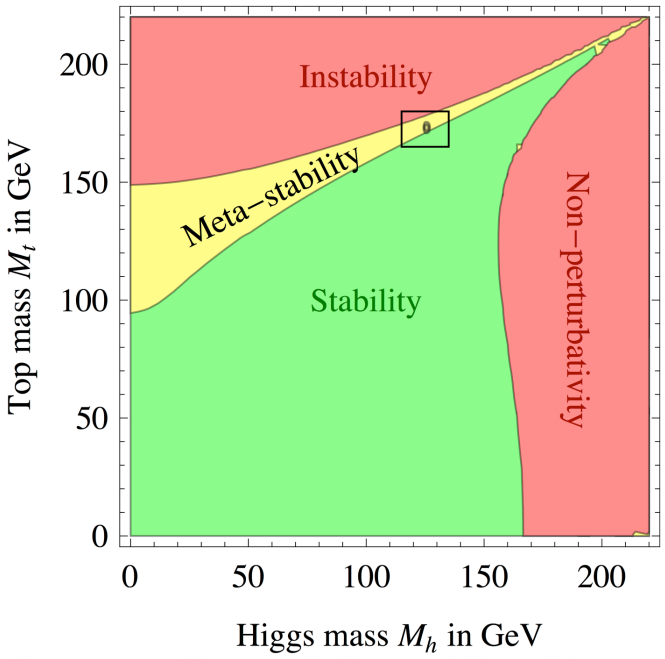
- **2012-2014: The Higgs boson era**
  - **2012: Discovery of the standard model Higgs boson at the LHC (ATLAS, CMS)**
    - **m_H = 125.4 ± 0.5 GeV (ATLAS), 125.0 ± 0.3 GeV (CMS)**
    - **Mass, couplings, spin, width in agreement with Standard Theory predictions**
  - **2010-2013: No new physics found at the LHC Run1 at the TeV scale**
  - **2014: Nobel Prize to Englert and Higgs**

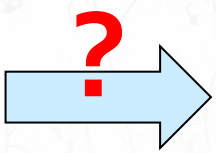


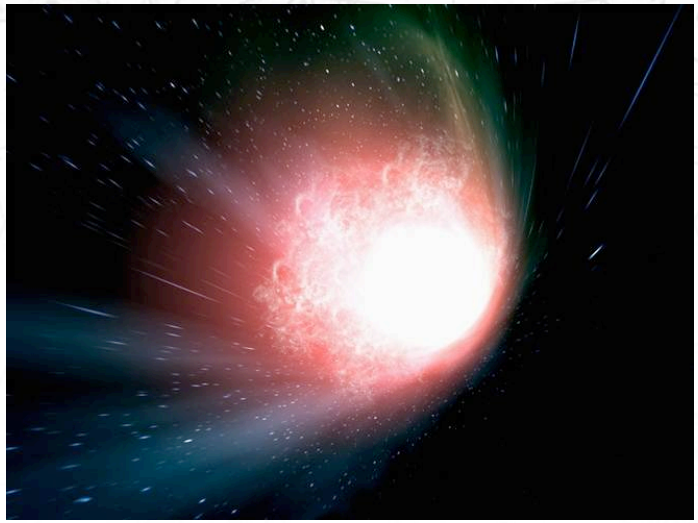


And now, what ?

- **The Standard Model has become the Standard Theory**
  - **It explains/describes all observations and measurements from high-energy colliders**
    - **It is also able, in principle, to predict all measurements at future colliders**
      - **As well as the fate of the Universe …**





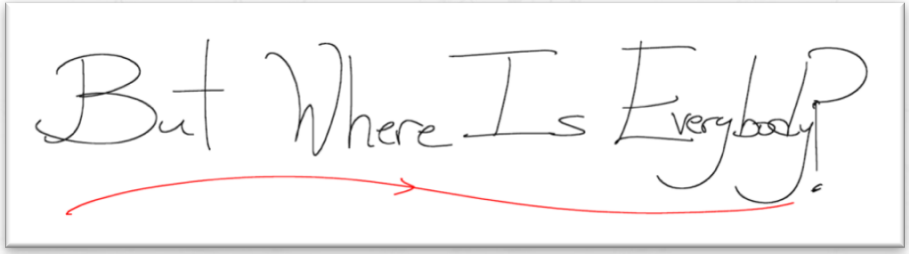


- **On the theory side, no new physics is needed beyond this Standard Theory**

- **Is this the end ?**

It is (most likely) not the end …

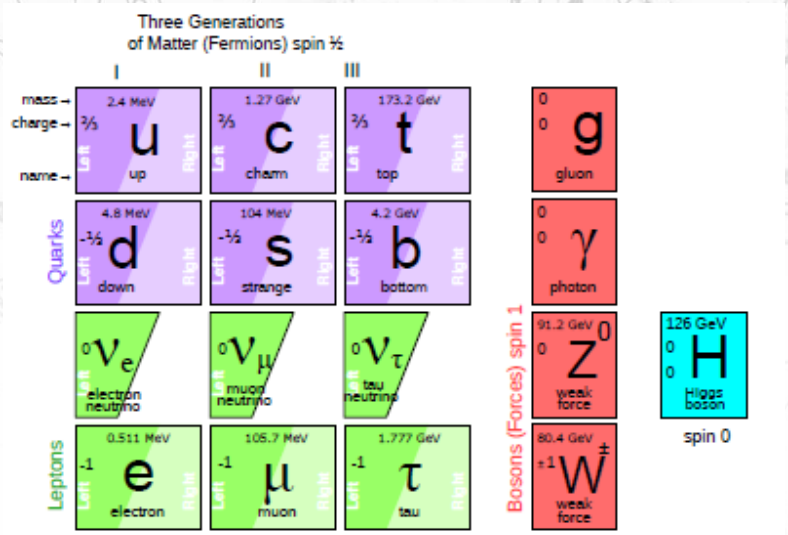
- There seems to be something beyond the Standard Theory
  - Many unanswered fundamental questions all based on experimental observations, e.g.
    - Why 3 generations of fermions ?
    - Why is the Higgs boson so light (so-called "naturalness" or "hierarchy" problem) ?
    - What is the origin of neutrino masses and oscillations ?
    - What is the composition of dark matter (5 times the mass of baryonic matter) ?
    - Why is gravity so weak ?
    - What is the origin of the matter-antimatter asymmetry in the Universe [BAU] ?
    - What is the origin of the Universe's accelerated expansion ?
- New Physics?
  - Many diverse theoretical ideas…

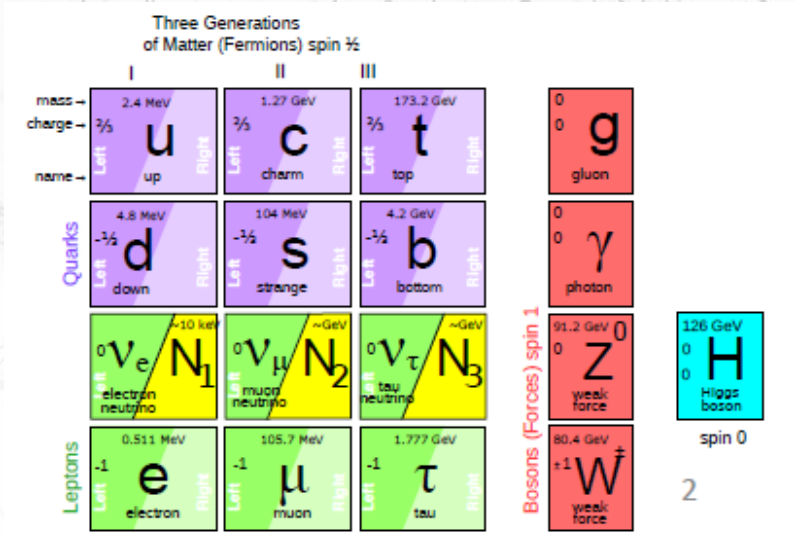


  - Is new physics at larger masses ? Or at smaller couplings ? Or both ?
    - Only way to find out: *go look*, following the historical approach:
      - Direct searches for new heavy particles
        - ⇒ Need colliders with ***larger energies***
      - Searches for the imprint of new physics on W, Z, top, and Higgs properties
        - ⇒ Need colliders / measurements with ***unprecedented accuracy***

Precision vs Energy (1)

- **The Standard Theory is complete ? Obviously three pieces missing !**

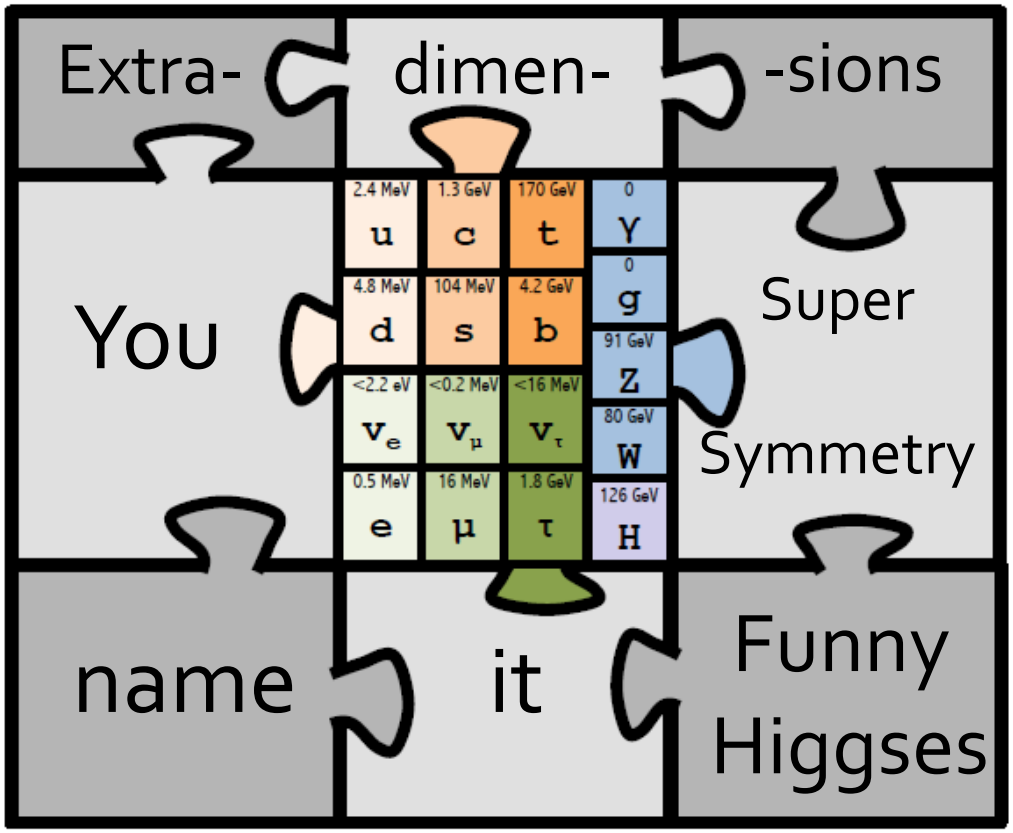




- **Three right-handed neutrinos ?**
  - **Extremely small couplings, nearly impossible to find but could explain quite a bit !**
    - **Small m_ν (see-saw), DM (light N_1), and BAU (leptogenesis)**
  - **Need very-high-precision experiments to unveil**
    - **Could cause a slight reduction (increase) in the Z (H) invisible decay width**
    - **Could open exotic Z and Higgs decays: Z, H → $\nu_i N_i$**
      - **Possibly measurable / detectable in precision e^+e^- collisions**
      - **Most likely out of reach for hadron colliders (small couplings)**

Precision vs Energy (2)

- Others lean towards higher-energy replicas of the standard theory



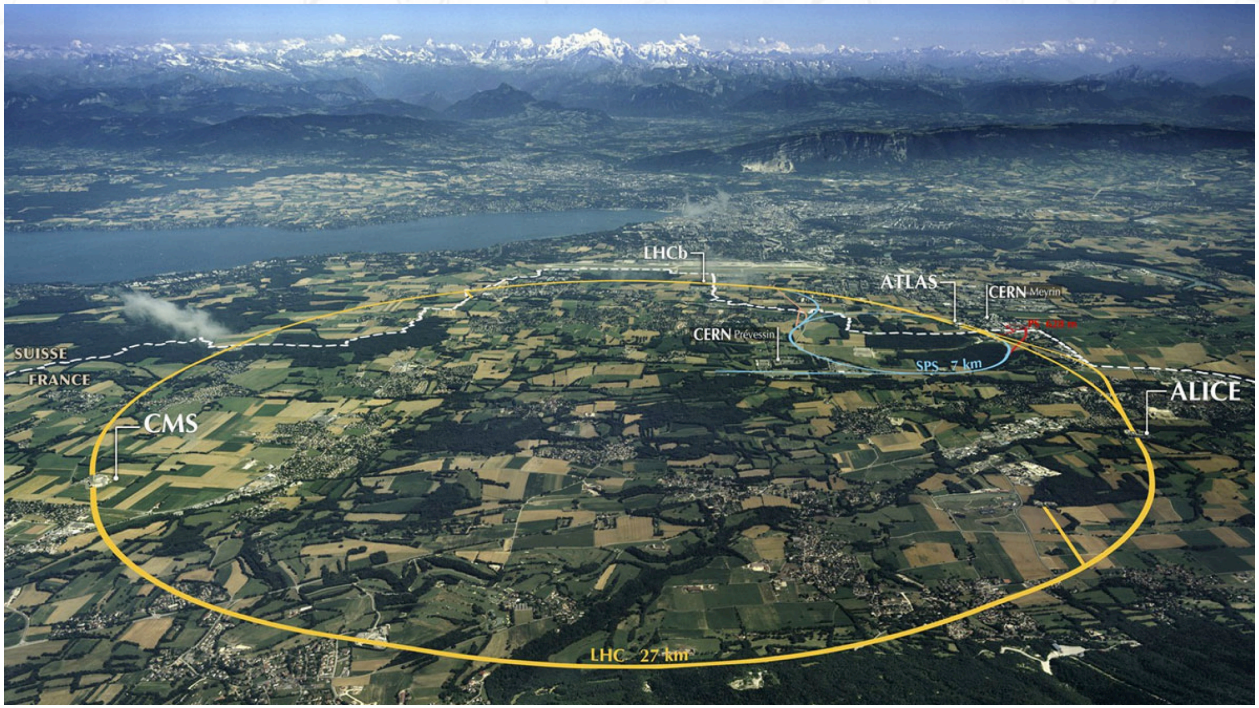
- Direct searches at larger energies may be the key – but how much larger ?
  - Rare decays and precise measurements may also unveil these extension's imprints

Lecture 1 (cont'd)

A strategy for the future:
Towards the precision and energy frontiers

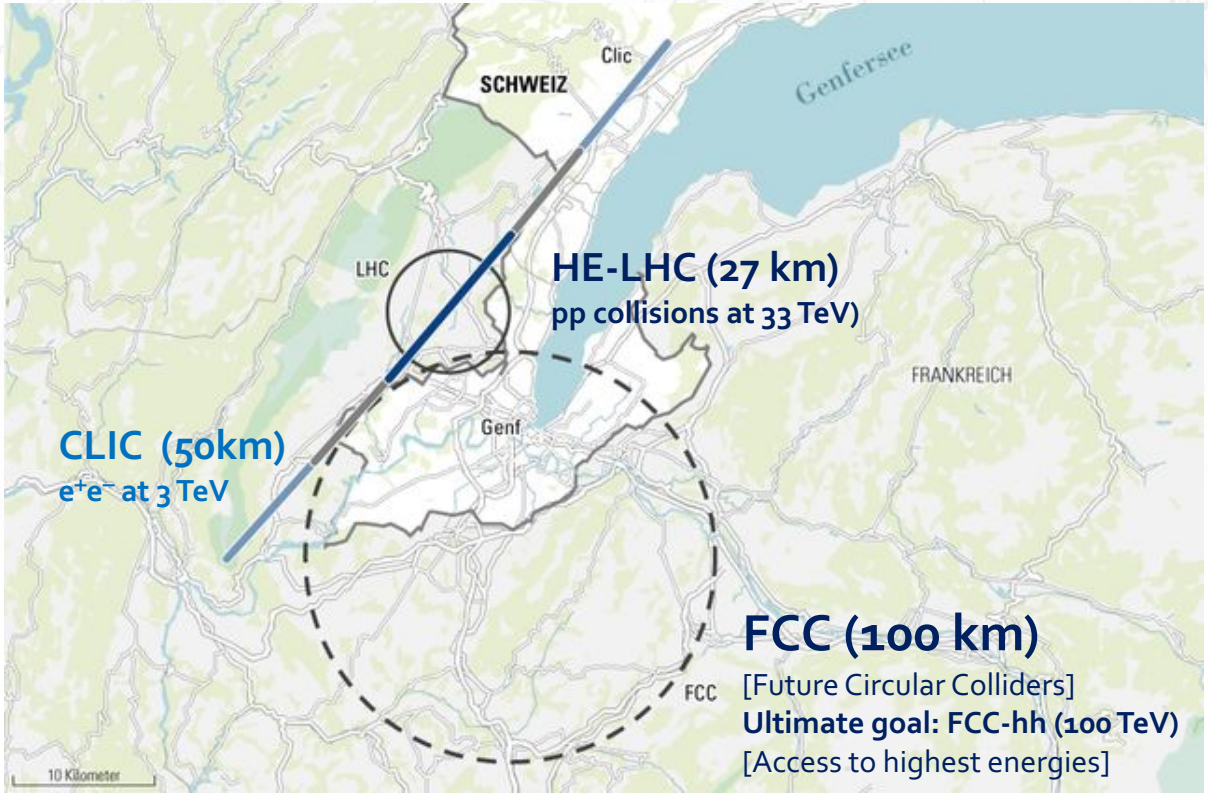
Short-term perspectives (2020-2035)

- In May 2013, European Strategy said (very similar statements from US)
  - Exploit the full potential of the LHC until ~2030 as the highest priority
    - Get 75-100 fb^{-1} at 13-14 TeV by 2018 (LHC Run2: running)
    - Get ~300 fb^{-1} at 14 TeV by 2022 (LHC Run3: approved)
    - Upgrade machine and detectors to get 3 ab^{-1} at 14 TeV by 2035 (HL-LHC: approved)
      - A first step towards both energy and precision frontier

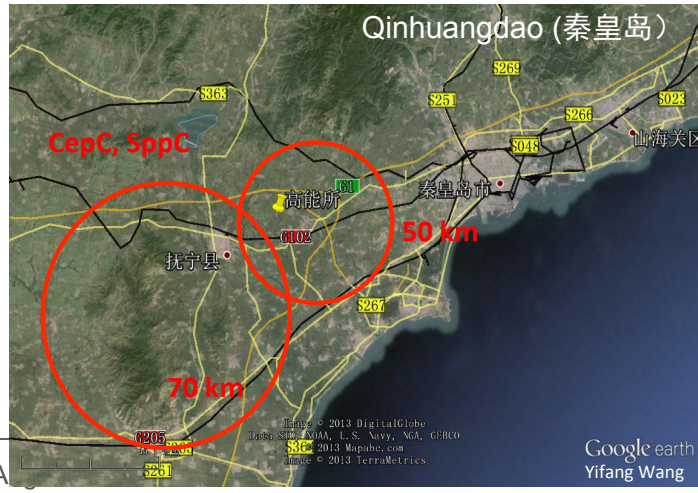


Long-term perspectives (2045-2080)

- In May 2013, European Strategy said (very similar statements from US)
  - Perform R&D and design studies for high-energy frontier machines *at CERN*
    - HE-LHC, a programme for an energy increase to 28 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at √s = 100 TeV
    - CLIC, an e^+e^- collider project with √s from 0.3 to 3 TeV



Similar circular projects
(50, 70, or 100 km) in China
pp collisions at √s ~ 50 or 70 TeV



Mid-term perspectives (2030-2045)

- **In May 2013, European Strategy said (very similar statements from US)**
  - **Acknowledge the strong scientific case of e^+e^- colliders with intermediate $\sqrt{s}$**
    - **Participate in ILC if Japan government moves forward with the project**
    - **In the context of the FCC, perform accelerator R&D and design studies**
      - **In view of a high-luminosity, high-energy, circular e^+e^- collider as a first step**

FCC (100 km)

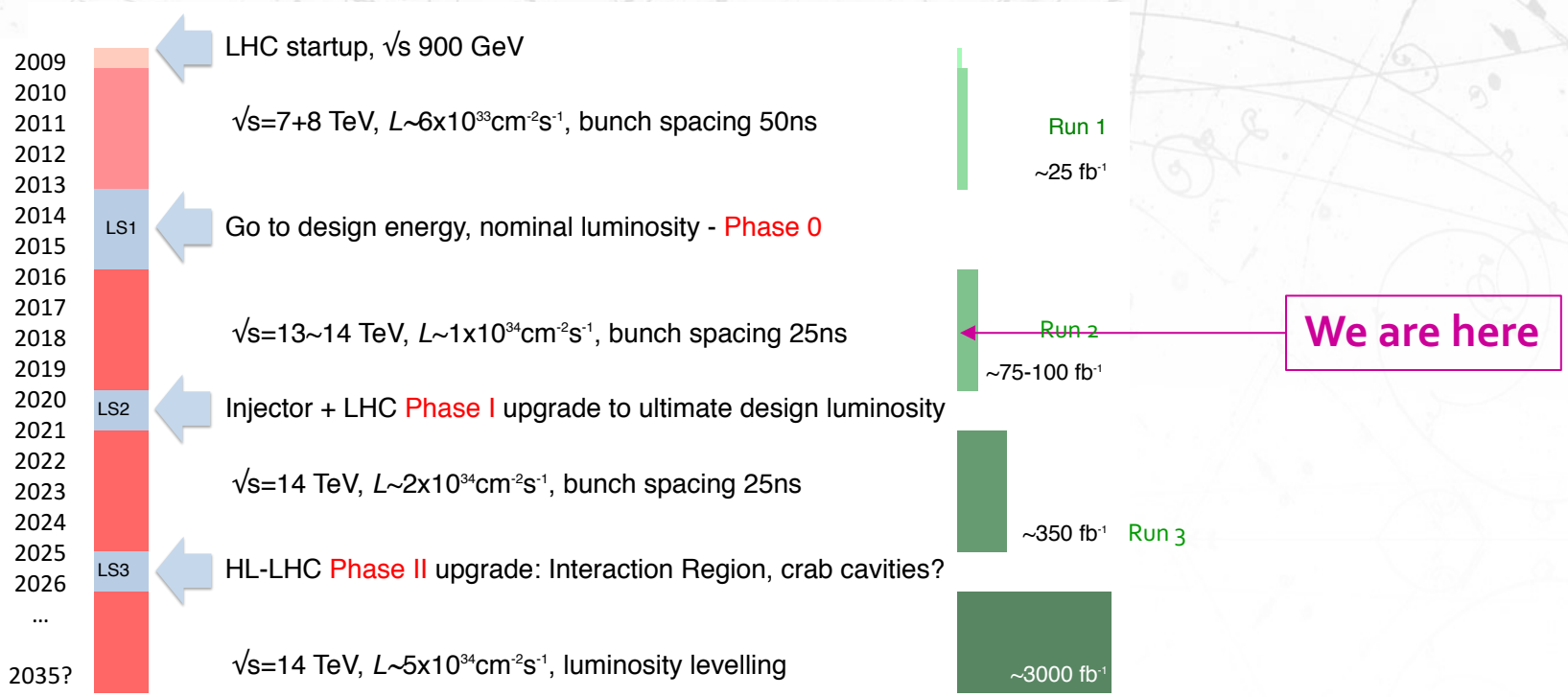
First step: FCC-ee (91-400 GeV)

[Use the tunnel ultimately aimed at FCC-hh]

Note: CLIC can also run at $\sqrt{s}$ ~380 GeV in ~2035-2040

Can / should we do everything ? (1)

- The cost (10's B$) and challenges of these projects are paramount
  - A choice will have to be made at one point, but it would be too early to make it now
    - The LHC, indeed, is still rather in its infancy



- The 14 TeV Run2 is under way: new data might bring a whole new light on the process
  - Next check point after LHC Run2 for the next European strategy update in 2019-20

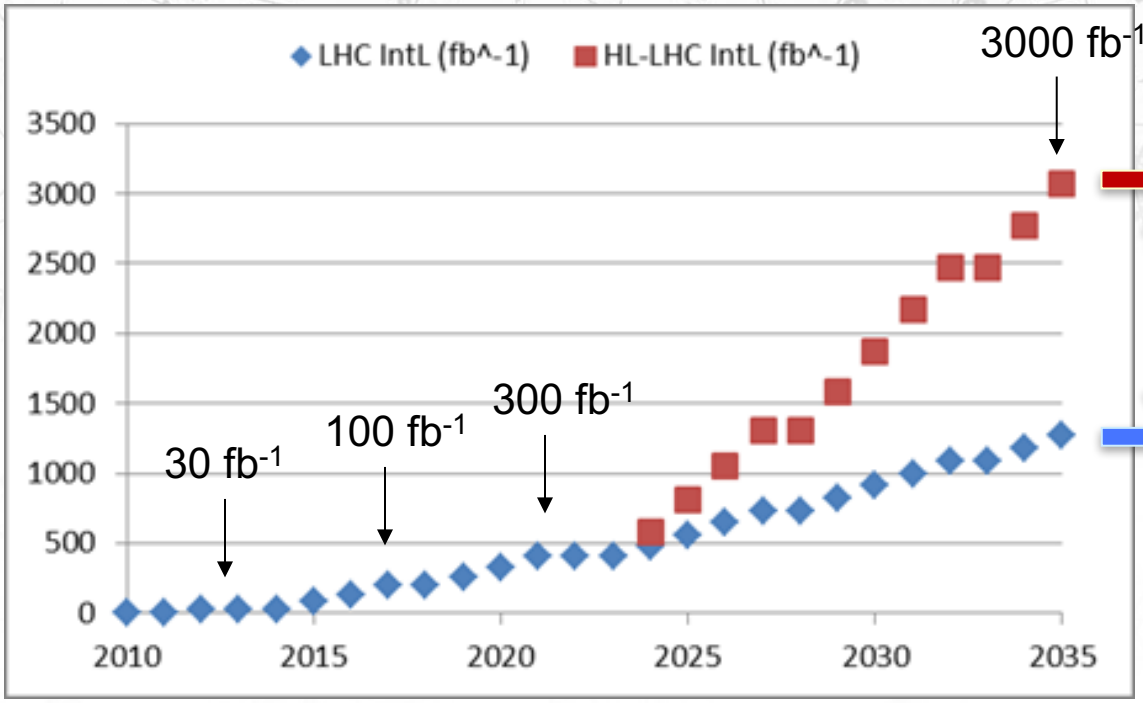
Can / should we do everything ? (2)

- **Hand-waving anticipation: With the 14 TeV LHC Run2 data, we may**
  - **Find a new heavy particle (or new heavy particles)**
    - The (HL-) LHC will study this (these) particles to some extent
    - If m < 3 TeV, CLIC becomes interesting (if copiously produced in e^+e^- collisions)
    - Larger energies might be needed to find & study the whole new spectrum (FCC-hh)
    - An e^+e^- Z factory (FCC-ee) might be useful to study the underlying quantum structure
      - Note: m_H and m_{top} were predicted *correctly* with no new physics
        - New physics will probably be very difficult to find anyway
  - **Find no new particle, but find a hint for non-standard Higgs properties**
    - The (HL-) LHC will improve the precision on these measurements to some extent
    - e^+e^- factories for Higgs (ILC, FCC-ee) become very interesting machines
    - Push the energy frontier to its limits (CLIC, FCC-hh)
  - **Find no new particle, and standard Higgs properties**
    - Push precision measurements to their limits (FCC-ee)
    - Possibly push energy frontier to its limits (CLIC, FCC-hh)
- **Let's now try to quantify the respective merits of all options**

Short-term perspective (2020-2035):
The (HL)-LHC: Physics prospects

Expected integrated luminosity at HL-LHC

- **The High Lumi upgrade of the LHC is an ambitious project**
  - **Target is to deliver ~ 10 times more luminosity (3 ab^{-1}) than the first 10 LHC years**



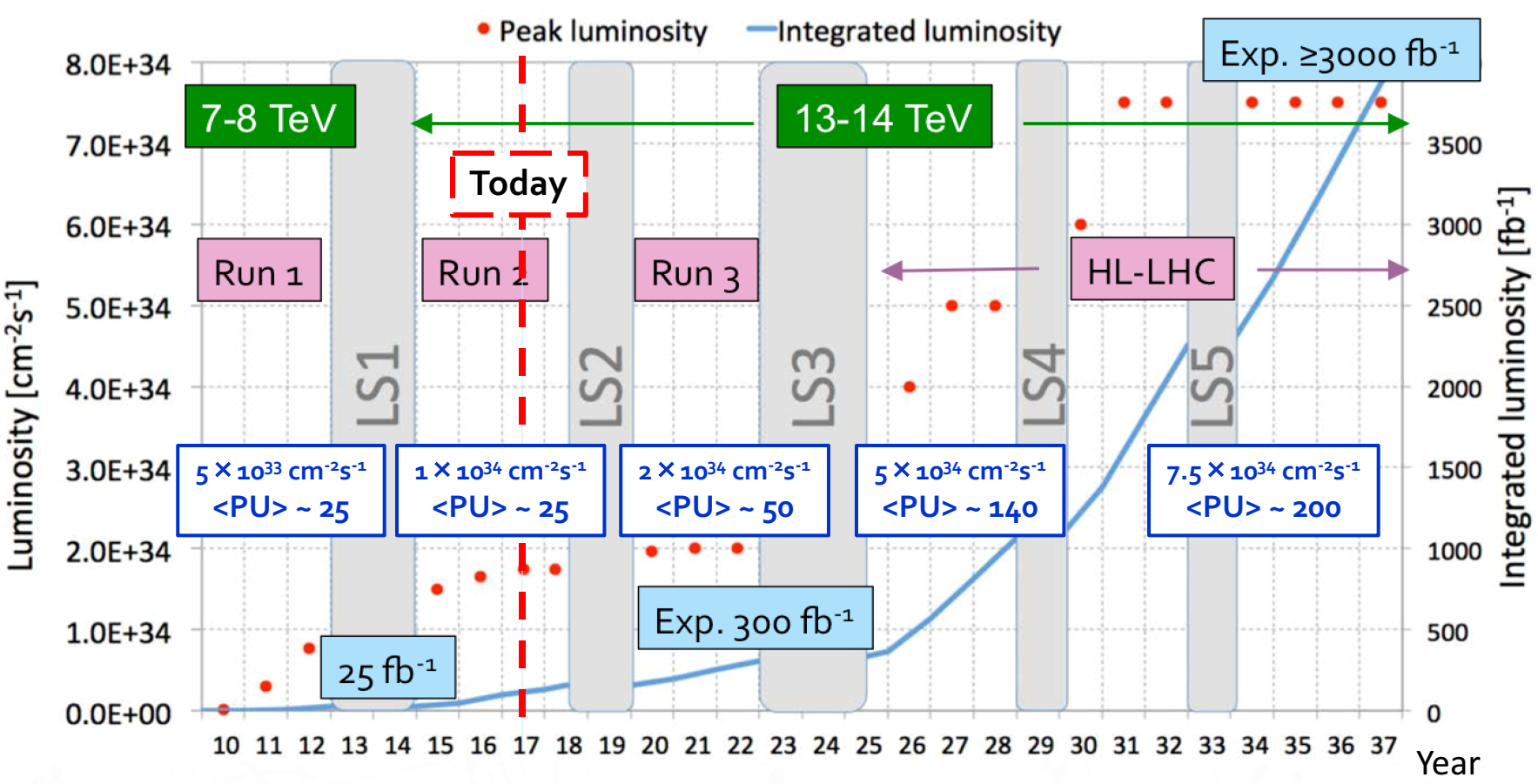
By implementing HL-LHC

Factor 2.5 - 3

By continuous performance improvement and consolidation

- **Project timeline driven by radiation damage to the machine components**
  - **Expected end of lifetime around 2023**

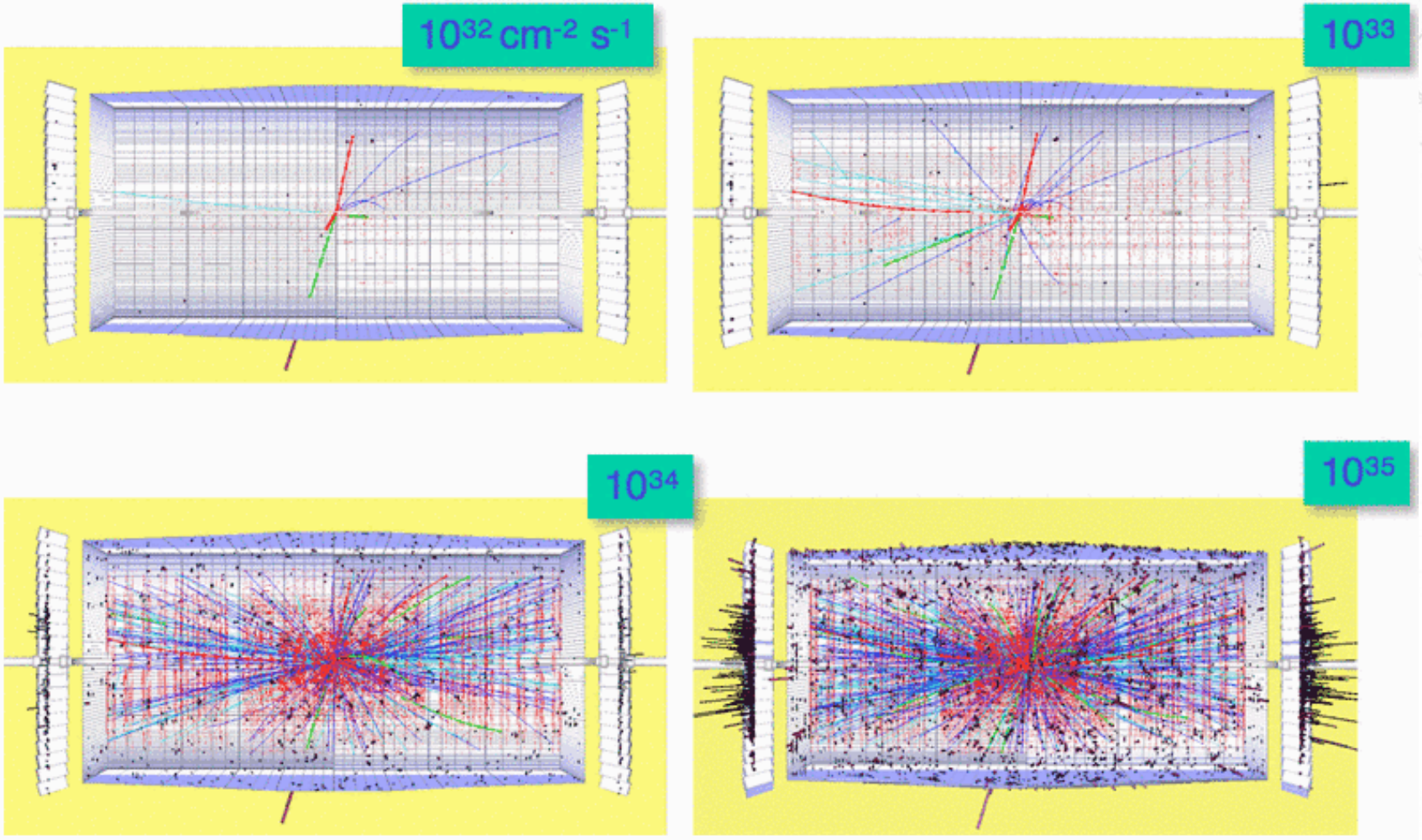
LHC Schedule



- **LHC Run2 (and, to a lesser extent, Run3)**
  - **Conditions similar to those of LHC Run1 for "in-time" pile-up**
    - **Increase of "out-of-time" pile-up from the 50 → 25 ns bunch separation**
- **HL-LHC**
  - **Large increase of "in-time" and "out-of-time" pile-up**

Expected pile-up interactions at HL-LHC (2)

- **Why do we care ?**
  - **A simulated H → ZZ → eeμμ with 0, 2, 20 and 200 in-time PU events (p_T^{cut} = 1 GeV)**



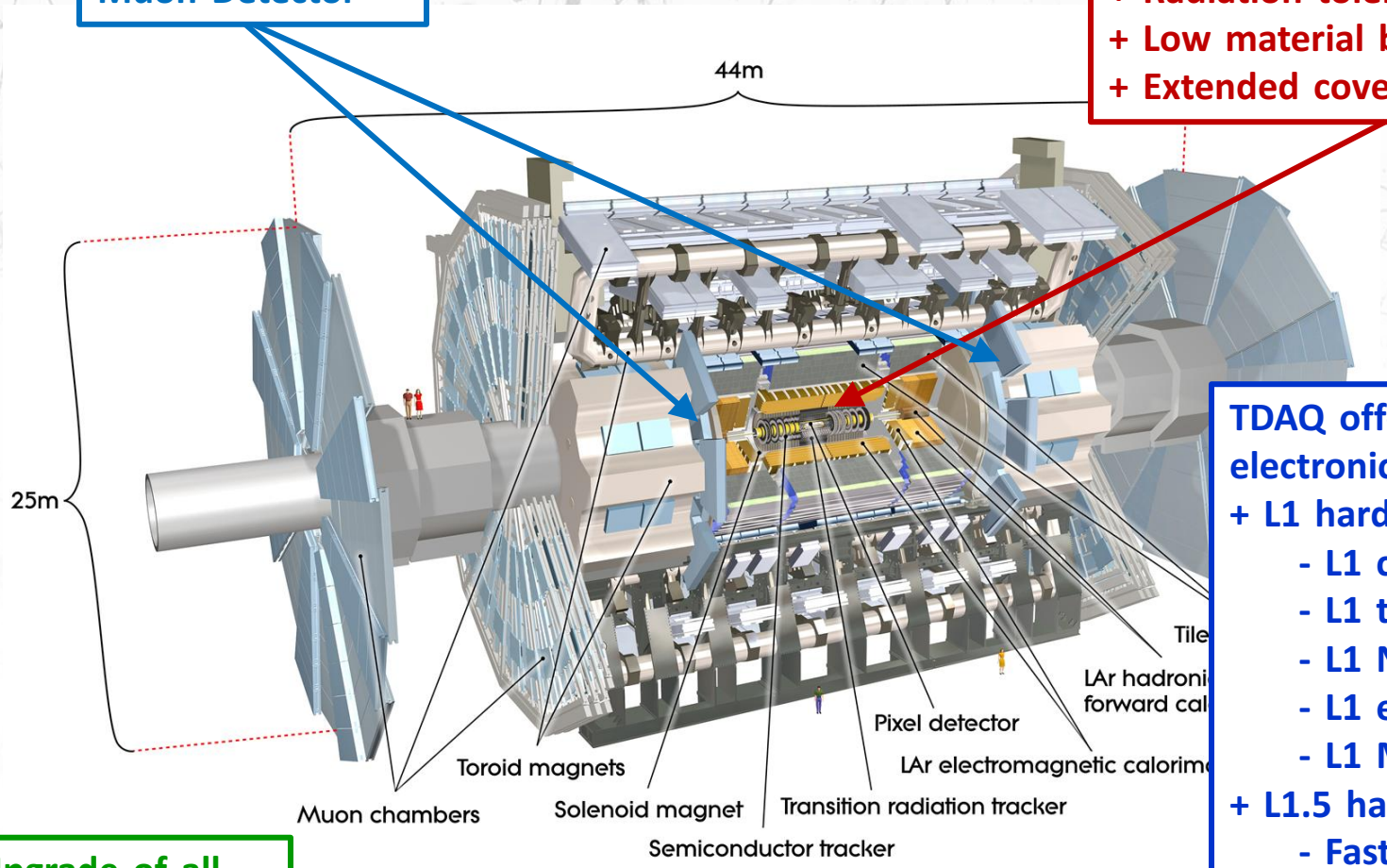
Expected pile-up interactions at HL-LHC (3)

- **Why do we care ? (cont'd)**
  - **Heavy new particles tend to decay to Z, W, H, top, dark-matter particles**
    - **Which in turn give characteristic signatures**
      - **Isolated leptons (e, μ, τ) and photons**
      - **Missing transverse energy (neutrinos, DM, …)**
      - **High-p_T b-quark jets**
  - **If nothing is done, intense pile-up degrades**
    - **The reconstruction of charged particle tracks**
      - **CPU, Fakes, Efficiency, b tagging**
    - **The separation of calorimetric clusters**
      - **Particle flow reconstruction performance**
    - **The effectiveness of isolation cuts**
      - **Lepton selection**
    - **The missing transverse energy resolution**
      - **Dominated by pile-up + all the above**
    - **The trigger capabilities – a killer !**
  - **Vigorous detector/trigger/software/algorithmic upgrades required at HL-LHC**

ATLAS Detector Upgrade

New Small Wheel
Muon Detector

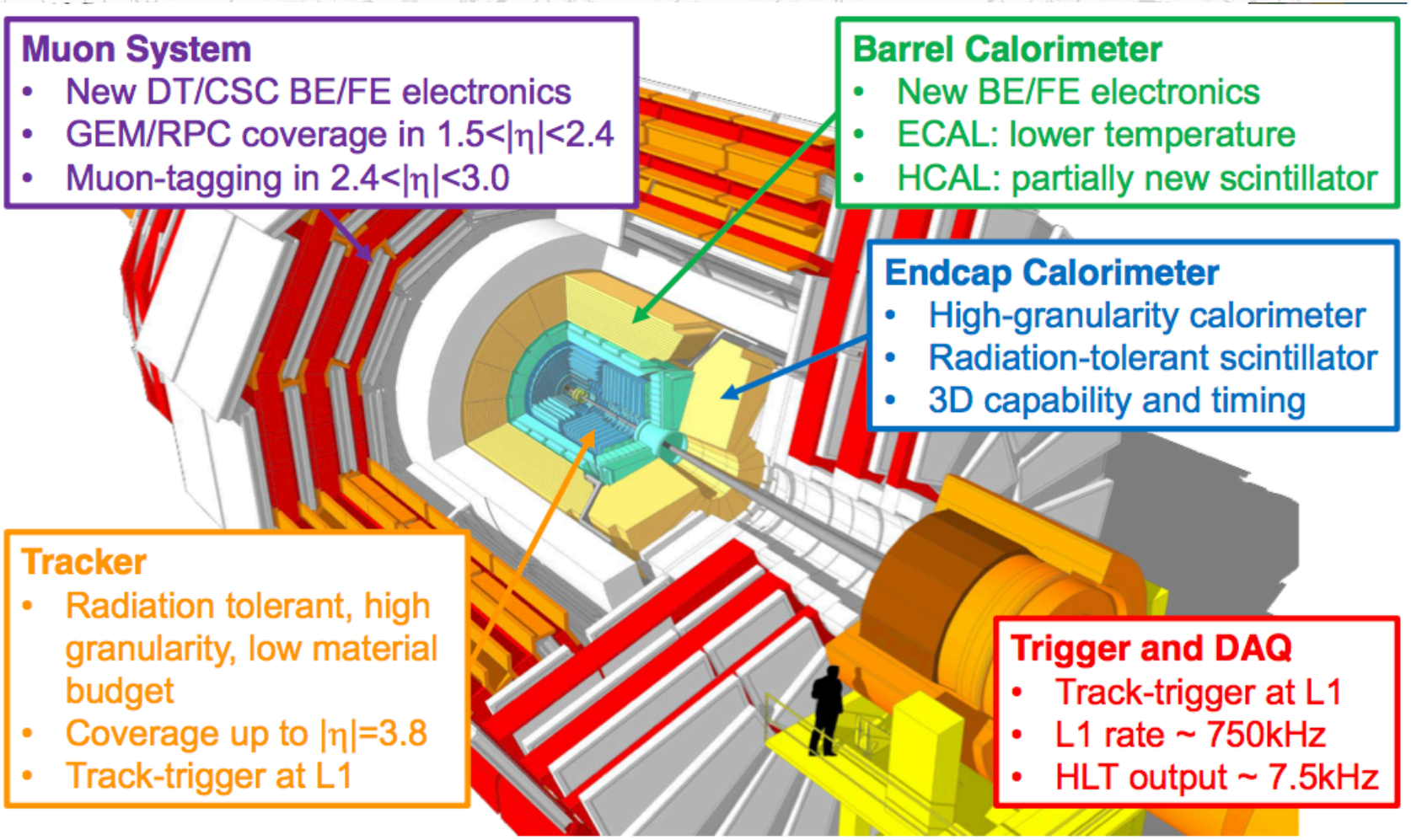
New all-silicon Inner Tracker:
+ Radiation tolerant
+ Low material budget
+ Extended coverage to $|\eta|<4.0$



TDAQ off-detector electronics:
+ L1 hardware trigger
  - L1 calorimeter
  - L1 topological
  - L1 NSW trigger
  - L1 endcap trigger
  - L1 MuCTPi
+ L1.5 hardware trigger:
  - Fast track trigger
+ Readout system
+ HLT

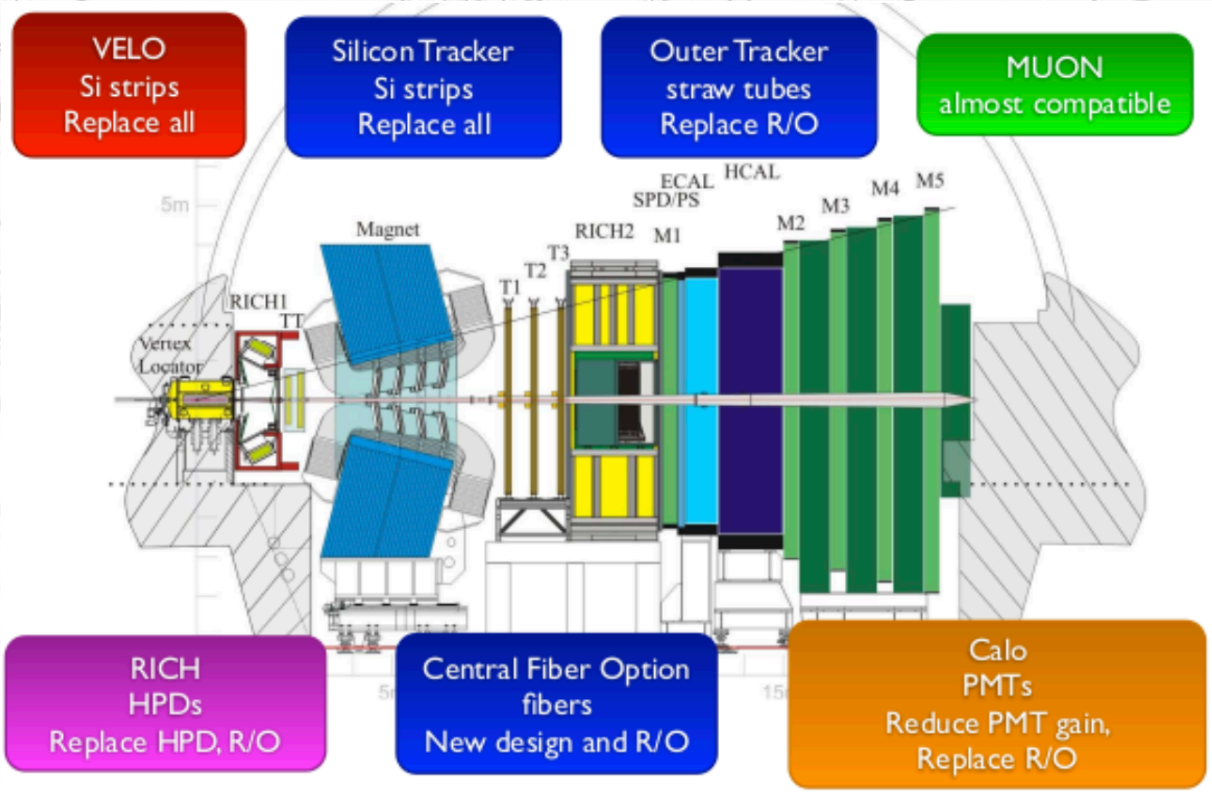
Upgrade of all front-electronics

CMS Detector Upgrade



LHCb Detector Upgrade

- Increased trigger rate
  - With 50,000 CPU
  - Offline-quality recostruction
- Lighter VELO
  - Twice better IP resolution
- More granular tracker
  - And radiation tolerant
- Improved RICH optics
  - Twice smaller pion misID
- New time-of-flight measurement: TORCH
  - Improved identification capabilities
- Calorimeter and muon system upgrades
  - To stand 50 fb^{-1}



Physics prospects with HL-LHC (1)

- **Preliminary remarks**
  - The HL-LHC was approved in June 2016
  - The final design choices for the upgraded detectors have been recently made
  - Large scale full simulation of the upgraded detectors is not yet available
    - Event reconstruction will need significant developments
      - Future performance for physics studies can only be inferred
  - The projections presented in the coming slides
    - Are often based on either parametric or fast simulations (or even extrapolations)
    - Rely on a number of assumptions (may be realistic … or not)
      - On the effect of pile-up on detector and reconstruction performance
      - On the statistical improvement of systematic uncertainties
      - On the improvement of theory calculations
    - Use simplified models, for simplified conclusions
    - But give a reasonable idea of the HL-LHC physics prospects
  - A lot of work remains to be done (by *You*) from detector R&D to physics analyses

Physics prospects with HL-LHC (2)

- **Physics programme at the (HL-)LHC in a nutshell**
  - **Electroweak physics**
    - Measure top (and W?) masses, rare top decays
    - Measure triple and quartic gauge couplings
    - Study vector boson scattering

    G. Hamel de Monchenault
  - **Higgs physics**
    - Measure Higgs mass, width, CP, …
    - Measure Higgs couplings to other particles, rare Higgs decays
    - Measure Higgs self-coupling

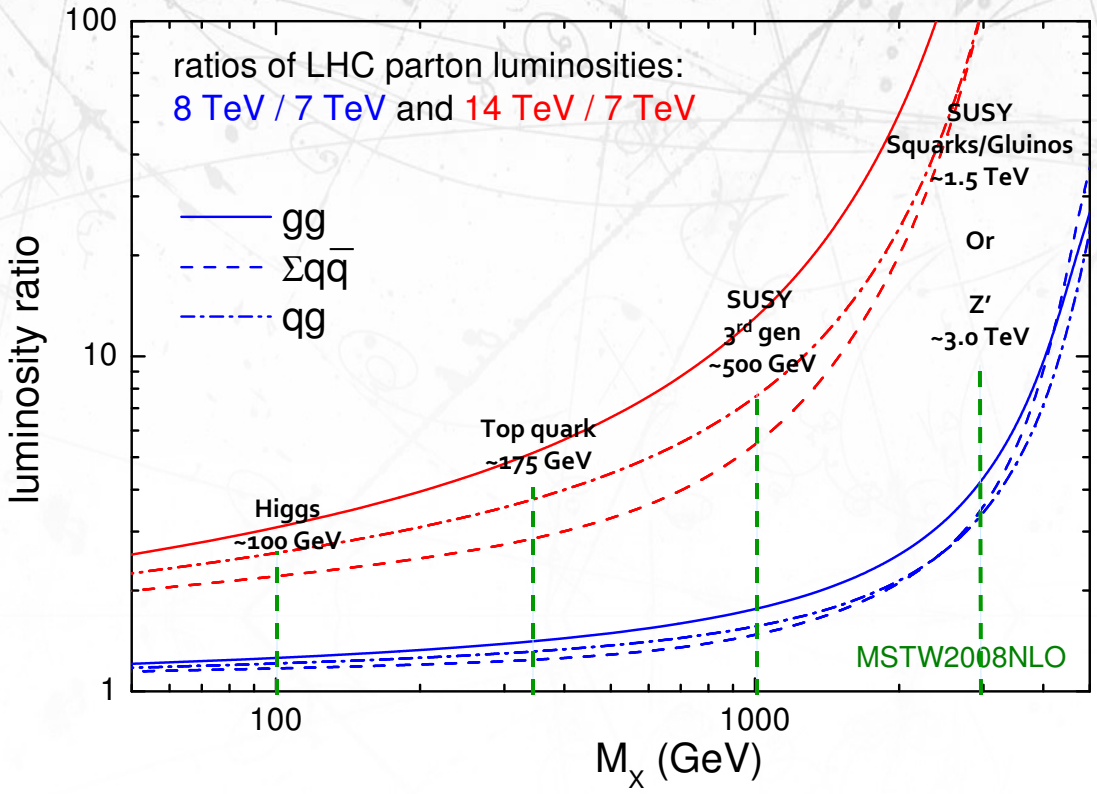
    G. Hamel de Monchenault
  - **Search for new heavy physics**
    - Supersymmetry
    - Extra-dimensions (new resonances, black holes)
    - Quark substructure (compositeness)
    - Fourth generation
    - New gauge bosons

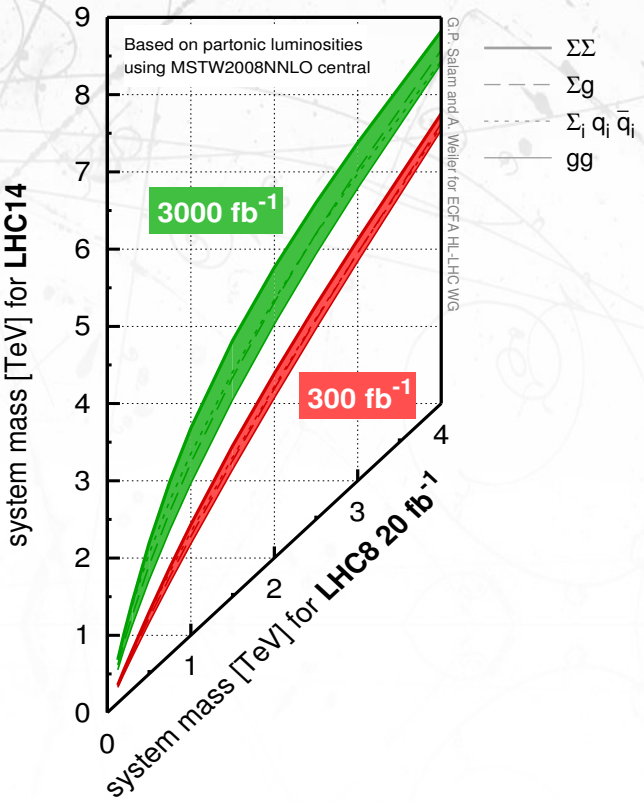
    G. Brooijmans
  - **Flavour physics**
    - Indirect sensitivity to very heavy new physics (10-10^5 TeV)

    G. Isidori
  - **Only a few highlights are given here. Details in Gautier's, Gustaaf's and Gino's lectures**

Physics prospects with HL-LHC (3)

- **Physics programme at the LHC in a nutshell (cont'd)**
  - **The energy increase from Run1 (7/8 TeV) to Run2 (13/14 TeV) is very exciting**

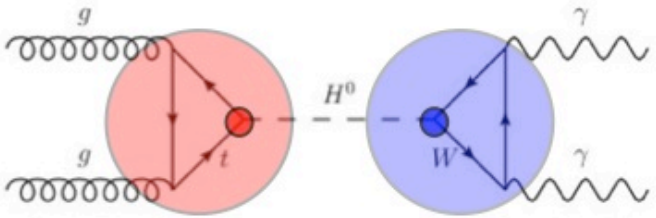




  - **More energy buys a lot, both for precision and new physics reach**
    - **Cross sections multiplied by 3, 5, 10, 100 at m = 0.1, 0.35, 1 and 3 TeV**
    - **Mass reach for new physics roughly doubled**

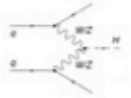
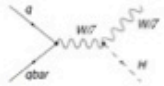
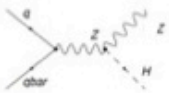
Precision Higgs physics (1)

- **Reminder: production and decays**
  - **Want to test if the Higgs particle couples as predicted by the Standard Model**



√s = 7 TeV

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

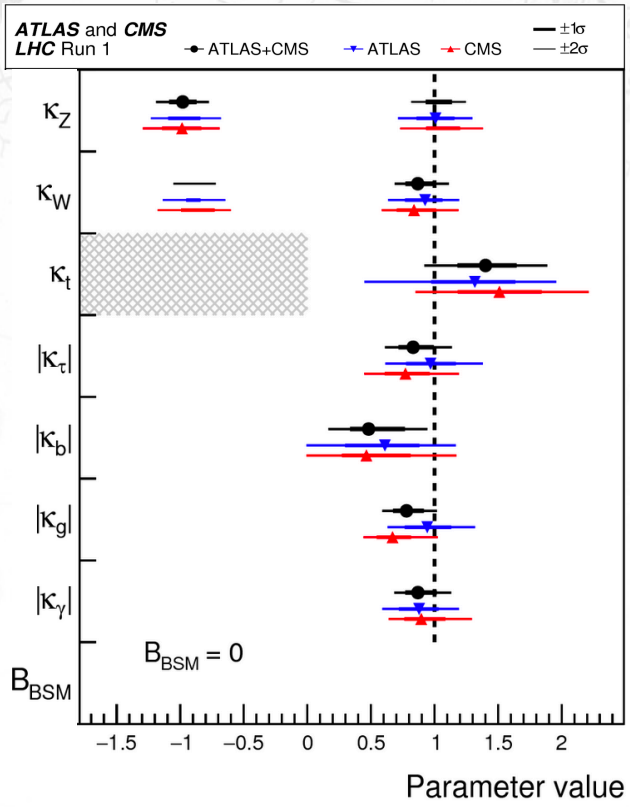
m_H = 125 GeV

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
ΓH [MeV]	4.07	4.0

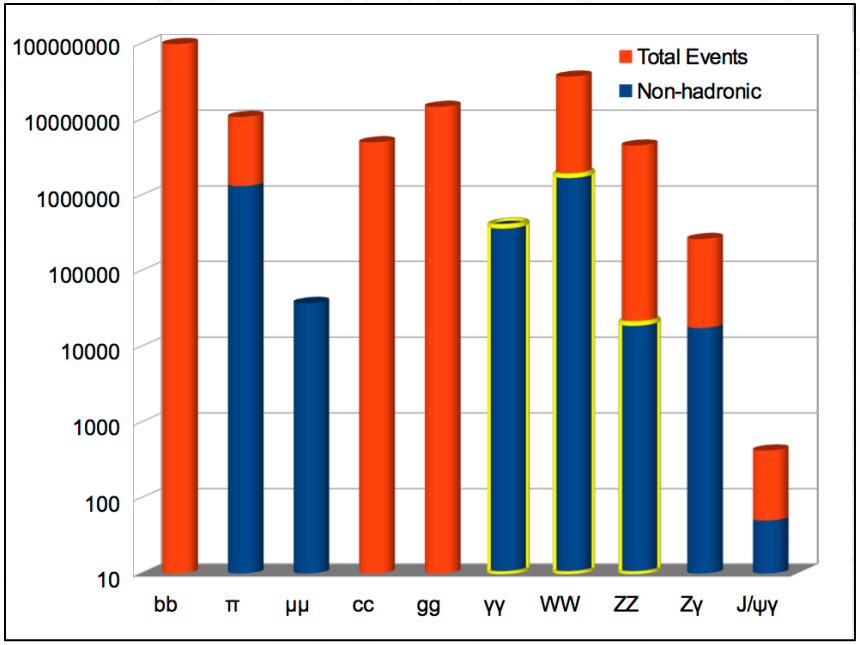
* uncertainties need improvements for future precision measurements

Precision Higgs Physics (2)

- **Higgs couplings after Run1**
  - 1400 Higgs events after selection
  - Measured couplings so far:
    - Z, W, top, b, τ, g, and γ



- **HL-LHC (3 ab^{-1})**
  - 170 M Higgs produced per experiment
    - ~ 1 million events after selection
  - HL-LHC will be the first Higgs factory
    - With access to rare decays
      - H → μμ, Zγ



- Typical precision: 15 to 50%

- Typical precision: 2 to 10%

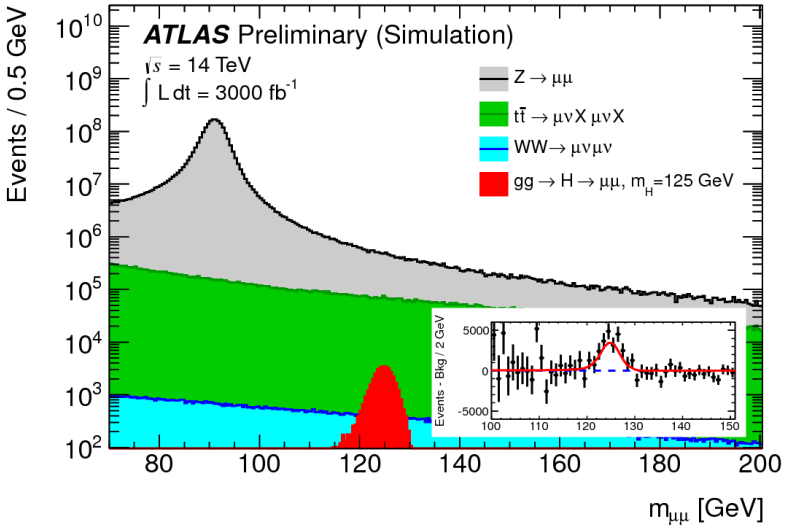
Precision Higgs physics (3)

- **Higgs couplings projections (cont'd)**

Coupling	LHC Run1	LHC (300 fb^{-1})	HL-LHC (3000 fb^{-1})
κ_W	12%	4-6%	2-5%
κ_Z	15%	4-6%	2-4%
κ_t	30%	14-15%	7-10%
κ_b	30%	10-13%	4-7%
κ_τ	16%	6-8%	2-5%

- HL-LHC would bring a factor 1.5 to 2 on top of 300 fb^{-1}
  - Limited by systematic uncertainties

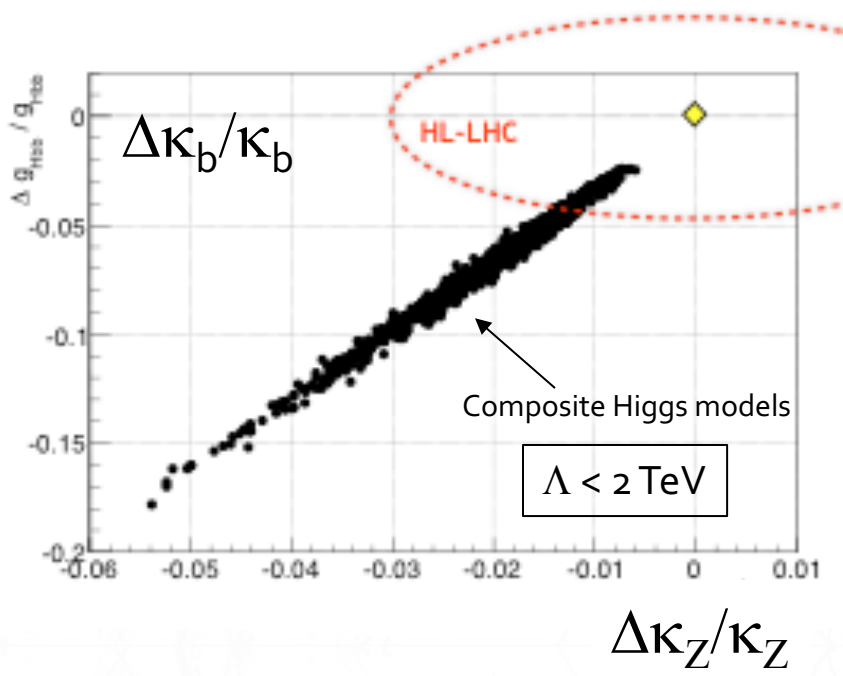
- Becomes sensitive to, e.g., H → μμ
  - Expect 35K signal events with 3 ab^{-1}
    - S/B ~ 0.3% → 10σ significance
  - Coupling measured to ~ 10%
    - 20-30% with 300 fb^{-1}



Precision Higgs physics (4)

- Is the precision good enough to make a "discovery" ?
  - Example of expected deviations if new physics scale is at 1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$



Typically, expect deviations:

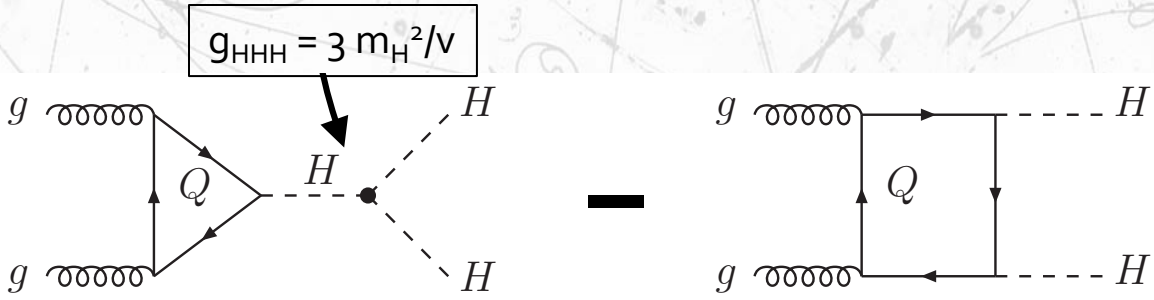
$\Delta\kappa/\kappa$ < ~5 % / Λ^2

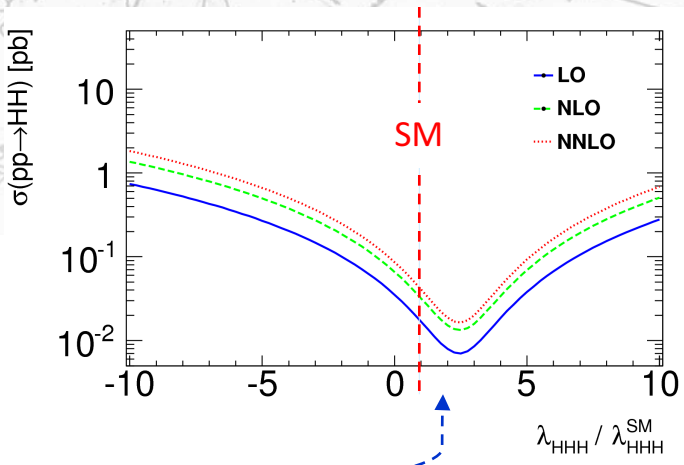
(with Λ in TeV)

- Need 1% precision on couplings for a 5σ discovery if Λ = 1 TeV
  - And much better for heavier new physics
- HL-LHC might be good enough for some new physics models
  - *If* the new physics scale is well below 1 TeV
    - The air is getting thin …

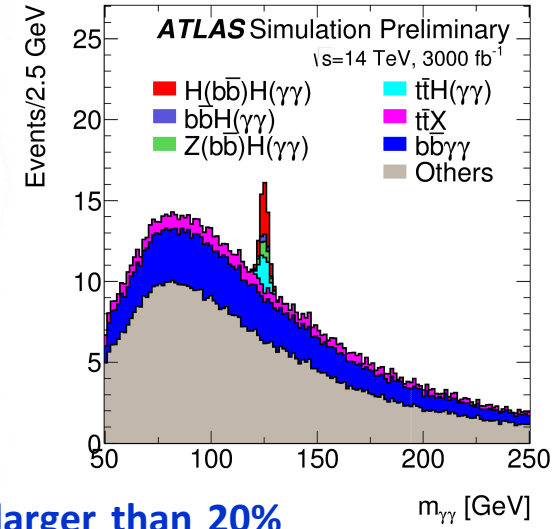
Precision Higgs physics (5)

- **Higgs self coupling**
  - **Measurable through double Higgs production**





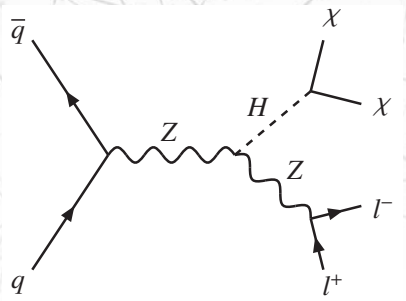
  - **(Accidential) negative interference reduces cross section and thus the sensitivity to g_{HHH}**
    - **Rule of thumb: Event yield is factor ~1000 smaller than for single H**
  - **Two channels studied so far**
    - **bbττ and bbγγ**
    - **Only 9000 + 320 events**
  - **Expected significance < 2σ**
    - **Precision on g_{HHH} < 50%**

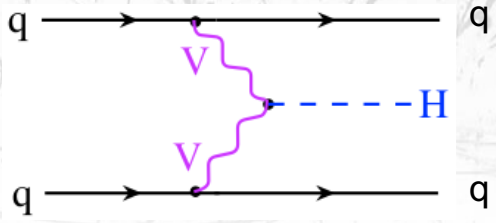


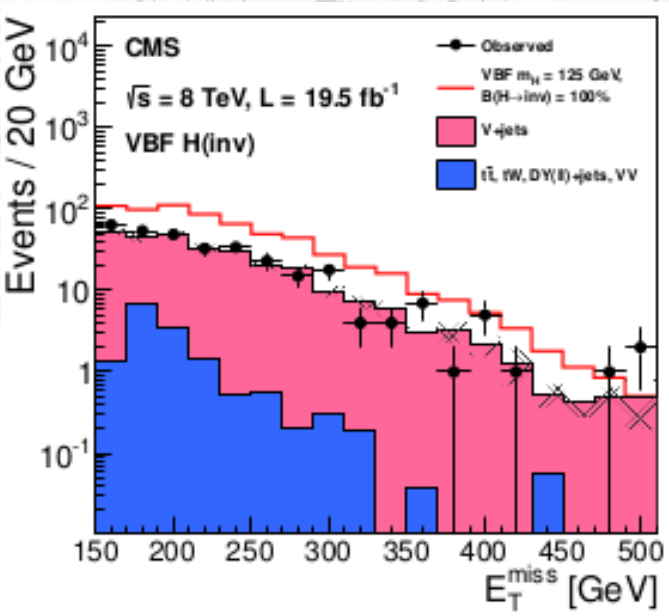
- **Is this precision enough ?**
  - **Not really: new physics models do not predict deviations larger than 20%**

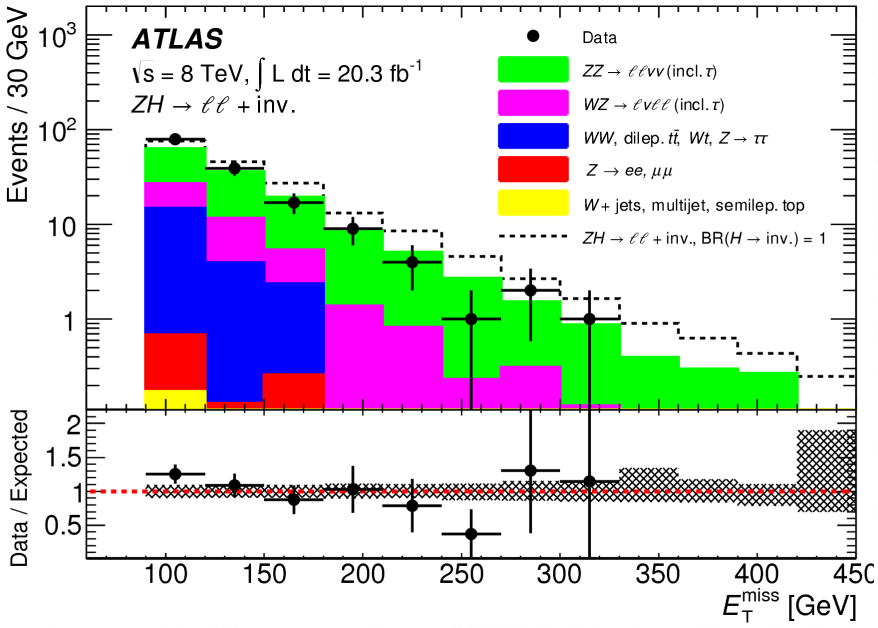
Precision Higgs physics (6)

- **Invisible Higgs decays**









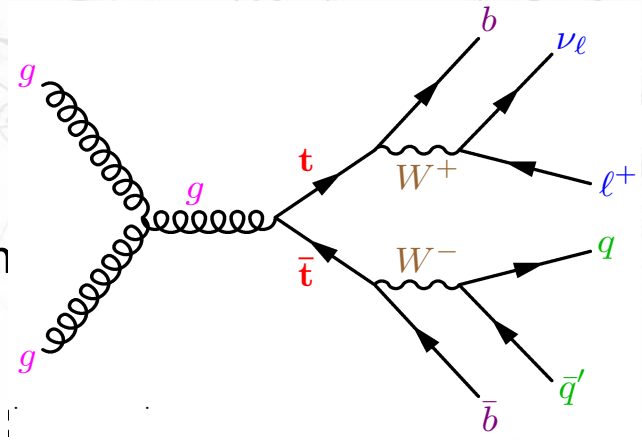
	BR_{inv} (95% CL)
LHC Run1	40-50%
LHC 300 fb^{-1}	20-30%
HL-LHC	10-15%

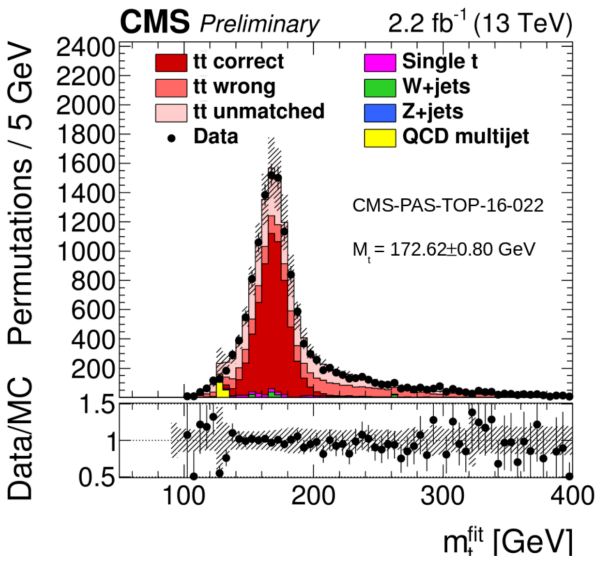
- **Improves DM search at low mass**

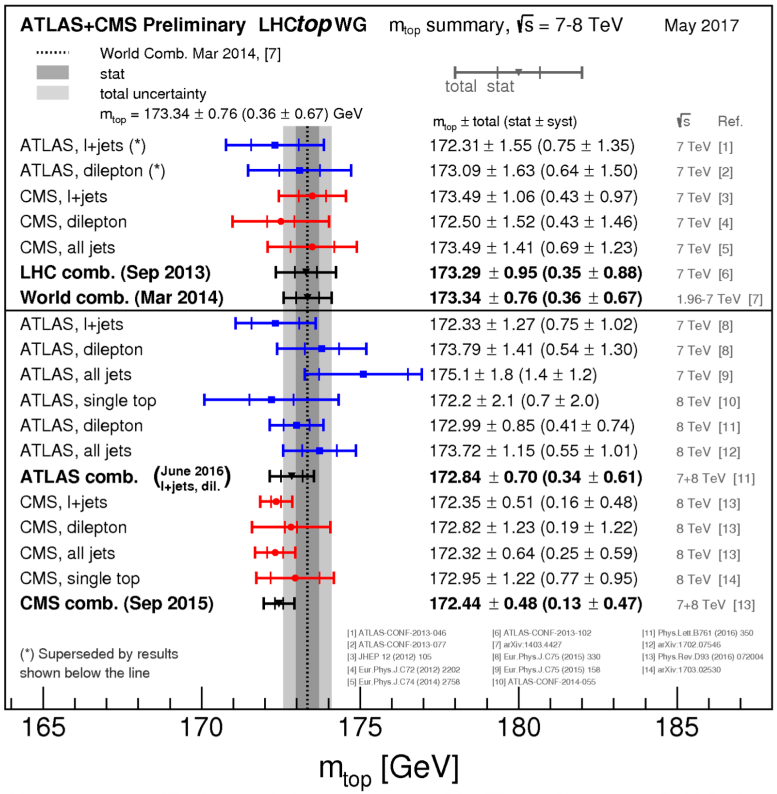
Top quark mass (1)

- **The top quark mass today**
  - **Standard method: final state with one lepton**
    - **Kinematic fit with mass constraints**

≥4 jets
2 b jets
1 lepton
MET



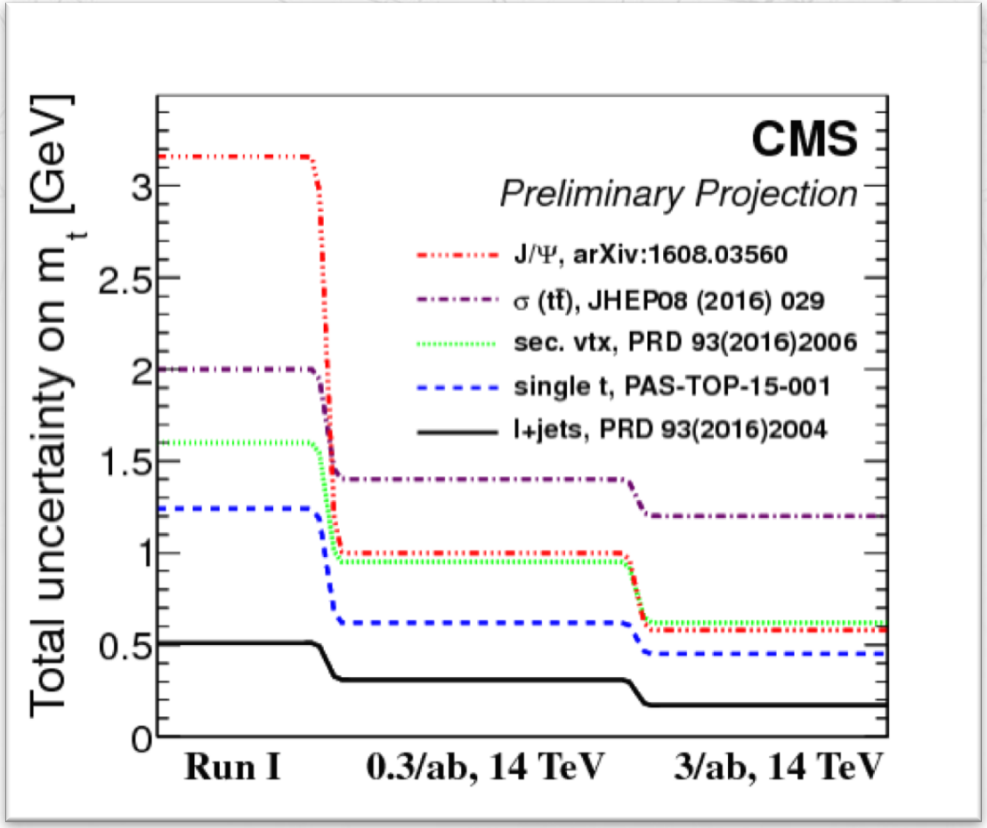




Today: $\delta m_{top} \simeq 0.5$ GeV

Top quark mass (2)

- The top quark mass at HL-LHC
  - There is still much more to come: systematic uncertainties are statistically limited
    - And there are more methods out there to try

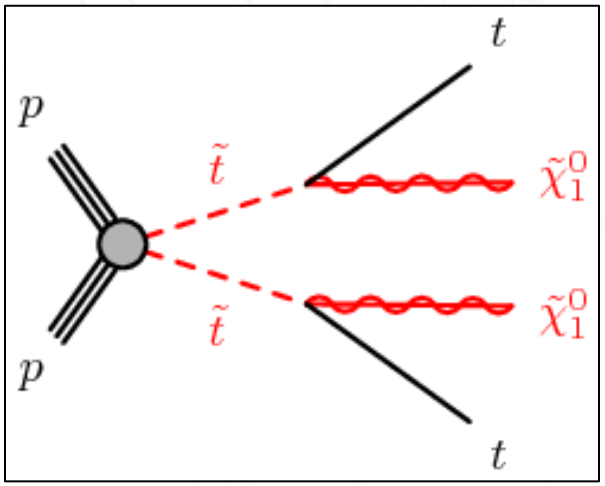


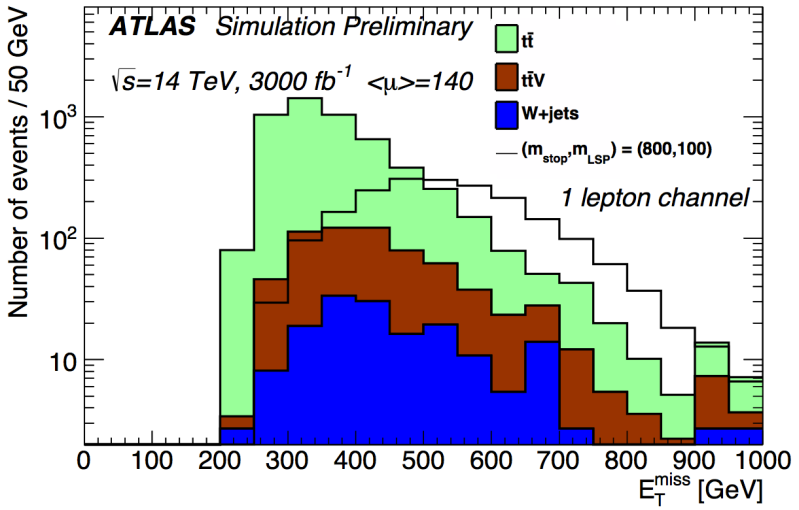
- Projected uncertainties
  - Reduction by a factor 2
    - After 300 fb^{-1}
    - Again after 3000 fb^{-1} @ HL-LHC
- Ultimate reach: ~ 200 MeV (exp.)
  - Theory uncertainty: ~ 500 MeV
    - What is the quantity that is being measured? "MC top mass"
  - Must answer this very question
    - Otherwise 3000 fb^{-1} won't do much better then 300 fb^{-1}

Supersymmetry (1)

- **Search for third generation squarks (stop)**
  - **Original motivation: make a small Higgs boson mass "natural"**

  - **To serve its purpose, the lighter stop should not be much heavier than 1 TeV**
    - **Search for light stop production, e.g.,**

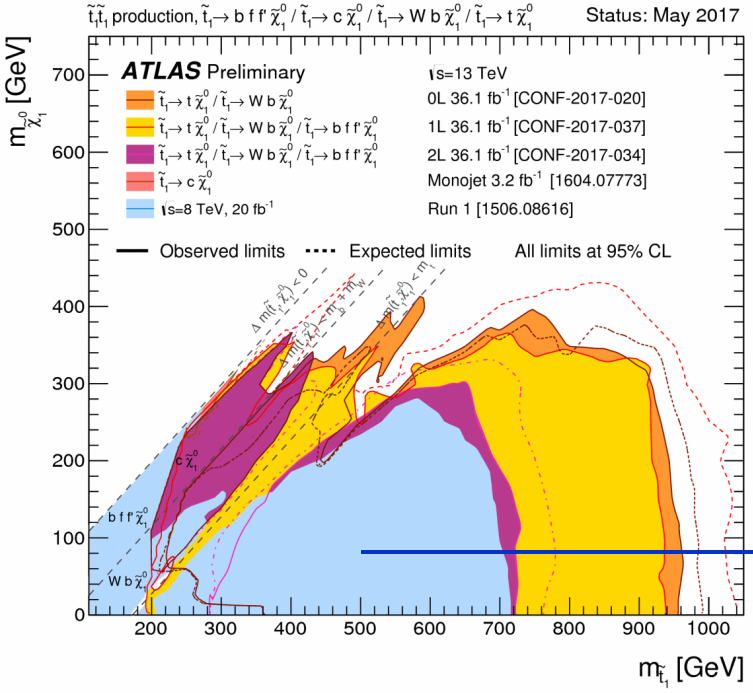




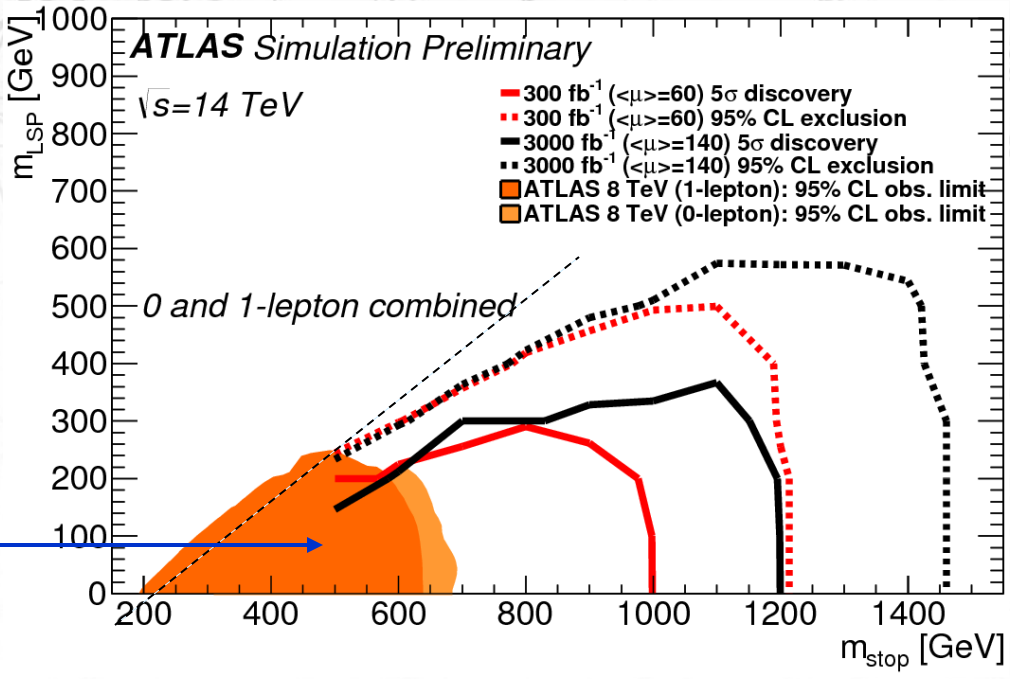
    - **Final state similar to top pair production, with larger missing energy**

Supersymmetry (2)

- **Search for third generation squark (cont'd)**
  - **Today :**



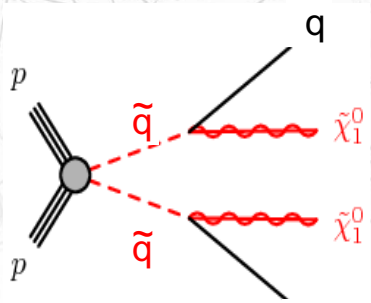
  - **Projections with 300 and 3000 fb^{-1}**

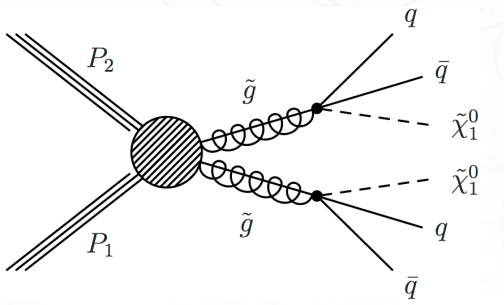


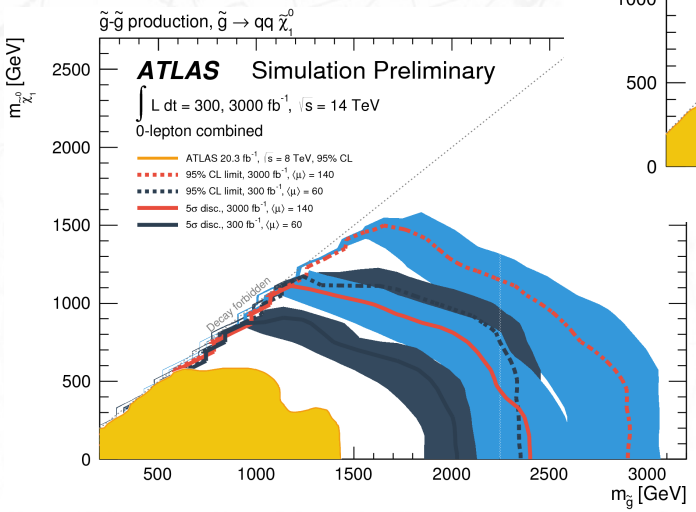
  - **Mass reach extended by a factor 2 with LHC at 14 TeV (300 fb^{-1}): covers the 1 TeV region**
    - **Further 20% extension with HL-LHC**
  - **If no excess is seen with 300 fb^{-1}**
    - **The HL-LHC discovery potential vanishes entirely**

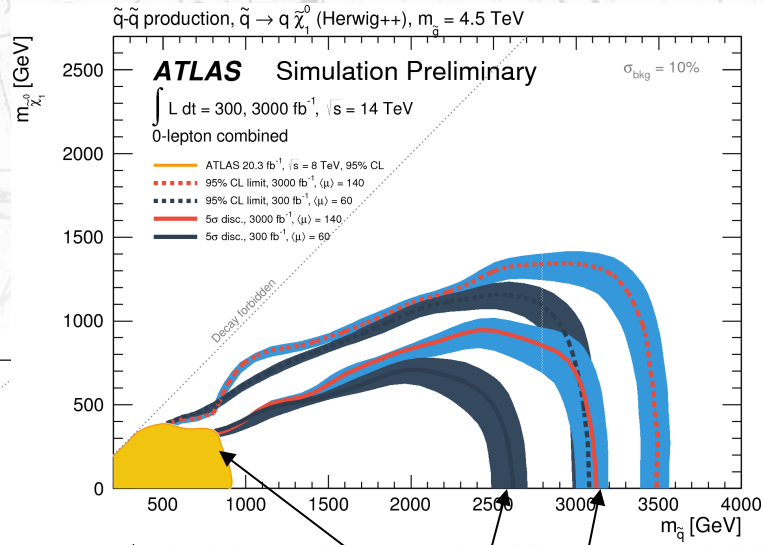
Supersymmetry (3)

- **Search for other squarks and gluinos**
  - **Can be heavier than the lighter stop – already excluded up to 1 TeV in Run1**







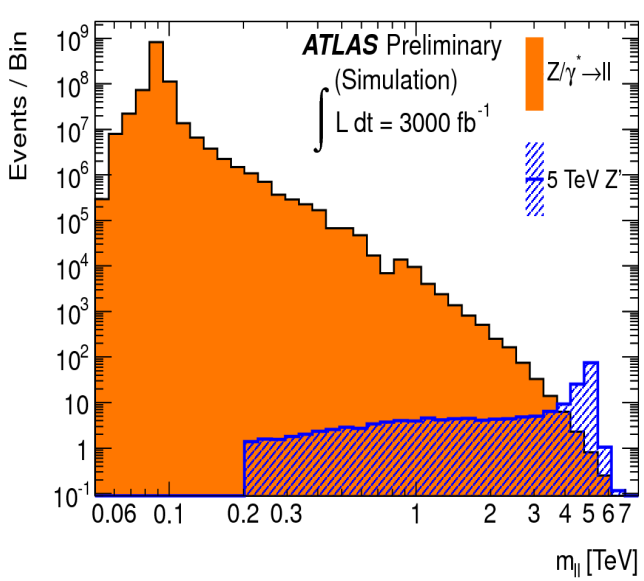


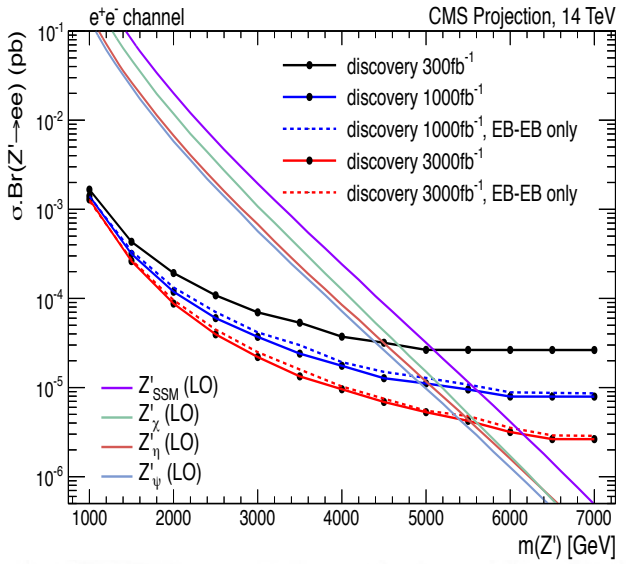
Run1: 20 fb^{-1} @ 8 TeV
Run2: 300 fb^{-1} @ 14 TeV
Run3: 3000 fb^{-1} @ 14 TeV

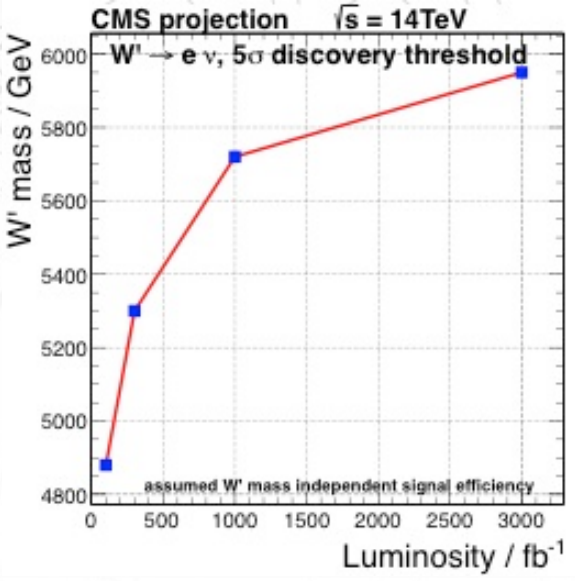
- **Mass reach extended by a factor 2 – 3 with LHC at 14 TeV (300 fb^{-1})**
  - **Further extended by 20% with HL-LHC**
- **Discovery potential of HL-LHC vanishes if no excess is seen with 300 fb^{-1}**

New gauge bosons: W', Z'

- Look for heavy di-lepton resonance: Z' → e^+e^-, $\mu^+\mu^-$, or W'$^+$ → $e^+\nu_e$, $\mu^+\nu_\mu$
  - Z' and W' masses up to 2-3 TeV excluded at LHC Run1



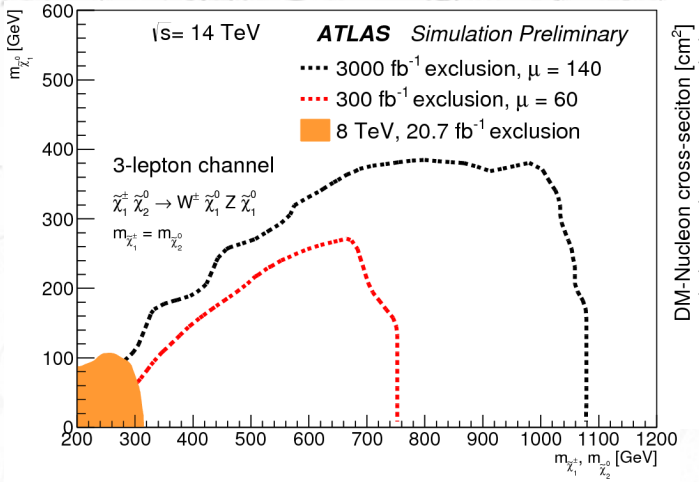


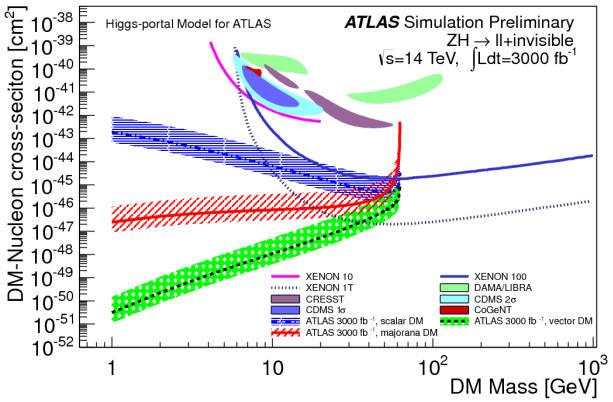


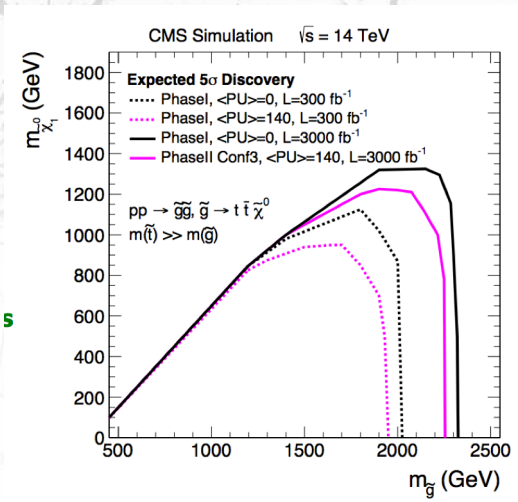
- Mass reach extended by a factor 2 with LHC at 14 TeV (300 fb^{-1})
  - Further extended by 20% with HL-LHC
- Discovery potential of HL-LHC vanishes if no excess is seen with 300 fb^{-1}
  - (Not visible in the graphs above)

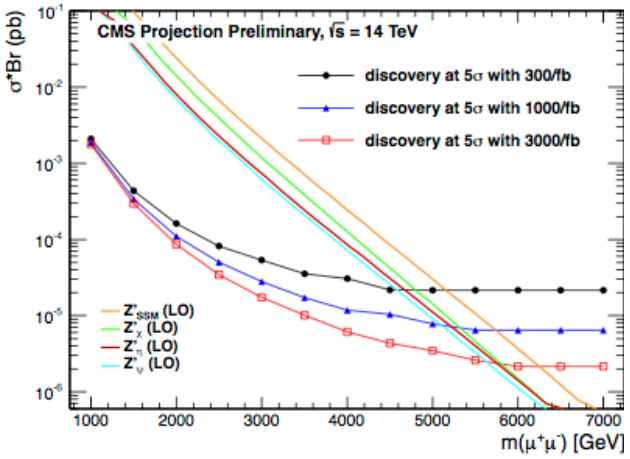
… and many others …

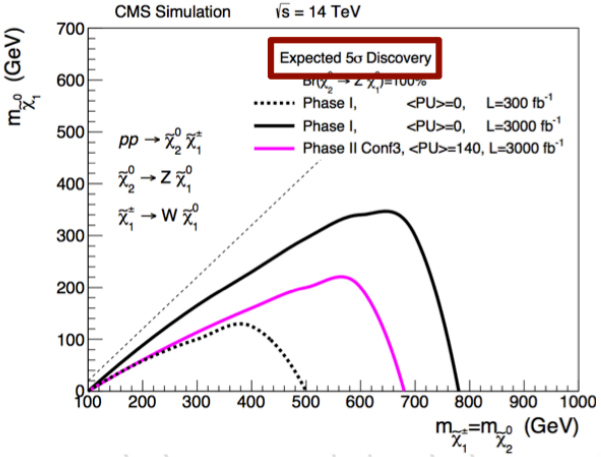
- All with a similar pattern

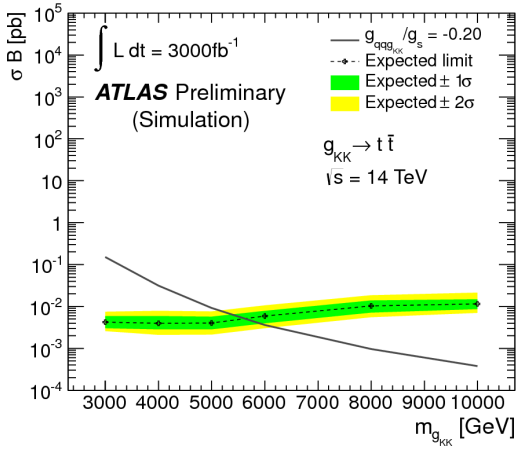












Conclusions of the first lecture (1)

- The LHC Run1 brought the last experimental proof of the Standard Theory
  - The Standard Theory of Particle Physics was already complete 40 years ago !
  - New physics with a scale below 1 TeV has become quite unlikely
    - The Standard Theory tested at the quantum level: new physics will be hard to find

- With the 8 → 14 TeV increase, the LHC Run2 and Run3 promise to be thrilling
  - The mass reach for new physics increased by a factor 2
    - Stop: 1.2 TeV; Squarks/Gluinos: 2.5 TeV; Z': 6 TeV; etc.
  - The measurement precision will improve by a factor ~4
    - Top mass: 300-400 MeV; Higgs couplings: 2-10%; etc.
  - The lighter particle(s) of a new physics spectrum may be discovered
    - However, beware of statistical fluctuations
      - Among ~1000 different searches in ATLAS + CMS, at least one can be expected to give a 3σ deviation per year. Keep calm and take more data.

- The HL-LHC will allow the first studies of any discovered new particle
  - But it is unlikely to allow the exploration of the heavier part of the spectrum
    - Only 20-25% mass reach increase from the tenfold increase of the luminosity

Conclusions of the first lecture (2)

- If no hint of a new particle is found in the LHC Run2 (even via a modest excess)
  - The HL-LHC is unlikely to make any discovery in 10-12 years of running

- The HL-LHC will allow precision measurements to improve
  - By a factor up to 2 with respect to LHC 300 fb^{-1}
    - The ultimate precision is unlikely to unveil new physics effects
      - Because deviations from BSM physics are not expected to be that large

- Whether a new particle is discovered at the LHC Run2 or not
  - Very significantly more energy will be eventually needed
    - Either to explore the heavier part of the spectrum
    - Or to extend the search for new physics towards significantly higher masses
  - Very significantly more precision will be eventually needed
    - To extend the search for new physics towards significantly smaller couplings
    - To see indirect effects of heavy new physics in precision measurements
      - And possibly compare with observations made at higher energy

See 2nd & 3rd lectures for the pertaining perspectives

Conclusions of the first lecture (3)

Questions…