Physics at Future Colliders

- **Lecture 1 (Thursday 28 July, 10:20)**
  - An historical perspective (1964-2014): 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 (Friday 29 July, 9:15)**
  - The quest for precision (2030-2050): Linear or Circular ?

- **Lecture 3 (Friday 29 July, 10:20)**
  - The energy frontier (2045-2080): Leptons or Hadrons ?
  - Thinking out of the box: Muon collider
  - Towards the next European Strategy update (2019-2020)

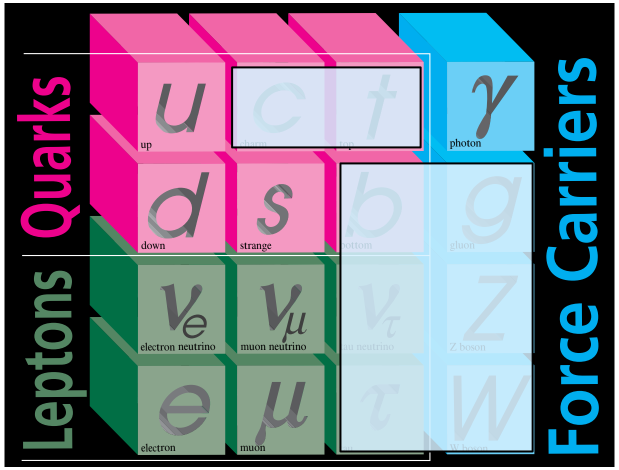
Lecture 1

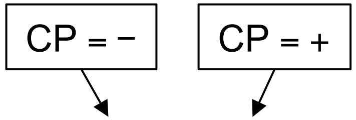
An historical perspective (1964-2014):

The need for precision and energy

1964-1974: The rise of the standard model

- Very little was known experimentally



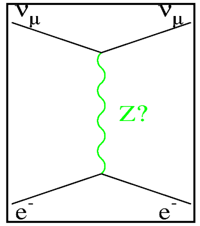


+ Discovery of CP violation in the $K^o_L \to \pi\pi$ decays

(Kronin, Finch: 1964)

+ Discovery of neutral currents $\nu_\mu e \to \nu_\mu e$

(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 $\sqrt{s}$: A-priori obvious way to discover heavier particles**

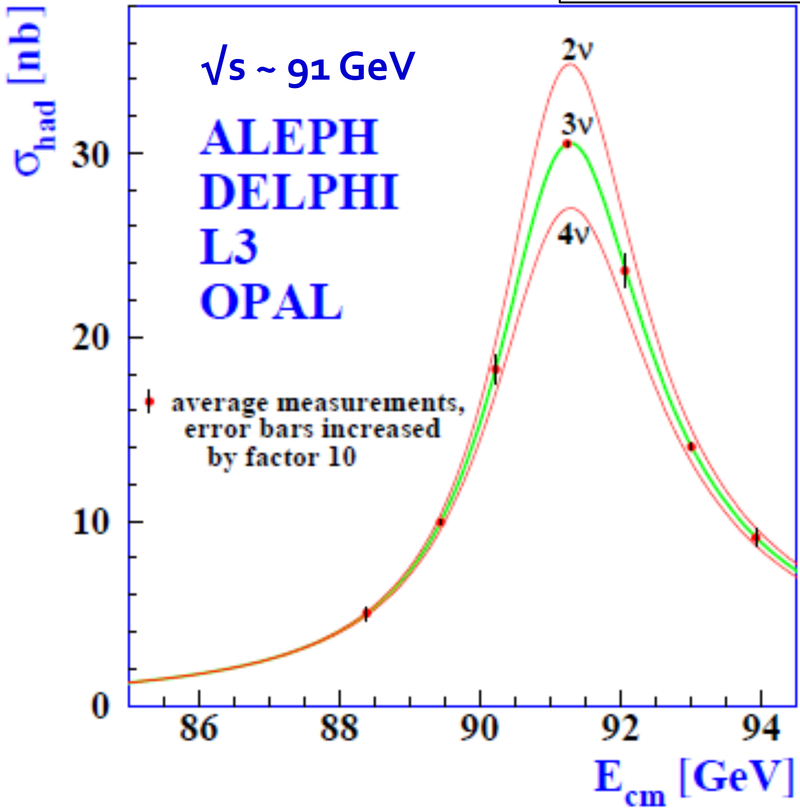
Year	Discovery	Experiment	$\sqrt{s}$ (GeV)	Observation
1974	c quark (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \to J/\Psi)$ $J/\Psi \to \mu^+\mu^-$
1975	τ lepton (m=1.777 GeV)	e^+e^- ring (SLAC)	8	$e^+e^- \to \tau^+\tau^-$ $e^+\mu^-$ events
1977	b quark (m~4.5 GeV)	Fixed target (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 and neutrino tau 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.
    - $e^+e^- \to Z \to$ hadrons at LEP1, measurement of the line shape

Discovery confirmed in 1996 with $W \to \tau\nu_\tau$



  - After 5 years at LEP1: per-mil precision

$N_\nu = 2.984 \pm 0.008$

(Note the 2σ deficit)

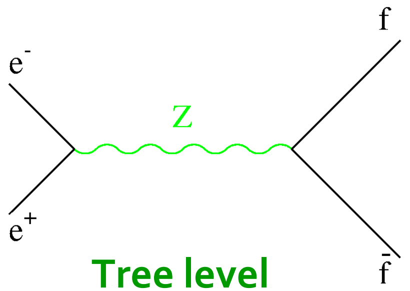
$\Gamma_Z = 2495.2 \pm 2.3$ MeV

$m_Z = 91187.5 \pm 2.1$ MeV

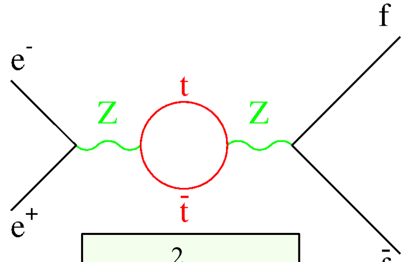
$\alpha_S = 0.1190 \pm 0.0025$

1987-2011: The rise of precision (2)

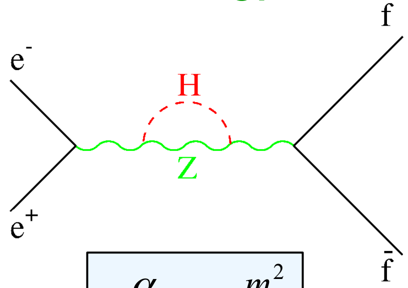
- **What's the use of such a precision anyway ?**
  - **1994 : Prediction of the top quark mass**
    - Remember quantum corrections from t'Hooft and Veltman work (1971) ?



Tree level



$$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$$

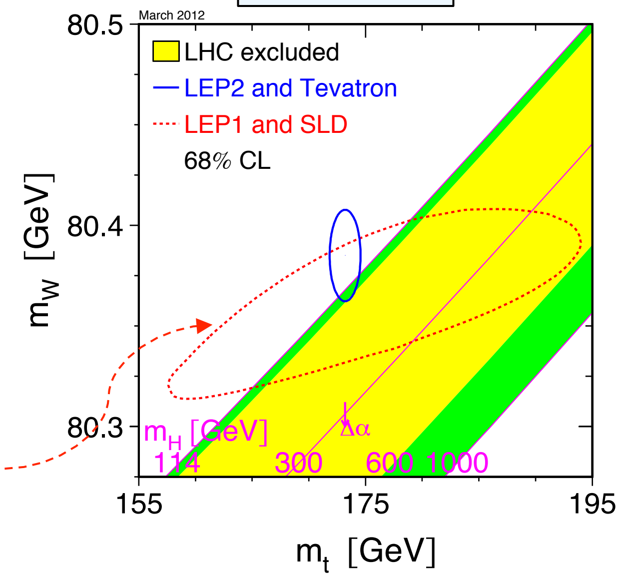


$$-\frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2}$$ [small correction]

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

$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots$$

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

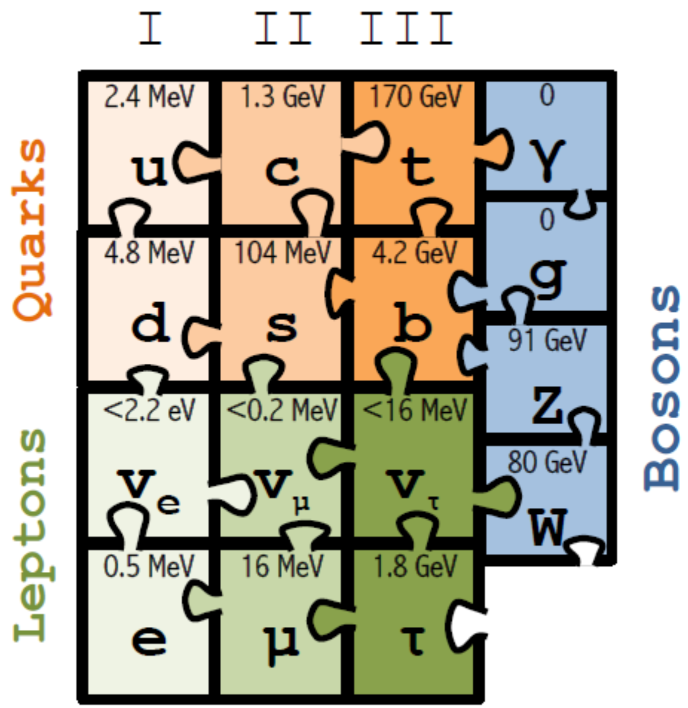


Predict m_W and m_{top} from precision Z measurements

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)
      - $m^2_W = m^2_Z \cos^2\theta_W (1+\Delta\rho)$

$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots$$

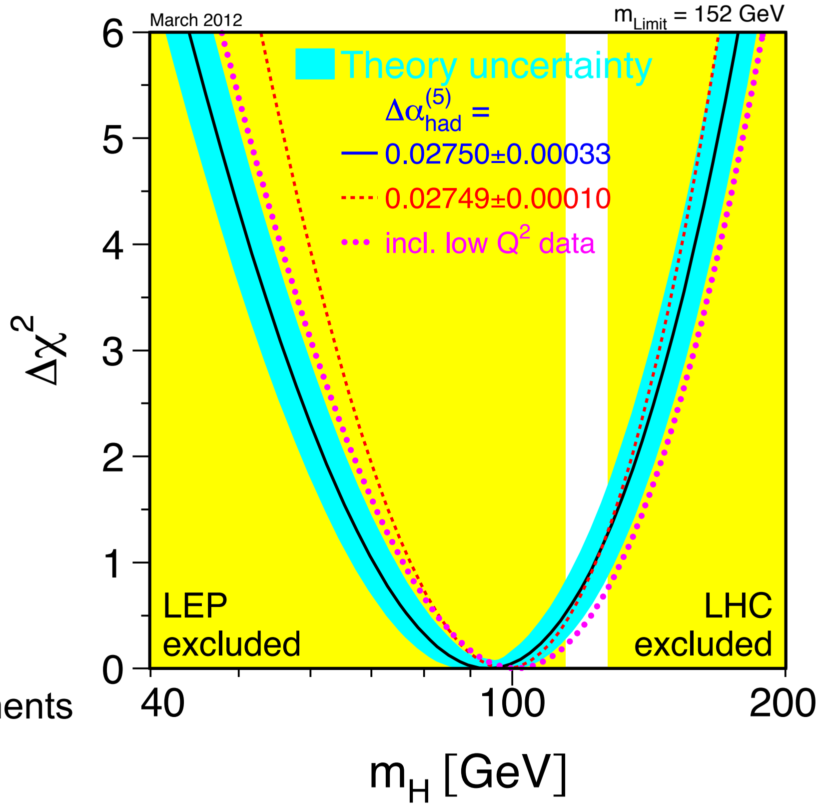
  - m_Z, m_{top} and m_W are known with precision
    - The standard model has nowhere to go !

114 GeV < m_H < 152 GeV

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

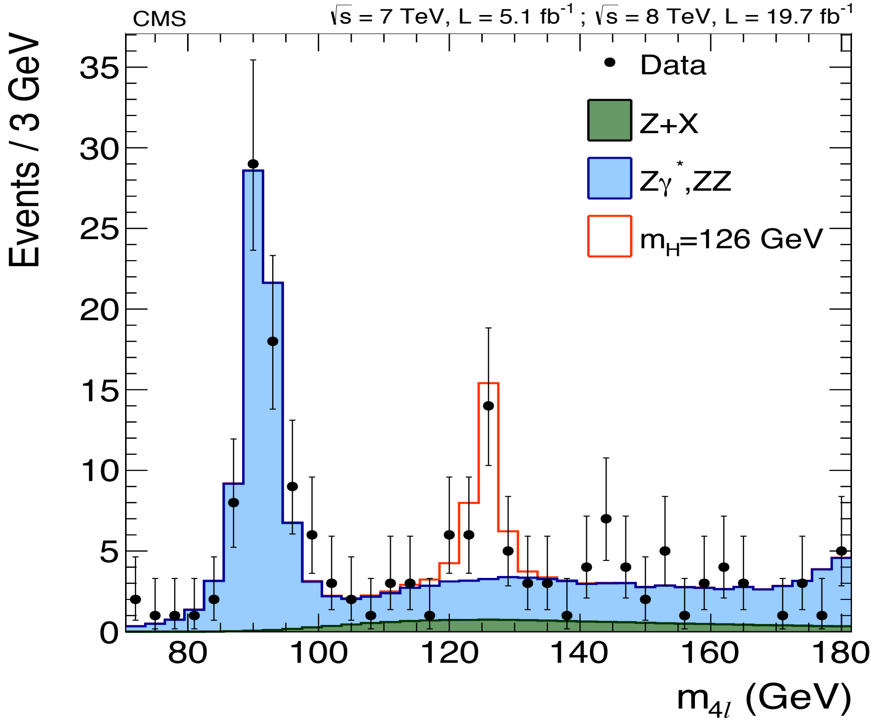
Direct searches @ LEP
Just 10 GeV below the target …

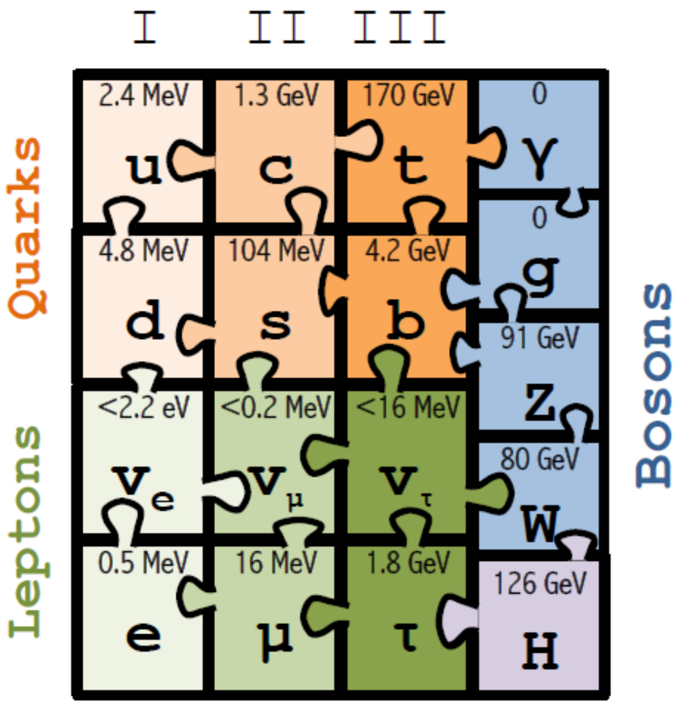
Fit to precision measurements



2012-14: The SM becomes the standard theory

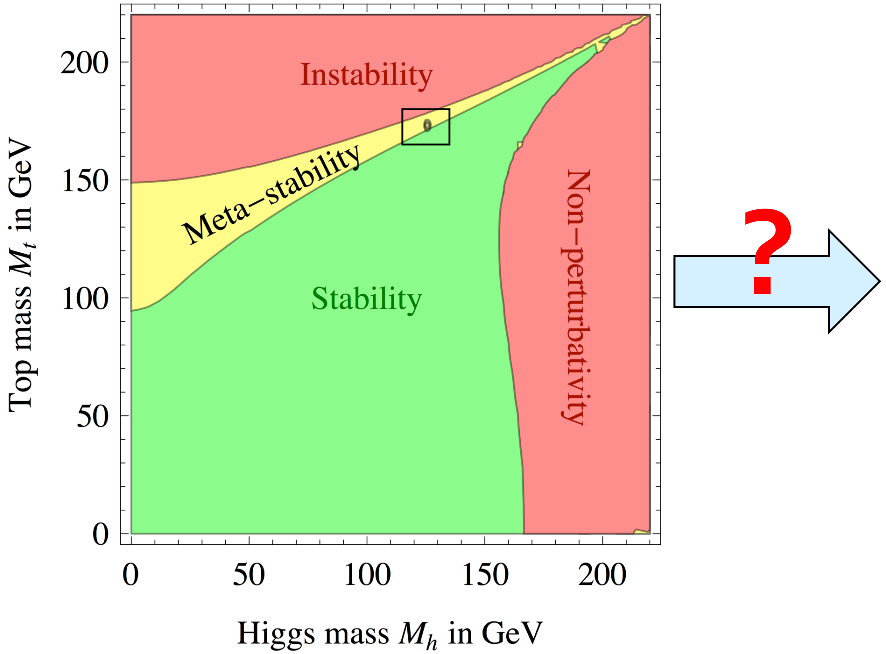
- **2012-2014: The Higgs boson era**
  - **2012: Discovery of the standard model Higgs boson at the LHC (ATLAS, CMS)**
    - m_H = 125.4 ± 0.5 GeV (ATLAS), 125.0 ± 0.3 GeV (CMS)
    - Mass, couplings, spin, width in agreement with Standard Theory predictions
  - **2010-2013: No new physics found at the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

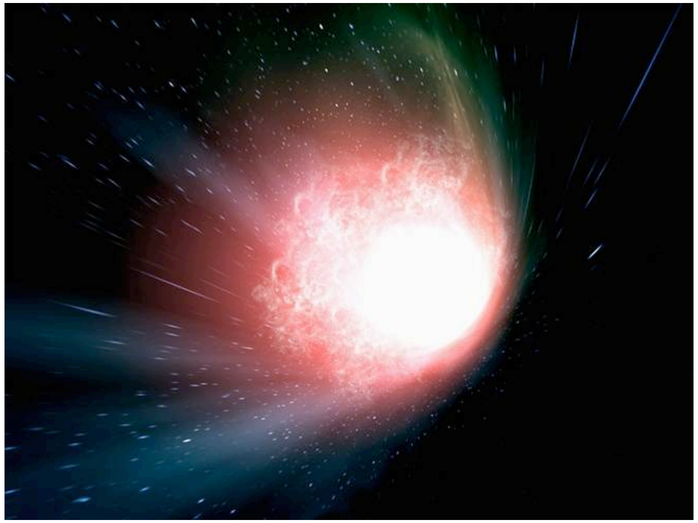




And now, what ?

- 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 it the end ?

It is not the end !

- **There is something beyond the standard theory**
  - **Many experimental proofs, e.g.,**
    - Cosmological dark matter (DM)
    - Baryon asymmetry of the Universe (BAU)
    - Non-zero, but very small, neutrino masses
  - **A mathematical hint : the small Higgs boson mass.**

But Where Is Everybody?

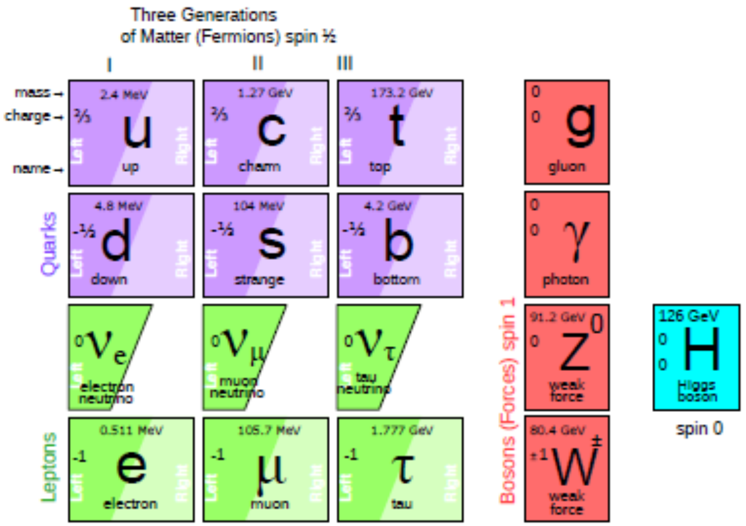
- **Often heard: New physics must be "around the corner"**
  - **Problem: there is no corner (so far) … and not much of theoretical guidance**
  - **Is new physics at larger masses ? Or at smaller couplings ? Or both ?**
    - Only way to find out: go look, following the historical approach:
      - ➨ Direct searches for new heavy particles

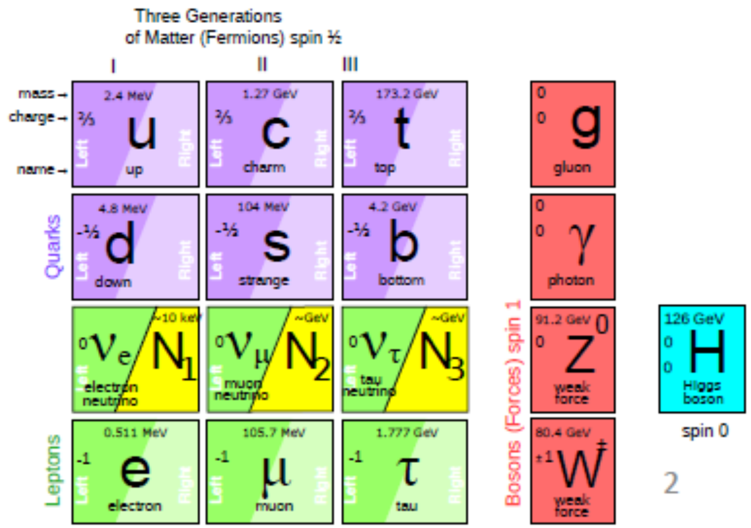
        Need colliders with larger energies
      - ➨ Searches for the imprint of new physics on W, Z, top, and Higgs properties

        Need colliders / measurements with unprecedented accuracy

Precision vs Energy (1)

- **The standard theory is complete ? Obviously three pieces missing !**

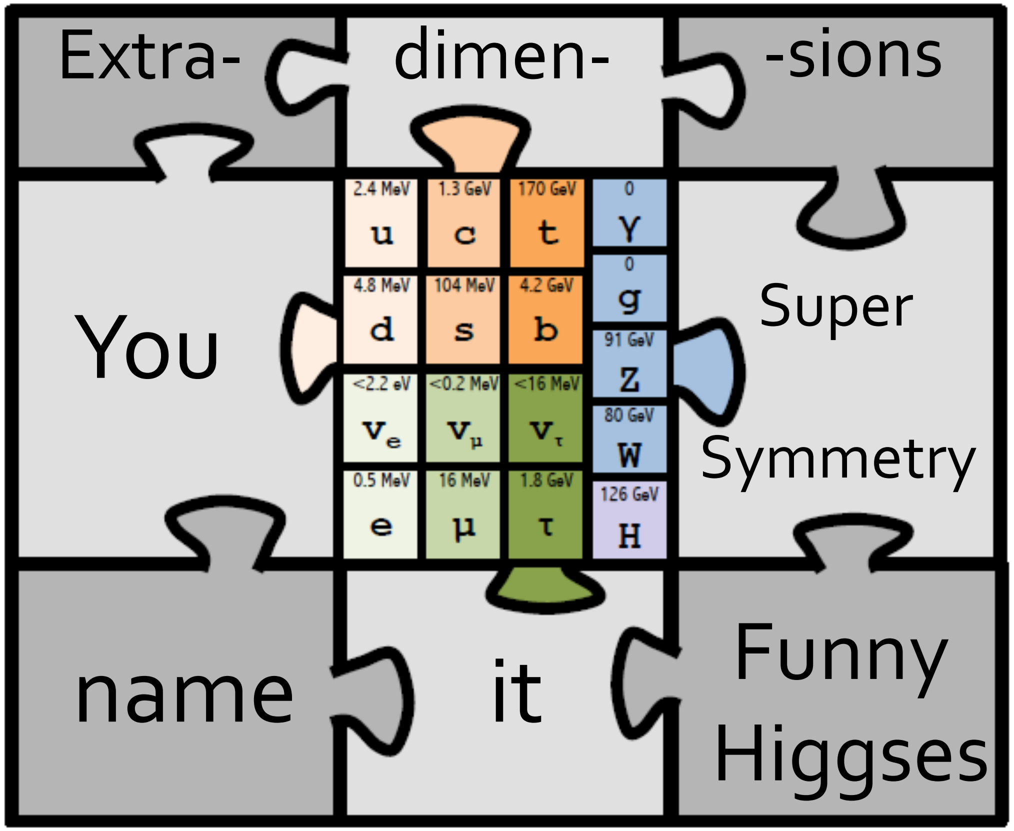




- **Three right-handed neutrinos ?**
  - **Extremely small couplings, nearly impossible to find, but could explain it all !**
    - ➨ **Small m_ν (see-saw), DM (light N_1), and B.A.U. (leptogenesis)**
- **Need very-high-precision experiments to unveil**
  - **Could cause a slight reduction (increase) of the Z (H) invisible decay width**
  - **Could open exotic Z and Higgs decays: Z,H → ν_i N_i**
    - ➨ **Possibly measurable / detectable in precision e^+e^- colliders**
    - ➨ **Almost certainly 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

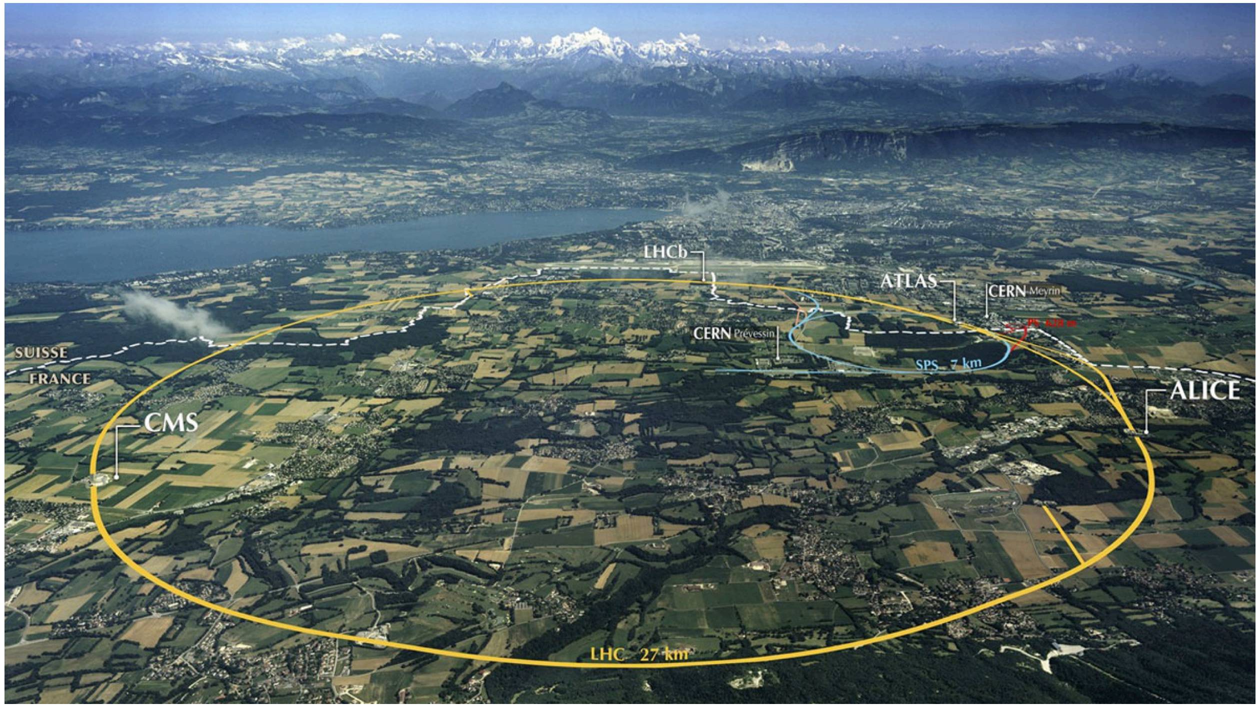
Lecture 1 (cont'd)

A Strategy for the future:

Towards the precision and energy frontiers

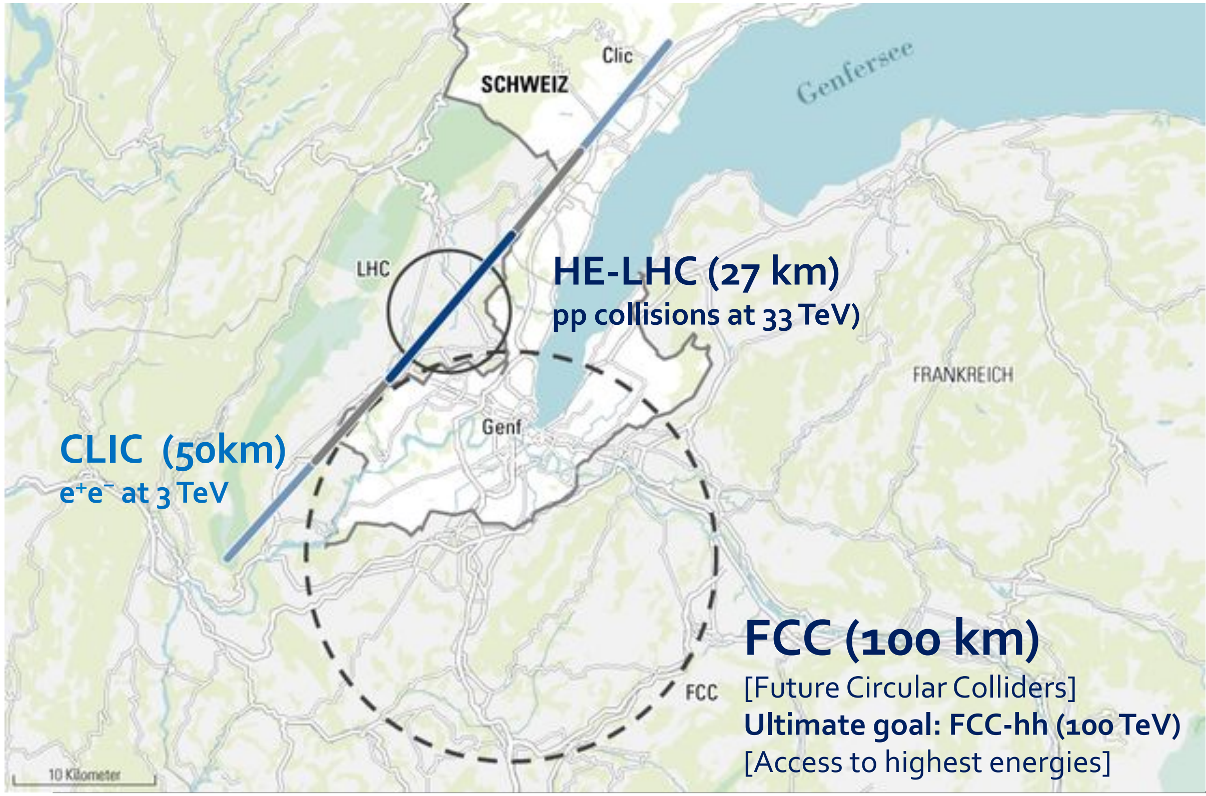
Short-term perspectives (2020-2035)

- In May 2013, European Strategy said (very similar statements from US)
  - Exploit the full potential of the LHC until ~2035 as the highest priority
    - Get 75-100 fb^{-1} at 13-14 TeV by 2018-2019 (LHC Run2: running)
    - Get ~300 fb^{-1} at 14 TeV by 2022-2023 (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

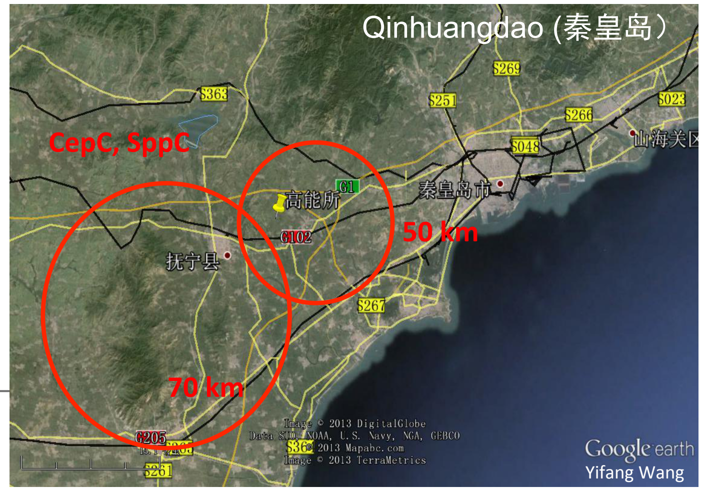


Long-term perspectives (2045-2080)

- 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 33 TeV in the LHC tunnel
    - FCC, a 100-km circular ring with a pp collider long-term project at $\sqrt{s}$ = 100 TeV
    - CLIC, an e^+e^- collider project with $\sqrt{s}$ from 0.3 to 3 TeV



Similar circular projects
(50 or 70km) in China
pp collisions at $\sqrt{s}$ ~ 50 or 70 TeV



Mid-term perspectives (2030-2045)

- In May 2013, European Strategy said (very similar statements from US)
  - Acknowledge the strong physics 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
      - ➨ For a high-luminosity, high-energy, circular e^+e^- collider as potential first step

FCC (100 km)

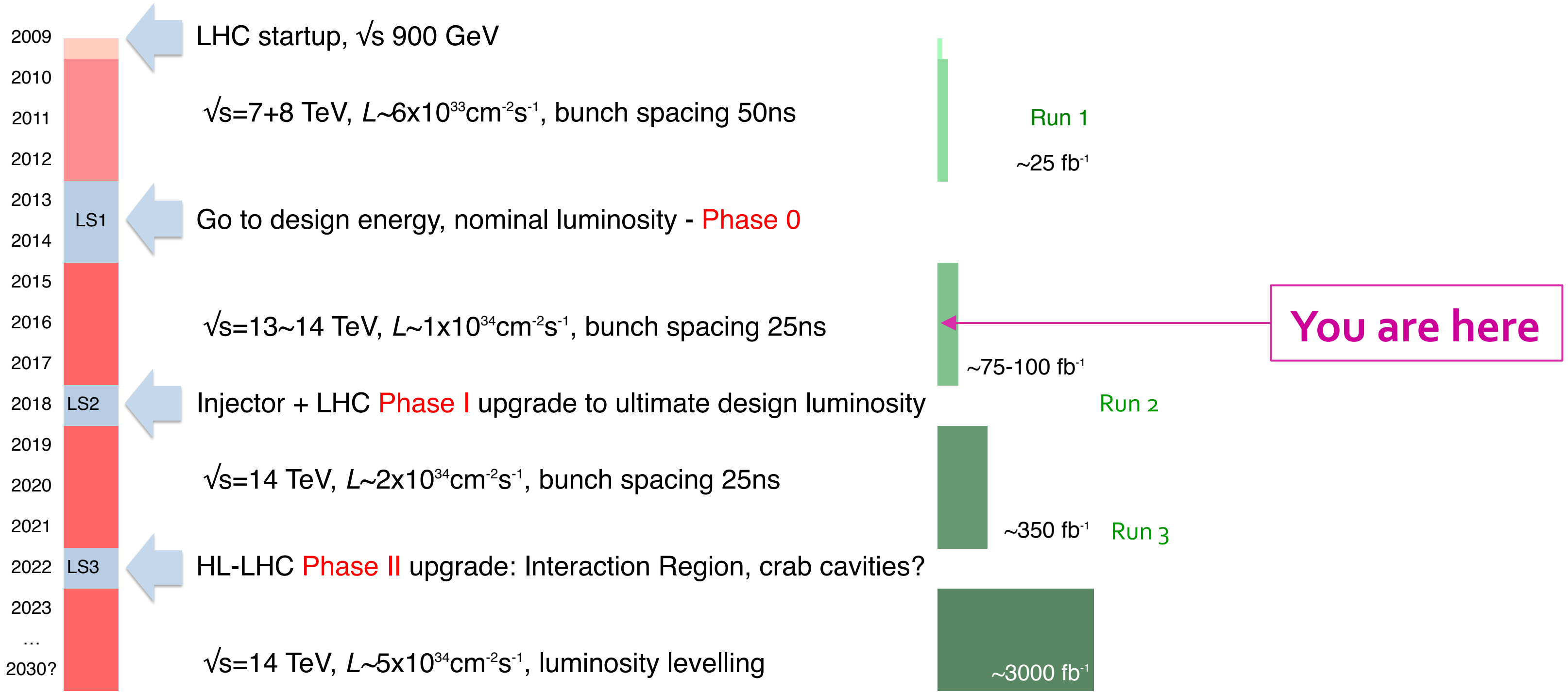
First step: FCC-ee (88-370GeV)

[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 in its early infancy**



  - **The 14 TeV Run2 is just starting: 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 become interesting (if copiously produced in e^+e^- or $\gamma\gamma$ collisions)
    - Larger energies might be needed to find & study the whole new spectrum (FCC-hh)
    - An e^+e^- Z factory (FCC-ee) will be unique to study the underlying quantum structure
      - ➨ Note: m_H and m_{top} were predicted without the need of additional new physics

        New physics will probably be very difficult to find anyway
  - Find no new particle, but finds 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) and Z (FCC-ee) become very interesting machines
    - Push the energy frontier to its limits (CLIC, FCC-hh)
  - Find no new particle, 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.**

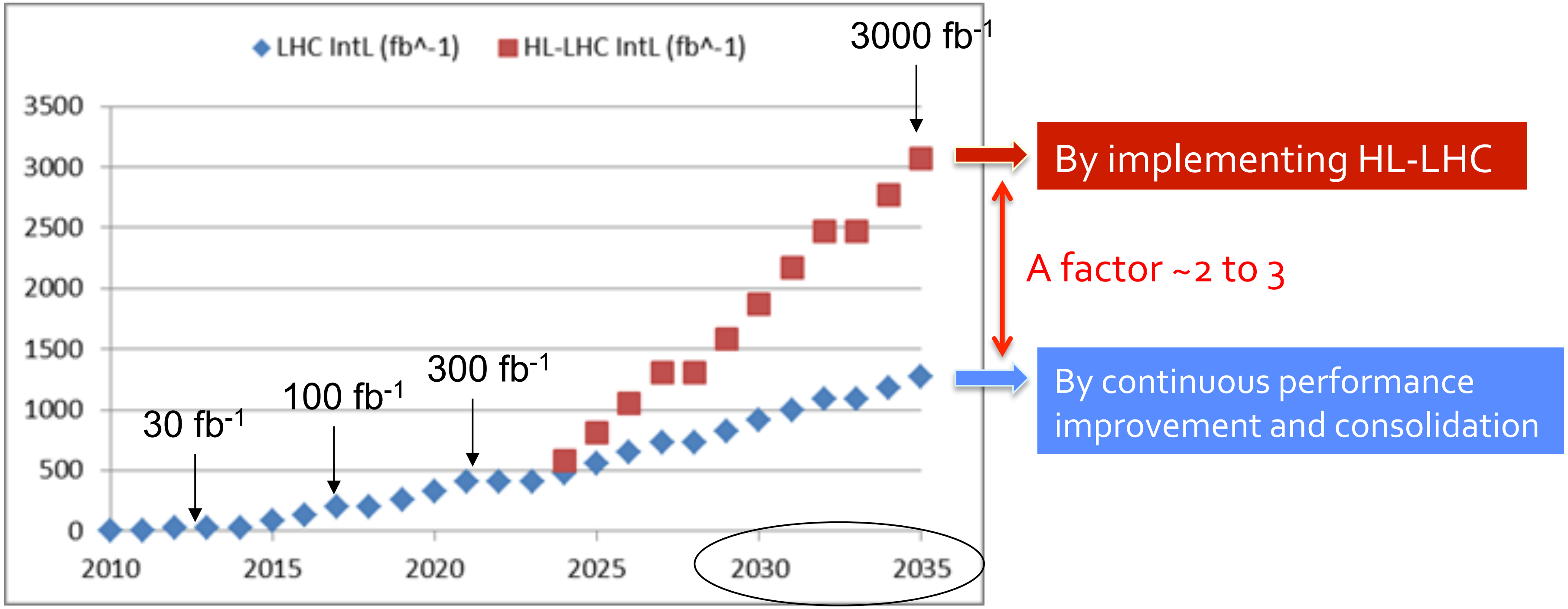
Lecture 1 (cont'd)

The short-term perspectives (2020-2035)

The (HL)-LHC: Physics prospects

Expected integrated luminosity at HL-LHC

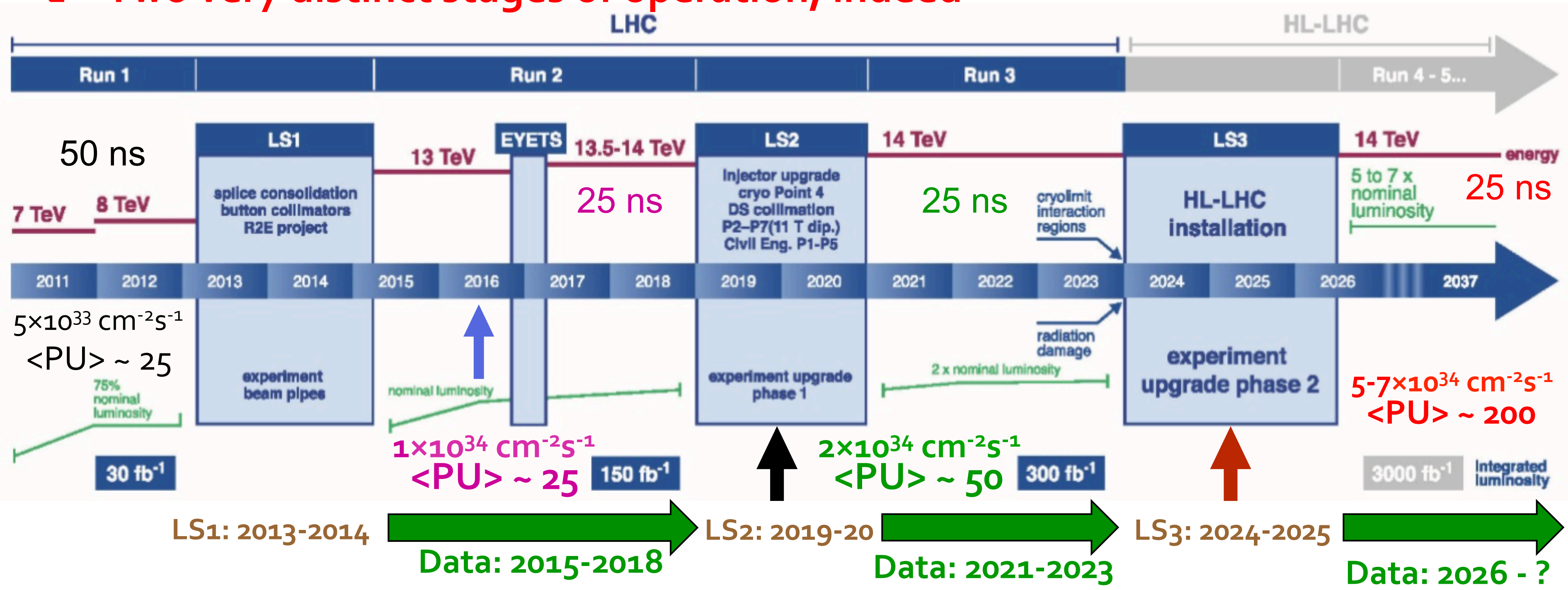
- **The High Lumi upgrade of the LHC is an ambitious project**
  - **Target is to deliver ~10 times more luminosity (3 ab^{-1}) than the first 10 LHC years**



  - **Project timeline driven by radiation damage to machine components**
    - **Expected end of lifetime around 2023**
  - **The results of the LHC Run2 in 2018 might argue for even more luminosity**
    - **But what do we do if there is no hint for new physics by then ?**

Expected pile-up interactions at HL-LHC (1)

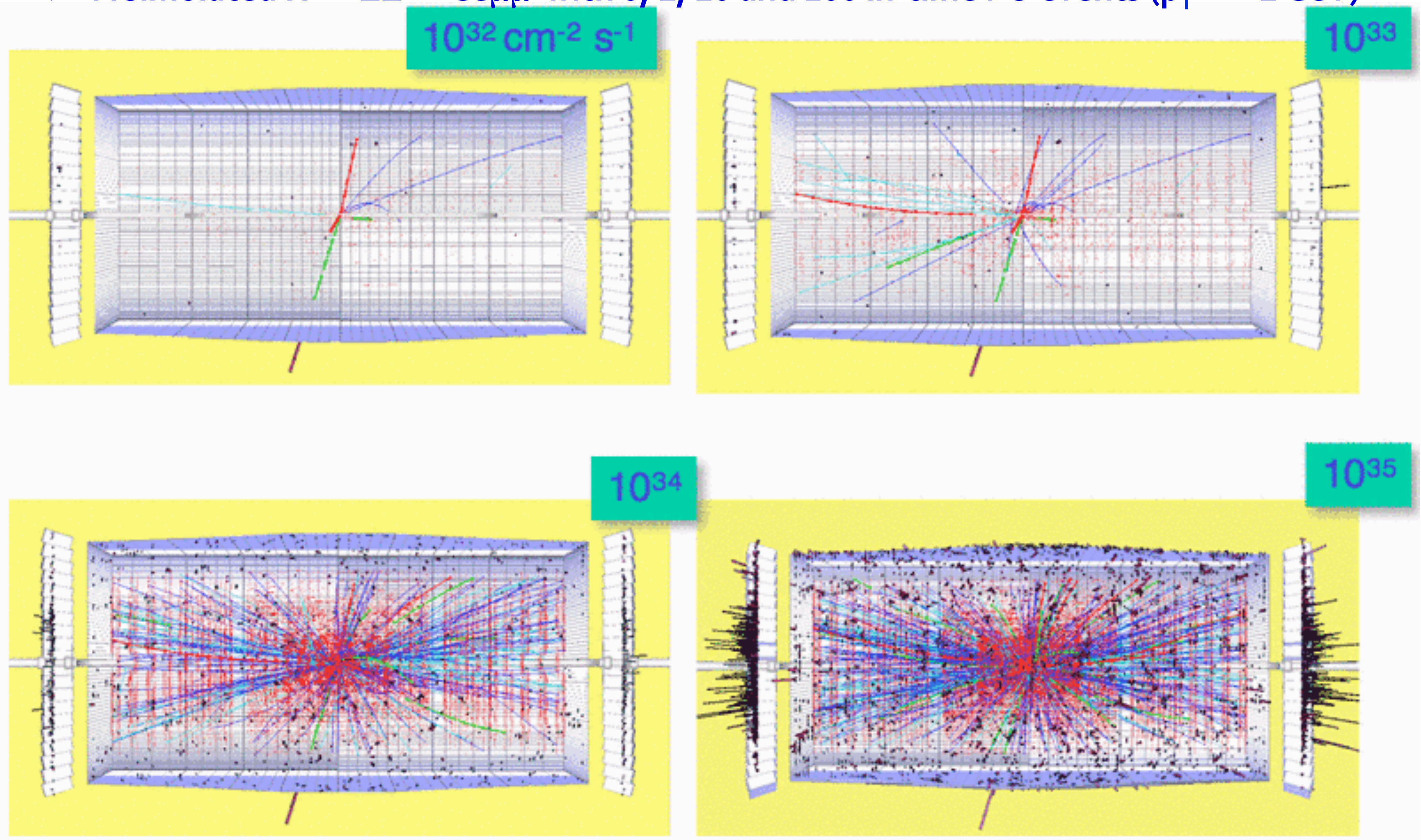
- Two very distinct stages of operation, indeed



- LHC Run 2 (and, to a lesser extent, Run 3)
  - Conditions similar to those of LHC Run 1 for "in-time" pile-up
    - Increase of "out-of-time" pile-up from the 50 → 25 ns bunch separation
- HL-LHC
  - Tremendous increase of "in-time" and "out-of-time" pile-up – and of radiation

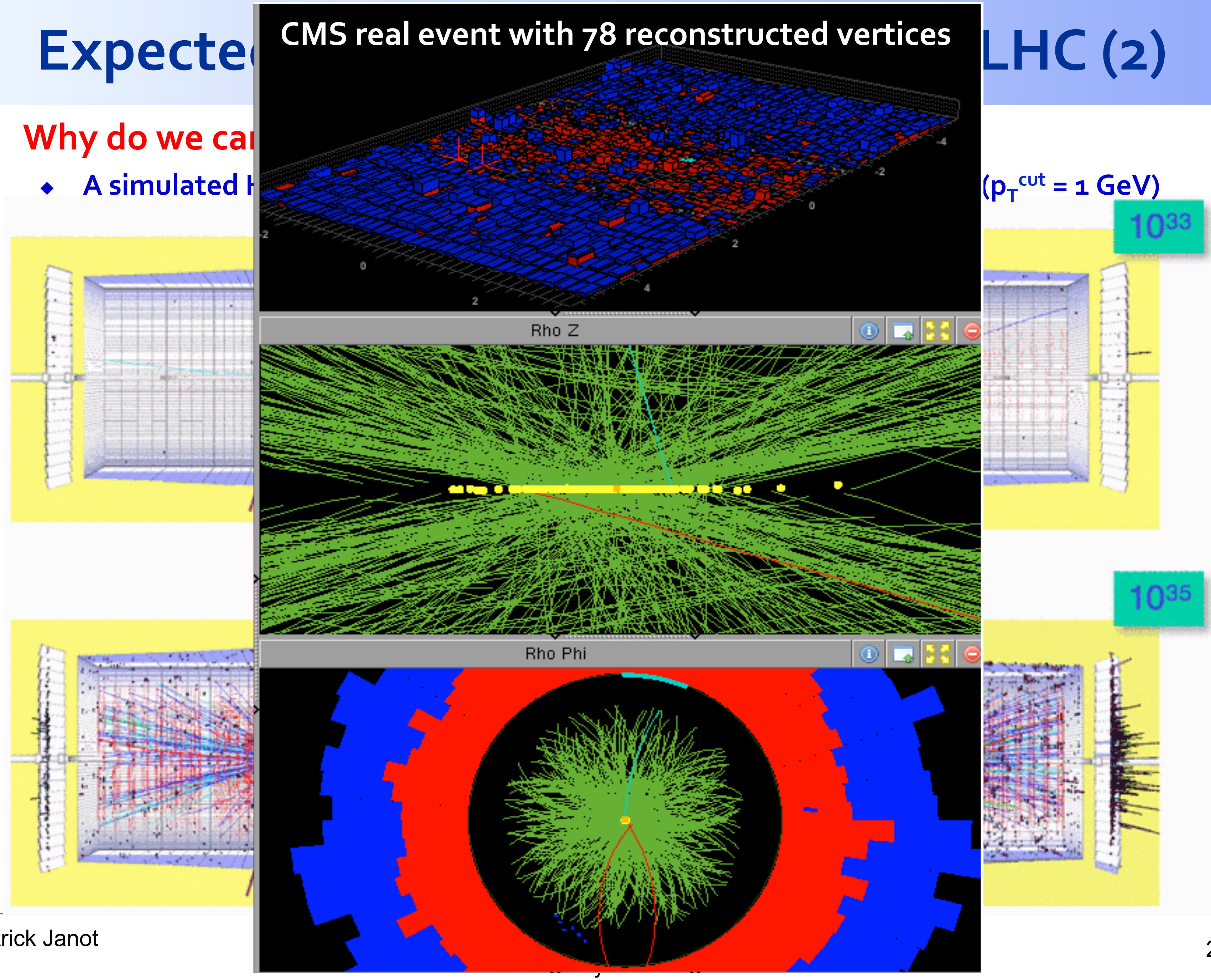
Expected pile-up interactions at HL-LHC (2)

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



Expecte… LHC (2)

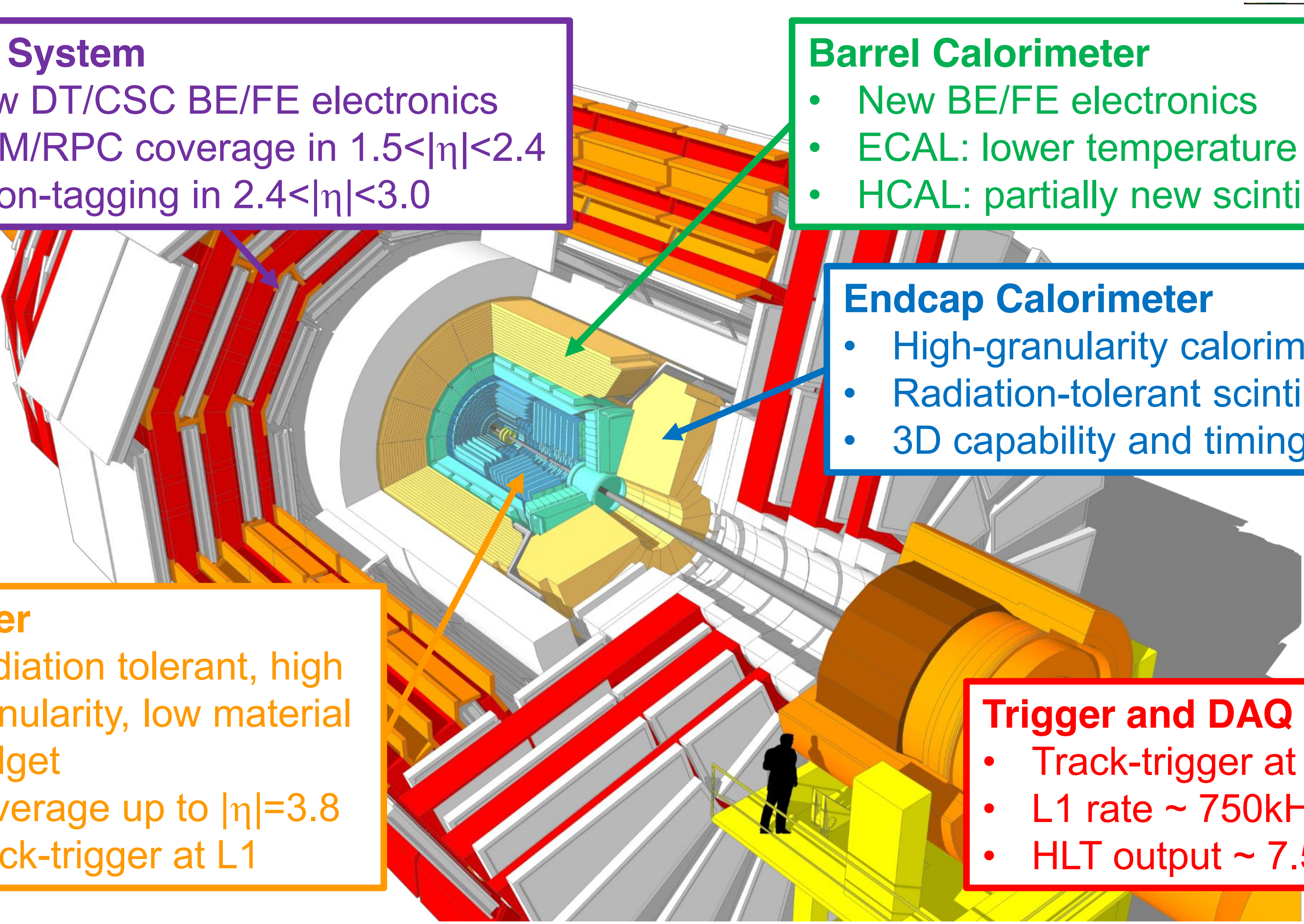
- Why do we ca…
  - A simulated H… (p_T^{cut} = 1 GeV)



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

- **Why do we care ? (cont'd)**
  - Heavy new particles like 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

Phase 2 CMS upgrades



Muon System
- New DT/CSC BE/FE electronics
- GEM/RPC coverage in $1.5<|\eta|<2.4$
- Muon-tagging in $2.4<|\eta|<3.0$

Barrel Calorimeter
- New BE/FE electronics
- ECAL: lower temperature
- HCAL: partially new scintillator

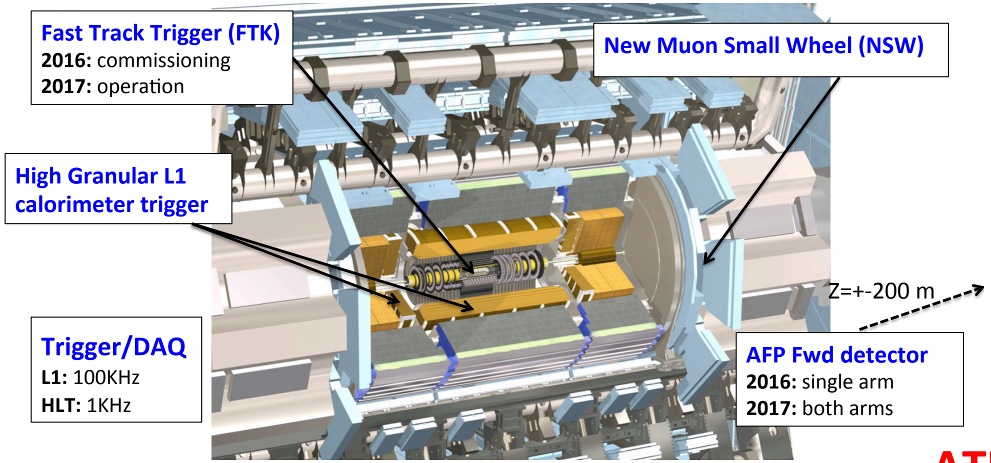
Endcap Calorimeter
- High-granularity calorimeter
- Radiation-tolerant scintillator
- 3D capability and timing

Tracker
- Radiation tolerant, high granularity, low material budget
- Coverage up to $|\eta|=3.8$
- Track-trigger at L1

Trigger and DAQ
- Track-trigger at L1
- L1 rate ~ 750kHz
- HLT output ~ 7.5kHz

Phase 1 and 2 ATLAS upgrades

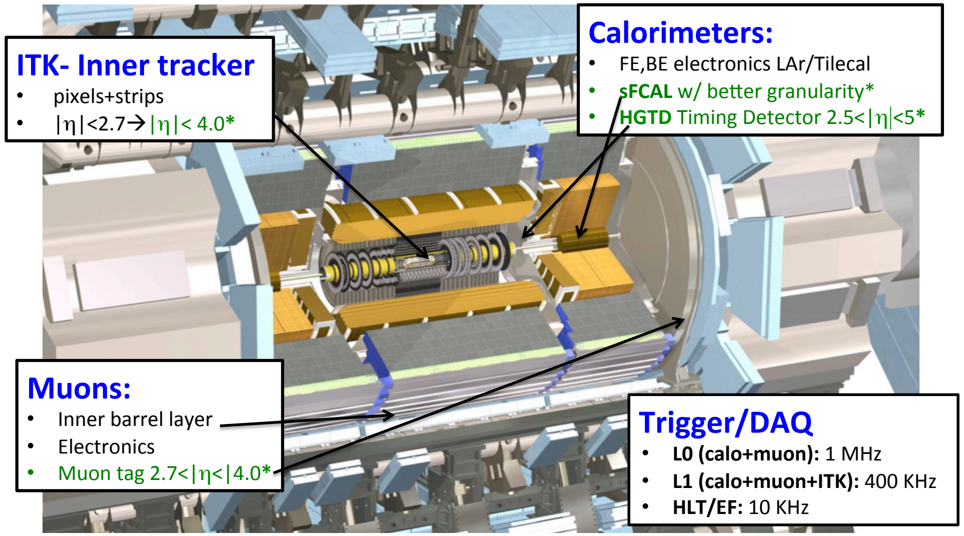
ATLAS Phase 1 upgrades (2019-2020)



Main target:

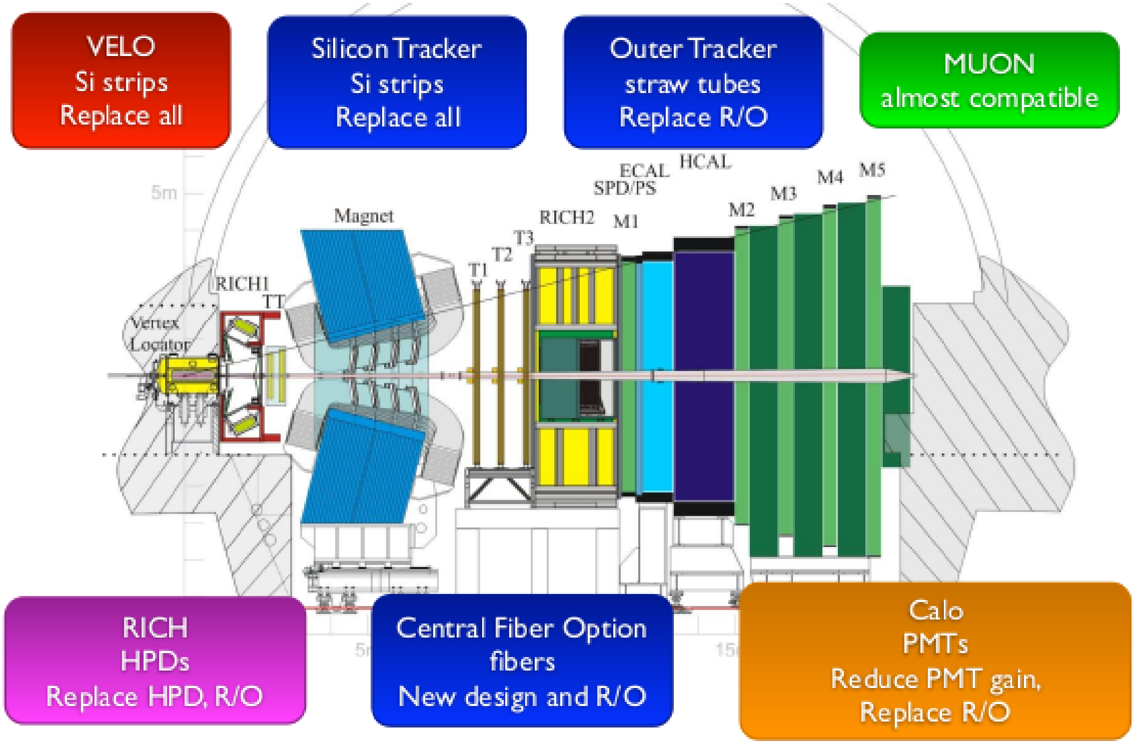
- Better trigger capabilities (efficiency, fake rejection)
- Maintain same acceptance/p_T thresholds at higher pileup

ATLAS phase 2 Upgrades for HL-LHC (2024-2026)



Phase 1 LHCb upgrades

- **Increased trigger rate**
  - With 50,000 CPU
  - Offline-quality reco
- **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 upgrades**
  - To stand 50 fb^{-1}



Physics prospects with HL-LHC (1)

- **Preliminary remarks**
  - The HL-LHC project has just been formally approved
  - The final design choices for the upgraded detectors have just been made
  - As a consequence, a 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 physics models, for simplified conclusions
    - But give a reasonably optimistic 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 couplings to other particles, rare Higgs decays
    - Measure Higgs self-coupling
    - Measure Higgs mass, width, CP, …

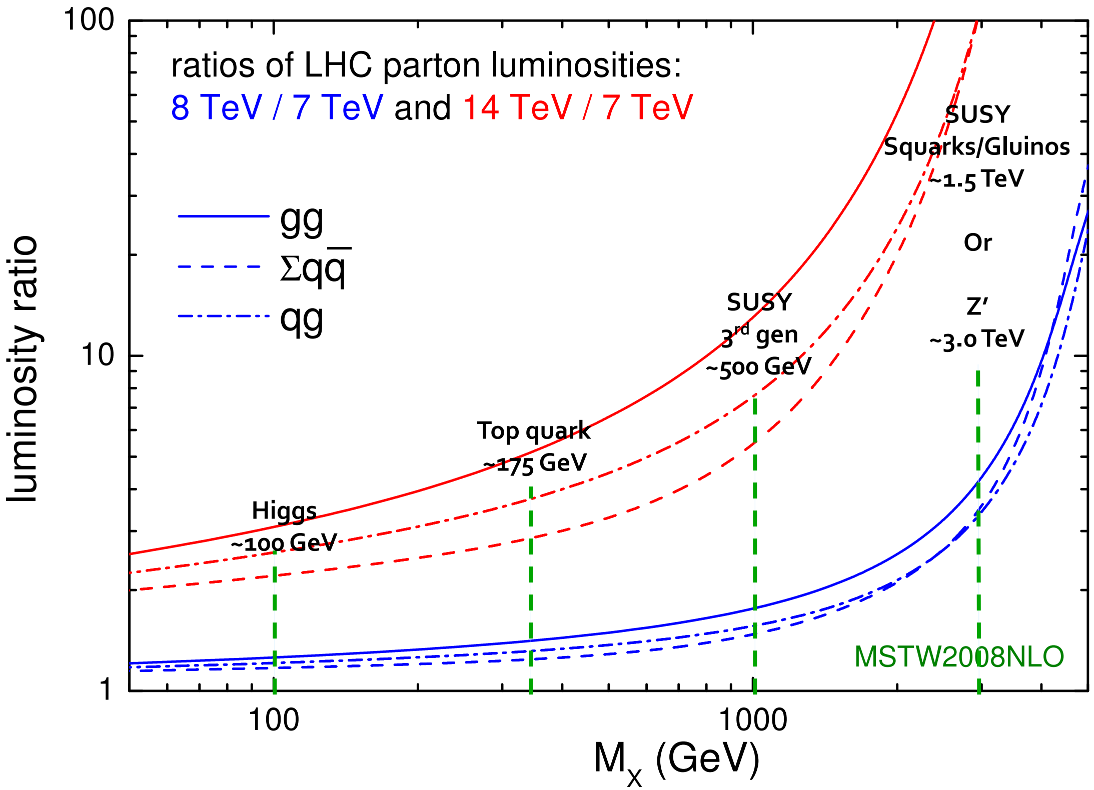
    G. Hamel de Monchenault
  - Search for new heavy physics
    - Supersymmetry
    - Extra-dimensions (new resonances, black holes)
    - Quark substructure (compositeness)
    - Fourth generation
    - New gauge bosons

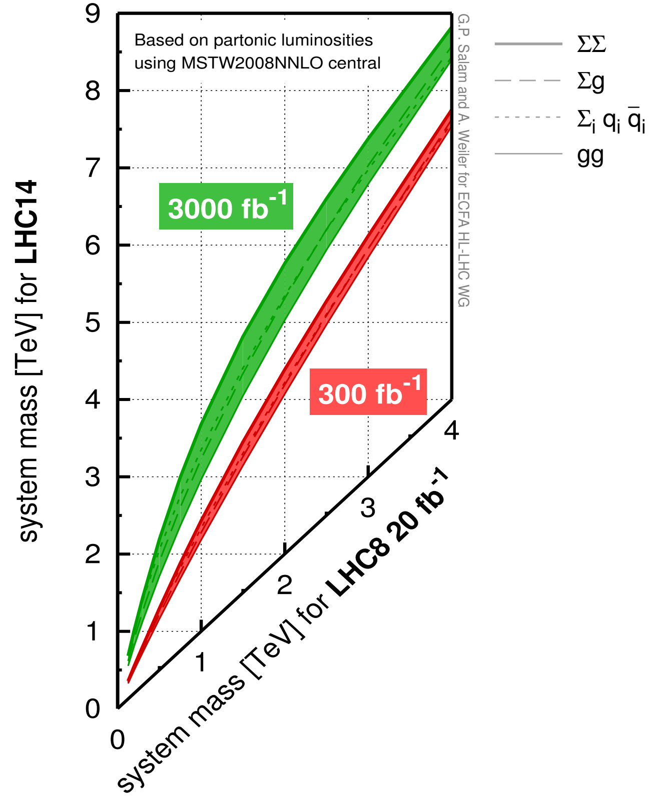
    G. Brooijmans
  - Flavour physics
    - Indirect sensitivity to very heavy new physics ($10 – 10^5$ TeV)

    T. Gershon
  - Only a few highlights are given here. Details in Gautier's, Gustaaf's, and Tim'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

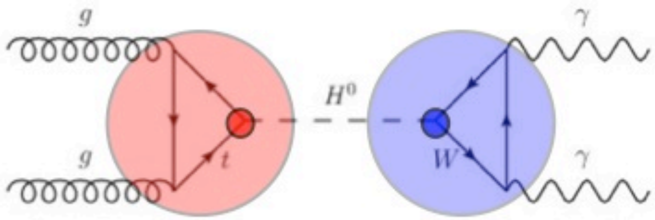




  - More energy buys a lot, both for precision and new physics reach
    - Cross sections multiplied by 3, 5, 10, 100 at m = 0.1, 0.35, 1 and 3 TeV
    - Mass reach for new physics roughly doubled

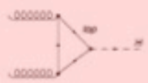
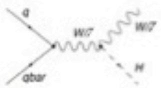
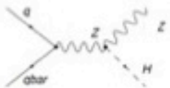
Precision Higgs physics (1)

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



m_H = 125 GeV

$\sqrt{s}$ = 7 TeV

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

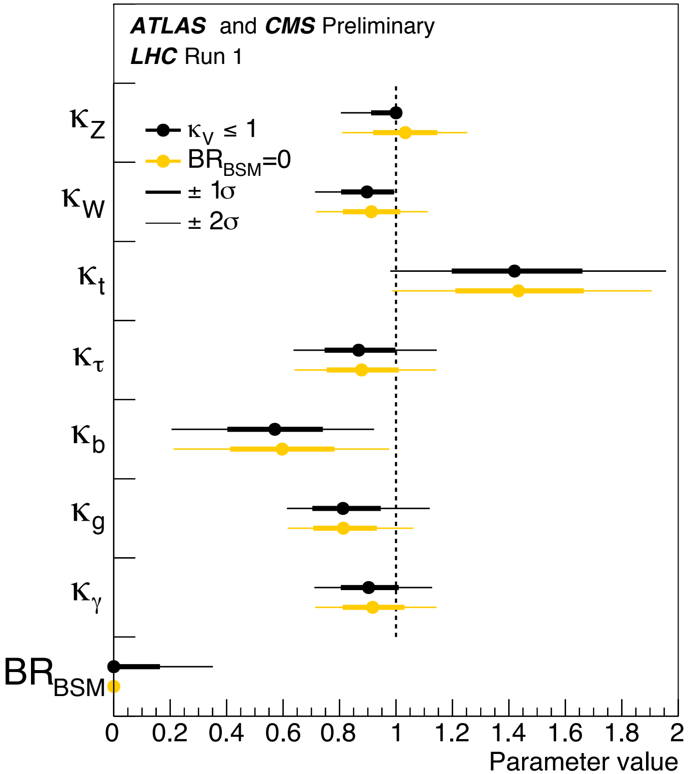
m_H = 125 GeV

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

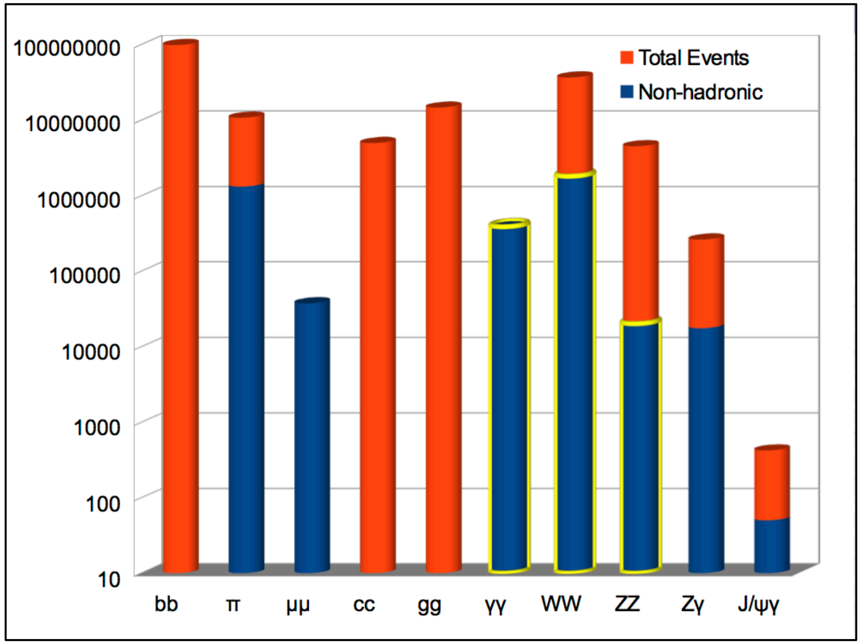
Precision Higgs physics (2)

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



- Typical precision: 15 to 50%

- **HL-LHC (3 ab^{-1})**
  - 170 M Higgs produced in each experiment
    - ~ 1/2 million events after selection
  - HL-LHC will be the first Higgs factory
    - With access to rare decays
      - ➨ H → μμ, Zγ …



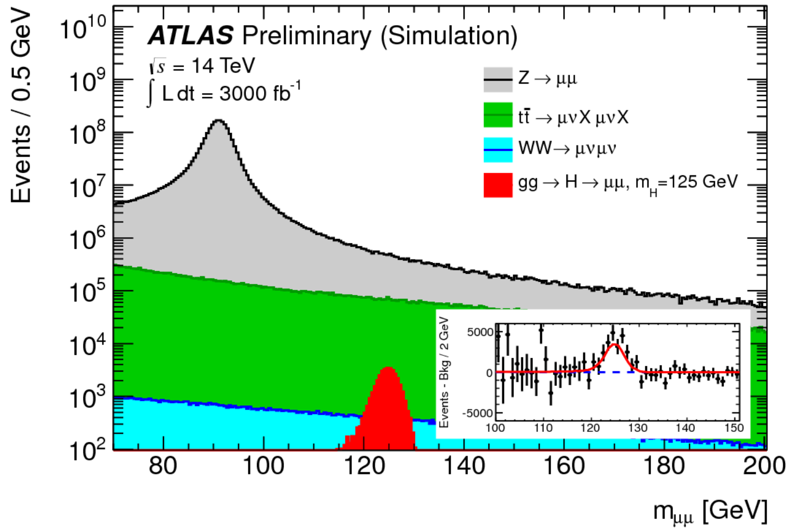
- Typical precision: 2 to 10%

Precision Higgs physics (3)

Higgs couplings projections (cont'd)

Coupling	LHC Run1	LHC (300 fb^{-1})	LHC (1 ab^{-1})	HL-LHC
κ_W	15%	4-6%	3-5%	2-5%
κ_Z	20%	4-6%	3-5%	2-4%
κ_t	50%	14-15%	10-12%	7-10%
κ_b	40%	10-13%	6-10%	4-7%
κ_τ	25%	6-8%	4-6%	2-5%

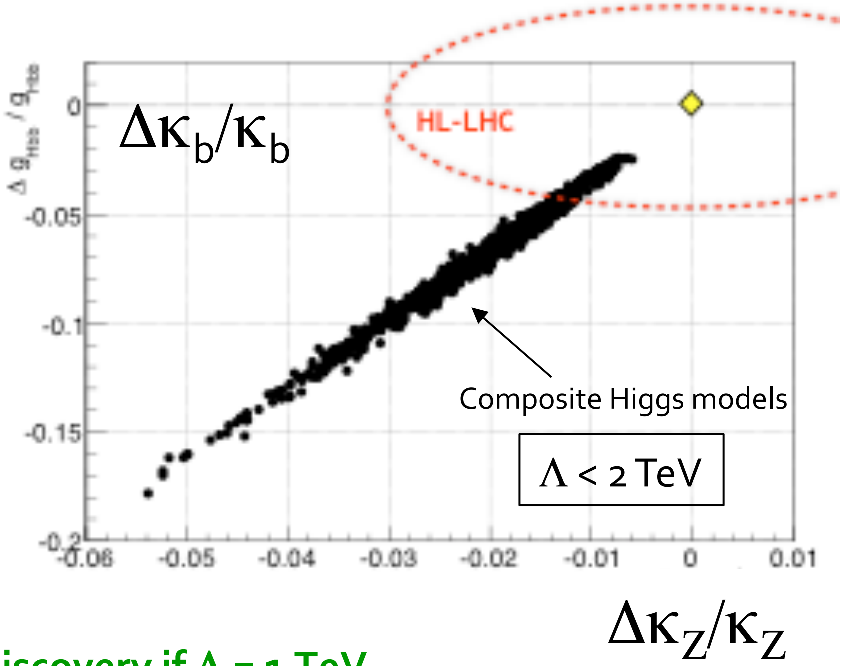
- HL-LHC will bring a factor 1.5 to 2 on top of 300 fb^{-1} (and 20-50% on top of 1 ab^{-1})
  - Limited by systematic uncertainties
- Becomes sensitive to, e.g., H → μμ
  - Expect 35K signal events with 3 ab^{-1}
    - ➨ S/B ~ 0.3% → 10σ significance
  - Coupling measured to ~10%
    - ➨ 20-30% with 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

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



Typically, expect deviations:

$\Delta\kappa/\kappa < \sim 5\ \% / \Lambda^2$

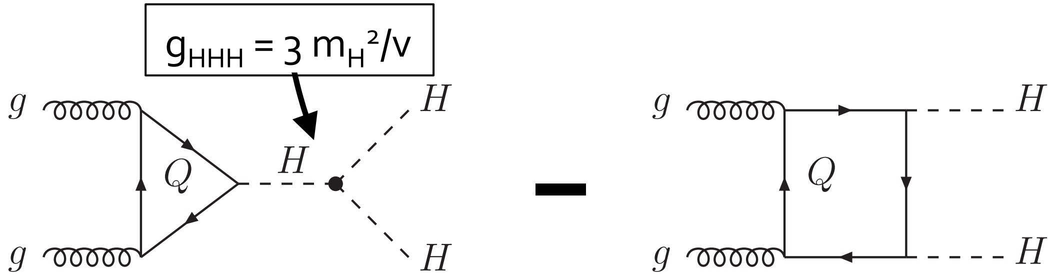
(with Λ in TeV)

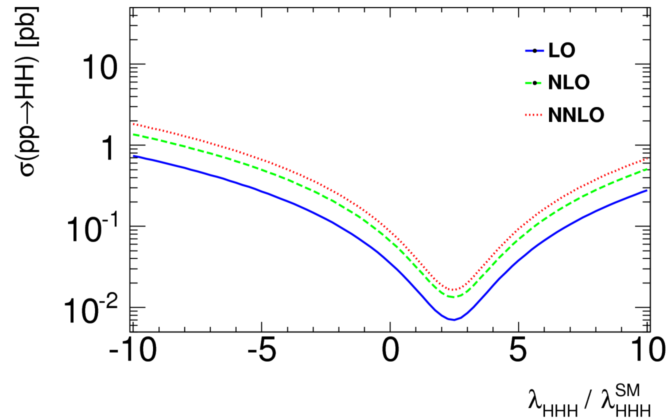
  - Need 1% precision on couplings for a 5σ discovery if Λ = 1 TeV
    - ➨ And much better for heavier new physics
- HL-LHC might be good enough for some new physics models
  - IF the new physics scale is well below 1 TeV
    - ➨ The air is getting thin …

Precision Higgs physics (5)

❑ Higgs self coupling

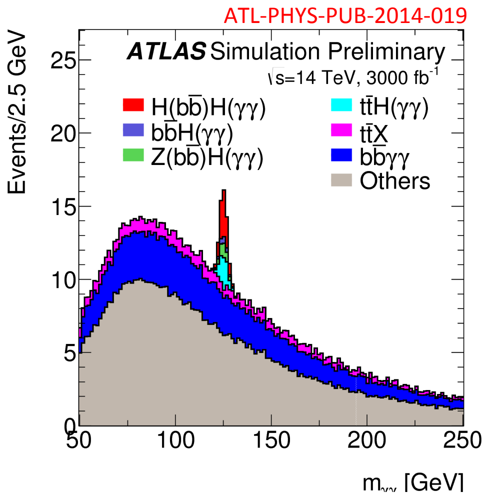
- Measurable through double Higgs production

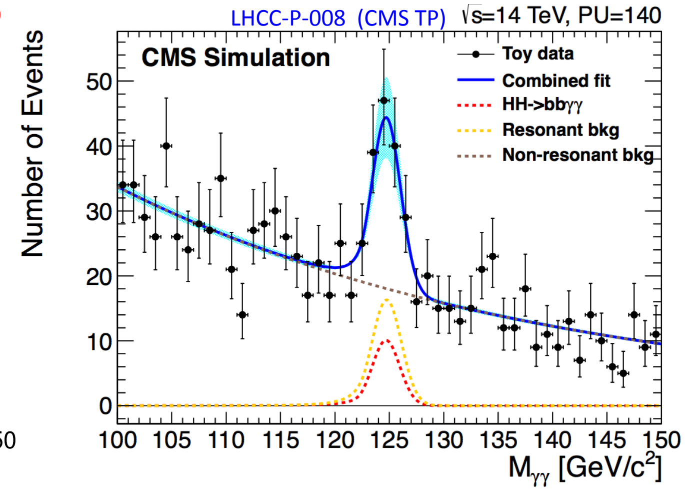




  - Negative interference reduces the sensitivity to g_{HHH}

- Two channels studied so far
  - bbττ and bbγγ
  - Only 9000 + 300 events
- Expected significance < 2σ
  - Precision on g_{HHH} > 50%

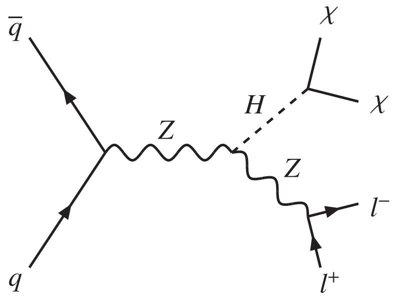


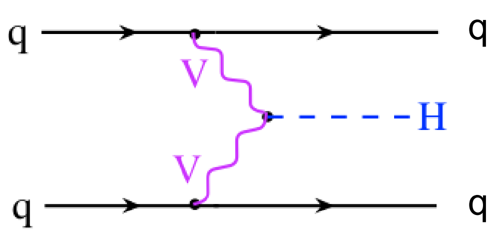


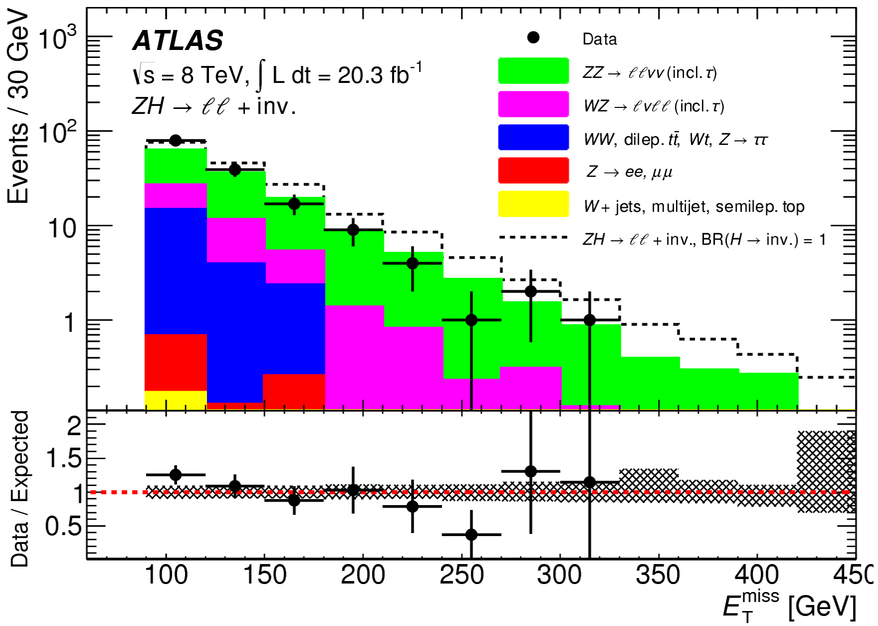
- Is this precision enough ?
  - Not really: new physics models do not predict deviations larger than 20%

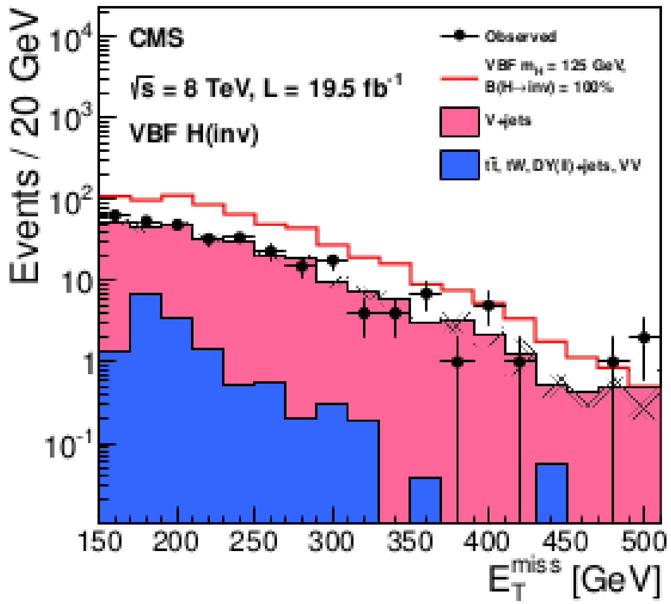
Precision Higgs physics (6)

❑ Invisible Higgs decays









Expected 95% CL upper limit

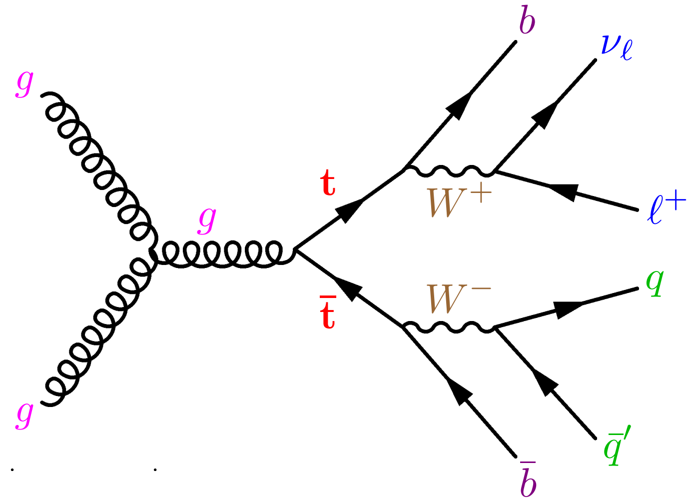
	BR_{inv} (95% CL)
LHC Run1	40-50%
LHC 300 fb^{-1}	20-30%
HL-LHC	10-15%

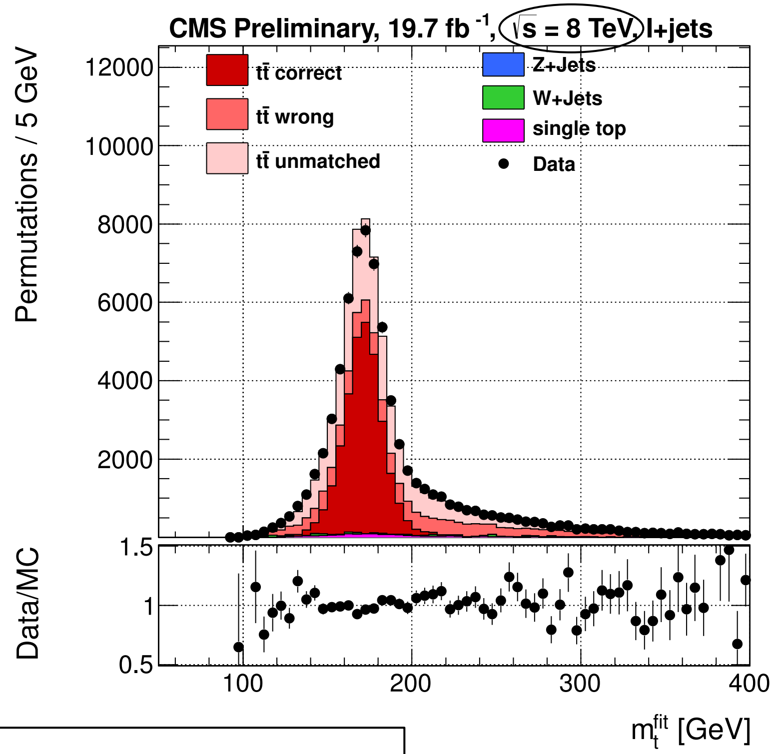
- **Improves DM search at low mass**

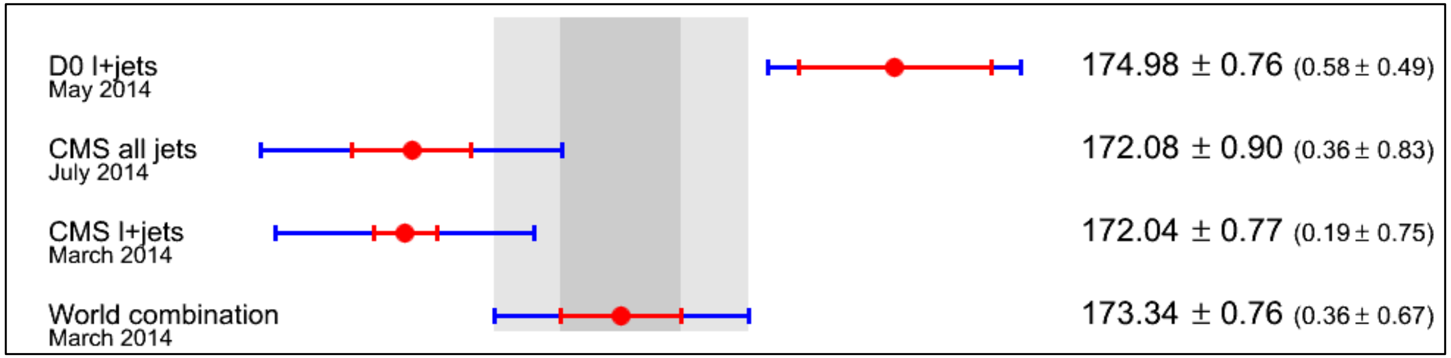
Top quark mass (1)

- **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



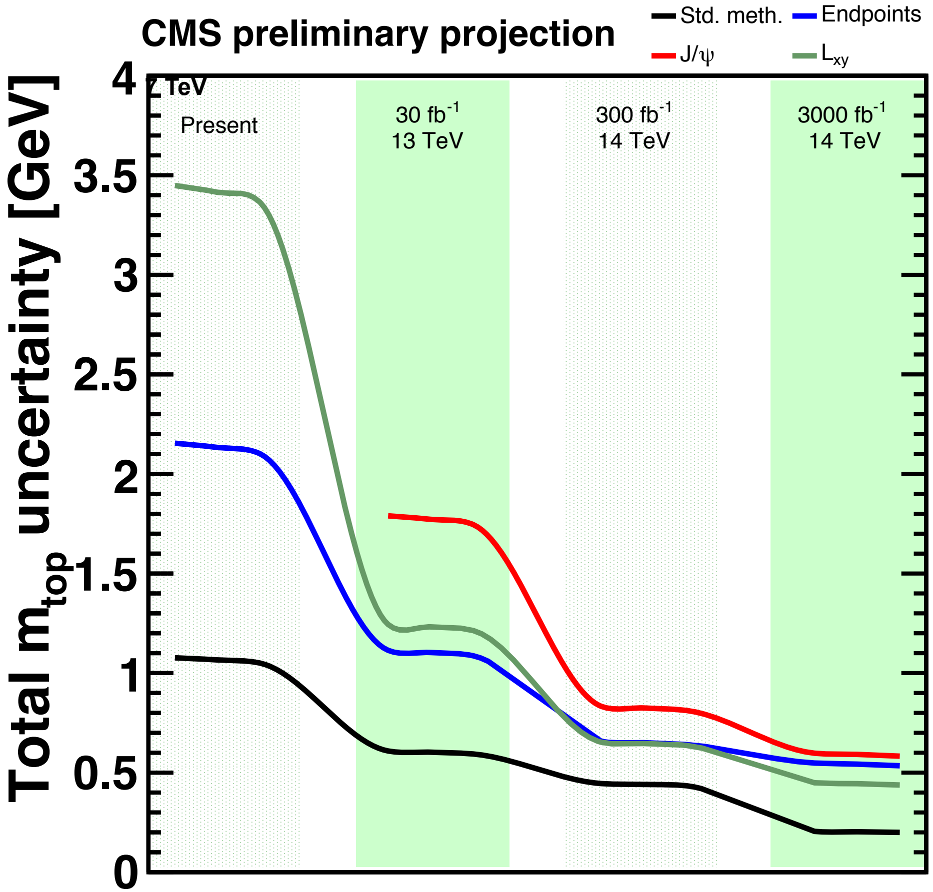




ATLAS 2015: 173.0 ± 0.9

Top quark mass (2)

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

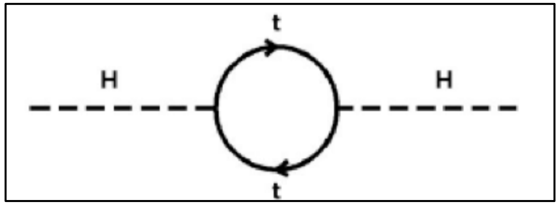


- Projected uncertainties
  - Reduction by a factor 2
    - After the first data of LHC Run2
      - One year
    - Then after the LHC Run3
      - Five more years
    - Then after 3 ab^{-1}
      - Ten more years

- Ultimate reach: ~ 200 MeV (exp.)
  - Theory uncertainties ~ 500 MeV
    - What is the quantity that is measured ? MC top mass ?
  - Must answer this very question
    - Otherwise 3 ab^{-1} won't do much better than 0.3 or 1 ab^{-1}

Supersymmetry (1)

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



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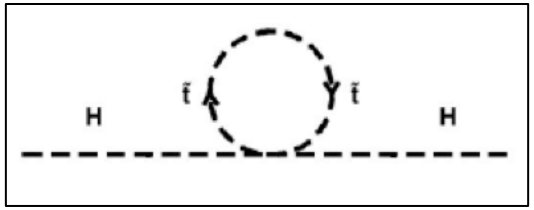
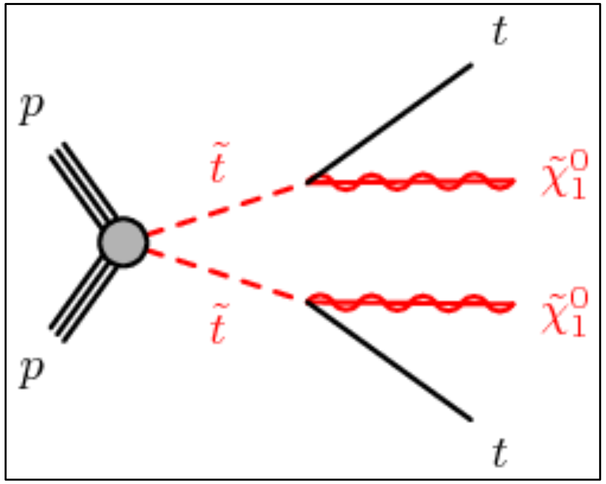
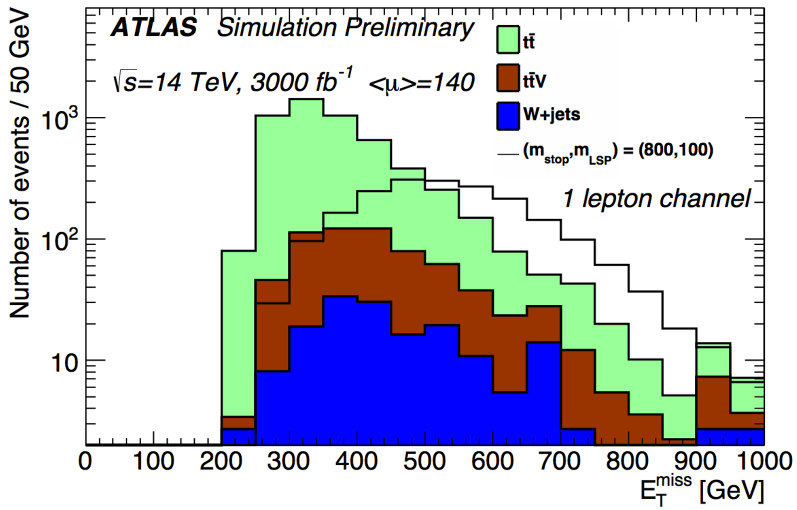


  - To serve its purpose, the lighter stop should not be much heavier than 1 TeV
    - Search for light stop production, e.g.,



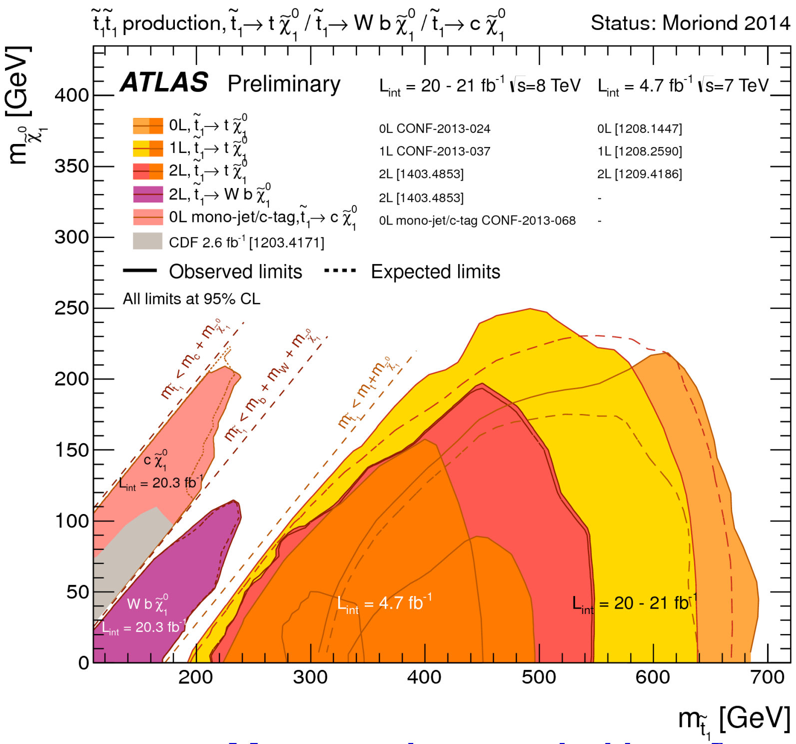


➨ Final state similar to top pair production, with larger missing energy

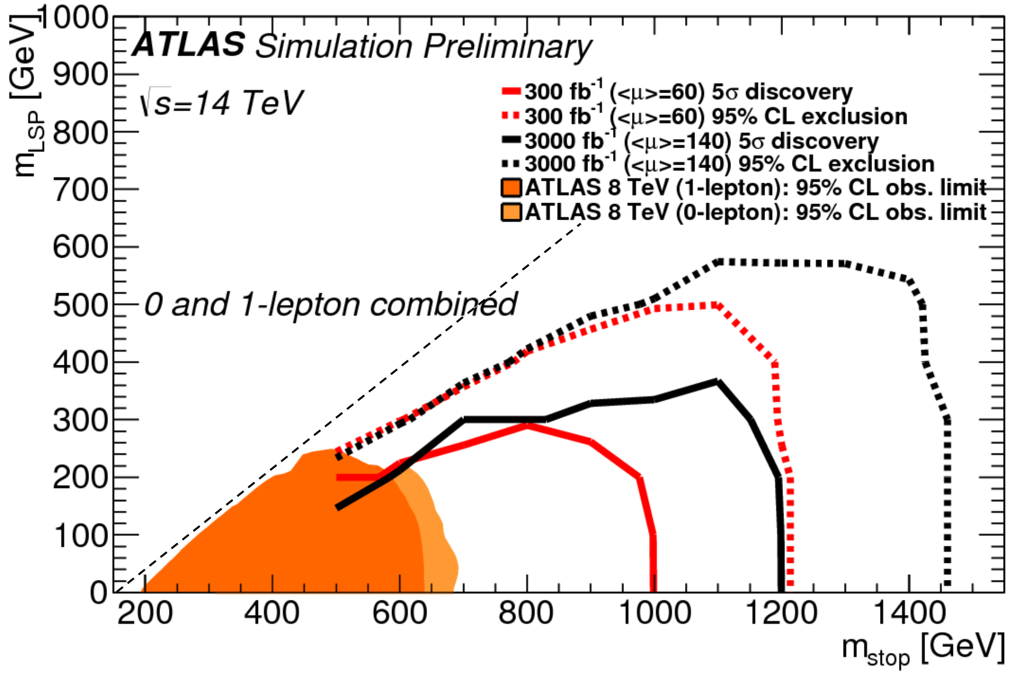
Supersymmetry (2)

❑ Search for third generation squark (cont'd)

- **Today :**



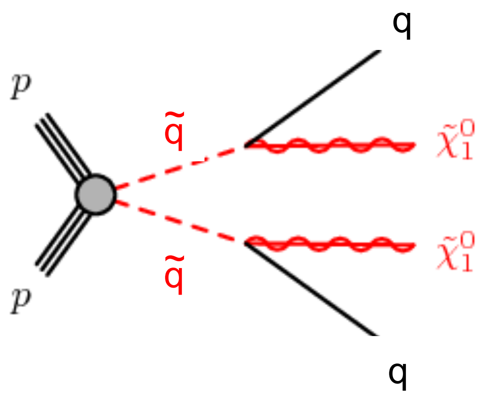
Projections with 300 and 3000 fb^{-1}

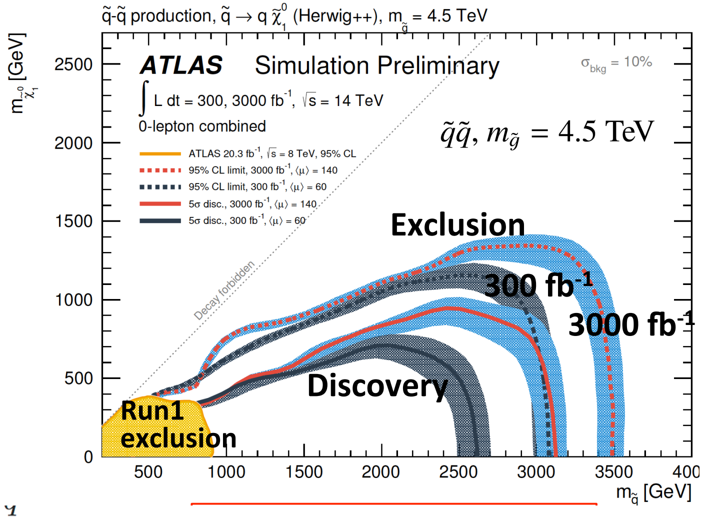


- **Mass reach extended by a factor 2 with LHC at 14 TeV (300 fb^{-1}): covers the 1 TeV region**
  - **Further 20% extension with HL-LHC**
- **If no excess is seen with 300 fb^{-1}**
  - **The HL-LHC discovery potential vanishes entirely**

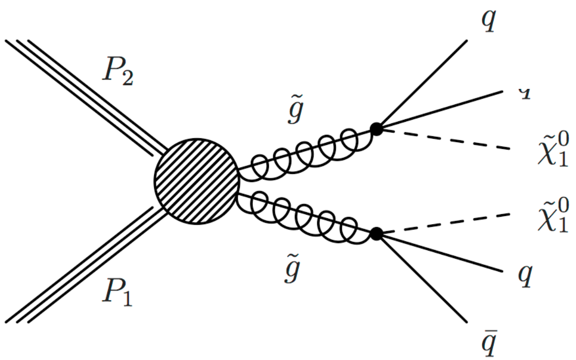
Supersymmetry (3)

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

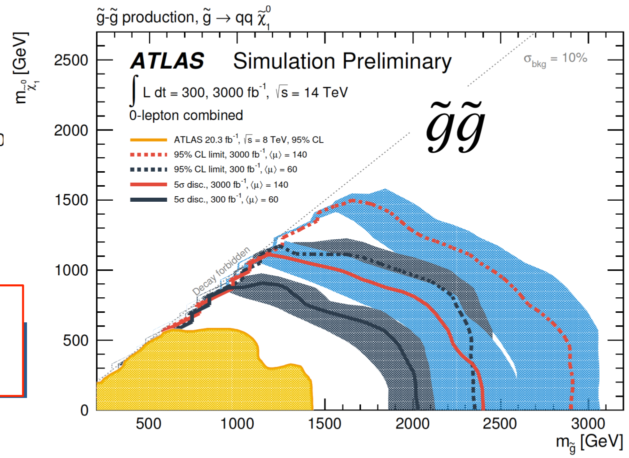




5σ Discovery: up to 2.4 TeV
Exclusion: up to 2.9 TeV



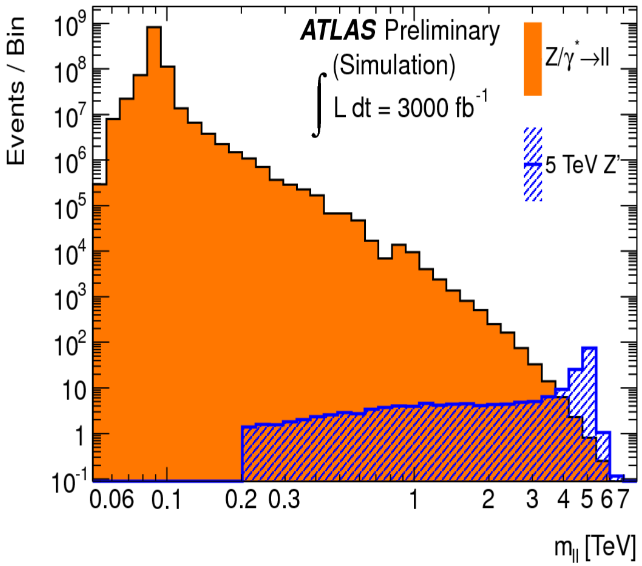
Discovery: up to 3.1 TeV
Exclusion: up to 3.5 TeV

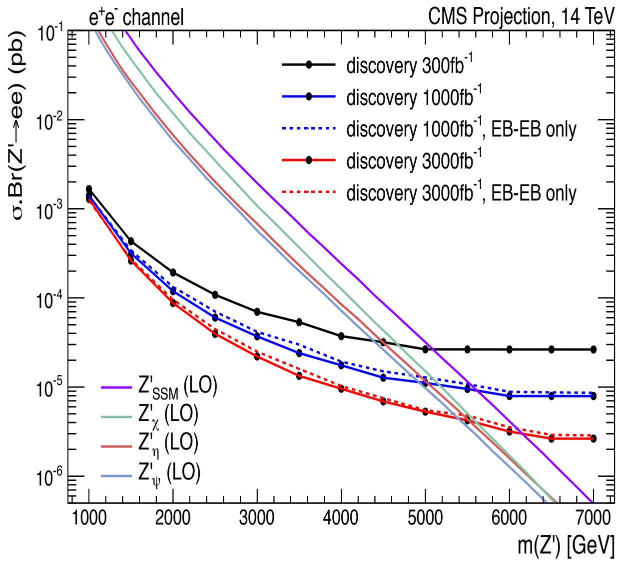


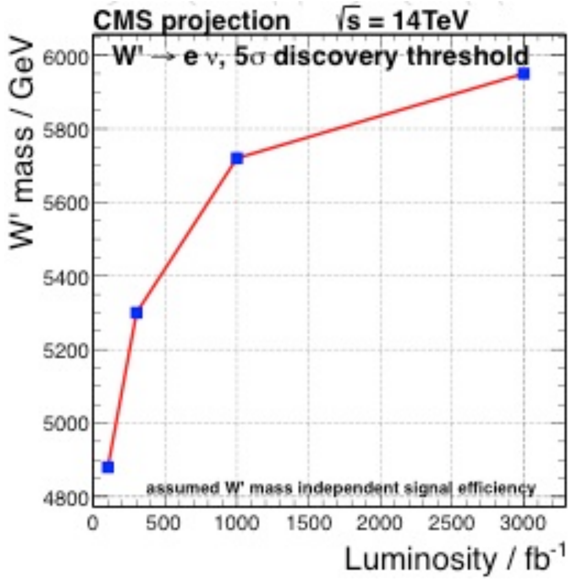
  - Mass reach extended by a factor 2 to 3 with LHC at 14 TeV (300 fb^{-1})
    - Further extended by 20% with HL-LHC
  - Discovery potential of HL-LHC vanishes if no excess is seen with 300 fb^{-1}

New gauge bosons: W', Z'

- Look for heavy di-lepton resonance: $Z' \rightarrow e^+e^-, \mu^+\mu^-$, or $W' \rightarrow e^+\nu_e, \mu^+\nu_\mu$
  - Z' and W' masses up to 2-3 TeV excluded at LHC Run 1



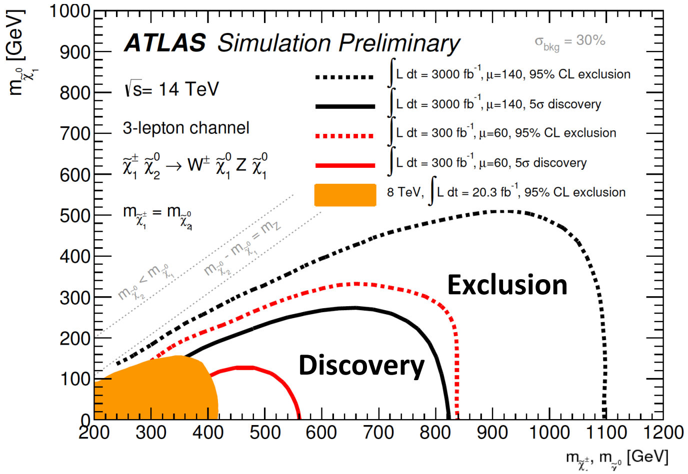


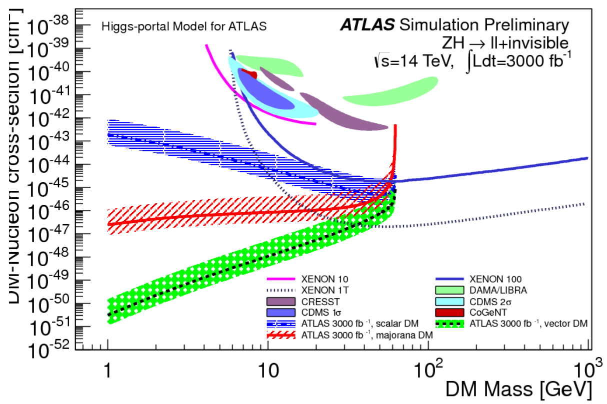


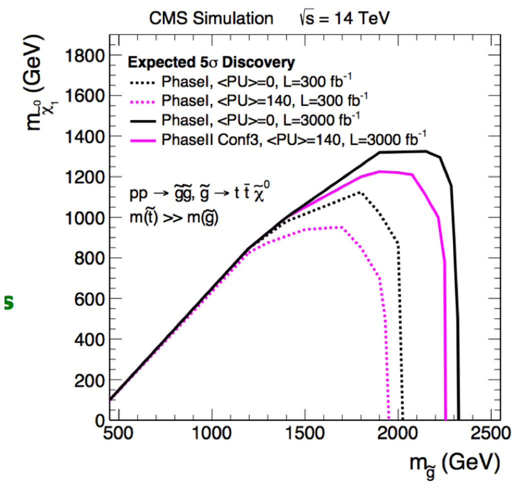
- Mass reach extended by a factor 2 with LHC at 14 TeV (300 fb^{-1})
  - Further extended by 20% with HL-LHC
- Discovery potential of HL-LHC vanishes if no excess is seen with 300 fb^{-1}
  - (Not visible in the graphs above)

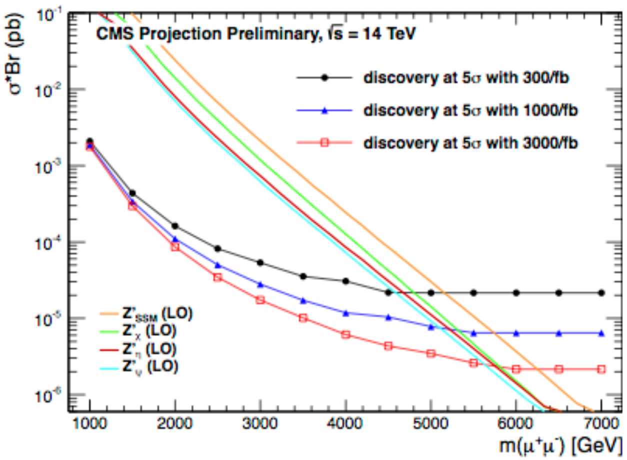
… and many others …

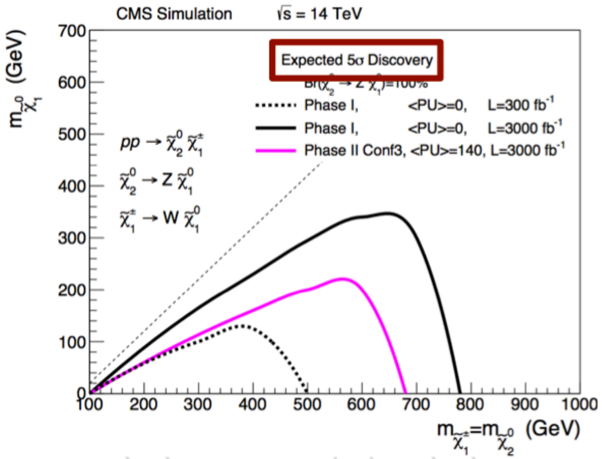
- **All with a similar pattern**

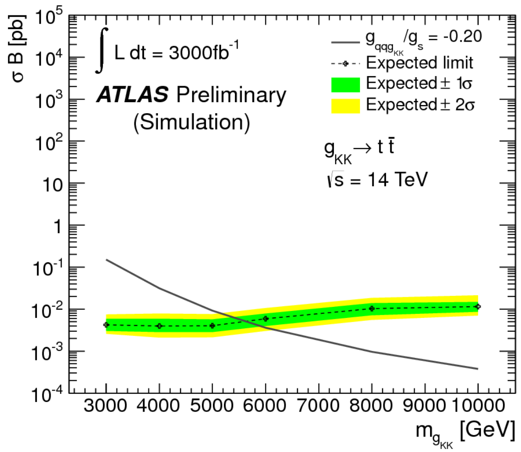












Conclusions of the first lecture (1)

- The LHC Run 1 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
      - ➨ Standard theory tested at quantum level: new physics will be hard to find

- With the 8 → 14 TeV increase, the LHC Run 2 and Run 3 promise to be thrilling
  - The mass reach for new physics will increase by a factor 2
    - Stop: 1.2 TeV; Squarks/Gluinos: 2.5 / 3 TeV; Z': 6 TeV; etc.
  - The measurement precision will improve by a factor ~4-5
    - Top mass: 300-400 MeV; Higgs couplings: 2-10%; etc.
  - The lighter particle of the new physics spectrum may even be discovered
    - Beware statistical fluctuations !
      - ➨ Among 1000 different searches in ATLAS and CMS, at least one is bound to give a >3σ effect every year (e.g., $X_{750} \to \gamma\gamma$?). 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% 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 or 3 (even via a modest excess)
  - The HL-LHC is unlikely to make any discovery in 15 years of running

- The HL-LHC will allow precision measurements to improve
  - By a factor up to 2 (1.5) with respect to LHC 300 fb^{-1} (1000 fb^{-1})
    - The ultimate precision is unlikely to unveil new physics effects
      - ➨ Because deviations from BSM physics are not expected to be large enough

- 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 understand the underlying physics quantum structure

See 2nd & 3rd lectures for the pertaining perspectives

Conclusions of the first lecture (3)

- You are going to be running the LHC until 2035
  - With significant upgrades to the machine and the detectors for the HL-LHC
    - In extreme running conditions (with an average of 140-200 PU collisions)

- It will be necessary to re-assess the strategy in depth in 2018/19
  - In view of the results of the LHC Run2
    - Will 300 fb^{-1} be enough ? Or 1000 fb^{-1} ?
    - Will the physics prospects compelling enough to justify the need of 3 ab^{-1} ?
      - ➨ with a luminosity increment of 10% / year, until 2030-2035

- "The HL-LHC project is not controversial"

Fabiola Gianotti, 23 June 2016
DG presentation to CERN personnel

TODAY, WHAT DO YOU THINK ?