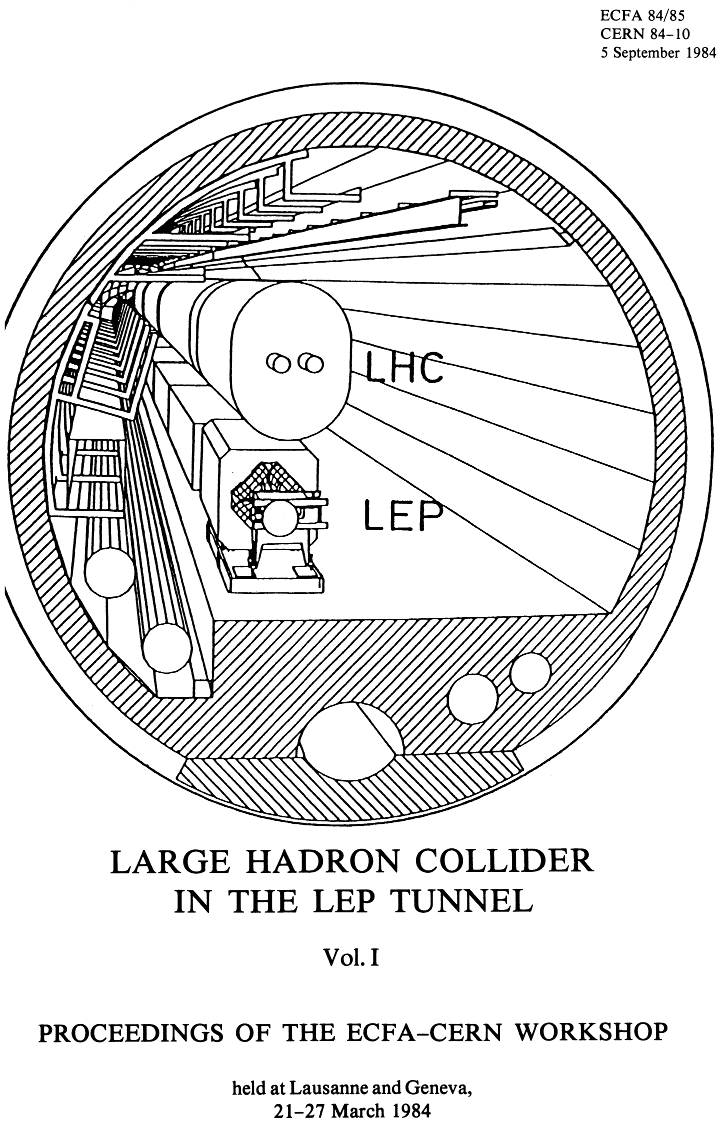
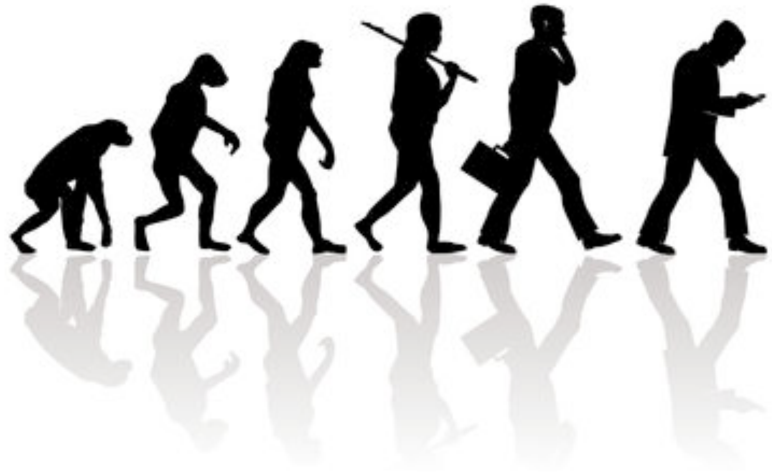

ECFA 84/85
CERN 84-10
5 September 1984

LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984



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Evolution of the LHC Program

Christopher S. Hill
The Ohio State University
on behalf of the ATLAS & CMS Collaborations

The Big Questions when the LHC was "born" (ca. 1984), from the Lausanne report ...

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" What is the deep origin of mass and what are the relations between masses and symmetry breaking processes, such as those which are at work in the Higgs mechanism?

Mass

Why is there a repetition of the quark and lepton families which our present theory can merely only accommodate but not explain? The origin of the different flavours is still a riddle. So is the origin of CP violation.

Flavor

What is gravitation and how does it relate to the other interactions as presently described in the framework of the standard model?...

Gravity

While drawing up such a list probably takes us beyond what we may reasonably hope to learn by studying in detail physics at LEP and in the multi-TeV range, there is one question which one thinks one can approach with success there: what is the nature of the symmetry breaking mechanism which is at work in the standard electroweak model? "

EWSB

Nearly 30 years later, we have significant progress on at least one of these (maybe two)

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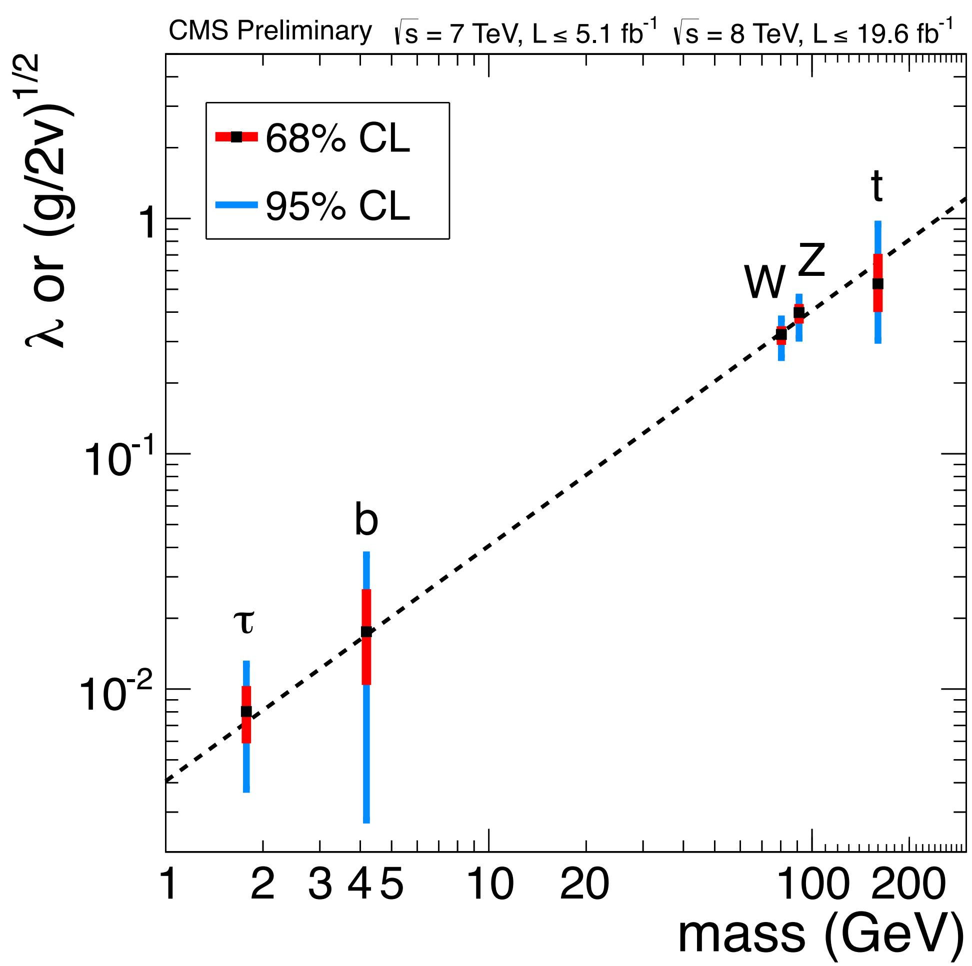
- We have discovered a new particle that certainly appears to have something to with the origin of mass, and
    - *It seems to have spin 0*
    - *It seems to be positive parity*
    - *It seems to couple to the EW gauge bosons as expected from EWSB due to the Higgs mechanism*
    - *It seems to couple to fermions proportional to their mass*
- The new particle looks very much like the Higgs boson of the SM



But what, if anything, is stabilizing the Higgs mass at 125 GeV (aka the Hierarchy problem)?

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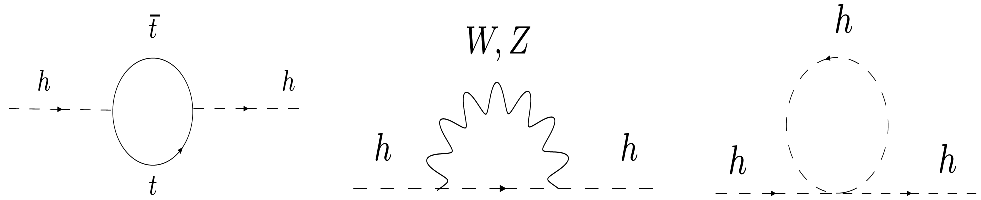
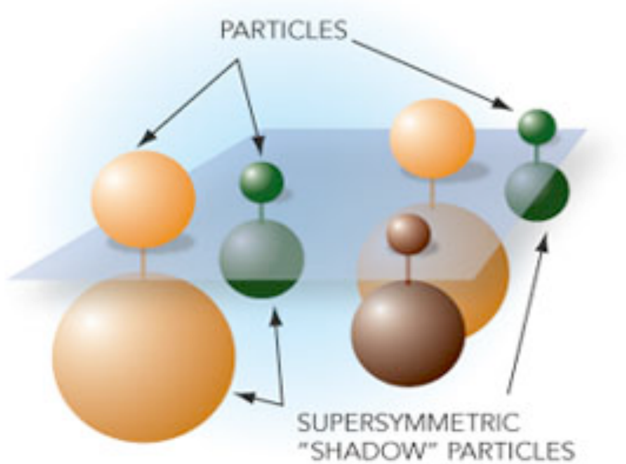
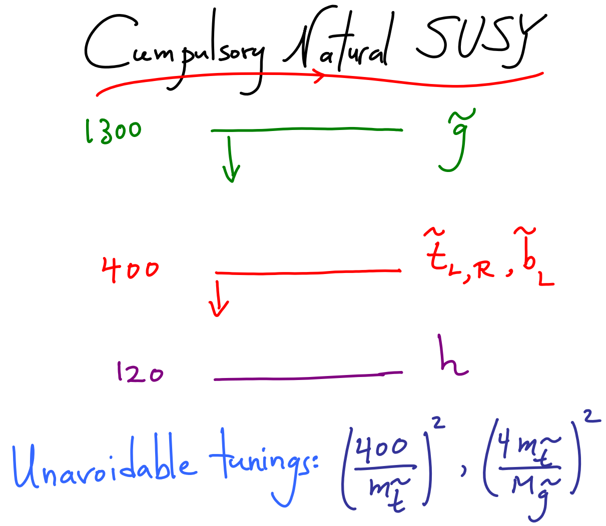
- *If we have discovered Nature's first fundamental scalar field, then*
- in QFT, scalar fields get loop **corrections that diverge quadratically,** so
- Either there is some **new (LHC accessible) physics** which "naturally" solves this problem
    - $\delta m^2{}_H \propto \Lambda^2{}_{cutoff}$
- **Or the universe is fine tuned,** i.e. it is a coincidence
- (Or QFT is wrong)



$$m_H^2 = m_H^{2\ tree} + \delta m_H^{2\ top} + \delta m_H^{2\ W,Z} + \delta m_H^{2\ self} \approx \mathcal{O}(125)\ GeV$$



$$\delta m^2{}_H + (-\delta m^2{}_H) = 0$$



Natural SUSY needs to show up soon (or maybe it's been missed)

This is not a new problem

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" Is the Higgs a fundamental field and if so why is the Higgs mass so light, when one might expect it to be driven up close to the GUT energy scale or even the Planck mass by radiative corrections? The answer may lie in the presence of supersymmetric particles, some of them, however, then with masses comparable to the energy scale characterizing the symmetry breaking of the electroweak interactions (say, the weak boson mass, or $G_F^{-\frac{1}{2}} \approx 250$ GeV). "

- So this argument, while still valid, is older than the LHC itself
  - *The "solution" via supersymmetry just as old*
  - *Some alternative solutions (e.g. ED) developed in intervening years, but there are no evidence for these either (yet)*

Is there anything new since the Higgs Discovery?

Here's one thing - now know *all* the parameters of the SM

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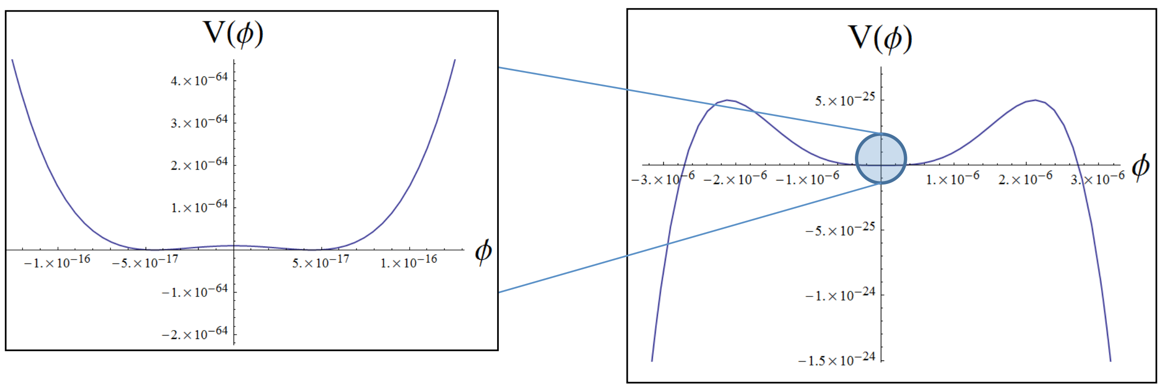
- Now that we know the Higgs mass, we can calculate the Higgs potential
- And people have done this (recently to NNLO)
  - *Point lies along critical line between stable/metastable phases*
  - *The vacuum (in the SM) is apparently a false minimum*



arXiv:1205.6497v1 [hep-ph]

To me, however, the fate of the universe is not the point here

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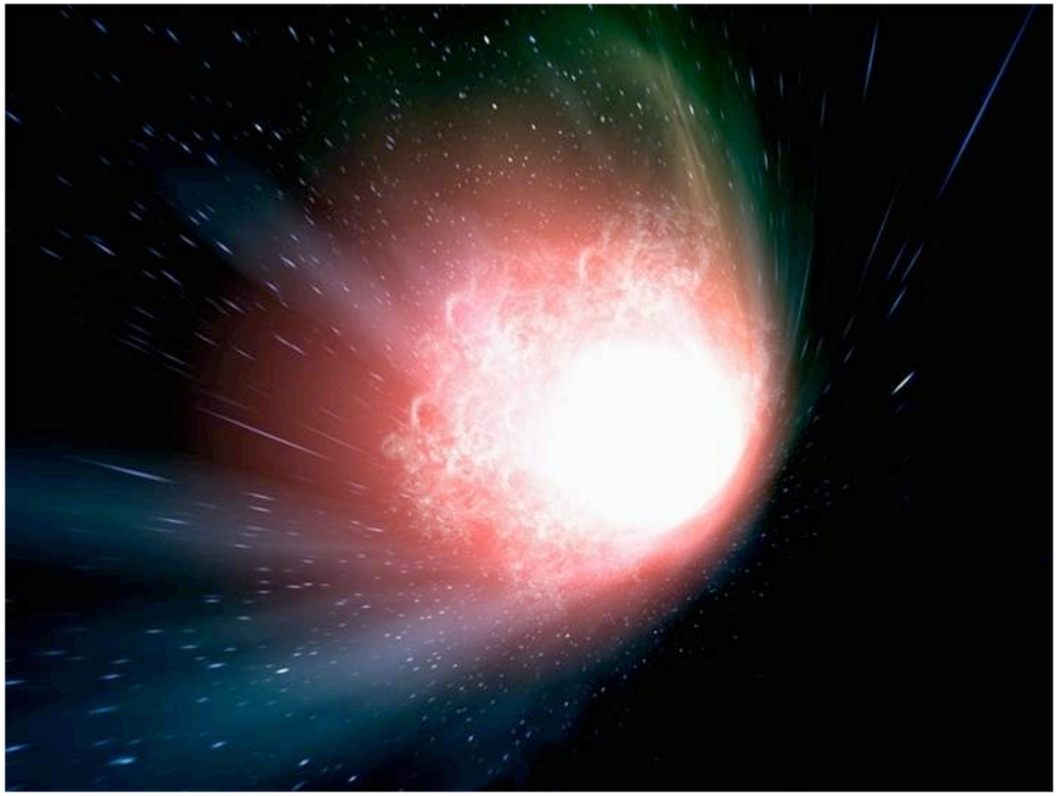
Will our universe end in a 'big slurp'? Higgs-like particle suggests it might

Alan Boyle, Science Editor, NBC News

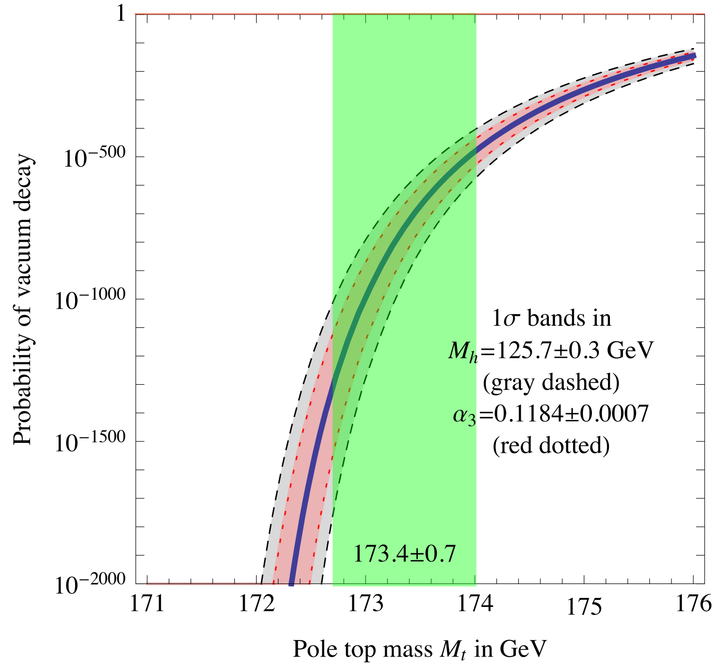
Feb. 18, 2013 at 5:02 PM ET



Corbis /

An artist's conception visualizes the beginning of the universe in the big bang — or could it be the end of the universe?

arXiv:1307.3536v1 [hep-ph]



- Firstly, the universe will likely die in other ways
    - *See above*
- The point (for me) is that apparent criticality is interesting in physics
    - *Because its investigation (often) leads to new physics*
        - **Supersymmetry or other BSM ...**

But LHC is still an early hominid

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

Fully evolved LHC

2x increase in E

100x increase in int. L

Two Distinct Stages of Operation

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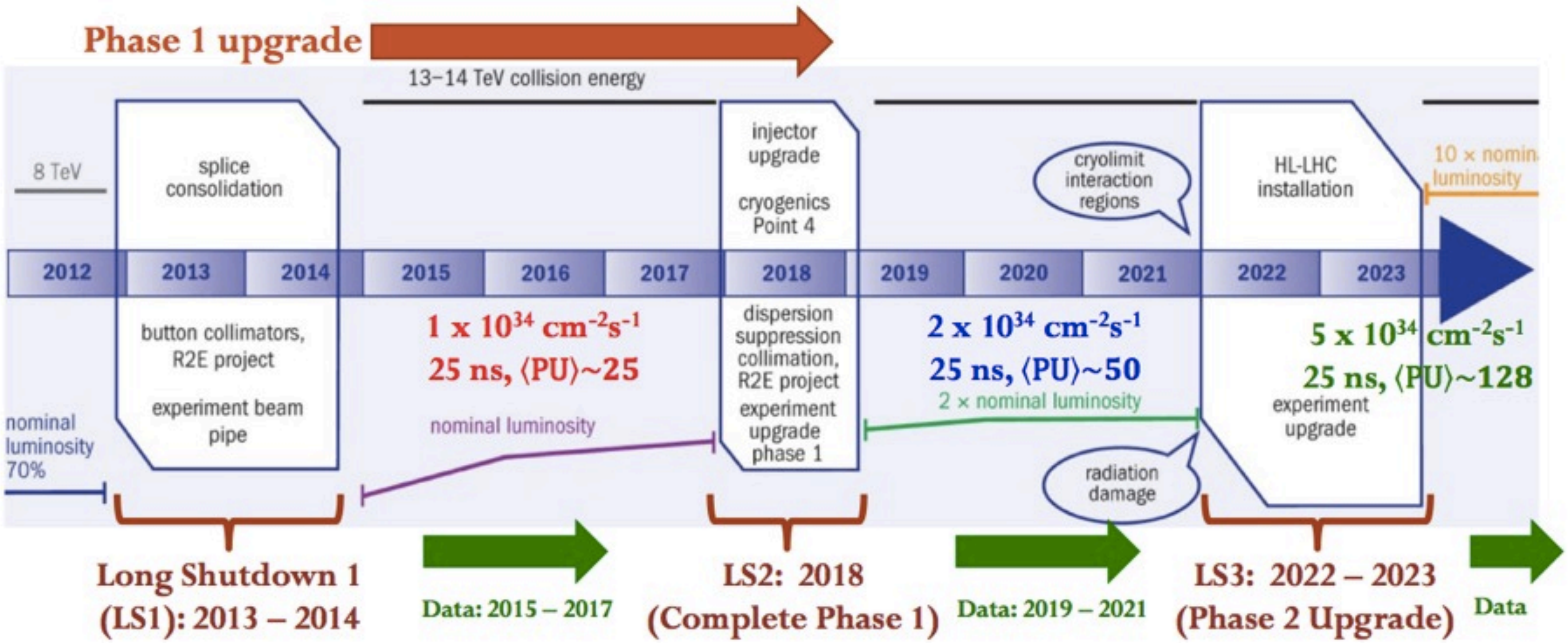

LHC

Reach $10^{34}cm^{-2}s^{-1}$ by LS2, double by LS3 and integrate $300fb^{-1}$ by 2022

<PU> = 50

HL-LHC

Lumi-level 5x $10^{34}cm^{-2}s^{-1}$ and integrate $3000fb^{-1}$after L3

<PU> = 140

What are the experimental challenges that this means for ATLAS + CMS?

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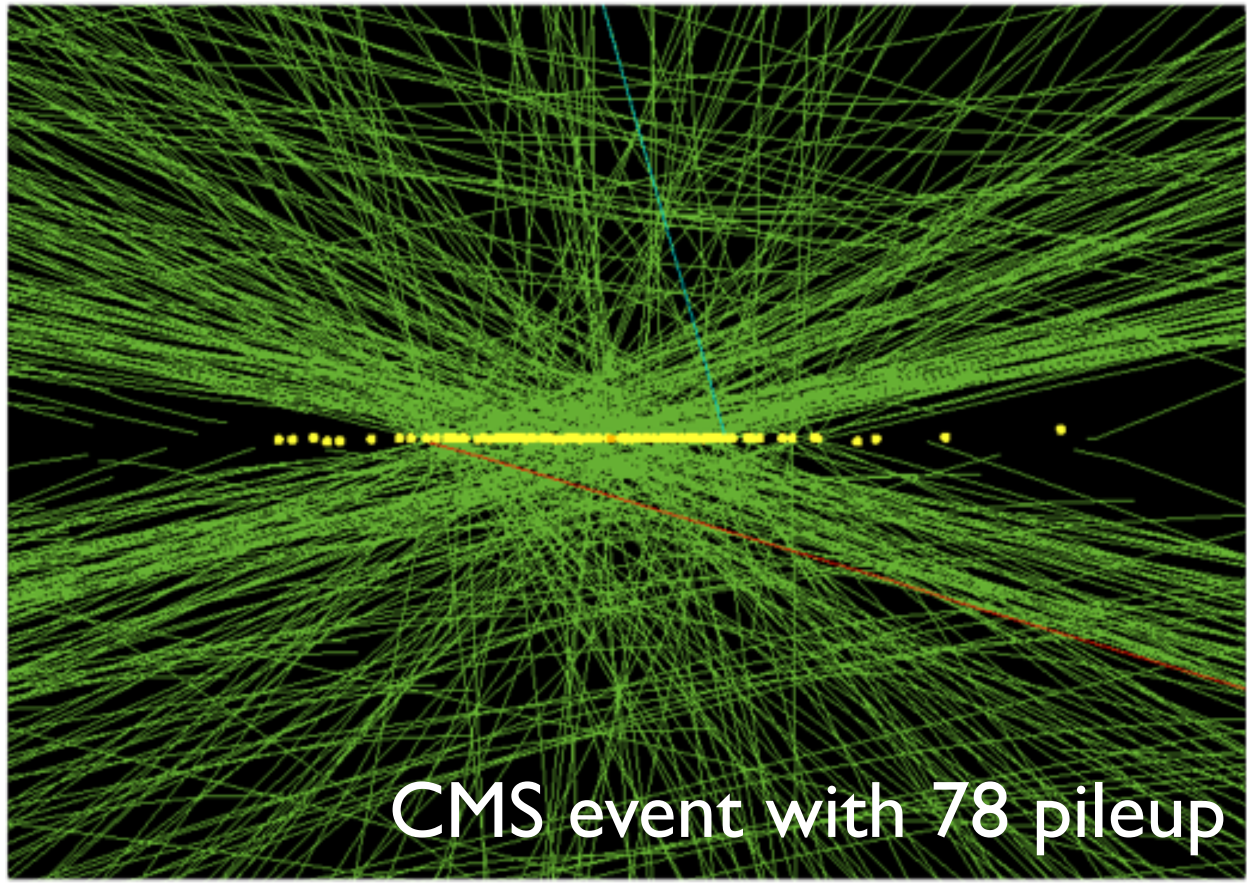
- The large factor in integrated luminosity comes at the price of high instantaneous luminosity
  - *Higher trigger rates*
  - *Higher particle densities*
    - **More rapid radiation damage**
    - **Larger data volumes**
  - *A large increase in the number of overlapping collisions ("pileup")*
    - **More confusing events**



Which vertex is the correct one?

Triggering becomes more challenging

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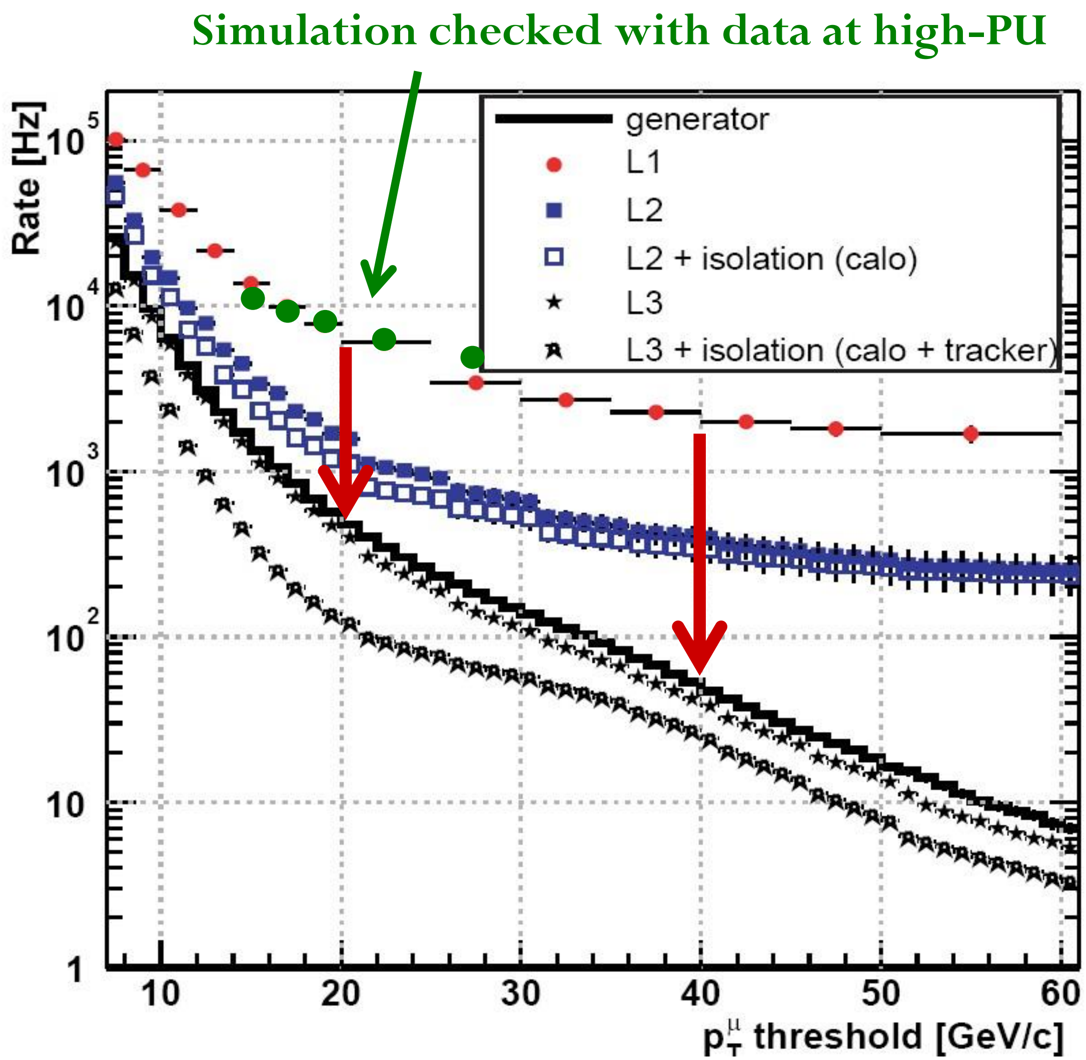
- At a hadron collider, triggering capabilities can make or break the success of the physics program
  - *At a minimum, want to record as many leptonic decays of W,Z,H as possible*
    - **Maintain relatively low thresholds**
  - *Challenge is with the highest pileup, it appears that for some triggers*
    - **No threshold, no matter how high, that provides adequate rate reduction**
  - *Need game-changing strategy*



Three Phases of Upgrades to Experiments

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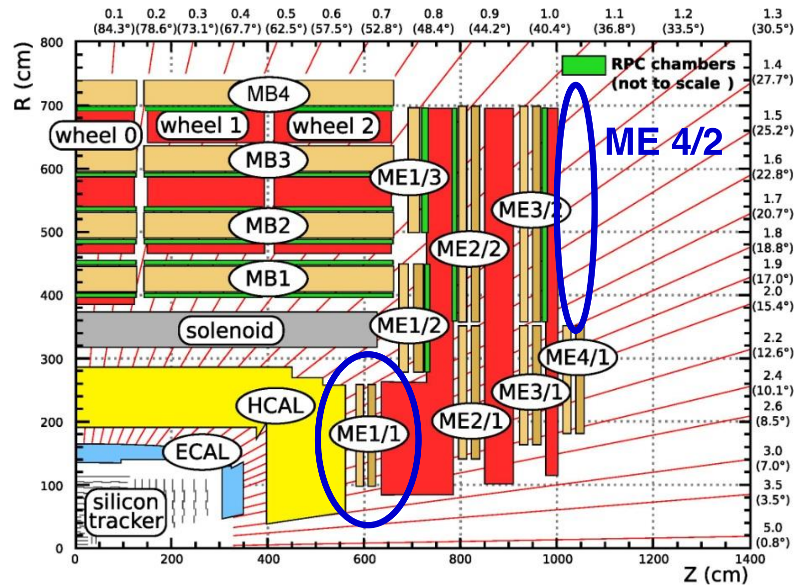
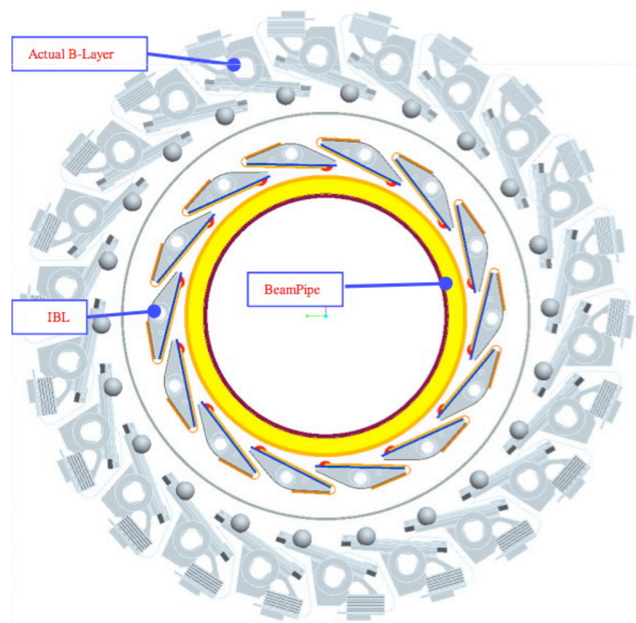
- Phase 0
  - *Installation Underway*
    - **Repairs & Completions**
    - **ATLAS IBL (new pixel layer)**
- Phase I
  - *Mature designs*
    - **CMS TDRs (pixels, HCAL, L1)**
    - **ATLAS TDRs (NSW, FTK)**
- Phase II
  - *Plans being finalized*
    - **ATLAS LOI (2013)**
    - **CMS Technical Proposal (2014)**

CMS
Phase 0

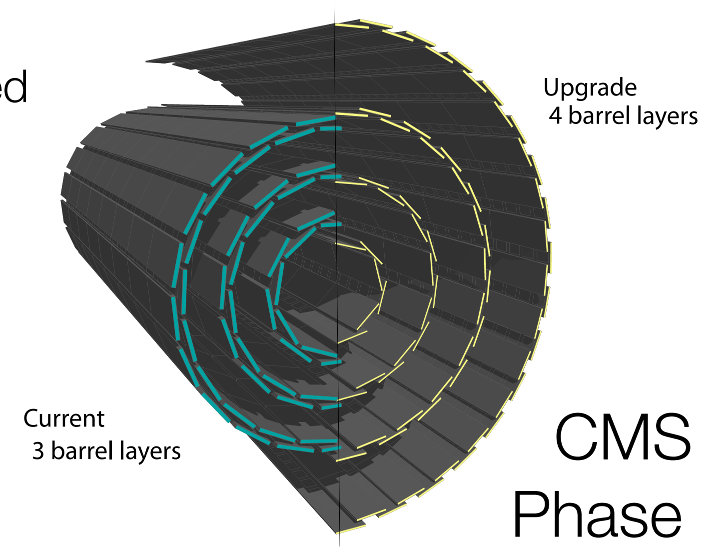




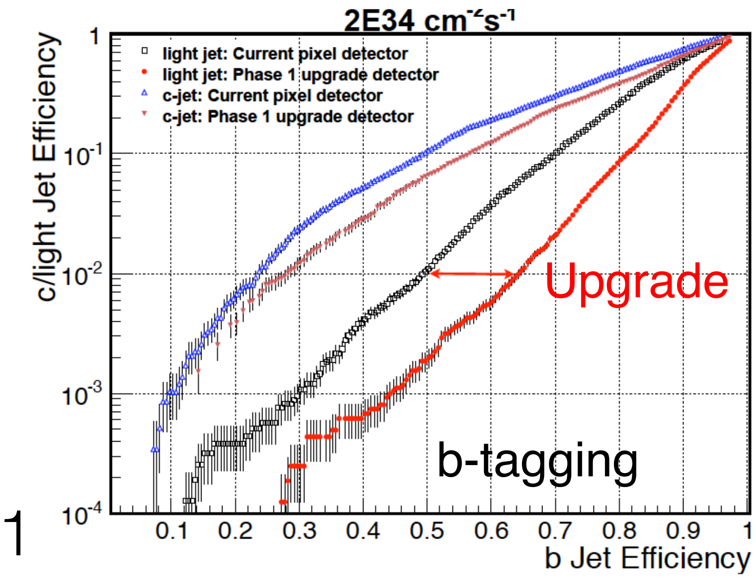
ATLAS
Phase 0

Upgrades to Tracking Detectors Crucial

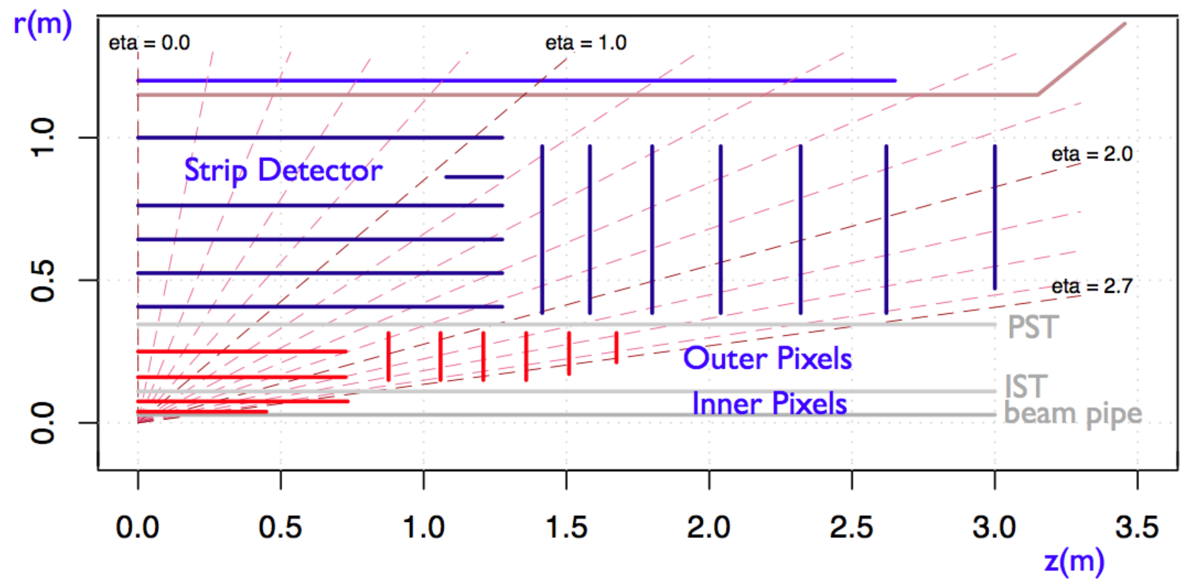
- Charged particle tracking detectors have to be replaced (inoperable by HL-LHC)
  - *Finer granularity*
    - **All silicon**
    - **Smaller pixels**
    - **Shorter strips**
  - *Radiation hard devices*
  - *Improved front-end chips*
  - *Low mass (c-fiber) mechanics & (CO_2) cooling*
  - *Expanded angular coverage*



CMS
Phase 1



ATLAS
Phase 2



Upgrades to Calorimeters & Muon Systems also planned

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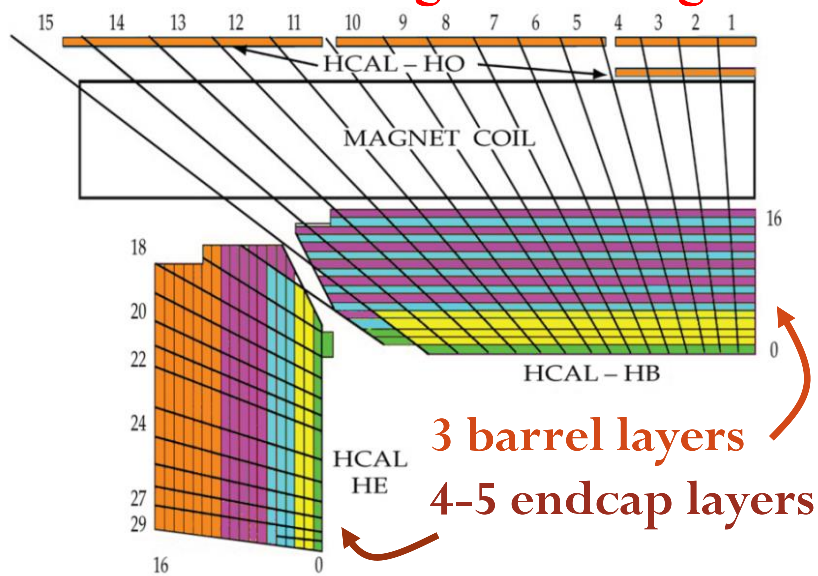
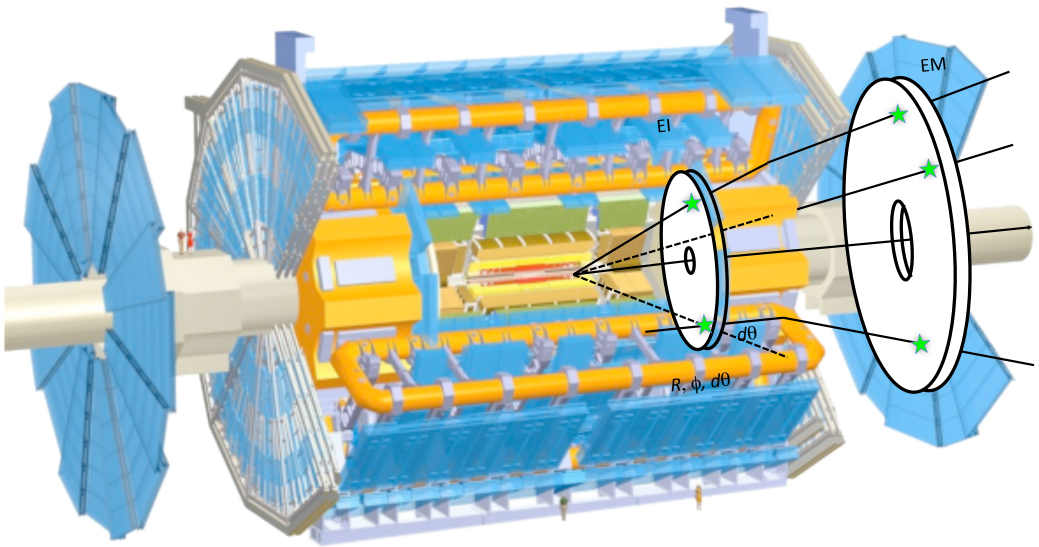
- Calorimeters
  - *Add longitudinal segmentation (CMS HCAL Phase 1)*
  - *New photodetectors -SiPMs (CMS Phase 1)*
  - *Endcap/Forward detector replacements (Phase 2)*
- Muons
  - *Fast track segment finding at L1 (ATLAS NSW Phase 1)*
  - *Higher p_T resolution*
  - *Possibilities of extending pseudorapidity coverage*
  - *Options to add redundancy*

Colors indicate longitudinal segmentation





Upgraded detectors will aid in Triggering

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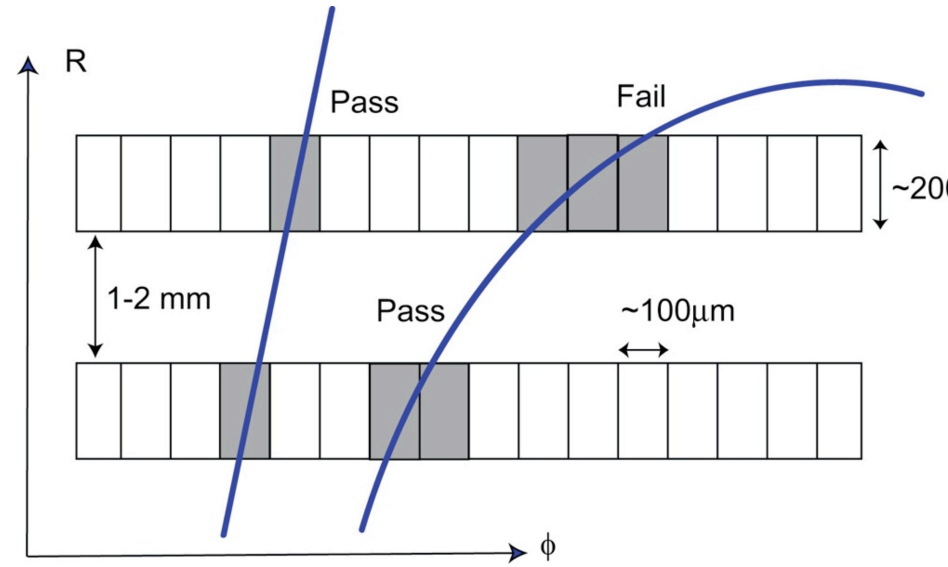
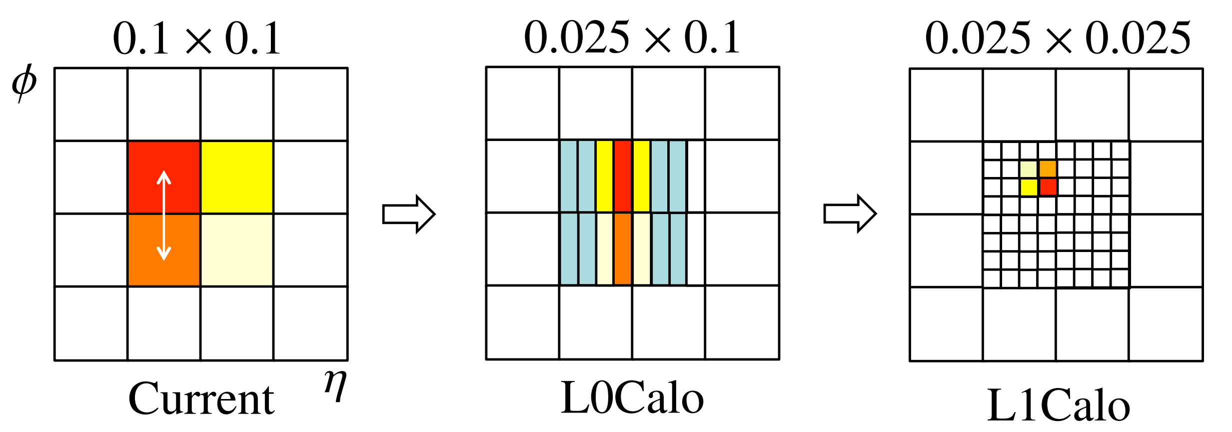
- All upgrades are being designed with goal of providing additional information to trigger system
  - *Possibility of tracking information at L1*
    - **significant reduction in rates if tracks can be linked to electrons/muons**
  - *Increased of granularity of towers available at L1*
  - *Possibility of precision timing in calorimeters*
    - **Could mitigate effects of pileup (spread in time as well as space)**

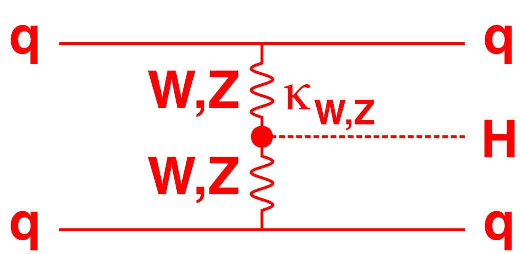


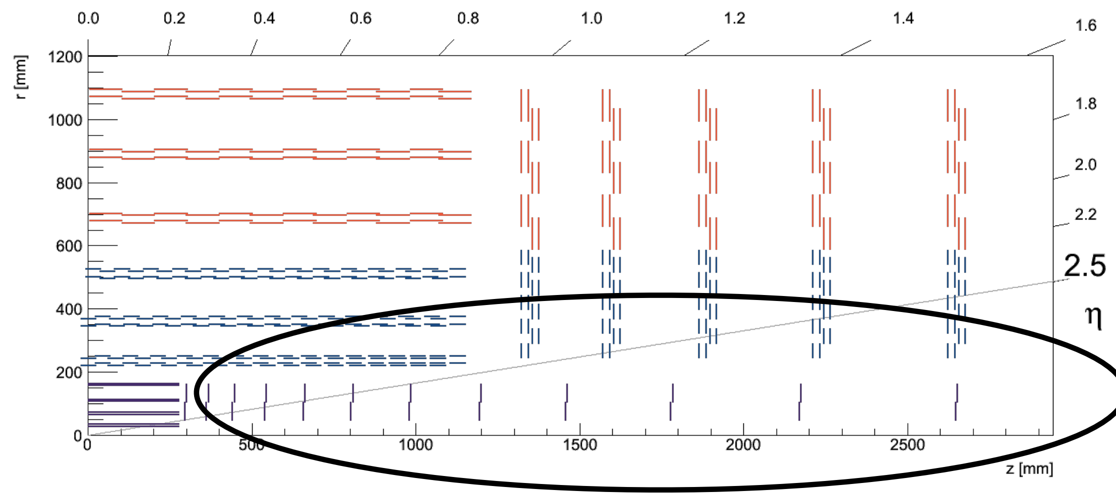


L1 Calo Current *L0 Calo Upgrade* *L1 Calo Upgrade*

Difficult forward region critical for HL-LHC Physics Program

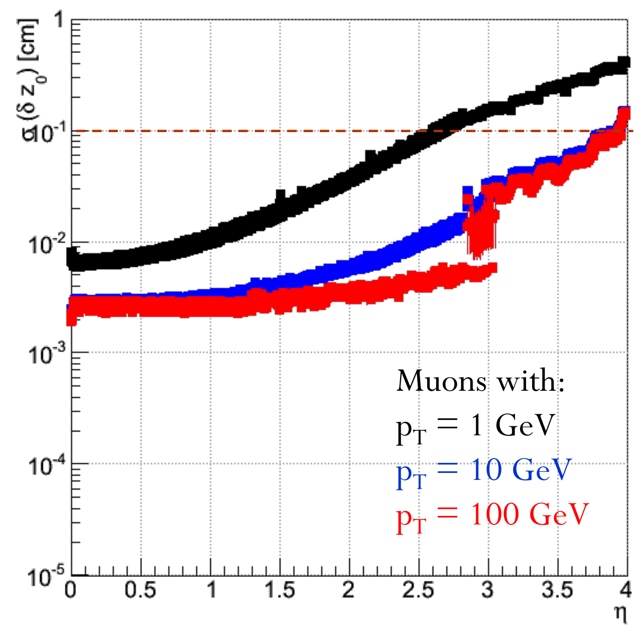
- At hadron colliders, increased forward coverage often yields diminishing returns in terms of signal acceptance
  - *Heavy (signal) particles tend to produced centrally*
  - *Backgrounds (e.g. pileup) increasingly difficult as approach beamline*
- However, for HL-LHC, VBF is a crucial production mode for the particles (e.g. Higgs) we want to study
  - *Need to be able to "tag" VBF jets*





CMS Phase 2 option being studied - extra pixel disks in far forward region

Longitudinal position resolution of ~few mm or better out to $|\eta| = 4$



What Physics will an evolved LHC do?

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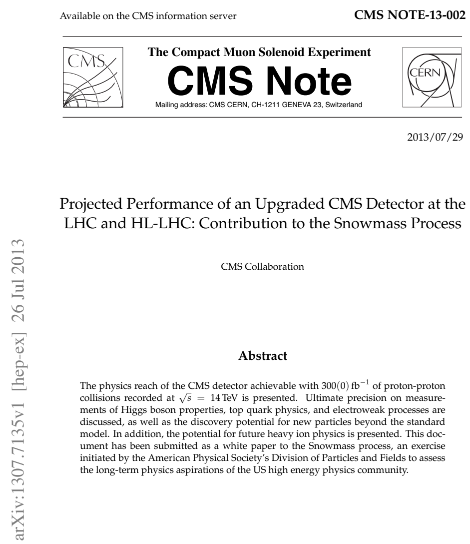
- Projections complicated by fact that (Phase II) upgraded experiments are not fully specified yet
  - *Even where geometry is decided, reconstruction may not be ...*
- Also, for systematic limited measurements must make assumptions about their evolution
- Experiments have taken two approaches (so far)
  - *Parametric simulations of detector performance (ATLAS)*
  - *Educated scaling of existing measurements (CMS)*

Latest projections, just released last week



Available on the CMS information server CMS NOTE-13-002

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

2013/07/29

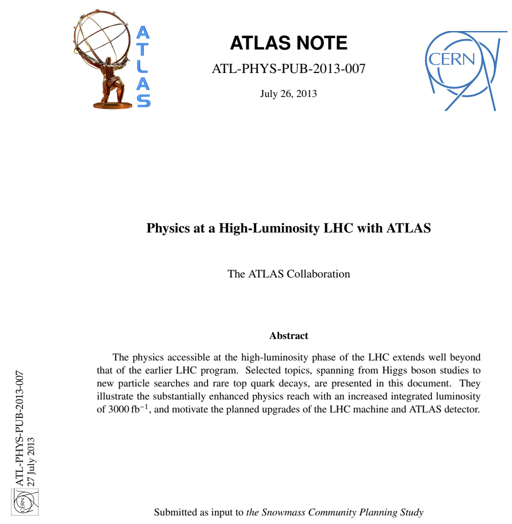
arXiv:1307.7135v1 [hep-ex] 26 Jul 2013

Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process

CMS Collaboration

Abstract

The physics reach of the CMS detector achievable with 300(0) fb^{-1} of proton-proton collisions recorded at $\sqrt{s}$ = 14 TeV is presented. Ultimate precision on measurements of Higgs boson properties, top quark physics, and electroweak processes are discussed, as well as the discovery potential for new particles beyond the standard model. In addition, the potential for future heavy ion physics is presented. This document has been submitted as a white paper to the Snowmass process, an exercise initiated by the American Physical Society's Division of Particles and Fields to assess the long-term physics aspirations of the US high energy physics community.



ATLAS NOTE

ATL-PHYS-PUB-2013-007

July 26, 2013

ATL-PHYS-PUB-2013-007
27 July 2013

Physics at a High-Luminosity LHC with ATLAS

The ATLAS Collaboration

Abstract

The physics accessible at the high-luminosity phase of the LHC extends well beyond that of the earlier LHC program. Selected topics, spanning from Higgs boson studies to new particle searches and rare top quark decays, are presented in this document. They illustrate the substantially enhanced physics reach with an increased integrated luminosity of 3000 fb^{-1}, and motivate the planned upgrades of the LHC machine and ATLAS detector.

Submitted as input to *the Snowmass Community Planning Study*

CMS and ATLAS white papers: arXiv:1307.7135 and 1307.7292

The first order of business - find the NP

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- For reasons old and new, we must try to find new physics that we hope will appear when the LHC turns back on
- Several possible scenarios of how this program might evolve:
  - *New physics appears early in Run 2*
    - **HL-LHC will study the BSM physics**
  - *BSM not discovered after 300 fb^{-1} but ~3σ hints in direct searches or precision SM measurements (e.g. Higgs couplings)*
    - **HL-LHC needs to finish the job and**
  - *Nothing but Higgs after 300 fb^{-1}*
    - **HL-LHC continues direct NP search, accessing smaller cross-section processes**
    - **HL-LHC to push Higgs precision to hopefully reveal discrepancy with SM**
    - **HL-LHC enables search for rare decays in SM (enhanced in BSM scenarios)**

Whitepaper focused on 3000 fb^{-1} projections of this program

Searches for Squarks & Gluinos

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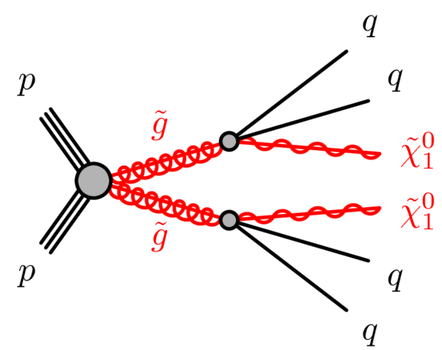
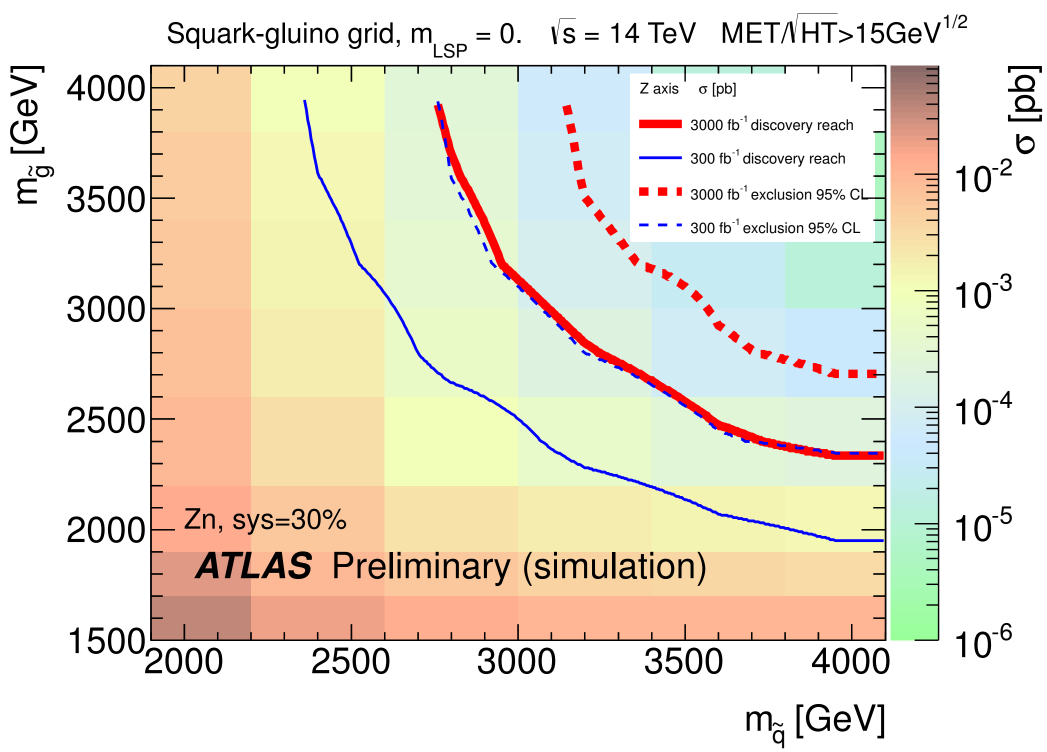
- Discovery of strongly produced SUSY particles (squarks/gluinos) should come quickly if Naturalness is to hold
    - *Mass limits already > 1 TeV*
        - **Discovery reach improves up to ~2.5 TeV with 300 fb^{-1}**
        - **Increases to ~3 TeV with HL-LHC**
    - *(More than) covers the interesting range for Natural SUSY*
- Caveat to this, there are loopholes ...
    - *Diluted/compressed spectra, 3rd generation, stealth, RPV SUSY, etc.*





Search for Low Mass Stops

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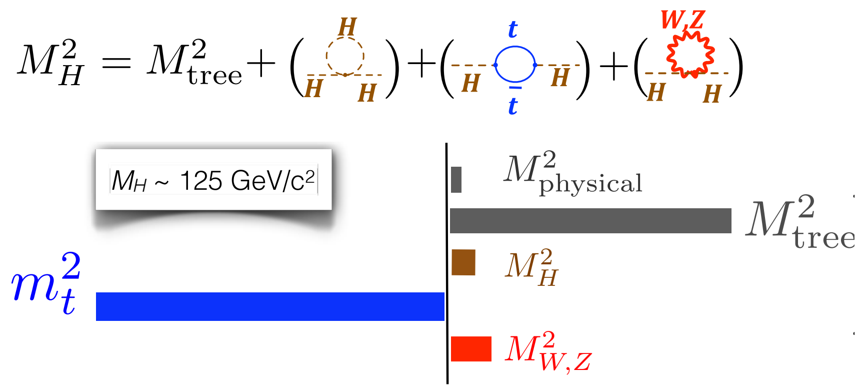
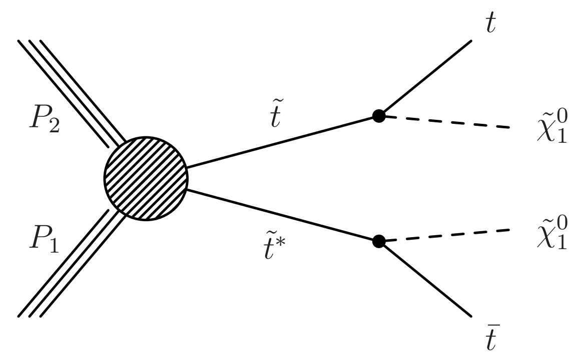
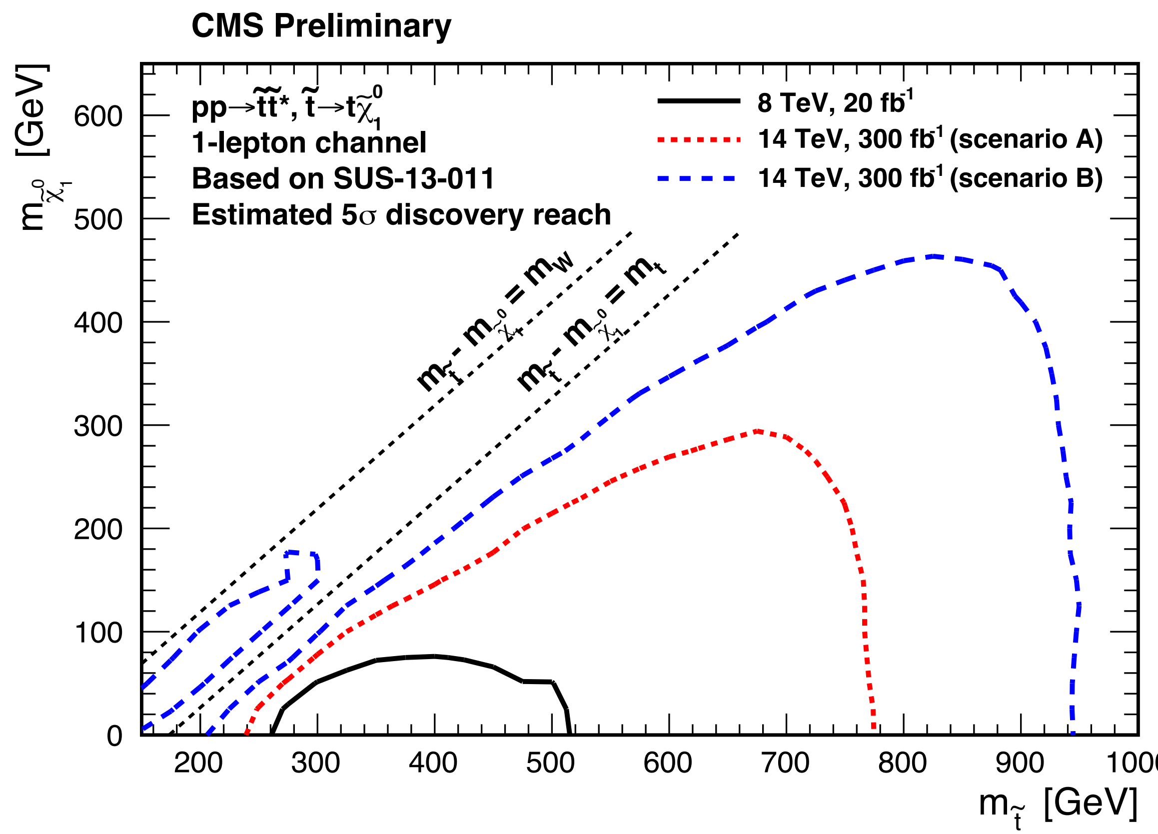




- Stop mass can't be too far from m_t in order for cancellation to work
  - *Natural SUSY requires "low" mass stops*
  - *Already with 300 fb^{-1}, discovery sensitivity for direct production mode up to ~900 GeV*
    - **More than covers* Natural SUSY range**



*there are of course similar loopholes in this coverage too

Unnatural Supersymmetry

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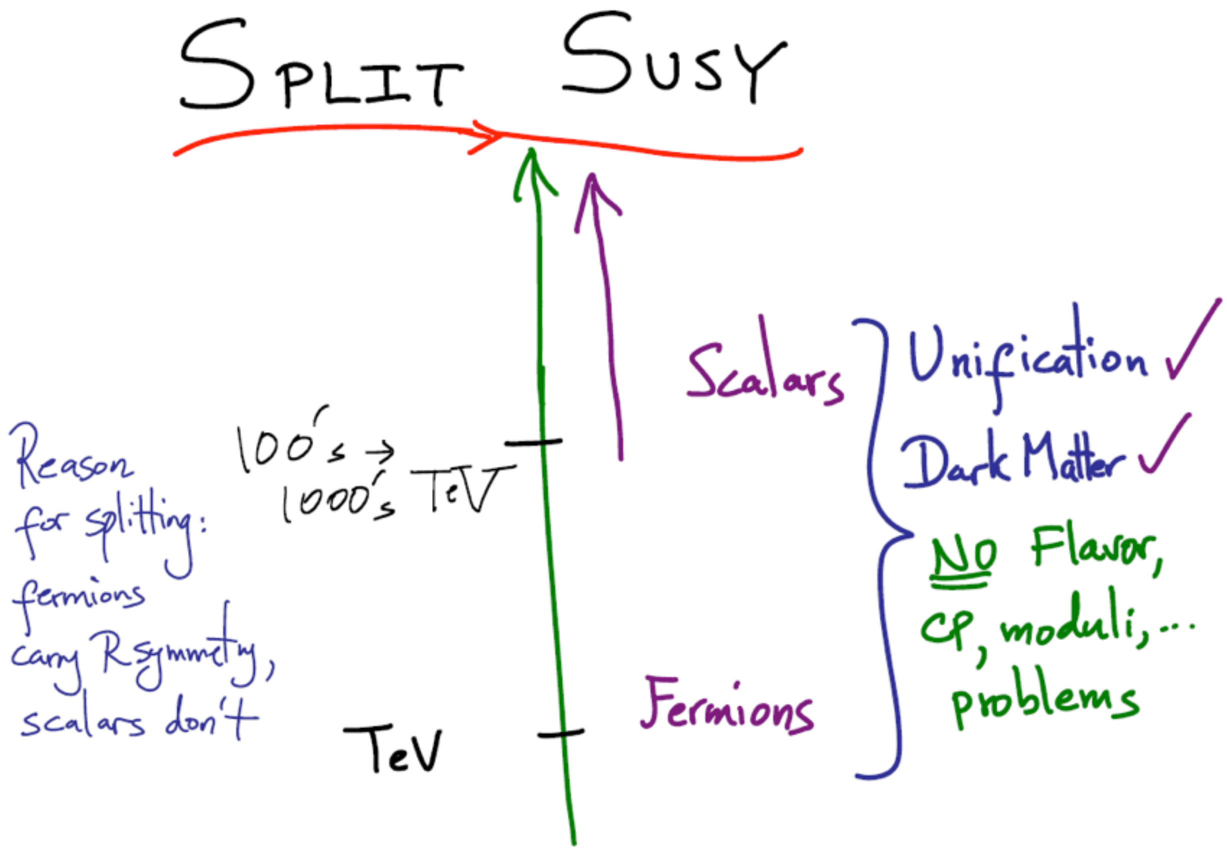
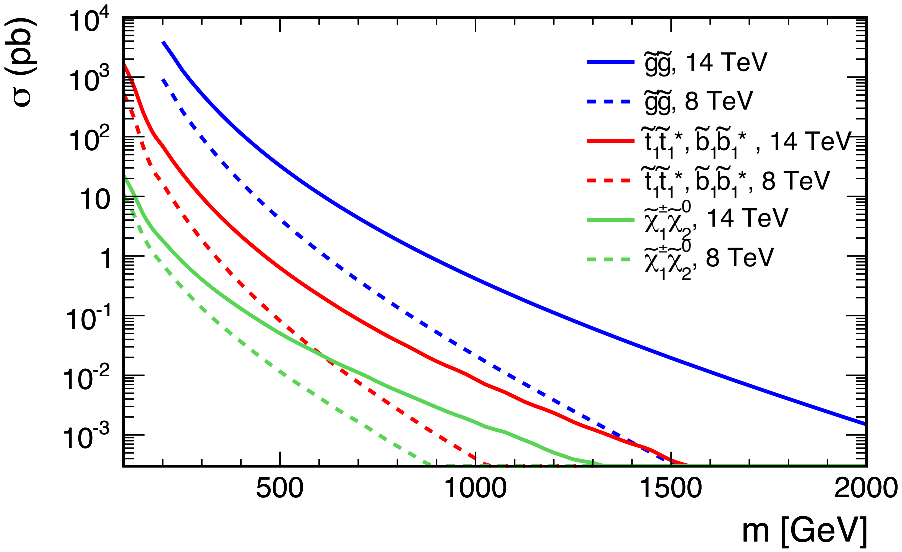
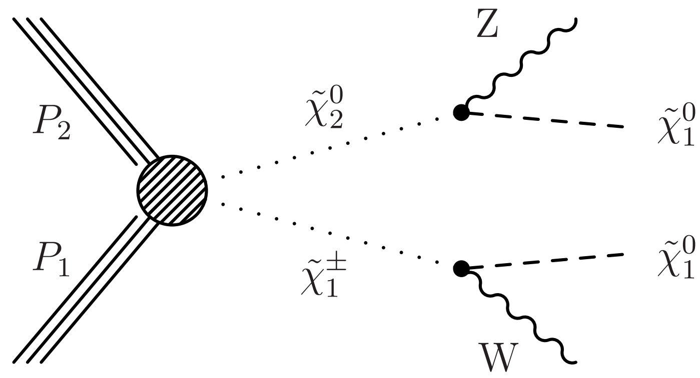
- The universe could be supersymmetric
  - *But could have nothing to do with the solving the hierarchy problem*
    - **Maybe sparticles not accessible to LHC**
    - **EW fine tuning is a feature of our world**
  - *Or could be "split" SUSY, wherein squarks are heavy, but gauginos are light*



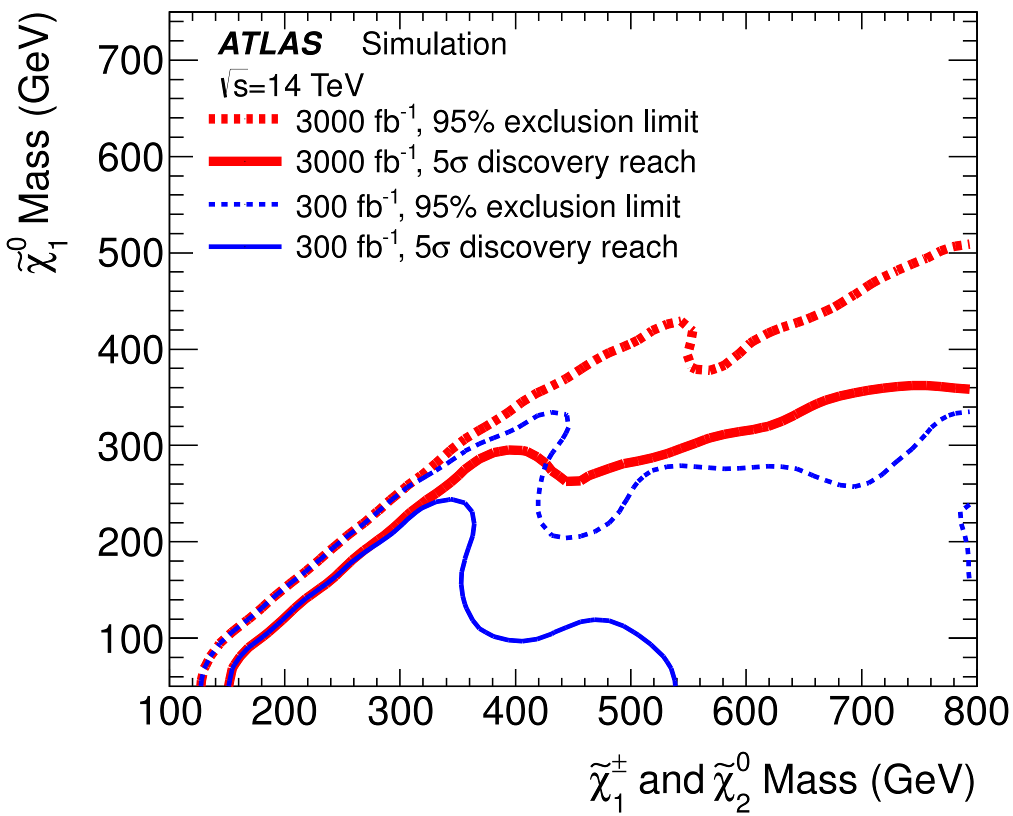
Retains many of the other motivations for SUSY

Electroweak Production of SUSY



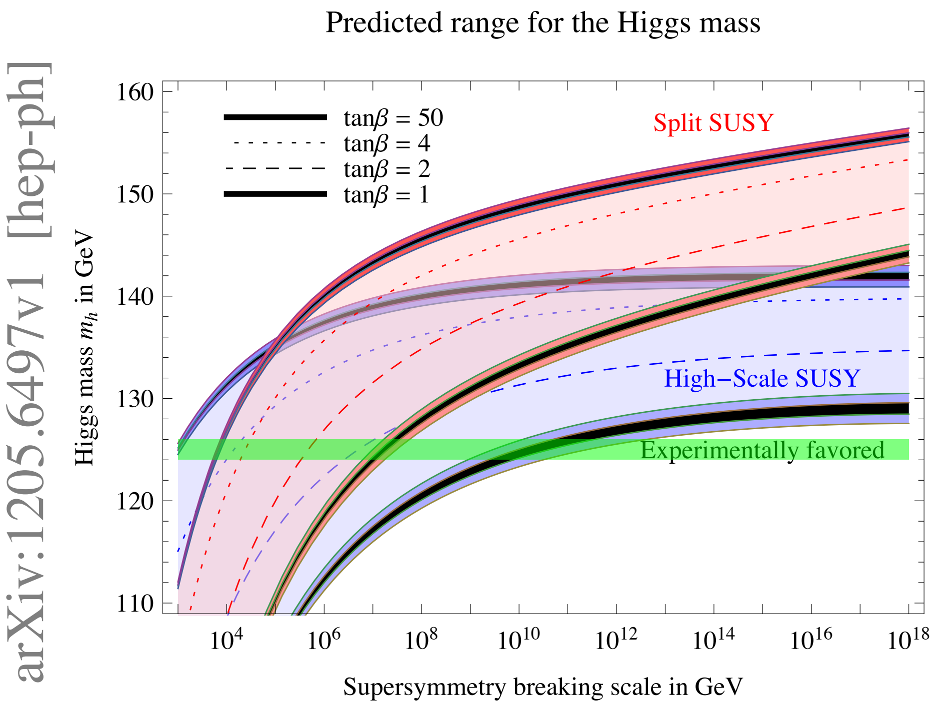


- In this case, one may need to search for SUSY through direct production of charginos/neutralinos
    - *Cascades via squarks not accessible*
    - *Much lower cross-section*
        - **HL-LHC luminosities necessary**

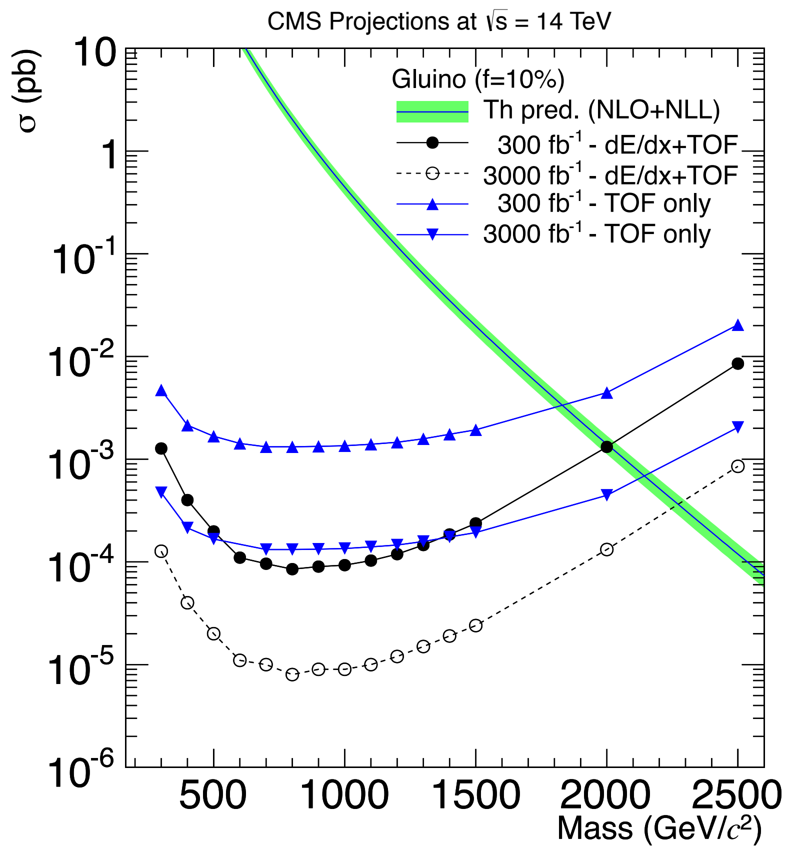


Long-lived Gluinos

- Or can search for strongly produced gluinos that would be long-lived
  - *Decay via squarks suppressed*



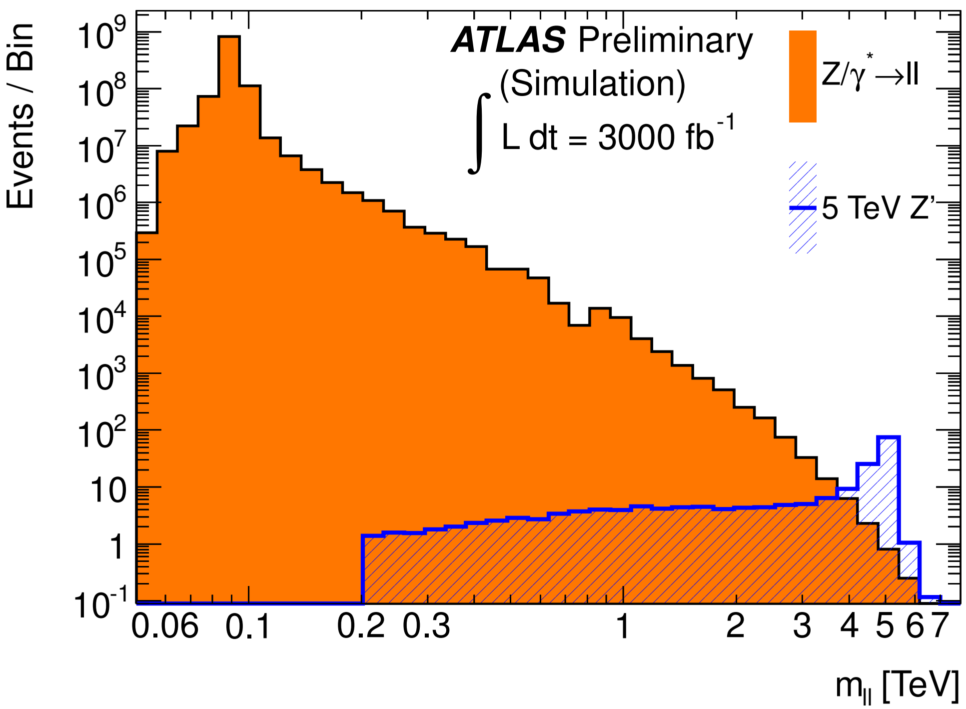
If the split is large, sensitivity from heavy stable particle searches to > 2 TeV

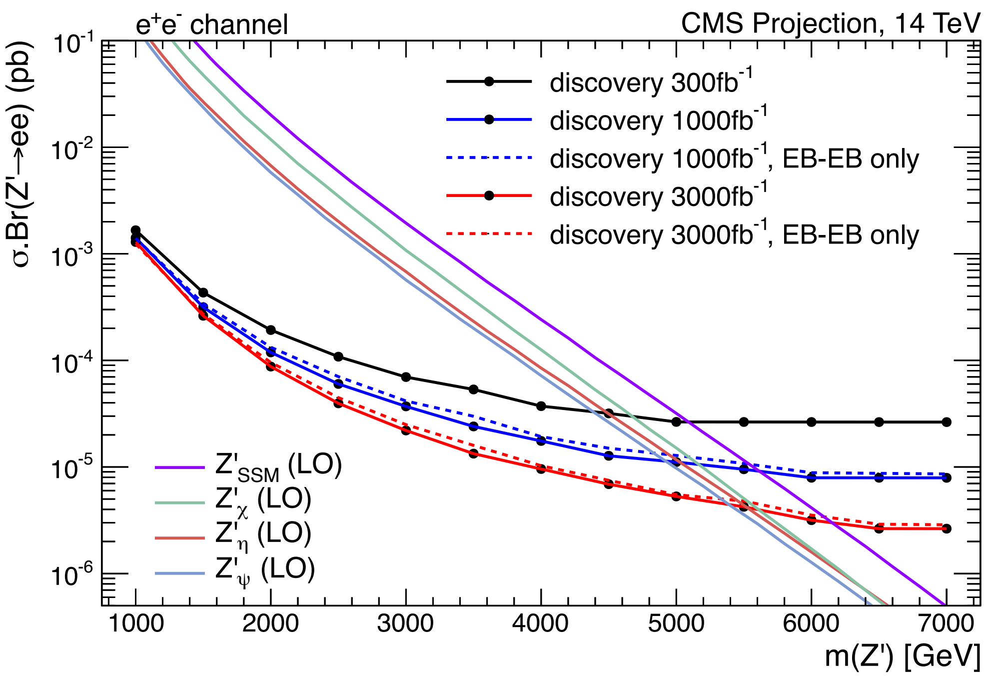


However, Higgs data suggest more of a “mini” split with cτ << radius of detector

New Heavy Particles

- Of course, CMS & ATLAS will take advantage of the jump in energy and luminosity to look for new heavy particles on the energy frontier
  - *E.g. dilepton resonances (Z', RS gravition, etc)*
    - **CMS projects discovery sensitivity to ~5.5 TeV with HL-LHC**





Measurements of Higgs Boson's Properties

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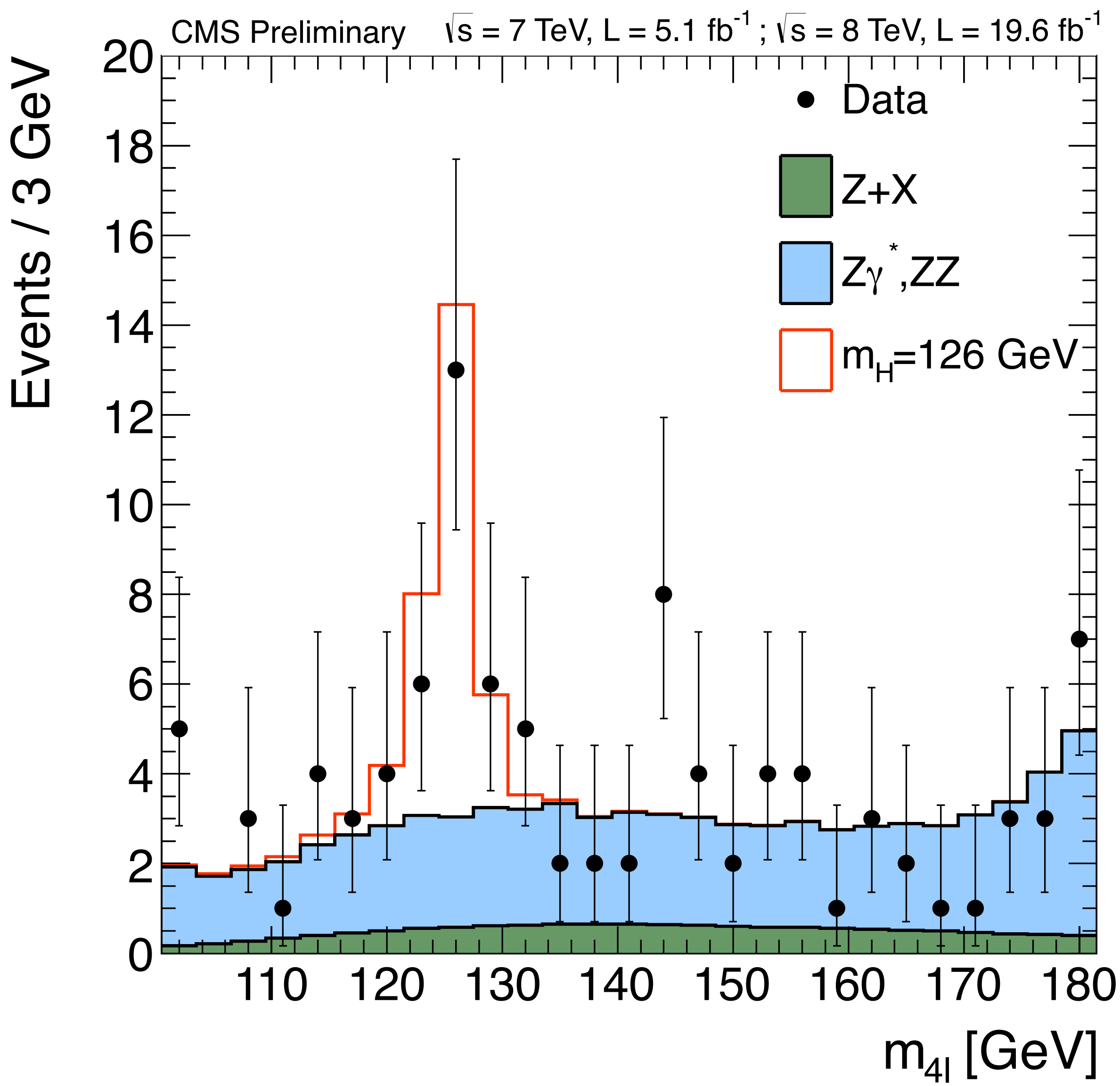
- Much of what is known about the properties (mass, spin, parity) of the Higgs is based on high resolution H to ZZ decays
  - *Very few events collected in Run 1*
- Obviously, much larger datasets of Run 2 and HL-LHC will greatly improve the precision of these measurements
  - *50 MeV precision achievable with 3000 fb^{-1}*



Precision Higgs Physics

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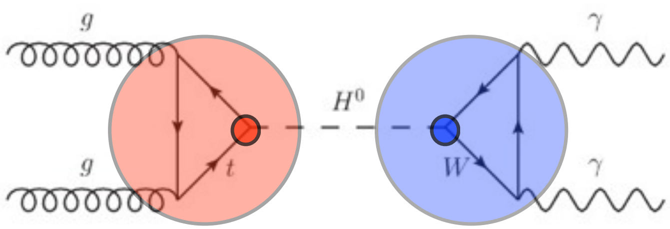
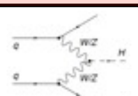
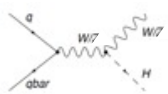
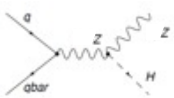
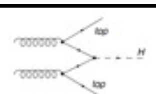
- Want to test if Higgs particle couples as expected in the Standard Model



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

Projected precision on the "signal strength"

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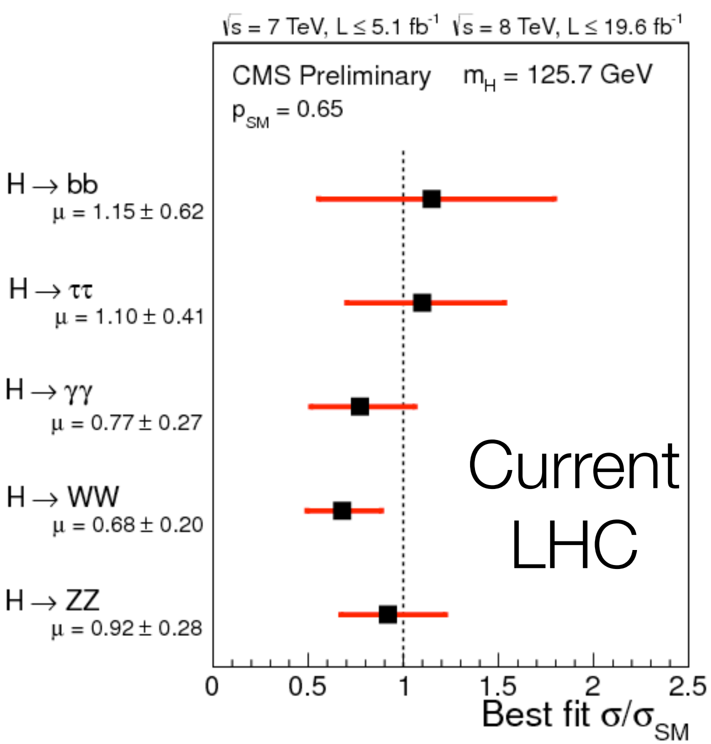
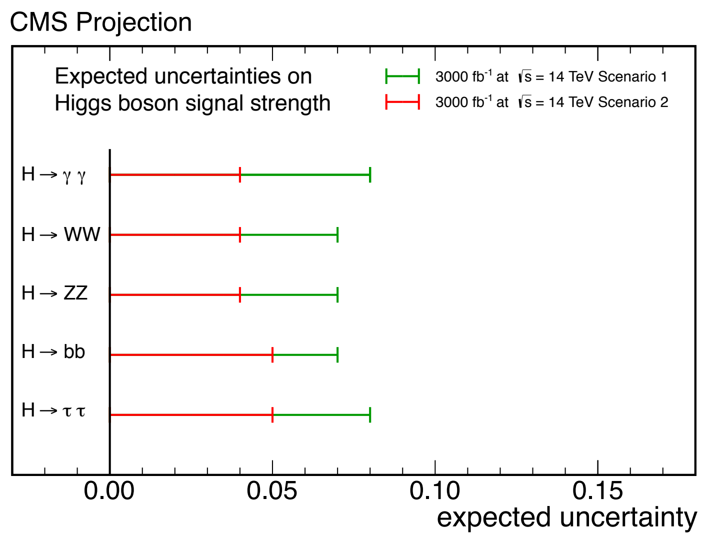
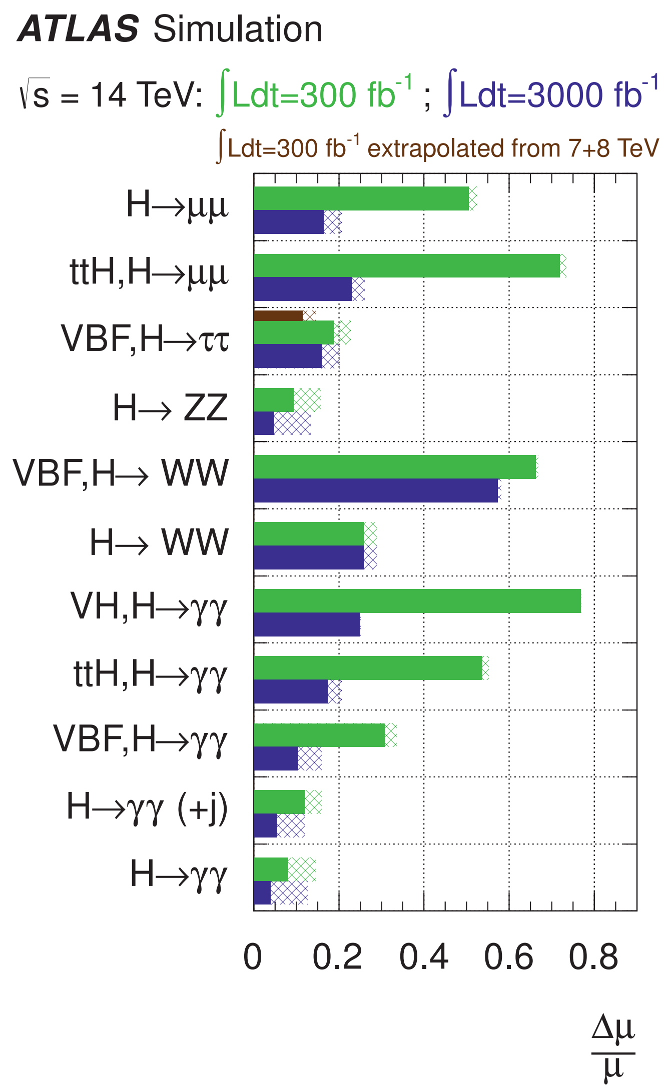
- The simplest thing you can do is to measure the cross-section x BR to a given decay and compare it with that expected from the SM
- We call this the signal strength:

$$\mu \equiv \sigma / \sigma_{SM}$$



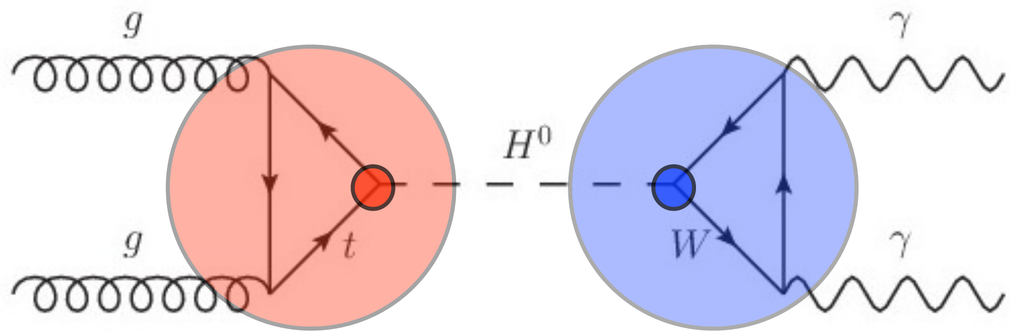




Couplings

- We look for deviations from the SM by adding coupling modifying parameters, κ
- Each explores different physics
  - κ_g, κ_γ, $\kappa_{Z\gamma}$: loop-effects
  - κ_W, κ_Z: vector-bosons
  - κ_t, κ_b: up/down-type quarks
  - κ_τ, κ_μ: charged leptons
- Assume no BSM decay modes
  - $\kappa^2_H = \Sigma \kappa_i \Gamma_j / \Gamma^{SM}_H$
    - **alternatively a free parameter**
- Then assume κ_W, $\kappa_Z < 1$ to allow absolute coupling measurement

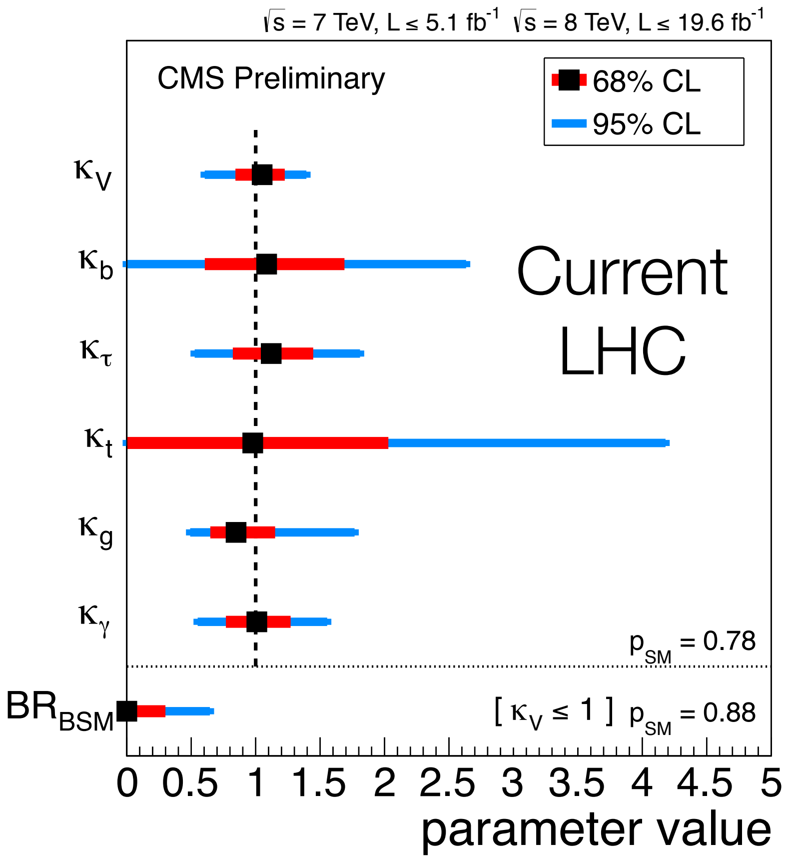
$$(\sigma \cdot BR)(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$



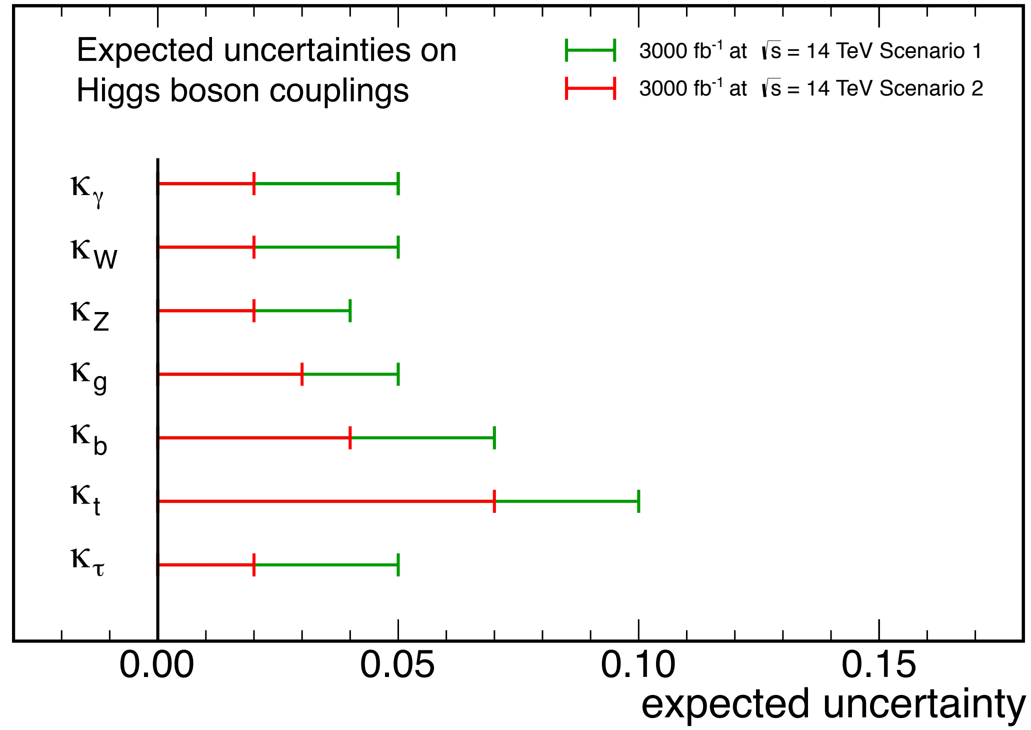
$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma)$$
$$= \kappa_g^2 \sigma_{SM}(gg \to H) \cdot \frac{\kappa_\gamma^2}{\kappa_H^2} BR_{SM}(H \to \gamma\gamma)$$

Projected precision on Higgs couplings

- Using this framework, CMS and ATLAS have projected their sensitivity to each of these couplings to the end of the HL-LHC run (3000 fb^{-1})



CMS Projection



L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]

2-10% precision on couplings with HL-LHC

Arbitrary precision is not the goal ... discovery is

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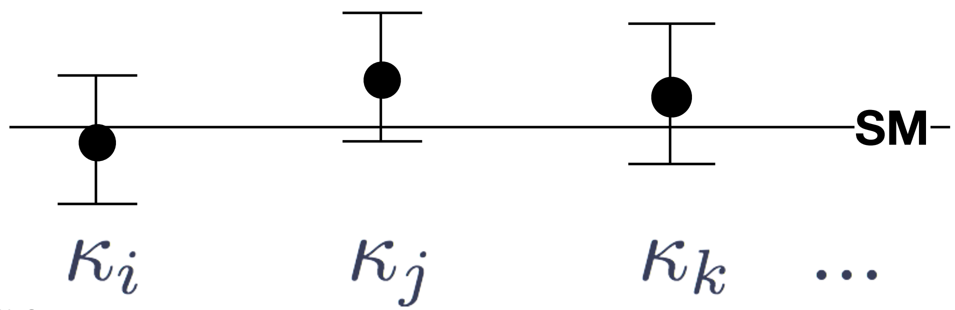
- Is the precision achievable by the HL-LHC good enough to make a discovery?
  - *Depends on what the new physics is!*
  - *Some models induce larger deviations from SM than others*
  - *Many models being investigated in this light*
  - *For some BSM scenarios*
    - **HL-LHC is good enough**
  - *If Nature is not cooperative, greater precision needed*

arXiv:1206.3560v3 [hep-ph]

	ΔhVV	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$

	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	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$



Brock/Peskin Snowmass 2013

To discover x% at 5σ: need x/5% measurement.

How much of this is due to theoretical uncertainties?

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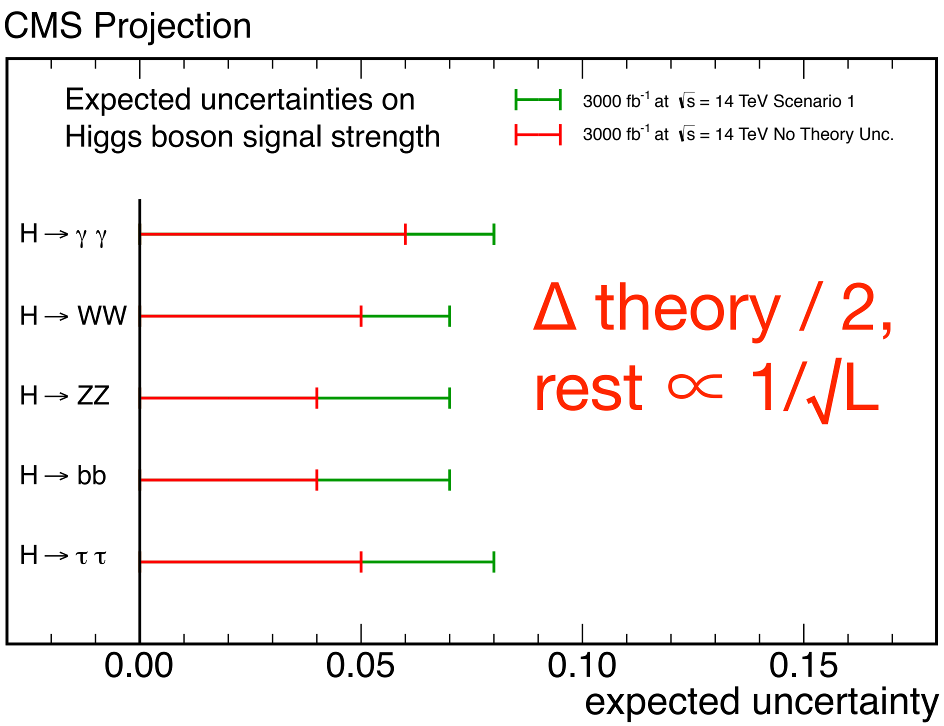
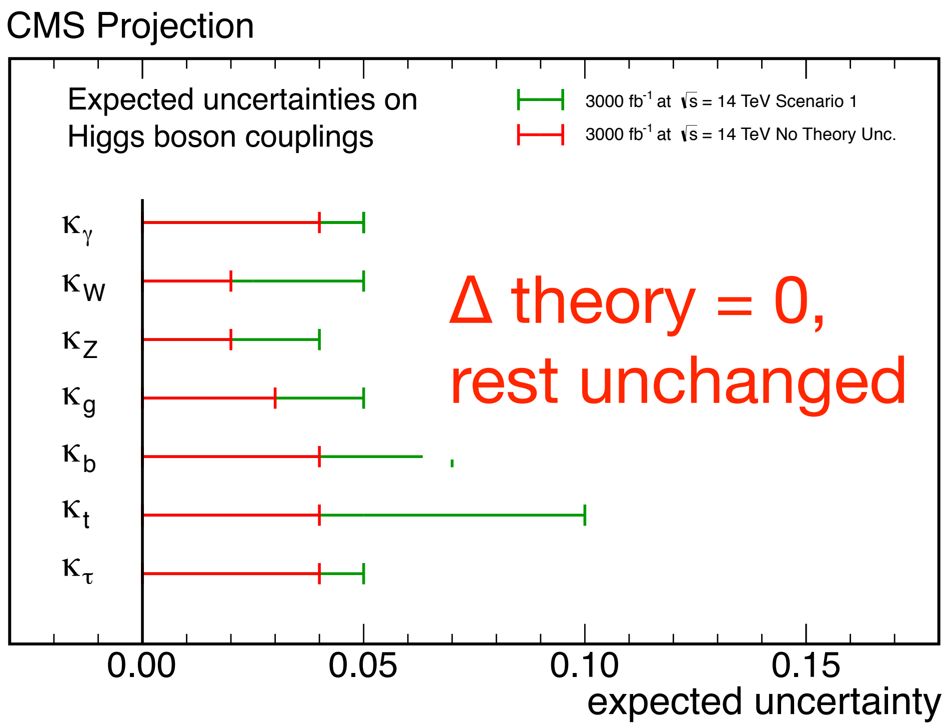
- To test the importance of theoretical uncertainties we show the effect of removing them
- Theoretical uncertainties dominated by QCD scale and PDF uncertainties.
  - *Uncertainty on BRs become relevant at few % precision*





Motivation for theoretical colleagues!

Can mitigate this somewhat with ratios

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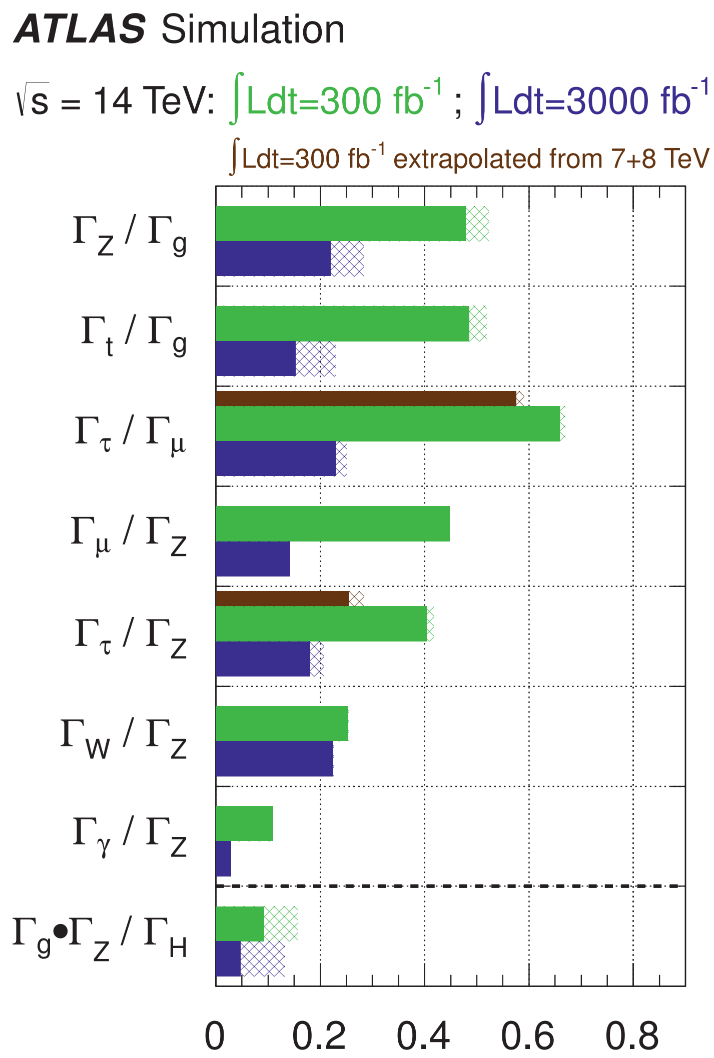
- Using appropriate ratios can eliminate some theoretical uncertainties
  - *production cross-section*
  - *branching ratios*
- Also some experimental ones
  - *luminosity*

	$300\ fb^{-1}$		$3000\ fb^{-1}$	
	w/theory uncert.	wo/theory uncert.	w/theory uncert.	wo/theory uncert.
Γ_Z/Γ_g	0.52	0.48	0.28	0.22
Γ_t/Γ_g	0.52	0.49	0.23	0.15
Γ_τ/Γ_μ	0.67	0.66	0.25	0.23
Γ_τ/Γ_μ (extrap)	0.59	0.58		
Γ_μ/Γ_Z	0.45	0.45	0.14	0.14
Γ_τ/Γ_Z	0.42	0.40	0.21	0.18
Γ_τ/Γ_Z (extrap)	0.28	0.26		
Γ_W/Γ_Z	0.25	0.25	0.23	0.23
Γ_γ/Γ_Z	0.11	0.11	0.029	0.029
$\Gamma_g \bullet \Gamma_Z/\Gamma_H$	0.16	0.093	0.13	0.047



$$\frac{\Delta(\Gamma_X/\Gamma_Y)}{\Gamma_X/\Gamma_Y} \sim 2\frac{\Delta(\kappa_X/\kappa_Y)}{\kappa_X/\kappa_Y}$$

But sizeable uncertainties remain for some modes

Higgs Self-Coupling

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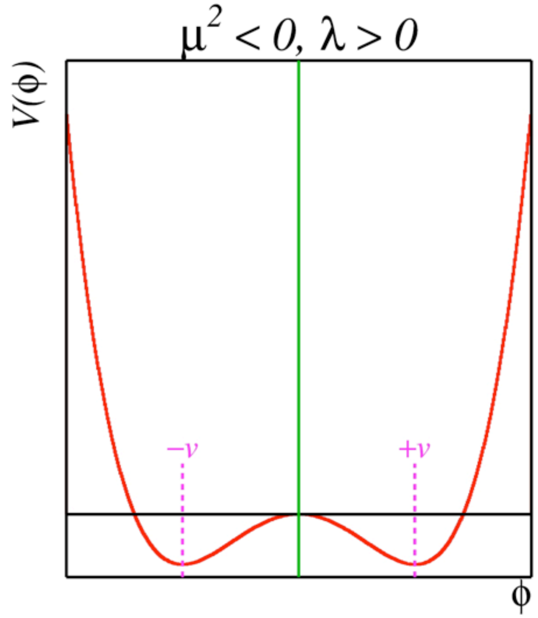
- If the observed Higgs particle is really the quanta of a field with non-zero expectation value responsible for EWSB
  - *Mass of the particle must be related to λ_{SM} of the potential*

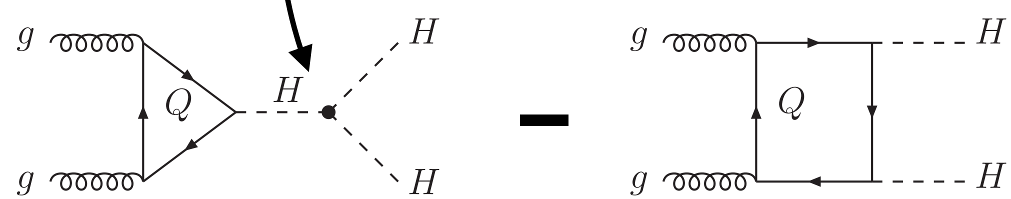
$$M_H^2 = \lambda v^2$$

  - *LHS is being measured directly by H to ZZ to 4l etc.*
  - *RHS can be accessed by studying rate of di-Higgs production*
    - **Contributing diagram involving Higgs self coupling, g_{HHH}**
    - **Negative interference with other diagrams**



$$V = \mu^2 \Phi^\dagger \Phi + \frac{1}{2}\lambda(\Phi^\dagger\Phi)^2$$

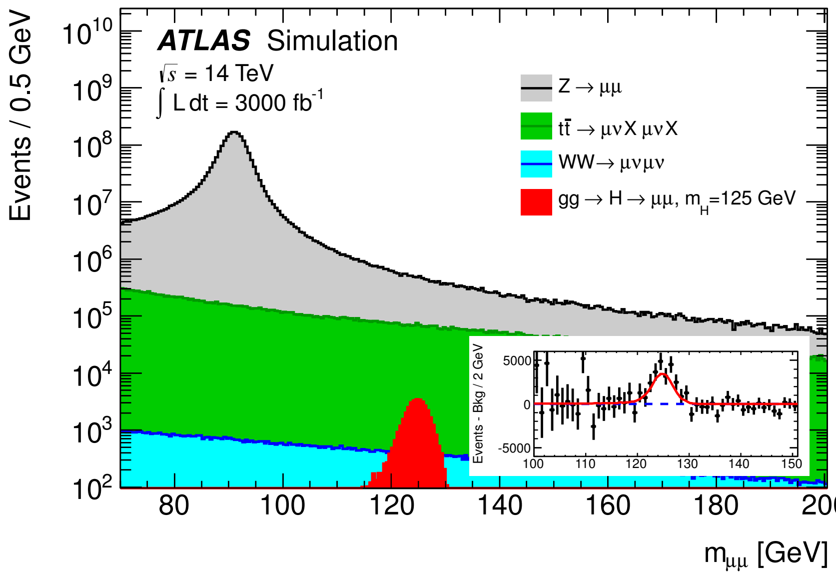
$$g_{hhh} \equiv 3\lambda v = \frac{3M_H^2}{v}$$

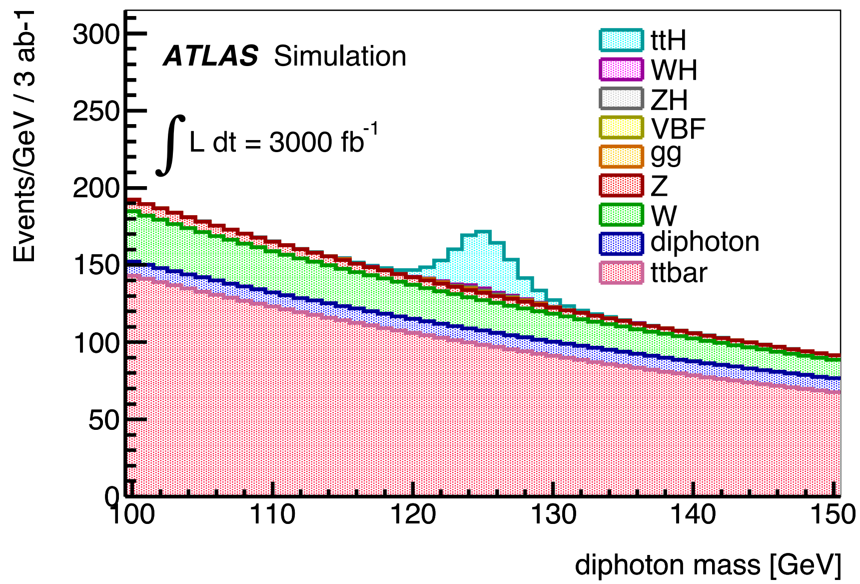


Preliminary expectation of ~30% precision, studies ongoing (bbττ,bbγγ,bbWW modes)

Rare Decays of the Higgs

- With HL-HLC, rare Higgs decays become accessible
  - *H to μμ, small coupling due to m_μ*
    - **BR ~2 x 10^{-4}**
    - **5σ observation expected**
    - **Will allow study of ratio of 2nd to 3rd generation lepton couplings (probe of flavor structure)**
  - *H to Zγ*
  - *ttH, H to γγ*
    - **Important mode for top Yukawa, NP**
    - **High S/B**

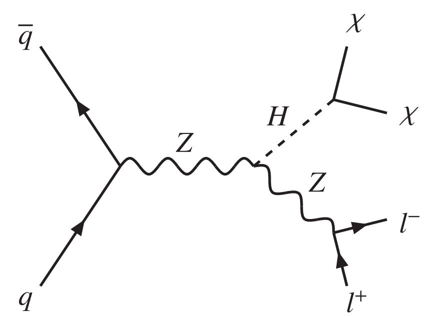


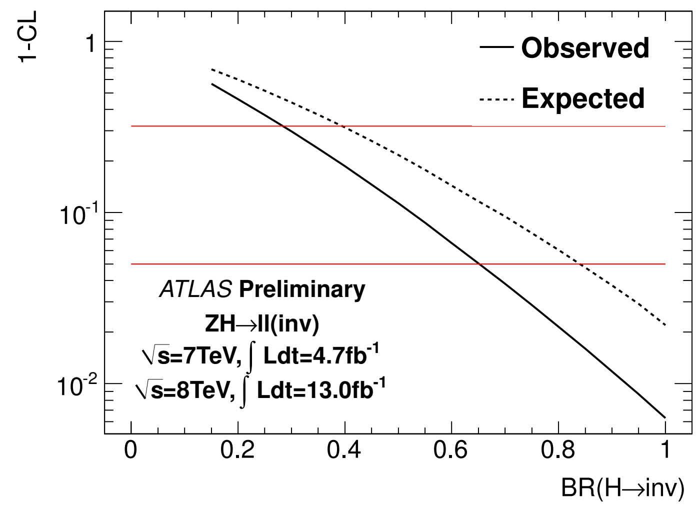


Invisible Decays of the Higgs

- As discussed, detection of any deviation in expected Higgs BR would be interesting
- Even more interesting if these deviations come at expense of some Higgs decaying to undetected particles
  - *Direct indication of BSM physics*
  - *Many BSM scenarios predict "Invisible" particles*
    - **SUSY LSP**
    - **Dark Matter candidates**
  - *Might be able to extract DM-nucleon cross-section*

Current limit is BR < 65% (ATLAS)



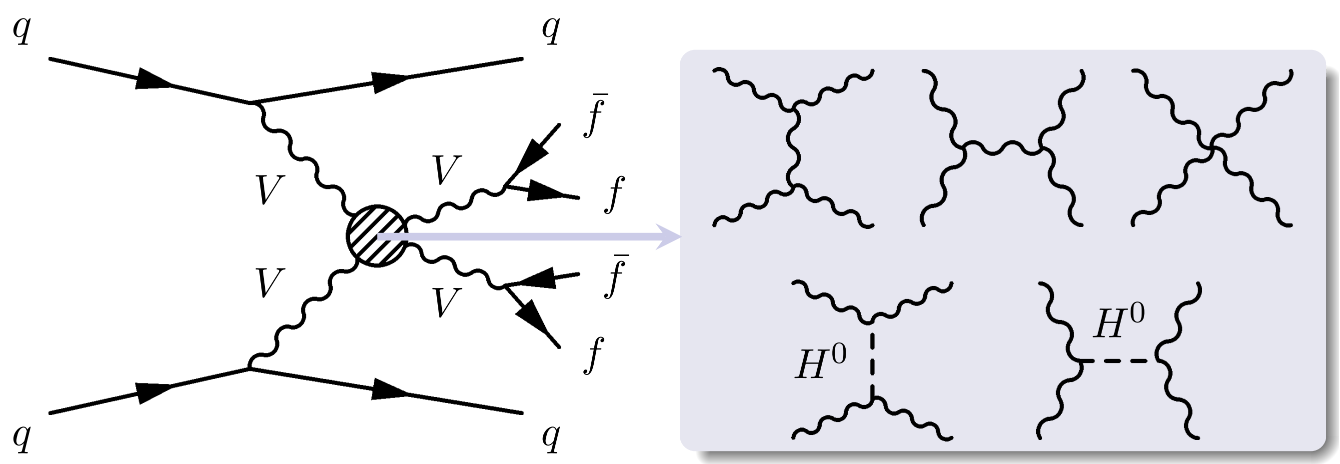


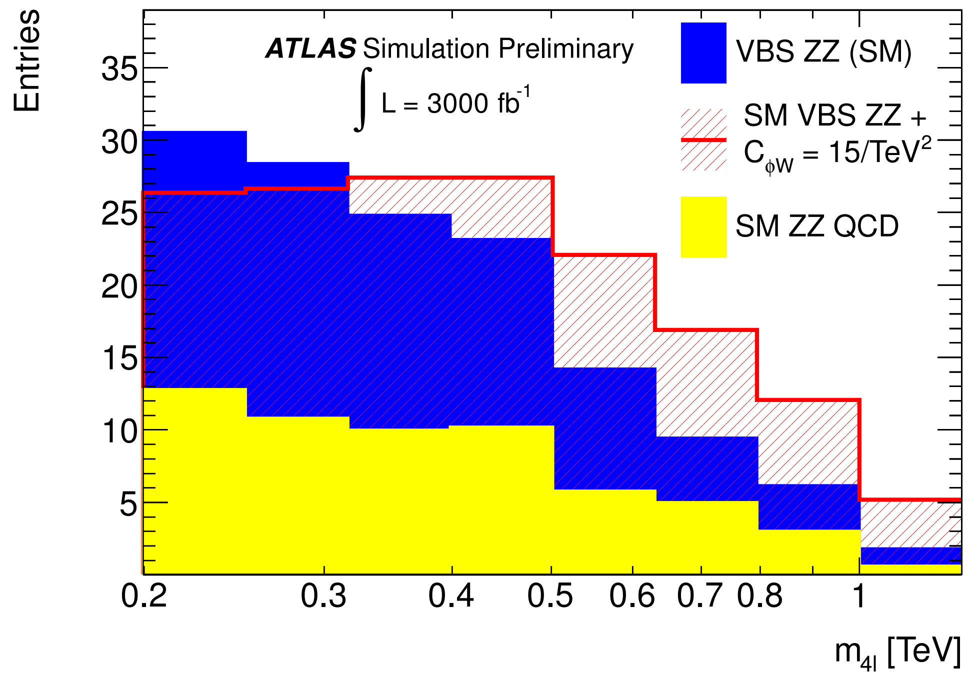
L (fb^{-1})	$H \to$ inv.
300	[17, 28]
3000	[6, 17]

CMS Scenario 2
HL-LHC projection
is BR < 6%

Vector Boson Scattering (VBS)

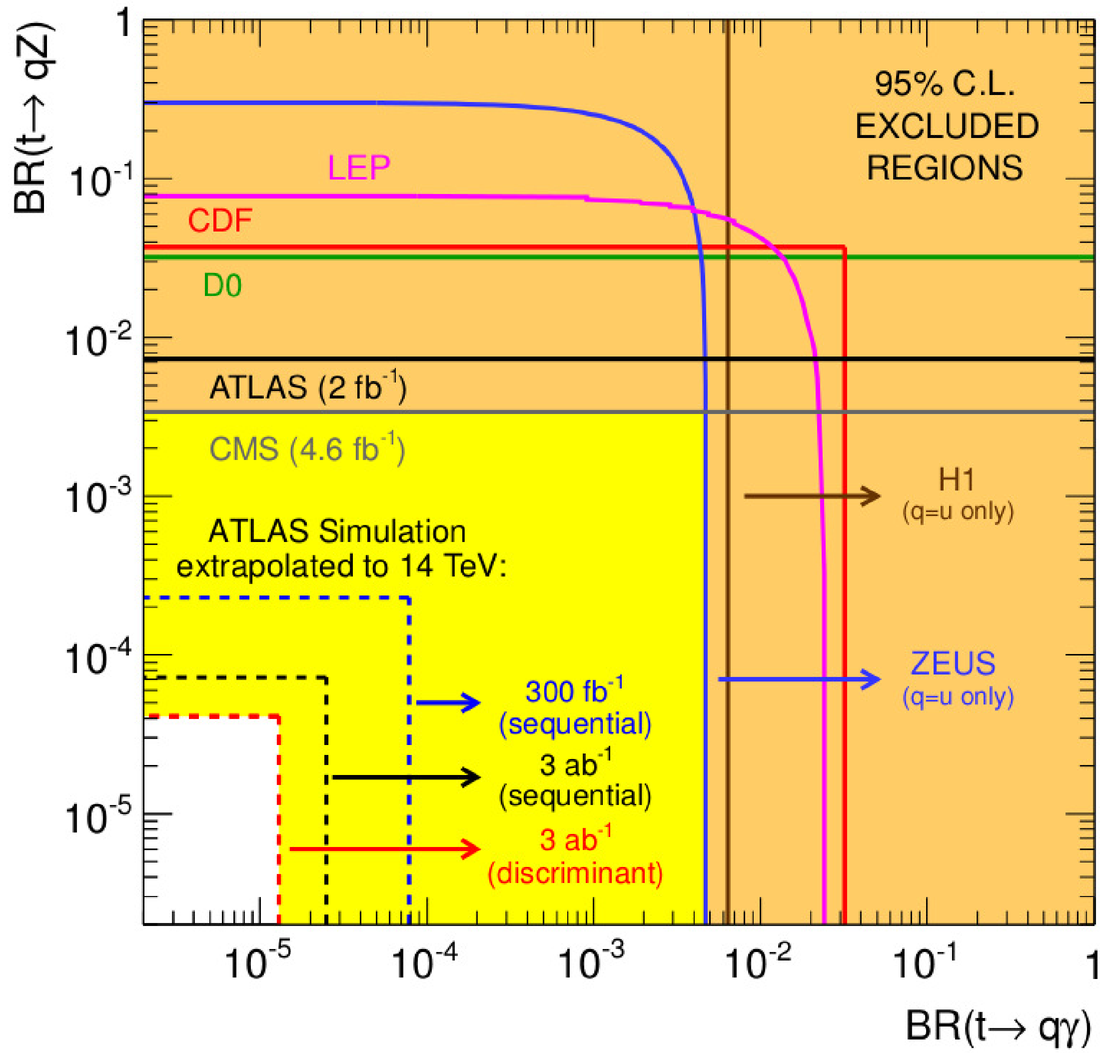
- Must experimentally verify Higgs's presumed role in canceling divergences in V V scattering processes
    - *Measure differential cross-sections*
    - *Look for deviations coming from extended EWSB sector*
- HL-LHC needed for such measurements





Other Rare SM Processes

- The large HL-LHC dataset also allows searches for other rare processes (besides Higgs)
    - *E.g. flavor changing neutral currents in top decays*
        - **t to qγ**
        - **t to qZ**
        - **t to qg**
    - *Heavily suppressed in SM, BR ~10^{-14}*
    - *Significantly enhanced in SUSY, other BSM (up to ~10^{-4})*
        - **CMS/ATLAS project sensitivity to ~10^{-5}**



Is HL-LHC the evolutionary end of the line?

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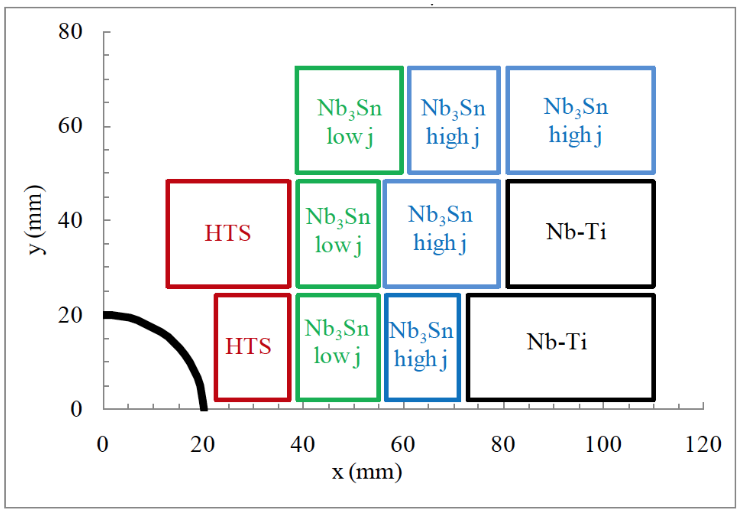
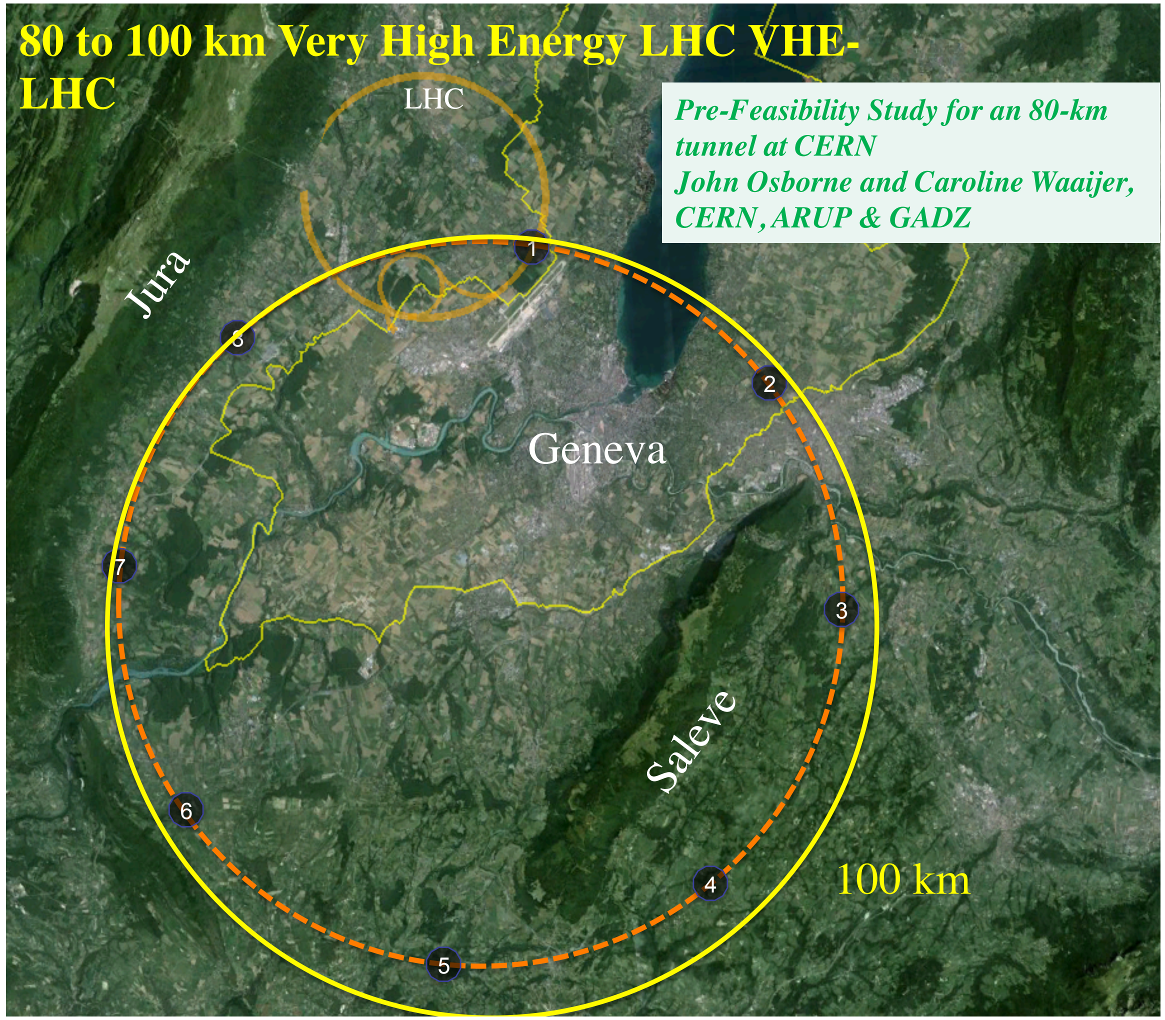
- Possibility for HE-LHC being examined
  - *Same tunnel*
  - *Magnets upgraded to 20 T*
    - **E_{cm} = 33 TeV**





New 100 km tunnel with E_{cm} = 100 TeV also being studied (more revolution than evolution though)

Conclusions

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" However, as happily always in physics, these brilliant successes should not be considered as only the end of an important chapter. They are also definitely the opening of a new one. Indeed, the standard model, with all its brilliant successes, does not explain enough. It merely describes interactions among actors which Nature presents with many different properties for whose origin we presently have very few clues. "

- There is much left to do at the LHC
  - *Upgrades to the LHC accelerator will open up a new regime in energy (x2) and luminosity (x100)*
    - **Substantial upgrades to ATLAS & CMS needed to exploit this opportunity**
  - *Broad discovery physics program*
    - **Continue direct search for SUSY or other solutions to the hierarchy problem**
    - **Enter era of precision Higgs physics**
    - **Search for rare SM processes**

Additional Material

European, US, and Global Planning

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European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

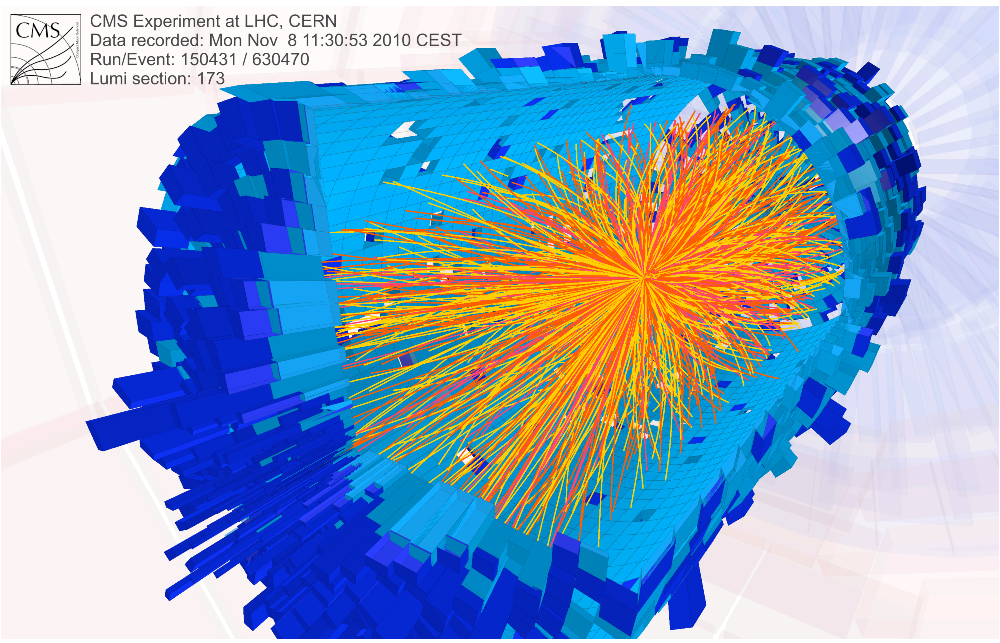
European Strategy Update

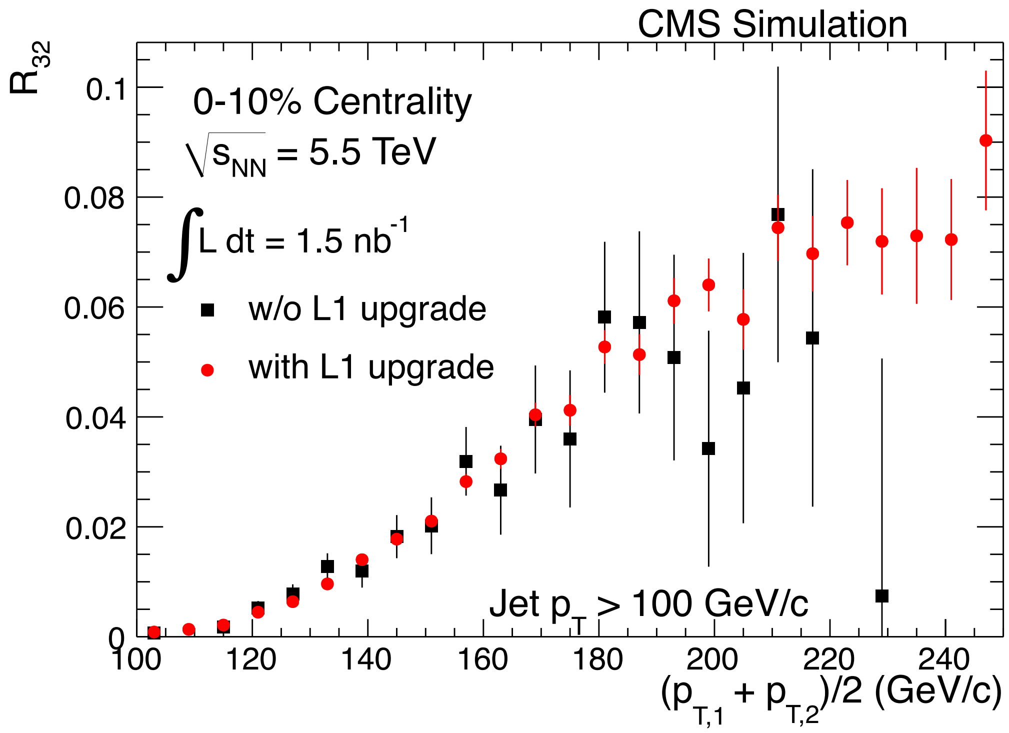
DPF Snowmass process concluding in US

DOE P5 prioritization panel to follow

Heavy Ions also part of LHC future program

- As this is a DPF (and not DNP) meeting, I have mainly spoken about pp operation
  - *However, continuation of the HI program is also foreseen in the HL-LHC era*
    - **Goal collect ~10 nb^{-1} PbPb collisions at E_{cm} = 5.5 TeV by ~2025**
    - **Significant increase in precision (60x larger dataset)**





How realistic are assumptions?

- There is historical precedent at hadron colliders to be optimistic about these ...