Higgs as Tool for Discovery

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CPAD Instrumentation Frontier Meeting 2016:

New technologies for discovery II

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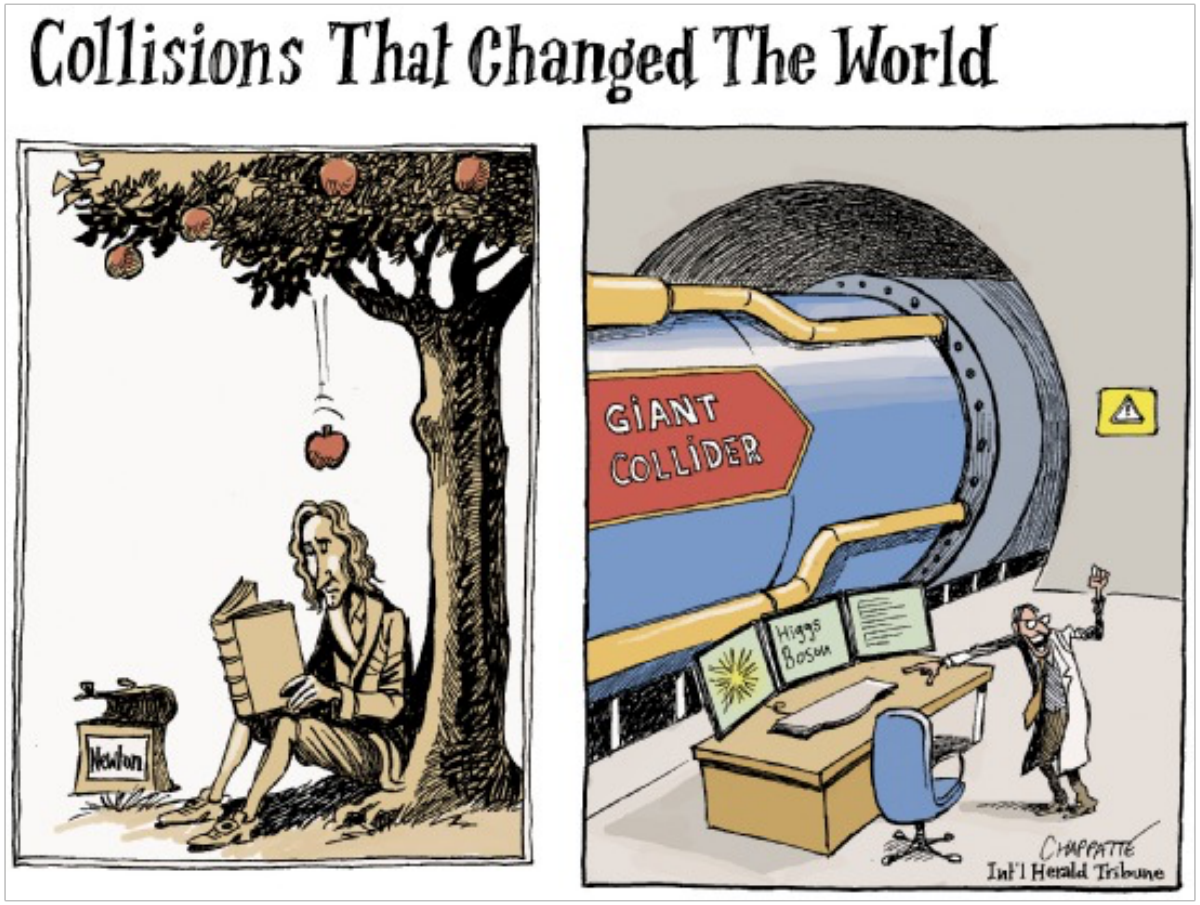
Caltech

Discovery of the Higgs Boson

The discovery of a SM-like Higgs boson during the LHC Run 1 was a ground-breaking event in physics history



Discovery of the Higgs Boson

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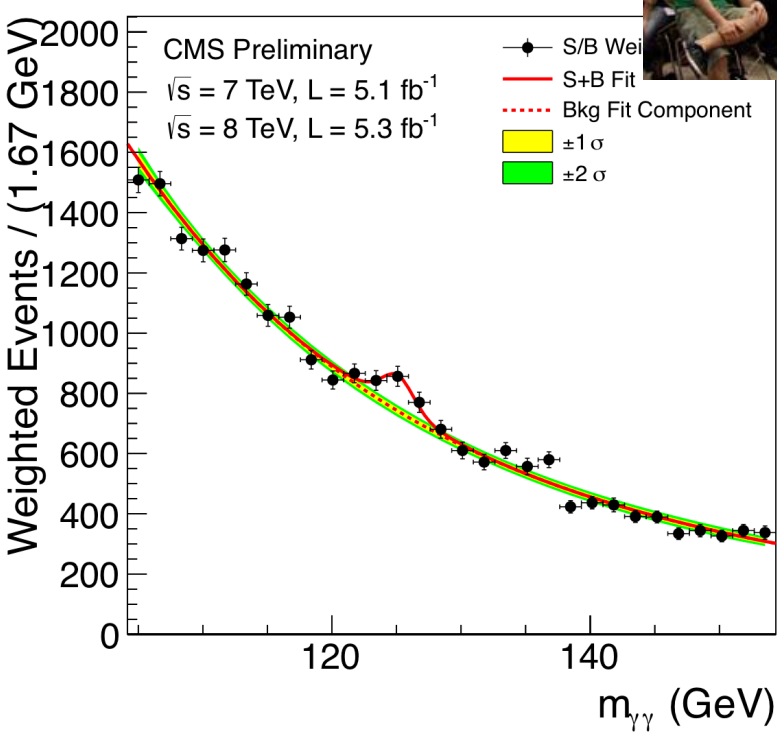
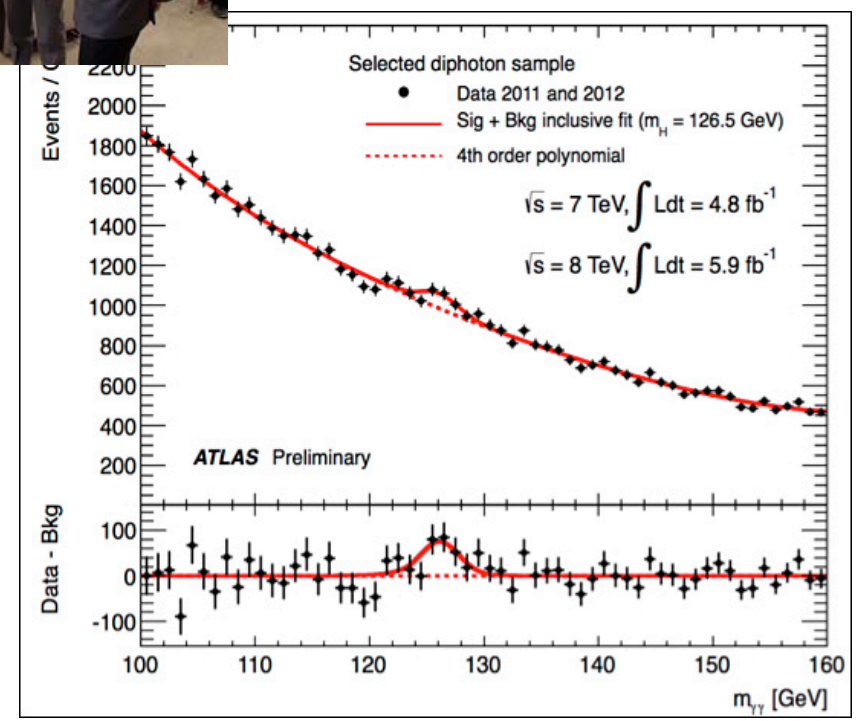


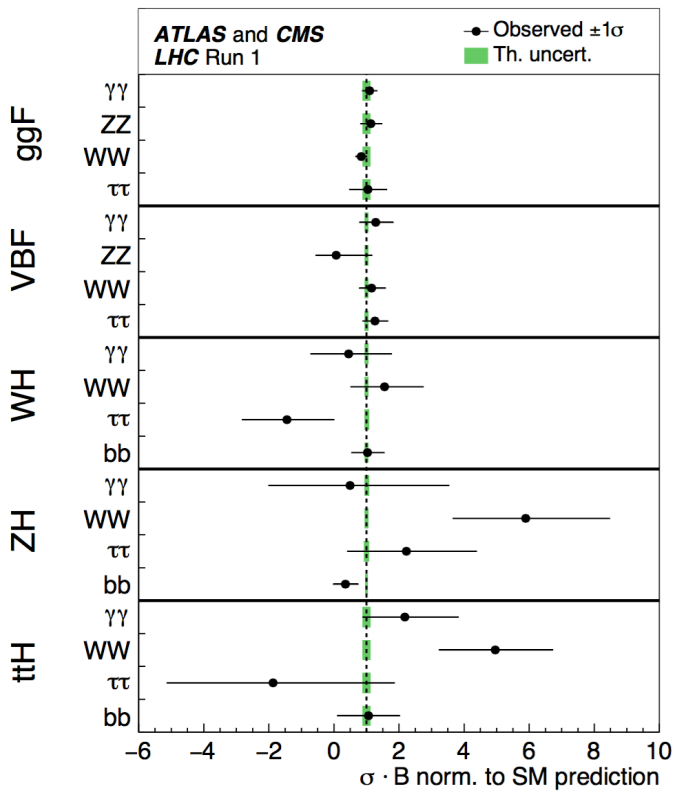


"Greetings Earth-people. We have been monitoring your progress. Now that you have discovered the Higg's boson you are qualified to join the Federation of Advanced Civilisations."

Higgs Summary

- Following its discovery, significant effort has been put into characterizing the properties of the Higgs Boson
- Objectives:
  - observe it in as many channels as possible to measure its properties
  - check of the coupling structure of the SM
  - interpret deviations of Higgs couplings as a sign of New physics

LHC Run 1 combination



JHEP 08(2016) 045

Mass has been measured to 0.2% precision
m_H=125.09 ± 0.24 GeV

Angular distributions consistent with spin 0 and even parity

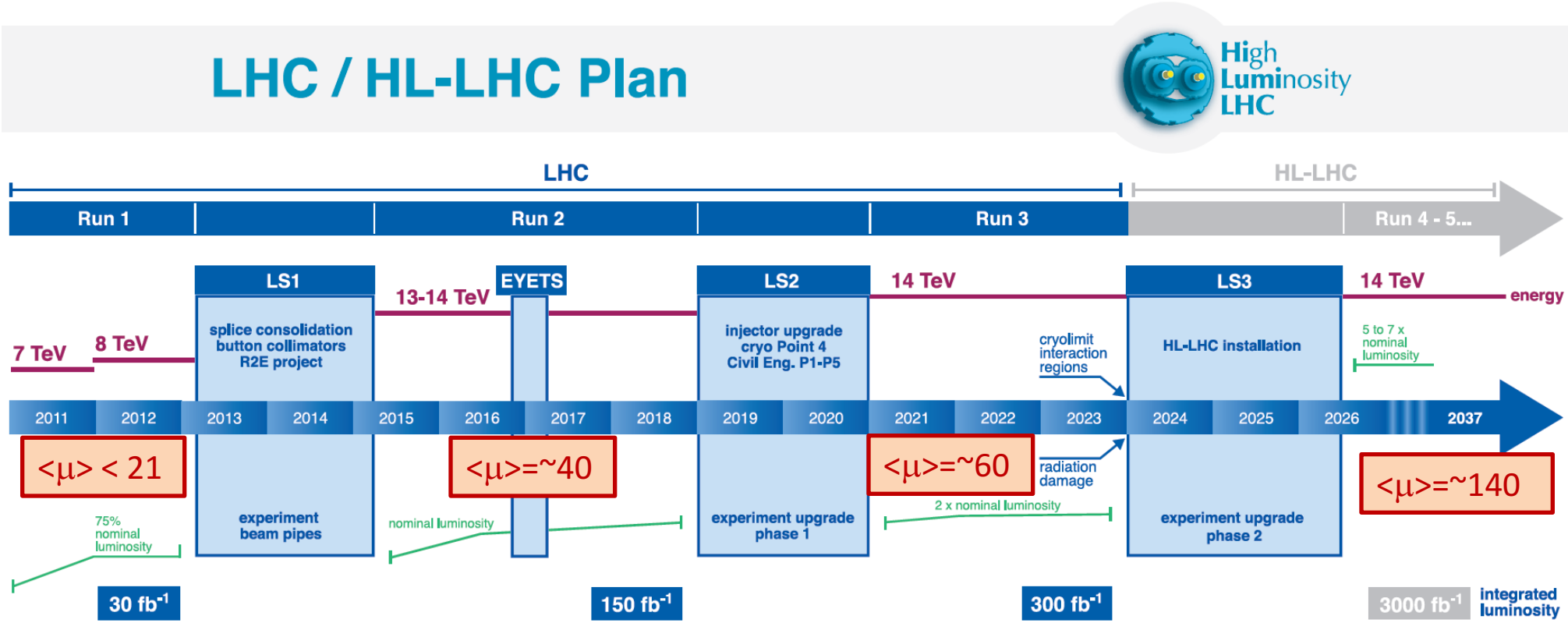
All couplings are consistent with SM within 2.5σ

What remains to be answered ?

- What is the solution to the hierarchy problem ?
- Are there exotic Higgs decays ?
- Are there additional Higgs bosons ?
- Does the Higgs interact with dark matter ?
- Is the Higgs elementary or composite?
- Higgs couplings to light particles (e.g. $h \rightarrow J/\Psi+\gamma$)
- Higgs coupling to top:
  - known indirectly ($gg \rightarrow h$) or via difficult tth channel

The Energy Frontier

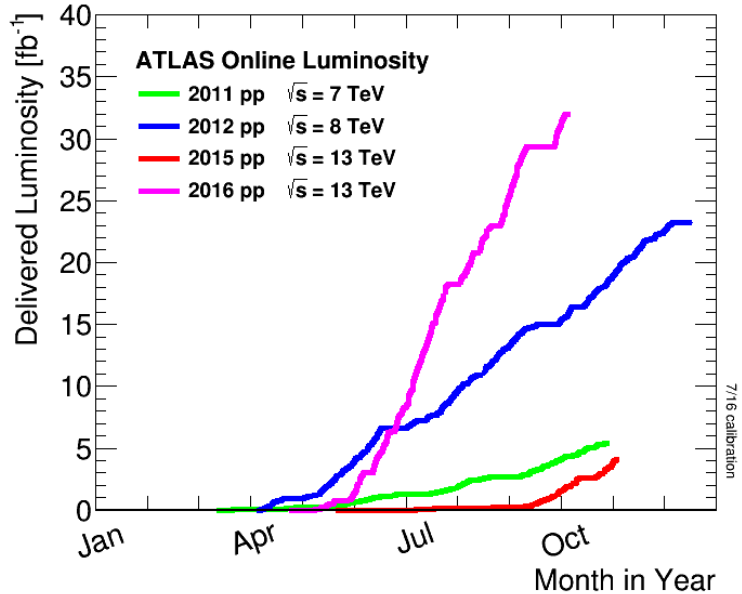
- Answers are being searched for at the Energy Frontier



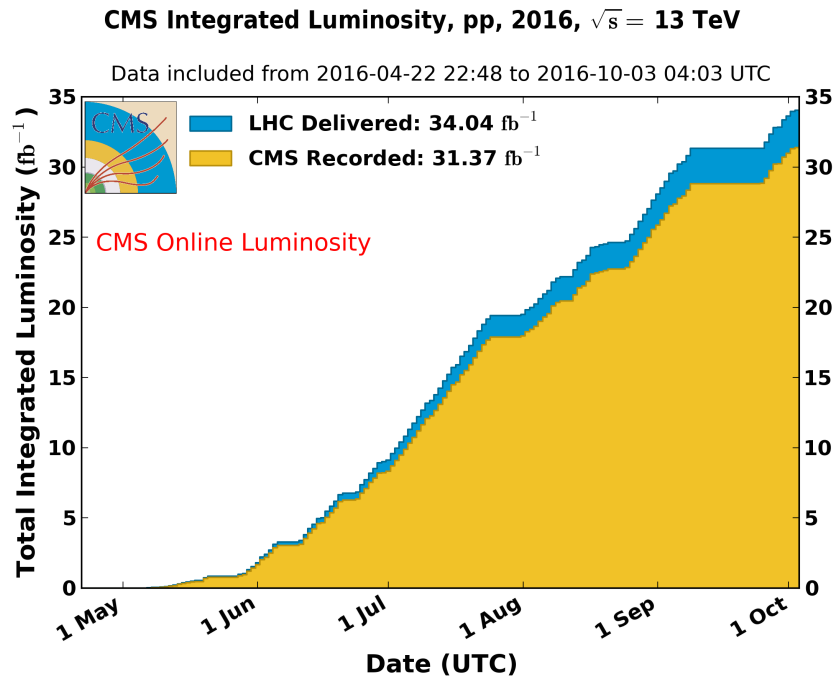
To reach 3000 fb^{-1} , a lumi of 7.5×10^{34} $cm^{-2}s^{-1}$ maybe needed => Pile-up of 200 events

Where are we now ?

- Excellent, record-breaking performance of the LHC in 2016
  - Exceeded even the most optimistic projections
  - Already produced many more Higgs bosons than in Run 1!



- LHC peak lumi > 1.35×10^{34} $cm^{-2}s^{-1}$, delivering @ record pace
  - ~40 fb^{-1} by end of 2016



- Detectors performing well; livetime >~90% and > 90% of logged data usable for any physics analysis

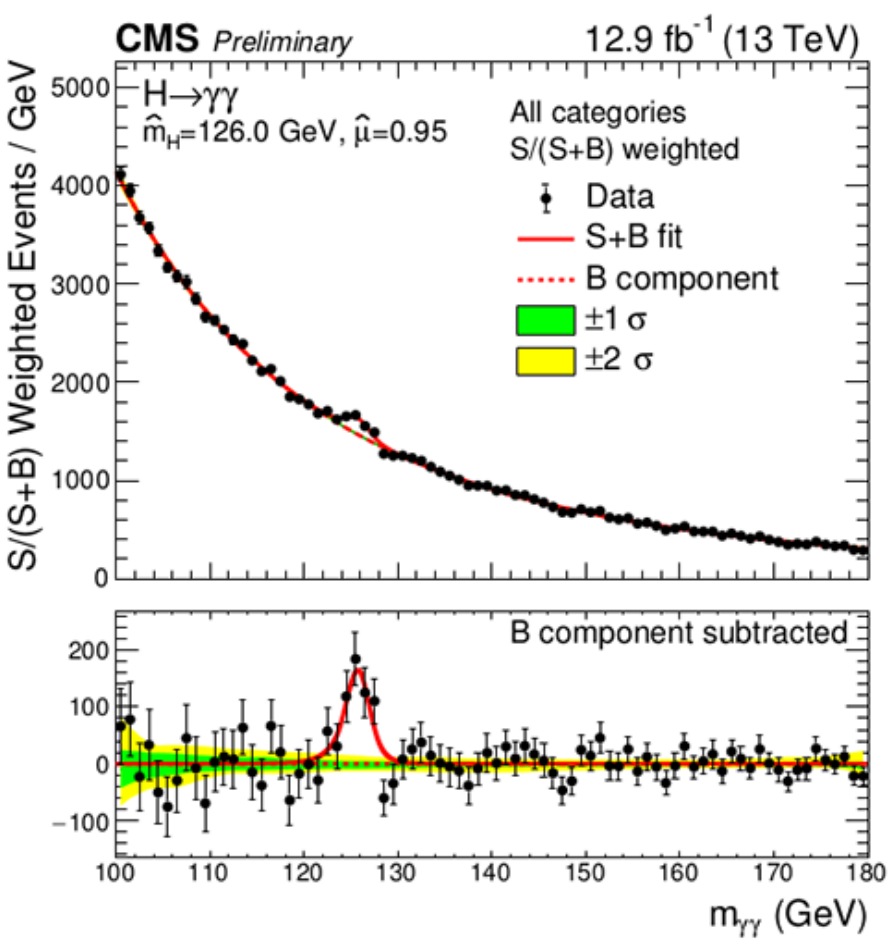
Higgs (re-)discovery: H->γγ

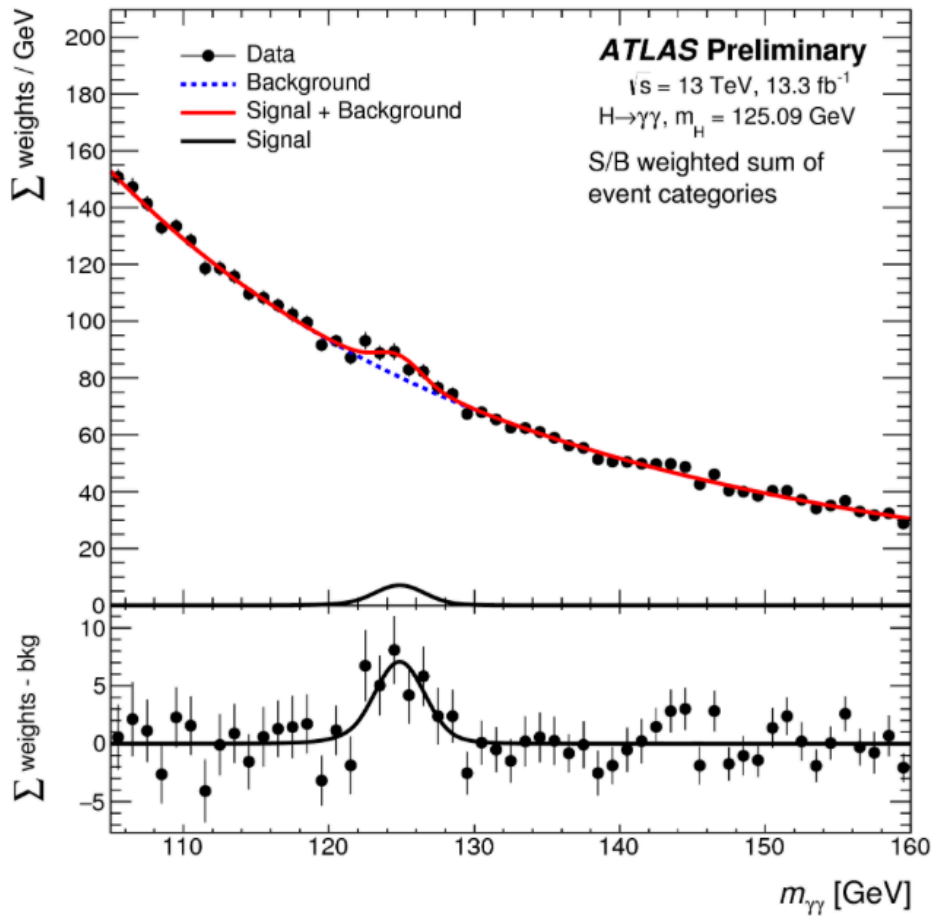
The Higgs has been re-discovered in Run 2 at 13 TeV

CMS-PAS-HIG-16-020

Achieved similar precision to Run 1
Measurements compatible with SM

ATLAS –CONF-2016-067





Also measuring fiducial cross section and diferential cross sections

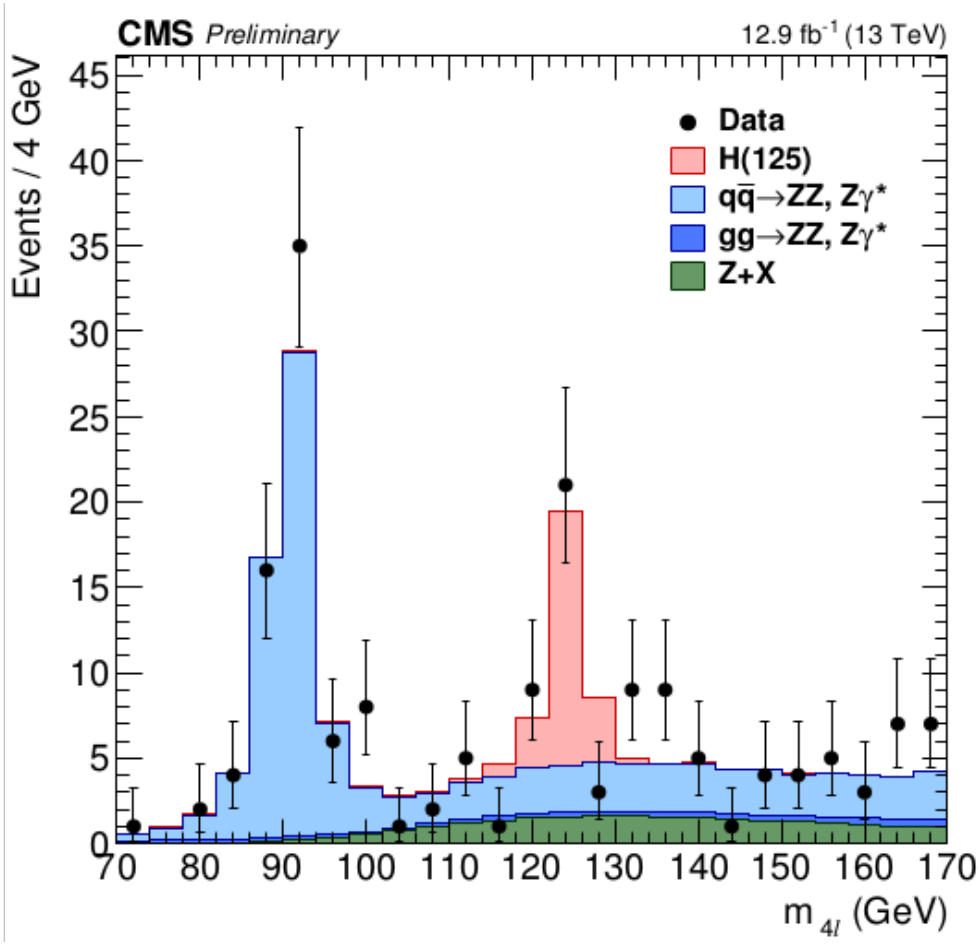
Higgs (re-)discovery: H->ZZ

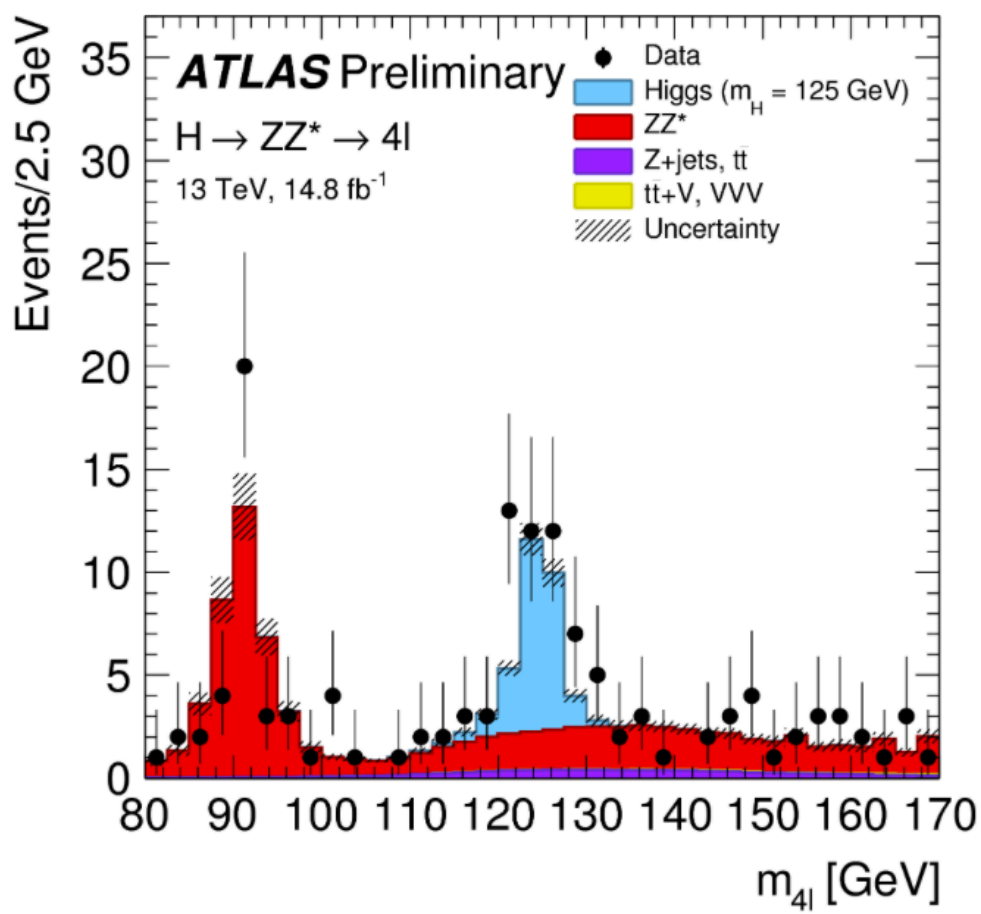
The Higgs has been re-discovered in Run 2 at 13 TeV

CMS-PAS-HIG-16-033

Achieved similar precision to Run 1
Measurements compatible with SM

ATLAS –CONF-2016-079





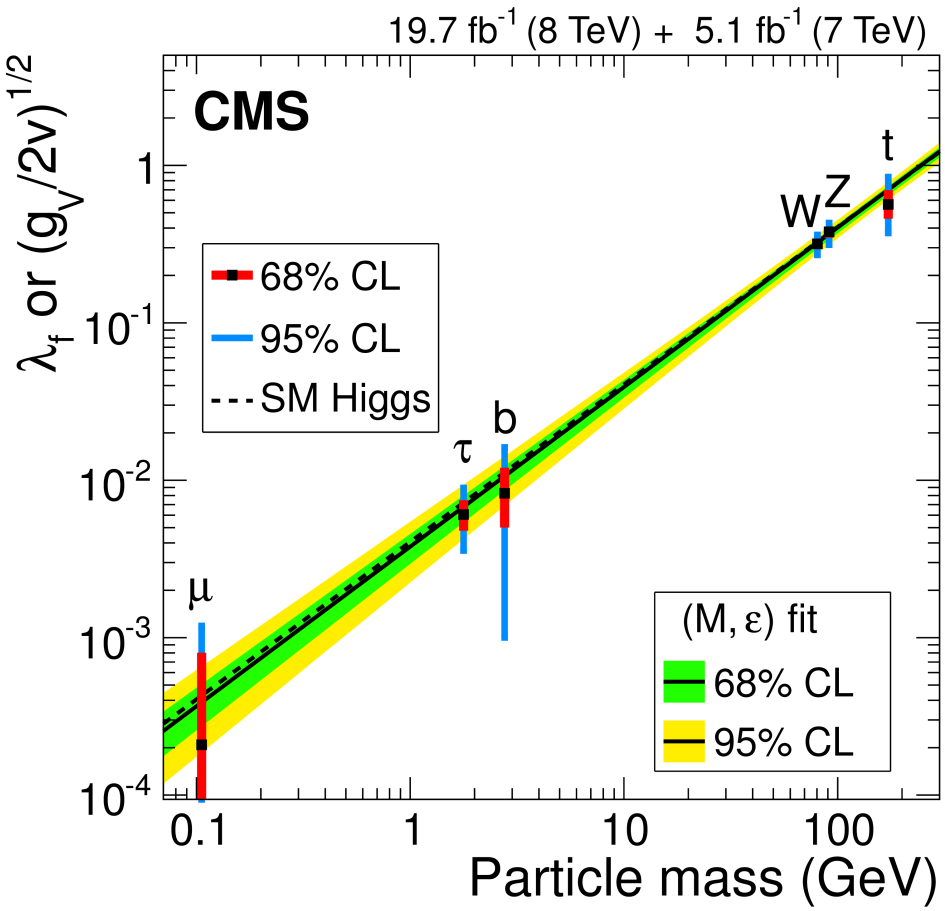
Also measuring fiducial cross section and diferential cross sections

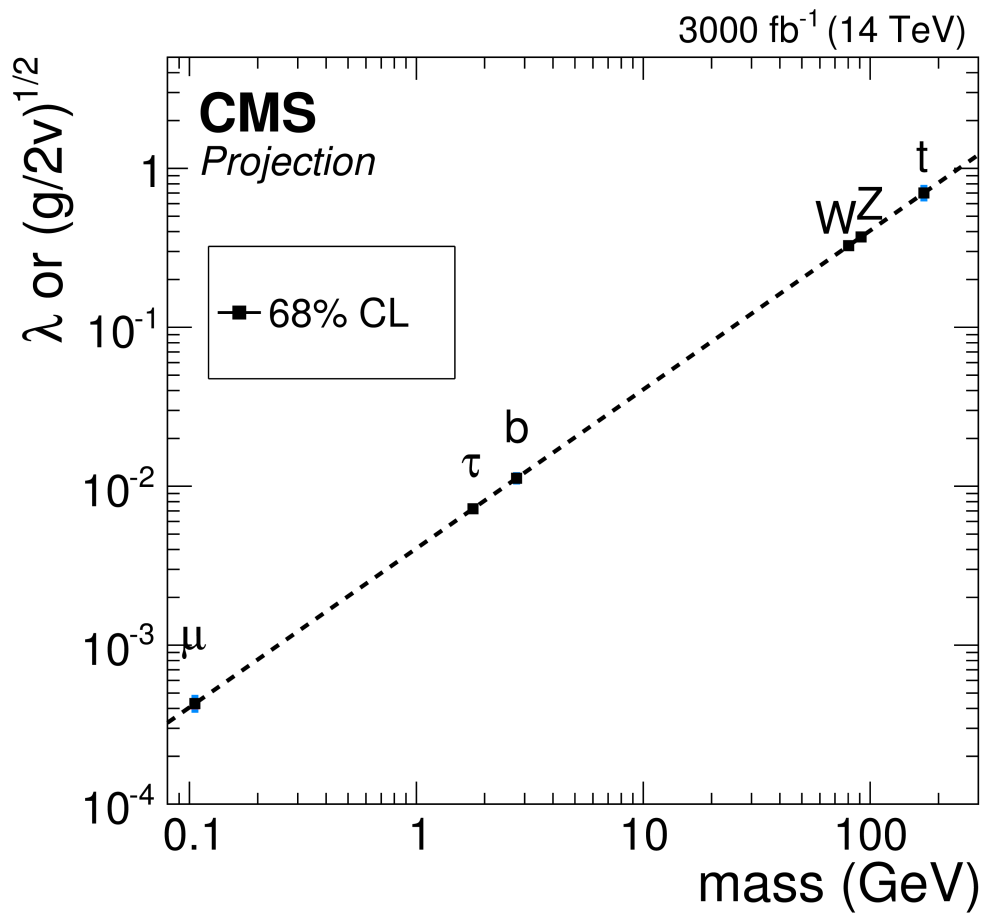
Stress-testing the Higgs sector:

- Precision measurements
- Rare processes

HL-LHC: the Higgs Factory

CMS TDR-15-002





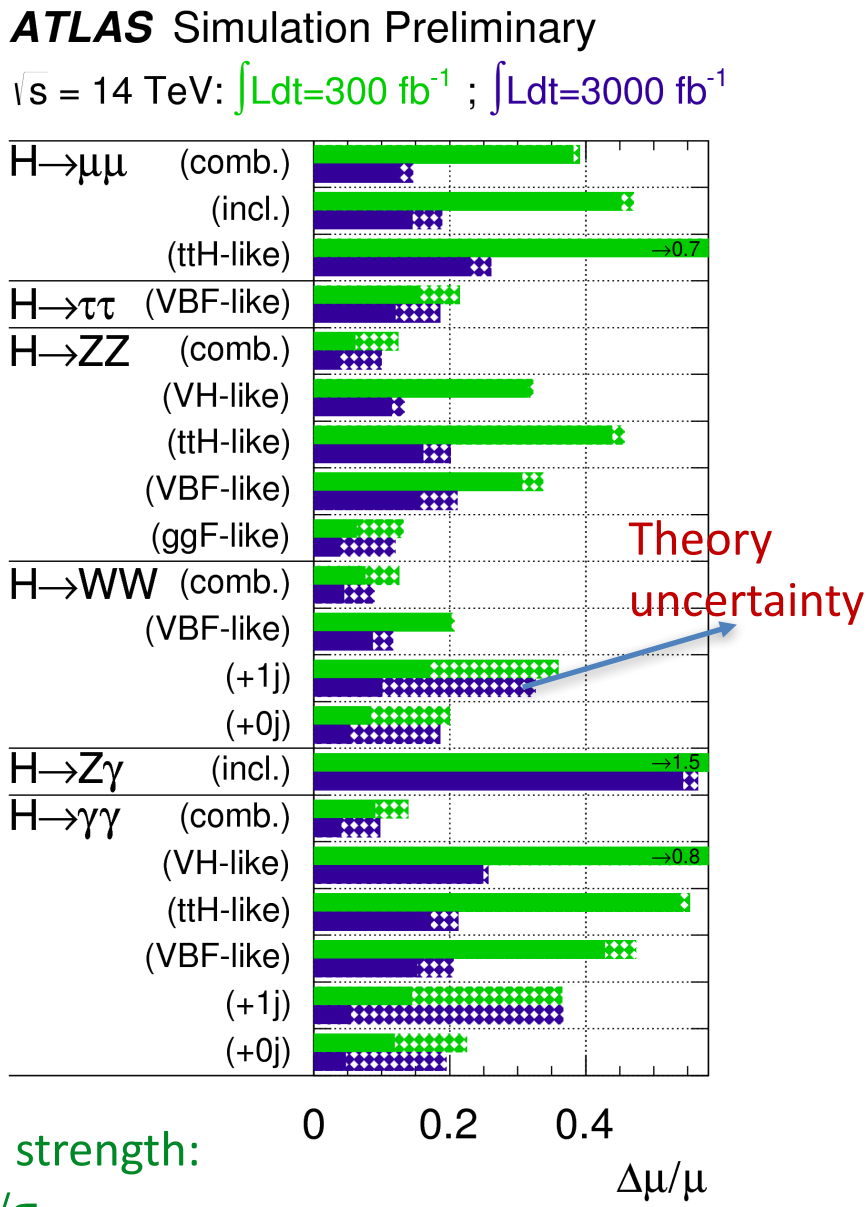
Compared to a precision of ~20% on Higgs boson couplings today, percent-level precision can be reached for most coupling measurements.

HL-LHC provides access to rare processes (e.g. H->μμ)

ATL-PHYS-PUB-2014-016

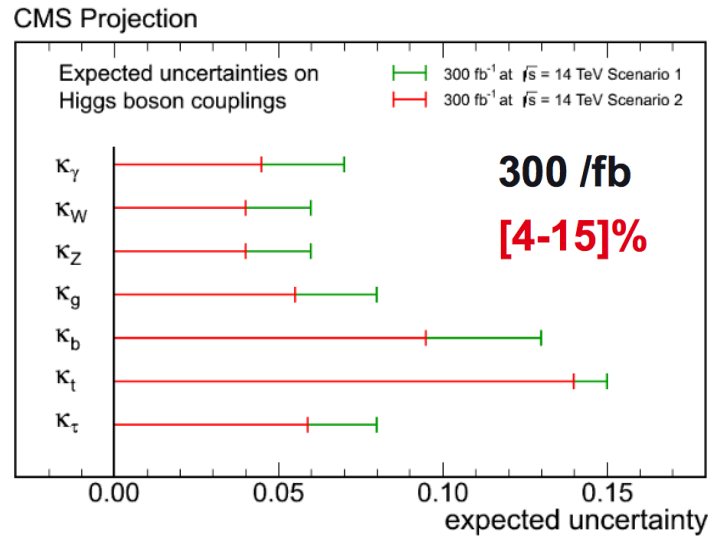
HL-LHC Projections

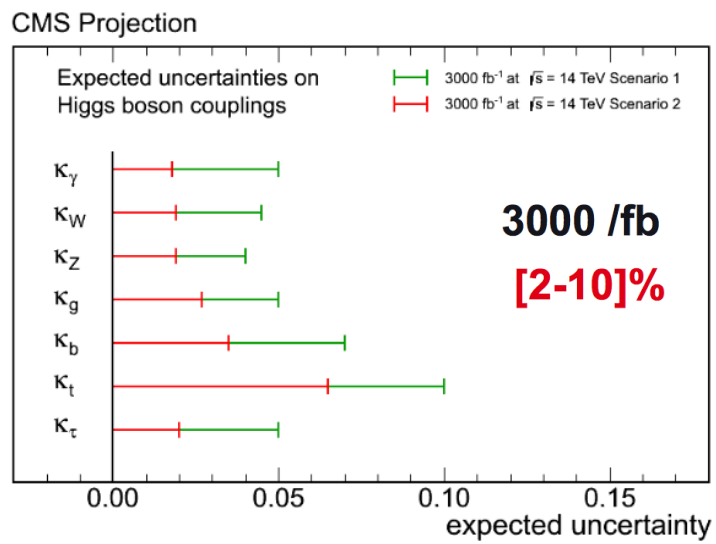
CMS TDR-15-002



signal strength:

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





Scenario 1: Syst. uncertainties remain the same

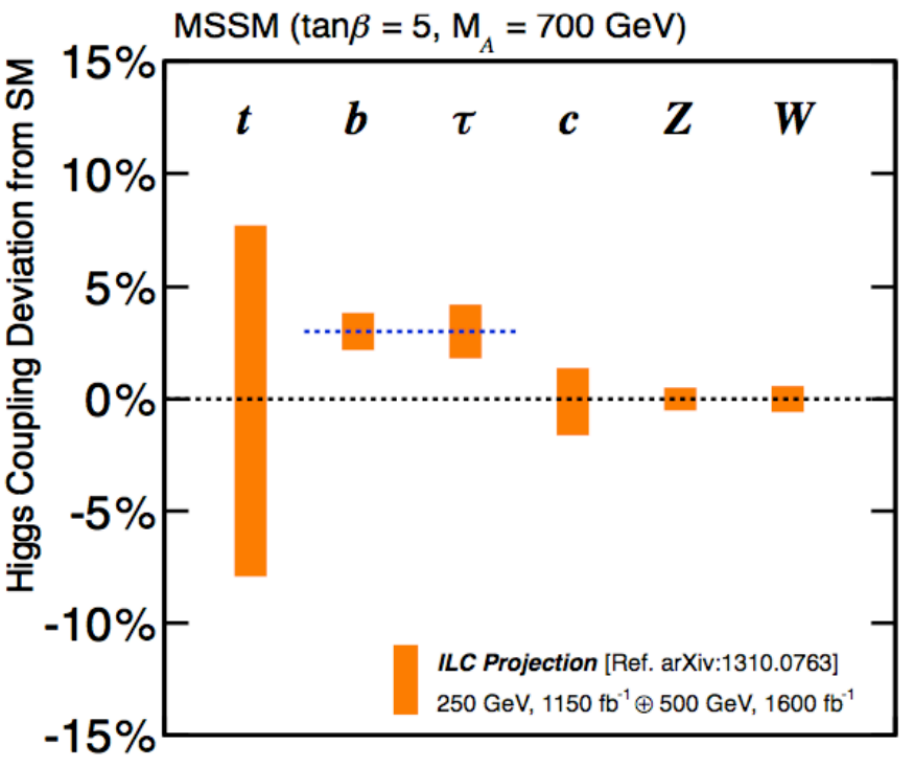
Scenario 2: Theory uncertainties scaled by 1/2, other syst. uncertainties scaled by $1/\sqrt{L}$

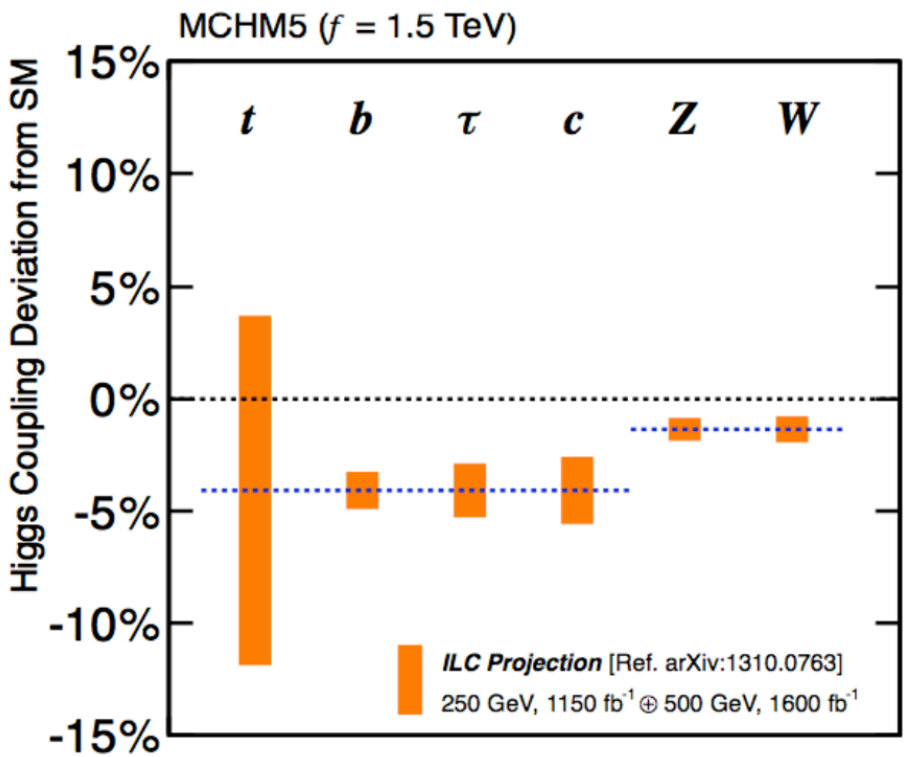
Theoretical uncertainties

Important to continue decreasing the uncertainties including the theoretical ones which are critical for estimating cross sections & acceptances

- Missing higher order QCD correction
- Electroweak corrections
- PDF uncertainties

SUSY Kanemura, Tsumura, Yagyu, Yokoya **COMPOSITE HIGGS**





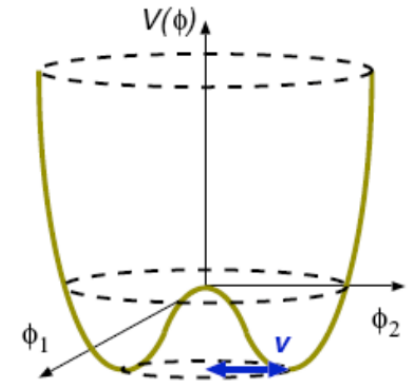
Stress-testing the Higgs sector:

- Precision measurements
- Rare processes

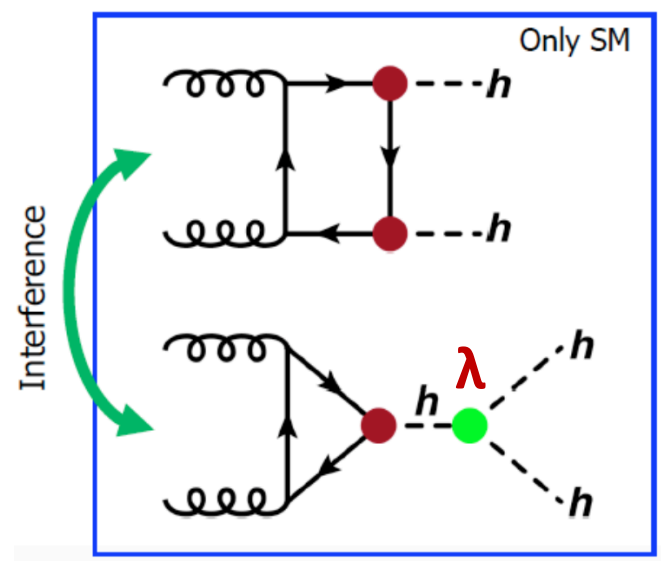
Higgs Pair Production

- Challenging measurement!
- Directly probes the Higgs field potential
  - Sensitive to the self-coupling **λ**
- Small cross section, destructive interference with box diagram
- Puts constraints on several new-physics scenarios
  - **Non-resonant:** New/modified vertices contributing to hh production
  - **Resonant:** new narrow width particle decaying into two **SM** Higgs

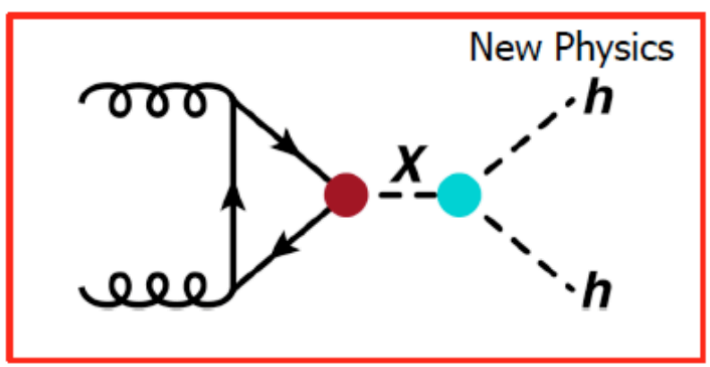
$$V = \mu^2\phi^2 + \lambda\phi^4$$



Non-resonance search



Resonance search



$\sigma\,(pp \rightarrow HH + X) \approx 34$ fb @ 14 TeV

($\sigma_{gg \rightarrow h} \sim 44$ pb)

Higgs Pair Production

- ATLAS and CMS are exploring different production modes (e.g. gg fusion, VBF, tthh) and decays
- Experimental challenges: b-tagging, merged jets, tau-tagging, pileup mitigation, photon identification efficiencies, and mass resolutions
- Need to combine many final states to maximize the sensitivity.

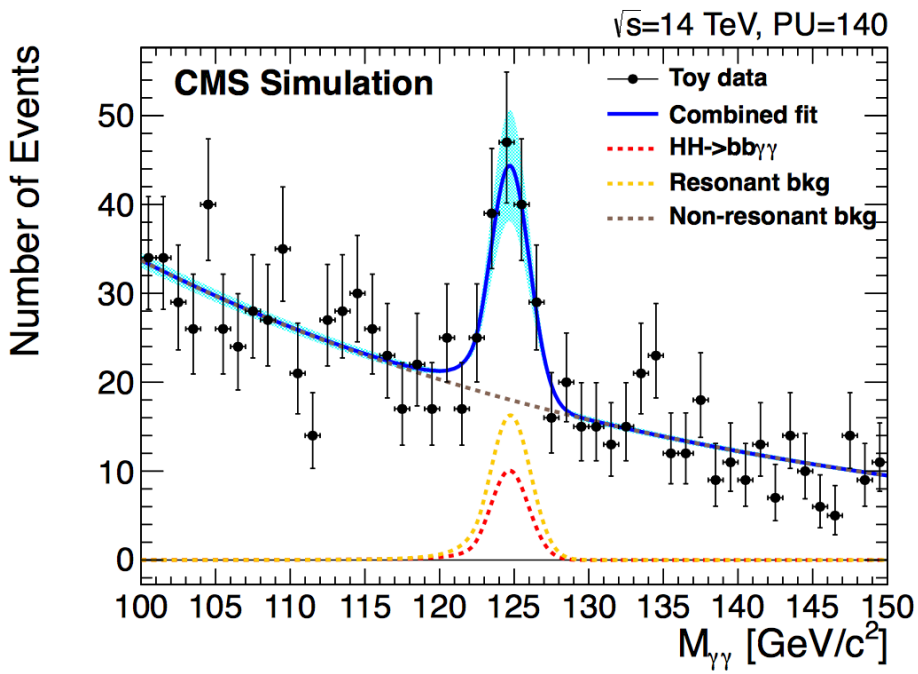
$HH \to b\bar{b}\tau^+\tau^-$

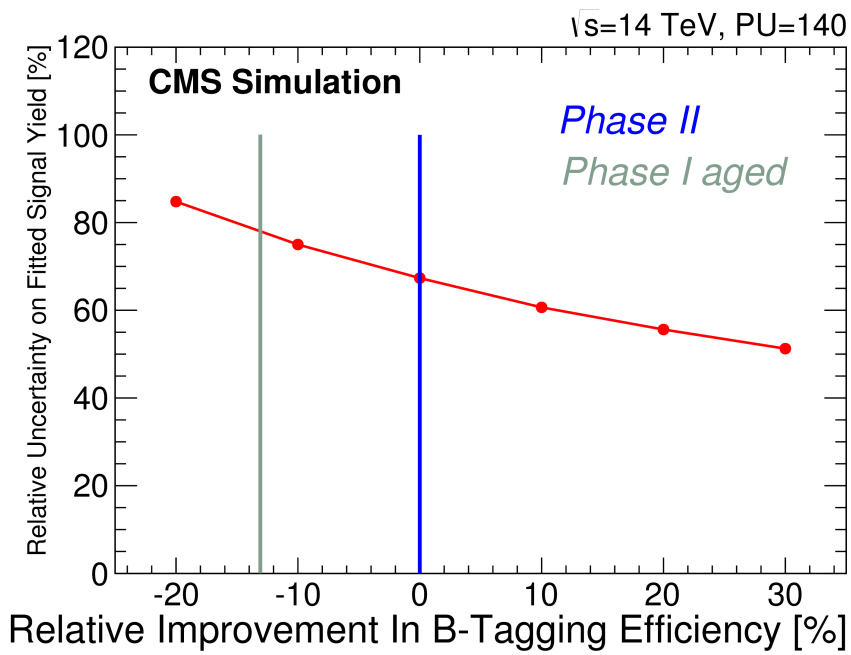
$HH \to b\bar{b}b\bar{b}$

$HH \to b\bar{b}\gamma\gamma$

$t\bar{t}HH,\ HH \to b\bar{b}b\bar{b}$

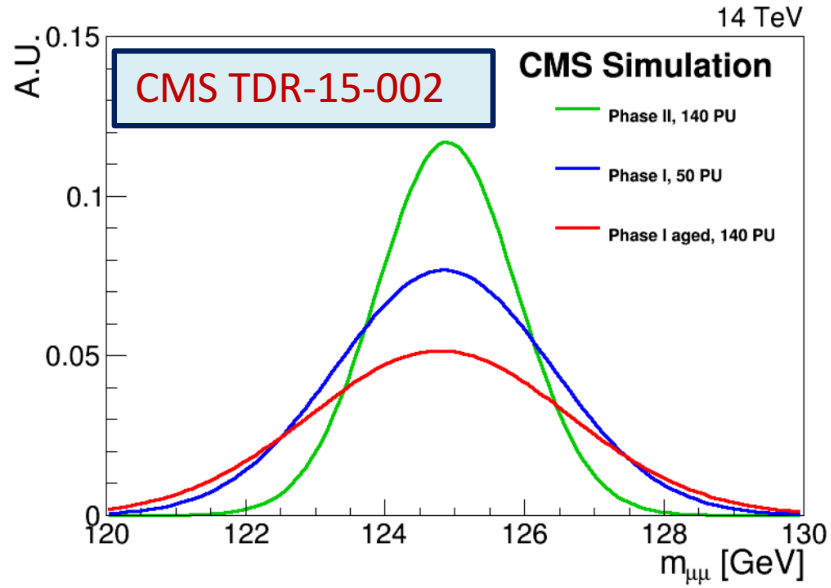
CMS TDR-15-002

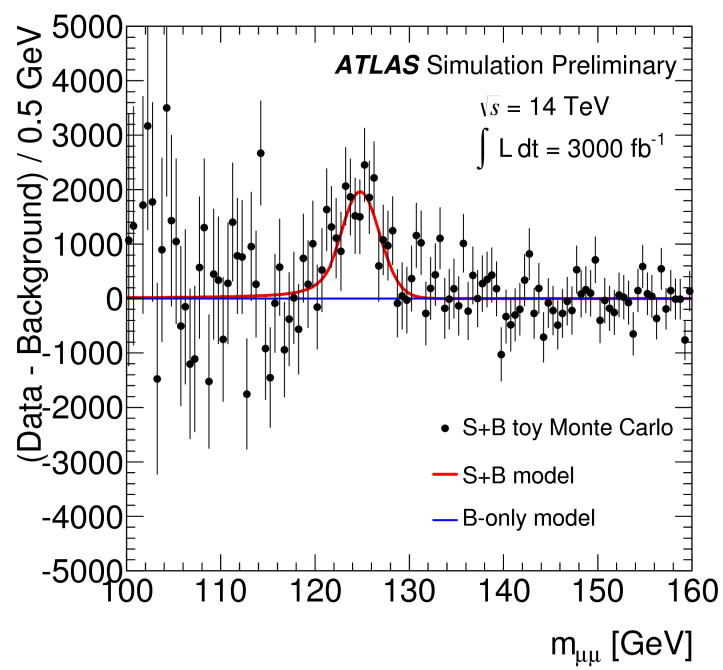




H-> μμ

- A very **rare decay** in the SM
  - Probe Yukawa-coupling to 2nd- generation fermions and mass dependence
  - Test of the Higgs coupling to leptons
- Small $BR(H \rightarrow \mu\mu) = 2.2 \times 10^{-4}$ @125 GeV
  - 10 times smaller than $BR(H \rightarrow \gamma\gamma)$ with a larger background
- Small bump over a large di-muon background from Drell-Yan events
  - excellent di-muon mass resolution crucial
  - Puts constraints on the tracking performance needed for the upgraded detector
  - VBF mode is imp. for reducing backgrounds





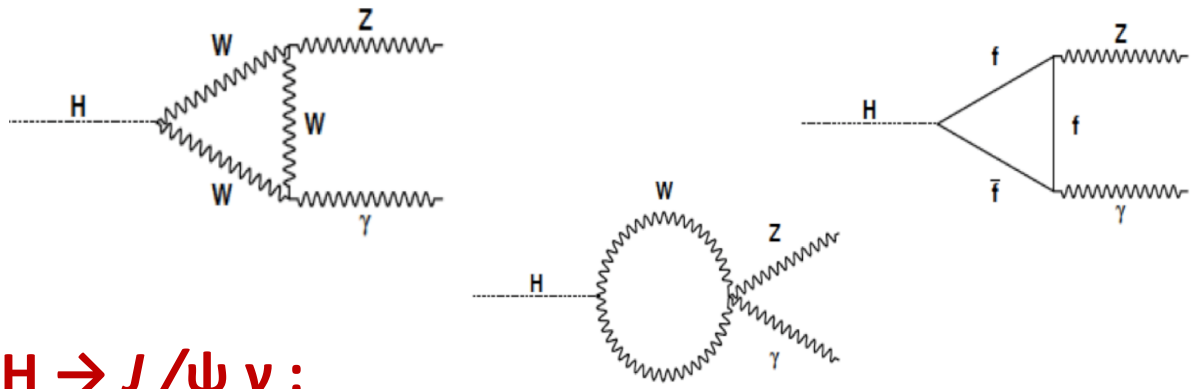
ATLAS-PHYS-PUB-2014-019

2.3 σ with 300 fb^{-1}
~7 σ with 3000 fb^{-1}

Other rare Higgs decays

$H \rightarrow Z\gamma$ channel:

- Can test the loop structure
- large background from Z boson radiative production and decay.



$H \rightarrow J/\psi\ \gamma$:

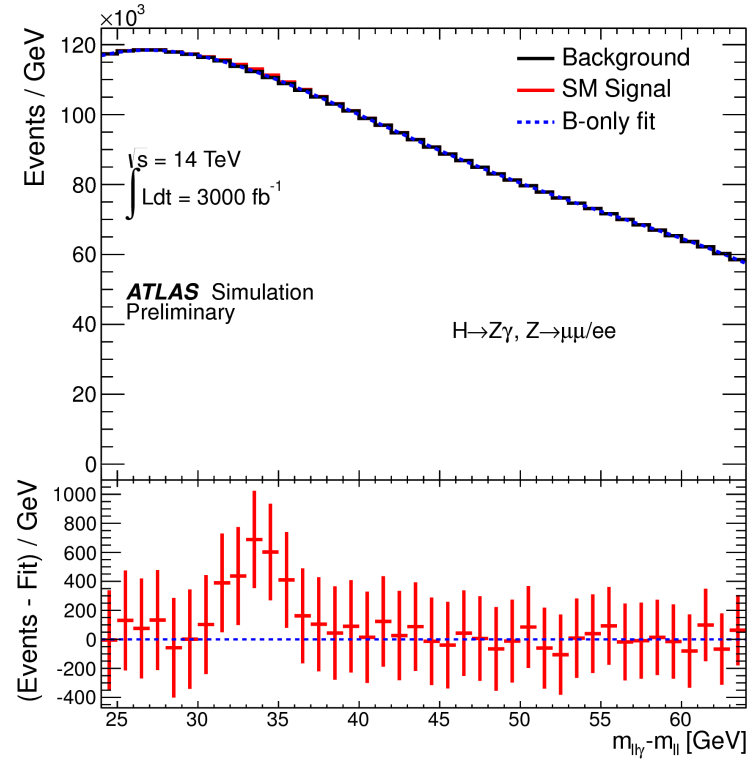
- Can use this decay to get a handle on Hcc coupling:

  $BR(H \rightarrow J\psi\gamma) = 2.5 \times 10^{-6}$ and $BR(J\psi \rightarrow ll) = 5.9\%$

  $\Rightarrow$ ~50 events in 3000 fb^{-1}

- Tough, but important to explore. New physics could enhance rate.

ATLAS-PHYS-PUB-2013-014

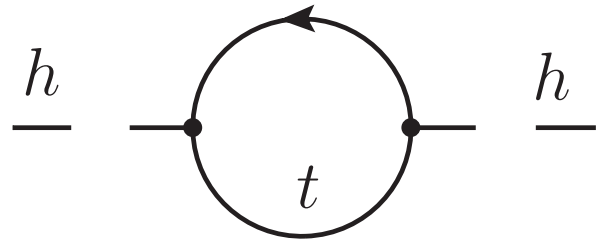


Bodwin et al., arXiv:1306.5770

Using the Higgs “tool”: portal to new physics

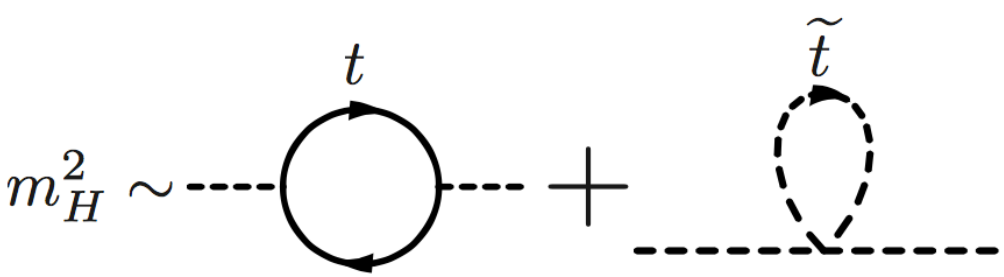
Natural searches

- With the discovery of the Higgs boson, the problem of the stability of M_h against radiative corrections has become urgent.
  - For m_h = 126 GeV, requires cancellation to *1 part in 10^{34}!*
- Many searches designed for signatures motivated by a "natural" solution to the gauge hierarchy problem.



Why is the Higgs so light ?

Is m_H stabilized by ~TeV scale new physics or is it fine-tuned ?



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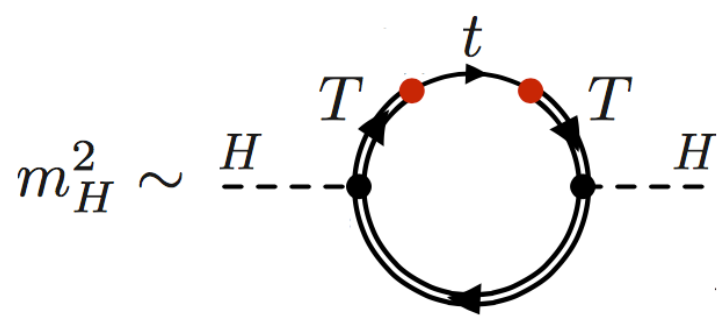
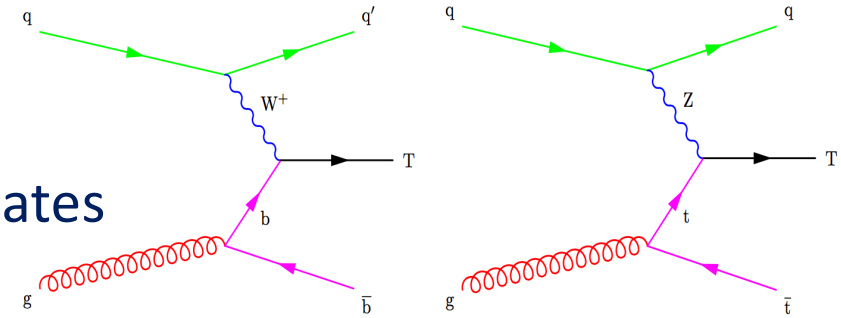


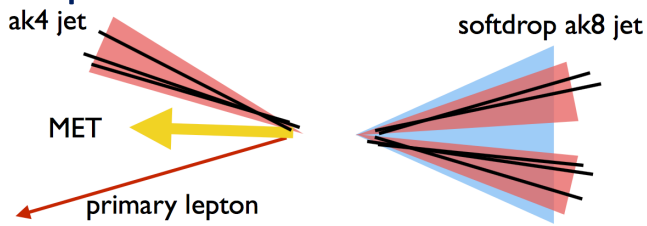
Top partner

- The lightest Higgs mass is allowed to *naturally* be at the electroweak scale, no fine tuning required.

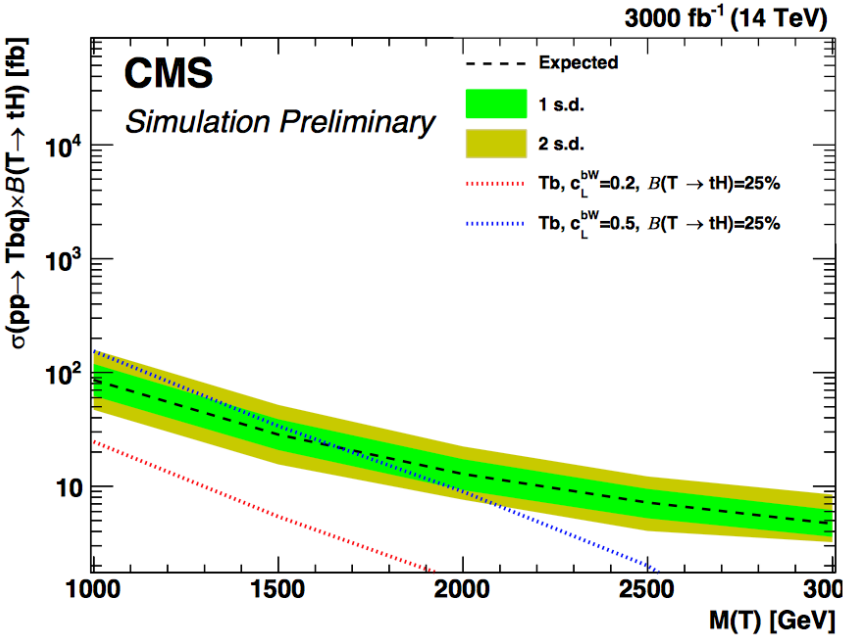
Search for T → tH

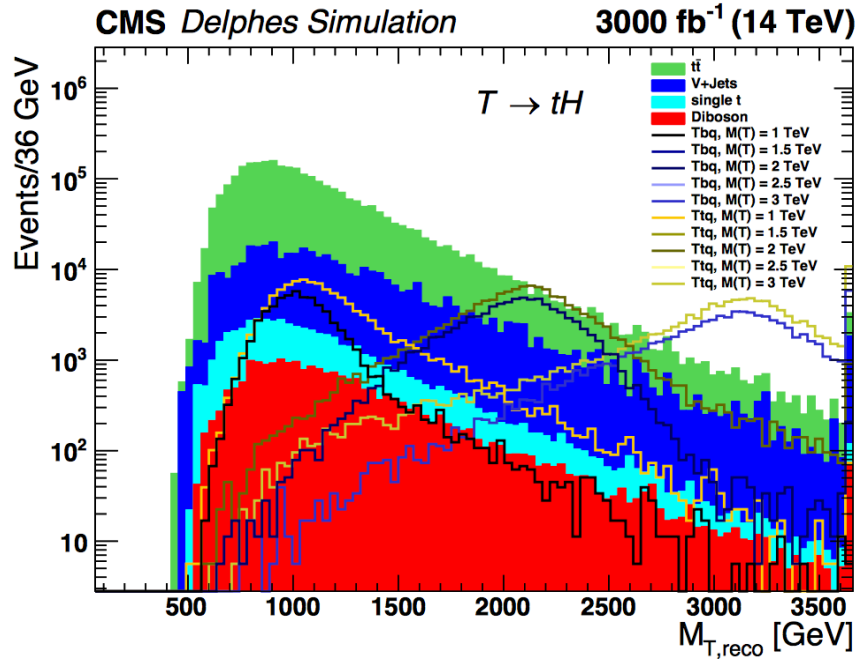
- Consider decay to tH
  - bW/tZ coupling in production
- Event reconstruction w/ top and H candidates
  - For large masses, top, H are boosted
  - Optimized for H → bb





Higgs tagging





Experimental challenges:

- Boosted topologies
- Use of forward jets for reducing backgrounds

Experimental requirements, challenges and detector upgrades

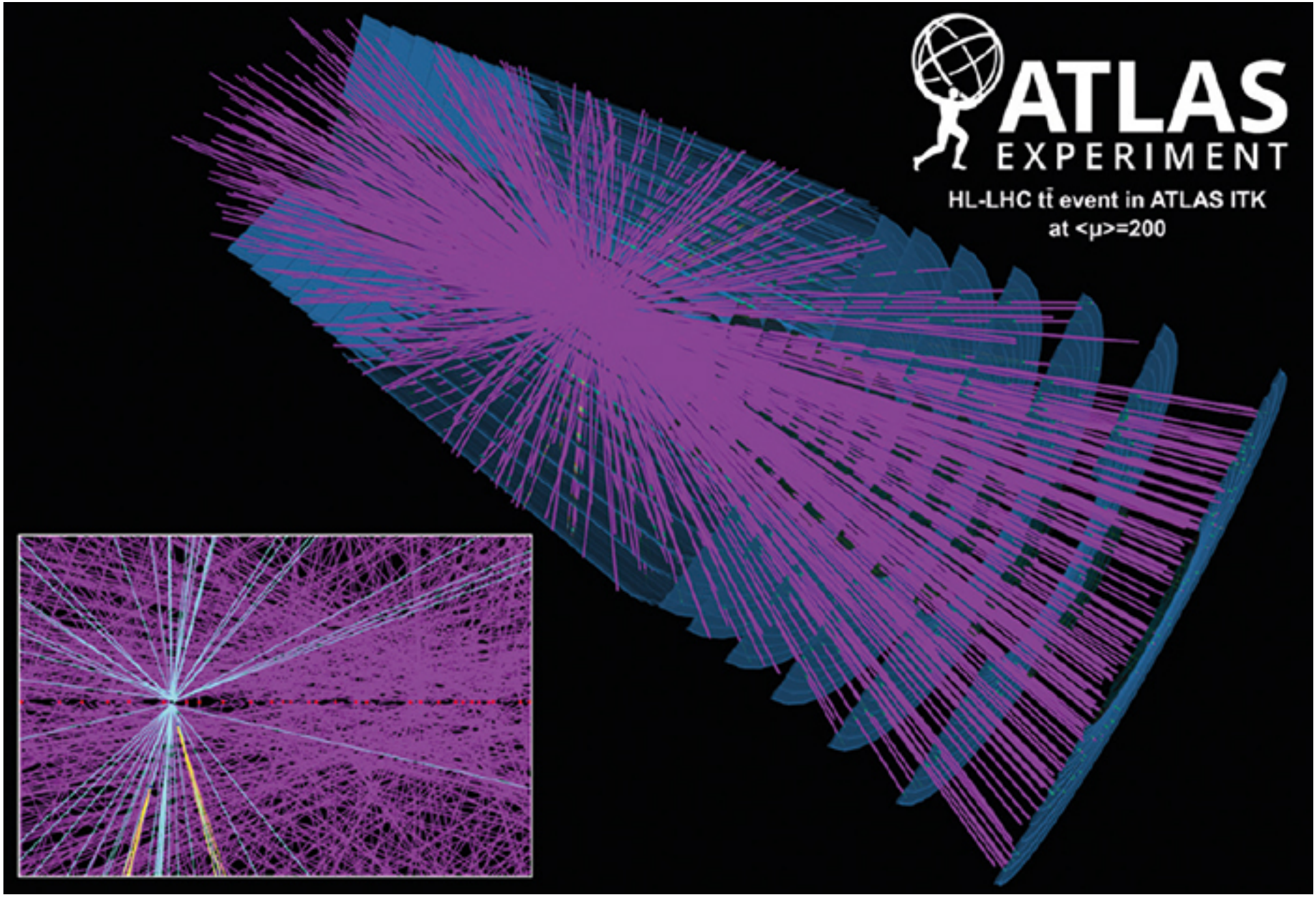
Experimental requirements

- Reconstruct all standard physics analysis objects:
  - Need high efficiency, low fake rate, and high resolution

- Requirements for success:
  - Excellent electron, photon, muon and jet reconstruction
  - Efficient b-quark tagging, precision reconstruction of primary and secondary vertices
  - Excellent missing Et resolution
  - Increased acceptance at high η
  - Boosted jet identification (W/Z/Higgs/Top jet tagging).

- For precision measurements and observations of very rare processes **need to at least maintain current performance for all physics objects**!

Challenge 1: Pileup



Challenge 1: Pileup

- Increases the combinatorial complexity and rate of fake tracks
- Adds extra energy to calorimeter measurements
- Increases the amount of data that has to be read out in each bunch crossing

Mitigation/solution:

- High granularity detectors (trackers, calorimeters) needed to identify particles associated with the primary hard scatter collision vertex with high efficiency
- Precise timing measurement can be used to unambiguously associate both tracks and neutral energy clusters to each vertex, providing ultimate pileup mitigation

Challenge 2: Trigger

- Trigger has to become increasingly selective as luminosity increases
- Need to maintain low thresholds for sensitivity/ flexibility for unknown physics
  - Higgs physics remains at low electroweak scale; HL-LHC is about precision and rare processes (e.g. HH)
  - weakly coupled new physics will still be open (e.g. final states with multiple low p_T leptons)
- Trackers and muon systems can saturate at high luminosity and readout rate
- Pileup is an issue as well
  - Can lead to an increase in trigger rates; decrease efficiency of isolated triggers

Period	$W \rightarrow l\nu$
Run1	80 Hz
Run 2	200 Hz
Run 3	400-600 Hz
HL-LHC	1KHz

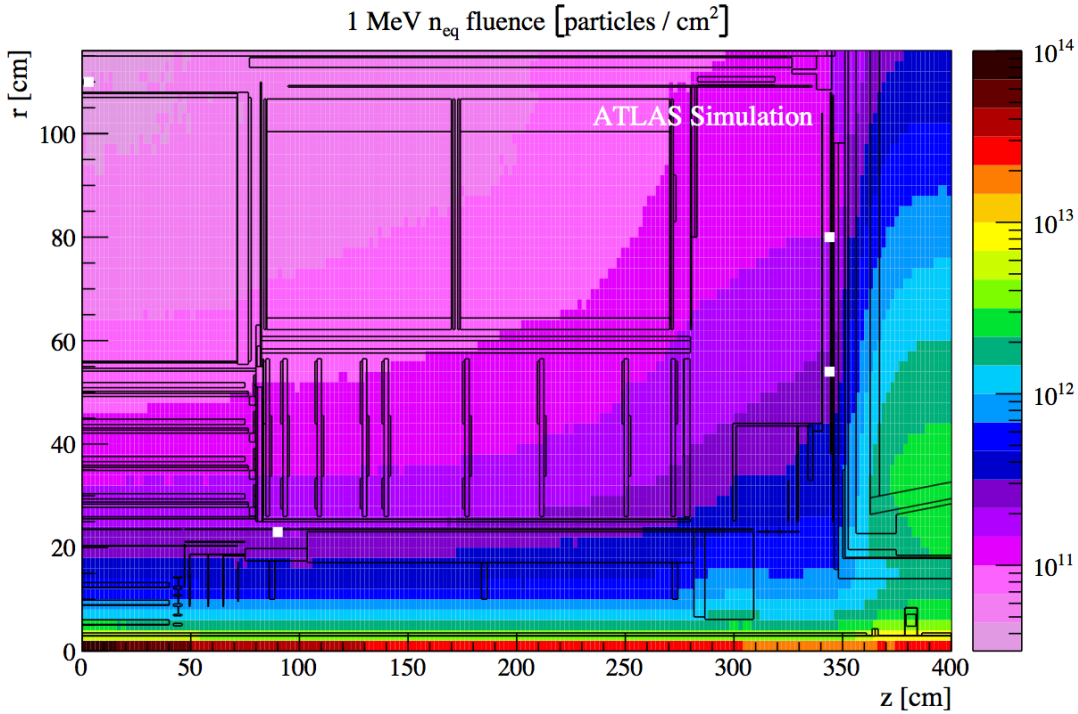
One might think we can make it up with l+X triggers (where X=jets, MET, more leptons,...)
But multi-object triggers scale badly with pile-up...

Mitigation/solution:

- Use track information in the hardware trigger (L1)
- Migrate Offline-like algorithms to High Level Trigger (software) then to L1

Challenge 3: Radiation Damage

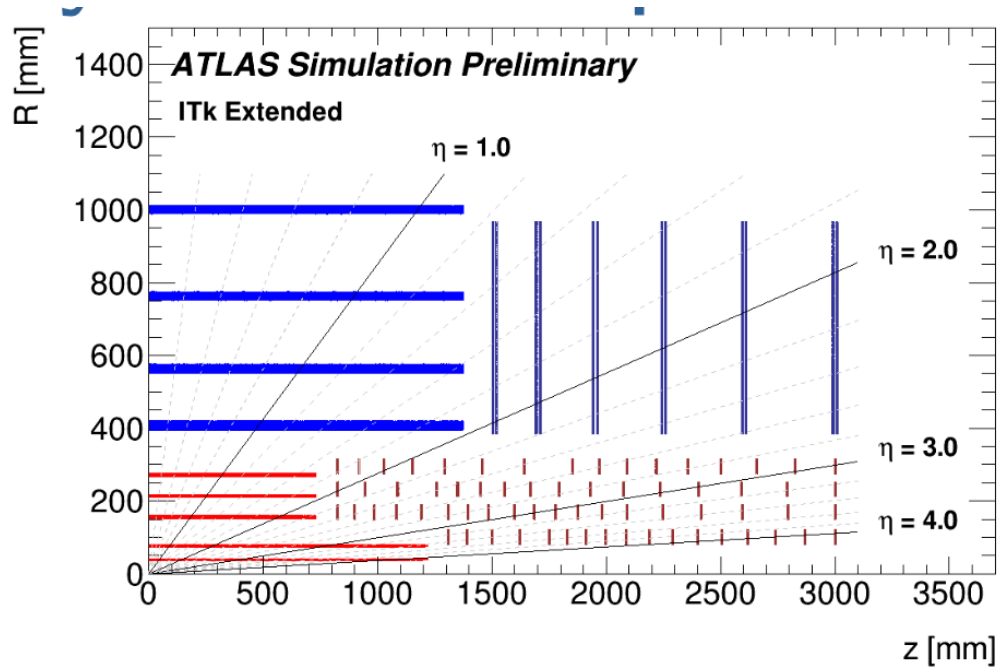
- Detector elements and electronics are exposed to high radiation dose
- Degrades signal, & limits life time of detectors
  - Inner trackers will be exposed to very high fluences and ionizing doses
  - High doses also in forward calorimeters

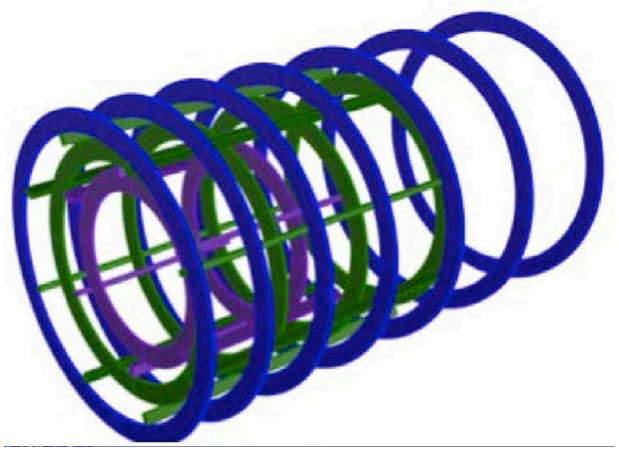


Mitigation/solution:
new tracker, and endcap calorimeters, new forward muons, replacement of most of the readout systems

ATLAS HL-LHC Tracker

- ITk (Inner Tracker) is a full upgrade of the ATLAS Inner Detector
  - includes new pixel and strip detectors, “all-silicon” detector
- Increased radiation hardness
- Higher granularity to keep occupancies low
- Larger readout bandwidth capabilities
- Reduced material in front of calorimeters
- Extended coverage at high η
  - Extension of pixel system proposed with “rings” in place of traditional endcap disks





offers more flexibility for placement of modules, services

ATLAS HL-LHC Calo/Muon Upgrades

Calorimeters:

- Tile and Liquid Argon calorimeters require full electronics replacements
  - Needed to cope with increased radiation levels and trigger rates

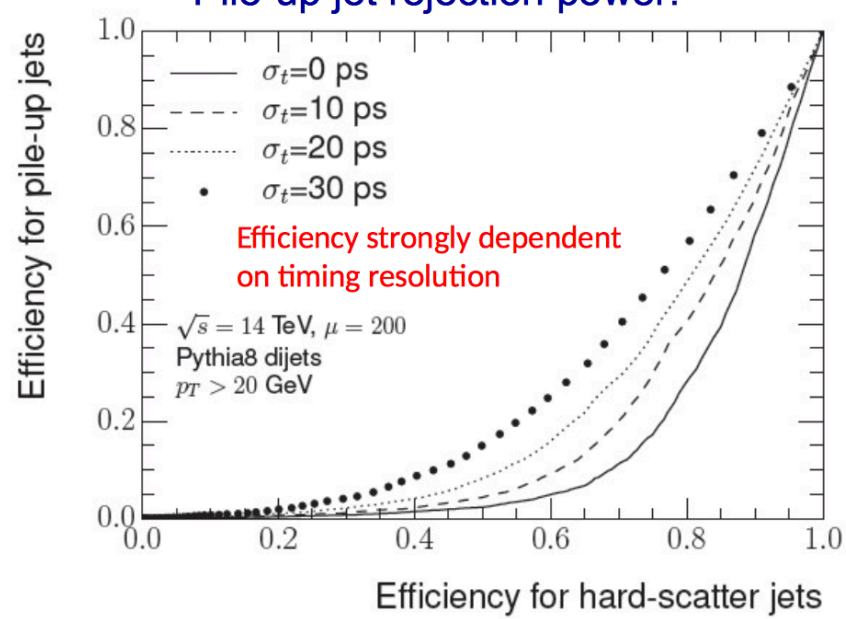
Muons:

- Readout electronics to be replaced to support higher trigger rate and MDT hardware trigger
- RPCs added to inner station to increase acceptance/robustness
- Studying options for large η muon tagger

Evaluating option of adding thin, high-granularity timing detector in front of end-cap calorimeter (2.5<|η|<4.2)

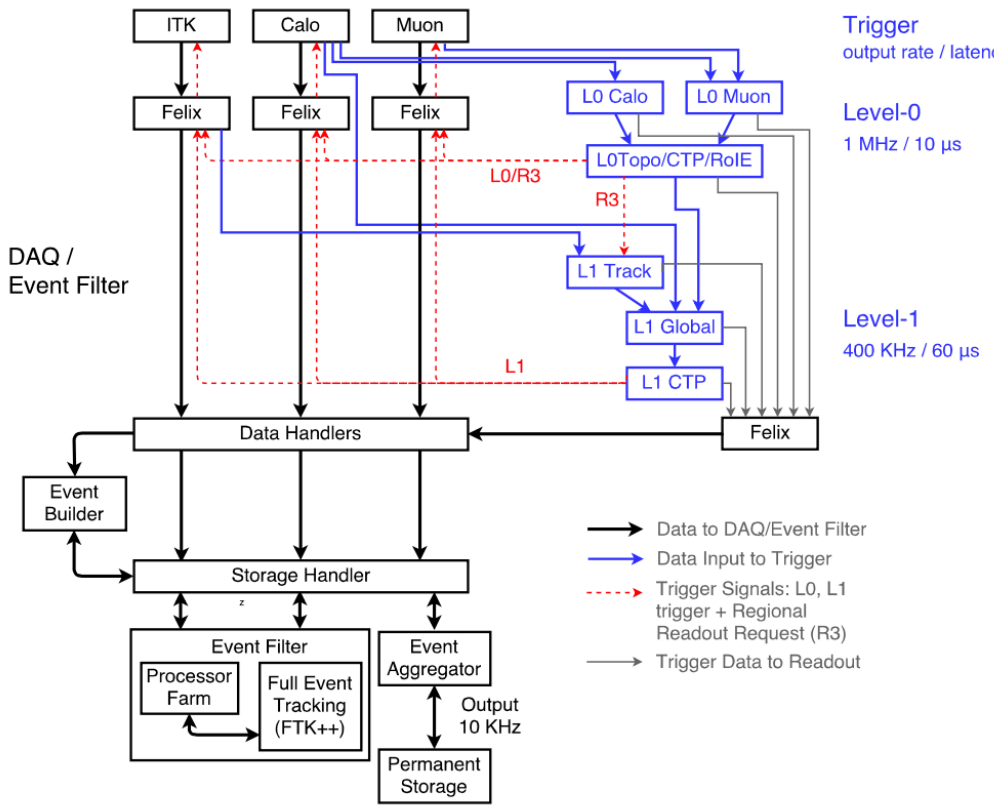
- Aim to reduce effect of pile-up on jets
- Multiple layers of silicon and optional tungsten absorber
- Timing precision: 30-50 ps

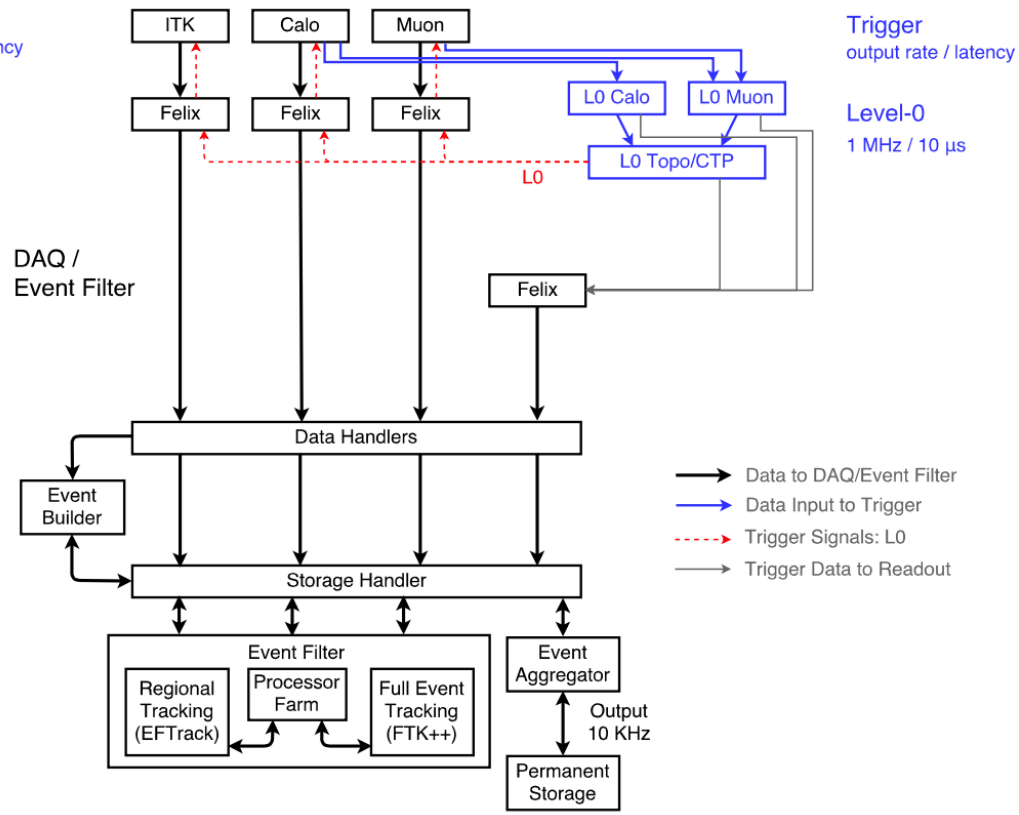
Pile-up jet rejection power:



ATLAS HL-LHC TDAQ Upgrade

Deciding between two-level hardware trigger with hardware tracking at Level-1 and a high bandwidth single-level trigger

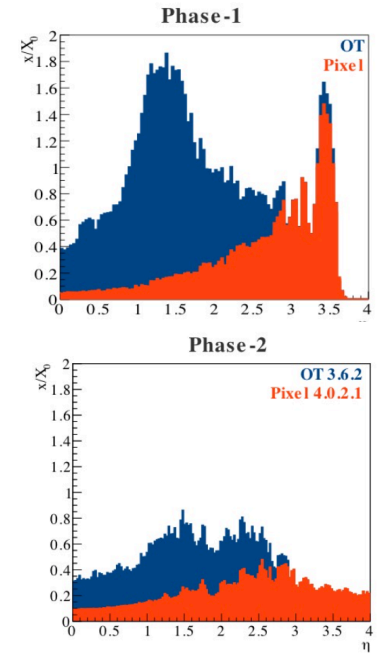


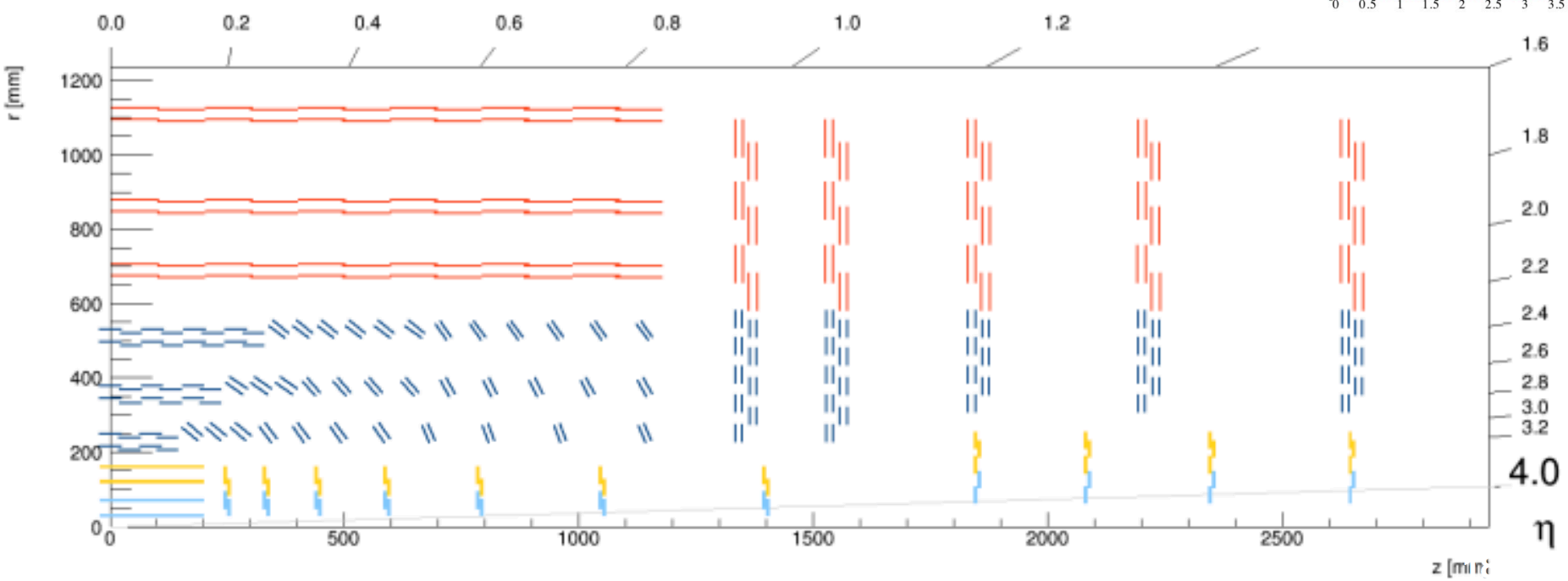


Low latency (25 µs) two-level hardware system also under consideration. Trades latency for higher trigger rate; thus increased trigger acceptance in certain channels – max rate TBD

CMS HL-LHC Tracker

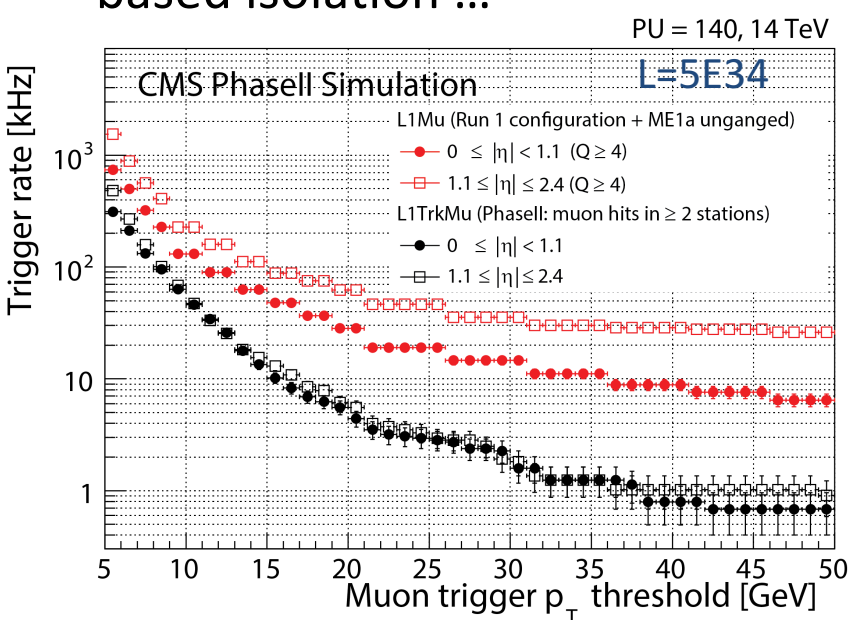
- Full tracker replacement
  - Minimize material and increase granularity, with ample hit coverage over tracking acceptance
  - Tracking coverage up to |η|<4
  - Specifically designed to provide inputs to L1 Trigger

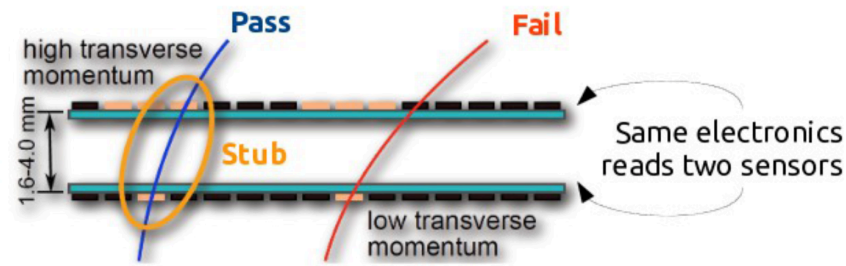




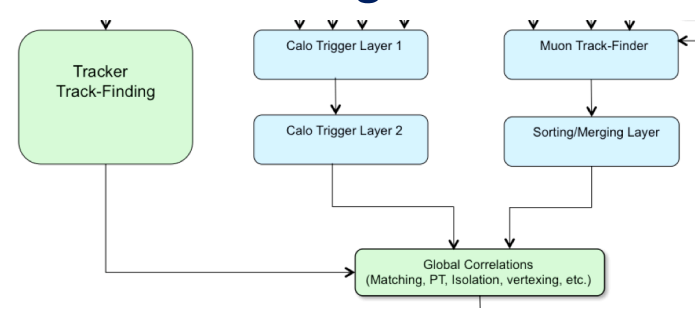
CMS HL-LHC Trigger Upgrade

- L1 (HLT) rates of 750 (7.5) kHz for 200 PU and 12.5 μs latency
- Incorporate tracking at L1
- Correlation of tracks with other Level-1 objects
  - Better lepton ID, refine (muon) momentum, assign jet vertex, determine primary vertex, provide track-based isolation …



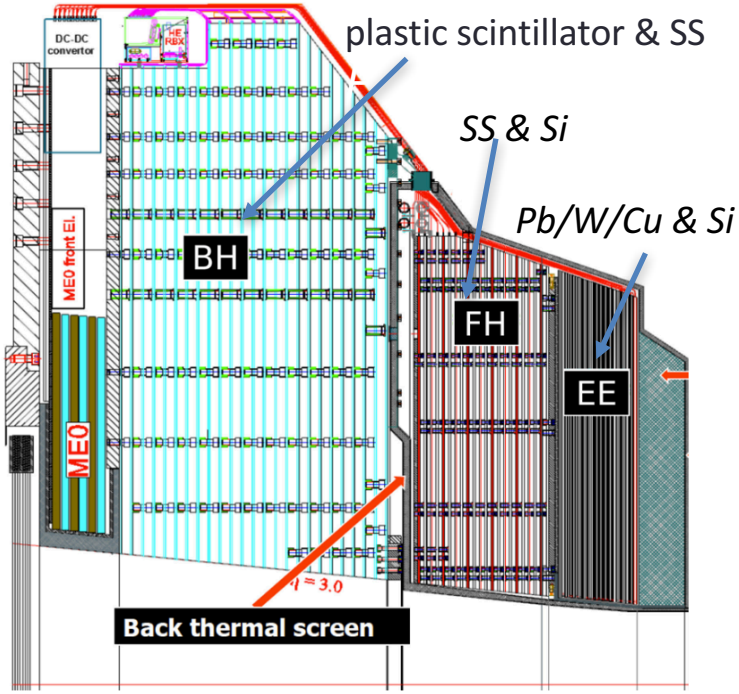


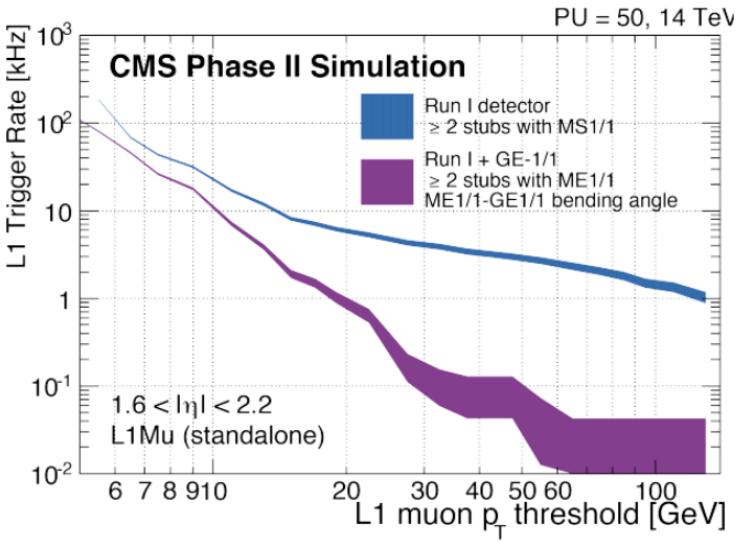
- Use outer tracker sensor doublets to trigger on high- p_T tracks
- Measure bending of particles in high B-field & filter data on-detector to select hit pairs from tracks with $p_T \gtrsim 2$ GeV
- Transfer to backend at 40MHz
- Different design options for track reconstruction in back-end electronics being studied



CMS HL-LHC Calo/muon Upgrades

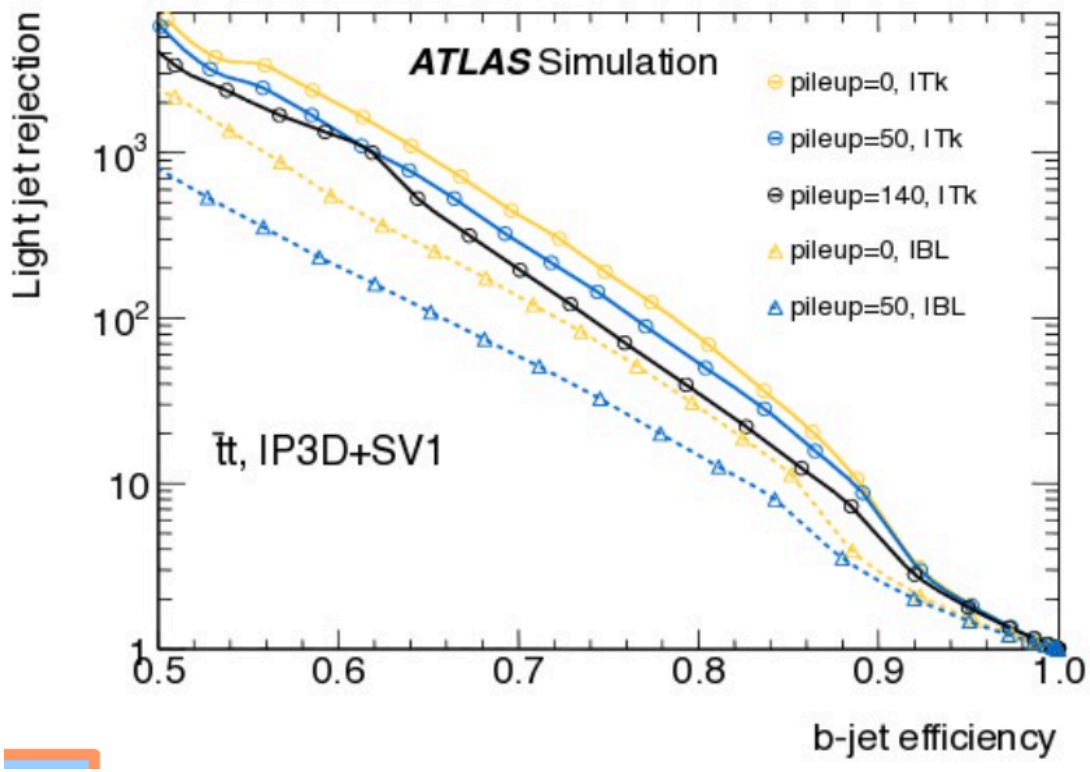
- Barrel calorimetry: New readout to provide full granularity to hardware trigger to improve isolation
- Forward calorimetry: will need replacement due to radiation-induced signal loss
  - New High Granularity Calorimeter using silicon sensors to allow detailed 4D (space-time) reconstruction of showers
- Improvements to Muon system
  - Electronics upgrades to comply with Trigger upgrade
  - iRPCs and GEMs in forward (1.6<|η|<2.4) region – enhanced redundancy and cope with higher rates
  - Very-Forward extension to higher η with GEMs – baseline 2.0<|η|<3.0

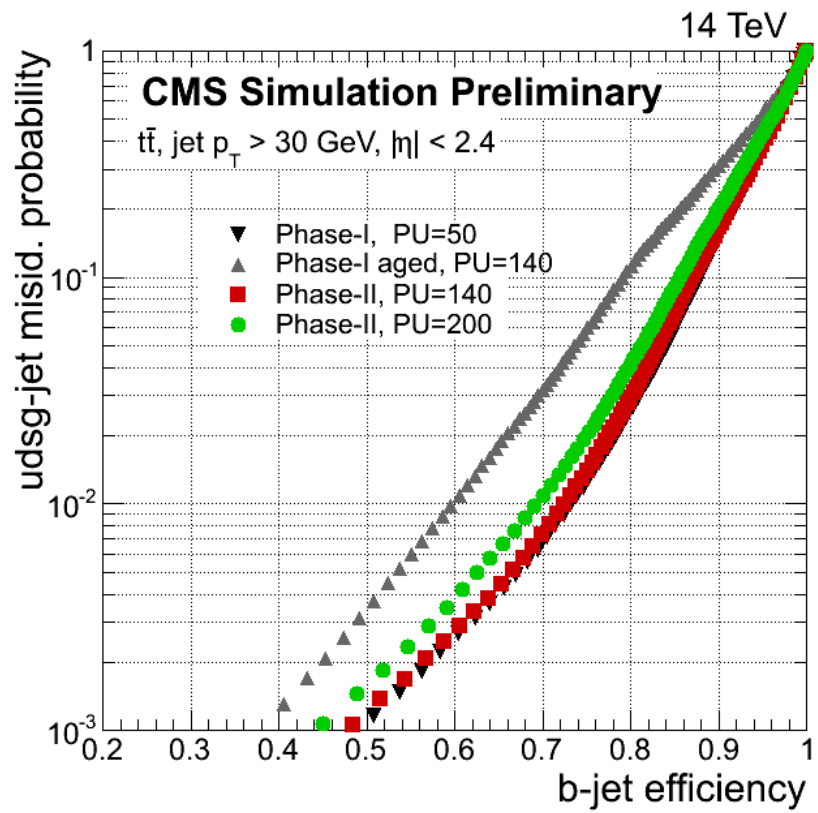




Performance: b-tagging

- The capability of tagging b-jets is critical to the success of the Higgs and search programs
  - Detector aging and high pile-up lead to higher mis-identification probability for fixed b-tagging probability
  - Phase 2 detectors recovering the b-tagging performance goals for Run 2



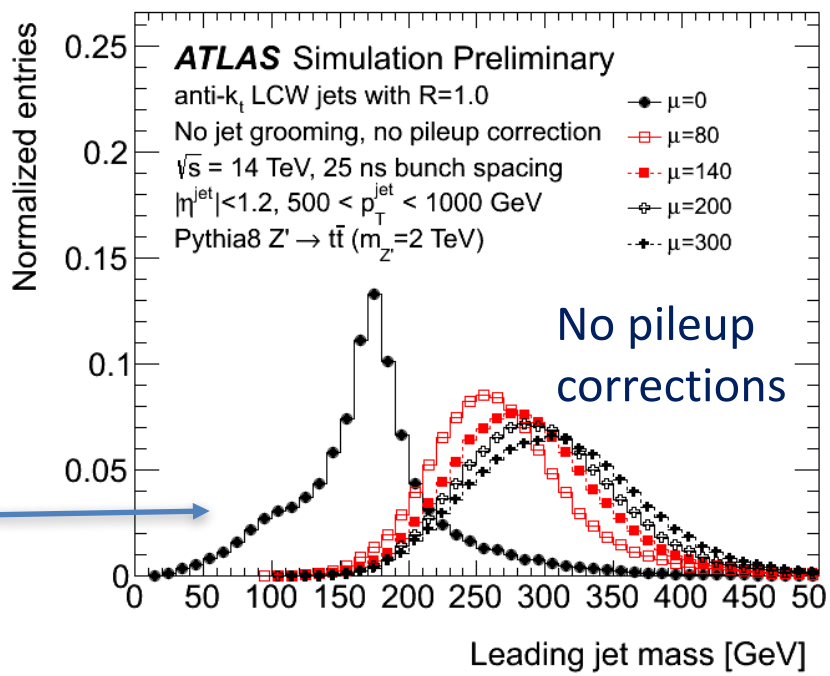


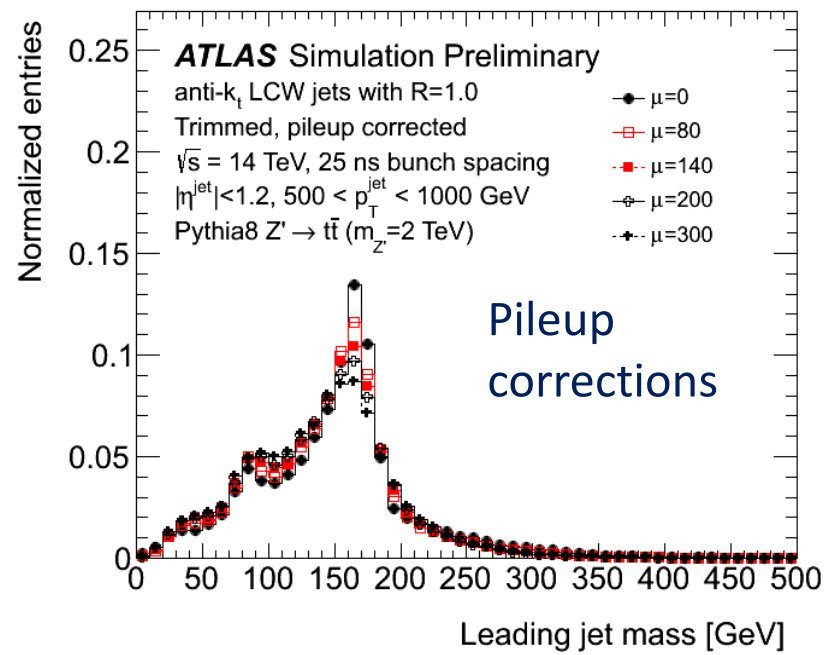
Performance: pileup mitigation

- Mitigation of pile-up effects and rejection of pile-up objects will be crucial to achieving optimum physics reach
- Timing information has proved promising as a way to mitigate pile-up effects in reconstruction
  - Feasibility of a dedicated timing detector being investigated
- Applying cuts on variables related to charged fraction helps reduce number of pile-up jets, as does requiring track-jet matching criteria

Pile-up corrections applied to restore scale and improve energy resolution

Z'→ ttbar





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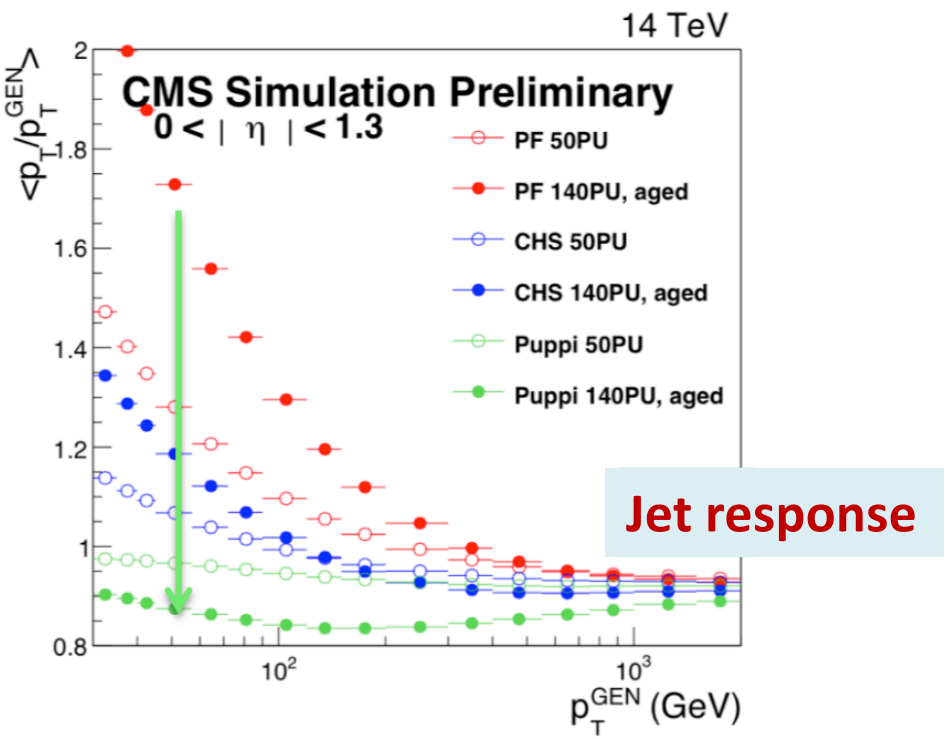

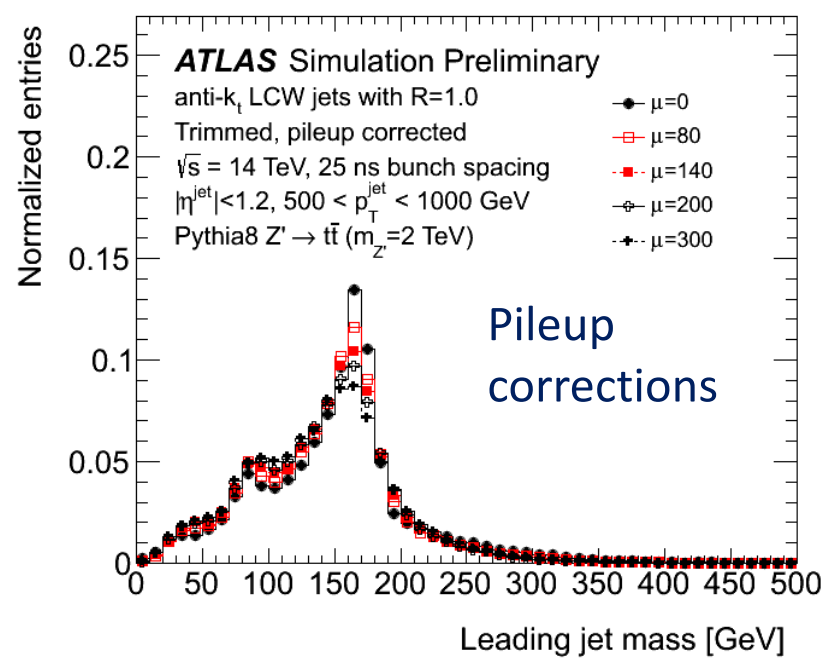

Beyond the LHC

Future colliders

- "Higgs factory" – a collider (most probably e+e-) with a center of mass energy 250 GeV and above and high luminosity [study the Higgs boson properties]
- "~100 TeV" pp collider to get to the "next energy frontier" an order of magnitude above LHC [study distances up to ~10^{-19} cm and particles masses up to ~50 TeV]
- Linear colliders:
  - **ILC : International Linear Collider [Japan]**
    - 500 GeV linear e+e- collider (upgradable to 1 TeV)
  - **CLIC: Compact Linear Collider [CERN]**
    - 380 GeV linear e+e- collider (upgradable to 3 TeV)
- Circular colliders:
  - **CepC : Circular Electron Positron Collider [China]**
    - ~250 GeV circular e+e- collider (the tunnel could be later used for pp collider)
  - **FCC: Future Circular Colliders [CERN]**
    - 90-350 GeV e+e- and/or ~100 TeV pp
    - HE-LHC**:** FCC-hh dipole technology (~16 T) in LHC tunnel → $\sqrt{s}$ ~ 30 TeV

Summary

- The LHC Run 1 and the ongoing Run 2 have been a fantastic success
  - We found a Higgs boson and set severe constraints on physics beyond the SM
- High Luminosity upgrade of the LHC offers huge potential to further explore the High Energy Physics landscape
  - Large gains in precision, discovery potential, and makes a number of important, low cross-section measurements possible
- Challenges presented by high pile-up necessitate extensive detector upgrades and use of advanced techniques for reconstruction and analysis
- Looking ahead, a number of collider possibilities are being studied
  - Will take precision to a new level and the search for new physics to a multi-TeV scale

Much more detail in parallel session talks!

References

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
- Slides at the CPAD15, ECFA16 and ECFA14 meetings that I borrowed from – thanks to the many speakers!