Physics with Upgraded CMS Detector

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Joint Experimental-Theoretical Seminar

Fermi National Accelerator Laboratory

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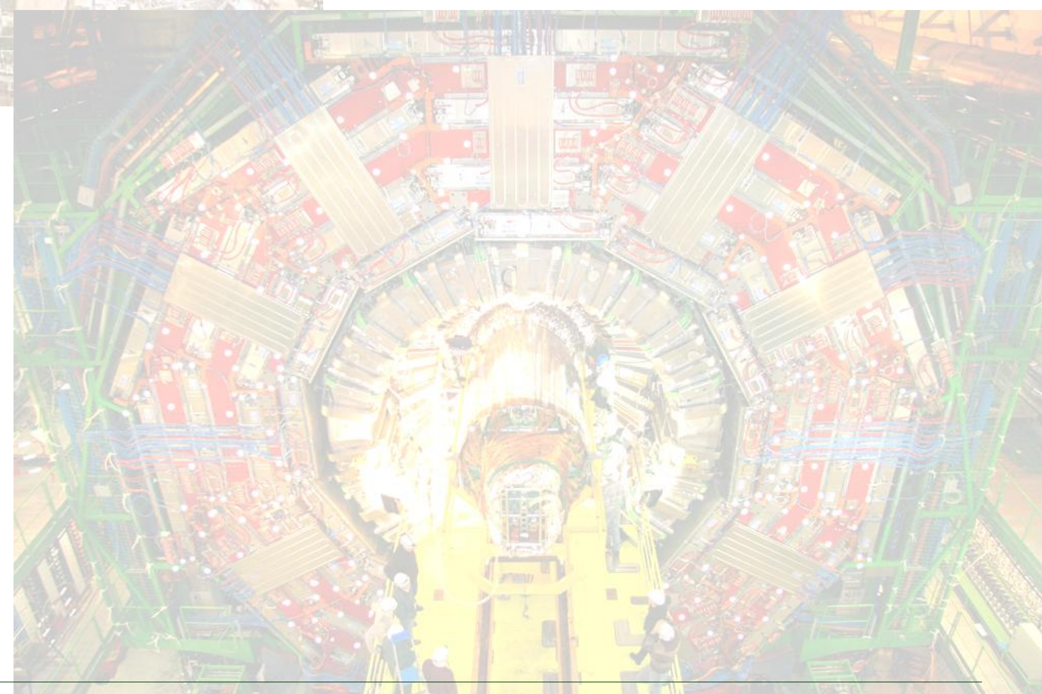
Current LHC Operation and CMS Performance

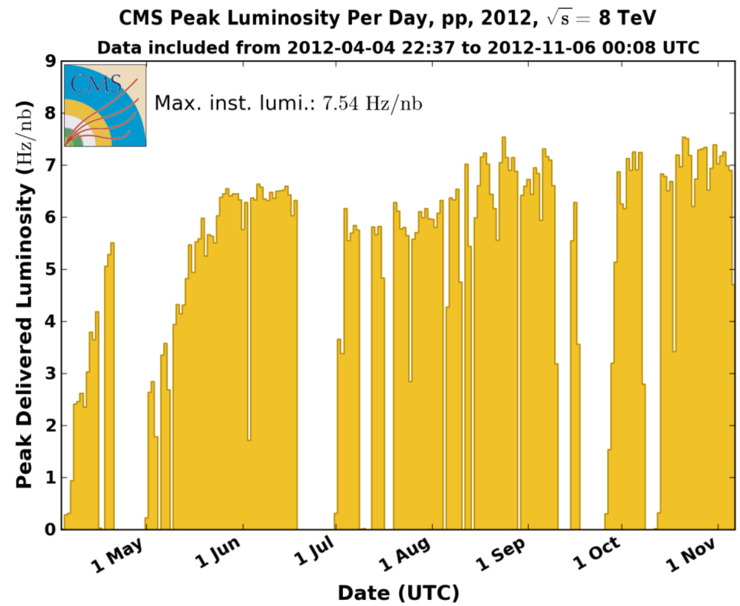


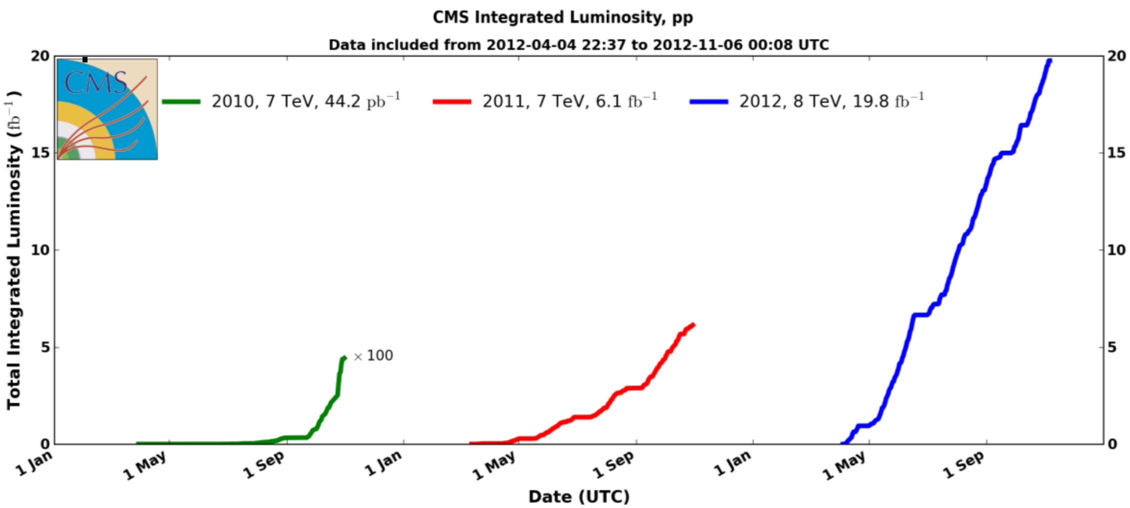
LHC and CMS Performance

The LHC has been performing extremely well.

Peak luminosity in 2012 is constantly 7×10^{33} Hz/cm^2 at 50 ns bunch crossing (~35 pileup pp interactions):

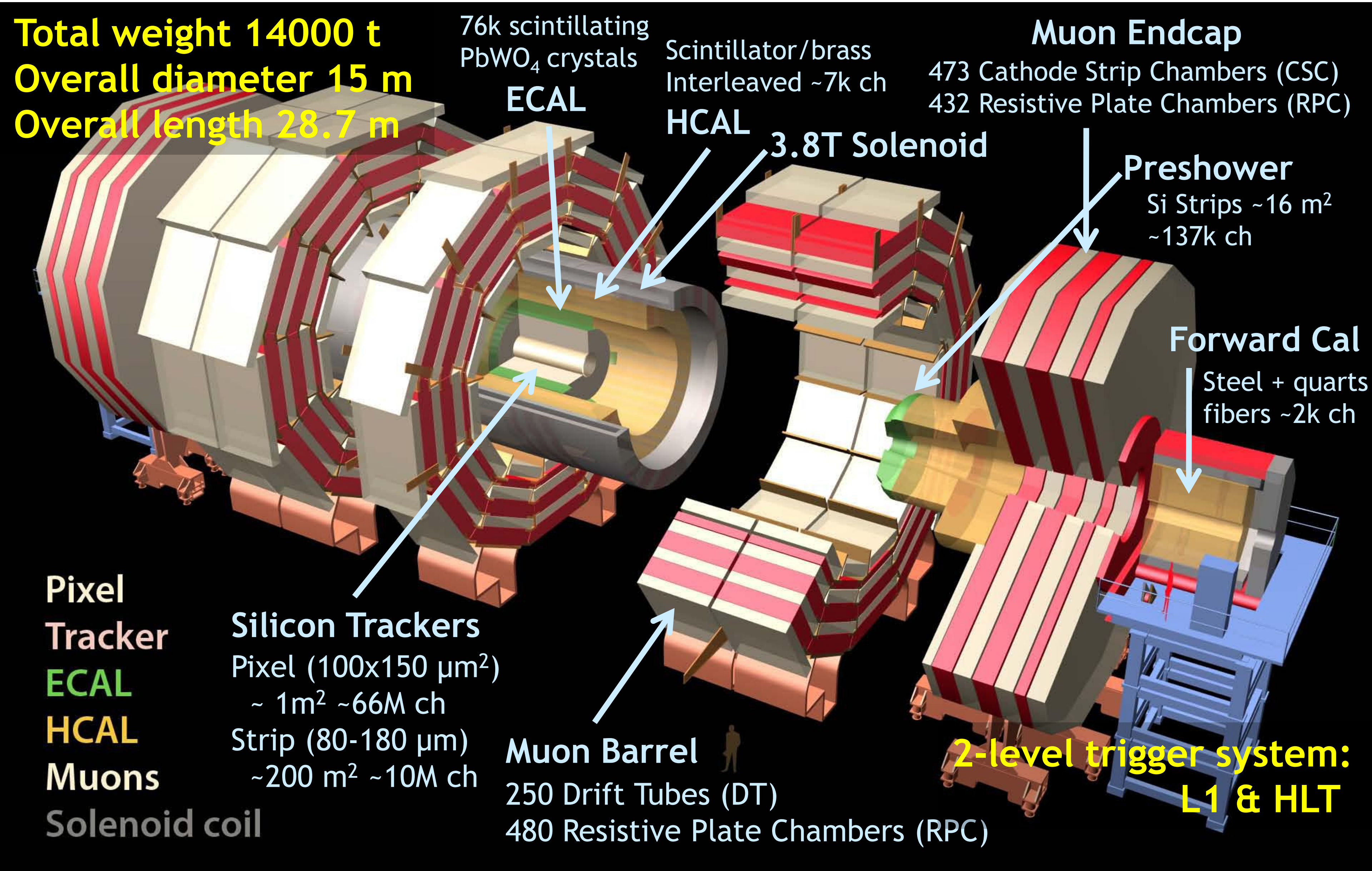
Expect 25-30 fb^{-1} by the end of the year





CMS too is performing extremely well in terms of operation efficiency (~95% up-time) and channels (~98% of detector readout)

CMS Detector Overview



Particle Flow Reconstruction

The PFlow algorithm is designed to:

- Reconstruct & identify all particles: γ, e, μ, charged & neutral hadrons, pileup, and converted photons
- Use a combination of all CMS subdetectors to get the best estimates of energy, direction, particle ID

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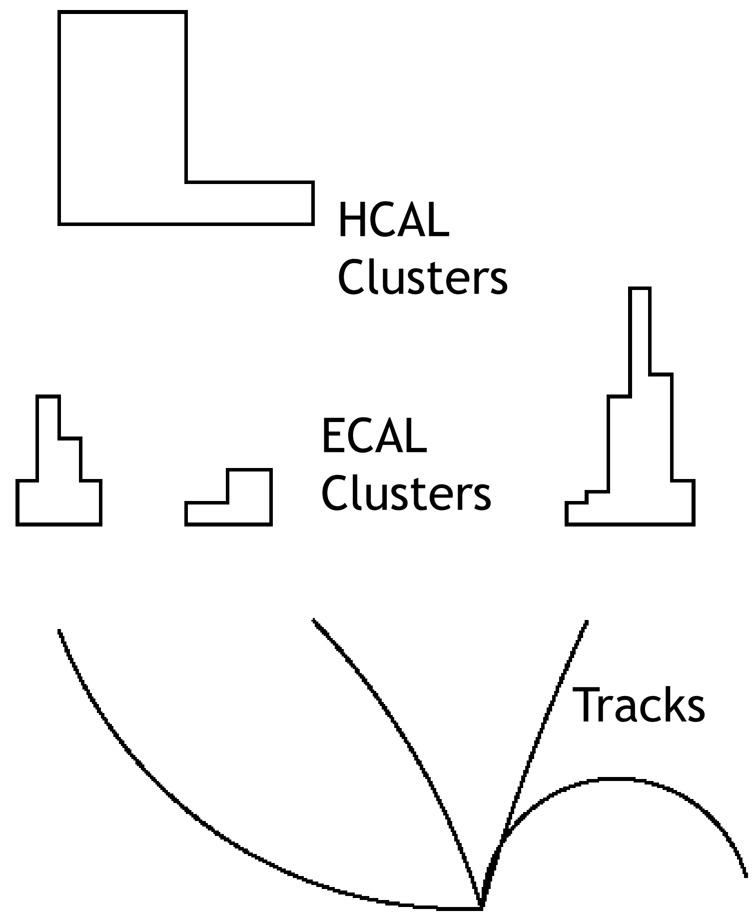

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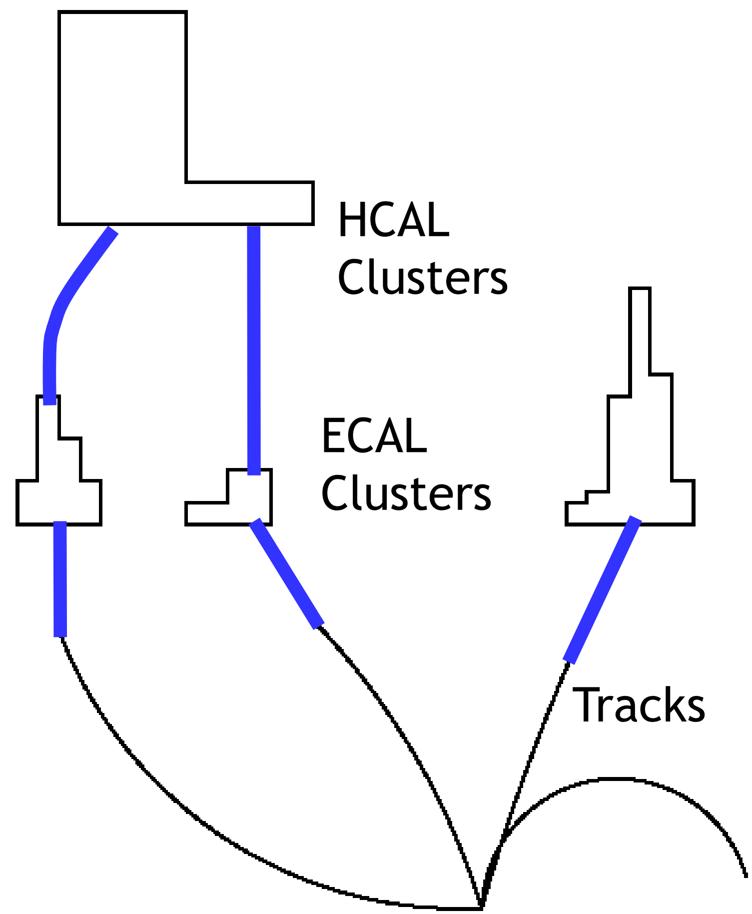
  2. Link across detectors



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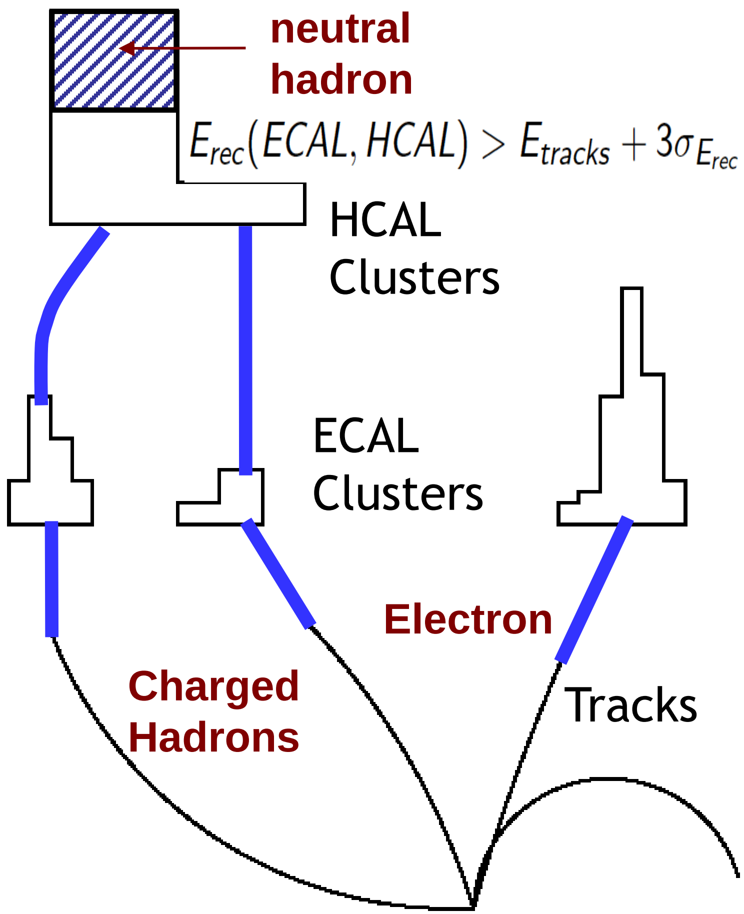
  3. Particle ID and separation



Particle Flow Reconstruction

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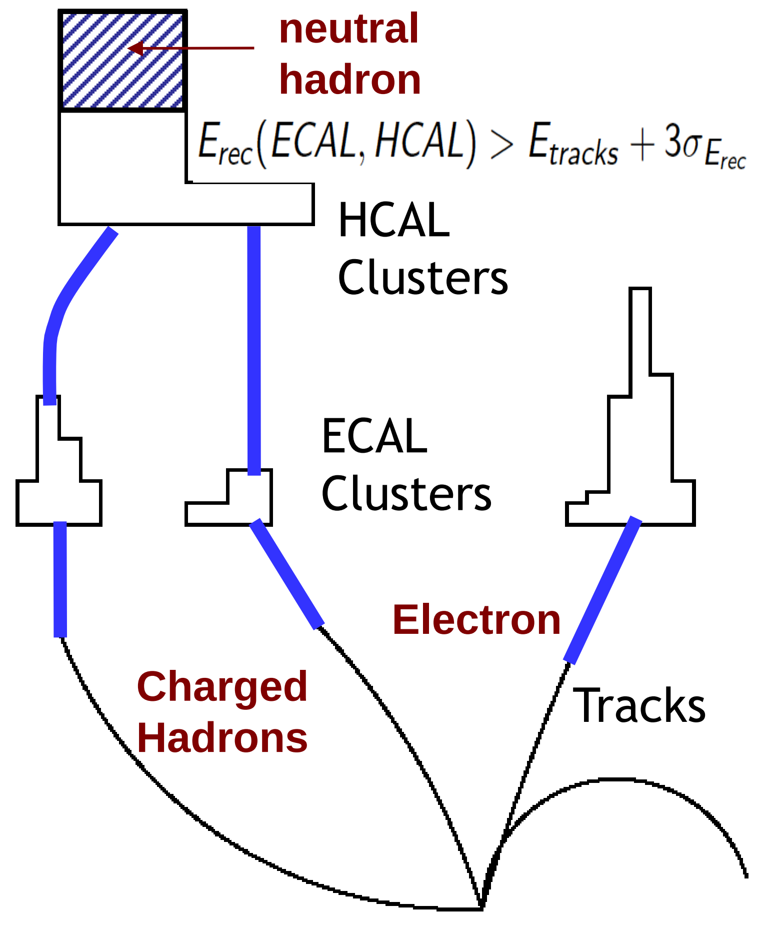
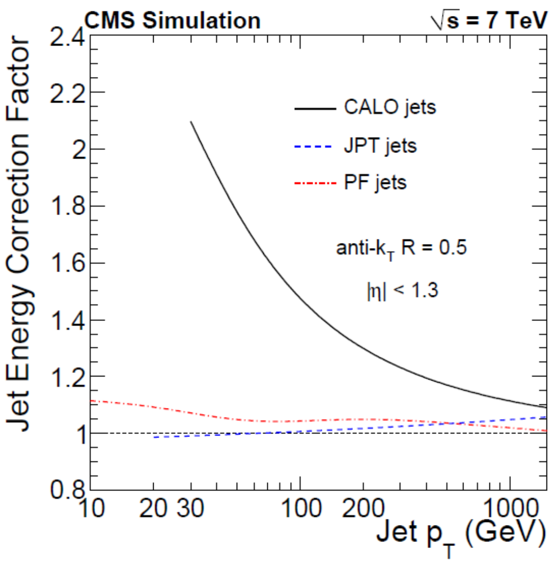
- Use a combination of all CMS subdetectors to get the best estimates of energy, direction, particle ID
  1. Associate hits within each detector
  2. Link across detectors
  3. Particle ID and separation
- Used in most CMS analyses



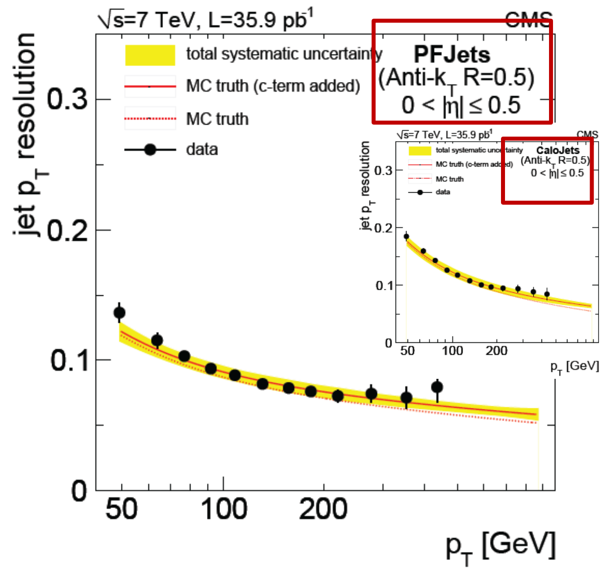
Particle Flow Jets & MET

- The benefit of particle flow reconstruction is readily visible in particular in jets and missing ET reconstruction.

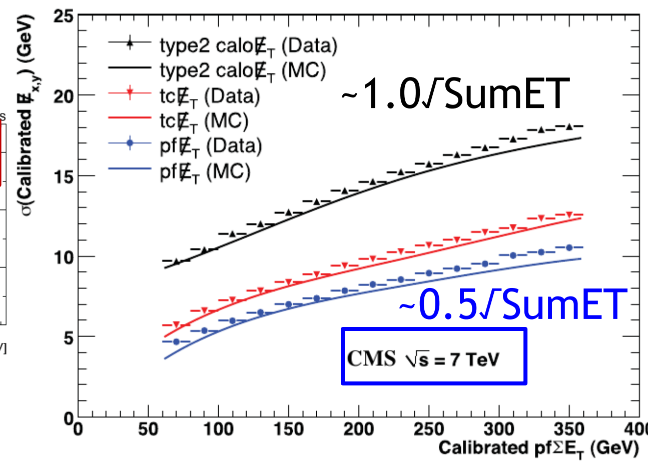
Jet correction



Jet resolution



MET resolution

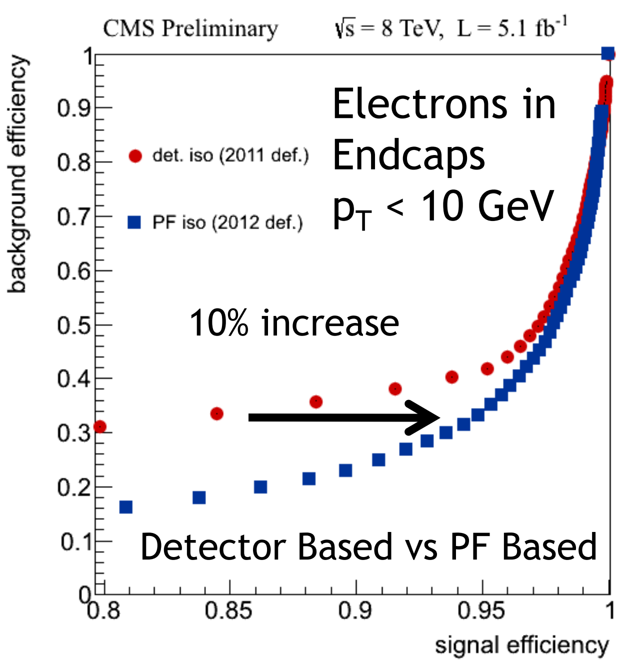


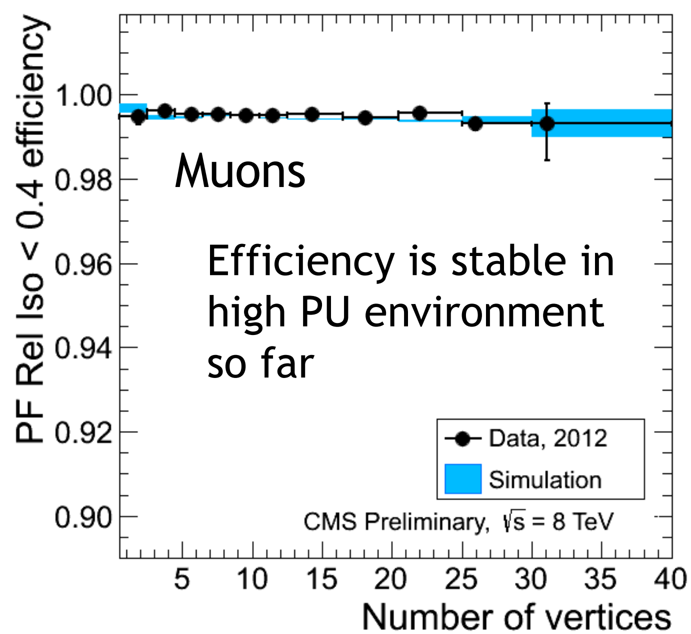
J. Instrum.6 (2011) P11002

J. Instrum.6 (2011) P09001

Particle Flow Isolation

- Created by summing energy deposits from individual particles in ΔR=0.4 cone around the lepton
  - Avoids double counting (track+calo) of the energy deposit in the calorimeters from charged particles
- Pileup contribution:
  - Negligible for charged hadrons from primary vertex
  - Neutral contribution corrected using the average energy density (ρ) from the pile-up and underlying event





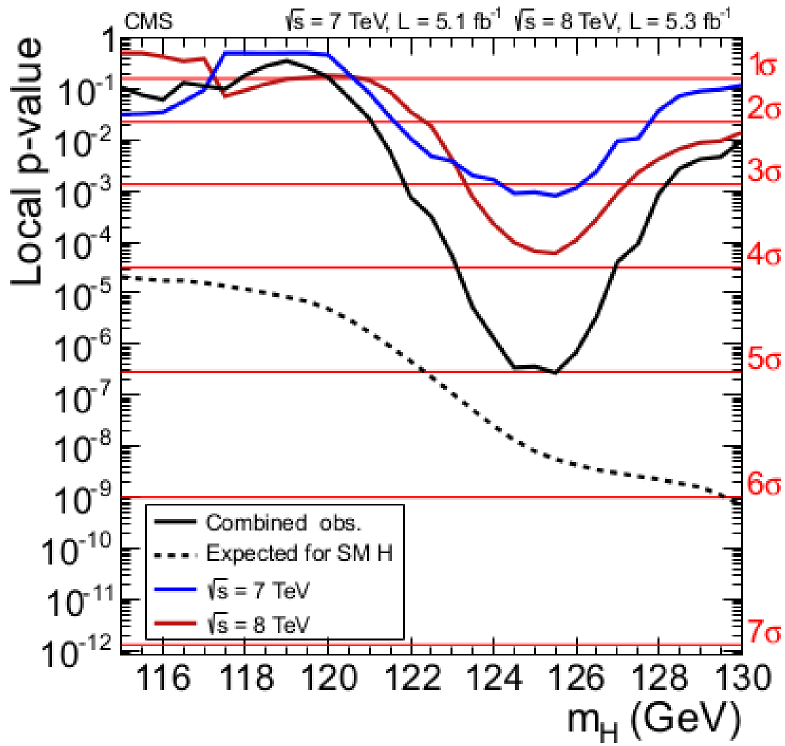
Recent Highlights

We Have It!

- Both CMS and ATLAS announced the discovery of the Higgs(-like) boson on July 4th, 2012!
- CMS combined local significance (γγ, ZZ, WW, ττ, bb)
  - 5.8σ expected
  - 5.0σ observed

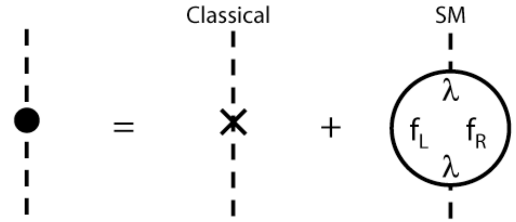
  Phys. Lett. B 716 (2012) 1-29
- ATLAS combined local significance (γγ, ZZ, WW)
  - 4.9σ expected
  - 5.9σ observed

  Phys. Lett. B 716 (2012) 30-61



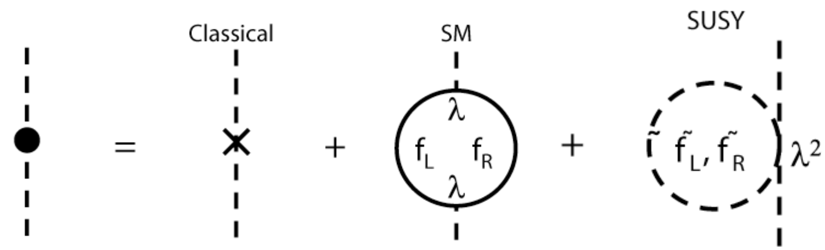
Fine Tuning & Supersymmetry

- The discovered new boson seems so far consistent with the SM Higgs boson, but now we are faced with an old problem: fine tuning



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

  - If there is no new physics beyond the SM below $\Lambda \sim 10^{18}$ GeV and SM is correct, there must be a tuning to a part in 10^{32}!
- Supersymmetry (SUSY) is a favorite solution



$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots$$

$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}) ,$$

  - Also offers a dark matter candidate, allows unification of gauge couplings
  - No experimental evidence so far

Inclusive Searches

- From the beginning of data taking, CMS deployed a series of inclusive searches to detect potentially-copiously-produced SUSY strong production
- Searches with different lepton categories
  - Different background (BG) compositions & less BG with more leptons
  - Different sensitivities to a variety of SUSY scenarios

All hadronic	Single lepton	OS dileptons	SS dileptons	Multileptons
• QCD • $Z \to \nu\nu$ • W+jets • ttbar	• W+jets • ttbar	• Z+jets • ttbar	• ZZ/ZW/WW • ttZ/W • Rare SM • ttbar	• ZZ/ZW/WW • ttZ/W • Rare SM

← More signal rate/more BG

Smaller rate/more BG control →

  - Very challenging due to large amount and wide ranges of backgrounds
  - However most sensitive search for strongly-produced SUSY particles

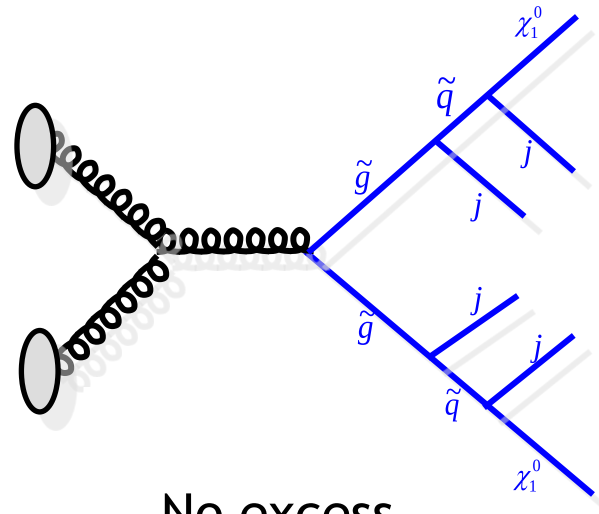
Hadronic Search in Jets + MET

Event selection

- Search variables:

$$H_T = \sum_{\mathrm{i}}^{\mathrm{jets}} |\vec{p}_{\mathrm{T,i}}|, \quad MH_T = \left| \sum_{\mathrm{i}}^{\mathrm{jets}} -\vec{p}_{\mathrm{T,i}} \right| .$$

- ≥3 jets with |η|<2.5, p_T>50 GeV
- Veto isolated e/mu
  - Suppress W & Top BGs
- Δφ(MHT,j1,2,3) > 0.5,0.5,0.3 (rad)
  - Suppress QCD background

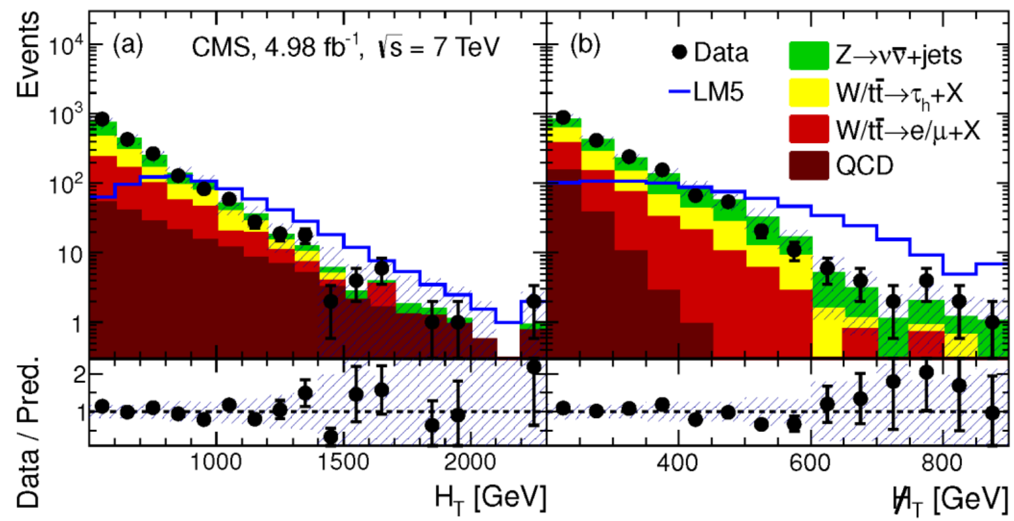


No excess

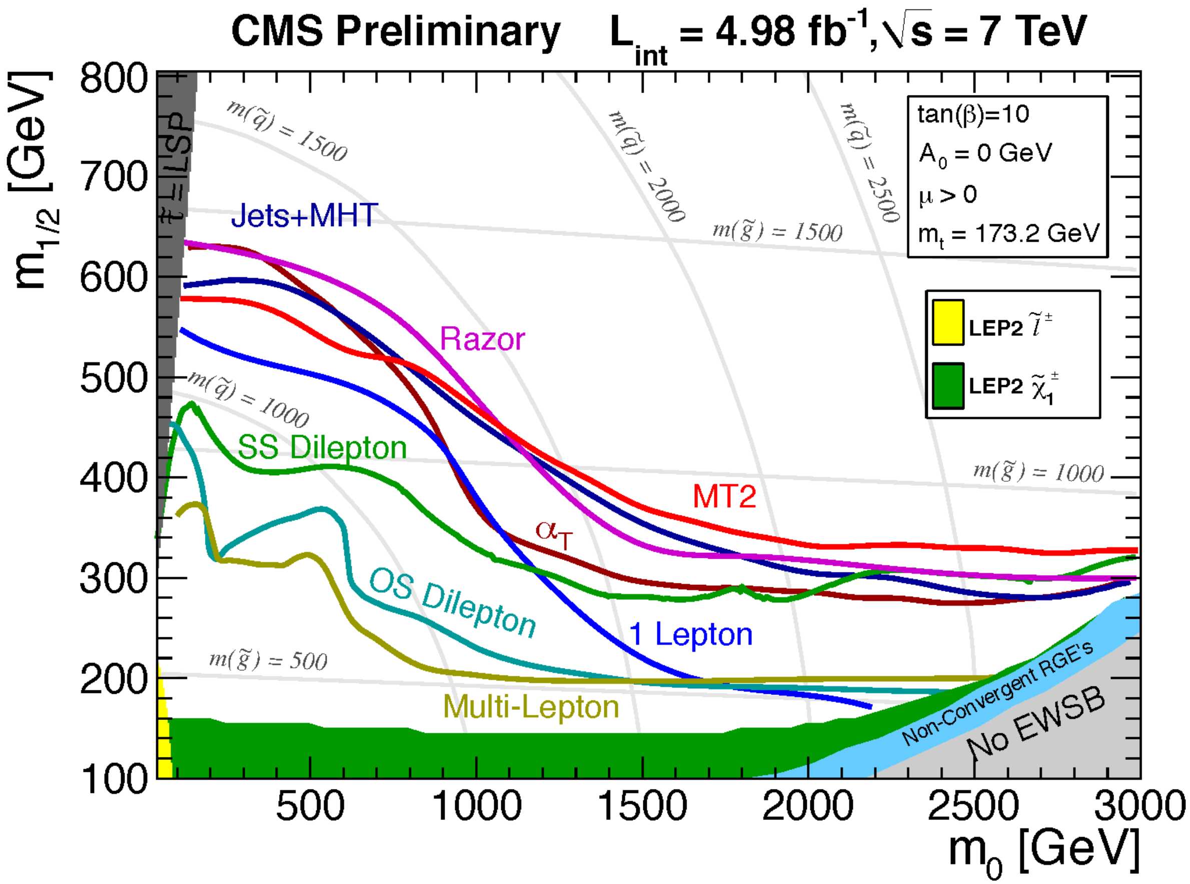
Backgrounds

- QCD
- Top & W+jets
- Z(→νν)+jets

Determined by data-driven techniques



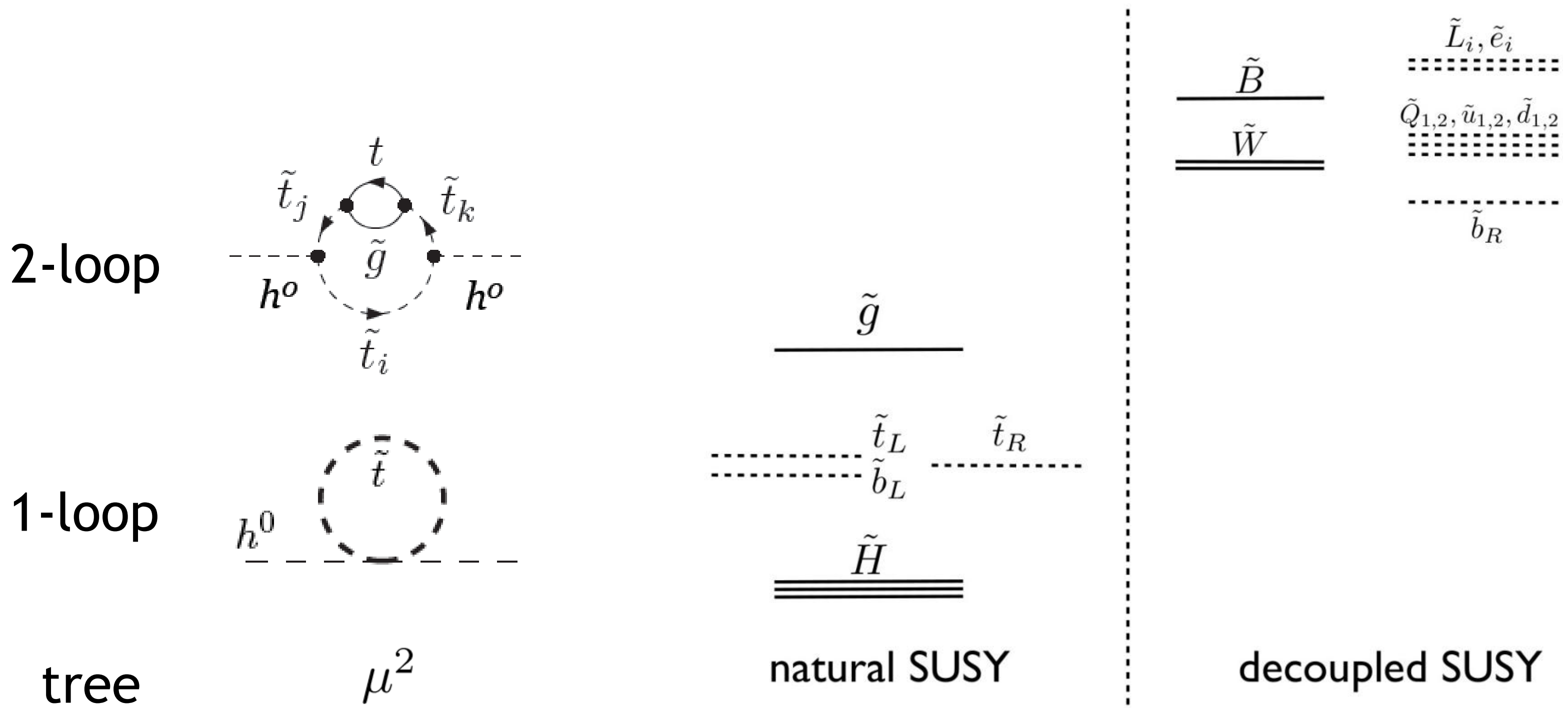
CMSSM Summary



- Impressive variety of inclusive model-independent SUSY searches
- Probing already 1 TeV mass scale and beyond for squarks or gluinos (with some assumptions, and not including stop/sbottom production)

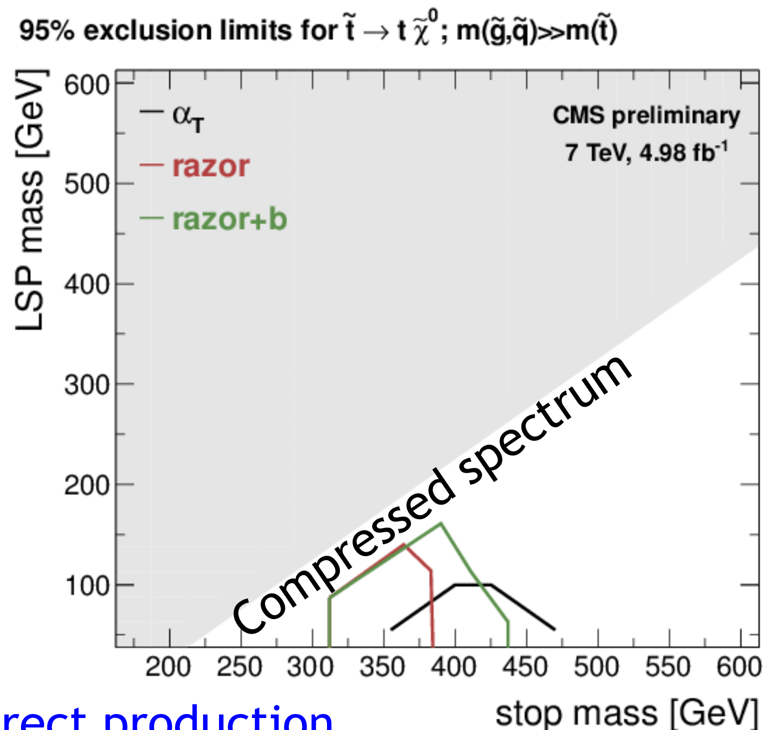
Natural SUSY

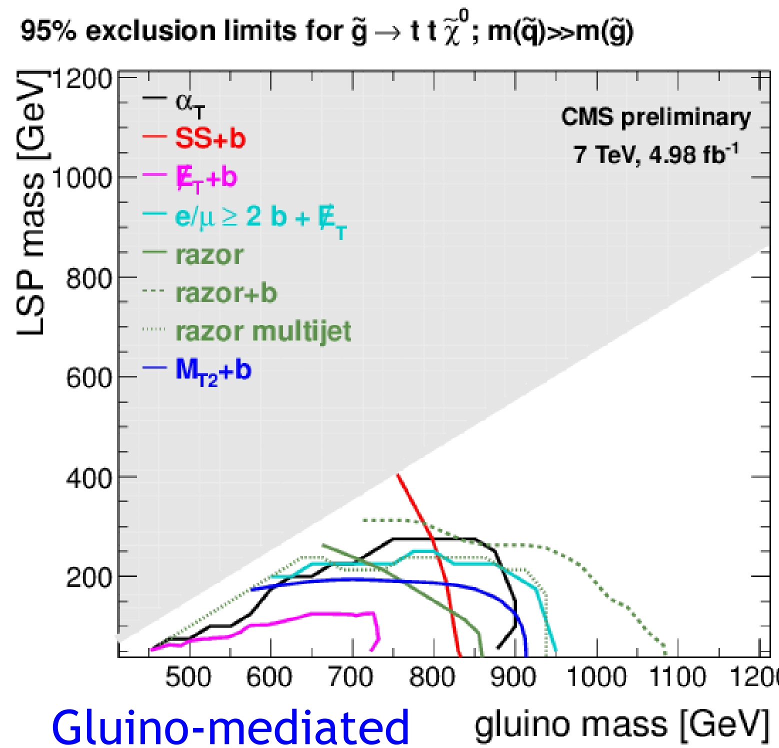
- Renewed focus on minimal SUSY requirements to protect Higgs mass, which motivates searches for scalar top/bottom quark & light gauginos/higgsinos: EWKinos and stops/sbottoms might be accessible with the current LHC



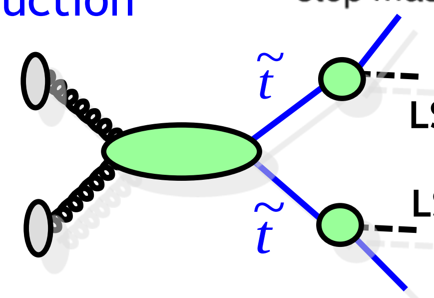
Papucci, Ruderman, Weiler, arXiv:1110.6926

Limits on Stop Production

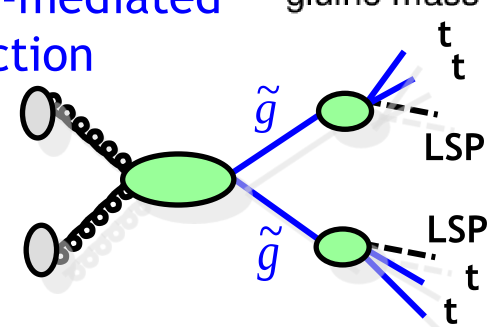




Direct production



Gluino-mediated production

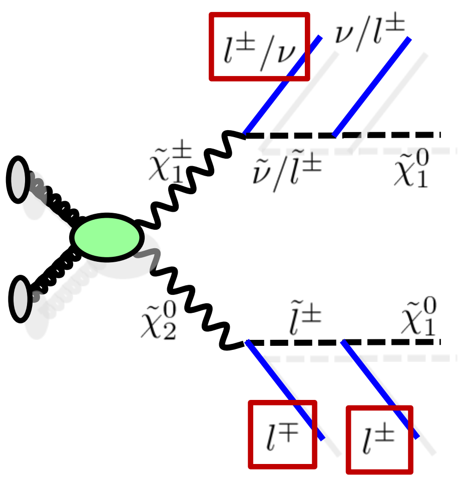


More dedicated searches in the pipeline

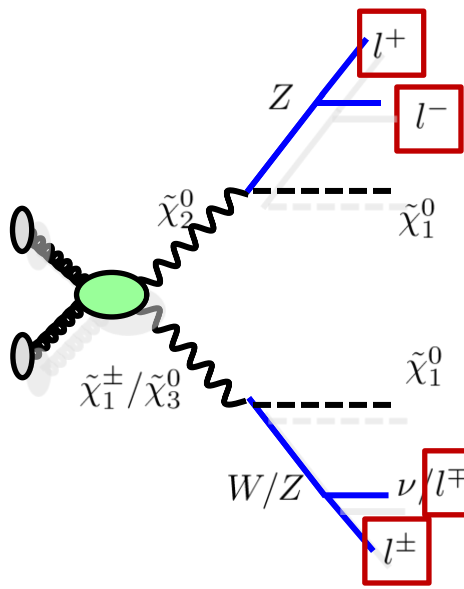
Direct Chargino/Neutralino Searches

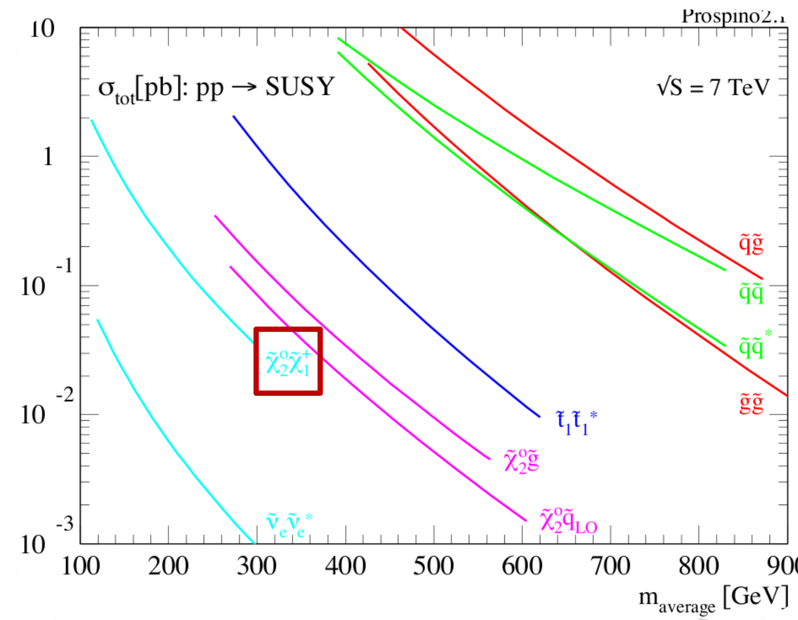
- Mass limits on gluinos and squarks have been pushed higher and higher. Direct production of gaugino may be dominant SUSY production at the LHC.
- Typical signature: multiple leptons + MET

Decays to sleptons



Decays to W/Z

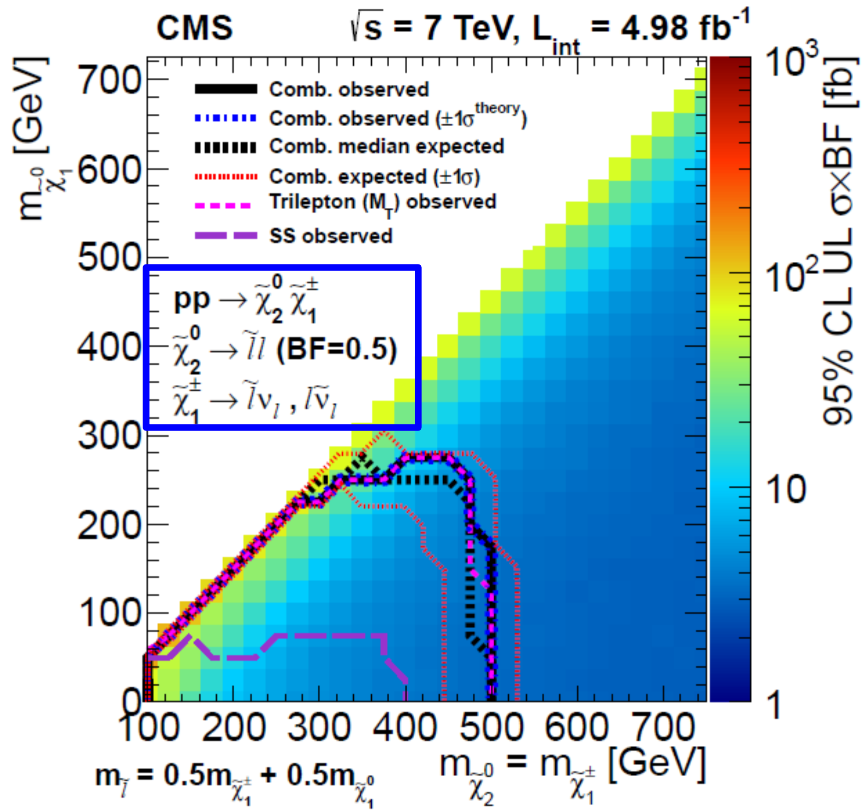


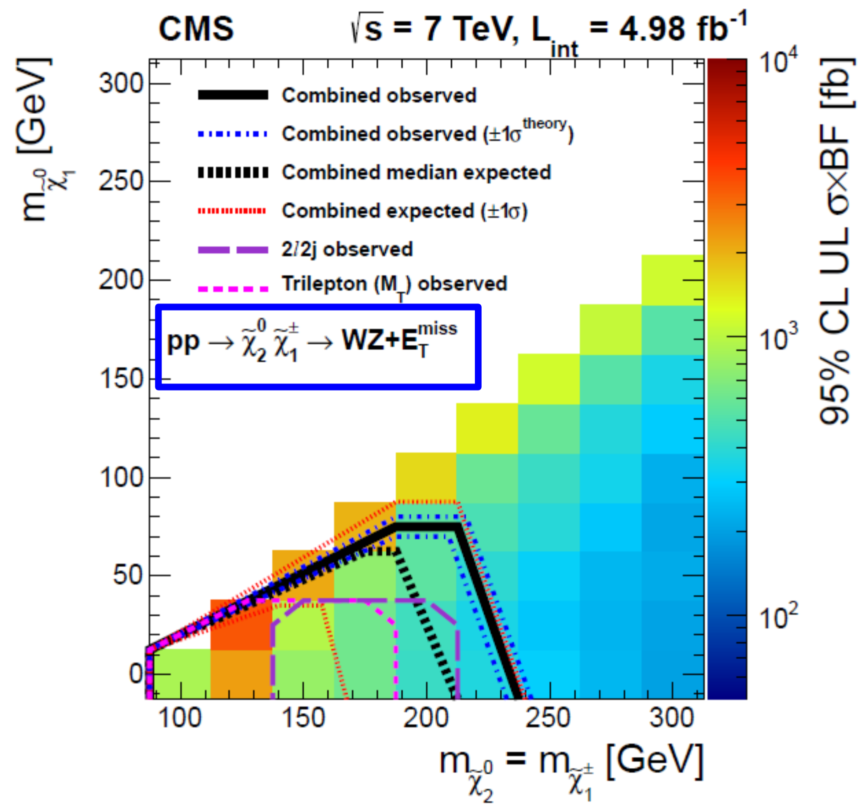


(slepton mass too heavy)

CMS-SUS-12-006, arXiv:1209.6620

Direct Chargino/Neutralino Searches





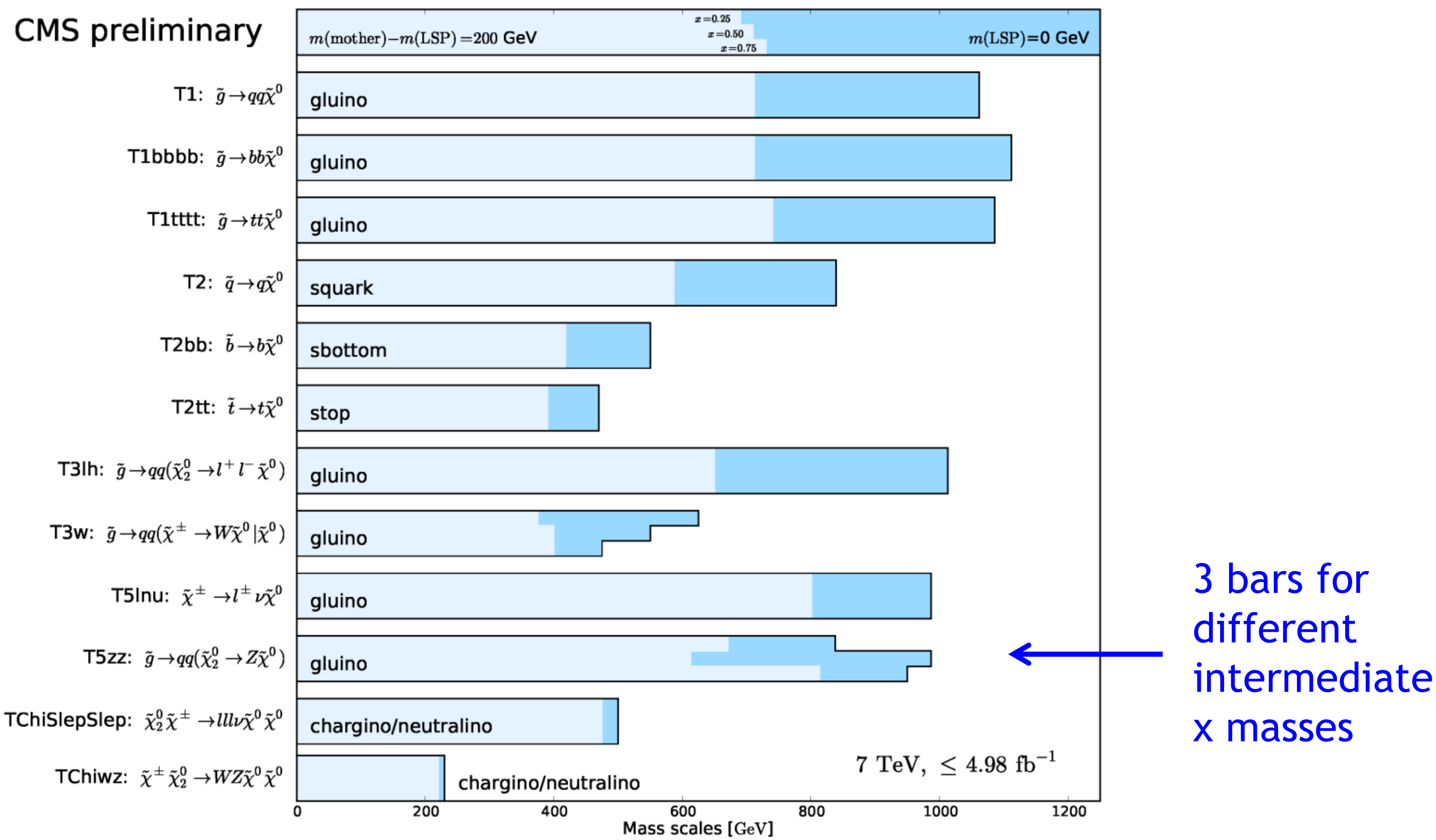
Limits are weaker for

- ☐ heavy $slepton_L$
- ☐ $\tilde{\chi}_2^0\tilde{\chi}_1^+$ being Higgsinos
- ☐ small mass difference (compressed spectra)

100% branching fraction is assumed: unlikely to be true in nature

Quoted mass limits are only under a simplifying assumption

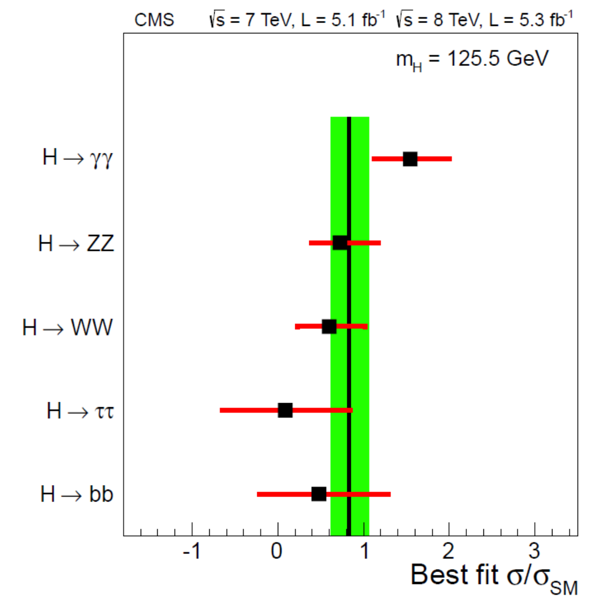
CMS SUSY Search Summary



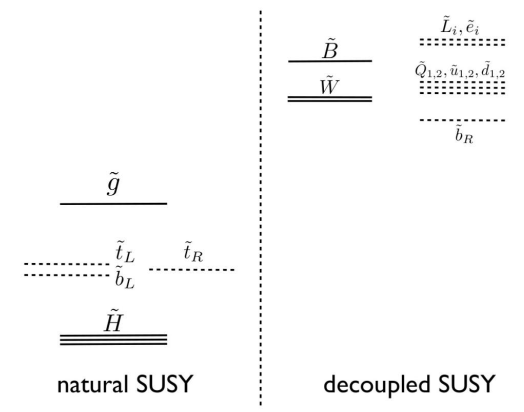
- ~1 TeV scale limits on light squarks & gluinos
- Up to ~500 GeV for top/bottom squark and charginos/neutralinos
  - Limits often strongly depends on M(LSP), still large phase space to cover

What's Next?

- Characterize the Higgs-like particle
  - Cover all possible production and decay channels
  - Measure Higgs signal strength and coupling
  - Precise mass determination
  - Measure J^{CP}
    - spin-0? spin-2? (spin-1 is already excluded)
    - scalar? pseudo-scalar?

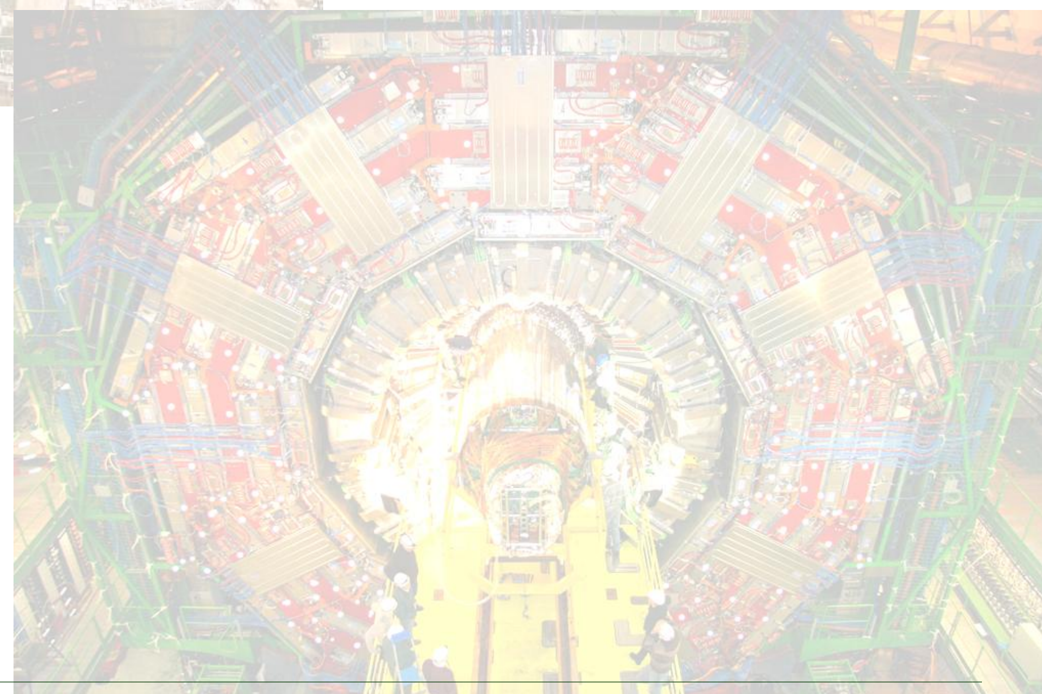


- Keep searching for supersymmetry and other BSM models
  - Particularly the signature which connects to the model that address the fine tuning problem!?

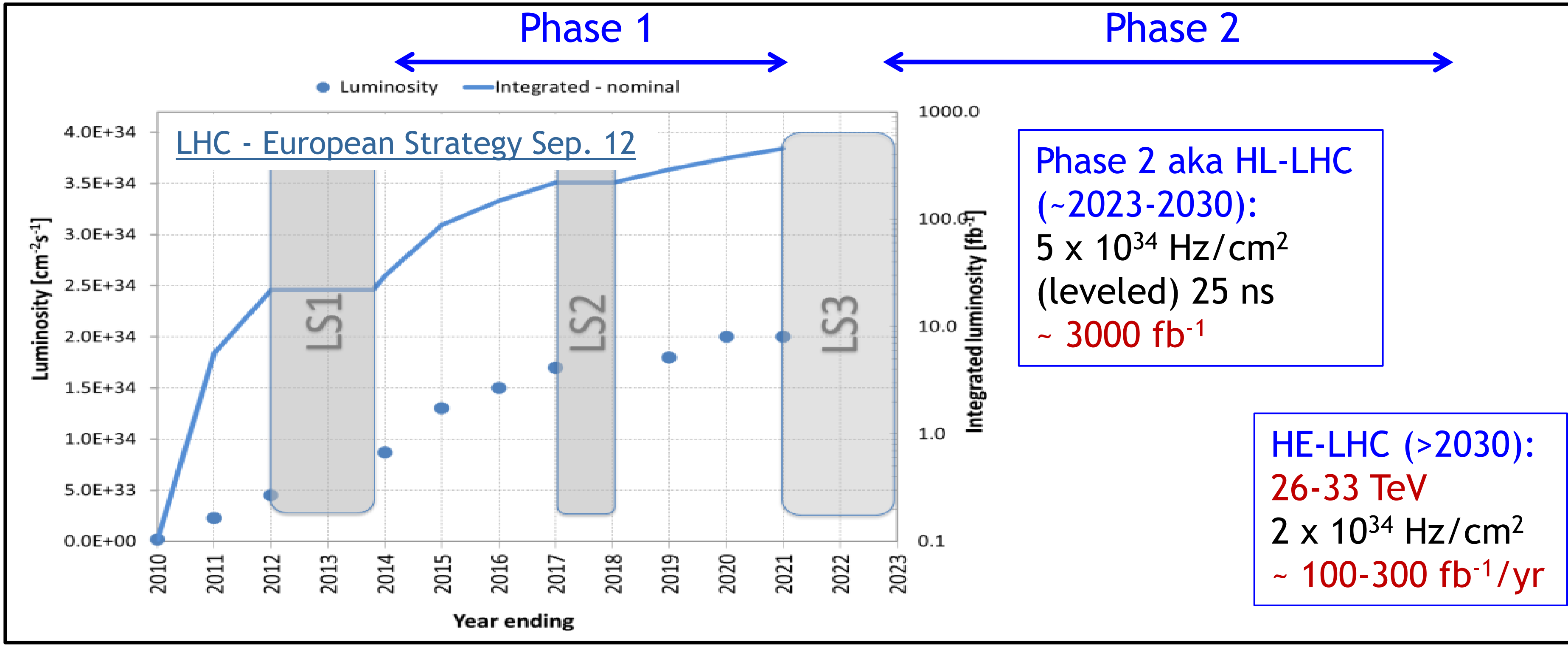


- And many other things…

LHC Projections & Pileup



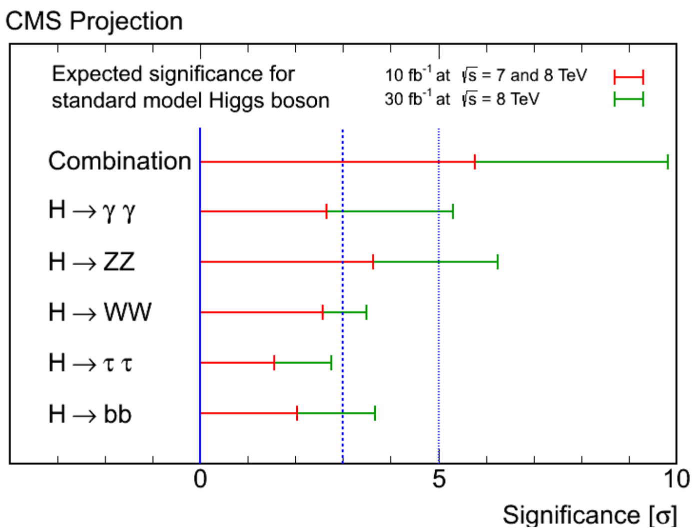
LHC Evolution

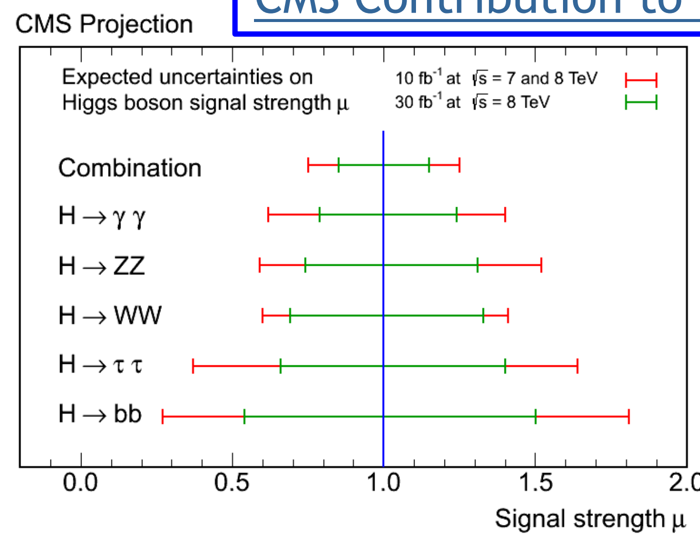


- 2012: ~25-30 fb^{-1} by LS1 @ 8 TeV
- LS1-LS2 baseline: 0.8→1.7 x 10^{34} Hz/cm^2 at 25 ns. ~200 fb^{-1} by LS2 @ 13-14 TeV
  - Alternative with 1.8 x10^{34} Hz/cm^2 at 50 ns with lumi-leveling. Easier to commission but no prospect for higher integrated luminosity without upgrades
- After LS2 injection chain upgrades: 25 ns will allow ≥ 2 x 10^{34} Hz/cm^2 and ~500 fb^{-1} by LS3

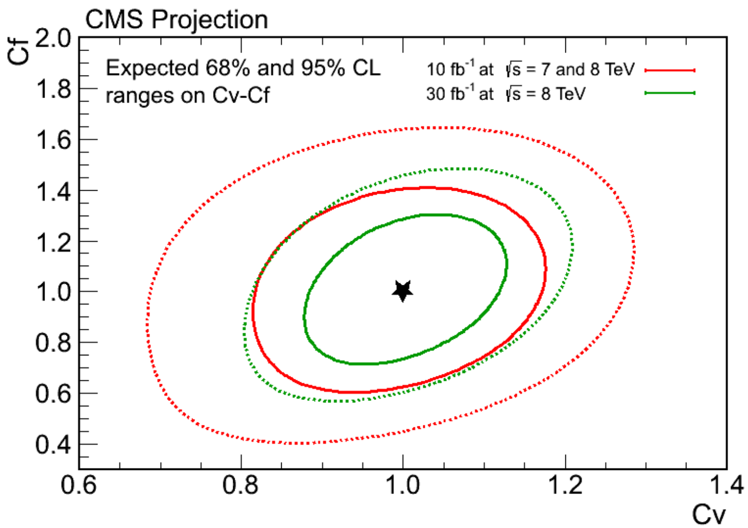
Higgs Projection for 2012

CMS Contribution to ESPG



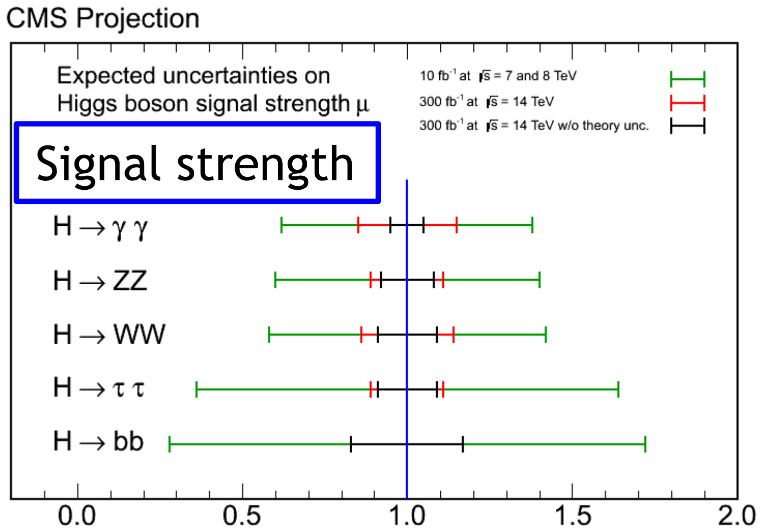


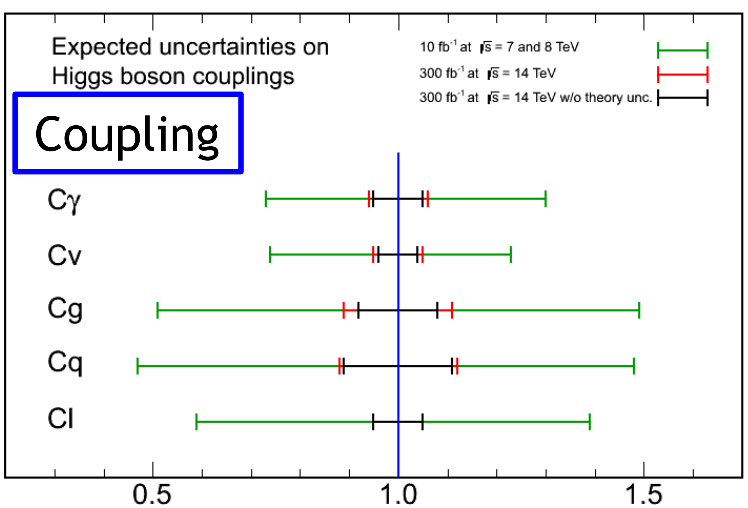
Expect >3σ
in most of channels



15% unc. on
signal strength
(combined)

Higgs Projection for 300@fb^{-1}





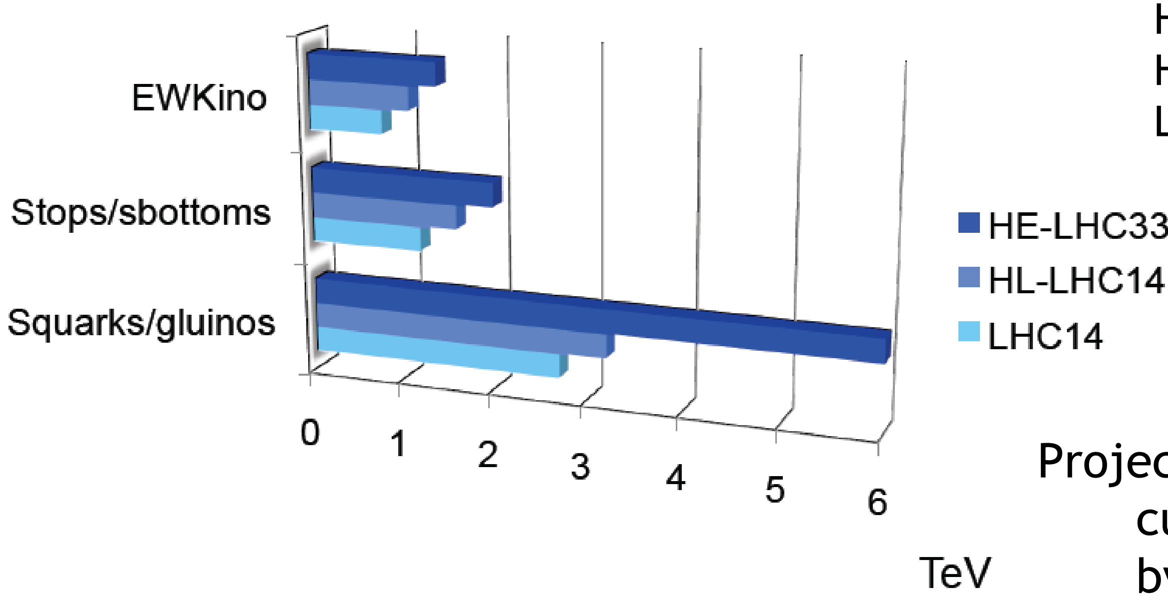
[CMS Contribution to ESPG]

Projection produced by scaling current 7/8 TeV Higgs analyses by cross section and luminosity

- ☐ Signal strength: ~10-15% unc.
- ☐ Coupling: 5-15 % unc.

for each channel @ 300 fb^{-1}

SUSY Projection for 300&3000 fb^{-1}



HE-LHC 300 fb^{-1} @ 33 TeV
HL-LHC 3000 fb^{-1} @ 14 TeV
LHC14 300 fb^{-1} @ 14 TeV

Projection produced by scaling current 7/8 TeV SUSY searches by cross section and luminosity

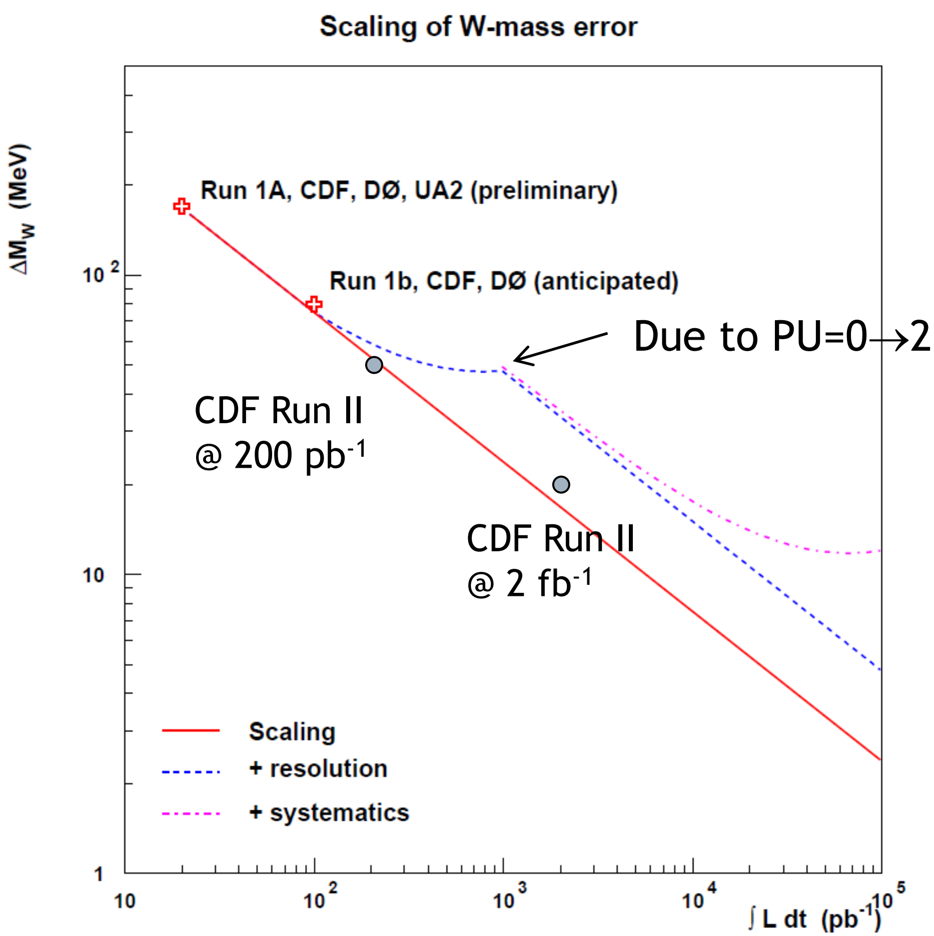
[CMS Contribution to ESPG]

Note: 125 GeV Higgs may suggest to multi-TeV SUSY mass spectrum
Need high luminosity and/or high energy LHC running to explore that region(!?)

Also, the sensitivities for compressed SUSY mass spectrum are much worse

Projection with Scaling?

Tevatron W Mass Measurements



- Is it reasonable to do a projection by scaling based on cross section and luminosity?
- The TeV2000 study group for future EWK physics attempted to project from 20 pb^{-1} to 100 pb^{-1} and beyond
- Simple luminosity and cross section may reasonably hold!?

  We are talking about PU~100.

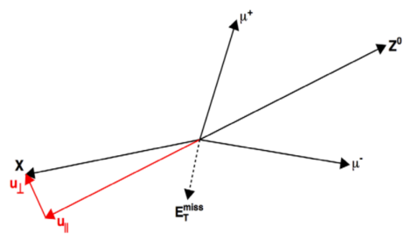
  The detector needs to be significantly upgraded.

Note: Tevatron experiments had a significant upgrade from Run 1 to Run 2

Degradation with Pileup

MET Resolution from Z(→μμ)+Jets:

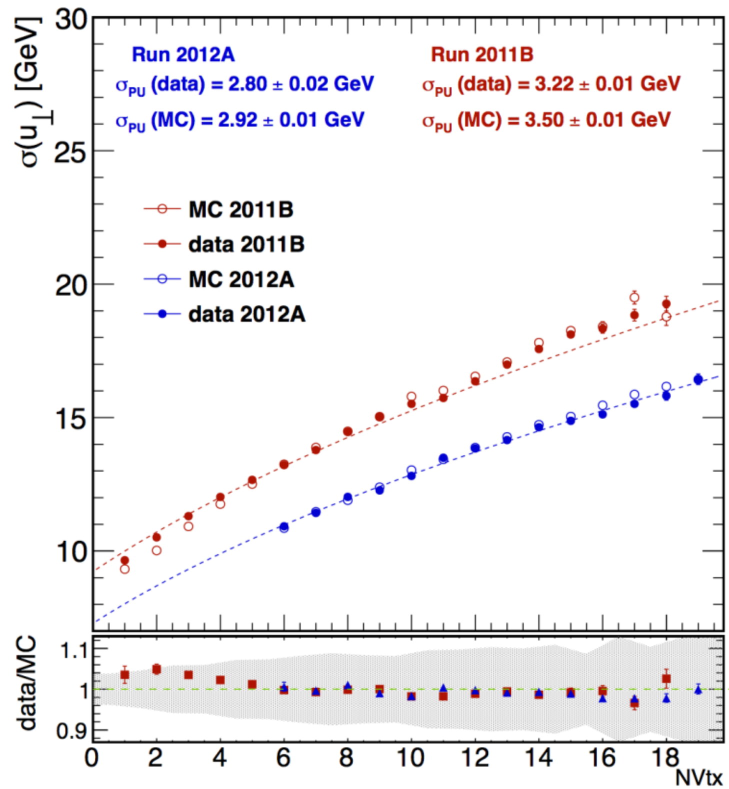
- Use dimuon p_T as a MET probe



- Clear pile-up dependence: σ_{PU}~3 GeV

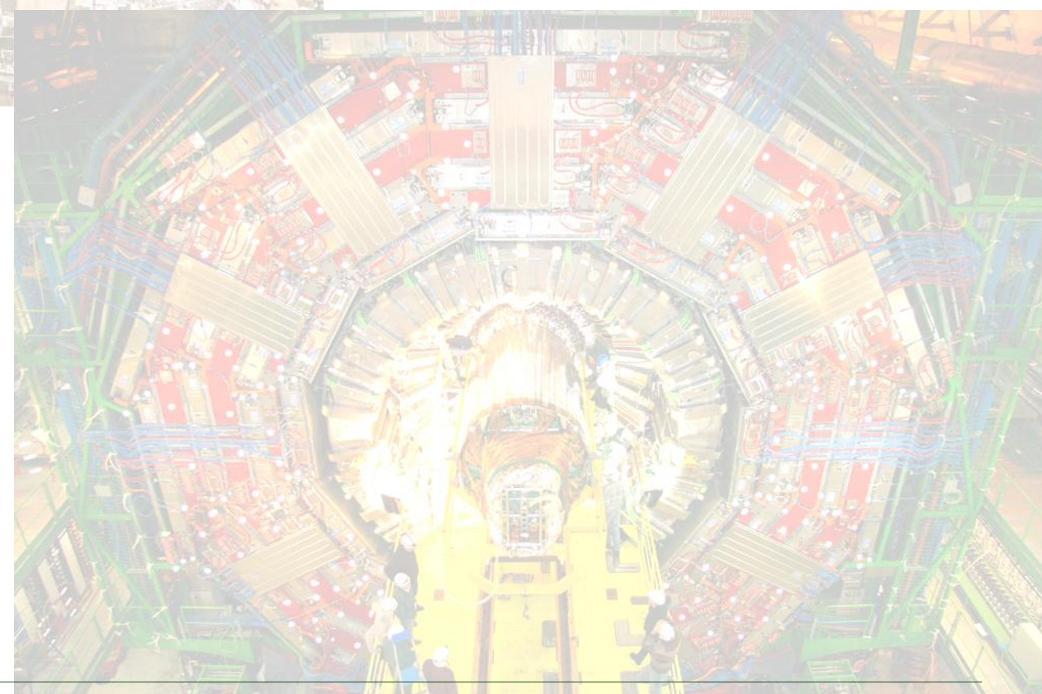
$$\text{Fit function} = \sqrt{c^2 + \frac{N_{\text{vtx}}}{0.7} \cdot \sigma_{\text{PU}}^2}$$

- Reduced pileup sensitivity in 2012 by
  - reducing # of HCAL time samples (100 ns → 50 ns)
  - applying timing cut on ECAL endcap in addition to barrel
  - alignment corrections etc



Pileup also deteriorates jet resolution, lepton/photon isolation, ID, b-tagging etc

CMS Upgrade & Physics Impacts

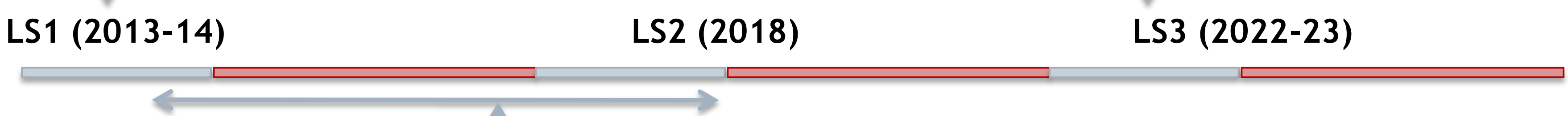


CMS Upgrade Overview

LS1 Projects: in production
- Completion of muon coverage (ME4)
- Improve muon operation (ME1), DT electronics
- HCAL: HF (new PMTs) and HO (SiPM)

Phase 1 “Preperation Work”
- Beampipe for pixel upgrade
- Splitters for parallel trigger development
- HF backend electronics (Phase 1)
- Interim L1-Trigger upgrade (Phase 1)

Phase 2 Projects: scope to be defined in 2013-2014
- Tracker replacement, track trigger
- Forward calorimetry and muons?
- Further trigger upgrade?



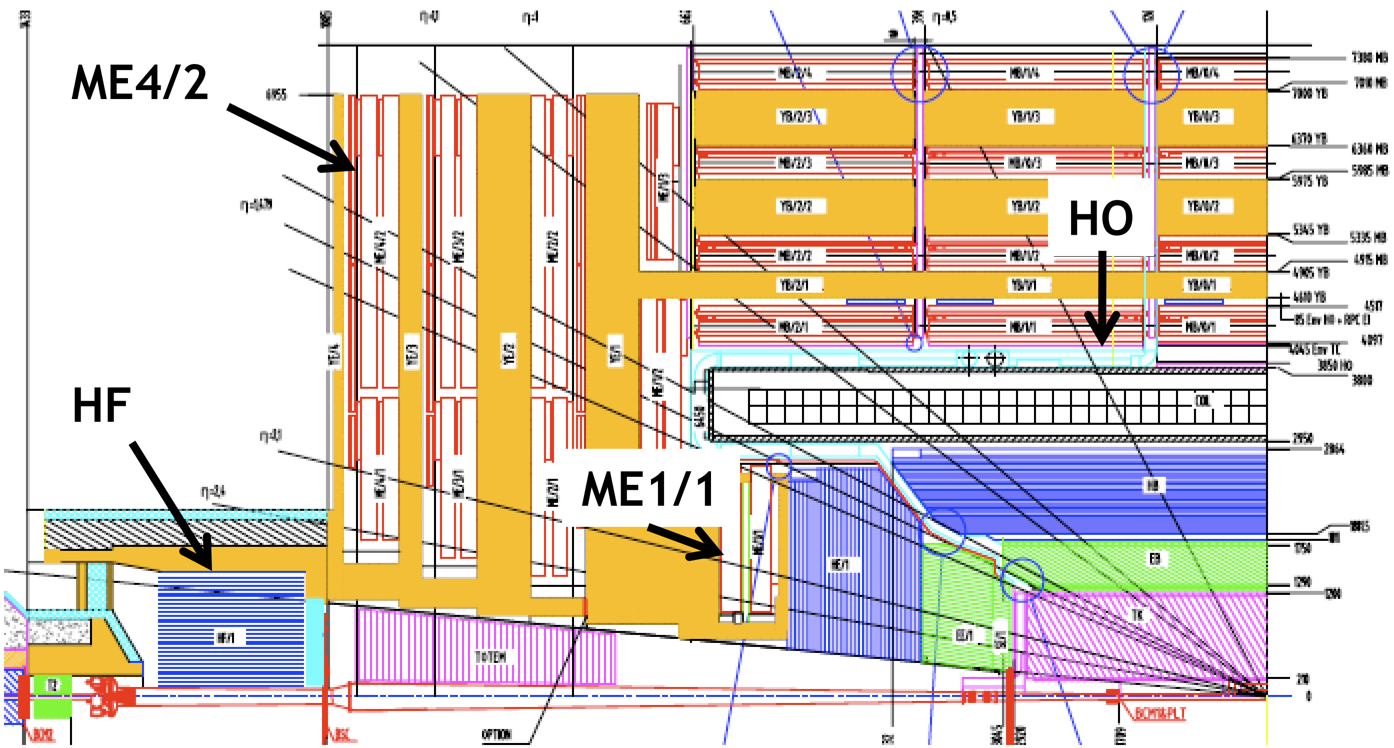
Phase 1 Upgrades: TDRs
- Pixel detector replacement
- HCAL electronics upgrade
- L1-Trigger upgrade

- Pixel and HCAL TDRs approved by LHCC September 2012
  Pixel: http://cdsweb.cern.ch/record/1481838/files/CMS-TDR-011.pdf
  HCAL: http://cdsweb.cern.ch/record/1481837/files/CMS-TDR-010.pdf
- L1-Trigger will be early 2013

LS1 Project

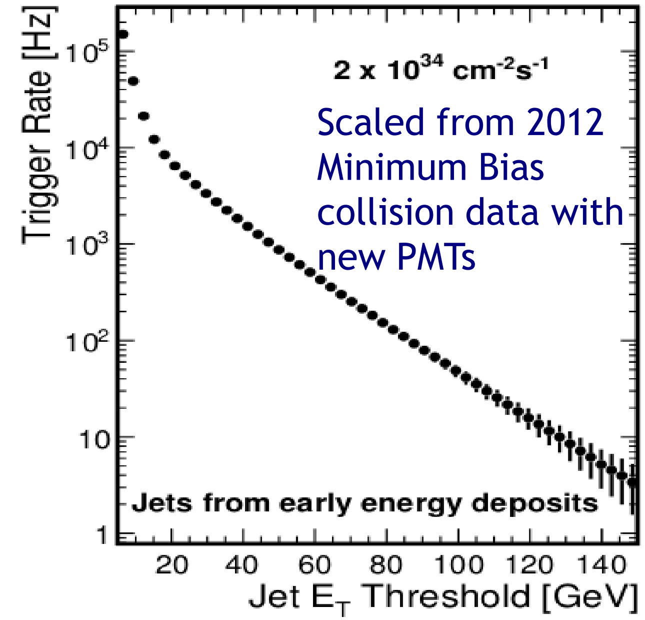
LS1 Projects in production

- Complete muon coverage: CSC and RPC (ME4/2)
- Improved operation: CSC (ME1/1) and DT electronics
- Replace HF PMTs with multi-anode PMTs and HO HPD with SiPM

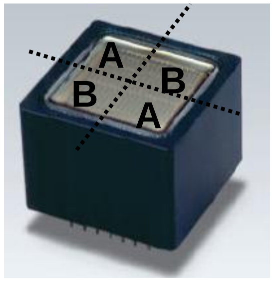


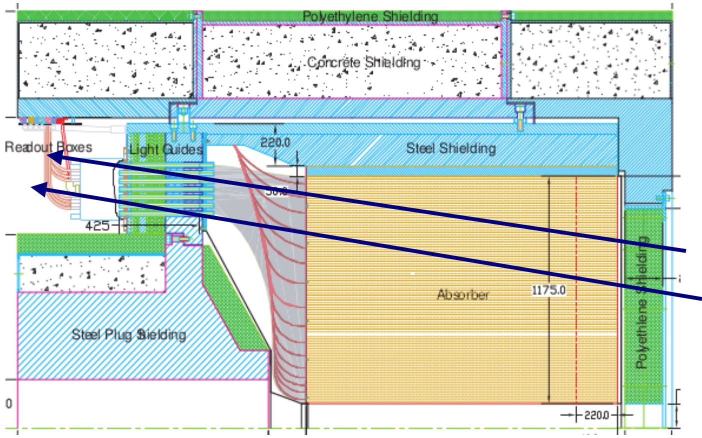
LS1 & Phase 1 Project on HF

- Anomalous signals in HF
  - Particles (muons from decay-in-flight, punch through particles) passing through the HF PMTs produce spurious signals in the PMTs
  - Currently mitigated by adjusting calorimeter phase to put (early) spurious signals outside the window. This is not possible @ 25 ns.
  - Critical for VBF Higgs performance



- Multianode phototubes
  - Will be installed during LS1 (2013/4)
  - During 2015, all four anodes will be ganged together and used with existing electronics
  - After electronics upgrade, dual anode readout will be available (from 2016?)

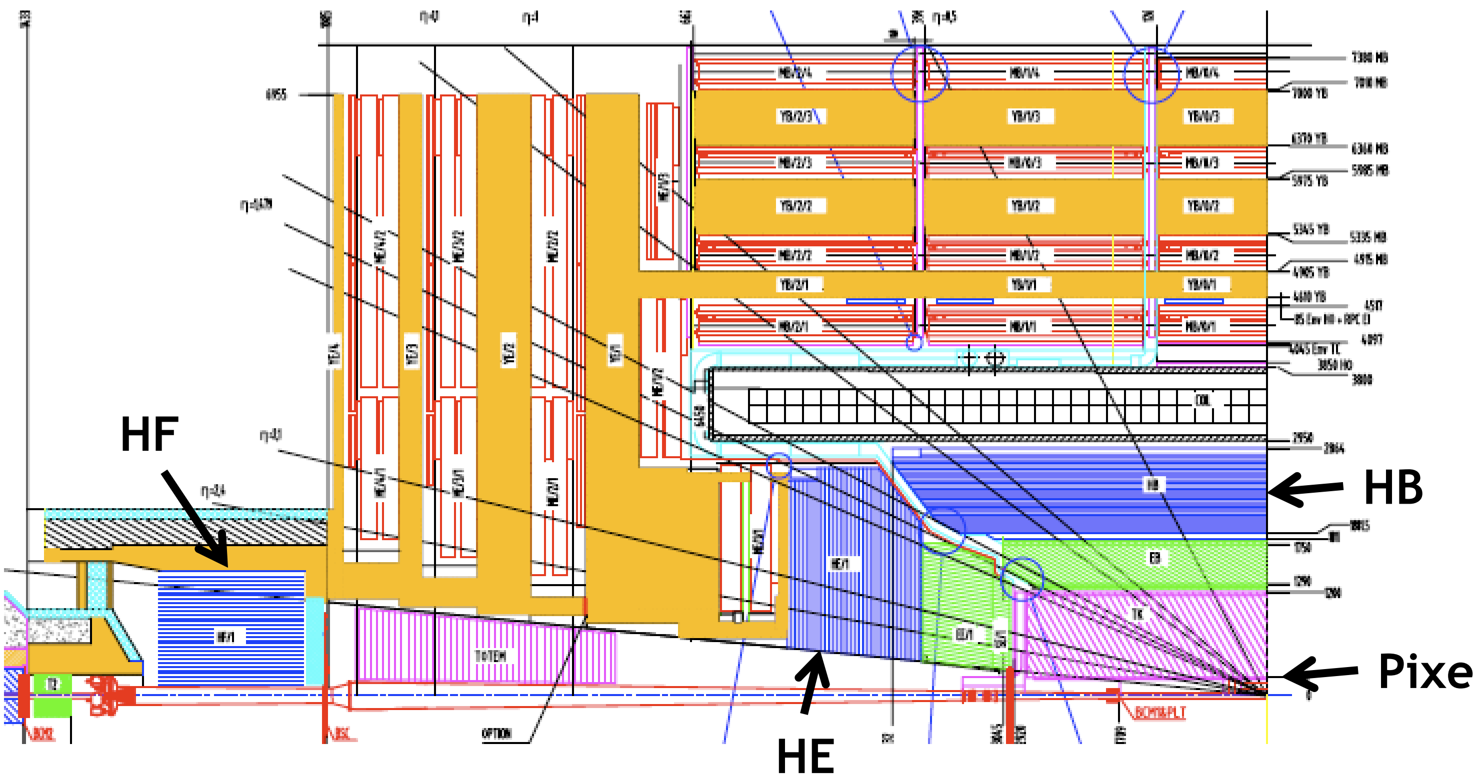




Phase 1 Projects

Phase 1 Upgrade at the TDR stage

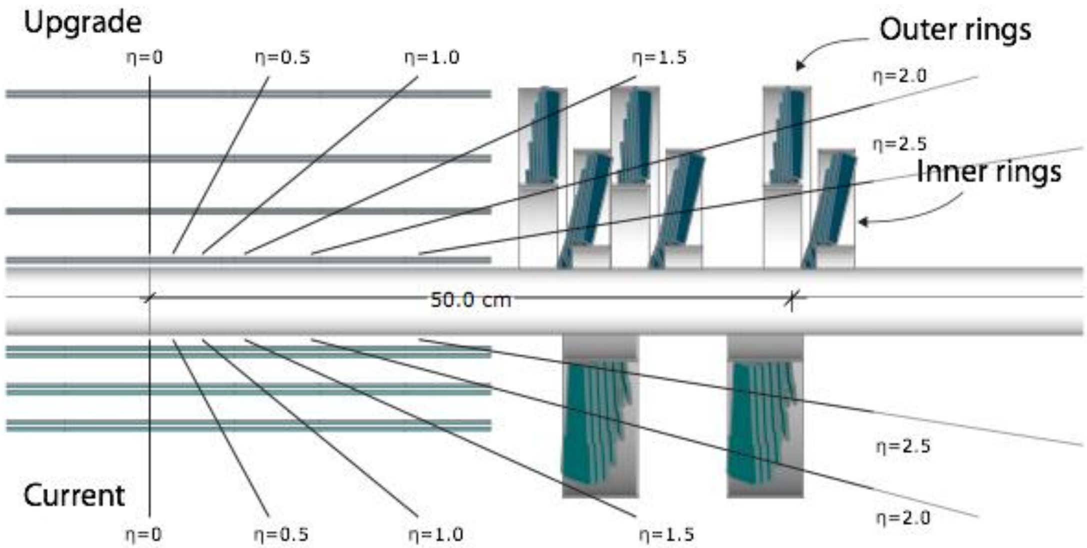
- New Pixel detector
- HCAL upgrade: photodetectors and electronics
- New L1-trigger systems (Calorimeter - Muons - Global)

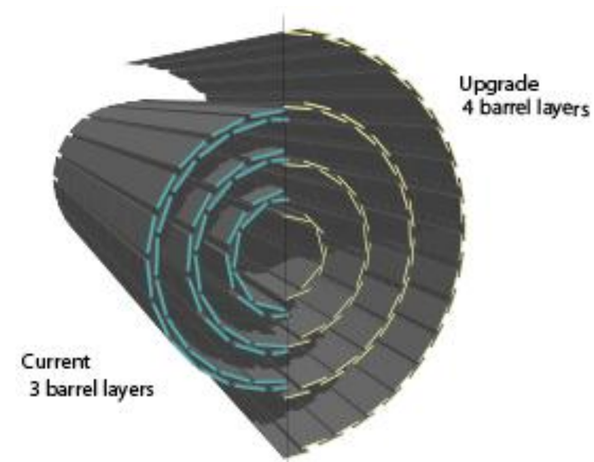


Phase 1 Pixel Detector Upgrade

Maintain high tracking performance and overcome the current detector limitation due to design for a luminosity of 1 x 10^{34} Hz/cm^2 with 25ns BS

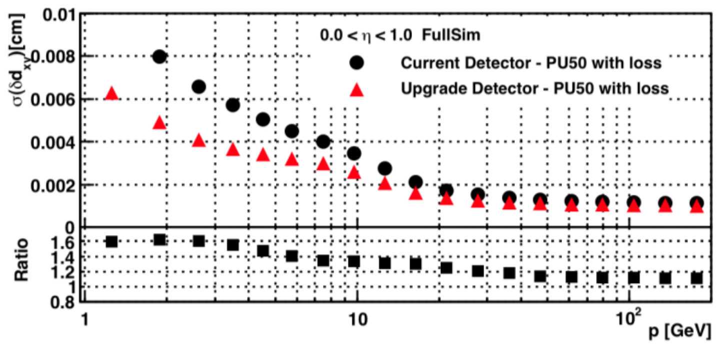
- The upgraded detector will have high rate capability and significantly improved tracking performance at high pile-up
  - 4 barrel layers and 3 endcap disks at each end with smaller inner & large outer radius
  - New readout chip with expanded buffers, embedded digitization and high speed data link
  - Reduced mass with 2-phase CO_2 cooling
  - Capitalize on current detector (technologies for sensor and ROC, overall RO architecture)
- Installation planned in an extended year-end shutdown in 2016/17

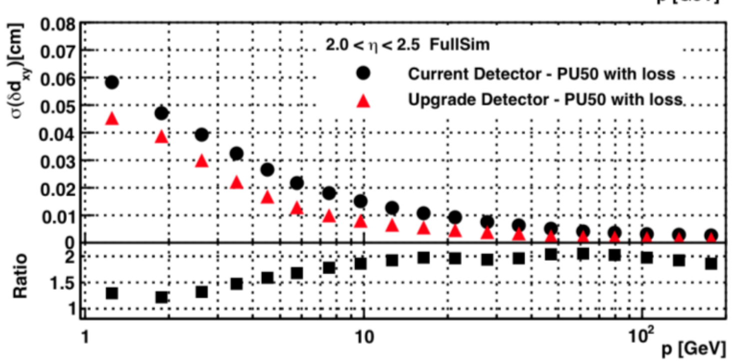




Tracking Performance

- Transverse impact parameter resolution with 50PU

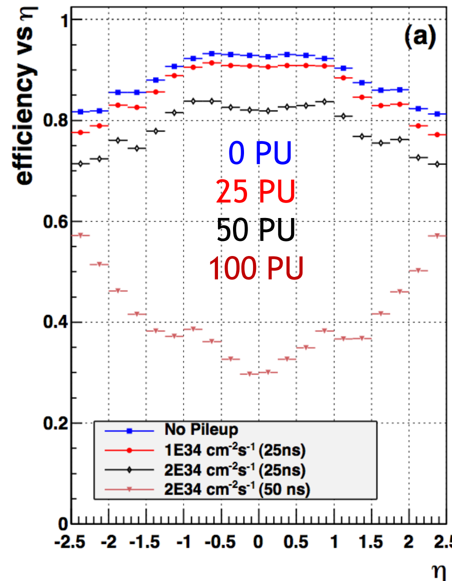




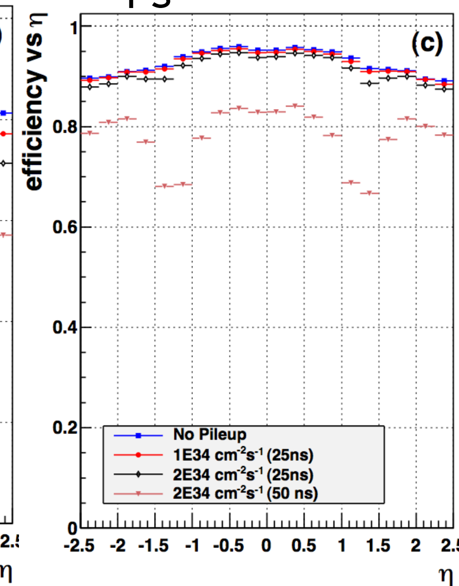
Gains in longitudinal impact parameter resolution even more pronounced!
e.g. |η|<1, p=100GeV → gain = 1.63!
(transversal impact parameter gain =1.15)

- Tracking efficiency for ttbar sample with ROC data losses etc with 100 PU

Current detector



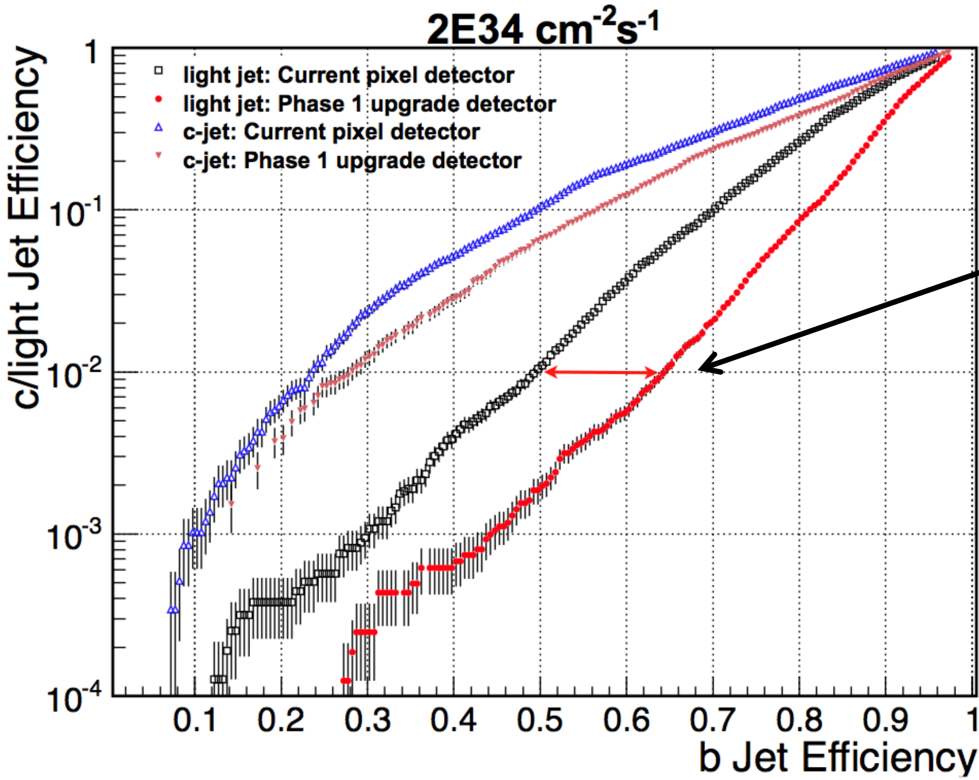
Upgrade detector



Fake Rate= 6% (η=0)

Fake Rate= 2% (η=0)

Performance in b-Tagging



b-jet efficiency
~ 1.3x better
@ 10^{-2} light flavor (udg) jet-rejection

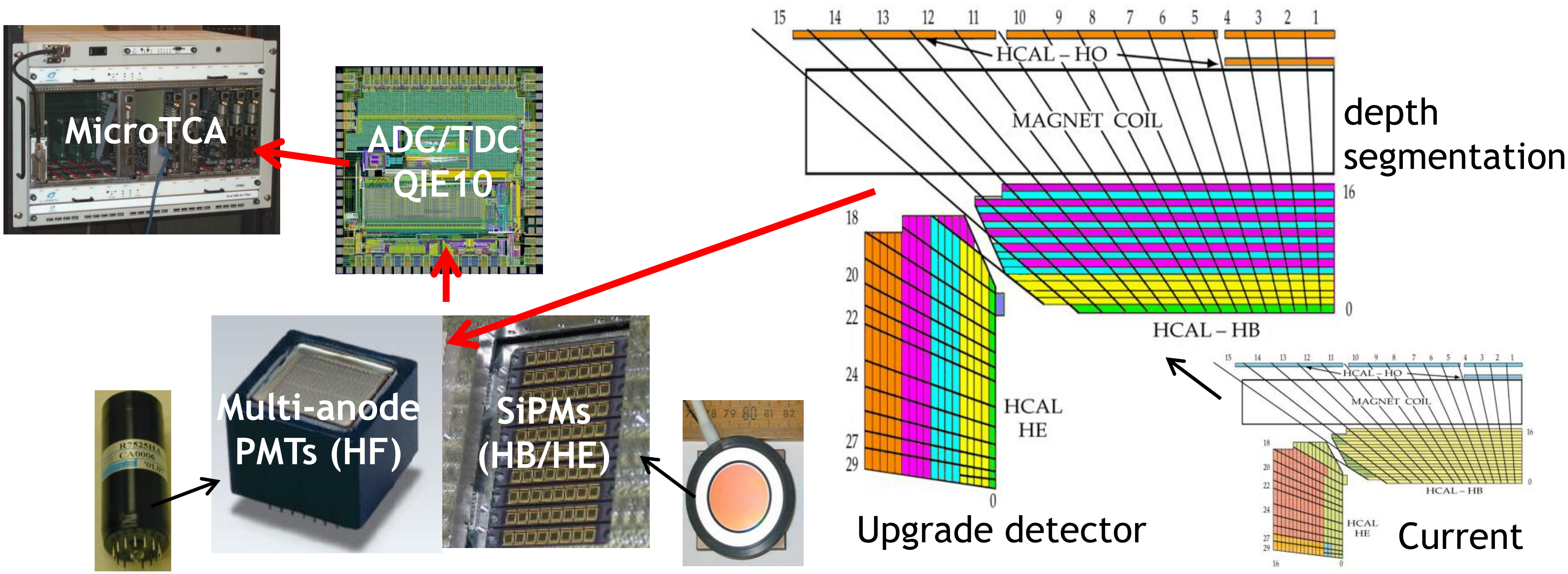
Primary vertex resolution is also improved by ~1.5 - 2

- Upgrade detector much more robust to pileup than current one.
- Upgrade @50 PU ~ Current @0 PU
  - maintain physics capability or better at large PU

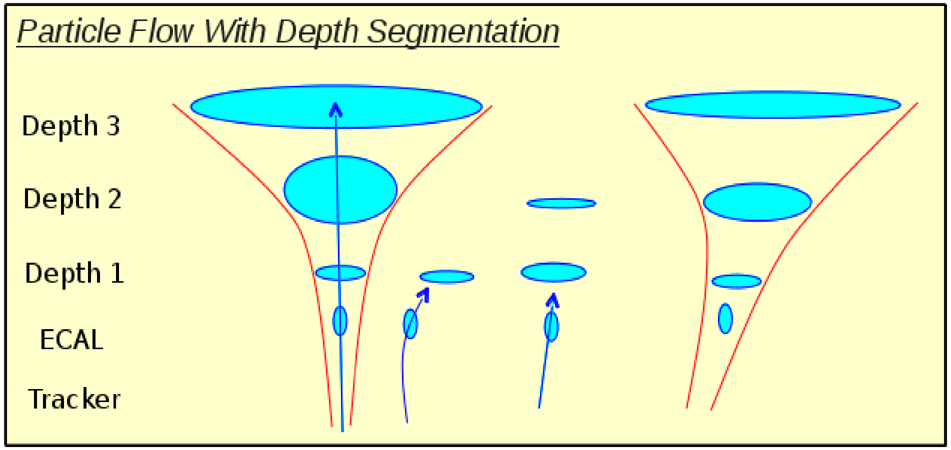
Phase 1 HCAL Detector Upgrade

Address sensitivity of present detector to anomalous signals generated in photodetectors and improve performance in high pileup environment

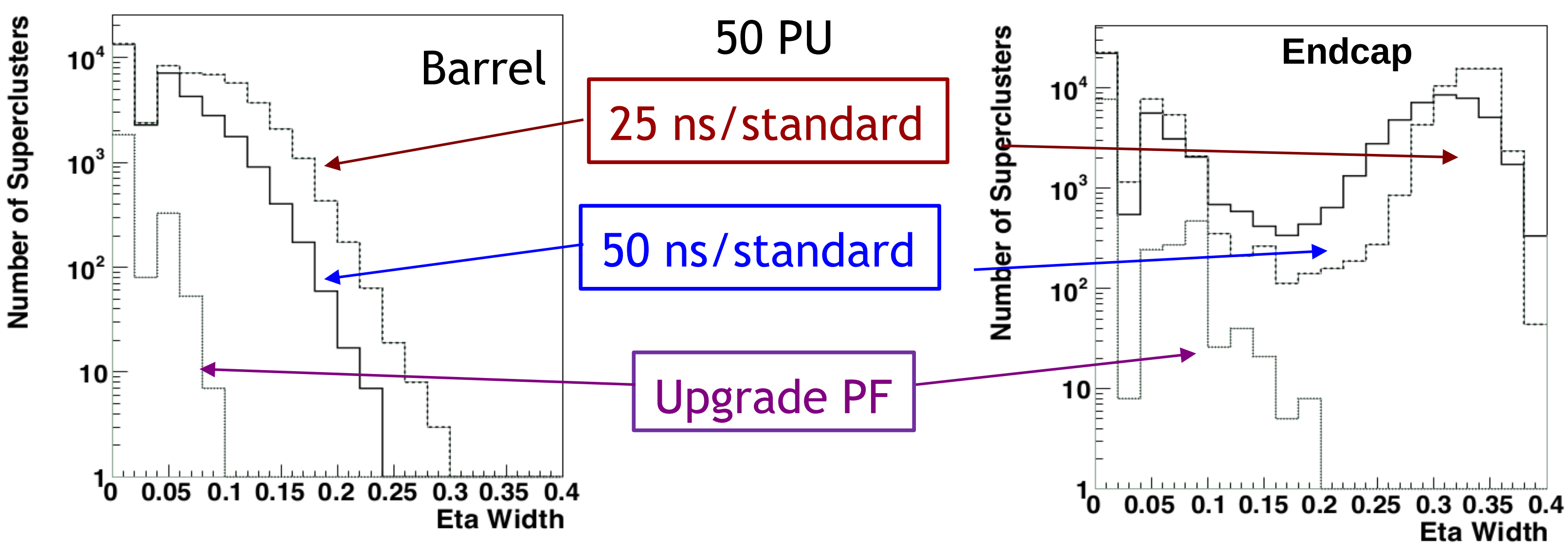
- With new photodetectors and read-out electronics, the upgraded detector will have improved background rejection, higher granularity, and S/N
  - HF 2-ch read-out per PMT and new TDC → in 2015/16 year-end technical shutdown (YETS)
  - HB/HE new optical links and μTCA backend electronics with increased bandwidth → 2015/16 YETS for L1-trigger upgrade and to prepare front-end replacement
  - HB/HE SiPM with depth segmentation and new front-end with TDC → during LS2



Particle Flow w/ High Pileup



- Hadronic showers spread out with increasing depth
  - With a single-depth readout, pileup energy will be pulled into a charged hadron cluster or true energy will be left out and labeled as a neutral hadron
  - Depth segmentation provides better pileup separation



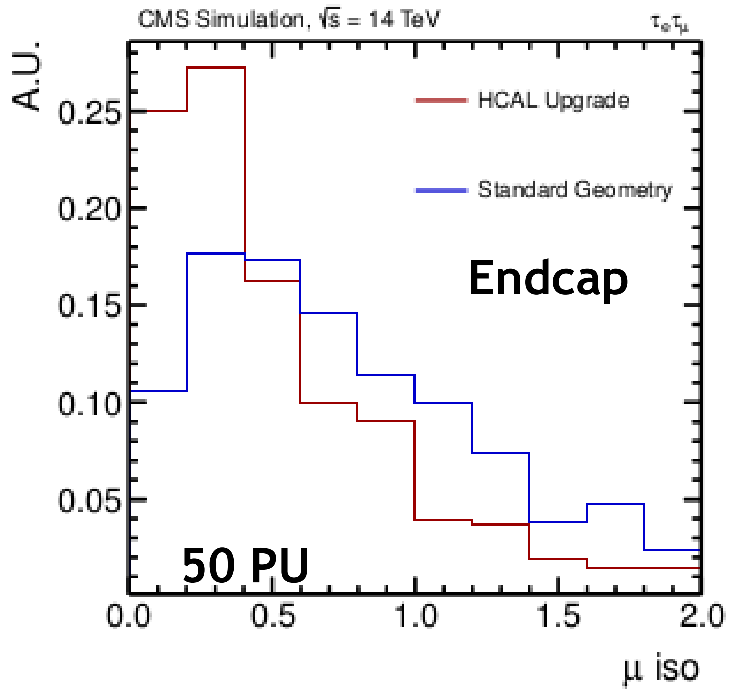
VBF H→ττ w/ Phase 1 Upgrade

- **Channel:**
  pp →Hjj →ττjj →eμjj
  Only probe of coupling to leptons
  Currently some tension w/ other channels

- **Event selection:**
  - Isolated leptons: One with p_T>20 GeV, one with p_T>10 GeV
  - Two VBF tagging jets: p_T> 30 GeV, opposite hemispheres, no jets in gap between VBF jets, m_{jj}> 600 GeV

- Isolation cuts tuned to provide same efficiency as current reference analysis performed at 8 TeV and current LHC luminosity

Isolation

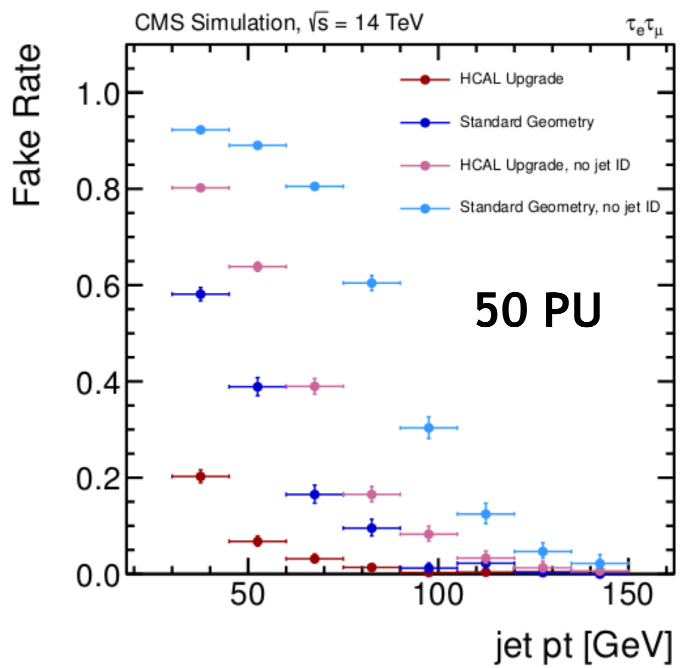


Reduced out-of-time pileup, better S/N in a finer granularity detector readout

$$I_{rel} = \frac{\sum p_T(\text{charged}) + \max\left(\sum E_T(\text{neutral}) + \sum E_T(\text{photon}) - \Delta\beta, 0\right)}{p_T(\mu \text{ or } e)}$$

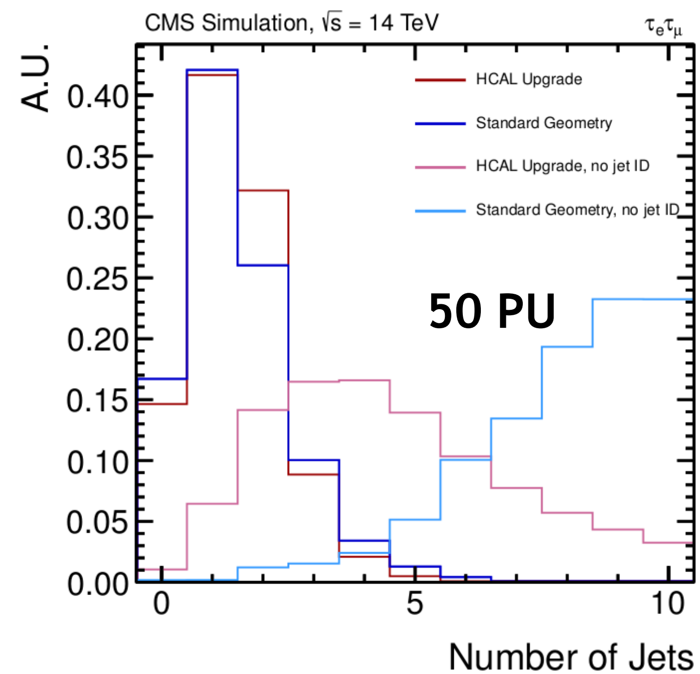
VBF H→ττ w/ Phase 1 Upgrade

- Significant reduction in jet fake (PU) rate, as defined as fraction of reconstructed jets not matched to generator jets
  - Jet ID: Multivariate analysis ID of pileup jets (tracking & jet shape)



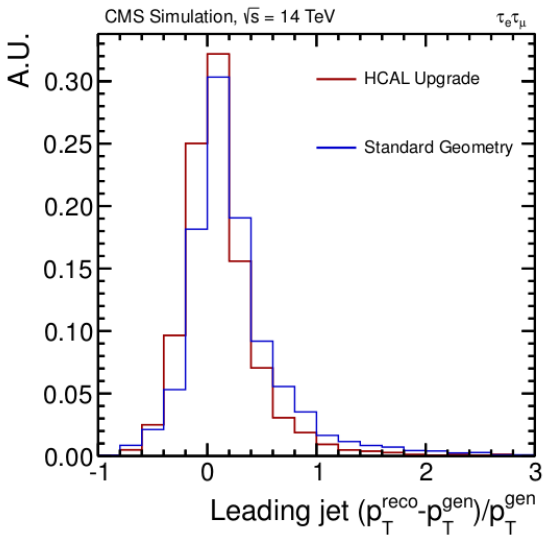
Jet Counting

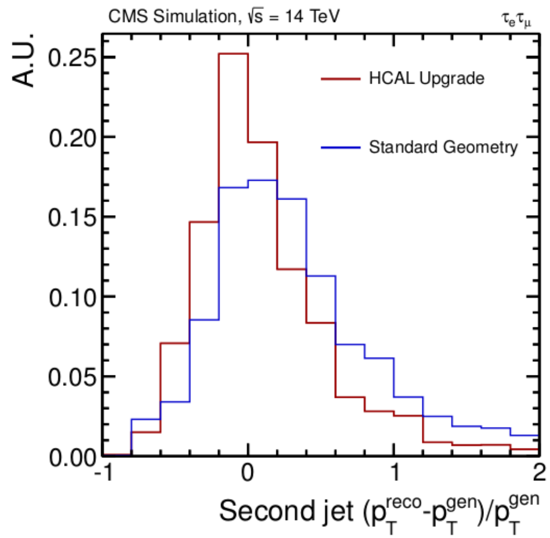
- Efficiency of identifying true tag jets is improved, without increase in fake jets

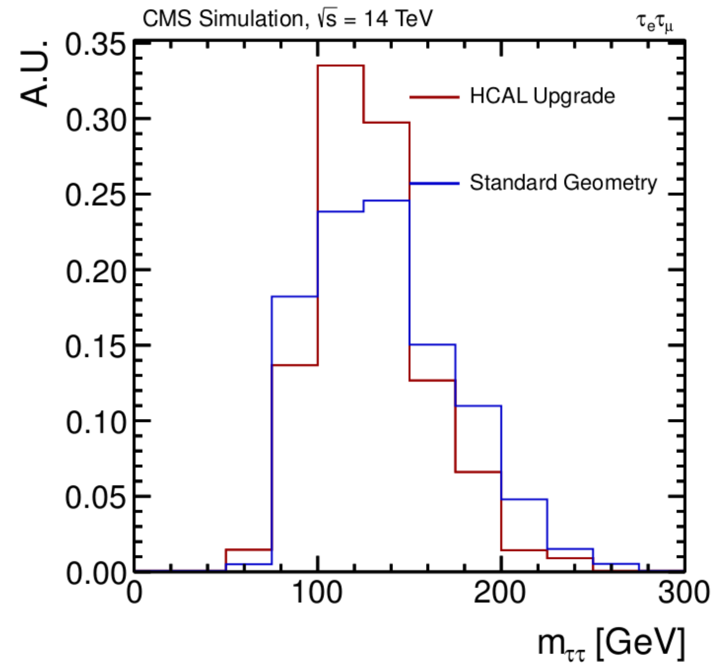


VBF H→ττ w/ Phase 1 Upgrade

Mass resolution







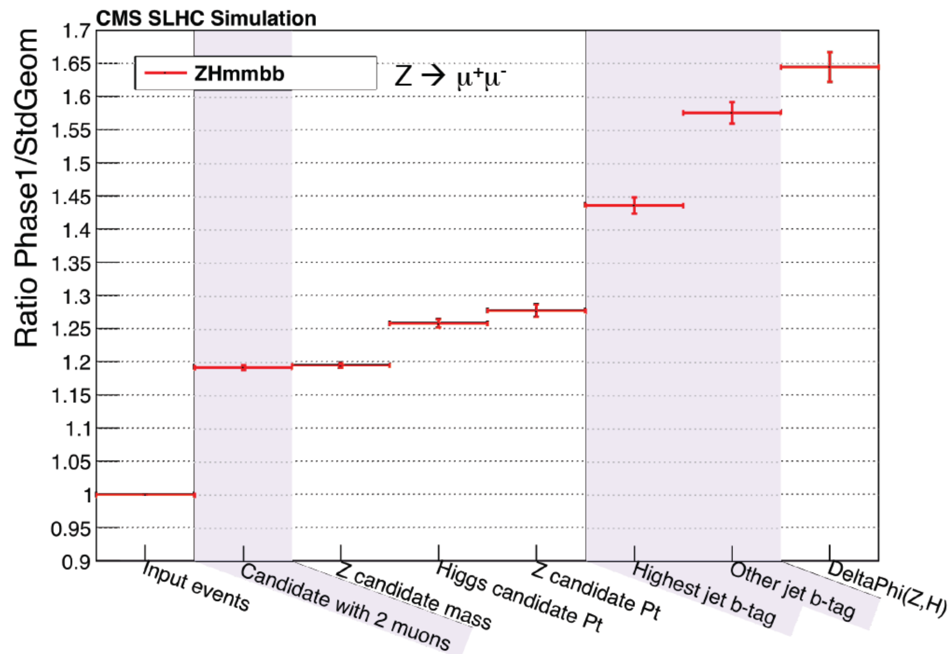
- Significantly-improved jet p_T resolution, particularly for lower p_T jets
- Improved jet and MET resolution allows 25% improvement in $m_{\tau\tau}$ resolution, as determined by multivariate likelihood technique
- Total efficiency improvement from upgrades: factor of 2.5 (4.5% → 11%)

Full improvements from particle flow upgrades not yet folded in

ZH→ll+2 b's w/ Phase 1 Upgrade

- Channel:
  pp →ZH →(ll)(bb)

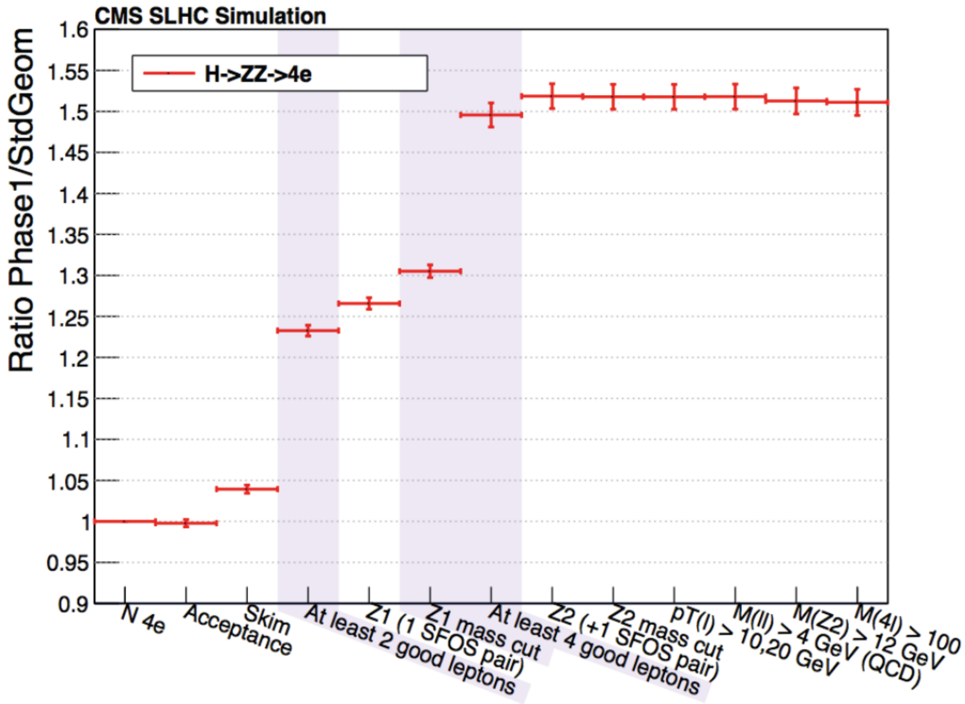
- Events selection:
  - ≥2 leptons + ≥2 jets w/ p_T > 20 GeV
  - 75 GeV < M_Z < 105 GeV
  - p_T >100 GeV for both H & Z
  - H & Z back to back: $\Delta\varphi$ < 2.9
  - CSV b-tag on both b-jets
  - light jet rejection <1%



- Both channels (μμ&ee) show 65% gain in signal efficiency for upgrade system
- HLT trigger with 3 out of 4 hits from upgraded pixel for muons may benefit significantly

H→ZZ→llll w/ Phase 1 Upgrade

- Channel:
  pp →H →ZZ →(ll)(ll)
- Events selection:
  - ≥ 4 isolated leptons
  - 2 leptons with p_T>17 & 8 GeV
  - PF ele w/ |η|<2.5, p_T>7GeV
  - PF μ and |η|<2.4, p_T>5GeV
  - 40 GeV < M_{Z1} < 120 GeV
  - 12 GeV < M_{Z2} < 120 GeV
  - p_T(l) >20, 10 GeV & M_{4l} >100 GeV



Significant gain in signal reconstruction efficiency: "
H → 4μ +41%
H → 2μ2e +48%
H → 4e +51%

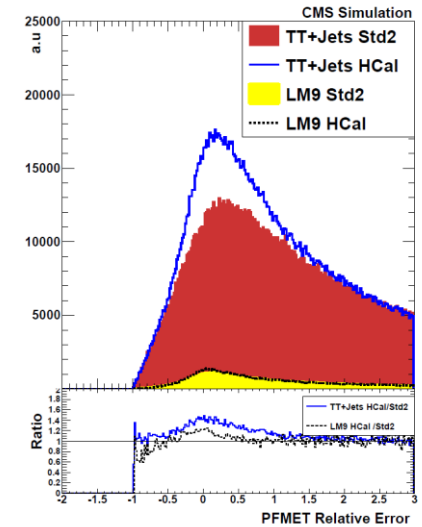
Upgrade detector provides physics reach as current detector with 40-50% more luminosity

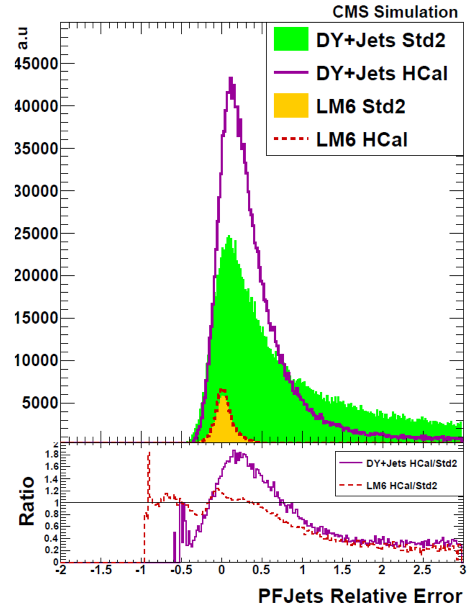
3^{rd} Gen SUSY w/ Phase 1 Upgrade

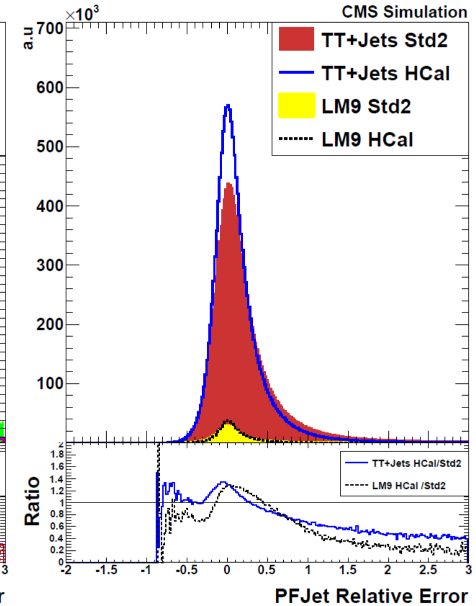
- **Channel:**
  e.g. $pp \rightarrow \tilde{g}\tilde{g};\ \tilde{g} \rightarrow \tilde{t}t \rightarrow tt\tilde{\chi}_1^0$

- **Event selection:**
  - An isolated μ w/ p_T> 20 GeV
  - ≥4 central (|η|<2.4) jets with p_T>40 GeV
  - Jet-lepton separation ΔR>0.3
  - ≥1 CSV b-tagging
  - MET > 60 GeV

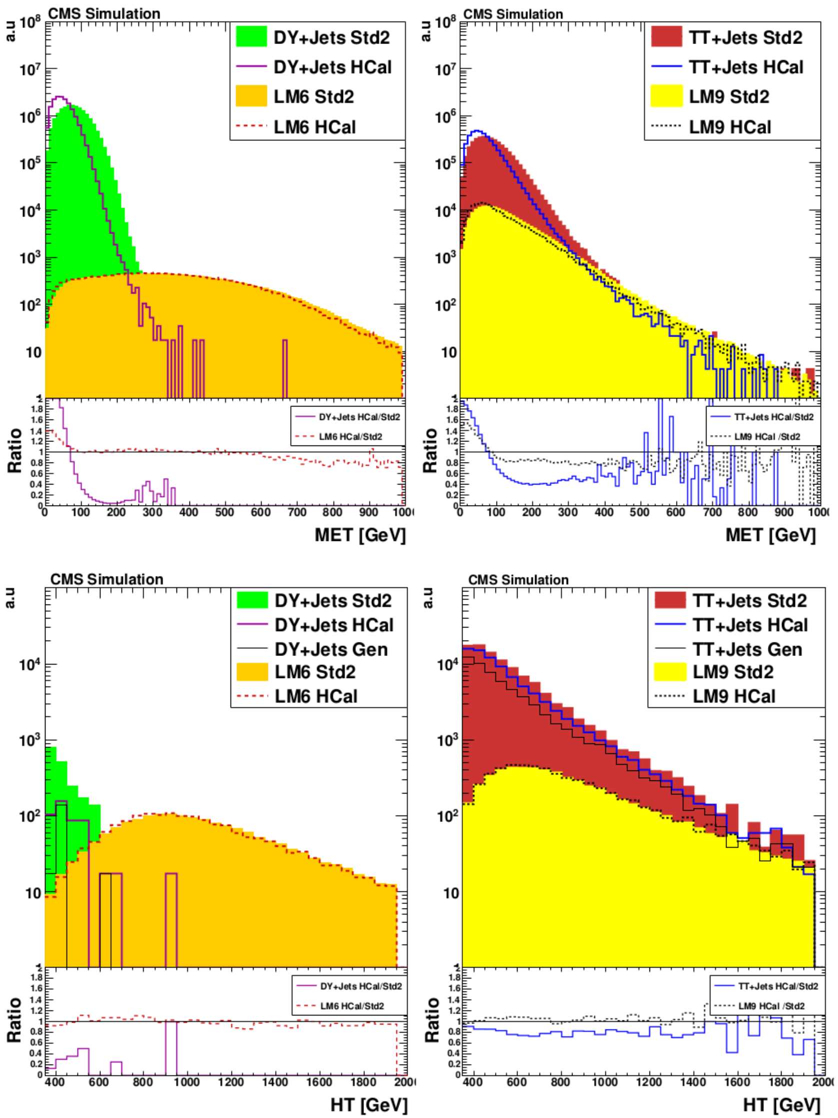
- Final analysis variable is the scalar sum of the jet p_T(HT)







SUSY μ+j+MET w/ Phase 1 Upgrade



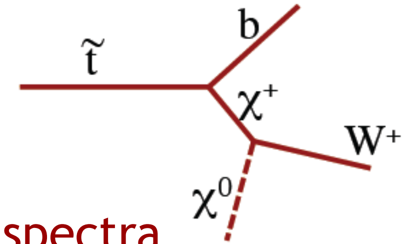
- Fake MET significantly reduced without affecting true MET in signal events
- Improved HT distributions as well
  - tt+jets distribution closer to generator-level HT
- S/B ratio improved by ~50% at high HT

Full particle-flow improvements not yet folded in

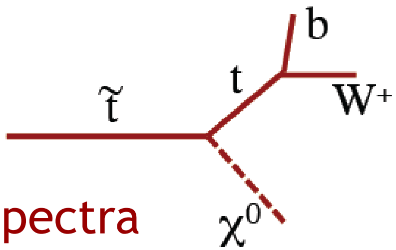
L1 Trigger Upgrade Study w/ Stop

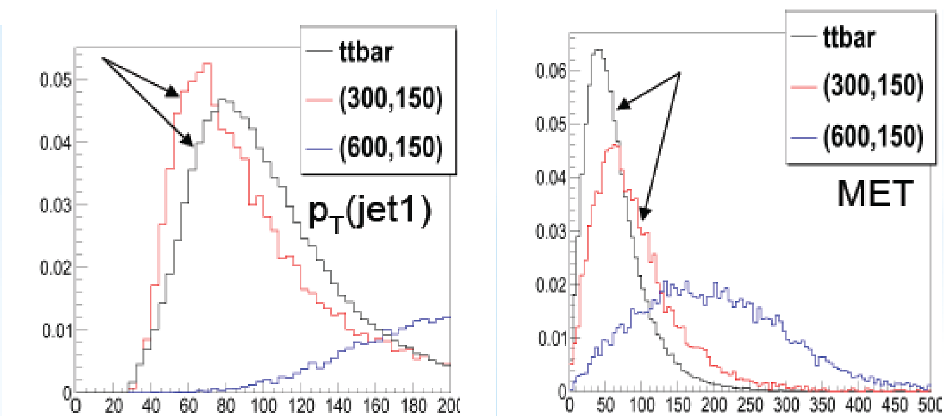
Direct stop with compressed spectra:

- stop → b W χ_1^0
  - m_{stop} = 300 GeV, $m_{neutralino}$ = 150 GeV } compressed spectra
  - m_{stop} = 600 GeV, $m_{neutralino}$ = 450 GeV }
  - m_{stop} = 600 GeV, $m_{neutralino}$ = 150 GeV → cross-check



- stop → top χ_1^0
  - m_{stop} = 300 GeV, $m_{neutralino}$ = 100 GeV } compressed spectra
  - m_{stop} = 600 GeV, $m_{neutralino}$ = 400 GeV }
  - m_{stop} = 600 GeV, $m_{neutralino}$ = 100 GeV → cross-check



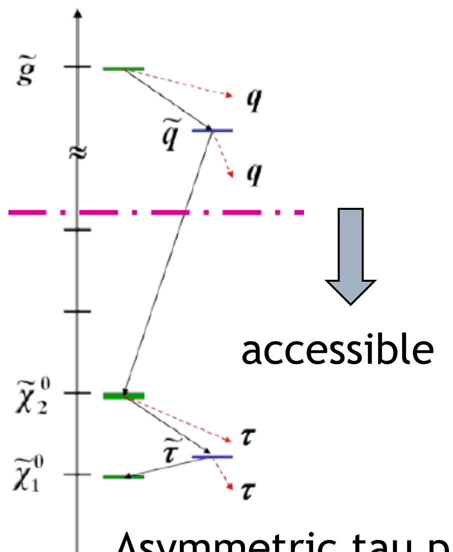


Compressed spectrum signal sits either on top of SM ttbar or even softer:
S/B separation and triggering are challenging

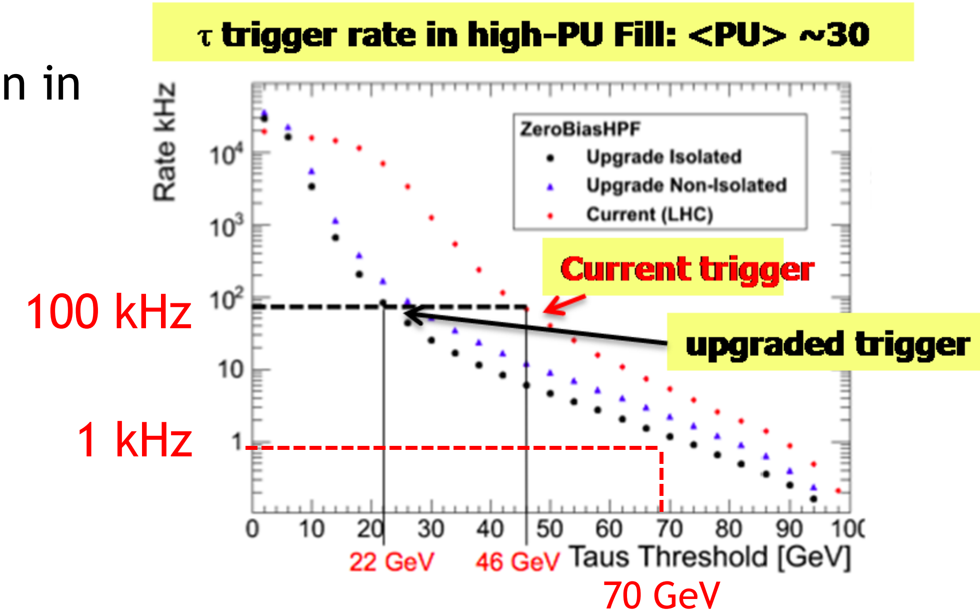
L1 Trigger Upgrade Study w/ Stau

EWKino production with taus:

- Chargino-neutralino producition in large tanβ CMSSM-like case: very heavy squark/gluinos or GMSB-like (stau NLSP)



Asymmetric tau p_T's

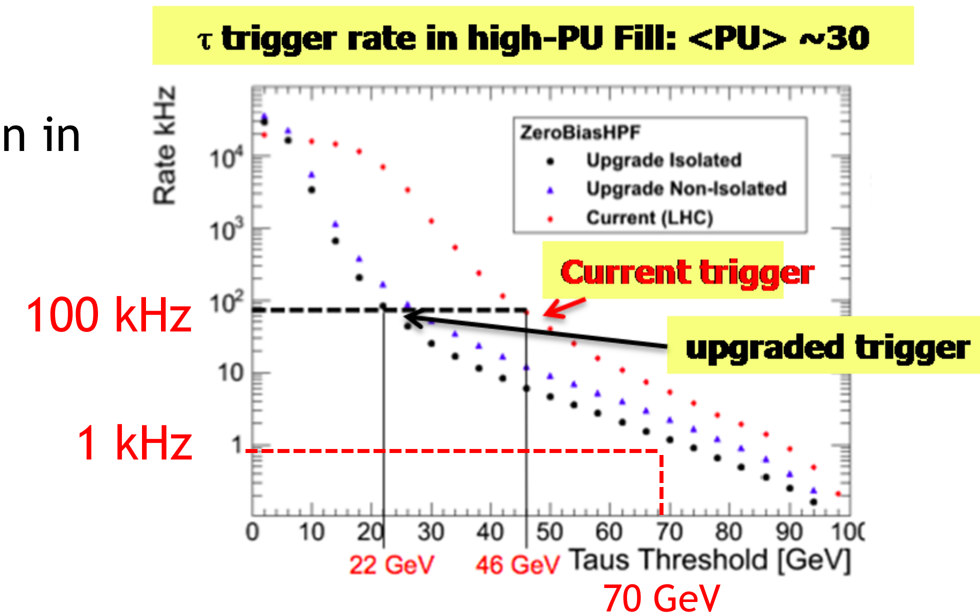


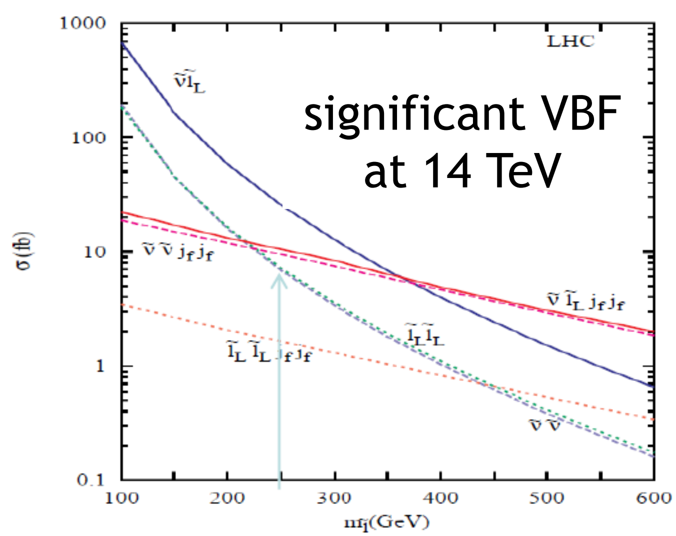
- Profit from improved tau trigger
  - 1x2 cells instead of 12x12
  - higher efficiency, less rate
  - … still too high rate for compressed spectra?

L1 Trigger Upgrade Study w/ Stau

EWKino production with taus:

- Chargino-neutralino producition in large tanb CMSSM-like case: very heavy squark/gluinos or GMSB-like (stau NLSP)





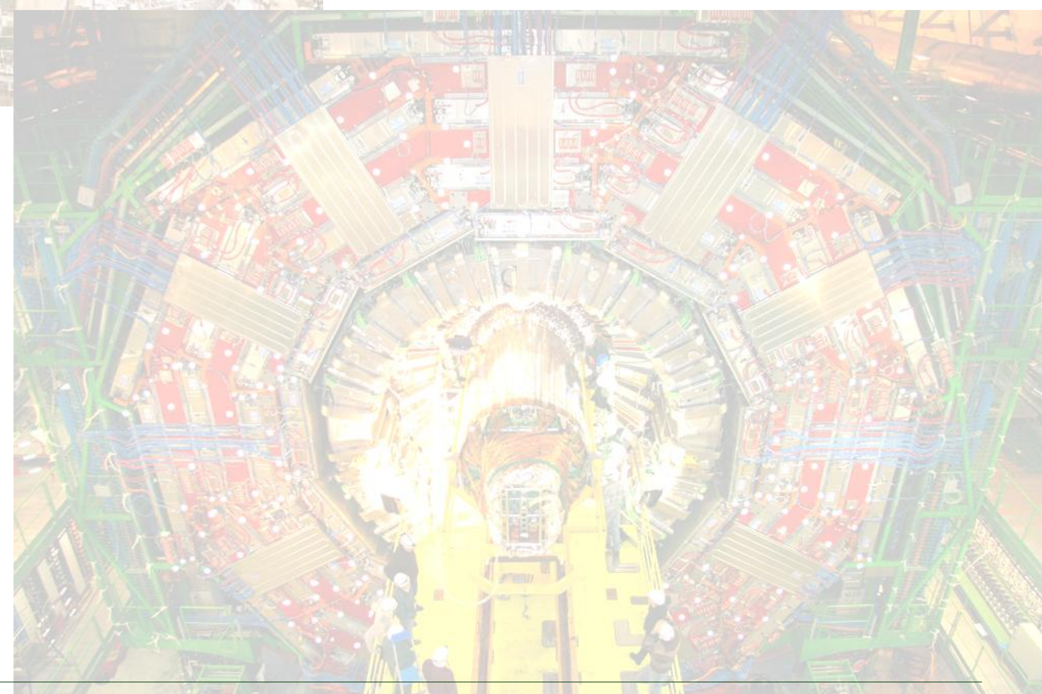
- Profit from improved tau trigger
  - 1x2 cells instead of 12x12
  - higher efficiency, less rate
  - … still too high rate for compressed spectra?

Exploit production via VBF, e.g. trigger two forward jets, and add low p_T central tau (if necessary)

Phase 2 Projects

- The HL-LHC era:
  - Total of ~3000 fb^{-1}
  - Expect lumi-leveling at ~5 x 10^{34} Hz/cm^2, <PU>~140 (tail to 200!)
- This leads to:
  - Severe occupancy problem in the tracker
  - Radiation issues for the pixel sensors and the forward calorimeters
    - Must tolerate as much each year as they did for the previous decade
  - Severe breakdown of the Level 1 trigger
  - Need to expand the data acquisition system and the high-level trigger
- What we already know:
  - Complete new silicon tracker and pixels – with L1-triggering capability.
  - Replacement/upgrade of forward calorimeters HF and EE, part of HE
- Under consideration:
  - Integrate new forward region: Calorimetry, tracking, muons, timing-optimized for object reconstruction at very high PU
  - Major upgrade for trigger to provide full physics program at relatively low p_T at very high PU (L1 output rate 1MHz, HLT output rate 10kHz)

Summary



Summary

- It is surely a very exciting time for particle physics due to the discovery of the Higgs(-like) particle at 125 GeV
- We have a lot to do in the coming years with future LHC running
  - Characterize this 125 GeV new boson
    - Coupling, spin, CP, etc

      How consistent with the Standard Model Higgs?
  - Why 125 GeV? Study the fine-tuning problem and naturalness by searching for physics beyond the Standard Model
- For all these studies, the significant detector upgrade is vital
  - Already the initial upgrade is planned in this upcoming LS1 (2013-14) shutdown
  - The phase 1 HCAL, Pixel, and L1 trigger upgrades (-2018) is at the TDR stage
    - The impacts of the upgrades on physics were discussed today
  - The phase 2 upgrade is under planning
    - Complete new silicon tracker with L1 trigger capability & upgrade/replacement of forward calorimeter is necessary
    - More upgrades are under consideration, but physics justification is needed.

      What is the right physics question to ask?

Snowmass 2013

http://www.snowmass2013.org/tiki-index.php

- Snowmass is an effort initiated by US DPF, provides input to P5
- Organized around a few "frontiers"
  - Energy Frontier
    - Subgroups: Higgs, BSM (New Particles), Top, EWK, QCD, Flavor
  - Also Intensity, cosmic, computing, Instrumentation, outreach and education frontiers, and frontier capabilities
- There will be a lot of discussions on physics questions we would like to address and options for future facilities
  - Hadron colliders: LHC, HL-LHC, HE-LHC, VLHC
  - Lepton colliders: ILC, CLIC, LEP3, Muon collider
  - Lepton-Hadron: LHeC
- A few pre-meetings before the meeting at Minneapolis
  - Higgs working group: January 14-15 at Princeton University
  - Beyond the SM working group: January 14-16 at UC Irvine
  - General meetings:
    - April 3-6 East coast US location
    - June 30- July 3 West coast US location

Get involved!

Acknowledgement

- Many thanks to:

  Boaz Klima, Chris Tully, Jeremy Mans, Roger Rusack, Wesley Smith, Isabell Melzer-Pellmann, Filip Moortgat for their inputs for this seminar

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