Institute for research in fundamental sciences
SCHOOL OF PARTICLES AND ACCELERATORS

The 2nd IPM meeting on
LHC PHYSICS

7 - 12 October 2013
Tehran, Iran

CMS upgrade plans and physics prospects at high luminosity

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IST/ LIP Lisbon

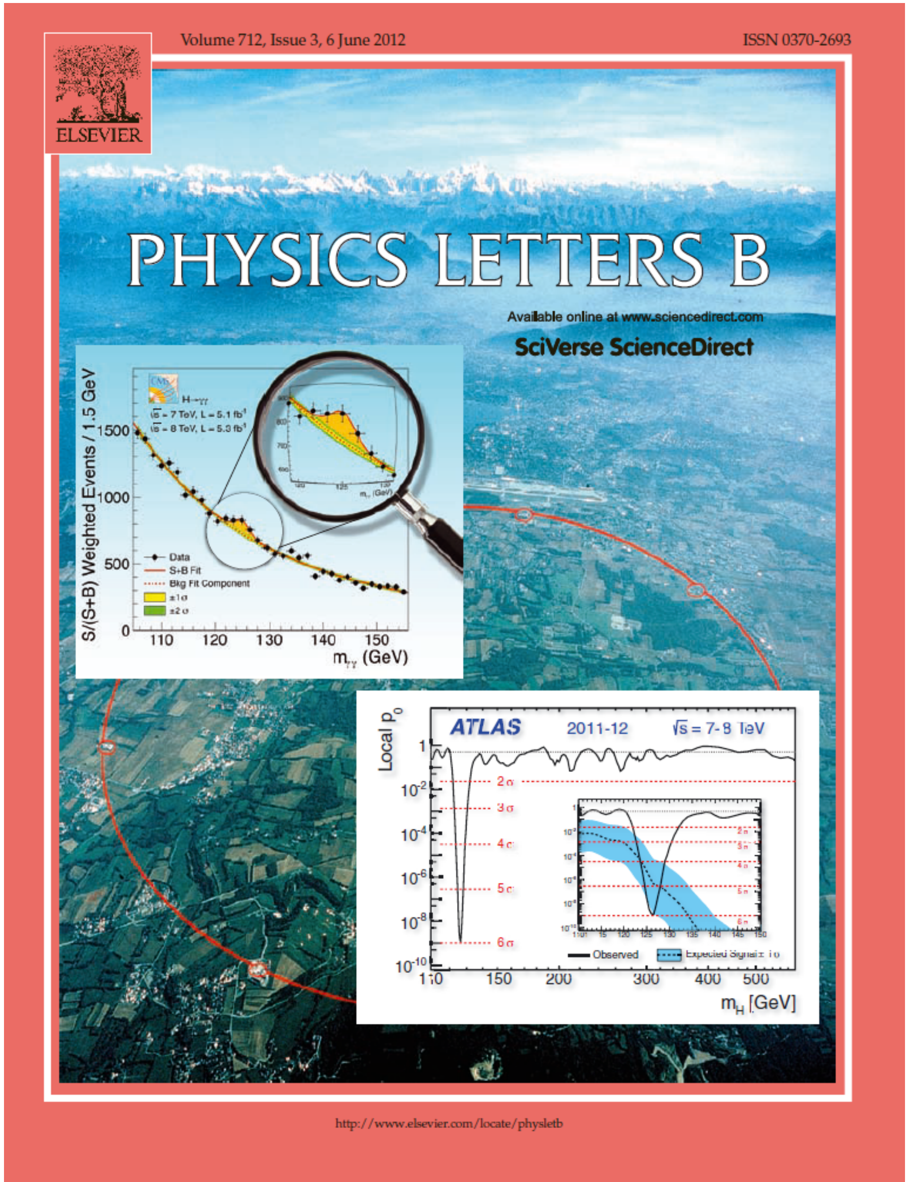
Sponsors:

IPMLHC2013: The 2nd IPM Meeting on LHC Physics
7-12 Oct 2013, IPM, Tehran, Islamic Republic of Iran

Outline

- Motivations
- LHC prospects in the next two decades
- CMS upgrade program
- Physics perspectives

A new boson was discovered

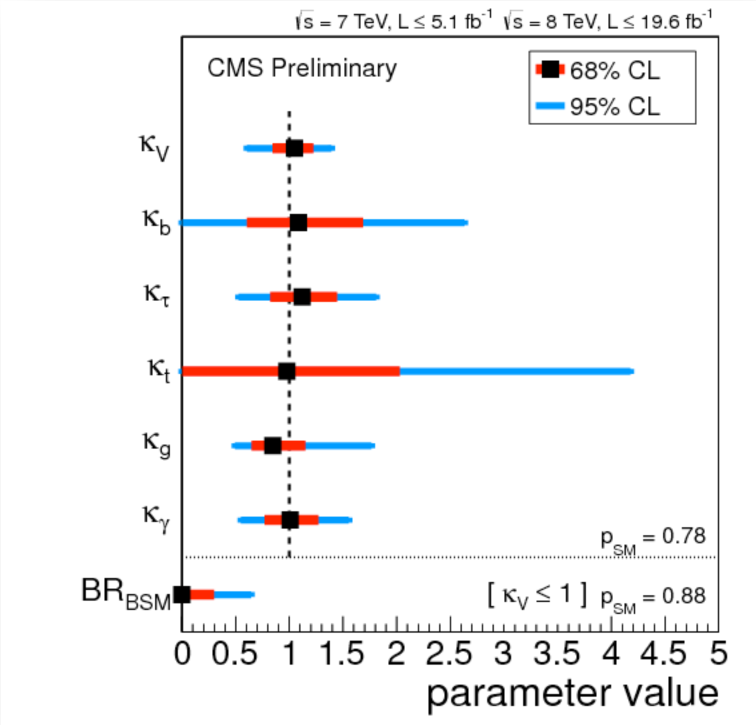


A Higgs Boson

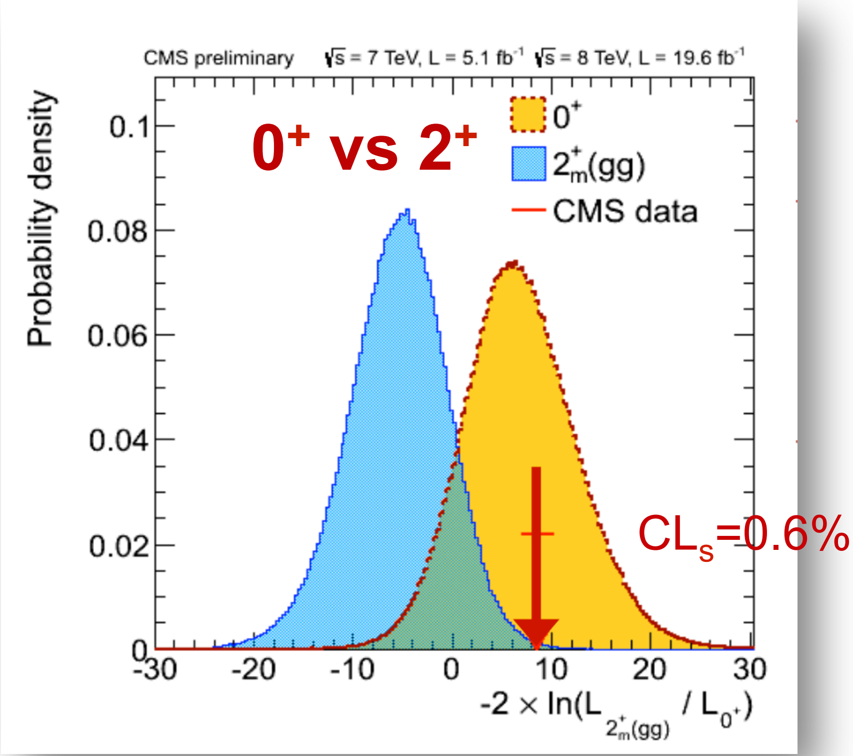
The 125 GeV resonance is a Higgs boson.

Signal strength: μ=0.80±0.14

Coupling modifiers:



Scalar hypothesis is strongly favored:



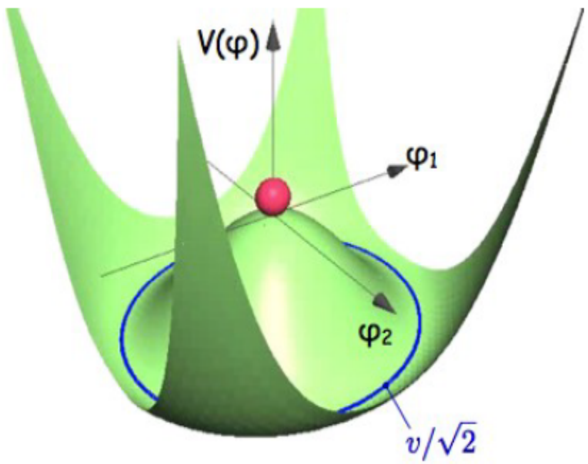
A major discovery in physics

The **new boson** is either the SM Higgs or a Higgs-like particle.

Electroweak symmetry breaking is very likely due to a Higgs field.

The confirmation of the Higgs field provides a more firm basis to understand the Universe.

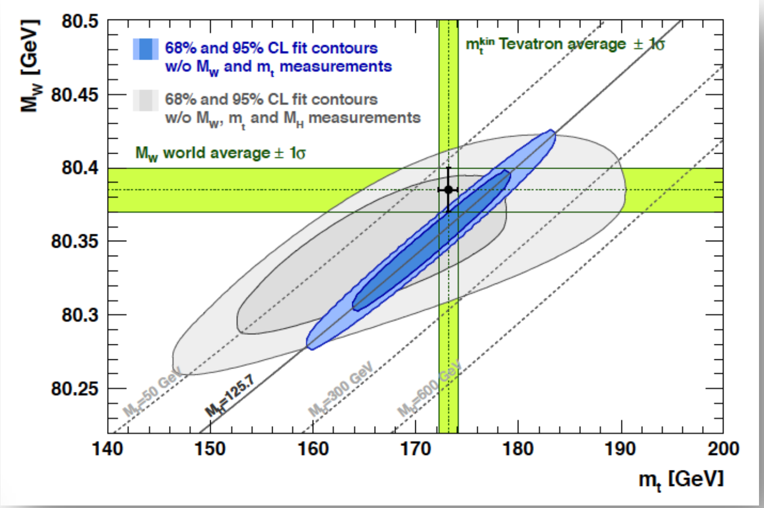
Inflation cosmological models become more plausible.

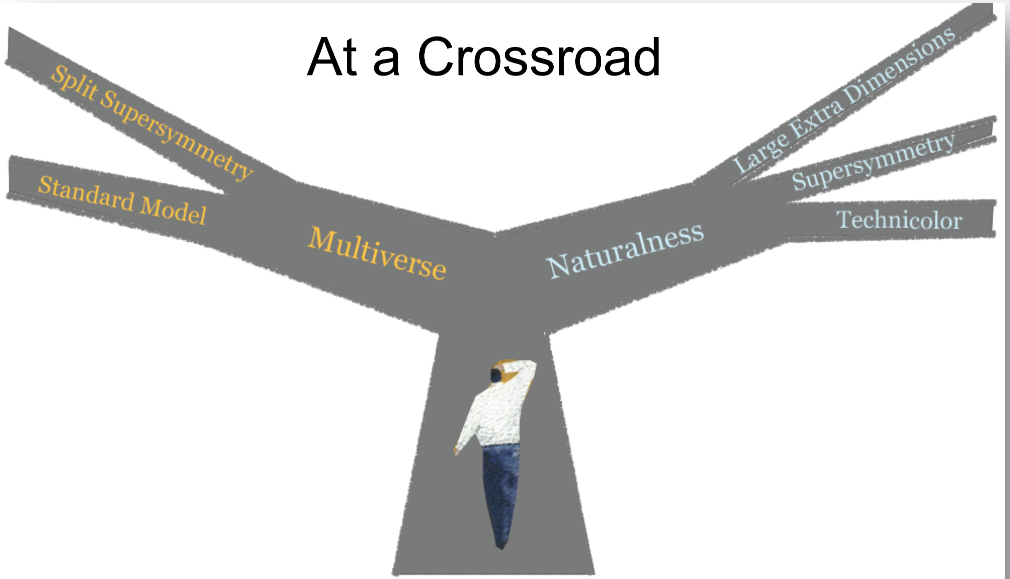


The standard model and beyond

Standard Model

The astonishing brain power of a certain ape species

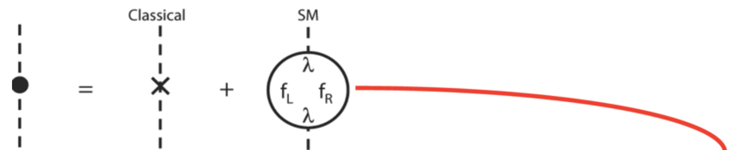




Savas Dimopoulos, CERN Colloquium, Sep 20, 2012

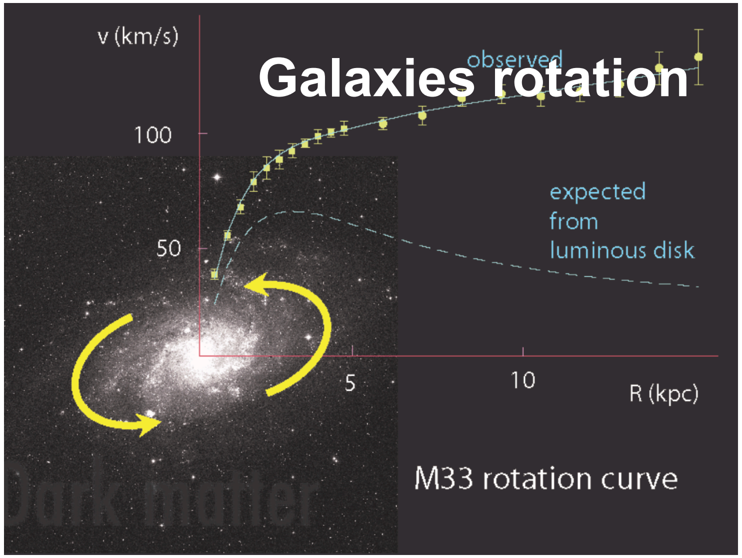
Higgs mass is a huge problem:

Miraculous cancelations are needed to keep the Higgs mass < 1 TeV



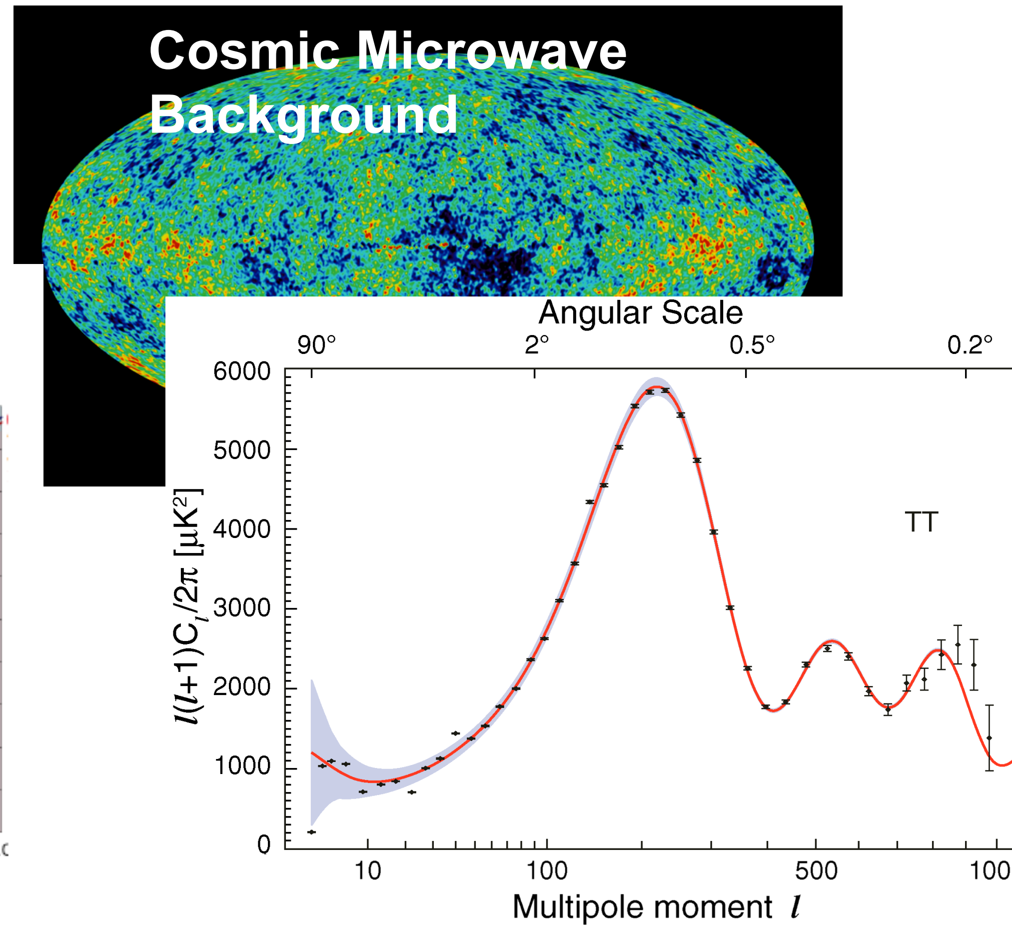
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \dots ,$$

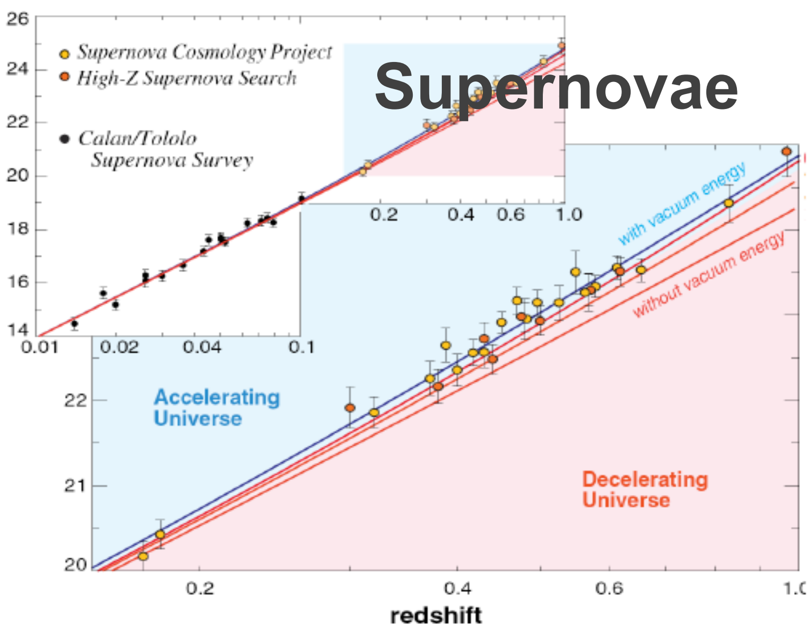
The connection to cosmology



Precision cosmology measurements give strong motivations for new physics:

Galaxies rotations, accelerating expansion, CMB uniformity, space flatness





Motivations for future physics at LHC

What's beyond the Standard Model?

Nominal LHC beam energy (14 TeV) will allow the full exploitation of the Terascale:

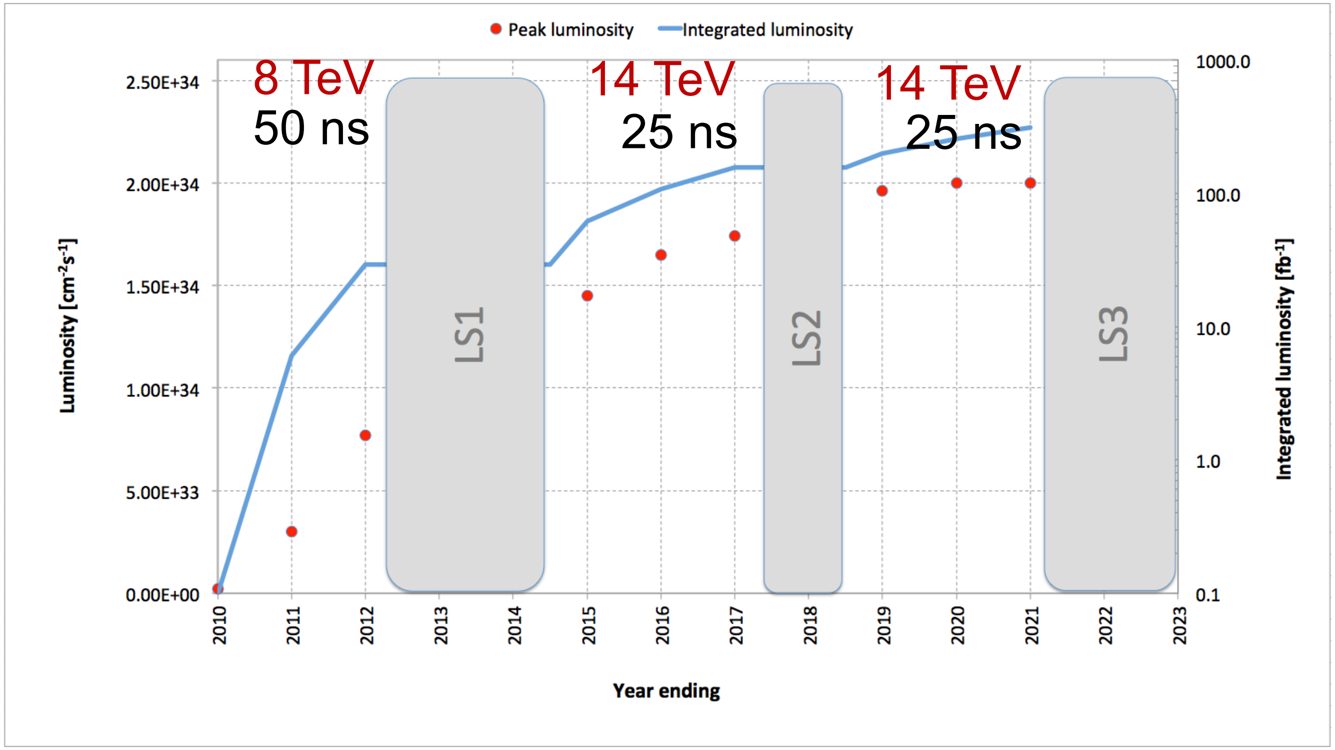
- search for SUSY, Extra Dimensions, etc.
- search for the unknown

High luminosity will allow very precise measurements of the Higgs sector:

- look for deviations to the Standard Model at the level of a few percent.

LHC prospects in the next two decades

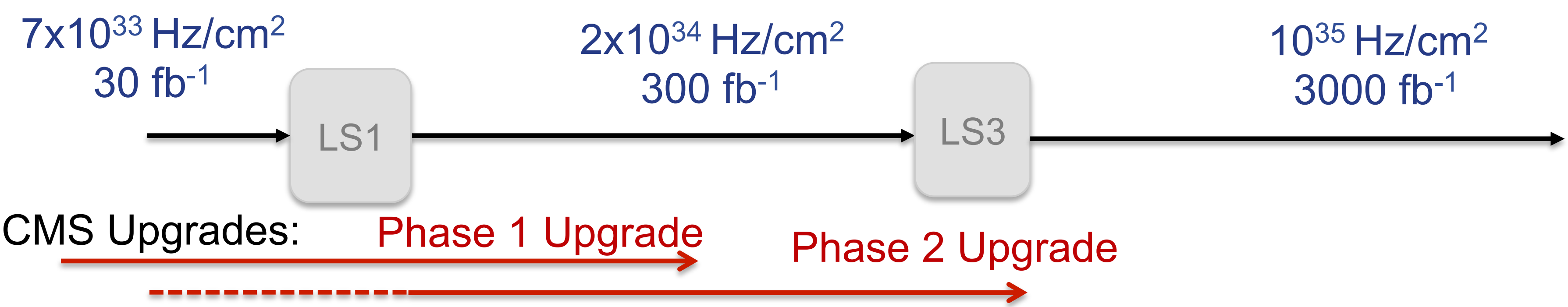
LHC projections



14 TeV

HL-LHC

Luminosity-leveled at $5x10^{34}$ Hz/cm^2



CMS physics program priorities

- With data collected until ~2022 **(~300 fb^{-1})**
  - Measure Higgs-like boson properties
    - individual couplings with 5-10% precision
  - Search for new physics at higher mass scale

- With data collected until ~2032 **(~3000 fb^{-1})**
  - Measure Higgs-like couplings with ultimate precision
  - Study vector boson scattering
  - Search for new physics in rare processes

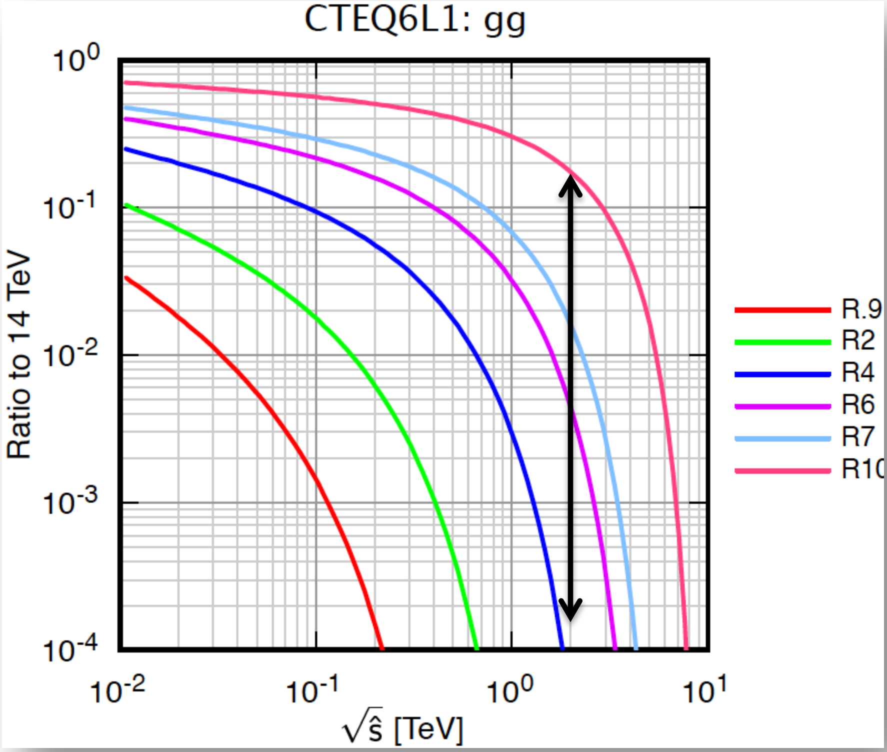
Energy increase

Increased sensitivity for new physics at the ~TeV mass scale

- probe SUSY up to m(gluino) ~ 2 TeV

At the mass scale of 2 TeV, the cross section for pair production of new particles is **~10^3 times higher at 13 TeV relative to 8 TeV**

Ratios of parton luminosities



Increasing challenges

- Detectors and trigger must maintain full sensitivity from low to high energy scales under severe pileup and radiation conditions
  - 125 GeV Higgs measurements
  - Multi-TeV new physics searches

- Phase 1 Upgrade: 2x LHC design peak luminosity
  - Event pileup reaches 50 collisions per beam crossing (@ 25 ns)
  - Factor 5 increase of trigger rates relative to 2012 run

- Phase 2 Upgrade: 5x LHC design peak luminosity
  - Event pileup reaches 125 collisions per beam crossing (@ 25 ns)
  - Extreme radiation doses:
    - light loss (calorimeters), increased leakage current (silicon detectors)

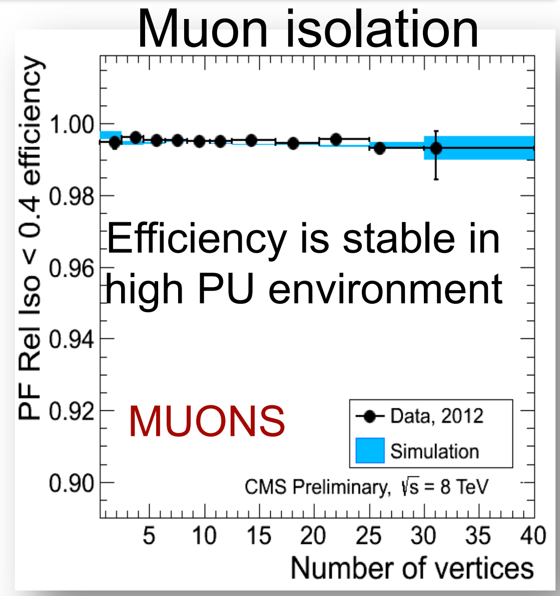
Pileup challenge

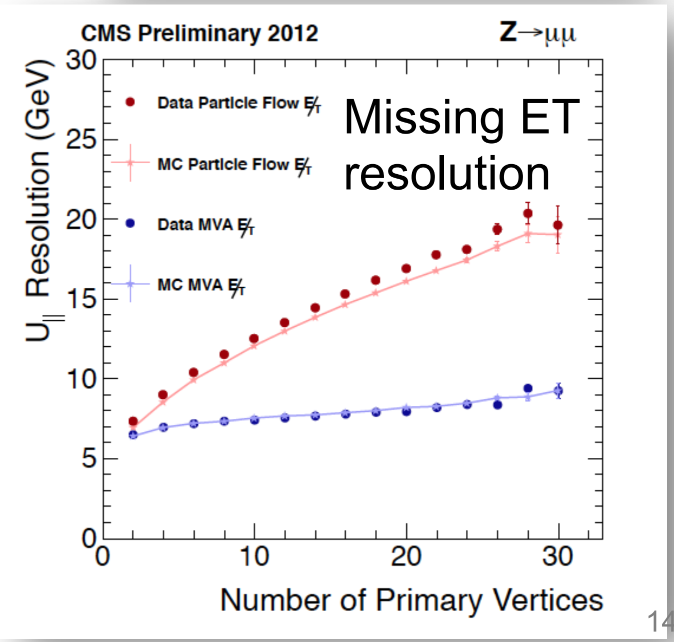
Reconstruction of hard collisions in high pileup environment requires detectors with very high granularity.

Physics with high pileup requires full particle flow reconstruction assuring:

- precise jet energy correction
- robust missing energy measurement
- efficient lepton isolation

Very efficient reconstruction code is needed to stay within computing budget

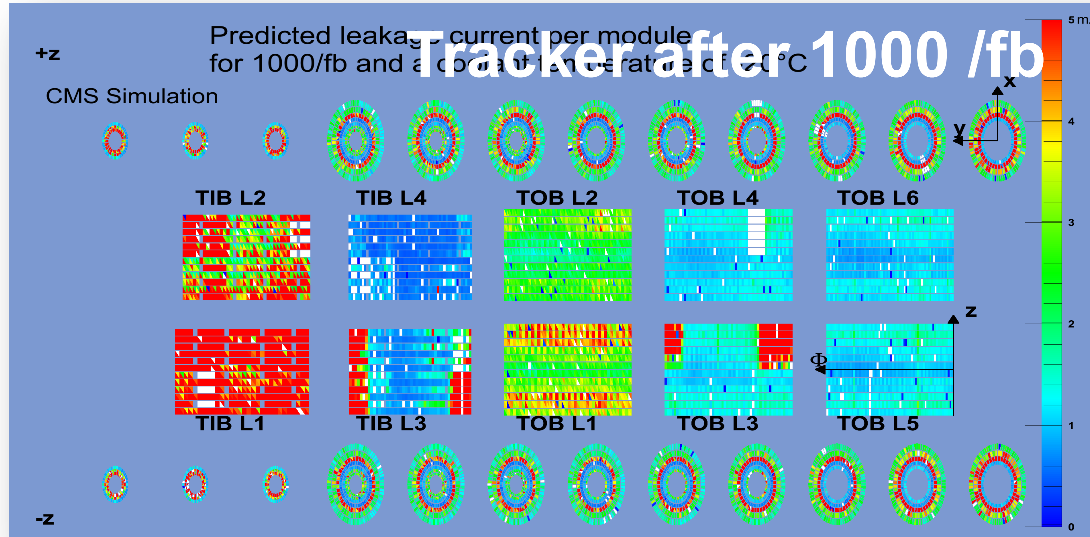




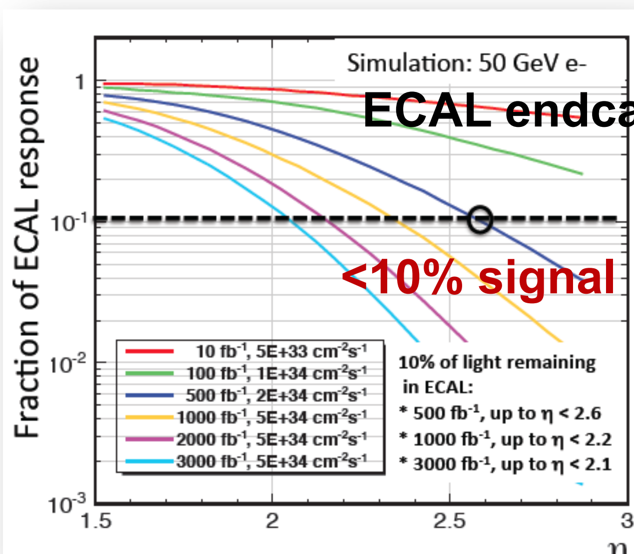
Radiation challenge

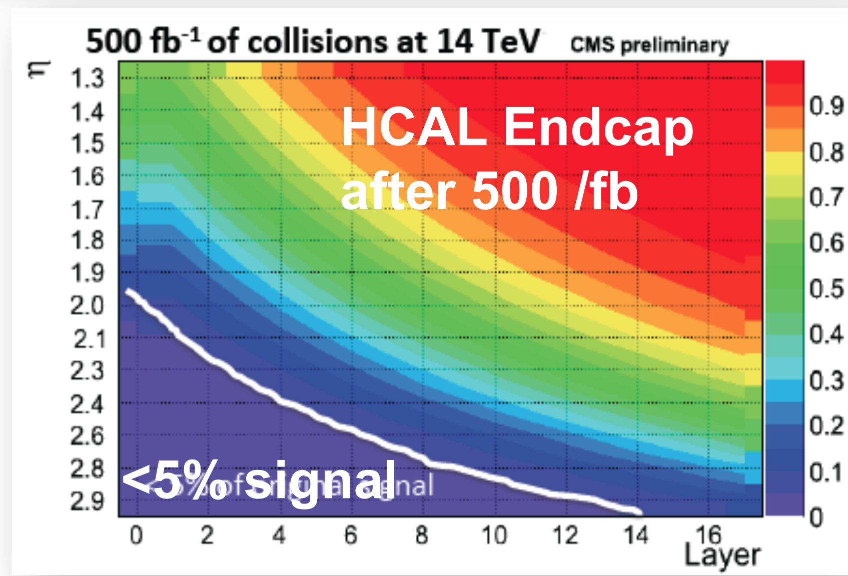
Present Tracker must be replaced after 500 /fb:

- Simulation of leakage currents and depletion voltages in Si Tracker using radiation model.
- Specification for leakage current was ≤ 1 mA



Present Endcap Calorimeters must be replaced after 500 /fb



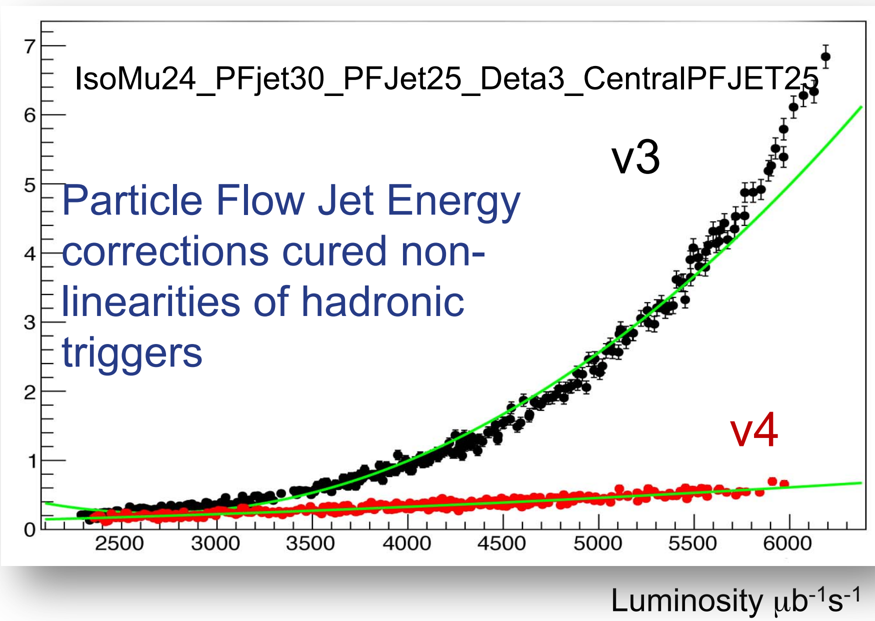


Trigger challenge

High trigger efficiency while keeping the trigger rate within budget was one of the biggest challenges of the CMS experiment in 2012

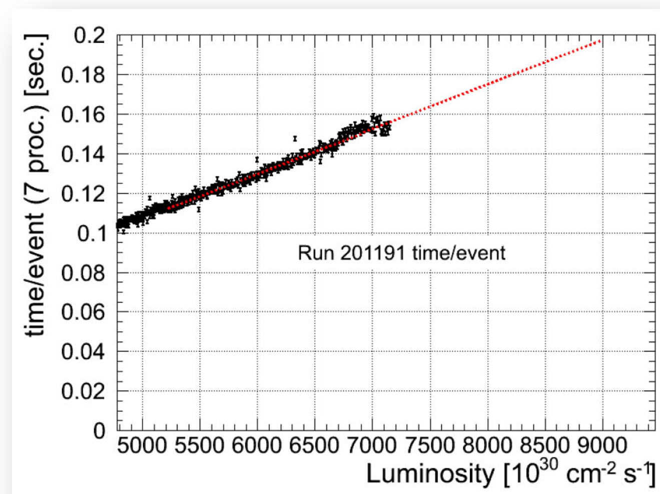
The experience obtained in 2012 with peak pileup of ~35 events gives confidence for high-luminosity running post Long Shutdown 1

Trigger Cross-sections:

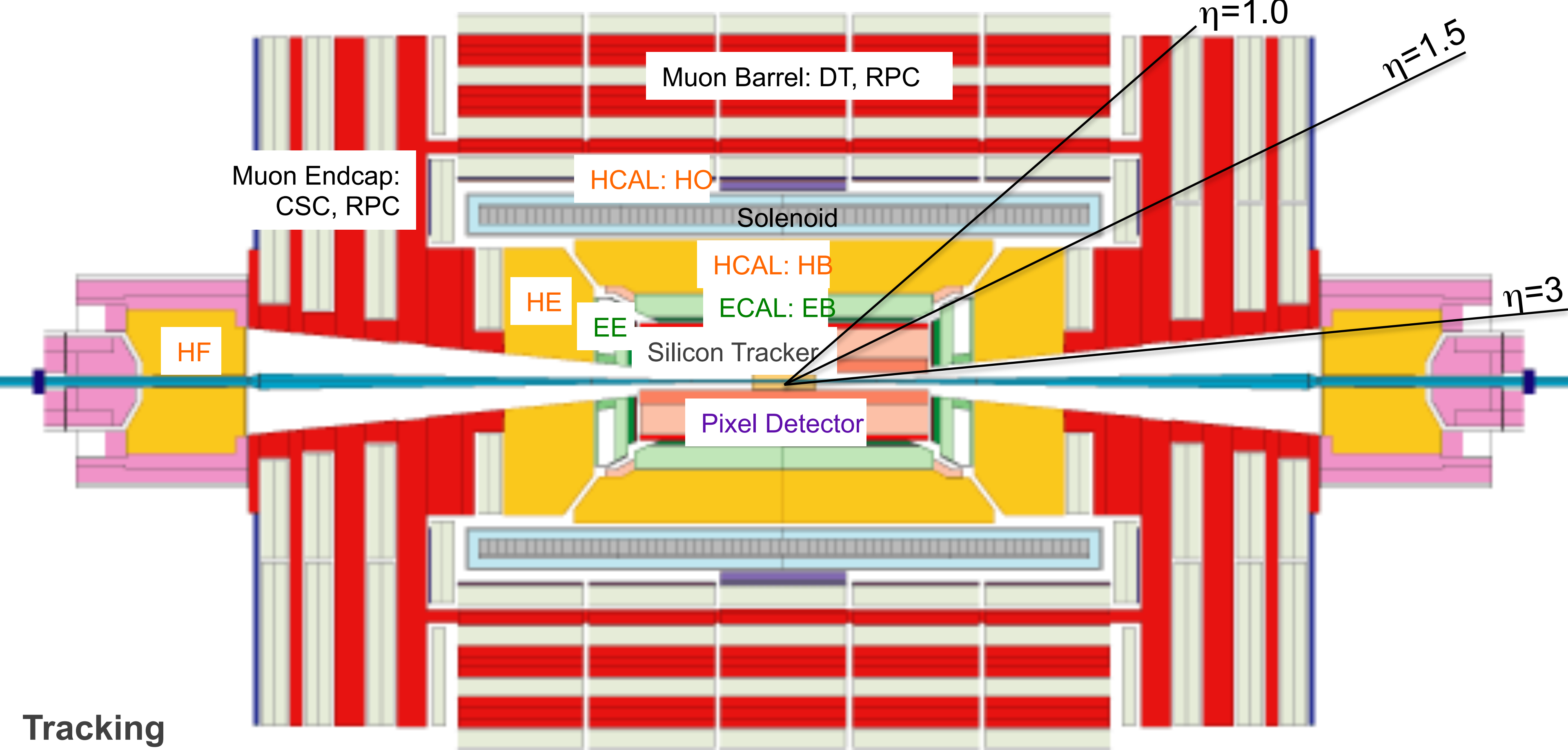


HLT CPU time:

- linear with PU, no sign of runaway



CMS Upgrades Programme



Tracking

More than 220m^2 surface and 76M channels (pixels & strips)
6m long, ~2.2m diameter
Tracking to $|\eta|<2.4$

ECAL

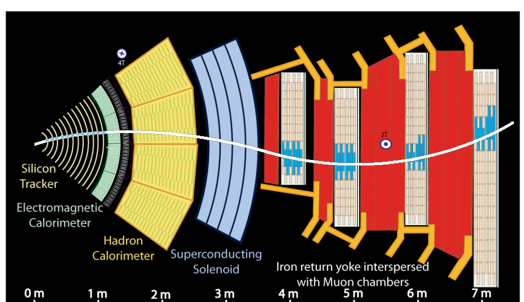
Lead Tungstate ($PbWO_4$)
EB: 61K crystals, EE: 15K crystals

HCAL

HB and HE: Brass/Plastic scintillator
Sampling calorimeter. Tiles and WLS fiber
HF: Steel/Quartz fiber Cerenkov calo.
HO: Plastic scintillator “tail catcher”

Muon System

Muon tracking in the return field
Barrel: Drift Tube & Resistive Plate Chambers
Endcap: Cathode Strip Chambers & RPCs



Trigger

Level 1 in hardware, 3.2μs latency ,100 kHz
ECAL+HCAL+Muon
HLT Processor Farm,1 kHz: Tracking , Full reco

CMS Upgrade Phases

LS1 Projects: Complete & consolidate detector for nominal LHC beam conditions
~13 TeV, 1 x Hz/cm^2 , <PU> ~25

- Completes muon coverage (ME4)
- Improve muon trigger (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD → SiPM)
- Preparatory work: New beam pipe; Tracker operation at -20◦C

Phase 1 Upgrades: 1.6 x 10^{34} Hz/cm^2 , <PU> ~40 by LS2, and 2.5 x 10^{34} Hz/cm^2, <PU> ~ 60, by LS3

- New L1-Trigger (2016)
- New Pixel Detector (2017)
- HCAL SiPMs and electronics

Phase 2 Upgrades: $\gtrsim$ 5 x 10^{34} Hz/cm^2 luminosity leveled, <PU> ~128

- New Tracker; forward pixels up η~4
- New Endcap Calorimetry
- New Muons stations at high η
- Further Trigger upgrade: Track Trigger

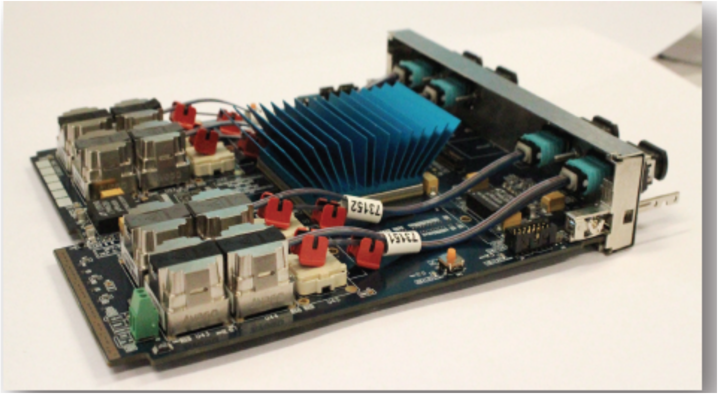
Phase 1 Upgrades – L1 Trigger

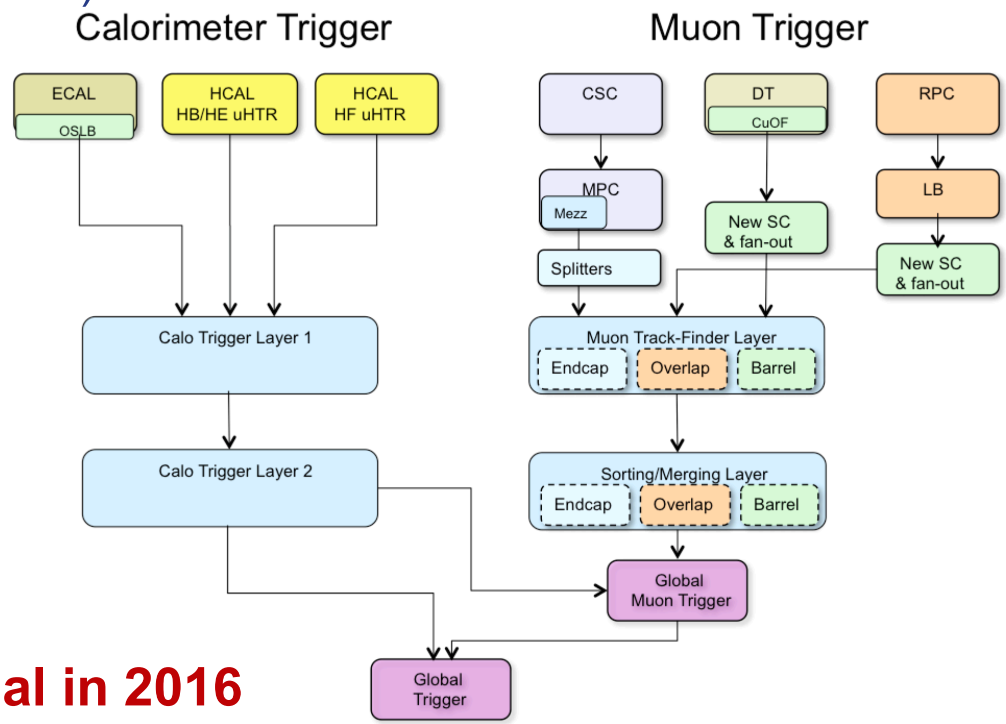
New trigger system based on powerful FPGAs and 10 Gb/s Optical Links in μTCA standard

Allows much improved algorithms for PU mitigation and isolation:

- Higher calorimeter granularity and improved algorithms
- Better muon reconstruction
- Global trigger with more inputs and algorithms for correlated quantities (e.g. invariant mass)

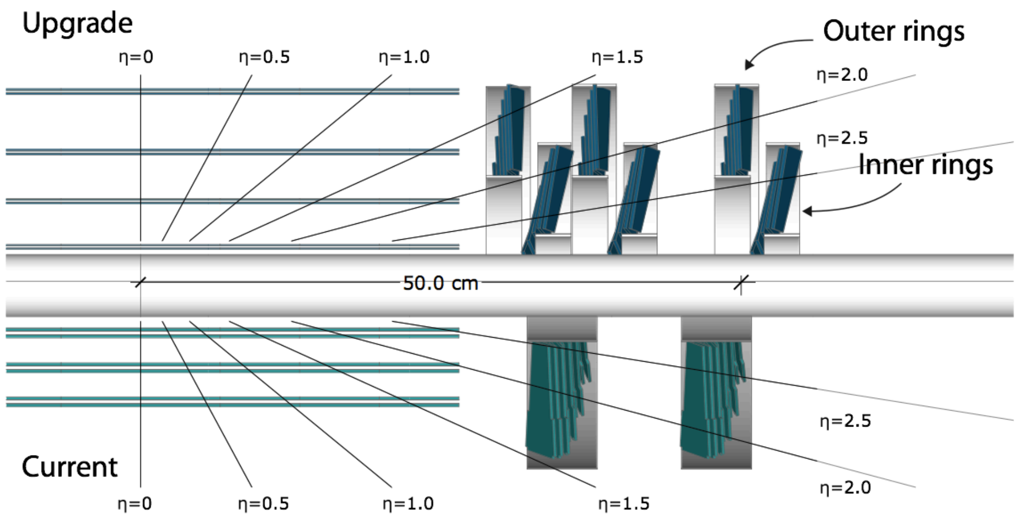
Entire upgrade of Calorimeter, Muon and Global triggers built with three types of boards.

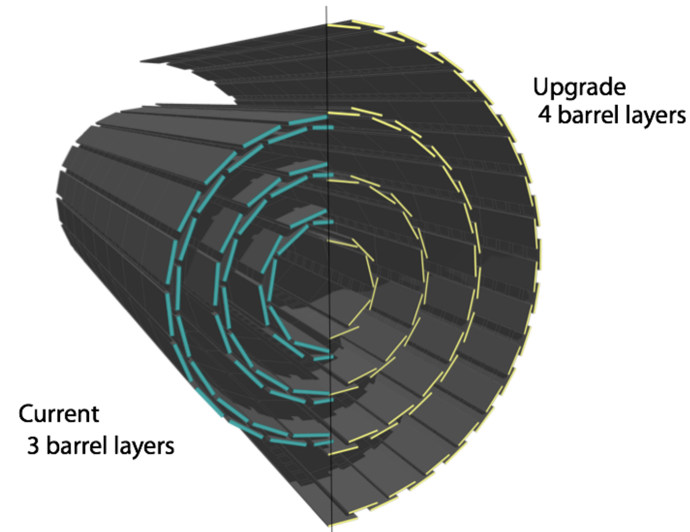




Expected to be fully operational in 2016

Phase 1 Upgrades – Pixel Detector





- **4 layers:** improved tracking efficiency (and lowers fake rate)
- **Less material**, better radial distribution
- **New readout chip** recovers inefficiency at high pileup

- Baseline L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & 25ns → 50 pileup
- Tolerate L = $2x10^{34}$ $cm^{-2}sec^{-1}$ & 50ns → 100 pileup
- Survive Integrated Luminosity of $500fb^{-1}$ (Layer 1 2x $250fb^{-1}$)

To be installed in Year End Technical Stop 2016-17

Phase 1 Upgrades – HCAL

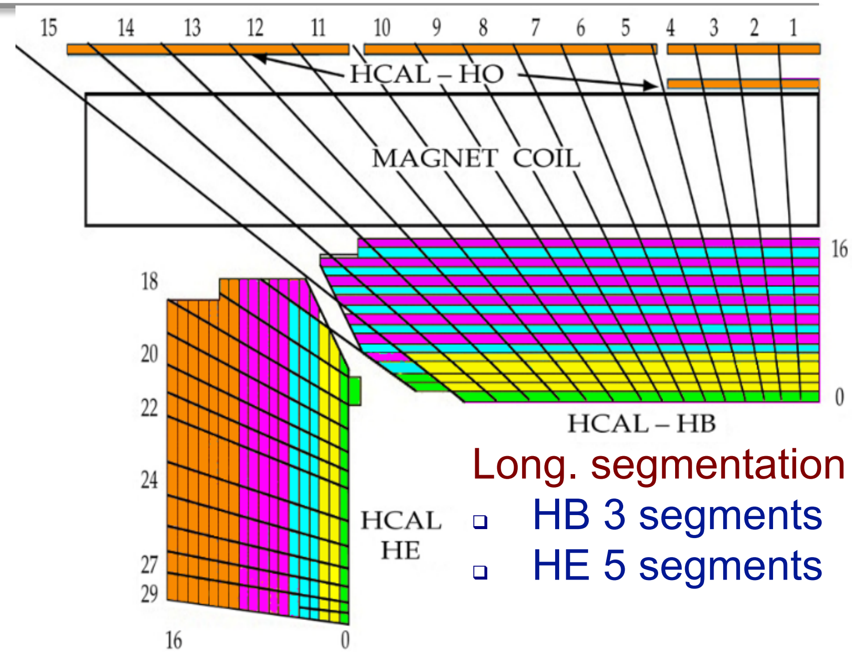
Replace HPDs in HB and HE with SiPMs

- Radiation tolerant, stable in magnetic field
- PDE improved x3, lower noise
- **Allows depth segmentation for improved measurement of hadronic clusters**

New readout chip (QIE10) with TDC

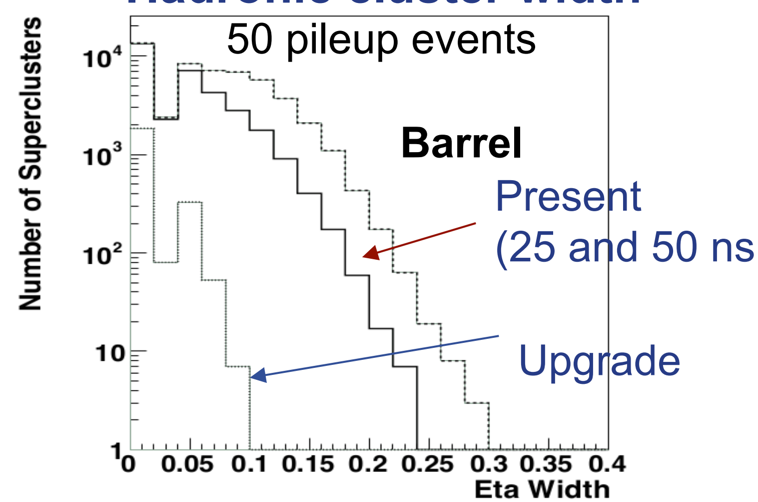
- Timing: improved rejection of beam-related backgrounds

Backend electronics upgrade to μTCA



Long. segmentation
- HB 3 segments
- HE 5 segments

Hadronic cluster width



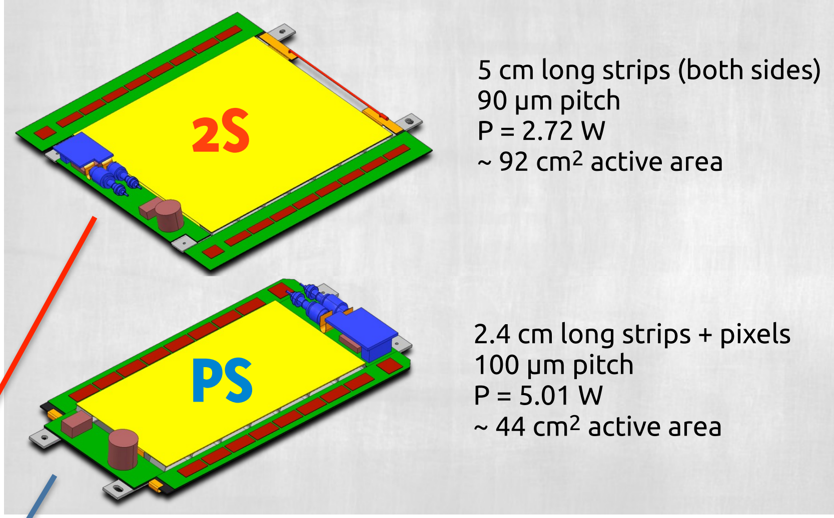
CMS phase 2 Upgrade

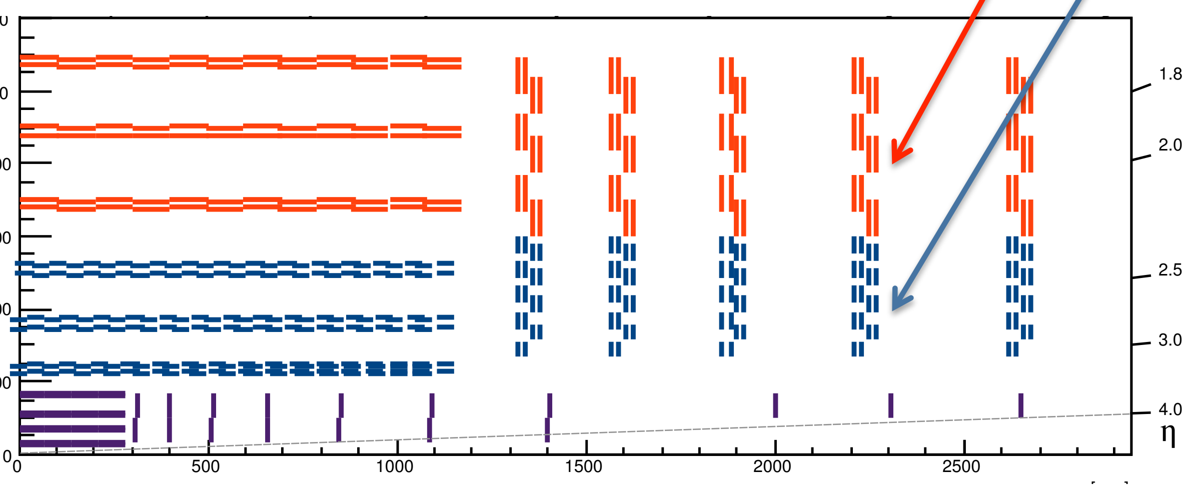
- Aiming operation at 5x LHC design luminosity and integrated luminosity of 3000 fb^{-1}
  - Event pileup reaches 125 collisions per beam crossing (@ 25 ns)
  - Present tracker and endcap calorimeters designed for radiation up to 500 fb^{-1} need to be replaced

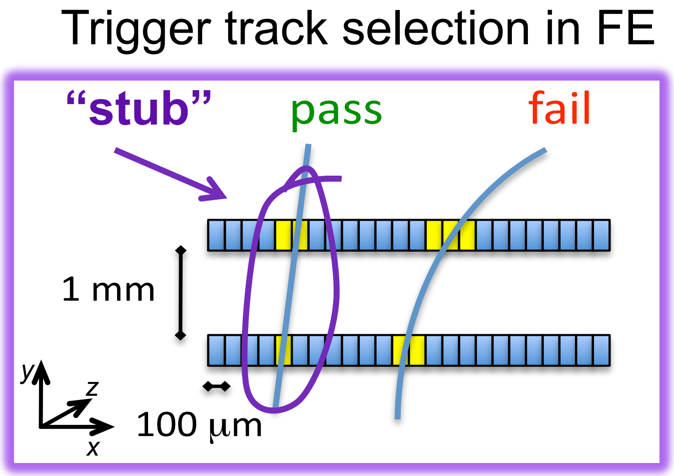
- **Main objectives of the Phase-2 Upgrade :**
  - **New Tracker** with increased resistance to radiation, extended to η=4 for VBF physics
    - The Phase 2 tracker design must maintain good performance at very high PU
  - **Trigger Upgrade** allowing to keep present acceptance for Higgs events
    - Addition of **Level1 Tracking Trigger** to reduce trigger rates
    - Increase data bandwidth to allow **L1 rate of 1 MHz**
  - **New endcap calorimeters** with increased resistance to radiation

Phase 2 Tracker: conceptual design

- **Outer tracker**
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor "Pt-modules" to provide trigger information at 40 MHz for tracks with Pt≥2GeV
- **Pixel detector**
  - Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to |η| = 4
  - Thin sensors 100 μm;
  - Smaller pixels 30 x 100 μm



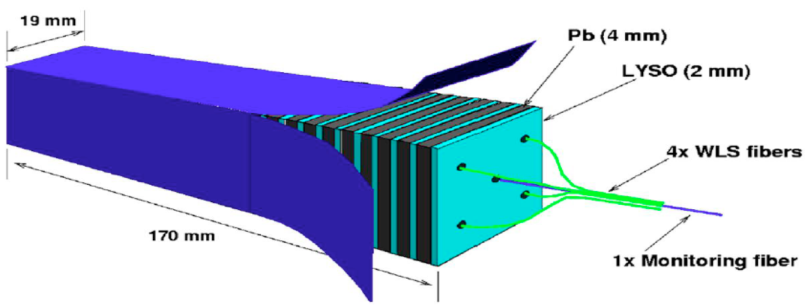


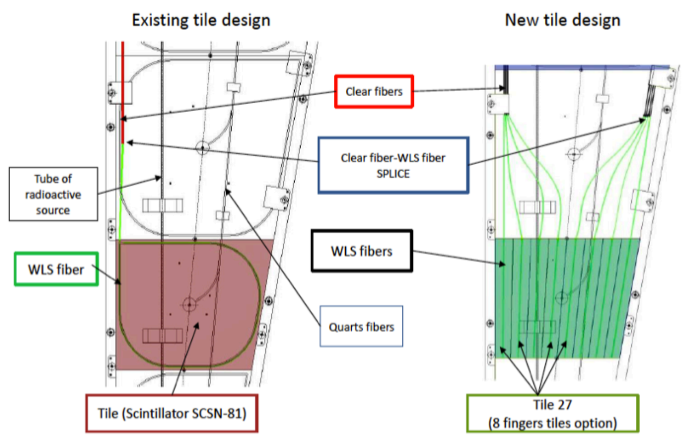


Phase 2 Endcap Calorimeters

Options under evaluation

- EE towers with Shashlik design (crystal scintillator: LYSO, CeF)
- Rebuild HE with more fibers, rad-hard scintillators
- Dual fiber read-out: scintillation & Cerenkov – following work of DREAM/ RD52
- Particle Flow Calorimeter (PFCAL) – following work of CALICE

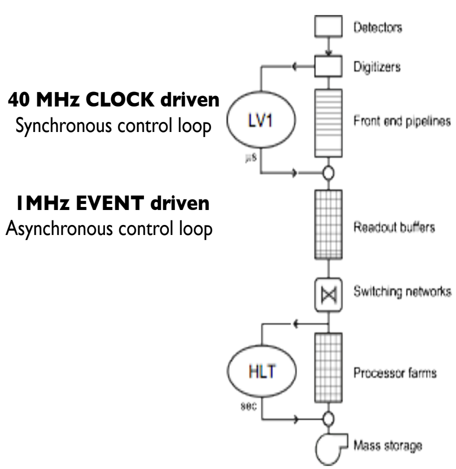




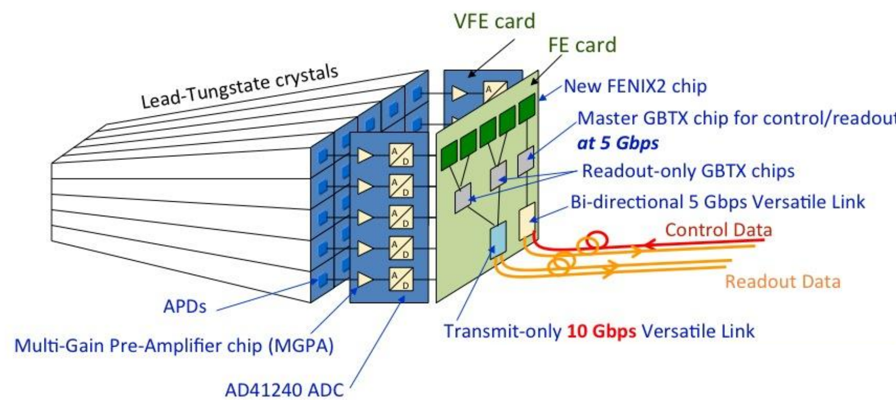
Phase 2 Trigger and DAQ

- The L1-trigger will build on the Phase 1 architecture, with
  - track information available to all trigger objects
  - increased granularity (EB at crystal level)
  - ability to operate up to 1 MHz

- HLT and DAQ will be upgraded to handle 10x trigger rates:
  - L1 rate=1 MHz and HLT rate=10 kHz
  - Same HLT rejection factor as present system
  - Require replacement of detector front-end electronics



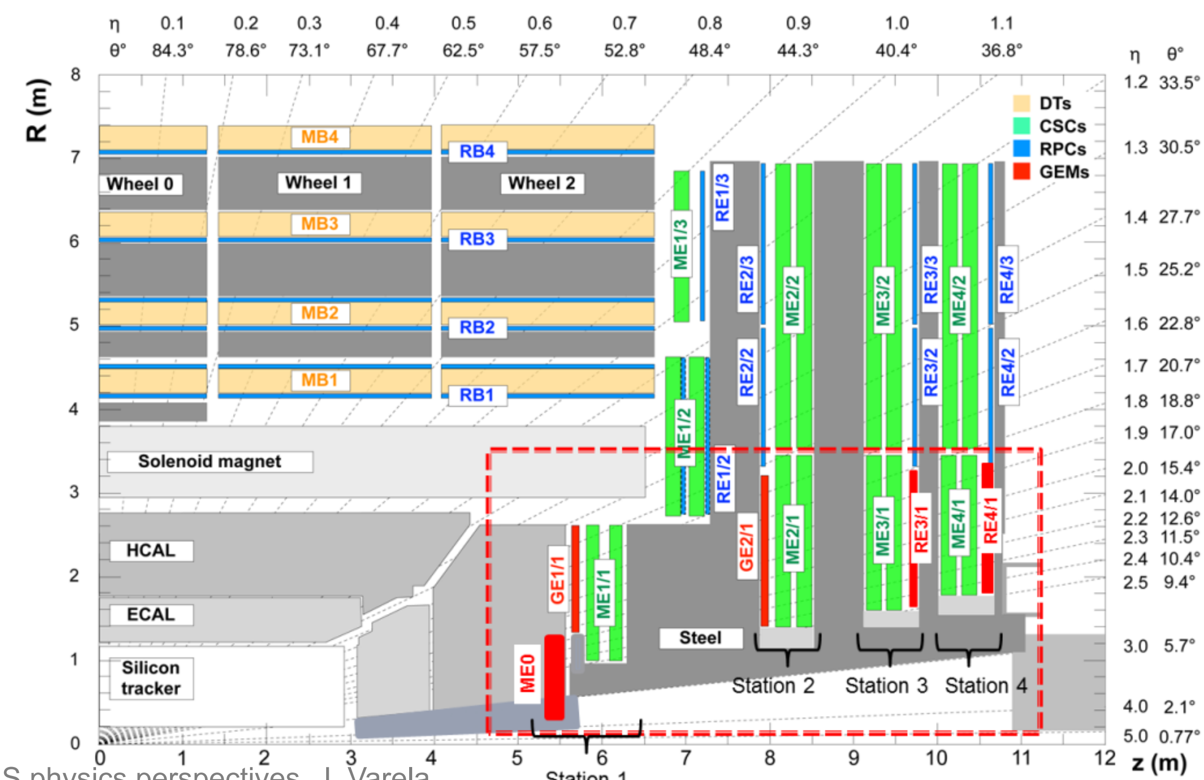
ECAL Barrel electronics



Muon systems

Improve trigger performance, and provide redundancy in the high rate, high occupancy forward region

- Concept under study to complete muon stations at $1.6 < |\eta| < 2.4$
  - GEM (2 first stations) and Glass-RPC (2 last stations)
- Investigating increase of the muon coverage beyond $|\eta| \sim 2.4$ with GEM tagging station (ME0)

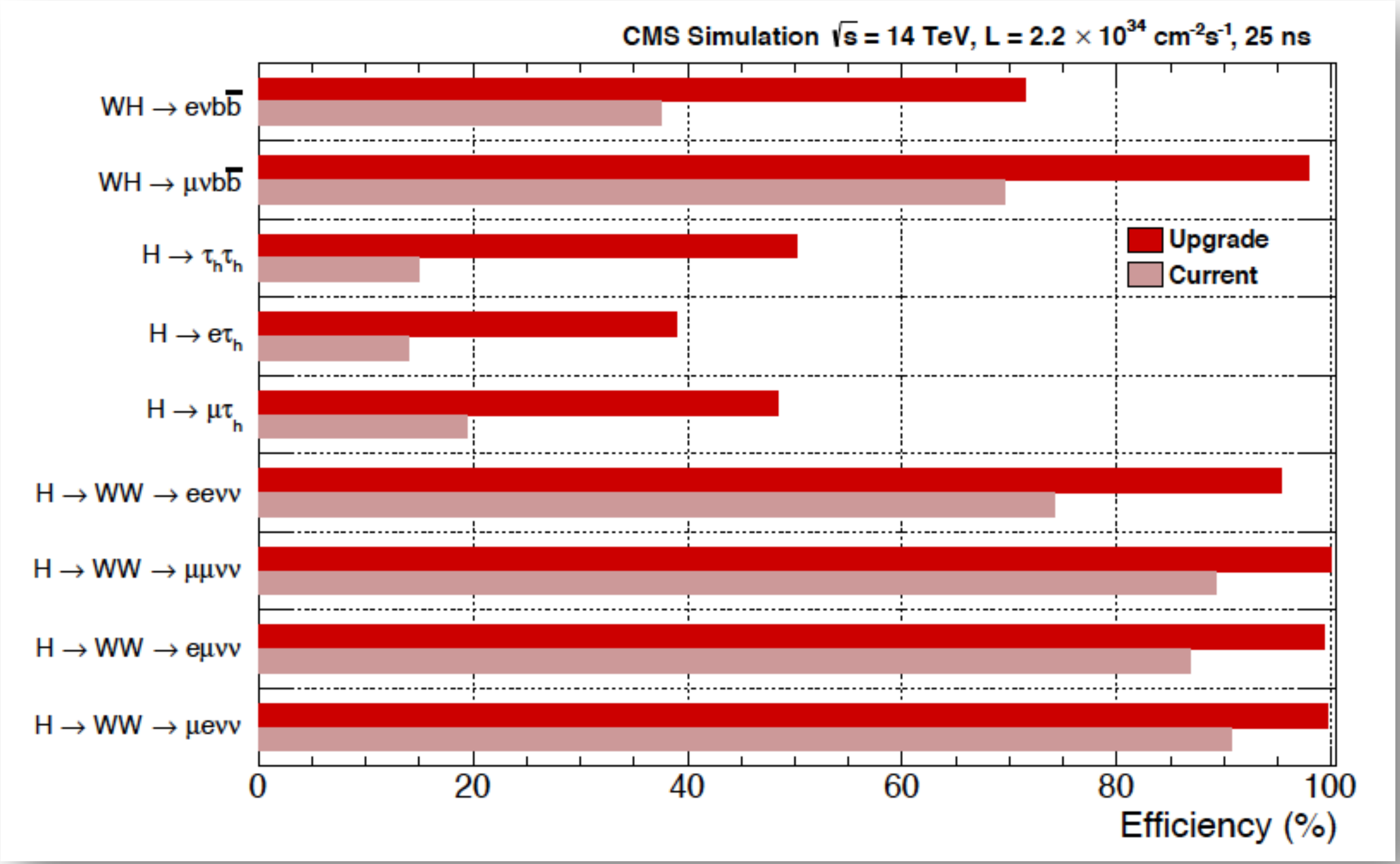


Physics projections

Phase 1 Trigger performance

Phase 1 Trigger efficiency for Higgs events compared to current trigger assuming $2.10^{34}cm^{-2}s^{-1}$ (50 PU events)

- Efficiency for **H decaying in tau pairs is increased by a factor ~2.5**



Phase 1 performance: H → ZZ → 4l

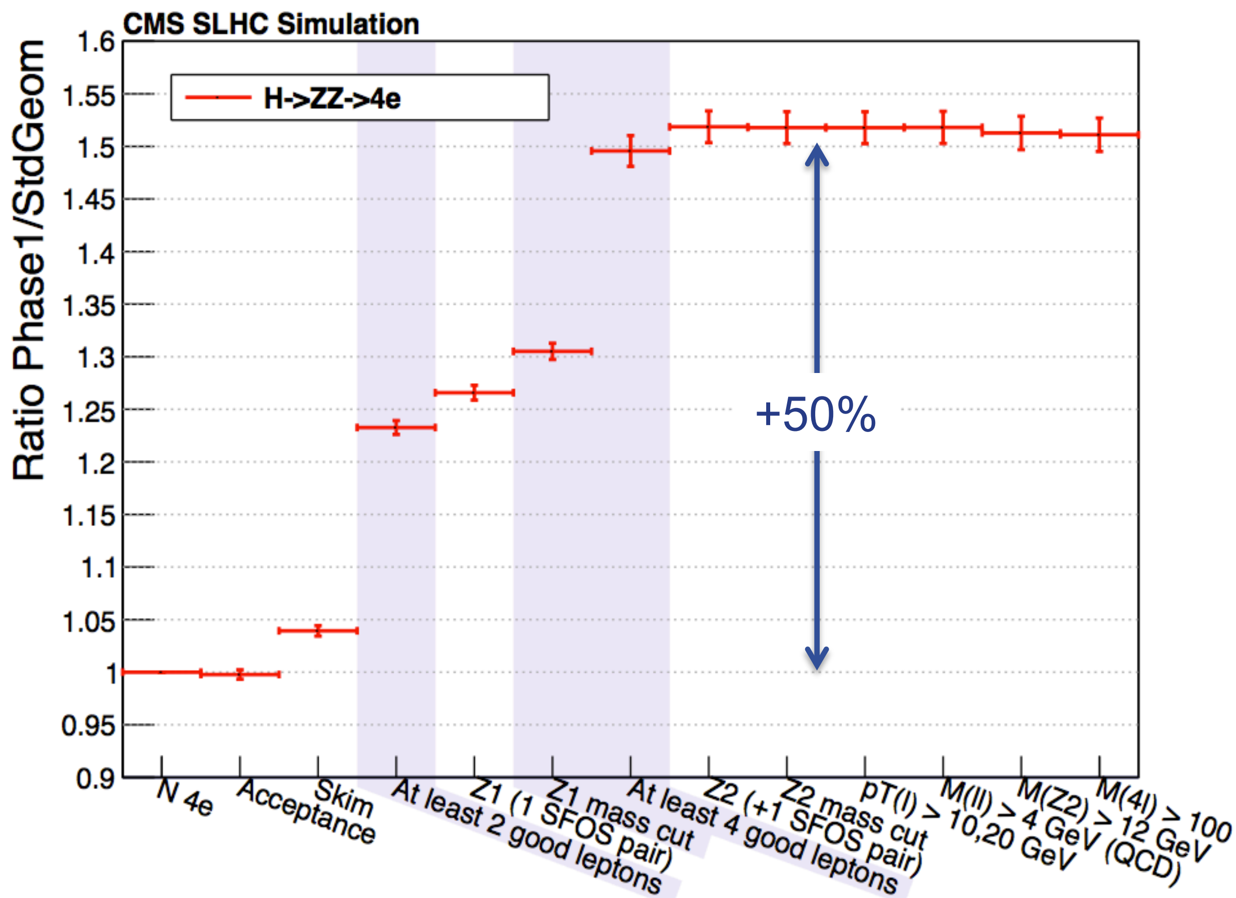
H → ZZ →4l

is sensitive to lepton tracking and isolation efficiency

Significant gain in signal reconstruction efficiency:

H→ 4μ +41%
H→ 2μ2e +48%
H→ 4e +51%

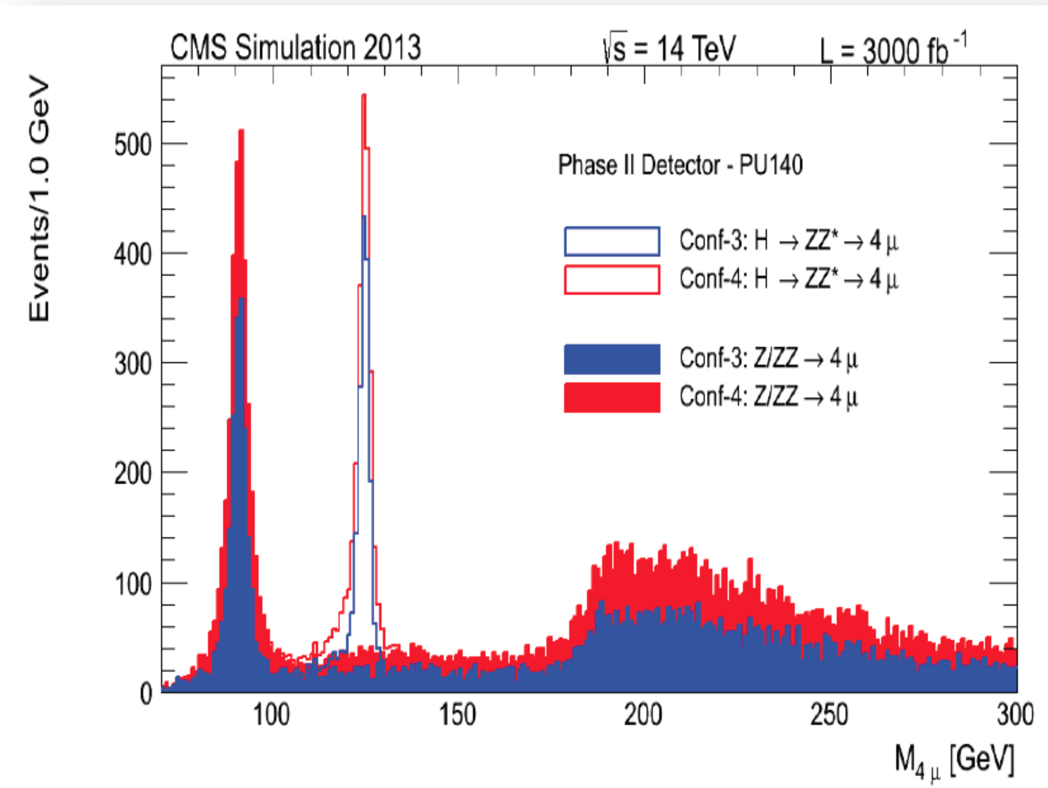
Improved signal yield (relative to current detector):



Detector acceptance and H → ZZ → 4l

Two Phase II detector configurations are considered:

- **Configuration 3: same angular acceptance** as the current version of the detector
- **Configuration 4:** tracking, electromagnetic and hadronic calorimeters as well as the muon detector acceptance, up to η **= 4.0**



Acceptance up to a η = 4.0, provides a relative selection **efficiency increase of ~ 40%,**

despite the much larger pileup value of 140 events expected at HL-LHC.

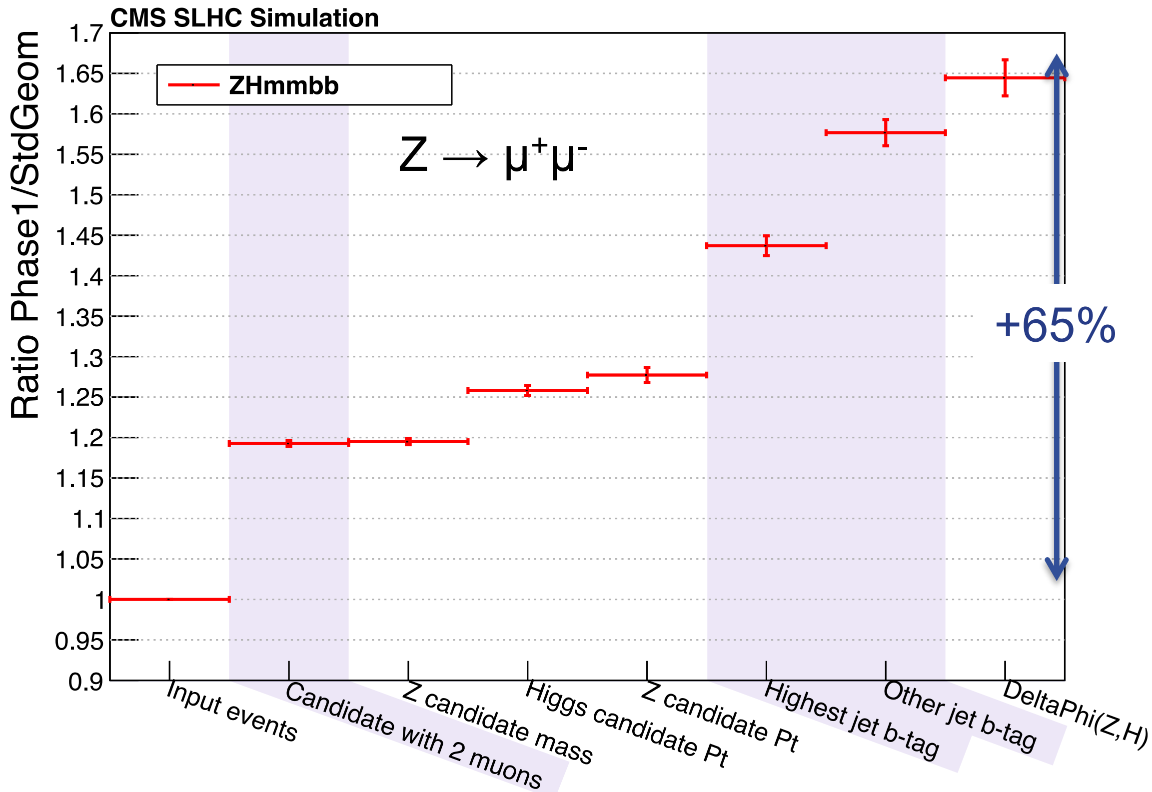
Study for Phase 2 Upgrade

Phase 1 performance: ZH → l^+l^- bb

Improved signal yield (relative to current detector):

ZH → l^+l^- bb requires

- High muon ID efficiency
- High b-tagging efficiency
- Good dijet mass resolution



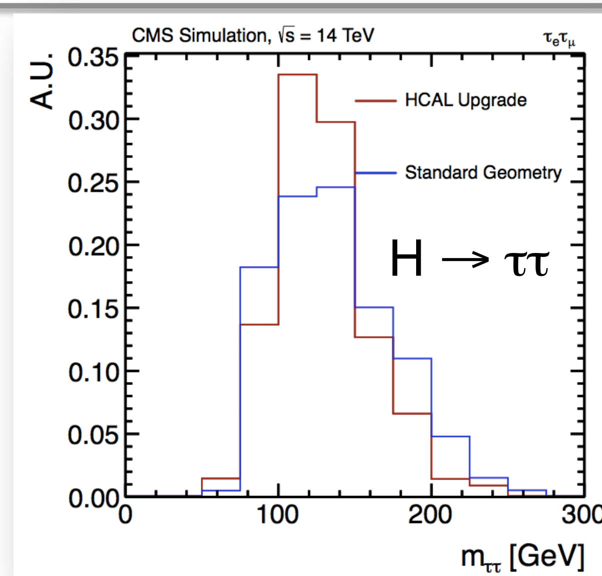
Both lepton channels (μμ, ee) show gain of 65% in signal efficiency for upgraded system.

Phase 1 performance: H → ττ

H → ττ (including VBF) requires

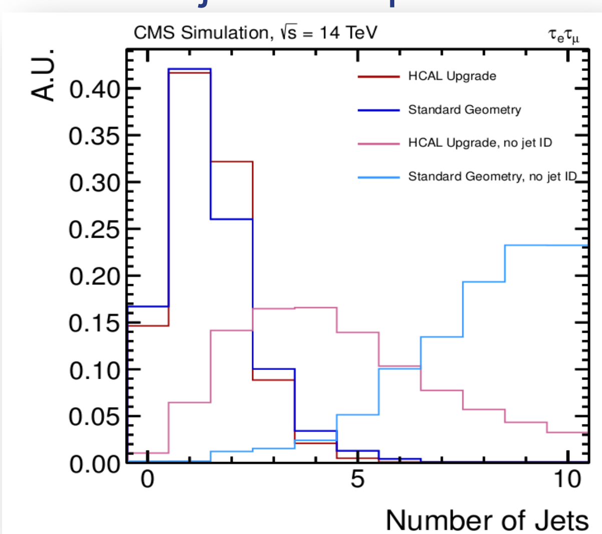
- good MET resolution
- forward jet tagging capability
- efficient lepton identification

Total efficiency improvement by factor of 2.5

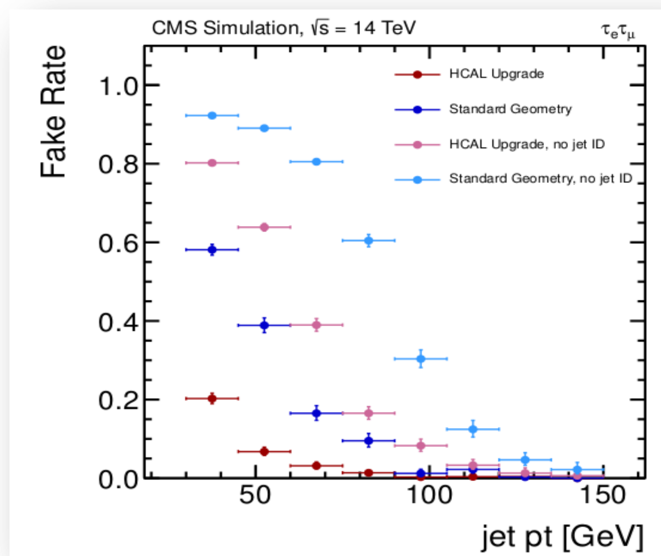


Improved jet and MET resolution allows 25% improvement in $m_{\tau\tau}$ resolution

Efficiency of identifying true tag jets is improved

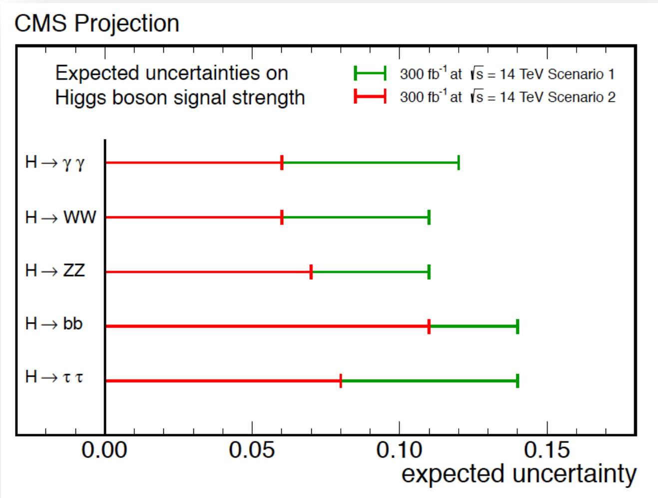


Significant reduction in jet fake rate



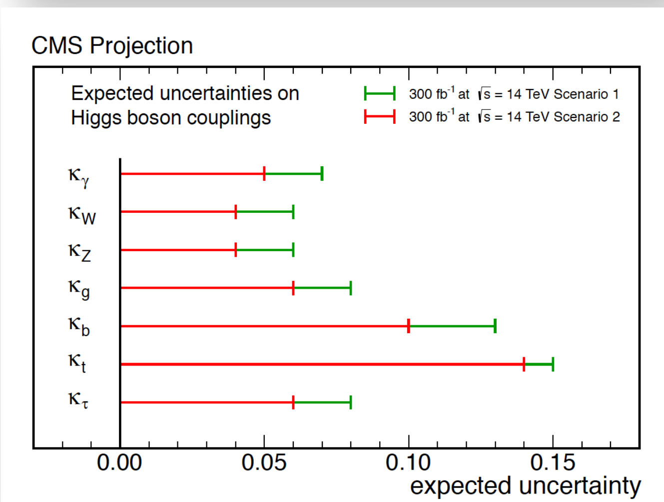
Higgs couplings with 300 fb^{-1}

- Scenario 1: same systematics as in 2012
- Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by 1/√L



Detector and trigger performances of Upgraded detector at PU=50 is assumed the same as Current detector in Run1

With 300 fb^{-1} the precision of signal strength is expected **6-14% per channel**



The uncertainties of the Higgs couplings are expected in the ranges:

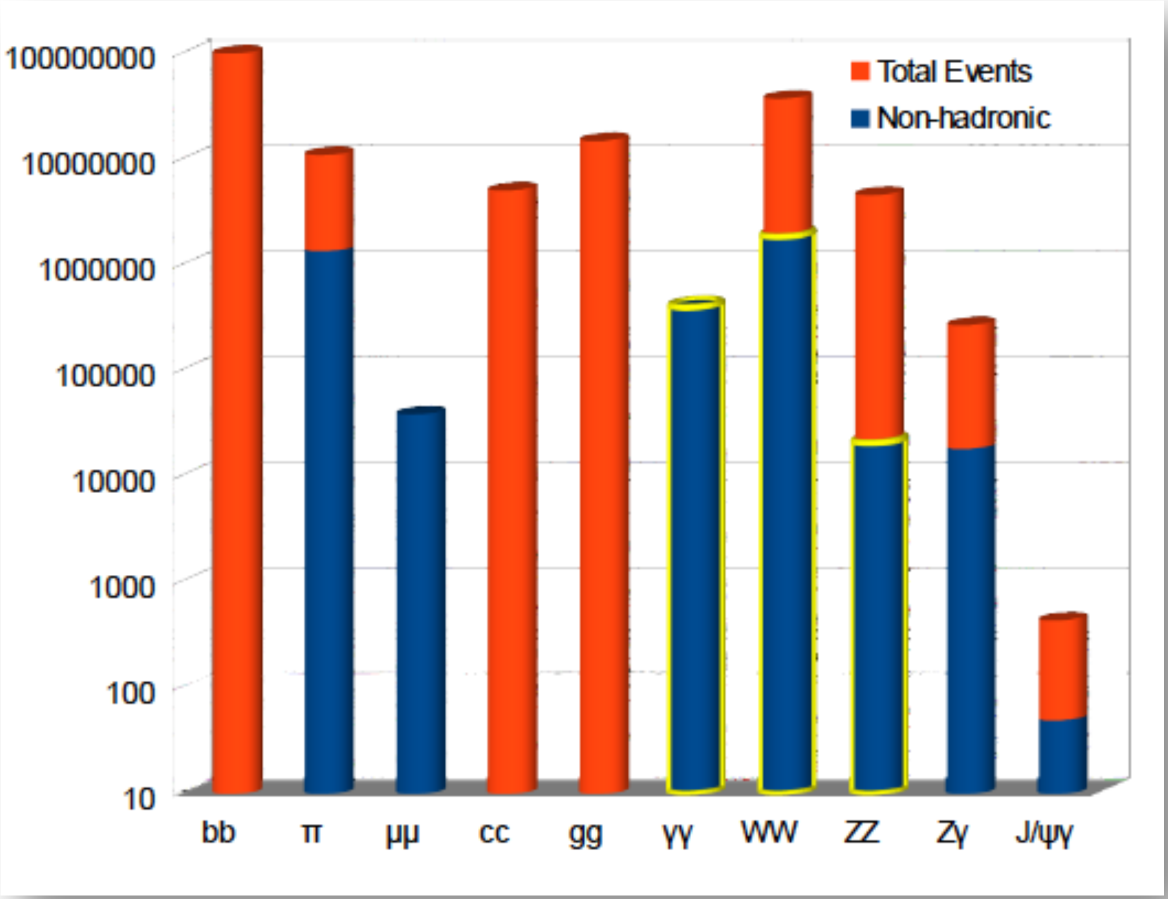
$\sigma(\kappa_V) \sim$ 4-6%

$\sigma(\kappa_t) \sim$ 14-15%

HL-LHC is a Higgs factory

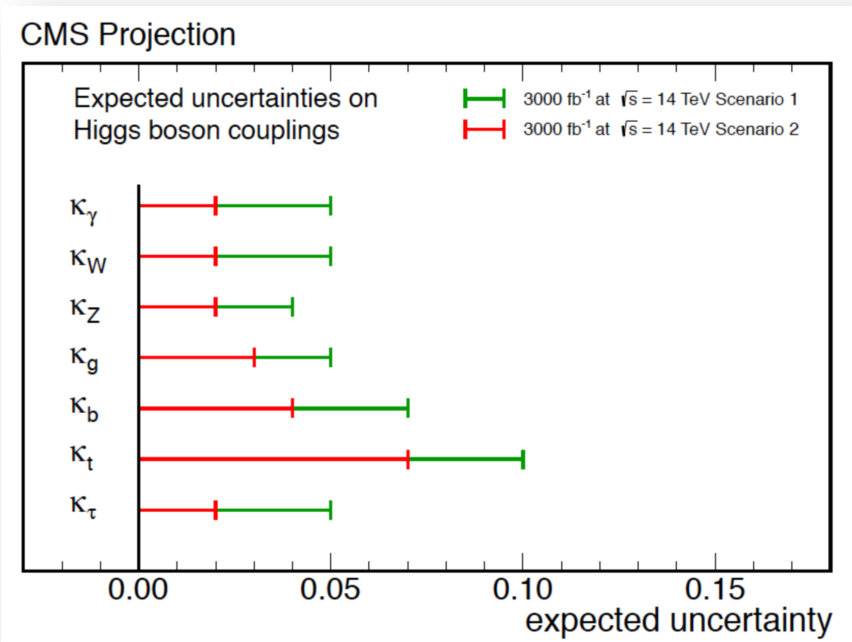
Over 100M Higgs bosons
- 400K $H\rightarrow\gamma\gamma$
- 20K $H\rightarrow ZZ\rightarrow llll$

14 TeV, 3000 fb^{-1}



Higgs couplings with 3000 fb^{-1}

- With 3000 fb^{-1} most Higgs couplings can possibly be determined with high precision (2-3%)
- Coupling to top and invisible width can be measured with precision ~10%



The decay $H \rightarrow \mu\mu$ can be observed with a significance of 5 sigma

Coupling to μ can be measured with a precision of ~10%

Scenario 1:
- 2012 systematics

Scenario 2:
- theory syst: scaled by a factor ½
- other systematics scaled by $1/\sqrt{L}$

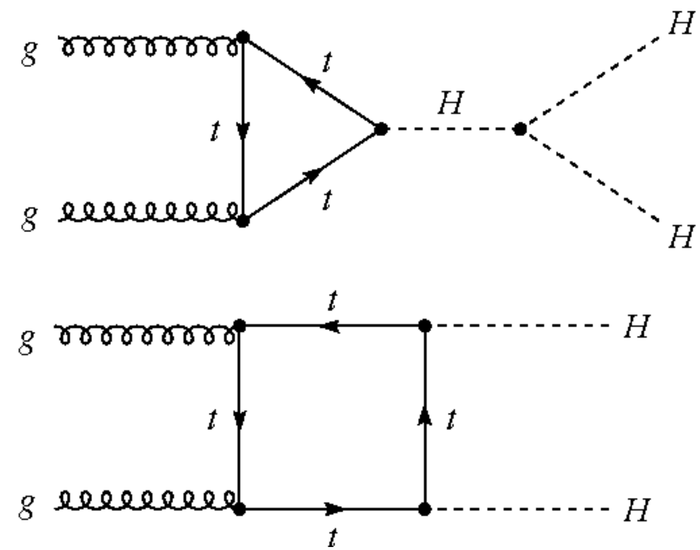
L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	BR_{inv}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[7, 11]

Higgs self-coupling

To demonstrate the Higgs potential we need to measure the self-coupling.

The observation of Higgs pair production is possible:

- expected σ_{HH}=40fb → 120K events



Both the above diagrams contribute

- negative interference

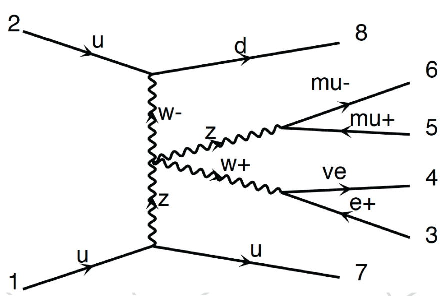
Very demanding on luminosity and detector performance

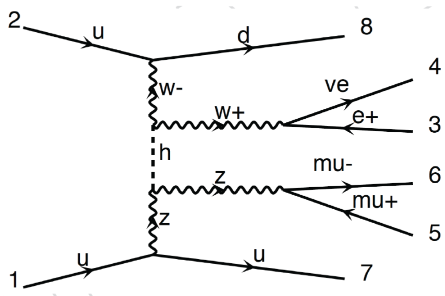
Expected numbers of HH events (for 3000 fb^{-1}):

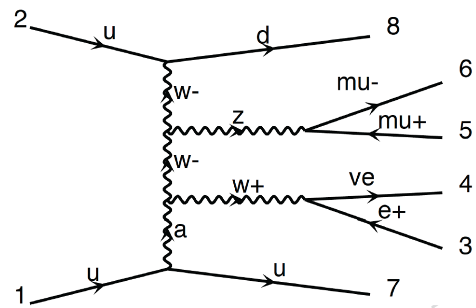
HH→bbWW	30000
HH→bbττ	9000
HH→WWWW	6000
HH→γγbb	320
HH→γγγγ	1

Vector Boson scattering

- Gives access to anomalous contributions to quartic gauge couplings (aQGCs)
- New physics contributions are studied using an effective field theory approach: $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$



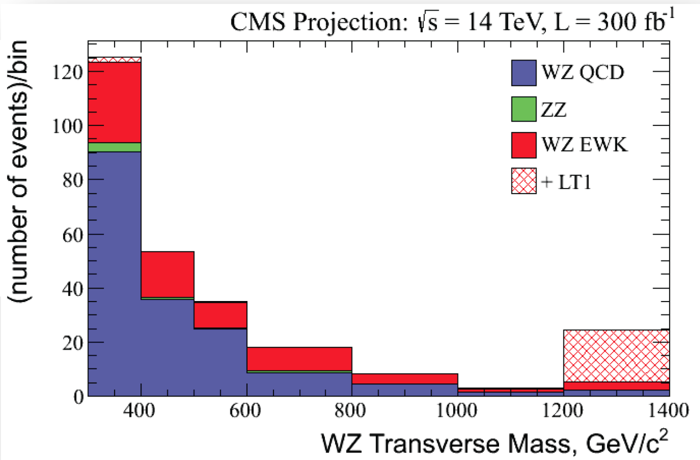




WWZZ coupling:

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
$\frac{f_{T1}}{\Lambda^4}$ at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}
$\frac{f_{T1}}{\Lambda^4}$ at 3000 fb^{-1}	0.45 TeV^{-4}	0.55 TeV^{-4}

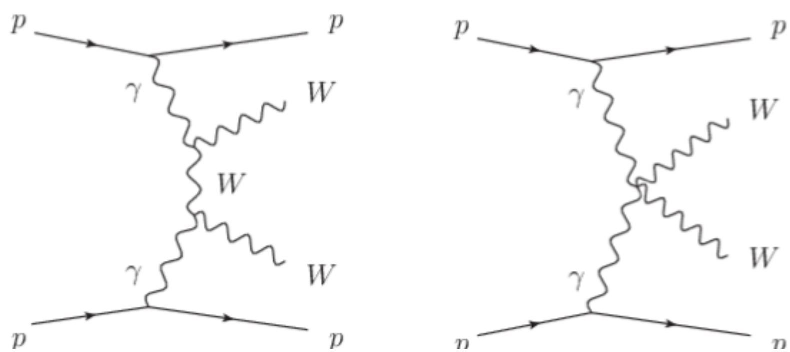
BSM contribution at TeV scale might be observed at 300 fb^{-1}



WWγγ coupling in CEP

Central Exclusive Production of W pairs : **p p → p p WW**

- Protons measured in **Forward Proton Spectrometer**
- WW measured in the central region
- Four-momentum of WW is fully constrained by the two protons kinematics



Expected sensitivity to anomalous quartic coupling WWγγ:

GeV^{-2}	a_0^W/Λ^2 Sensitivity	
	5σ	95% C.L.
$\mathcal{L} = 40\ fb^{-1}, \mu = 23$	$5.5\ 10^{-6}$	$2.4\ 10^{-6}$
$\mathcal{L} = 300\ fb^{-1}, \mu = 46$	$3.2\ 10^{-6}$	$1.3\ 10^{-6}$

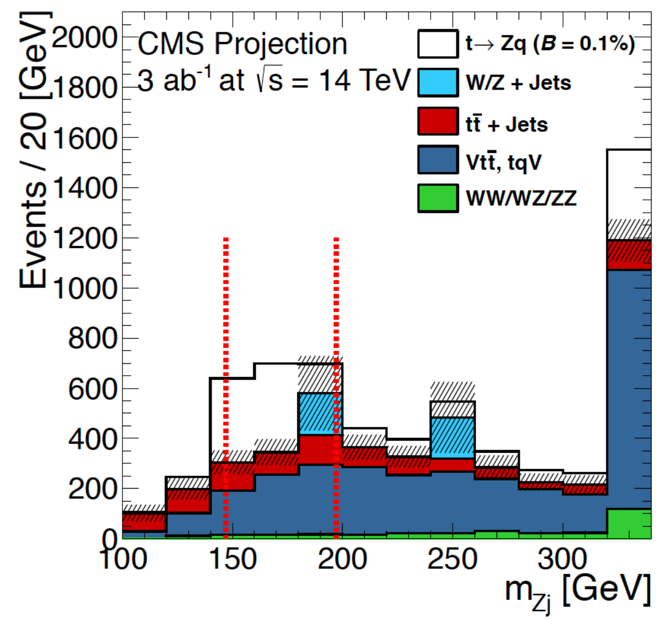
σ (SM) = 96fb

Sensitivity to anomalous couplings at TeV scale with 300 fb^{-1}

$10^{3\text{-}4}$ times better than the limits established at LEP and Tevatron

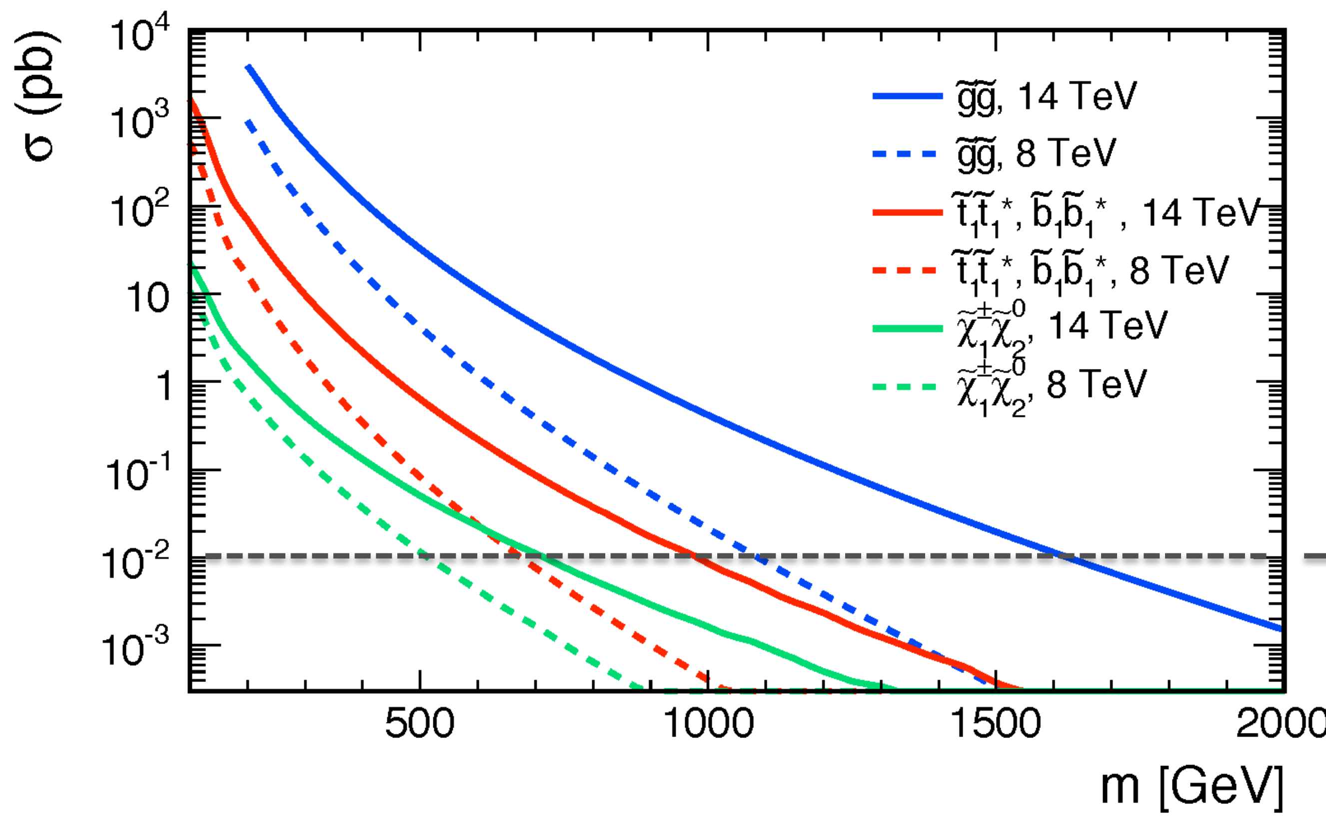
Top FCNC with 3000 fb^{-1}

- In some BSM models BR($t \rightarrow Zq$) could be as large as O(10^{-4}).
- CMS result with 8 TeV data:
  BR < 7. 10^{-4} at 95% CL
- Projection of searches for $t \rightarrow Zq$ decays in ttbar events with Phase II detector (Config 4)



$\mathcal{B}(t \rightarrow Zq)$	19.5 fb^{-1} @ 8 TeV	300 fb^{-1} @ 14 TeV	3000 fb^{-1} @ 14 TeV
Exp. bkg. yield	3.2	26.8	268
Expected limit	< 0.10%	< 0.027%	< 0.010%
1 σ range	0.06 – 0.13%	0.018 – 0.038%	0.007 – 0.014%
2 σ range	0.05 – 0.20%	0.013 – 0.051%	0.005 – 0.020%

SUSY cross-section



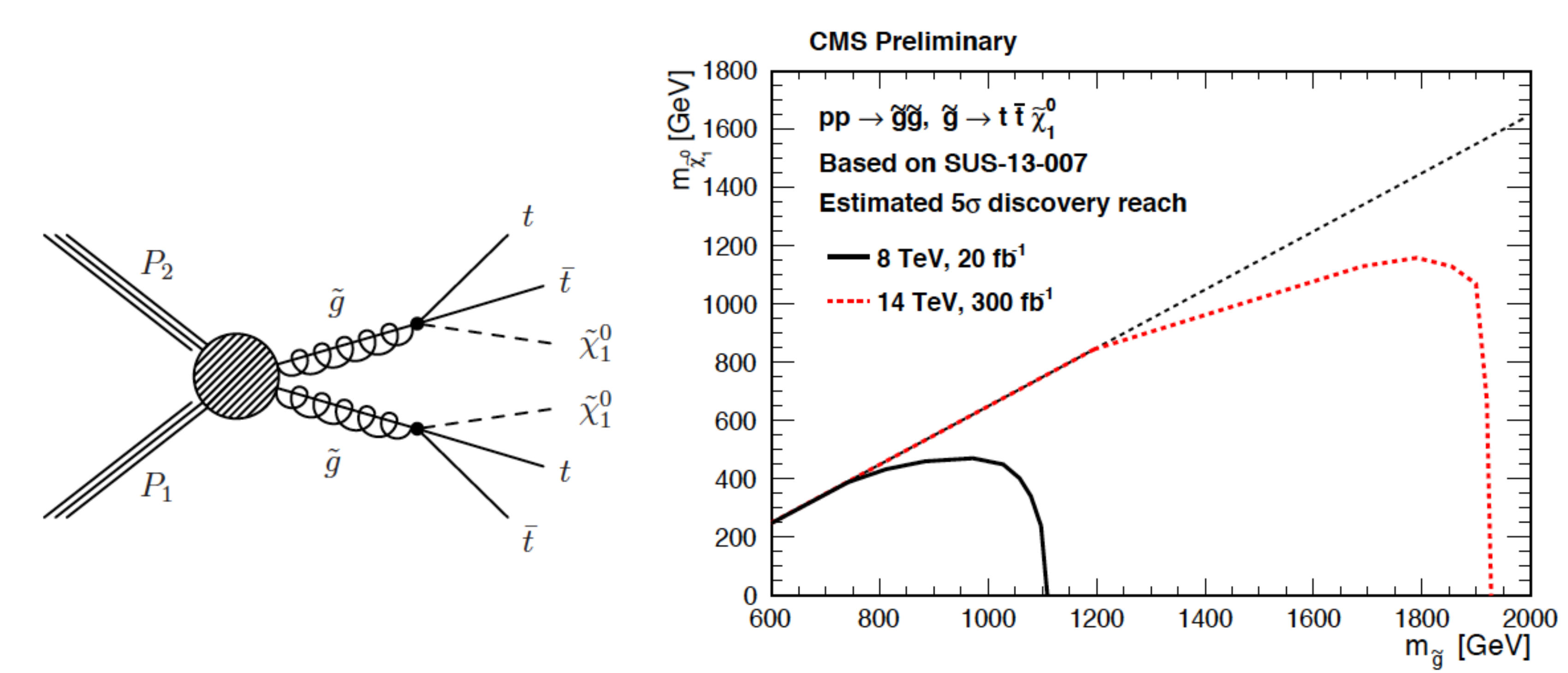
30 k events at 3000 fb^{-1}

Production cross sections of neutralino/chargino ~500 GeV and stop ~1 TeV are very small

gluino → stop searches with 300 fb^{-1}

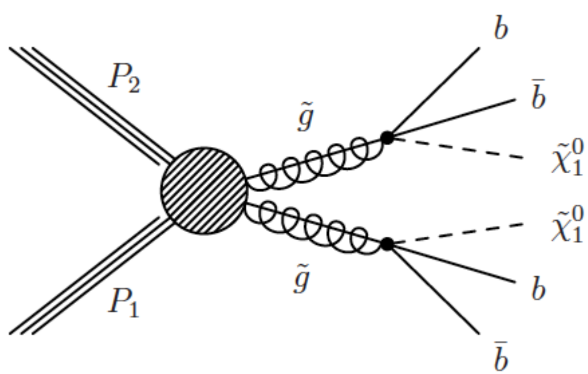
General SUSY searches: Simplified Model Spectra (SMS)

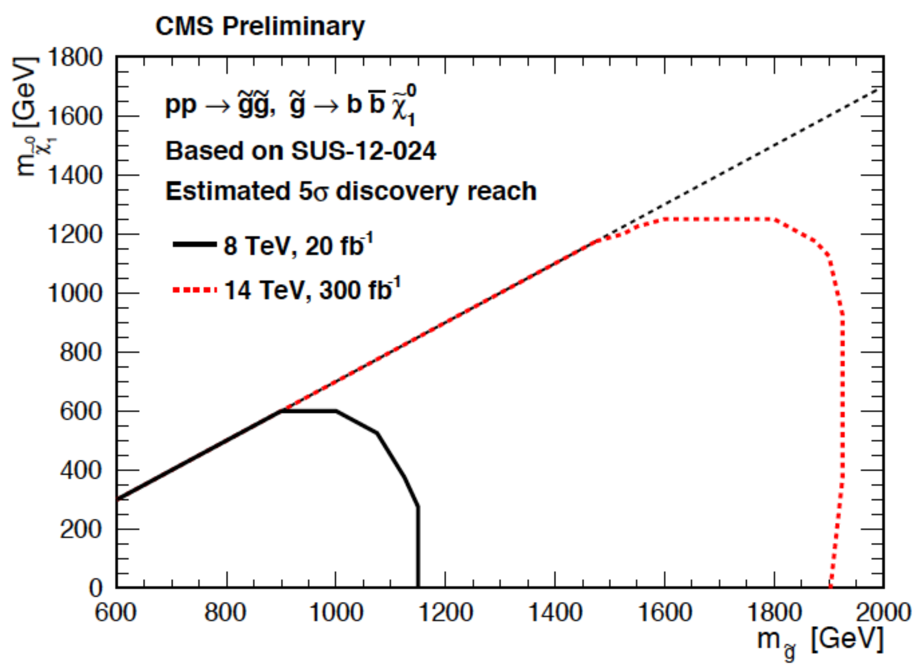
- Gluino production, where the gluinos decay to two top quarks and an LSP each
- Projection based on the 8 TeV search in events with a single lepton, multiple jets, and b-tags (CMS-PAS-SUS-13-007)



gluino → sbottom searches with 300 fb^{-1}

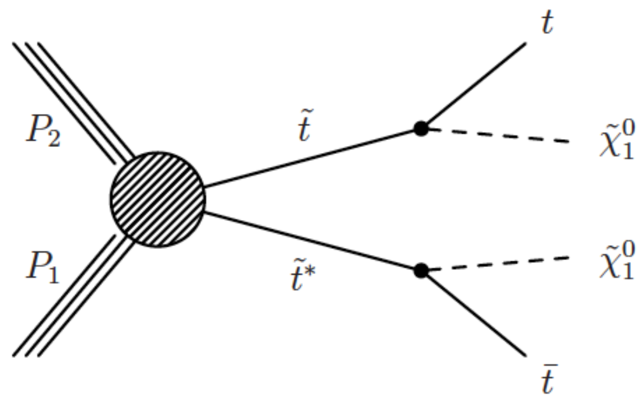
- Gluino production, where the gluinos decay to two bottom quarks and an LSP each
- Projection based on the 8 TeV search in events with multiple jets, large missing transverse energy, and b tags (CMS-SUS-12-024)

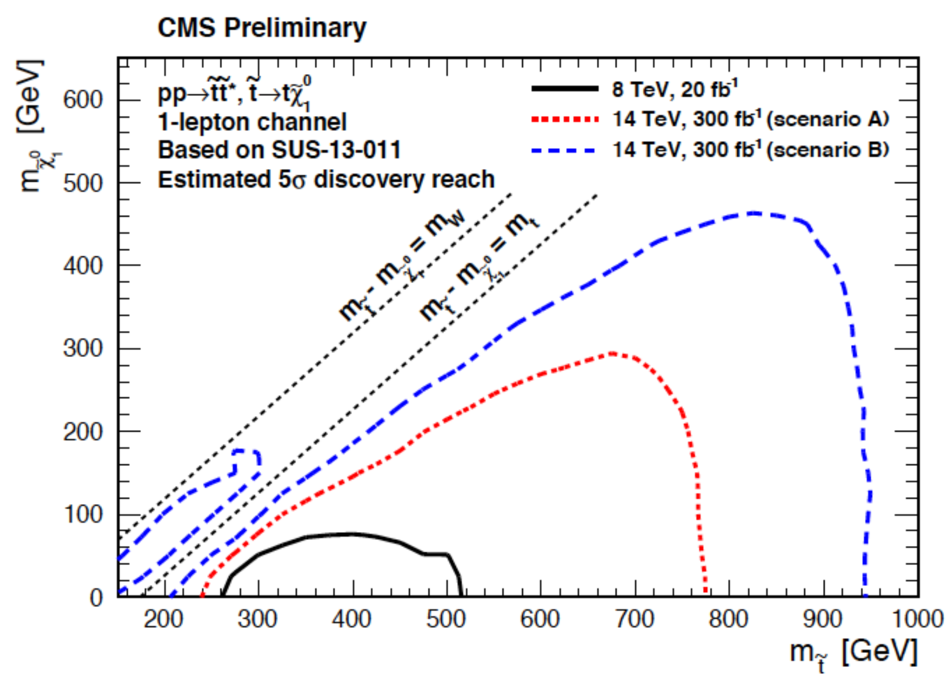




Direct stop production with 300 fb^{-1}

- Direct stop production: the stops decay to a top quark and an LSP each
- The projection is based on the search in the single lepton final state (CMS-SUS-13-011)
- Two scenarios for the systematic uncertainties.

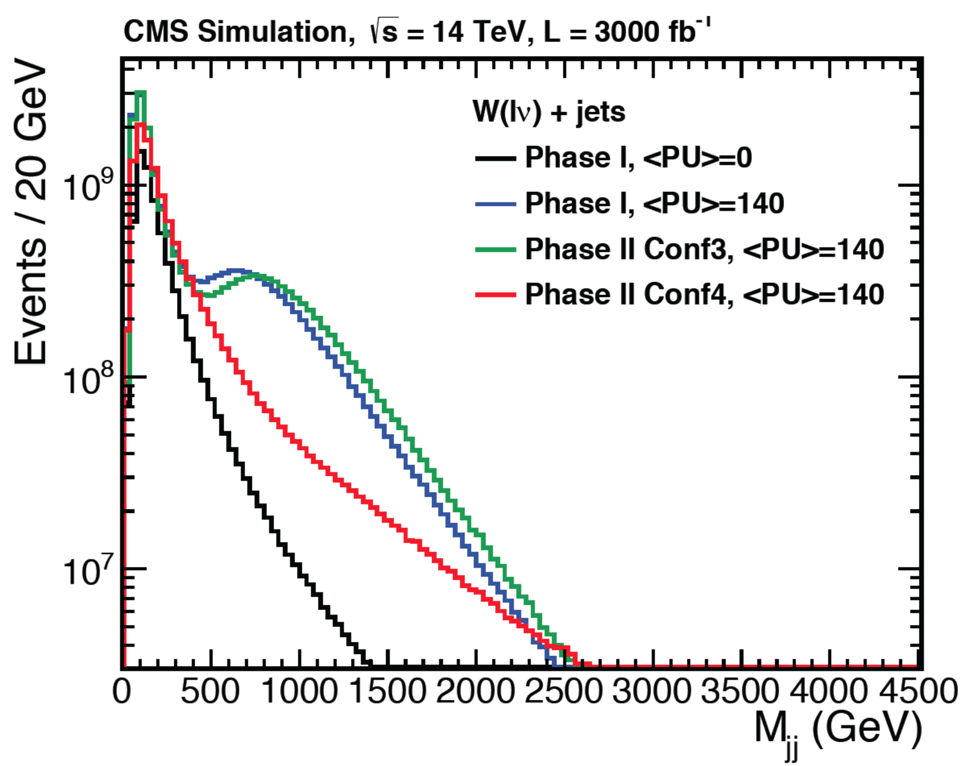


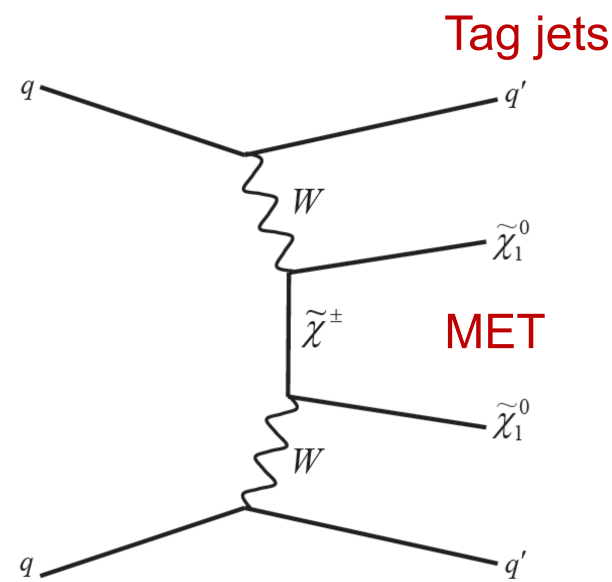


Dark matter search in VBF

The Phase II Conf4 detector ($\eta < 4$) allows:

- Increased lepton acceptance to reject W+jets background (factor 5)
- Better rejection of pileup jets





Outlook

- CMS has exceeded the design performance at high luminosity and pileup, showing that precision physics can be made under these extreme conditions.

- A sound program of Phase 1 upgrades will allow CMS to meet the physics expected with $300fb^{-1}$, at instantaneous luminosity up to $2.10^{34}cm^{-2}s^{-1}$.

- CMS studies for Phase 2 are growing at fast pace, building up a solid physics case for HL-LHC.

- The CMS plans for the Phase 2 Upgrade are taking a more precise shape. The present process should end-up in the next milestone, the Technical Proposal in 2014.