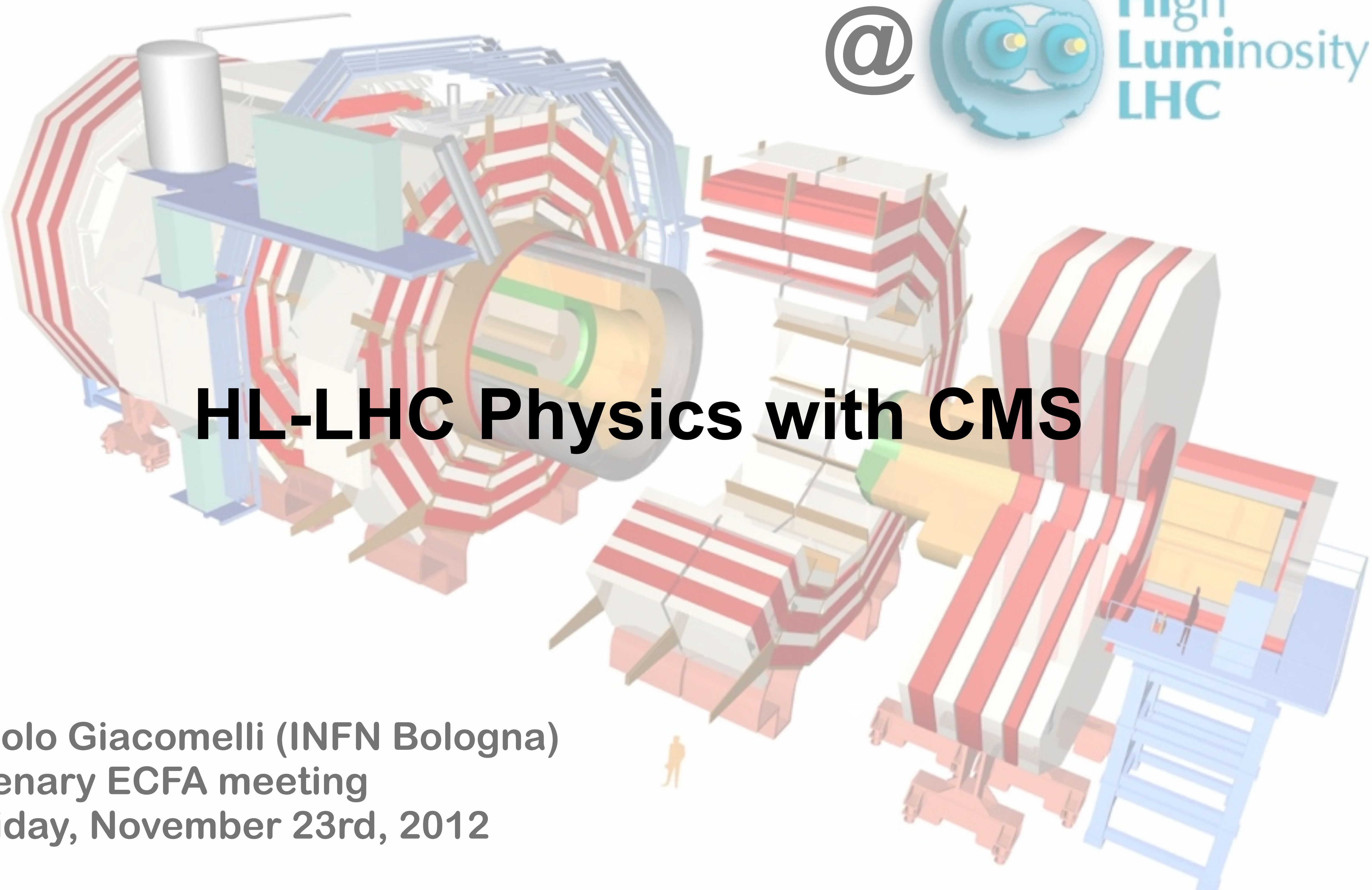


HL-LHC Physics with CMS

Paolo Giacomelli (INFN Bologna)

Plenary ECFA meeting
Friday, November 23rd, 2012

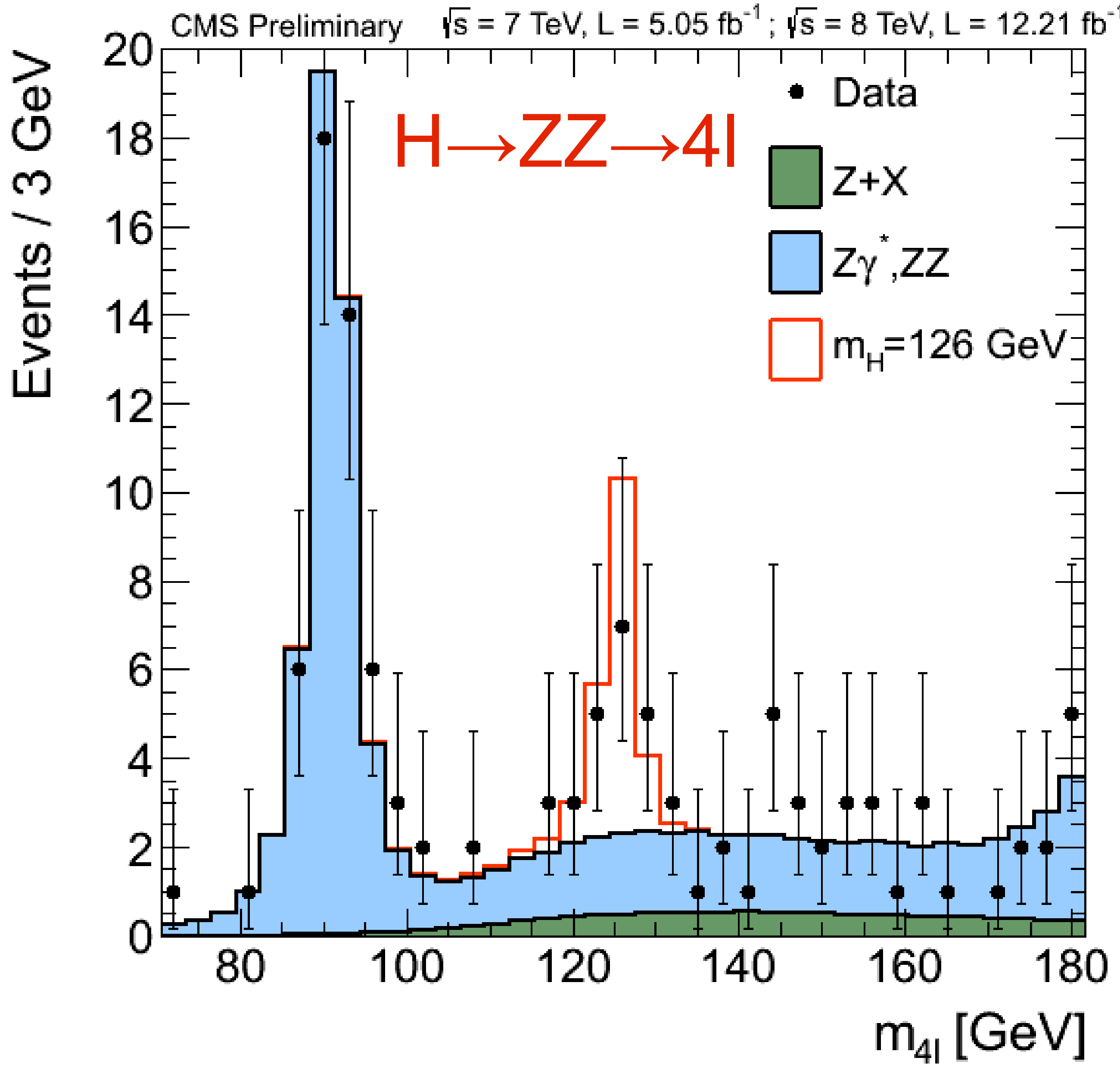
Many thanks to several colleagues, in particular: M. Klute and J. Varela

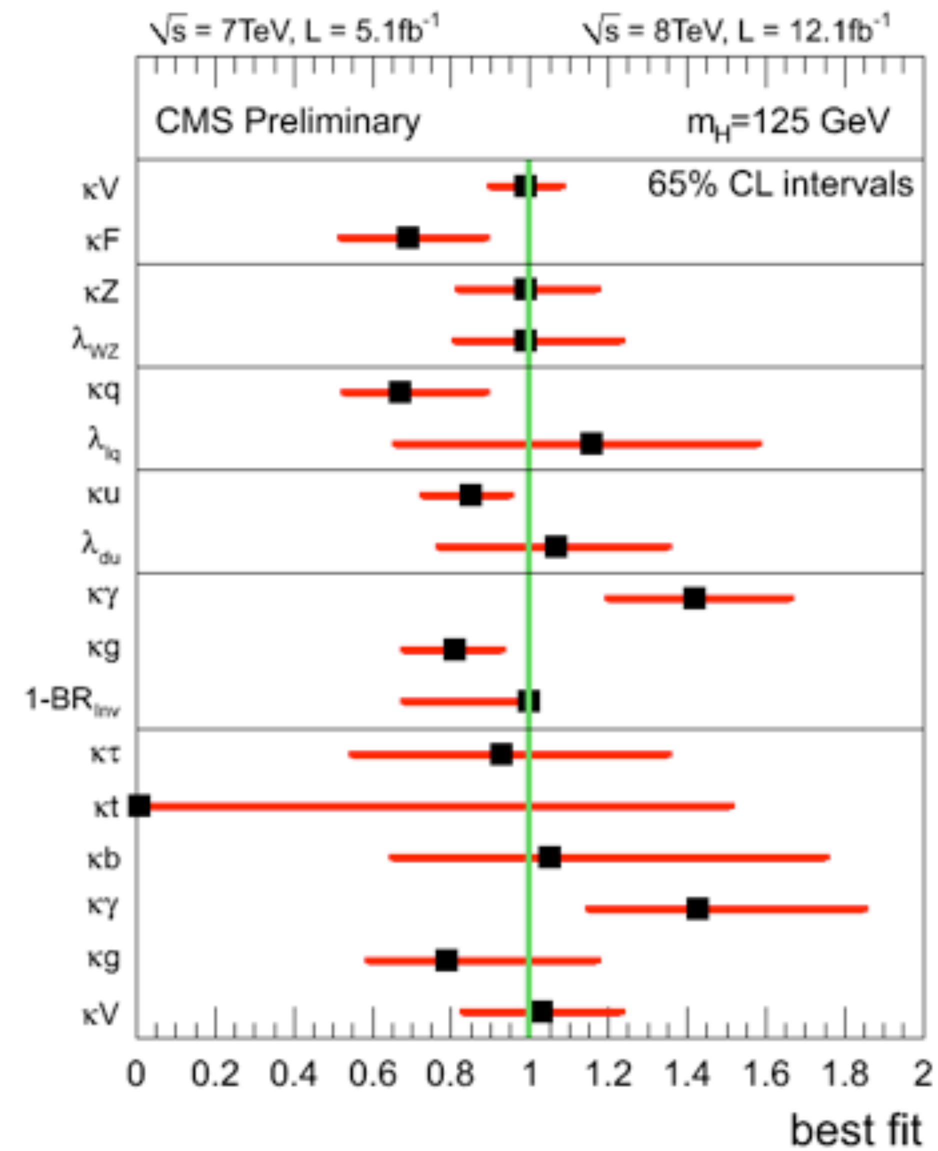
Outline

- Where we stand today
- LHC and HL-LHC luminosity projections
- CMS physics priorities
- CMS upgrade program
- Higgs physics projections
- SUSY and LQ projections

New boson with a mass of ~125 GeV

- We have discovered a Higgs-like boson with a mass of ~125 GeV.
- We must now measure precisely its properties.
- Mass, J^{PC}, will be done this year, couplings will need more data.





Overall best-fit signal strength:

σ/σ_{SM} = 0.88±0.21

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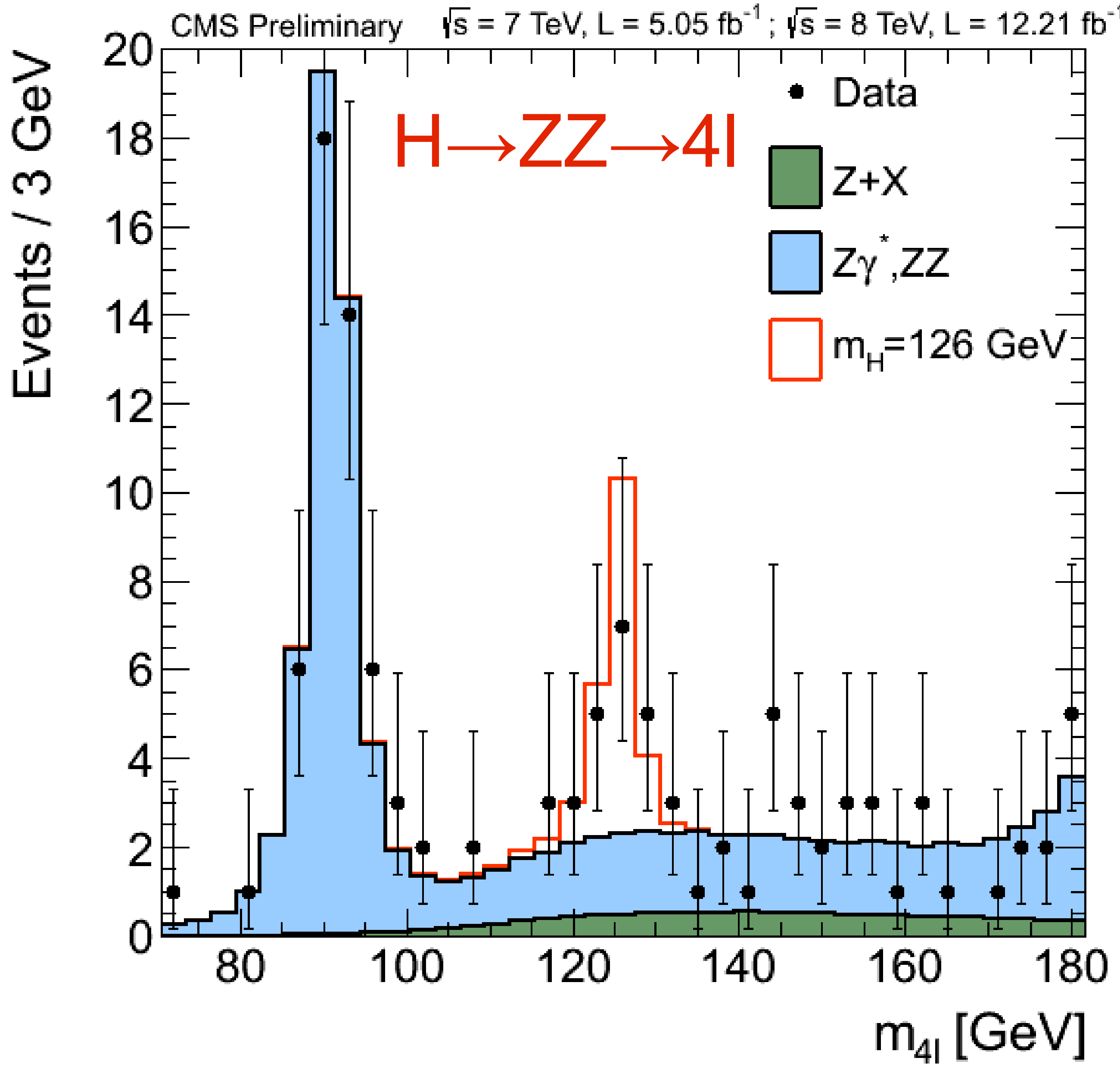
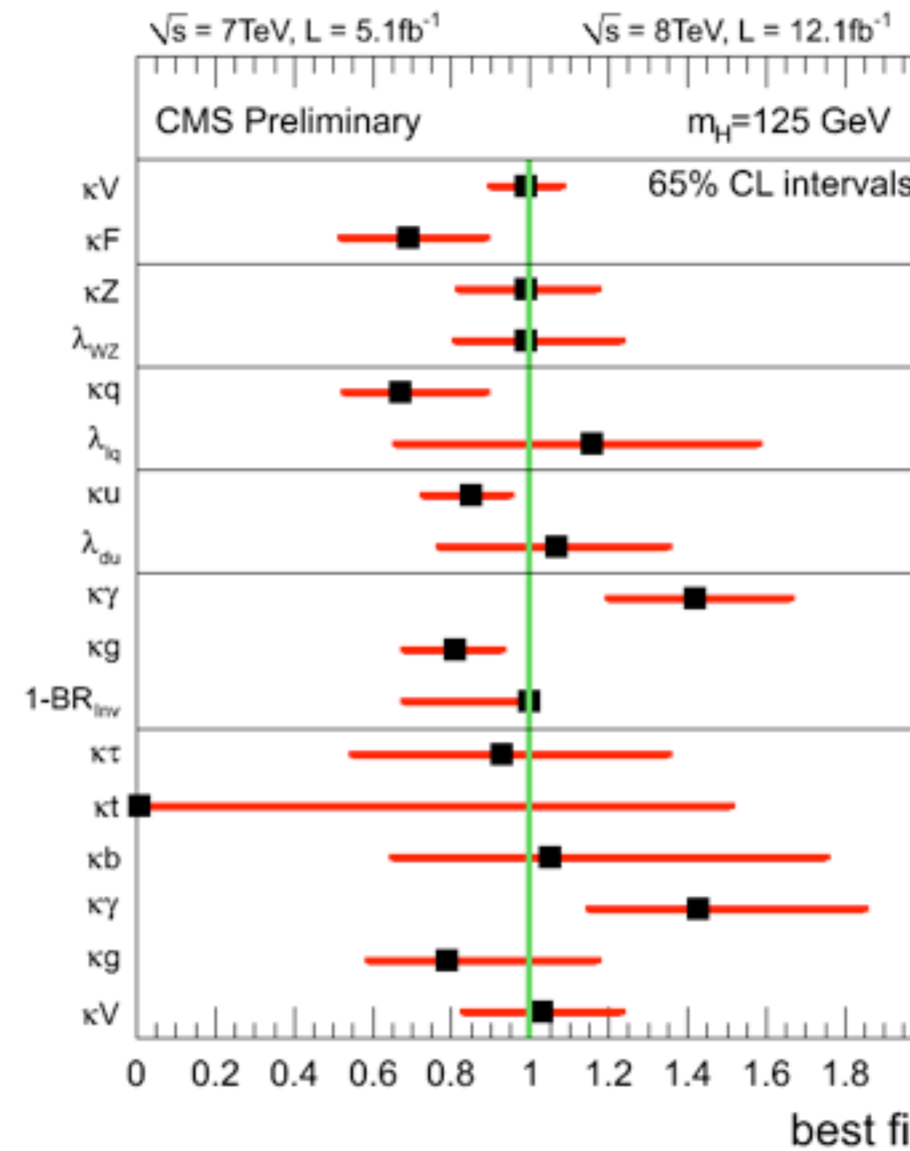




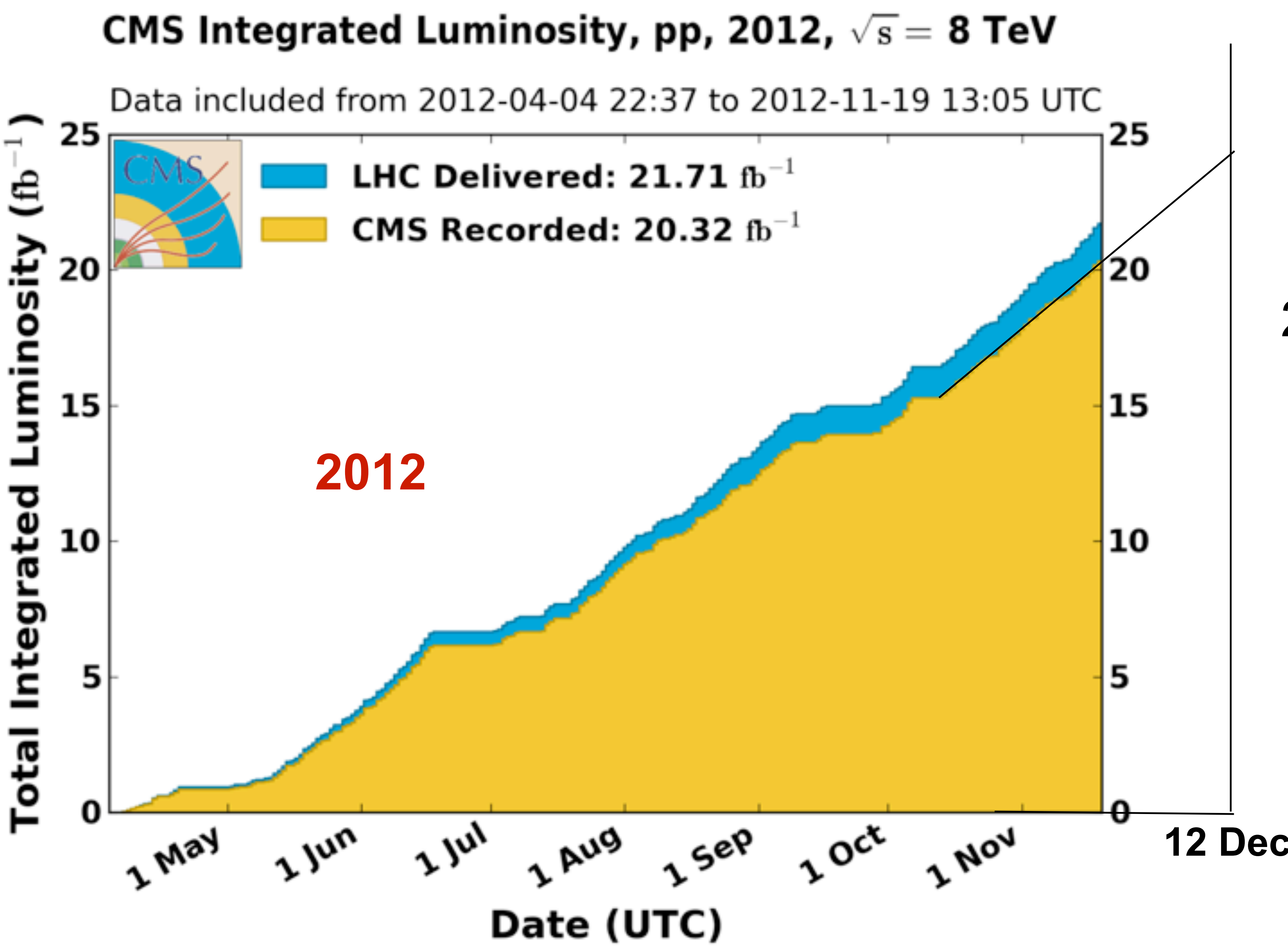
So far the new boson is consistent with being the SM Higgs boson

Overall best-fit signal strength:

$\sigma/\sigma_{SM} = 0.88 \pm 0.21$

Integrated luminosity in 2012

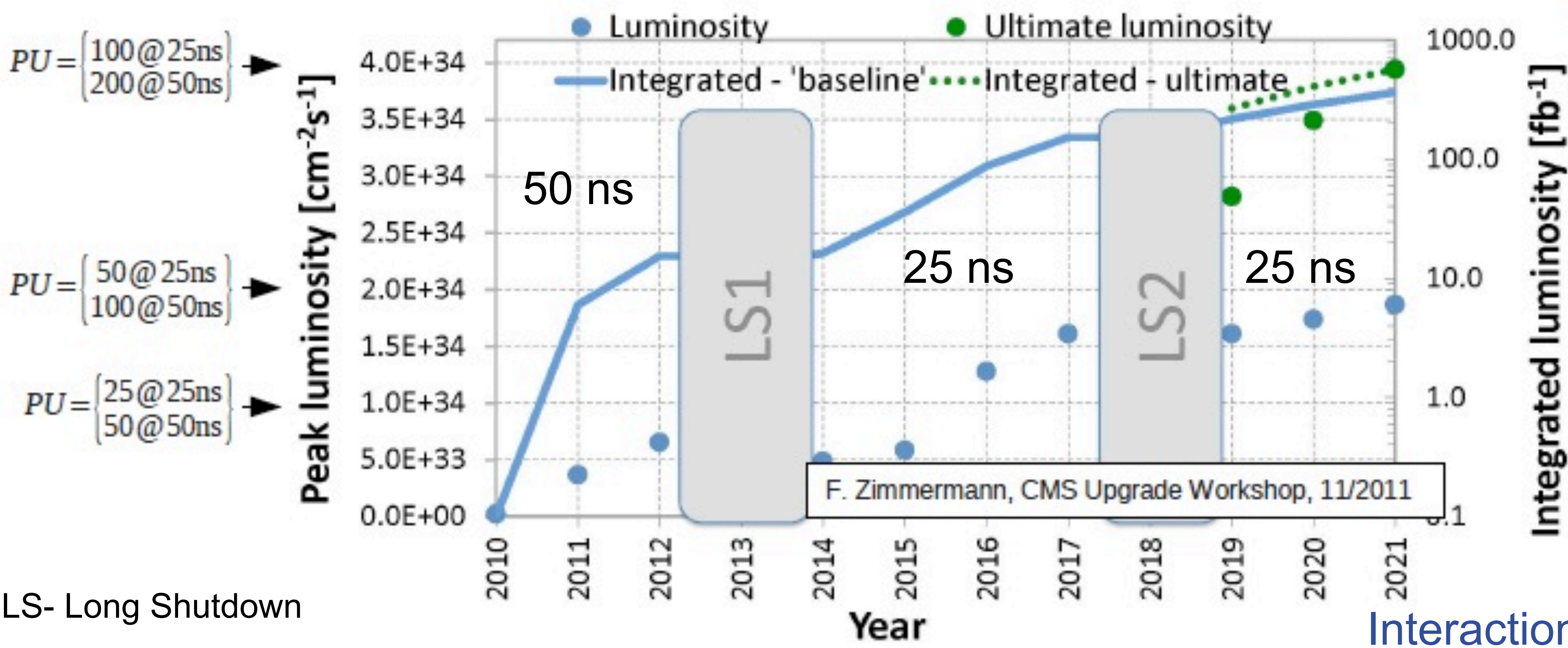
Projection of integrated luminosity at end of 2012: **~25 fb^{-1}**



2011: L=6 fb^{-1}

LHC and HL-LHC

LHC | Energy increase 8 TeV to 13/14 TeV | Injection upgrade | **HL-LHC**



Luminosity-leveled at $5x10^{34}$ $cm^{-2}s^{-1}$ in HL-LHC

LS- Long Shutdown

Interaction region upgrade

$8x10^{33}$ Hz/cm^2
30 fb^{-1}

LS1

$2x10^{34}$ Hz/cm^2
300 fb^{-1}

LS3

10^{35} Hz/cm^2
3000 fb^{-1}

CMS Upgrade plan

Phase 1 Upgrade

Phase 2 Upgrade

Detector and trigger challenges

- Need detectors and trigger with high performances from low to high energy scales
  - 125 GeV Higgs-like measurements
  - Multi-TeV new physics searches

- Phase 1 Upgrade: twice LHC design 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 luminosity
  - Event pileup reaches 125 collisions per beam crossing (@ 25 ns)
  - Need solutions to cope with very high rates, radiation and pileup

CMS Physics program priorities

The discovery of a Higgs-like boson at m_H~125 GeV defines our physics priorities

- With LHC 7-8 TeV data until end of 2012 (~30 fb^{-1})
  - First characterization of Higgs-like boson
    - spin/parity at 3-4 sigma level
    - combined signal strength, $\mu=\sigma/\sigma_{SM}$, with ~15% precision
  - Search for natural SUSY and other possible new physics

- With LHC 13/14 TeV data until ~2022 (~300 fb^{-1})
  - Measure Higgs-like boson properties
    - individual couplings at 5-10% precision
  - Search for new physics at higher mass scale

- With HL-LHC 13/14 TeV data until ~2032 (~3000 fb^{-1})
  - Measure Higgs-like couplings with ultimate precision
  - Study WW scattering
  - Search for new physics in rare processes

From 2012 to HL-LHC

- From 30 to 3000 fb^{-1}: two orders of magnitude extrapolation in luminosity

To calculate physics projections at HL-LHC

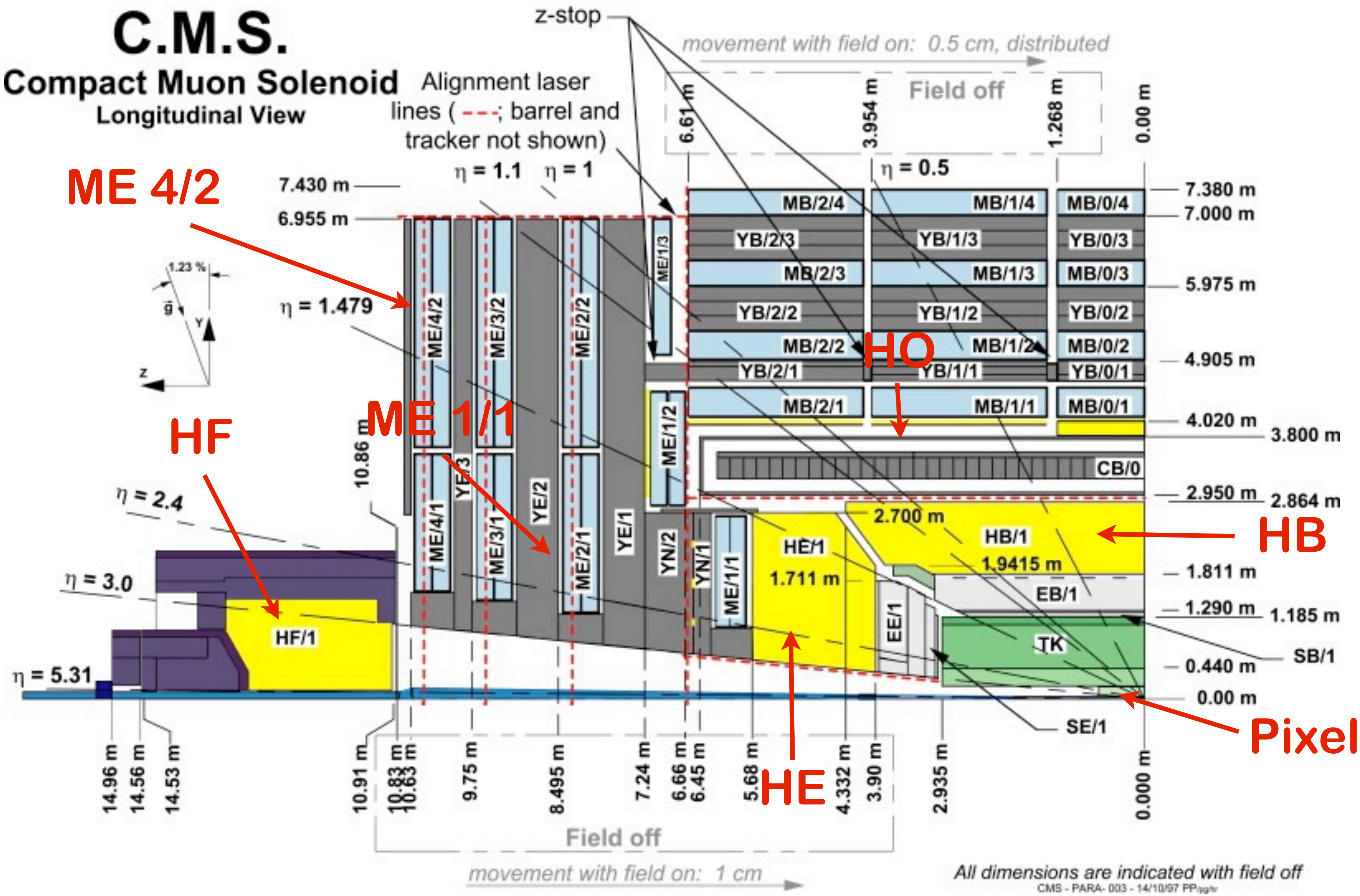
Same trigger and reconstruction peformances as in 2012

Assume that a CMS upgraded detector will offset the much harsher LHC conditions and radiation damage

CMS has launched a comprehensive upgrade program

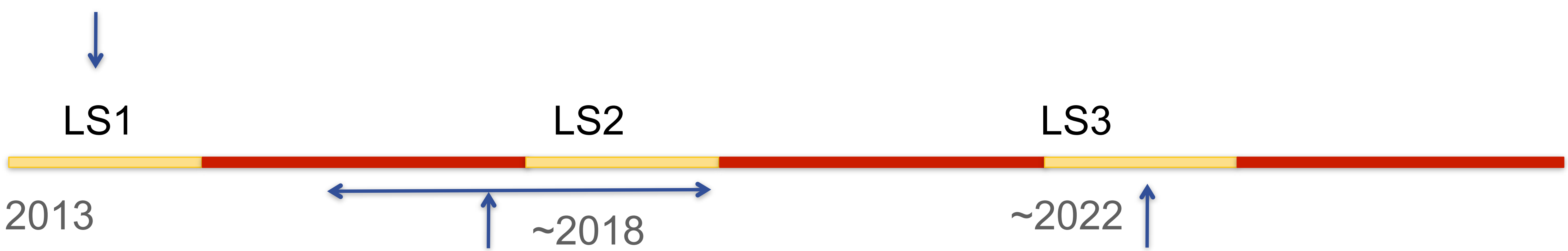
CMS Upgrade program

LS1 and Phase 1



CMS Upgrade phases

LS1 Projects:
- Complete endcap muon coverage (ME4)
- Improve muon trigger (ME1), DT electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Outer (HPD → SiPM)



Phase 1 Upgrades:
- New Pixels, HCAL SiPMs and electronics, and L1-Trigger
- Preparatory work during LS1:
  - new beam pipe
  - test slices of new systems

Phase 2 Upgrades: scope to be defined in Technical Proposal (2014)

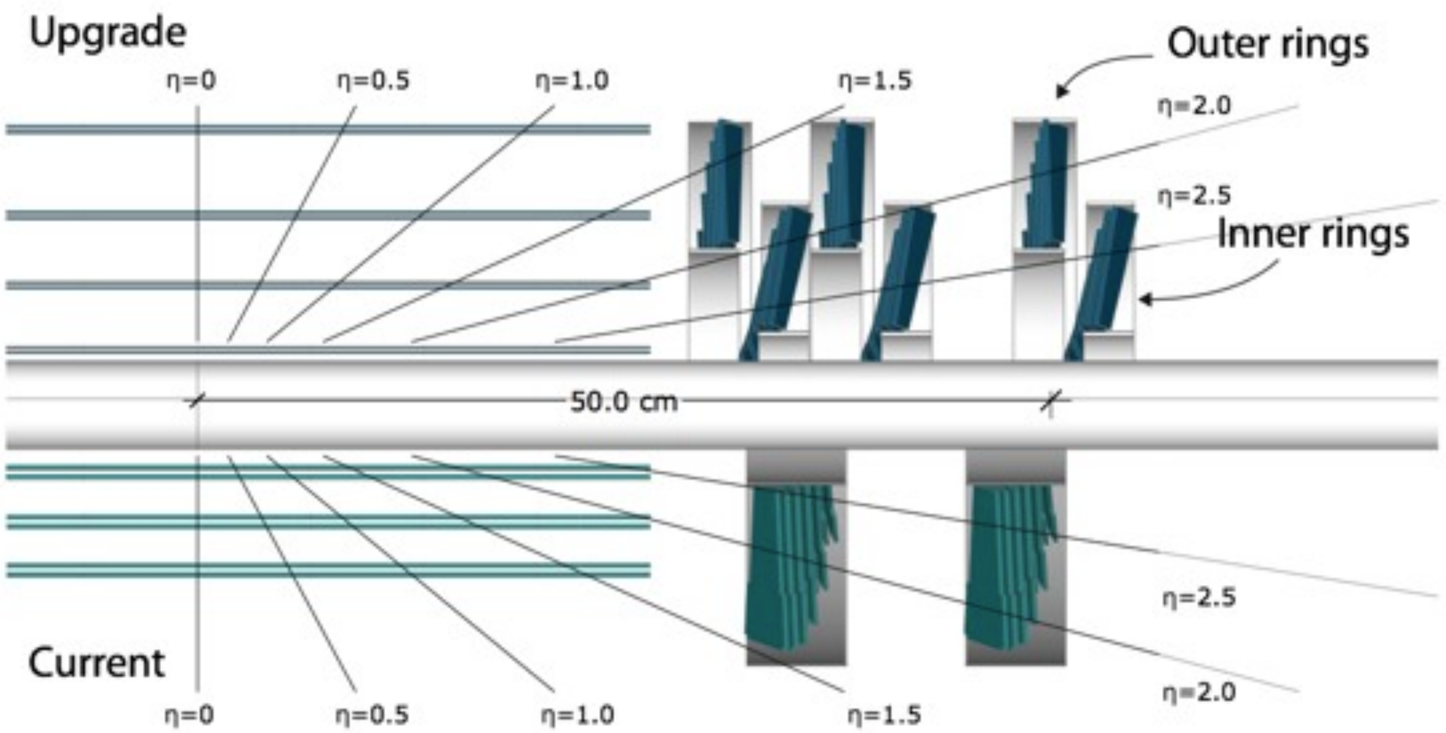
- Tracker Replacement
- Forward Calorimetry and Muons
- Further Trigger upgrade: Track Trigger

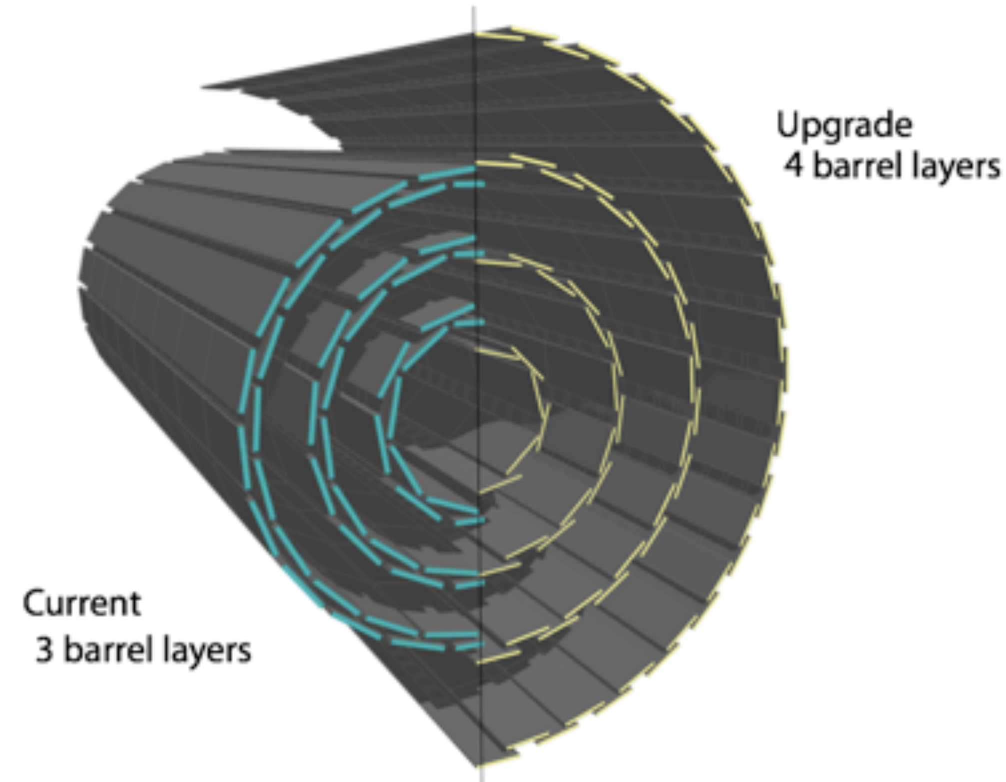
Phase 1 Upgrade

- Designed to operate at twice LHC design luminosity
  - Event pileup reaches 50 collisions per beam crossing (@ 25 ns)
    - LHC operation at 50 ns is not excluded → 100 PU events

  - Additional layer of Muon detectors in the endcaps
    - improved muon trigger and reconstruction efficiency
  - New L1 Trigger system
    - keep low trigger thresholds
      - trigger with high efficiency on low mass Higgs
  - New Pixel detector
    - guarantees better tracking and b-tagging efficiency with high pileup
  - Improved Hadron Calorimeter longitudinal segmentation
    - improved pileup rejection
    - use new compact and robust photo-detectors (SiPMs)

Pixel detector phase 1 upgrade





Upgraded Pixel Detector

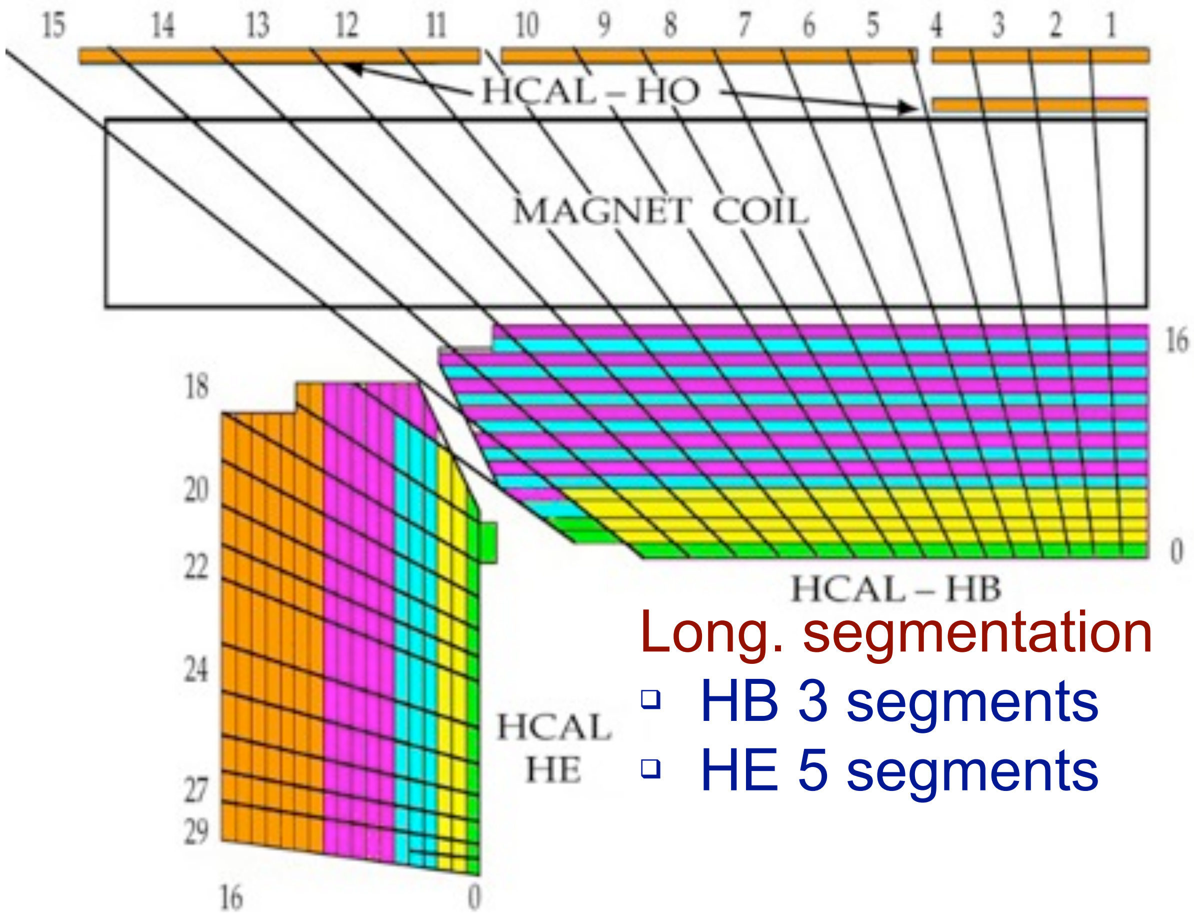
- **4 layers**: improved tracking efficiency (and lower fake rate)
- **Less material**, better radial distribution
- **New readout chip** recovers inefficiency at high pileup

- 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

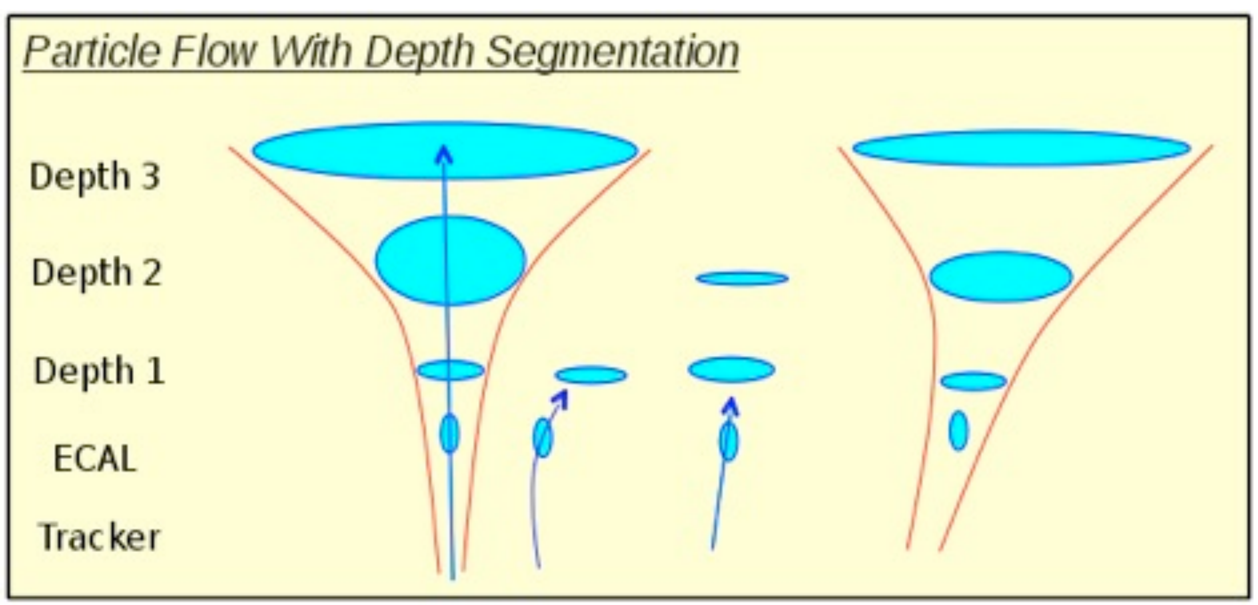
HCAL Upgrade

- Upgraded HCAL
  - New photodetectors
  - New electronics (frontend, backend)
  - Improved longitudinal segmentation
  - Improved background rejection, Missing E_T resolution and Particle Flow reconstruction

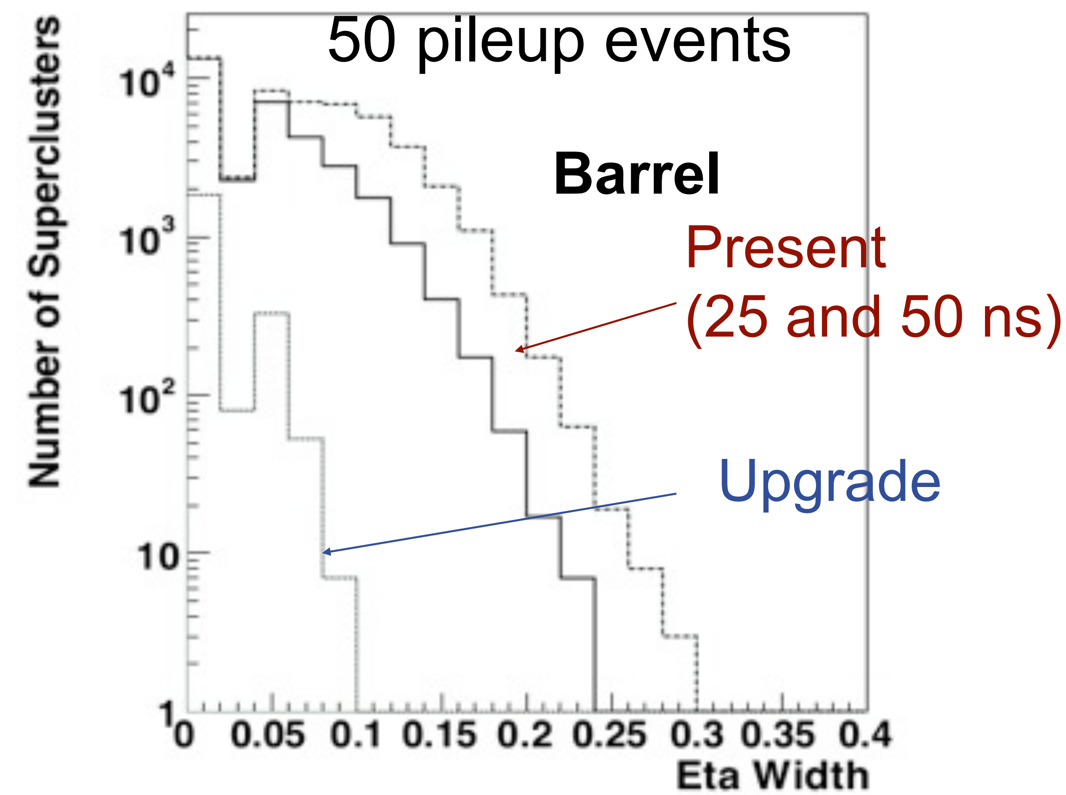


Long. segmentation
- HB 3 segments
- HE 5 segments

- Hadronic showers spread out with increasing depth



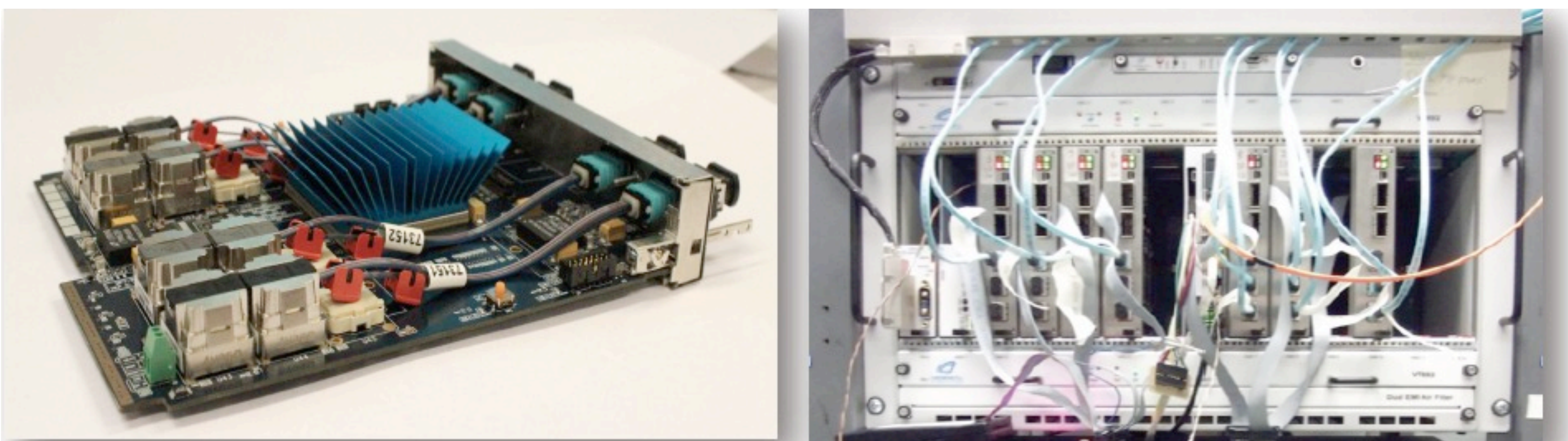
Hadronic cluster width
50 pileup events



L1 Trigger Upgrade

- New system allows low trigger thresholds
  - FPGAs and 10 Gb/s Optical links in μTCA standard for
    - Higher calorimeter granularity and improved algorithms
    - Better muon reconstruction
    - Global trigger with more inputs and algorithms for correlated quantities (e.g. invariant mass)
  - Expected to be operational after 2015-16 Year End Tech Stop

Considering a bandwith increase for L1 and HLT after LS2



Calorimeter Trigger board prototype and demonstrator

Phase 2 Upgrade - HL-LHC

- Aiming operation at 5x LHC design luminosity in HL-LHC
  - Event pileup reaches 125 collisions per beam crossing (@ 25 ns)
- Present tracker and endcap calorimeters designed for radiation up to 500 fb^{-1}
- **Main objectives of the Phase-2 Upgrade :**
  - **New Tracker** with increased resistance to radiation
  - The new tracker will incorporate a **L1 Tracking Trigger**
  - **New forward calorimeters and tracking** detectors for VBF physics
  - Considering **Increased muon coverage**

Impact of Phase 1 on Higgs

- Analysis of various physics channels to evaluate performance improvements
  - select a few exemplar Higgs decay channels ($\sqrt{s}$=14 TeV)
  - standard CMS Monte Carlo for signal samples & some backgrounds
  - no tuning for 14 TeV data, use analyses as developed for 7-8TeV
  - upgraded & current detector with <PU>=50

  - Compare signal selection efficiency with upgraded detector vs. current detector

- Examples of decay channels studied:
  - $H \rightarrow ZZ^*$ with $Z^{(*)} \rightarrow \mu^+\mu^-, e^+e^-$
  - $ZH \rightarrow l^+l^- + 2$ b-jets
  - $H \rightarrow \tau\tau$ (including VBF)

$H \rightarrow ZZ \rightarrow 4l$

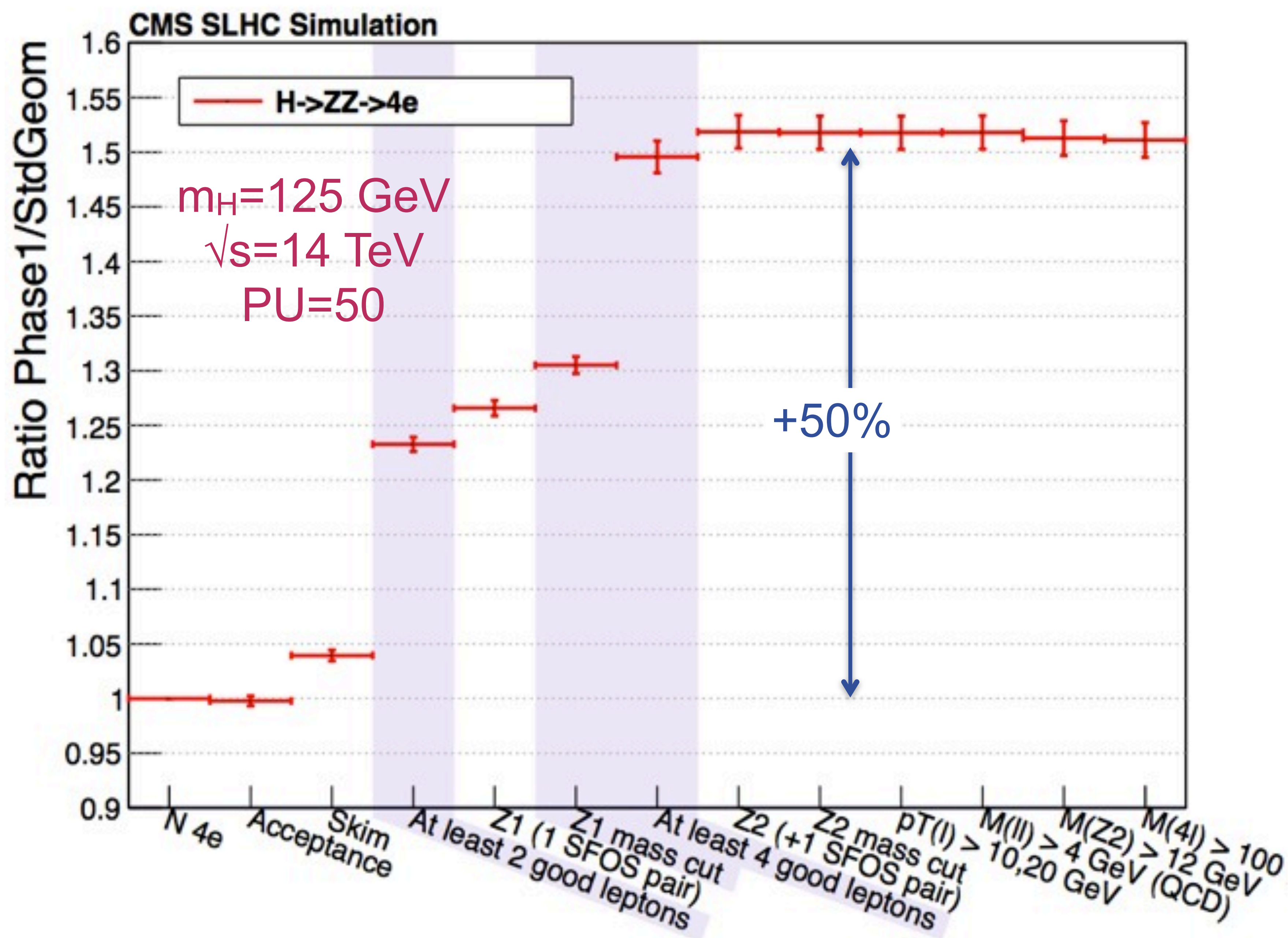
$H \rightarrow ZZ \rightarrow 4l$

is sensitive to lepton tracking, identification and isolation efficiency

Significant gain in signal reconstruction efficiency:

$H \rightarrow 4\mu$ +41%
$H \rightarrow 2\mu 2e$ +48%
$H \rightarrow 4e$ +51%

Improved signal yield (relative to current detector):

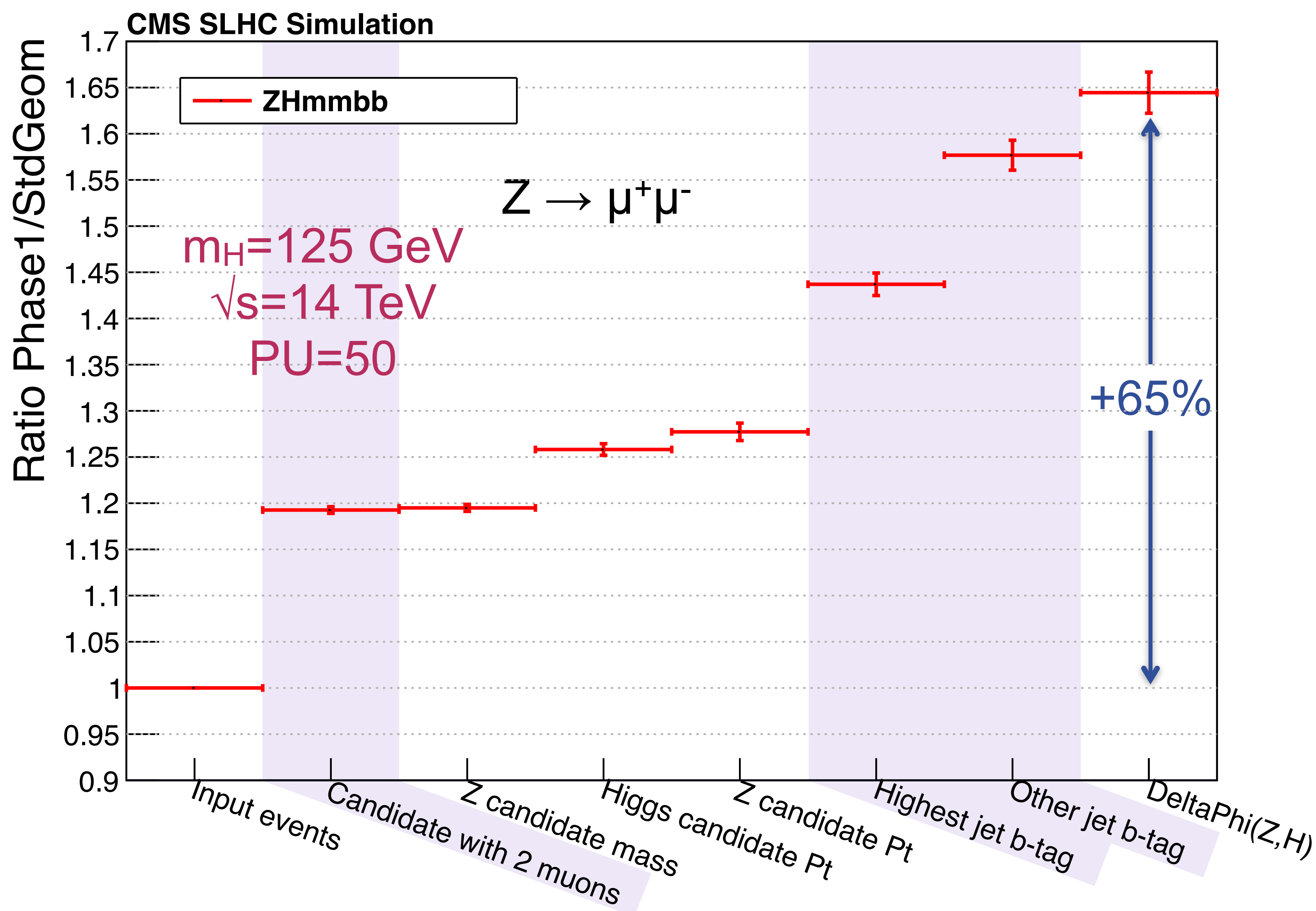


$ZH \rightarrow l^+l^- bb$

$ZH \rightarrow l^+l^- bb$ requires

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

Improved signal yield (relative to current detector):

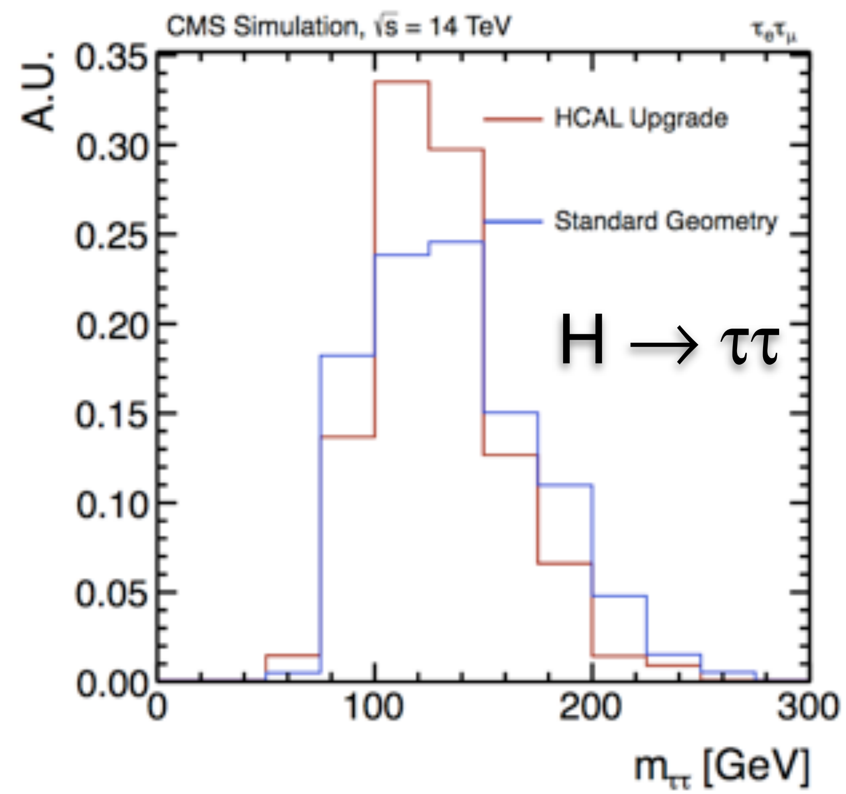


Both lepton channels (μμ, ee) show a gain of 65% in signal efficiency with the upgraded pixel detector.

H → τ τ (including VBF)

H → ττ (including VBF) requires

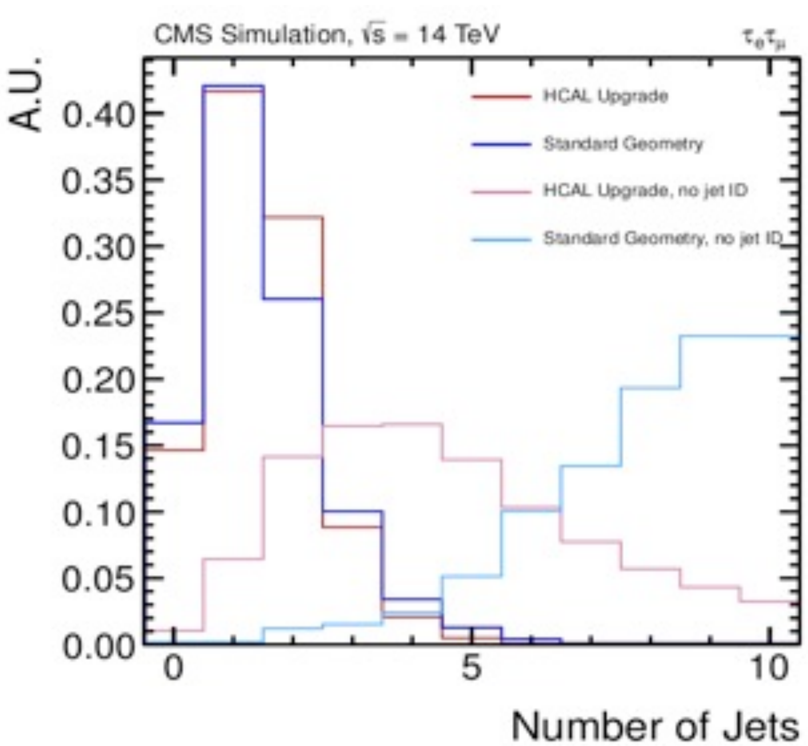
- good $\not{E}_T$ (MET) resolution
- forward jet tagging capability
- efficient lepton identification



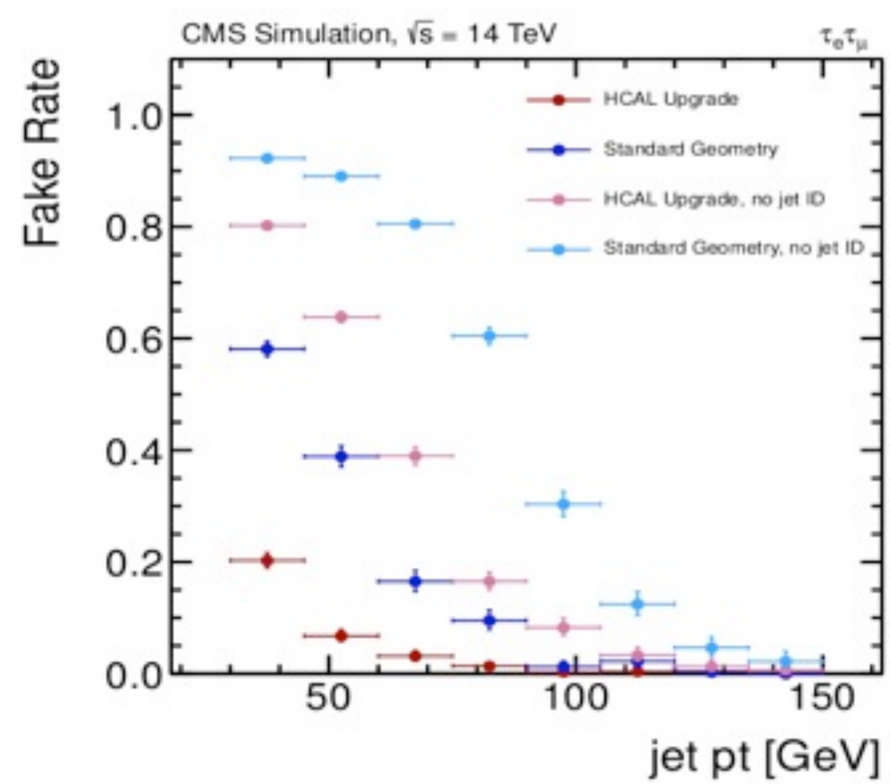
Improved jet and MET resolution allows 25% improvement in $m_{\tau\tau}$ resolution

Total efficiency improvement: factor of 2.5 (4.5% → 11%)

Efficiency of identifying true tag jets is improved

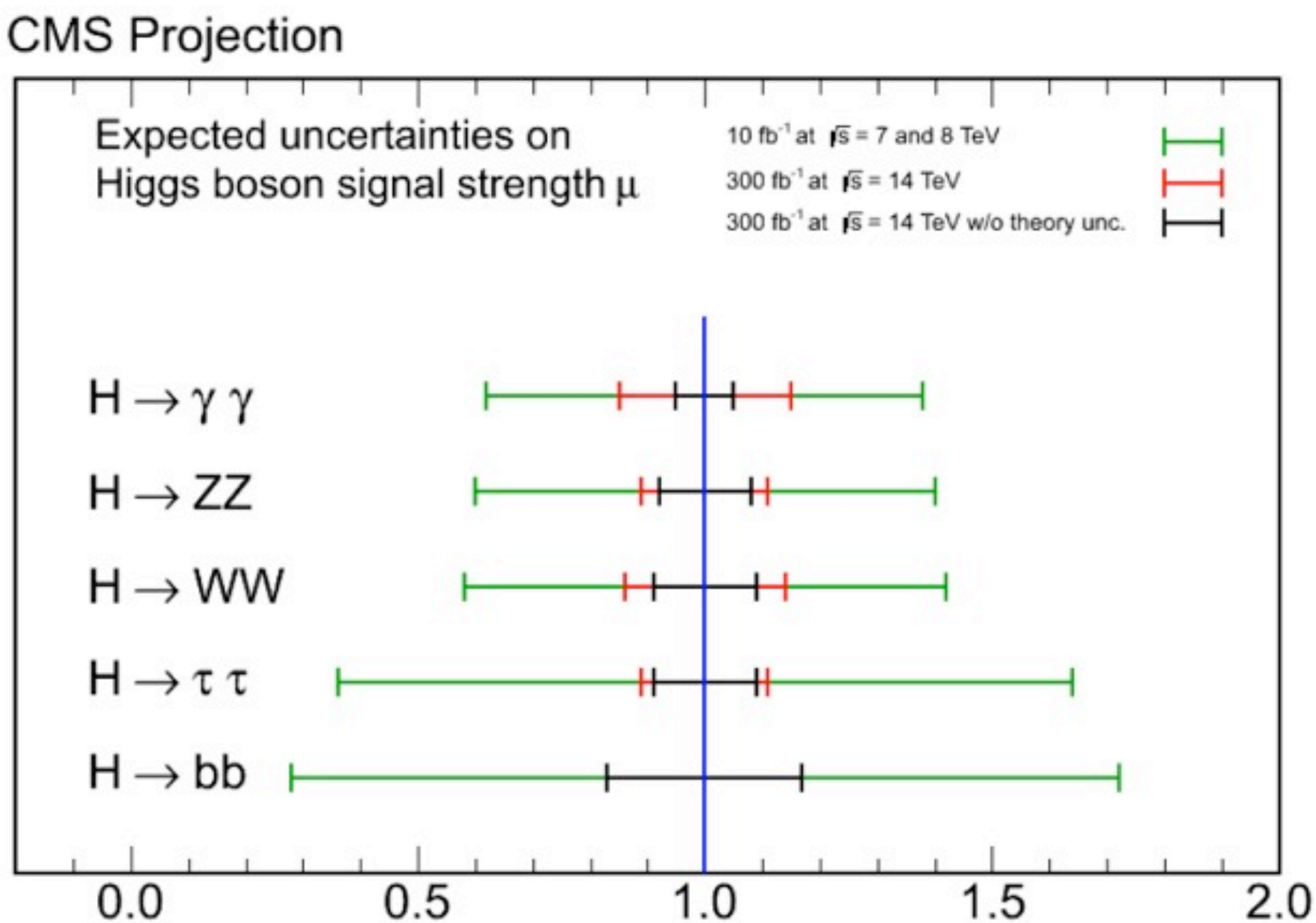


Significant reduction in jet fake rate



Higgs signal with 300 fb^{-1}

- Upgraded detector performances assumed the same as 2012 detector
- Three scenarios:
  - Scenario 1: same systematics as in 2012
  - Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by 1/√L
  - Scenario 3: same exp. syst. as in 2012, w/o theory uncertainty



10 fb^{-1}, 7 and 8 TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 3)

With 300 fb^{-1} the precision of signal strength is expected 10-15% per channel

Higgs couplings @300 fb^{-1}

- Three scenarios:
  - Scenario 1: same systematics as in 2012
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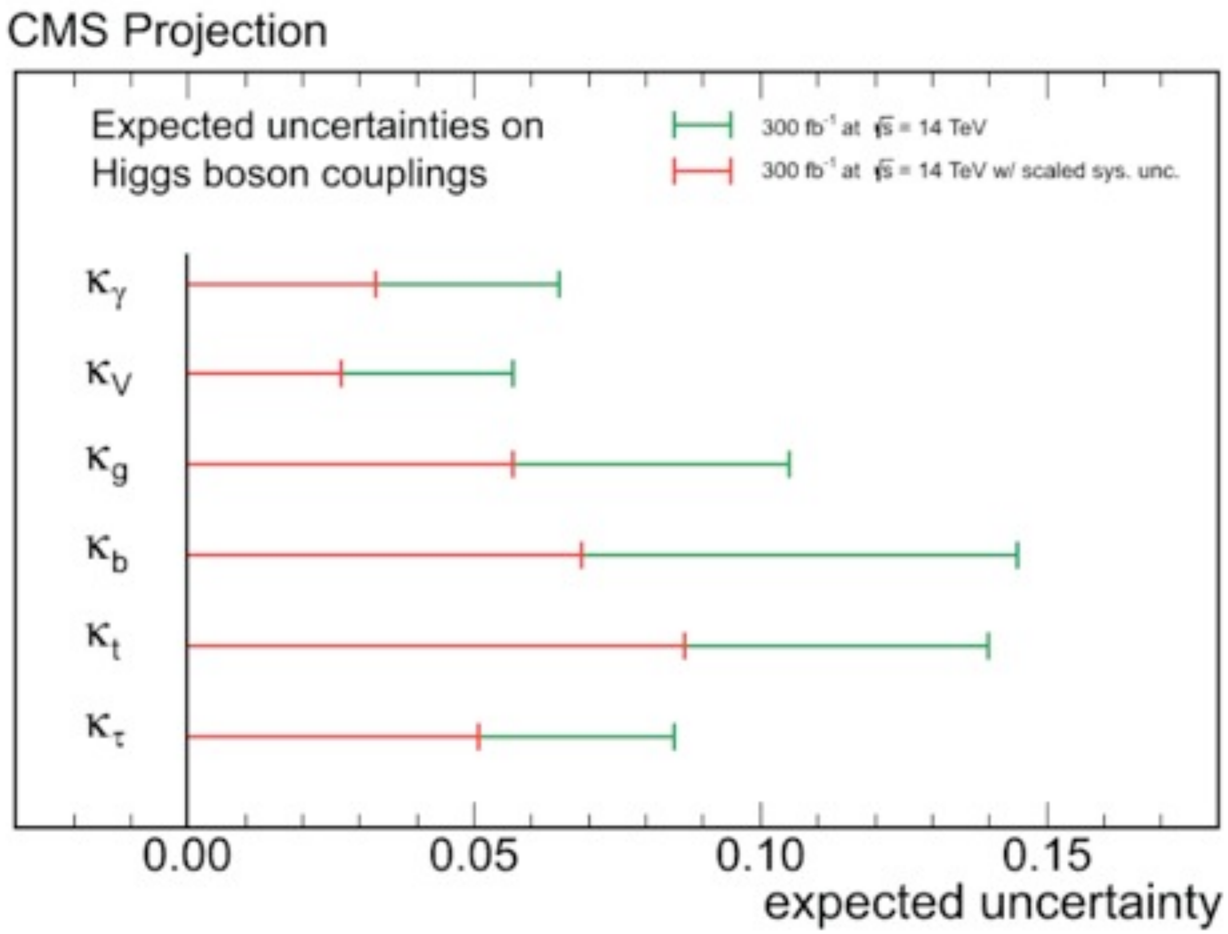
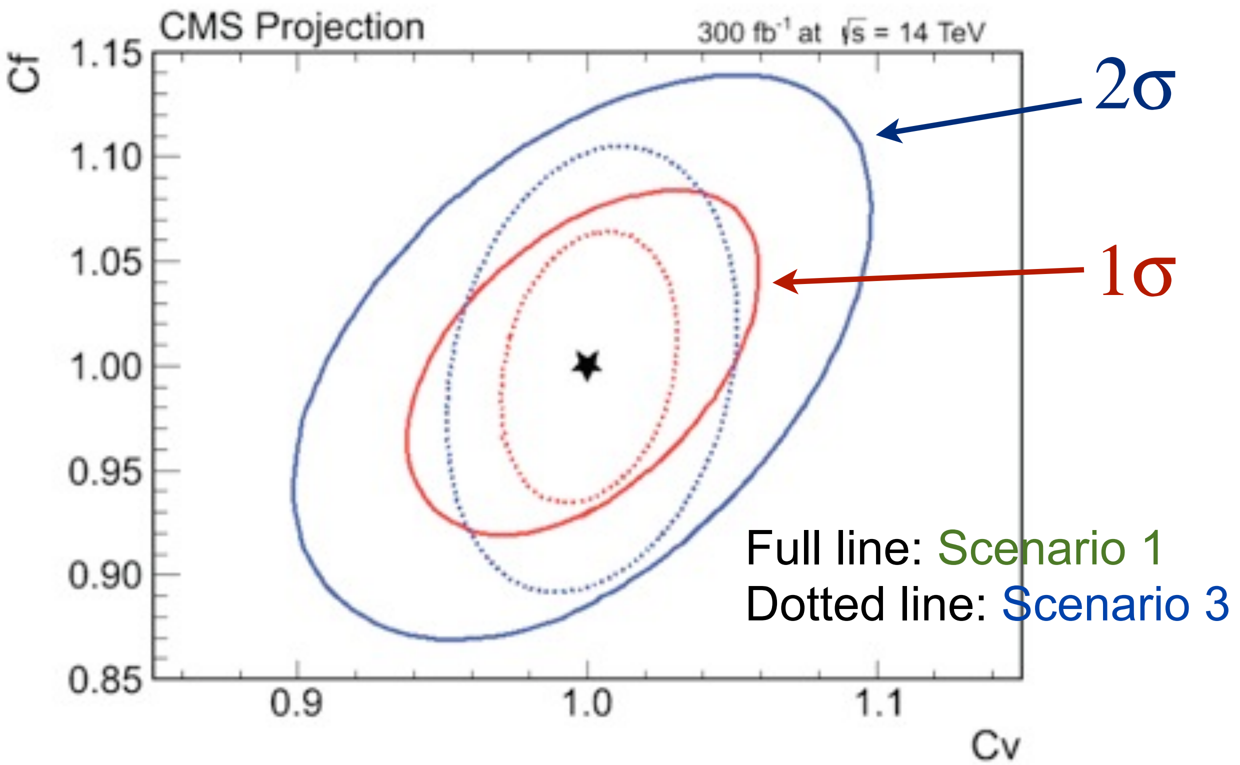


300 fb^{-1} 14 TeV, Scenario 1
300 fb^{-1} 14 TeV, Scenario 2



With 300 fb^{-1} the uncertainties on the Higgs couplings are expected in the range $\sigma(\kappa_V) \sim$ 3-6%
$\sigma(\kappa_f) \sim$ 5-15%

HL-LHC Higgs couplings @3000 fb^{-1}

- Extrapolation by two orders of magnitude to higher luminosity
  - is subject to large uncertainties
  - scenarios 1 and 2 provide likely upper and lower bounds
- Experience at LEP and Tevatron indicates that scaling with 1/√L is not unrealistic

- With 3000 fb^{-1} the Higgs couplings can be determined with high precision (1-3%)
- The decay H→μμ can be observed with a significance of 5 sigma
  - measurement of the Hμμ coupling with a precision of ~10%
- Measurement of multiple Higgs boson (self-coupling) production is possible
  - The SM cross section for di-Higgs boson production is 33 fb at 14 TeV.
  - Measurement of the Higgs potential

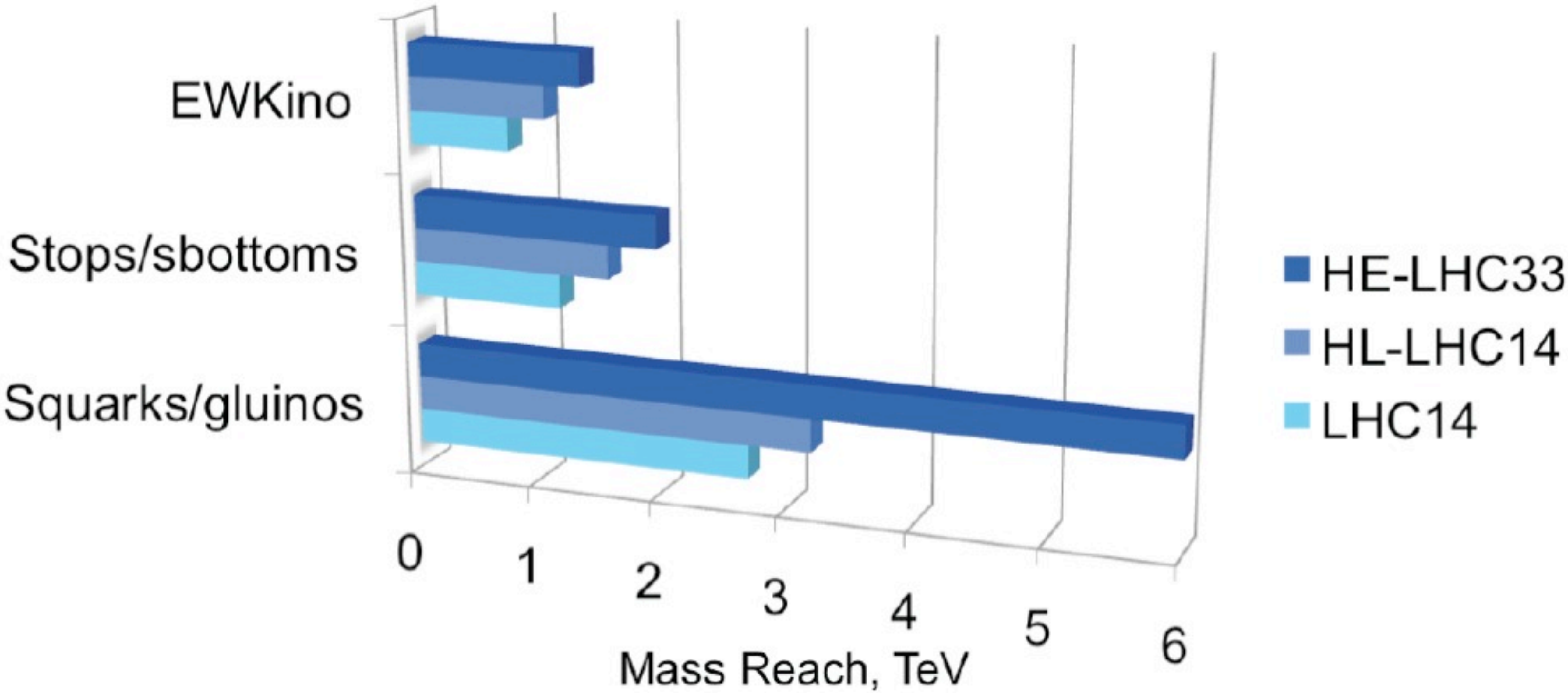
Coupling	Uncertainty (%) 3000 fb^{-1}	
	Scenario 1	Scenario 2
κ_γ	5.4	1.5
κ_V	4.5	1.0
κ_g	7.5	2.7
κ_b	11	2.7
κ_t	8.0	3.9
κ_τ	5.4	2.0

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

SUSY reach at HL-LHC

LHC at 14 TeV and HE-LHC at 33 TeV expand the reach for SUSY particles to much higher masses.

As expected, the gain of HL-LHC is modest in this case.



LQ at HL-LHC

Mass reach (in TeV) for the leptoquark search in the ee jetjet channel

Scenario	LHC	HL-LHC	HE-LHC
Low S/B	1.6	1.8	2.5
High S/B	1.7	2.3	3.5

Outlook

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

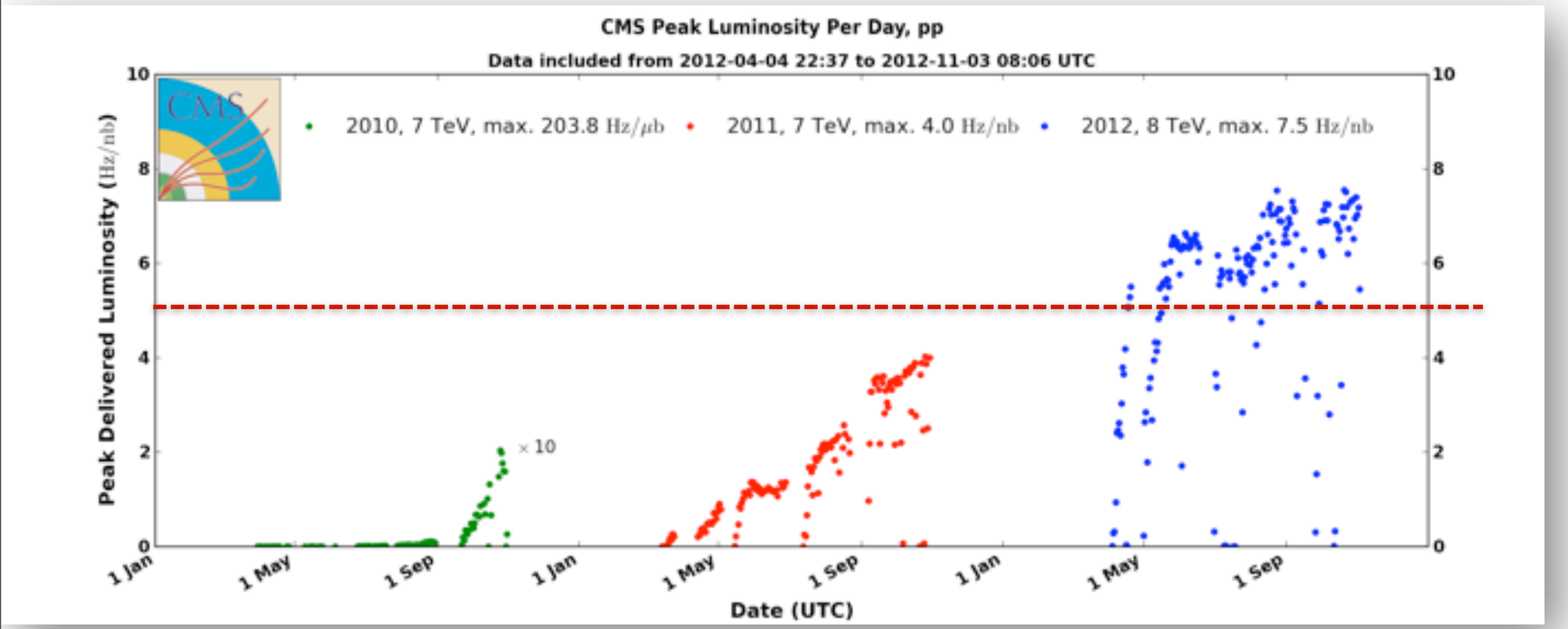
- The experience already gained and a sound program of upgrades gives us confidence that CMS will meet the physics expected with 300 fb^{-1}, collected at instantaneous luminosities up to $2x10^{34}cm^{-2}s^{-1}$.

- Precision Higgs physics with 3000 fb^{-1} at HL-LHC is an attractive future scenario deserving substantial studies and R&D
  - it is a challenging project involving major upgrades of full detectors.
  - the CMS community is highly motivated and willing to move forward.

- We look forward to an exciting physics program at LHC for the next twenty years

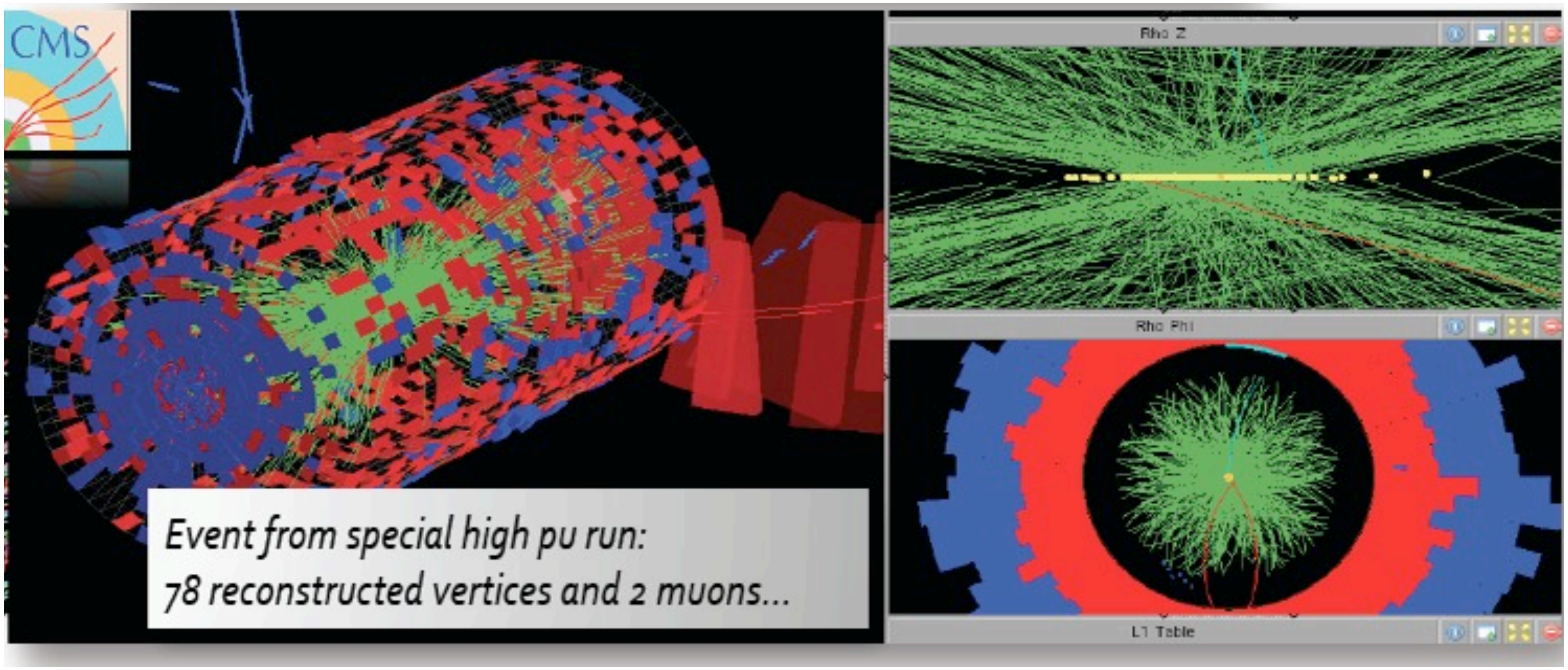
Backup

Pileup in 2012



Peak: 37 pileup events

Design value
25 pileup events
($L=10^{34}$, 25 ns)

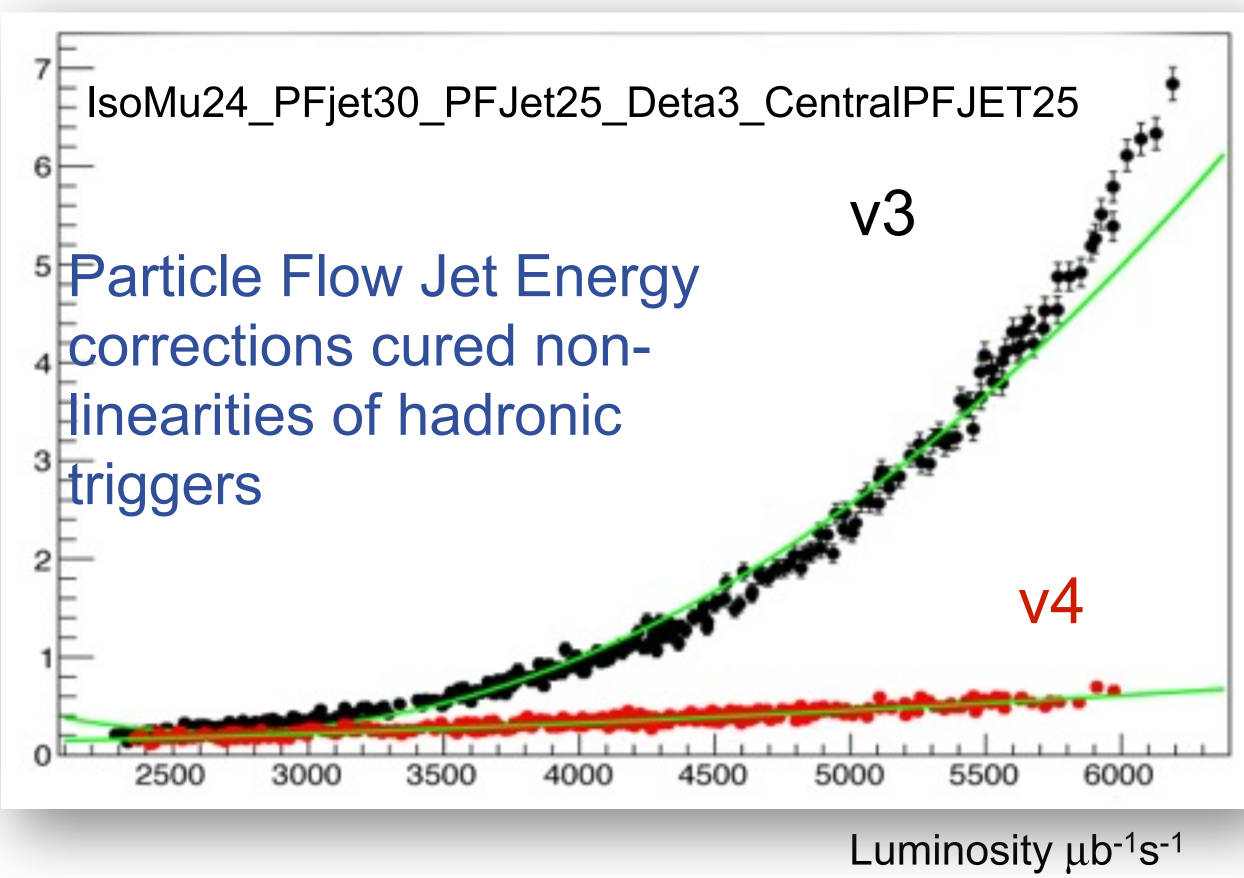


Trigger challenge in 2012

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

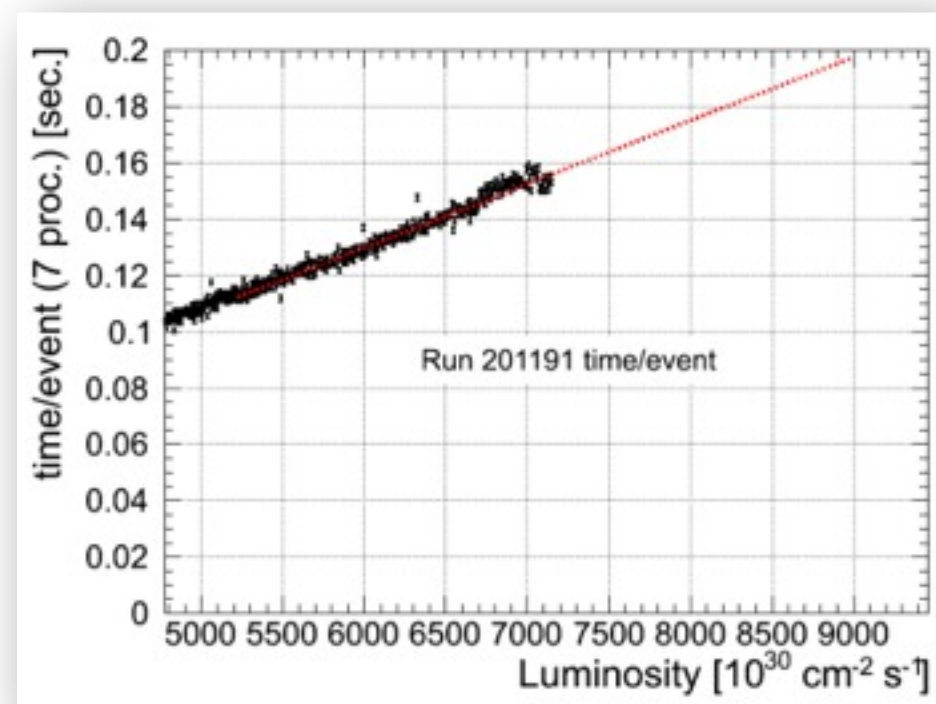
The experience obtained in 2012 with peak pileup of ~35 events gives us confidence for high-luminosity running post Long Shutdown 1

Trigger Cross-sections:



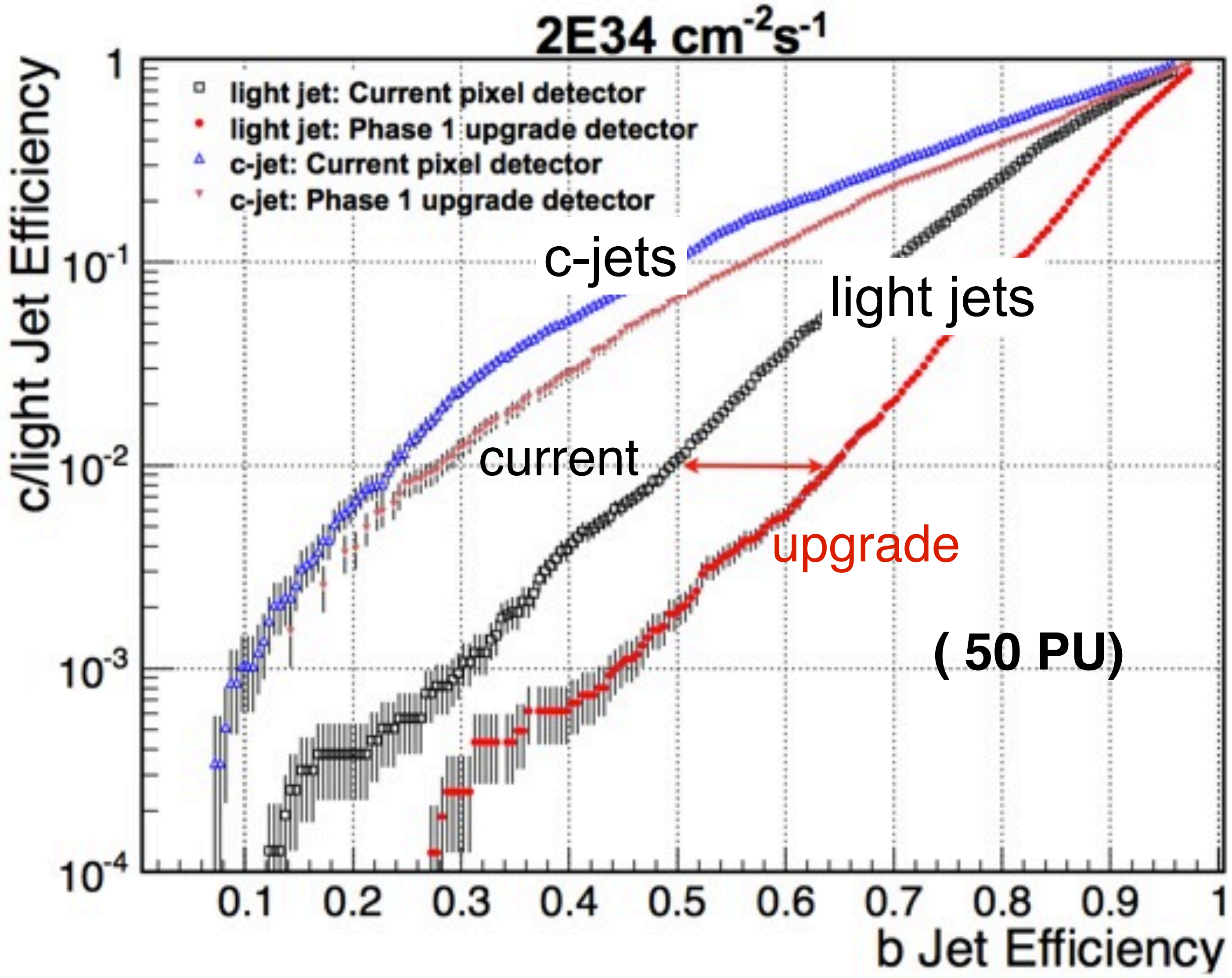
HLT CPU time:

- linear with PU, no signs of runaway

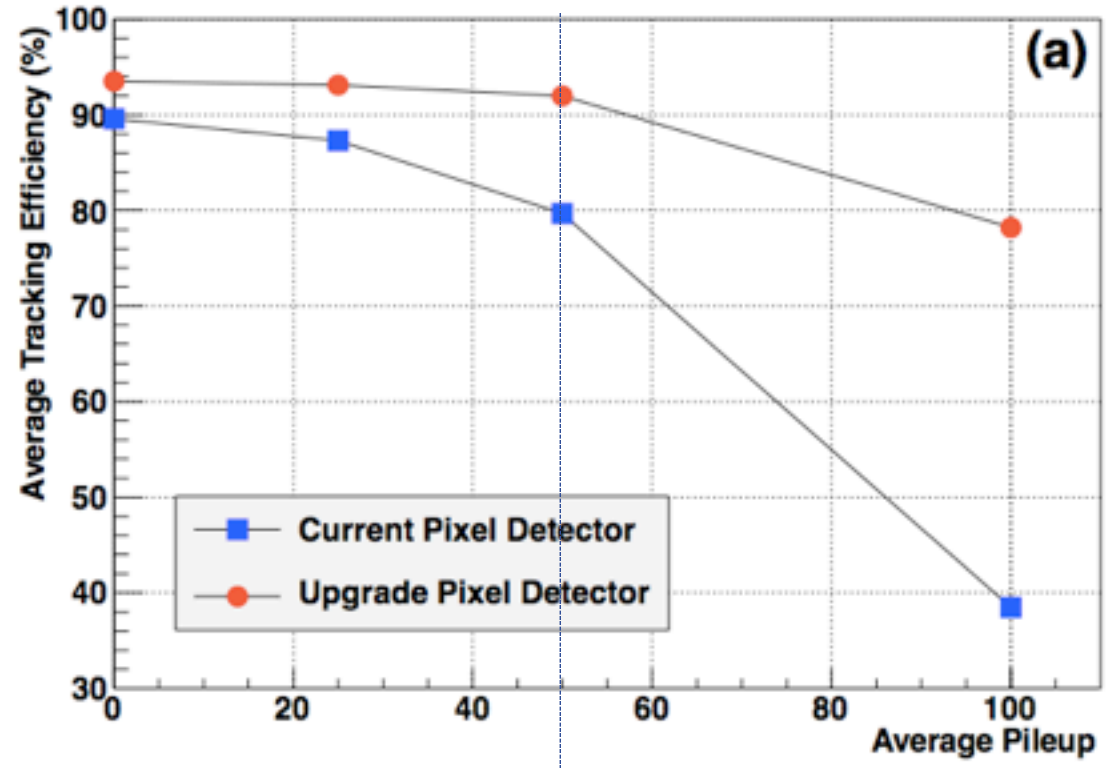


Tracking and b-tagging performance

Improvement of b-tagging efficiency with new pixel detector



Improvement in tracking efficiency w/ new pixel detector, in ttbar events, as a function of pileup



50 pileup

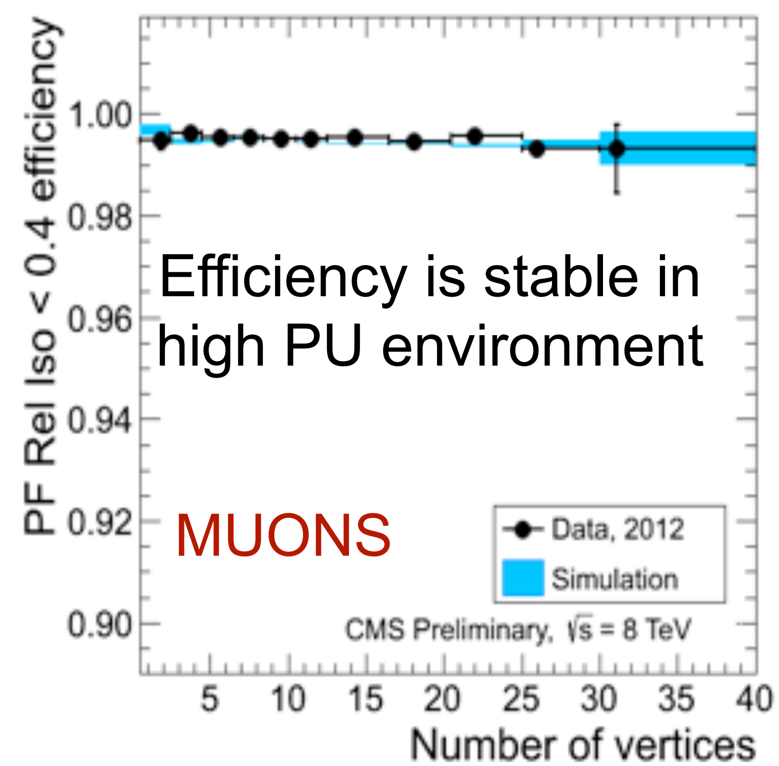
b-tagging efficiency ~ 1.3x better

2 b-jets → $(1.3)^2$ ~1.69

Primary vertex resolution improved by factor ~1.5 - 2

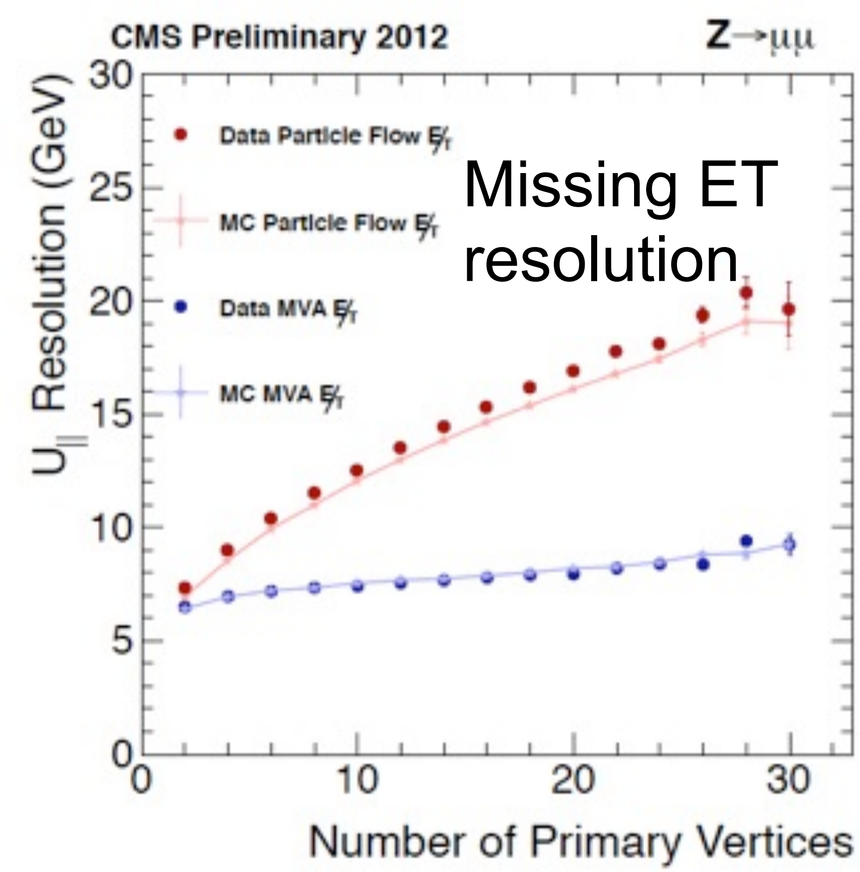
Pileup challenges

Muon isolation



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

- efficient association of charged tracks to collision vertices
- reconstruction of charged and neutral particles in jets
- pileup neutrals corrected w/global energy density (ρ)



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