CMS: HIGGS AT RUN II

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Higgs Hunting 2015

Outline

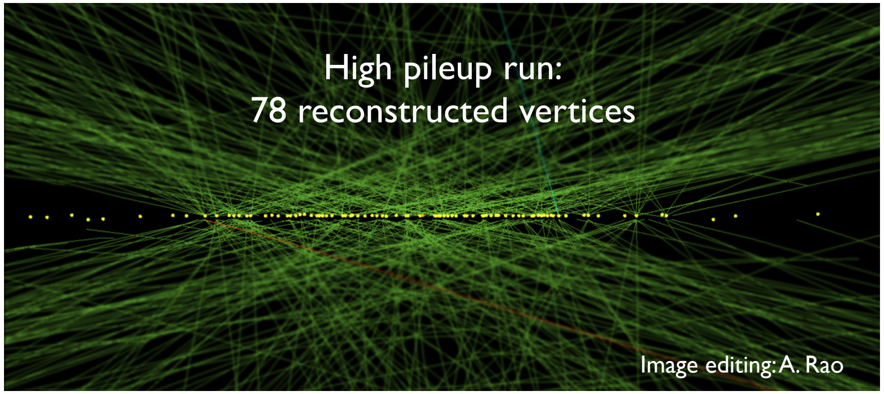
- **What's new for Run II**
  - LHC: Now through Run III
  - CMS:
    - Phase I upgrades and their impact
    - Reconstruction improvements for Run II
- **Higgs boson physics at 13 TeV**
  - Roadmap for next year and for Run II
  - Longer term projections (Run II + III)
    - Signal strengths, couplings
    - Spin-parity
    - Rare and exotic decays
    - Probing EWK symmetry breaking: VV scattering

LHC: now through Run III

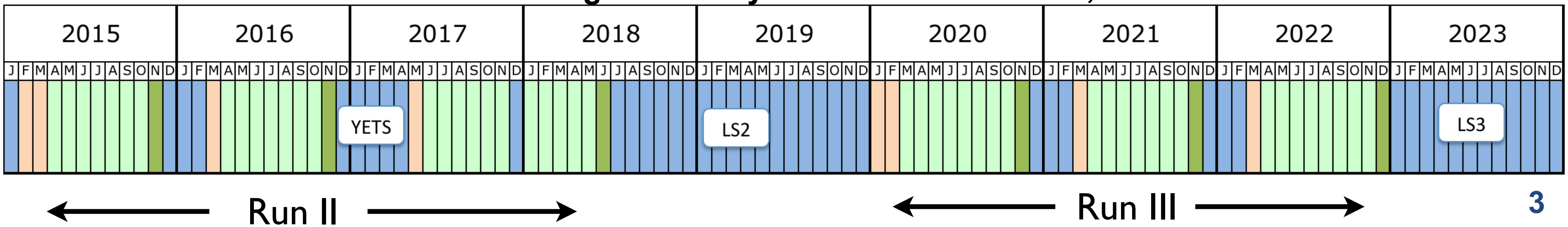
	CM Energy	Peak <N_{PU}>	Bunch spacing	Peak inst. lumi.	Cumulative int. lumi.
Run I	7-8 TeV	up to 35	50 ns	7.7×10^{33} cm^{-2} s^{-1}	29.5 fb^{-1}
Run II	13-14 TeV	~40	25 ns	1.5×10^{34} cm^{-2} s^{-1}	~100 fb^{-1}
Run III	14 TeV	~60	25 ns	~2.0×10^{34} cm^{-2} s^{-1}	~300 fb^{-1}

- Of the future accelerator options under study, LHC is the only facility currently operating and will be the only one in the next 10 years

- Run II started, Run III approved

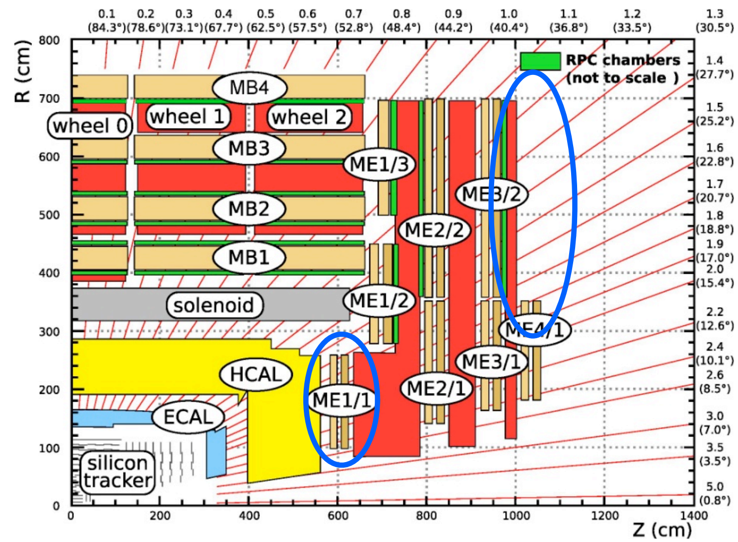


This schedule below has changed recently: LS2 will start in 2019, LS3 will start in 2024



CMS: during LS1

- **New beampipe**
- **Pixel:** repairs, pilot blades
- **Tracker:** lower temperatures
- **ECAL:** repairs, crystal monitoring
- **HCAL:** new photo-diodes
- **Muons systems:**
    - DT: repairs, trigger boards
    - RPC: installation of the 4th disk, completion of muon coverage $1.25<|\eta|<1.8$
    - CSC: prep. for new electronics
- **DAQ upgrade, Improved HLT**



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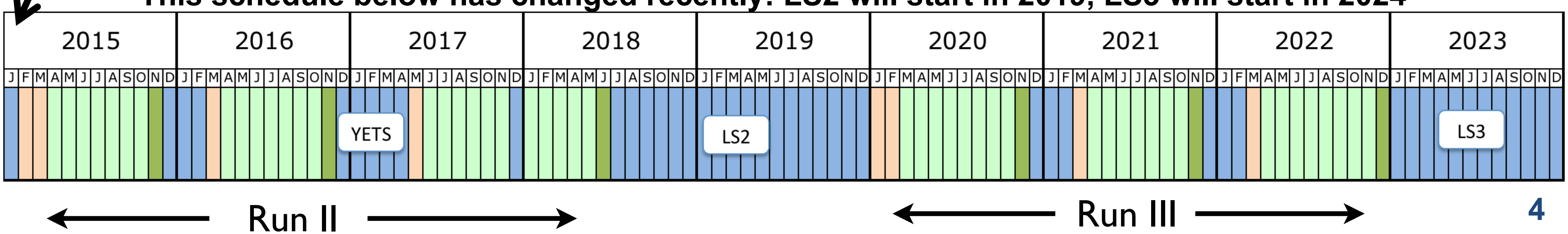
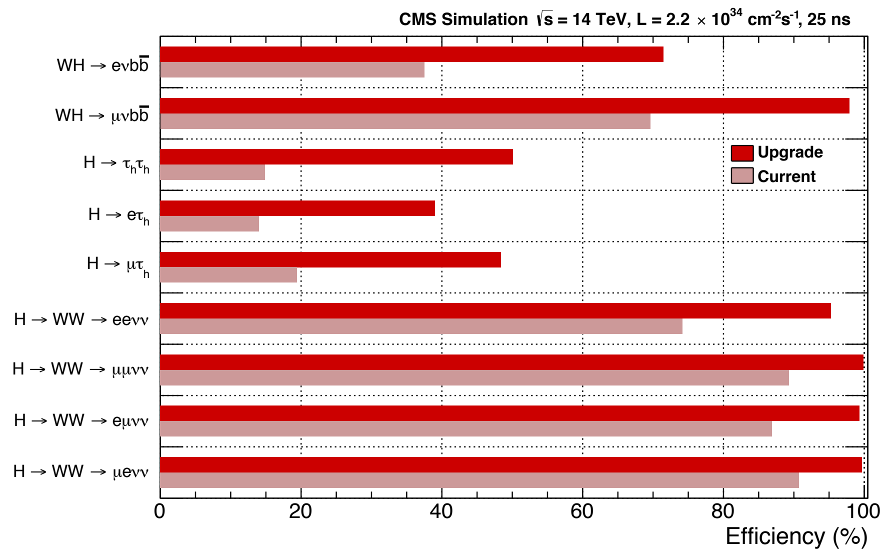


CMS: now through Run III

L1 trigger upgrade:
Algos approaching HLT sophistication. Calo and muon objects improved resolutions, PU subtraction, improved granularity, flexibility

HCAL upgrade:
photodetectors and electronics, forward



CMS NOTE-13-002

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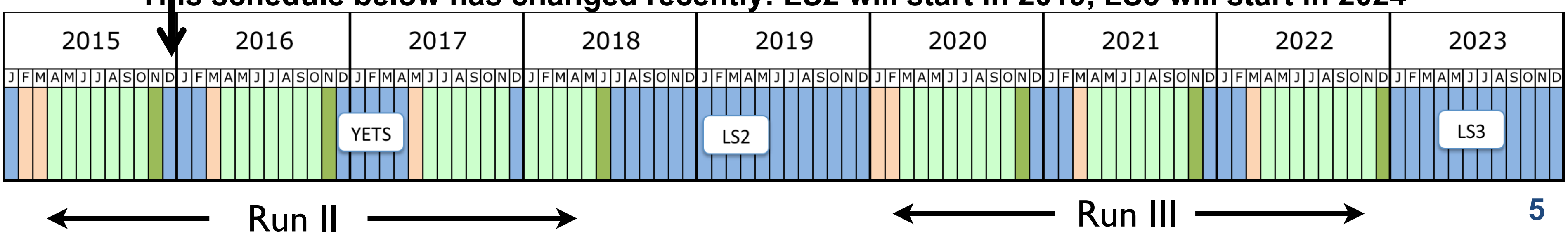
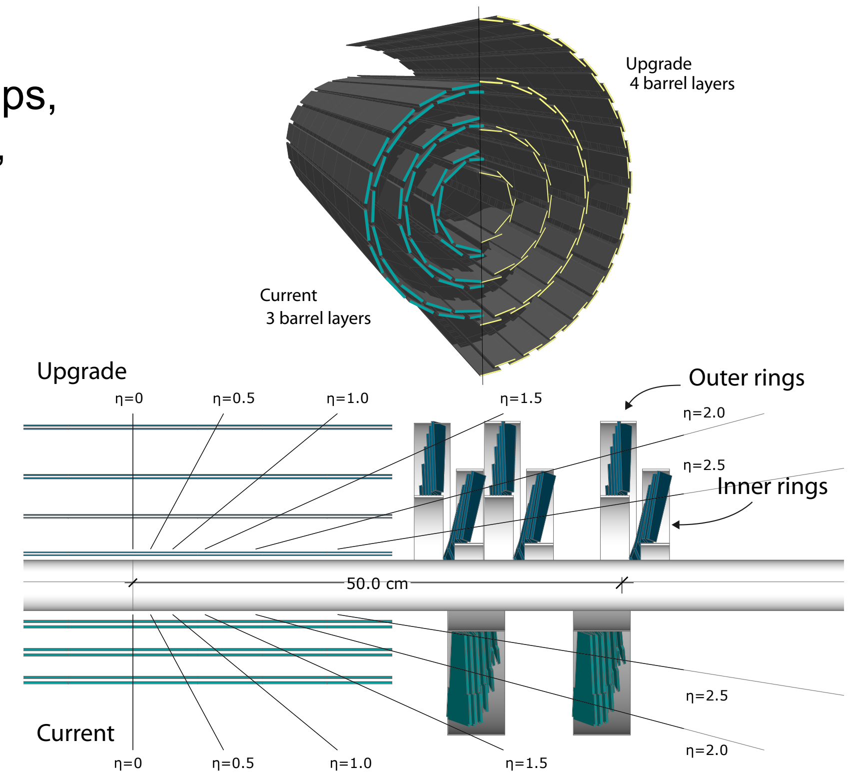


CMS: now through Run III

Pixel detector upgrade:
4 layers in the barrel, 3 disks in the endcaps, better tracking efficiency, lower fake rates, improved b-tagging



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CERN-LHCC-2012-016

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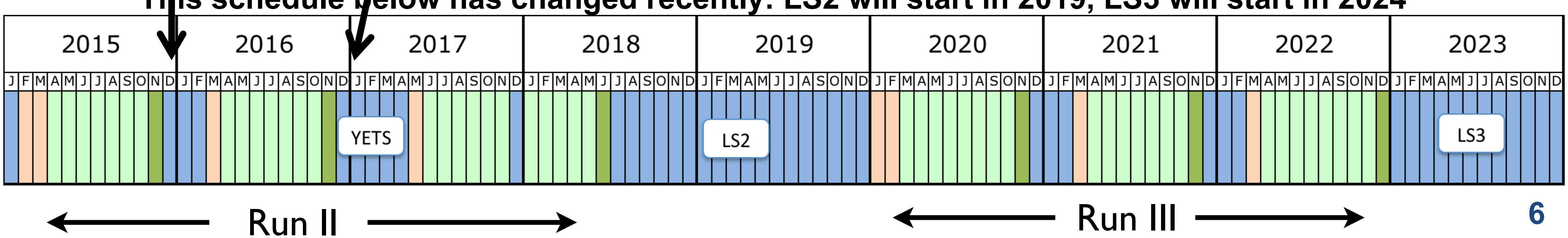

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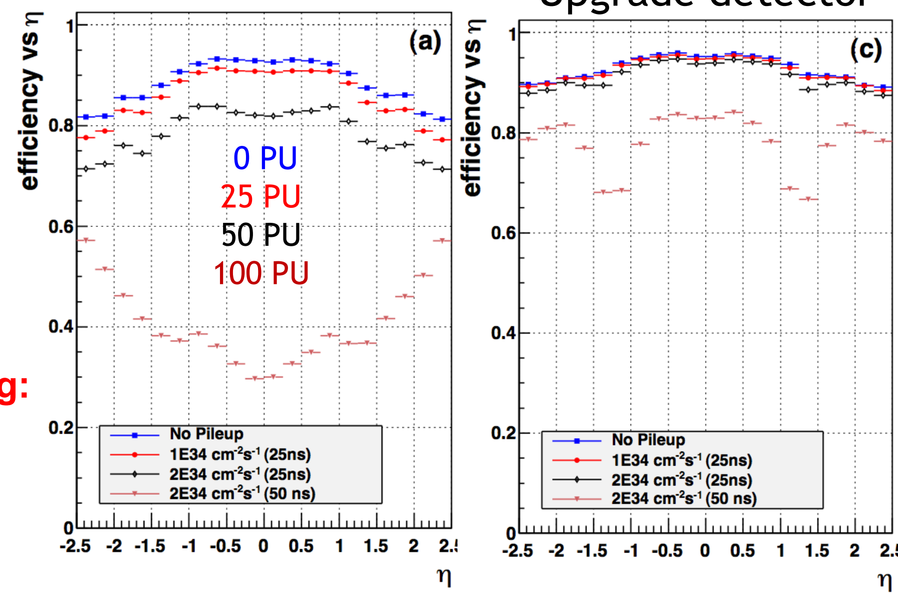
Tracking and b-tagging:

New pixel at 50 PU = Current pixel at 0 PU

Current detector Upgrade detector



Fake Rate= 6% (η=0) Fake Rate= 2% (η=0)

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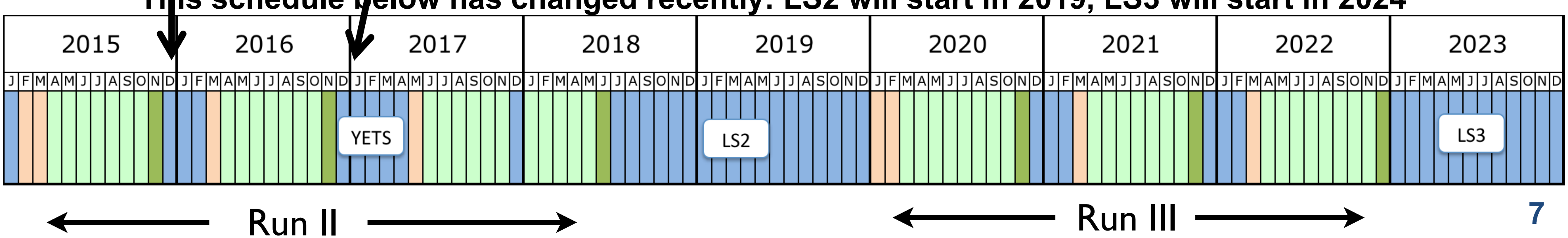

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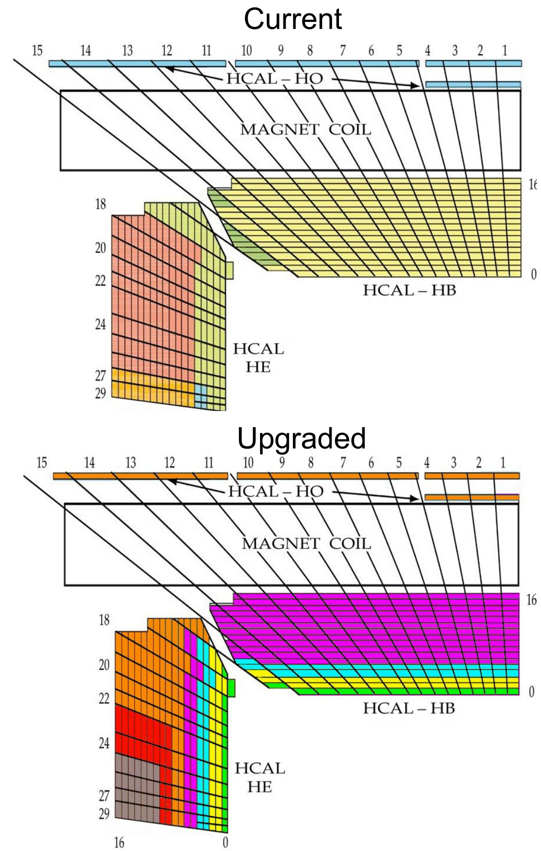
photodetectors/ electronics barrel/endcap depth segmentation allows PU mitigation



CERN-LHCC-2012-015

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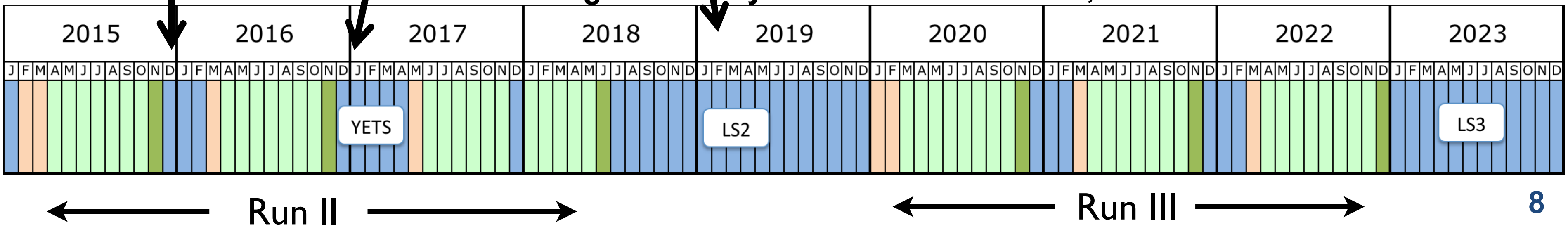

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photodetectors and electronics, forward

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Phase I upgrades → no degradation of performances up to the end of Run III
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Assumption for the prospective studies presented thereafter

NB: In some cases, could be better

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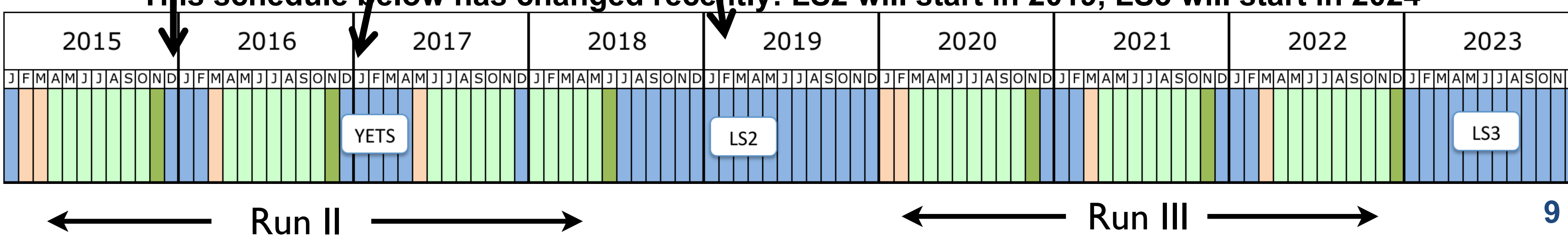
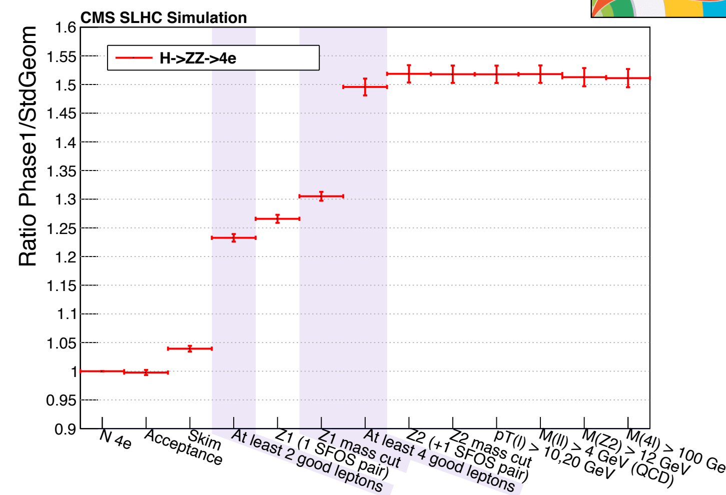
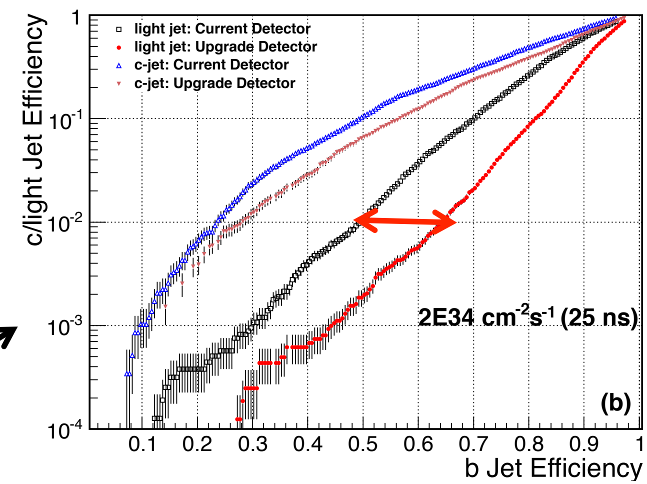


Impact of phase I upgrades: examples

1. H➔ZZ➔4l
- Sensitive to improved lepton tracking and isolation efficiency
- Significant gain in signal reconstruction efficiency (PU=50): 41% to 51%



2. ZH➔llbb
- Sensitive to lepton tracking, b-tagging and dijet mass resolution
- Both channels with 65% gain in signal efficiency (~30% b-tagging, ~20% tracking)
- HLT trigger efficiency not included, using 3 of the 4 hits in upgraded pixel detector could improve also trigger efficiency significantly



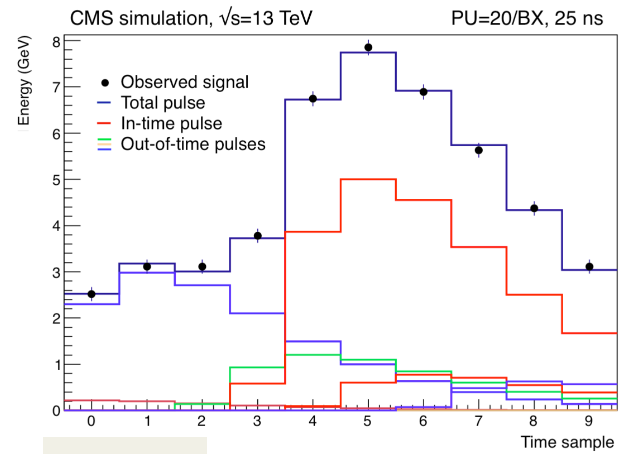
CERN-LHCC-2012-016

- b-jet efficiency 1.3 x better for a 1% light flavour jet rejection, for PU = 50
- Detector much more robust to PU: upgrade at 50 PU ~ current at 0 PU

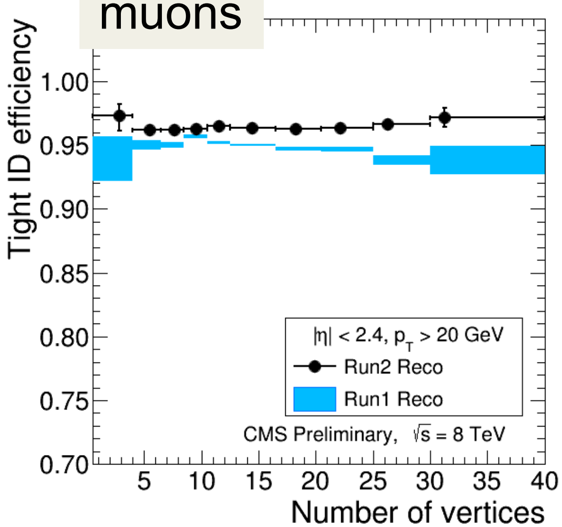
Further actions for Run II

Significant effort on algorithm improvements with emphasis on pile-up mitigation, namely:

- Improvement of track reconstruction: fast, efficient
- New tau ID
- Out of time PU mitigation in the calorimeters, pulse fit to extract the in-time energy per cell
- Revisiting of Particle Flow event reconstruction

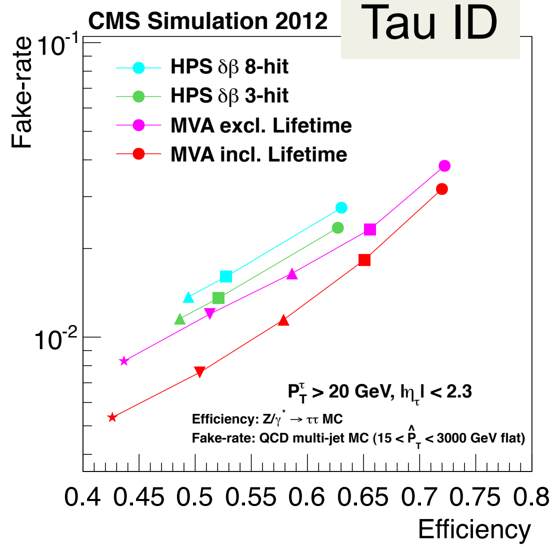


muons



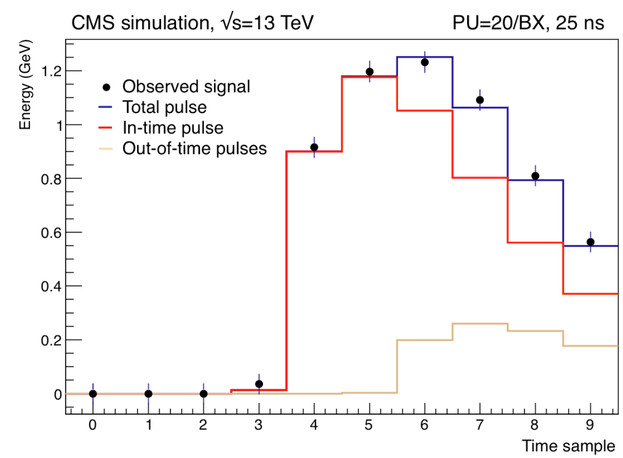
CMS-DP-2015-015

Tau ID



CMS-DP-2014-015

ECAL

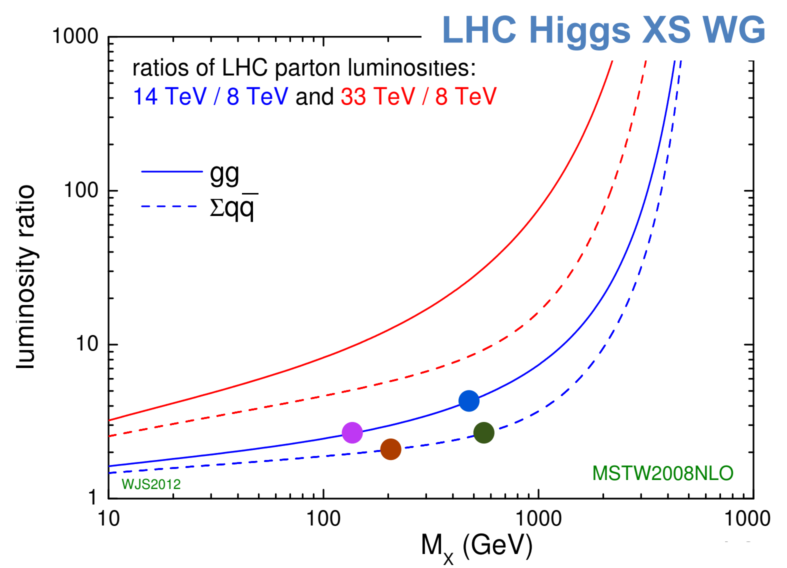


CMS CR -2014/410

Higgs physics at 13/14 TeV

With 4 x more luminosity at the end of Run II and ~ 2 to 4 x cross sections

	σ 13(14) TeV / σ 8 TeV	Events 20fb^{-1} √s = 8 TeV	Events 100 fb^{-1} √s = 13 TeV
ggH	2.3 (2.6)	390k	4500k
VBF	2.4 (2.6)	32k	370k
WH	2.0 (2.1)	14k	140k
ZH	2.0 (2.1)	8k	90k
ttH	3.9 (4.7)	3k	50k



Early Run II: **with 5 to 10 fb^{-1} (Moriond 2016), Higgs boson rediscovery, sensitivities comparable to Run I**

- Results on ggH/VBF/VH production with H to ZZ/WW/γγ/ττ/bb decays
- ttH combination foreseen with full 2015 dataset with a better sensitivity than for Run I
- Many searches will update with the full 2015 dataset: reaching Run I statistics with ~1 fb^{-1} of data at M = 3 TeV, ~5 fb^{-1} of data at M = 1 TeV (Salam & Weiler)

Up to now: Focusing on Run II preparation, 50 ns data mostly used for object commissioning

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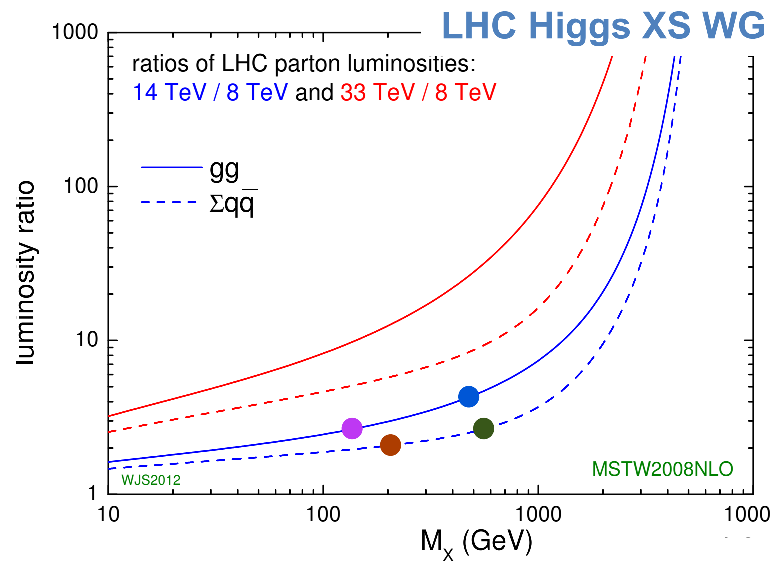


Run II (100 fb^{-1}): complete transition from discovery to precision physics

- Precise measurements of Higgs production, couplings and mass
- Fiducial cross sections, differential cross sections
- Search for rare or exotic decay modes
- Spin-parity, possible CP violating contributions
- Search for additional Higgs bosons beyond the SM
- Probing EWK symmetry breaking: VV scattering

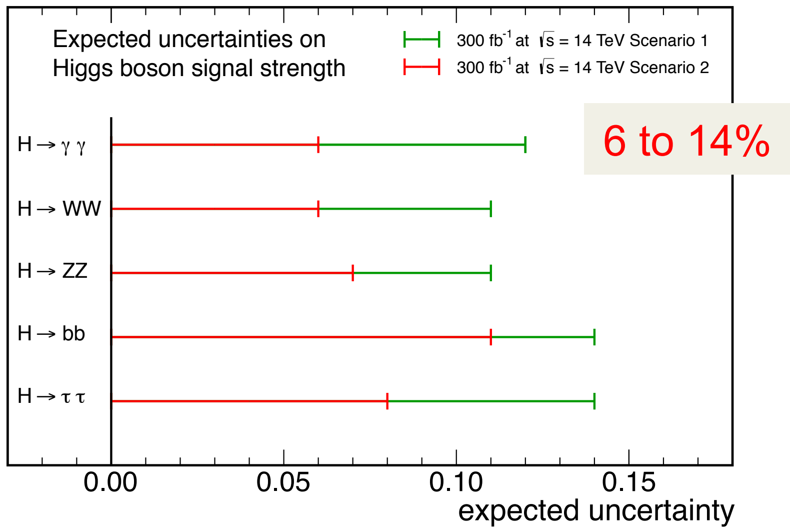
Couplings projections: methodology

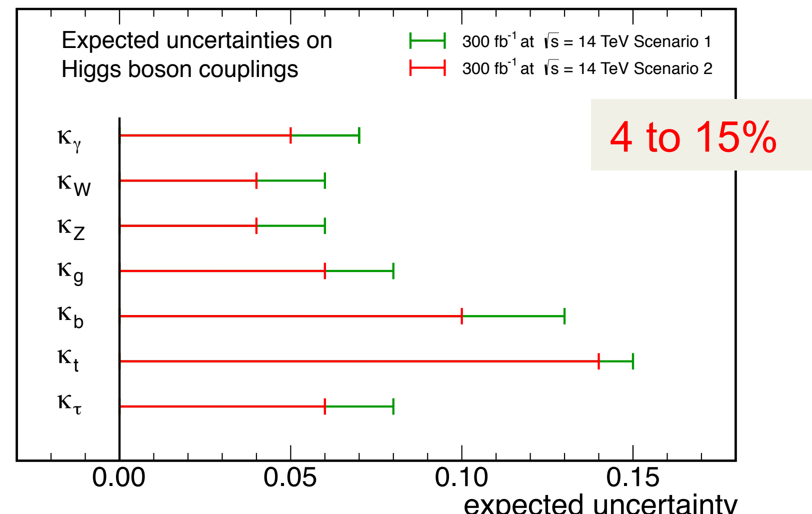
- Estimate uncertainties on signal strength, couplings, and coupling ratios at the end of LHC phase I (Run II+III)
- Extrapolate from numbers of signal and background events in Run I analysis, scaling statistics to 300 fb^{-1} at $\sqrt{s}$ = 14 TeV
- New channels not considered

- 2 scenarii for systematic and theoretical uncertainties:
  - **Scenario 1:** all systematics remain the same as Run I
  - **Scenario 2:** experimental syst. scaled by $1/\sqrt{\mathcal{L}}$, theory scaled by ½
- Procedure assumes 2012 CMS performance
  - Assumes object resolutions are maintained
  - No optimizations

Signal strength and couplings

Measurements σ(XX➔H) . BR(H➔YY) ~ $\Gamma_X \Gamma_Y / \Gamma_H$ (in "small width approx.")





Signal strengths $\mu = \sigma.BR/(\sigma.BR)_{SM}$ determined directly for each production and decay channel

Δμ/μ [%]	γγ	WW	ZZ	ττ	bb
Run I	21	25	29	31	52
Run III	12(6)	11(6)	11(7)	14(8)	14(11)

Improves sensitivity with regard to Run I by about a factor 2 to 4 (3 to 5)

Coupling modifiers $\kappa_Y^2 = \Gamma_Y/(\Gamma_Y)_{SM}$ defined so that relevant rates scale with κ_Y^2

Determined from fit to σ.BR measurements

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

Most NP scenarios predict smaller deviations

http://arxiv.org/abs/1307.7135

http://arxiv.org/abs/1401.6081

Spin-parity with H➔ZZ

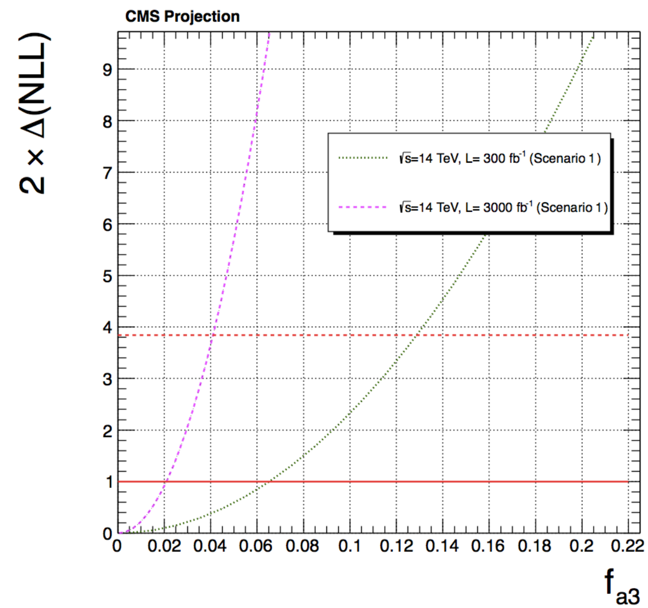
$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

scalar SM **scalar anomalous** **pseudo-scalar**

- Constraint anomalous couplings from simultaneous fit to m(H) and kinematics of the 4-leptons system
- Example: f_{a3} effective fraction of ZZ cross section from CP-odd contribution

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_3|^2\sigma_3}$$

- Increasingly precise limits on CP-odd contribution to Higgs boson



http://arxiv.org/abs/1307.7135

95% CL limit at 300fb^{-1}:
f_{a3} < 0.13 (current limit: 0.51)

Rare and exotic decays

1. H➔μμ

Exclusion can be settled with < 200 fb^{-1}

Evidence with ~ 450fb^{-1} (~2.5σ with 300 fb^{-1})

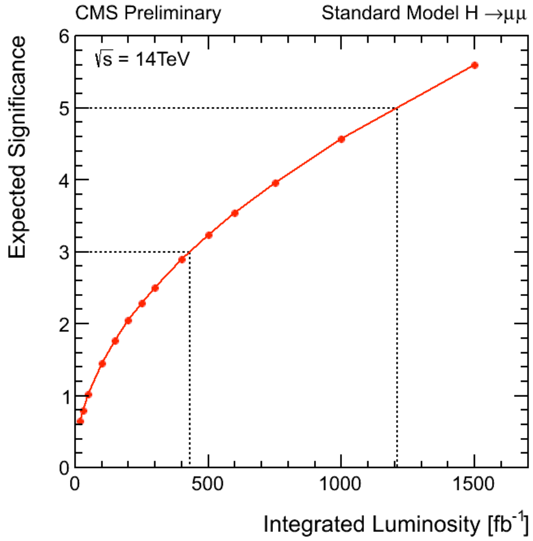
2. H➔Zγ

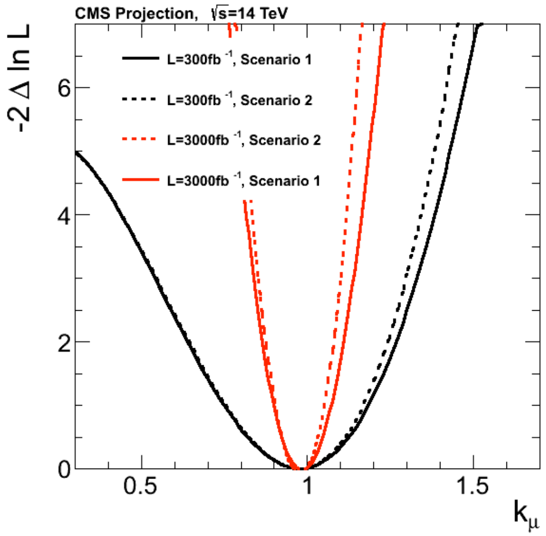
Loop induced, sensitive to non-SM contributions

3. Direct search for H➔invisible

ZH or VBF tagged

	300fb^{-1} at 14 TeV
κ_{μ}	23%
$\kappa_{Z\gamma}$	41%
Invisible BR (95% limit)	17%



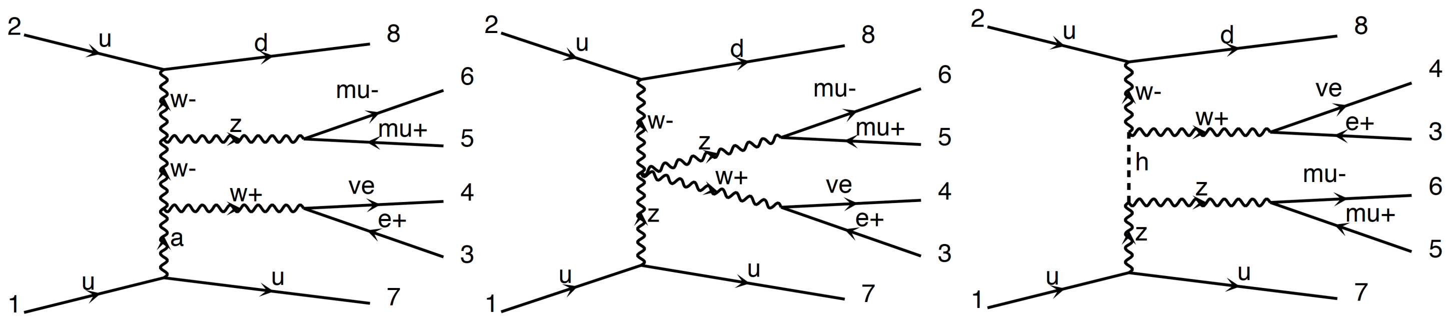


http://arxiv.org/abs/1307.7135

HIG-13-007

Probing EWK symmetry breaking: VV scattering

Example prospective study including detector phase I upgrades at 14 TeV



***WZ* scattering (leptonic decays + energetic forward scattering jets)**

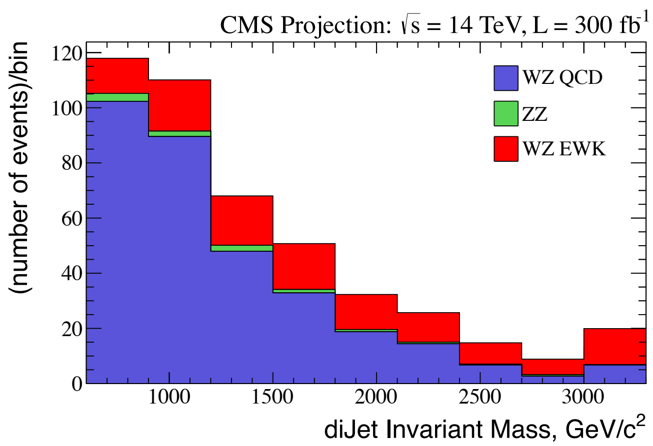
- Double TGC, QGC, t-channel Higgs boson scattering
- Strong interference leading to finite cross section, σ*NLO* predicted
- Scattering topology sensitive to new physics: any addition to the scattering process would alter this cancelation ➔ changes in the cross section at high scattering center of mass energy

CMS-PAS-FTR-13-006

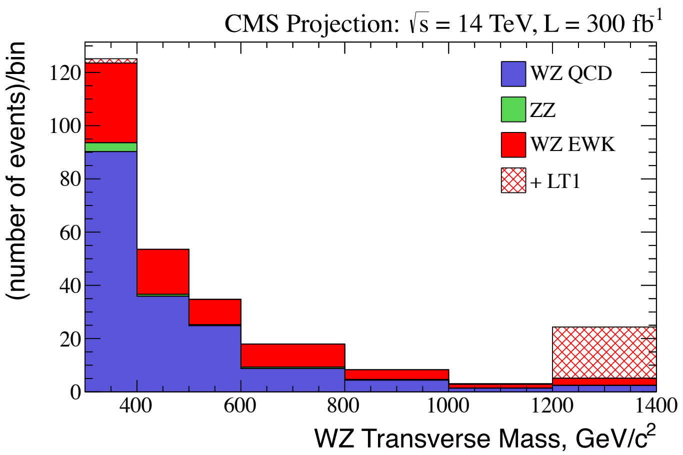
2 goals:

- Assess the discovery potential of SM WZ scattering
- Assess the sensitivity to new physics (anomalous QGC) with effective field theory (EFT)

Probing EWK symmetry breaking: VV scattering



Used for SM WZ scattering discovery potential



Used for sensitivity to new physics

CMS-PAS-FTR-13-006

EFT approach for modelling aQGCs

- Operator: $L_{T1} = (f_{T1}/\Lambda^4)\, Tr[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}]\, Tr[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}]$
- f_{T1} coupling constant for the new physics, Λ energy scale of the new physics

Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1}	0.8 TeV^{-4}	1.0 TeV^{-4}

Conclusions

- Run II: 100fb^{-1} with Higgs boson production cross sections x 2 to 4

➔ Run II Higgs boson statistics equivalent to 8 to 16 times the Run I one

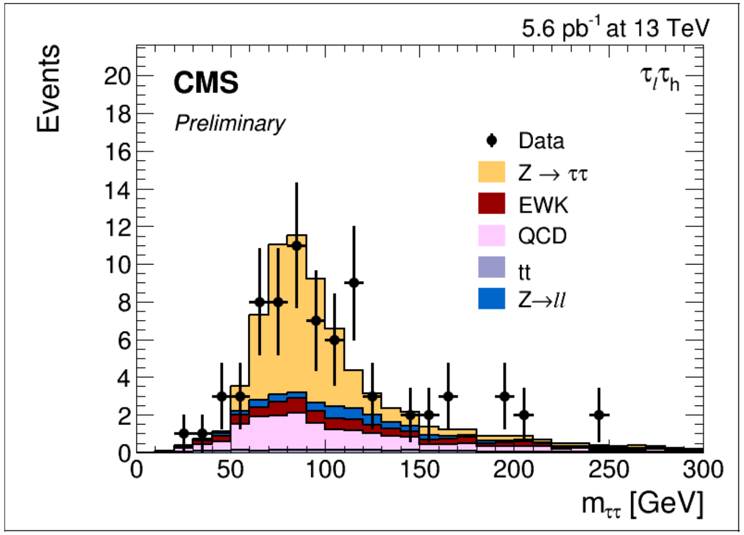
➔ Within a year, most channels should reach or exceed Run I sensitivities

- LHC environment more challenging with higher PU
- Detector upgrades and reconstruction improvements designed to cope with this challenging environment

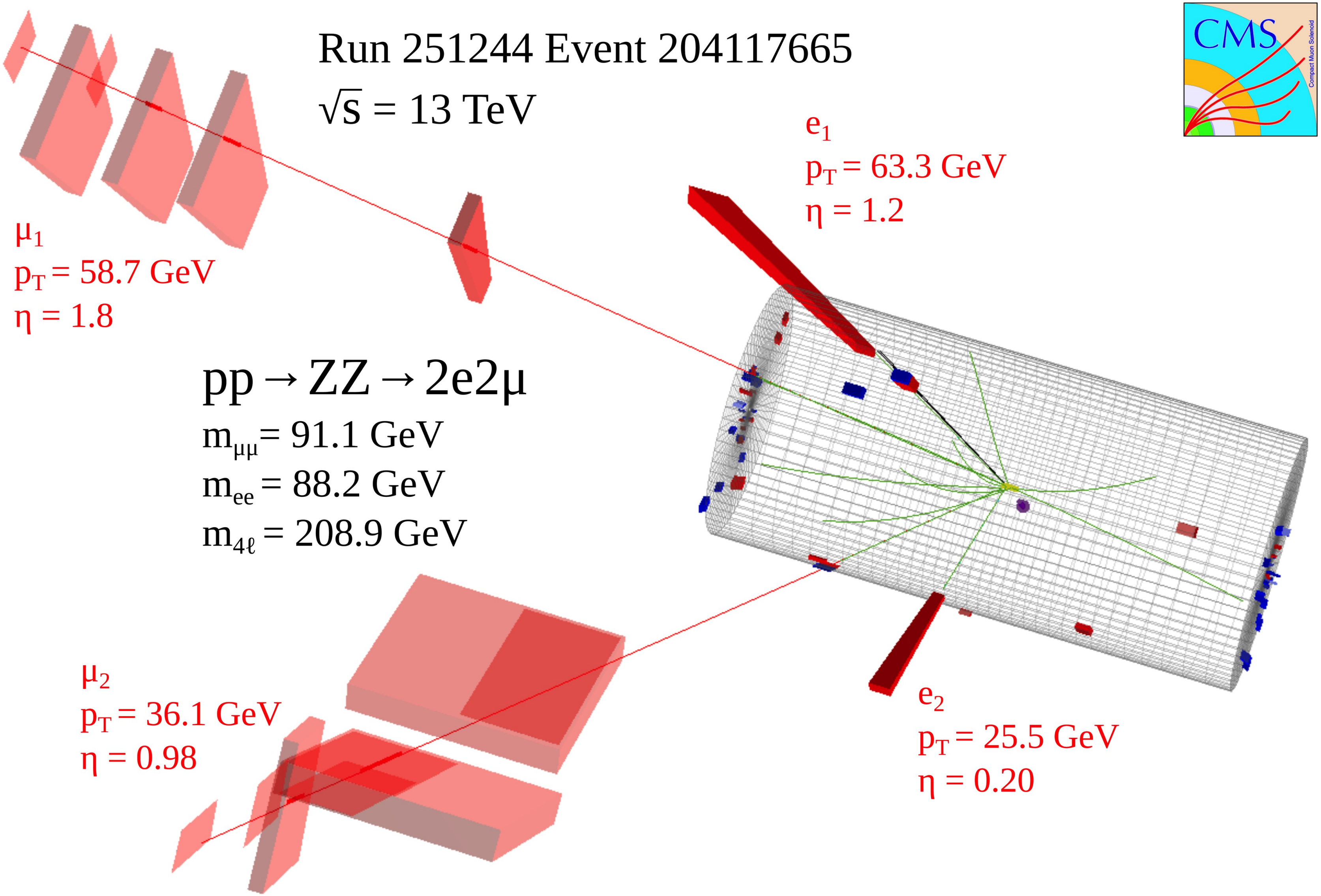
➔ CMS performances should be maintained or even better for Run II

- Physics at 13 TeV has already started: see Kerstin Borras's talk at EPS & https://twiki.cern.ch/twiki/bin/view/CMSPublic/PublicPlotsEPS2015

CMS is back in business



Reconstruction of Z → ττ 13 TeV data



Event display of a SM ZZ →2e2μ candidate @ 13TeV

Backup

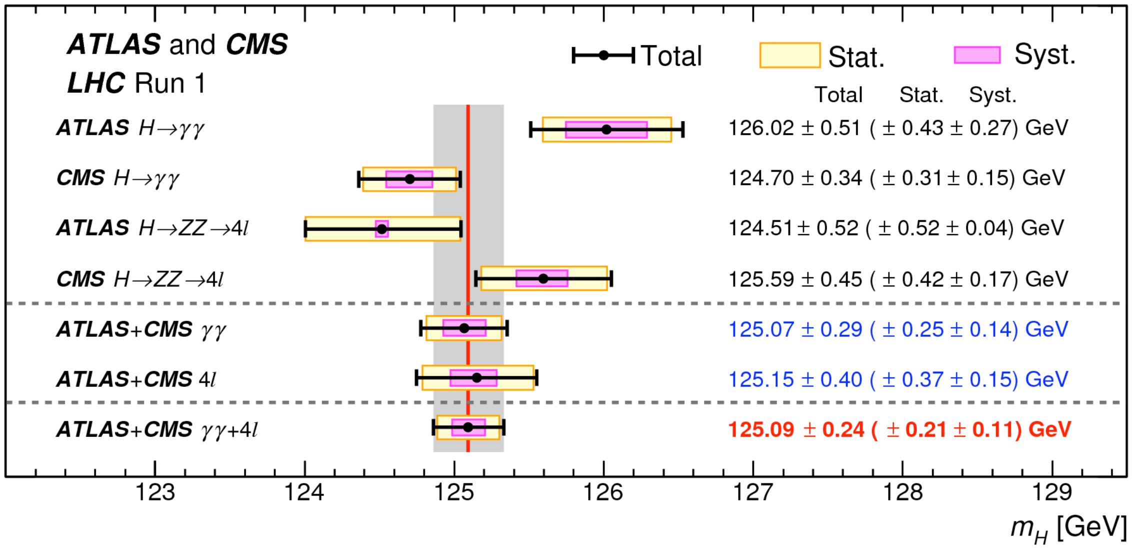
Bibliography

All projections results can be found here:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

- http://arxiv.org/abs/1307.7135 **CMS Submission to snowmass**
- http://cds.cern.ch/record/1607076?ln=en **H to ZZ to 4l**
- http://cds.cern.ch/record/1606835?ln=en **Vector Boson Scattering and Quartic Gauge Coupling Studies in WZ Production at 14 TeV**
- http://cds.cern.ch/record/1607086?ln=en **2HDM Neutral Higgs Future Analysis Studies**
- http://cds.cern.ch/record/1605864?ln=en **Sensitivity study for ECFA: heavy vector-like charge 2/3 quarks**
- http://cds.cern.ch/record/1355706?ln=en **Technical proposal for the upgrade of the CMS detector through 2020**
- https://cms-mgt-conferences.web.cern.ch/cms-mgt-conferences/conferences/pres_display.aspx?cid=1159&pid=7875 **Higgs properties CMS paper**
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13007TWiki **H to muons**
- **http://cds.cern.ch/record/1481837?ln=en** **Pixel upgrade TDR**
- **http://cds.cern.ch/record/1481837?ln=en** **HCAL upgrade TDR**
- **EPS-HEP 2015 talks: Frederick Bordry, Kerstin Borras**

Precision on mass in CMS

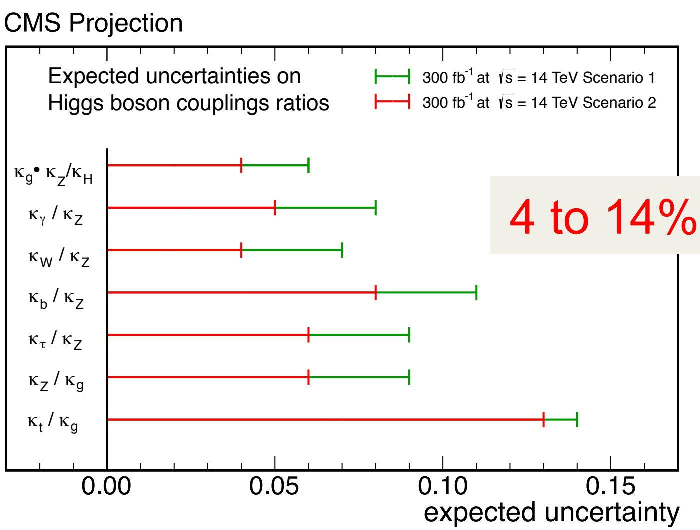
- Current CMS mass measurement largely dominated by statistics (syst x 2 in γγ, syst x 2.5 in ZZ) and slightly dominated by the diphoton channel (weights 65%, 35%)
- Statistical errors will reach current systematics with ~ 40 to 70 fb^{-1}



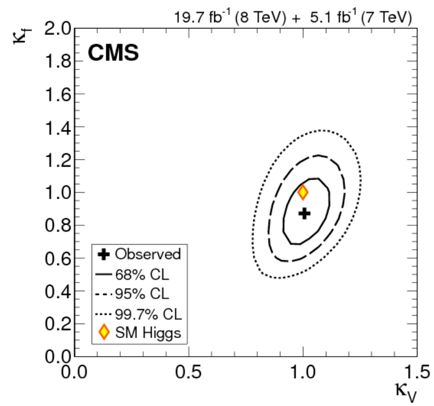
- But: many systematics will also scale with statistics! ZZ systematics can already be greatly reduced with Run I data.
- Other ones can also be reduced when high statistics available with the use of golden events where syst. are under better control

Couplings projections

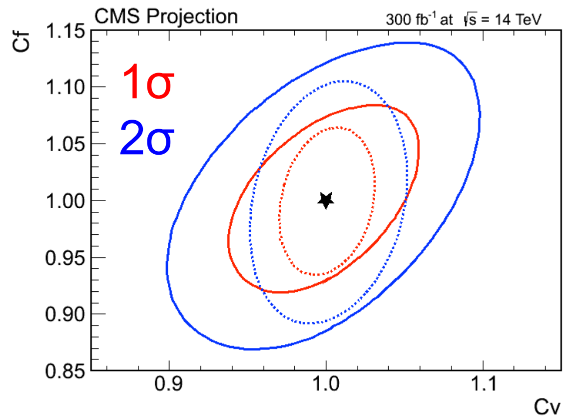
Coupling scale factor ratios $\lambda_{XY}=\kappa_X/\kappa_Y$ independent of assumptions on Higgs boson total width



Test of universal couplings κ_V and κ_F to gauge bosons and fermions (b, t, τ)



Current



Projection 300 fb^{-1}

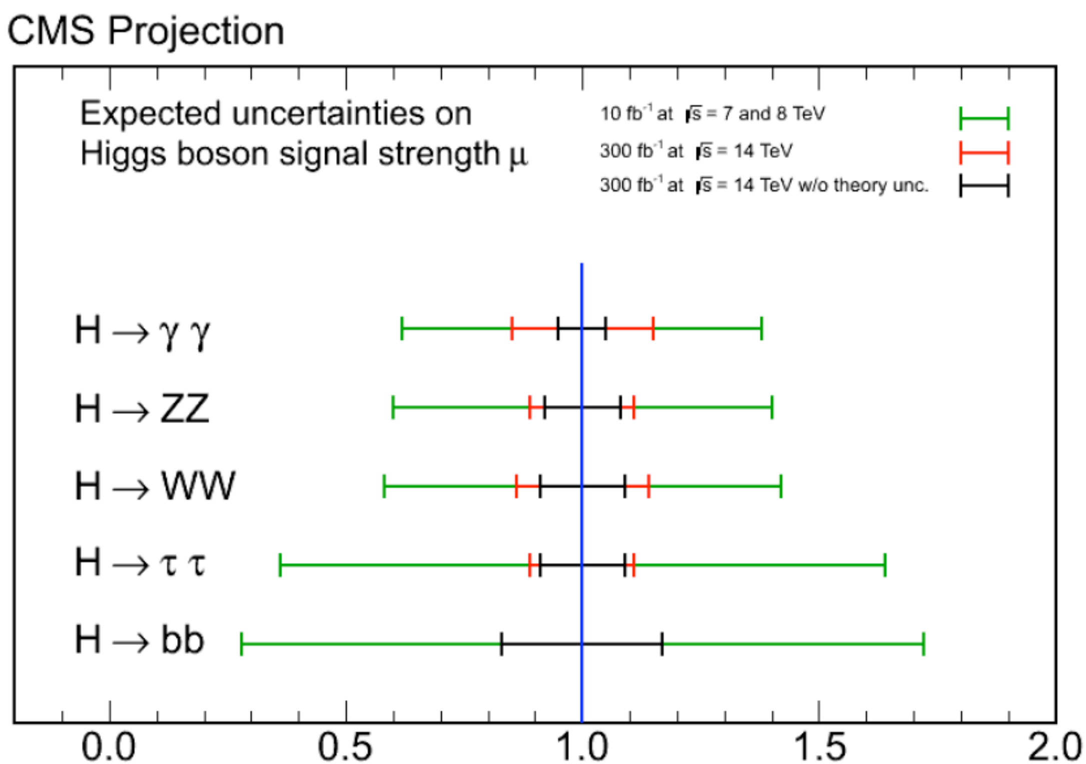
CMS-NOTE-2012-006

Full lines: with current theory errors
Dashed: without theory errors

- About 5% (10%) precision in Higgs couplings to vector bosons (fermions) reachable with run 2&3, compared to current values about 10% (25%)
- Theory improvements could reduce the uncertainty on κ_V significantly

Higgs 300fb^{-1}

- Assume the same trigger and reconstruction performances as in 2012
  - Need upgraded detectors to cope with large pileup and radiation damage
- Scenario 1: same systematics as in 2012
- Scenario 2: theory systematics scaled by a factor ½, other systematics scaled by $1/\sqrt{L}$
- Scenario 3: same exp. syst. as in 2012, w/o theory uncertainty



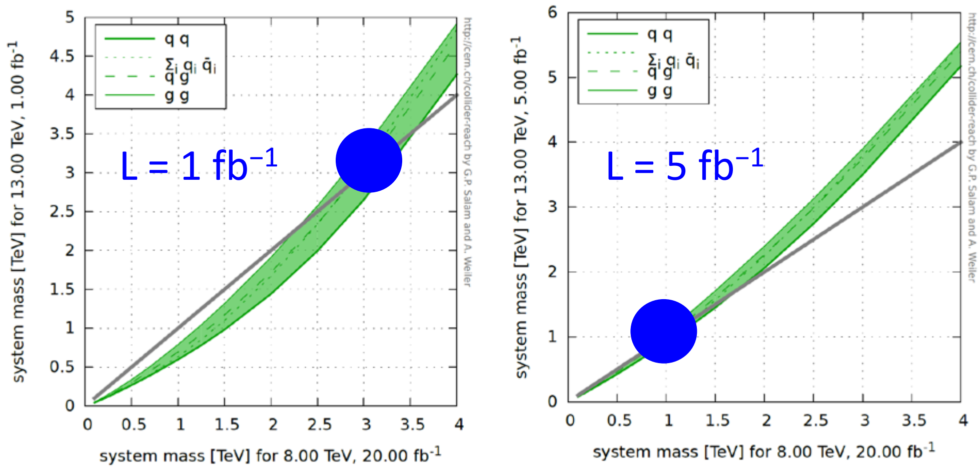
10 fb^{-1}, 7 and 8 TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 1)
300 fb^{-1} , 14TeV (Scenario 3)

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

Searches

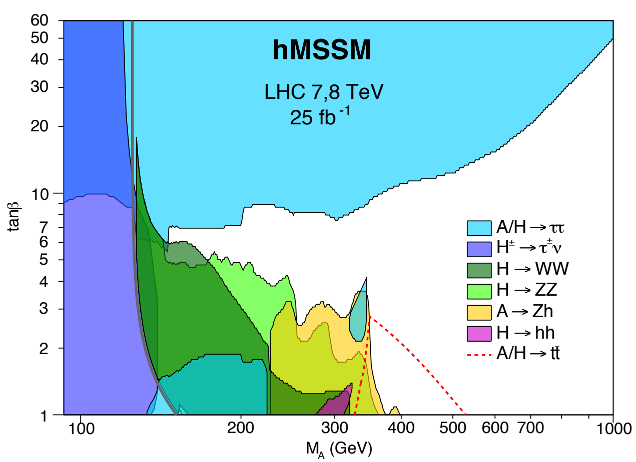
- At √s = 13 TeV, searches reach Run-I sensitivity:
  - with ~**1 fb^{-1}** of data, at M = **3 TeV**
  - with ~**5 fb^{-1}** of data, at M = **1 TeV** *(most of EXO analyses)*

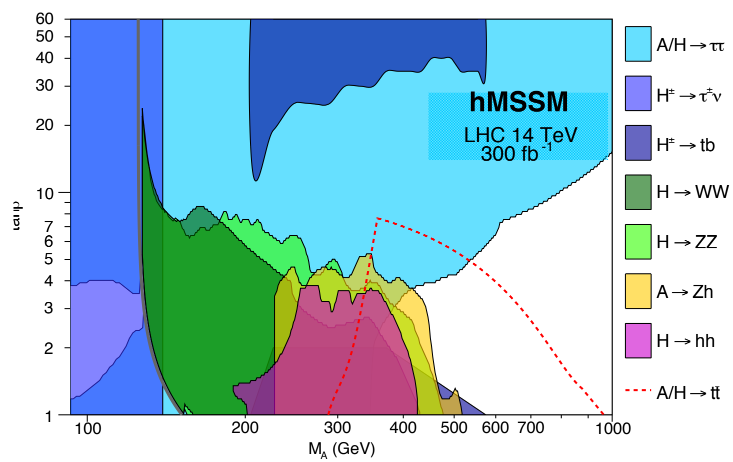
G. Salam and A. Weiler, from ratio of parton luminosities



http://collider-reach.web.cern.ch/collider-reach/

- Additional Higgs bosons?
- Exotic production (enhanced di-Higgs, mono-Higgs, tH)
- Exotic/rare decays?



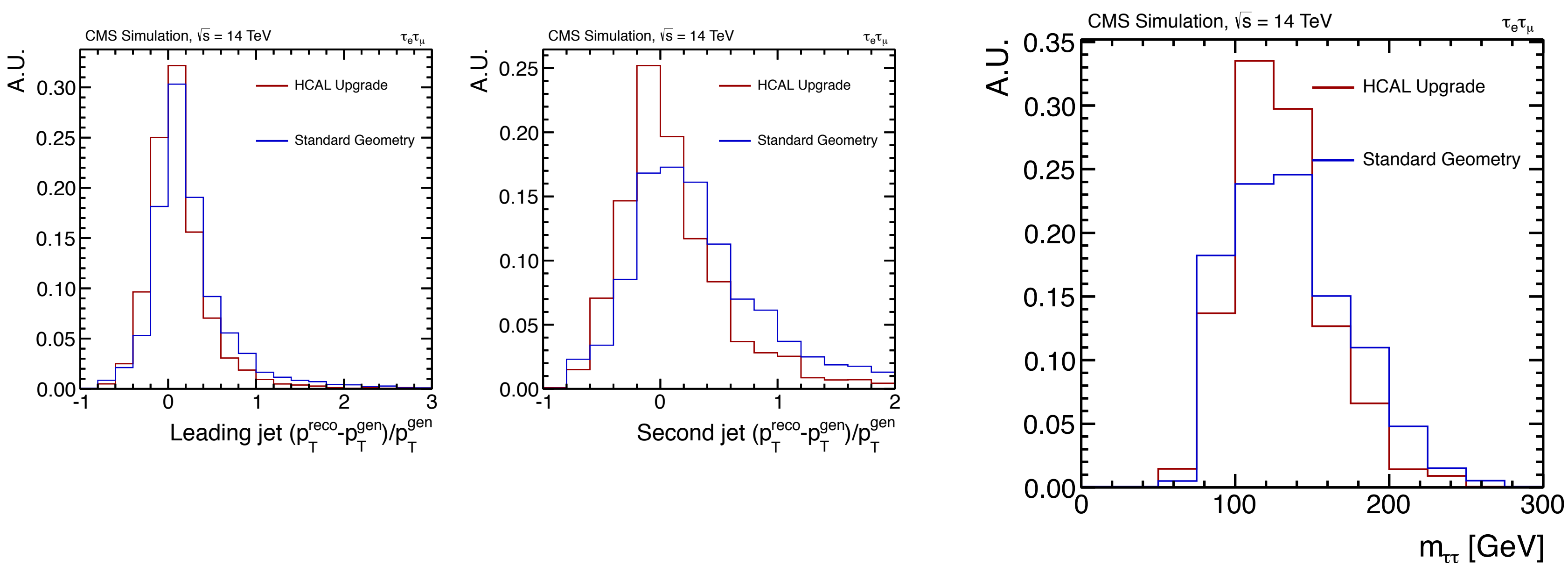


arxiv.1502.05653

All searches pursued in CMS – also beyond MSSM context

VBF H➔ττ with phase I upgrades

- Study in the Hjj➔$\tau_e\tau_\mu$ jj channel with PU=50
- Sensitive to MET resolution, jet p_T resolution, lepton tracking and isolation
- Improved jet and MET resolution allows a 25% improvement on the ττ invariant mass resolution
- Total efficiency improvement from upgrades: factor 2.5 (4.5% to 11%)
- Full improvement from particle flow not yet folded in

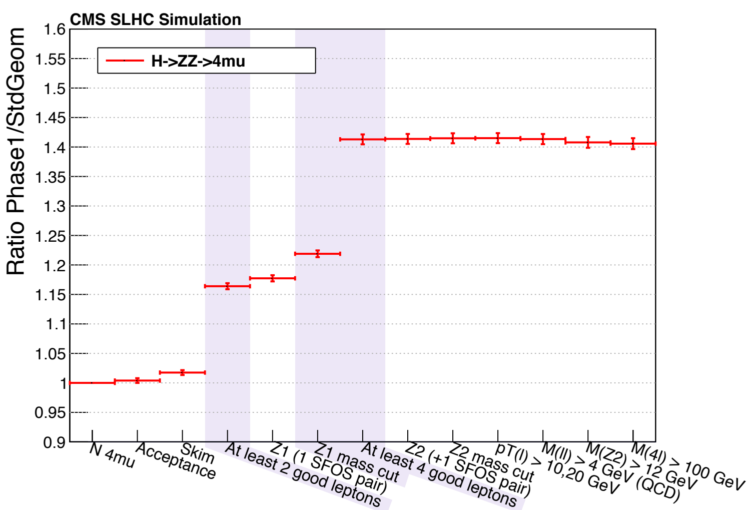


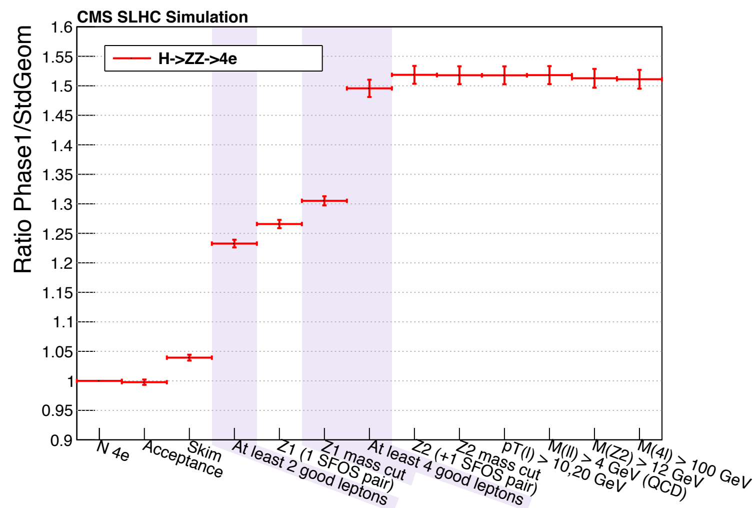
CERN-LHCC-2012-015

H→ZZ→4l with phase I upgrades

- Sensitive to improved lepton tracking and isolation efficiency
- Significant gain in signal reconstruction efficiency (PU=50 scenario): 41% to 51%

Channel	Overall Efficiency Phase 1 Pixels	Overall Efficiency Current Pixels	Efficiency gain
$H \to 4\mu$	$(36.0 \pm 0.2)\%$	$(25.6 \pm 0.2)\%$	1.41
$H \to 4e$	$(18.7 \pm 0.2)\%$	$(12.4 \pm 0.1)\%$	1.51
$H \to 2e2\mu$	$(25.9 \pm 0.1)\%$	$(17.5 \pm 0.1)\%$	1.48

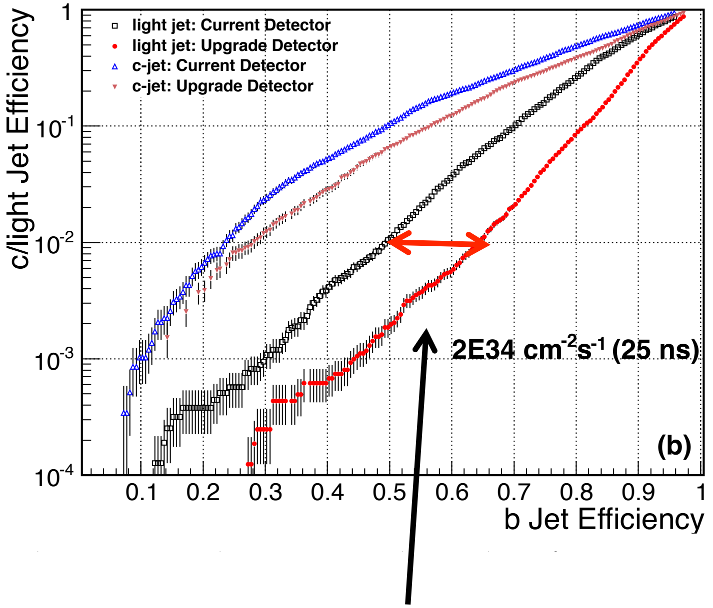


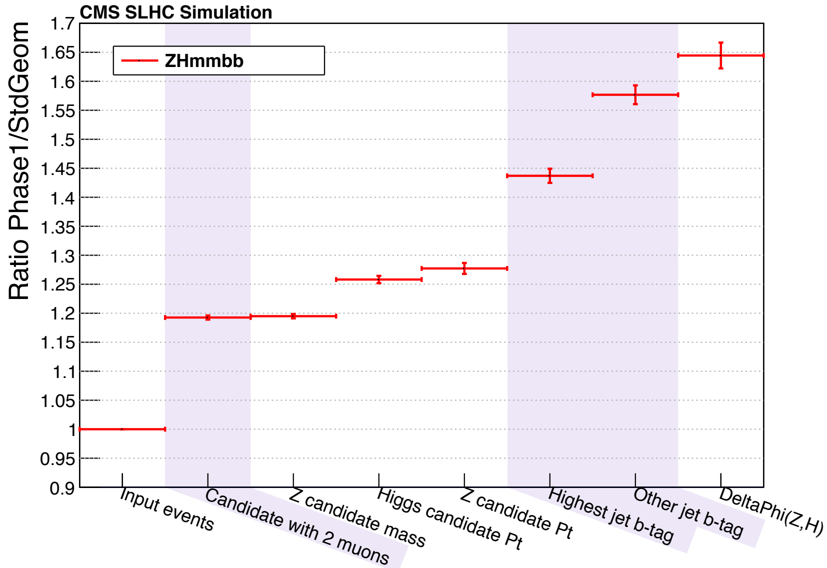


CERN-LHCC-2012-016

ZH→llbb with phase I upgrades

- Sensitive to lepton tracking, b-tagging and dijet mass resolution
- Both channels with 65% gain in signal efficiency (~30% from b-tagging, ~20% from lepton tracking)
- NB: HLT trigger efficiency not included, using 3 of the 4 hits in upgraded pixel could improve also trigger efficiency significantly





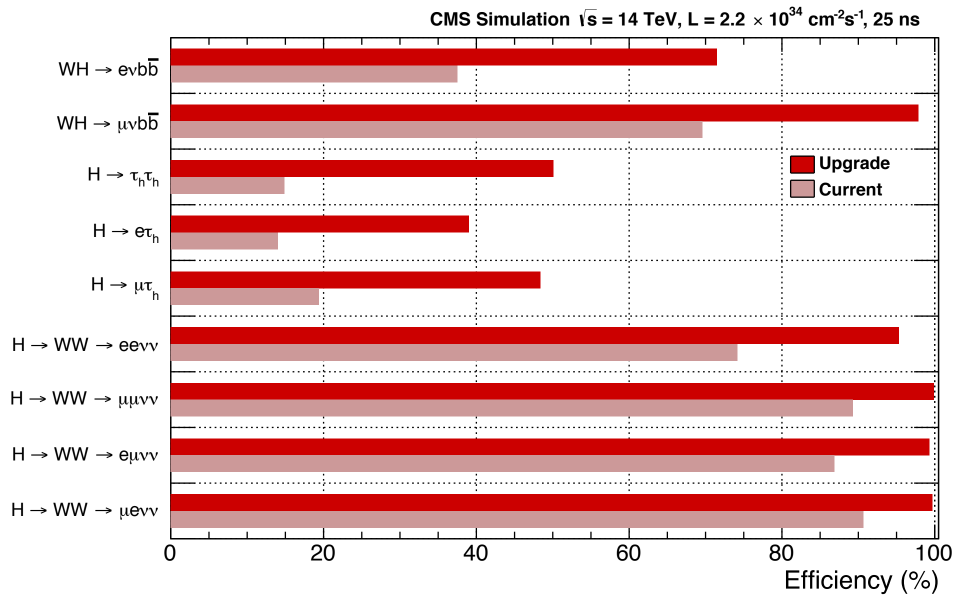
CERN-LHCC-2012-016

- b-jet efficiency 1.3 x better for a 1% light flavour jet rejection, for PU = 50
- Detector much more robust to PU: upgrade at 50 PU ~ current at 0 PU

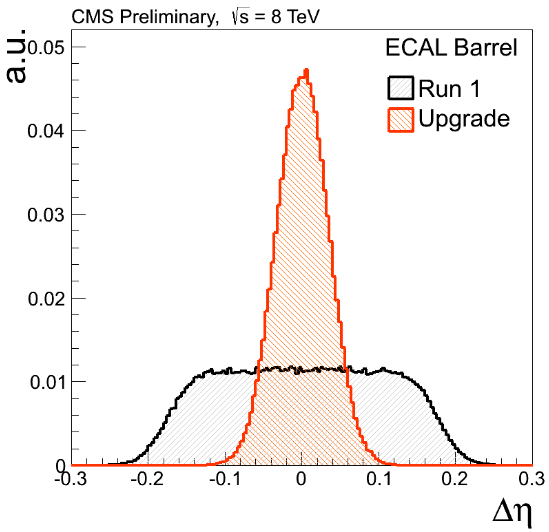
CMS L1 trigger upgrade

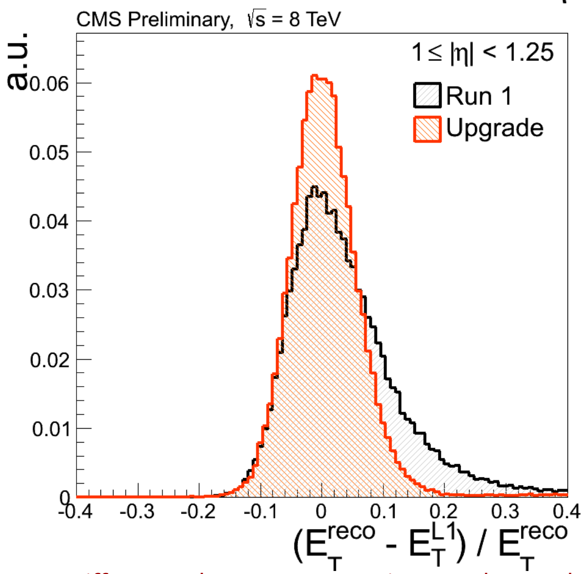
Use HCAL/ECAL granularity, flexibility and scalability

- Improved EM isolation using calo energy distributions with PU substraction
- Improved jet finding with PU substraction
- Improved hadronic tau id
- Improved muons pt resolutions in difficult regions
- Improved muon isolation using calo energy distributions with PU substraction
- Improved global L1 trigger menu with a greater number of triggers



CMS L1 trigger upgrade e/γ





- Difference in pseudorapidity for L1 e/γ candidates with respect to the offline reconstructed pseudorapidity. The distributions of the upgrade trigger (red) are compared with those of the Run-1 system (black)

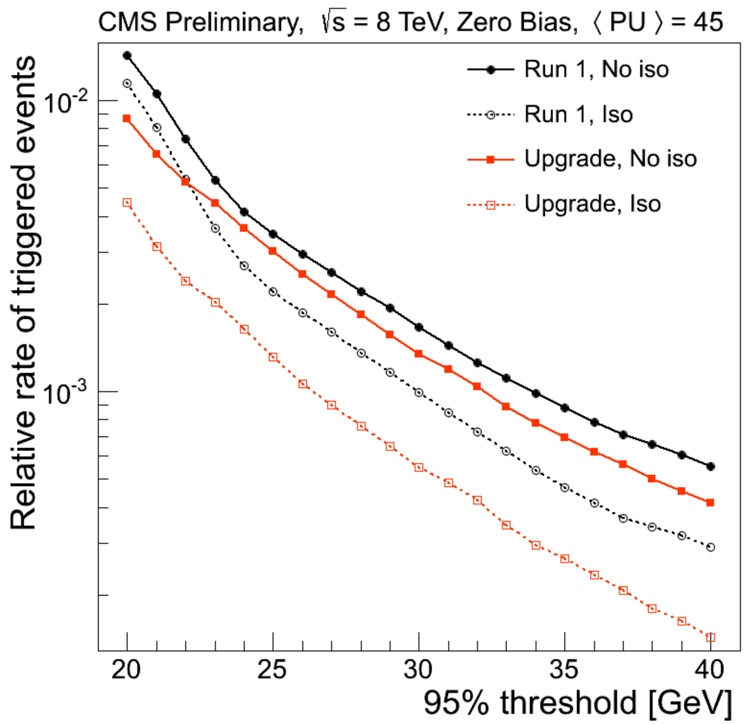
- Differences between Run-1 trigger and upgrade trigger

↳ The Run-1 trigger uses the granularity of the Regional Calorimeter Trigger (4x4 trigger towers)

↳The upgrade trigger uses the granularity of a trigger tower (ΔηxΔφ = 0.087x0.087)

CMS-DP-2015-003

CMS L1 trigger upgrade e/γ



e/γ trigger rates
zero bias data: rates lower for the same signal efficiency

- Difference in pseudorapidity for L1 e/γ candidates with respect to the offline reconstructed pseudorapidity. The distributions of the upgrade trigger (red) are compared with those of the Run-1 system (black)

- Differences between Run-1 trigger and upgrade trigger

↳ The Run-1 trigger uses the granularity of the Regional Calorimeter Trigger (4x4 trigger towers)
↳The upgrade trigger uses the granularity of a trigger tower ($\Delta\eta x \Delta\varphi$ = 0.087x0.087)

CMS-DP-2015-003

CMS L1 trigger upgrade taus

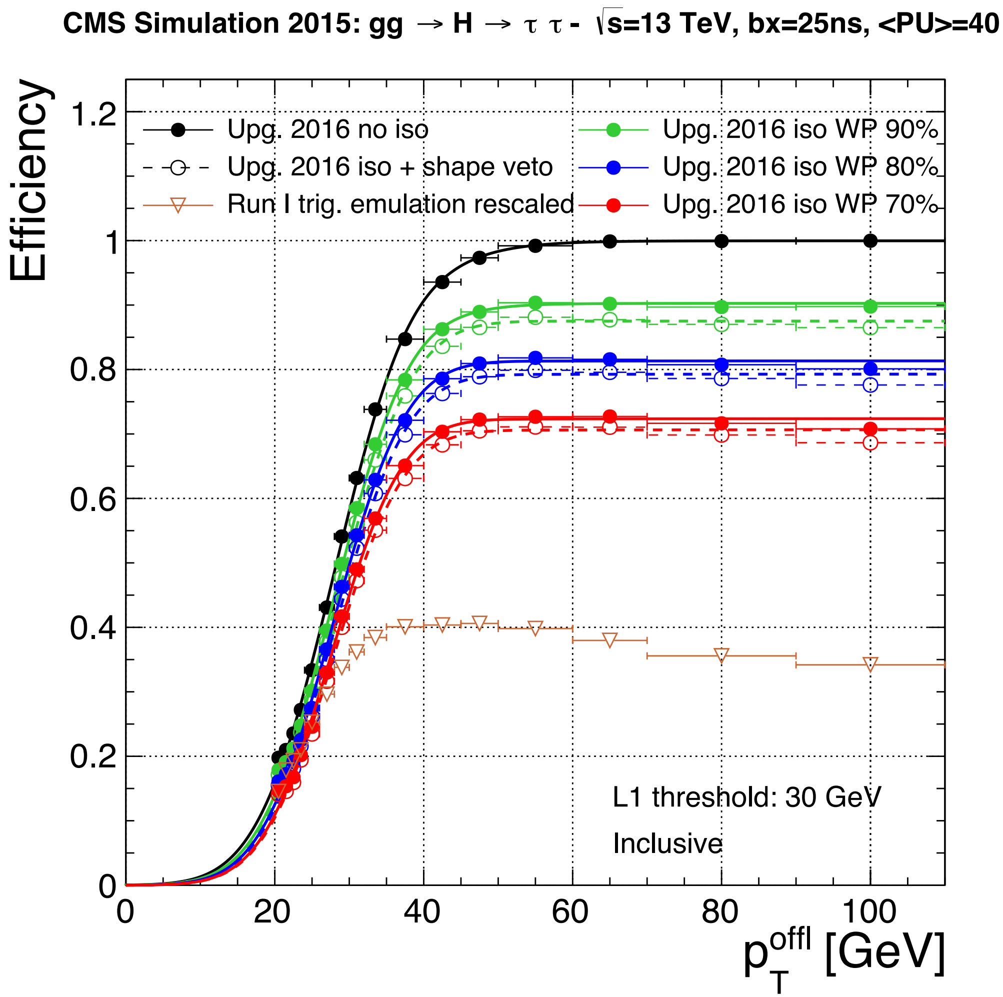
- **Run I algorithm:**
  - granularity is limited to the size of a Regional Calorimeter Trigger (RCT) region 4x4 TT in the (η,φ) plane
  - tau candidates are formed from jets, a simple shape plus isolation criteria is applied to "promote" a jet to be a tau candidate
  - shape veto consists in the check of the TT pattern extension and rejects all patterns that extend by more than 2 TT in η or φ

- **2016 upgrade algorithm:**
  - has access to the single TT granularity i.e. 0.087x0.087 in the (η,φ) plane over most of the detector
  - runs a dedicated algorithm for tau leptons
  - refined shape veto that takes into account the full cluster shape and not its extension only
  - Isolation threshold is a function of the three variables (Et, PU, η), giving a flat efficiency under all PU conditions, over the whole detector and over a broad spectrum of hadronic tau energies. PU estimator = number of TT with $E_T > 0$ in the 8 central calo rings

CMS-DP-2015-009

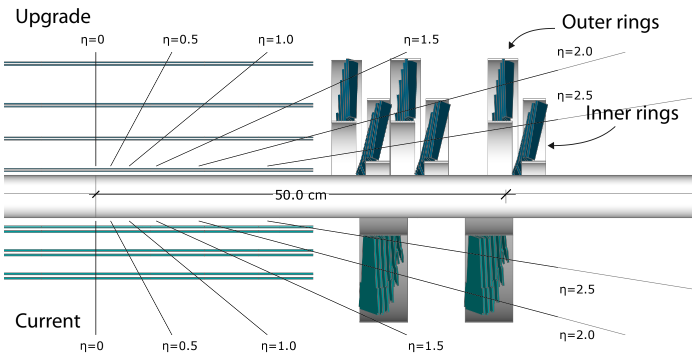
CMS L1 trigger upgrade taus

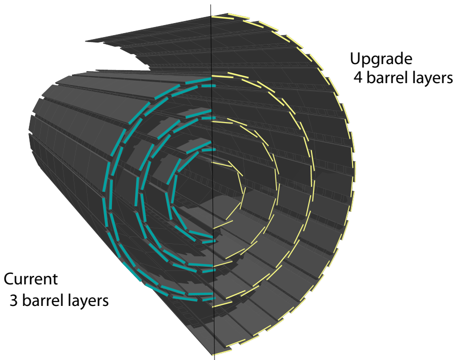
- Efficiency is computed as the fraction of the offline tau candidate for a L1 energy threshold of 30 GeV
    - 30 GeV is a typical threshold value that is applied in di-tau trigger at L1 (due to rate constraints, see rate plots)
- Inclusive distribution (barrel plus endcap) is shown
- In Run I algorithm, the application of shape veto and isolation requirements causes the large efficiency reduction. It is highly inefficient under Run II collisions conditions
- 2016 upgrade shape veto hasn't a large impact on the turn-on curve shape and sharpness

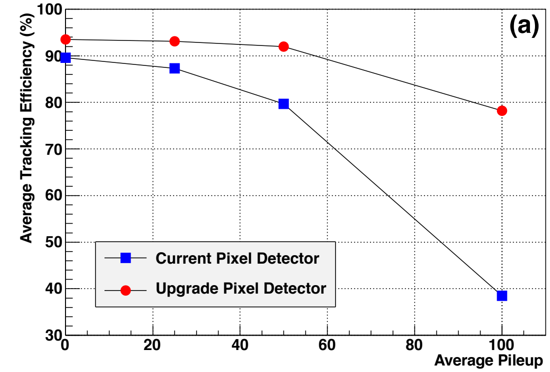


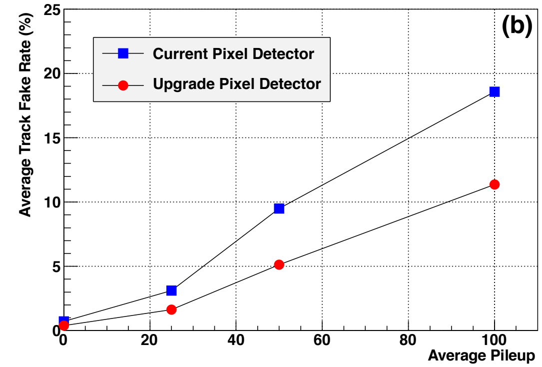
CMS-DP-2015-009

CMS pixel detector upgrade

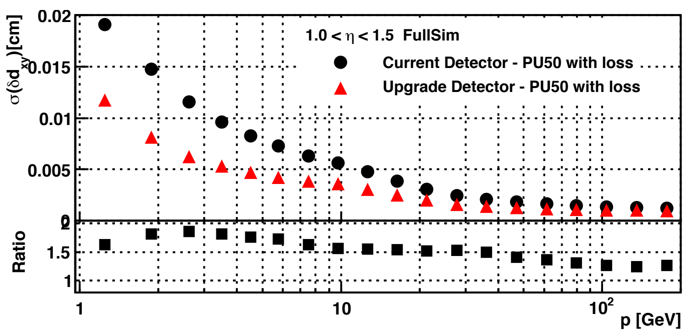








- Optimized configuration for 4-hit coverage up to η=2.5, with 4 layers in the barrel and 3 disks in the endcaps
- New readout chip with high hit rate capability
- Reduced material budget, new optical links and DAQ system, higher output bandwidth
- Improves tracking efficiencies, reduces fake rates
- Improves track impact parameter resolution and primary vertex position resolutions and thus b-tagging capabilities



➔ No degradation with higher pileup, and in several cases improvements of physics performances for Run III, for tracking and b-tagging

New reco calo

New calorimeter reconstruction to mitigate out of time PU with 25 ns bunch spacing

Run I:

- Amplitude linear combination of the 10 samples S_i
- w_i calculated minimizing the variance A

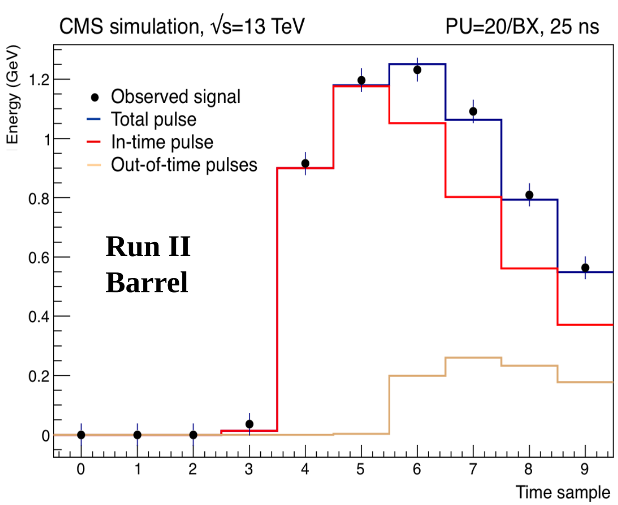
$$\hat{A} = \sum_{i=1}^{N} w_i \times S_i$$

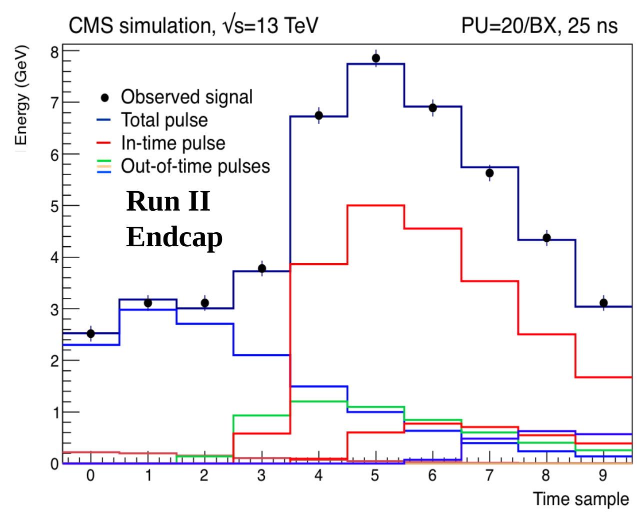
Run II: 40 PU instead of 20, bunch spacing of 25 ns instead of 50ns

- Multi-fit algorithm: in-time signal amplitude and up to 9 out-of-time amplitudes by minimization of the χ^2

where A_j are the amplitudes, p_{ij} are the pulses (all identical, shifted by 25ns), σ_{Si} is the noise covariance matrix.

$$\chi^2 = \sum_{i=1}^{N} \frac{\left(\sum_{j=1}^{M} A_j p_{ij} - S_i\right)^2}{\sigma_{S_i}^2}$$

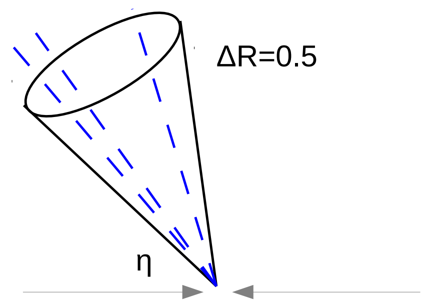




Photons reconstruction

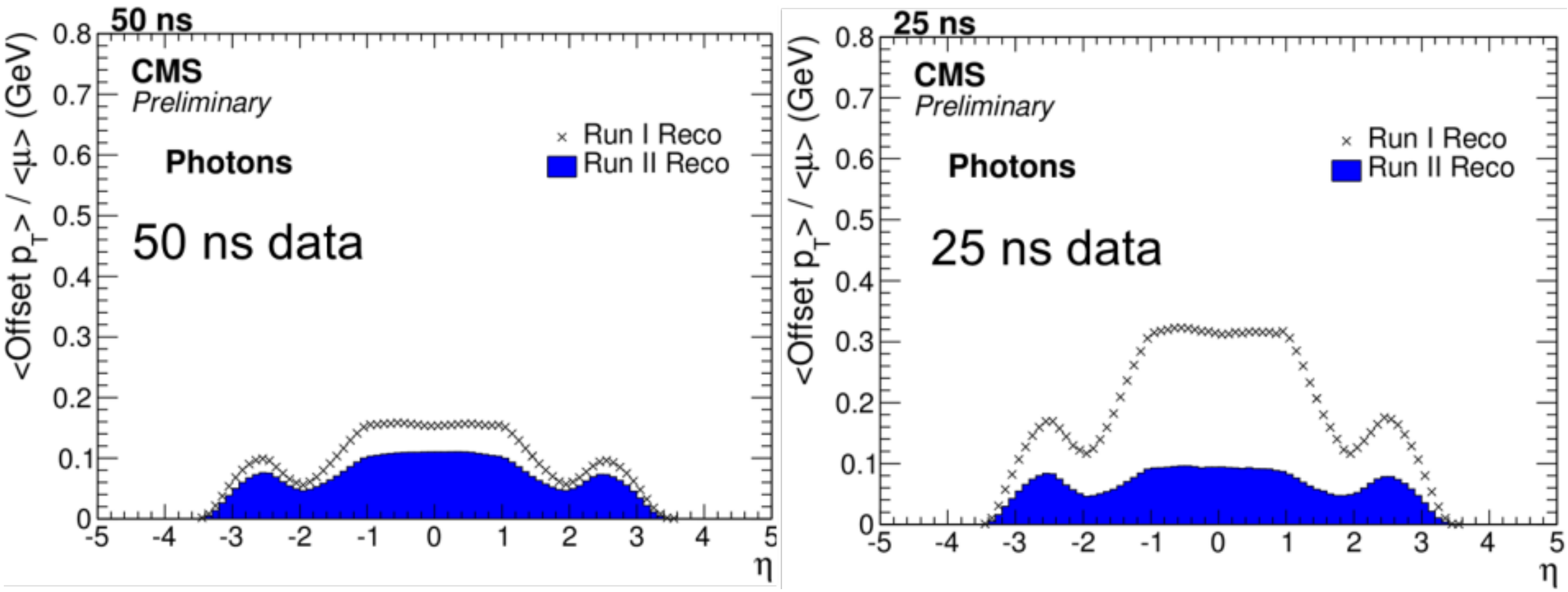
Out of time PU mitigation in the calorimeters

Kerstin Borras @ EPS 2015

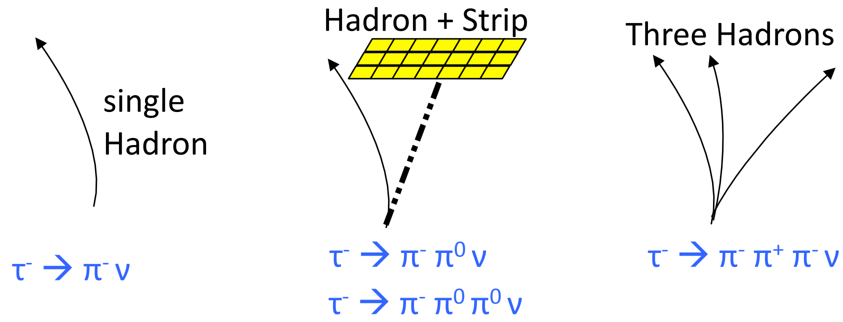


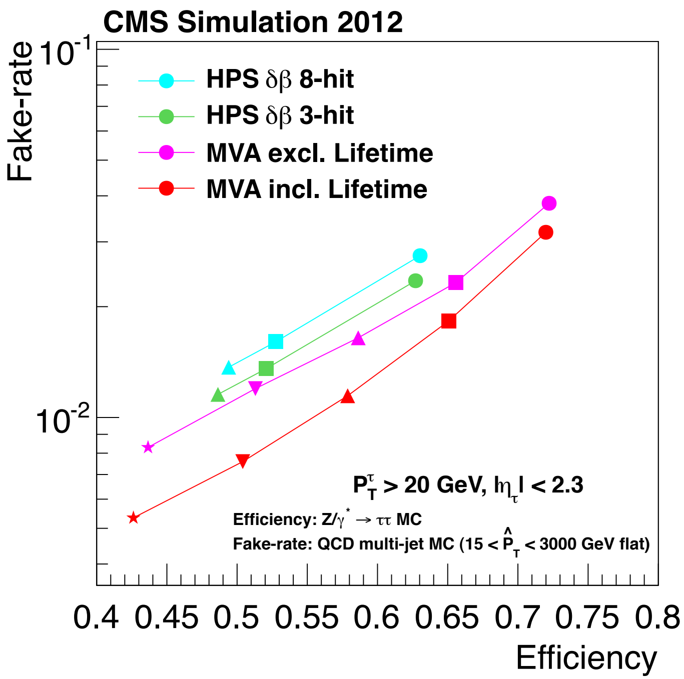
Summing particle energy in random cones in φ across η
Indicator of the PU energy to be subtracted for a given cone

New reconstruction: bunch spacing independent



Tau ID





- **Cut-based tau ID:** 2011: 8 hits, 2012: 3 hits

Tau isolation computed by summing momenta of particles within cone of size dR = 0.5 around tau direction

$Iso = \Sigma\, PTh\pm(dZ < 2mm) + PT\gamma + \delta\beta$

δβ correction compensates for pile-up effects, using as input charged particles associated to PU vertices:

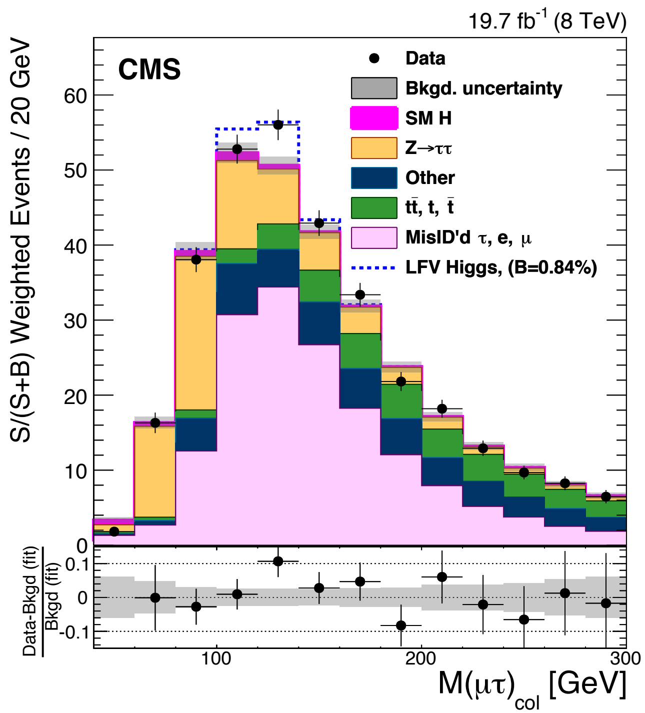
$\Delta\beta = 0.4576 \bullet \Sigma\, PTh\pm(dZ > 2mm)$

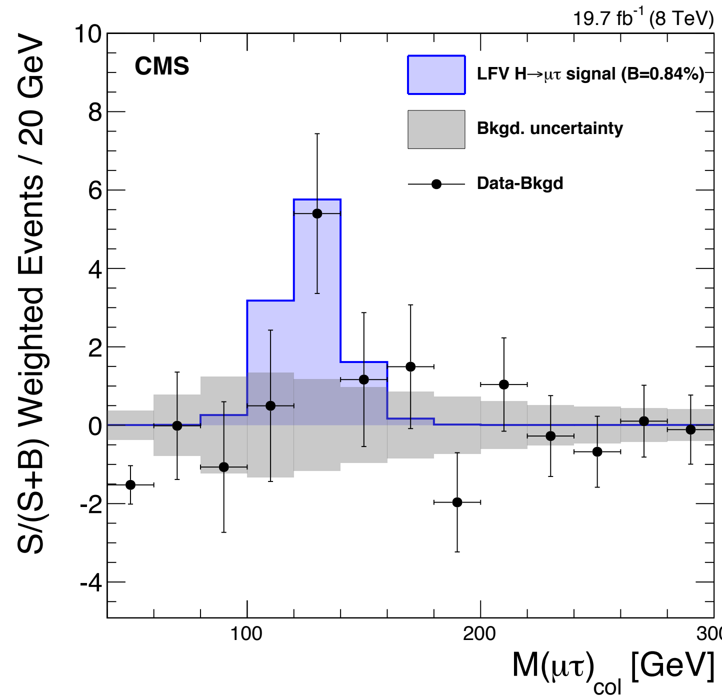
- **New tau ID: MVA based**

Tau isolation + tau lifetime (transverse impact parameter (1 prongs, 3 prongs) and reconstructed tau vertex position (3 prongs only)

- **Reduces fake rates by 40 to 50% for same efficiency**
- **Improves signal efficiency by ~20% for same fake rates**

Lepton flavor violation: $H \rightarrow \mu\tau_e$ and $H \rightarrow \mu\tau_h$





- Sensitivity an order of magnitude better than existing indirect limits
- Slight excess with a significance of 2.4σ, with p-value at 125 GeV: 0.010
- Best fit branching fraction: $B(H \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$
- 95% CL limits:
  - $B(H \rightarrow \mu\tau) < 1.51\%$
  - μ-τ Yukawa couplings to be $< 3.6 \times 10^{-3}$.

ATLAS:
Best fit BR: 0.77 +/- 0.62 %
Limit: 1.85 % @ 95% CL (1.24% exp.)