2017 Startup and Highlights from Recent CMS Analyses

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Fermilab Wine & Cheese Seminar
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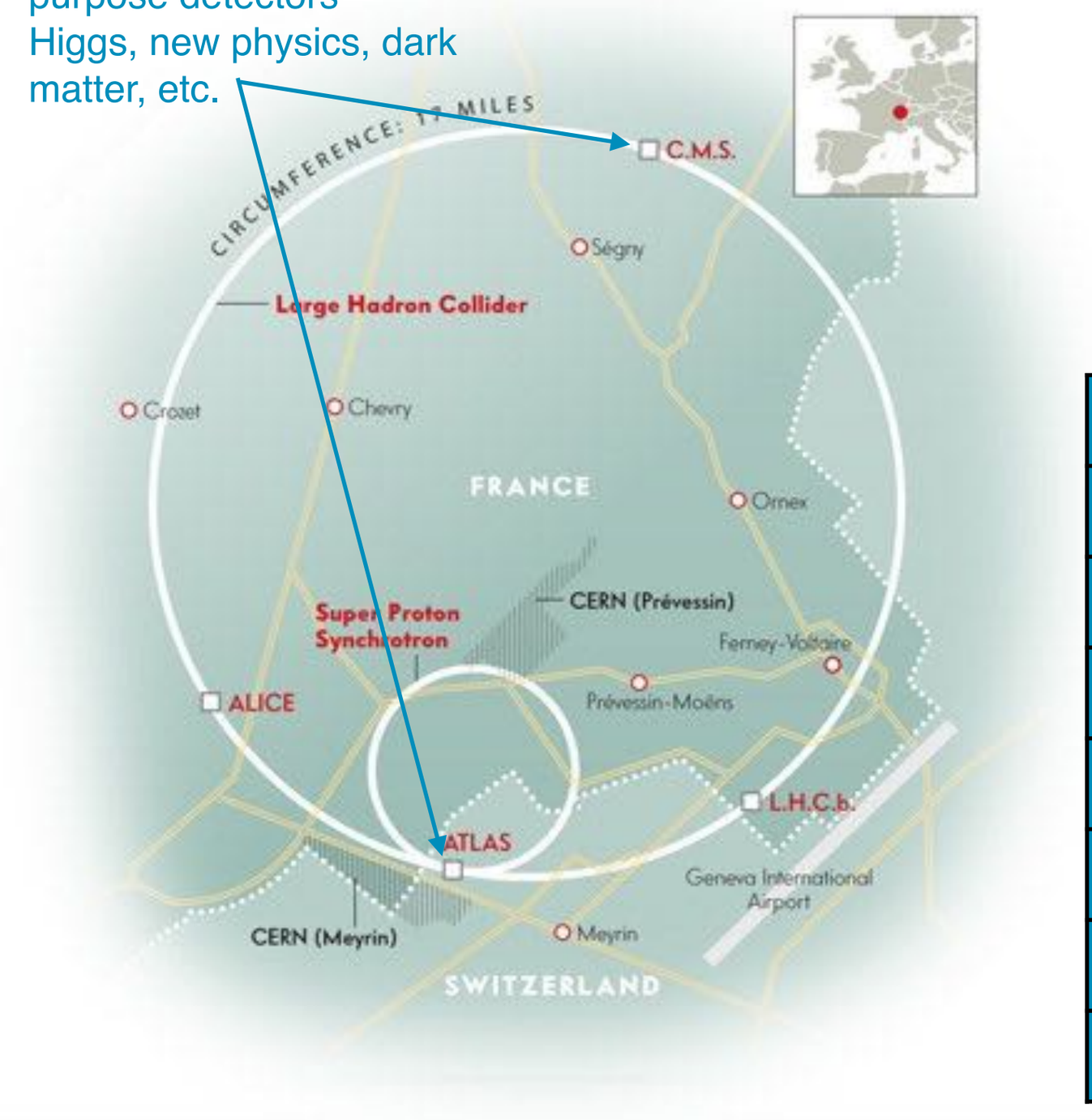
Outline

- Introduction
- A little history
- Latest results on VH associated production
- CMS improvements during the 2016-2017 shutdown
- First look at 2017 data
- Conclusion

Large Hadron Collider (LHC)

High luminosity general purpose detectors—Higgs, new physics, dark matter, etc.



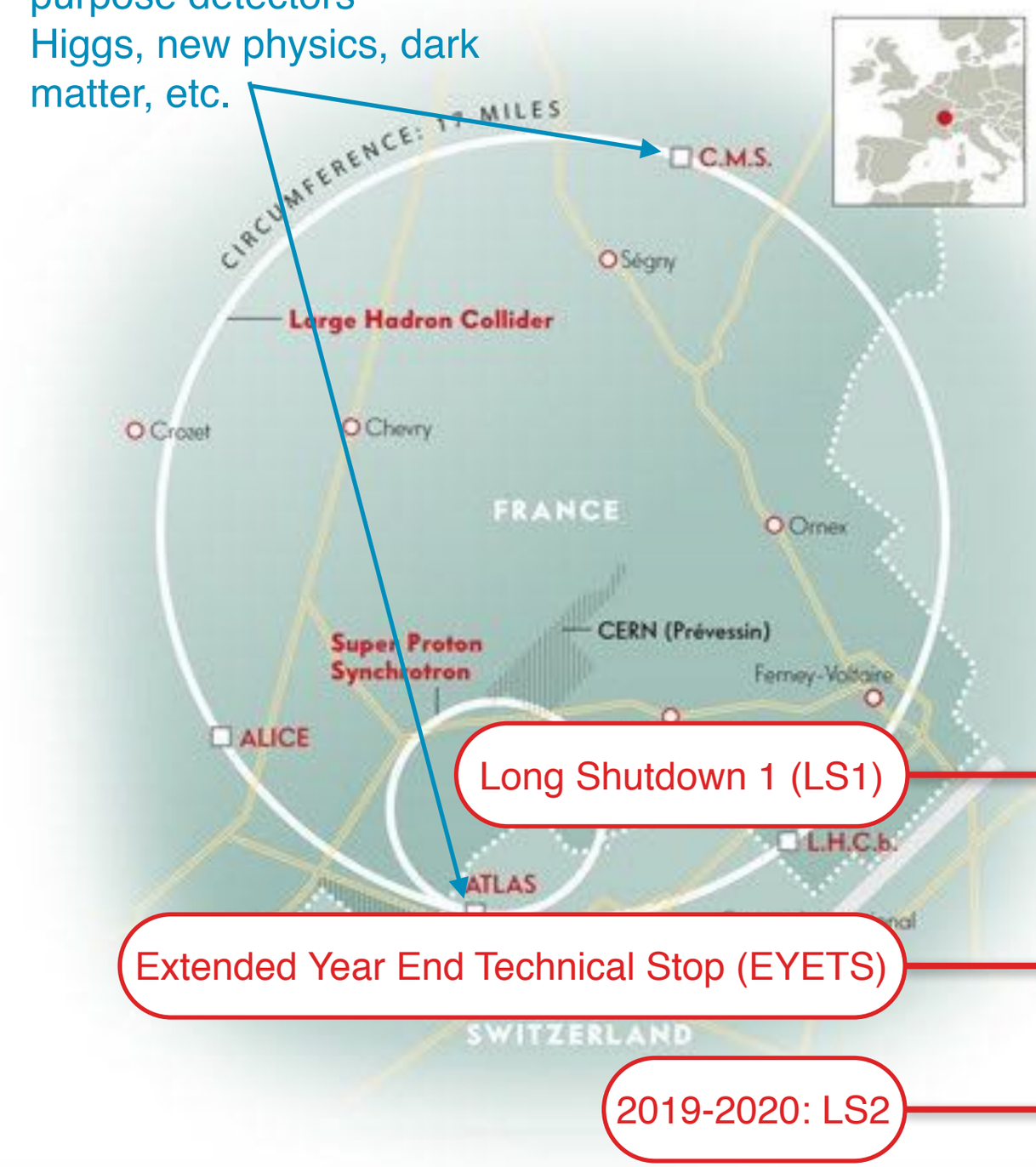
- 25 ns proton bunch spacing
- 27 pp interactions per crossing on average
- Average 2016 duty cycle: 58%
  - 10 hours of stable beams for experiment data collection
  - 7.1 hours of machine turnaround

Year	E_{cm} (TeV)	L_{int} (fb^{-1})	L_{peak} ($\times 10^{33}$ cm^{-2} s^{-1})
2010	7	0.04	0.2
2011	7	6.0	4.0
2012	8	20	8.0
2015	13	4.2	5.0
2016	13	38	15
2017†	13	15†	17†
2017-2023	13*	220*	20*

†Up till now *Projected

LHC lingo

High luminosity general purpose detectors—Higgs, new physics, dark matter, etc.



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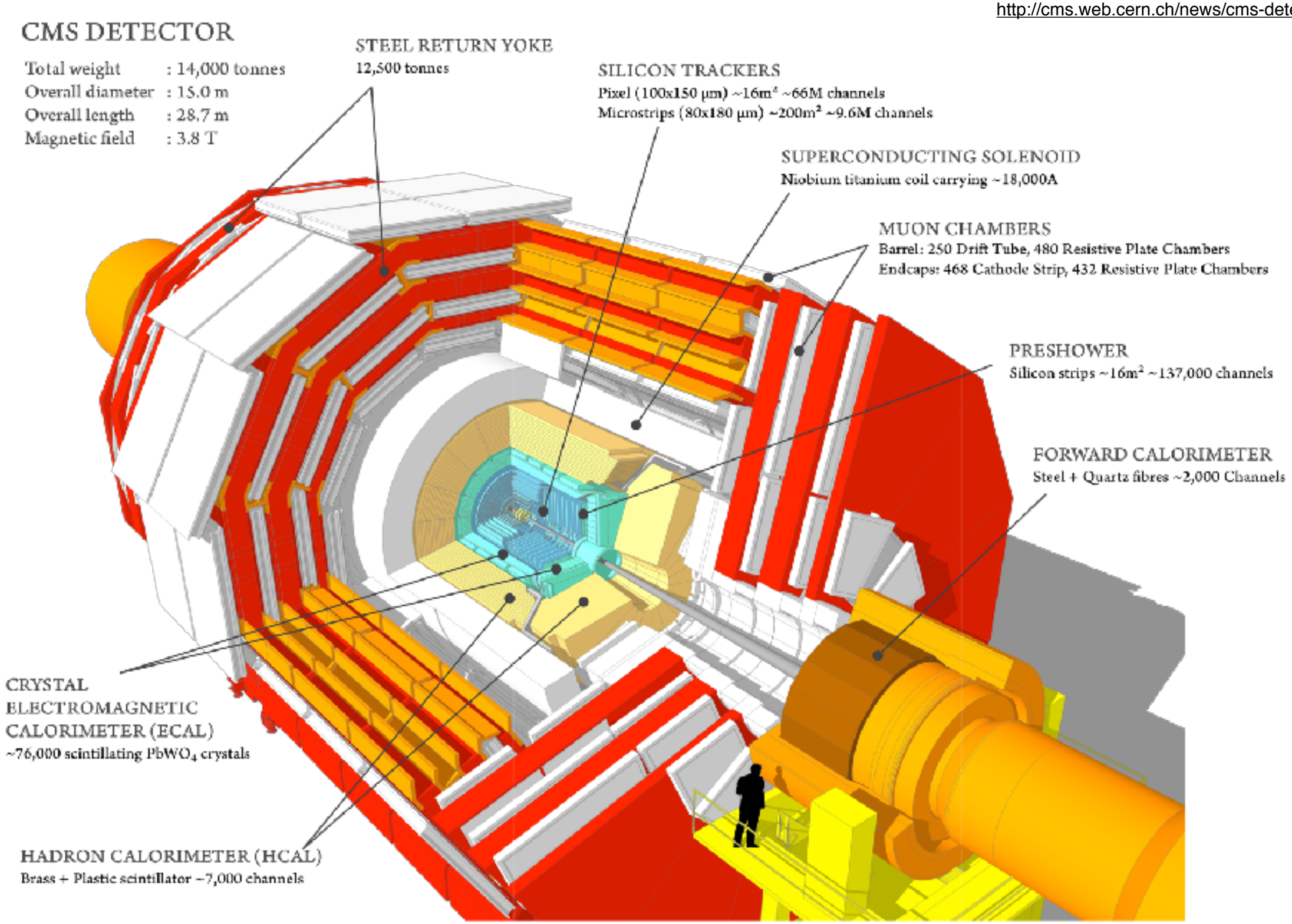
Run 1

Run 2

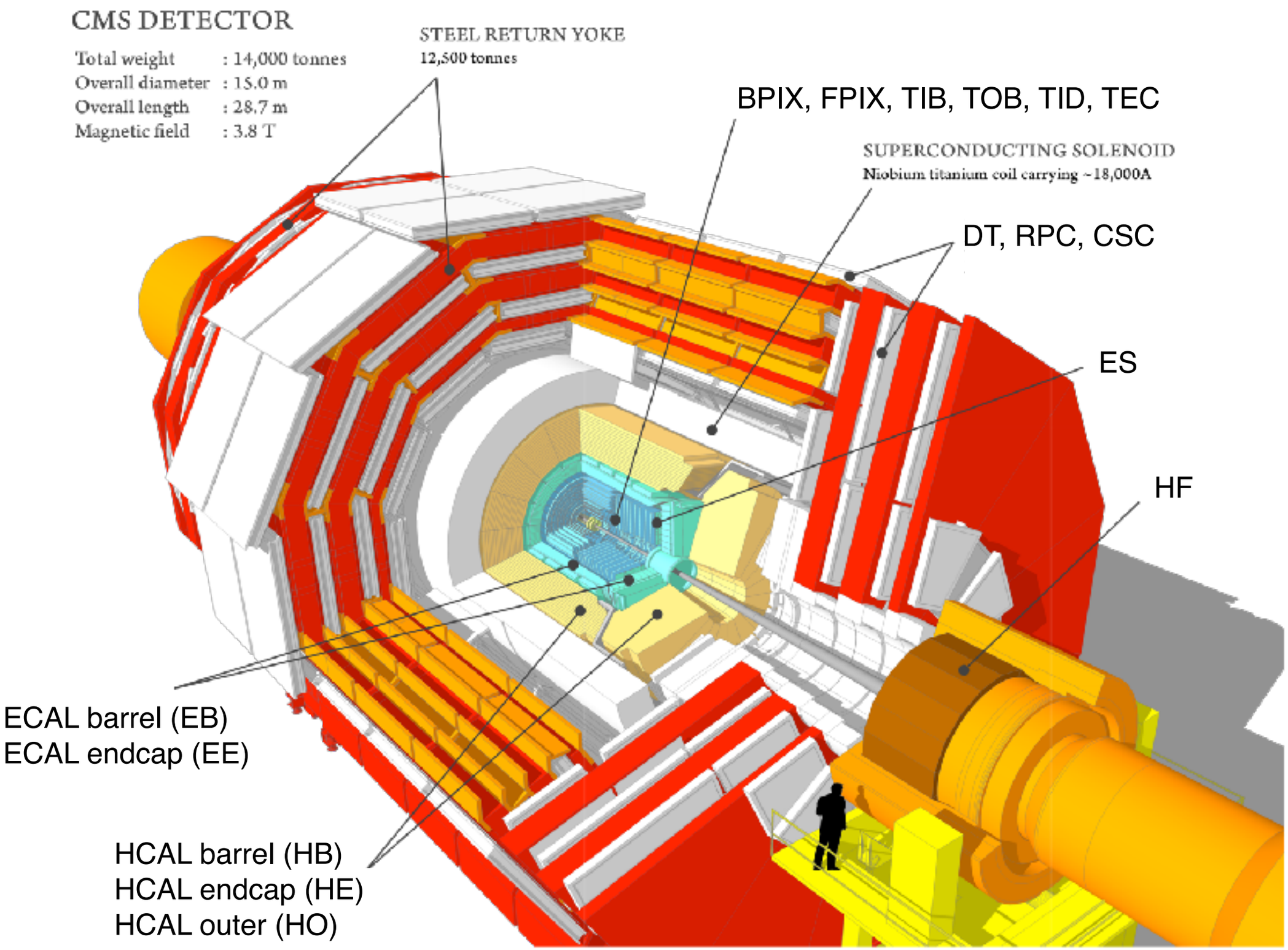
†Up till now *Projected

Compact Muon Solenoid (CMS)

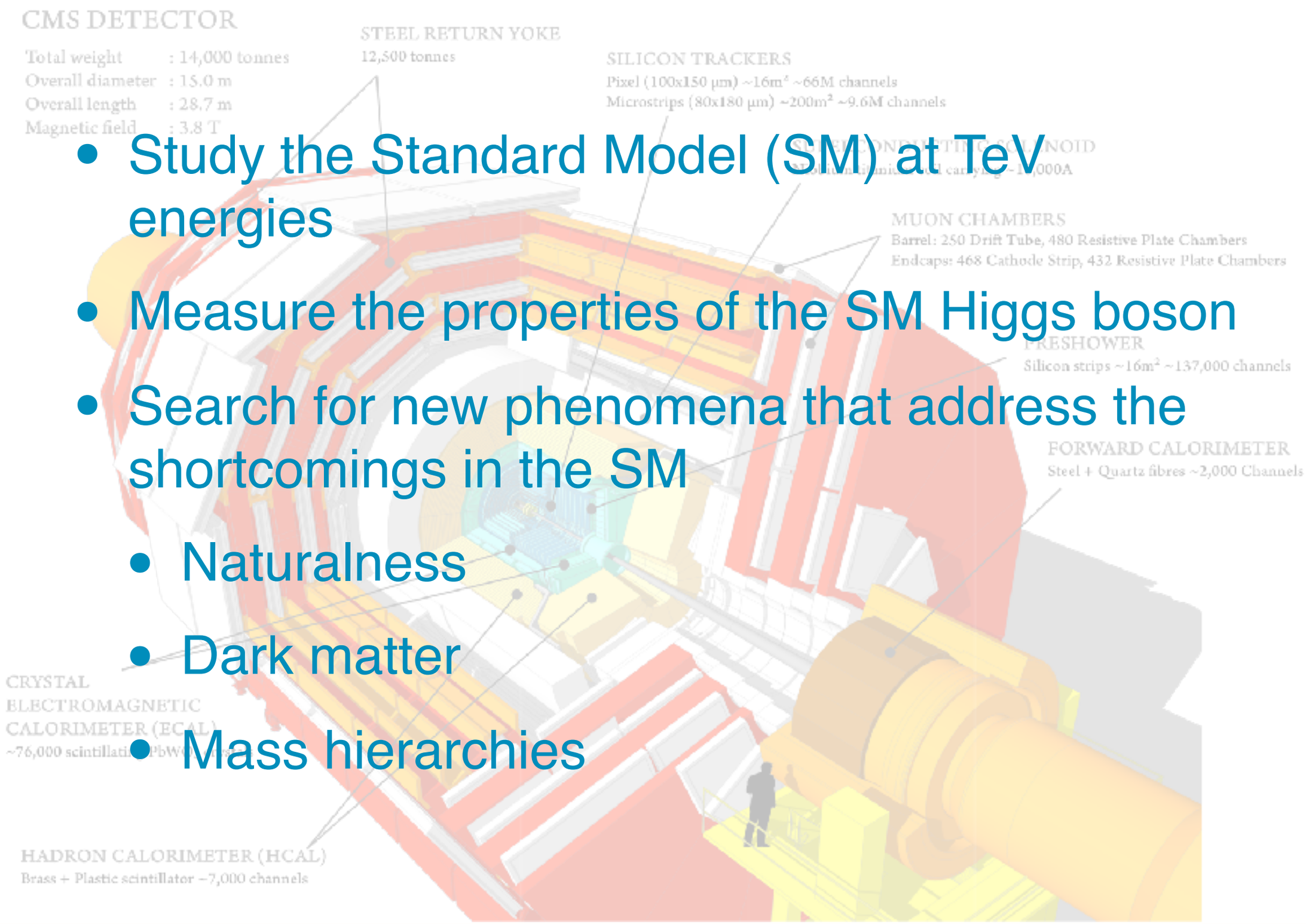
http://cms.web.cern.ch/news/cms-detector-design



CMS lingo

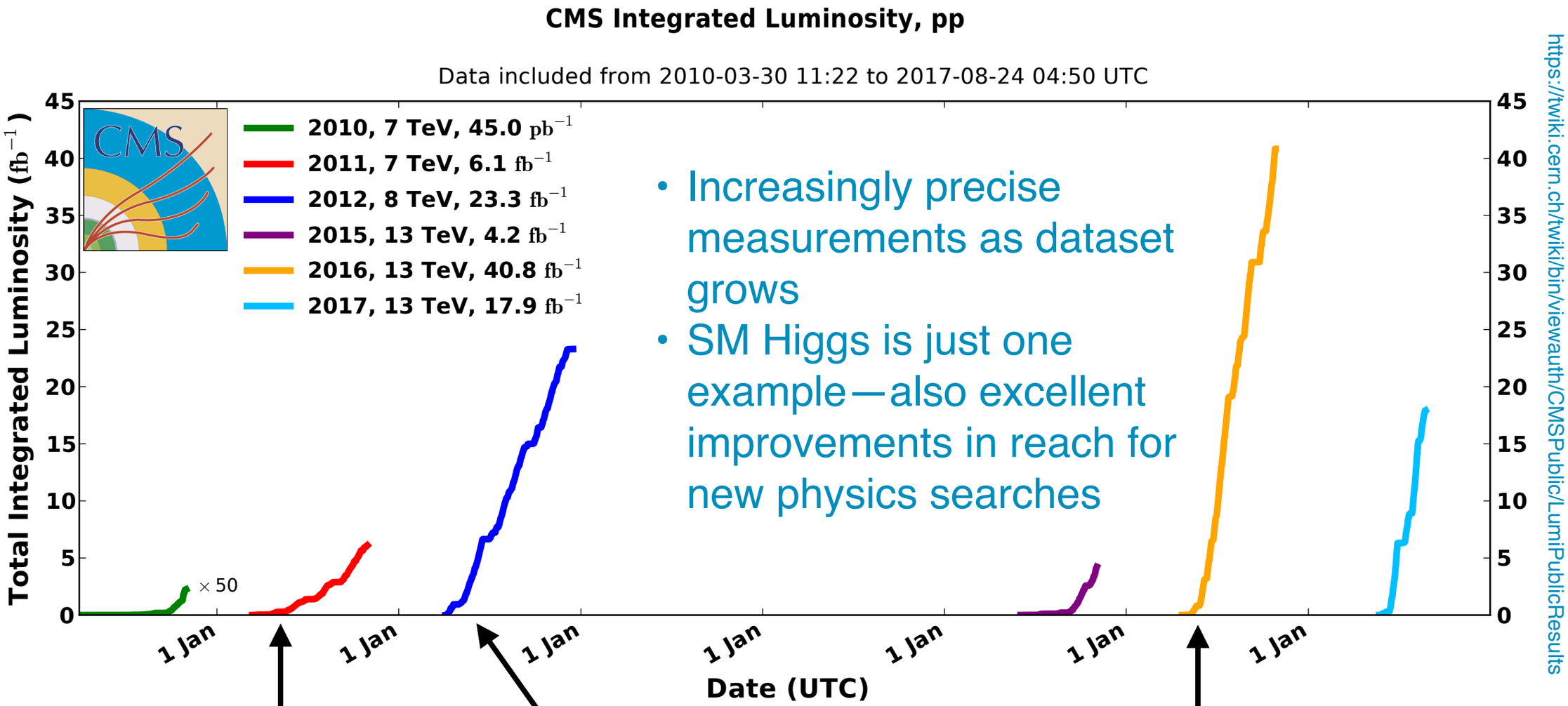

CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
BPIX, FPIX, TIB, TOB, TID, TEC
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
DT, RPC, CSC
ES
HF
ECAL barrel (EB)
ECAL endcap (EE)
HCAL barrel (HB)
HCAL endcap (HE)
HCAL outer (HO)

CMS scientific goals

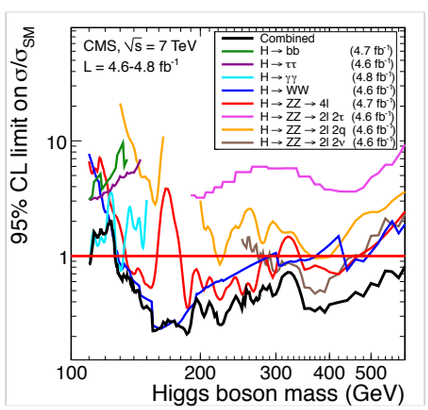


- Study the Standard Model (SM) at TeV energies
- Measure the properties of the SM Higgs boson
- Search for new phenomena that address the shortcomings in the SM
  - Naturalness
  - Dark matter
  - Mass hierarchies

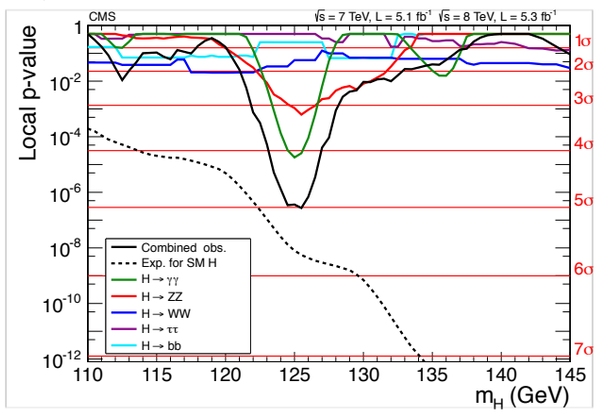
A little history…



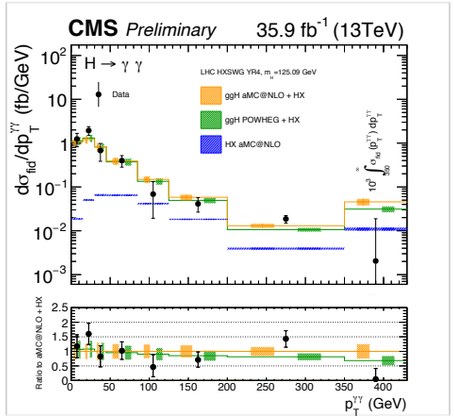
- Increasingly precise measurements as dataset grows
- SM Higgs is just one example—also excellent improvements in reach for new physics searches



PLB 710 (2012) 26

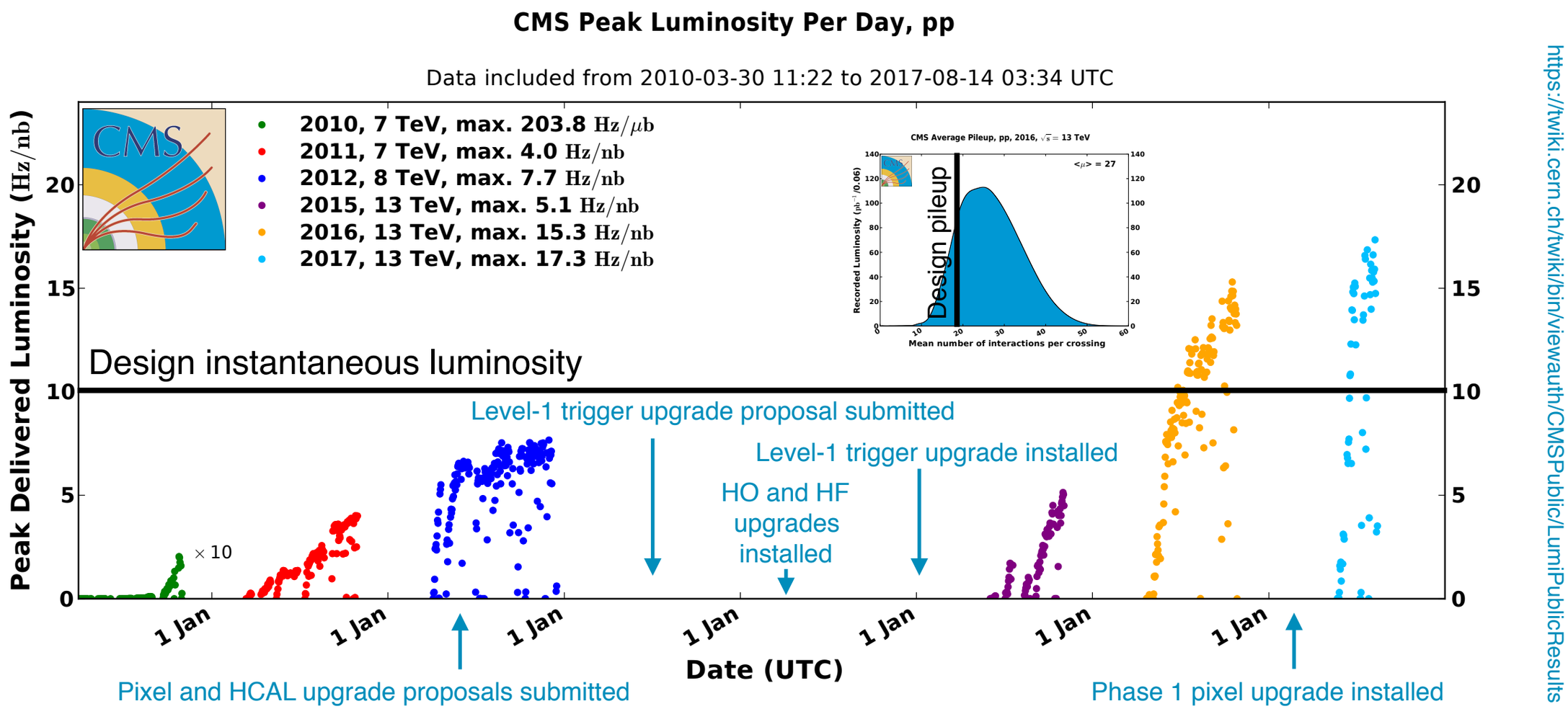


PLB 716 (2012) 30



CMS-PAS-HIG-17-015

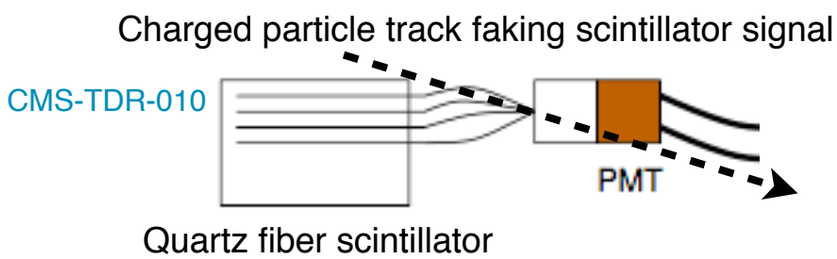
A little history…



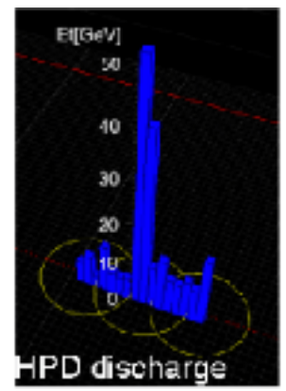
https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/LumiPublicResults

- 1.5× design instantaneous luminosity and 1.4× design pileup already achieved in 2016
- To exploit the growing LHC dataset, CMS must be able to handle the increasing particle flux

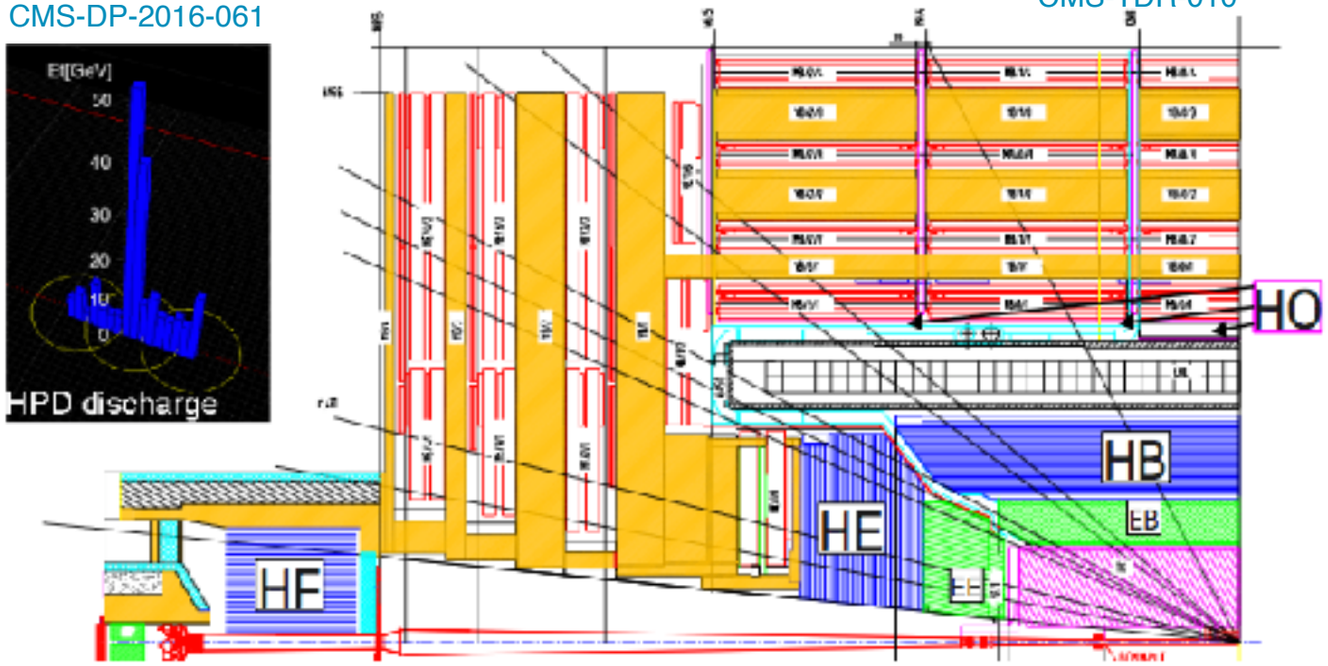
Issues limiting performance



CMS-DP-2016-061

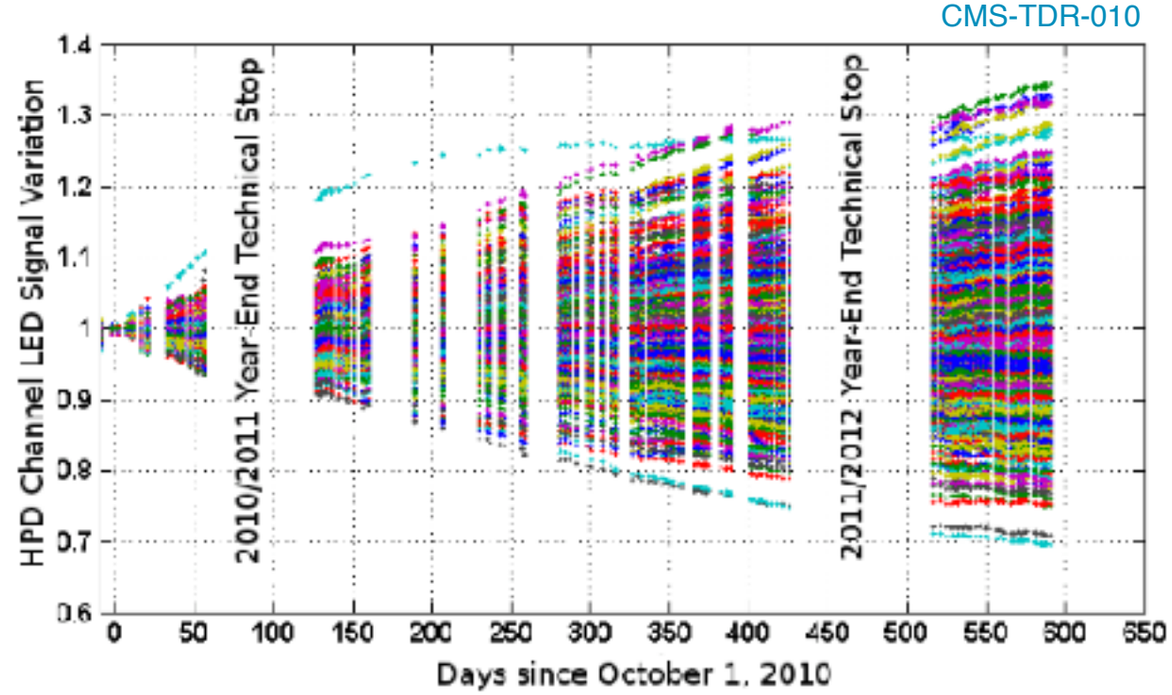


CMS-TDR-010



- HF photomultiplier tube (PMT) window hits fake high energy signals
- HB/HE/HO hybrid photodiode (HPD) discharges leading to accelerated aging, wandering gain, and fake high energy signals
- Poor HB/HE longitudinal segmentation couples channels with very different radiation damage
- **All effects exacerbated by increasing instantaneous luminosity**

CMS-TDR-010



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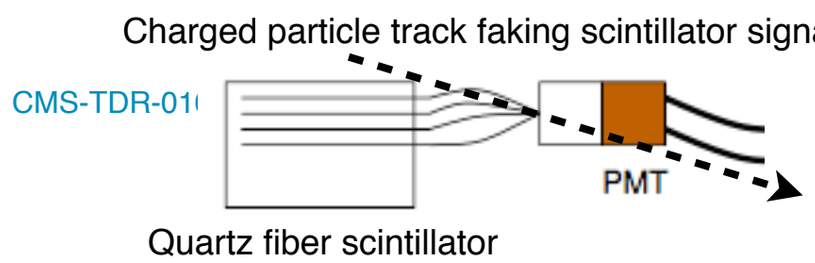

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Old PMTs replaced during LS1 with thin-window PMTs with multi-anode readout for fake discrimination

- HO HPDs replaced with silicon photomultipliers (SiPMs) during LS1
- Single HE demonstrator sector outfitted with SiPMs during EYETS
- Full HB/HE SiPM upgrade planned for LS2

Issues limiting performance

CMS-TDR-012

Level-1 Trigger, 2012 Threshold	95% Threshold [GeV]	Rate [kHz] $L = 0.4$ $\langle PU \rangle$=15	Rate [kHz] $L = 1.1$ $\langle PU \rangle$=45	Rate [kHz] $L = 1.6$ $\langle PU \rangle$=66	Rate [kHz] $L = 1.1$ (14 TeV) $\langle PU \rangle$=50
Single iso e/γ, 18 GeV, $\lvert\eta\rvert < 2.1$	26	6.3	19	27	40
Single Mu, 14 GeV, $\lvert\eta\rvert < 2.1$	19	4.1	11	15	27
Single Jet, 128 GeV	150	1.0	3.6	6.6	14
H_T, 150 GeV	280	0.9	55	$\sim 10^3$	$\sim 10^2$
Double e/γ, 13, 7 GeV	20,13	5.4	15.4	24	47

- Fixed 100 kHz Level-1 accept (L1A) rate implies significant energy threshold increases with increasing particle flux
- Less flexible hardware prevents implementation of rate-reducing algorithms
- **All effects exacerbated by increasing instantaneous luminosity**

Issues limiting performance

CMS-TDR-012

Level-1 Trigger, 2012 Threshold	95% Threshold [GeV]	Rate [kHz] $L = 0.4$ $\langle PU \rangle$=15	Rate [kHz] $L = 1.1$ $\langle PU \rangle$=45	Rate [kHz] $L = 1.6$ $\langle PU \rangle$=66	Rate [kHz] $L = 1.1$ (14 TeV) $\langle PU \rangle$=50
Single iso e/γ, 18 G					
S 14 G					
D					

- L1 trigger replaced during LS1
  - Consolidated hardware with fewer variants
  - Reliance on powerful, flexible FPGAs wherever possible
  - Electrical links replaced with high bandwidth optical links
  - Increased granularity of trigger primitives
  - Increased complexity of algorithms

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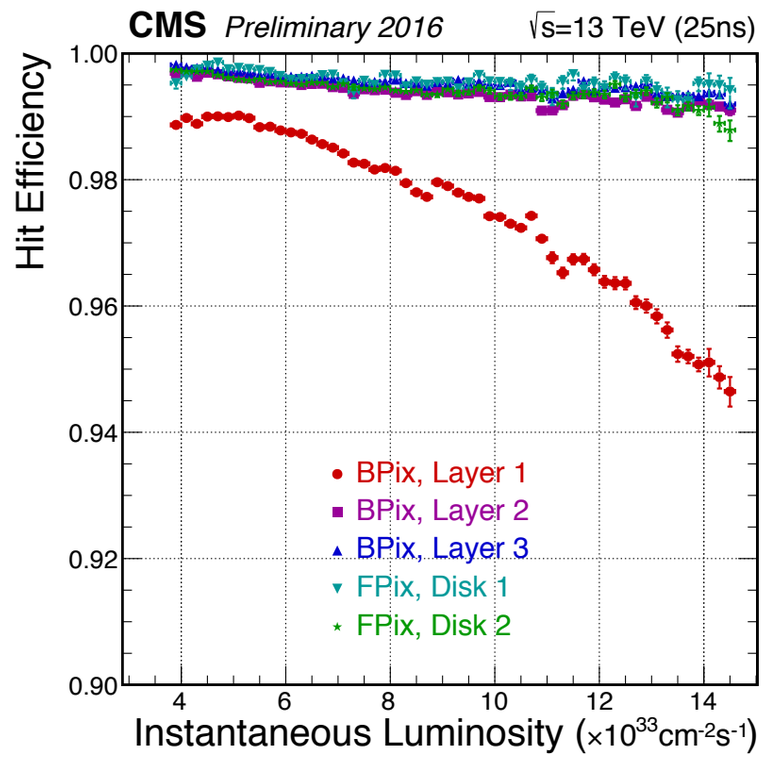
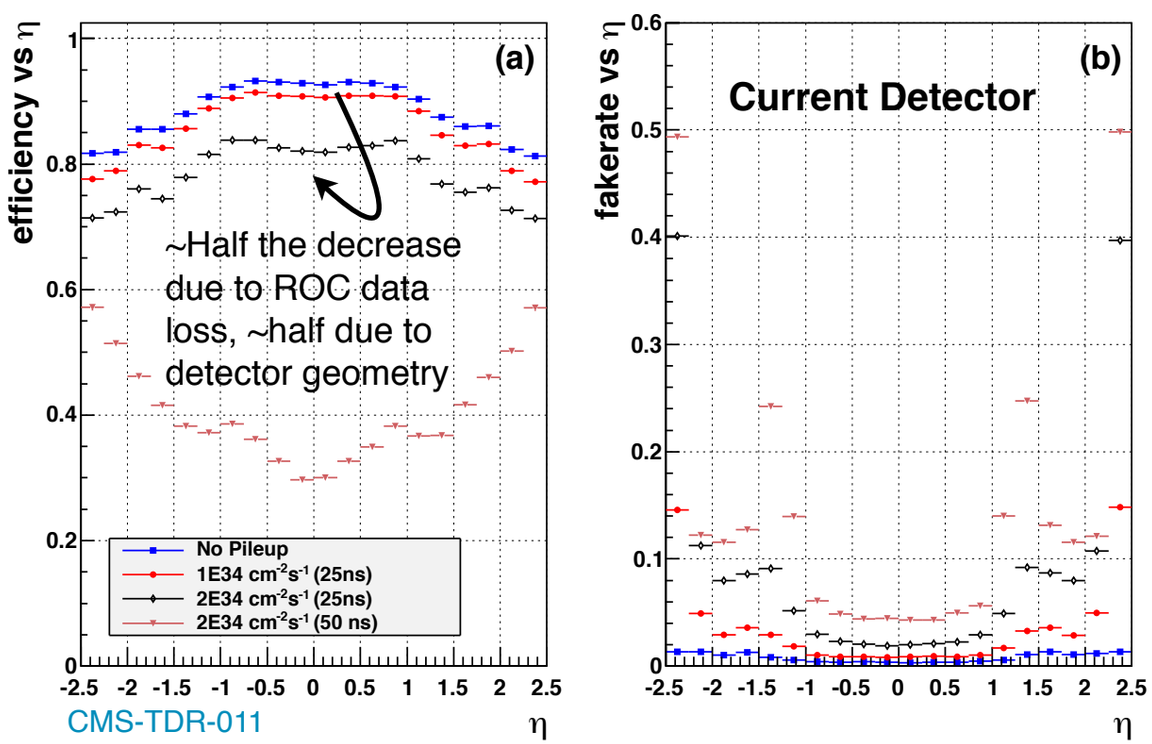
- **All effects exacerbated by increasing instantaneous luminosity**

Issues limiting performance



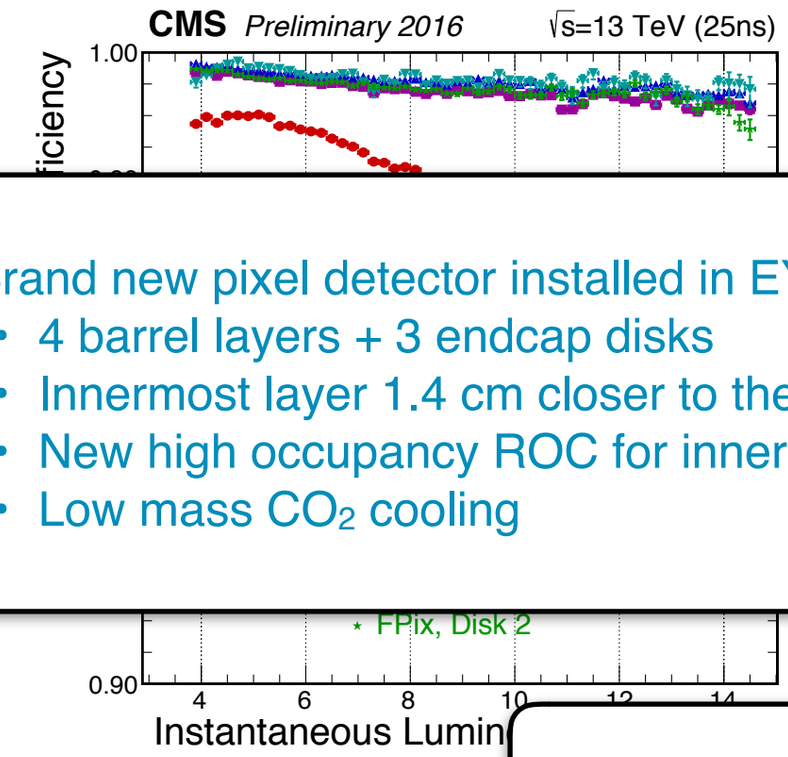


CMS-TDR-011

- Data loss due to pixel readout chip (ROC) buffer overflows as occupancy increases
- Number and placement of pixel layers and disks optimized for 1×10^{34} cm^{-2} s^{-1} and $\langle\mu\rangle = 20$ —tracking worsens as occupancy increases
- **All effects exacerbated by increasing instantaneous luminosity**

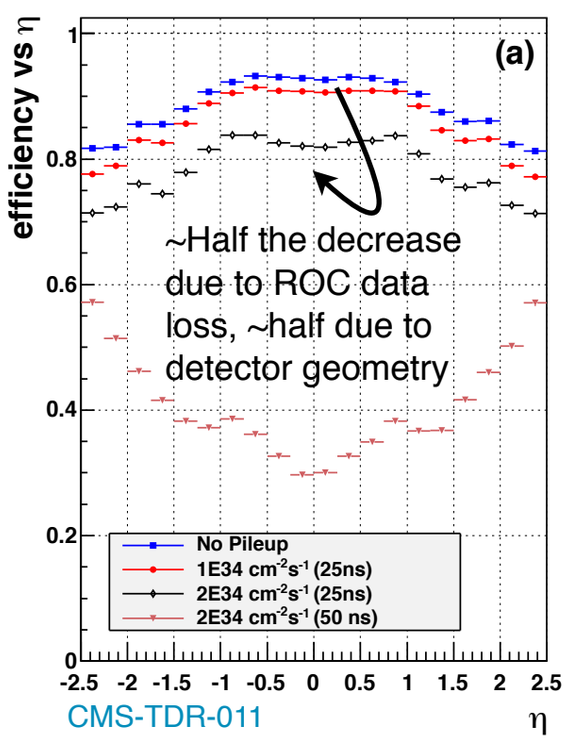
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlots2016

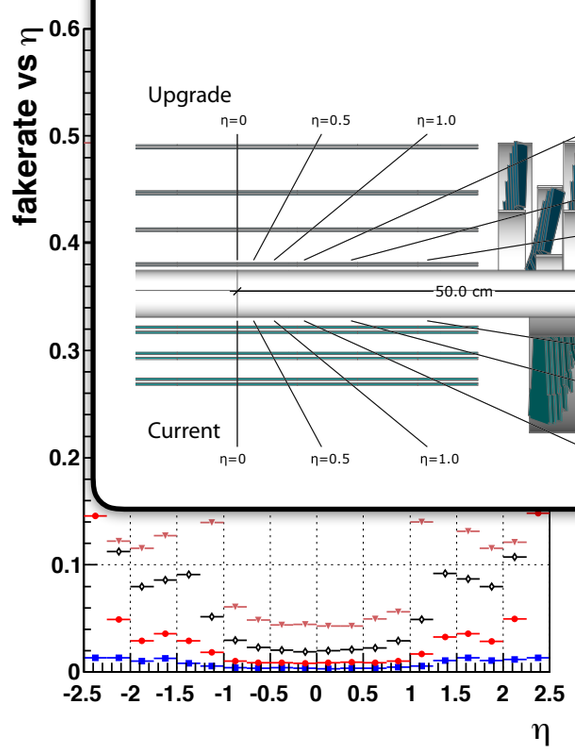
Issues limiting performance

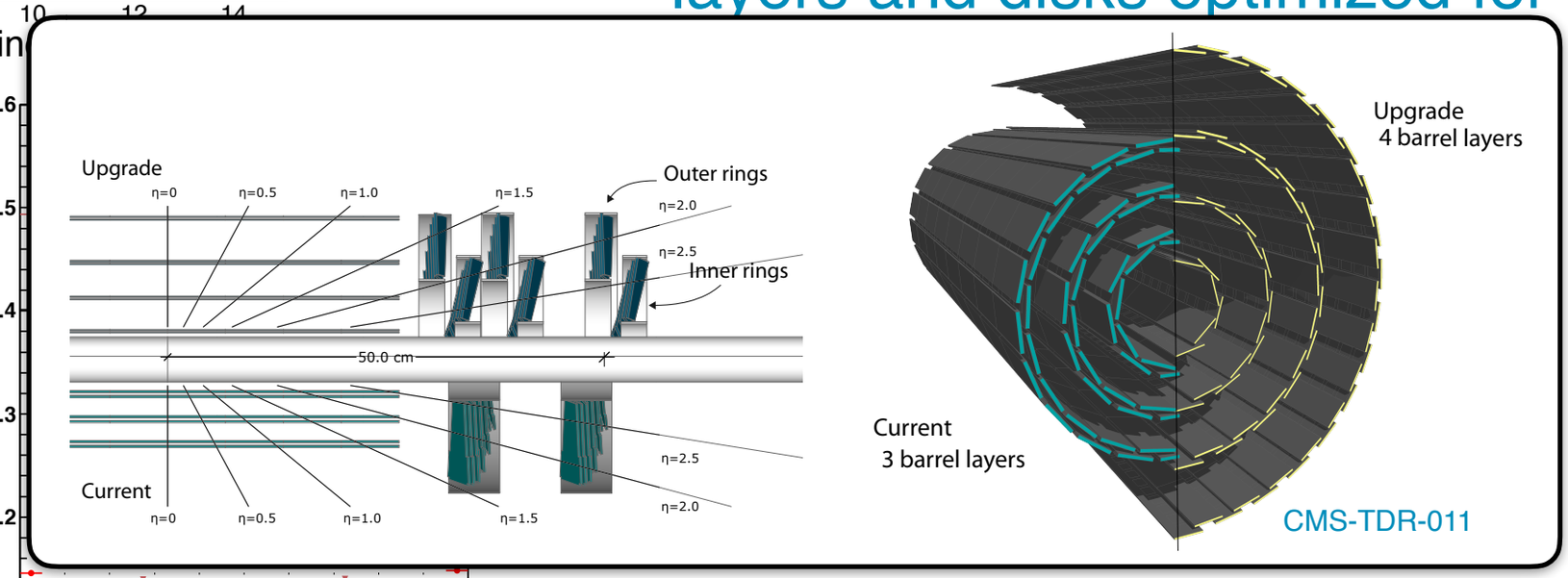


- Brand new pixel detector installed in EYETS
  - 4 barrel layers + 3 endcap disks
  - Innermost layer 1.4 cm closer to the beam line
  - New high occupancy ROC for innermost layer
  - Low mass CO_2 cooling

- Data loss due to pixel readout chip (ROC) buffer overflows as occupancy increases
- Number and placement of pixel layers and disks optimized for







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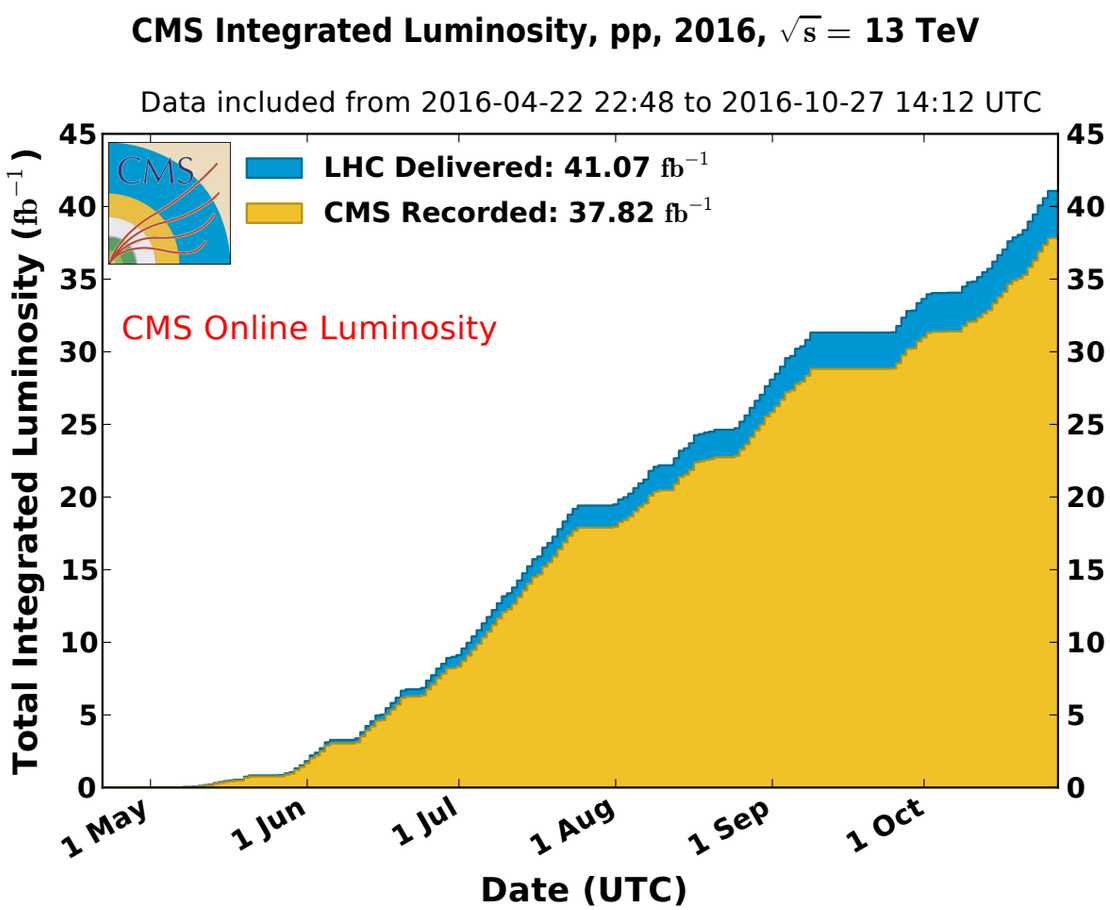
Status in 2016



https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/LumiPublicResults

- CMS is constantly evolving to meet its scientific goals in the increasingly challenging LHC collision environment
- 2016 was a banner year
  - >40 fb^{-1} delivered (>50% of the data collected up to December 2016)
  - 88% recorded by CMS in optimal conditions
  - L1 trigger, HF, and HO upgrades incorporated
  - **First large dataset at an increased collision energy of 13 TeV**

Hot off the press

Available on the CERN CDS information server **CMS PAS HIG-16-044**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-higgs@cern.ch 2017/08/10

Evidence for the decay of the Higgs Boson to Bottom Quarks

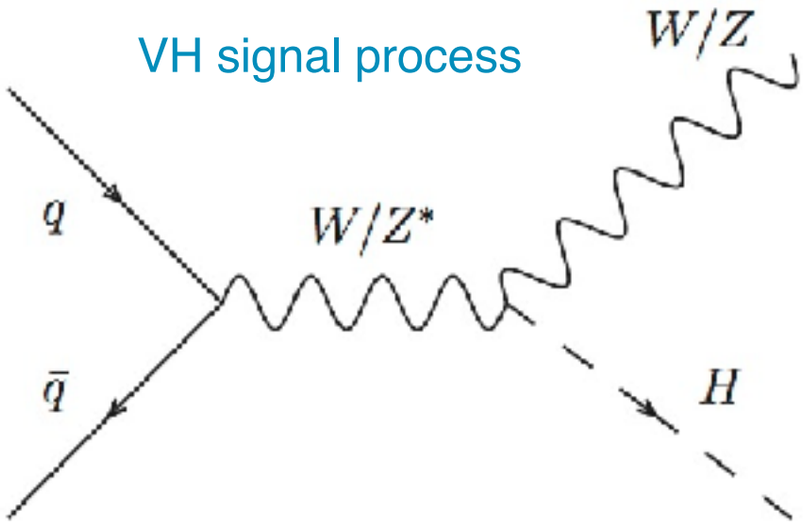
The CMS Collaboration

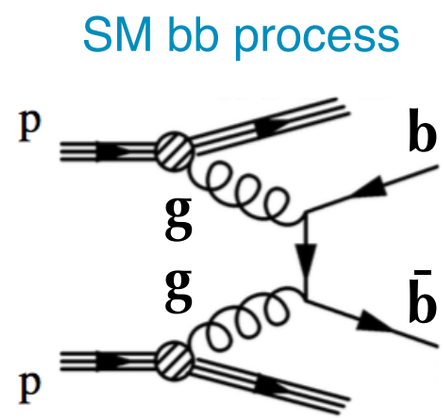
Abstract

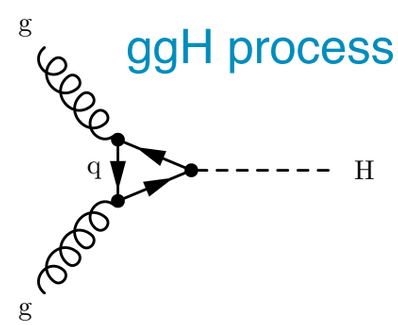
A search for the standard model (SM) Higgs boson (H) decaying to $b\bar{b}$ when produced in association with a weak vector boson (V) is reported for the following processes: $Z(\nu\nu)H$, $W(\mu\nu)H$, $W(e\nu)H$, $Z(\mu\mu)H$, and $Z(ee)H$. The search is performed in data samples corresponding to an integrated luminosity of 35.9 fb^{-1} at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC during Run 2 in 2016. An excess of events is observed in data compared to the expectation in the absence of a $H \to b\bar{b}$ signal. The significance of this excess is 3.3 standard deviations, where the expectation from SM Higgs boson production is 2.8. The signal strength corresponding to this excess, relative to that of the SM Higgs boson production is 1.2 ± 0.4. This result is combined with the one from the search for the same processes performed by the CMS experiment in Run 1 of the LHC (using proton-proton collisions at $\sqrt{s} = 7$ and $\sqrt{s} = 8$ TeV with data samples corresponding to luminosities of up to 5.1 fb^{-1} and 18.9 fb^{-1}, respectively). The observed combined signal significance is 3.8 standard deviations, where 3.8 are expected from a SM signal. The corresponding signal strength, relative to that of the SM Higgs boson, is $1.06^{+0.31}_{-0.29}$.

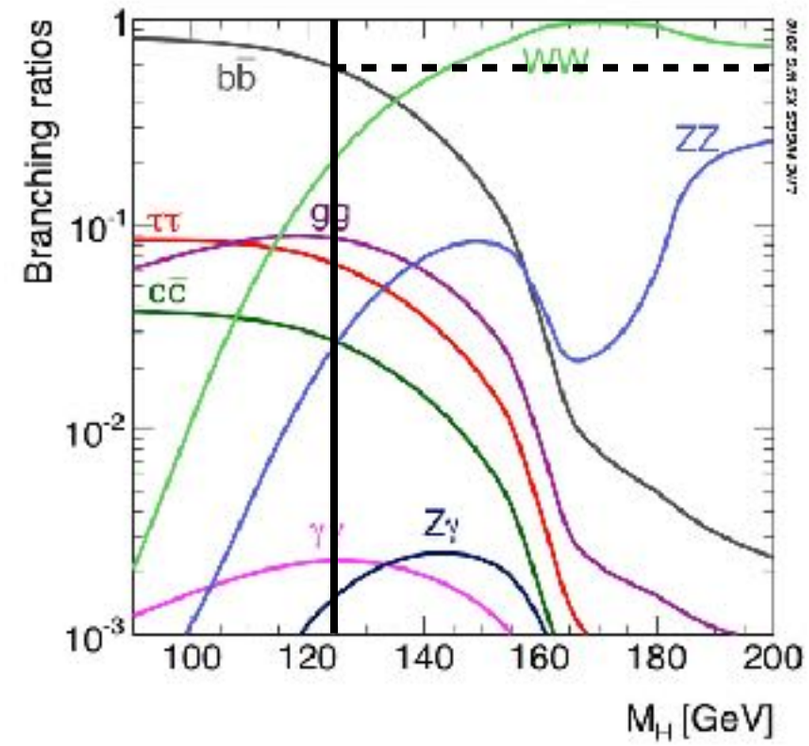
CMS-PAS-HIG-16-044

Motivation

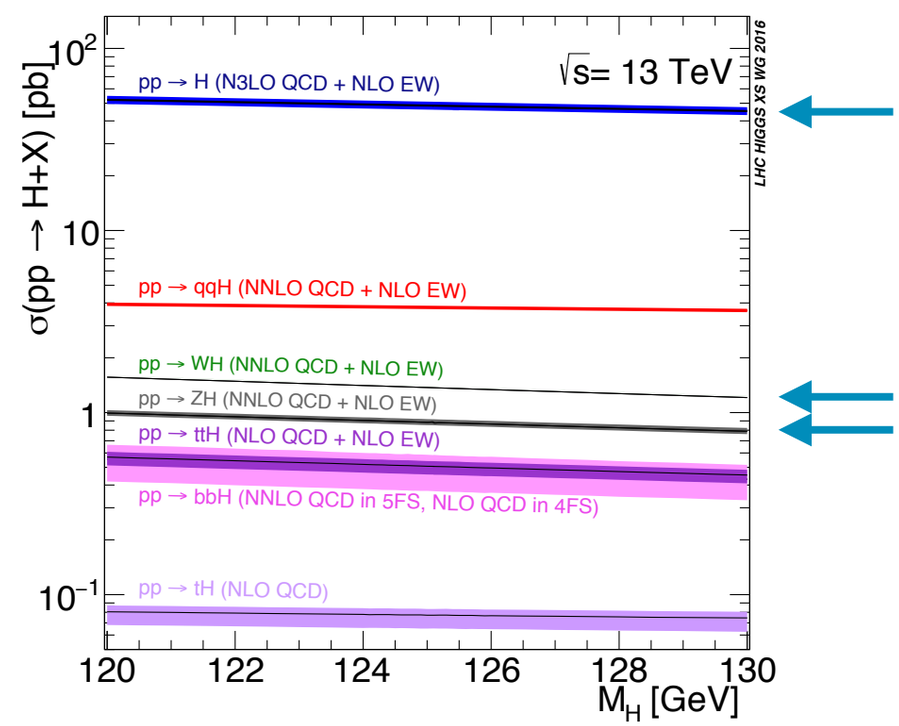








- BR(H→bb) ~ 58%
- Test of the Higgs Yukawa couplings as the generators of fermion mass
- Dominant gluon fusion Higgs production mode swamped by SM bb background
- VH associated production (V = Z, W) with V→leptons provides triggerable final states with manageable backgrounds



Search channels and backgrounds

	0l	1l	2l
Signals	Z(→νν)H(→bb)	W(→lν)H(→bb)	Z(→ll)H(→bb)
Backgrounds	Z(→νν) + >0b	W(→lν) + >0b	Z(→ll) + >0b
	Z(→νν) + >0q,g	W(→lν) + >0q,g	Z(→ll) + >0q,g
	W(→lν) + >0b	t(→lνb)t(→qqb)	t(→lνb)t(→lνb)
	W(→lν) + >0q,g	W(→lν)Z(→bb)	Z(→ll)Z(→bb)
	t(→lνb)t(→qqb)	W(→lν)V(→qq)	Z(→ll)V(→qq)
	Z(→νν)Z(→bb)	t→lνb	
	Z(→νν)V(→qq)	q refers to u, d, s, or c quarks l refers to e or μ	
	t→lνb		

2 1l channels (e and μ)
4 2l channels (e and μ × 2 boost regions)

Search channels and backgrounds

	0l	1l	2l
Signals	Z(→νν)H(→bb)	W(→lν)H(→bb)	Z(→ll)H(→bb)
Backgrounds	Z(→νν) + >0b	W(→lν) + >0b	Z(→ll) + >0b
	Z(→νν) + >0q,g	W(→lν) + >0q,g	Z(→ll) + >0q,g
	W(→lν) + >0b	t(→lνb)t(→qqb)	t(→lνb)t(→lνb)
	W(→lν) + >0q,g	W(→lν)Z(→bb)	Z(→ll)Z(→bb)
	t(→lνb)t(→qqb)	W(→lν)V(→qq)	Z(→ll)V(→qq)
	Z(→νν)Z(→bb)	t→lν	
	Z(→νν)V(→qq)	q refers to u, d, s, or c quarks l refers to e or μ	
	t→lνb		

Dominant

Search channels and backgrounds

Somewhat reducible with kinematic selection

Signals	Z(→νν)H(→bb)	W(→lν)H(→bb)	Z(→ll)H(→bb)
Backgrounds	Z(→νν) + >0b	W(→lν) + >0b	Z(→ll) + >0b
	Z(→νν) + >0q,g	W(→lν) + >0q,g	Z(→ll) + >0q,g
	W(→lν) + >0b	t(→lνb)t(→qqb)	t(→lνb)t(→lνb)
	W(→lν) + >0q,g	W(→lν)Z(→bb)	Z(→ll)Z(→bb)
	t(→lνb)t(→qqb)	W(→lν)V(→qq)	Z(→ll)V(→qq)
	Z(→νν)Z(→bb)	t→lνb	
	Z(→νν)V(→qq)	q refers to u, d, s, or c quarks l refers to e or μ	
	t→lνb		

Search channels and backgrounds

	0l	1l	2l
Signals	Z(→νν)H(→		
Backgrounds	Z(→νν) + >0b	W(→lν) + >0b	Z(→ll) + >0b
	Z(→νν) + >0q,g	W(→lν) + >0q,g	Z(→ll) + >0q,g
	W(→lν) + >0b	t(→lνb)t(→qqb)	t(→lνb)t(→lνb)
	W(→lν) + >0q,g	W(→lν)Z(→bb)	Z(→ll)Z(→bb)
	t(→lνb)t(→qqb)	W(→lν)V(→qq)	Z(→ll)V(→qq)
	Z(→νν)Z(→bb)	t→lνb	
	Z(→νν)V(→qq)	q refers to u, d, s, or c quarks l refers to e or μ	
	t→lνb		

Mistagged light jets

Search channels and backgrounds

	0l	1l	2l
Signals	Z(→νν)H(→		
Backgrounds	Z(→νν) + >0b	W(→lν) + >0b	Z(→ll) + >0b
	Z(→νν) + >0q,g	W(→lν) + >0q,g	Z(→ll) + >0q,g
	W(→lν) + >0b	t(→lνb)t(→qqb)	t(→lνb)t(→lνb)
	W(→lν) + >0q,g	W(→lν)Z(→bb)	Z(→ll)Z(→bb)
	t(→lνb)t(→qqb)	W(→lν)V(→qq)	Z(→ll)V(→qq)
	Z(→νν)Z(→bb)	t→lνb	
	Z(→νν)V(→qq)	q refers to u, d, s, or c quarks l refers to e or μ	
	t→lνb		

Lost lepton + ME_T

Triggers

0l	1l	2l
$ME_T > 110$ GeV, $MH_T > 110$ GeV	Electron $p_T > 27$ GeV, electron well identified and isolated	First electron $p_T > 23$ GeV, second electron $p_T > 12$ GeV, both electrons loosely identified and isolated
	Muon $p_T > 24$ GeV, muon well identified and isolated	First muon $p_T > 17$ GeV, second muon $p_T > 8$ GeV, both muons loosely identified and isolated

ME_T-MH_T cross-trigger

Single lepton trigger

Double lepton trigger

- Same lepton trigger thresholds as at the end of 2012, but twice the instantaneous luminosity and ~20% more pileup on average

Event selection

Variable	0-lepton	1-lepton	2-lepton
$p_{\mathrm{T}}(\mathrm{V})$	> 170	> 100	$[50, 150], > 150$
$M(\ell\ell)$	-	-	$[75, 105]$
p_{T}^{ℓ}	-	$(> 25, > 30)$	> 20
$p_{\mathrm{T}}(j_1)$	> 60	> 25	> 20
$p_{\mathrm{T}}(j_2)$	> 35	> 25	> 20
$p_{\mathrm{T}}(\mathrm{jj})$	> 120	> 100	-
$M(\mathrm{jj})$	$[60, 160]$	$[90, 150]$	$[90, 150]$
$\mathrm{CMVA}_{\mathrm{max}}$	> 0.9432	> 0.9432	> -0.5884
$\mathrm{CMVA}_{\mathrm{min}}$	> -0.5884	> -0.5884	> -0.5884
N_{aj}	< 2	< 2	-
N_{al}	$= 0$	$= 0$	-
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 170	-	-
Anti-QCD	Yes	-	-
$\Delta\phi(\mathrm{V}, \mathrm{H})$	> 2.0	> 2.5	> 2.5
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{T}}^{\mathrm{miss}}{}_{\mathrm{trk}})$	< 0.5	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell)$	-	< 2.0	-
Lepton Isolation	-	< 0.06	-
Event BDT	> -0.8	> 0.3	> -0.8

CMS-PAS-HIG-16-044

Event selection

Variable	0-lepton	1-lepton	2-lepton
$p_T(V)$	> 170	> 100	$[50, 150], > 150$
$M(\ell\ell)$	-	-	$[75, 105]$
p_T^ℓ	-	$(> 25, > 30)$	> 20
$p_T(j_1)$	> 60	> 25	> 20
$p_T(j_2)$	> 35	> 25	> 20
$p_T(jj)$	[illegible]	[illegible]	-
$M(jj)$	[illegible]	[illegible]	$[90, 150]$
$CMVA_{ma}$	[illegible]	[illegible]	> -0.5884
$CMVA_{mi}$	[illegible]	[illegible]	> -0.5884
N_{aj}	[illegible]	[illegible]	-
N_{al}	$= 0$	$= 0$	-
E_T^{miss}	> 170	-	-
Anti-QCD	Yes	-	-
$\Delta\phi(V, H)$	> 2.0	> 2.5	> 2.5
$\Delta\phi(E_T^{miss}, E_T^{miss}{}_{trk})$	< 0.5	-	-
$\Delta\phi(E_T^{miss}, \ell)$	-	< 2.0	-
Lepton Isolation	-	< 0.06	-
Event BDT	> -0.8	> 0.3	> -0.8

In VH signal, V boosted due to recoil off H

CMS-PAS-HIG-16-044

Event selection

Variable	0-lepton	1-lepton	2-lepton
$p_T(V)$	> 170	> 100	$[50, 150], > 150$
$M(\ell\ell)$	-	-	$[75, 105]$
p_T^{ℓ}	-	$(> 25, > 30)$	> 20
$p_T(j_1)$	> 60	> 25	> 20
$p_T(j_2)$	> 35	> 25	> 20
$p_T(jj)$	> 120	> 100	-
$M(jj)$	$[60, 160]$	$[90, 150]$	$[90, 150]$
$CMVA_{max}$		> 0.9432	
$CMVA_{min}$	4	> -0.5884	
N_{aj}		< 2	
N_{al}	$= 0$	$= 0$	-
E_T^{miss}	> 170	-	-
Anti-QCD	Yes	-	-
$\Delta\phi(V, H)$	> 2.0	> 2.5	> 2.5
$\Delta\phi(E_T^{miss}, E_T^{miss}{}_{trk})$	< 0.5	-	-
$\Delta\phi(E_T^{miss}, \ell)$	-	< 2.0	-
Lepton Isolation	-	< 0.06	-
Event BDT	> -0.8	> 0.3	> -0.8

p_T^{μ}

p_T^{e}

CMS-PAS-HIG-16-044

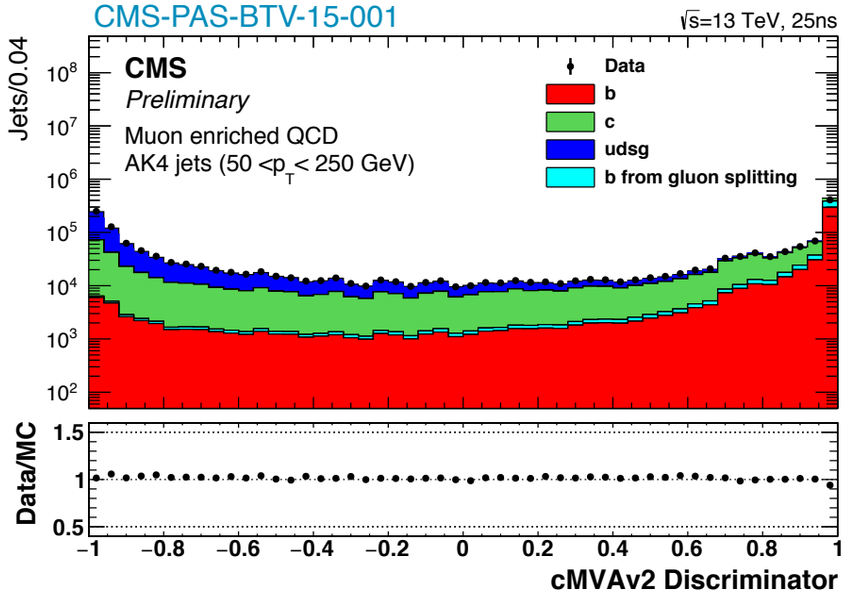
Event selection

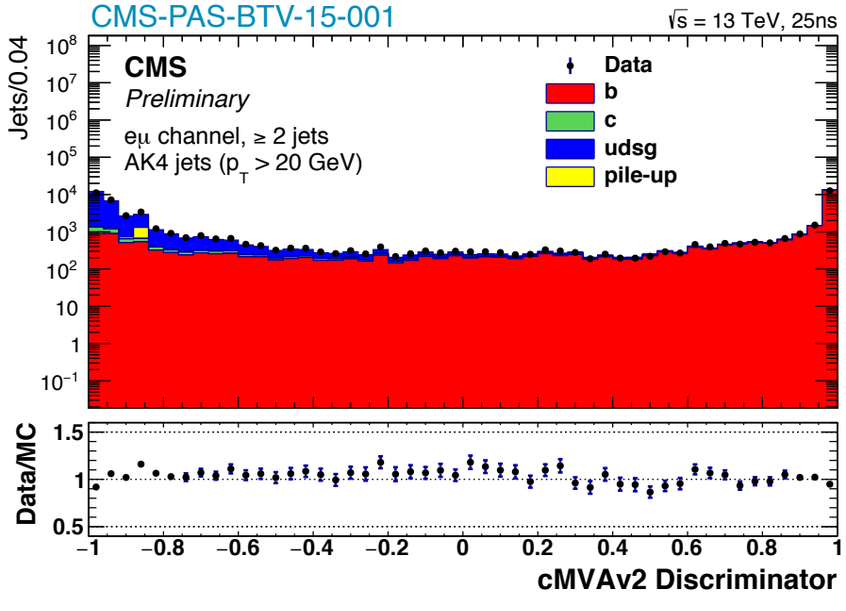
Variable	0-lepton	1-lepton	2-lepton
$p_T(V)$	> 170	> 100	$[50, 150], > 150$
$M(\ell\ell)$	-	-	$[75, 105]$
p_T^ℓ	-	$(> 25, > 30)$	> 20
$p_T(j_1)$	> 60	> 25	> 20
$p_T(j_2)$	> 35	> 25	> 20
$p_T(jj)$	> 120	> 100	-
$M(jj)$	$[60, 160]$	$[90, 150]$	$[90, 150]$
$CMVA_{max}$	> 0.9432	> 0.9432	> -0.5884
$CMVA_{min}$	> -0.5884	> -0.5884	> -0.5884
N_{aj}	< 2	< 2	-
N_{al}	$= 0$	$= 0$	-
E_T^{miss}			
Anti-QC			
$\Delta\phi(V, H$			
$\Delta\phi(E_T^{miss}, E_T^{m}$			
$\Delta\phi(E_T^{miss}$			
Lepton Isolation			
Event BDT	> -0.8	> 0.3	> -0.8

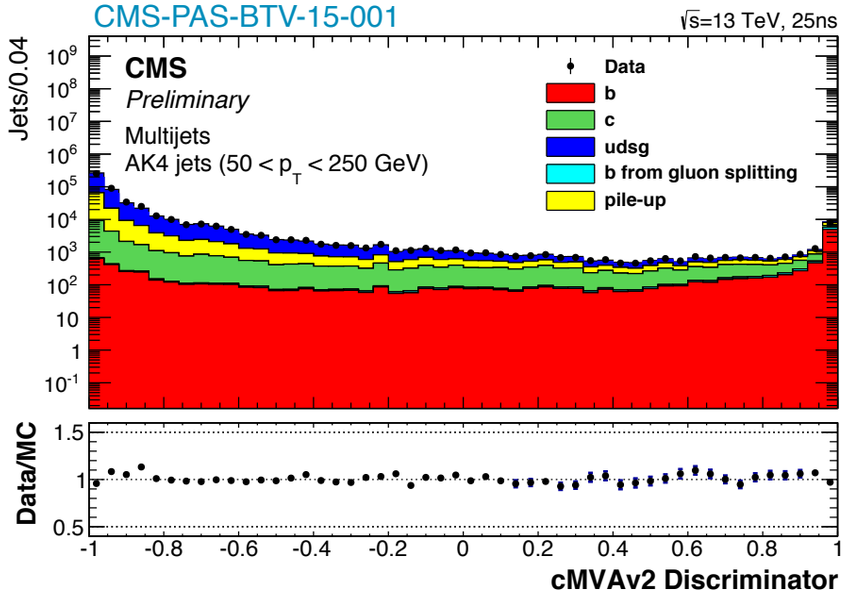
- $j_1(j_2)$ is the jet in the event with the (second) highest CMVA b tag score
- $CMVA_{max(min)}$ is the CMVA score of $j_{1(2)}$

CMS-PAS-HIG-16-044

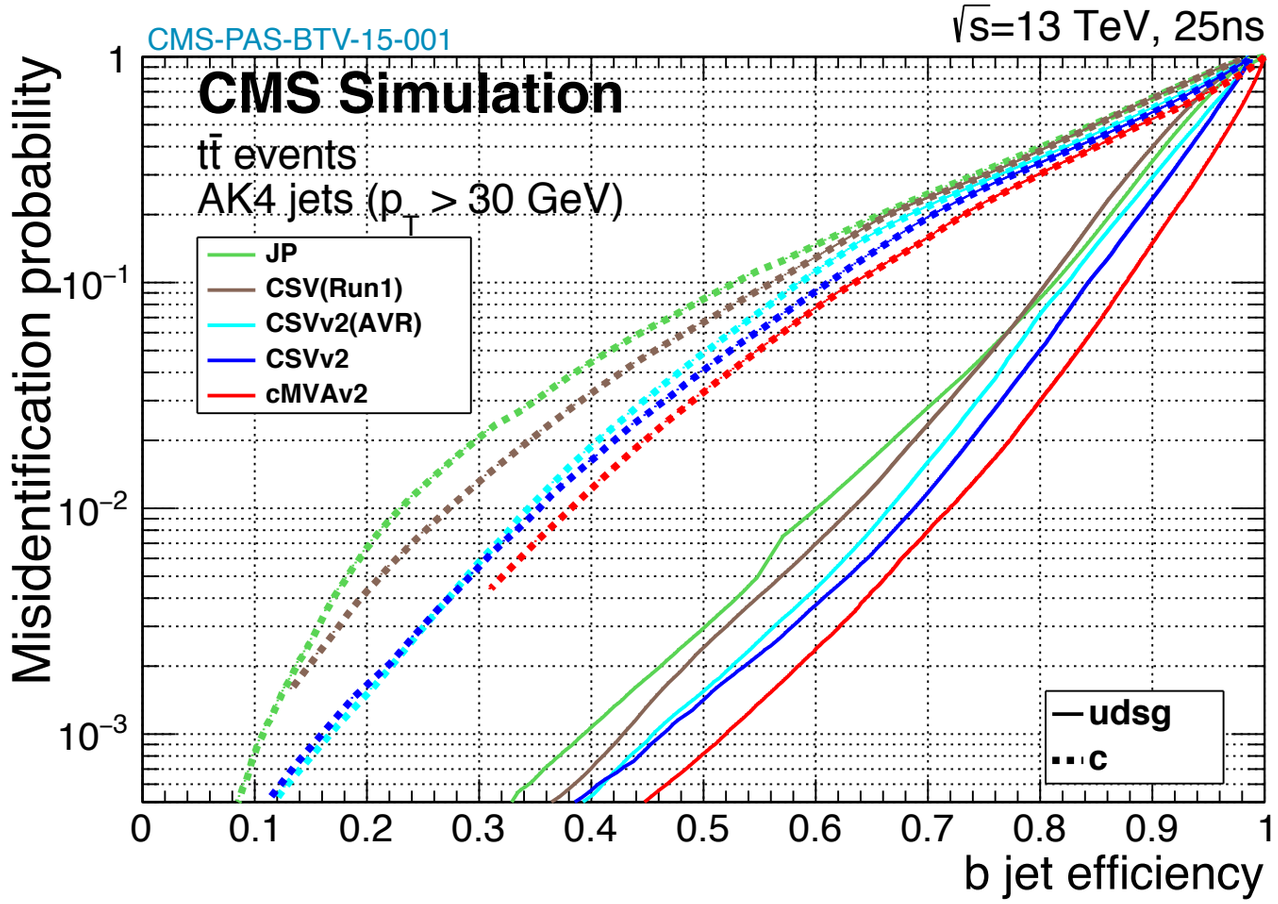
b tagging







- CMVA: Combined Multivariate Algorithm
- Boosted decision tree (BDT) classifier with six b tagger discriminants as inputs
  - Two variants of Jet Probability (JP) tagger (uses information from impact parameters of tracks inside jets w.r.t. primary vertex)
  - Two variants of Combined Secondary Vertex (CSV) tagger (uses information from secondary vertices and displaced tracks inside jets)
  - Soft electron and soft muon tagger



Event selection

Variable	0-lepton	1-lepton	2-lepton
$p_T(V)$	> 170	> 100	$[50, 150], > 150$
$M(\ell\ell)$			$[75, 105]$
p_T			
p_T			
p			
M			$0]$
$\mathrm{CMVA_{max}}$	> 0.9432	> 0.9432	> -0.5884
$\mathrm{CMVA_{min}}$	> -0.5884	> -0.5884	> -0.5884
N_{aj}	< 2	< 2	-
N_{al}	$= 0$	$= 0$	-
E_T^{miss}	> 170	-	-
Anti-QCD	Yes	-	-
$\Delta\phi(V, H)$	> 2.0	> 2.5	> 2.5
$\Delta\phi(E_T^{miss}, E_T^{miss}{}_{trk})$	< 0.5	-	-
$\Delta\phi(E_T^{miss}, \ell)$	-	< 2.0	-
Lepton Isolation	-	< 0.06	-
Event BDT	> -0.8	> 0.3	> -0.8

- N_{aj} is the number of additional central jets (reject tt)
- N_{al} is the number of additional leptons with $p_T > 20$ GeV (reject tt and WV and maintain orthogonality to 2-lepton sample

CMS-PAS-HIG-16-044

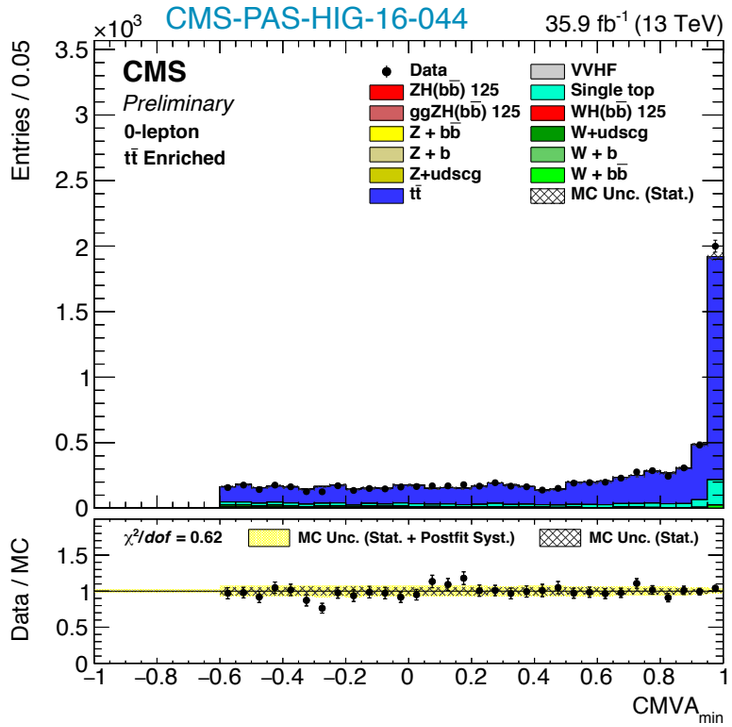
Event selection

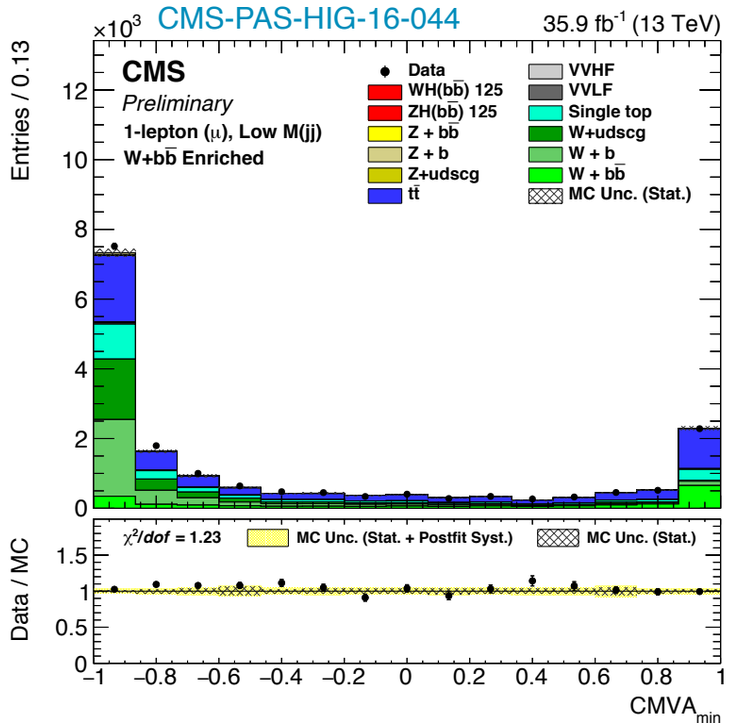
Variable	0-lepton	1-lepton	2-lepton
$\mathrm{CMVA_{max}}$	> 0.9432	> 0.9432	> -0.5884
$\mathrm{CMVA_{min}}$	> -0.5884	> -0.5884	> -0.5884
N_{aj}	< 2	< 2	-
N_{al}	$= 0$	$= 0$	-
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 170	-	-
Anti-QCD	Yes	-	-
$\Delta\phi(\mathrm{V,H})$	> 2.0	> 2.5	> 2.5
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, E_{\mathrm{T}}^{\mathrm{miss}}{}_{\mathrm{trk}})$	< 0.5	-	-
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell)$	-	< 2.0	-
Lepton Isolation	-	< 0.06	-
Event BDT	> -0.8	> 0.3	> -0.8

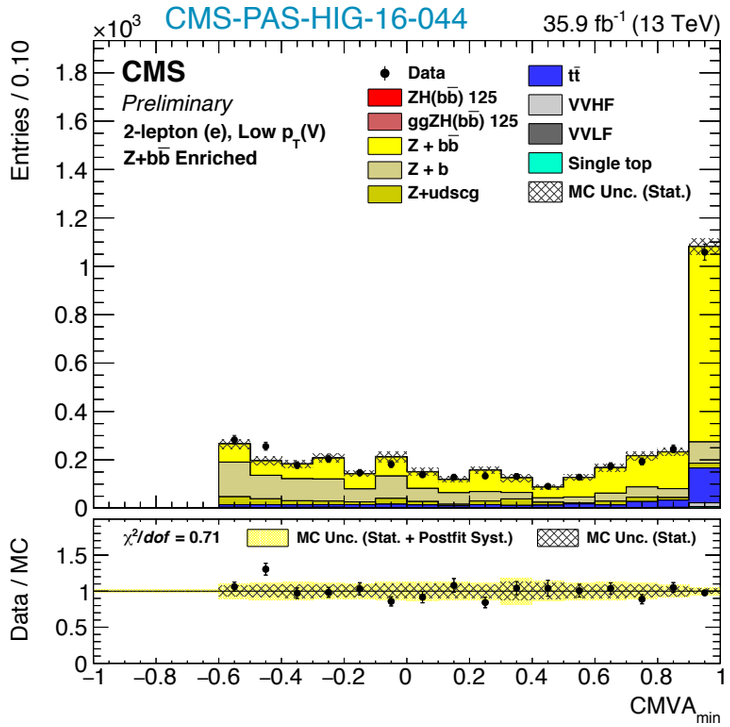
- Additional cuts to reduce QCD multijet background in 0- and 1-lepton channels
- Anti-QCD: $\Delta\Phi(E_T^{miss}$, nearest central jet with $p_T > 25$ GeV$) > 0.5$
- $E_T^{miss}{}_{trk}$ is computed only from tracks with $p_T > 0.5$ GeV and $|\eta| < 2.5$

CMS-PAS-HIG-16-044

Background estimation







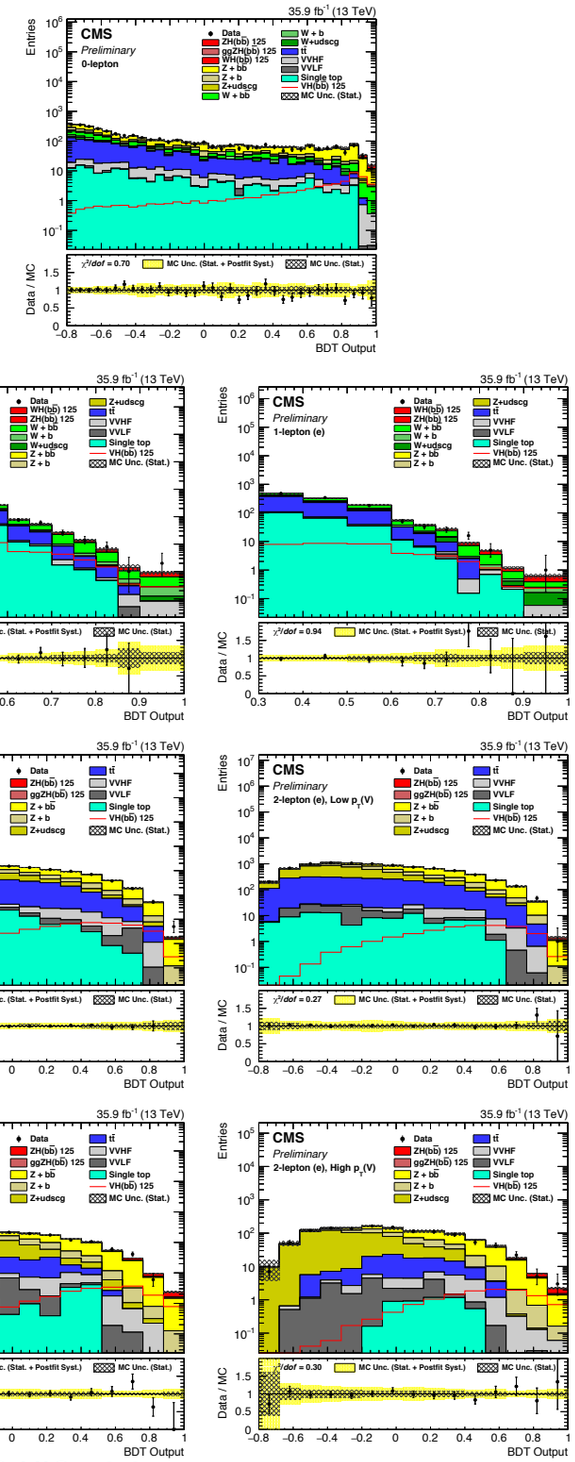
- 4 search channels: 0-lepton, 1-lepton, 2-lepton low boost, 2-lepton high boost
- Three background control regions defined for each search channel: tt, V+LF(light flavor), and V+HF(heavy flavor)
- Simultaneous binned likelihood fit (in the three control regions) of Monte Carlo (MC) simulated background CMVA$_{min}$ distribution to data
  - Purity of specific background in specific control region not perfect
  - All background component normalizations are free parameters of the fit—maximum independence from simulation uncertainties
  - Component shapes allowed to vary within systematic errors

Process	0-lepton	1-lepton	2-lepton low-p_T	2-lepton high-p_T
W0b	1.14 ± 0.07	1.14 ± 0.07	-	-
W1b	1.66 ± 0.12	1.66 ± 0.12	-	-
W2b	1.49 ± 0.12	1.49 ± 0.12	-	-
Z0b	1.03 ± 0.07	-	1.01 ± 0.06	1.02 ± 0.06
Z1b	1.28 ± 0.17	-	0.98 ± 0.06	1.02 ± 0.11
Z2b	1.61 ± 0.10	-	1.09 ± 0.07	1.28 ± 0.09
$t\bar{t}$	0.78 ± 0.05	0.91 ± 0.03	1.00 ± 0.03	1.04 ± 0.05

CMS-PAS-HIG-16-044

Signal extraction

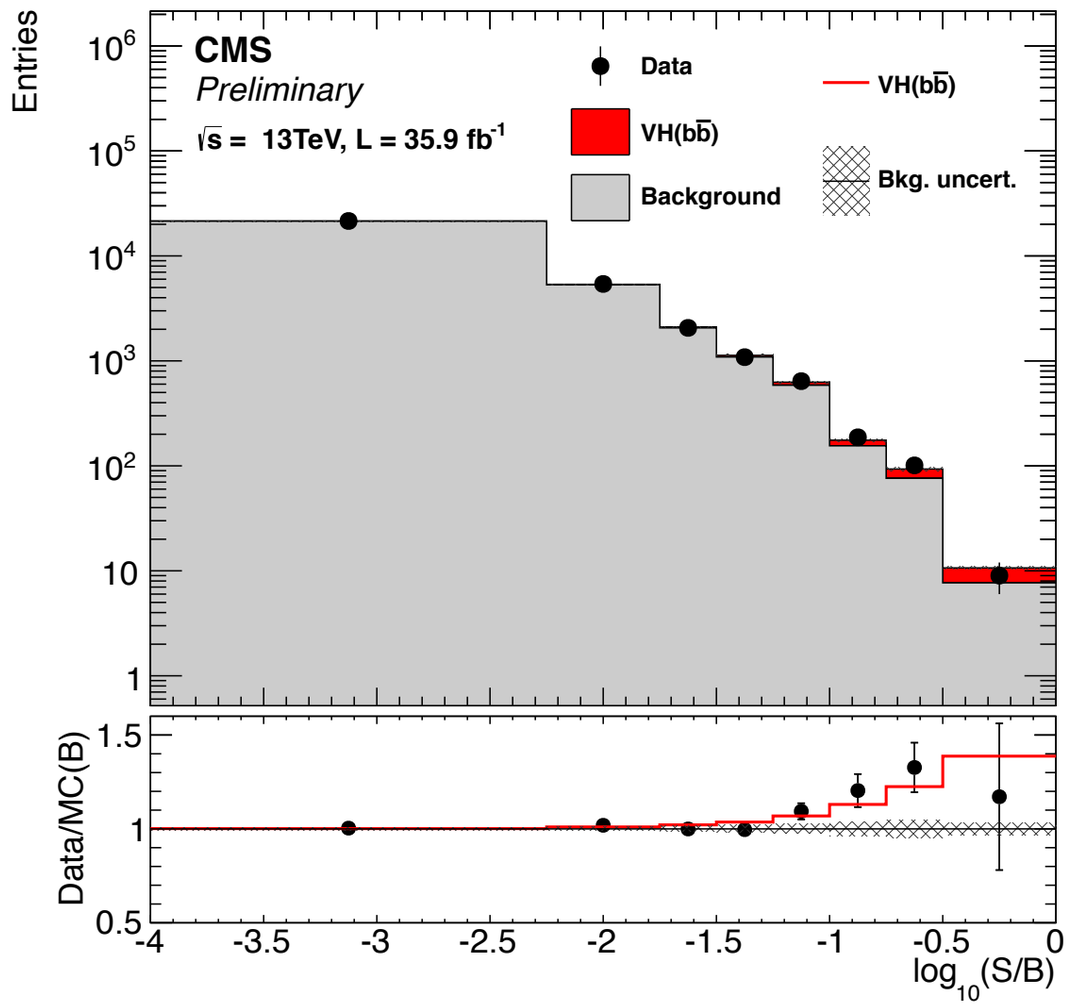
- BDT classifier trained on MC VH signal and backgrounds
- Most discriminant variables: M(jj), N_{aj}, $CMVA_{min}$, and ΔR(jj)
- Search region and three control regions fit simultaneously for each of the seven search channels
  - MC signal and background BDT distributions fit to data in search region
  - MC background $CMVA_{min}$ distributions fit to data in control regions



CMS-PAS-HIG-16-044

Result

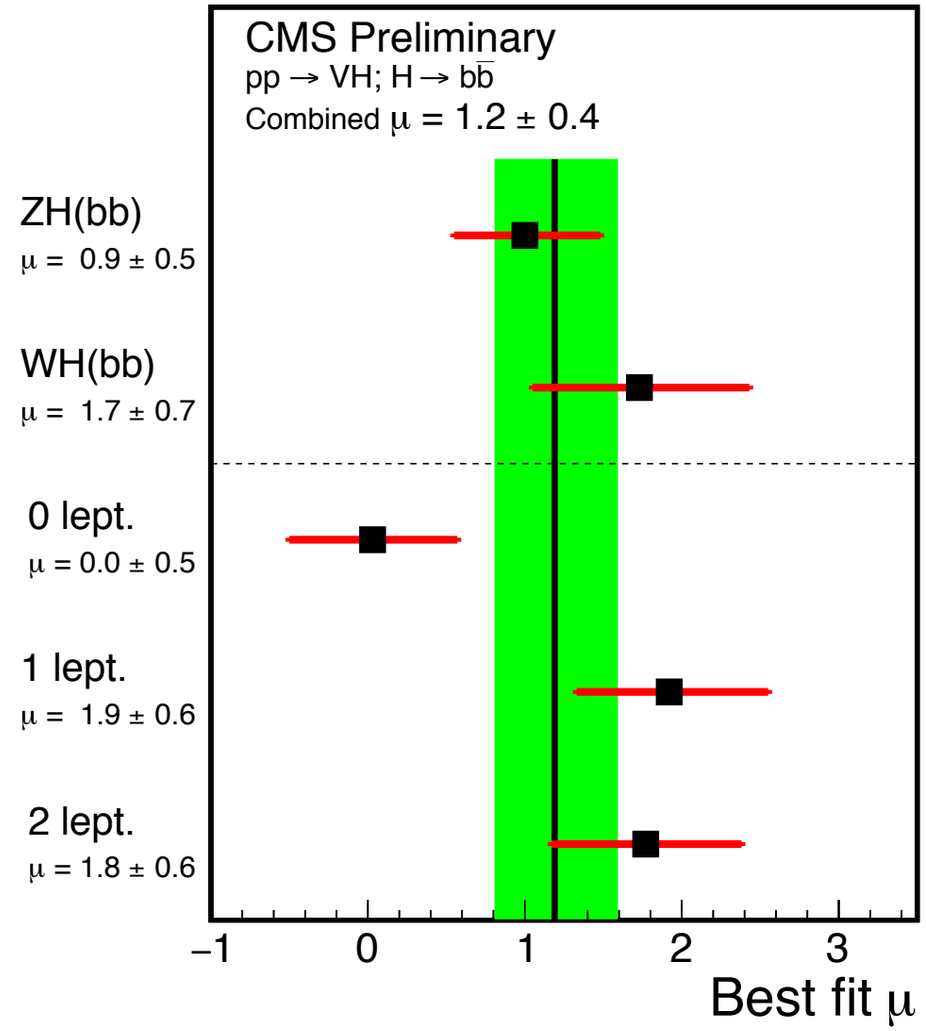
CMS-PAS-HIG-16-044



$mH = 125\,\text{GeV}$	Significance expected	Significance observed
0-lepton	1.5	0.0
1-lepton	1.5	3.2
2-lepton	1.8	3.1
All channels	2.8	3.3

CMS-PAS-HIG-16-044

CMS-PAS-HIG-16-044 35.9 fb^{-1} (13 TeV)



$mH = 125\,\text{GeV}$	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$

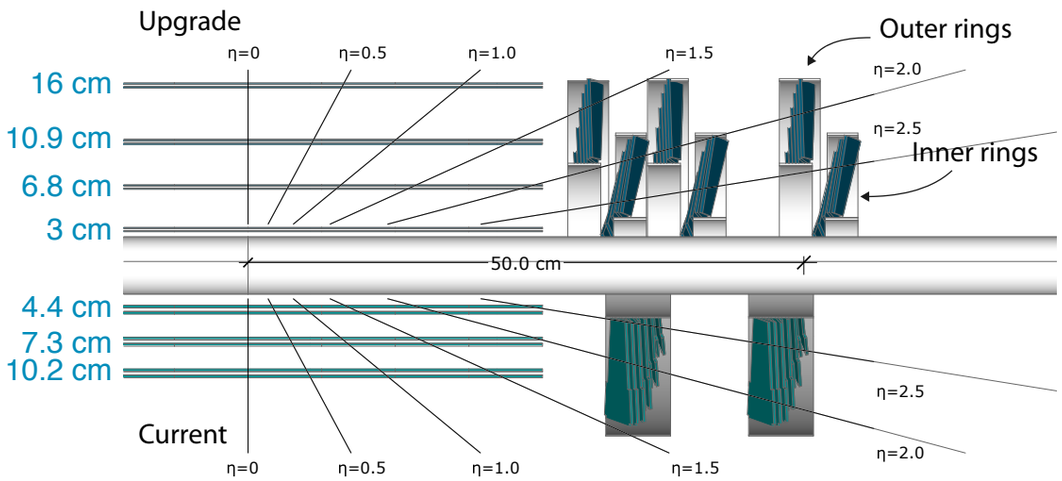
CMS-PAS-HIG-16-044

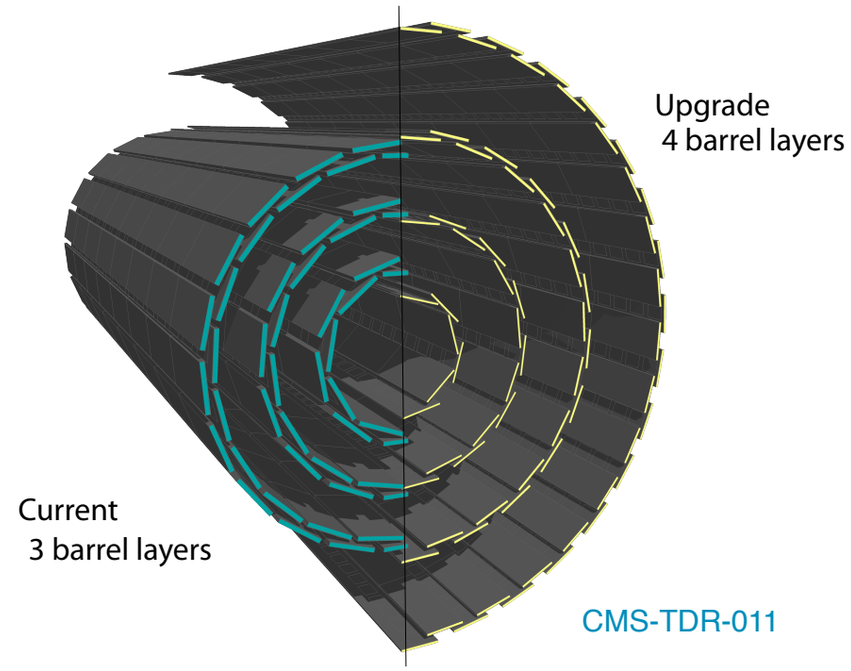
Moving forward

- A smashing success
  - For the SM ¯_(ツ)_/¯
  - For the 2016 pp run

But what have you done for me lately?

Phase 1 pixel upgrade

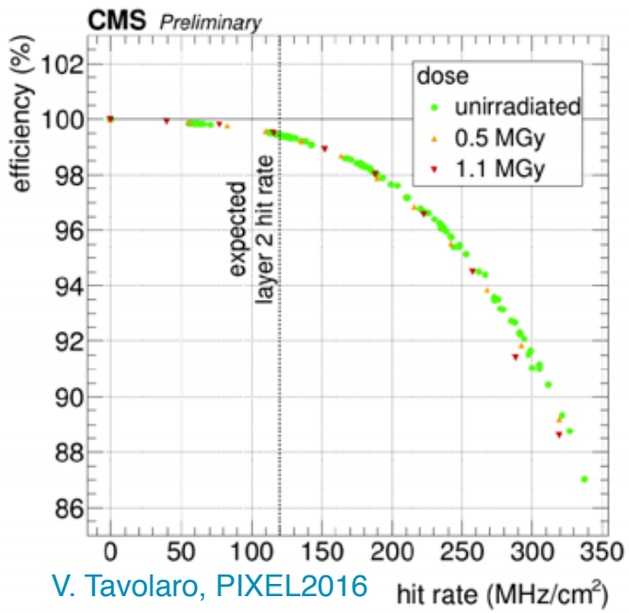




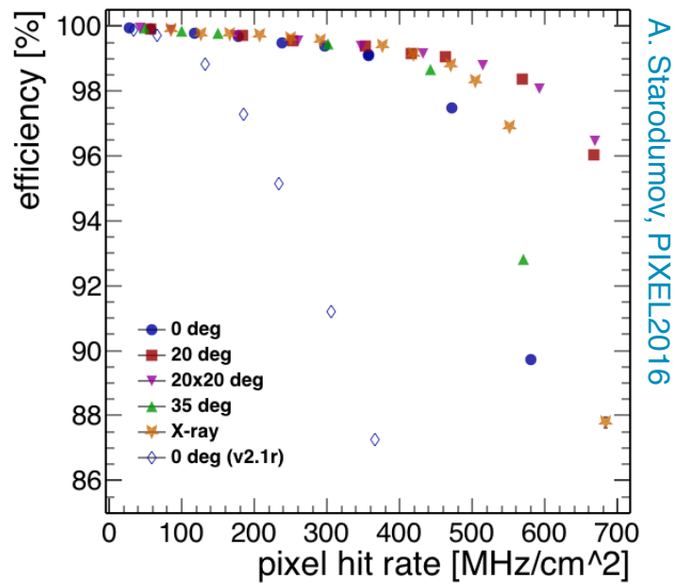
- 3→4 barrel layers
- 2→3 endcap disks
- Layer 1 closer to the beam line
- Layer 4 closer to first layer of strips
- New ROCs with less data loss at high rate
- Full digital readout from the front end
- Reduced material
- C_6F_{14}→CO_2 cooling
- VME→μTCA back end electronics

Design goal: **maintain** or improve on **Run 1** tracking and vertexing performance at **2 × 10^{34} cm^{-2} s^{-1}** and **50 pileup**

Phase 1 ROCs



V. Tavolaro, PIXEL2016

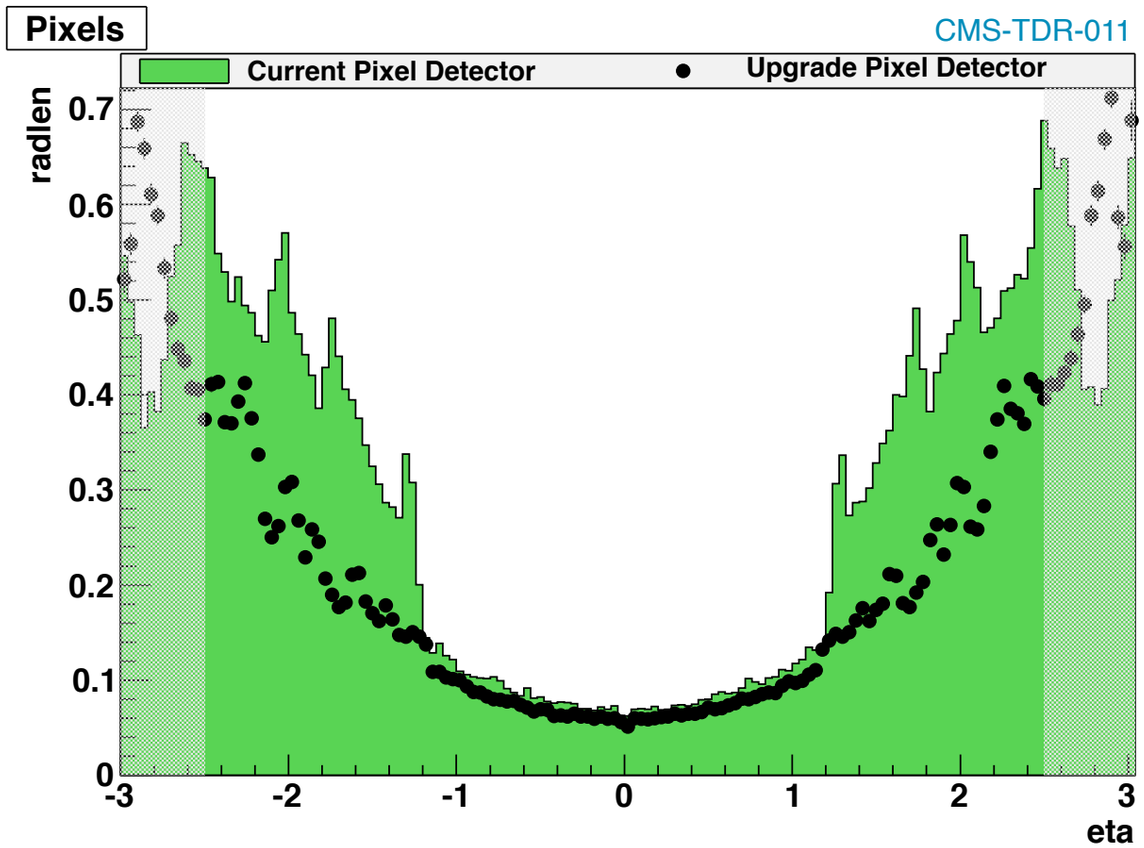


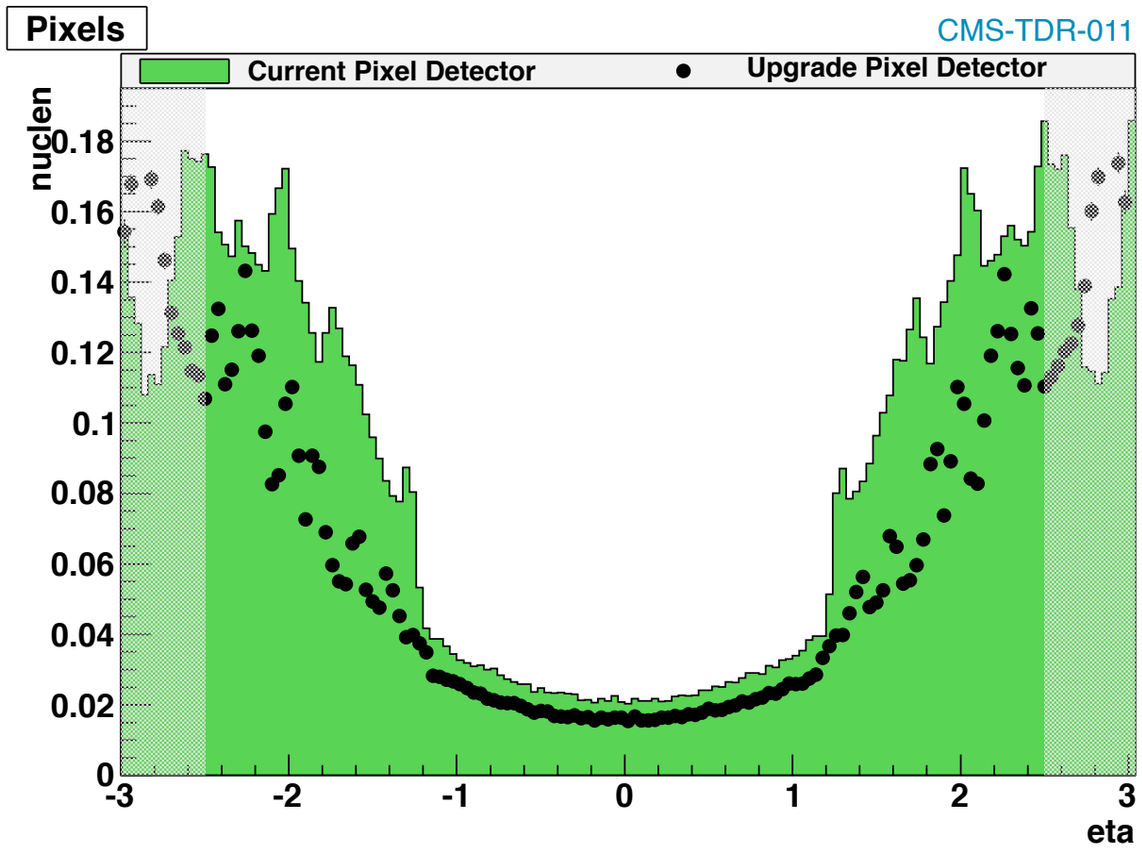
A. Starodumov, PIXEL2016

CMS-TDR-011	PSI46V2	PSI46DIG
ROC size	7.9 mm x 9.8 mm	7.9 mm x 10.2 mm
Pixel size	100 μm x 150 μm	100 μm x 150 μm
Smallest radius	4.3cm	2.9cm
Settable DACs / registers	26 / 2	19 / 2
Power Up condition	not defined	default values
pixel charge readout	analog	digitized, 8bit
Readout speed	40 MHz	160 Mbit/s
Time stamp Buffer size	12	24
Data Buffer size	32	80
Output Buffer FIFO	no	yes
Double column Speed	20 MHz	20 MHz (40 MHz)
Metal layers	5	6
Leakage current compensation	yes	no
in-time threshold	3500 e	$<$ 2000 e
PLL	no	yes
Data loss at max Operating flux	$\sim$3.8% at 120 MHz/cm^2	1.6% at 150 MHz/cm^2 ($\sim$3% at 580 MHz/cm^2)

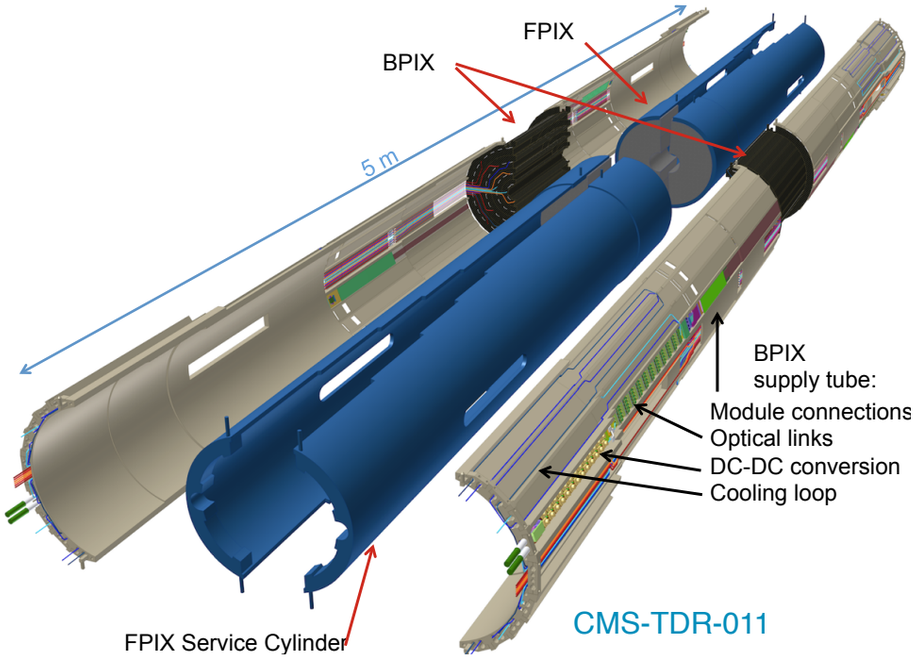
- Power up should not draw large currents
- 8b digitization on front end (compare 10b digitization at back end for Phase 0 detector)
- Faster digital readout
- Deeper (and additional) buffers for event data
- Lower threshold and less timewalk $\Rightarrow$ better sensitivity to small charge deposits

Phase 1 geometry





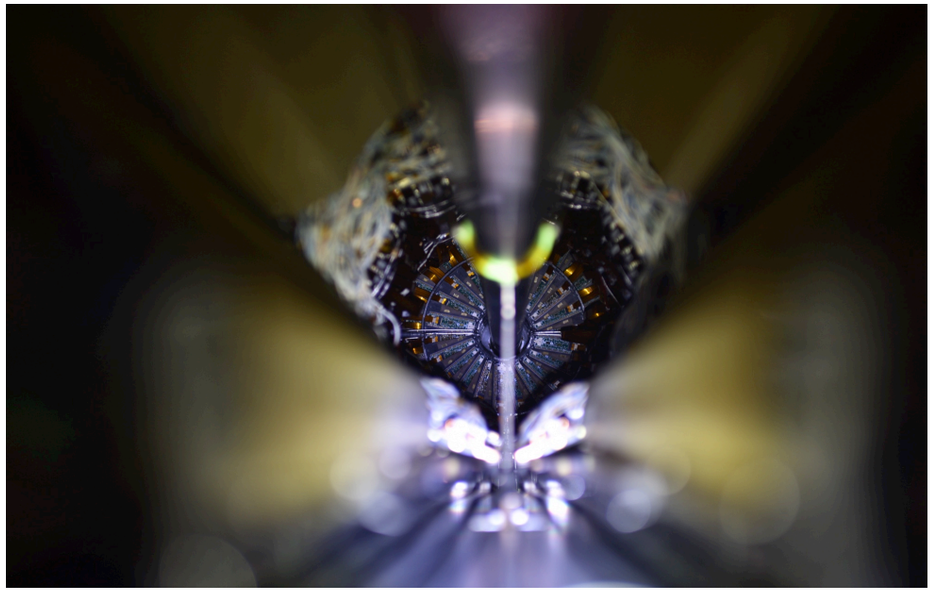
- Bulky services (e.g. electrical-optical converters, DC-DC converters) moved to higher η
- Heavy C_6F_{14} system replaced with lightweight CO_2 coolant and pipes



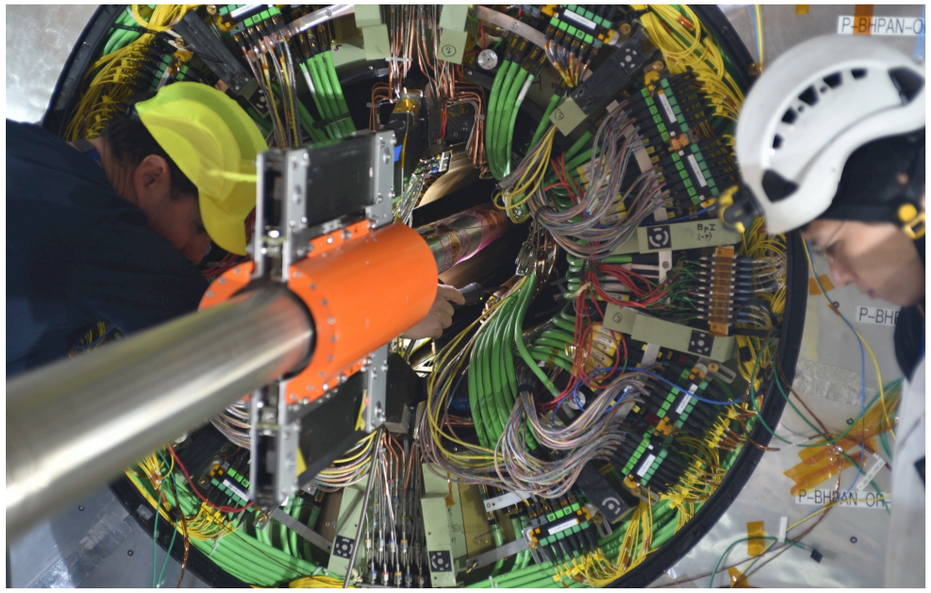
Installation

- Installation hewed to tight EYETS schedule
- Detector checked out and declared ready for CMS closing within two weeks after installation completed
- No significant issues with new cooling system or power supplies

S. Grünendahl, Forum on Tracking Detector Mechanics 2017



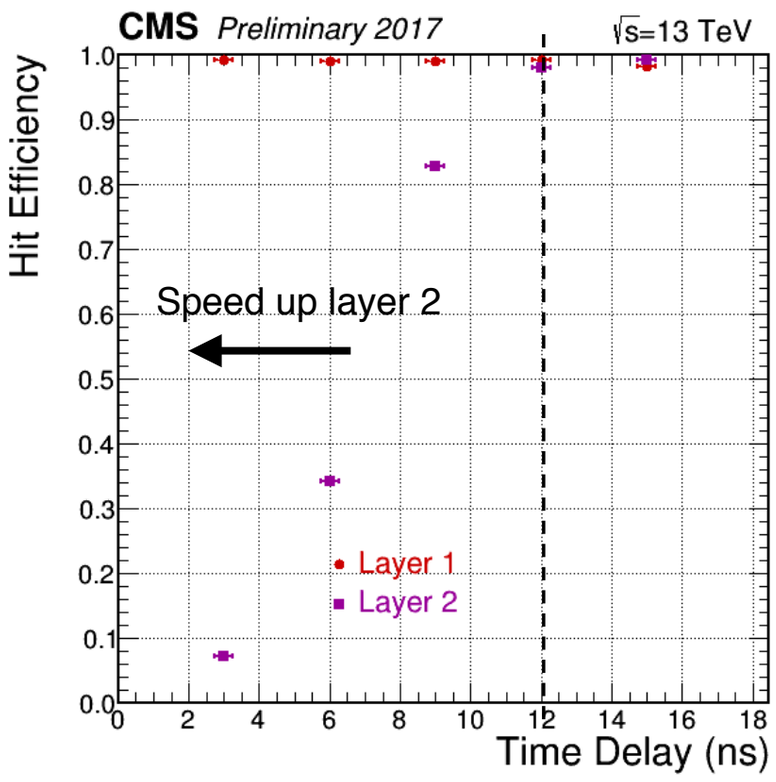
S. Grünendahl, Forum on Tracking Detector Mechanics 2017

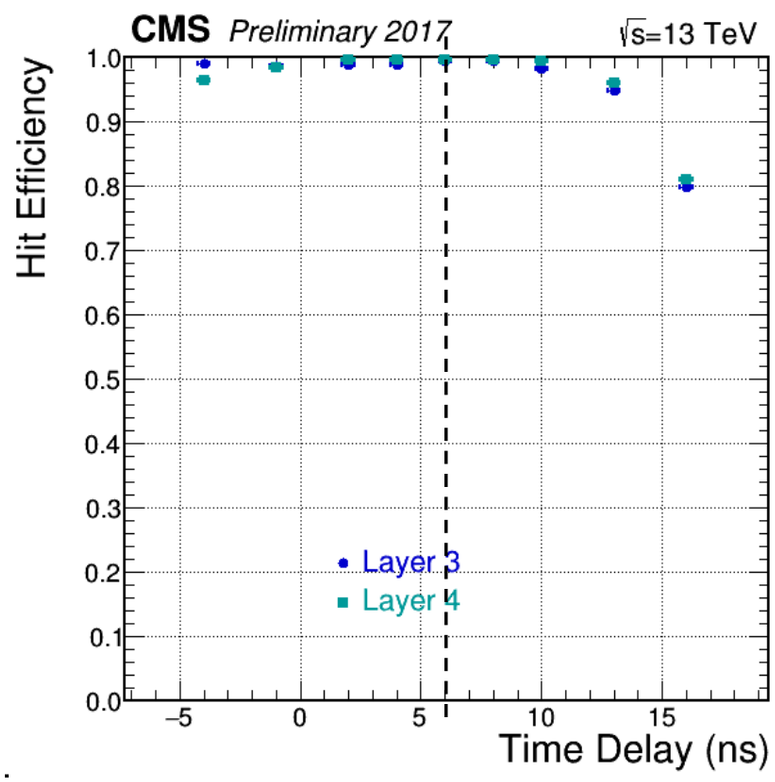


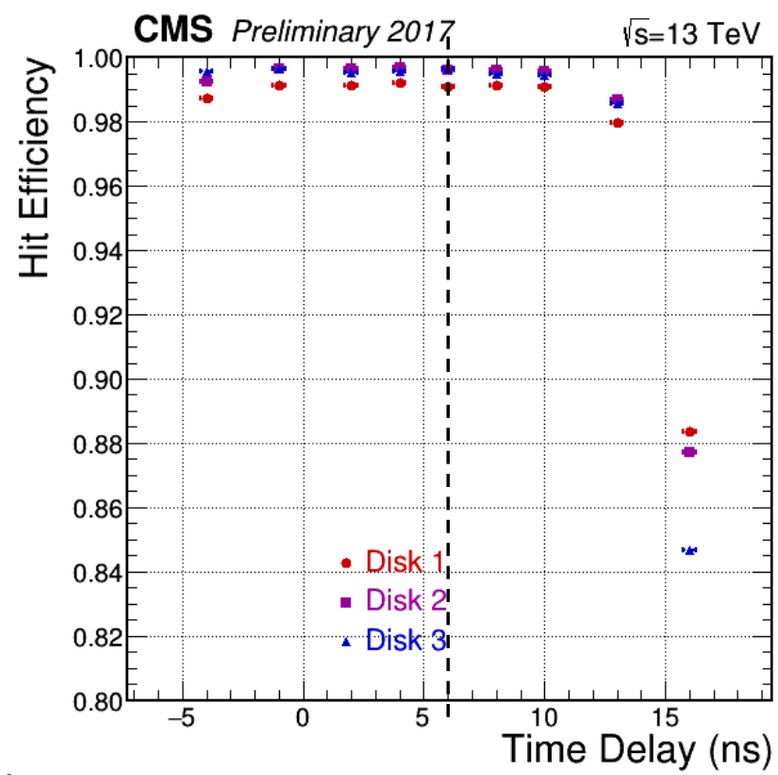
Current status

- LHC luminosity ramp up used for commissioning
  - Timing scan
  - Initial HV bias scans
- Startup issues encountered
  - Simultaneous timing of layer 1 and layer 2
  - Stuck Token Bit Manager (TBM) chip
    - Single event upset in a specific TBM register leaves it stuck in a “pause readout” state from which it can only be recovered with a power cycle
    - Automatic power cycle mechanism being implemented
- **Active channel fraction: 95.5%**
- **Operations August 15-23: 10 pb^{-1} pixel downtime / 2250 pb^{-1} CMS recorded**

Layer 1 timing

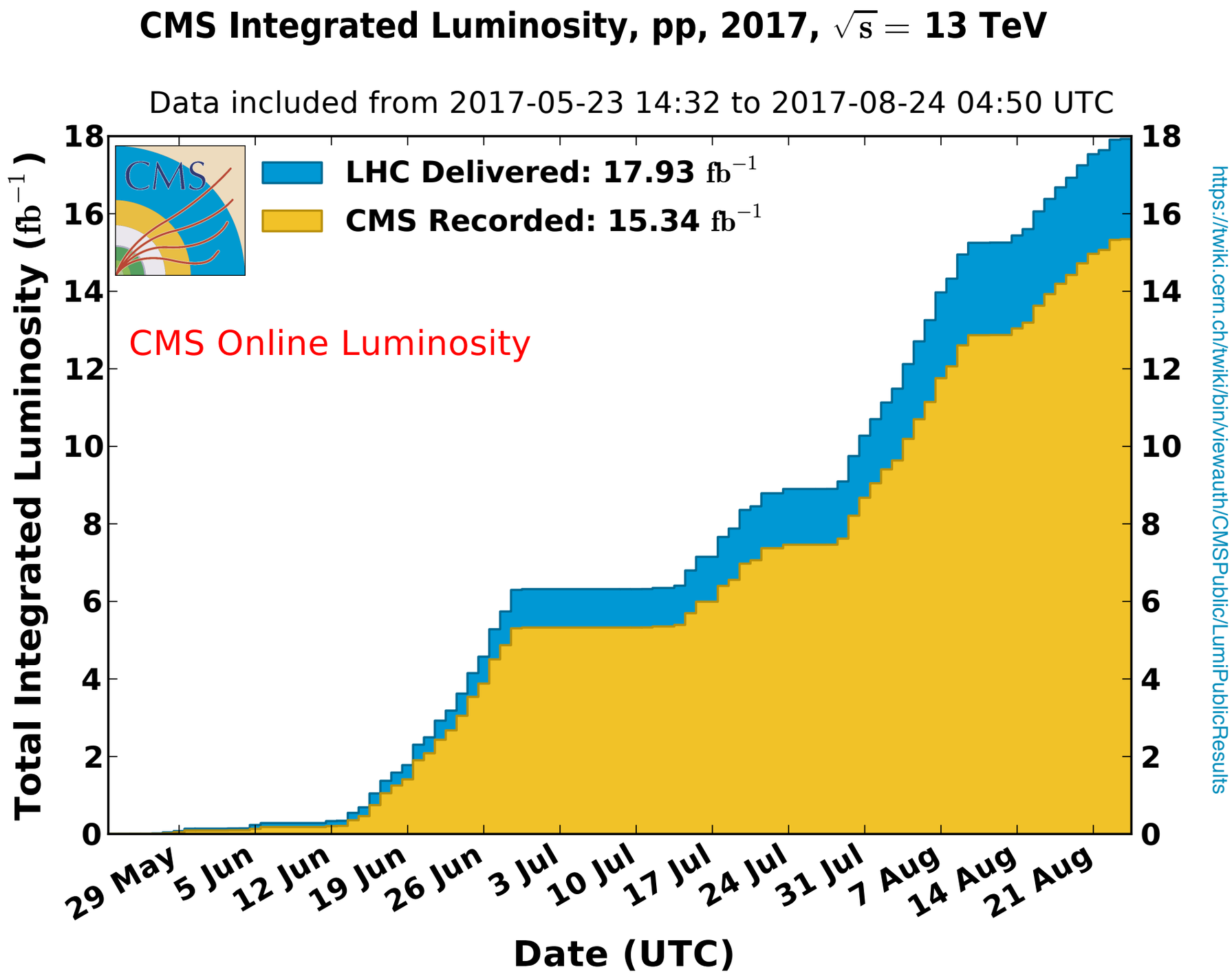




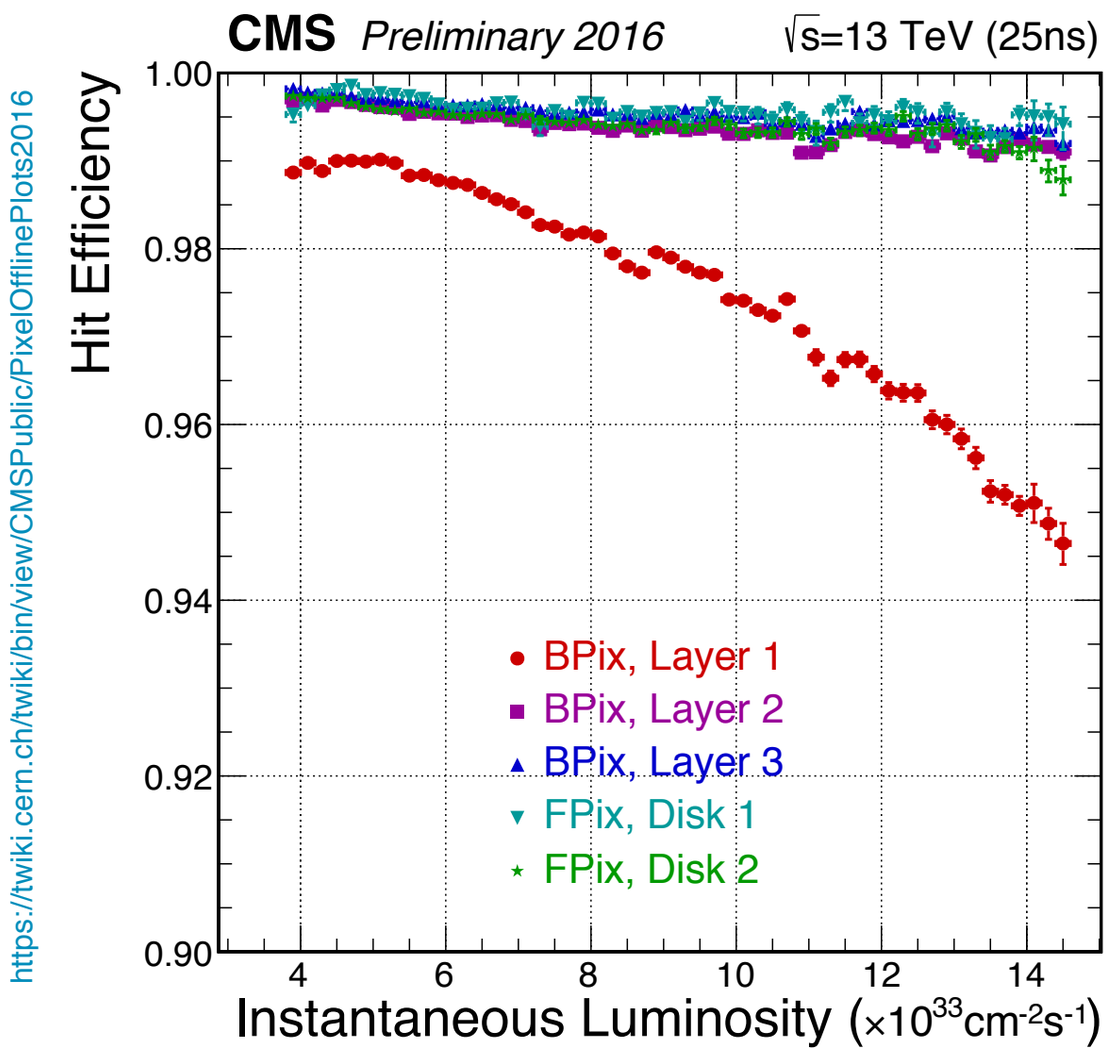


- Delay chip shared (within single Φ sector) between layers 1 and 2 of BPIX
- Different ROCs in layers 1 (PROC600) and 2 (PSI46dig)
- To increase overlap in efficiency plateau between layers 1 and 2, HV in layer 2 increased to 250 V (speed up layer 2)
- Working point found with >98% efficiency in layers 1 and 2 and maximized cluster charge

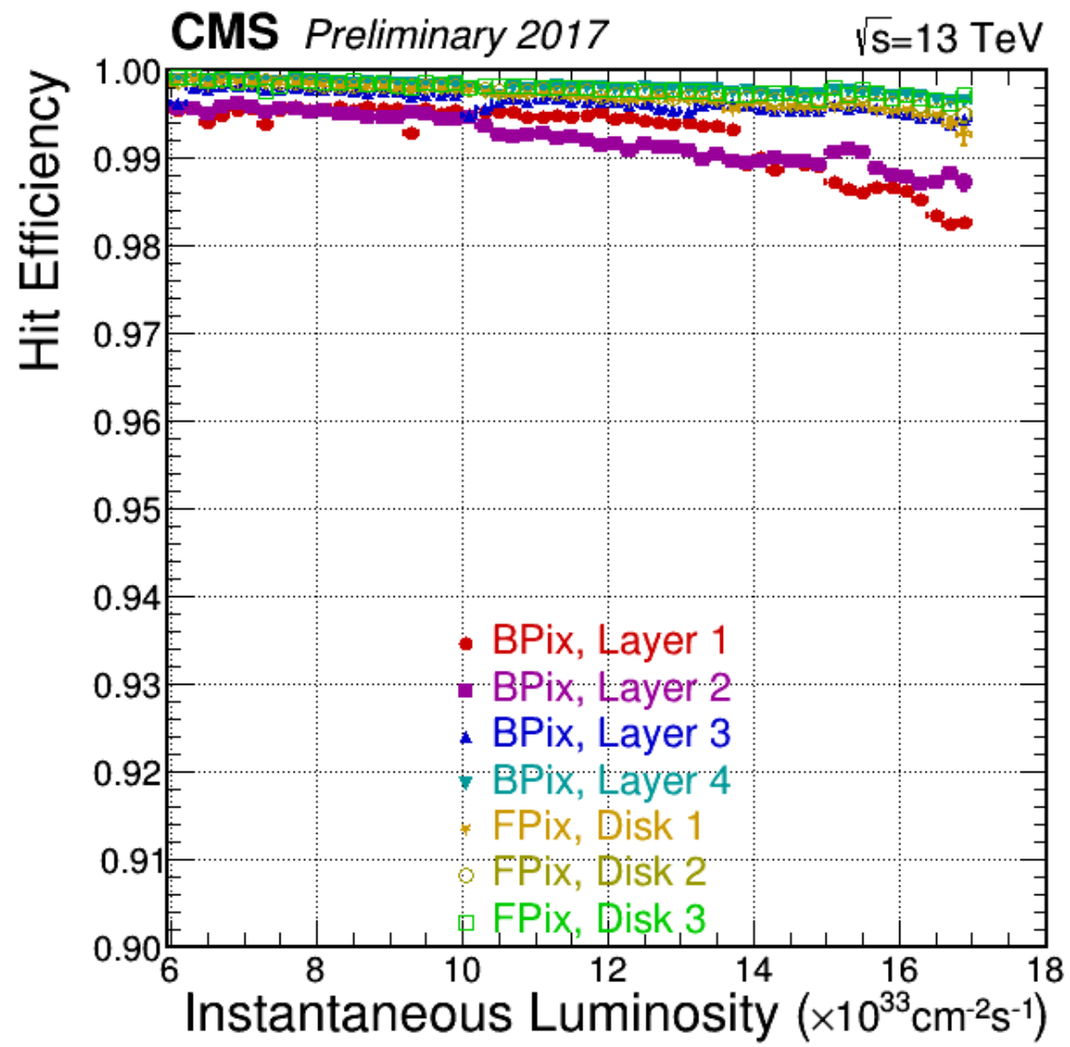
2017 performance



Pixel efficiency



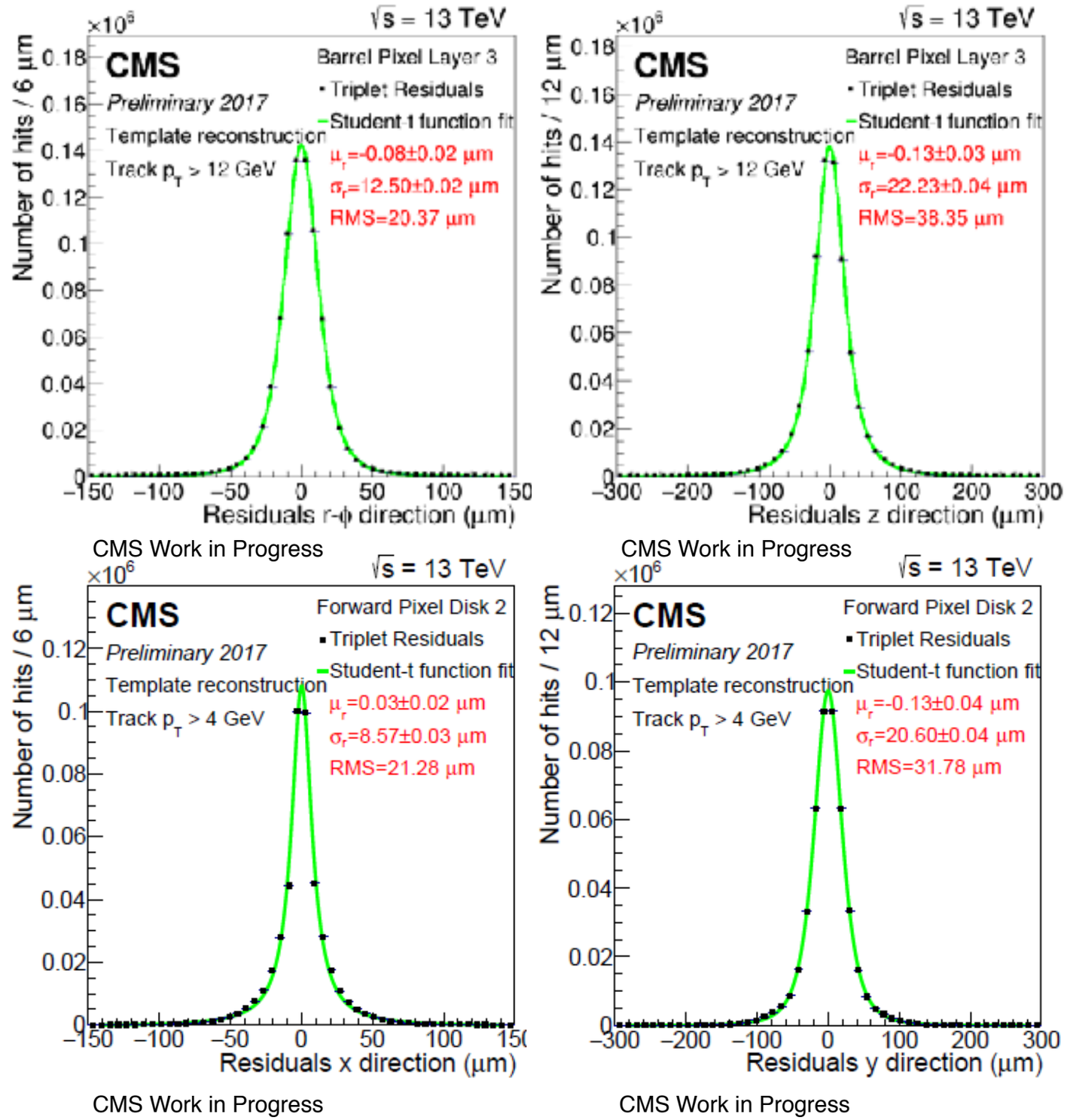
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PixelOfflinePlots2016



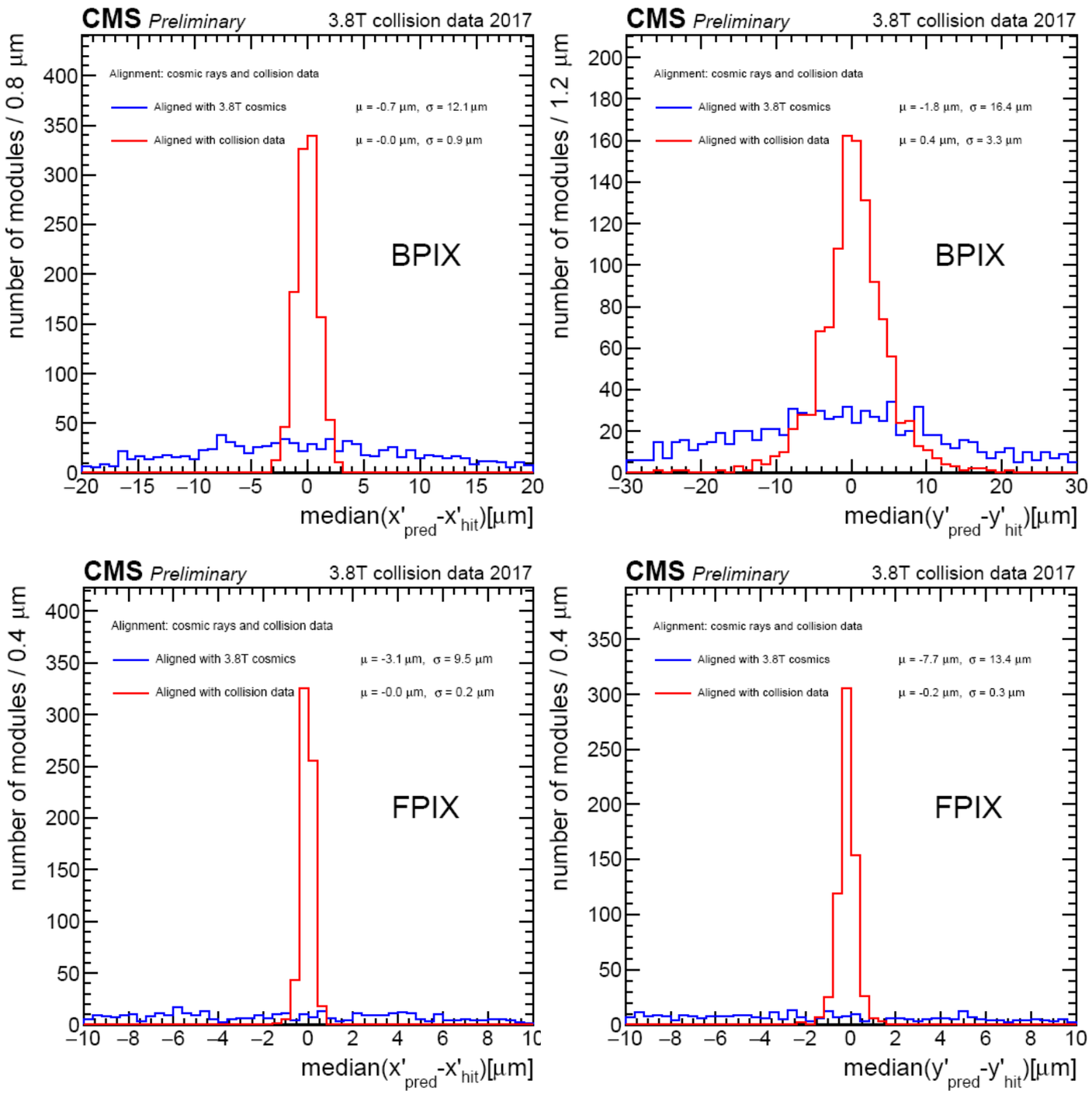
- Dynamic inefficiency observed at a lower rate than in 2016, as expected

Pixel hit resolution

- Triplets (tracks with 3 hits in the BPIX or FPIX) refit with one layer missing
- Residual between propagated track and actual hit position fitted to estimate resolution
- FPIX residuals better than simulation
- BPIX layer 3 residuals comparable to Phase 0

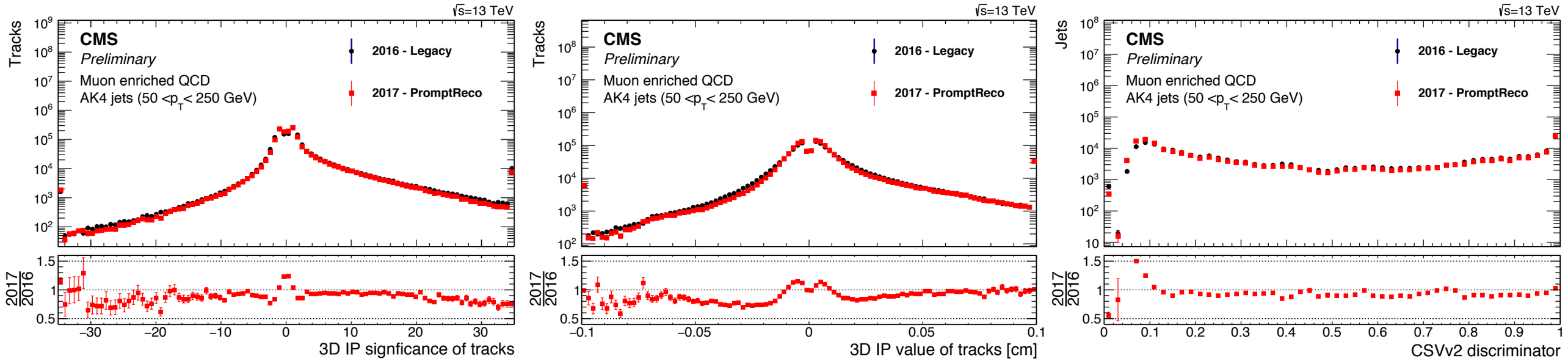


Pixel alignment



- Alignment precision significantly improved with collisions data
- FPIX well aligned
- BPIX alignment still suboptimal—improvement expected with better timing and detector understanding

b tagging



- At least 2 jets with $p_T > 40$ GeV and $|\eta| < 2.5$, of which at least 1 contains a muon with $p_T > 5$ GeV
- Plots are area normalized
- Compatibility between 2016 data with Phase 0 detector and 2017 data with Phase 1 detector despite higher 2017 instantaneous luminosity—**b tagging looks okay** so far despite commissioning headaches

Conclusion

- 2016 was a banner year for the CMS physics program
  - LHC delivered luminosity nearly doubled in 2016 alone
  - Evidence unearthed for the rare VH→bb signal, made possible by excellent data quality and detector availability
  - The quest to understand the SM (and what lies beyond?) continues…

Conclusion

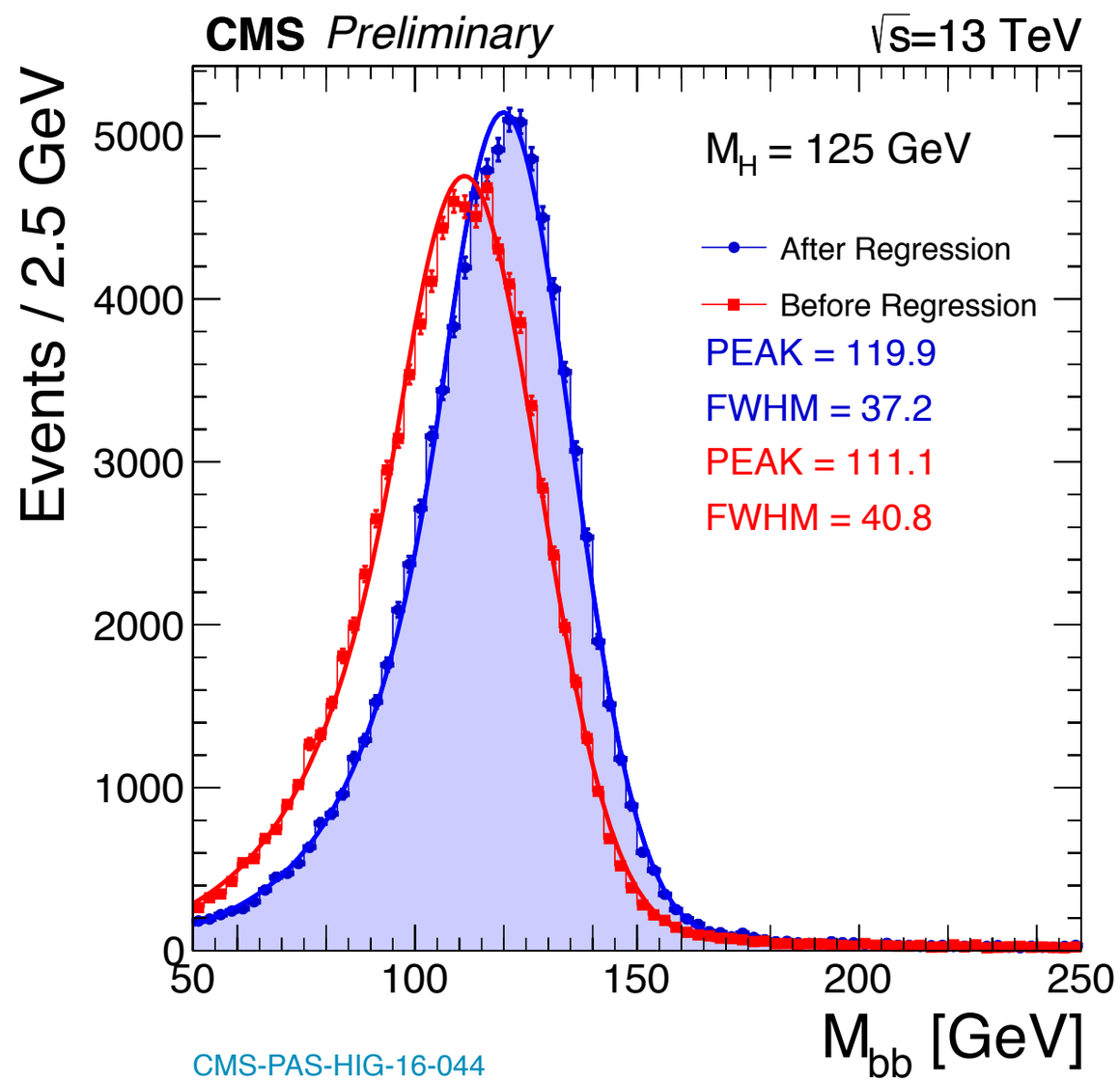
- …as CMS adapts to increasing instantaneous luminosity and radiation damage
  - Phase 1 pixel upgrade successfully installed during winter 2016-2017 EYETS
  - Significant milestone in the CMS Phase 1 upgrade project
- 2017 pixel commissioning very challenging (and not yet finished!), but performance benefits are starting to be realized

Bring on 2e34!

Backup

b jet corrections

- b jet energy corrections applied to improve M_{bb} resolution in Higgs decays
- Corrections derived from BDT trained on tt events



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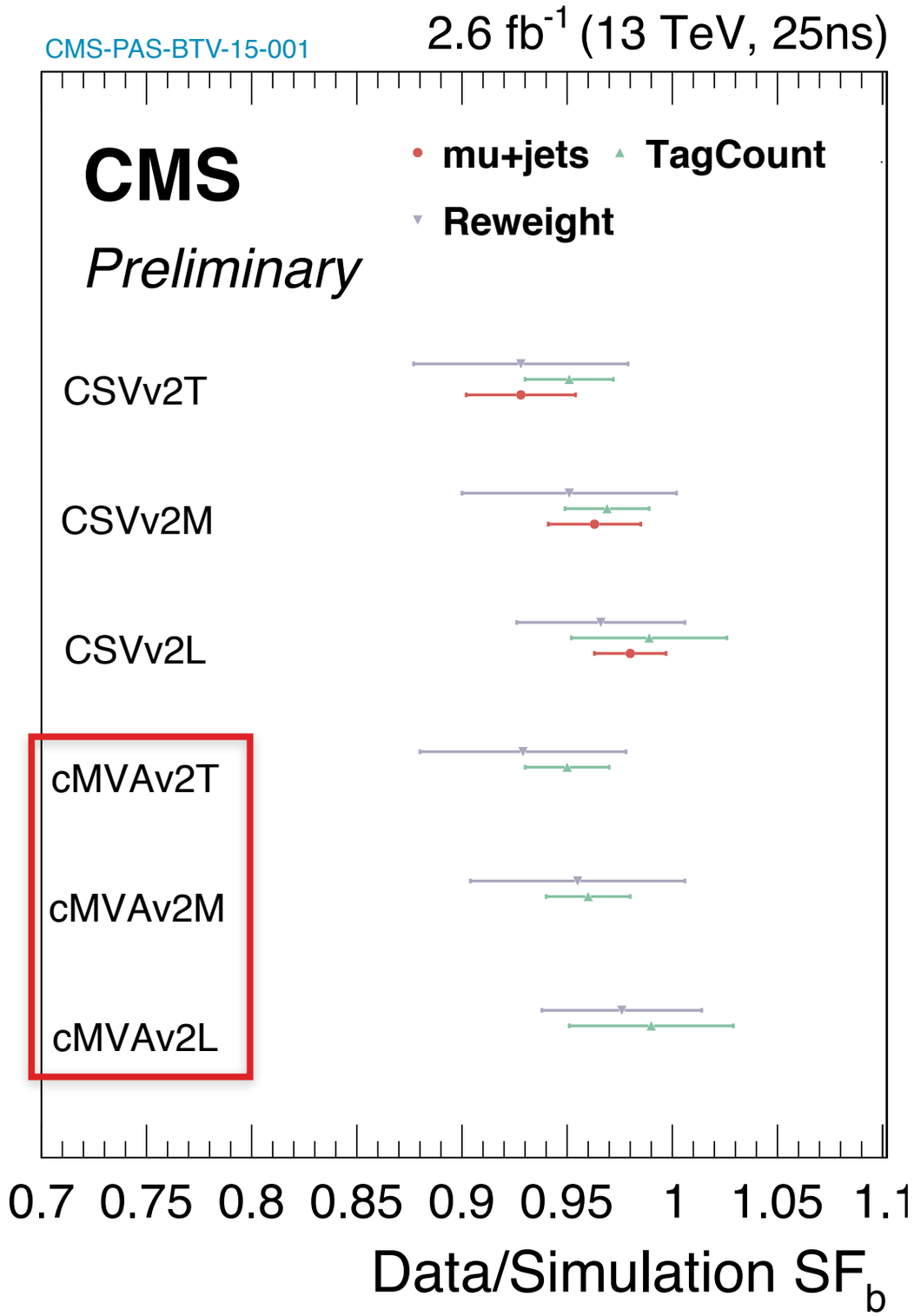
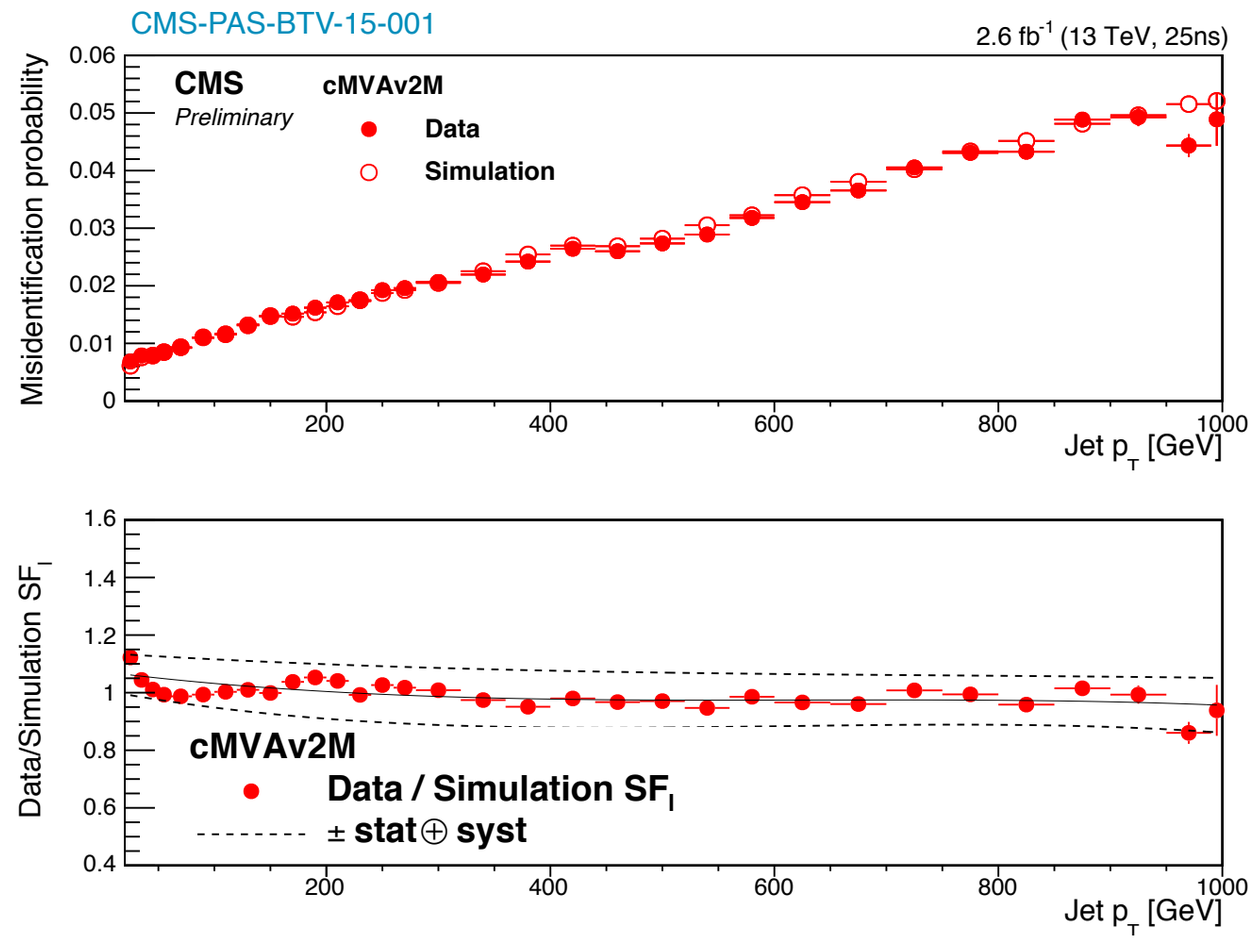
CMVA data/MC efficiency scale factors





- Top: medium (M) working point mistag efficiency scale factors
- Left: range of tight (T), medium (M), and loose (L) working point b tag efficiency scale factors

BDT input variables

Variable	Channels utilizing
$M(\mathrm{jj})$: dijet invariant mass	All
$p_{\mathrm{T}}(\mathrm{jj})$: dijet transverse momentum	All
$p_{\mathrm{T}}(\mathrm{V})$: vector boson transverse momentum	All
$\mathrm{CMVA}_{\mathrm{max}}$: value of CMVA for the Higgs boson daughter with largest CSV value	2-lepton, 0-lepton
$\mathrm{CMVA}_{\mathrm{min}}$: value of CMVA for the Higgs boson daughter with second largest CSV value	All
$\mathrm{CMVA}_{\mathrm{add}}$: value of CMVA for the additional jet with largest CSV value	0-lepton
$\Delta\phi(\mathrm{V},\mathrm{H})$: azimuthal angle between V and dijet	All
$p_{\mathrm{T}}(j)$: transverse momentum of each Higgs boson daughter	2-lepton, 0-lepton
$p_{\mathrm{T}}(\mathrm{add.})$: transverse momentum of leading additional jet	0-lepton
$\lvert\Delta\eta(\mathrm{jj})\rvert$: difference in η between Higgs boson daughters	2-lepton, 0-lepton
$\Delta R(\mathrm{jj})$: distance in η–ϕ between Higgs boson daughters	2-lepton
N_{aj}: number of additional jets N.B. definition slightly different per channel	1-lepton, 2-lepton
$p_{\mathrm{T}}(\mathrm{jj})/p_{\mathrm{T}}(\mathrm{V})$: p_{T} balance between Higgs boson candidate and vector boson	2-lepton
: Z boson mass	2-lepton
SA5: number of soft activity jets with $p_{\mathrm{T}} > 5$ GeV	All
M_{t}: reconstructed top quark mass	1-lepton
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\ell)$: azimuthal angle between $E_{\mathrm{T}}^{\mathrm{miss}}$ and lepton	1-lepton
$E_{\mathrm{T}}^{\mathrm{miss}}$: missing transverse energy	1-lepton, 2-lepton
$m_T(W)$: W transverse mass	1-lepton
: difference in ϕ between Higgs boson daughters	0-lepton
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}},\mathrm{jet.})$: azimuthal angle between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the closest jet with $p_{\mathrm{T}} > 30$ GeV	0-lepton

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Uncertainties

Source	Type	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
Scale factors ($t\bar{t}$,V+jets)	norm.	9.4	3.5
Size of simulated samples	shape	8.1	3.1
Simulated samples' modeling	shape	4.1	2.9
Btag	shape	7.9	1.8
Jet energy scale	shape	4.2	1.8
Signal cross sections	norm.	5.3	1.1
Cross section uncertainties (single-top, VV)	norm.	4.7	1.1
Jet energy resolution	shape	5.6	0.9
Mistag	shape	4.6	0.9
Luminosity	norm.	2.2	0.9
Missing transverse energy	shape	1.3	0.2
Lepton efficiency and trigger	norm.	1.9	0.1

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Channel composition

	0-lepton	1-lepton	2-lepton	
Process			Low $p_T(V)$	High $p_T(V)$
$V\bar{b}b$	216.8	102.5	617.5	113.9
$V\bar{b}$	31.8	19.9	141.1	17.2
$V + udscg$	10.2	9.8	58.4	4.1
$t\bar{t}$	34.7	98.0	157.7	3.2
Single-top-quark	11.8	44.6	2.0	0.2
$VV(udscg)$	0.4	1.5	6.4	0.6
$VZ(b\bar{b})$	7.7	6.9	22.9	3.8
Total backgrounds	267.0	283.3	1005.9	142.9
VH	34.7	26.0	33.5	22.1
Data	334	320	1030	179
S/B	0.13	0.11	0.033	0.156

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20% most sensitive region of the BDT spectrum

VZ(→bb) validation

Channel	Expected signal strength VZ($b\bar{b}$)	Observed signal strength VZ($b\bar{b}$)	Expected significance VZ($b\bar{b}$)	Observed significance VZ($b\bar{b}$)
0-lepton	1.00 ± 0.33	0.57 ± 0.32	3.1	2.0
1-lepton	1.00 ± 0.38	1.67 ± 0.47	2.6	3.7
2-lepton	1.00 ± 0.31	1.33 ± 0.34	3.2	4.5
Combined	1.00 ± 0.22	1.02 ± 0.22	4.9	5.0

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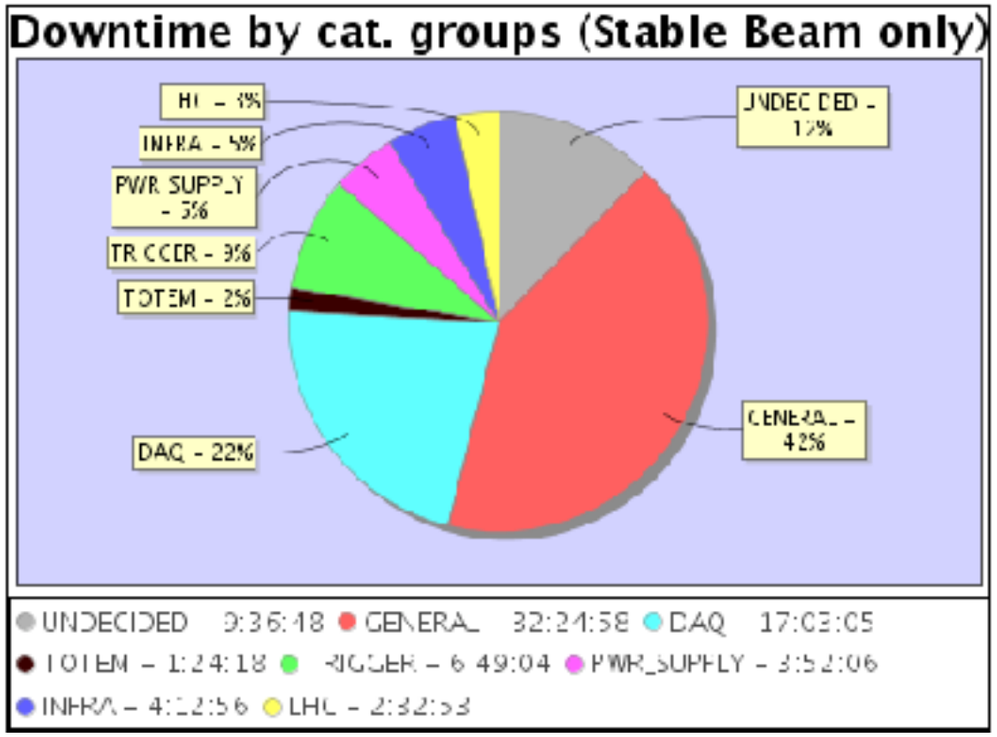
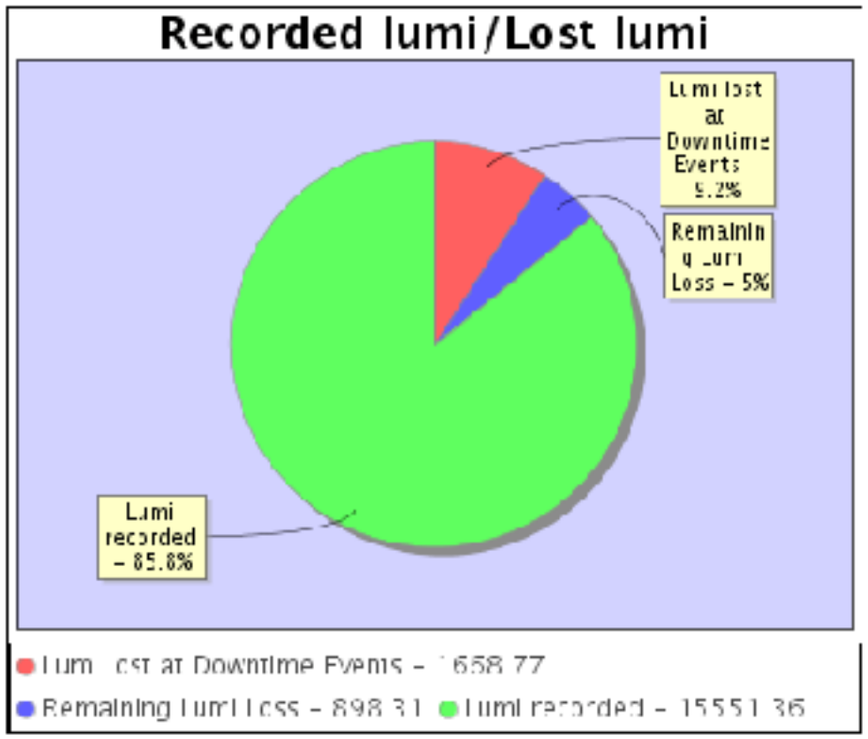
2017 downtime





- 2570 pb^{-1} lost / 18100 pb^{-1} delivered (14.2%)
- 1670 pb^{-1} lost due to downtimes (run stoppages) (9.23%)
  - 543 pb^{-1} lost due to agreed pixel commissioning activities (3.00%)
  - 239 pb^{-1} lost due to pixel DAQ and power supply problems (1.32%)

Simulated data loss rates in Phase 1 pixel Technical Design Report

Detector	Radius (cm)	% Data loss for ($cm^{-2}s^{-1}$ @ ns) 1×10^{34} @ 25	2×10^{34} @ 25	2×10^{34} @ 50
Current detector				
BPIX1	4.4	4.0	16.0	50.0
BPIX2	7.3	1.5	5.8	18.2
BPIX3	10.2	0.7	3.0	9.3
FPIX1 and 2		0.7	3.0	9.3
Upgrade detector				
BPIX1	3.0	1.19	2.38	4.76
BPIX2	6.8	0.23	0.46	0.93
BPIX3	10.2	0.09	0.18	0.36
BPIX4	16.0	0.04	0.08	0.17
FPIX1–3		0.09	0.18	0.36

CMS-TDR-011

Pixel timing

Timing Scans

Hit Efficiency vs Delay Setting

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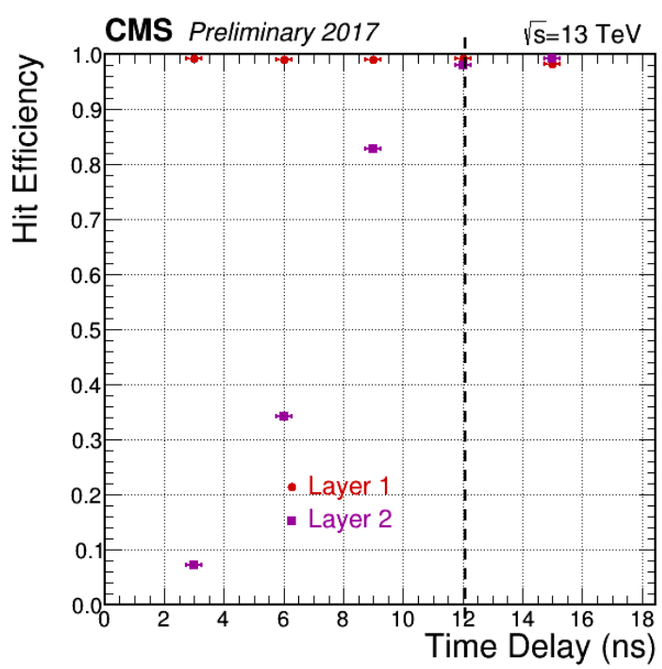
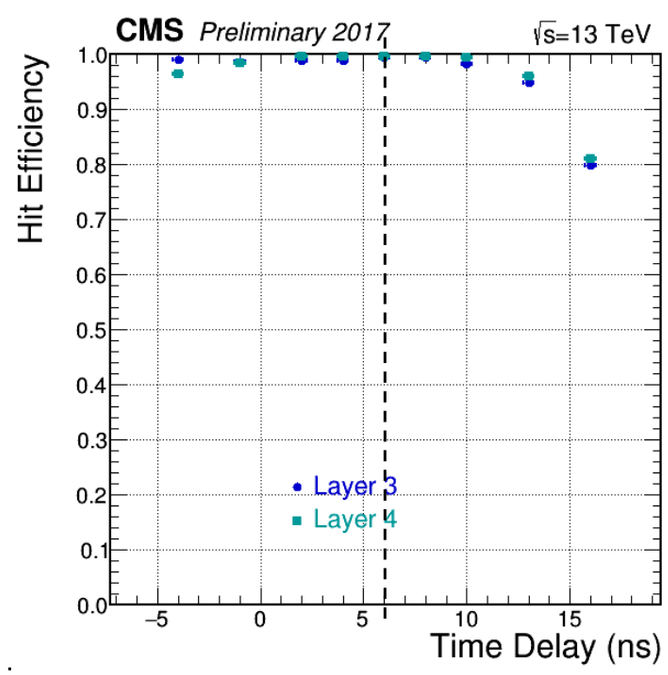
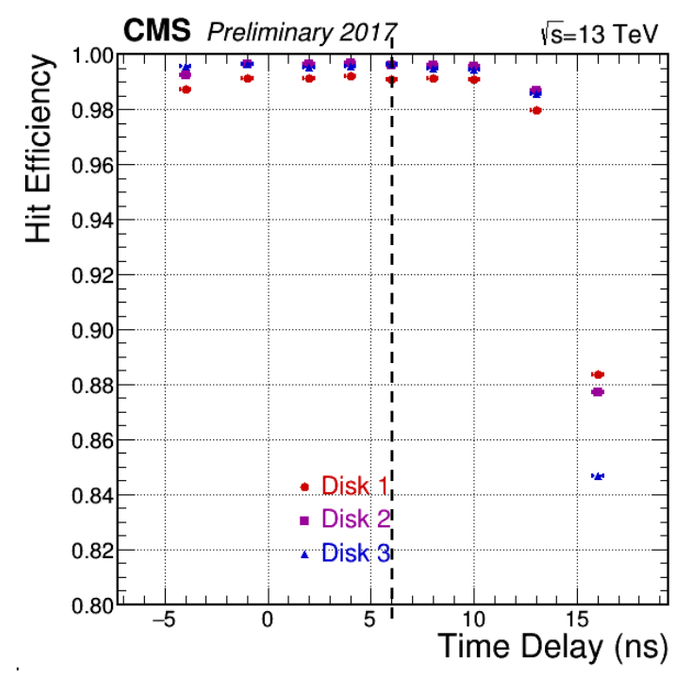
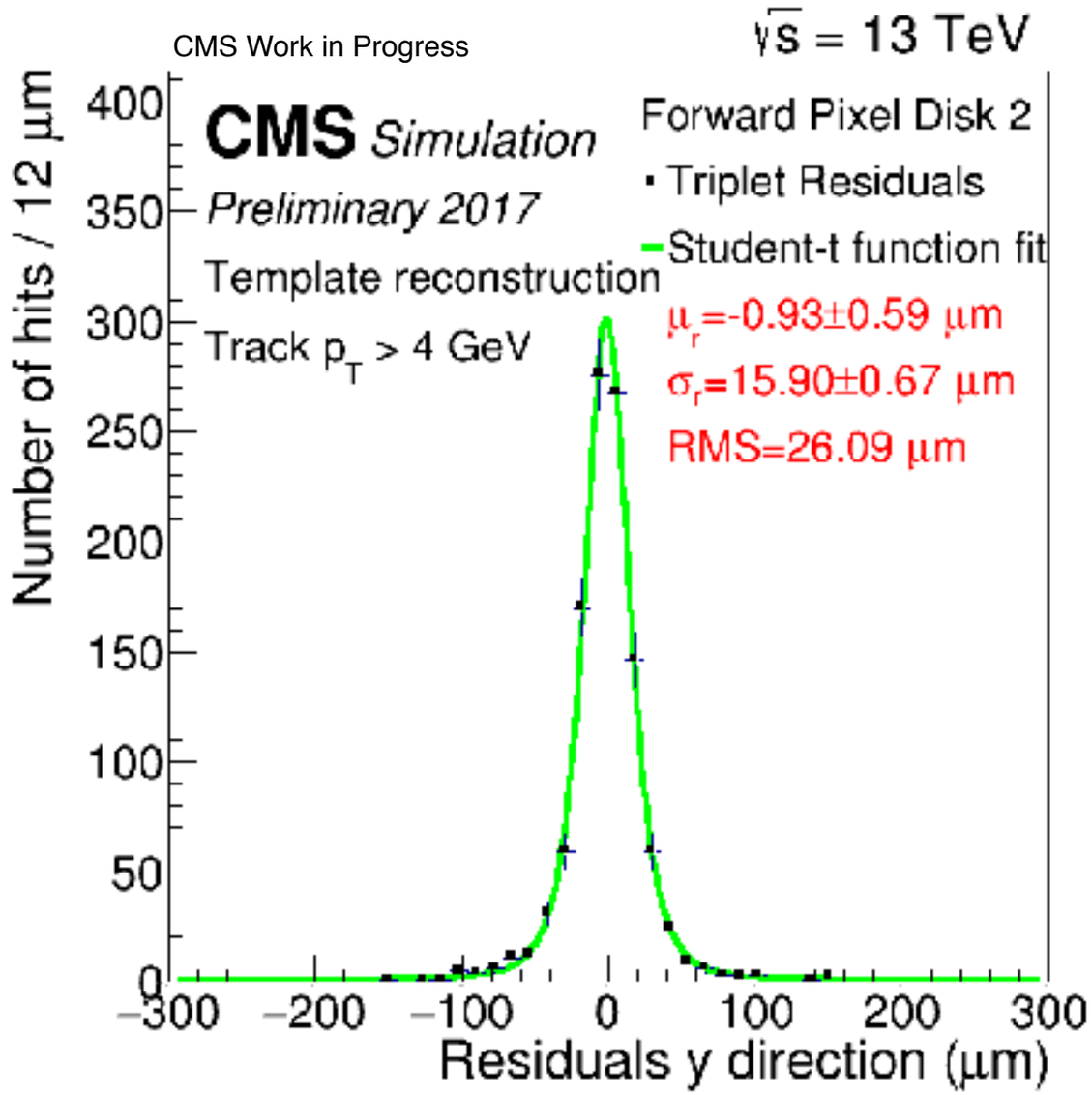
- Pixels are read out in 25 ns time frames. The beginning of this time-window depends on the relative phase between the LHC collisions and the clock signal in the modules' control loop
  - Too early read-out results in a loss of small pixel charges – small loss in cluster charge and size leading to loss of resolution
  - Too late read-out leads to dramatic loss of cluster charge and fractional clusters
- Goal is to set window as late as possible in order to maximize resolution
  - Layers/disks are operated at delay setting shown by dashed lines in the plots
- All modules receive clock signal with phase difference corresponding to their respective time of flight
  - Layer 1 and 2 chips, however, work at different phases. Since Layer 1 and 2 modules are connected in the same control loop, their relative clock phase cannot be adjusted
    - Chose to maximize Layer 1 performance
    - Layer 2 is read-out at already full efficiency but early → working on increasing the overlap in order to gain resolution
  - All other Layers/Disks operate at optimal setting

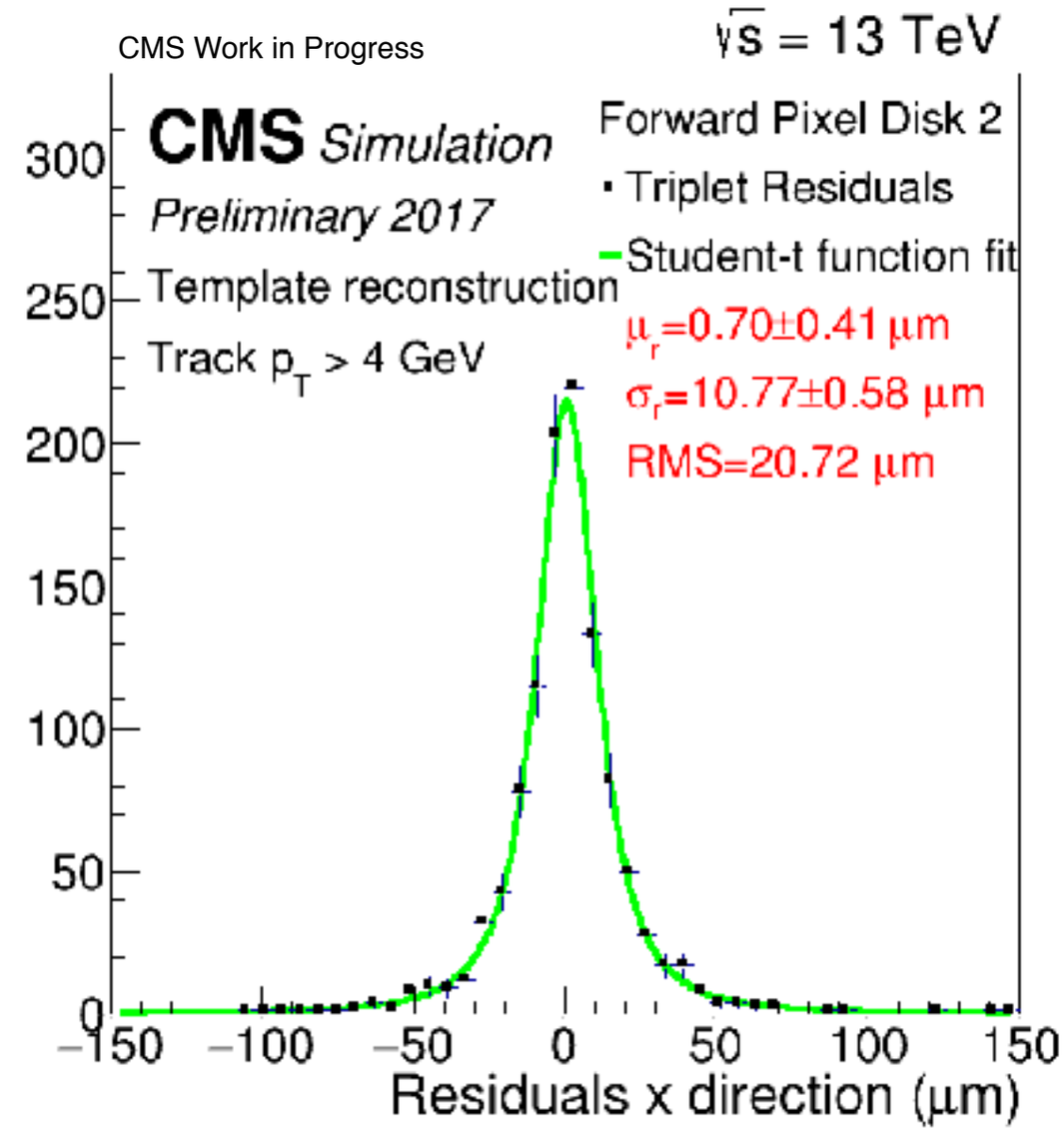




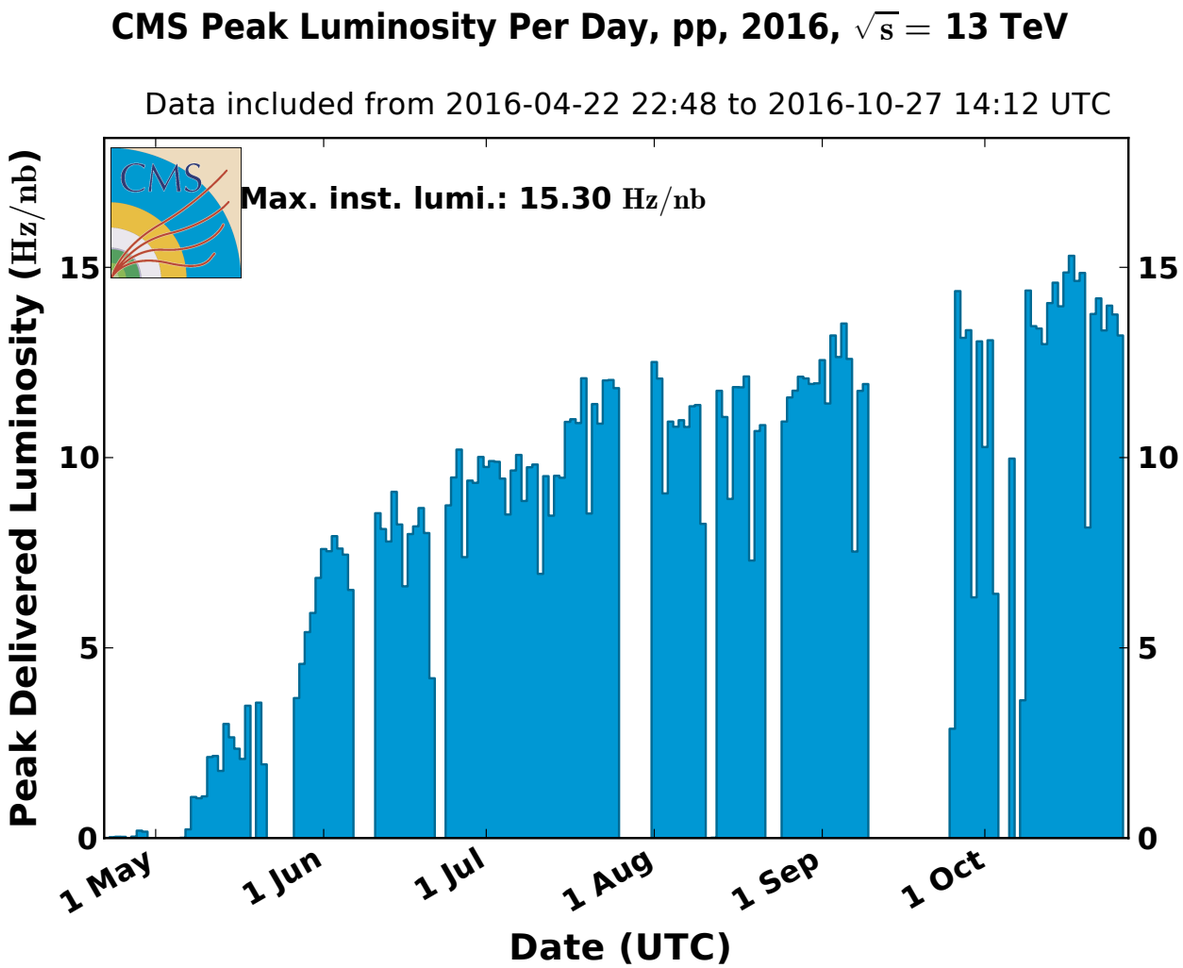


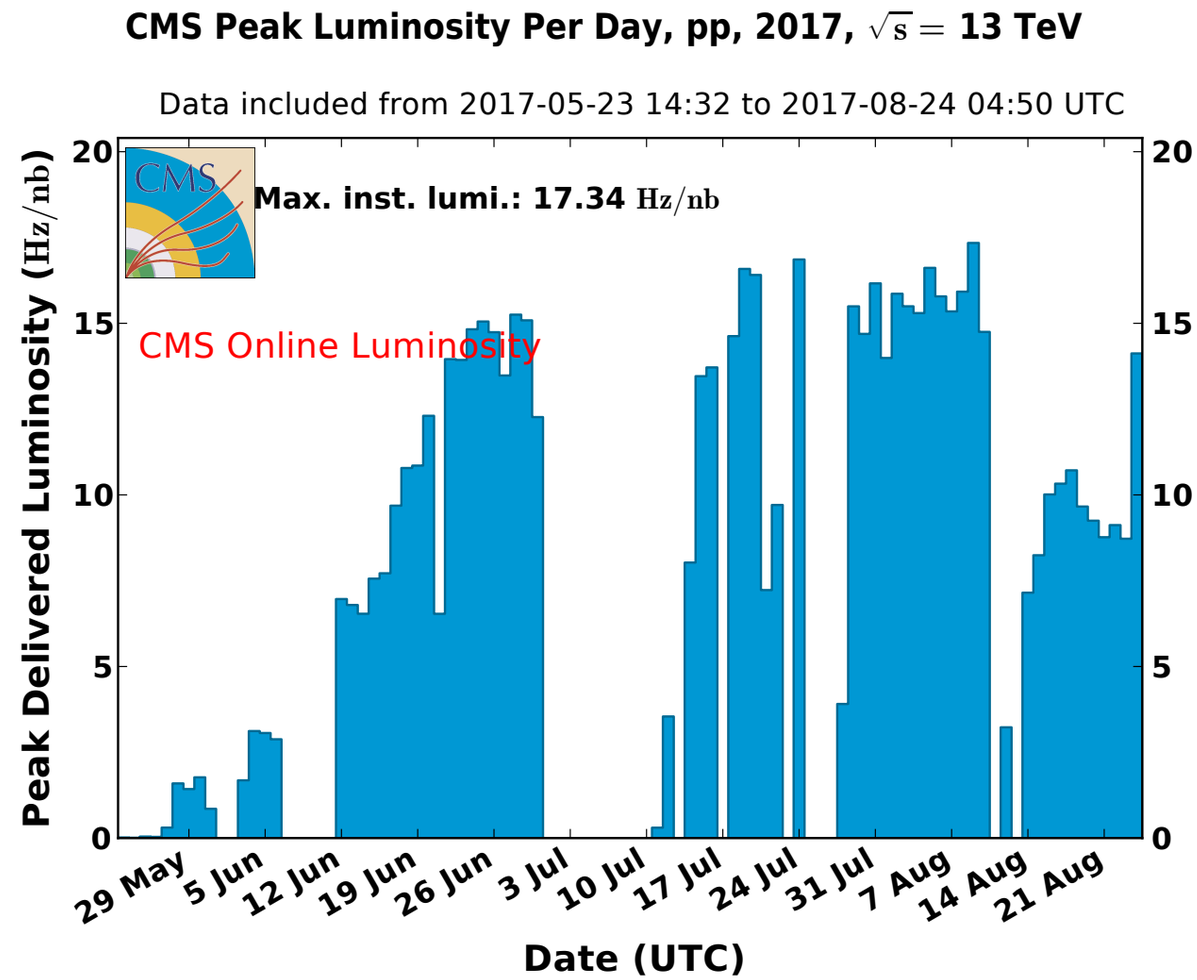
Phase 1 FPIX simulated resolution





2016 vs. 2017 luminosity





https://twiki.cern.ch/twiki/bin/viewauth/CMSPublic/LumiPublicResults