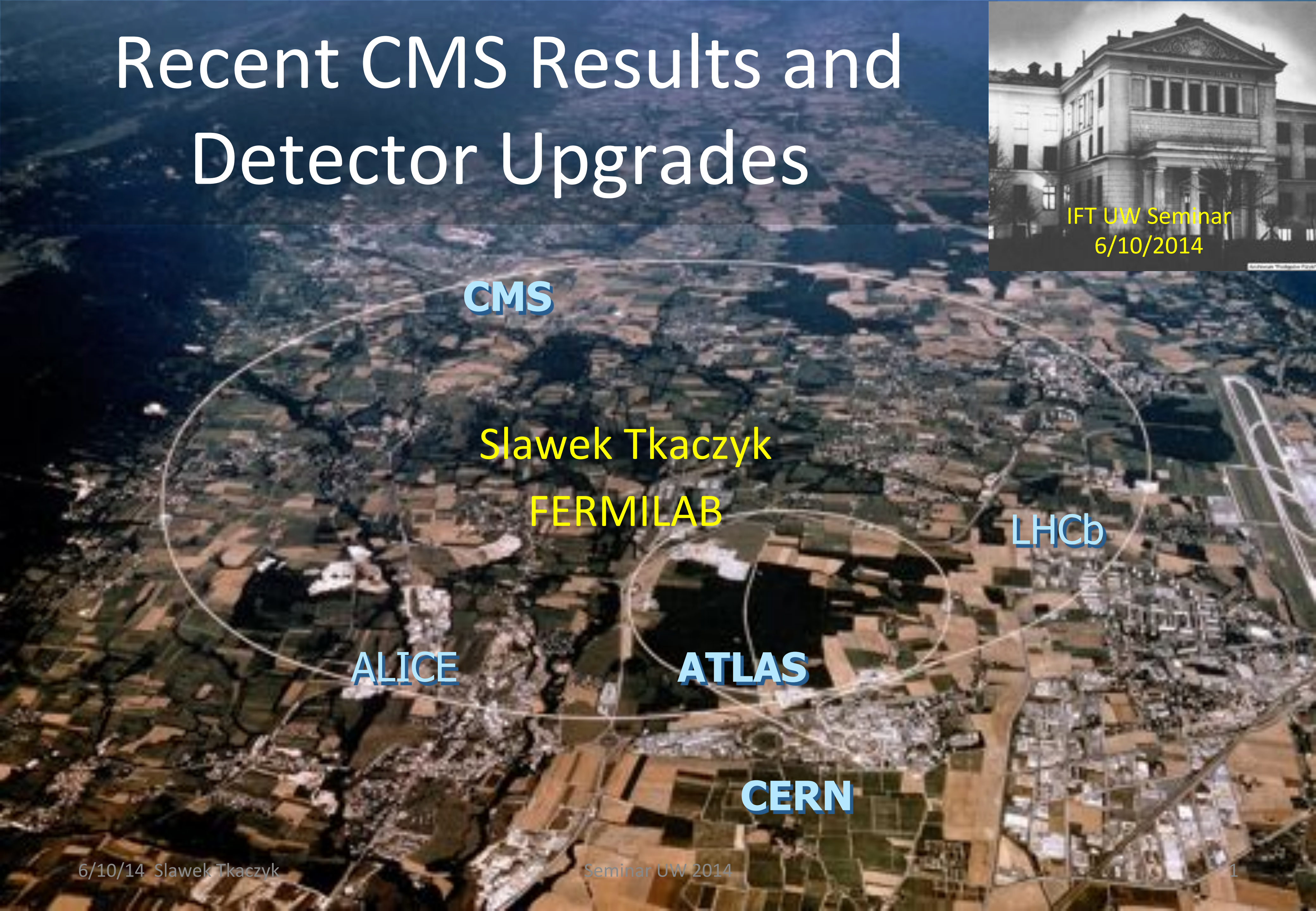
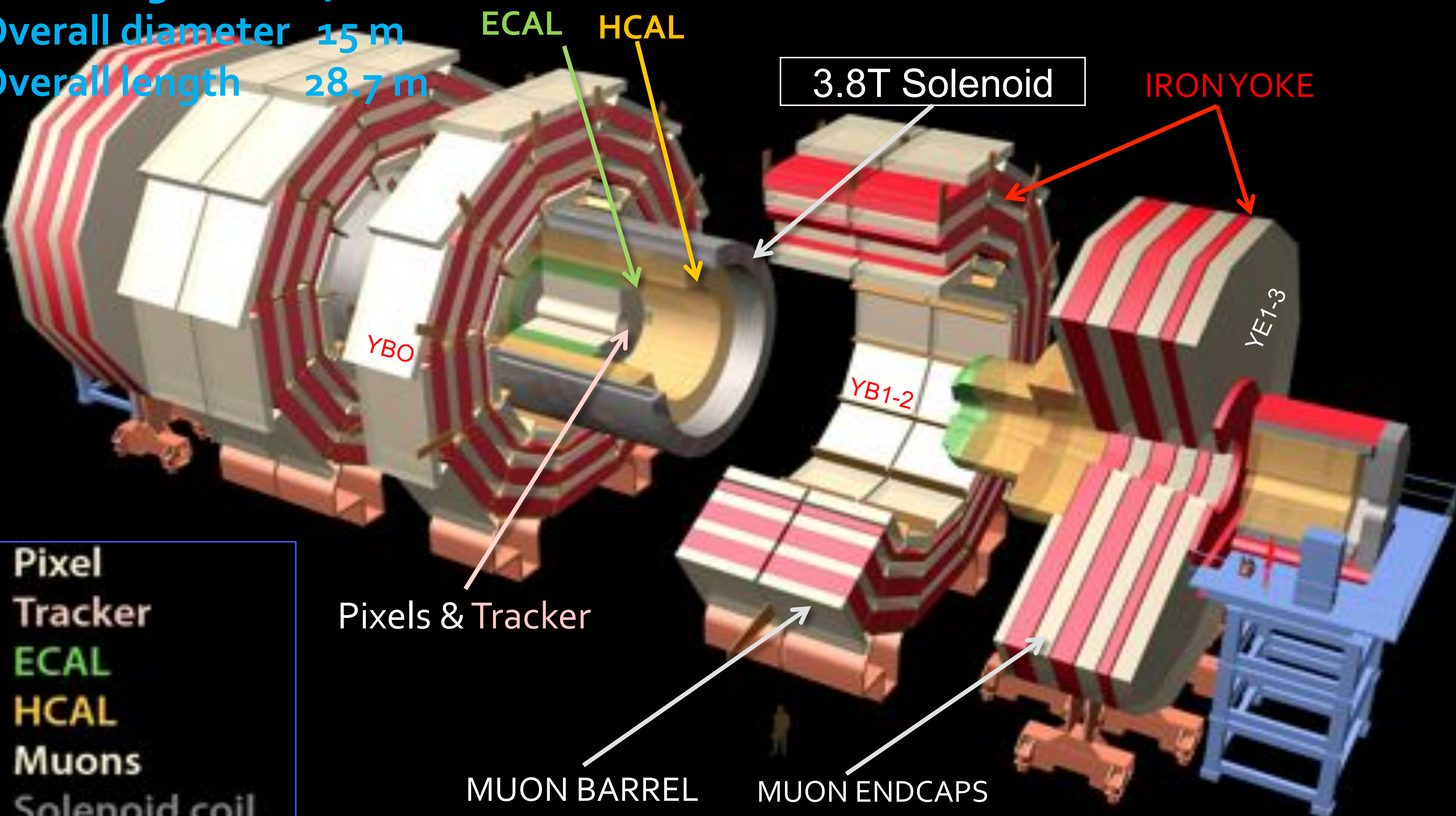
Recent CMS Results and Detector Upgrades

Slawek Tkaczyk
FERMILAB



CMS Detector

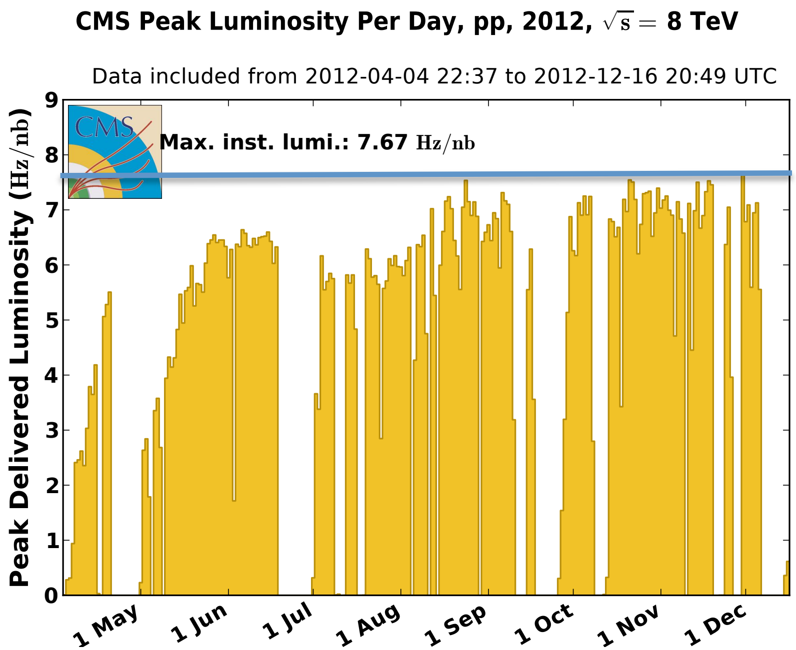
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m

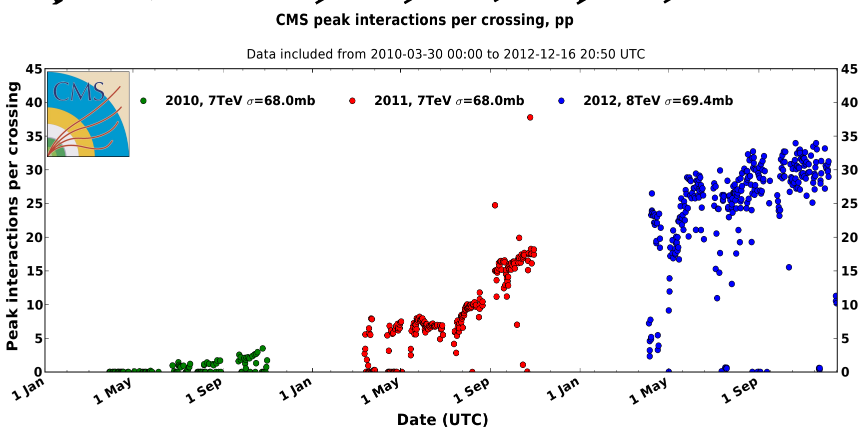


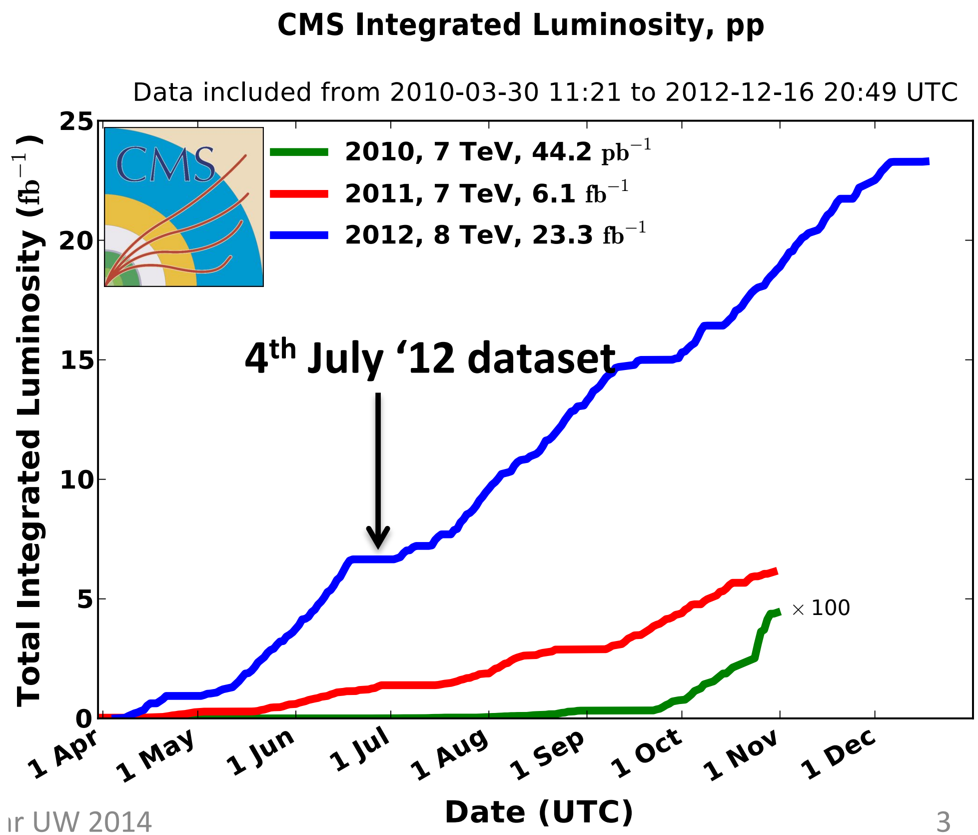
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

LHC Performance 2010-2011-2012

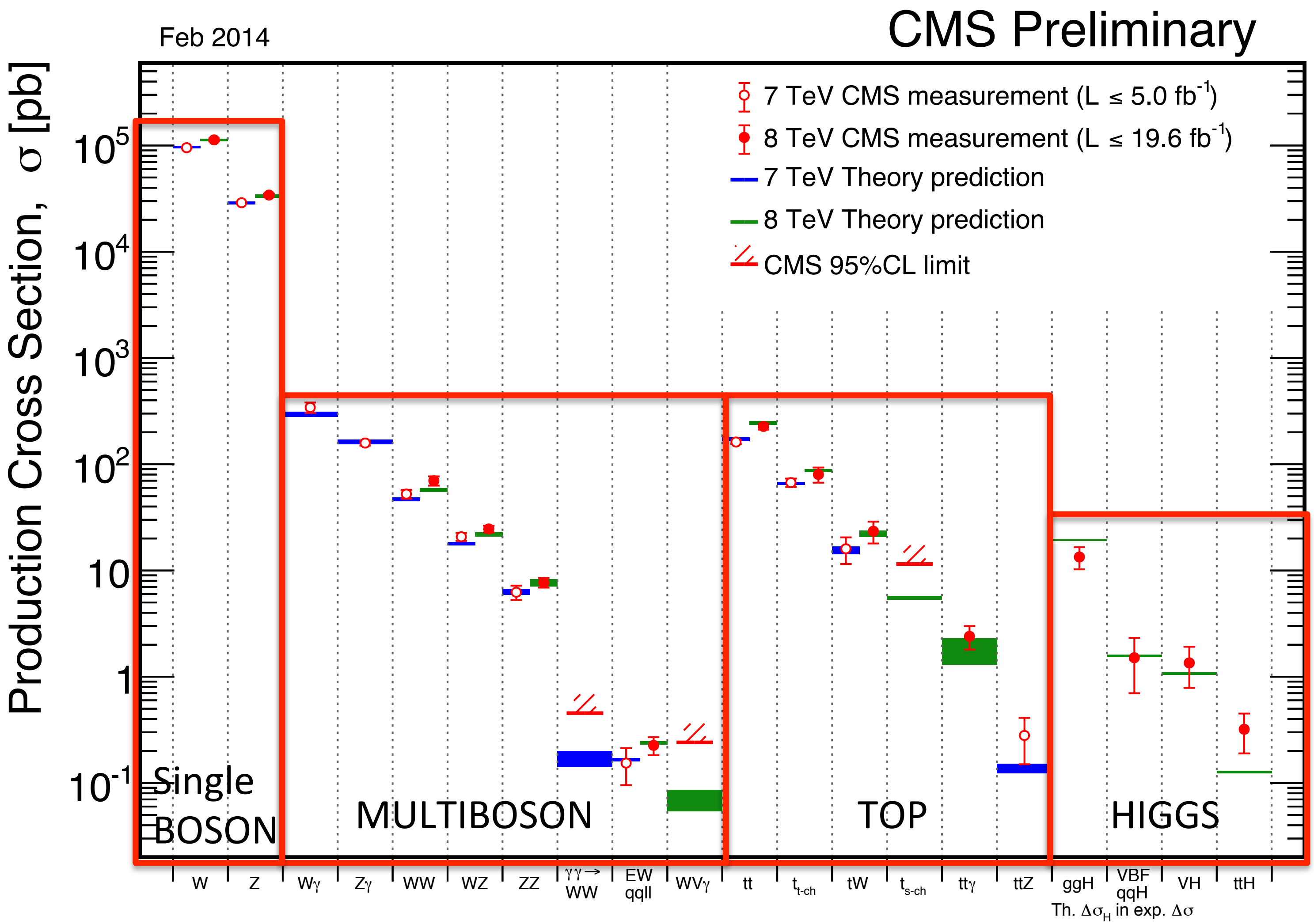
- Amazing performance of the LHC since the turn on!
- Inst. Lumi. [Hz/cm^2]: 2010: 10^{27} – **2**x10^{32} 2011: **3.6**x10^{33} 2012: **7.7**x10^{33}







Standard Model Tests



- Fabulous agreement
- 100's of measurements
- High precision
- **Higgs Discovery in 2012!**

Yesterday's discoveries are todays calibrations, and tomorrow's backgrounds!

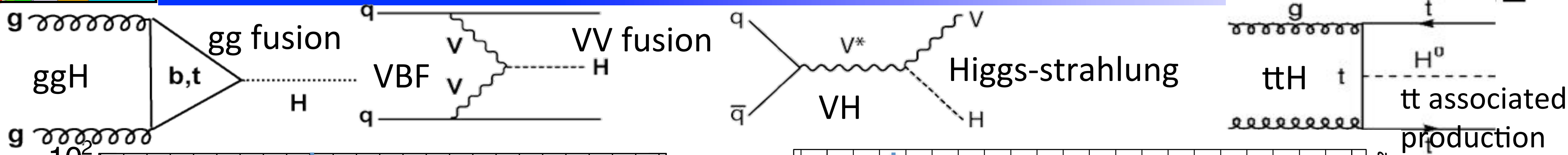
OUTLINE

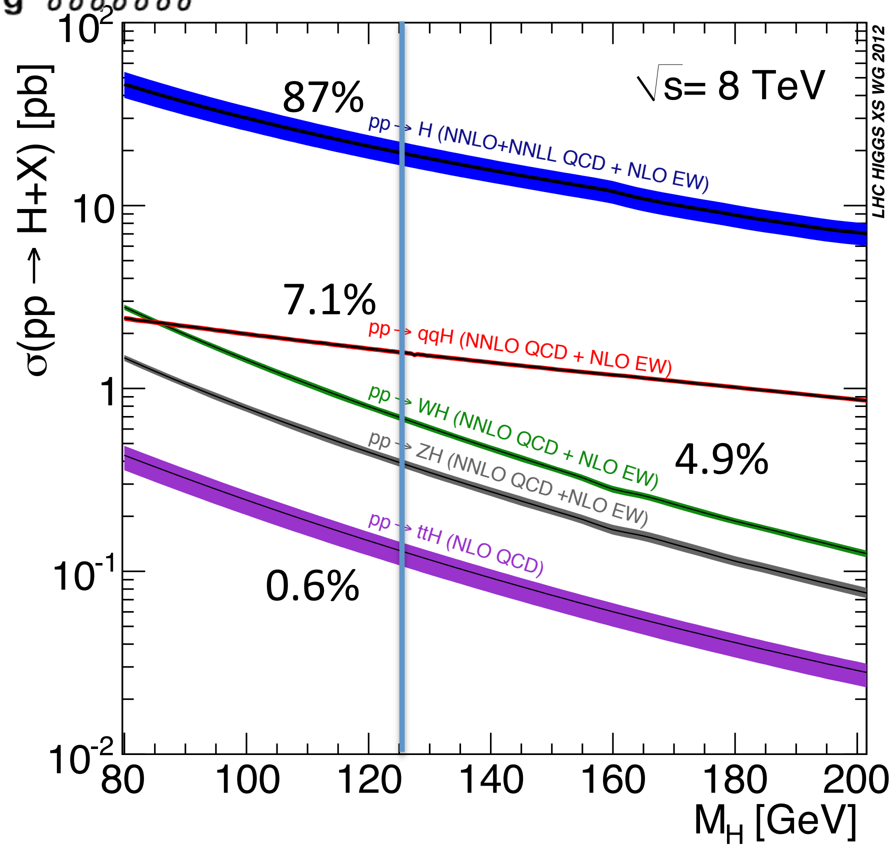
- Selected Run 1 physics results
  - Final Higgs Results
  - Dark Matter
  - Multiboson Production
- Machine Status before start of Run 2
- Planned Detector Upgrades
  - Phase 1 Upgrades
  - Phase 2 Upgrade Detector Concept
- Conclusions

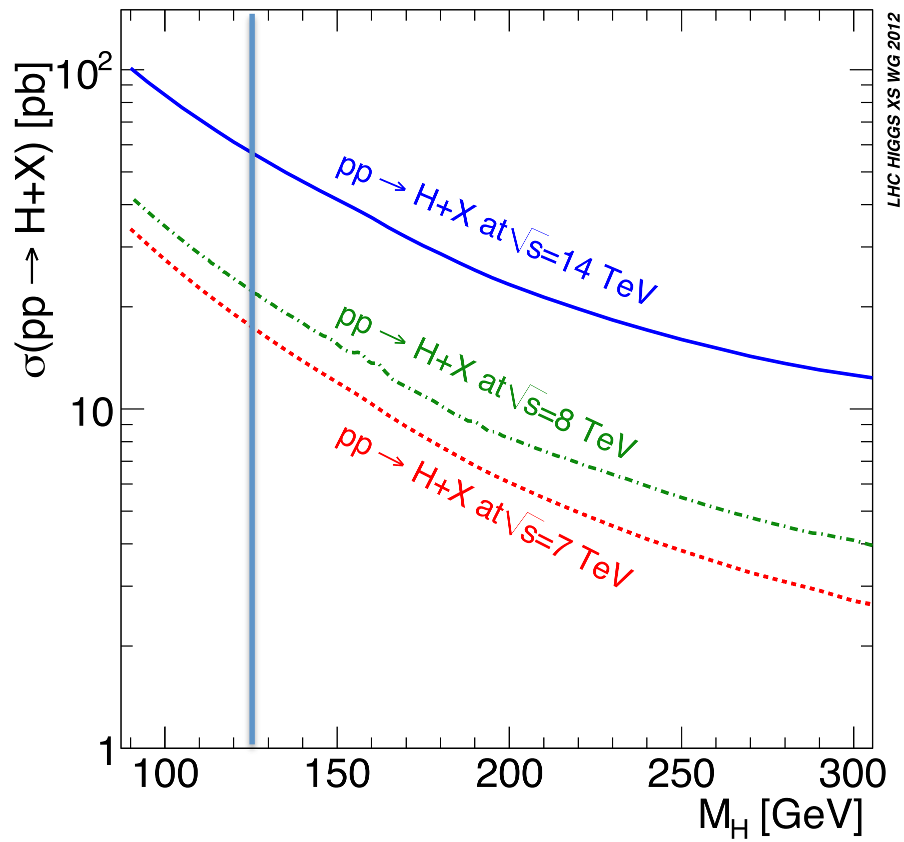
Higgs Boson 2014

- Spectacular progress in the past two years
  - Observations in three boson channels
  - Evidence for coupling to fermions
  - Precision mass measurement ~125GeV <0.5%
  - Spin/parity determination
  - Limits on the Total width
- Higgs observations and properties two years after the Discovery completed for all channels
- “Higgs-like” particle looks like the SM Higgs boson
  - No evidence for new Higgs particles
  - No evidence for non-SM decays

Higgs Production at LHC

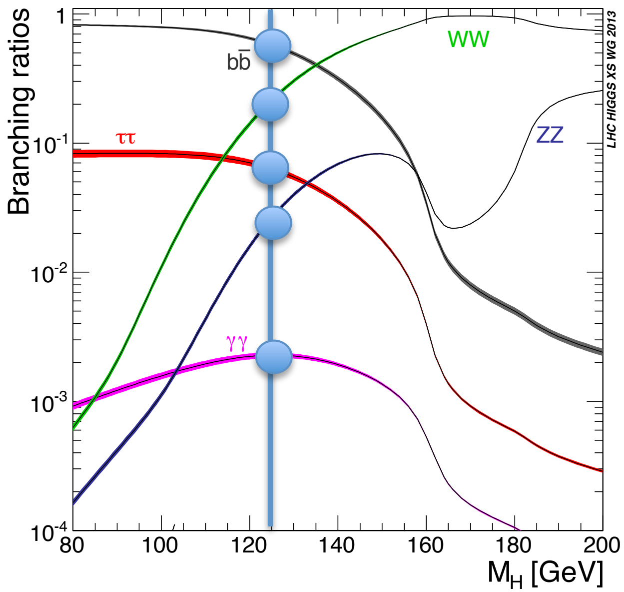


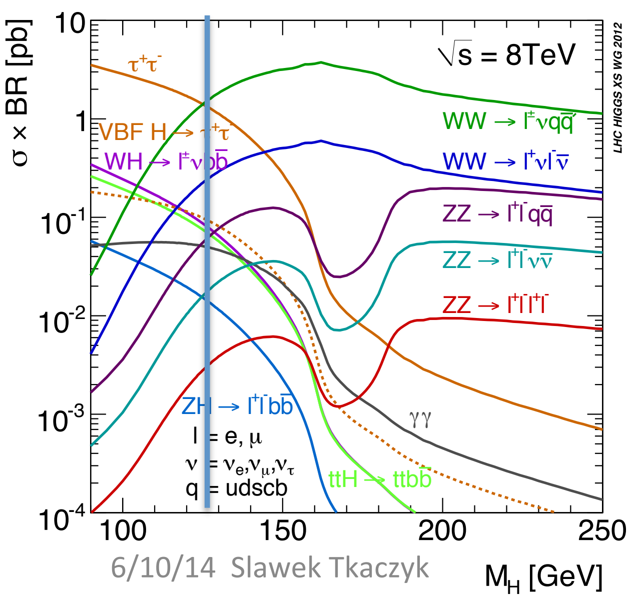




- Higgs x-sec higher at 8 TeV by **25-20%** than at 7 TeV
- Last three production modes have smaller x-sec but better **S/N**

SM Higgs Decay Modes





- **High mass resolution channels ΔM/M =1-2%**
- **γγ:** small BR, **Rare, S:B < 1**
- **ZZ(*):** 4l channel: Even more rare, but S/B >>1
- **Medium mass resolution channels ΔM/M =10-20%**
- **ττ:** large production; six decay channels; S/B <1
  - can benefit from VBF production
- **bb:** very high backgrounds; S/B <<1
  - Challenging - boosted H technique
- **Low mass resolution channels ΔM/M >30-40%**
- **WW:** High rates ; S/B <1
  - lνlν: clean signature; lνqq: highest rates
- **ZZ(*):** 2l2q, 2l2ν, 2l2τ with degraded resolution

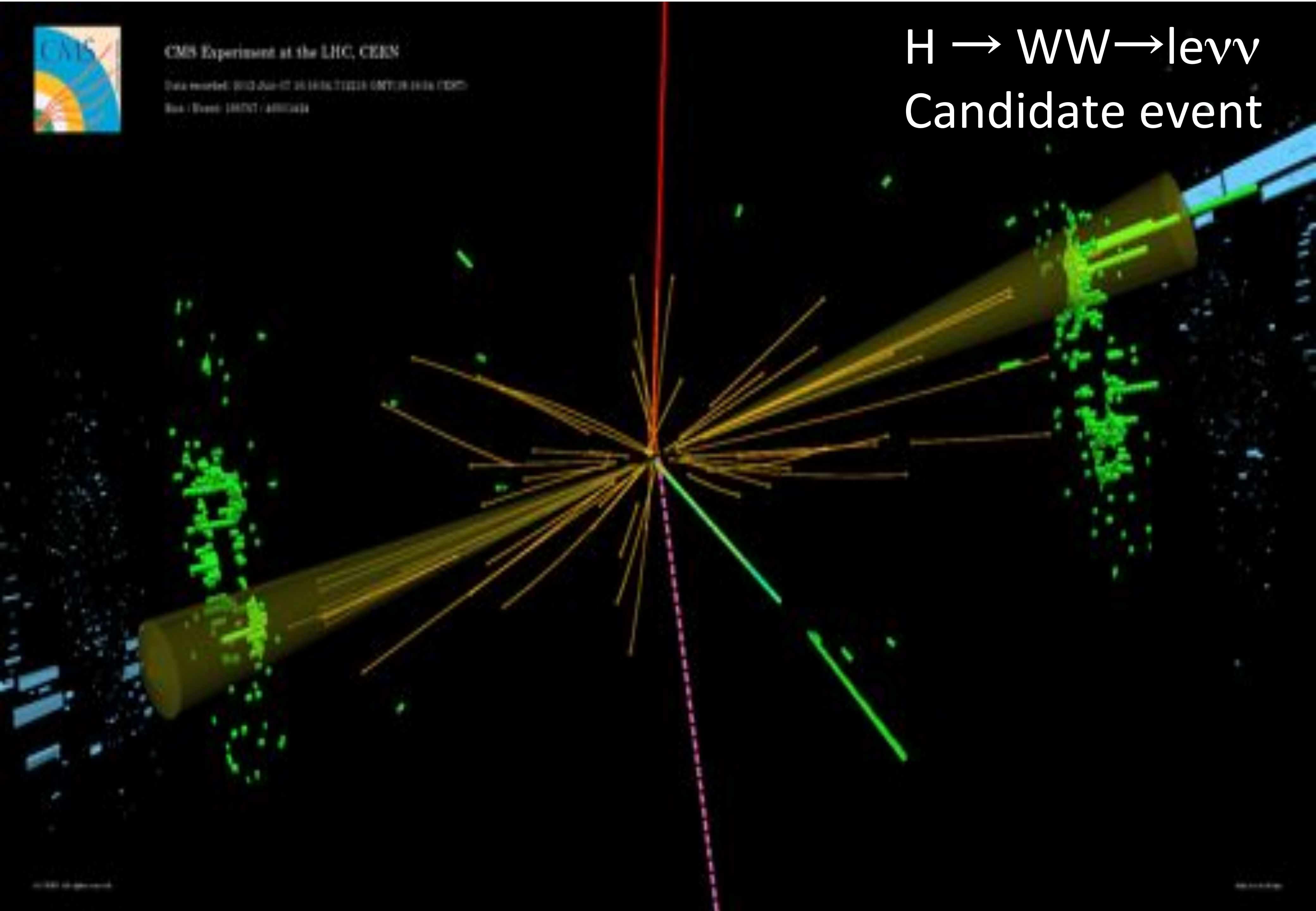
- **4 production x 5 decay modes x event categories**
- **Over 100 exclusive final states contributing to Higgs studies**

(including rare decays or production modes)

Higgs Boson 2014 – Summary

Channel	Lumi [1/fb]	Usage	Signature	σ Obs(Exp.)	Mass [GeV]	Signal strength	Spin/ Parity
$H \rightarrow ZZ \rightarrow 4l$	5.1 + 19.6 arXiv:1312.5353 PRD89(2014)092007	Mass Discovery Spin/Parity	4 leptons	6.8 (6.7)	125.6 ±0.5(stat) ±0.2 (sys)	0.93±0.29 ±0.25	Yes
$H \rightarrow WW \rightarrow 2l2\nu$	4.9 + 19.5 arXiv:1312.1129 JHEP 01(2014)096	X-sec Coupling	2 leptons MET	4.3 (5.8)	125±4	0.72±0.20 ±0.18	Yes
$H \rightarrow \gamma\gamma$	5.1 + 19.6 HIG-PAS-13-001 arXiv:1407.0558 (EPJC)	Mass Discovery Couplings	2 photons	5.7 (5.2)	124.7 ±0.31(stat) ±0.15(sys)	1.14±0.26	Yes
$H \rightarrow bb$	5.0 + 18.9 arXiv:1310.368 PRD89(2014)012003	Total width Coupling to fermions	2 b-jets	2.1 (2.1)	consistent	1.0±0.5	
$H \rightarrow \tau\tau$	4.9 + 19.4 arXiv:1401.5041 JHEP05(2014)104	Couplings to fermions	Hadronic taus,MET, leptons	3.2 (3.7)	122±7	0.78±0.27	

$H \rightarrow WW \rightarrow l e \nu \nu$ Candidate event



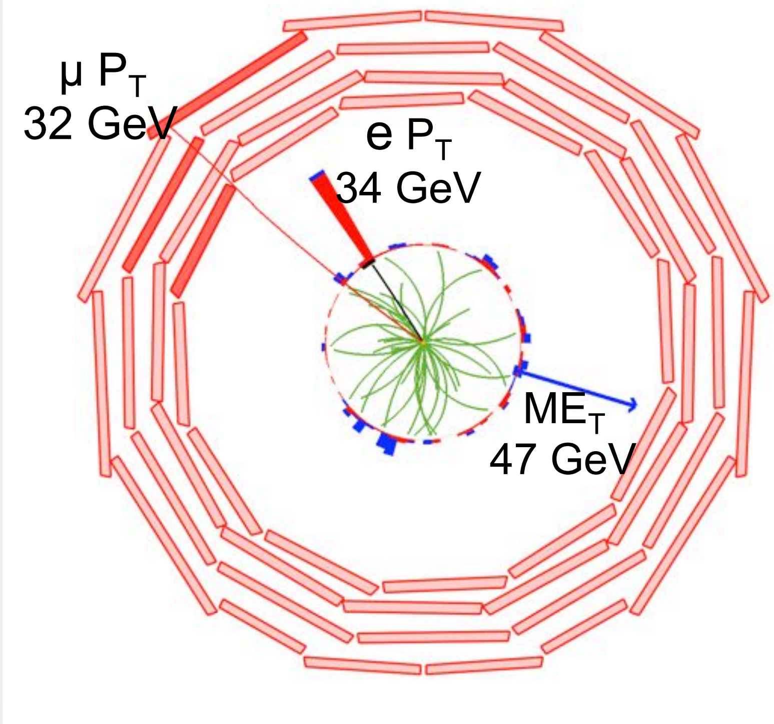
$H \to WW^{(*)} \to 2l\ 2\nu$ Channel

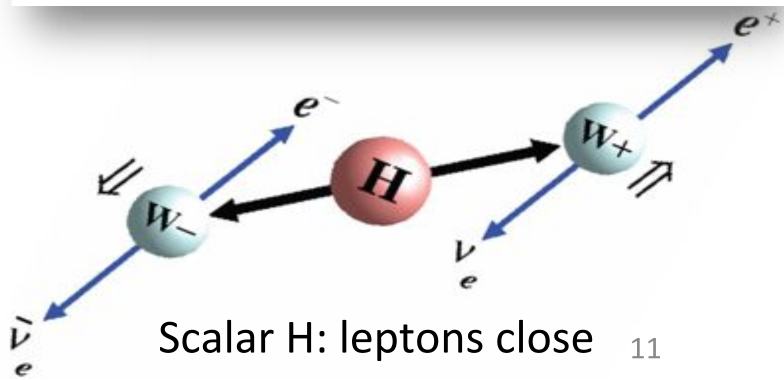
- Large rates, poor mass resolution and large backgrounds
- Signature: 2 opposite sign isolated leptons and MET
  - Using lepton ID and MET optimized for high pile-up
- Discriminating variables: $p_T^{ll}, M_T, M_{ll}, \Delta\phi_{ll}$
- Background estimation from data driven and MC methods:

Top, WW, W+jets, DY(ee, $\mu\mu$),DY($\tau\tau$), Wγ, WZ, ZZ

- Scalar H nature and V-A structure of EWK

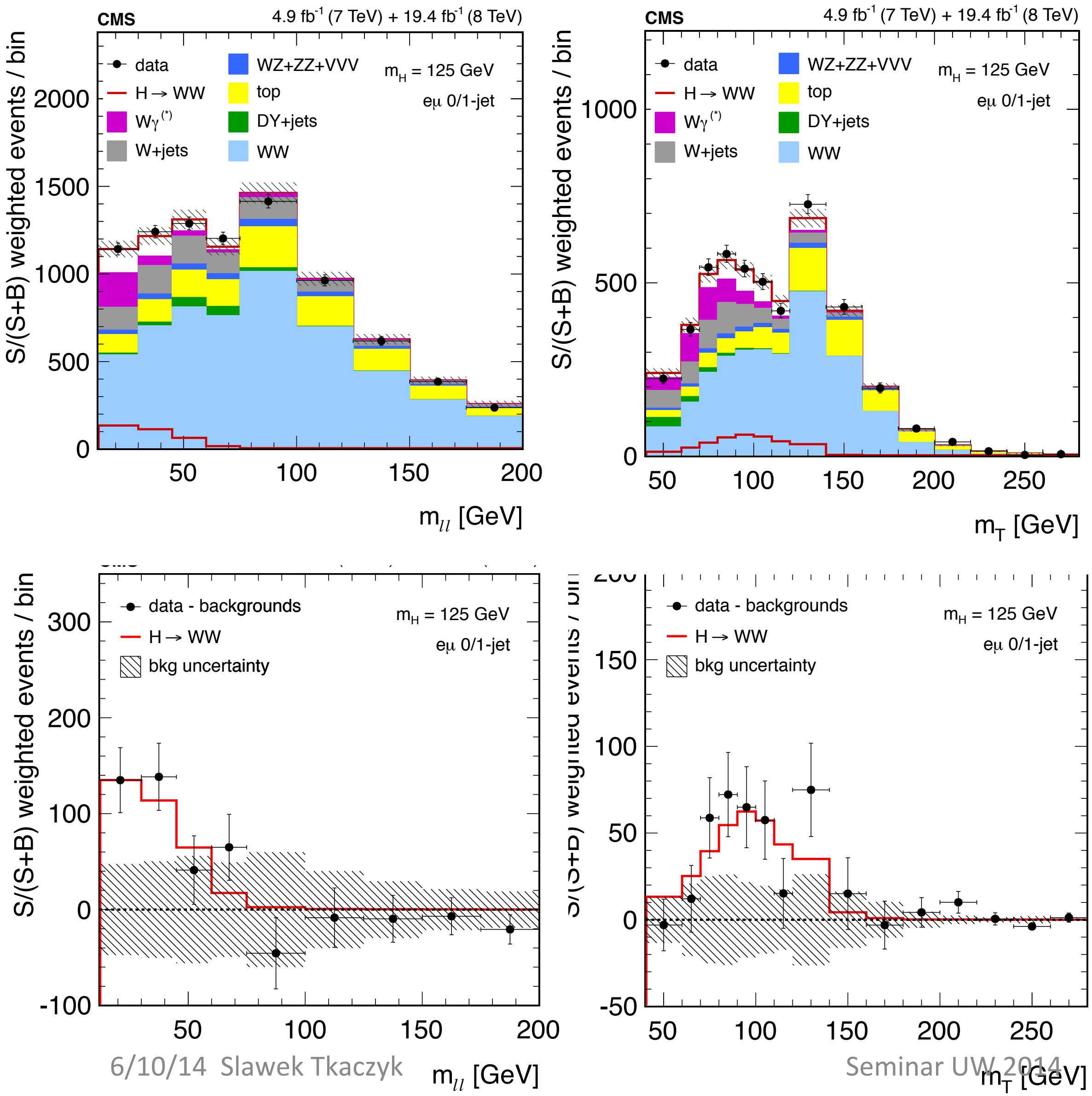
reflected in the angular correlations between final state leptons
  - opposite spins expected
  - small azimuthal angle between the leptons





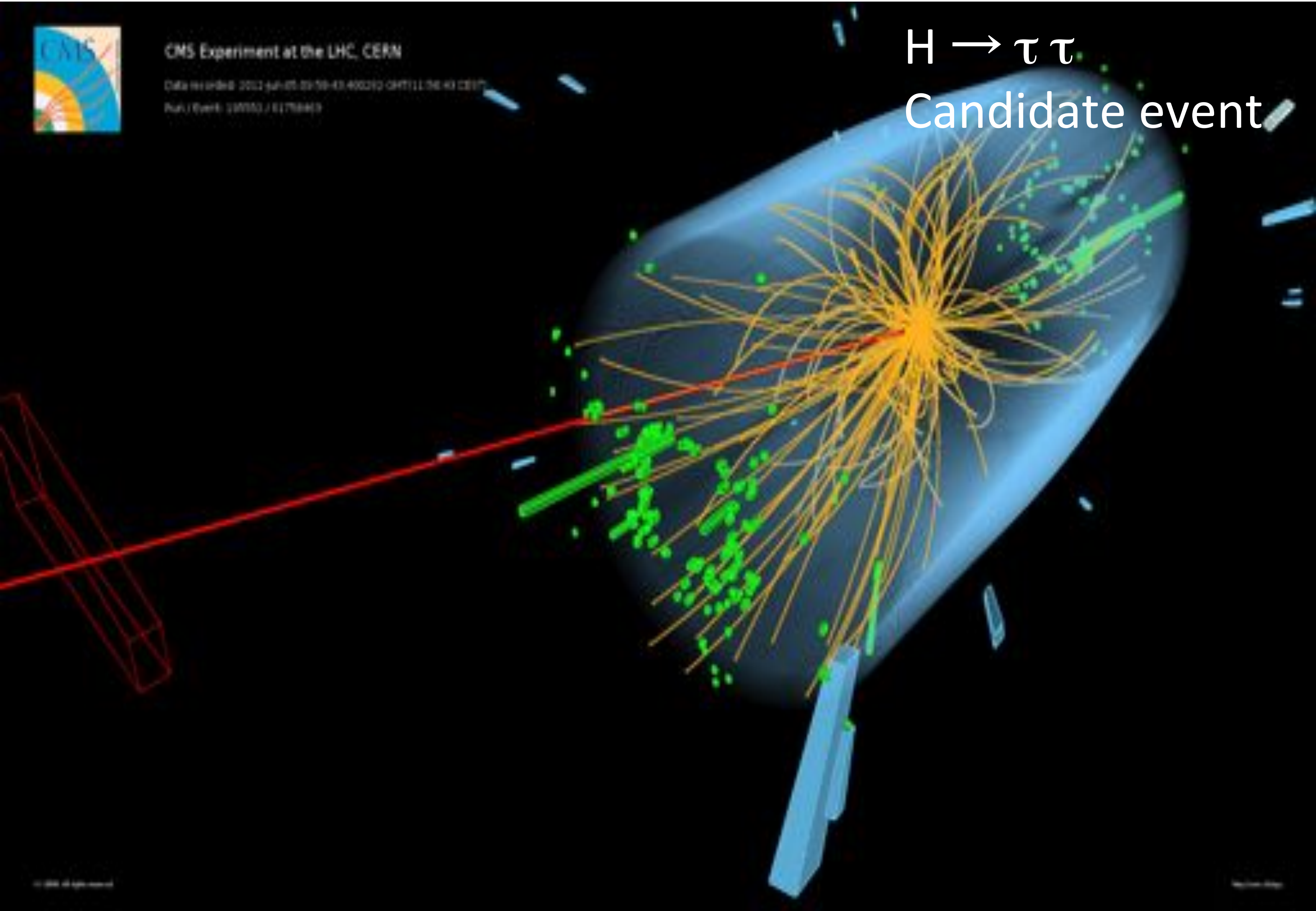
Scalar H: leptons close

H→WW*→2l2ν Channel

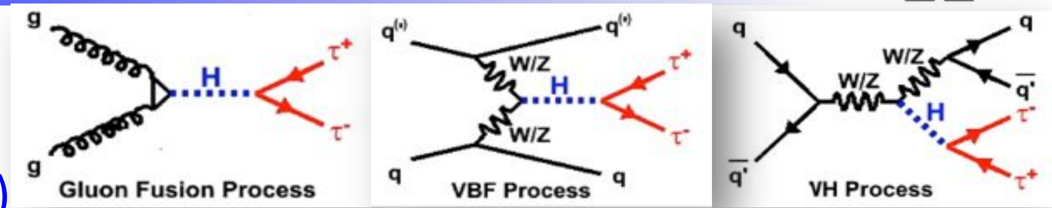


WW Event selection:
- Exactly 2 well identified isolated leptons (e.g.: eμ) of opposite sign with 0/1-jet
- Large Missing Energy (MET) thus no mass peak
- 2D templates in the m_{ll} vs m_T plane

- Results:
  - **Significance**:
    - **4.3σ** observed
    - 5.8σ expected
- Run I final results paper: CMS: JHEP01(2014)096


H → τ τ
Candidate event
CMS Experiment at the LHC, CERN

Higgs $\rightarrow \tau\,\tau$



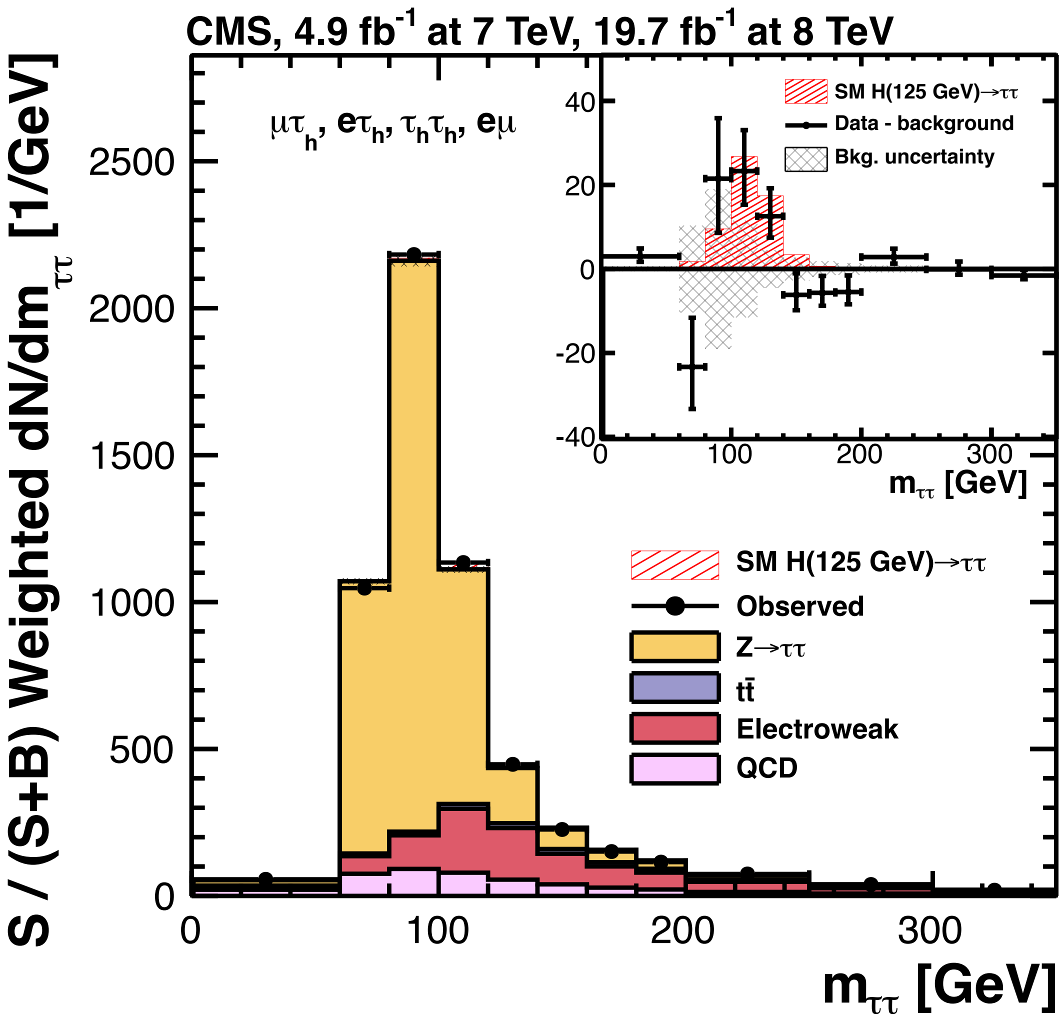
- Important in verification of the **H** identity
  - Probes **H** couplings to leptons (no mu,e)
  - Complementary to H→bb in down type fermion couplings
- Large production rates
  - Sensitive to all production mechanisms
  - VBF and VH most sensitive
- **Signature:** broad excess in $m_{\tau\tau}$
  - Mass reconstruction using MVA methods
  - All signal decay modes considered:

  $e\tau_{had}$, $\mu\tau_{had}$, $e\mu$, $\mu\mu$, ee, $\tau_{had}\tau_{had}$
- Large backgrounds: DY→ττ, W+Jets, QCD

- Multiple event categories by production channel and kinematics

  mass resolution and **S/B**, p_T, including **VBF, GGF, VH, ttH**
- New **$m_{\tau\tau}$** reconstruction with event-by-event likelihood: **20%** gain in resolution

Higgs → τ τ Results



CMS: arXiv:1401.5041 JHEP

Strong evidence for H->tau tau decays

Results: H(m_h=125 GeV)

Excess of events:

3.2σ observed (3.7σ expected)

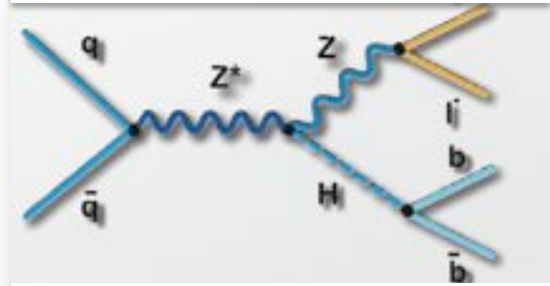
Best fit:

Signal strength: μ=0.78±0.27

H⟶ bb: V+H ⟶ V+bb, V=ll, lν, νν

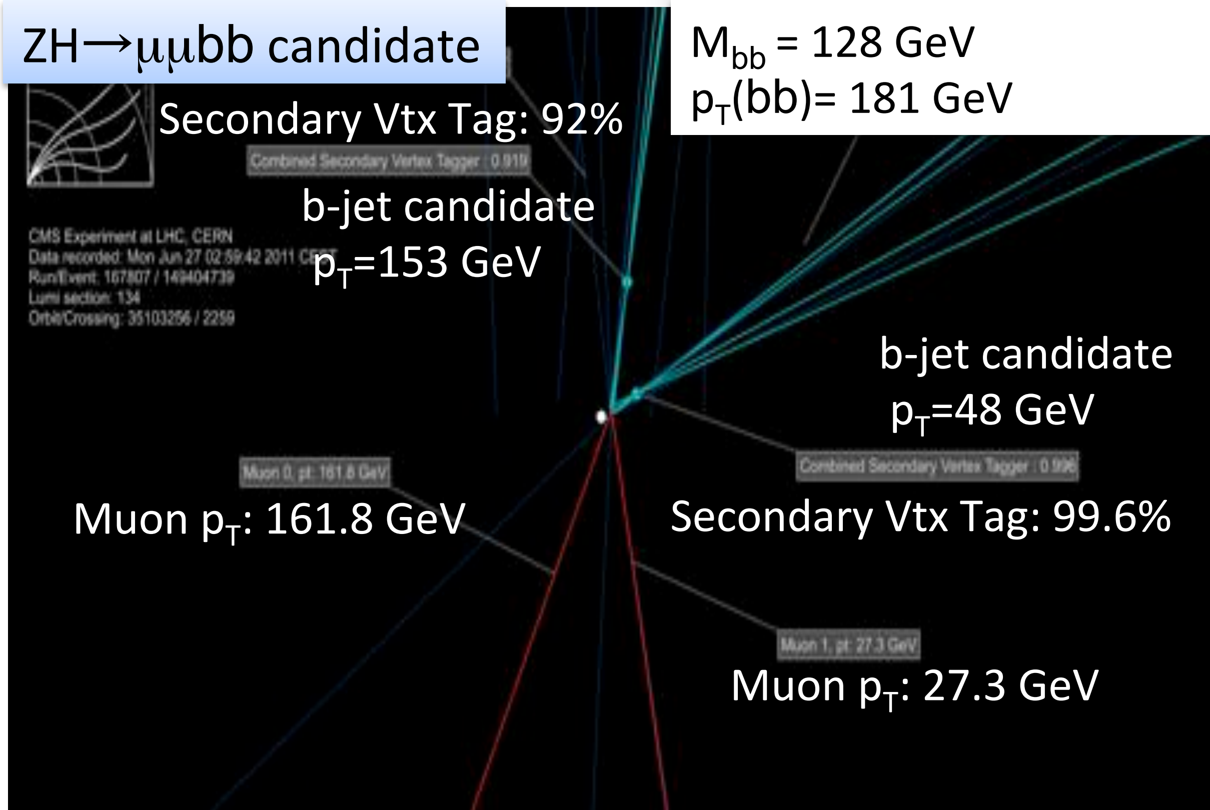
- Important tests of production and decay couplings
- Largest **BR** for **H⟶bb** for M_H=125GeV
- Signal signature: at least 1 lepton and b-jets
- Signal saturated by large backgrounds from V+HF:
  - σ_{bb}(QCD) ~10^7 σ(H⟶bb)*BR
  - V+jets, tt (reducible)
  - V+bb, VZ(bb)(less reducible)

Search in associated production with W or Z

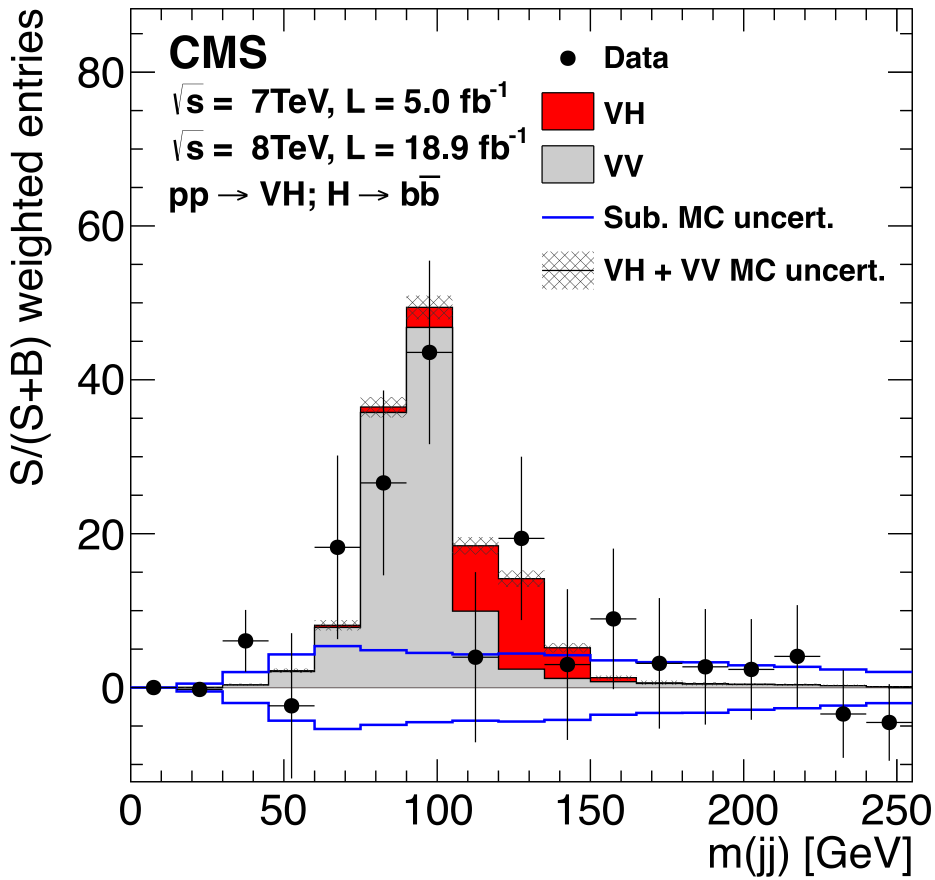


- **Boosted Higgs Analysis**
- Selection of V boson with high $\mathbf{p_T}$ reduces bkg and improves S/B
  - high $\mathbf{p_T}$ **V** and **2 b**-tagged jets
  - **V** and **H** back to back
- Main backgrounds estimated from data in control regions
- BDT for signal extraction

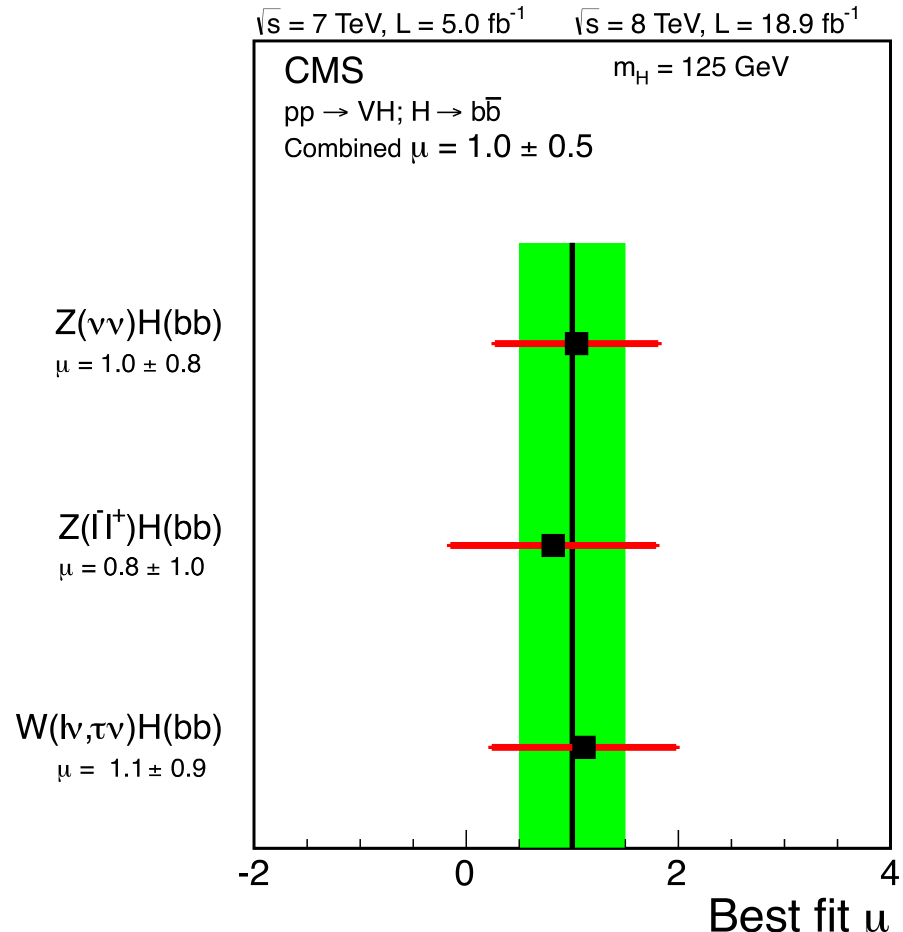
ZH⟶μμbb candidate



V+H→V+bb



CMS: PRD 89, 012003 (2014)



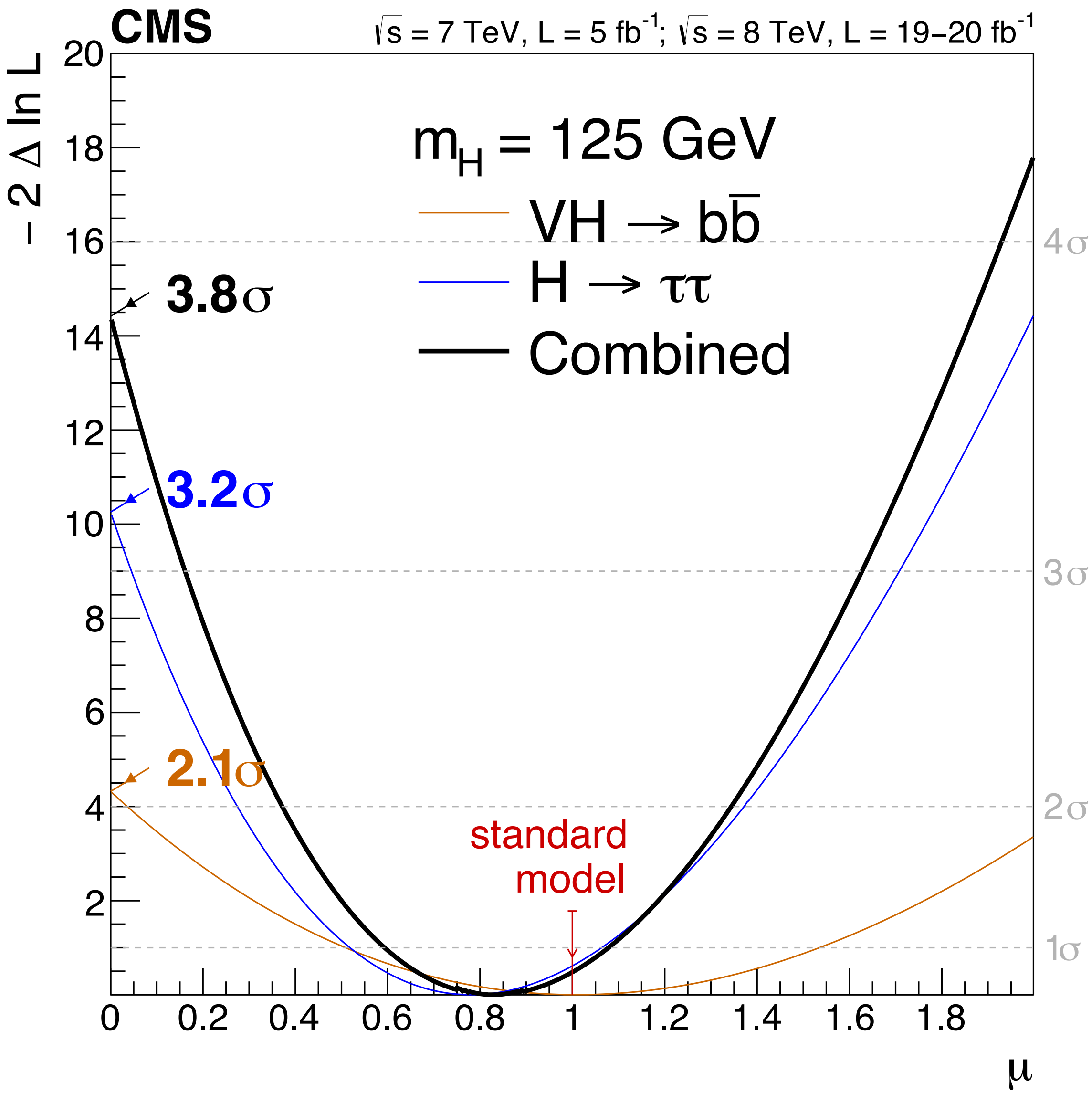
Results: **M_h=125** GeV

Best fit: 2.1σ **observed (**2.1σ **expected)**

Signal strength: ***μ*=1.0±0.5**

Wait for clear H→bb signal till Run 2!

Combination of Higgs Decays to Fermions

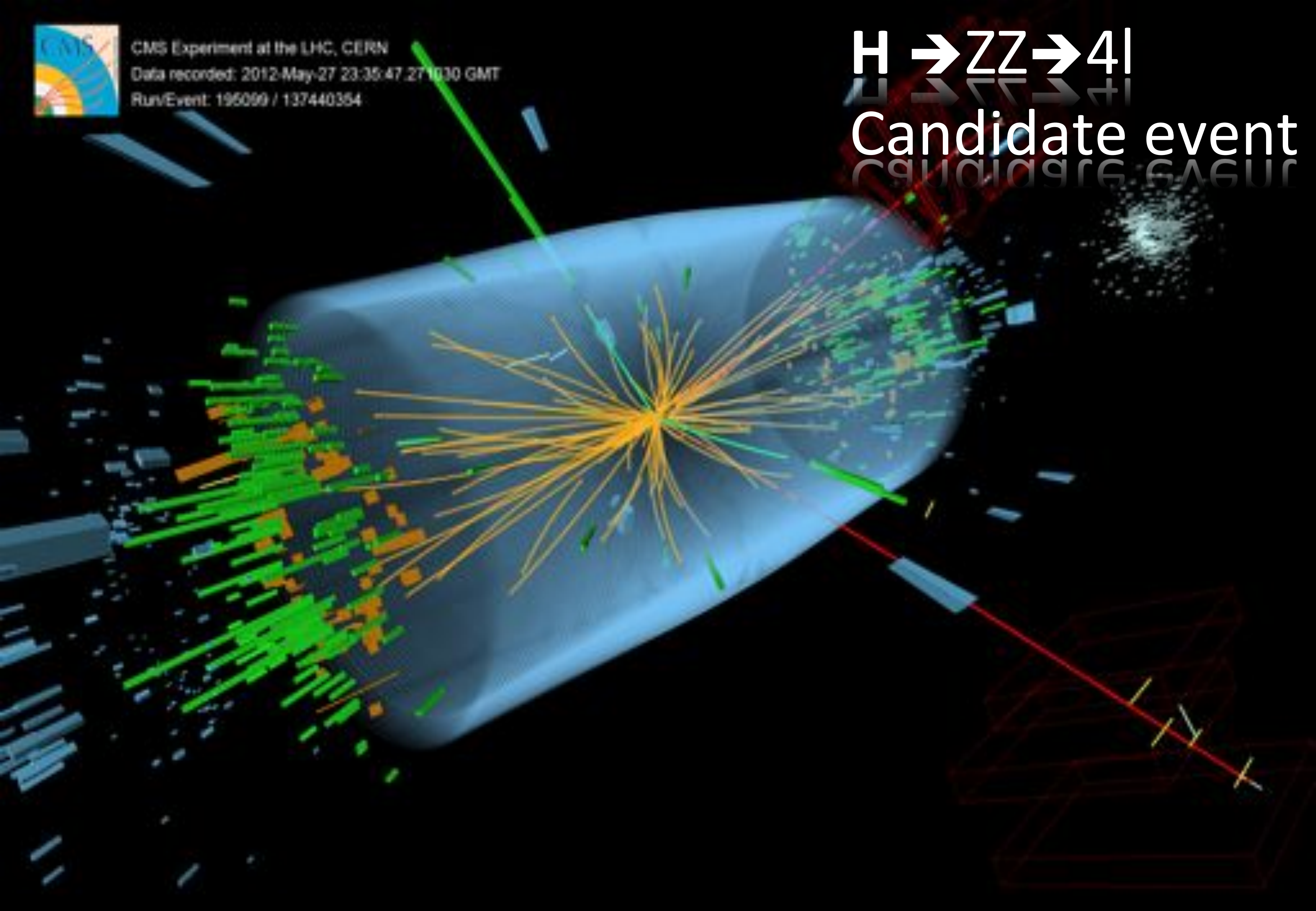


CMS-HIG-13-033, by Nature

Direct evidence of decays to fermions

CMS: ττ + bb → **3.8σ**

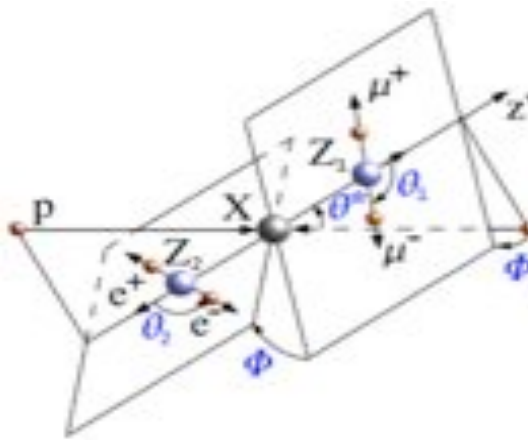
Signal strength: **0.83±0.24**


H → ZZ → 4l
Candidate event
CMS Experiment at the LHC, CERN
Data recorded: 2012-May-27 23:35:47.271030 GMT
Run/Event: 195099 / 137440354

H⟶ZZ*⟶4l events

- **Signature:** 4 leptons
- Very good mass resolution and S/B>>1
- Narrow peak over the continuum
- Enrich the signal content using the Kinematic Discriminant $\mathbf{D}_{kin}^{bgd}$

M_{Z1}, M_{Z2}, 5 angles from the decay chain



Results:

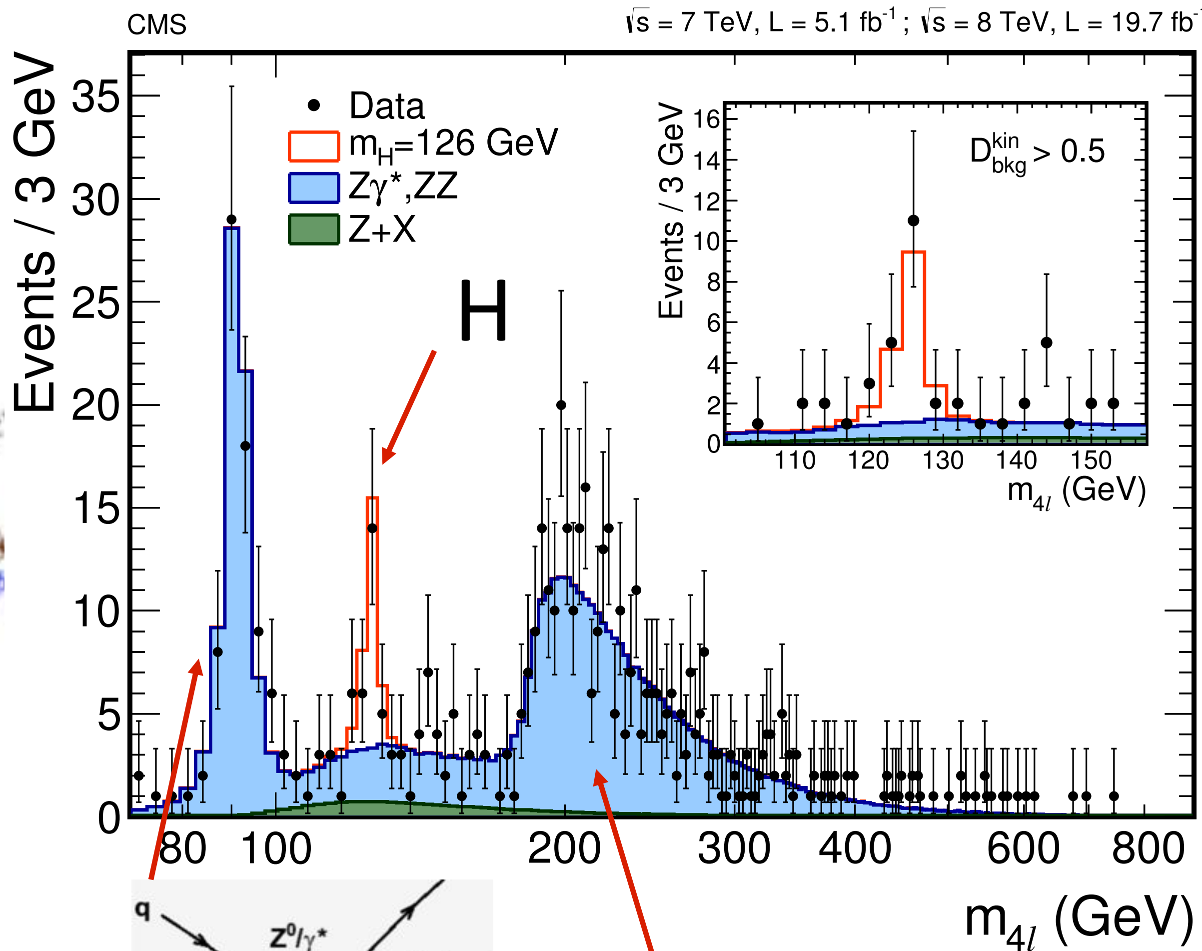
Significance:

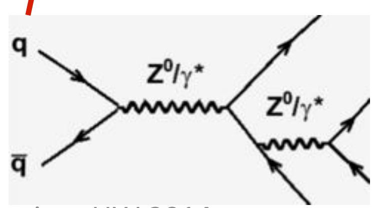
Observed: **6.8σ**

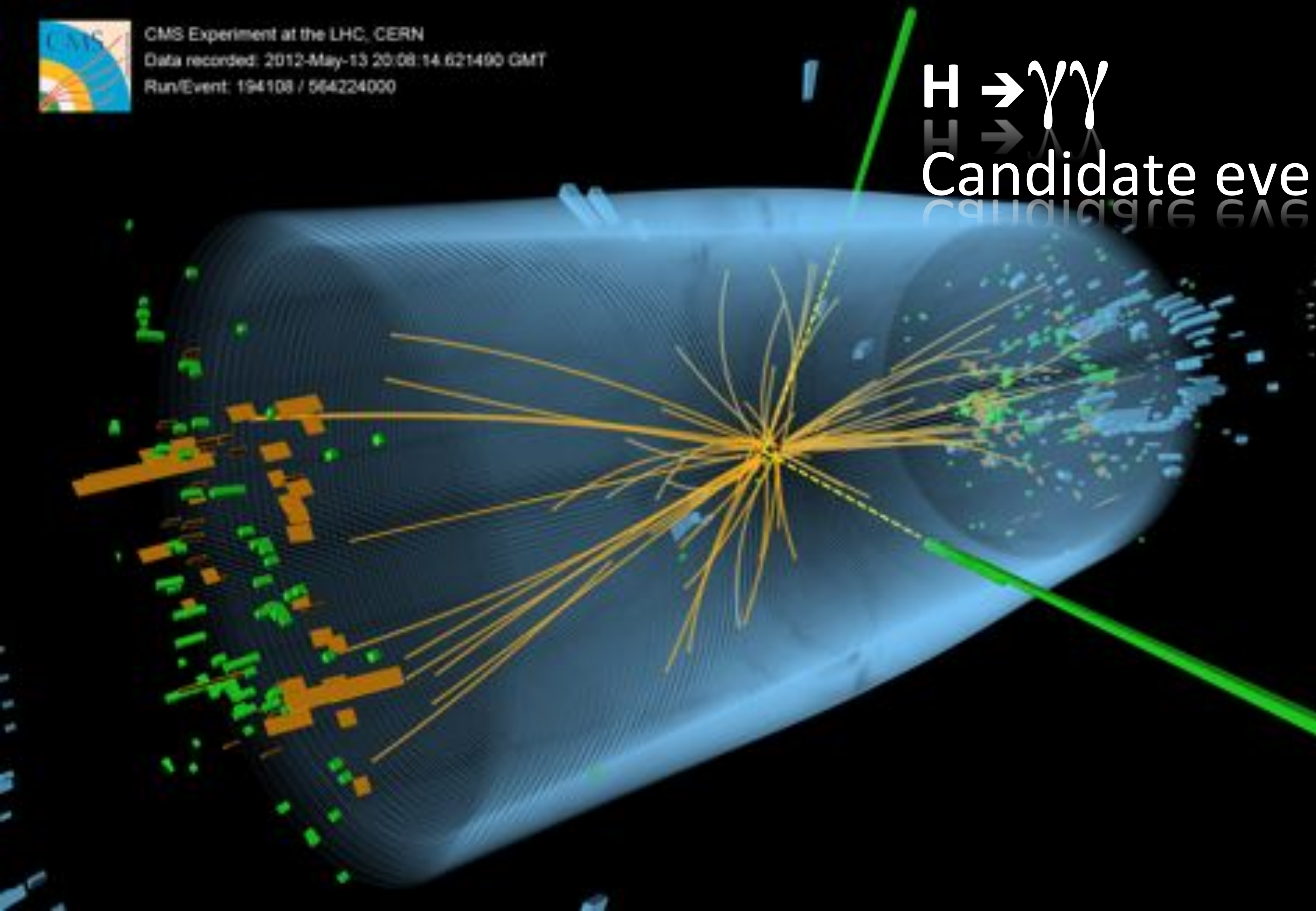
Expected: 6.7σ

Mass: 126±0.4(stat.)±0.2(syst.) GeV

Final Run I analysis: arXiv: 1312.5353 (PRD 2014)

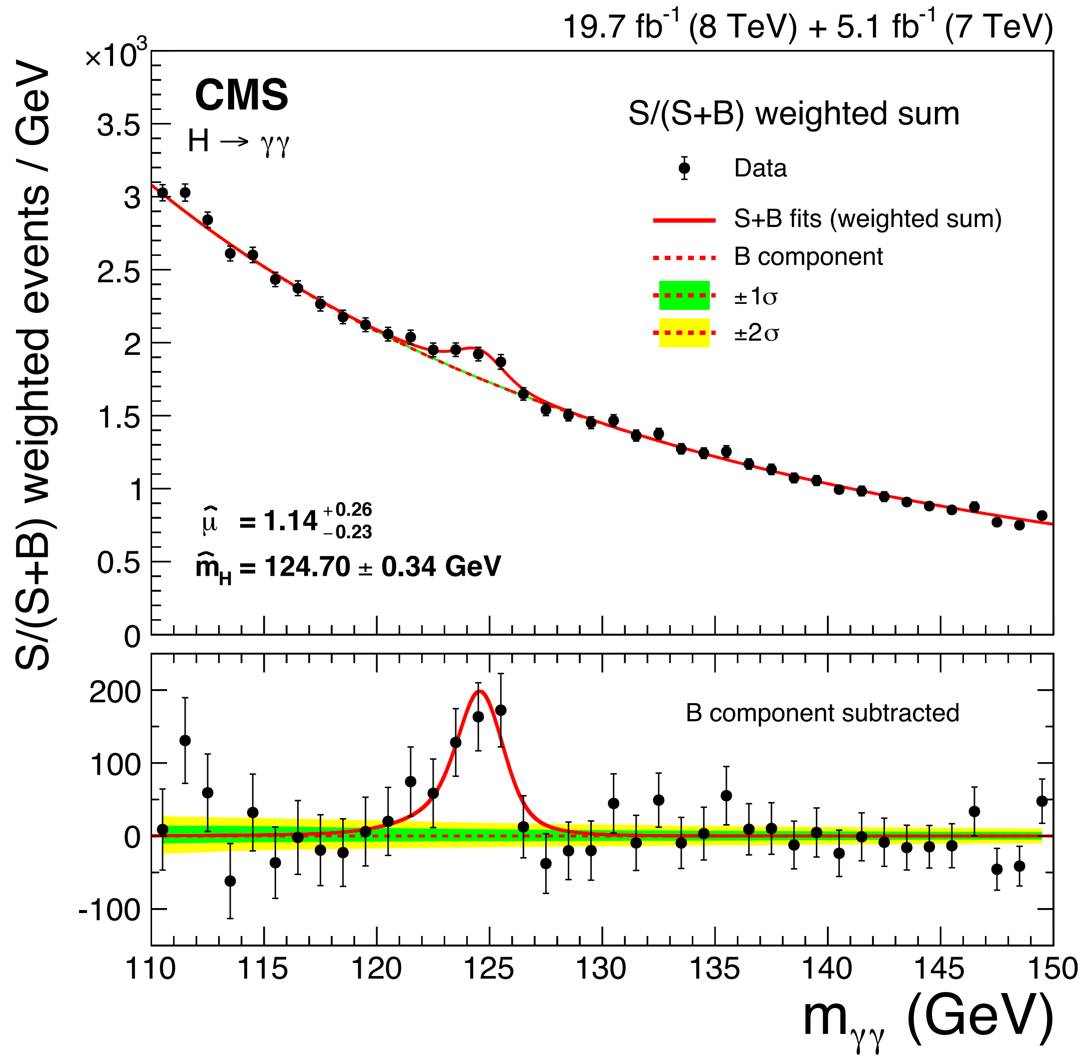





CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
Candidate eve

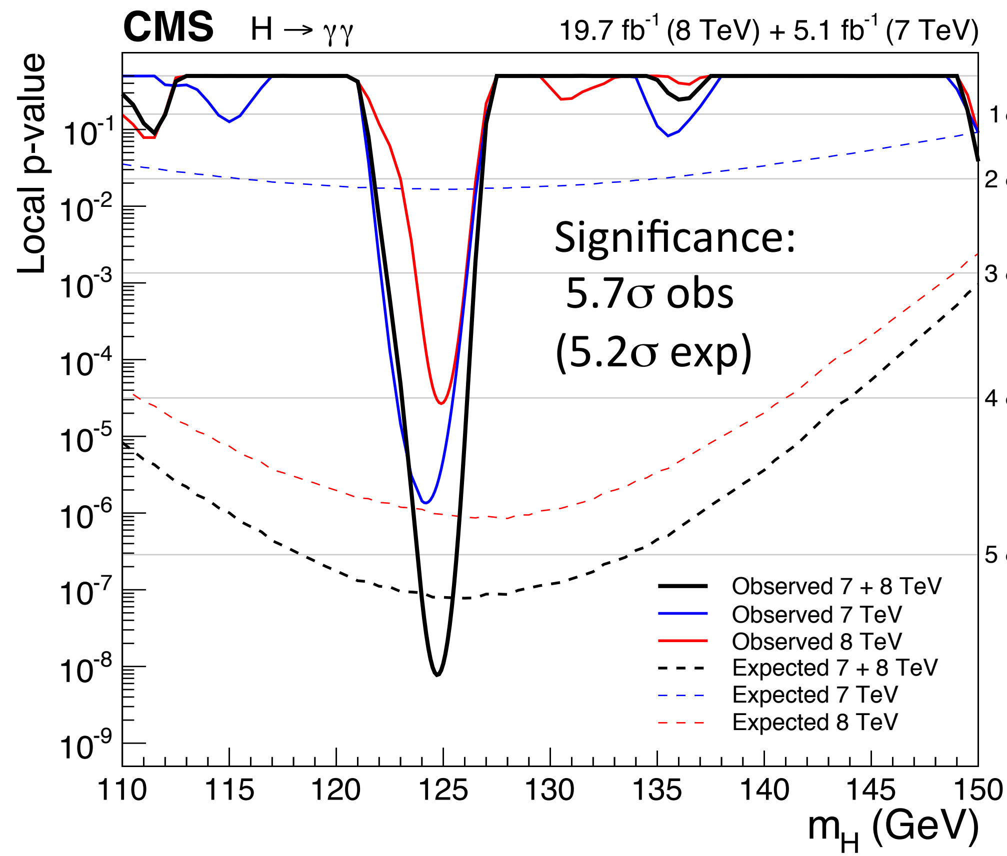
H→γγ channel

- Narrow mass peak with **2 isolated high E_T photons** on a falling background
- High mass resolution: **~1% barrel**
- low rates: S/B <1
- Backgrounds: prompt **di-photons** and **γ+jet(fake γ)**
- Multi-Variate-Analysis (MVA) used for photon ID and event classification – 4 classes
  - Optimize sensitivity to different resolution or production modes
- Fits performed in all event categories (25)
  - **Di-jet tagging**: high S/B but low rate
  - **VBF topology**: 2 high P_T jets with larg $\Delta\eta$ and M_{jj}



H⟶γγ channel

- Final calibration of ECAL for Run 1 data analysis
- Improvements:
  - ECAL Noise evolution with time
  - Effects of out-of-time pile-up
  - Distribution of material in front
  - Description of energy scale uncertainties
- New background modeling
  - Multiple functional forms



Improvements in significance:
9% energy resolution
9 % new event selection
7% background modeling

H→γγ channel

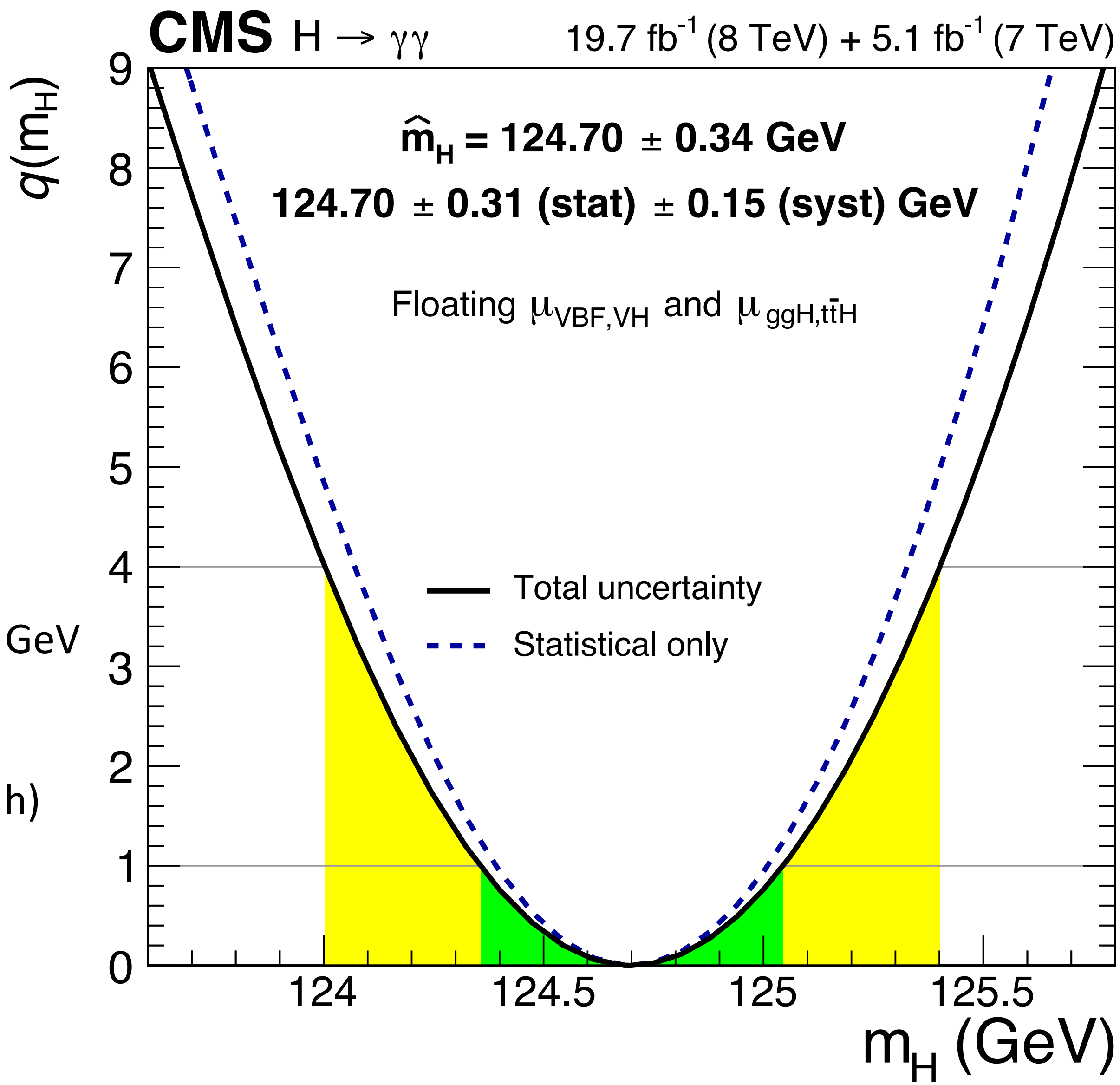
Final Run I analysis:
arXiv:1407.0558 (EPJC)

RESULTS:
Signal strength:
μ=1.14+0.26-0.23
Mass: 124.7±0.34 GeV

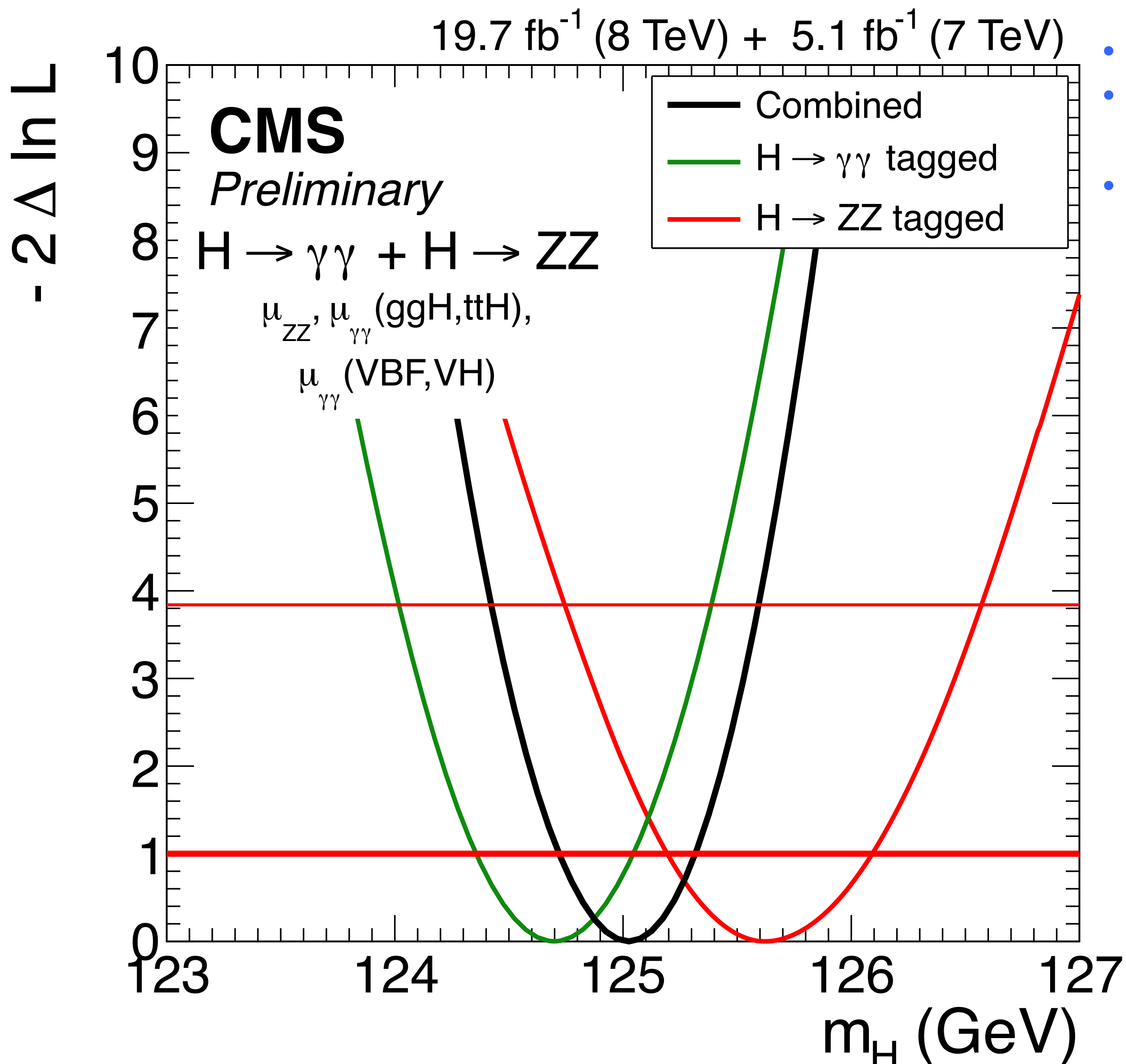
$M_{\gamma\gamma}$ systematics:
- the E_γ scale and resolution: ±0.05 GeV estimated from Z→ee

- Non-linearity uncertainty (Mz->Mh) ±0.10GeV

- Electron –photon differences: ±0.10GeV



Higgs Mass Measurement

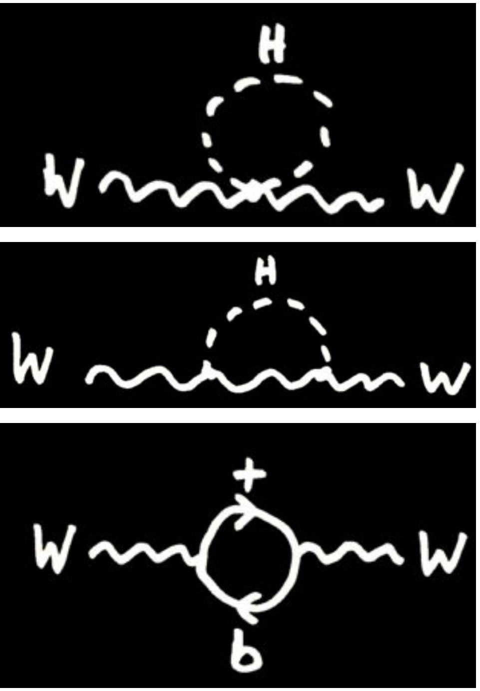


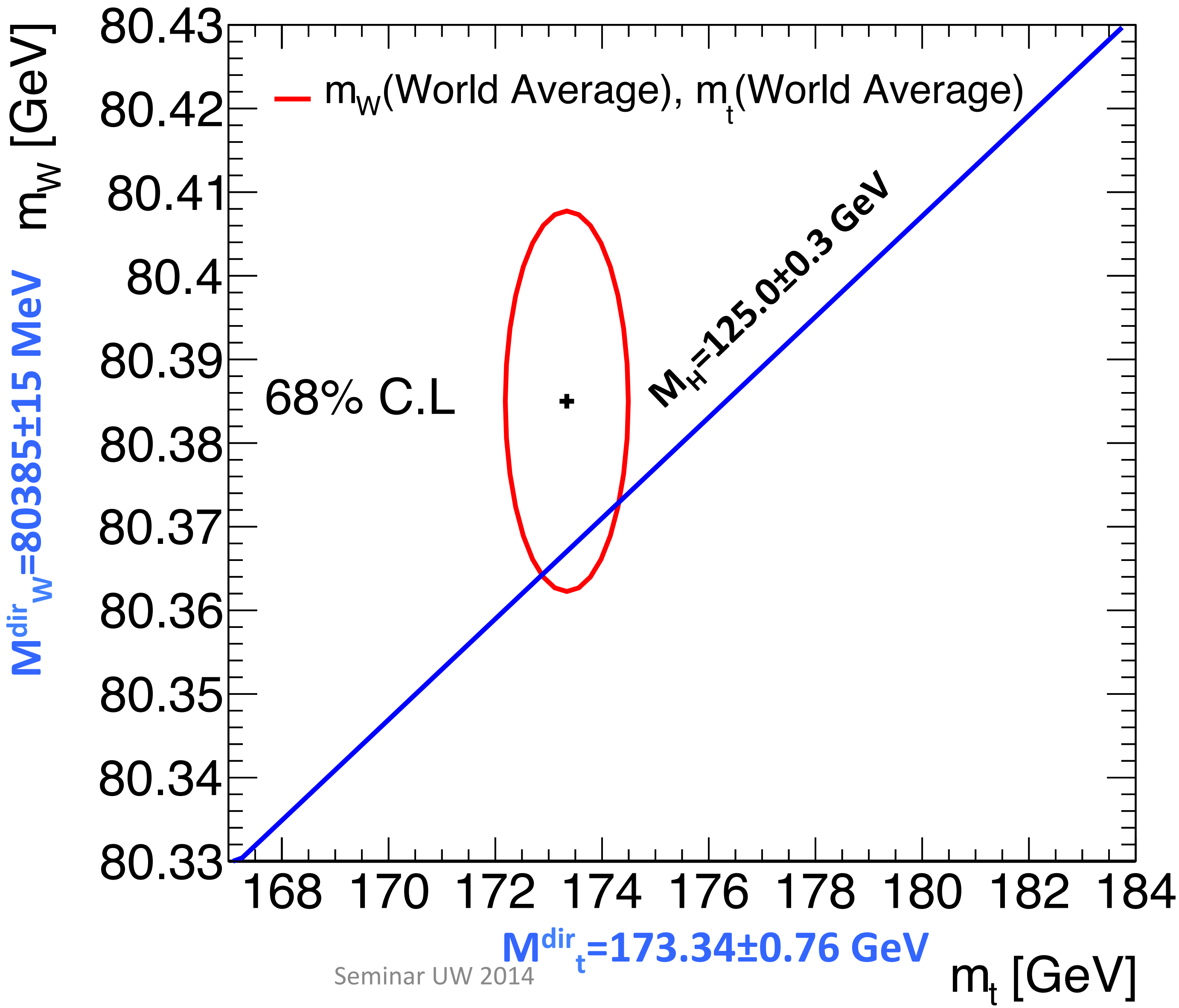
- 2014 Mass Combination
- Precision mass measurements from **H→γγ** and **H→ZZ*→4l**
- Consistent measurements across channels

Mass: 125.03±0.27(stat.)±0.15(syst.)

CMS-PAS-HIG-14-009 ICHEP'14

Consistency of the SM

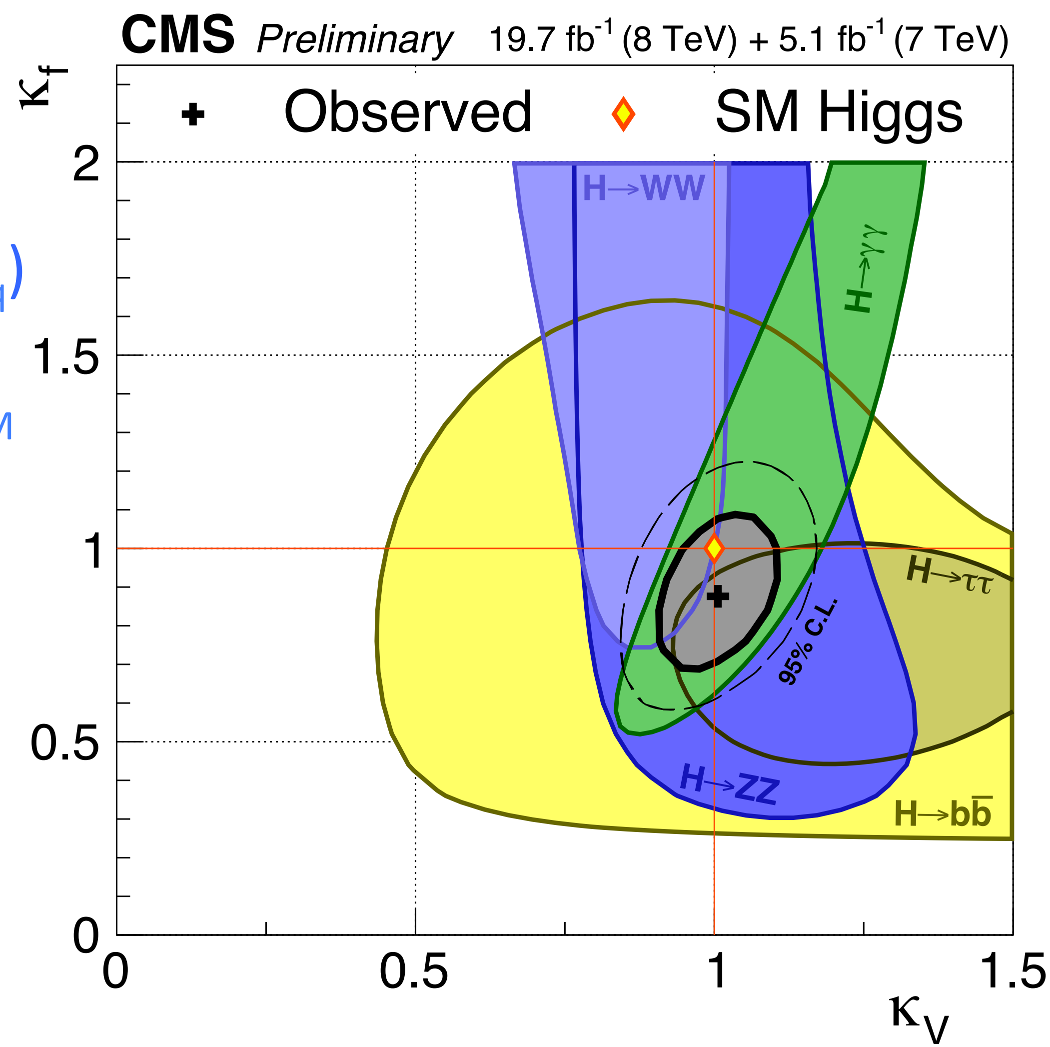




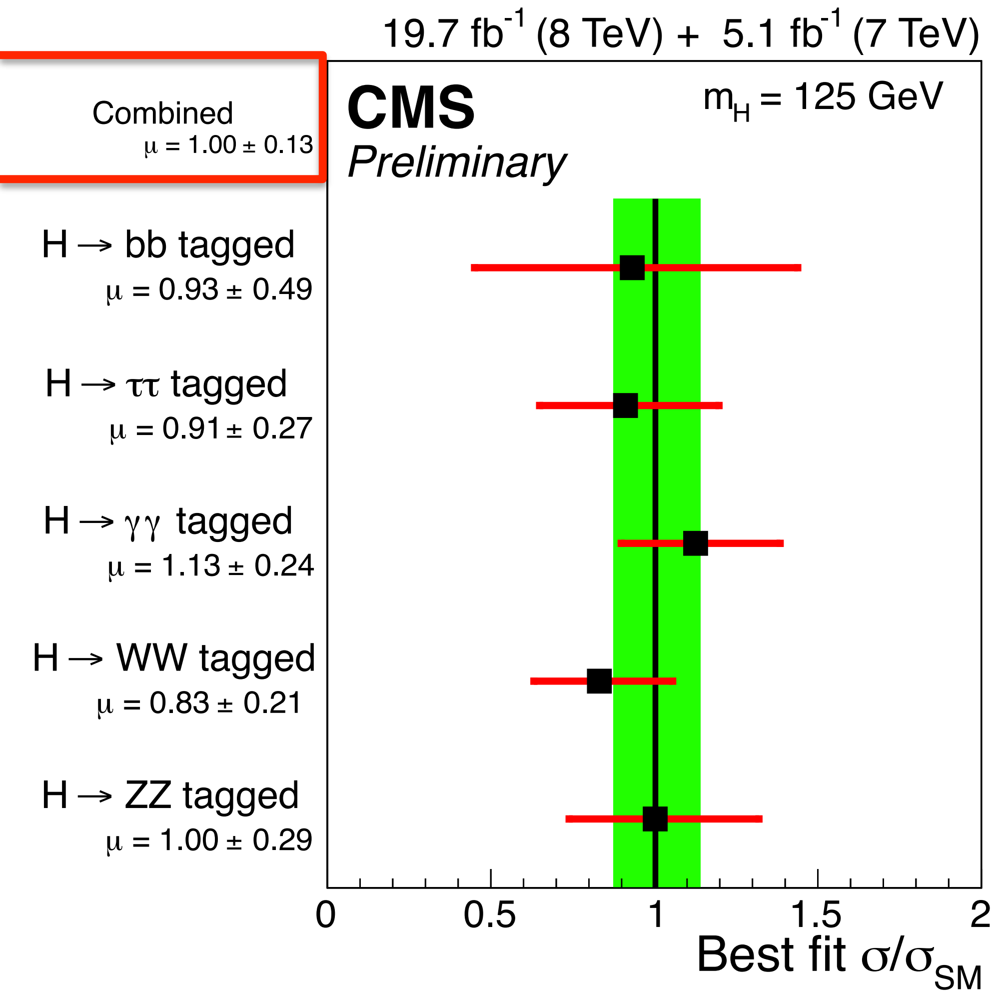
Consistent agreement between the world average masses of M_t, M_W, in the presence of the measured M_H

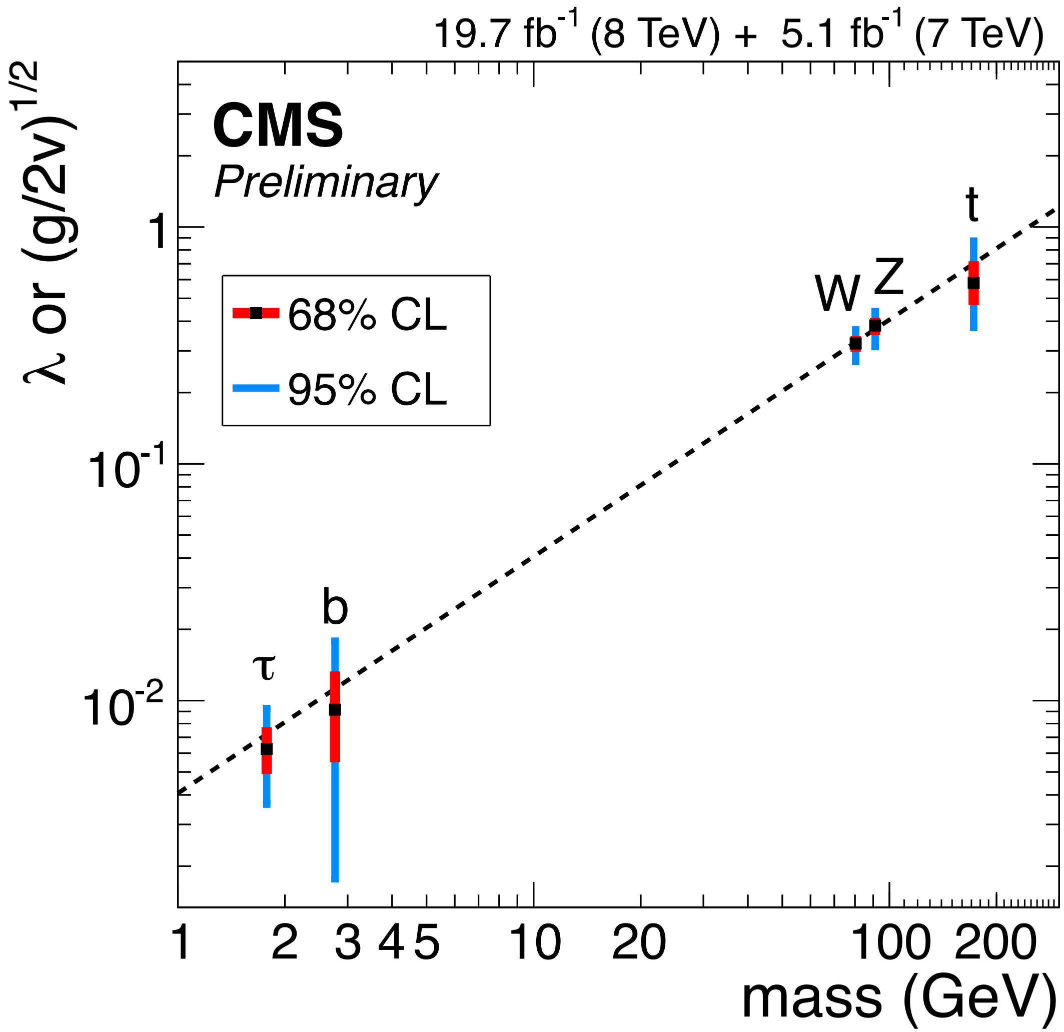
Higgs Couplings to Fermions and Vector Bosons

- SM modifiers (Scale Factor):
  $\kappa_i^2=\sigma_i/\sigma_i^{SM}$ and $\kappa_i^2=\Gamma_i/\Gamma_i^{SM}$
- One SF each for vector boson $\kappa_V(=\kappa_W=\kappa_Z)$ and fermion $\kappa_F(=\kappa_l=\kappa_q)$ couplings
- No BSM physics $\Gamma_{BSM}=0$, only Γ_H^{SM}
- Partial width scales either with
  κ_V^2 or κ_F^2, except $\Gamma_{\gamma\gamma} = |\alpha\kappa_V + \beta\kappa_F|^2$
- Plot: contours for individual channels and combination



Higgs Signal Strength and Couplings





Higgs Decay Width at LHC

- SM decay width Γ_H=4.2MeV for the Higgs mass M_H=125GeV

Direct

Measurement of the width at LHC limited by the experimental precision

- Domain of lepton colliders

CMS limits: at 95% CL

- $H \rightarrow \gamma\gamma$: Γ_H < 2.4 GeV
- $H \rightarrow 4l$: Γ_H < 3.4 GeV

Indirect

Two possible techniques:

Interferometry: Interference between Higgs signal $gg \rightarrow H \rightarrow \gamma\gamma$ and continuum $gg \rightarrow \gamma\gamma$

change of sign of the interference term around the resonance shifting its mass

Small effect; large statistics; Run II ?

Propagator: off-shell H* production in $H^* \rightarrow ZZ(^*)$

- relative intensity of the on- and off-peak signals with the background interference term taking into account
- **the first RunI results from $H \rightarrow 4l$ channel**

Higgs Decay Width

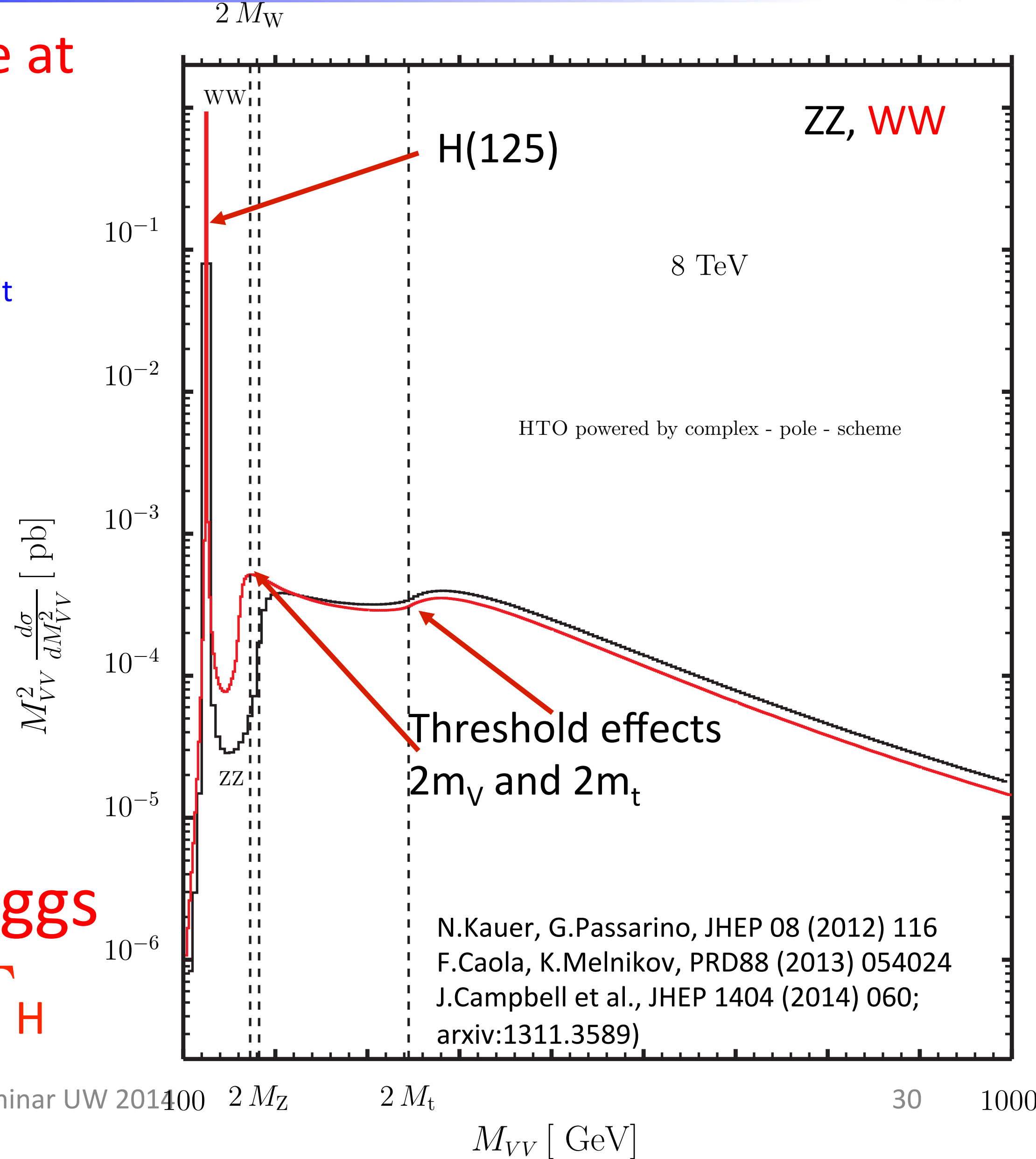
- Higgs off-shell production sizeable at high VV invariant mass
  - e.g.:8% of $\sigma(H\to ZZ)$ above $2m_Z$
  - Enhancement effects seen at the $2m_t$ and $2m_V$ thresholds

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM^2_{4l}} \sim \frac{g^2_{Hgg}g^2_{HZZ}}{(M^2_{4l}-m^2_H)^2+m^2_H\Gamma^2_H}$$

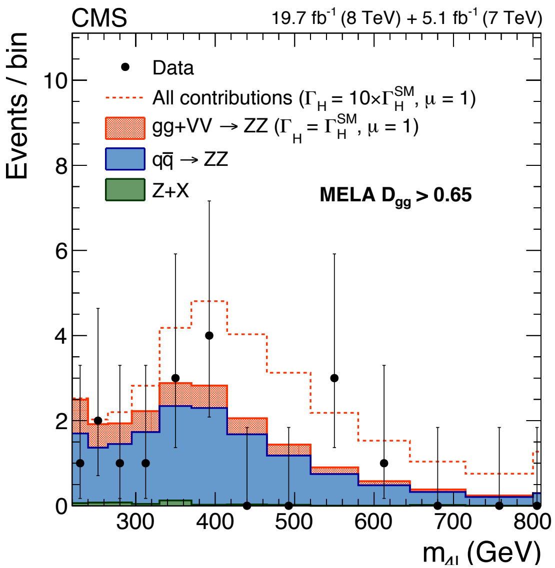
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$

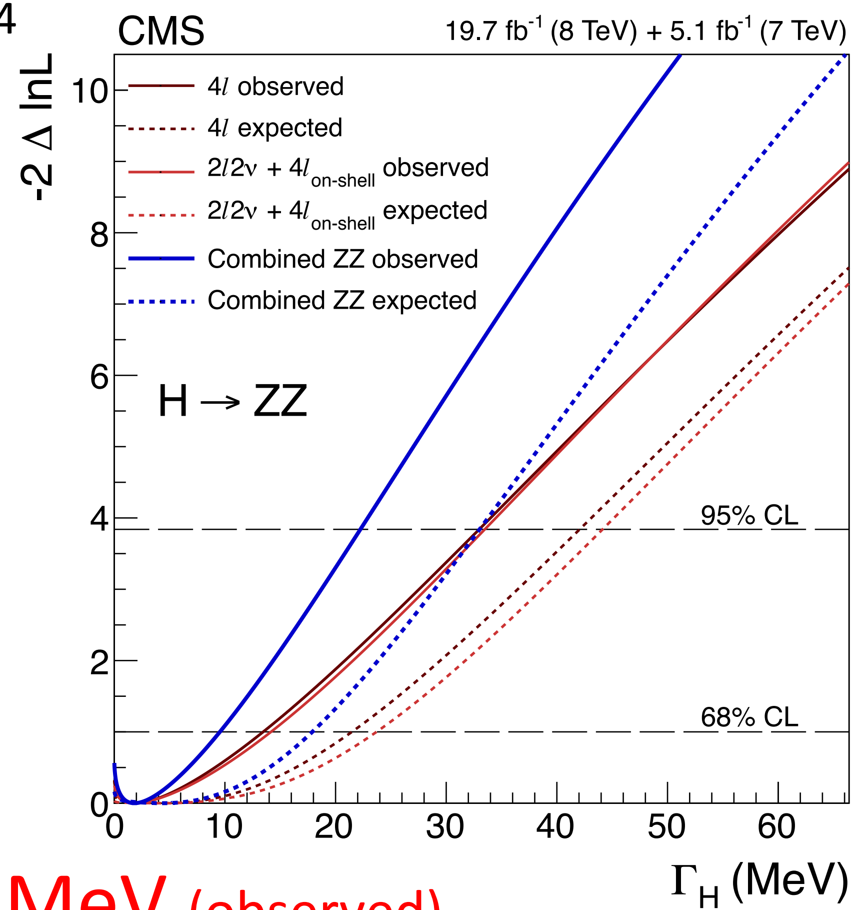
- Ratio of on- and off-shell Higgs cross sections sensitive to Γ_H

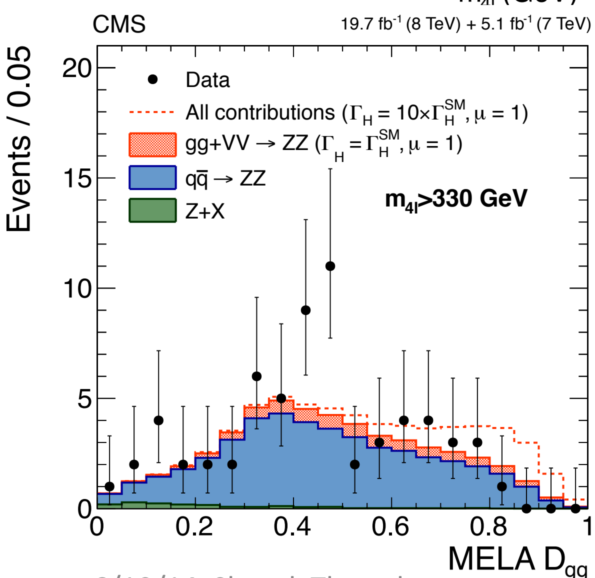


Higgs Decay Width at CMS



Phys. Lett. B 736 (2014) 64
arxiv:1405.3455



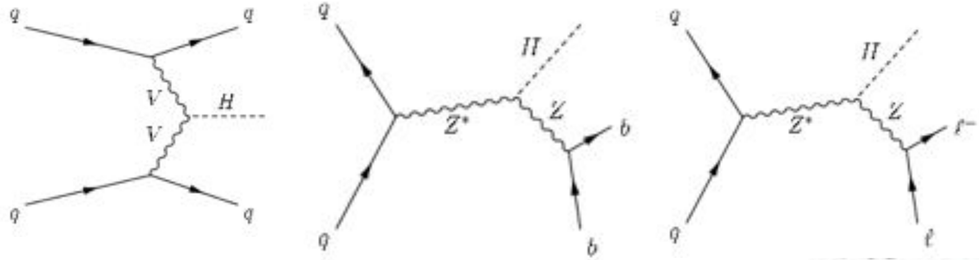


Results: Γ_H < 22MeV (observed)
(33 MeV expected) @95%CL

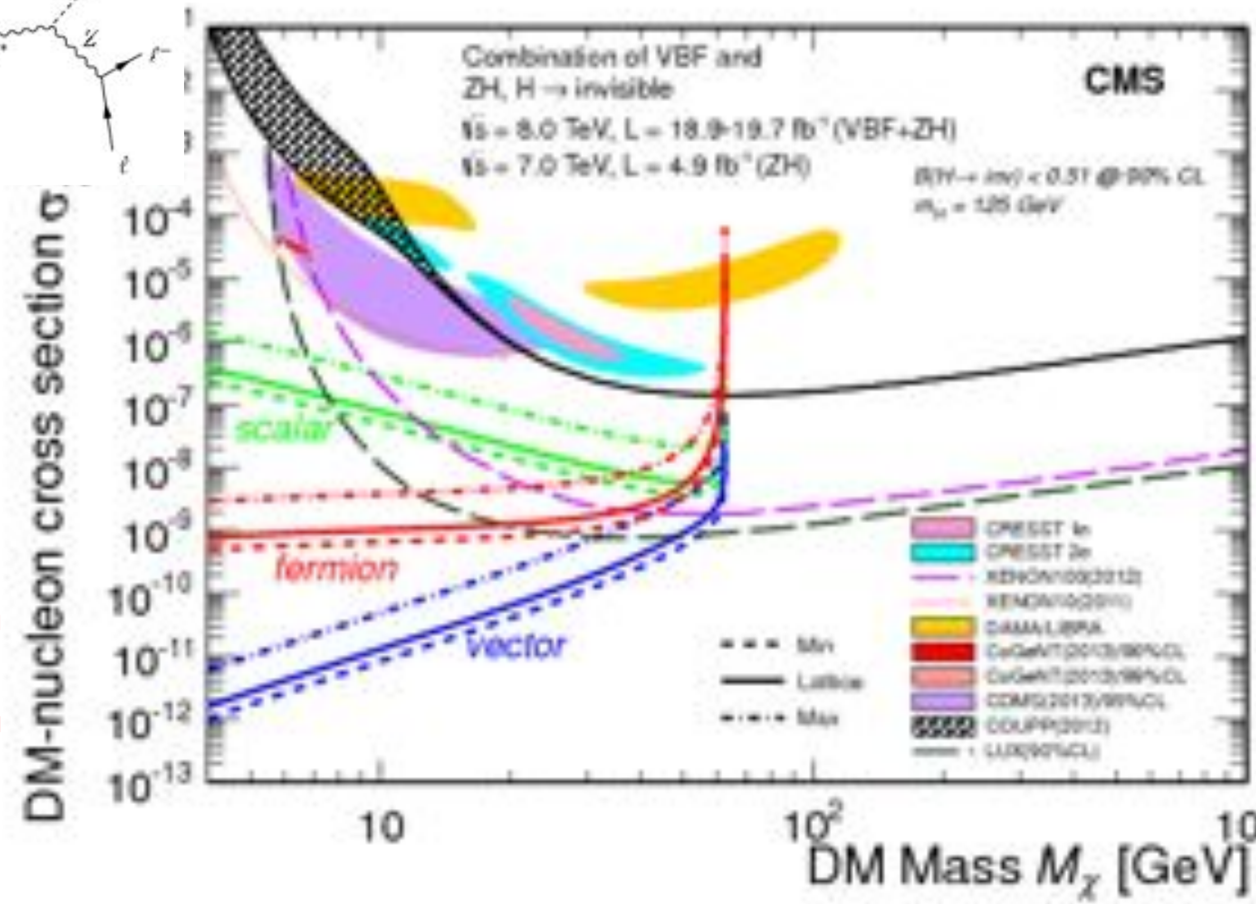
(Γ_H^{SM} = 4.2 MeV)

Best Fit: Γ_H = 1.8+7.7-1.8MeV @95%CL

Higgs Invisible Decays



arXiv: 1404:1344



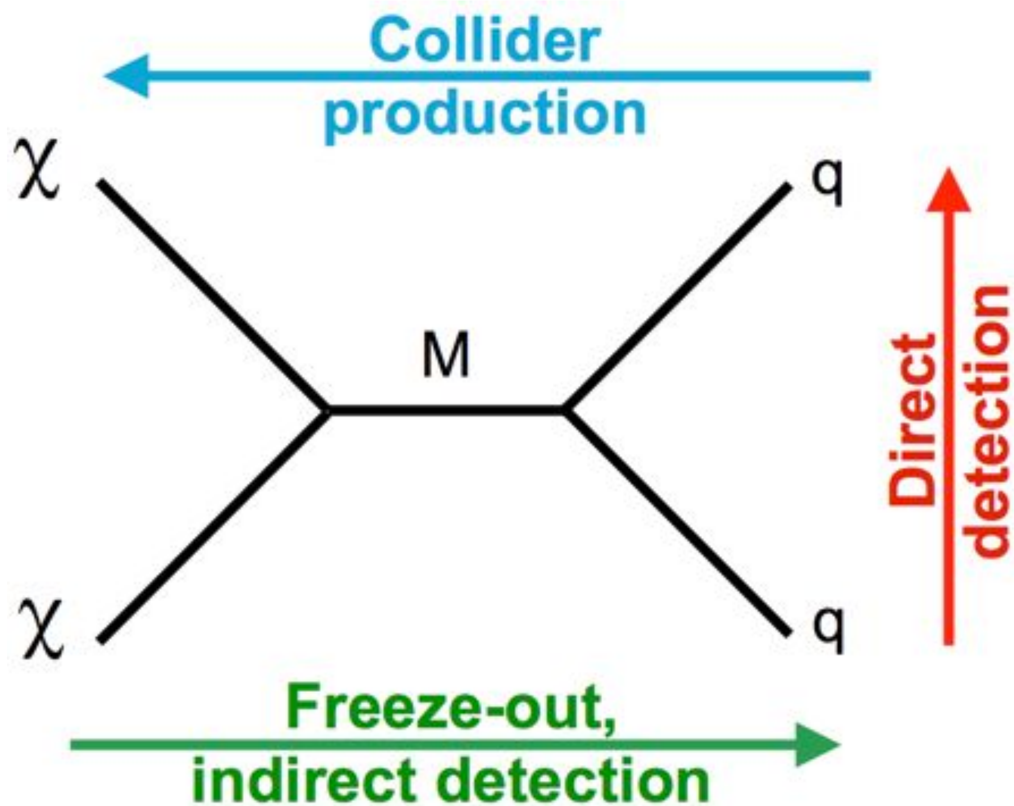
- Direct searches for invisible decays
- VBF and ZH production as tags
- **Higgs couples to mass; DM is massive !**
- DM interpretation of the results
  - Complimentary to direct searches
- Comparison with direct detection methods under scalar, vector, Majorana fermion assumption on the DM nature

Br(H→invisible) < **58**% (44% exp.) at 95CL

Dark Matter

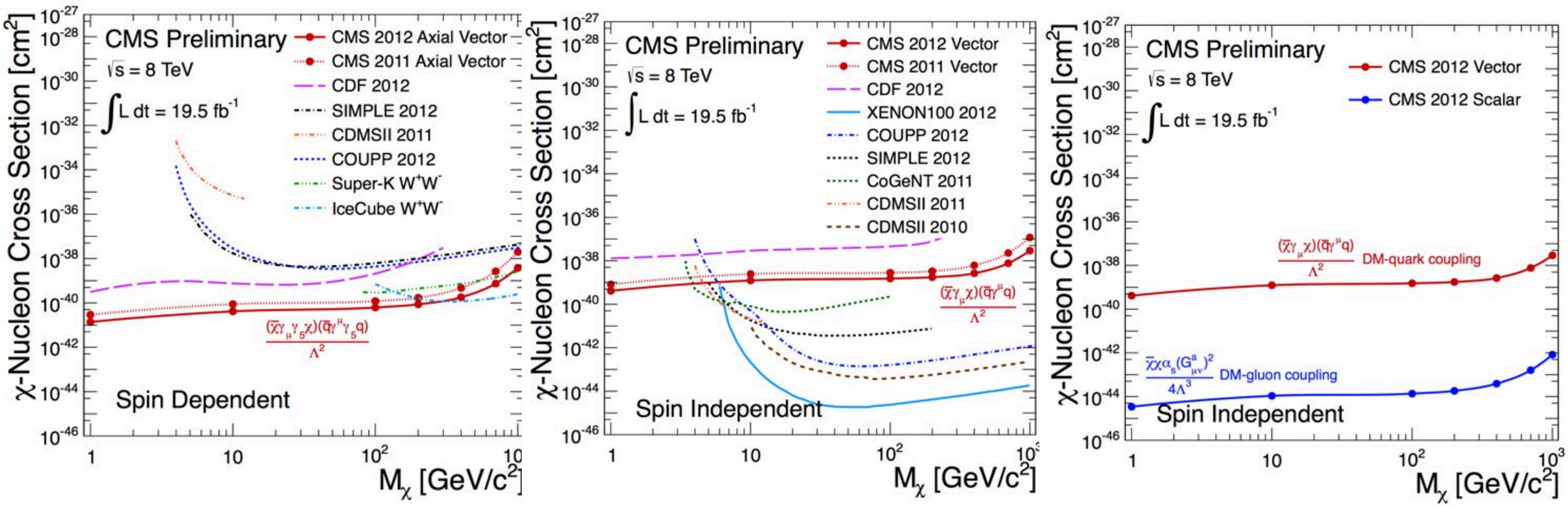
- Detection:
  - Direct – DM-nucleon scattering
  - Indirect – co-annihilation
  - Production – DM pairs at colliders; Higgs portal to DM
- How to trigger on a pair of DM at LHC?
- Three ways to look for the coupling:
  - Direct search for the invisible Higgs decays
  - Indirect constraints on the Higgs invisible width from global fits
  - Mono-X analysis with scalar operators and Higgs boson as a messenger
- Original idea:
  - Bertran, Hooper, Kolb Krusberg, Tait ,arXiv: 1002.4137
  - Later work: Fox, Harnik, Kopp, Tsai, arXiv:1109.4398
- CMS publications:
  - Monphotons: arXiv:1204.0821 7TeV
  - Monojets: EXO-12-048 (20fb^{-1})
    - Channel with more sensitivity

All three processes described by permutations of the same Feynman diagram



Mono-Jet Searches

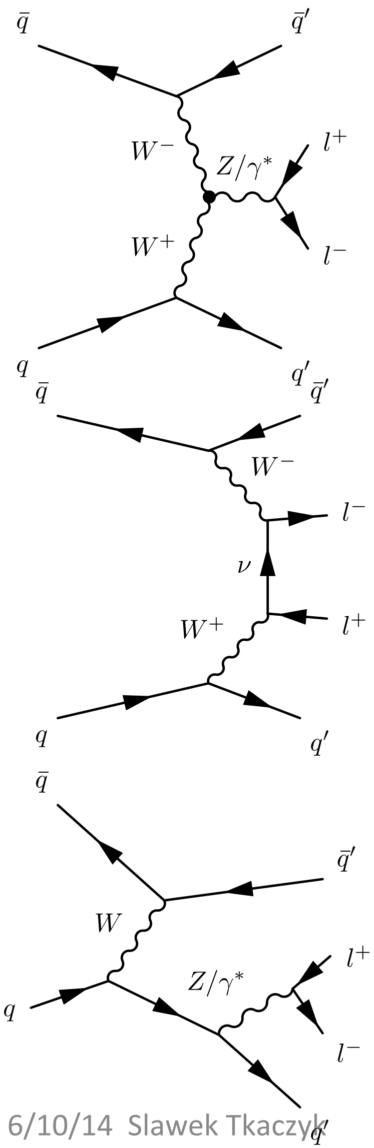
- Signature: Large transverse missing E_T and a high p_T jet (mono-jet)
- Comparison with direct searches using EFT approach with **heavy mediator**

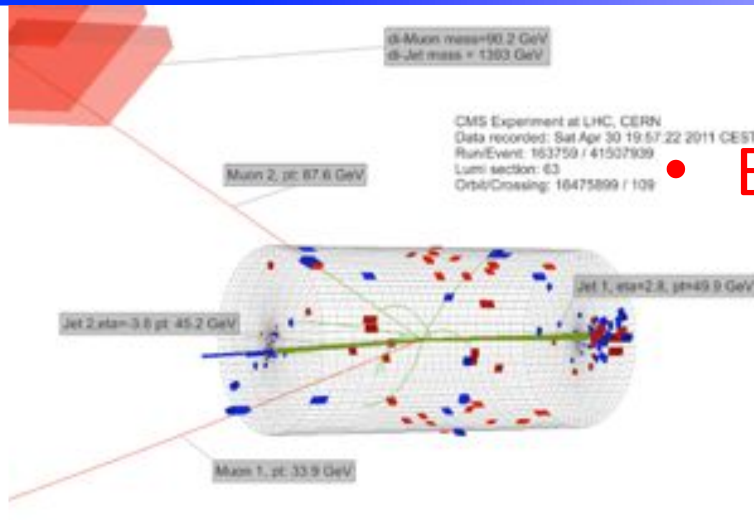


- Expand the searches for mono-object production: **mono-jet, mono-photon, mono-lepton, mono-V, mono-top** by triggering on ISR jet, photon, lepton, V(W,Z)
- Limits somewhat model dependent – sensitive to the mediator mass, yet complimentary to Direct detection experiments

- Vector Boson Production

EWK Boson Production: Z+2Jet





Clean signatures

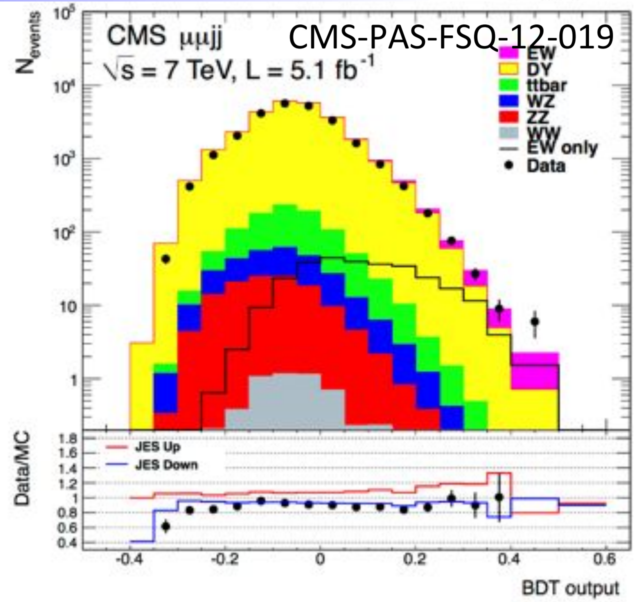
- EWK Z+2jet production
  - Unique process to study the VBF jet dynamics and rapidity gaps
  - 1% of inclusive Z+2Jet x-sec
- VBF selection:
  - Dijet mass: 250-1000GeV
  - Dijet Δy: large (>4)
  - Other kinematics (V, Jet) to differentiate from QCD Z +2jet processes

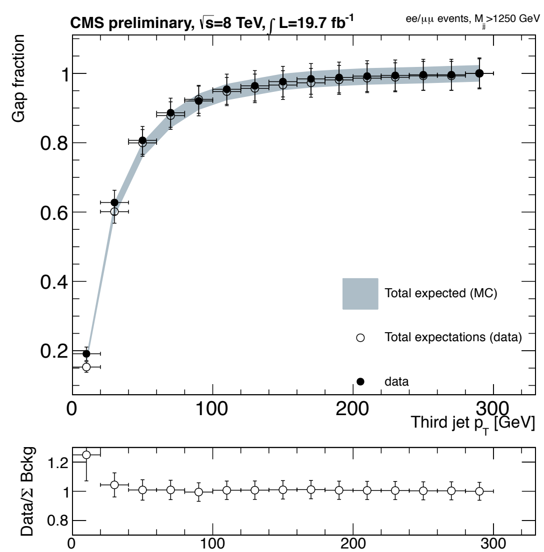
EWK Boson Production: Z+2Jets

- Kinematic discriminant based analysis
  - Z+2jet Model built from γ+2jet data
- **2.6σ (5σ)** signal evidence in 7 (8) TeV data
- Cross sections in agreement with SM predictions
  - σ EWK=226±44 fb
  - σ VBFNLO=239 fb
- Jet dynamics well modeled

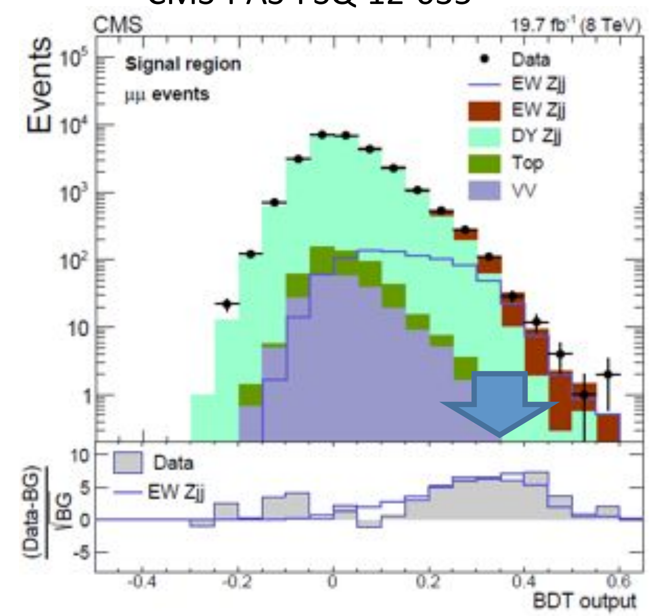
in and around search regions

- **Channel to study the generator behavior in VBF/VBS processes**





CMS-PAS-FSQ-12-035

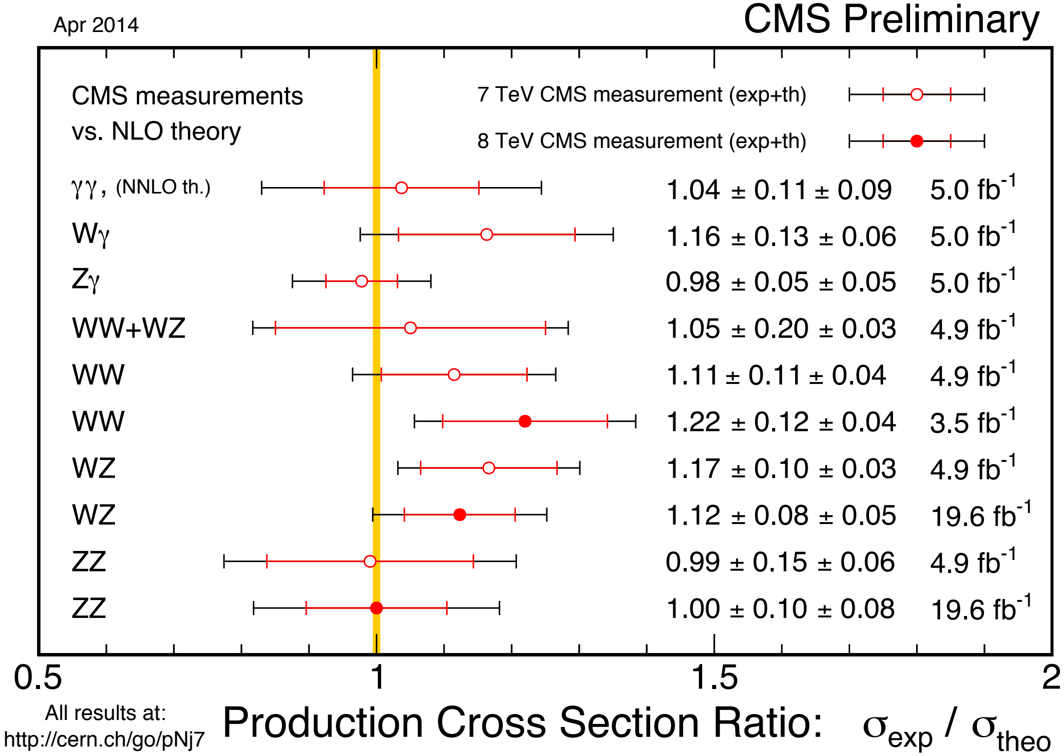


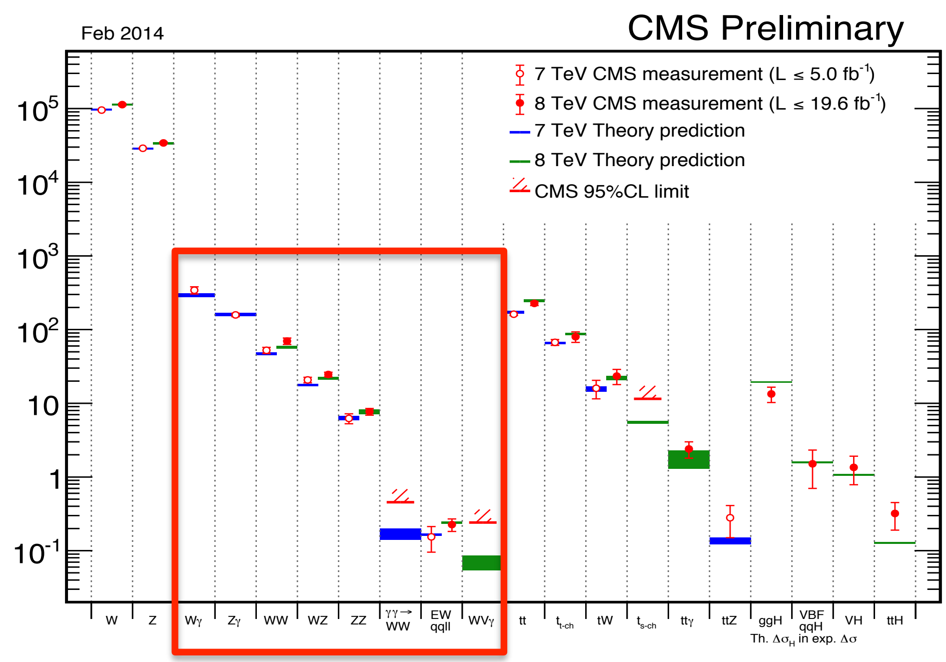
- Multi-boson production at CMS

Vector Boson Production

- Provide fundamental tests of the SM
  - Measurements of self-interactions and gauge couplings (TGC, QGC)
  - Probe of new physics
    - Direct – resonances with dibosons final states
    - Indirect – deviations from SM expectations

- Interesting final states:
  - Single boson from VV scattering – TGC
  - Di-bosons from VV scattering – multiple graphs
  - Di-bosons inclusive – also TGC
  - Tri-bosons – QGC



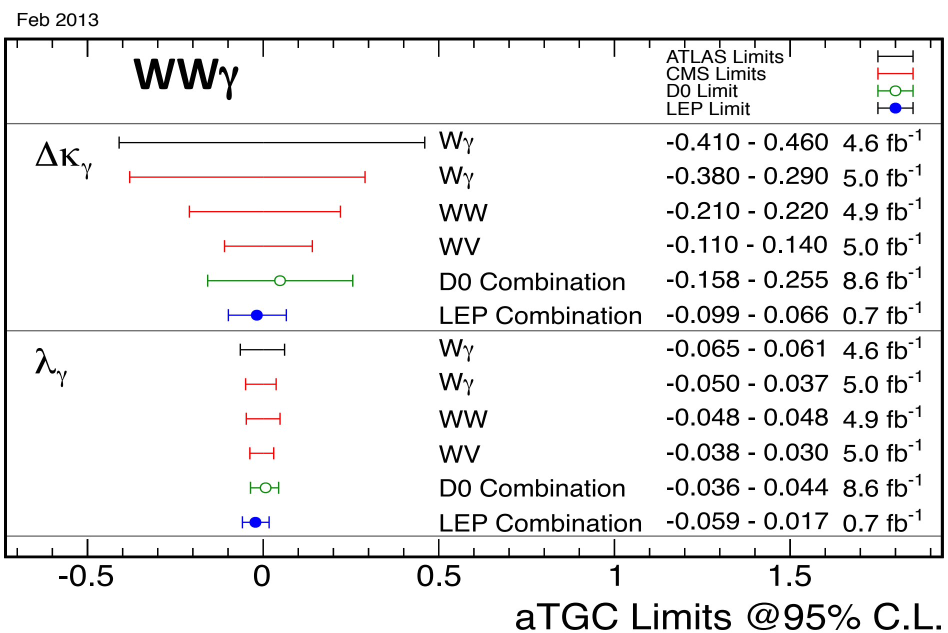


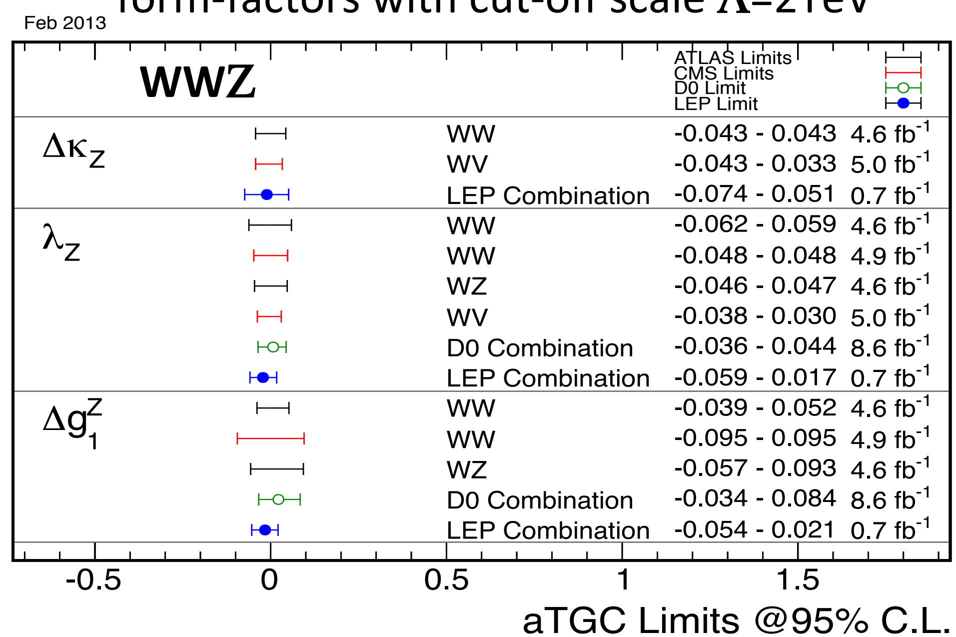
Production Consistent with the SM

Limits on Triple GC

- Analysis of the **WWZ** and **WWγ** final states
- Effective lagrangian method with 5 parameters
  - SM: $(g_1^Z, K_{\gamma,Z}, \lambda_{\gamma,Z}) = (1,1,0)$
- Limits obtained from P_T distributions
- Consistent with SM expectations

Tevatron results with scale dependent form-factors with cut-off scale Λ=2TeV





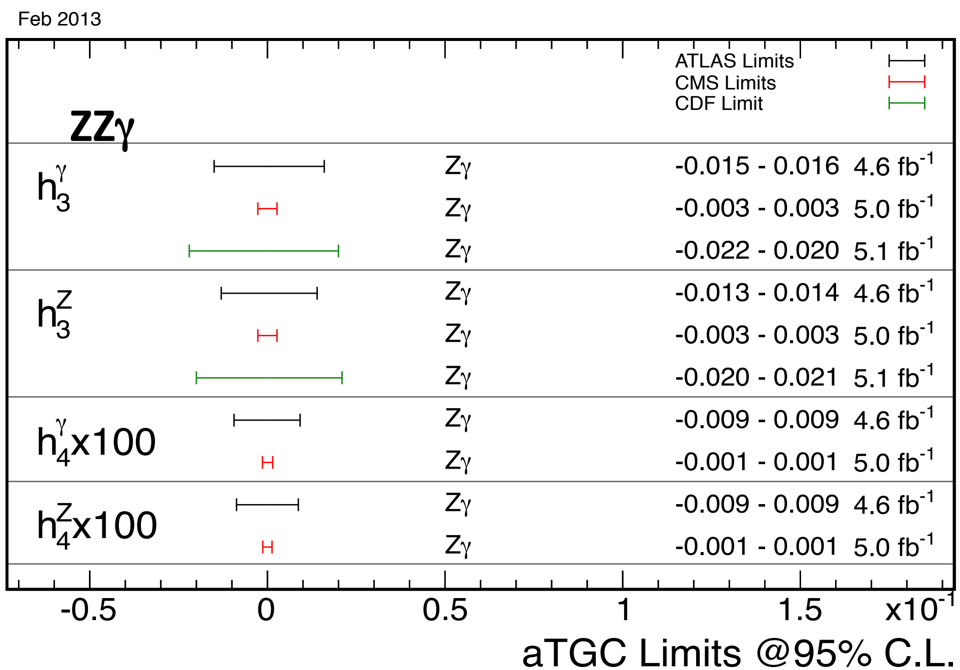
Limits on Triple GC

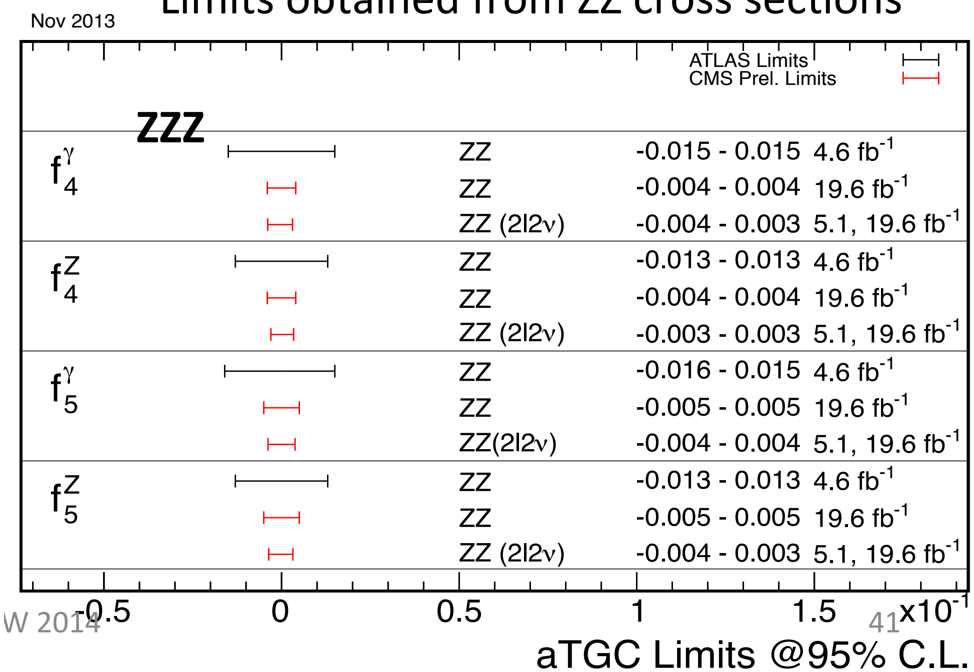
- Analysis of the **ZZZ** and **ZZγ** final states
- ZZ: Effective lagrangian method with 2 parameters
- SM: $(\mathbf{f_4}^{\gamma,Z}, \mathbf{f_5}^{\gamma,Z}) = (\mathbf{0,0})$
- Zγ: Vertex function approach method with 2 parameters
- SM: $(\mathbf{h_3}^{\gamma,Z}, \mathbf{h_4}^{\gamma,Z}) = (\mathbf{0,0})$

- No signs of deviations from the SM

Scale dependent form-factors used with various cut-off scales

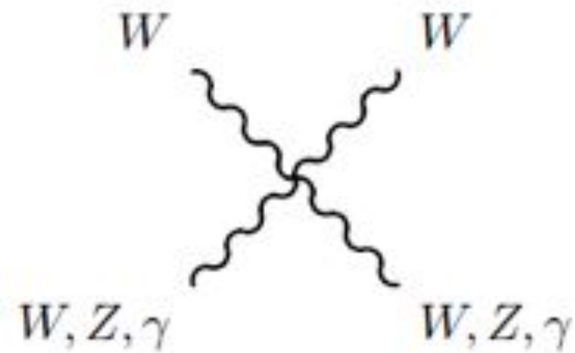
Limits obtained from ZZ cross sections





SM Quartic Gauge Couplings

- 4 Quartic Gauge couplings in the SM



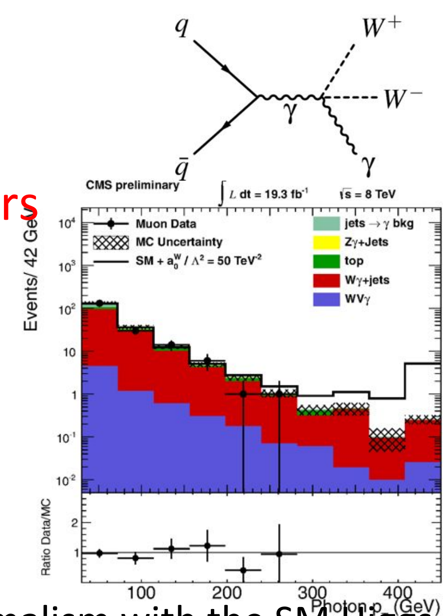
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}$, $\mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}$, $\mathcal{L}_{M,1}$, $\mathcal{L}_{M,6}$, $\mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}$, $\mathcal{L}_{M,3}$, $\mathcal{L}_{M,4}$, $\mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}$, $\mathcal{L}_{T,1}$, $\mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}$, $\mathcal{L}_{T,6}$, $\mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}$, $\mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

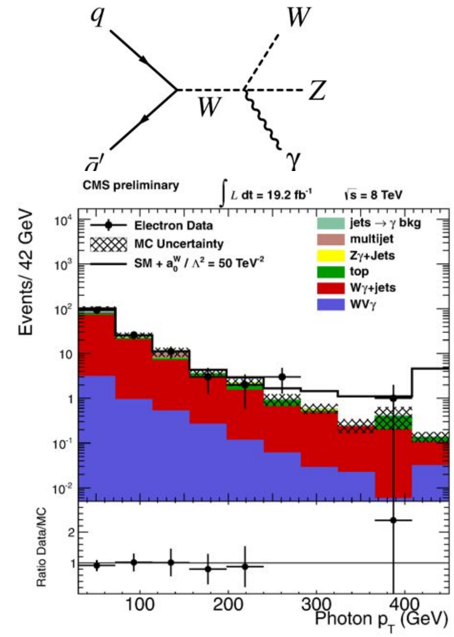
- In EFT with Dim-8 operators 19 new quartic terms present
- Triboson production or Vector Boson scattering (VBS) phenomena

Limits on QuarticGC in WWγ/ WZγ

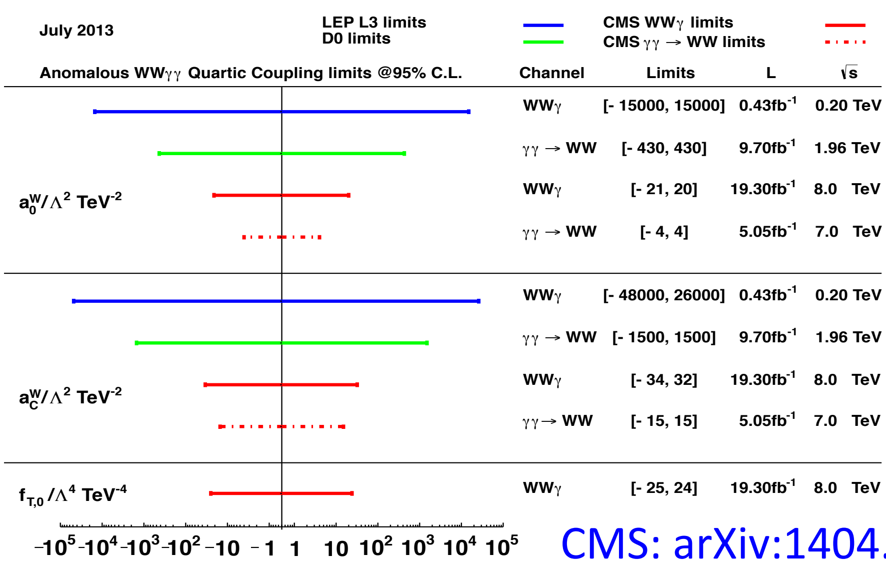
- QGC Analyses
  - in scattering topologies (VBS) – dibosons
  - **with tri-boson final states**
- QGC limits set on dim-6 and dim-8 EFT operators
  - dim-6: $a^W_{0,C}$,(WWγγ); $k^W_{0,C}$,(WWZγ); dim-8: $f_{T,0}$; $f_{M,i}$
- No deviations from the SM expectations:

  in pt spectrum of the photons





For comparison with earlier results the EFT formalism without SM Higgs



EFT formalism with the SM Higgs

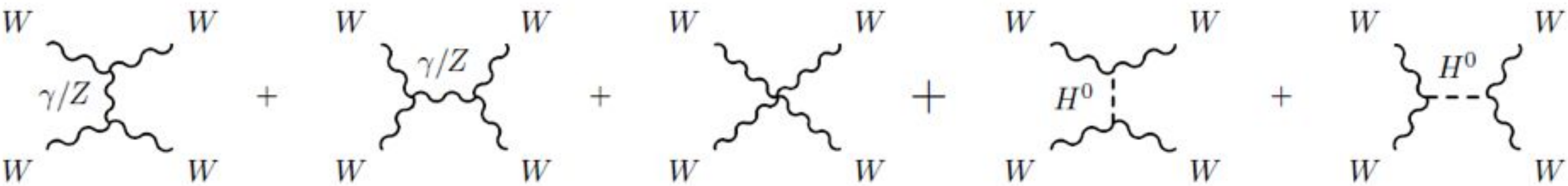
Observed Limits	Expected Limits
$-77\ (TeV^{-4}) < f_{M,0}/\Lambda^4 < 81\ (TeV^{-4})$	$-89\ (TeV^{-4}) < f_{M,0}/\Lambda^4 < 93\ (TeV^{-4})$
$-131\ (TeV^{-4}) < f_{M,1}/\Lambda^4 < 123\ (TeV^{-4})$	$-143\ (TeV^{-4}) < f_{M,1}/\Lambda^4 < 131\ (TeV^{-4})$
$-39\ (TeV^{-4}) < f_{M,2}/\Lambda^4 < 40\ (TeV^{-4})$	$-44\ (TeV^{-4}) < f_{M,2}/\Lambda^4 < 46\ (TeV^{-4})$
$-66\ (TeV^{-4}) < f_{M,3}/\Lambda^4 < 62\ (TeV^{-4})$	$-71\ (TeV^{-4}) < f_{M,3}/\Lambda^4 < 66\ (TeV^{-4})$
$-12 TeV^{-2} < k^W_0/\Lambda^2 < 10 TeV^{-2}$	$-12 TeV^{-2} < k^W_0/\Lambda^2 < 12 TeV^{-2}$
$-18 TeV^{-2} < k^W_C/\Lambda^2 < 17 TeV^{-2}$	$-19 TeV^{-2} < k^W_C/\Lambda^2 < 18 TeV^{-2}$

CMS: arXiv:1404.4619

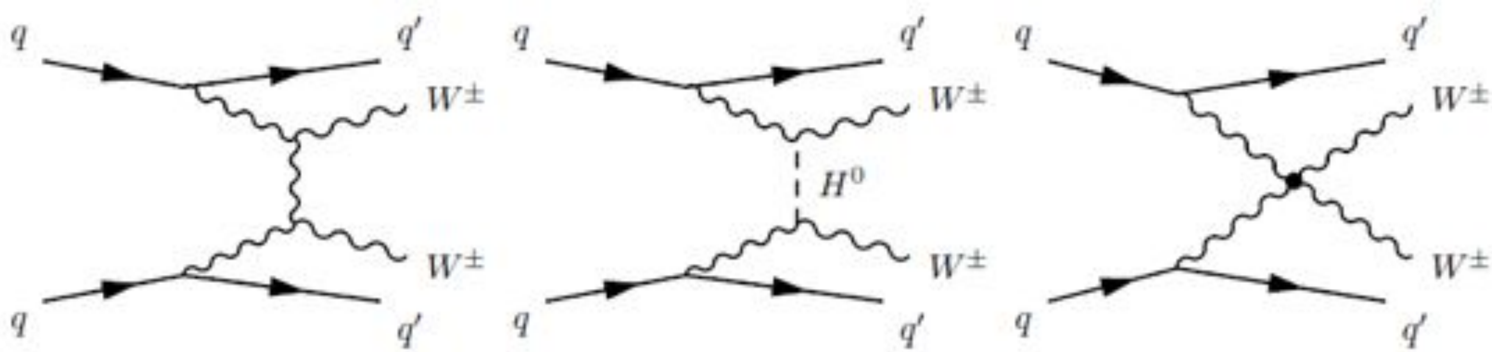
First limit on dim-8 parameter $F_{T,0}/\Lambda^4$

WW Scattering at LHC

- Vector boson scattering cross section unitarity in EWSB with the Higgs



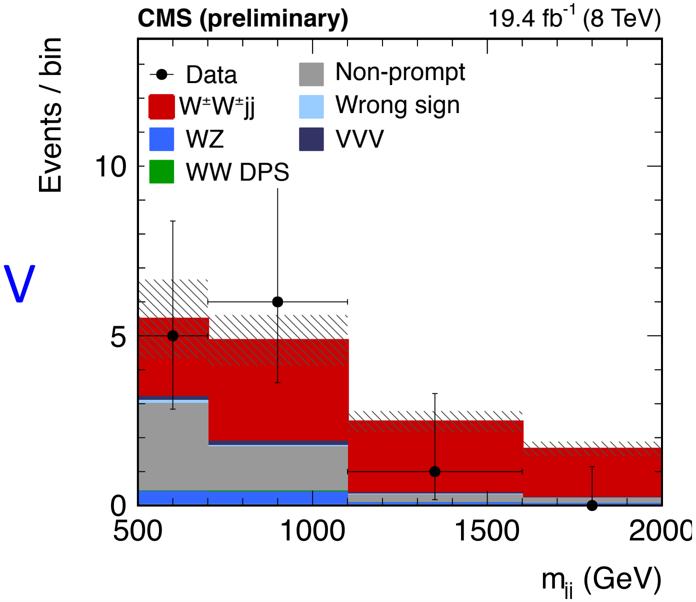
- SAME sign Vector boson scattering with attractive Signal/ Background ratio

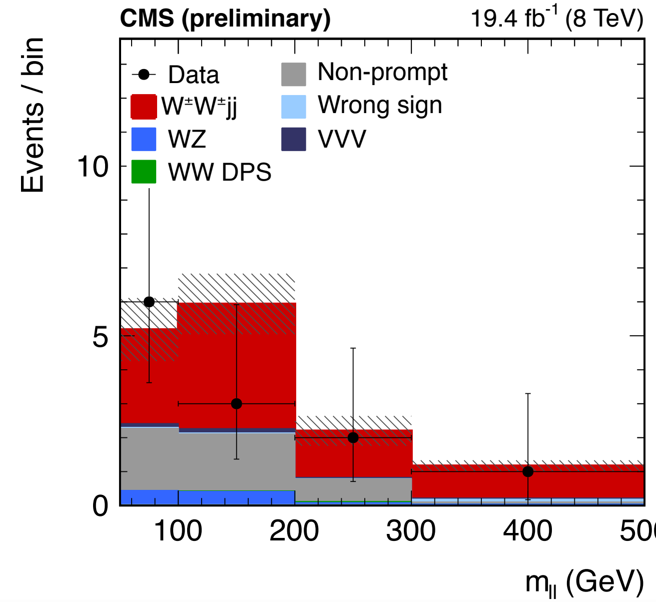


- Deviations in the differential cross sections indicate presence of New BSM Physics (aQGC, new particles, H++, etc…)

$pp \to W^+W^+jj \to ll\nu\nu jj$

- VBF selection:
  - Dijet mass: >500GeV
  - Dijet Δy: >2.5
  - Dilepton mass: > 50GeV
  - Veto Z and top
  - Fakes/non-prompt remain





	Data	$W^\pm W^\pm jj$	Total bkg.	Non-prompt	WZ	VVV	Wrong sign	WW DPS
$W^\pm W^\pm$	12	8.8 ± 0.2	5.7 ± 0.8	4.2 ± 0.8	1.0 ± 0.1	0.3 ± 0.1	0.1 ± 0.08	0.1 ± 0.1
W^+W^+	10	7.0 ± 0.2	3.1 ± 0.6	2.1 ± 0.6	0.6 ± 0.1	0.2 ± 0.1	0.1 ± 0.08	0.1 ± 0.1
W^-W^-	2	1.8 ± 0.1	2.6 ± 0.6	2.1 ± 0.5	0.4 ± 0.1	0.1 ± 0.1	—	—

- Observed events agree with SM expectations

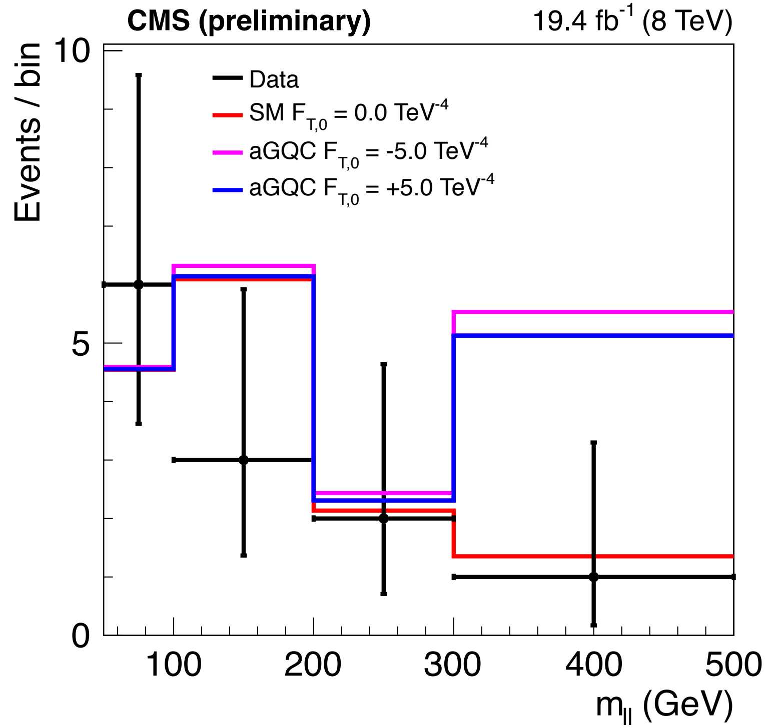
Significance:	VBS
Observed:	2.0σ
Expected:	3.1σ

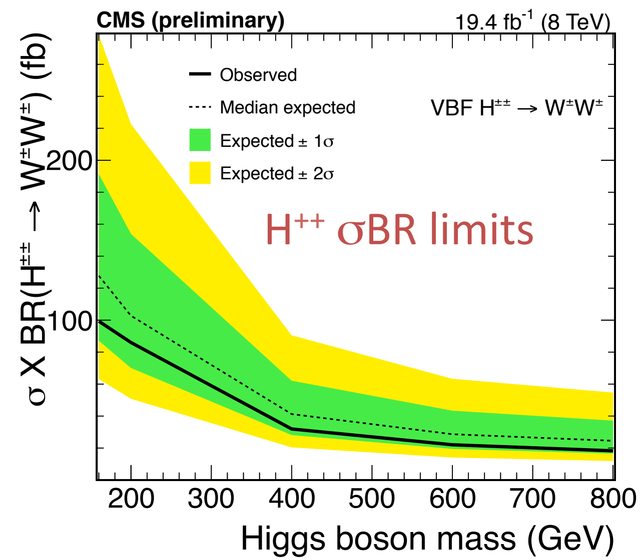
arxiv:1405.6241

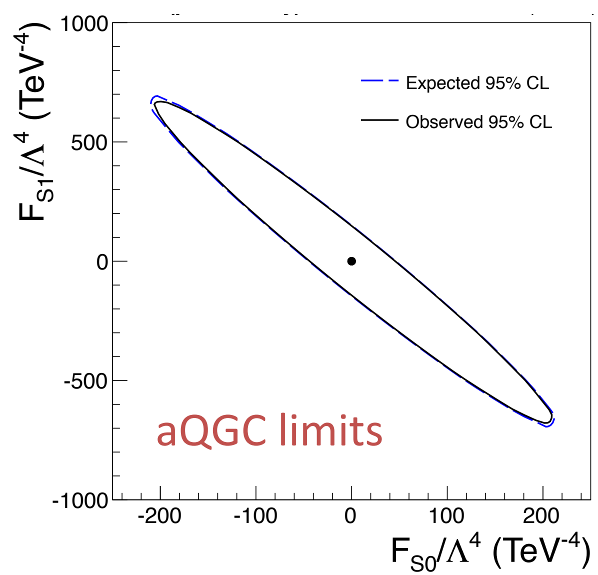
Cross section:
VBS: σ= 4.0±2.4(stat)±1.1(sys) fb
VBFNLO: 5.8±1.2 fb

$pp \to W^+W^+jj \to ll\nu\nu jj$

- aQGC limits obtained from M_{LL} spectrum







[TeV^{-4}]

Operator coefficient	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity limit
$F_{S,0}/\Lambda^4$	−42	43	−38	40	0.016 [@ 8 TeV]
$F_{S,1}/\Lambda^4$	−129	131	−118	120	0.050
$F_{M,0}/\Lambda^4$	−35	35	−33	32	80
$F_{M,1}/\Lambda^4$	−49	51	−44	47	205
$F_{M,6}/\Lambda^4$	−70	69	−65	63	160
$F_{M,7}/\Lambda^4$	−76	73	−70	66	105
$F_{T,0}/\Lambda^4$	−4.6	4.9	−4.2	4.6	0.027
$F_{T,1}/\Lambda^4$	−2.1	2.4	−1.9	2.2	0.022
$F_{T,2}/\Lambda^4$	−5.9	7.0	−5.2	6.4	0.08

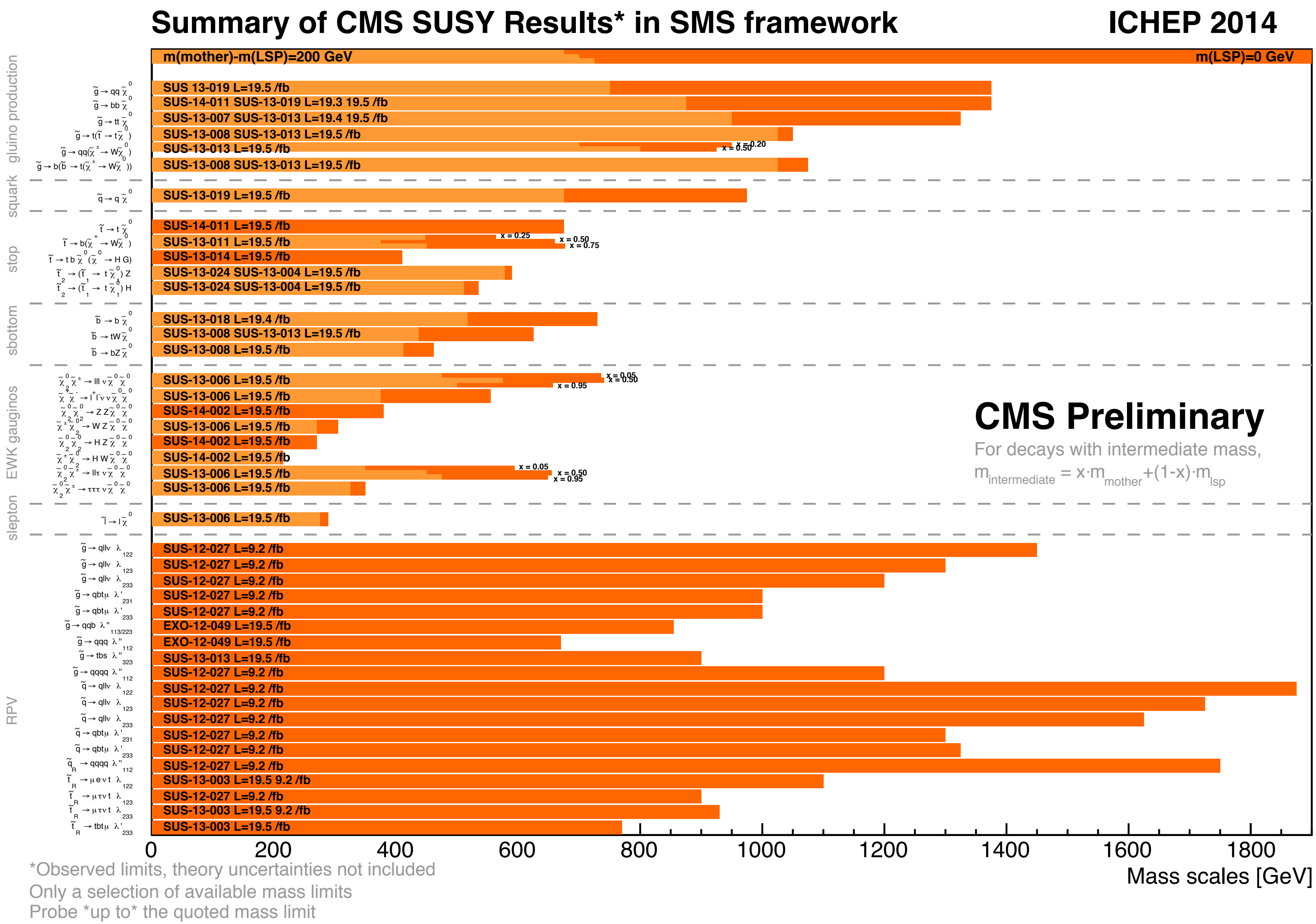
WHAT NEXT ?

Attention to

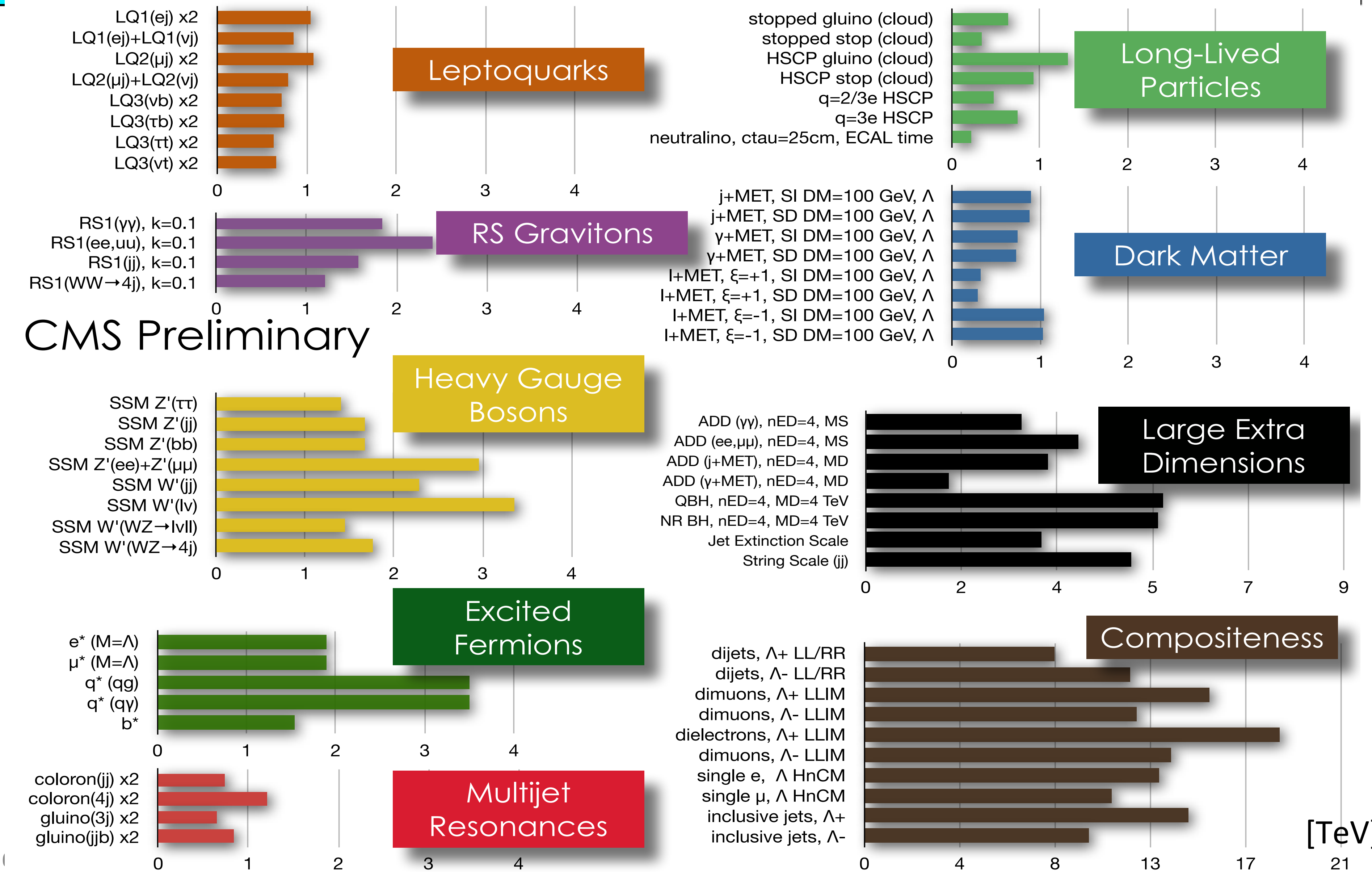
BEYOND the STANDARD MODEL

No guaranteed discoveries!

SUSY Summary

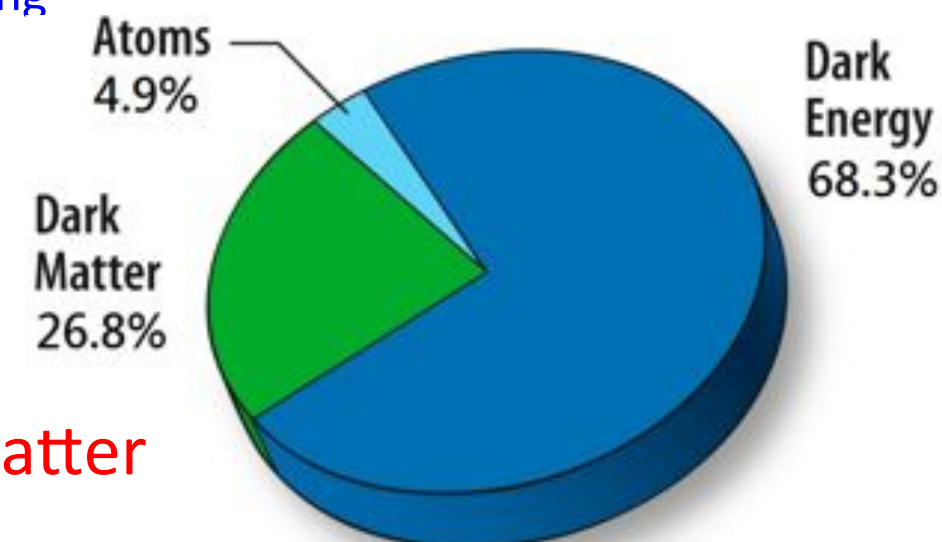


Exotica Physics Summary



Beyond the SM

- So far Higgs boson consistent with SM within the current uncertainties
- Open question remains whether the Higgs is the only responsible for EWSB
- Answers from studies:
  - Higgs properties
  - Direct searches for other Higgs bosons
  - Study of longitudinal vector boson scattering
- Dark matter
  - interacts gravitationally
  - no light emission
- Next new particle ?<=>? Dark Matter
  - Could be produced at the LHC

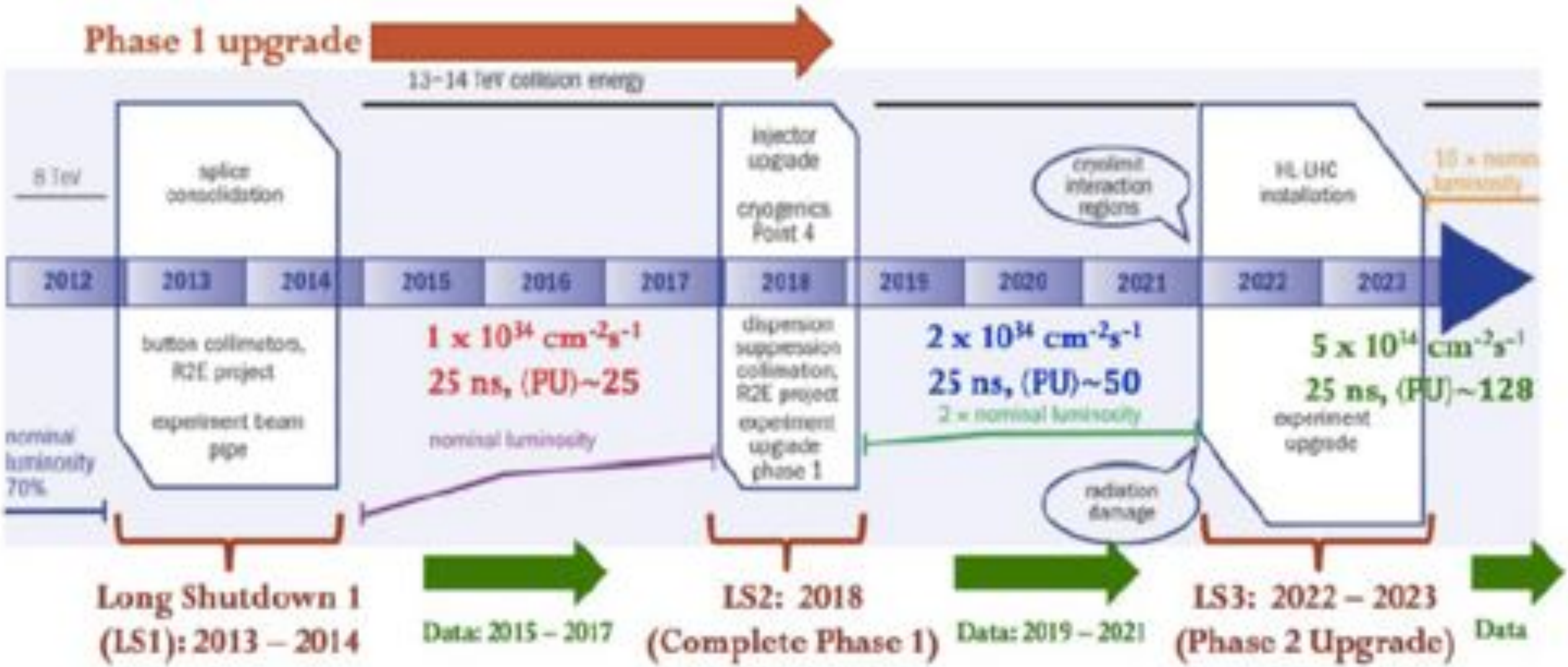


Energy-Mass of the known Universe
TODAY

Towards the Future

- **LHC upgrades and the experimental program on TOP of the priority lists**
  - European Strategy report May 2013
  - US Particle Physics Project Prioritization Panel (aka P5) report May 2014
- Science drivers to be pursued at the LHC
  - Use the Higgs boson as a new tool for discovery
  - Identify the new physics of dark matter
  - Explore the unknown: particles, interactions, and physical principles

LHC Upgrade Plans



2015-2017 and 2018-2021

~**300** fb^{-1} integrated luminosity

>2024 High Luminosity LHC

~**3000** fb^{-1} integrated luminosity

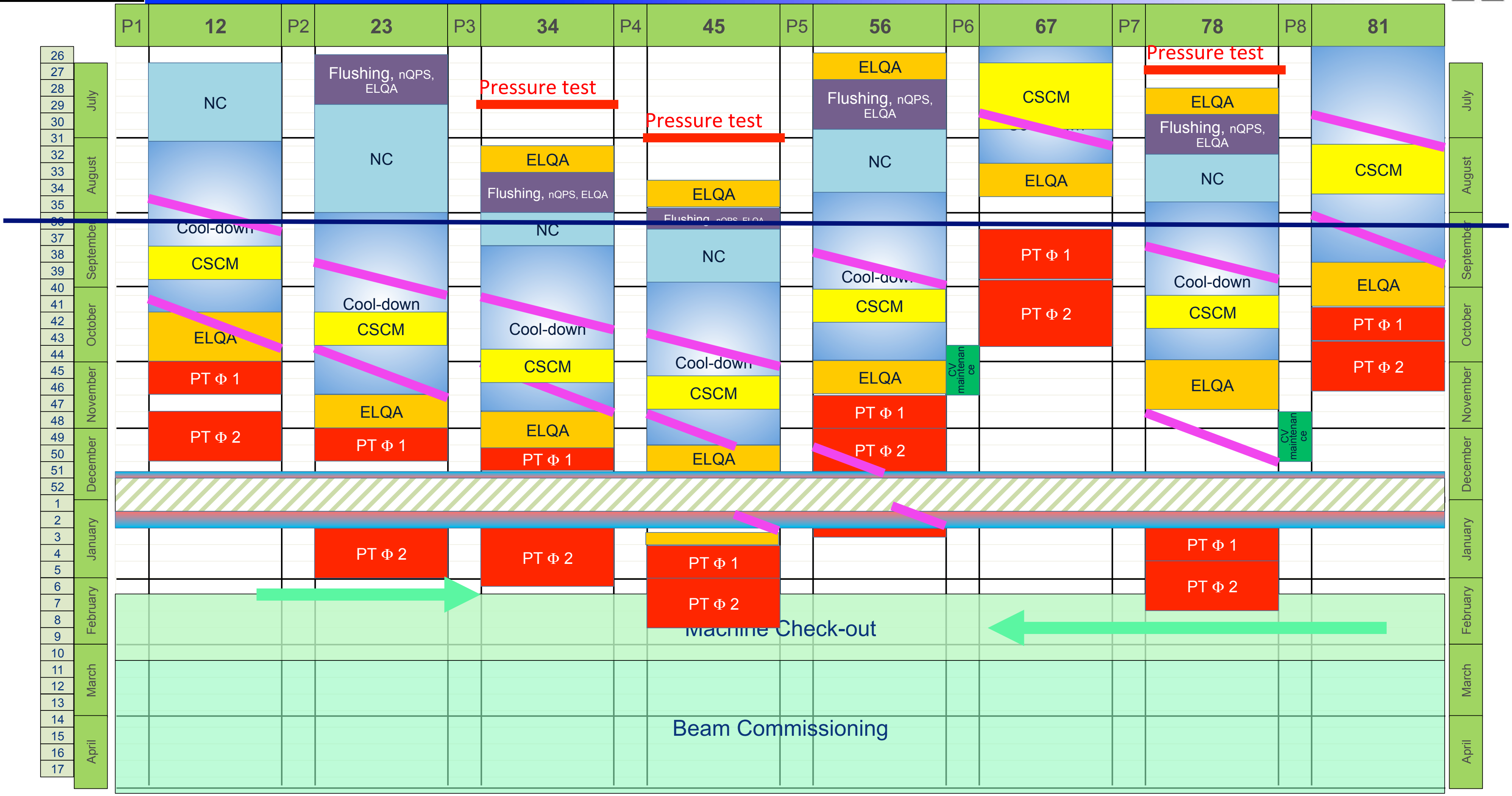
LHC in Run 2

- New possibilities of discoveries of Beyond-SM physics
  - Higher energy, cross section and luminosities
  - But also … higher pile-up, higher trigger rates and data volumes
- Detector improvements to match the LHC challenges:
  - trigger, calorimeters, muons, pixel vtx, tracker

- **Run 1 (2010-2012)**
  - 7 and 8 TeV CM energy
  - Luminosity: **7x 10^{33} cm^{-2}s^{-1}**
  - Pile up: 25 events
  - Integrated luminosity: 30 fb^{-1}

- **Run 2 (start in 2015)**
  - 13 TeV CM energy
  - Luminosity: **16x 10^{33} cm^{-2}s^{-1}**
  - Pile up: 25-50 events
  - Integrated luminosity: 300 fb^{-1}

LHC Schedule V4.1



Safety First, Quality Second, Schedule Third

The First beams starting **on 9th March 2015**

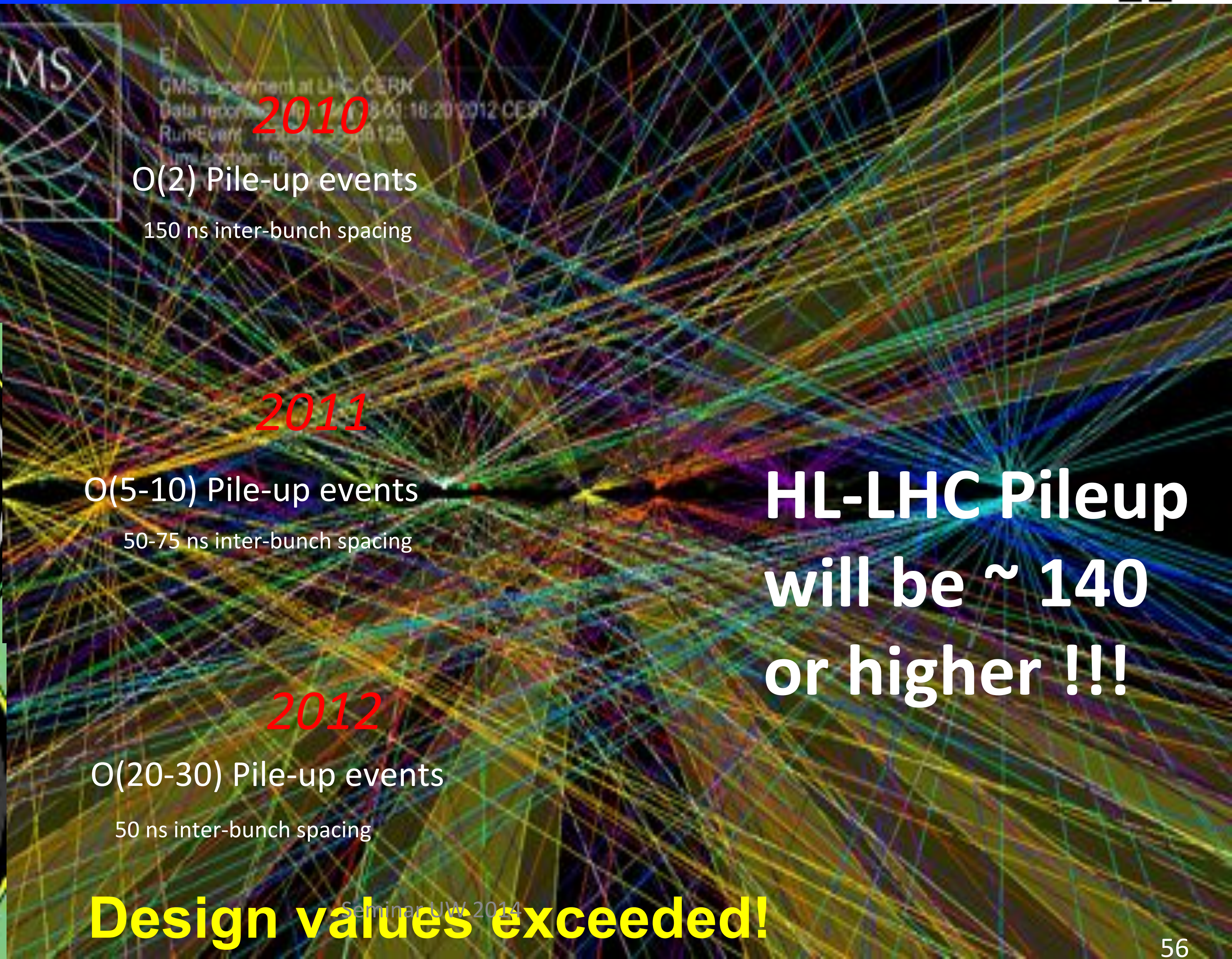
CMS Detector Evolution

- Maintain sensitivity for discovery and precision measurements at low p_T under severe conditions
- CMS Upgrades driving considerations
  - Pile-up: <PU> ~50 by LS2, 60 by LS3; 140 in HL_LHC with lumi $5x10^{34}cm^{-1}s^{-1}$
  - Radiation damage: light loss(calo) and increased leakage currents(tracker)
- CMS detector improvements and upgrades:

  Phase 1(LS1,LS2), Phase 2 (LS3)

  - Regular maintenance /improvements
  - End of hardware support (FPGA) replaced with more powerful components
  - Replacement of components and subsystems subject to accelerated aging due to radiation effects
  - LHC performance well above expectations: ~$1x10^{34}$ $cm^{-1}s^{-1}$ in Run 1

The Pileup challenge



2010

O(2) Pile-up events

150 ns inter-bunch spacing

2011

O(5-10) Pile-up events

50-75 ns inter-bunch spacing

2012

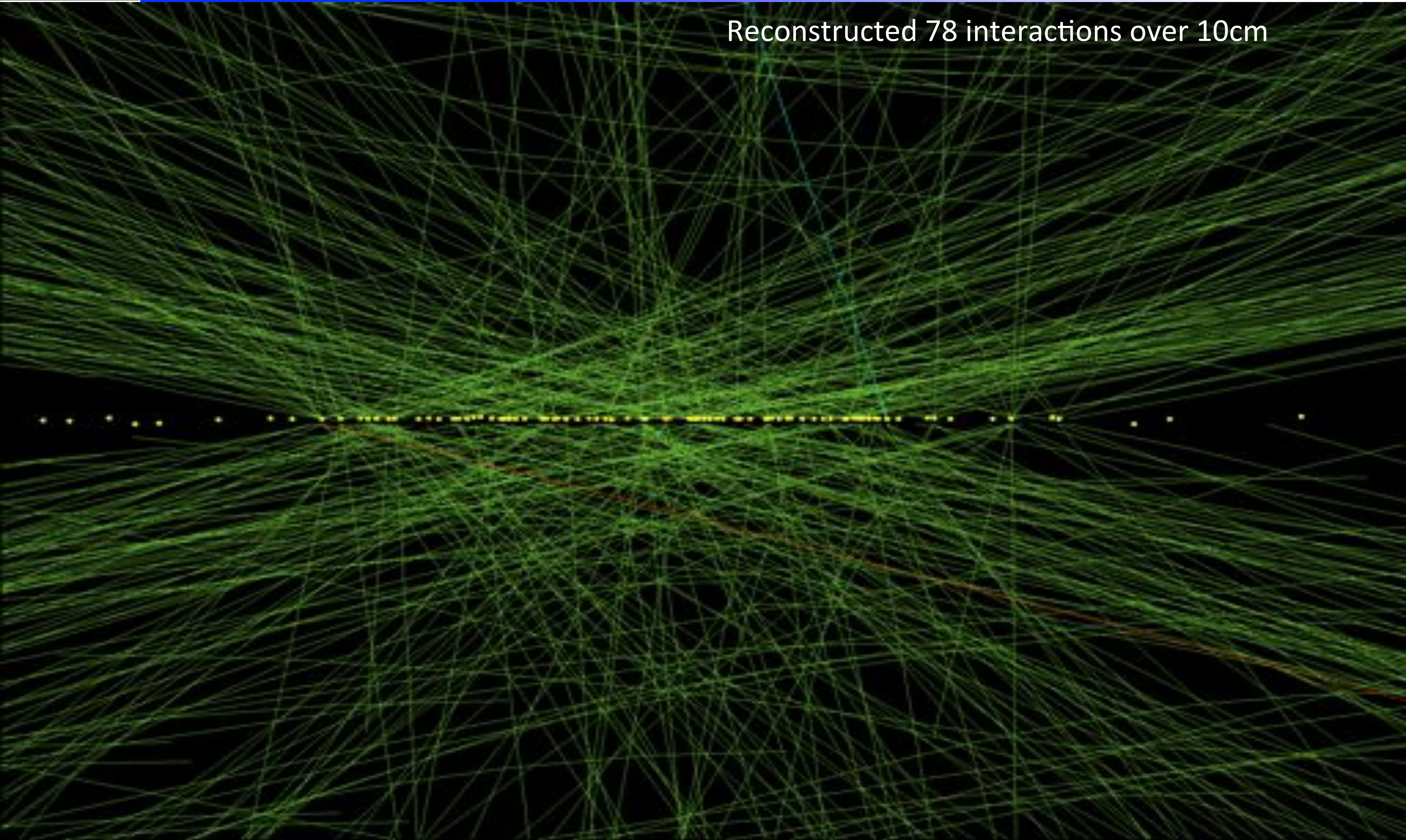
O(20-30) Pile-up events

50 ns inter-bunch spacing

HL-LHC Pileup will be ~ 140 or higher !!!

Design values exceeded!

Pile Up of Multiple Interactions per Crossing



CMS Upgrade Path

LS1
2013-14

LS1 : Prep CMS for ~13 TeV, >1 x 10^{34} Hz/cm^2, <PU> >25, 25ns bunch spacing

- 4^{th} Endcap Muon station, improve readout of CSC ME1/1 & DTs
- Replace HCAL HF and HO photo-detectors
- Tracker operation at -20$\circ$C
- Prepare for further Phase 1 upgrades

LS2
2019

Phase 1 upgrades: Prepare for 1.6 x 10^{34} Hz/cm^2, <PU> ~40, $\leq$200 fb^{-1} by LS2,
and up to 2.5 x 10^{34} Hz/cm^2, <PU> ~ 60, <500 fb^{-1} by LS3

- New L1-trigger system (Calorimeter - Muons - Global) (ready for physics 2016)
- New Pixel detector (installation in technical stop, start of 2017)
- HCAL upgrade: photodetectors and electronics

LS3
2023-25

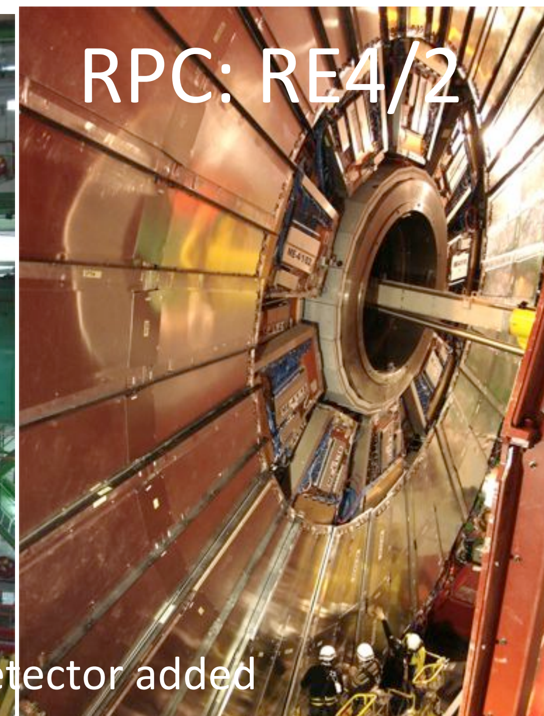
Phase 2 upgrades: $\gtrsim$ 5 x 10^{34} Hz/cm^2 luminosity leveled, <PU> $\gtrsim$ 140
Reach total of 3000 fb^{-1} in ~10 yrs operation

- Replace detector systems whose performance is significantly degrading due to radiation damage
  - Tracker (pixels and strips), Endcap calorimeters
- Maintain physics performance at this very high PU
  - Trigger, electronics, enhanced tracker coverage

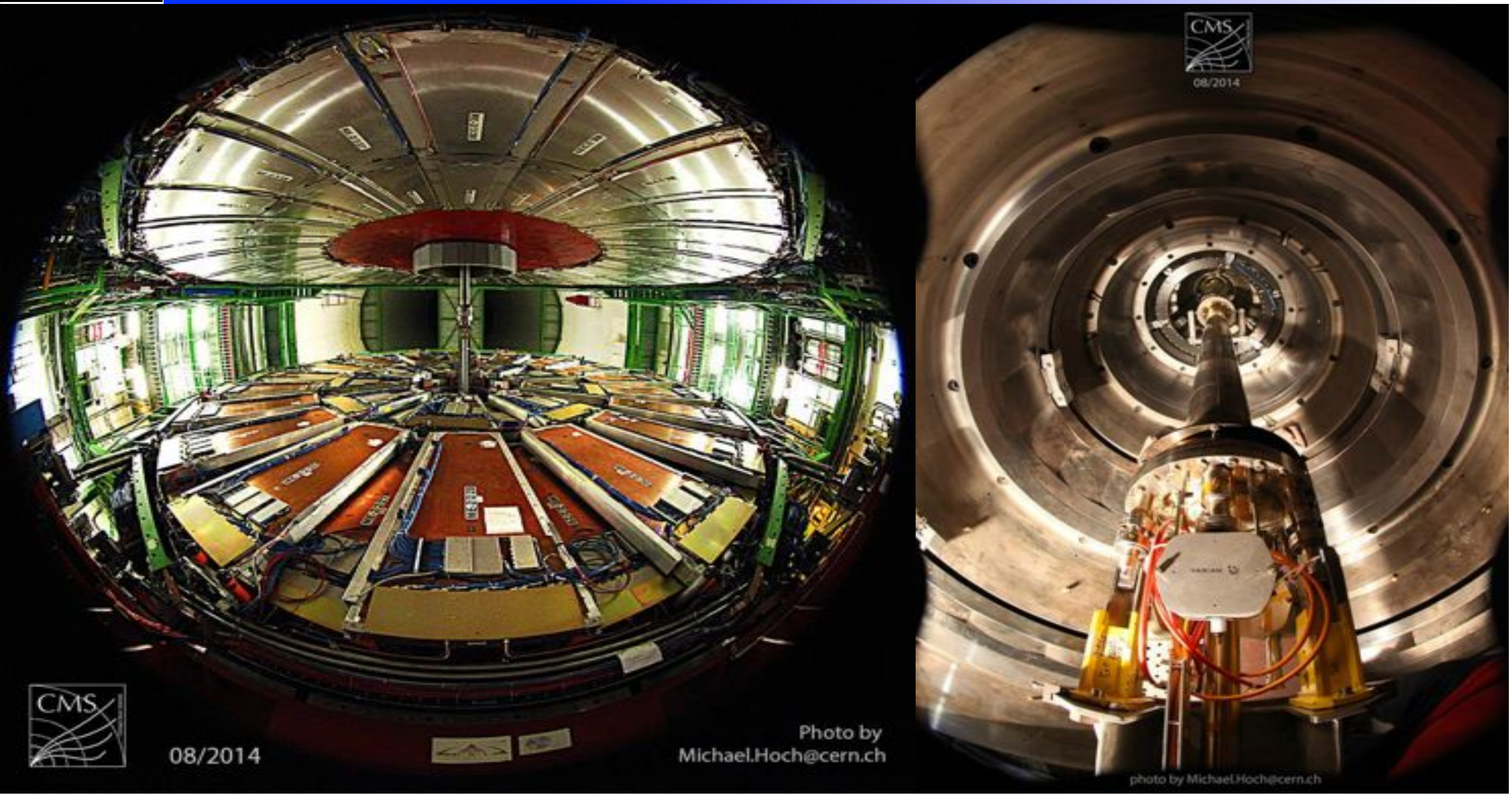
k Tka

CMS Improvements during LS1

- Detector: numerous repairs and improvements
  - HCAL, (new photo-transducers),ECAL, Muons, Tracker, Pixels
  - Beam Instrumentation (Pixel Luminosity Telescope, Beam Loss/Condition Monitors
  - New DAQ2 and Timing and Control System
  - Online/Offline Software updates



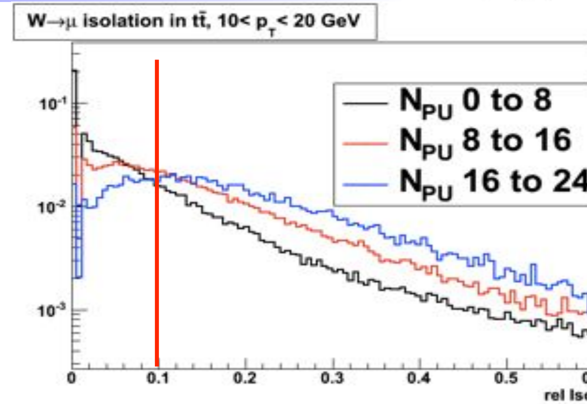
CMS Improvements during LS1

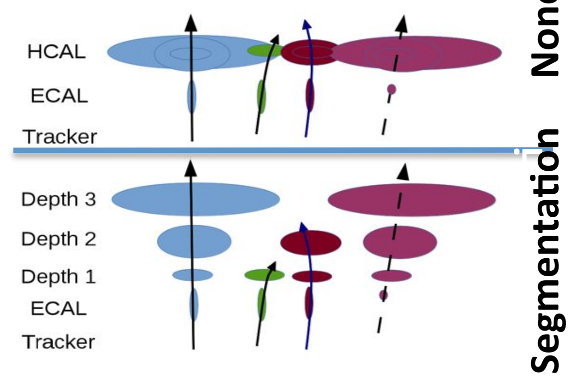


- New reduced diameter beam pipe installed for upgraded pixel detector installation in Year-End-Technical-Stop 2016

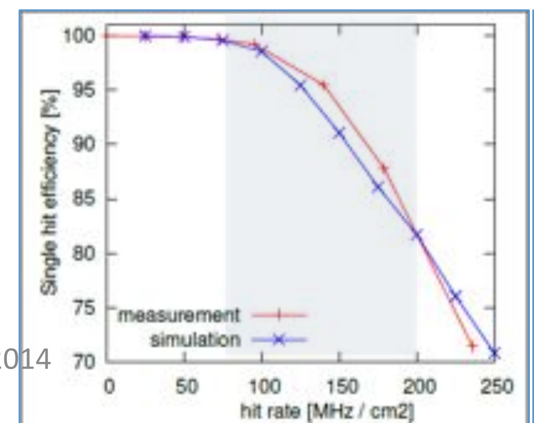
Phase 1 Upgrades - 2018

- HCAL
  - Concerns:
    - gain degradation, discharges, radiation darkening
    - Performance with pile-up: fakes, isolation, leptonID
  - Solutions:
    - Adding depth segmentation
      - Radial correction dependence
      - Better separation and matching to tracks
    - Adding Time information (TDC)
      - Veto pile-up
- Pixels:
  - Concerns:
    - Inefficiency and radiation damage
  - Solutions:
    - Extra-layer and reduced mass
- Trigger:
  - Concerns:
    - Inadequate to handle higher rates/pileup
  - Solutions:
    - Rebuild with high bandwidth optical links, FPGA and improved trigger algorithms

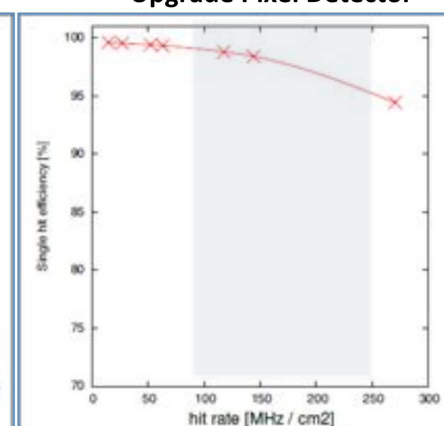




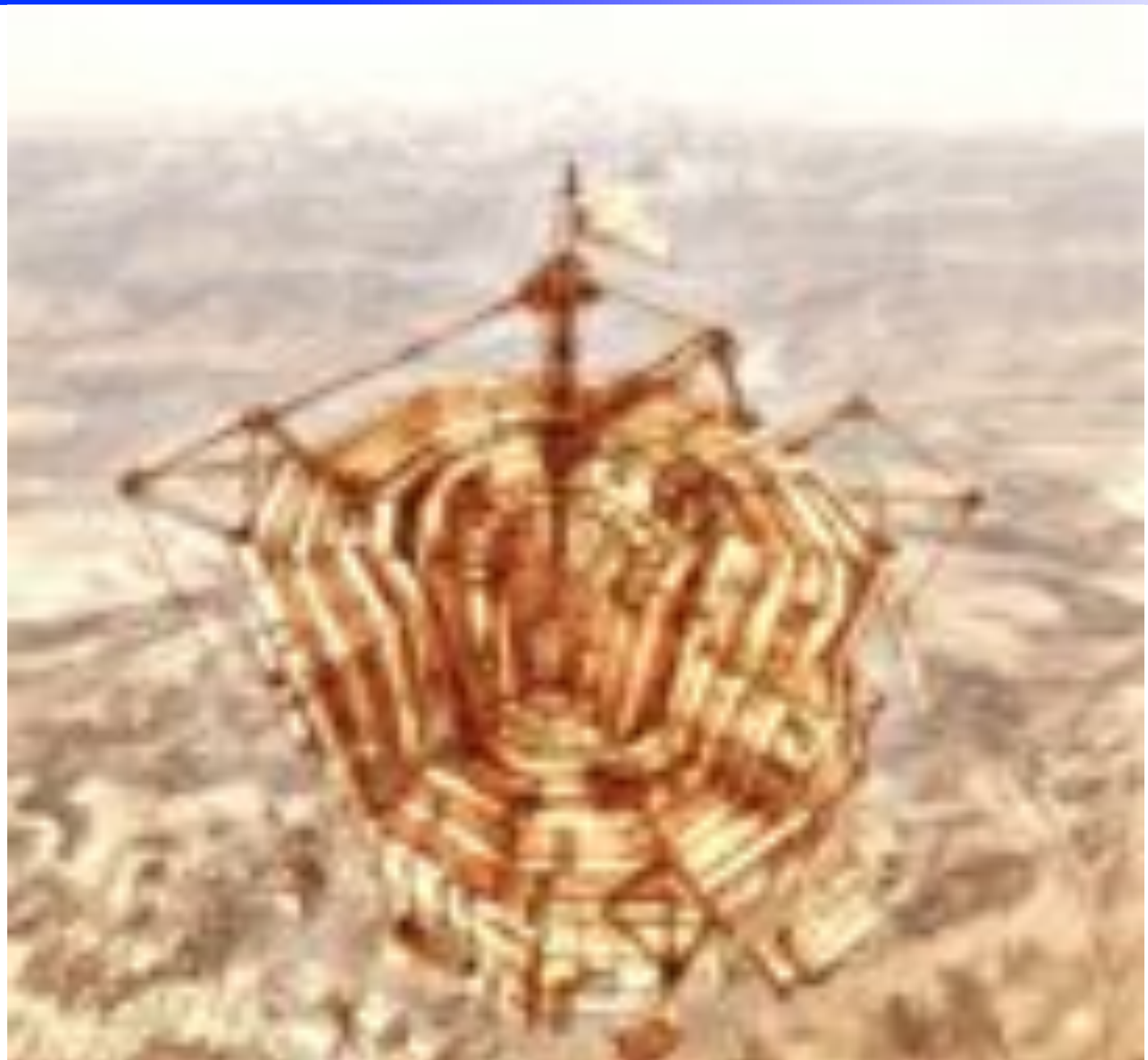
Current Pixel Detector



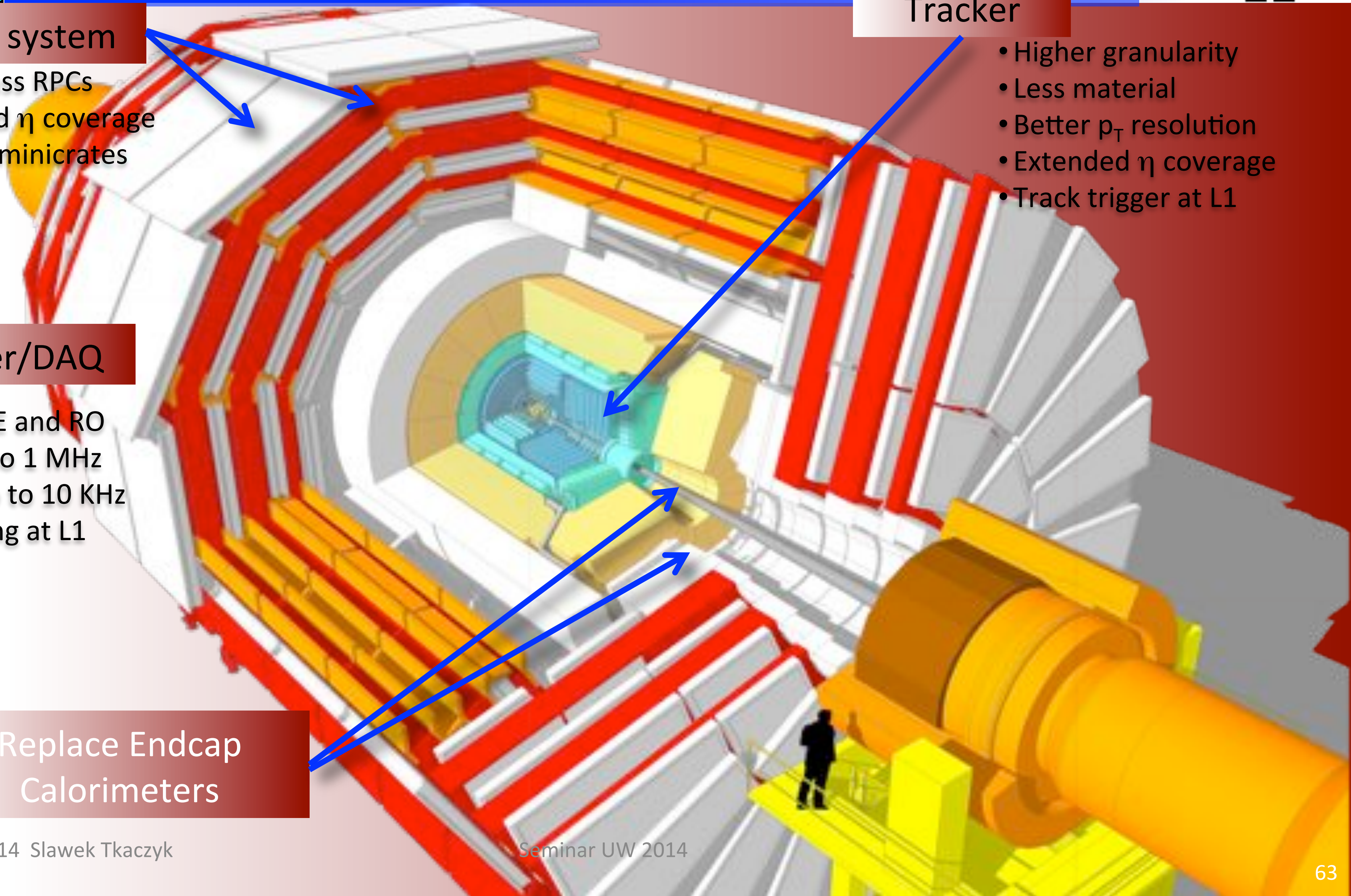
Upgrade Pixel Detector



CMS PHASE 2 Upgrades



Phase 2 Upgrades



Muon system

- GEM Glass RPCs
- Extended η coverage
- New DT minicrates

Tracker

- Higher granularity
- Less material
- Better p_T resolution
- Extended η coverage
- Track trigger at L1

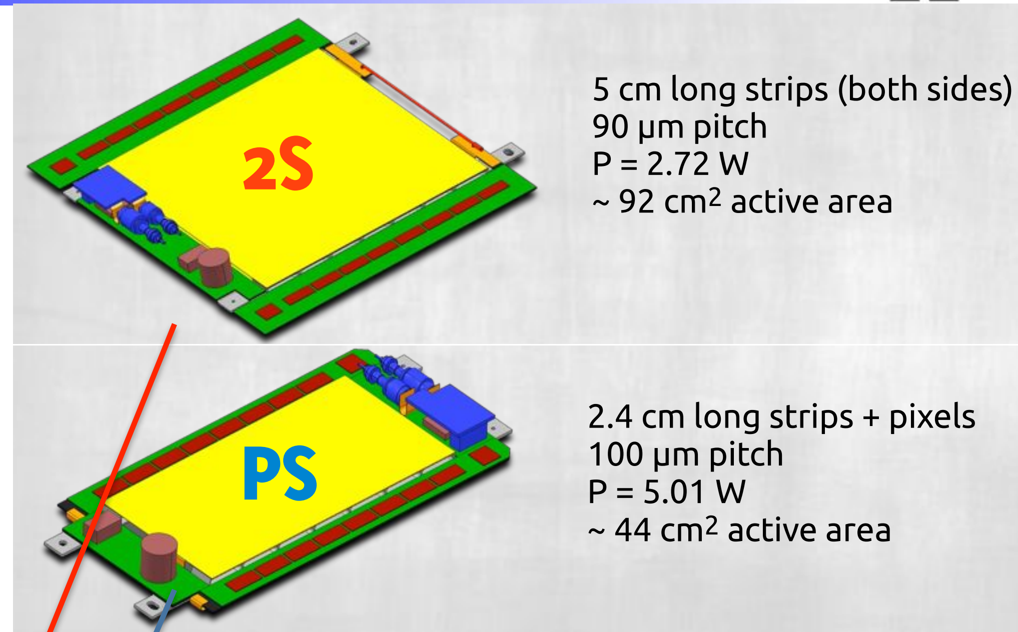
Trigger/DAQ

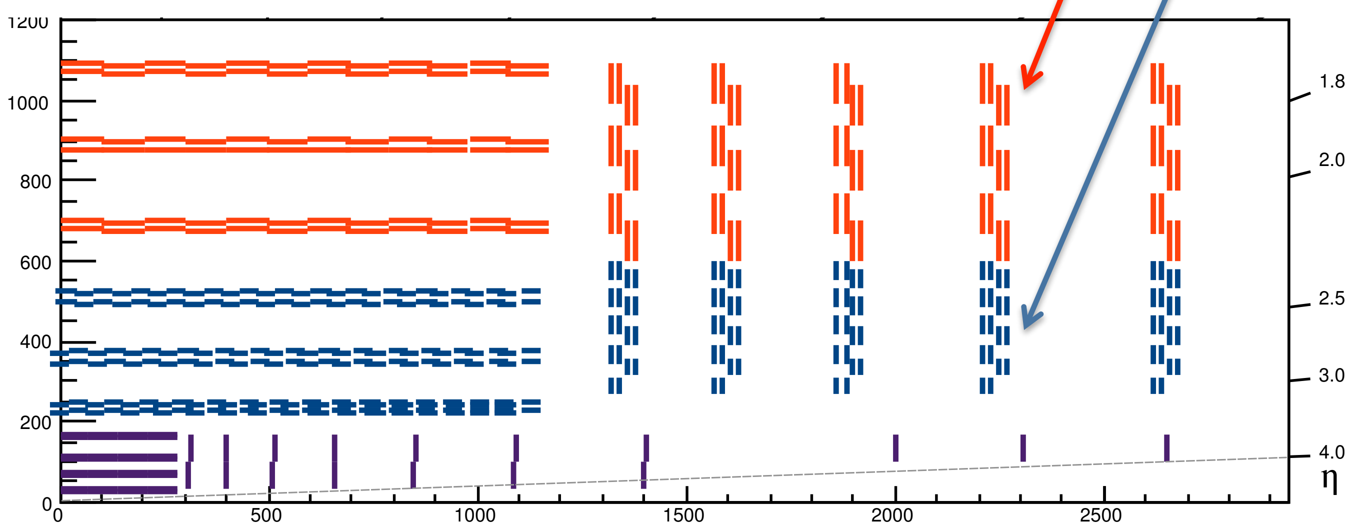
- New FE and RO
- L1 up to 1 MHz
- HLT up to 10 KHz
- Tracking at L1

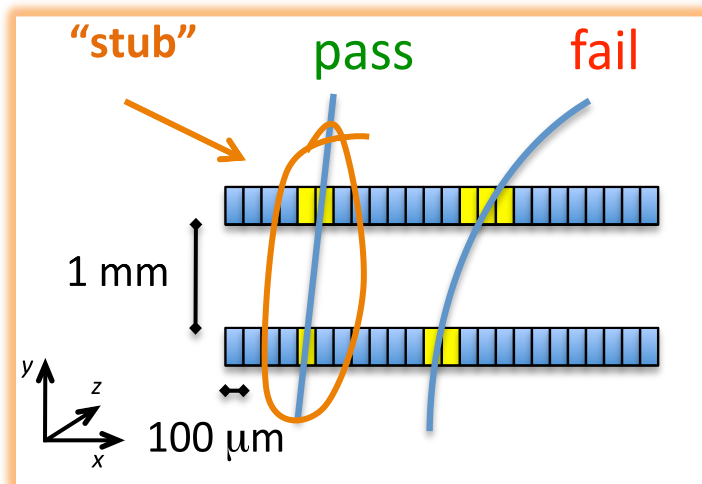
Replace Endcap Calorimeters

Tracker

- Tracker:
  - Higher granularity
  - Less material
  - Radiation tolerant
  - Provide L1 trigger info at 40MHz and p_T>2 GeV
- Pixels: 100um thick
  - 4 barrel layers
  - 10 disks covering up to $|\eta| = 4$

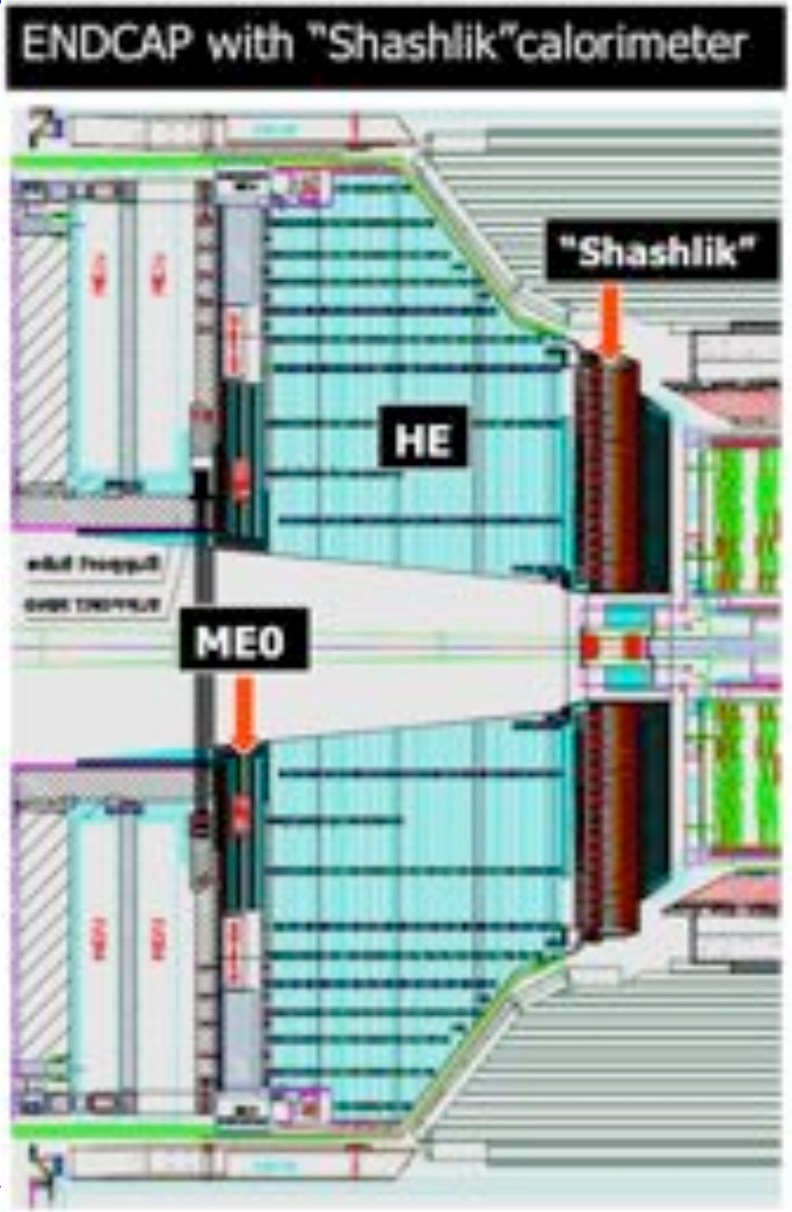


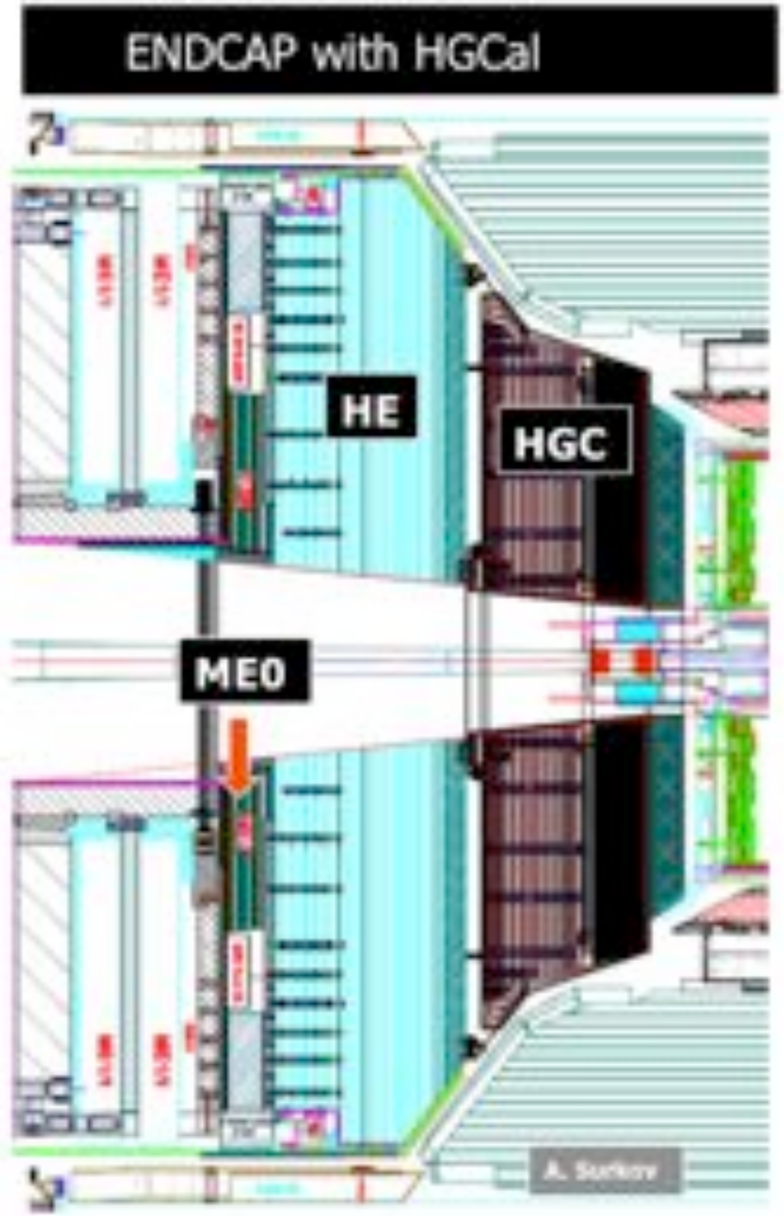




EndCap Calorimeter Upgrade

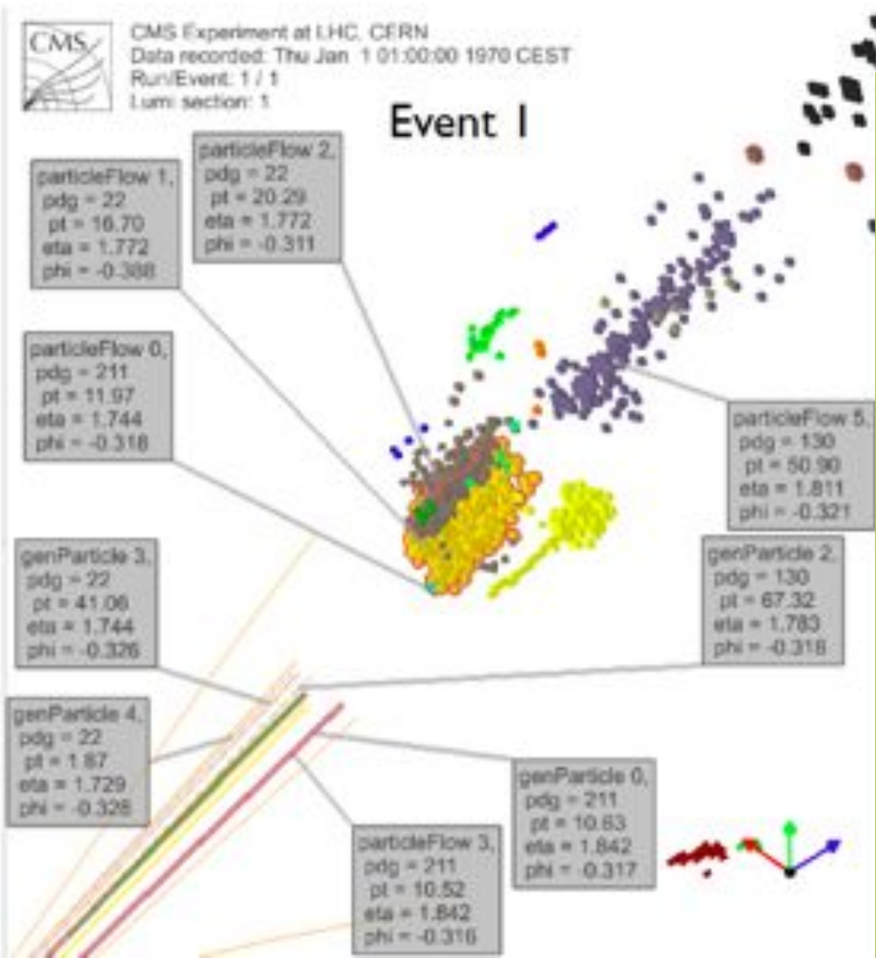
EndCap Calorimeter Rebuild

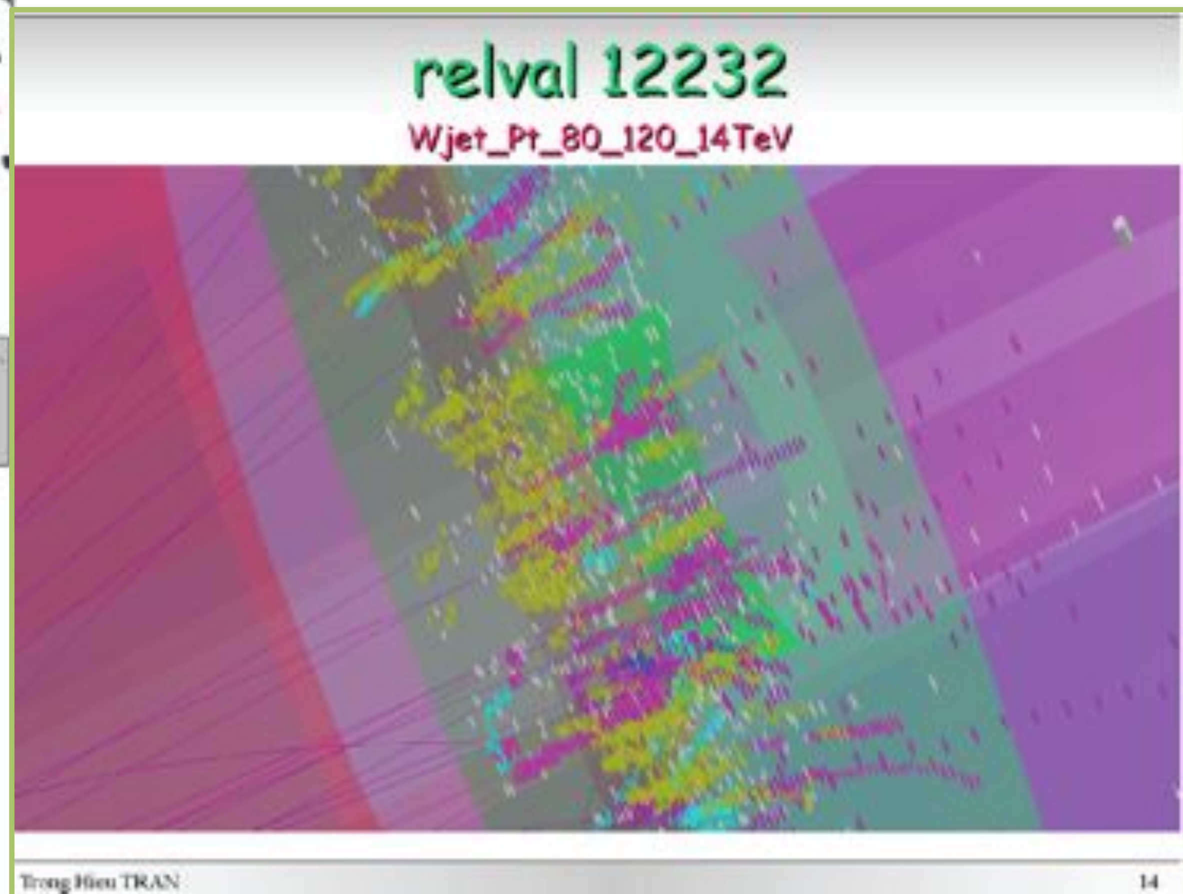




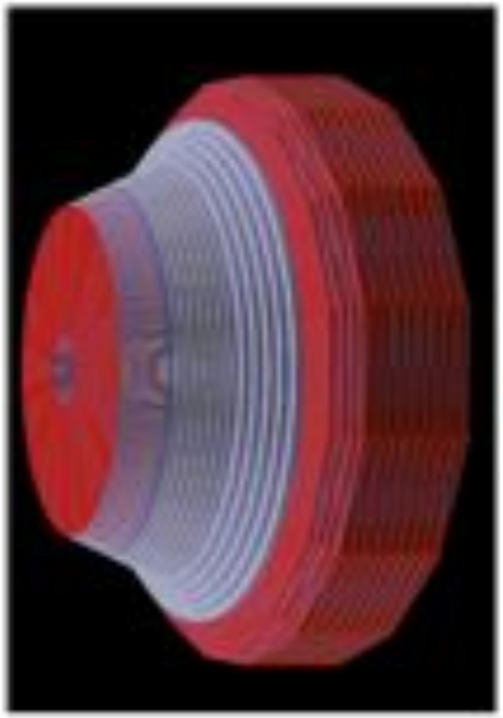
End-Cap Calo Upgrade: HGCAL

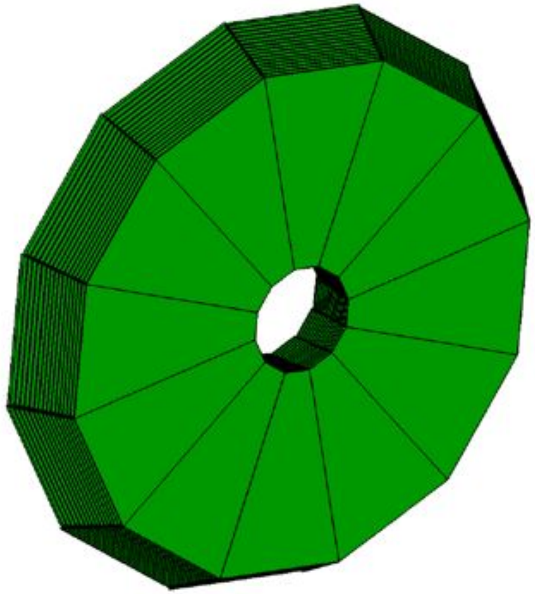
- Si-High-Granularity-Calo extends Tracking into Calorimeter
  - Good cluster energy resolution, with detailed topological information
  - Ideal for Particle Flow reconstruction in a high density environment

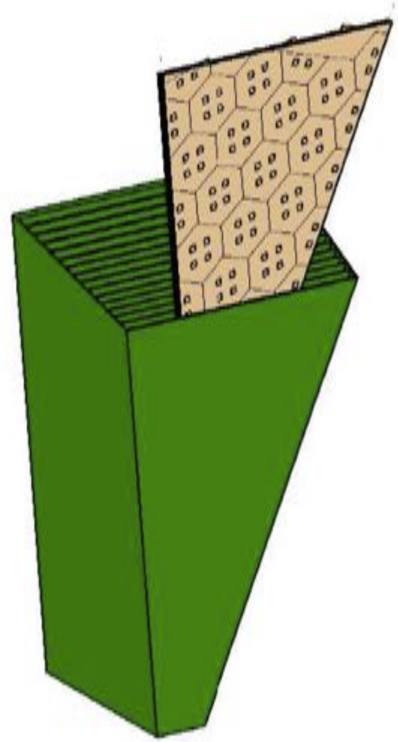


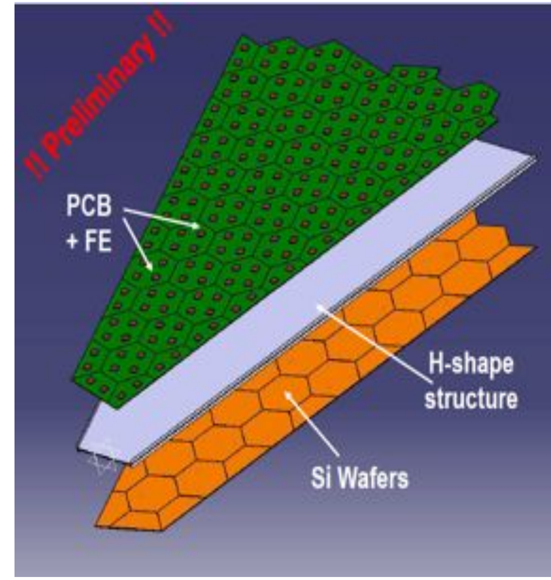


End-Cap Calo Upgrade: HGCAL

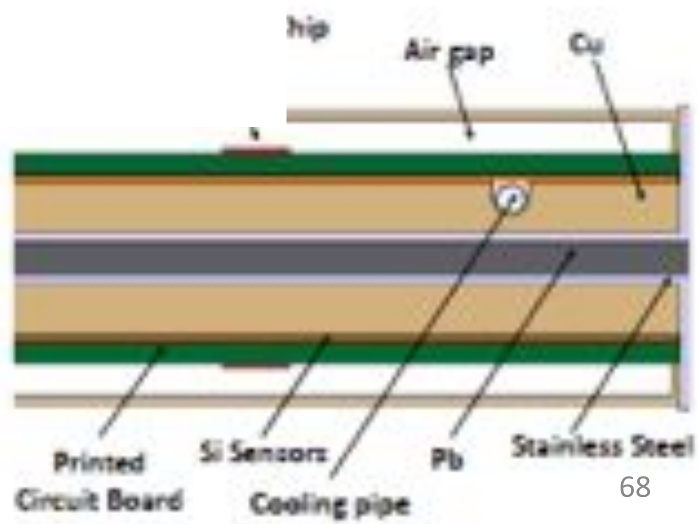






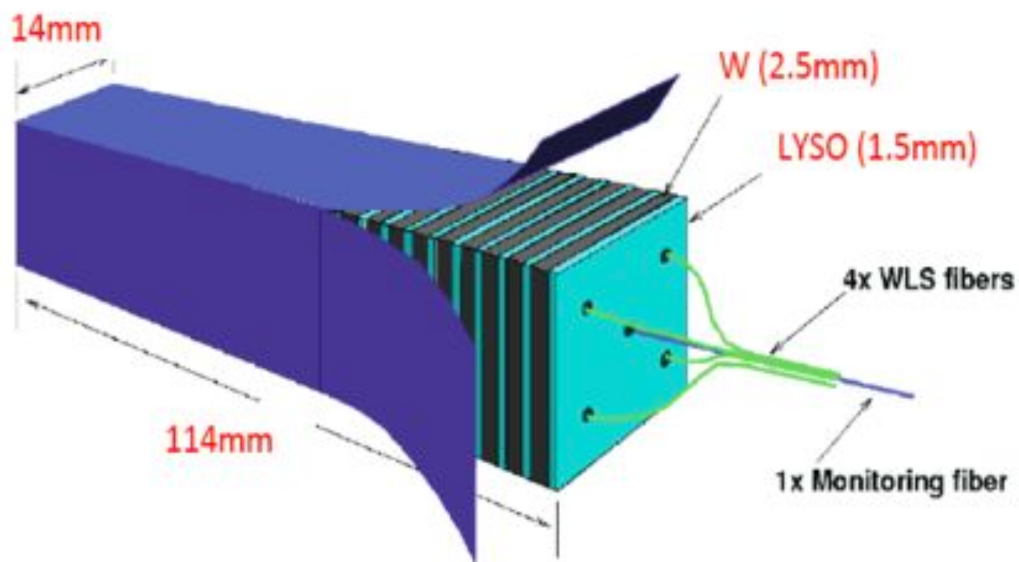


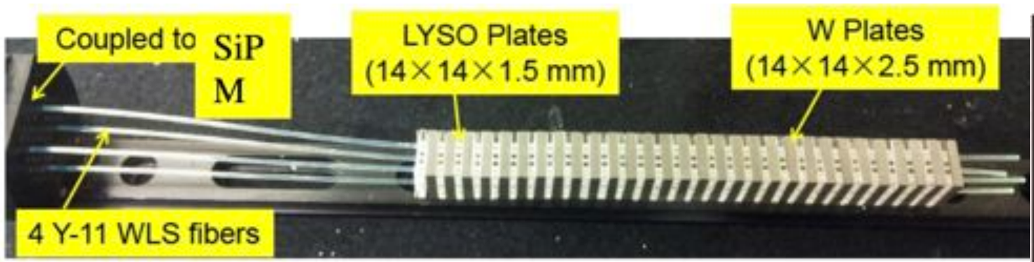
- Power:
  - Barrel: ~100W/m^2 (300um sensors and ~cm^2 cell size)
  - End-Cap: ~250W/m2 (100um sensors and ~0.5cm^2 cell size)
- Si Operating temp.: -30C (-35C if possible)
- Data transfer rates:
  - ~1 to 8 Gbps/Module at high $|\eta|$

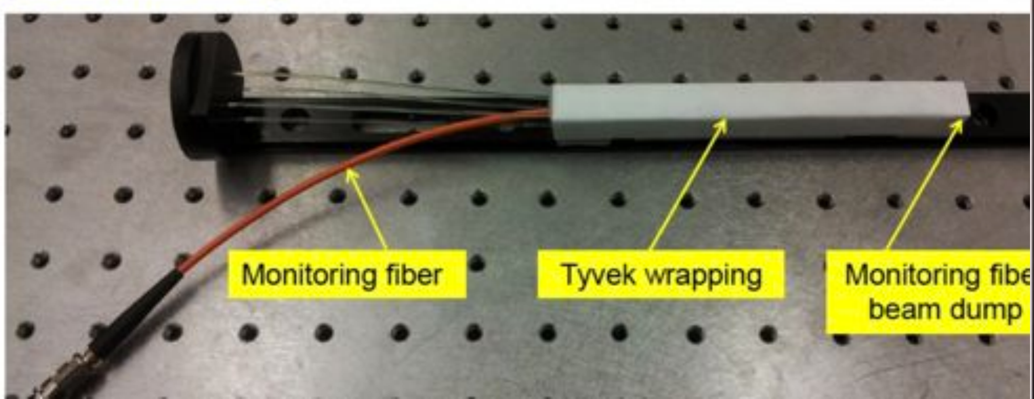


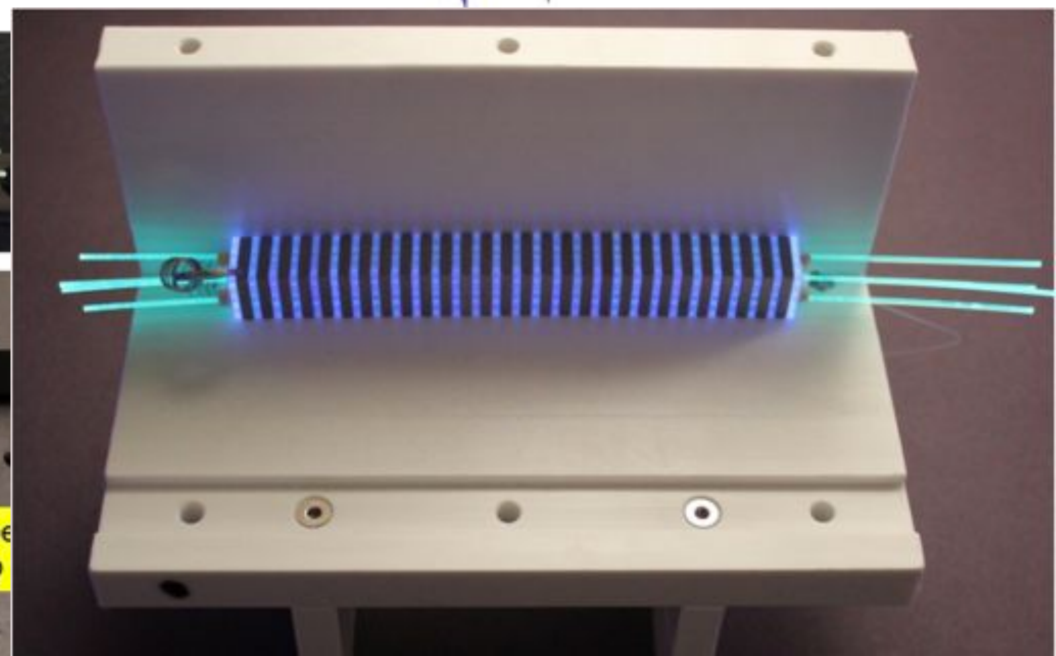
End-Cap Calo Upgrade: Shashlik

- Good energy resolution
- Fine granularity
- Capillary WLS
- LYSO(YE3) crystals

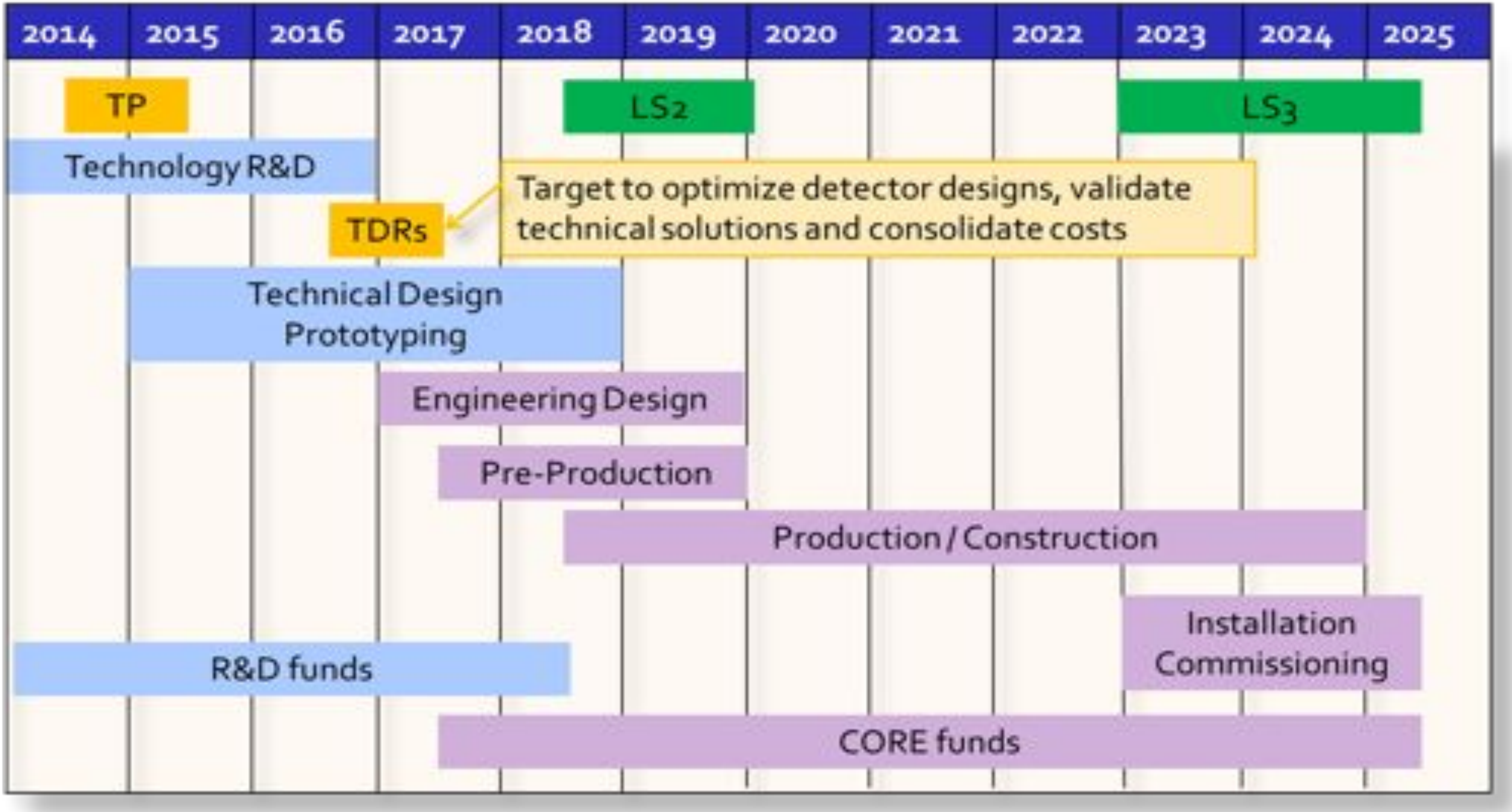








CMS Phase 2 Upgrade Plan



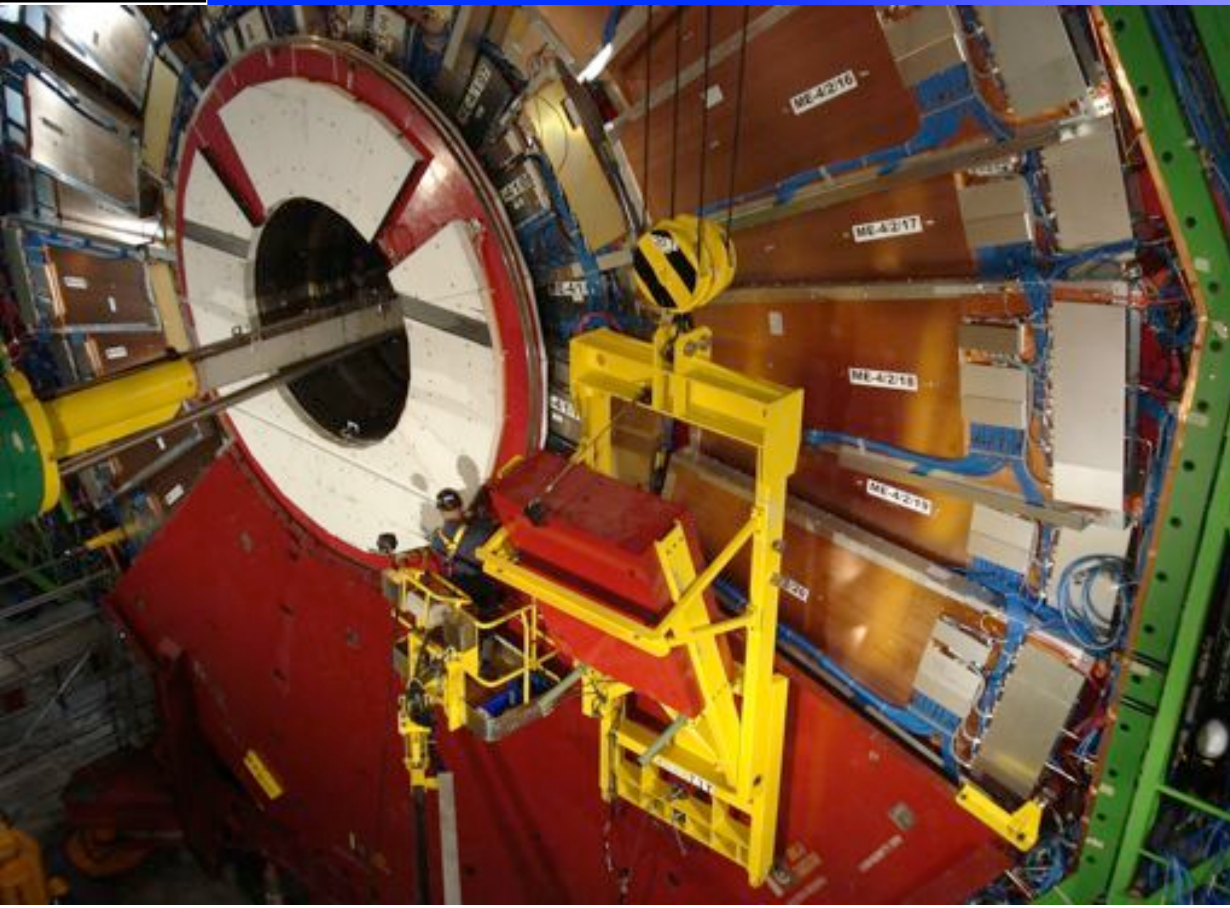
SUMMARY

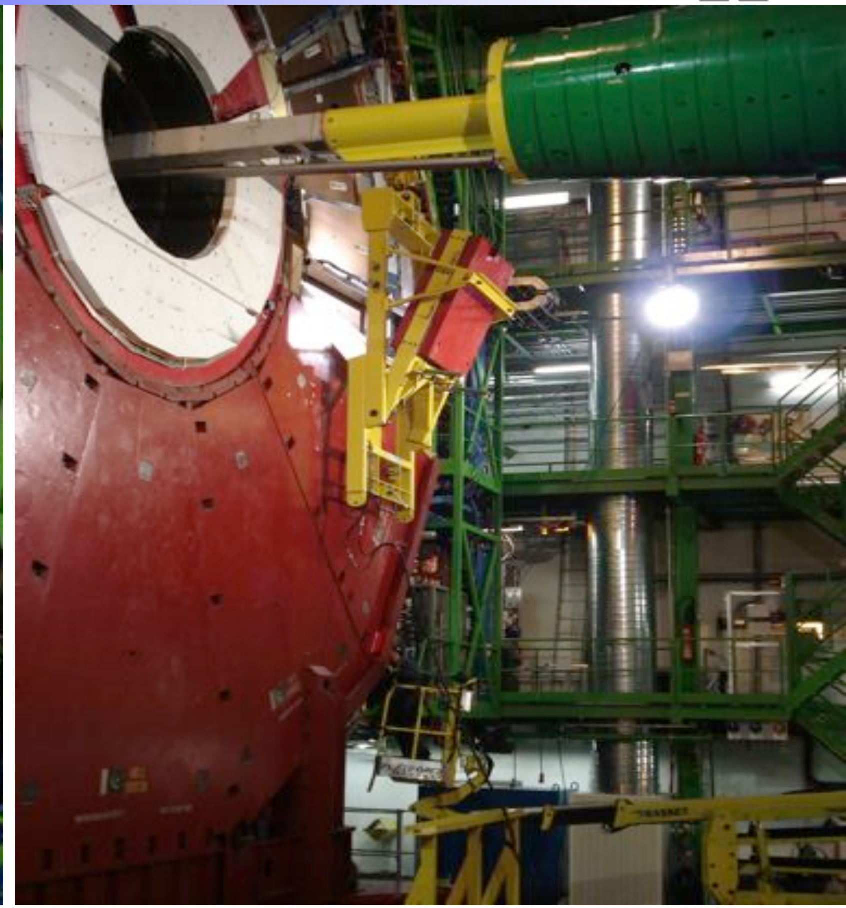
- LHC Run 1 provided many interesting results
  - led to the discovery of a Higgs boson and the first measurements of its properties
  - Higgs boson compatible with the Standard Model
  - other physics results show no deviations from the SM

- Understanding of the EWSB and searches of new physics will benefit from the future LHC runs and the Detector upgrades.

Additional Slides

CMS Improvements during LS1





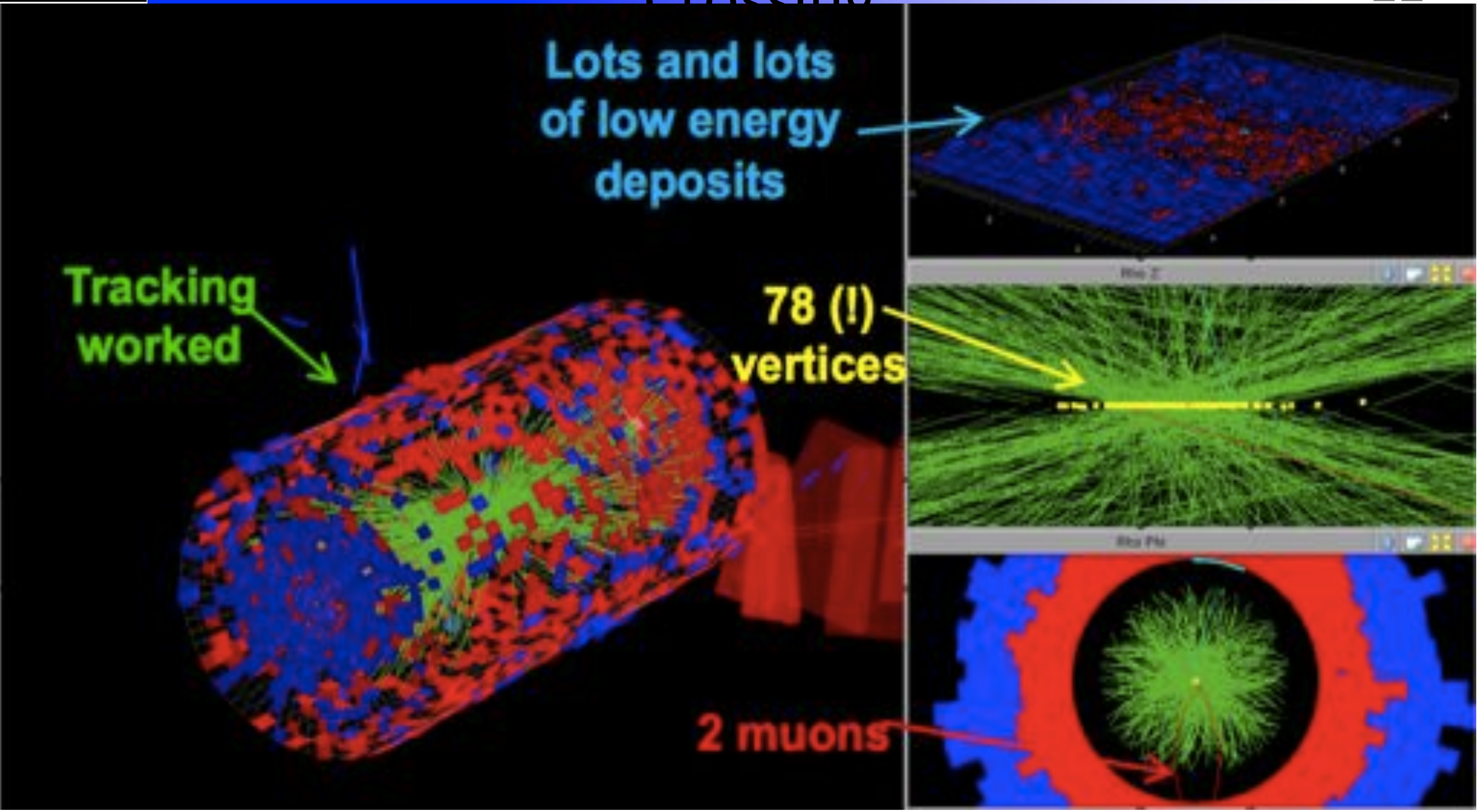
- New Shielding walls (disks) YE4 installed in both endcaps

Higgs Couplings

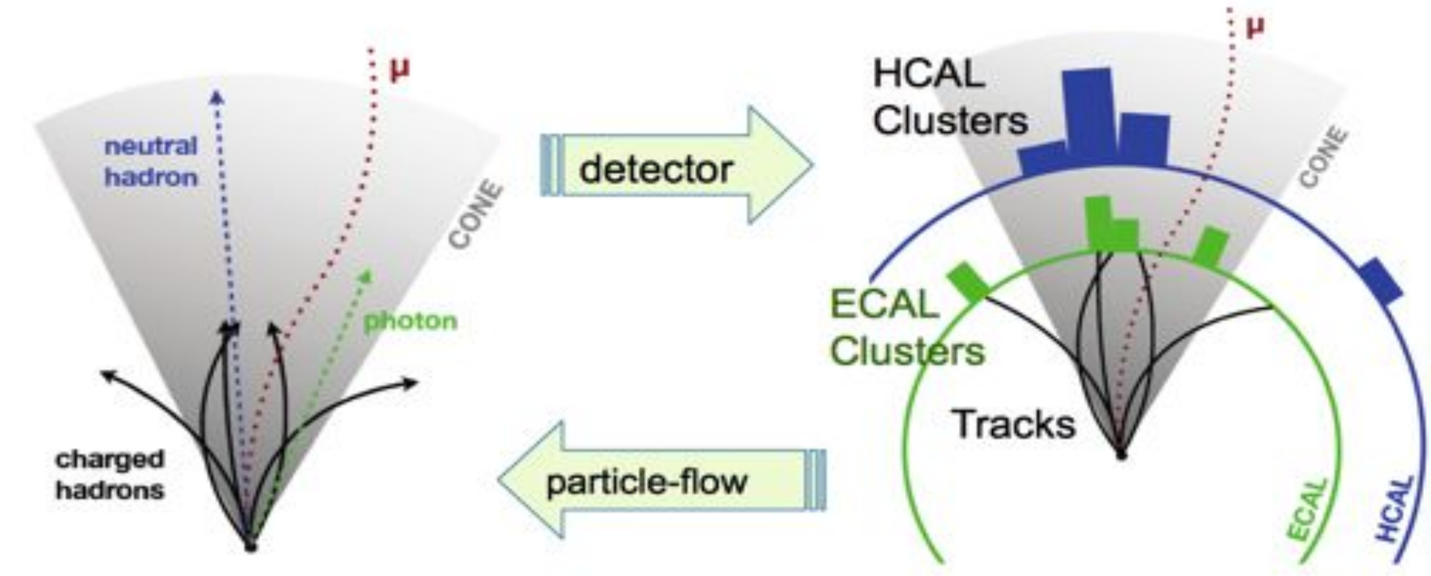
- HXSWG prescription: arXiv:1209.0040
- Assumptions:
  - Narrow Width Approximation: $\sigma \times \beta_i = \sigma_i \times \Gamma_i / \Gamma_H$
  - parameterize deviations from the SM in production, decay and total width
  - SM modifiers: $\kappa_i^2 = \sigma_i / \sigma_i^{SM}$ and $\kappa_i^2 = \Gamma_i / \Gamma_i^{SM}$
  - Implies precise knowledge of the SM predictions

- Probing beyond the SM physics effects:
  - Simultaneous fit of all couplings with assumption on the total width
  - SM only or new physics in the loops or width (with H invisible decay)
  - Search for new physics in loops: κ_γ, κ_g, BR_{BSM}
  - H coupling to fermions and V bosons: κ_V, κ_f,
  - Probing asymmetries: κ_W/κ_Z; κ_u/κ_d, κ_l/κ_q
  - Overall scaling of signal strength: μ

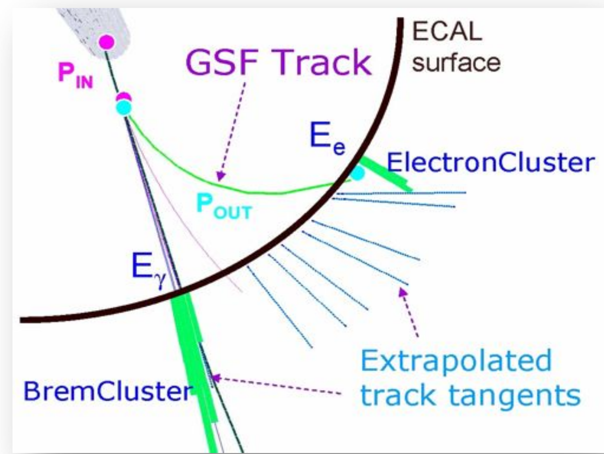
Pile Up of Multiple Interactions per Crossing



Global Event Reconstruction



Electron



- **Exploitation of CMS granularity and high magnetic field**
- Optimized combination of information from all subdetectors
- Lists reconstructed particles: **e,μ,γ**, **charged** and **neutral** hadrons
- Used in the analysis like MC generated particles
- Used as building blocks for **Jets, τ's, Missing Transverse Energy-MET, Isolation and Pile-Up particle identification**

Tau