Measurement of properties of Higgs boson in four-lepton final state at $\sqrt{S}$ = 13 TeV

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Outline

- Motivation
- Object selections
- Event reconstruction and selections
- Observables and categorization
- Background estimation
- Systematics Uncertainties
- Results
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  - Combination based on 2016 and 2017 data
- Conclusion

Motivation

➢ Standard model of particle physics

- Describle elementary particles and interactions except for gravity
- Local gauge symmetry assumed for interaction generation enforces massless particles contradicting with W and Z boson

➢ Using Higgs mechanism found in 1964

- Generate W/Z mass through spontaneous electroweak symmetry breaking
- Predict a scale field responsible for boson mass and would also for fermion mass by adding Yukawa interaction

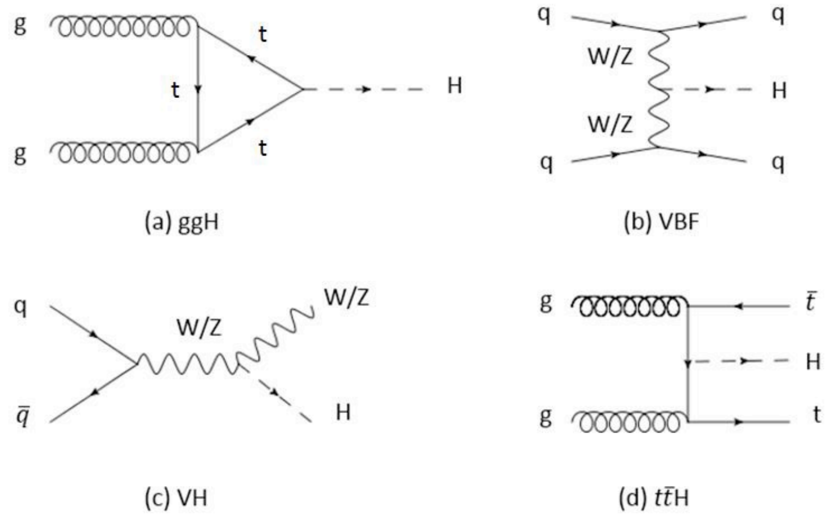
➢ Higgs boson

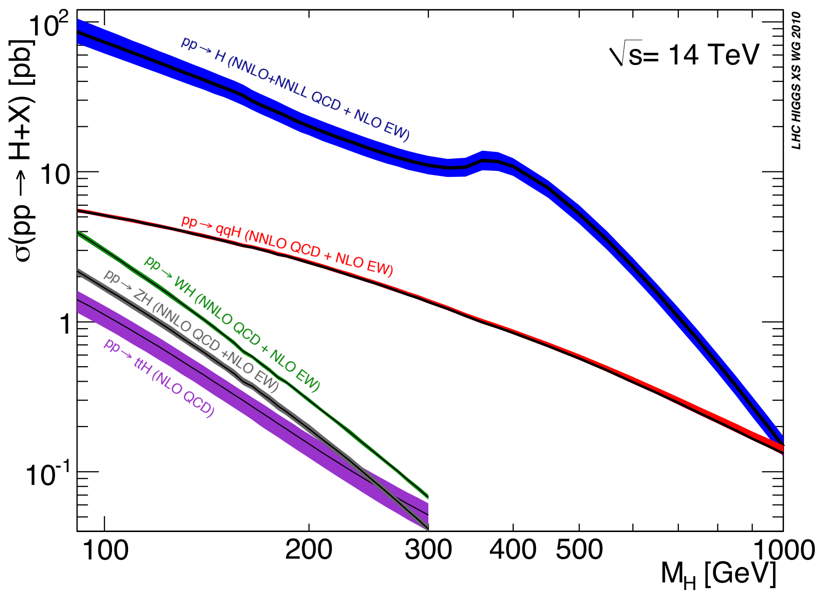
- Particle corresponding to excitation of the scalar field
- Coupling to boson/fermion proportional to boson mass squared/fermion mass
- Mass M_H unknown
- Key to verify the current understanding of boson/fermion mass generation

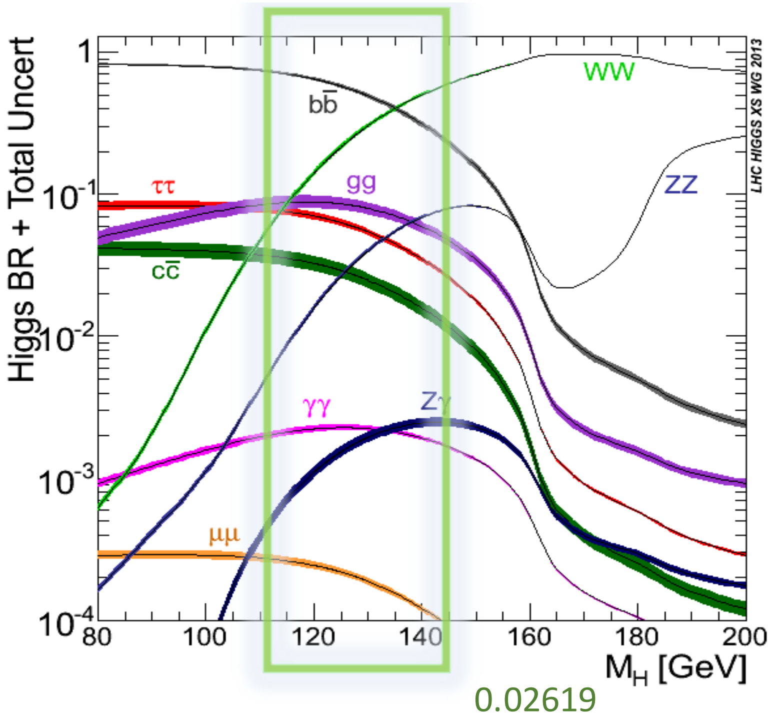
➢ Experimental observation of the Higgs boson

- 4th July 2012, CMS experiment together with ATLAS experiment at LHC announced the discovery of Higgs boson-like particle
- $\sim 5.0\ \sigma$ combined with data of 5.1 fb^{-1} (7TeV) +5.3 fb^{-1} (8TeV)

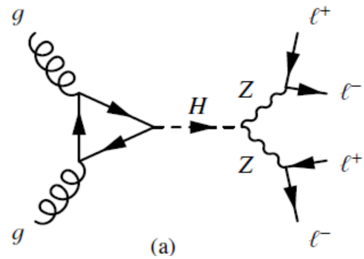
Higgs Production and Decay at LHC







- In spite of low BR, Higgs to 4l channel is one of the most important channel to measurement properties. (mass, spin-parity, width, fiducial cross section)
- A large signal-to-background ratio
- Complete reconstruction of final state decay products
- Excellent lepton momentum reconstruction



Objects

➢ Selected electrons

- Loose electrons
  - $P_T > 7\text{GeV}; |\eta| < 2.5$
  - $d_{xy} < 0.5\ cm;\ d_z < 1\ cm; SIP_{3D} < 3$
- BDT ID+Iso in 6 ($|\eta|$, P_T)bins

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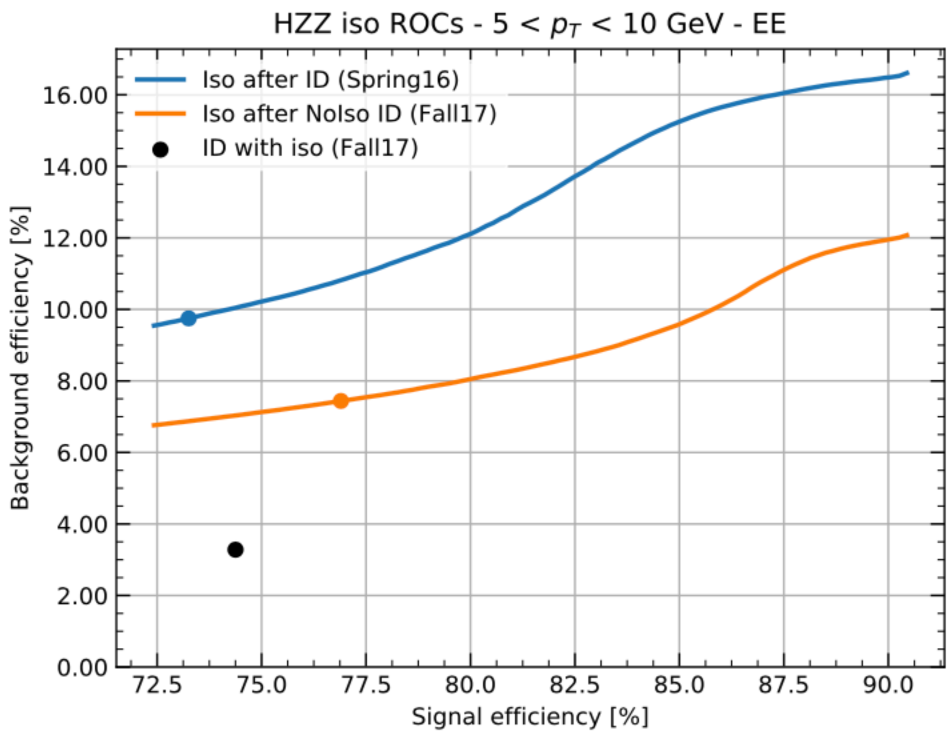
- Significant reduction of election fakes thanks to the new BDT and pixel detector upgrade.

➢ Selected muons

- Loose electrons
  - $P_T > 5\text{GeV}; |\eta| < 2.4$
  - $d_{xy} < 0.5\ cm;\ d_z < 1\ cm; SIP_{3D} < 3$
- PF D and tracker high P_T ID
- RelPFIso($\Delta R = 0.3$)< 0.35

➢ FSR photon

- $P_{T,\gamma} > 2$ GeV;$|\eta^{\gamma}| < 2.4$;relPFIso<1.8
- Electron SC veto by PF reference
- Associated γ to the closest loose lepton
- $\Delta R(\gamma, l) < 0.5; \frac{\Delta R(\gamma,l)}{E^2_{T,\gamma}} < 0.012$; choose photon with lowest $\frac{\Delta R(\gamma,l)}{E^2_{T,\gamma}}$
- Remove selected FSRs from lepton isolation cone for all loose leptons



➢ JETS

- AK4 PFCHs jets, JEC_v6
- $P_T > 30$ GeV; $|\eta| < 4.7$; Tight PF jet ID
- Cleaned $\Delta R(jet, l/\gamma) > 0.4$
- Tight PU Jet ID
- B-tagger:
  - new b-tagged algorithm: DeepCSV medium WP = 0.4941
  - B-tagging SF applied

Event reconstruction and selections

- Z candidate
  - Any OS-SF pair that satisfy $12 < m_{ll(\gamma)} < 120$ GeV

- Build all possible ZZ candidates defined as pairs of non-overlapping Z candidate; define Z_1 candidate with $m_{ll(\gamma)}$ closest to the POG m(Z) mass
  - $m_{Z1} > 40$ GeV; $P_T(l1) > 20$ GeV; $P_T(l2) > 10$ GeV
  - $\Delta R > 0.02$ between each of the four leptons
  - $m_{ll} > 4$ GeV for OS pairs (regardless of flavour)
  - Reject 4μ and 4e candidates where the alternative pair Z_aZ_b satisfies $|m_{Z_a} - m_Z| < |m_{Z_1} - m_Z|$ and $m_{Z_b} < 12$ GeV
  - $m_{4l} > 70$ GeV
- If more than one ZZ candidate is left, choose the one of highest $\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}$.
- If $\mathcal{D}_{\mathrm{bkg}}^{\mathrm{kin}}$ is the same, take the one with Z_1 mass closest to m_Z.

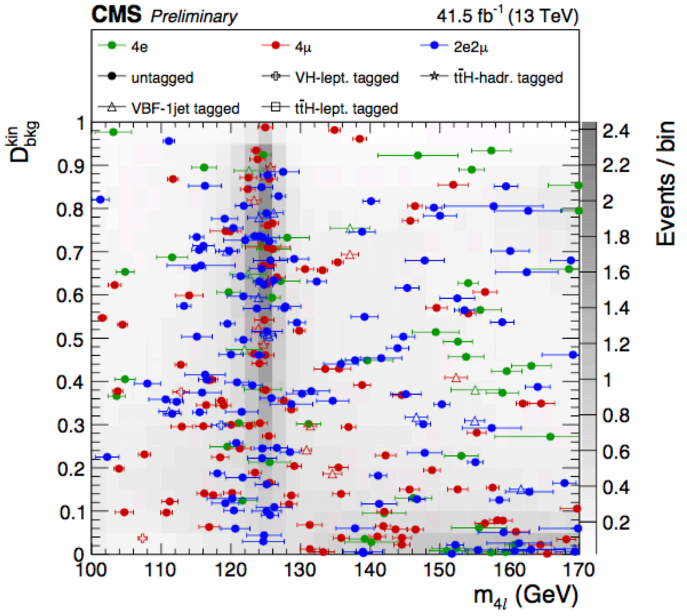
Observables

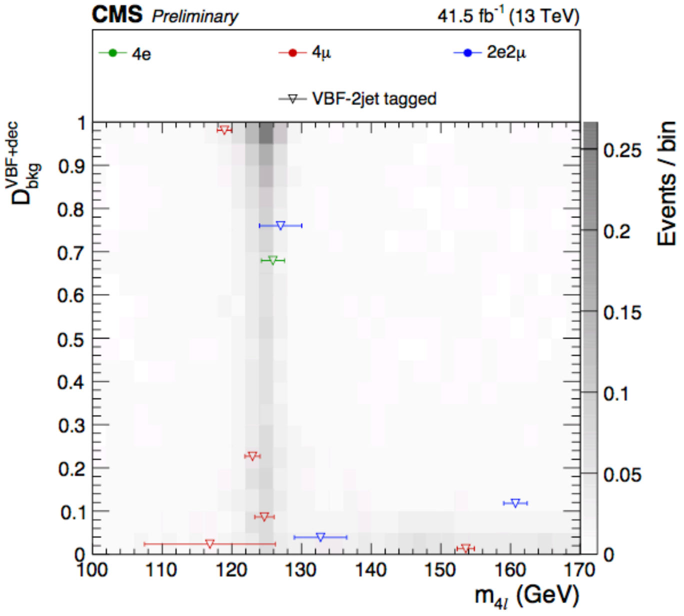
- Two observables used: m_{4l}; kd
- Three different kd discriminant applied.
  - Discriminant sensitive to $gg/q\bar{q} \rightarrow 4l$ kinematics
  - New dedicated production-dependent $\mathcal{D}_{\rm kgd}$ discriminants used in VBF-2jet tagged and hadronic VH tagged categories
- An improvement in sensitivity of about 10 to 15% was observed.

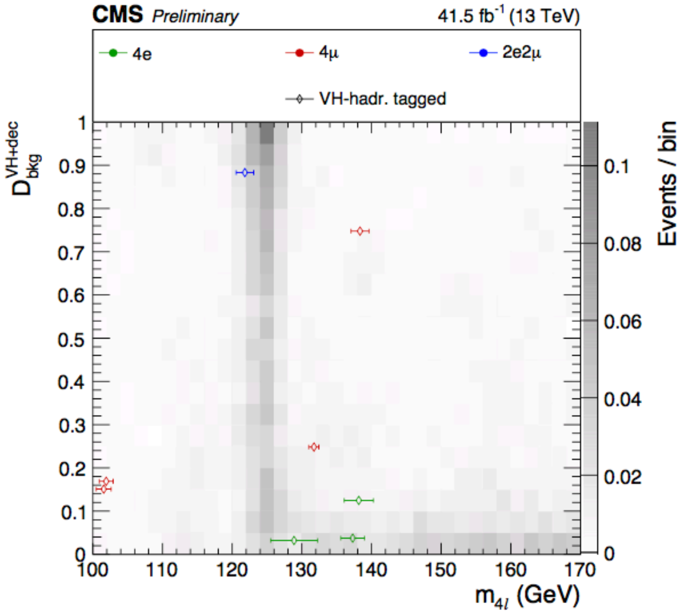
$$\mathcal{D}^{\rm kin}_{\rm bkg} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\rm bkg}(\vec{\Omega}^{\rm H\to 4\ell}|m_{4\ell})}{\mathcal{P}^{gg}_{\rm sig}(\vec{\Omega}^{\rm H\to 4\ell}|m_{4\ell})}\right]^{-1} \qquad (1)$$

$$\mathcal{D}^{\rm VBF+dec}_{\rm bkg} = \frac{\mathcal{P}^{\rm VBF+VH+dec}_{\rm sig}(\vec{\Omega})}{\mathcal{P}^{\rm VBF+VH+dec}_{\rm sig}(\vec{\Omega}) + c^{\rm VBF2jet}(m_{4\ell}) \times (\mathcal{P}^{\rm VBS+VVV}_{\rm bkg}(\vec{\Omega}) + \mathcal{P}^{\rm QCD+dec}_{\rm bkg}(\vec{\Omega}))} \qquad (2)$$

$$\mathcal{D}^{\rm VH+dec}_{\rm bkg} = \frac{\mathcal{P}^{\rm VBF+VH+dec}_{\rm sig}(\vec{\Omega})}{\mathcal{P}^{\rm VBF+VH+dec}_{\rm sig}(\vec{\Omega}) + c^{\rm had.VH}(m_{4\ell}) \times (\mathcal{P}^{\rm VBS+VVV}_{\rm bkg}(\vec{\Omega}) + \mathcal{P}^{\rm QCD+dec}_{\rm bkg}(\vec{\Omega}))}, \qquad (3)$$







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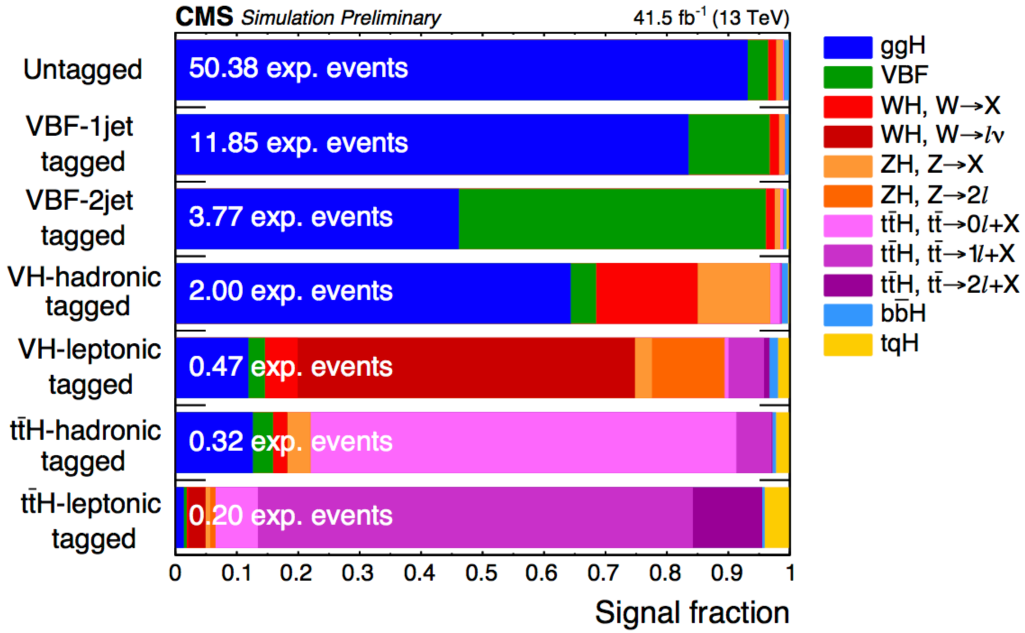
Event categorization

- Selected events are classified into seven exclusive categories to improve the sensitivity to the Higgs boson production mechanisms.



- **The VBF-2jet-tagged category** requires exactly four leptons. In addition, there must be either two or three jets of which at most one is b tagged, or four or more jets none of which are b-tagged. Finally, $\mathcal{D}_{2jet} > 0.5$ is required.
- **The VH-hadronic-tagged category** requires exactly four leptons. In addition, there must be two or three jets, or four or more jets none of which are b-tagged. $\mathcal{D}_{VH} \equiv \max(\mathcal{D}_{ZH}, \mathcal{D}_{WH}) > 0.5$ is required.
- **The VH-leptonic-tagged category** requires no more than three jets and no b-tagged jets in the event, and exactly one additional lepton or one additional pair of OS, same-flavor leptons. This category also includes events with no jets and at least one additional lepton.
- **The tt̄H-hadronic-tagged category** requires at least four jets of which at least one is b tagged and zero additional leptons.
- **The tt̄H-leptonic-tagged category** requires at least one additional lepton.
- **The VBF-1jet-tagged category** requires exactly four leptons, exactly one jet and $\mathcal{D}_{1jet} > 0.5$.
- **Untagged category** consists of the remaining selected events.

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Background estimation

- Irreducible background
  - Production of $q\bar{q}$ annihilation or gluon fusion
  - Estimated using simulation

- Two dependent methods used to estimated Z+X background: OS and SS
- Fake rates calculated in Z+l control region
- Z+X yields estimated in 2 orthogonal regions of Z+ll control region
- Final estimate combination of 2 methods

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \to ZZ$	235^{+32}_{-36}	443^{+36}_{-40}	572^{+50}_{-54}	1250^{+104}_{-114}
$gg \to ZZ$	$49.1^{+8.7}_{-8.8}$	$81.8^{+11.2}_{-10.7}$	$121.5^{+17.1}_{-16.3}$	$252.4^{+35.1}_{-33.5}$
$Z + X$	$17.1^{+6.4}_{-6.1}$	$35.4^{+12.7}_{-11.4}$	$47.8^{+16.4}_{-15.8}$	$100.3^{+21.3}_{-20.6}$
Sum of backgrounds	301^{+39}_{-43}	560^{+43}_{-47}	741^{+62}_{-65}	1602^{+126}_{-135}
Signal ($m_H = 125$ GeV)	$13.9^{+1.9}_{-2.1}$	$28.9^{+2.5}_{-2.6}$	35.8 ± 3.3	$78.5^{+7.0}_{-7.1}$
Total expected	315^{+41}_{-45}	589^{+45}_{-49}	777^{+64}_{-67}	1681^{+131}_{-140}
Observed	307	602	797	1706

- Reducible background
  - Secondary leptons produced by heavy-flavor jets
  - Misidentified as leptons from decay of heavy-flavor hadron, in-flight decays of light mesons within jets, or (for electrons) decay of charged hadrons overlapping with π^0decays.

(Main prosesses of producting these background: Z+jets, $t\bar{t}$+jets, $Z\gamma$+jets, WW+jets, WZ+jets)

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Systematics Uncertainties

- Systematics calculated with 2017 MC and data
- Switched to recommended WG1 uncertainty scheme for gluon fusion

Summary of inclusive theory uncertainties	
QCD scale (gg)	± 3.9 %
PDF set (gg)	± 3.2 %
Bkg K factor (gg)	± 10 %
QCD scale (VBF)	+0.4/-0.3 %
PDF set (VBF)	± 2.1 %
QCD scale (WH)	+0.5/-0.7 %
PDF set (WH)	± 1.9 %
QCD scale (ZH)	+3.8/-3.1 %
PDF set (ZH)	± 1.6 %
QCD scale ($t\bar{t}$H)	+5.8/-9.2 %
PDF set ($t\bar{t}$H)	± 3.6 %
BR($H \to ZZ \to 4\ell$)	2 %
QCD scale ($q\bar{q} \to ZZ$)	+3.2/-4.2 % %
PDF set ($q\bar{q} \to ZZ$)	+3.1/-3.4 %
Electroweak corrections ($q\bar{q} \to ZZ$)	± 0.1 %

Summary of relative systematic uncertainties	
Common experimental uncertainties	
Luminosity	2.3 %
Lepton identification/reconstruction efficiencies	3. – 12.5 %
Background related uncertainties	
Reducible background fake rate variation (Z+X)	31 – 45 %
Signal related uncertainties	
Lepton energy scale	0.05 – 0.3 %
Lepton energy resolution	20 %

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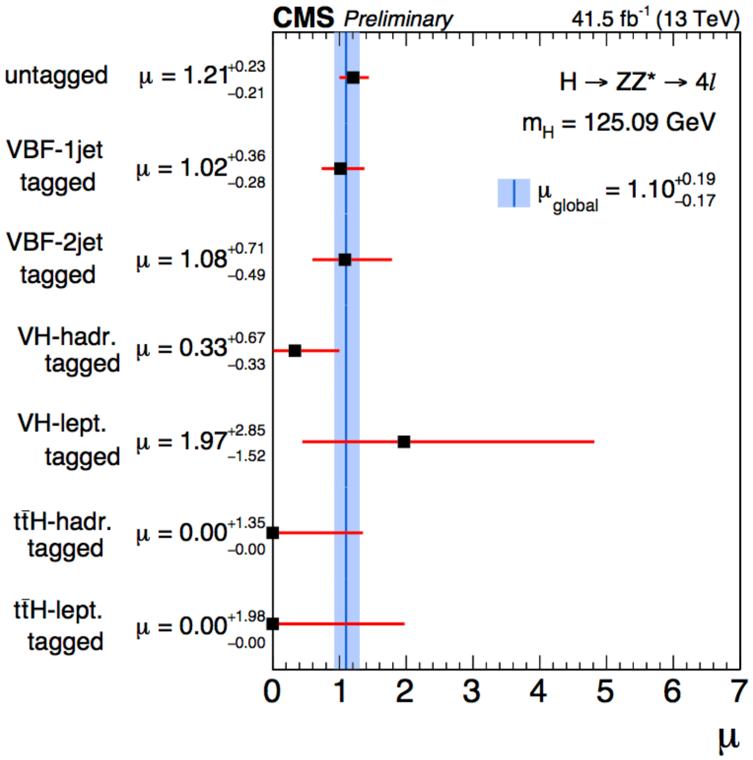
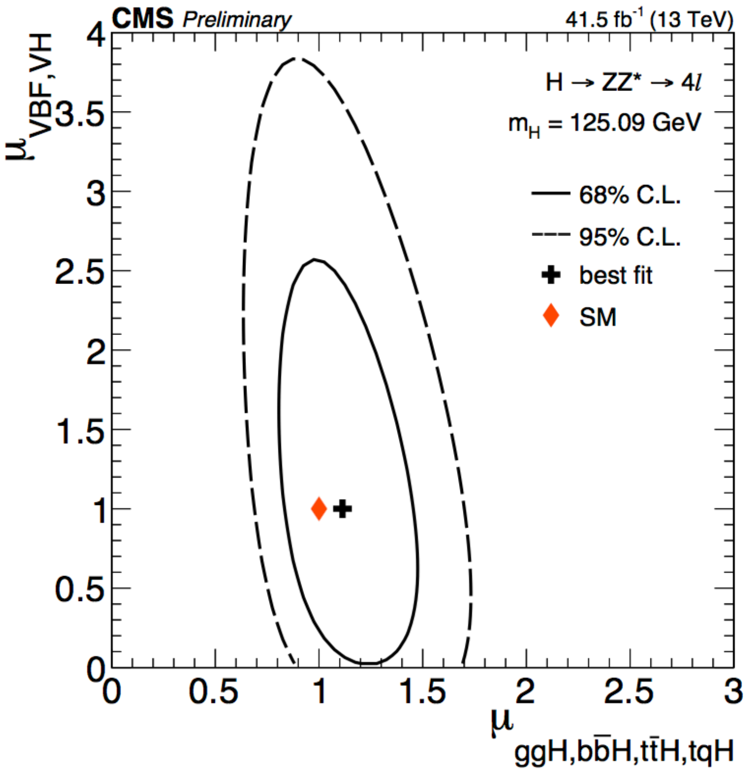
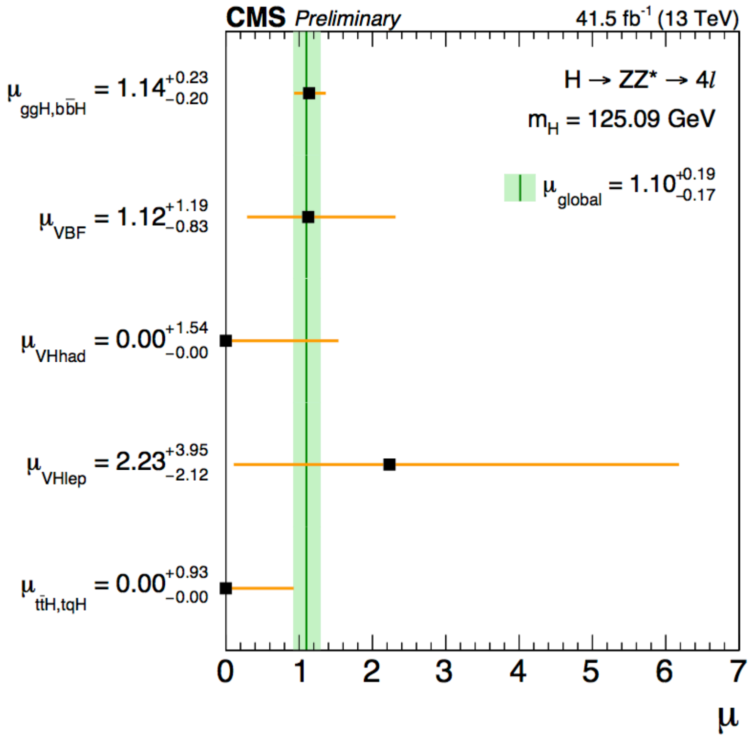
Signal Strength – Production Models







	Inclusive	$\mu_{ggH,b\bar{b}H}$	μ_{VBF}	μ_{VHhad}	μ_{VHlep}	$\mu_{t\bar{t}H,tqH}$
Expected	$1.00^{+0.14}_{-0.13}(\text{stat})^{+0.11}_{-0.09}(\text{syst})$	$1.00^{+0.22}_{-0.20}$	$1.00^{+1.19}_{-0.79}$	$1.00^{+3.24}_{-1.00}$	$1.00^{+3.36}_{-1.00}$	$1.00^{+2.47}_{-1.00}$
Observed	$1.10^{+0.14}_{-0.13}(\text{stat})^{+0.13}_{-0.11}(\text{syst})$	$1.14^{+0.23}_{-0.20}$	$1.12^{+1.19}_{-0.83}$	$0.00^{+1.54}_{-0.00}$	$2.23^{+3.95}_{-2.12}$	$0.00^{+0.93}_{-0.00}$

- Perform multidimensional maximum likelihood fit to (m_{4l},KD) templates in 21 channels (3×7)
- Total PDF is defined as: $\mathcal{L}_{2D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}}) = \mathcal{L}(m_{4\ell})\mathcal{L}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4\ell})$.

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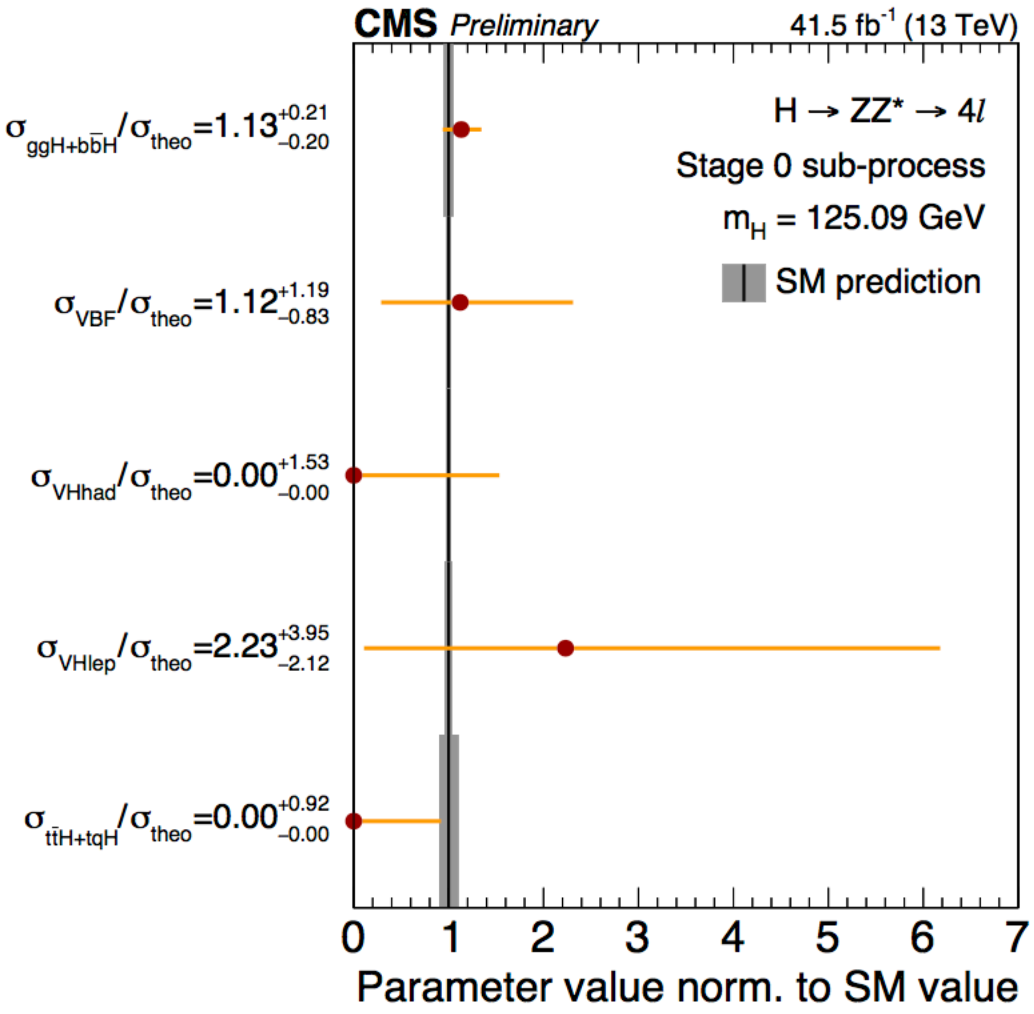
STXS – Stage 0

- Simplified template cross section (stage zero) with removed σ_{SM} theoretical uncertainties on overal signal cross section
- Theoretical uncertainties which can cause migration of events between the various categories are kept
- bbH (floated with μ_{ggH}) and tqH (floated with μ_{ttH}) contributions considered in the fit



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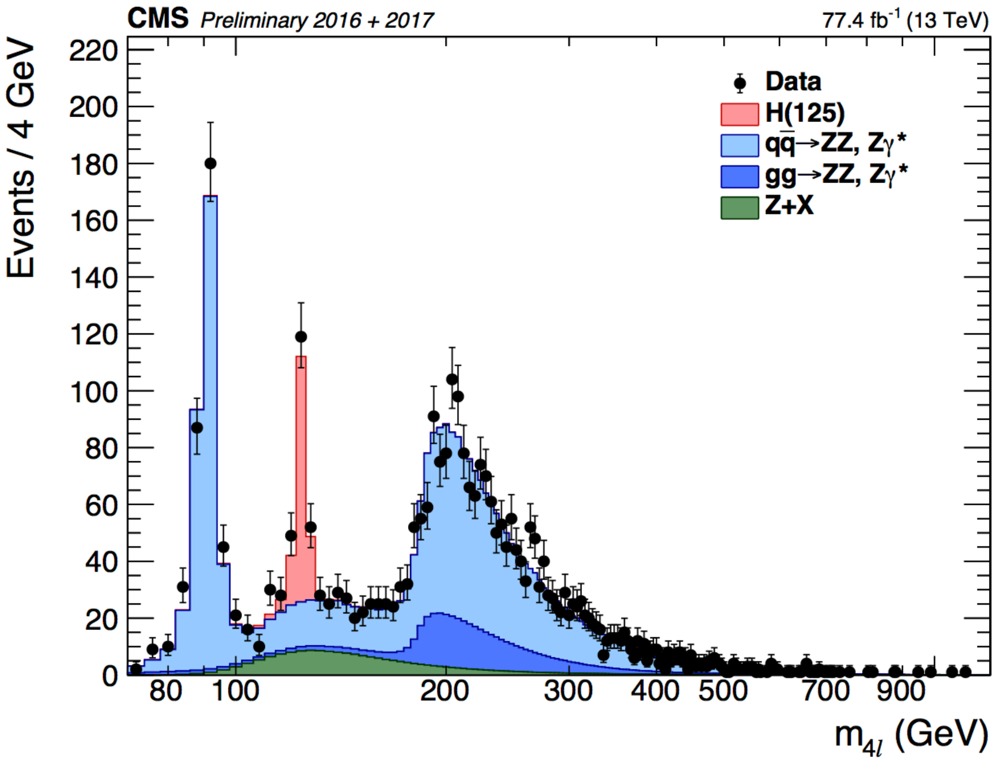
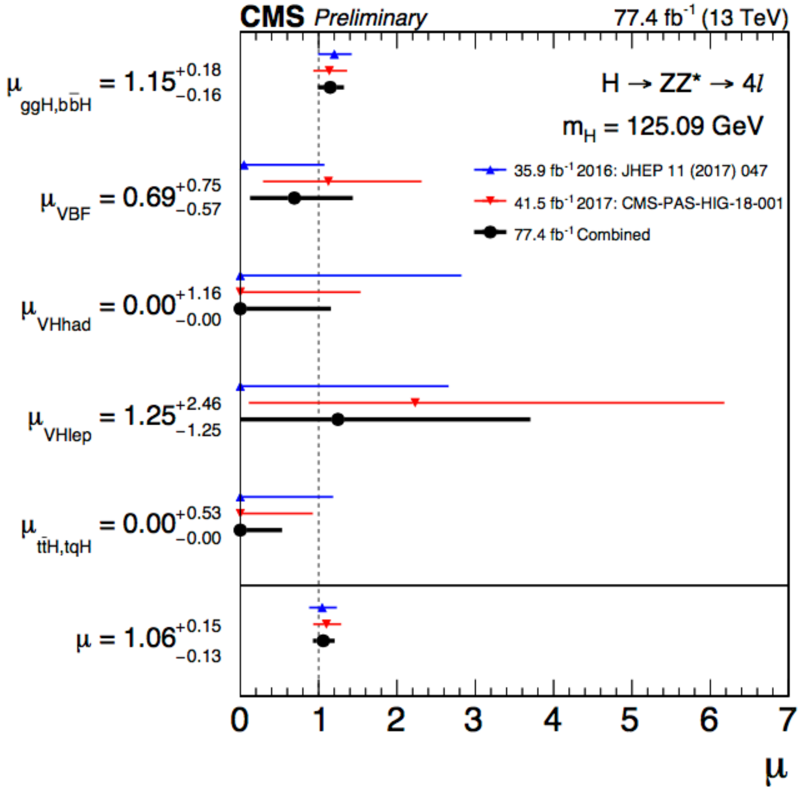
Combination

	Inclusive	$\mu_{ggH,b\bar{b}H}$	μ_{VBF}	μ_{VHhad}	μ_{VHlep}	$\mu_{t\bar{t}H,tqH}$
Expected	$1.00 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$	$1.00^{+0.17}_{-0.16}$	$1.00^{+0.86}_{-0.67}$	$1.00^{+2.39}_{-1.00}$	$1.00^{+2.30}_{-1.00}$	$1.00^{+1.80}_{-1.00}$
Observed	$1.06 \pm 0.10(\text{stat})^{+0.08}_{-0.06}(\text{exp. syst})^{+0.07}_{-0.05}(\text{th. syst})$	$1.15^{+0.18}_{-0.16}$	$0.69^{+0.75}_{-0.57}$	$0.00^{+1.16}_{-0.00}$	$1.25^{+2.46}_{-1.25}$	$0.00^{+0.53}_{-0.00}$





Results are combined based on the data of 2016 and 2017.

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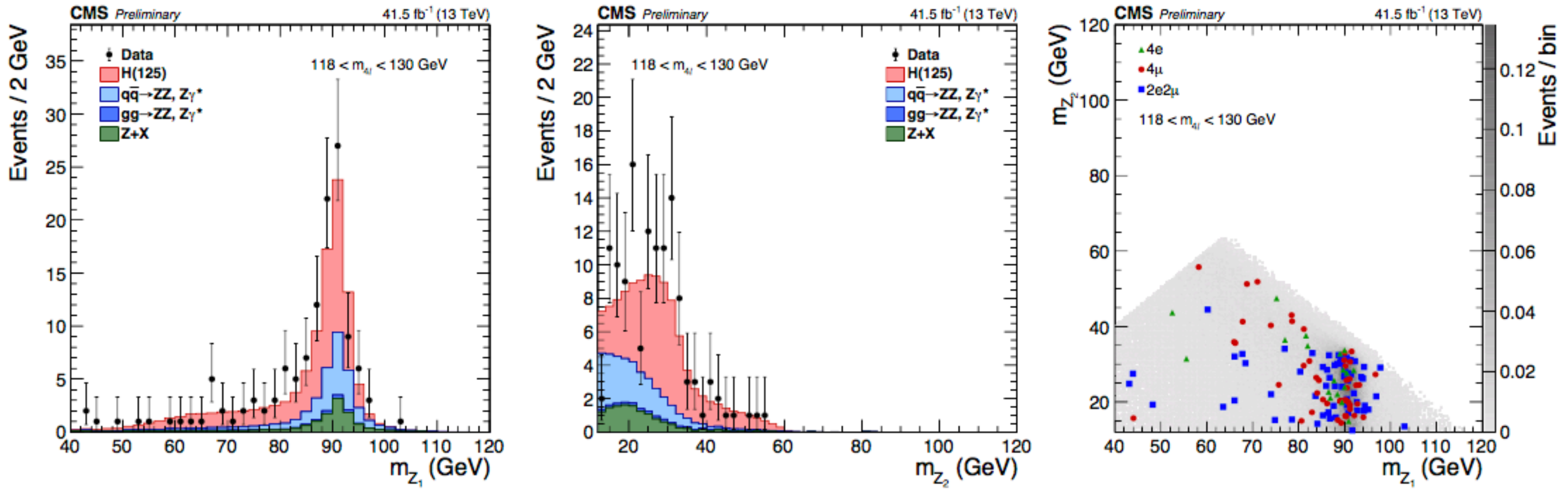
Conclusion

- Several measurement of Higgs boson in four-lepton final states at $\sqrt{S}$= 13TeV have been presented with data samples corresponding to an integrated luminosity of 41.5fb^{-1}
- Several improvements with respect to the published paper.
    - New electron BDT identification with isolation
    - Splitting of ttH category
    - New discriminants for VBF and VH production mechanism.
- Combination with 2016 and 2017 data are performed.
- Results are consistent with the SM expectation.

Backup

Distribution of Z_1 and Z_2



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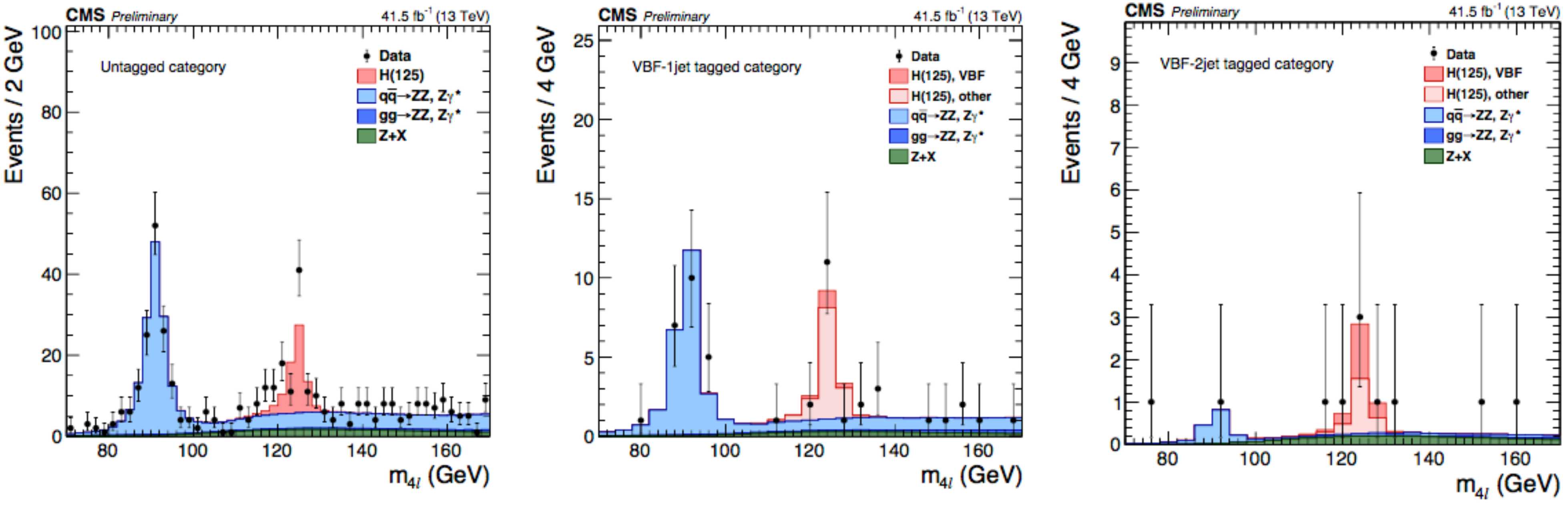
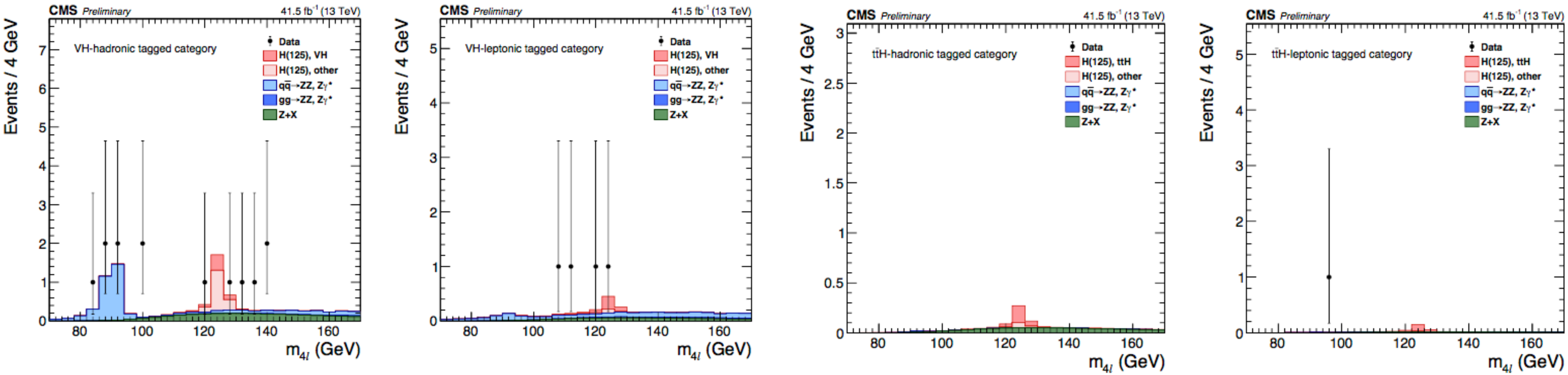
Distribution of m_{4l} in seven event categories



(a)

(b)

(c)



(d)

(e)

(f)

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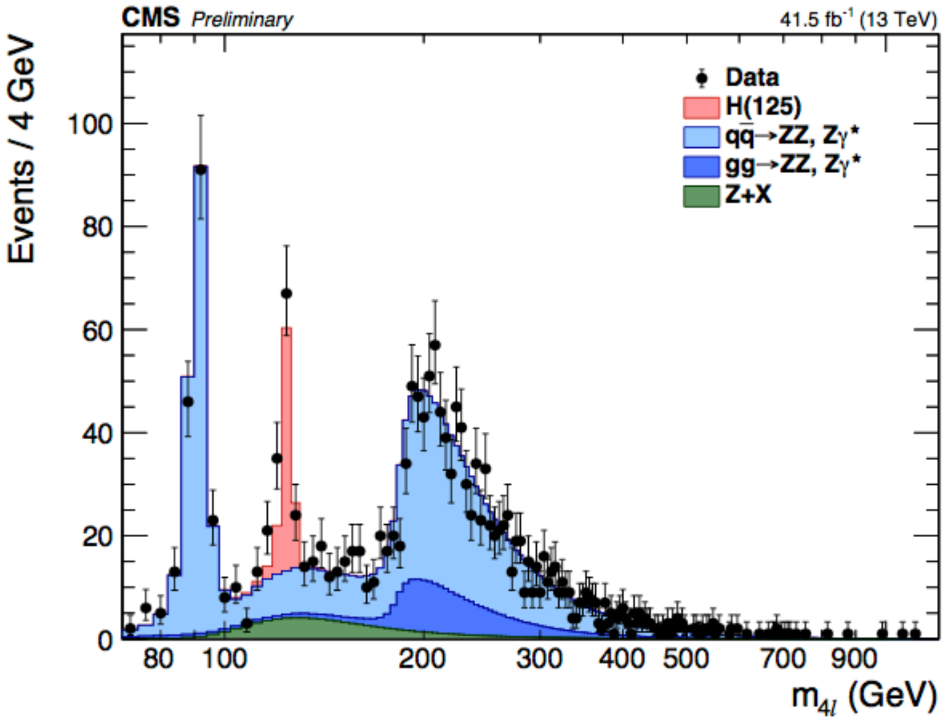
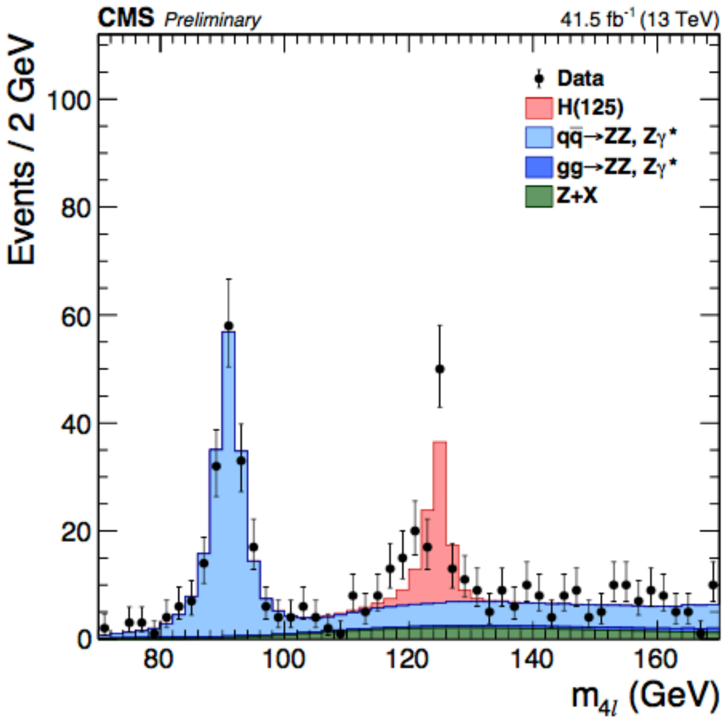
(g)

Distribution of m_{4l} of 2017 data





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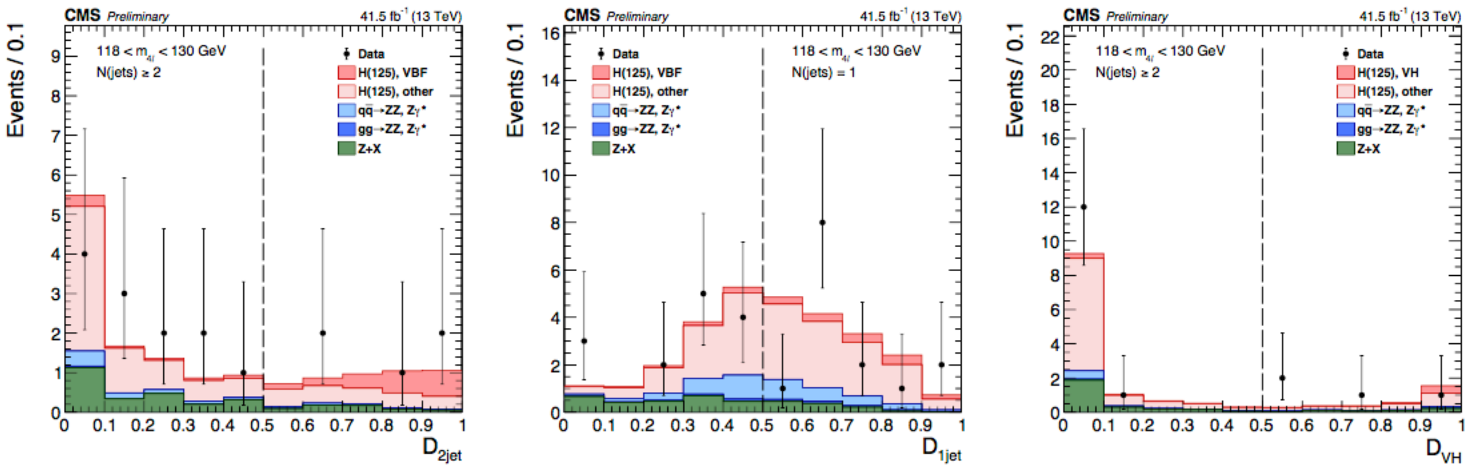
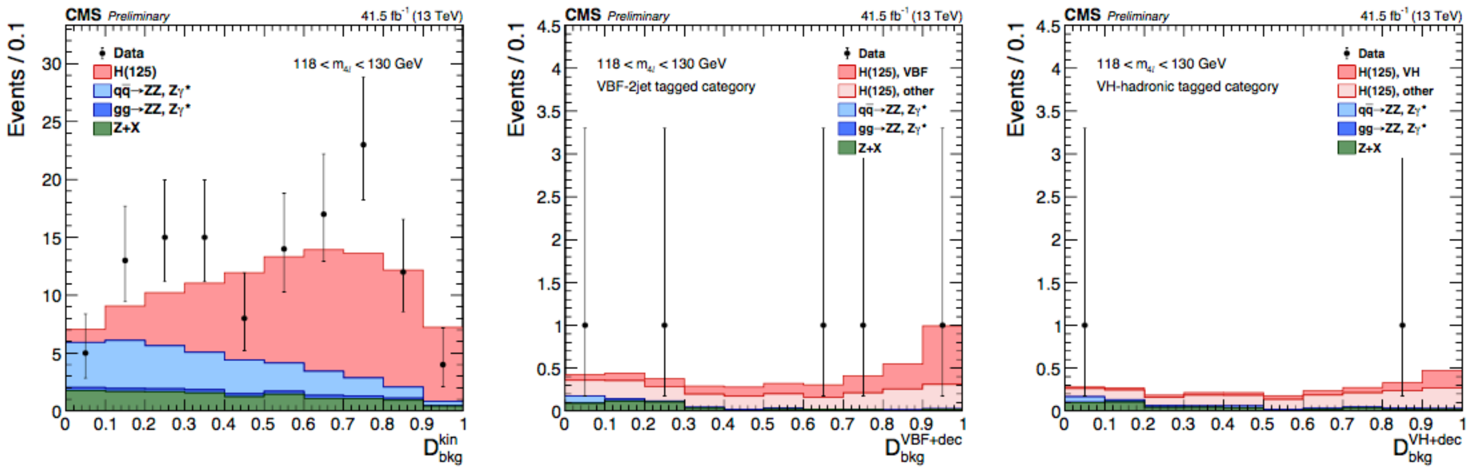
Distribution of discriminant



Category discriminant



Kinematic discriminant

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Data

Run-range	Dataset	Integrated luminosity
297046-299329	/DoubleMuon/Run2017B-17Nov2017-v1/MINIAOD /DoubleEG/Run2017B-17Nov2017-v1/MINIAOD /MuonEG/Run2017B-17Nov2017-v1/MINIAOD /SingleElectron/Run2017B-17Nov2017-v1/MINIAOD /SingleMuon/Run2017B-17Nov2017-v1/MINIAOD	4.792 fb^{-1}
299368-300676	/DoubleMuon/Run2017C-17Nov2017-v1/MINIAOD /DoubleEG/Run2017C-17Nov2017-v1/MINIAOD /MuonEG/Run2017C-17Nov2017-v1/MINIAOD /SingleElectron/Run2017C-17Nov2017-v1/MINIAOD /SingleMuon/Run2017C-17Nov2017-v1/MINIAOD	9.755 fb^{-1}
302030-303434	/DoubleMuon/Run2017D-17Nov2017-v1/MINIAOD /DoubleEG/Run2017D-17Nov2017-v1/MINIAOD /MuonEG/Run2017D-17Nov2017-v1/MINIAOD /SingleElectron/Run2017D-17Nov2017-v1/MINIAOD /SingleMuon/Run2017D-17Nov2017-v1/MINIAOD	4.319 fb^{-1}
303824-304797	/DoubleMuon/Run2017E-17Nov2017-v1/MINIAOD /DoubleEG/Run2017E-17Nov2017-v1/MINIAOD /MuonEG/Run2017E-17Nov2017-v1/MINIAOD /SingleElectron/Run2017E-17Nov2017-v1/MINIAOD /SingleMuon/Run2017E-17Nov2017-v1/MINIAOD	9.424 fb^{-1}
305040-306462	/DoubleMuon/Run2017F-17Nov2017-v1/MINIAOD /DoubleEG/Run2017F-17Nov2017-v1/MINIAOD /MuonEG/Run2017F-17Nov2017-v1/MINIAOD /SingleElectron/Run2017F-17Nov2017-v1/MINIAOD /SingleMuon/Run2017F-17Nov2017-v1/MINIAOD	13.50 fb^{-1}

DRAFT

During 2017, data samples recorded by CMS detector collected 41.37fb^{-1}

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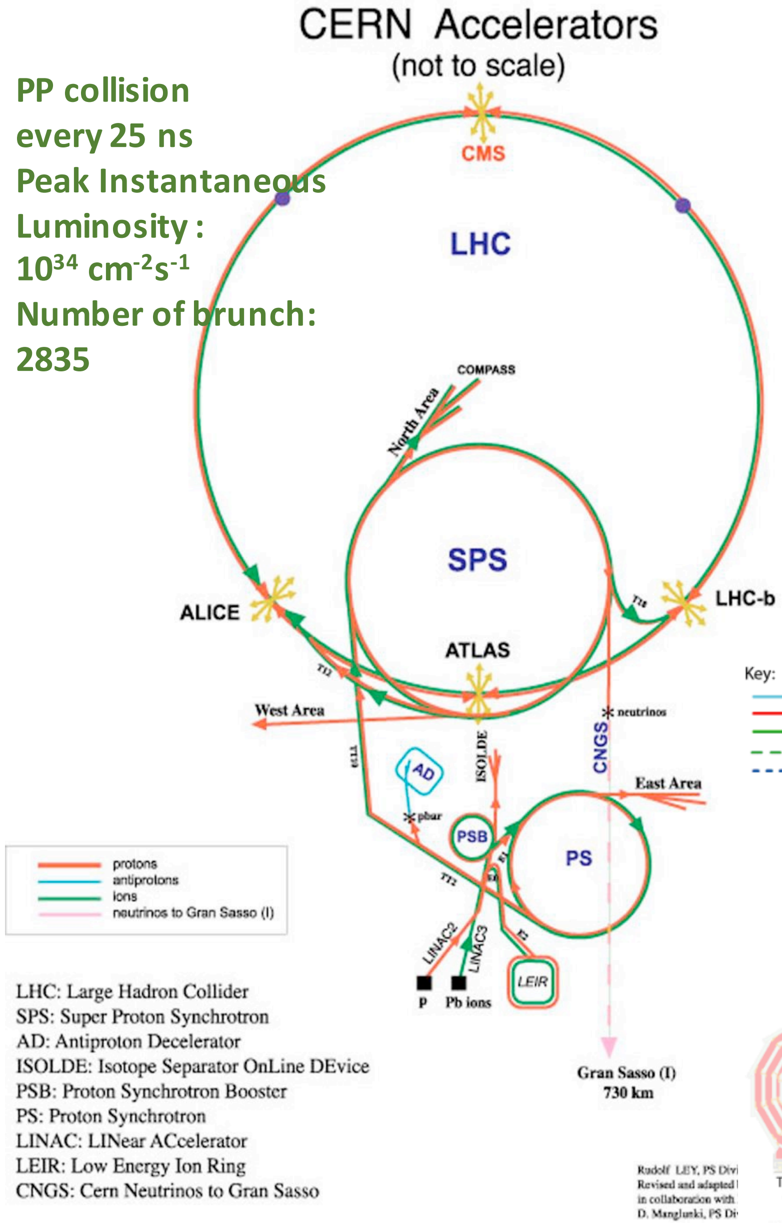
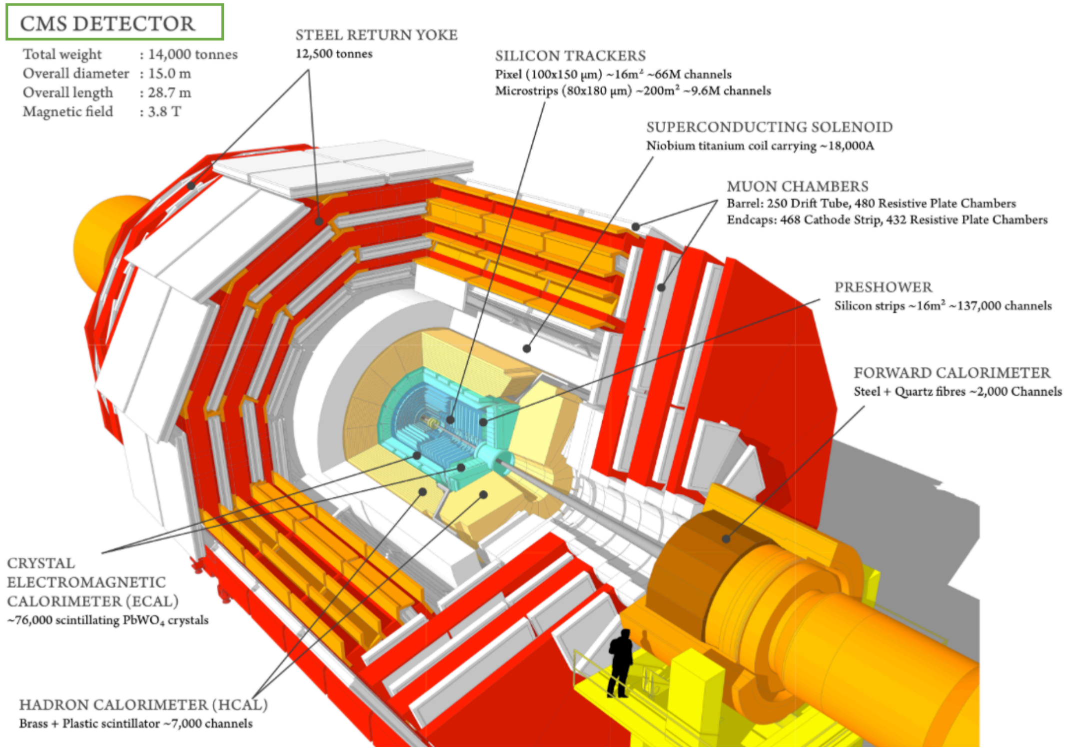
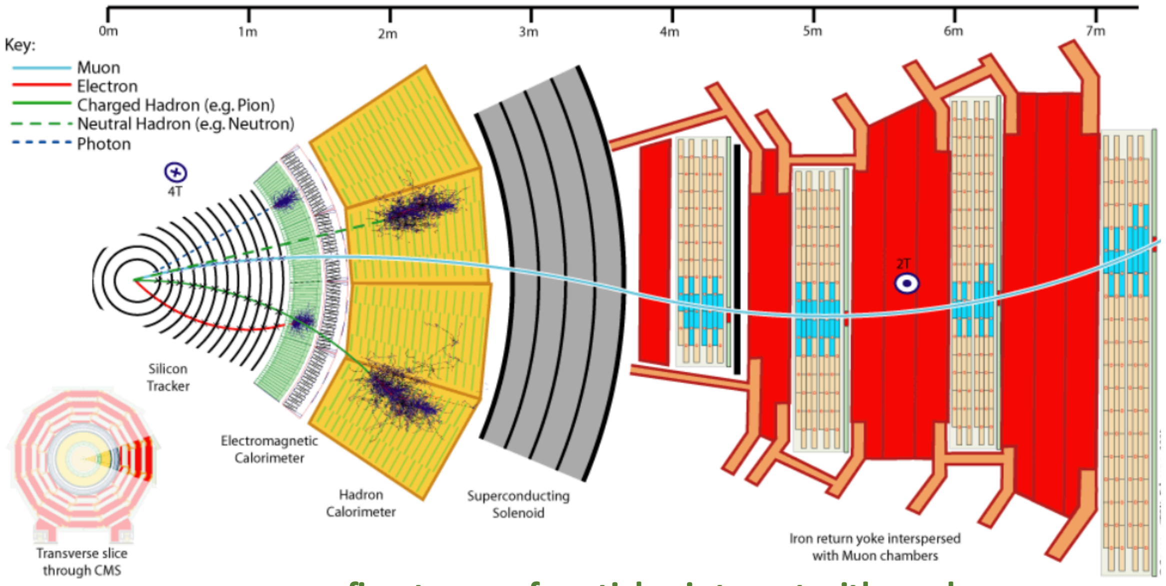
LHC and CMS

PP collision every 25 ns
Peak Instantaneous Luminosity : 10^{34} $cm^{-2}s^{-1}$
Number of brunch: 2835







five types of particles interact with each sections of the detector.