Higgs production with jets @ CMS

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On Behalf of the CMS Collaboration

IPPP Durham : Workshop on Jet Vetoes and Jet Multiplicity Observables at the LHC

Talk Overview

Jets reconstruction in CMS

↓

Analyses using Jets

↓

Higgs cross section measurements

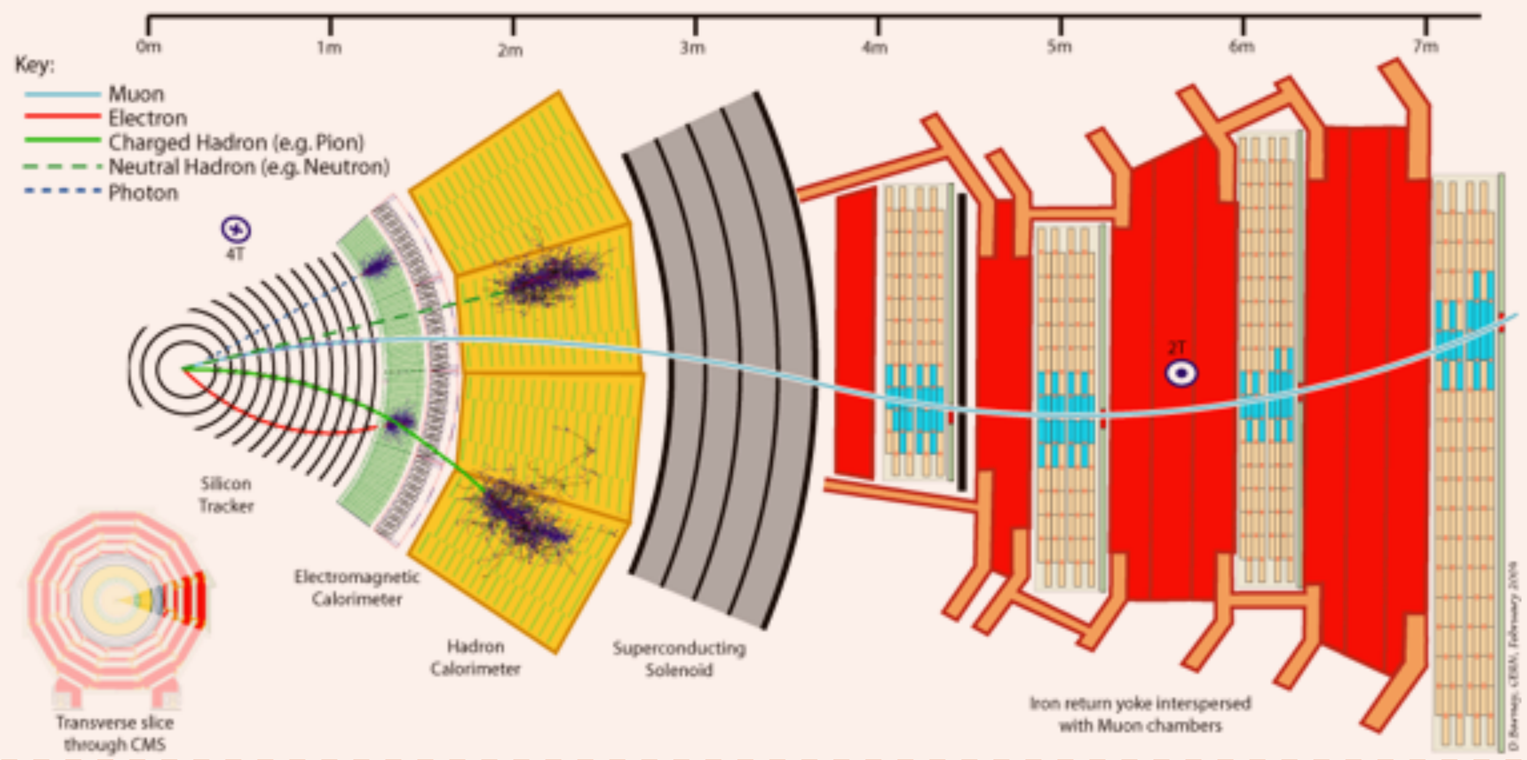
↓

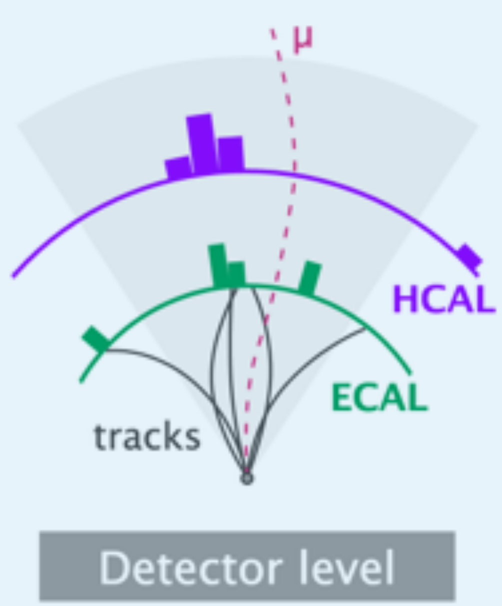
Outlook

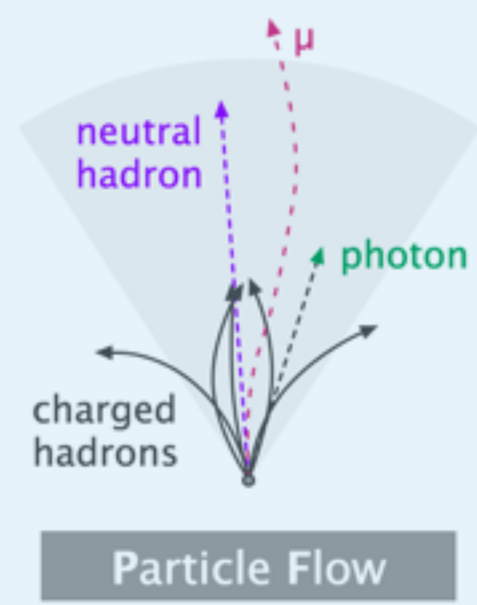
- Jets play crucial role in enhancing sensitivity in most Higgs analyses, so it is important to have a good reconstruction and modelling of the jets.

- **Review of the latest results from $H\rightarrow ZZ^{*}\rightarrow 4\ell$, $H\rightarrow\gamma\gamma$ and $H\rightarrow bb$ with a special focus:**
  - **Different methods/tools for tagging production modes using jets**
- **Quick overview of selected results from BSM Higgs searches.**

Jet @ CMS



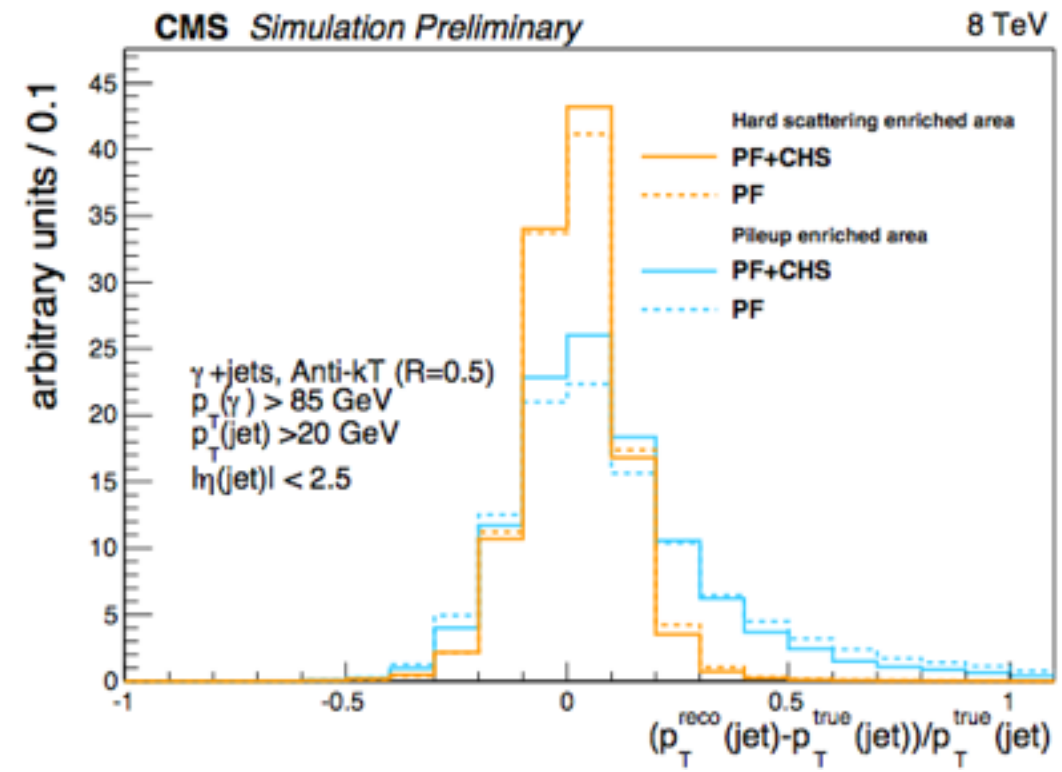


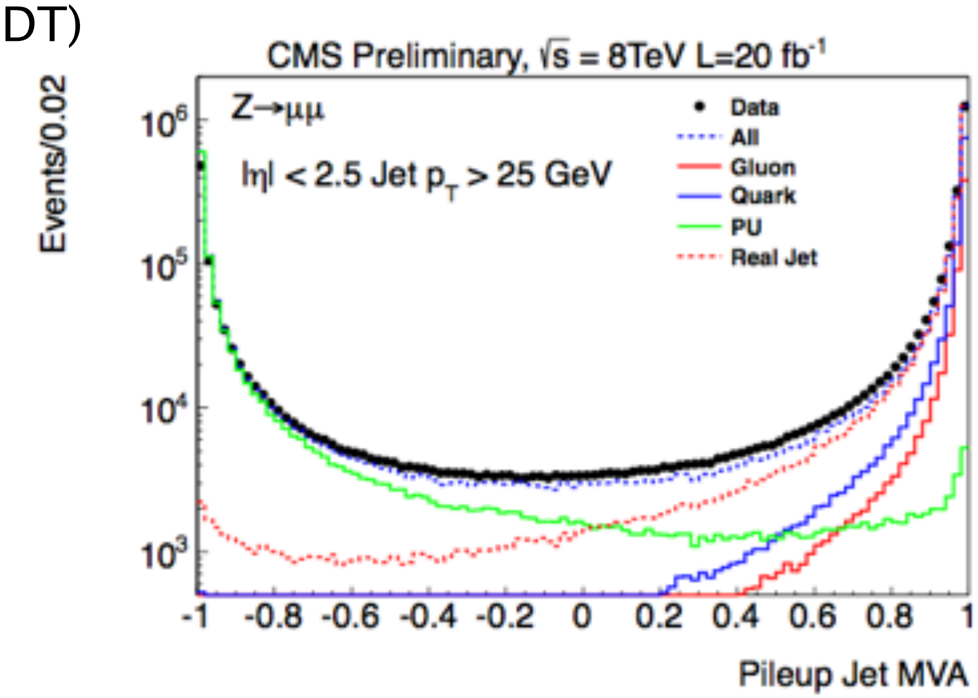


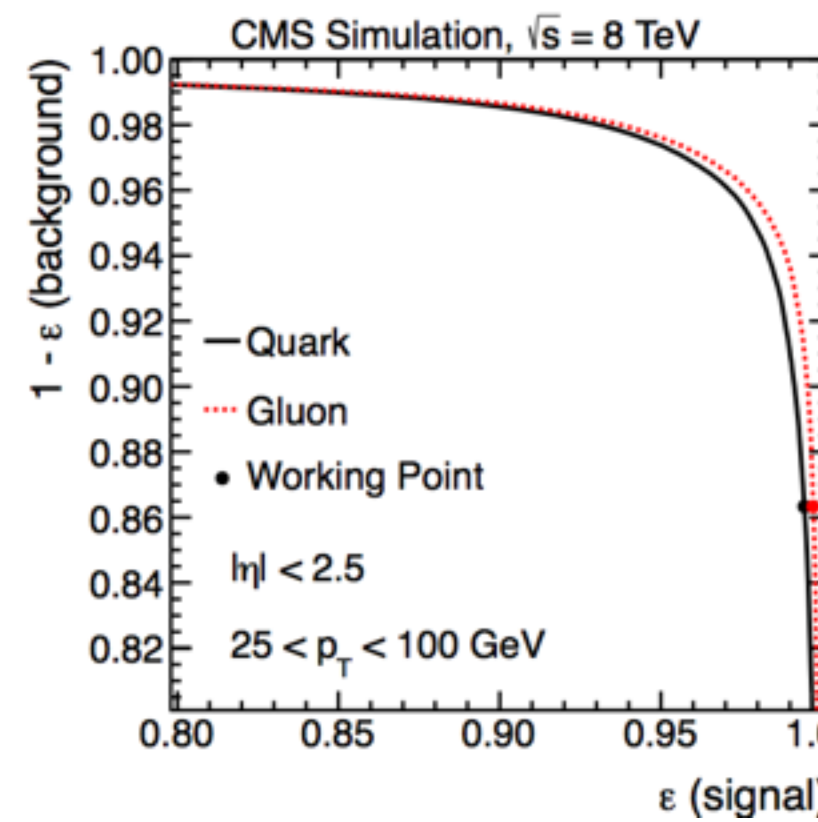
- PFA: Particle-Flow Algorithm Combine all the information from several sub-detectors
- Individual particles are reconstructed using the PFA and then clustered into jets
- Jet definition : **PF Particle clustered Anti-k_t algorithm with R=0.4**

PileUp mitigation

- CMS has developed and implemented various techniques:
  - Timing of calorimeter @ hardware level, effective to remove out-of-time pileup.
  - Subtracting pileup contribution in average from jets and lepton isolation.
  - **Charged Hadron Subtraction(CHS)** removes charged particles associated with pileup vertices from reconstructed physics objects, **before the jet clustering.**
  - **Pileup Jet ID** : Remove jets from pileup using tracking information and jet shape combined in an boosted decision tree (BDT)



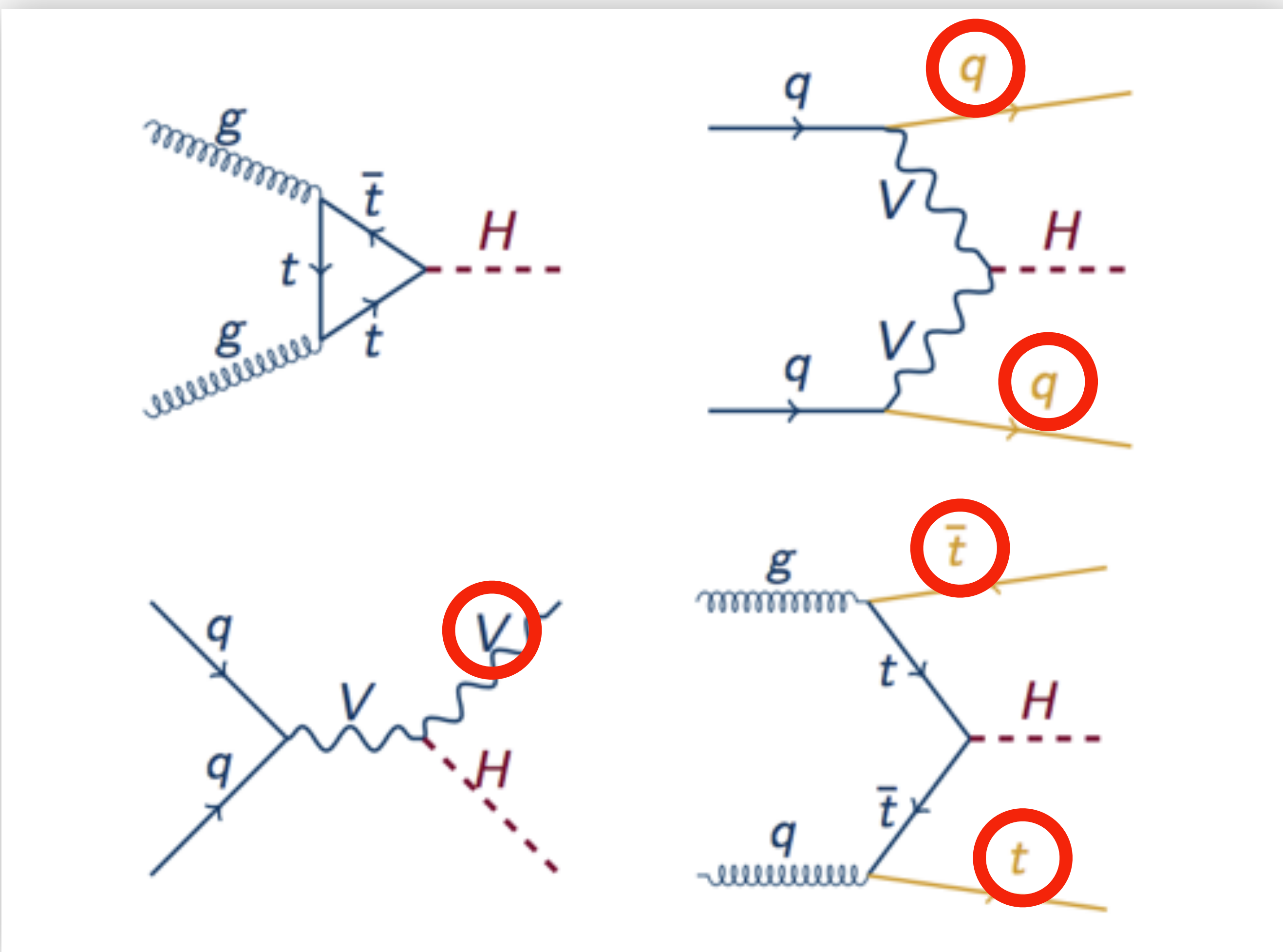


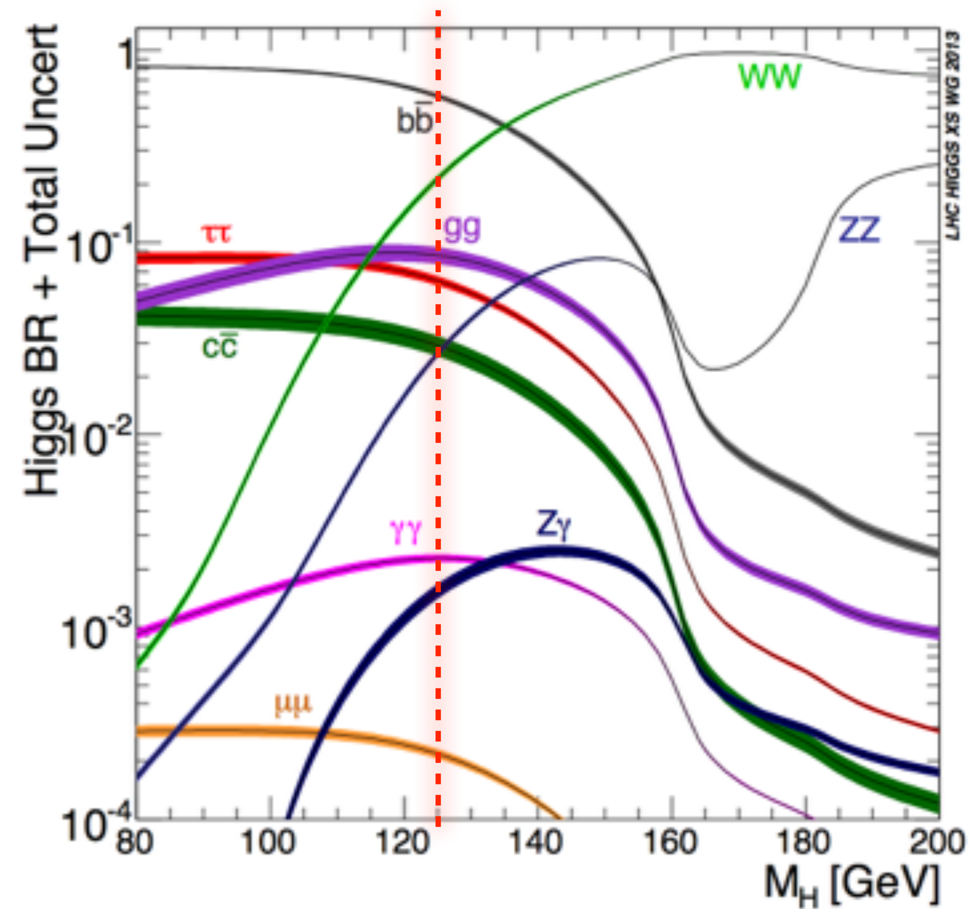


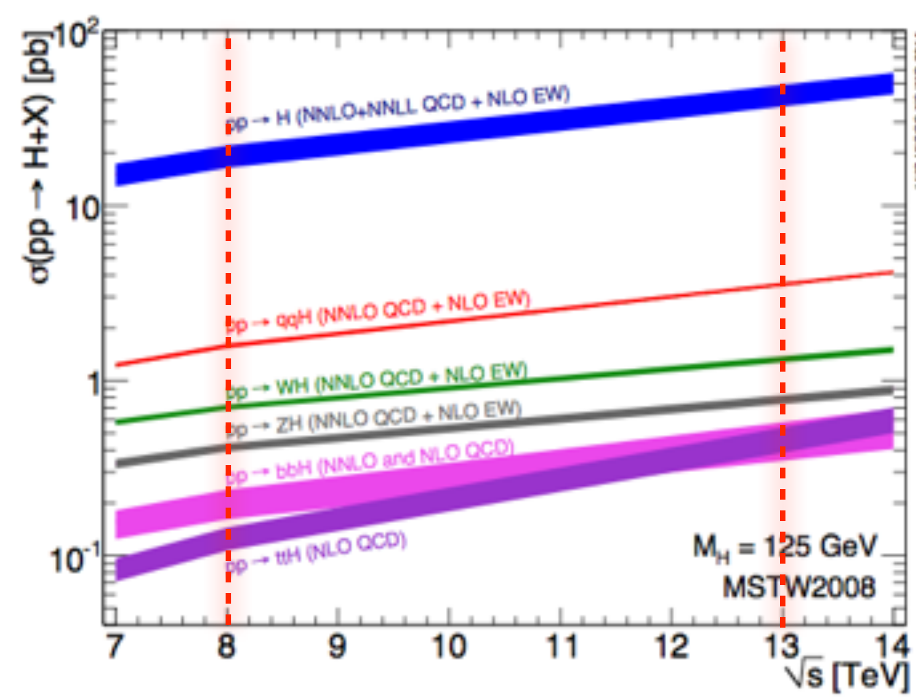
- **Other methods have been studied in addition to CHS**, the most promising one is **PileUp Per Particle Identification (PUPPI)**
  - more details in technical proposal for the phase-II Upgrade of the CMS Detector **http://cds.cern.ch/record/2020886**

Overview of Higgs production modes

- Most of the channels use jets to gain sensitivity and to test coupling strength of certain production modes





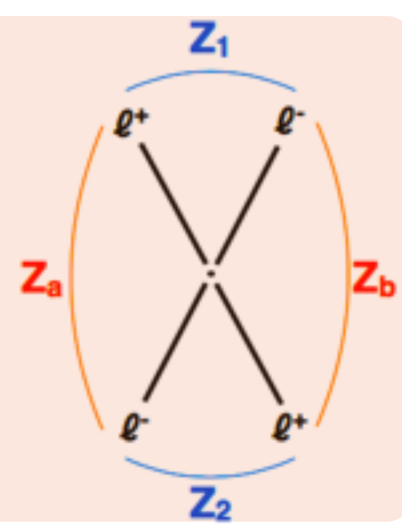


$H \to ZZ^* \to 4\ell$: Analysis strategy

CMS-PAS-HIG-16-033

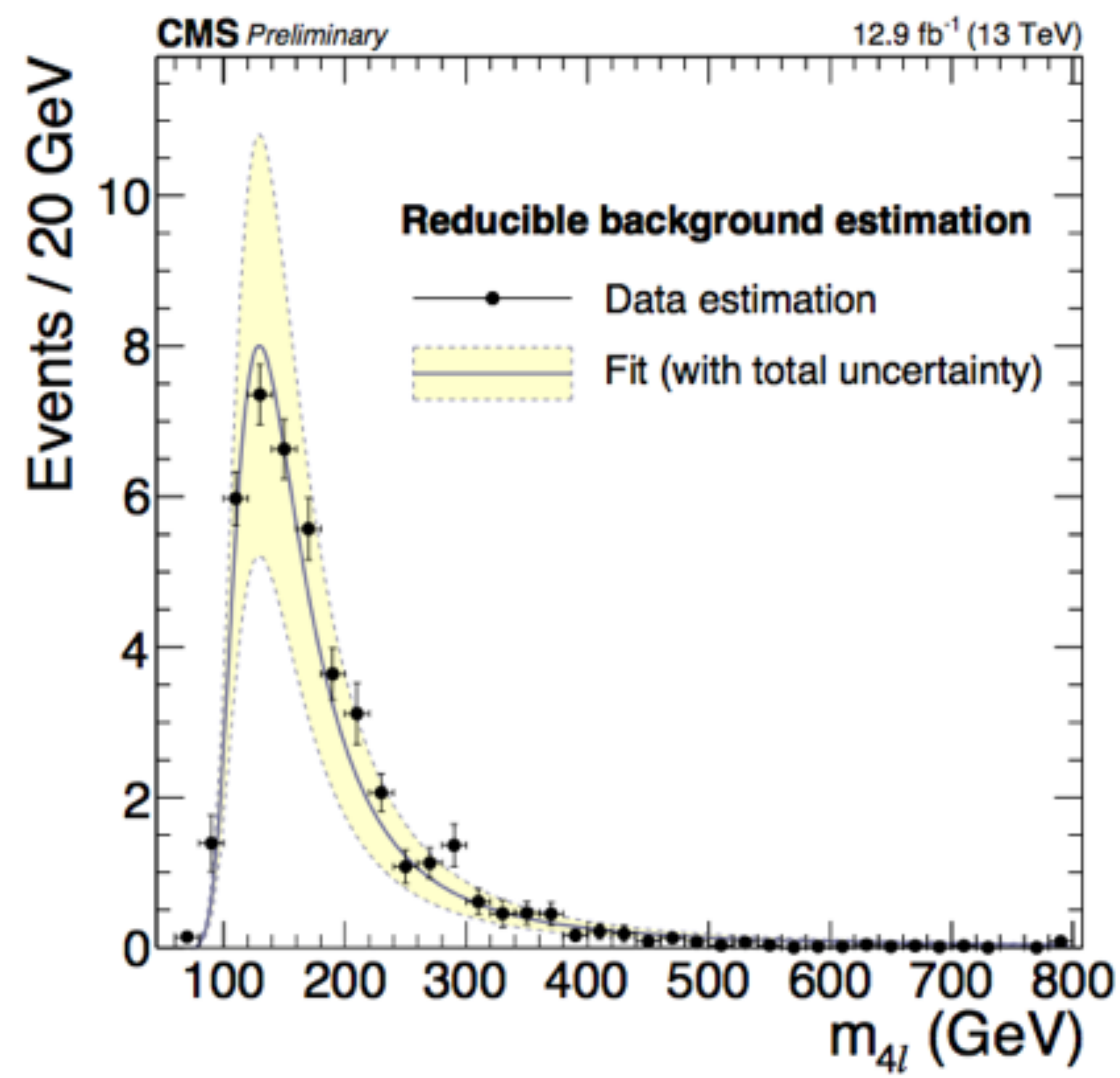
- Large S/B ratio, excellent resolution, final state fully reconstructible
- Looking for **$H \to ZZ^* \to 4\ell$ ($\ell = \mu, e$)**
- Higgs properties:
  - Signal Strength
  - Fiducial/differential cross section measurement
- Analysis steps optimised for the new conditions @13TeV
  - Analysis relies on efficient leptons selection
  - FSR recovery and ZZ candidate selection
- Two same-flavour, opposite-sign lepton pairs

- Event Selection
  - e (μ) pT > 7 (5) GeV, |η| < 2.5 (2.4)
  - Leading 2 leptons: pT > 20, 10 GeV
  - FSR Recovery: attached to closest lepton
- Reject candidates with alternating pairing $Z_a Z_b$:
  - $|m_{Z_a} - m_Z| < |m_{Z_1} - m_Z|$ and m_{Z_b} < 12 GeV



- Jets reconstructed using PF candidates, clustered by anti-k_T R=0.4
  - must satisfy p_T > 30 GeV with |η| < 4.7
  - must be isolated from lepton/FSR photon: $\Delta R(\ell/\gamma, \text{jet}) > 0.4$

- Background estimation:
  - Main background = non-resonant qq→ZZ and gg→ZZ. Apply NNLO/NLO (resp NNLO/LO) QCD k-factor as a function of m_{ZZ}
- Reducible background (Z+X):
  - data-driven estimation from control regions, 2 independent methods



H→ZZ*→4ℓ : VBF tagged event

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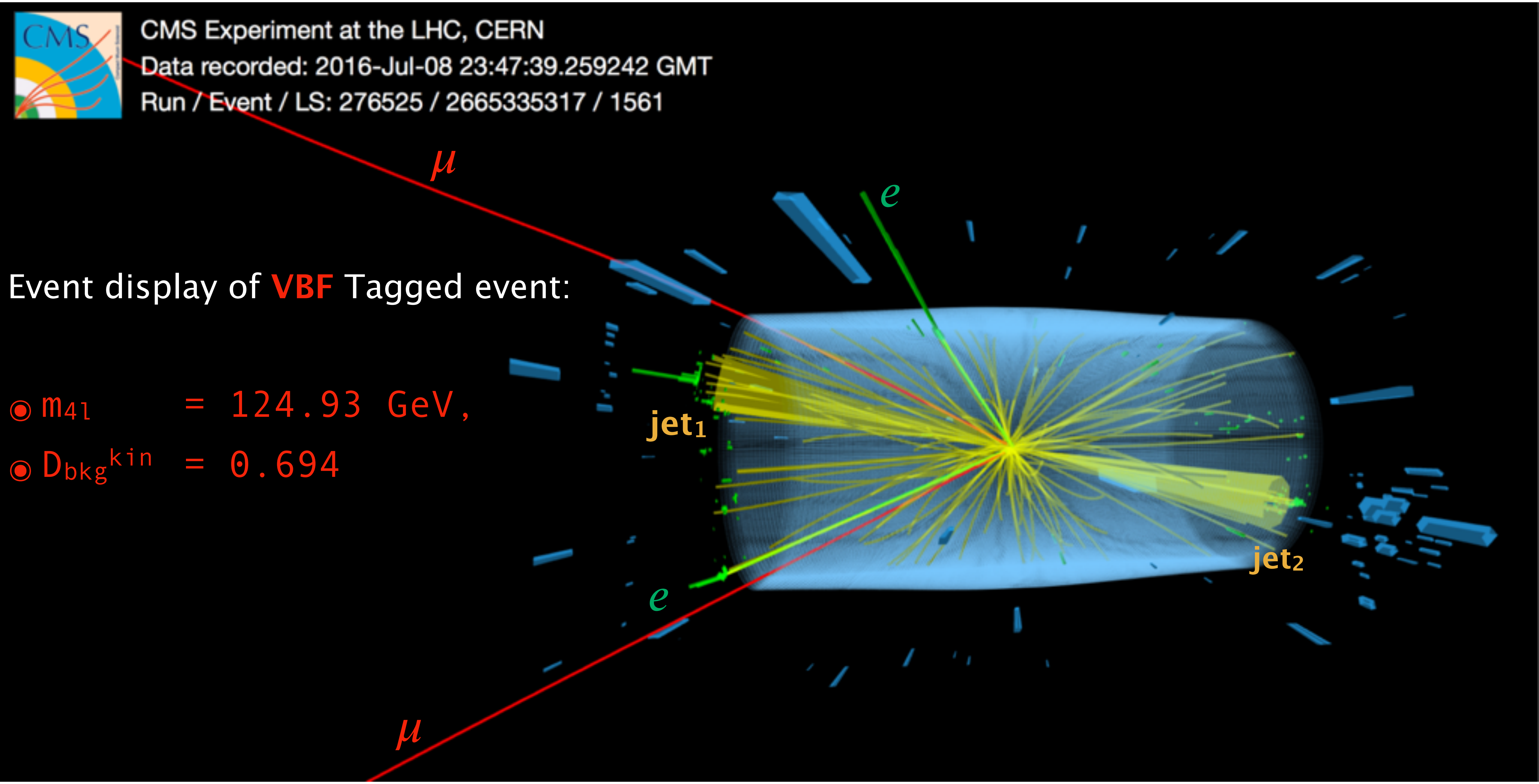

Event display of **VBF** Tagged event:

- m_{4l} = 124.93 GeV,
- D_{bkg}^{kin} = 0.694

H→ZZ*→4ℓ :Production mode

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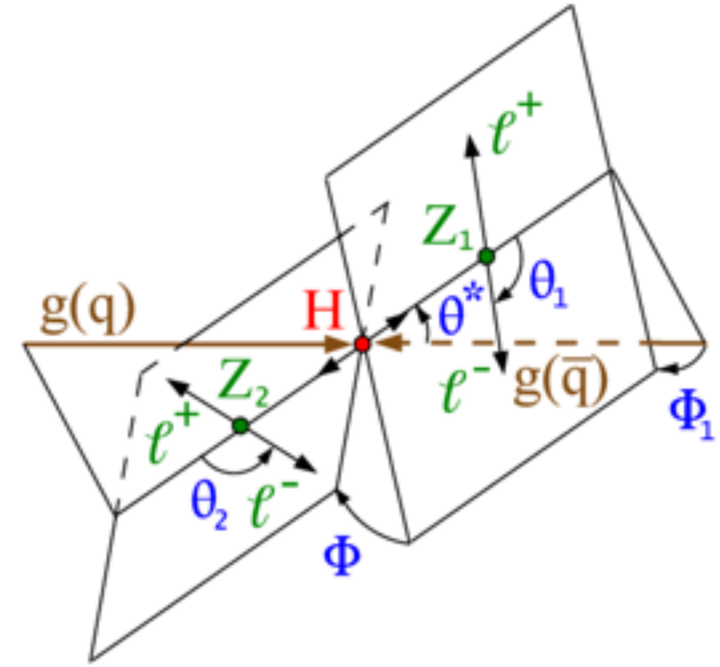
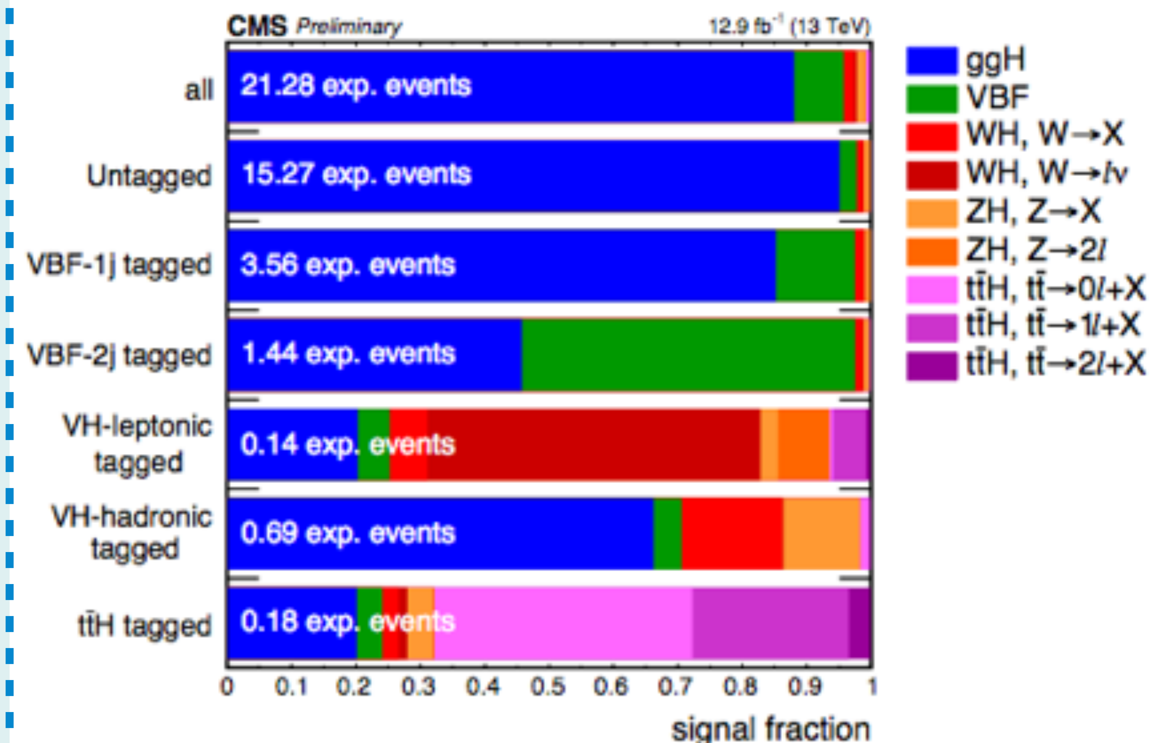
- Encode angular information in **matrix-element based discriminants**
- A global discriminant sensitive to gg/qq →4ℓ kinematics:

$$\mathcal{D}^{\mathrm{kin}}_{\mathrm{bkg}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\mathrm{bkg}}(\vec{\Omega}^{\mathrm{H}\to4\ell}|m_{4\ell})}{\mathcal{P}^{gg}_{\mathrm{sig}}(\vec{\Omega}^{\mathrm{H}\to4\ell}|m_{4\ell})}\right]^{-1}$$

- A discriminant for each production mode topology :
  - VBF (D_{2jet} & D_{1jet}) , D_{WH} , D_{ZH}
- Define **6 event categories** for each H(125) decay mode ($4e$, 4μ, $2e2\mu$):
  - **VBF-2jets category:** exactly 4 leptons, 2 or 3 jets (at most 1 b-tag) or at least 4 jets + High D_{2jets} value
  - **VH-hadronic category:** exactly 4 leptons + 2 or 3 jets (at most 1 b-tag) or at least 4 jets + High D_{ZH} or D_{WH} value.
  - **VH-leptonic category:** ≤ 3 jets + 1 additional lepton or 1 opposite sign lepton-pair
  - **ttH category :** ≥4 jets (at least 1 b-tag) + 1 additional lepton
  - **VBF-1jet category :** 4 leptons + 1 jet + high D_{1jet} value
  - **Untagged category :** remaining events





Expectation in [118, 130 GeV]

H→ZZ*→4ℓ : Event selection

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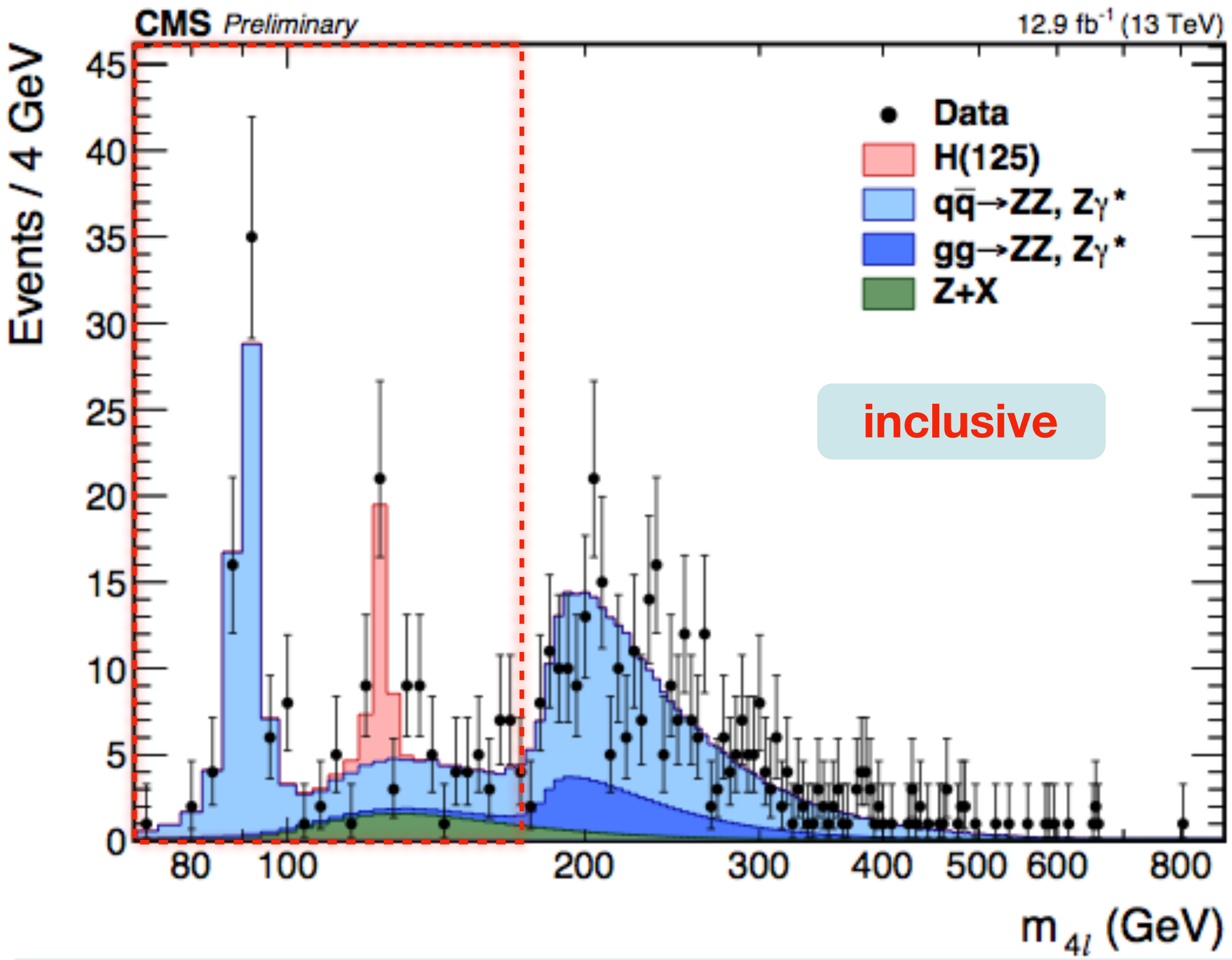

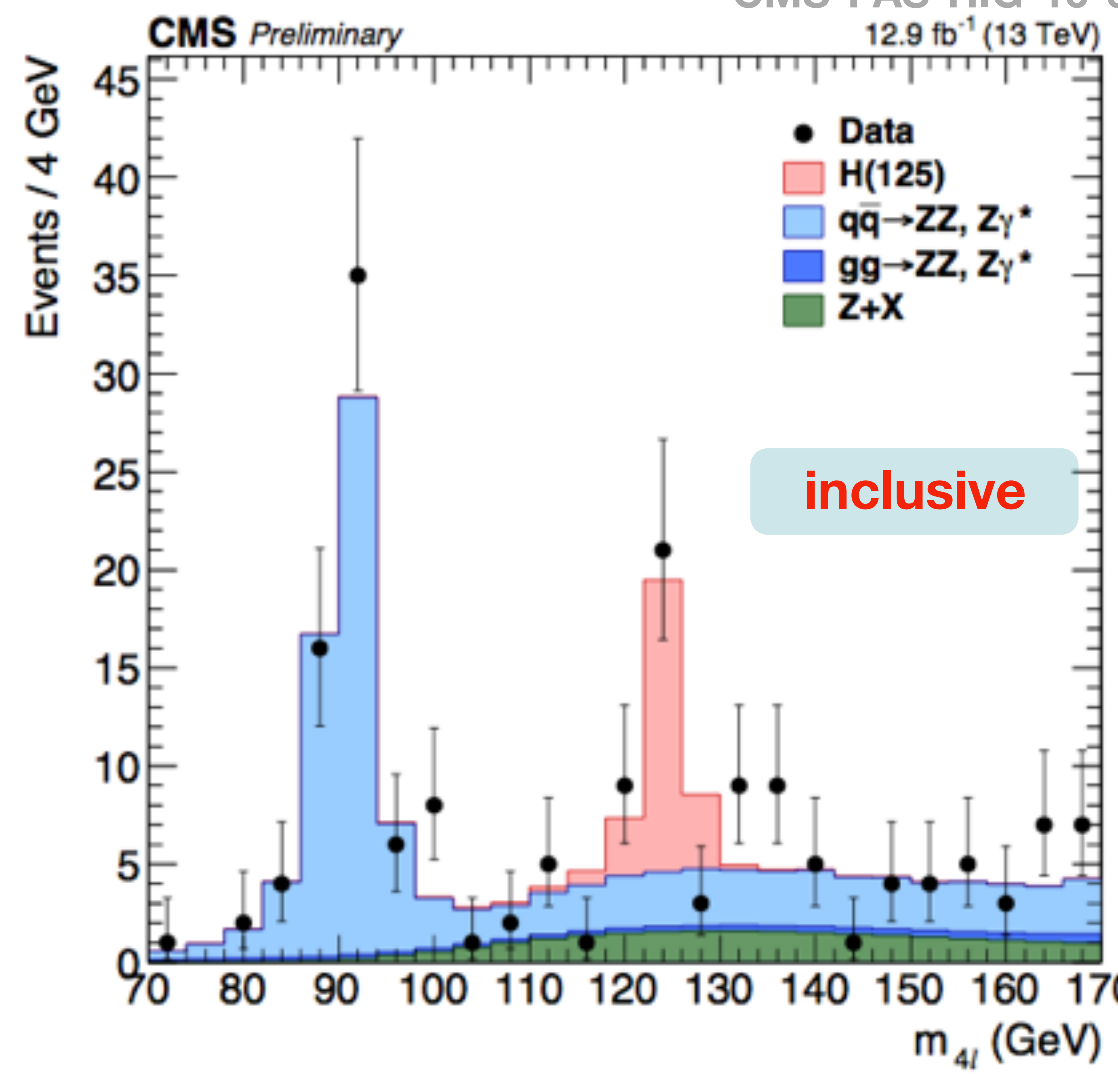

yields for each event category in [118, 130] GeV

Category	Untagged	VBF-1j	VBF-2j	VH-lept.	VH-hadr.	$t\bar{t}H$	Total
$q\bar{q}\to ZZ$	7.27	0.82	0.06	0.10	0.11	0.01	8.36
$gg\to ZZ$	0.62	0.11	0.01	0.01	0.01	0.00	0.77
Z + X	3.83	0.32	0.24	0.05	0.08	0.10	4.64
Sum of backgrounds	11.73	1.25	0.32	0.16	0.20	0.11	13.77
Signal (m_H = 125 GeV)	15.51	3.62	1.45	0.14	0.70	0.19	21.61
Total expected	27.24	4.87	1.77	0.30	0.90	0.30	35.38
Observed	29	1	2	0	1	0	33

- Good data/MC in the full m_{4l} range and for the 3 final states (**4e, 4μ, 2e2μ**)

H→ZZ*→4ℓ : Signal extraction

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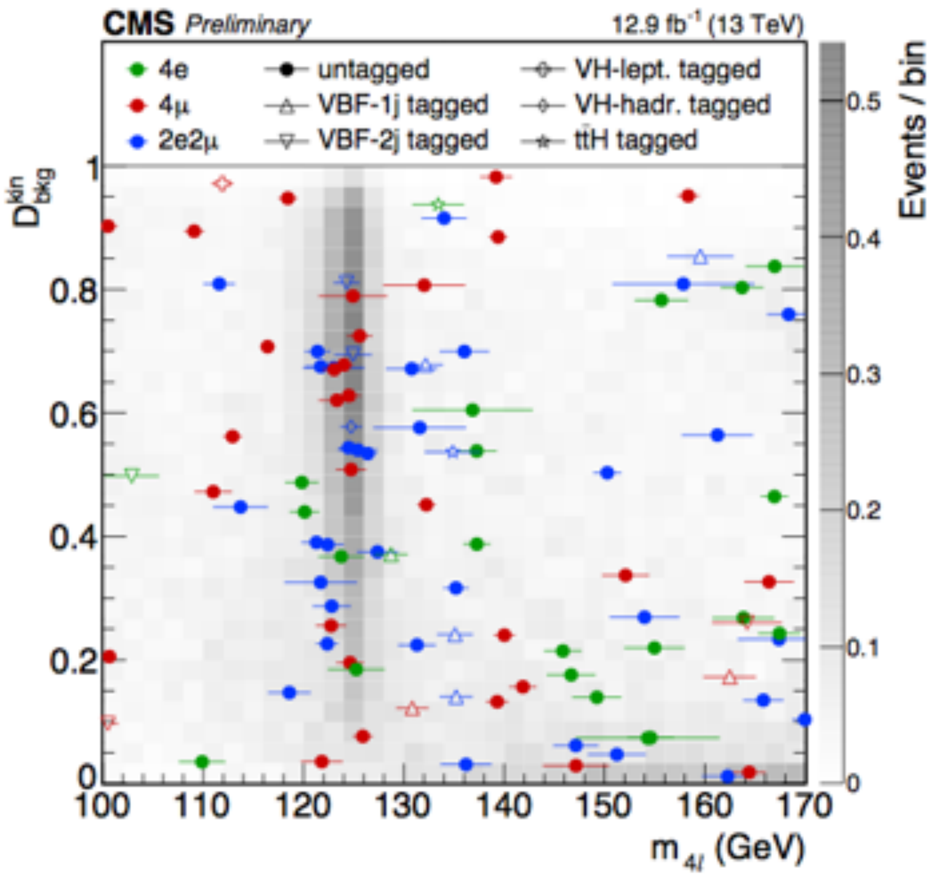
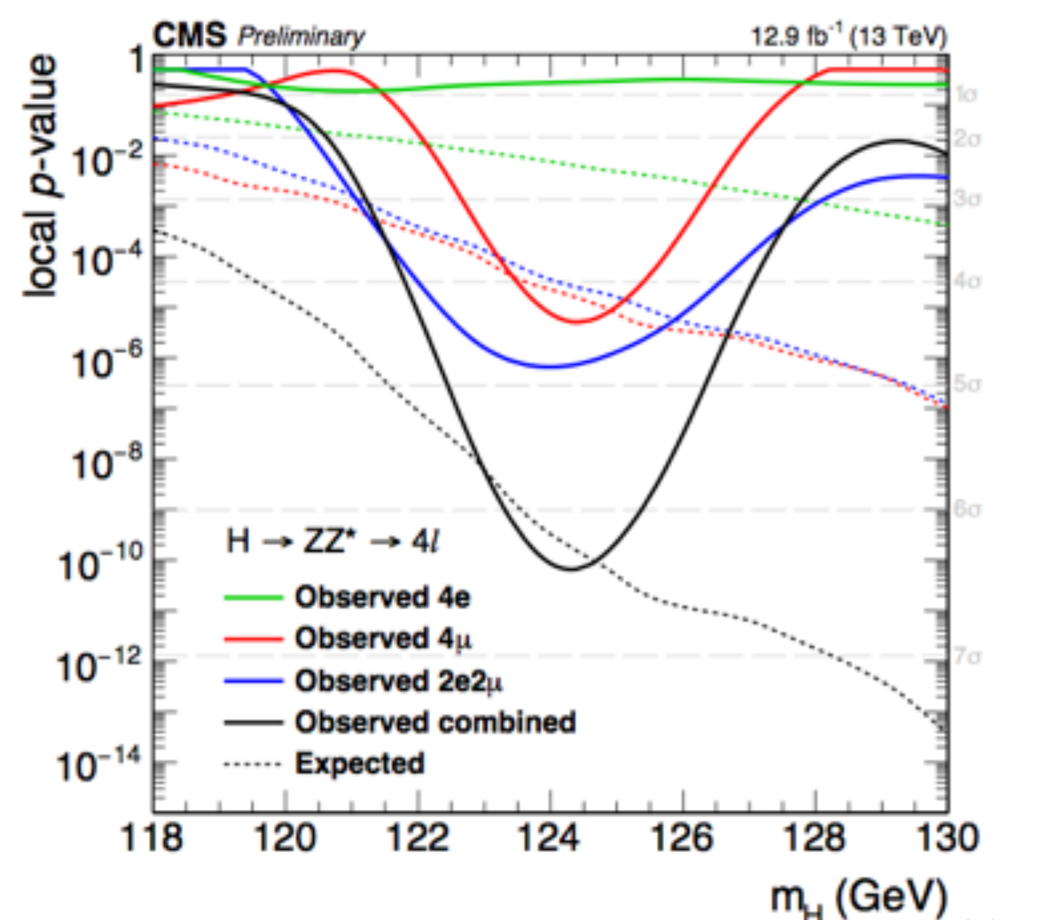


- p-value, mass, and signal strength extracted using a 2D likelihood fit defined by:
  - $\mathcal{L}_{2D}(m_{4l}, \mathcal{D}^{\text{kin}}_{\text{bkg}}) = \mathcal{L}(m_{4l})\mathcal{L}(\mathcal{D}^{\text{kin}}_{\text{bkg}}|m_{4l})$
  - in **3 final states x 6 categories**.
- Minimum of p-value at 124.3 GeV with **6.4σ obs. (6.3σ exp.) significance**
- **6.2σ obs. (6.5σ exp.)** at m_H=125.09 GeV (Run1 LHC average)

Channel	4e	4μ	2e2μ	4ℓ
$q\bar{q} \to ZZ$	$1.37^{+0.16}_{-0.15}$	$3.09^{+0.27}_{-0.27}$	$3.90^{+0.46}_{-0.43}$	$8.36^{+0.81}_{-0.79}$
$gg \to ZZ$	$0.16^{+0.03}_{-0.03}$	$0.32^{+0.05}_{-0.05}$	$0.30^{+0.05}_{-0.05}$	$0.77^{+0.12}_{-0.12}$
Z + X	$0.90^{+0.38}_{-0.37}$	$1.40^{+0.52}_{-0.51}$	$2.34^{+0.91}_{-0.89}$	$4.64^{+1.11}_{-1.09}$
Sum of backgrounds	$2.42^{+0.42}_{-0.40}$	$4.81^{+0.59}_{-0.59}$	$6.54^{+1.03}_{-1.00}$	$13.77^{+1.41}_{-1.38}$
Signal (m_H = 125 GeV)	$3.90^{+0.53}_{-0.54}$	$7.92^{+0.88}_{-0.93}$	$9.80^{+1.34}_{-1.36}$	$21.61^{+2.63}_{-2.71}$
Total expected	$6.32^{+0.78}_{-0.76}$	$12.73^{+1.21}_{-1.24}$	$16.34^{+1.92}_{-1.90}$	$35.38^{+3.43}_{-3.45}$
Observed	5	12	16	33



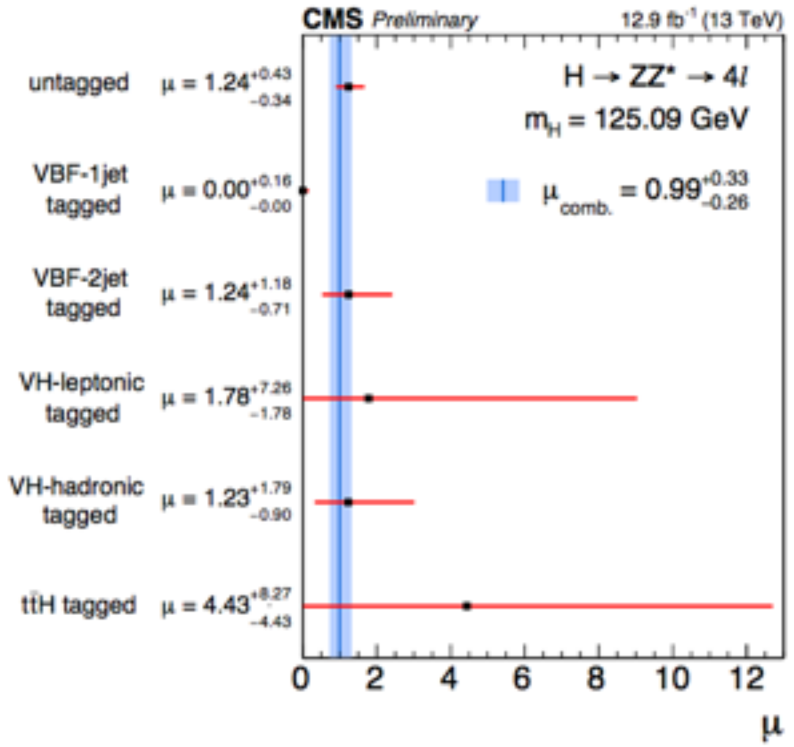
H→ZZ*→4ℓ: H(125) production modes

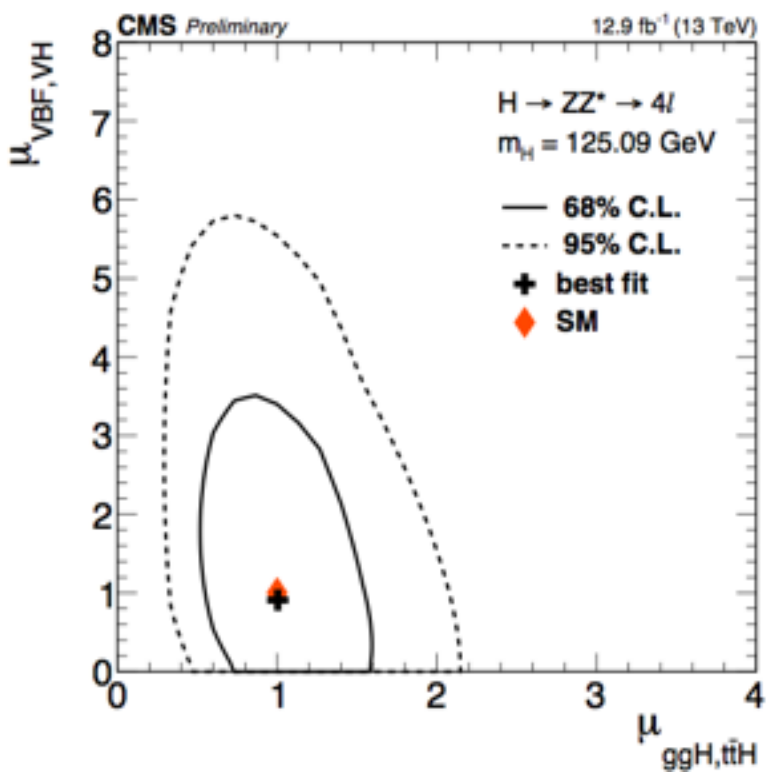
CMS-PAS-HIG-16-033

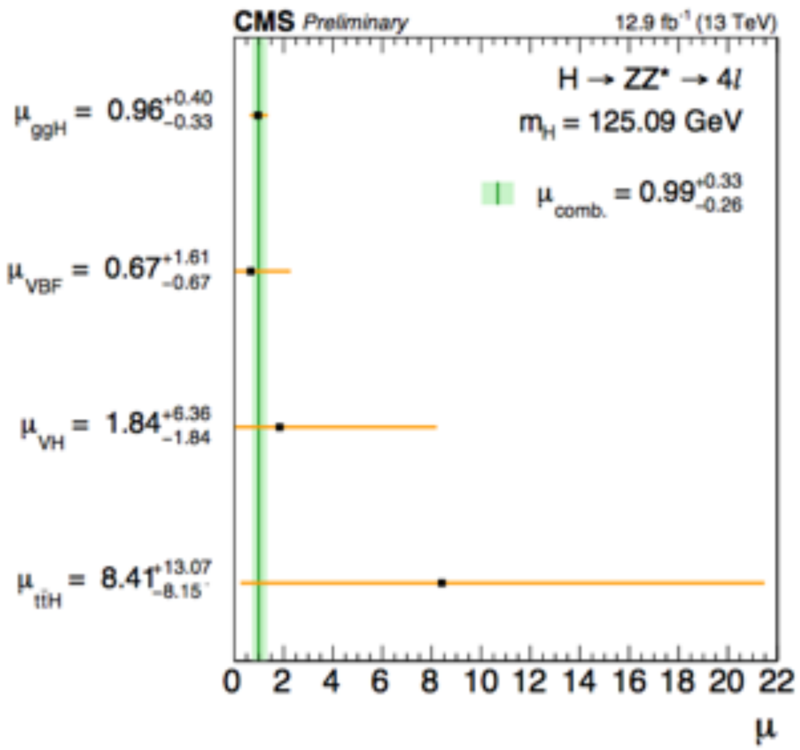
- Combined signal strength at m_H = 125.09 GeV

$$\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$$

- Extract signal strength in each category
- Extract strength production processes in a 2-parameter and a 4-parameter model







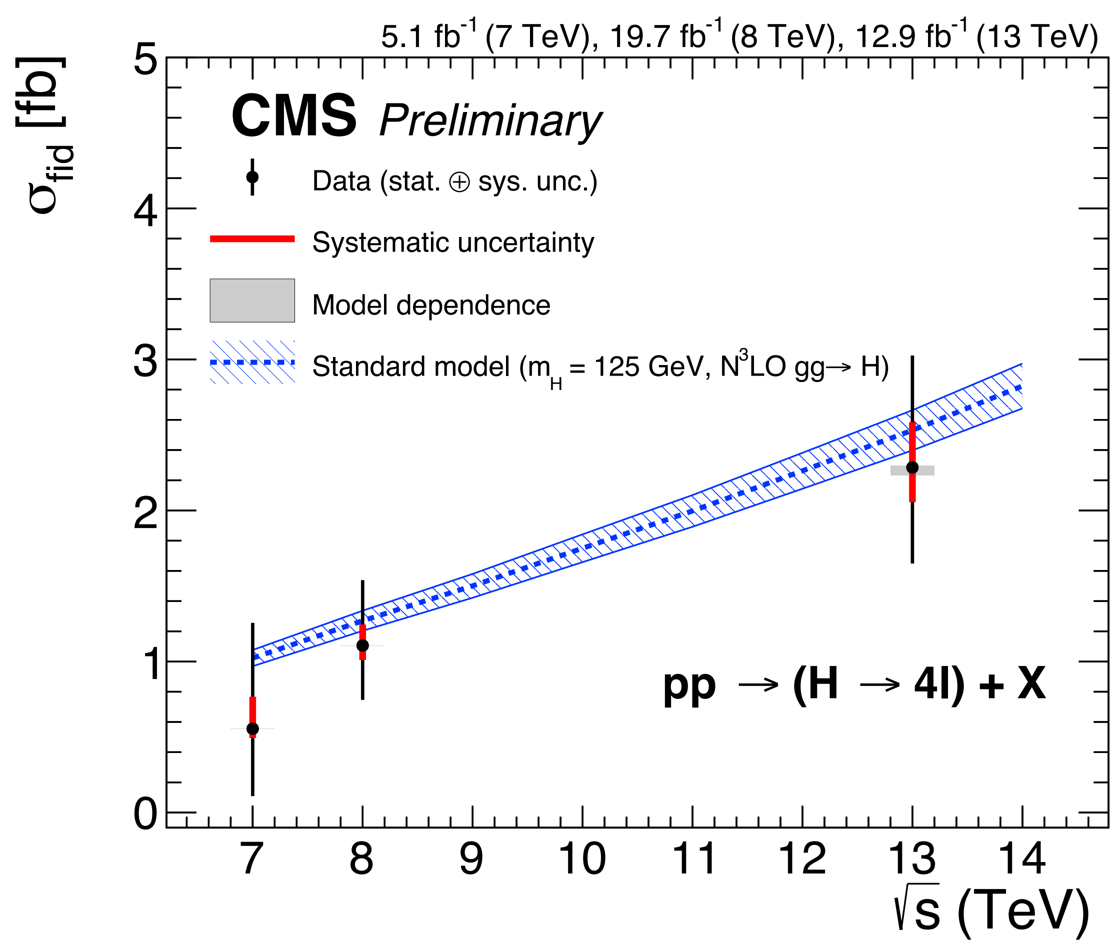
H→ZZ*→4ℓ: fiducial cross-section

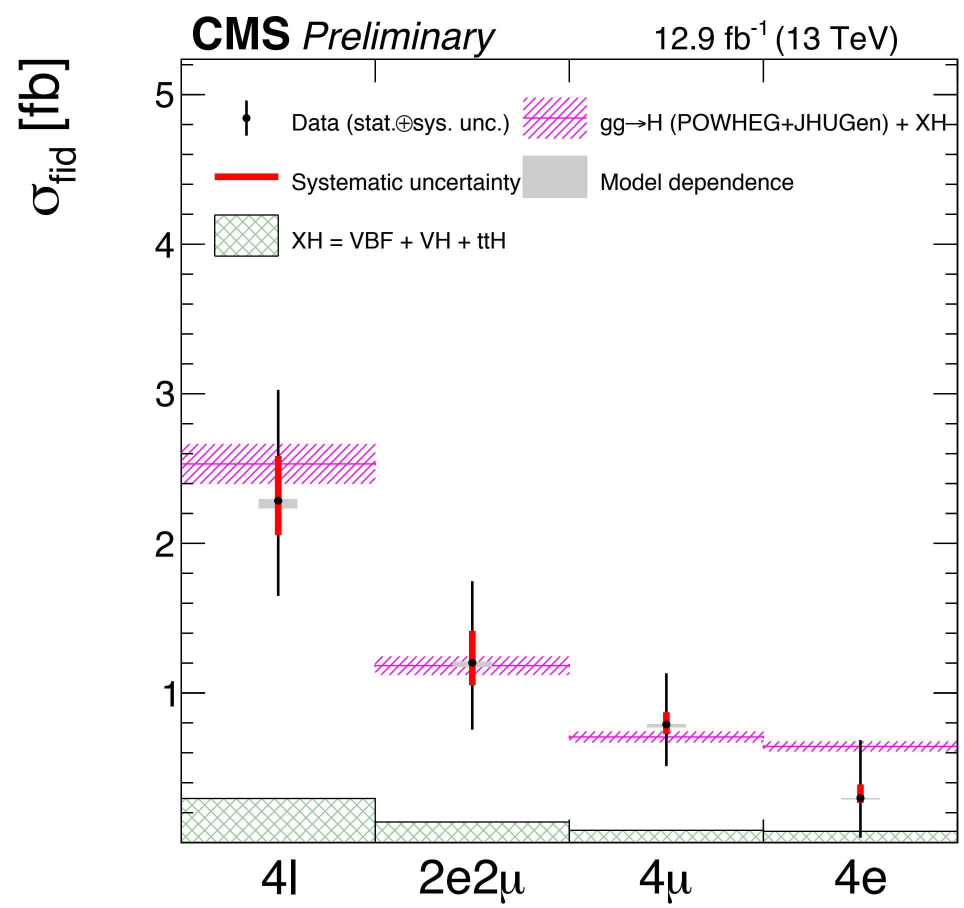
CMS-PAS-HIG-16-033

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Next-to-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7(5)$ GeV
Pseudorapidity of electrons (muons)	$\|\eta\| < 2.5(2.4)$
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 \cdot p_T$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40\,\mathrm{GeV} < m_{Z_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12\,\mathrm{GeV} < m_{Z_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+\ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105\,\mathrm{GeV} < m_{4\ell} < 140\,\mathrm{GeV}$

- Maximum likelihood fit to the uncategorised m_{4l} distribution, assuming m_H= 125 GeV

$$\sigma_{\mathrm{fid.}} = 2.29^{+0.74}_{-0.64}(\mathrm{stat.})^{+0.30}_{-0.23}(\mathrm{sys.})^{+0.01}_{-0.05}(\mathrm{model\ dep.})\ \mathrm{fb}$$





H→ZZ*→4ℓ: differential cross-section

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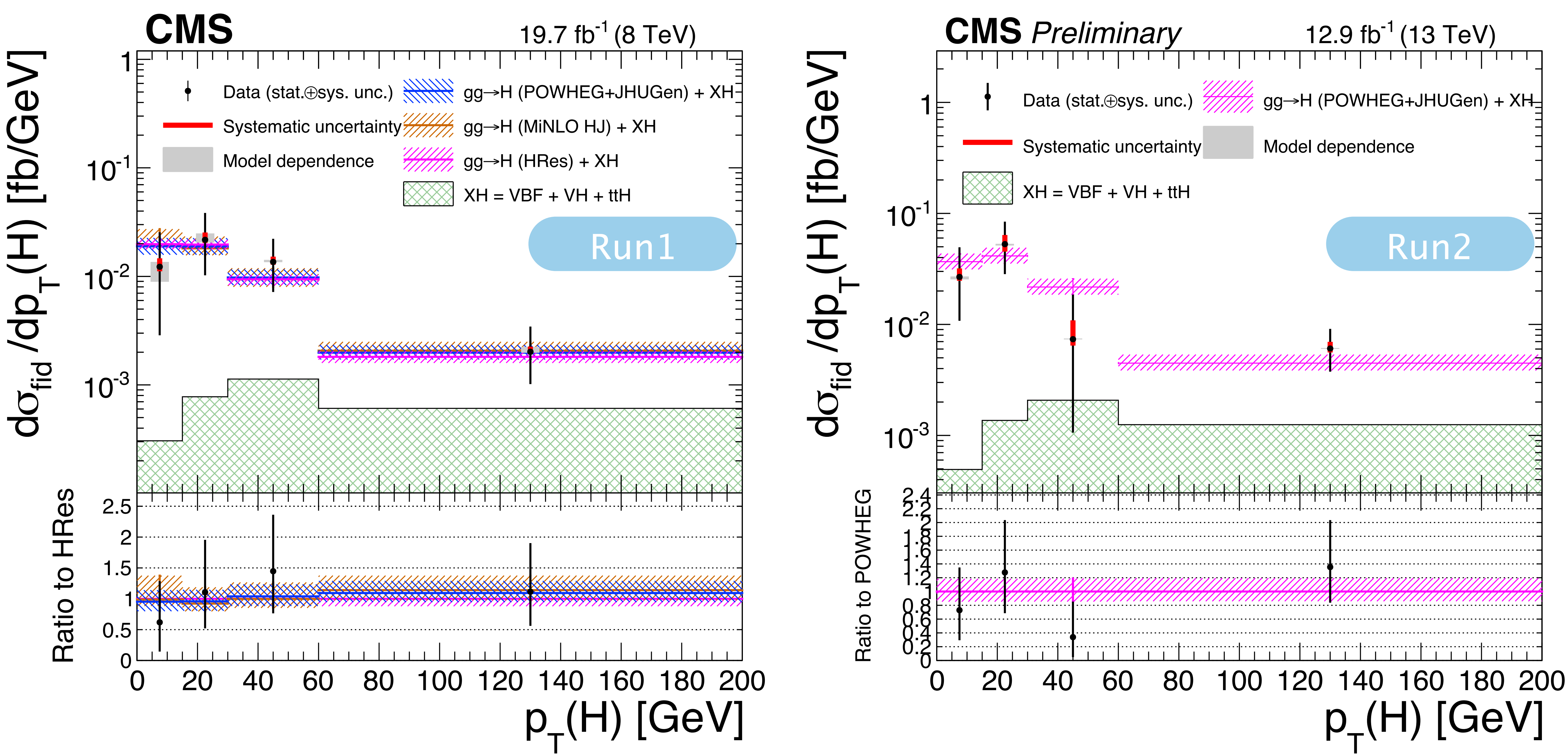

H→ZZ*→4ℓ: differential cross-section

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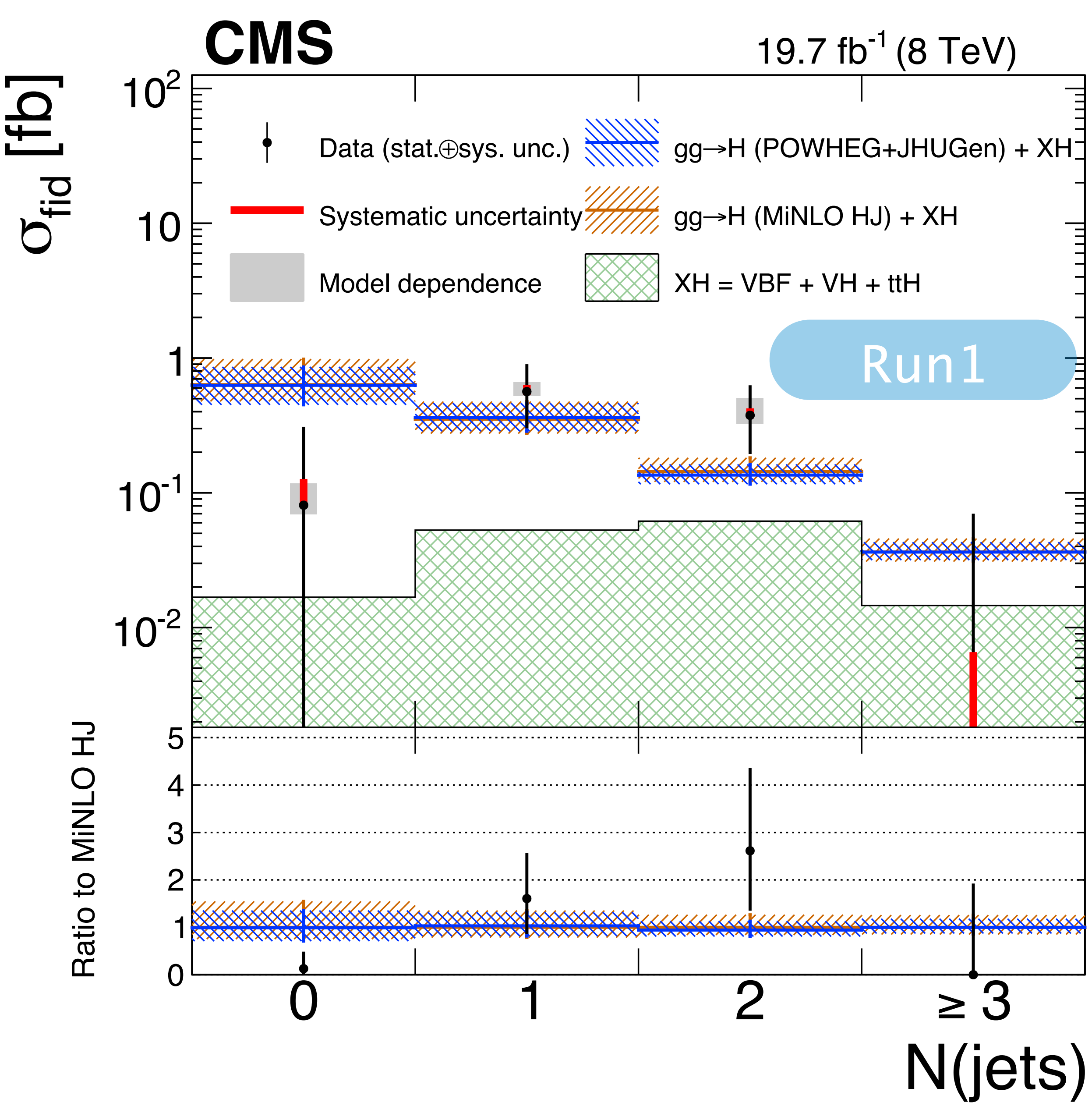
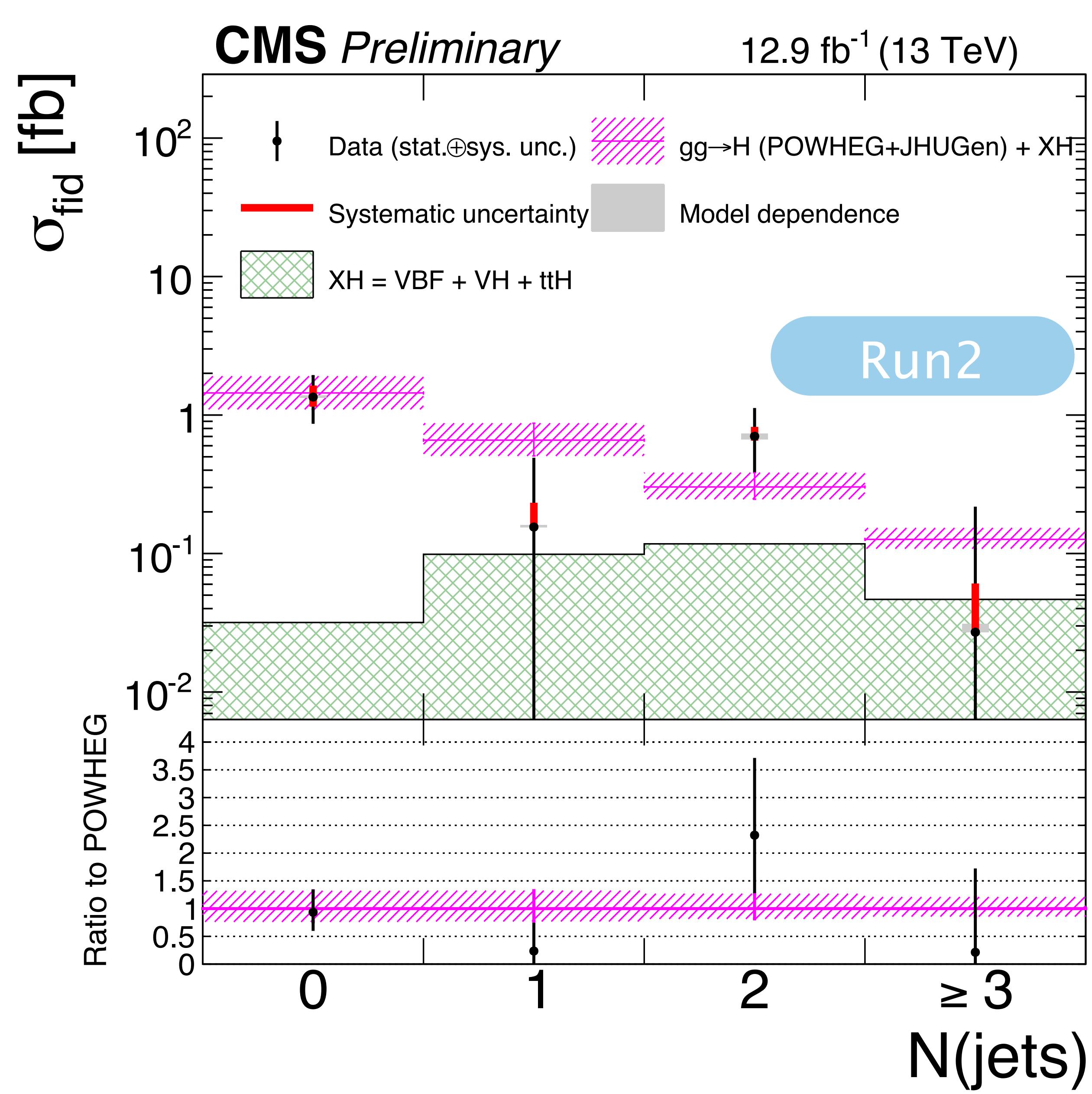
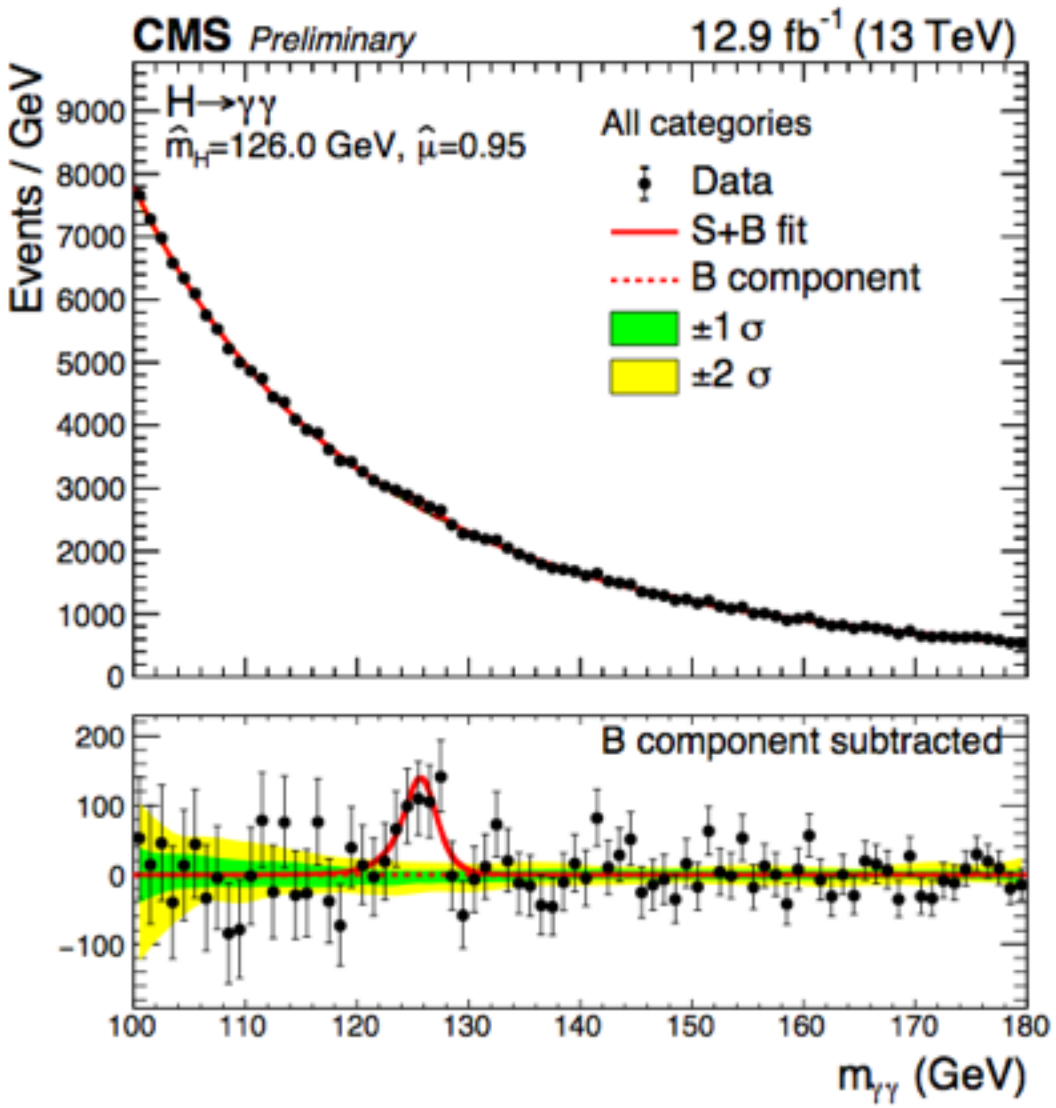


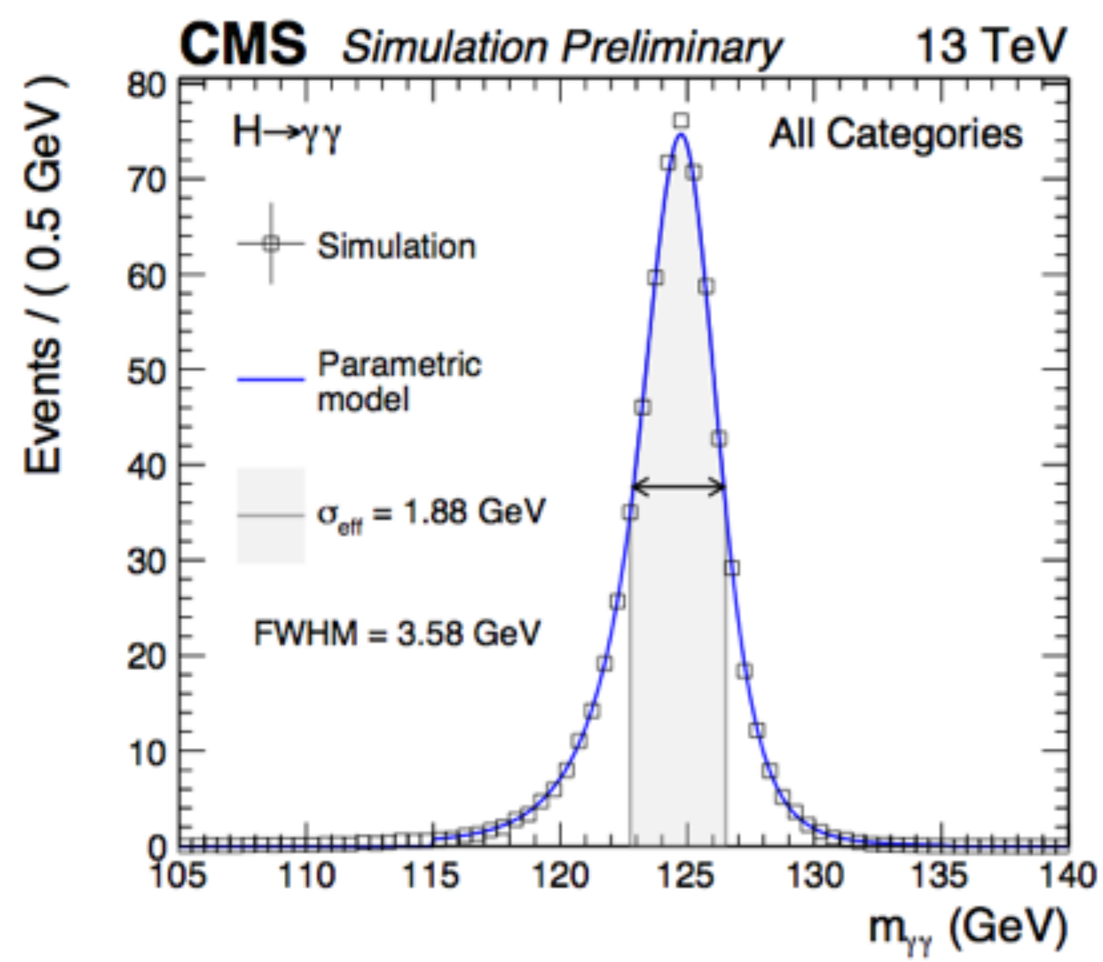


H→γγ: analysis strategy

CMS-HIG-16-020



- Looking for a small signal in a large falling background
- Background composed by :
  - γ–γ (irreducible) ~ 70%
  - γ–jet (reducible) ~ 30%
  - jet–jet (reducible) < 1%
- General strategy: categorise events by resolution and production topology



- Good precision mass measurement

$$m_{\gamma\gamma}^2 = E_{\gamma_1} E_{\gamma_2} (1 - \cos\alpha)$$

- Requires a good energy reconstruction and correct vertex assignment

H→γγ : categorisation

ttH (leptonic)

- (sub-)lead-photon pT/mγγ >1/2(1/4), at least one lepton (ℓ=μ,e) away from Z peak
- at least two jets with pT>25GeV, |η|<2.5
- at least one of the jet is b-tag

ttH (Hadronic)

- at least two jets with pT>25GeV, |η|<2.5
- no lepton + at least 5 jets (≥1 b-tag)

ttH (leptonic)
ttH (Hadronic)
VBF (0-1)
Untagged (0-3)

$H \to \gamma\gamma$: categorisation

ttH (leptonic)

- (sub-)lead-photon $pT/m_{\gamma\gamma} > 1/2(1/4)$, at least one lepton ($\ell=\mu,e$) away from Z peak
- at least two jets with $pT > 25$GeV, $|\eta| < 2.5$
- at least one of the jet is b-tag

ttH (Hadronic)

- at least two jets with $p_T > 25$GeV, $|\eta| < 2.5$
- no lepton + at least 5 jets (≥ 1 b-tag)

VBF (0-1)

- Require at least 2 jets with $p_{T1} > 30$GeV, $p_{T2} > 20$ GeV, $|\eta| < 4.7$, $m_{jj} > 250$ GeV
- A diphoton pair with (sub)lead $p_T/m_{\gamma\gamma} > 1/2(1/4)$
- Construct a BDT to identify VBF dijet-like events using:
  - $p_T/m_{\gamma\gamma}$ of both photons, p_T of both jets, m_{jj}, $\Delta\eta_{jj}$, Zeppenfeld variable, $\Delta\phi(jj,\gamma\gamma)$
- Final VBF classification combines dijet BDT with BDT estimating diphoton quality (see next slide)
- 2 VBF categories are then defined by sensitivity (VBF tag 0-1)

ttH (leptonic)

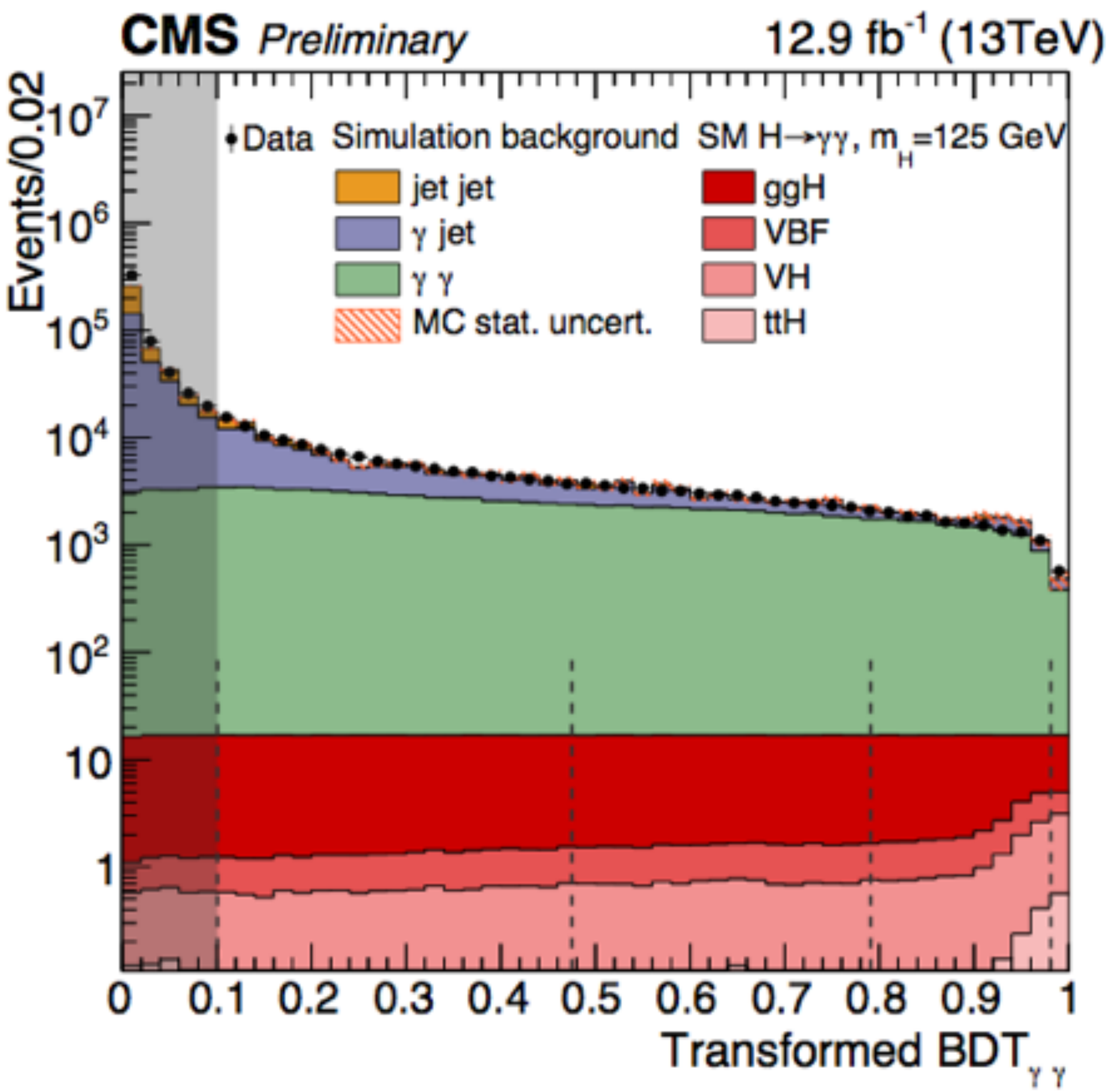
ttH (Hadronic)

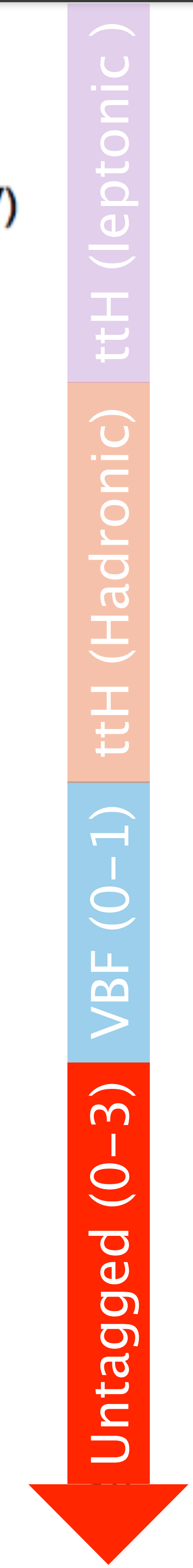
VBF (0-1)

Untagged (0-3)

H→γγ : categorisation

- Remaining events fall into the untagged category
- Construct MVA to select diphoton pairs with signal like kinematics, high photon ID score and good mass resolution
- Split events into categories based on output of classifier exploiting S/B ratios and mass resolution
- 4 untagged categories → **8 non-overlapping categories in total**





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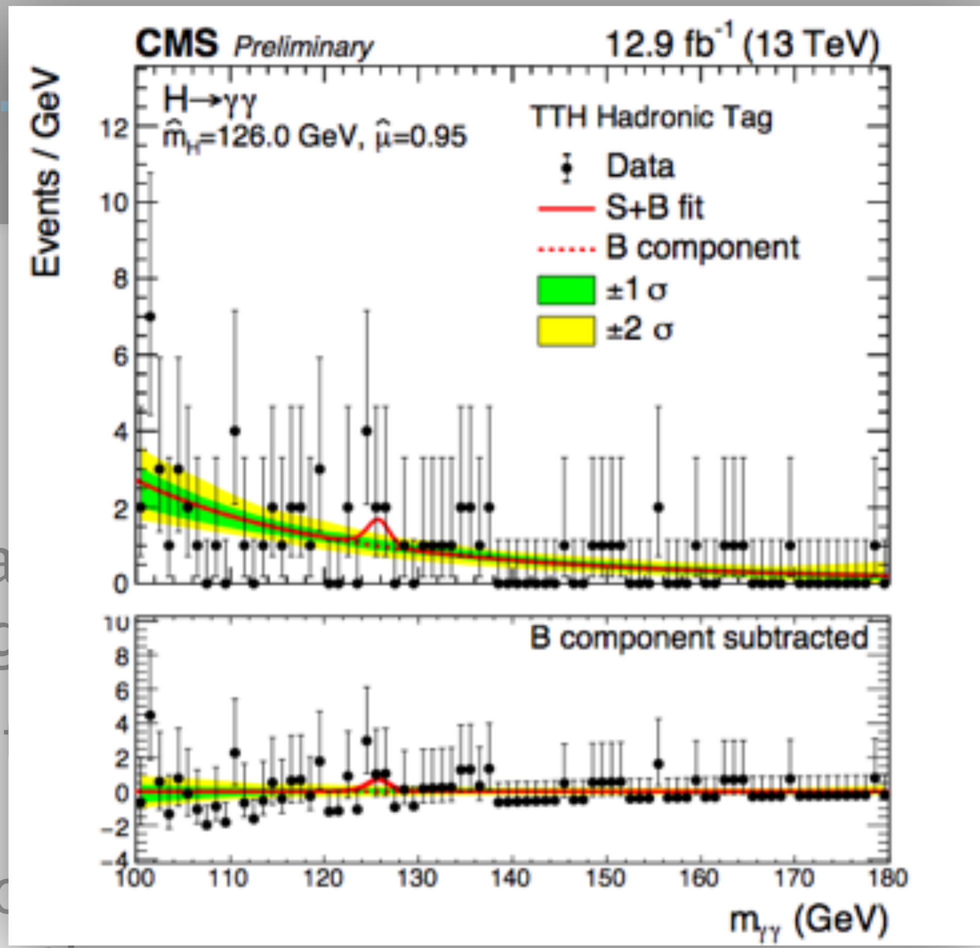

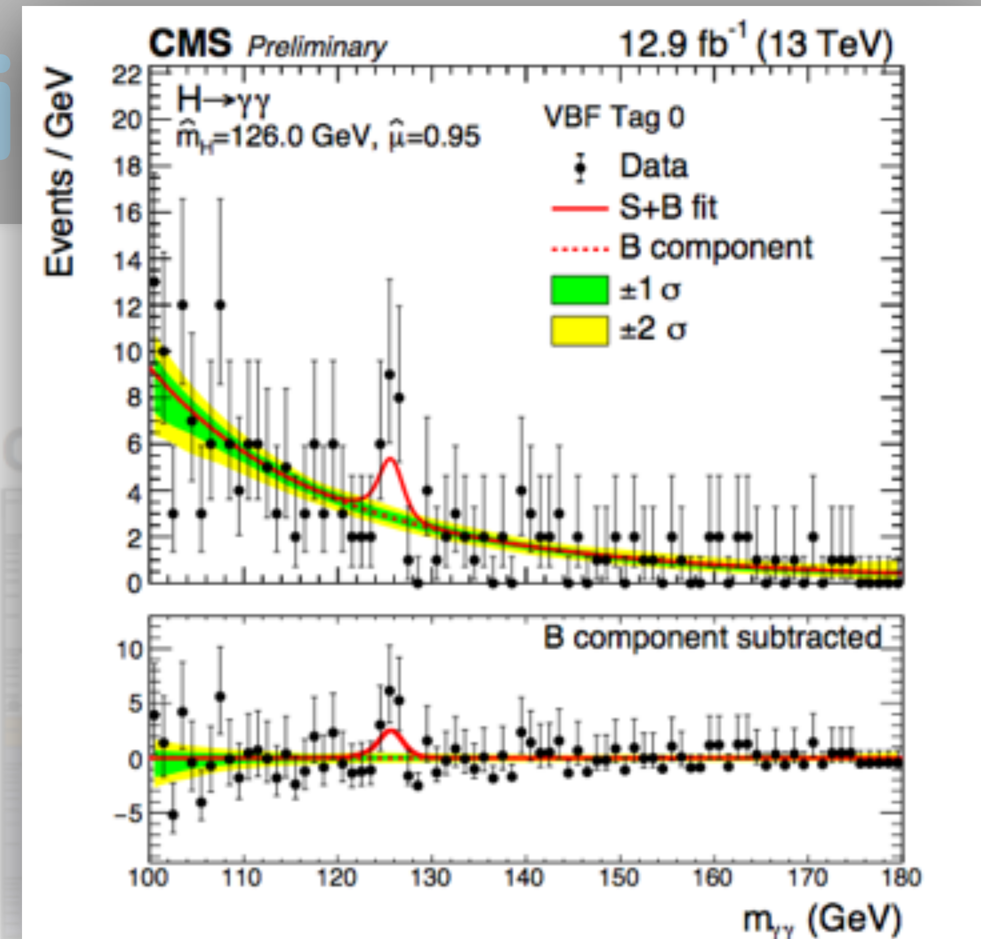

- Rema… untag…
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- Split … outpu… ratios
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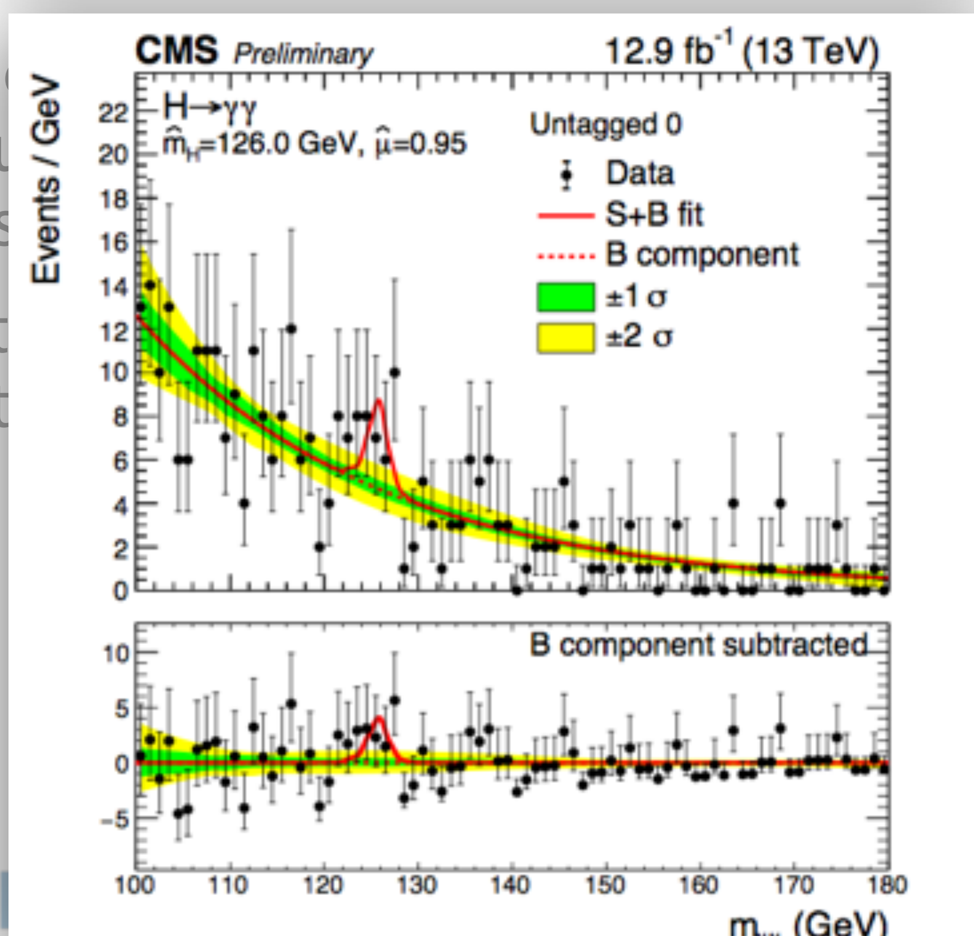
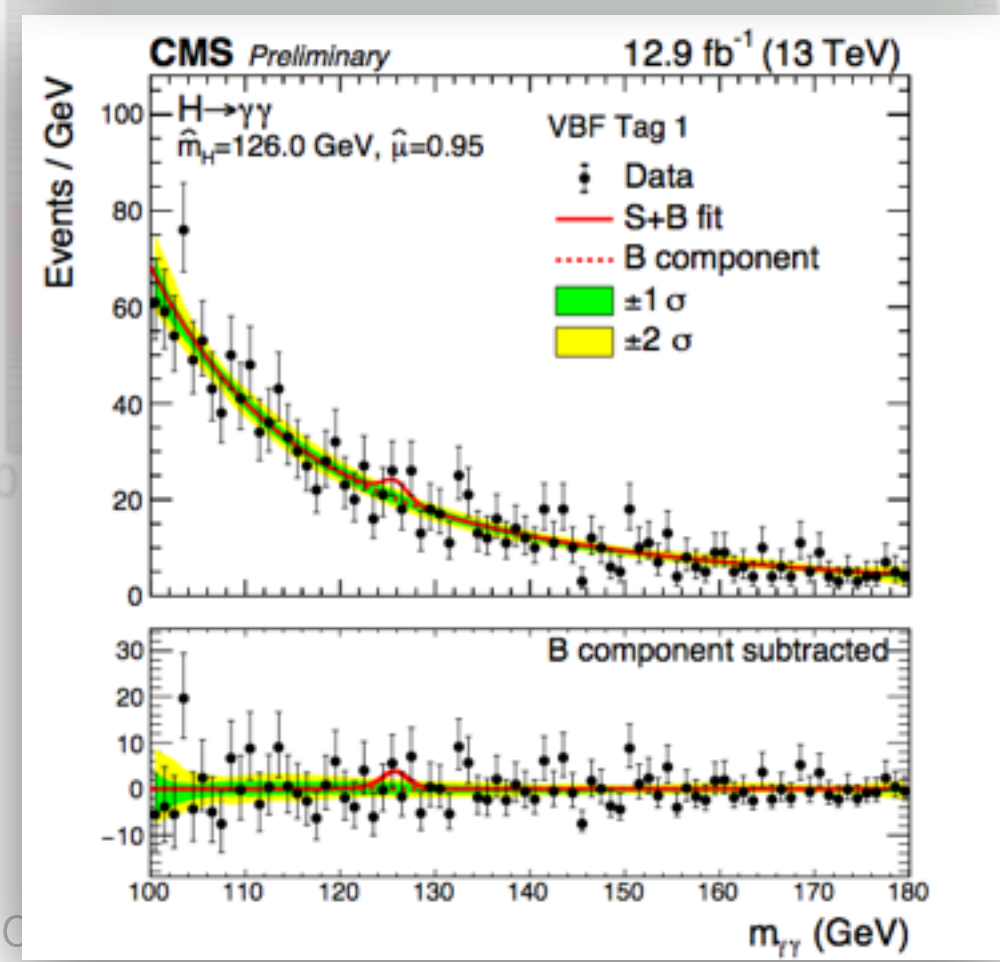
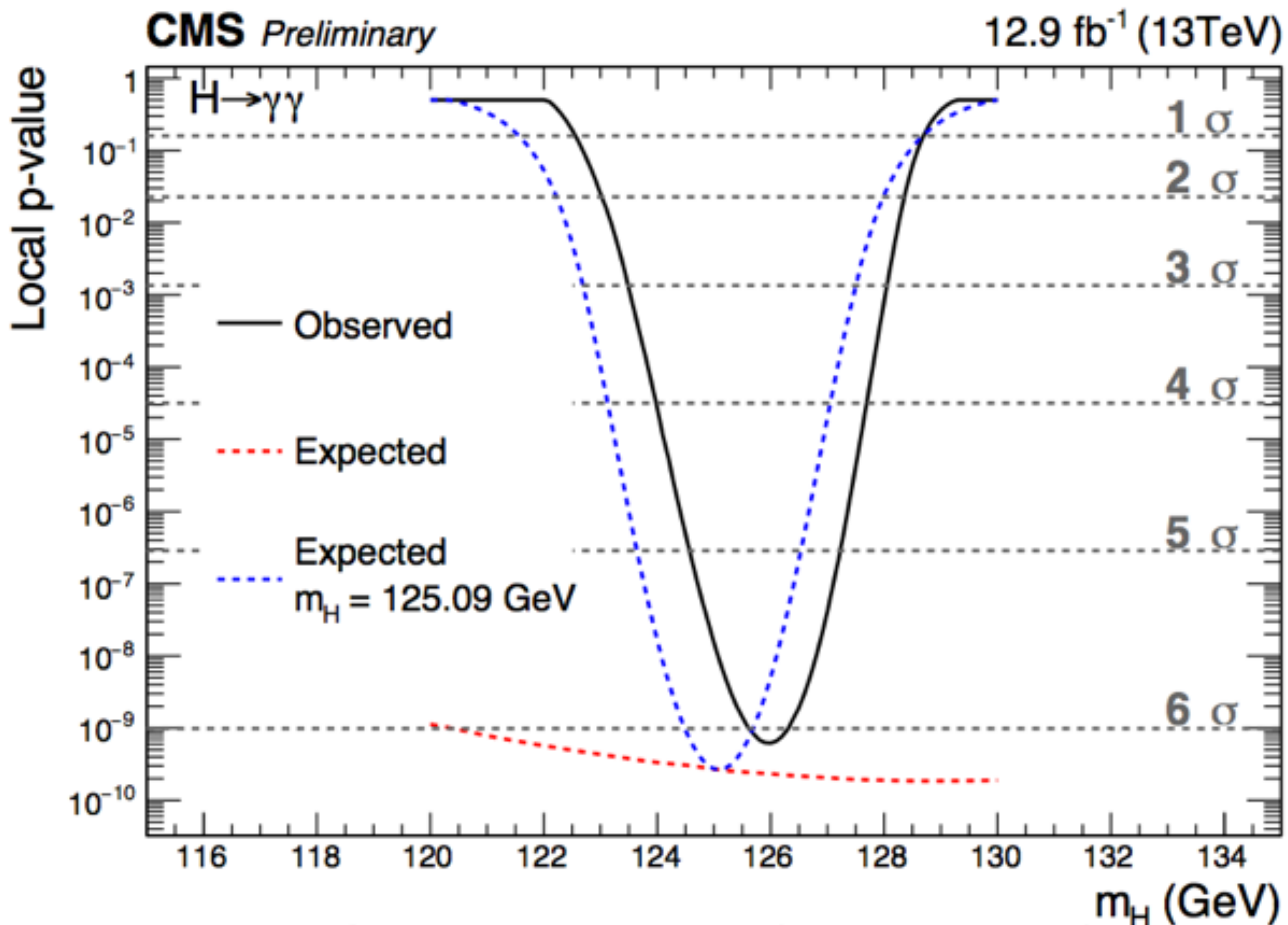




ttH (leptonic) ttH (Hadronic) VBF (0–1) Untagged (0–3)

H→γγ : Signal extraction

CMS-HIG-16-020



- **Significance** at 125.09 GeV: **5.6σ observed** (6.2σ expected)
- **Maximum observed** significance is **6.1σ** at 126.0 GeV
- Best-fit signal strength $\hat{\sigma}/\sigma_{SM} = 0.95^{+0.21}_{-0.19} = 0.95 \pm 0.17(stat.)^{+0.08}_{-0.05}(theo.)^{+0.10}_{-0.07}(syst.)$

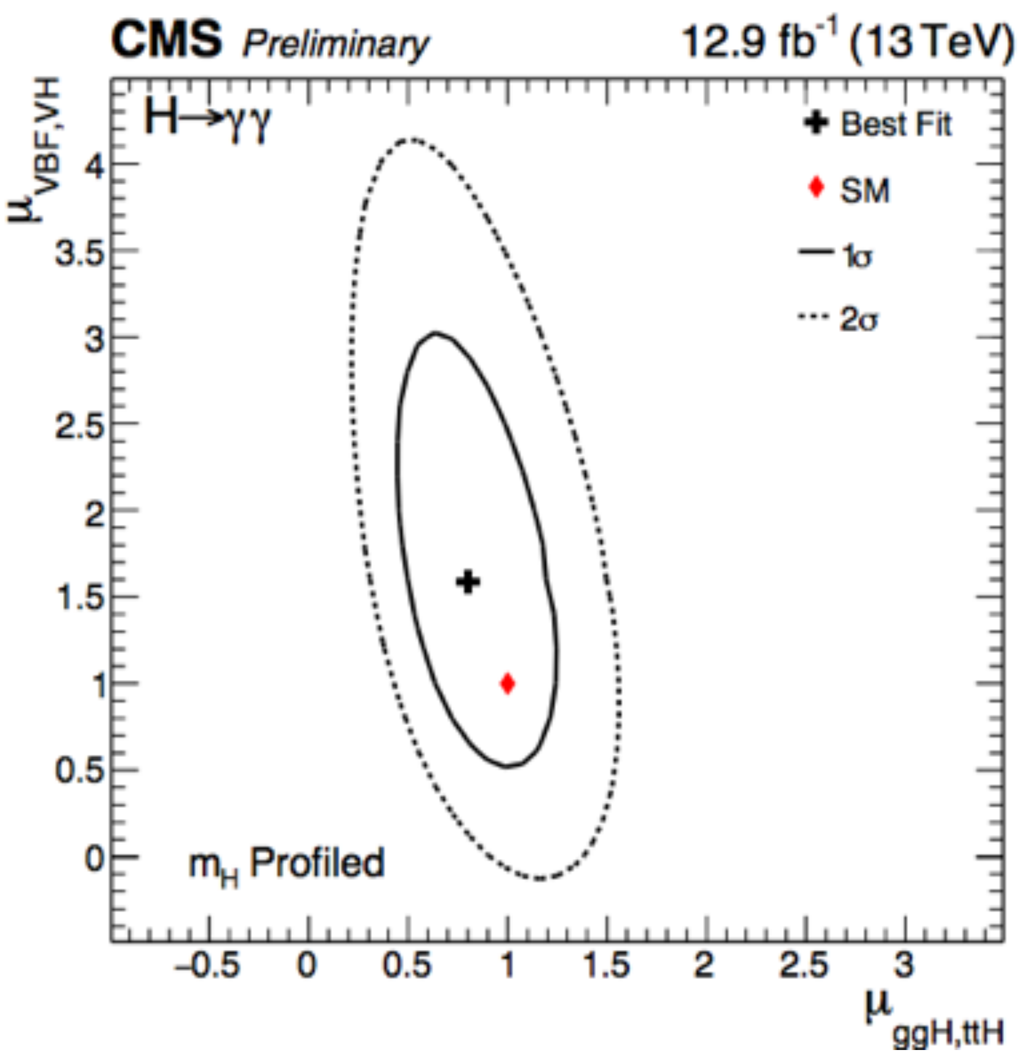
H→γγ: Production modifier

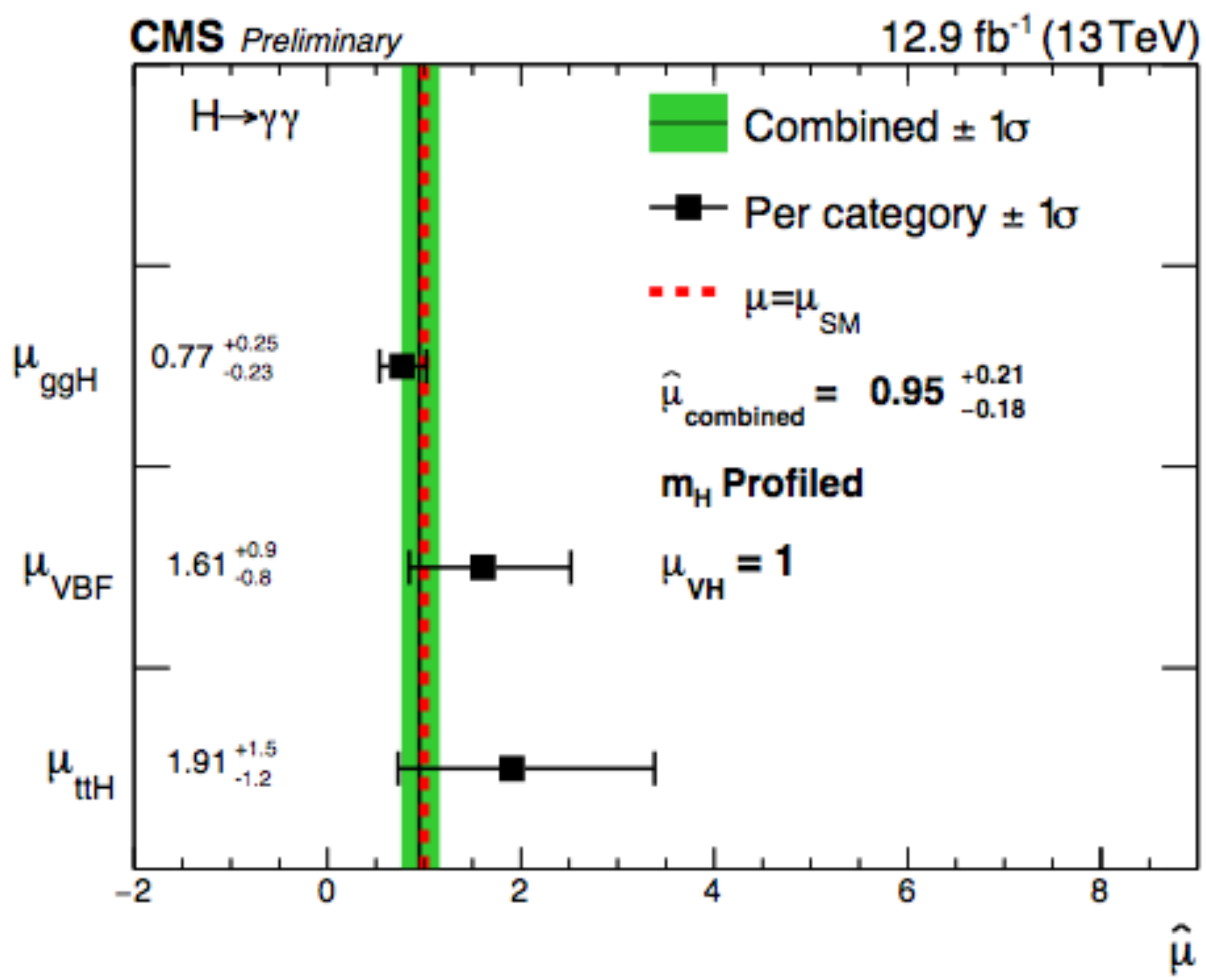
CMS-HIG-16-020

- Best fit signal strength split into boson and fermionic production modes:

$$\hat{\mu}_{VBF,VH} = 1.59^{+0.73}_{-0.45} \text{ and } \hat{\mu}_{ggH,t\bar{t}H} = 0.80^{+0.14}_{-0.18}$$

- Also split the signal strength by individual production mode





H→γγ: Fiducial cross section

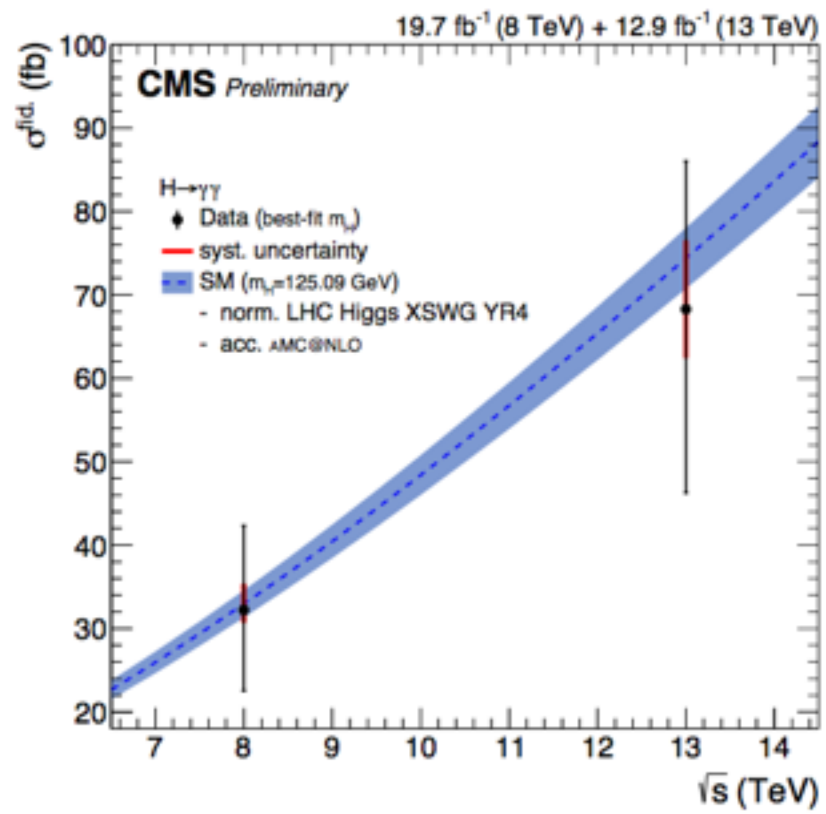
CMS-HIG-16-020

- Fiducial cross section measured profiling m_H:

$$\hat{\sigma}_{fid} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst.})\text{fb}$$

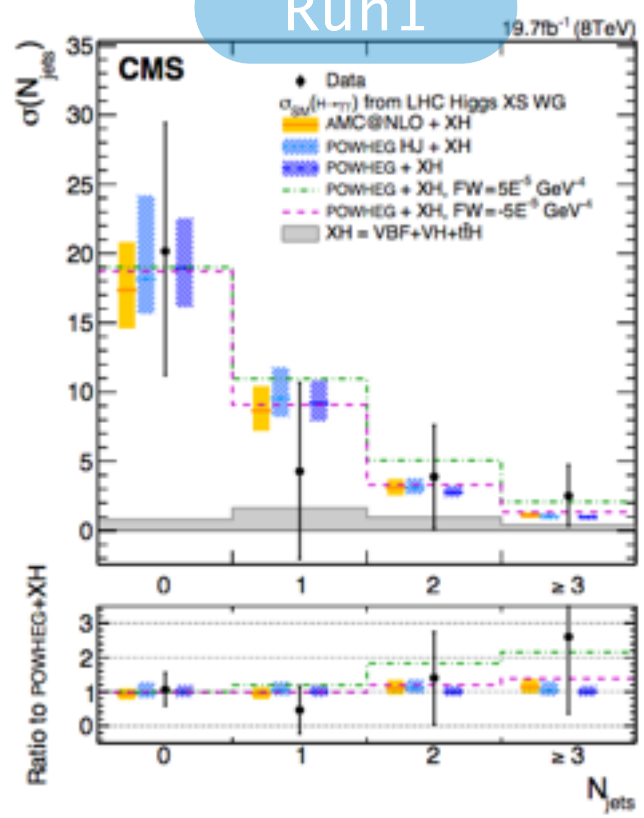
- Theoretical prediction for m_H=125.09 GeV

$$\sigma^{th.}_{fid} = 73.8 \pm 3.8\text{fb}$$

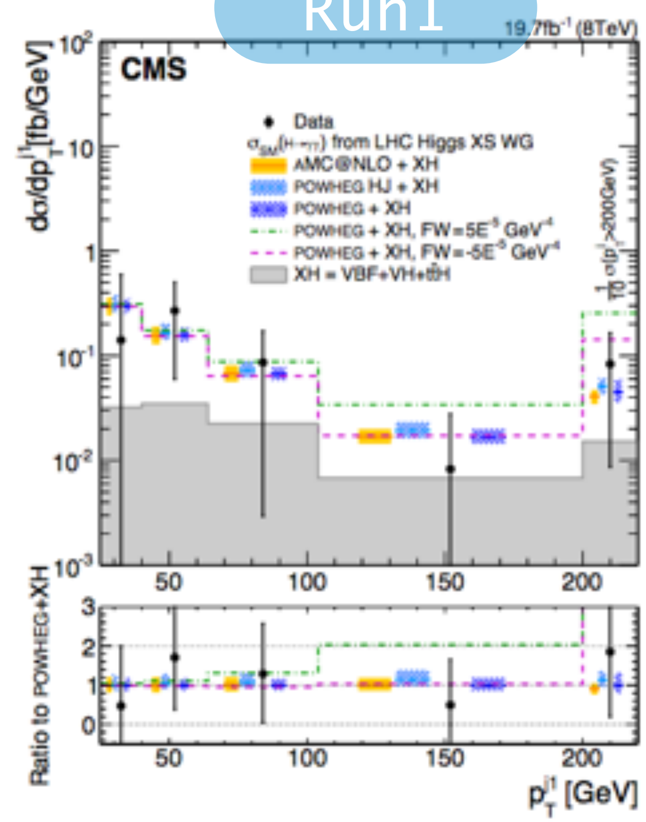


- Differential XS measurement done in Run1 for H+jets
- Similar results @13TeV are in preparation

Run1



Run1



Imperial College London

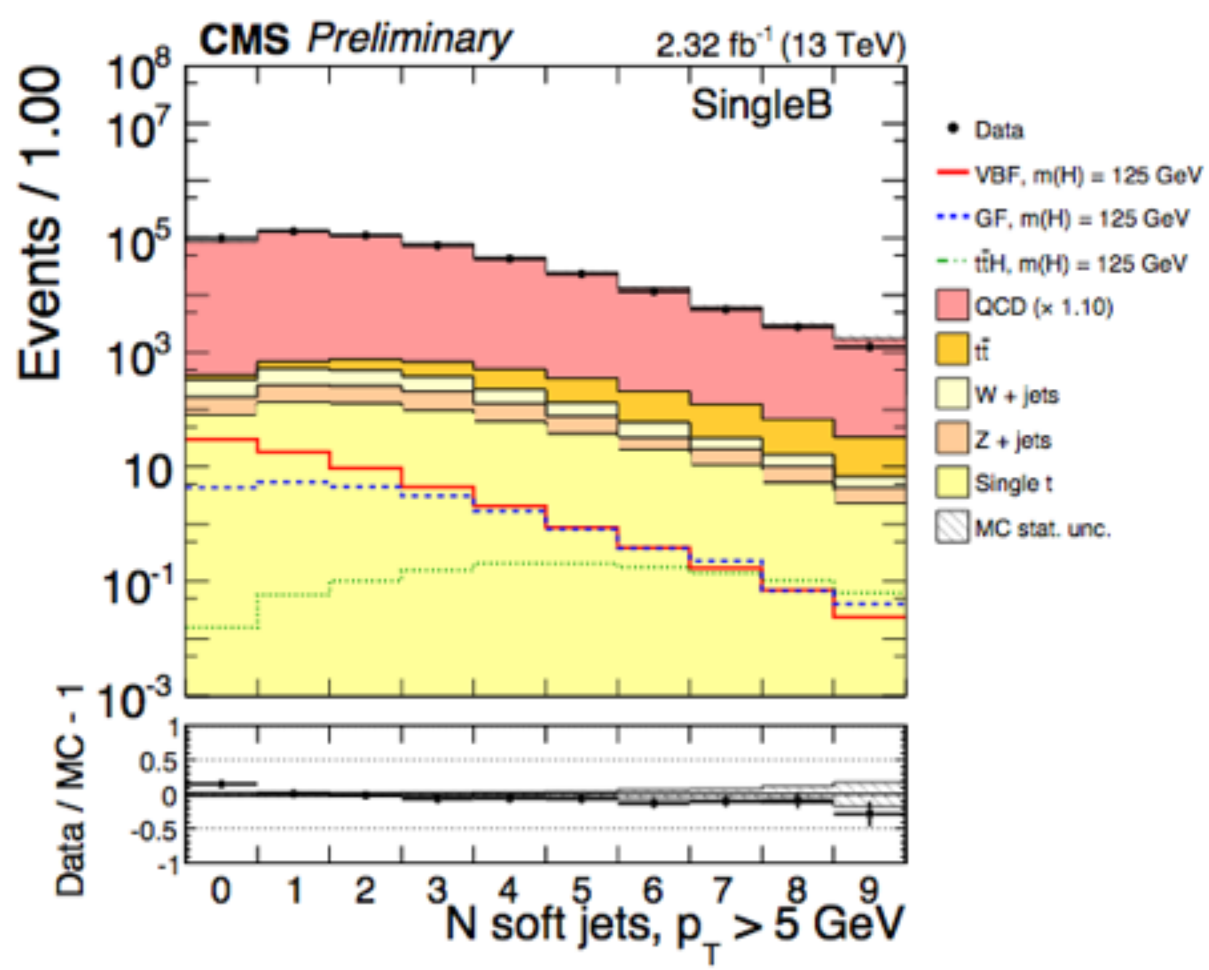
VBF H→bb : Analysis strategy

CMS-HIG-16-003

- Signal signature:
  - 2 b-jets + 2 forward VBF jets with:
    - large separation in η
    - large di-jet invariant mass
  - Main background : Multi-jet QCD
- Analysis separated into two parts from complementary trigger strategies

	SingleB	DoubleB
Trigger	one b-tagged jet	two b-tagged jets
jets p_T	$p_T^{1,2,3,4} > 92, 76, 64, 30$ GeV	
jets $\|\eta\|$	<4.7	
b tag	no cut	two jets with CSV>0.5
$\Delta\phi_{bb}$	<1.6 radians	<2.4 radians
VBF topology	$m_{qq} > 460$ GeV $\|\Delta\eta_{qq}\| > 4.1$	$m_{qq} > 200$ GeV $\|\Delta\eta_{qq}\| > 1.2$
Veto	None	Events that belong to SingleB

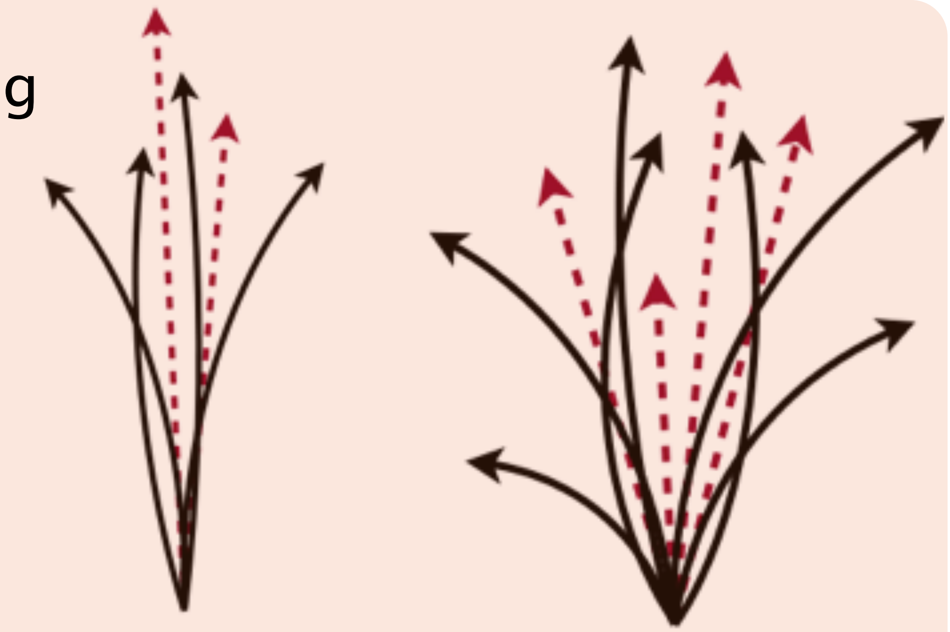
- Construct a MVA discriminant based on:
  - 1 or 2 b-tagged jets
  - VBF di-jet signature (tighter selection for 1 b-jet)
  - PU rejecting with "soft activity" jet counting



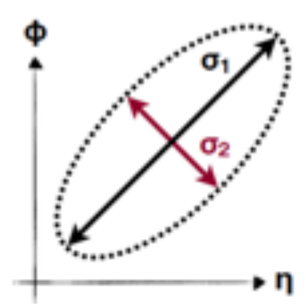
H→bb : Quark/Gluon Tagger

CMS PAS JME-13-002

- Quarks and gluons have different color interaction, resulting in in different hadronisation
- At a given energy a gluon jet will, on average
  - have a **higher multiplicity**
  - be **angularly wider**
  - have more **uniform energy fragmentation**
- **Different variables** have been studied → 3 chosen



quark jet gluon jet



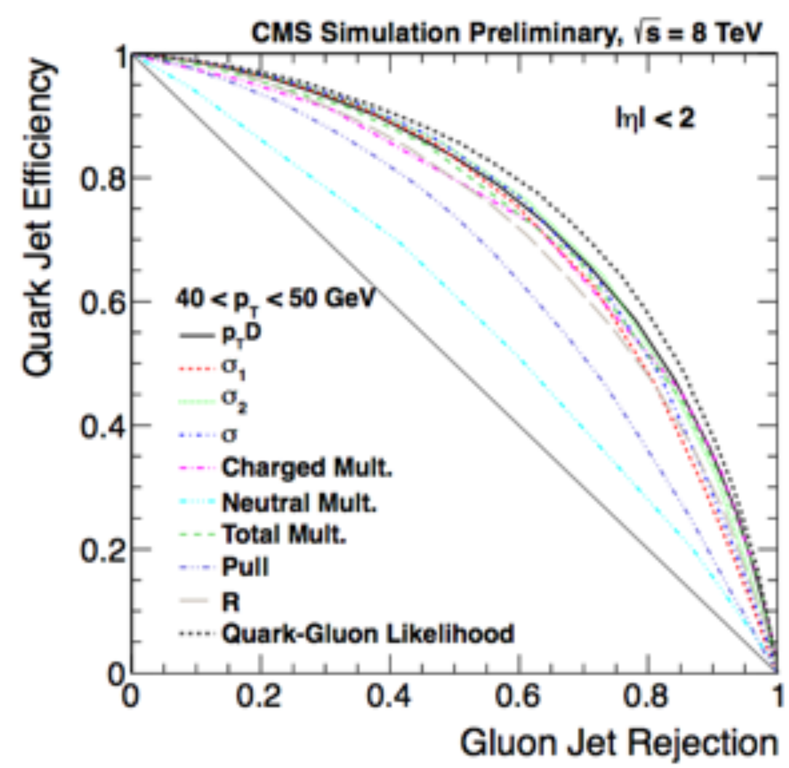
$$|\vec{t}| = \left|\frac{\sum_i p_{T,i}^2 |\vec{r}_i| \vec{r}_i}{\sum_i p_{T,i}^2}\right|$$

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

From PFlow
- Charged multiplicity
- Neutral multiplicity
- **Total multiplicity**

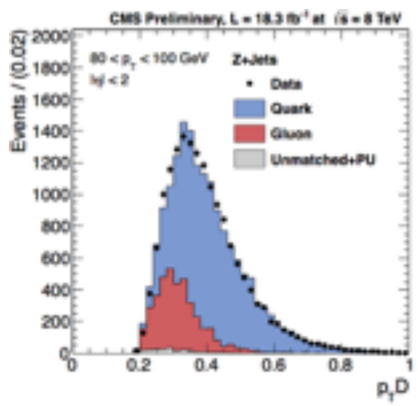
Jet shape variables
- RMS of PF candidate in η−ϕ plan
- Major axis in η−ϕ
- **Minor axis in η−ϕ**

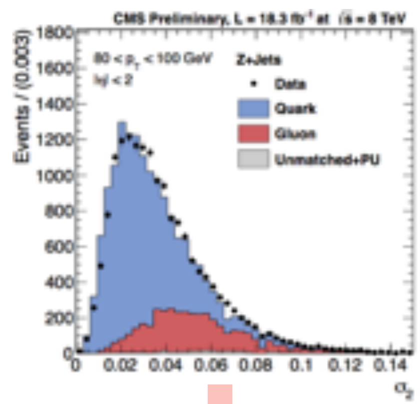
Energy variables
- Pull
- R, energy fraction carried by the leading consistent
- **Fragmentation variable : P_T^D**

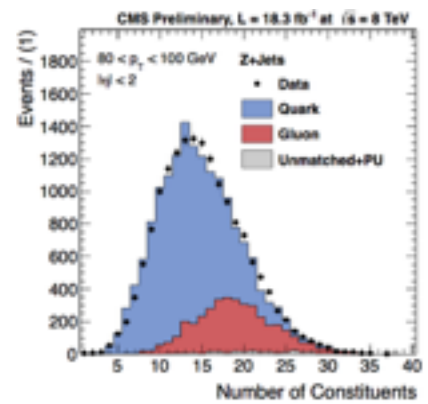


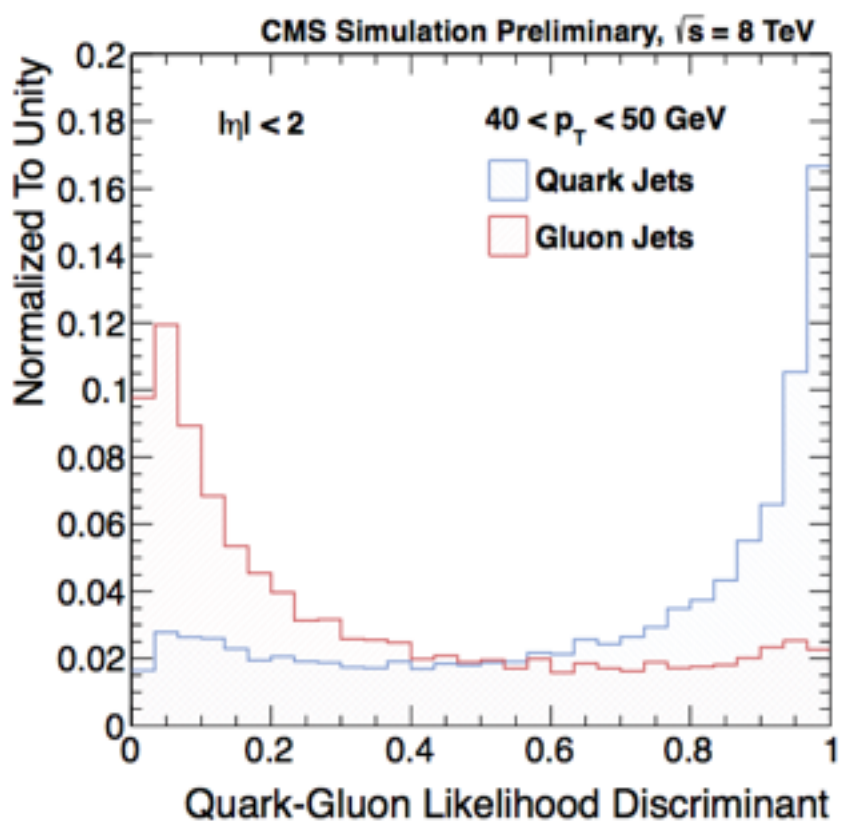
H→bb : Quark/Gluon Tagger

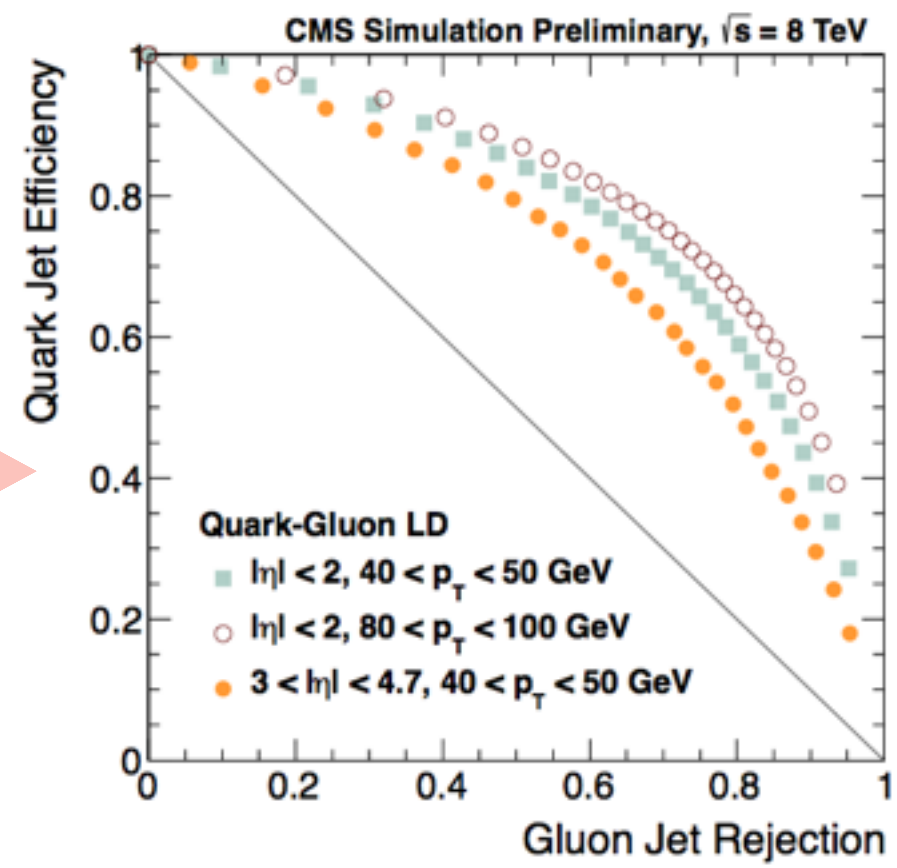
CMS PAS JME-13-002









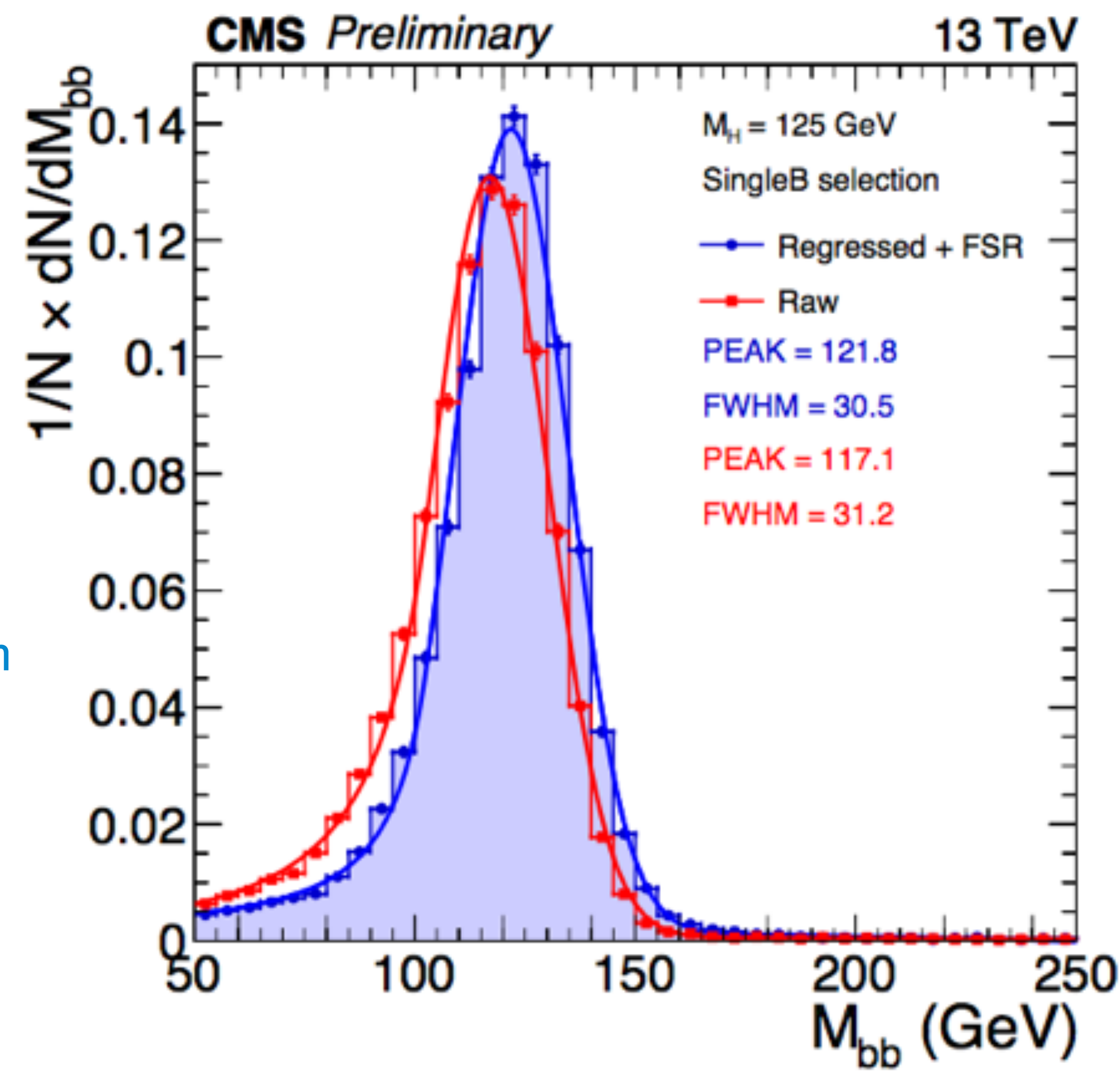


- Construct a likelihood discriminant (up to η=4.7) based on the chosen of three variables
- Extracted on di-jet sample. Applied also on the Z+jet sample for validation

VBF H→bb : Mass resolution

CMS-HIG-16-003

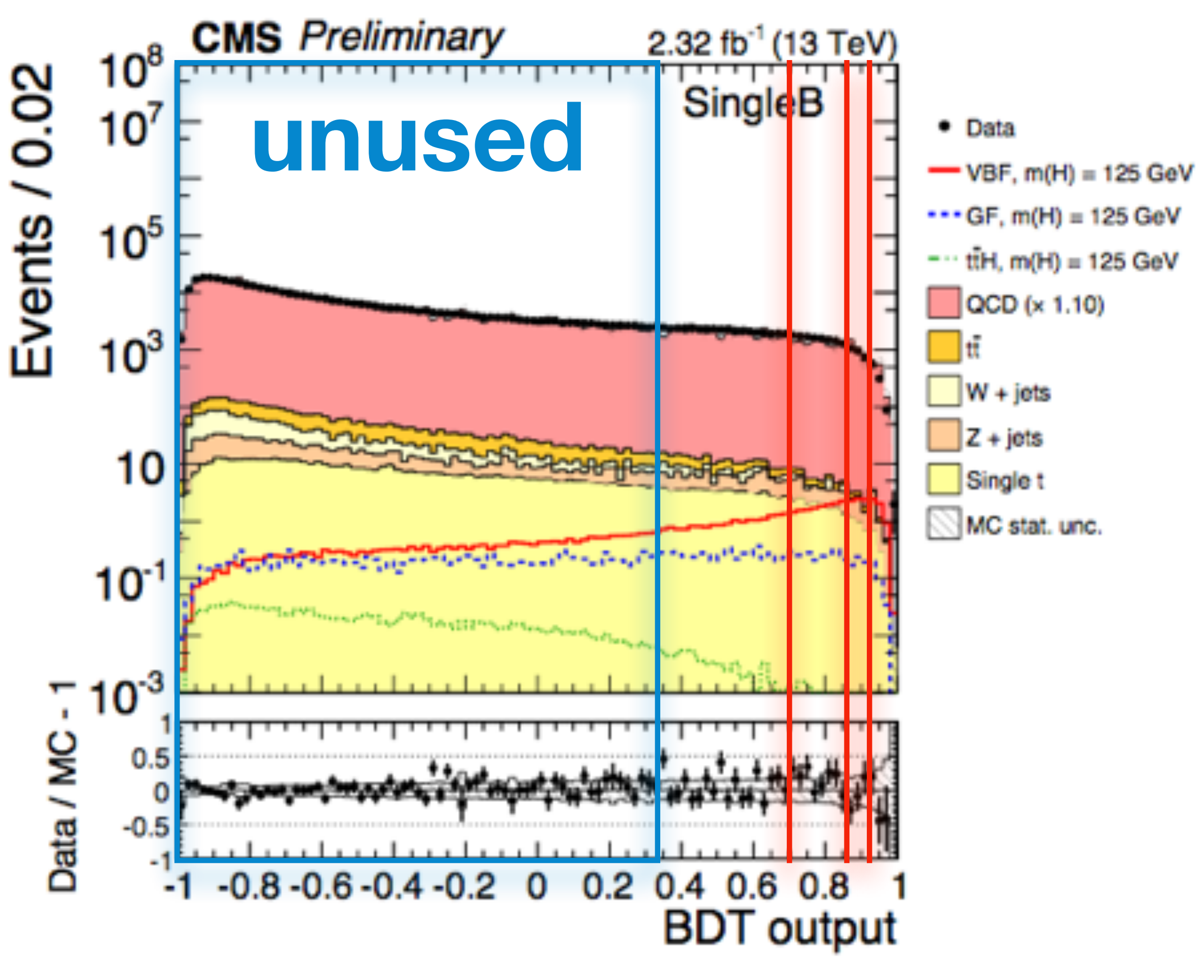
- b-jet energy response and resolution are worse than one for light quarks(due to neutrinos)
- Improvement of m_{bb} resolution using regression targeting jet pT at get level given 5% improvement:
  - dedicated training for VBF analysis
  - jet kinematics
  - sub-jet quantities (leading track pT, hadrons & photon fractions)
  - secondary vertex information
- recovering of hard FSR outside b-jet cone($\Delta R<0.8$) gives further improvement of 2%

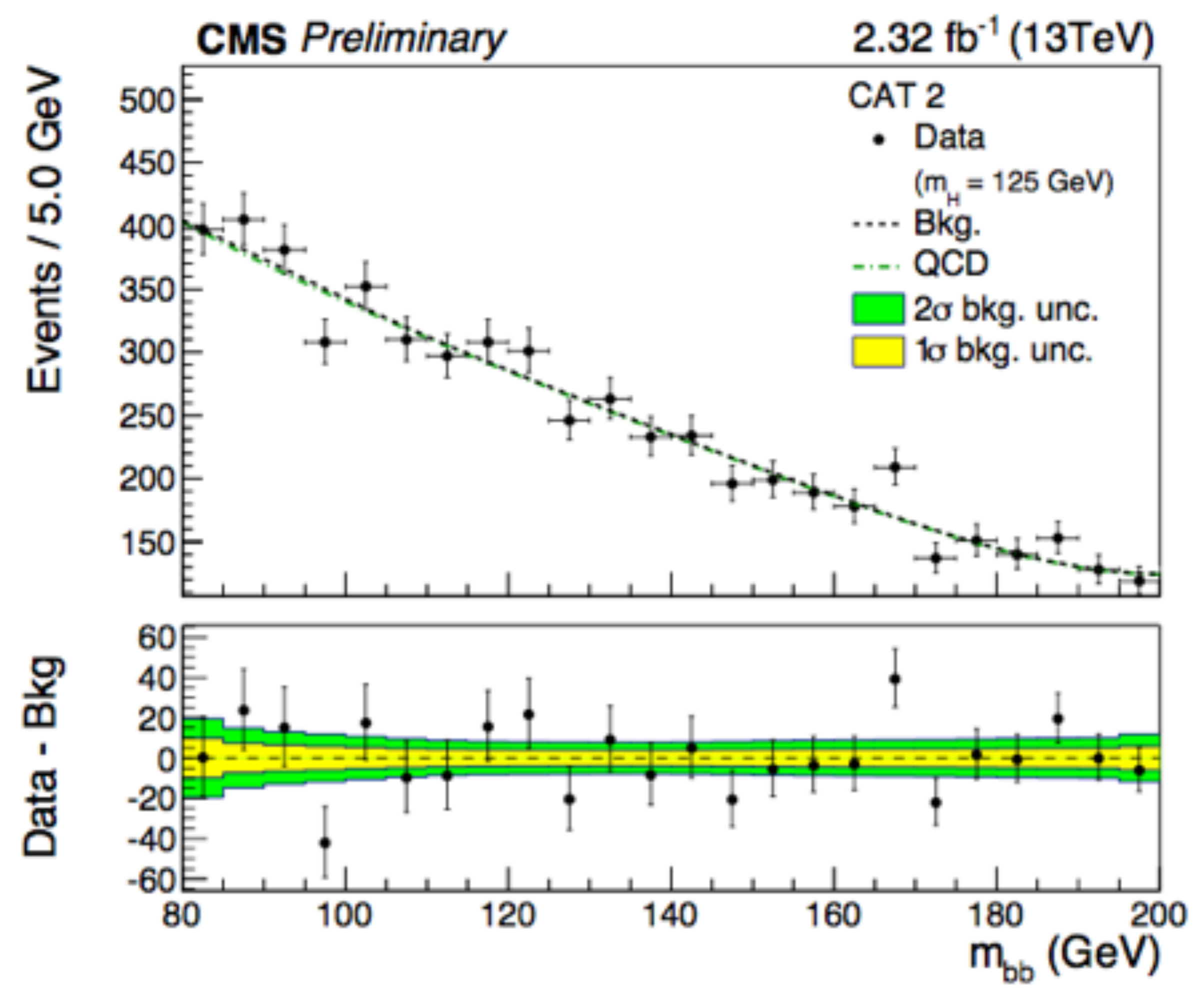


VBF H→bb : event categories

CMS-HIG-16-003

- All the discriminating variables (VBF kinematics + jet properties) are combined by means of a BDT:
  - There is a separate training for 1 or two b-tagged categories
- Categories defined in ranges of BDT output, chosen to maximise significance (similar to H→γγ):
  - Four (three) from the single (double) b-jet : seven categories in total
- QCD background template is extracted from a fit on the m_{bb} in the unused region, then a transfer correction is applied to the shape per category





VBF H→bb :Run1+2015 Data

CMS-HIG-16-003

- Using 2.3 fb-1 of 2015 Data @ 13TeV, the analysis shows a deficit of data at m_{bb}=125 GeV

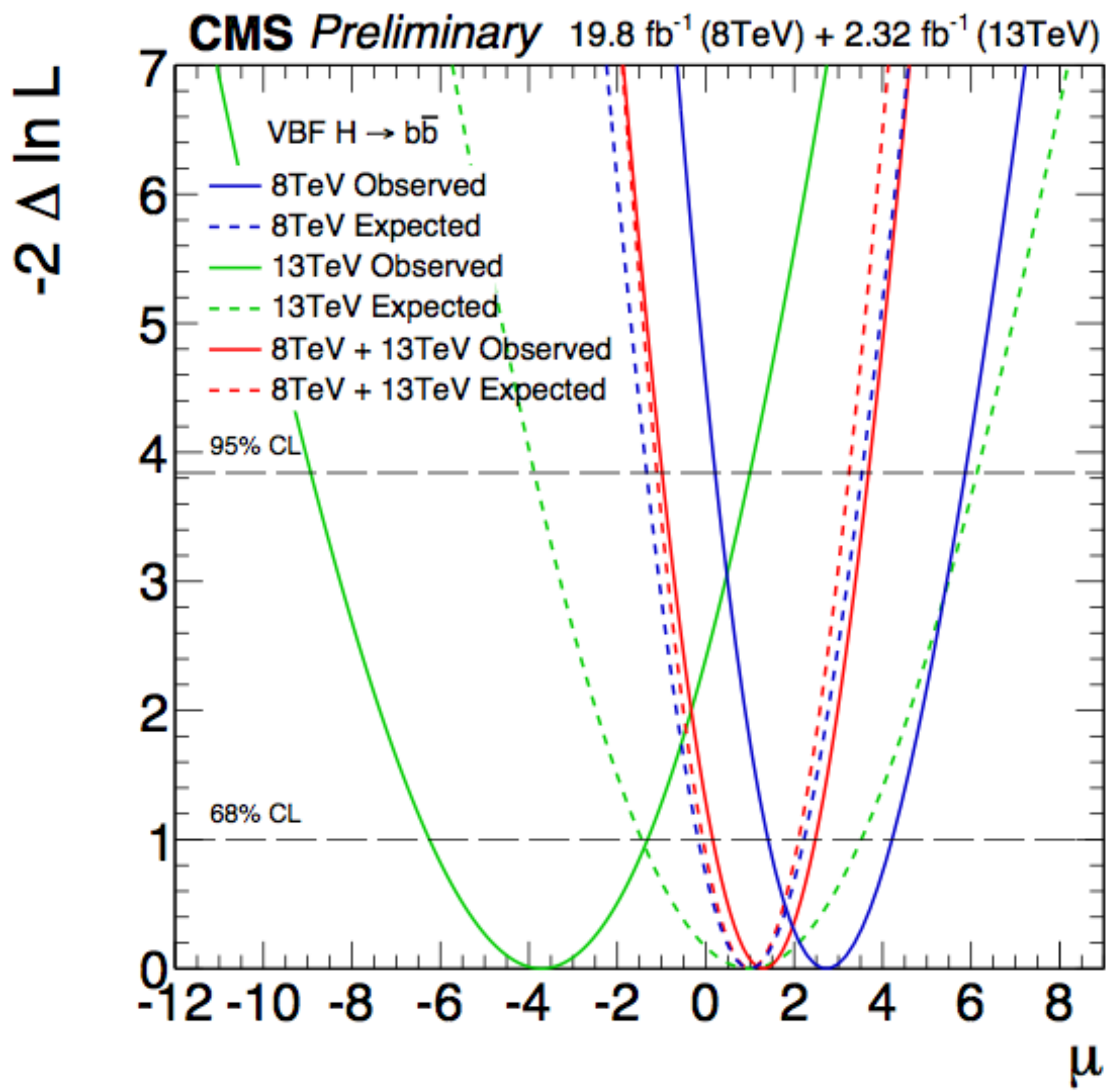
$$\mu_{2015} = -3.7^{+2.4}_{-2.5}$$

- Combined with run-1 analysis, the signal strength is :

$$\mu_{\text{Run1+2015}} = 1.3^{+1.2}_{-1.1}$$

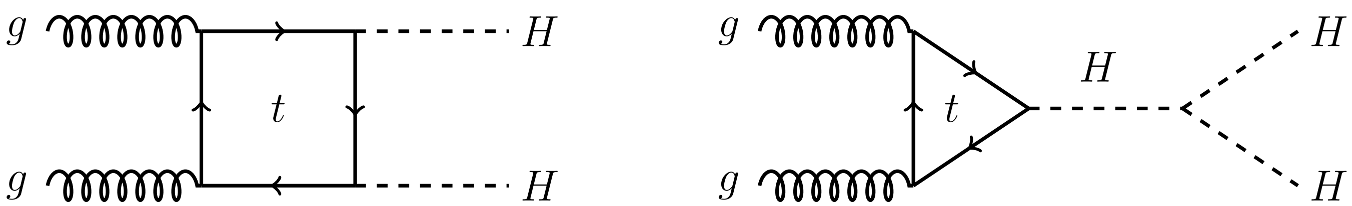
- With

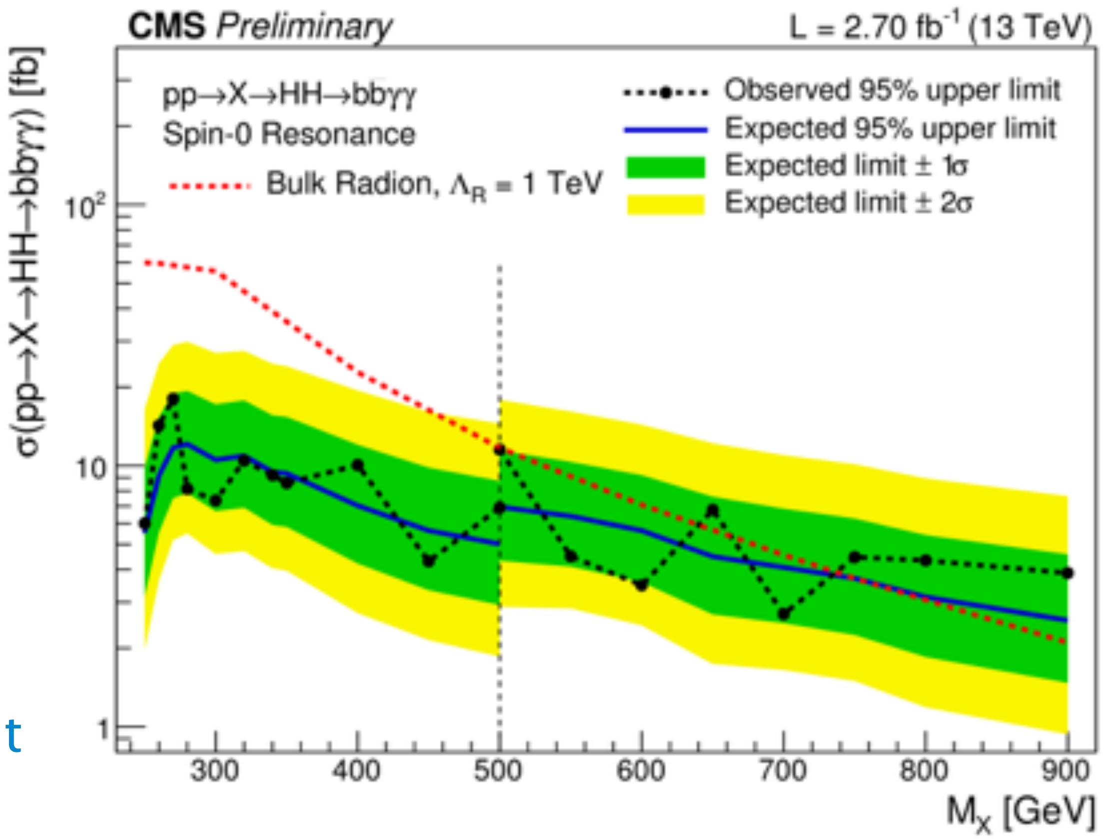
$$\mu_{\text{Run1}} = 2.8^{+1.6}_{-1.4}$$



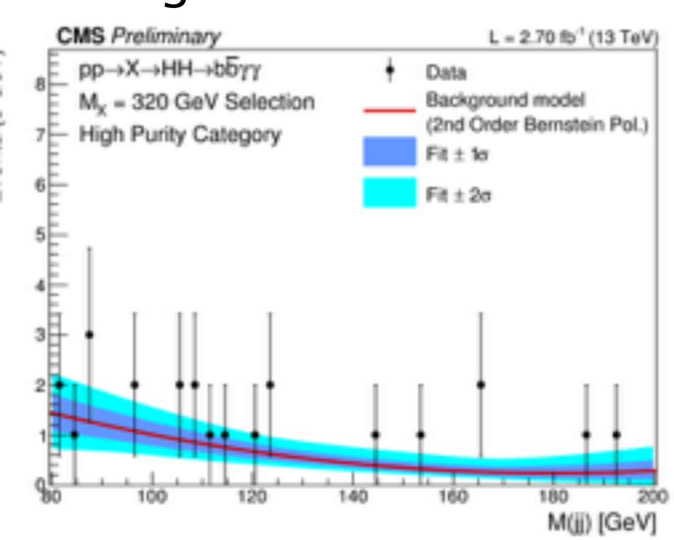
HH→bbɣɣ

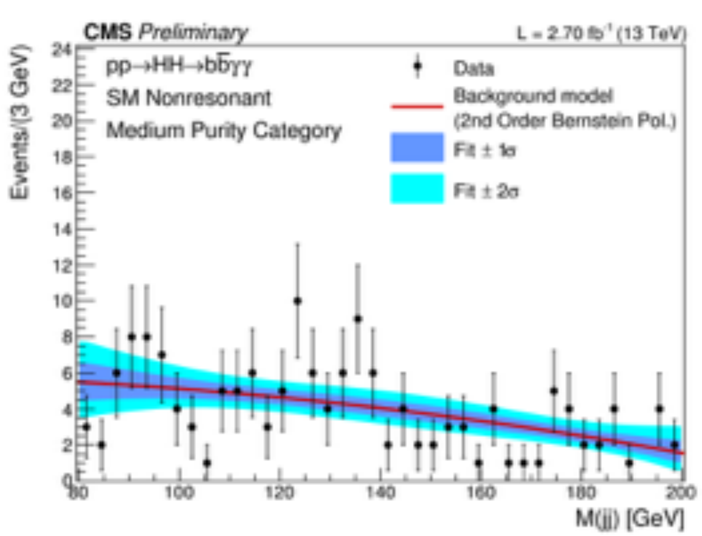
CMS-PAS-HIG-16-032





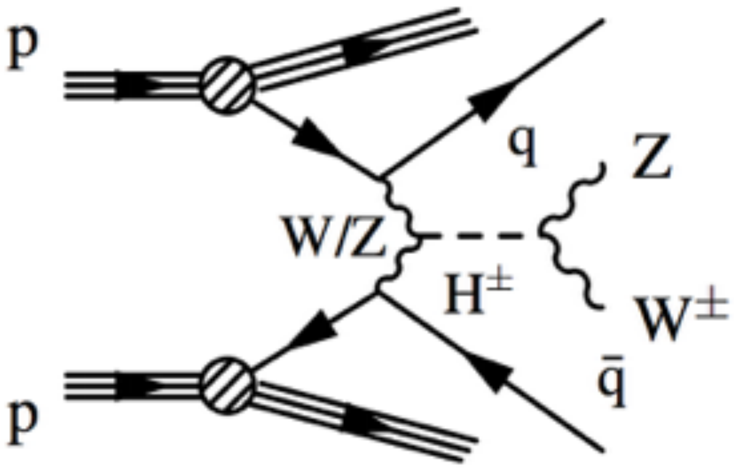
- Large cross section from bb, good resolution from ɣɣ
- Main background :
  - SM ɣɣ + jets production
  - SM ɣ + jets (1 jet identified as a photon)
  - QCD Mutijet (two jets identified as photons)
- Two strategies :
  - Resonant low mass (m_X < 500GeV) : two categories based o b-tag, signal extracted using 2D unbinned fit in m_{jj} and $m_{ɣɣ}$
  - Resonant High mass (>500GeV) : same as low mass but 1 category
- Non-Resonants : no mass window in m(jjɣɣ), 2 b-tag categories





- Other analyses exploring double Higgs production
  - hh→bbbb : CMS-PAS-HIG-16-002 CMS-PAS-HIG-16-026
  - hh→bbWW : CMS-PAS-HIG-16-011 CMS-PAS-HIG-16-024
  - hh→bbττ : CMS-PAS-HIG-16-028 CMS-PAS-HIG-16-029

VBF charged Higgs to WZ



3 leptons (μ, e)
- ◉ pT > 20, 10, 20 GeV
- ◉ |η| < 2.4 (2.5) e (μ)

◉ 2 jets
- ◉ pT > 30 GeV

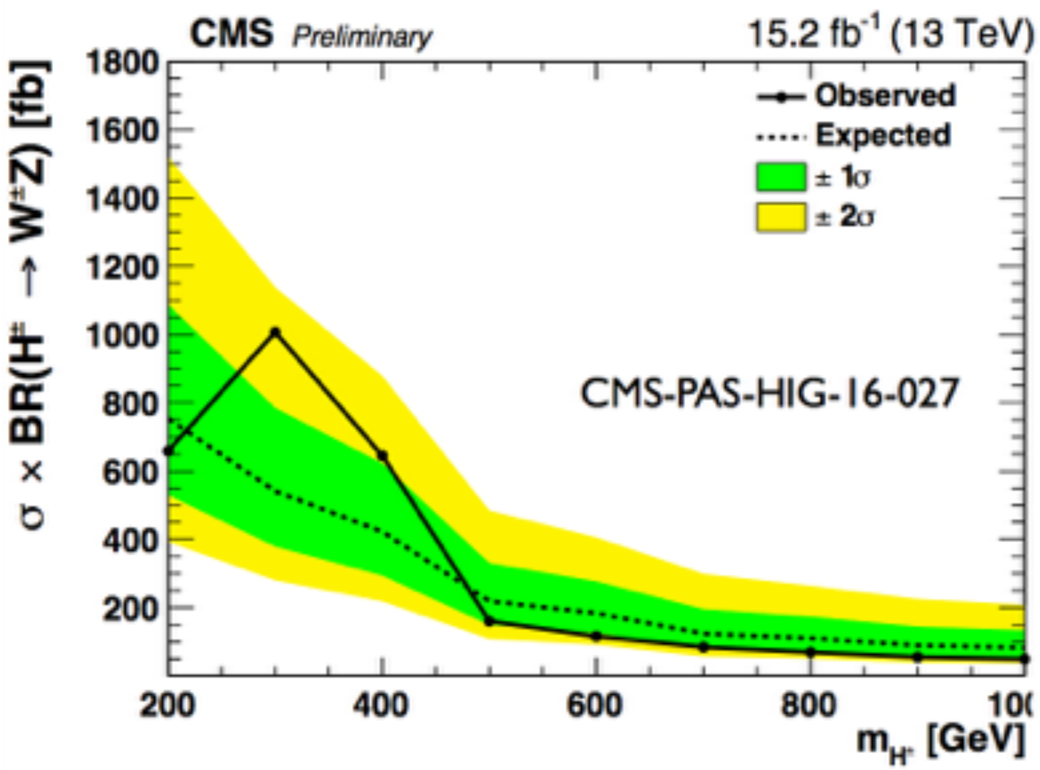
◉ MET > 30 GeV

◉ One Z:
- ◉ Opposite sign same flavour leptons with |mll – mZ| < 15 GeV

◉ VBF:
- ◉ mjj>500, GeV η(j,j) > 2.5

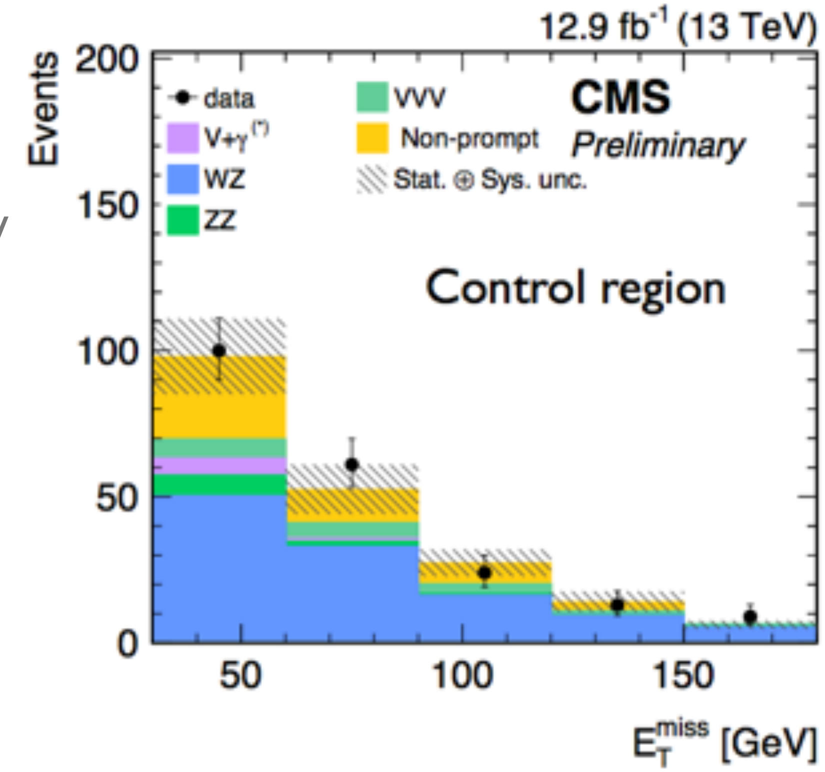
◉ anti b-tag

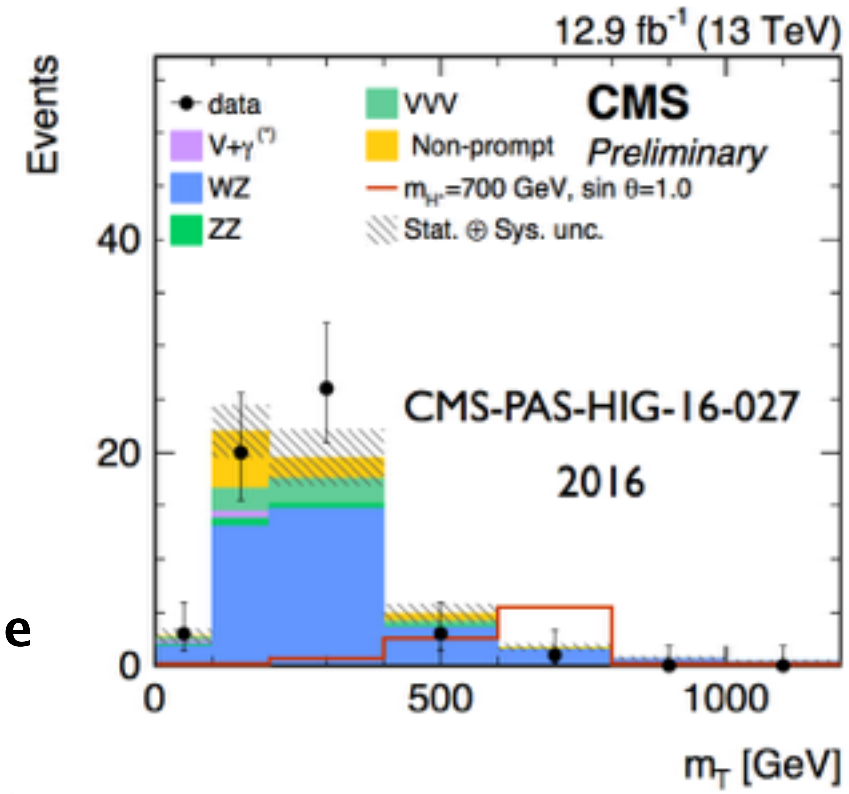
- ◉ WZ background: largest irreducible background
  - ◉ Normalisation is derived data-driven in 2-jet control region (100 GeV < mjj < 500 GeV). Systematic uncertainty dominated by the size of the dataset
- ◉ Estimation of backgrounds with at least one fake lepton is data driven
- ◉ VVV&TTV, Z+gamma and ZZ background from MC



- ◉ **95% CL limits (CL_s criterion) on the production cross section (in agreement with SM)**

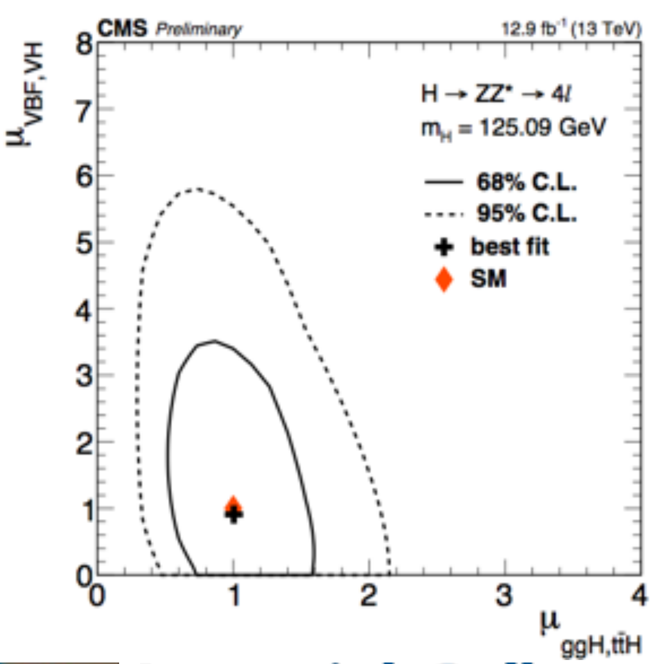
CMS-PAS-HIG-16-027

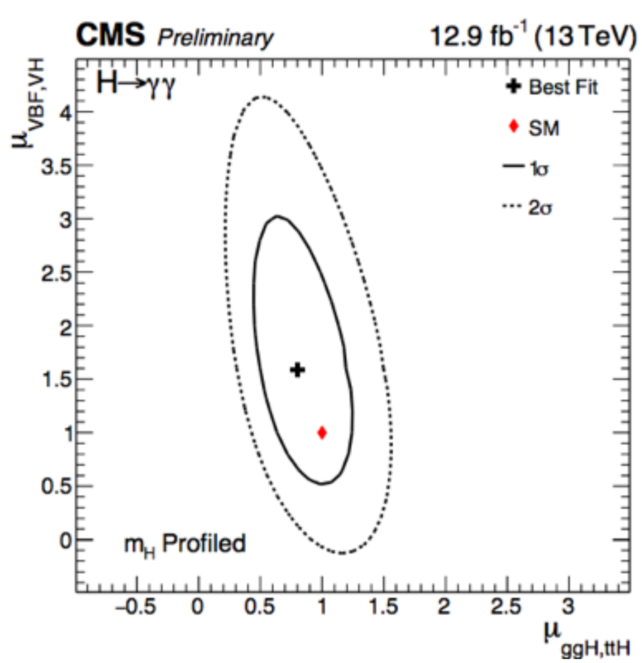


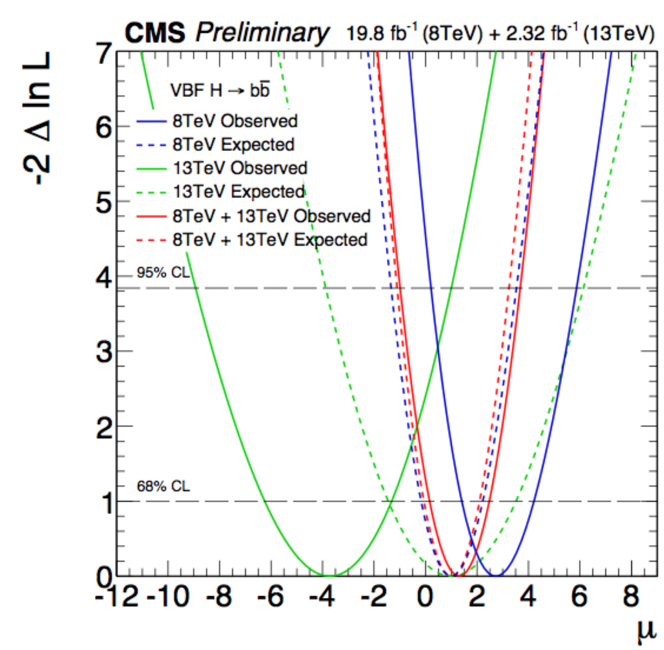


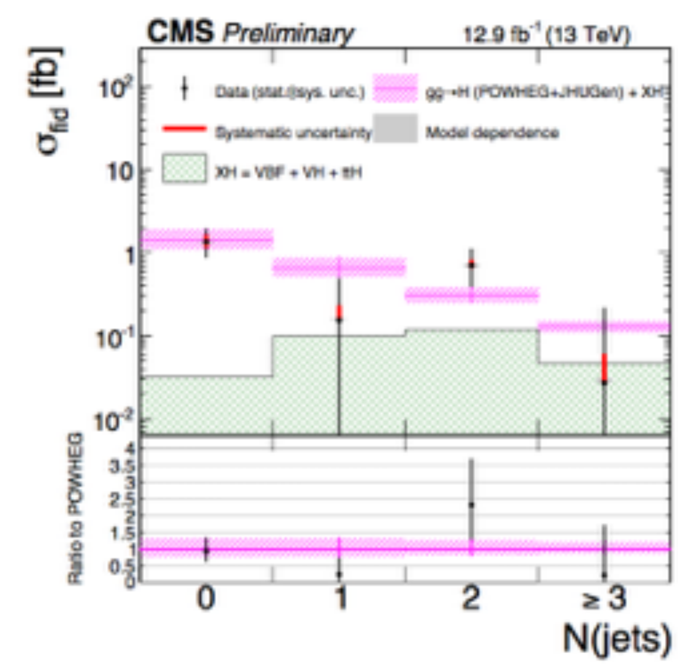
Conclusion

- Jets play an important role improving analyses sensitivity and hunting Higgs production modes
- Coupling and production cross section measurements can be then measured
  - Fiducial measurements of jet cross sections using RunII have started to emerge from CMS
  - Fiducial cross section + differential measurement from 4ℓ analysis (Future measurements are in preparation)
- Review of different methods for tagging techniques used in CMS + latest CMS Higgs results @13TeV





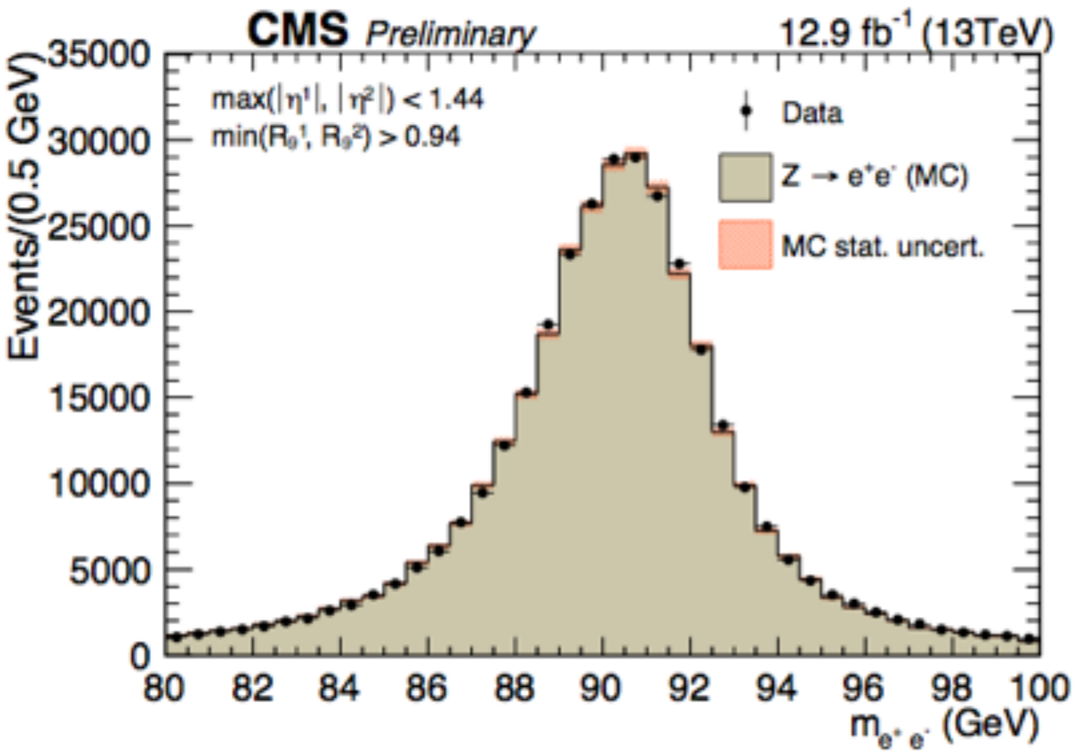


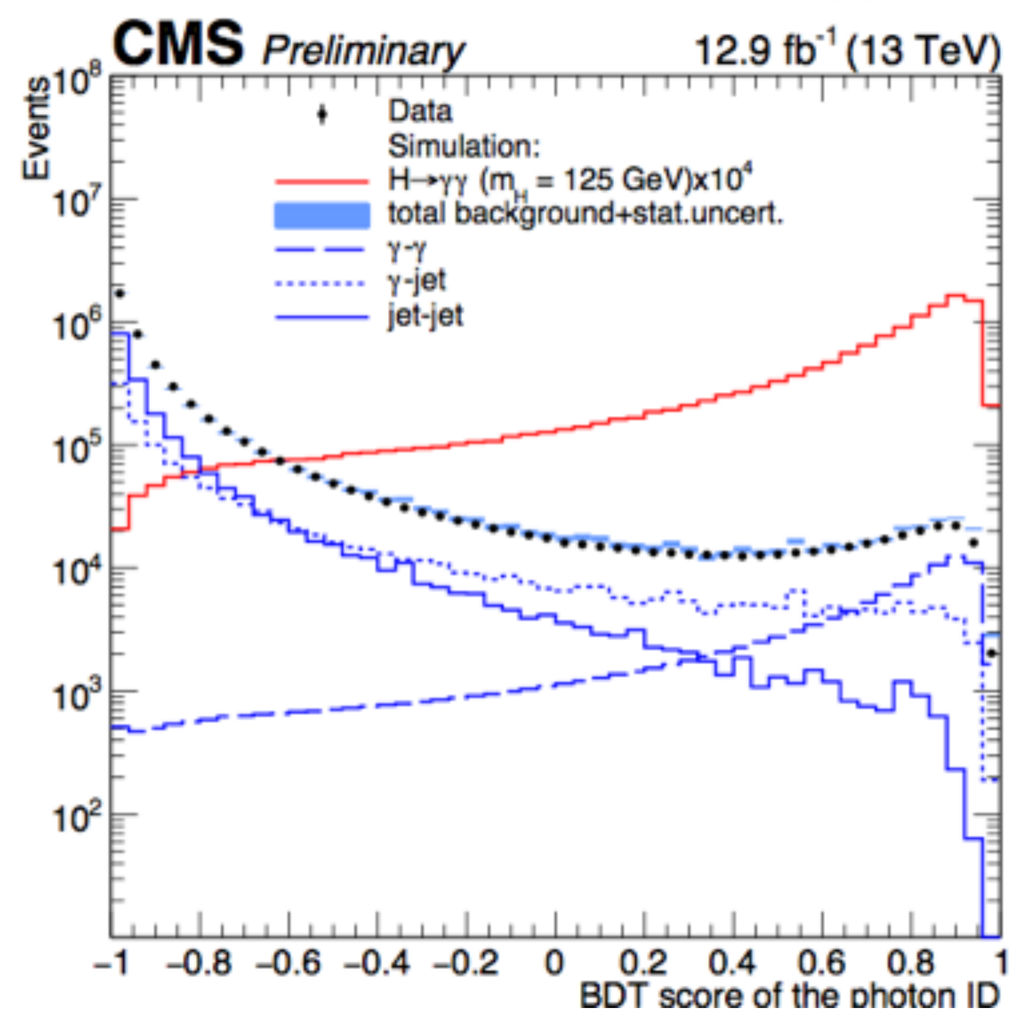


Extra slides

H→γγ : photons

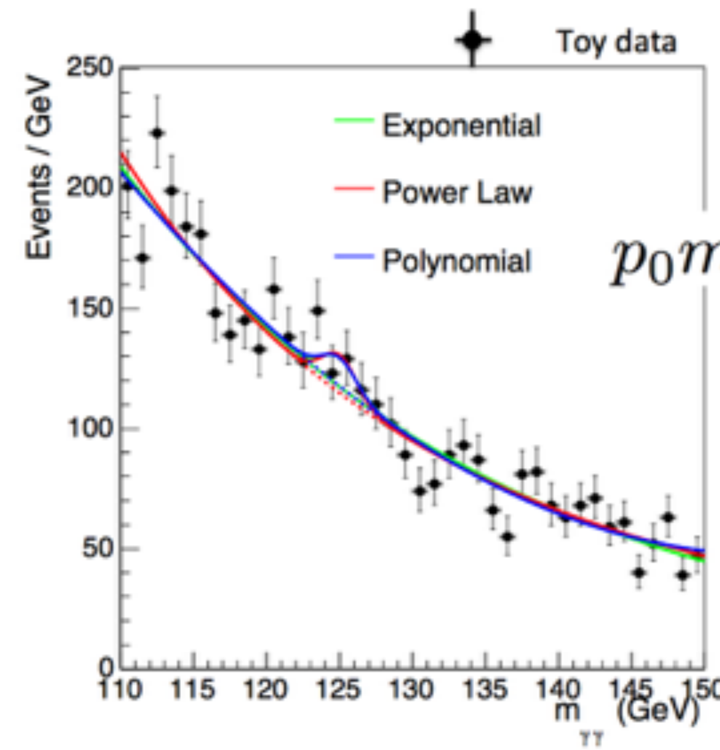
- Electromagnetic calorimeter response:
  - corrected through time
  - inter-calibration in η/φ
  - adjustment of absolute scale
- Energy and its uncertainty corrected for local and global shower containment:
  - regression targeting E_{true}/E_{reco}
- Scale/Resolution corrected over time using Z→ee peak as reference
- Corrected energy and resolution used in the analysis
- MVA based photon ID classifier to differentiate between prompt and fake photons
  - Uses shower shape variables, PF isolations, photon's kinematics and median energy density (ρ)





Envelope method

- For background parameterisation, several families functions might provide decent fits to a background distribution → Model Choice problem.
- The different choices of function can lead to different results! So which to choose?
- Common solutions to this:
  - Chose a model based (sometime) on some physics motivation.
  - Look at how different your results would be and assign a systematic uncertainty.
    - how do we choose the model?
    - How do we quote the result?
    - How do we correctly assign a systematic for any choices we made?

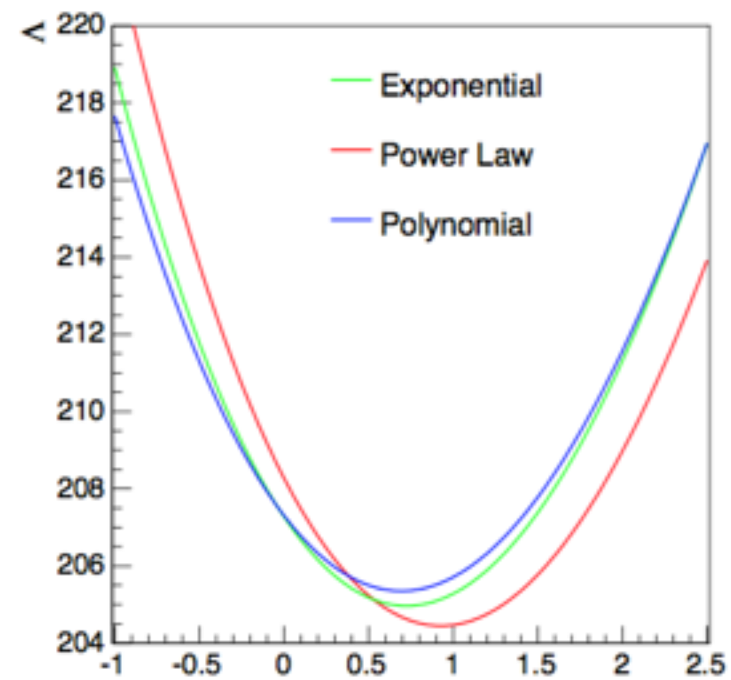


$e^{-p_0 m}$

m^{-p_0}

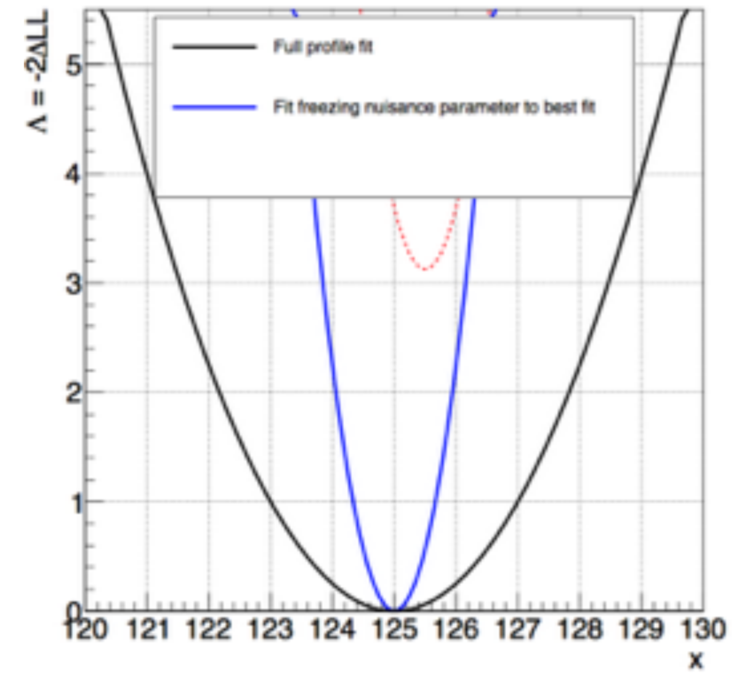
$p_0 m + p_1 m^2 + p_2$

illustration

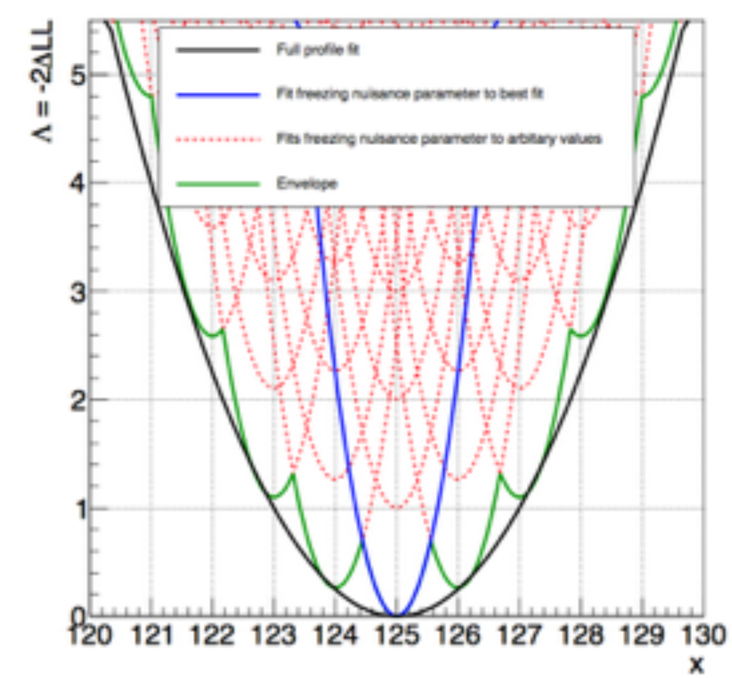


Envelope method

- The envelope method seeks to provide some answers to these questions.
- Scan −2NLL of parameter of interest whilst profiling some set of nuisance parameters.
- If the true values of nuisances were known perfectly, curve would be much narrower (equivalent to stat-only uncertainty). Eg, fix nuisances to best fit values.
- Fixing nuisances to any other values give another curve, not necessarily at the minimum. Can do this for different values of background params.
- If we do sample sufficient possible values of nuisance params, the minimum envelope of all curves begins to approximate the original −2NLL !
- In principle we can do this also for discrete nuisances (like choice of background function, even if the different functions has different numbers of parameters!)



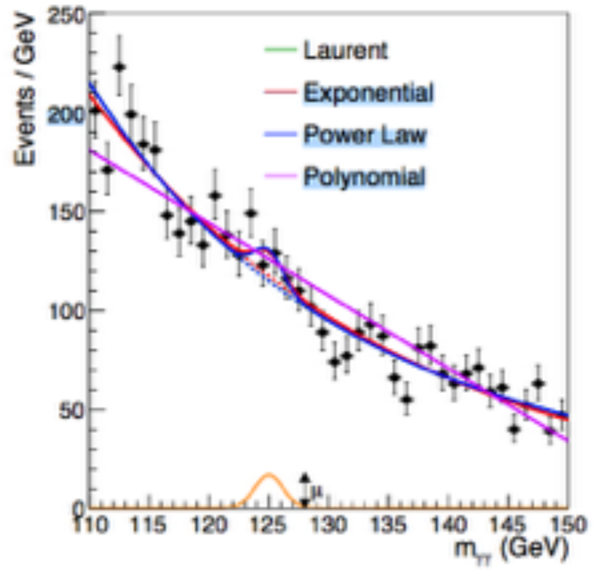
illustration

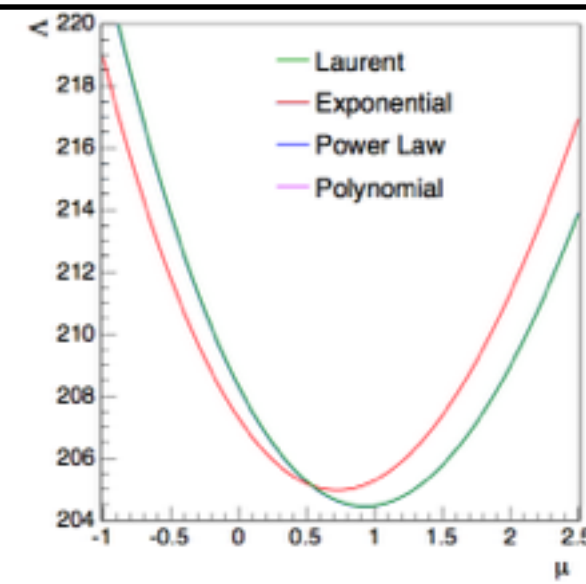


Envelope method

- In SM Hgg example: pick μ as POI.

- Choices which are similar shouldn't effect our result (**Laurent** and **Power Law**)
- Choices which are poor should have little impact (**Polynomial**)
- Choices which seem equally valid but disagree should increase our uncertainty (**Exponential**)





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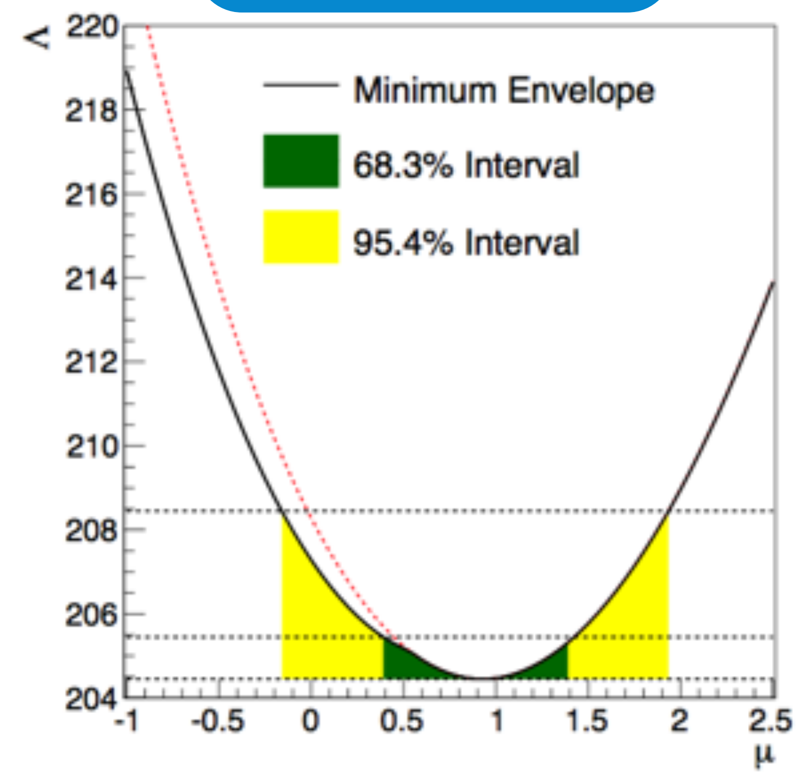
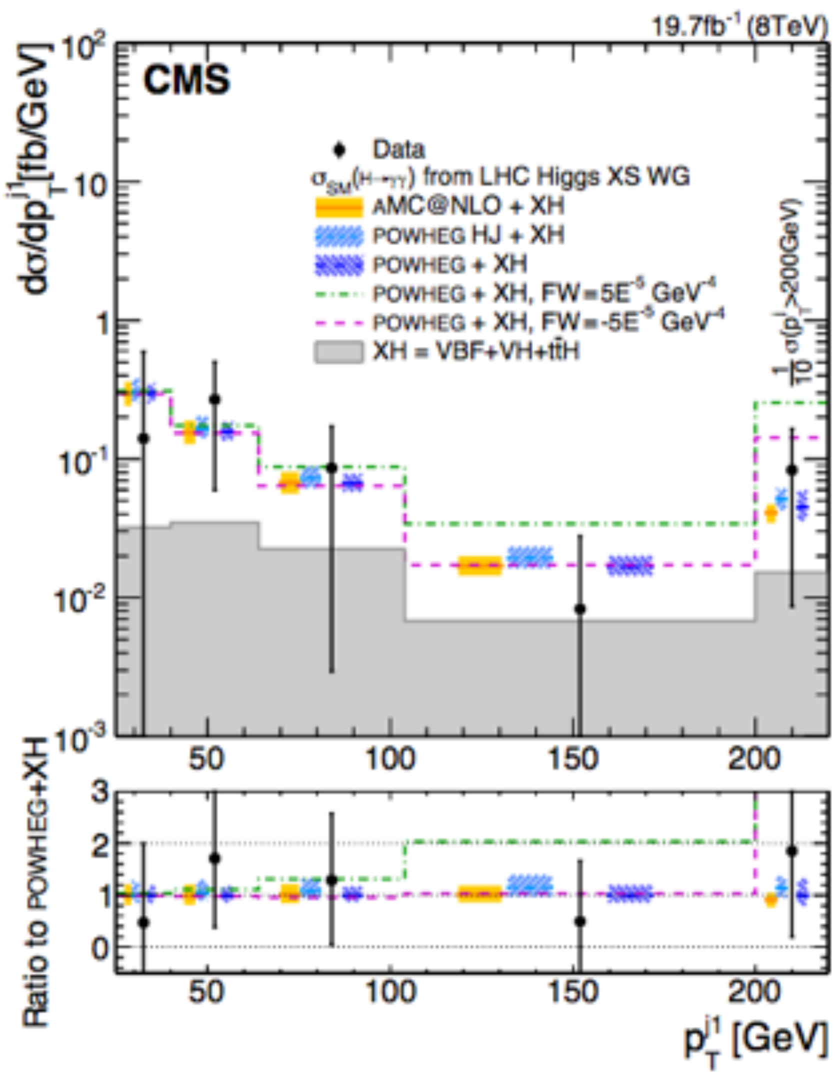


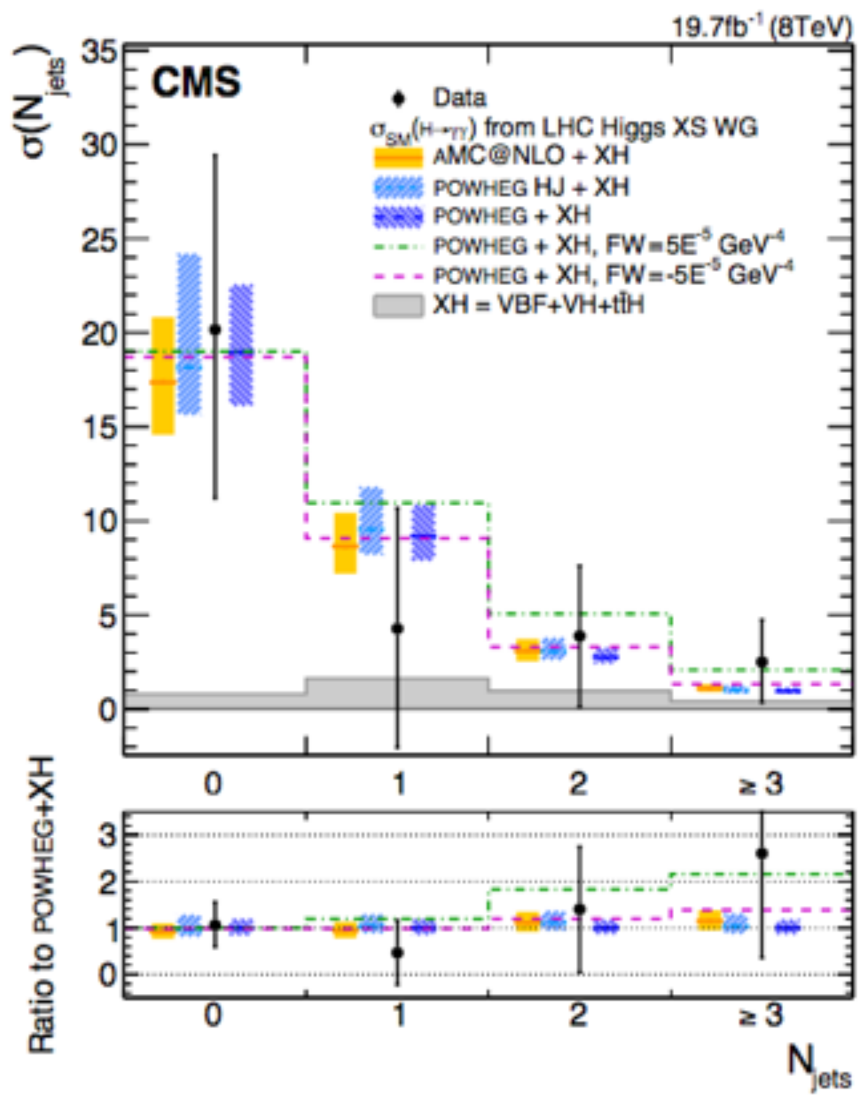
- Take the minimum of all the curves as a function of μ (the envelope). If more than one function contributes then that envelope is wider than any of the individual curves → parameter uncertainty is increased

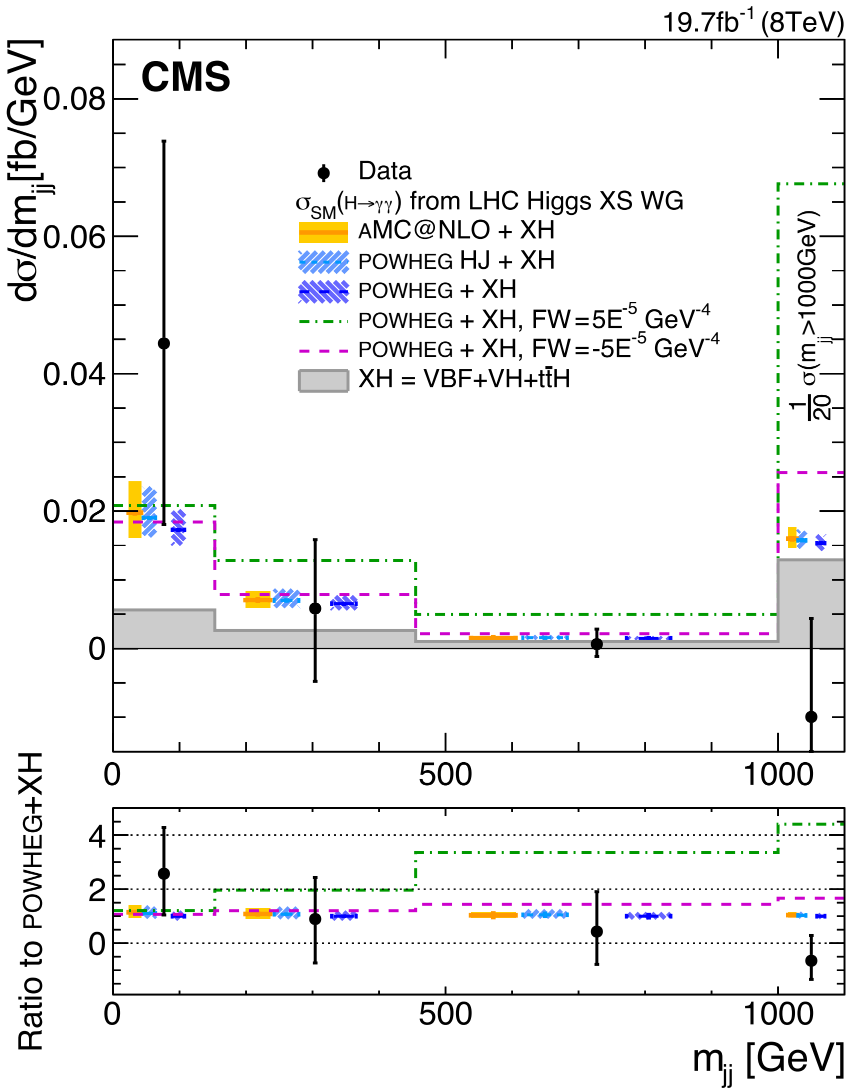
- No explicit model choice has to be made, since this choice is dynamic in the scan .

- Result: Best fit value, confidence interval and systematic for model choice!

Differential XS from RunI: H(γγ)

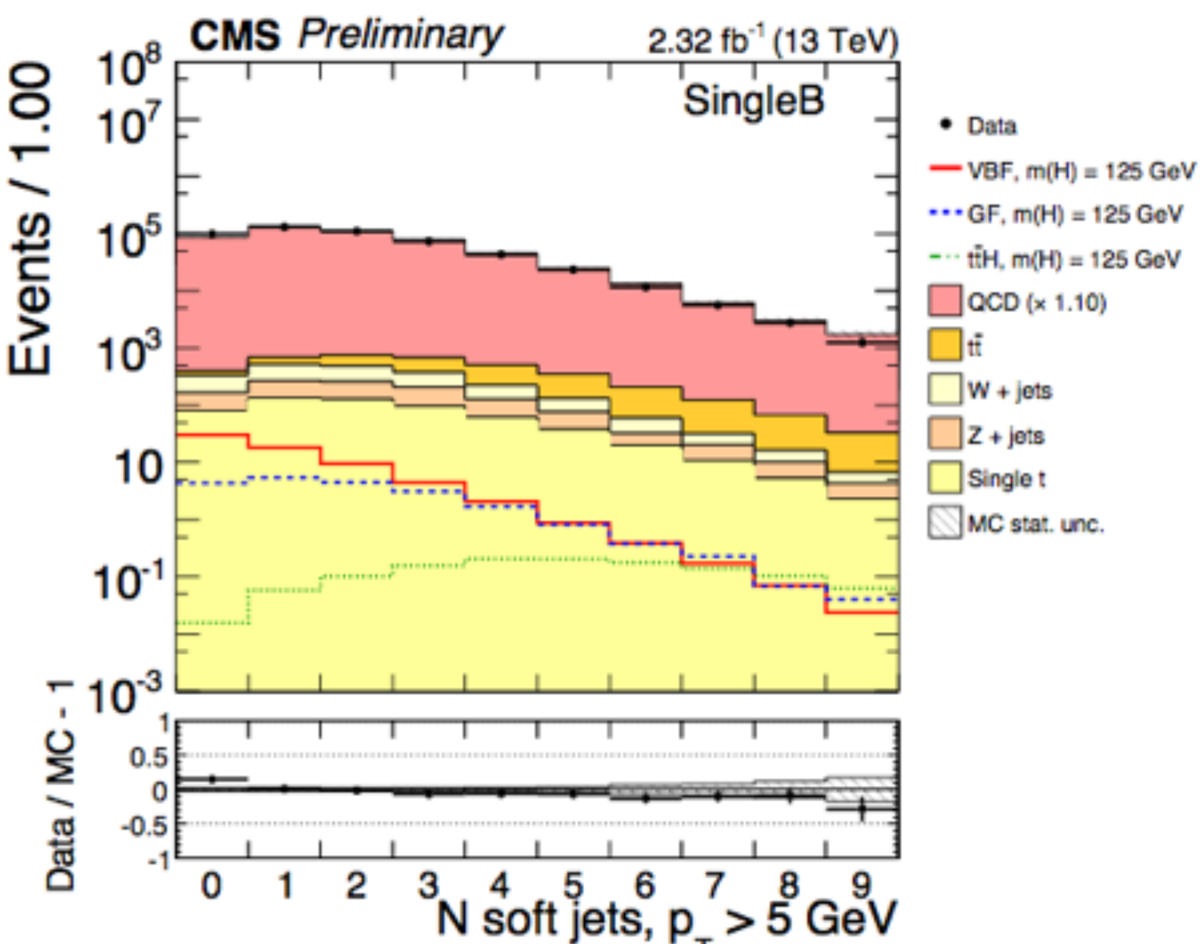




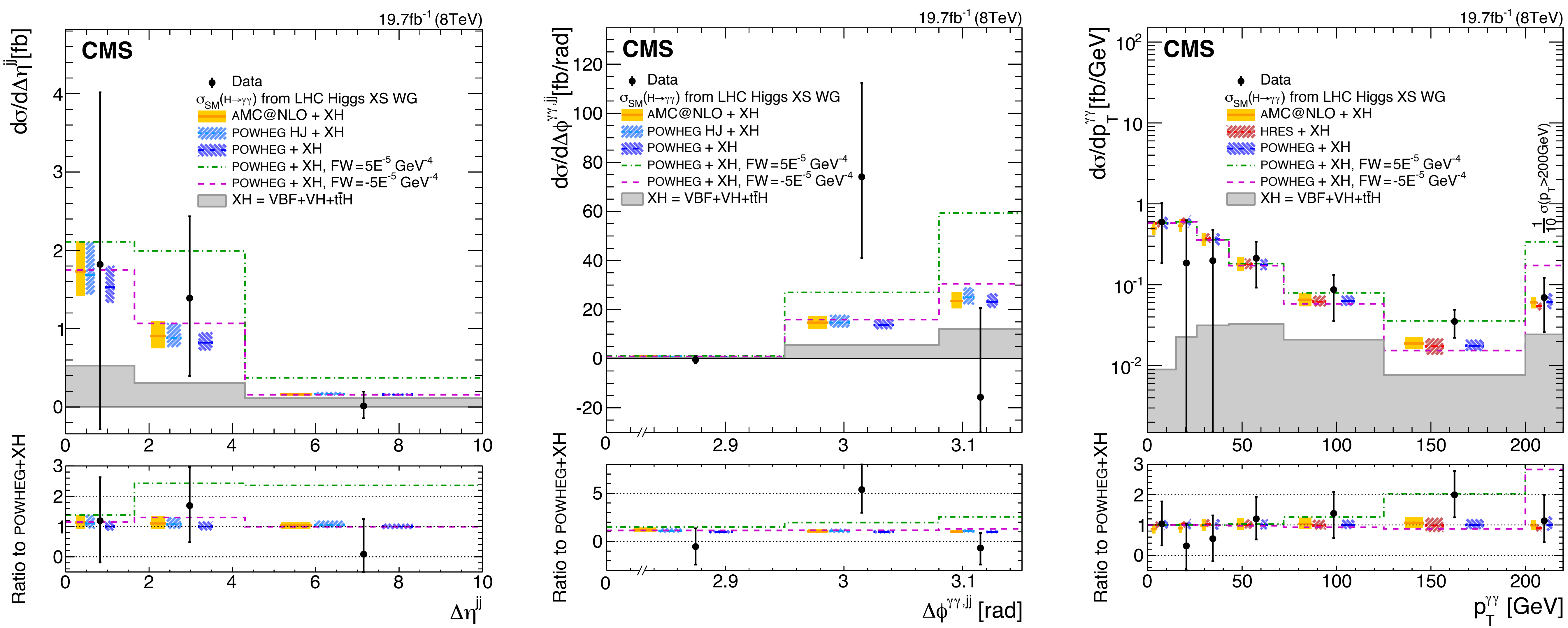


Soft activity pileUp mitigation

- **VBF signal events: electroweak production of jets → no QCD colour exchanged:**
  - rapidity gap of suppressed activity between the two VBF tagging jets
  - only little hadronic activity(soft)
- **Additional tracks:**
  - satisfy the high purity quality requirements and pT > 300 MeV
  - are not associated with any of the four leading PF jets in the event
  - are not in the region between the two best b-tagged jets
- **Clustered into AK4 soft TrackJets**
  - use only multiplicity of soft track jets with pT > 5 GeV with good Data/MC agreement



Differential XS from RunI: H(γγ)



A word about PileUp Per Particle Identification

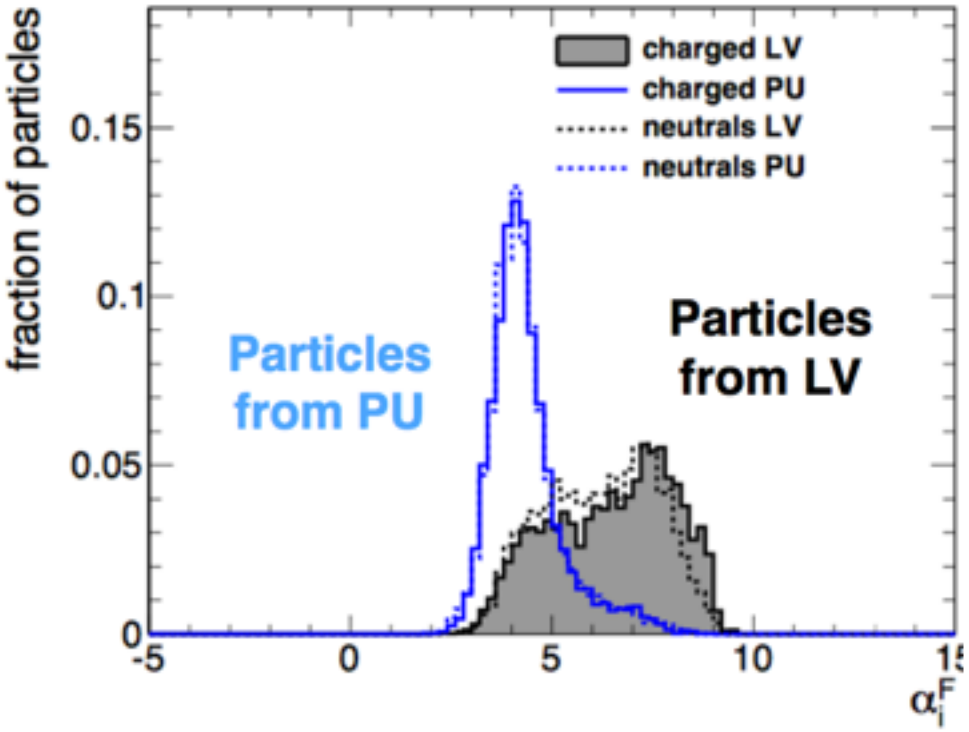
- **PileUp Per Particle Identification** (**PUPPI**)
- It takes as input particle flow objects (charged/neutral hadrons, photon and charged leptons)
  - and it gives weight for each of them.
- Defines ***a*** of each particle (i)

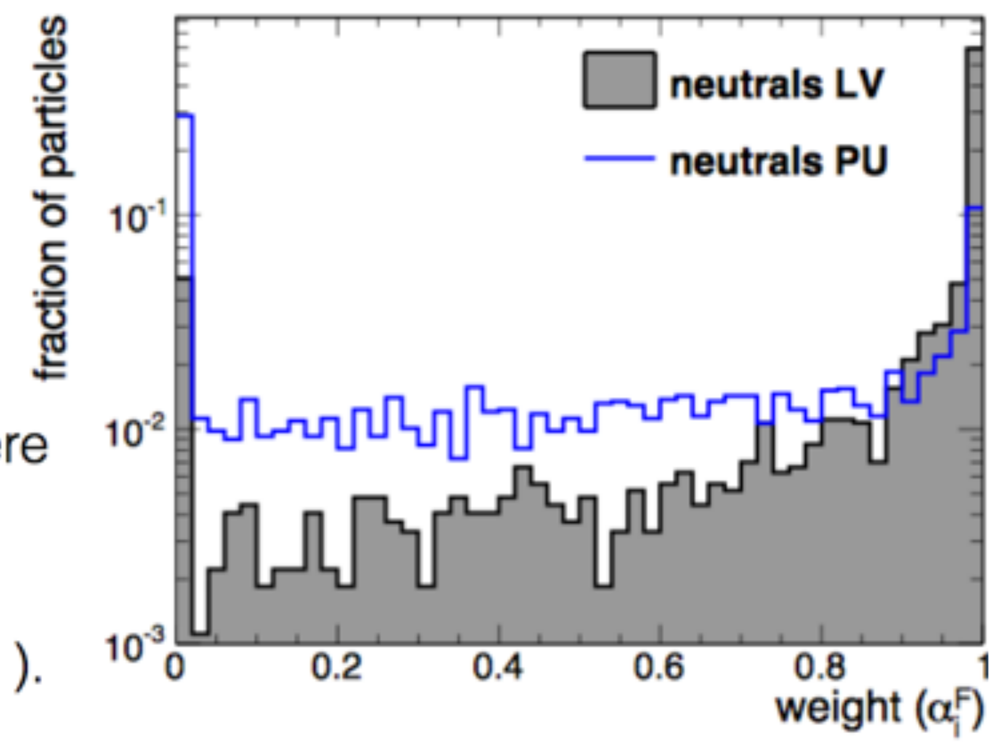
  using other particles (j) around it.

  For example

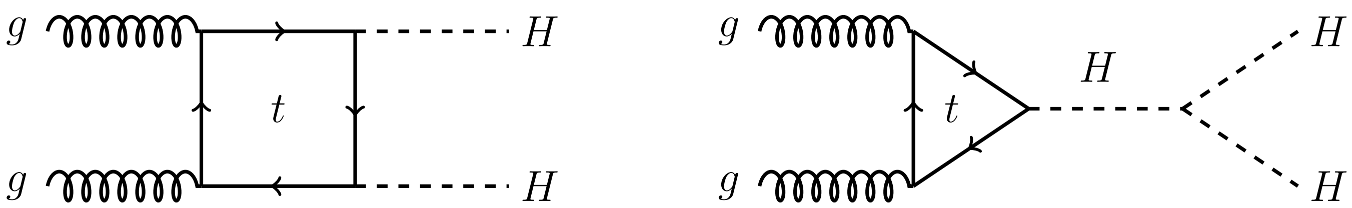
$$\alpha_i = \log \sum_{j \in \text{event}} \underbrace{\frac{P_T^j}{\Delta R_{ij}}}_{\text{PT sum weighted with distance}} \underbrace{\Theta(R_{\min} < \Delta R_{ij} < R_0)}_{\text{Step function to take into account only particles around it.}}$$

- Transforms the distribution of ***a*** in a **weight** (1 for particle from LV, 0 for particles from PU)
- This weight can be also defined at large rapidities where there is no coverage from the tracker.
- Then, jet reconstruction algorithm can run on the particles with the **weight** (but PUPPI is not only for jet.).

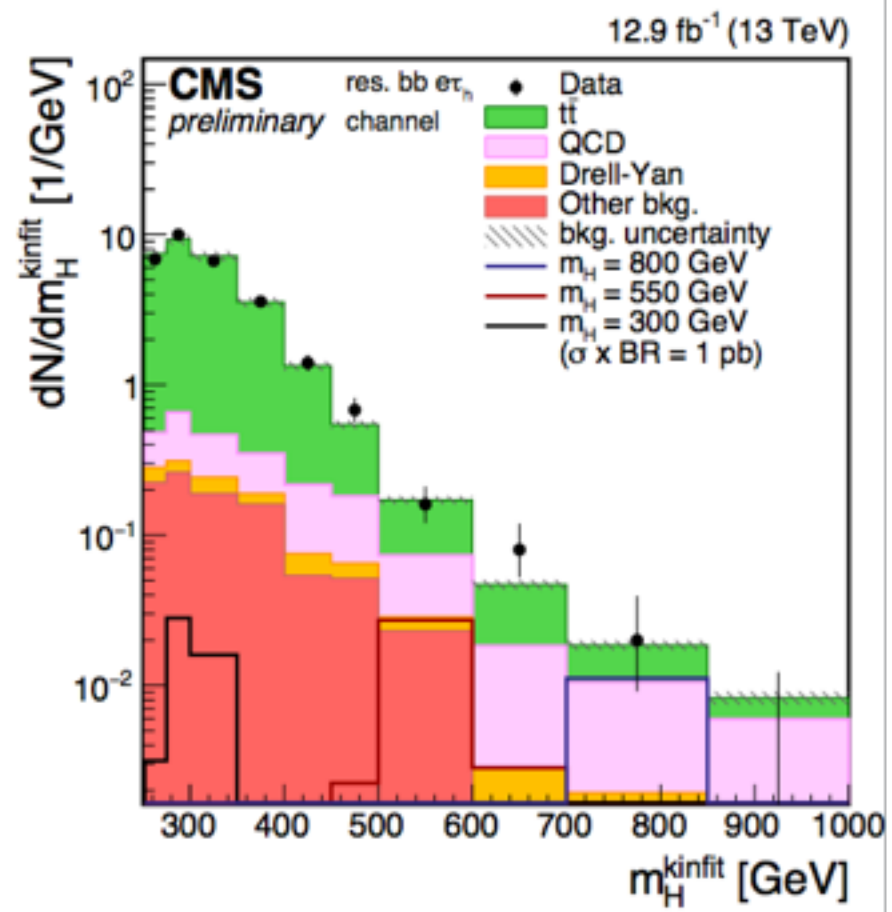


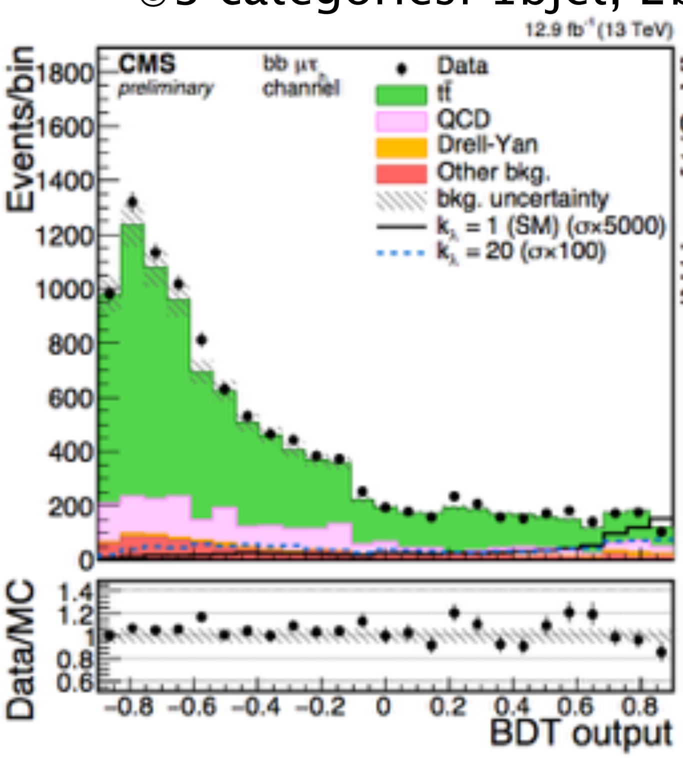


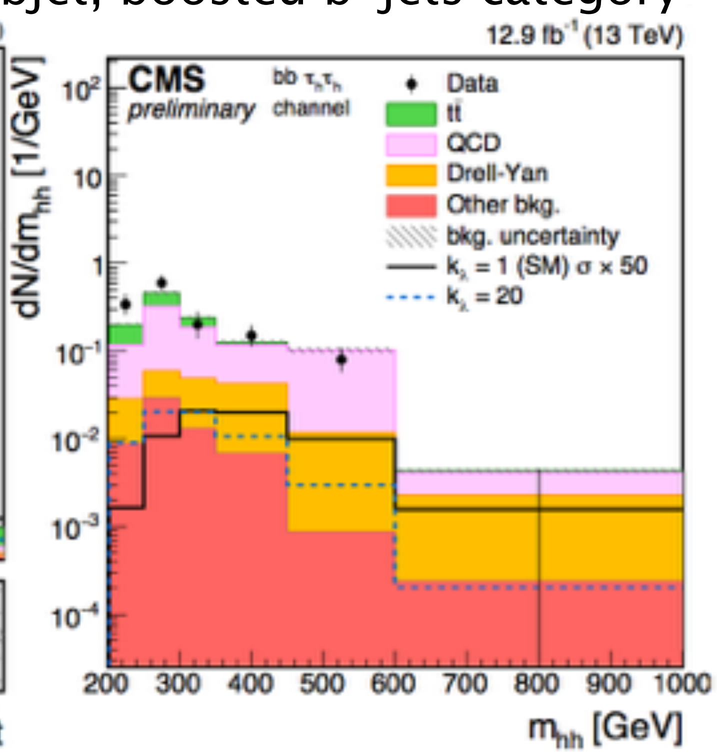
HH→bb$\tau\tau$



- Intermediate BR, fully reconstructed final state:
  - 1H+1 isolated leptons (e, ,H)+2 b-jets in the final state
  - 3 final states: eτ_H, μτ_H, $\tau_H\tau_H$
  - **Main backgrounds: tt (from MC) , mutijet QCD (from data in control regions)**
- Resonant search:
  - Limit extraction on kinematic fit of the 4-body invariant mass:
    - 3 categories: 1bjet, 2bjet, boosted b-jets category







- Non-resonant analysis:
  - kinematic BDT discriminant to reduce tt (uses only angular information)
  - visible mass as final variable

- **Only results on 2016 data shown.**
- **Results with 2015 data:**
  - **CMS-PAS-HIG-012**
  - **CMS-PAS-HIG-013**