DE LA RECHERCHE À L'INDUSTRIE

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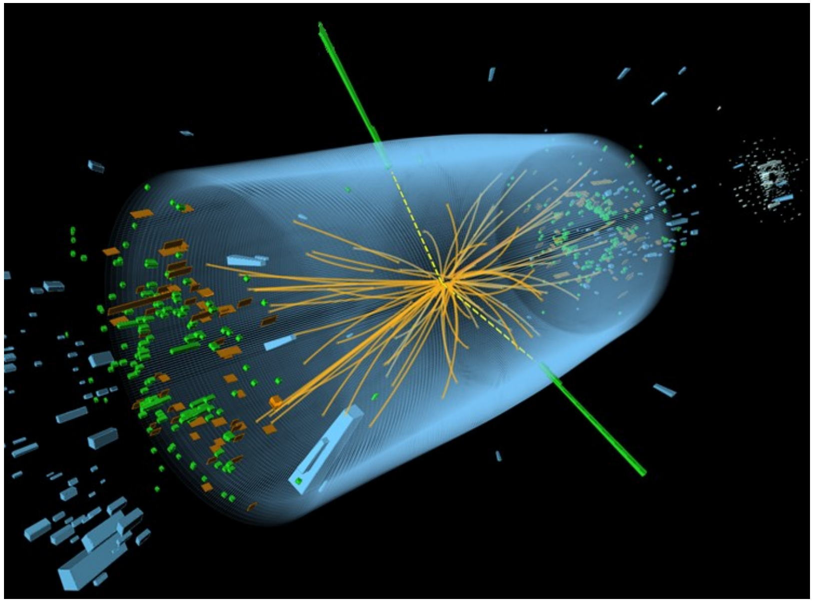
# PHENIICS DAYS

***Title :*** ***Search for the Higgs boson decaying to two photons and produced in association with a pair of top quarks in the CMS experiment at LHC***



***Thématique :*** *Particle physics*

***Encadrant CEA - Unité d'accueil :*** *Julie Malclès – IRFU-SPP*

***Directeur de thèse - Labo d'appartenance :*** *Gautier Hamel de Monchenault (DR-CEA, HDR) – IRFU-SPP-CMS*

***Université d'inscription - Ecole doctorale :*** *Paris 11 – Pheniics*

***Partenaire académique/industriel :*** *CERN*

***Référence THOT :*** *SL-DSM-14-048*

# STANDARD MODEL AND HIGGS BOSON

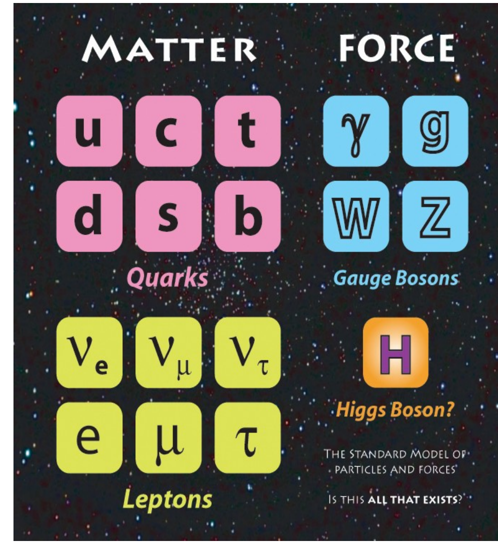
## Standard model

Fermions : fundamental particles
Gauge bosons : mediators of interactions

3 different interactions:
- ElectroMagnetic (EM) }
- Weak
- Strong (QCD)

EW theory: all gauge bosons are massless

BUT : W and Z bosons are carriers of weak force (short range interaction), they are massive

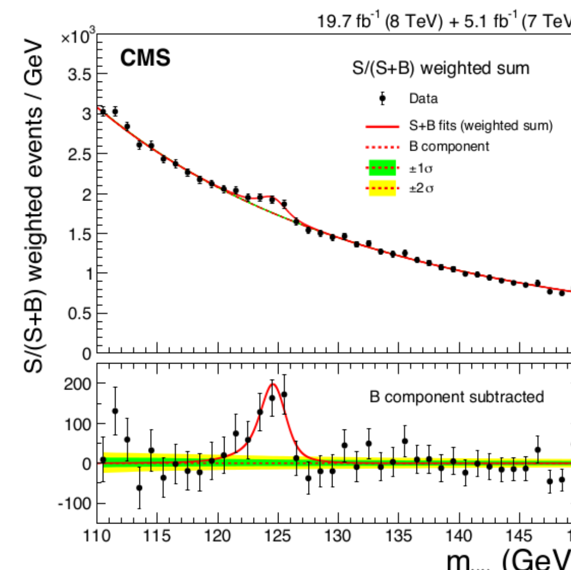



## Higgs mechanism

Spontaneous symmetry breaking of electroweak interaction → W and Z mass

- There must exist a new particle, responsible for the mechanism (Higgs boson, predicted by Higgs, Englert and Brout)
- Discovered in 2012 at LHC, mass ~ 125 GeV
- The Nobel prize in 2013 to Higgs and Englert

One of the main goals of LHC now: study properties of the discovered particle (mass, width, couplings to other particles)



# MOTIVATION AND STATE OF ART

## $ttH$

- ttH production measurement – the only direct access to the Top-Higgs coupling, a fundamental parameter of SM
- Significant deviation in the ttH production rate with respect to the SM prediction would be an indirect indication of new physics

## $H \to \gamma\gamma$

Excellent diphoton invariant mass resolution (1%) :

- provides a clear signal as a narrow peak
- reduces the relative background contribution which has falling $m_{\gamma\gamma}$ spectrum

→ **good sensitivity**

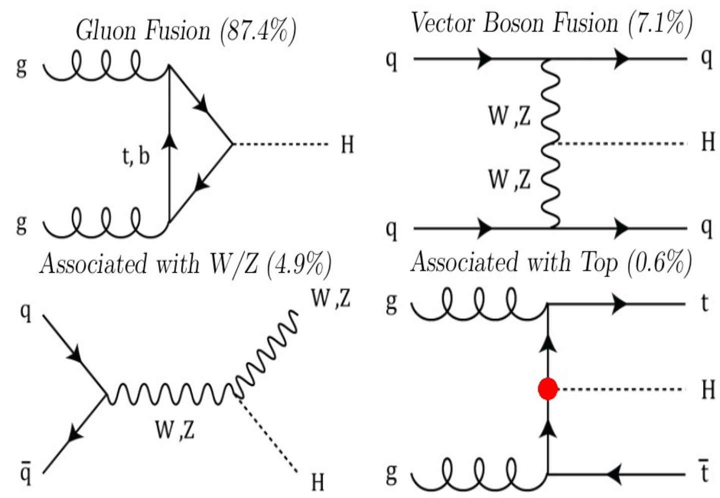
Most promising channel for long-term since it is dominated by statistical uncertainty

**First limits on ttH cross-section in $H \to \gamma\gamma$ from Run I :**

CMS: $\sigma/\sigma_{SM} <$ 5.4 at 95% CL (5.3 expected)

ATLAS: $\sigma/\sigma_{SM} <$ 5.3 at 95% CL (6.4 expected)

**Higgs production and decay modes at LHC:**




| Decay | BR |
|---|---|
| bb | 57% |
| WW | 21% |
| $\tau\tau$ | 6.4% |
| ZZ | 2.6% |
| $\gamma\gamma$ | 0.2% |

ttH, $H \to \gamma\gamma$ is very rare process

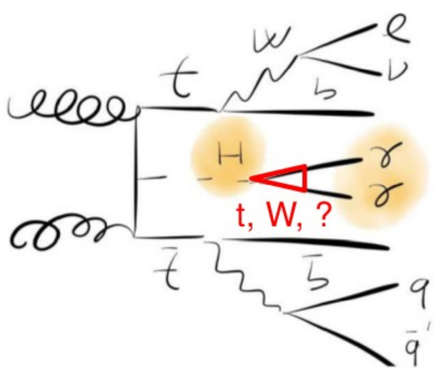
Its cross-section is 4 times higher wrt Run I

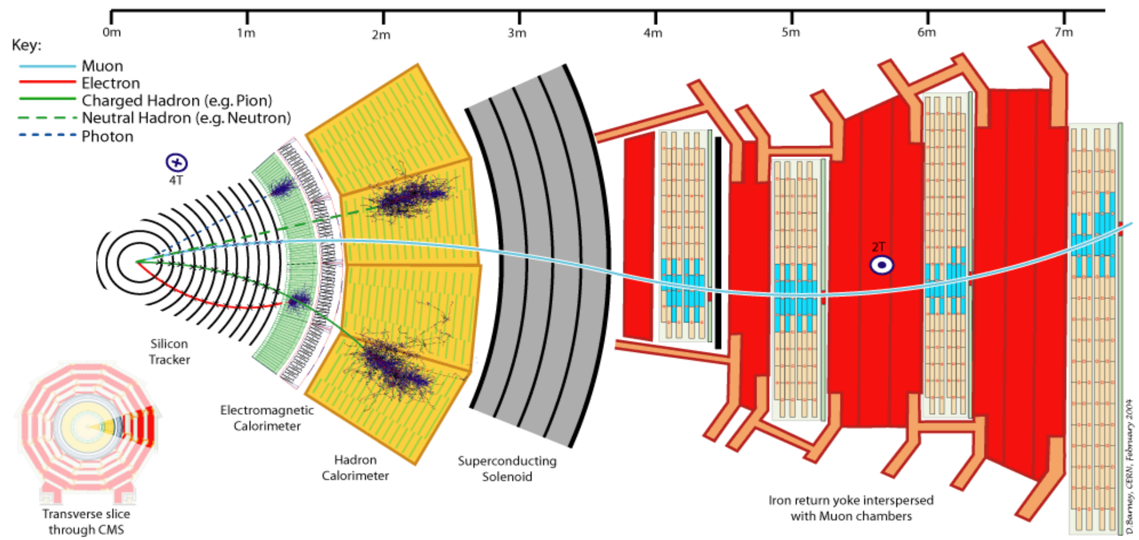
# LHC OPERATION AND PARTICLE DETECTION AT CMS

## LHC operations

- Run I (2010-2012) at center of mass energies 7 TeV ($5.1\ fb^{-1}$) and 8 TeV ($19.7\ fb^{-1}$)
- 2-year shutdown to prepare LHC for higher energies
- Run II (2015-2018) at 13 TeV. In 2015 CMS collected $2.7\ fb^{-1}$ , 2016 data-taking starts now
  CMS is expected to collect $100\ fb^{-1}$ during Run II
- HL-LHC (Phase II) should start after 2025 with major upgrades to record $3\ 000\ fb^{-1}$

## Compact muon solenoid – general purpose detector:




ECAL – crucial for $H \to \gamma\gamma$ analysis, measures photons' energy. It consists of PbWO4 crystals
For ttH production mode other subdetectors needed to reconstruct leptons and jets

# SUMMARY OF MY THESIS

**$H \to \gamma\gamma$ analysis for in Run II** ( Higgs boson rediscovery) :

- Primary vertex identification algorithm is crucial for diphoton mass resolution

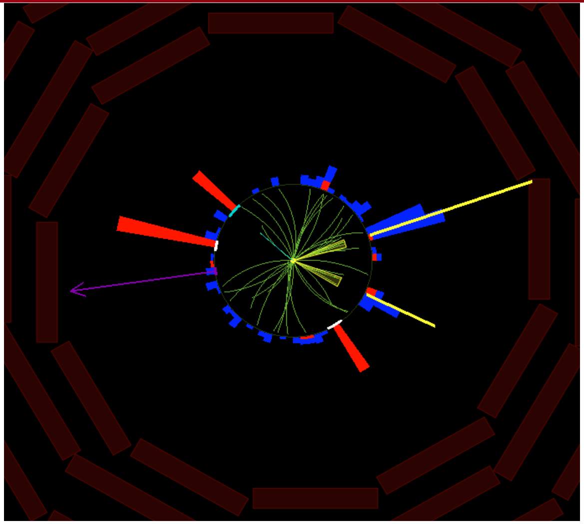
**ttH , H $\to \gamma\gamma$ analysis** is a part of $H \to \gamma\gamma$ :

- Selection cuts implementation and optimization

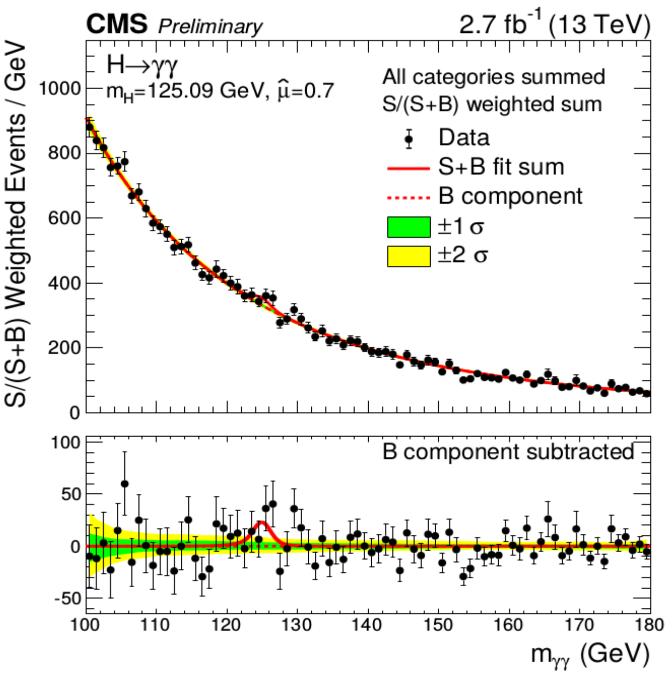
**ECAL Laser monitoring system upgrade for LHC Phase II** :
(not described in this talk)

- Photons' energy is calibrated using crystals transparency measurements done by laser monitoring system
- This system will not be operational during Phase II, because of radiation → upgrade needed
- A test bench was built in CEA Saclay
- I participated in its installation
- I studied its precision

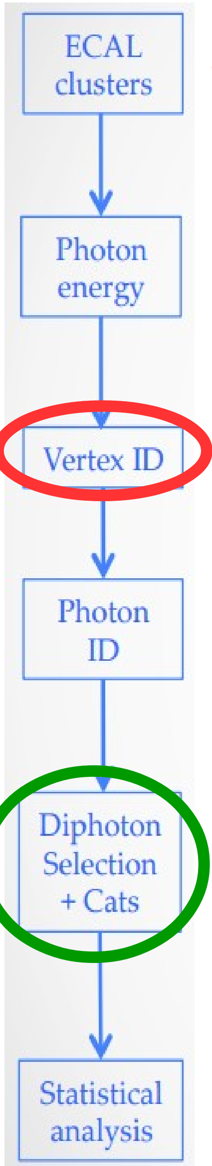
# $H \to \gamma\gamma$ ANALYSIS WORKFLOW



- Select events with two high energy, isolated photons
- Select the primary vertex (because of several interactions per pp bunch-crossing (Pileup))
- Classify events with additional objects from different production modes (ttH, VH, VBF) for coupling measurements
- Other events are classified according to diphoton kinematics and mass resolution
- Signal and background extraction done with $m_{\gamma\gamma}$ distribution fit



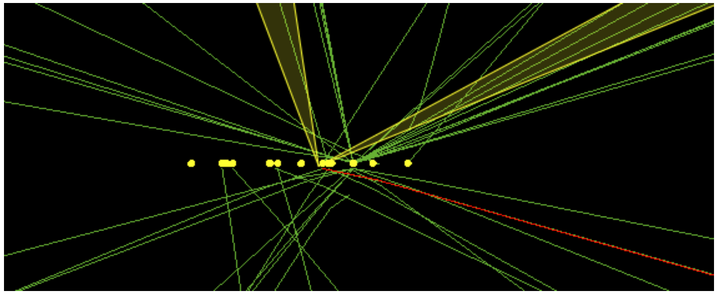
# VERTEX IDENTIFICATION : MOTIVATION

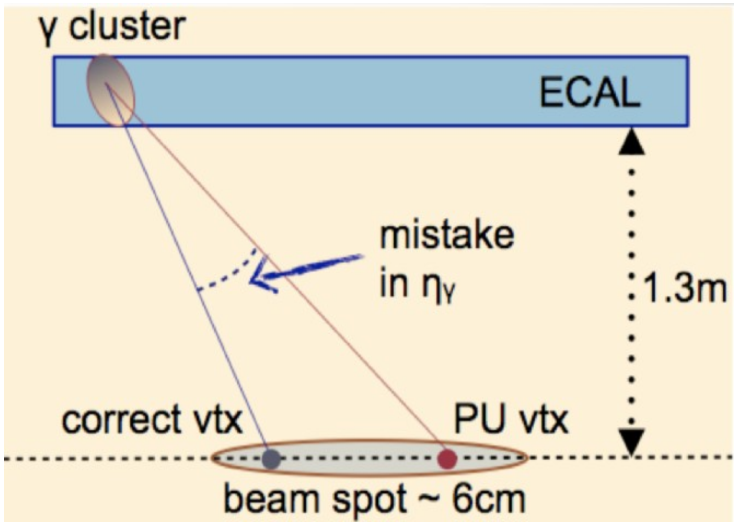



## Vertex identification

- <Pileup> = 11 (spread in z ~ 6cm) in 2015
- Photon – neutral object, can not be detected in the tracker
- Crucial for diphoton mass resolution

$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\theta)}$$






A wrong vertex choice implies a mistake in the angle between two photons → worsen mass resolution

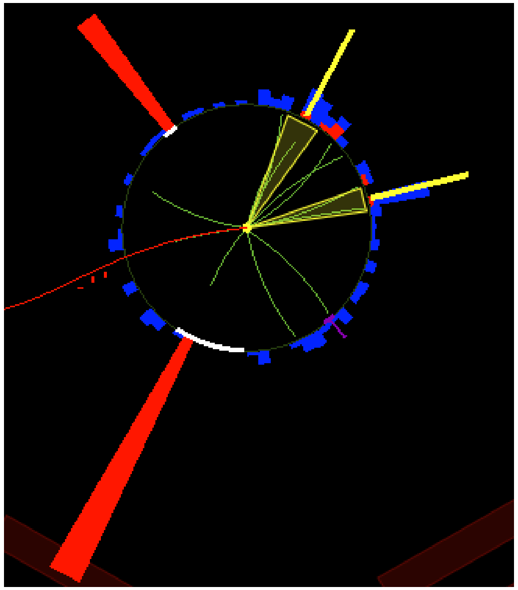
## Per-event correct vertex probability

(not described in this talk)

- Used for event categorization based on mass resolution

# VERTEX IDENTIFICATION

Information : recoiling tracks and their balance with the $p_T^{\gamma\gamma}$



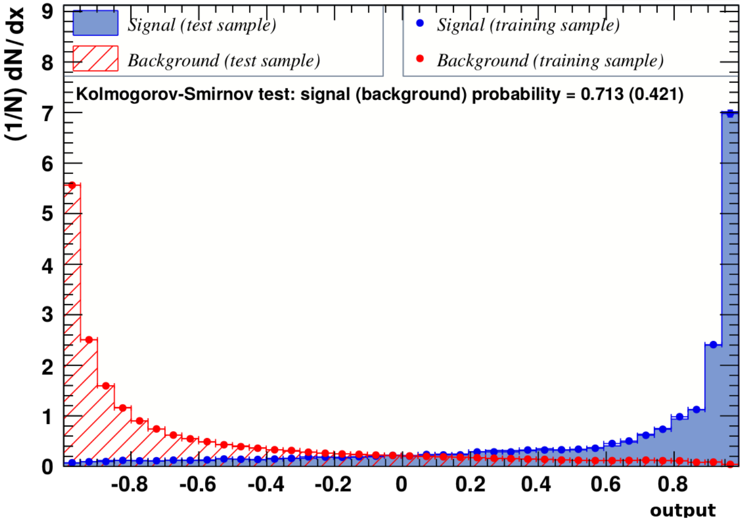
Principle : combine discriminating variables in one optimal variable

- Optimized on Higgs simulation
- The vertex with the most signal-like output is chosen

Performance : Efficiency - fraction of events with

$$|z_{chosen\ vtx} - z_{true\ vtx}| \leq 1\ cm$$

→ where the photons opening angle makes a negligible contribution to the diphoton mass resolution

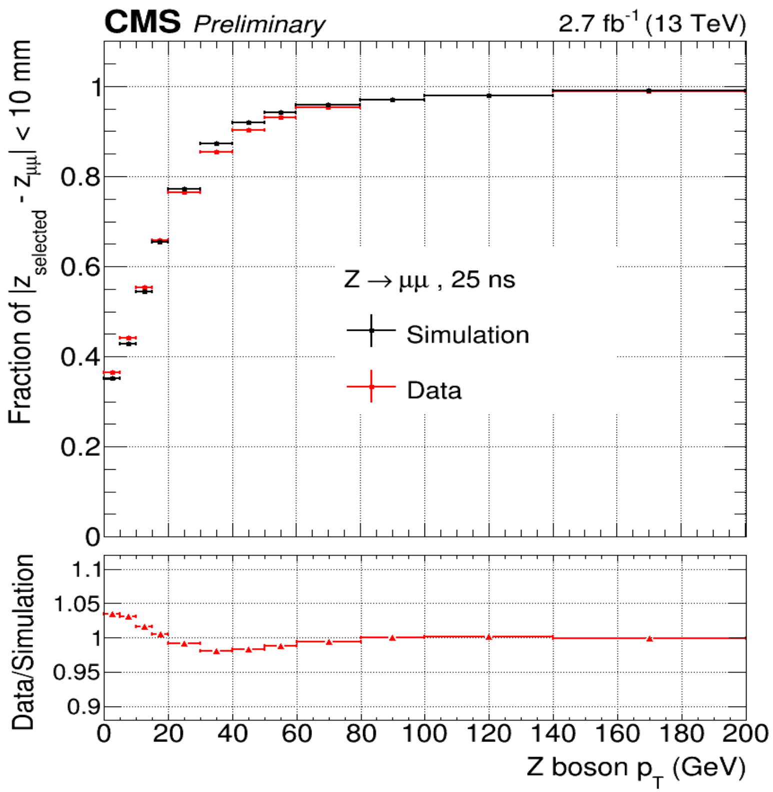



The efficiency ~ 83% for 2015 data

# VERTEX IDENTIFICATION : VALIDATION

$Z \to \mu\mu$ data events used in same procedure for data and simulation :

→ remove muon tracks and re-reco vertices in order to mimic the diphoton system
→ choose the primary vertex with vertex ID algorithm




$Z \to \mu\mu$ data/simulation vs $p_T$ used to correct simulation and compute systematic uncertainty

# TTH ANALYSIS : SELECTIONS

$$\mathrm{ttH}, \quad \mathrm{H} \to \gamma\gamma$$
$$t \to Wb$$

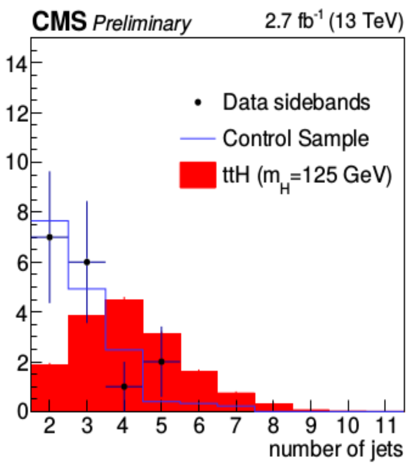
$W \to l\nu$ $\qquad$ $W \to q\bar{q}$

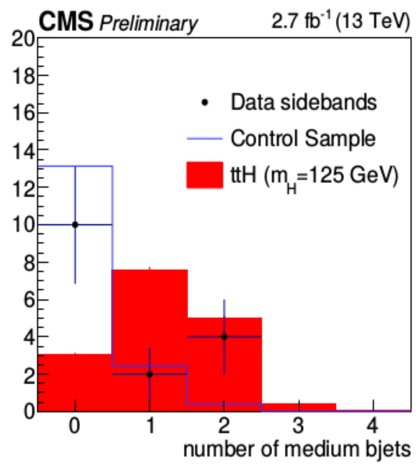
**Leptonic:** $t\bar{t} \to bl\nu_l\bar{b}q\bar{q}' \quad t\bar{t} \to bl\nu_l\bar{b}l'\nu_{l'}$

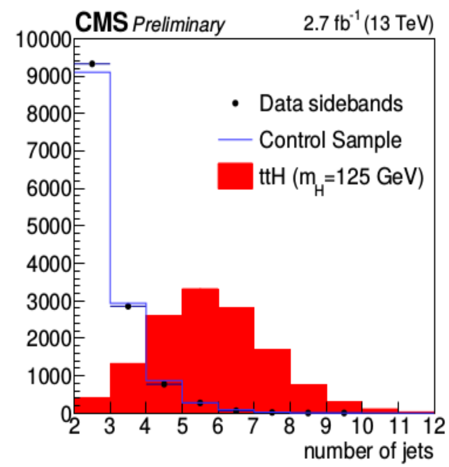
- at least one isolated lepton with pT > 20 GeV
- at least 2 jets with pT > 25 GeV
- at least one of the jets - b-tagged

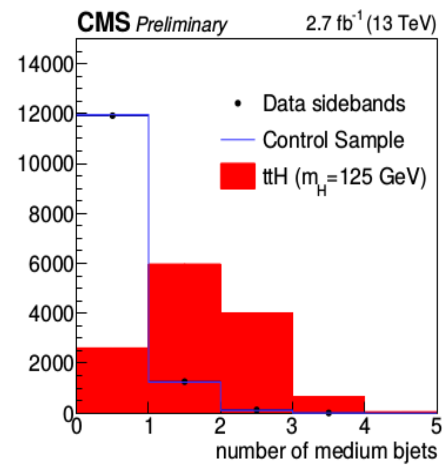
**Hadronic:** $t\bar{t} \to bq\bar{q}'\bar{b}q\bar{q}'$

- no leptons
- at least 5 jets with pT > 25 GeV
- at least one of the jets - b-tagged



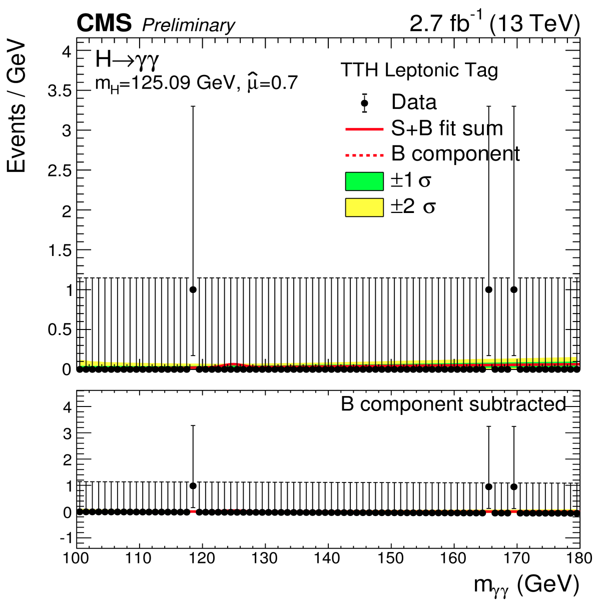

Signal - simulation, background - data :

- Data sidebands: data events with $m_{\gamma\gamma}$ range 100-115 and 135-180 GeV
- Control sample: data events with one photon ID requirement inverted → one photon - fake

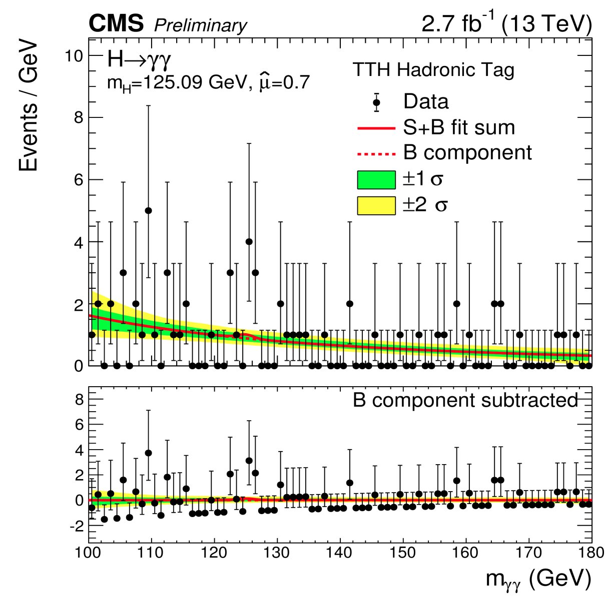
# TTH FIRST RESULTS AT 13 TEV

| Category | Expected signal events | Expected bkg events / GeV |
|---|---|---|
| ttH leptonic | 0.23 | 0.03 |
| ttH hadronic | 0.64 | 0.90 |

Leptonic




Hadronic




- Not enough data to have a sensitivity to ttH
- Positive fluctuations in hadronic channel
- Signal strength $(\sigma/\sigma_{SM})$ is above SM expectation, but with large uncertainties : $\hat{\mu} = 3.8^{+4.5}_{-3.6}$
- More data needed to observe ttH

# CONCLUSION AND PROSPECTS

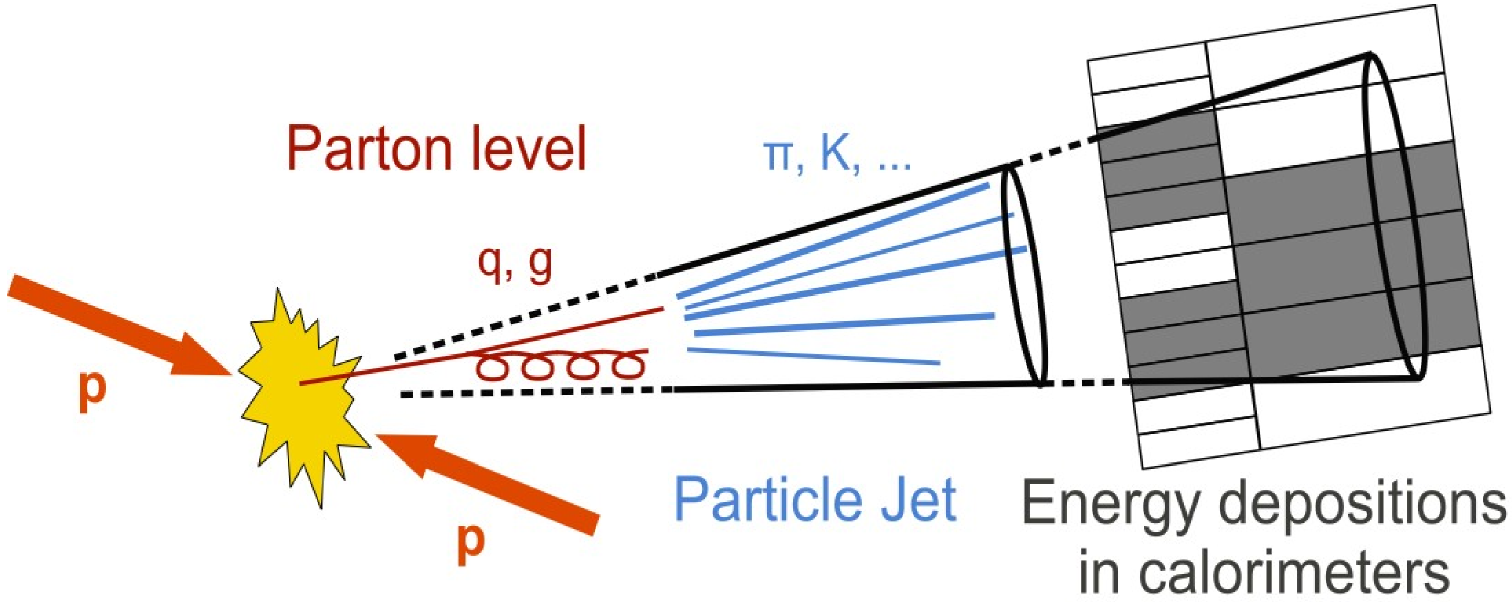
- H→γγ analysis was presented at 13 TeV with Run II data
- Vertex identification studies were presented at 13 TeV for H→γγ analysis
- First ttH results in Run II were shown
- Statistics is too low to be sensitive now to ttH
- Work is ongoing to improve ttH sensitivity
- We expect to have 30 $fb^{-1}$ by the end of 2016, which should allow us to have first constraint on the ttH cross-section

# THANK YOU!

# BACKUP SLIDES

# JETS

Jets: experimental signature of quarks and gluons



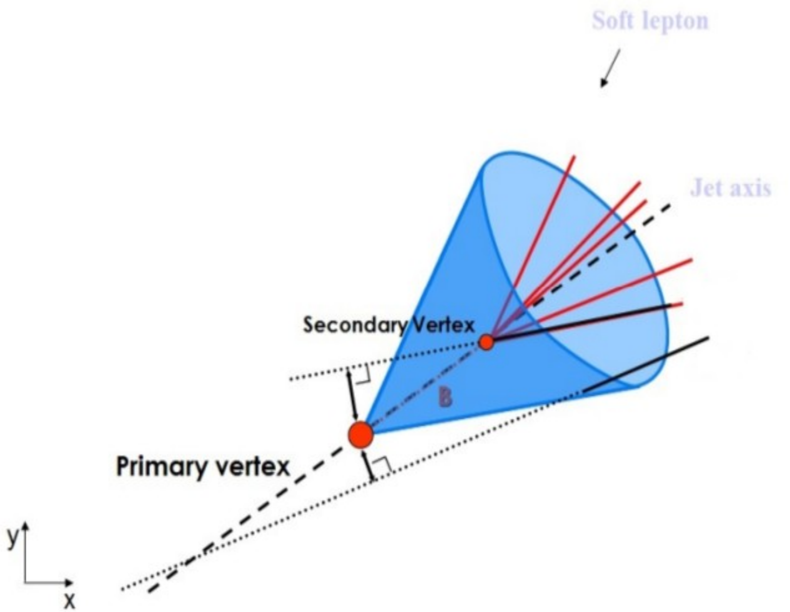

- Jet - collimated cone of particles associated with a final state parton (gluon or quark)
- Fragmentation - process of producing final state particles from the parton
- The hard scatter - initial scattering between partons

# B-JETS

<u>B-jets:</u> originate from B hadrons

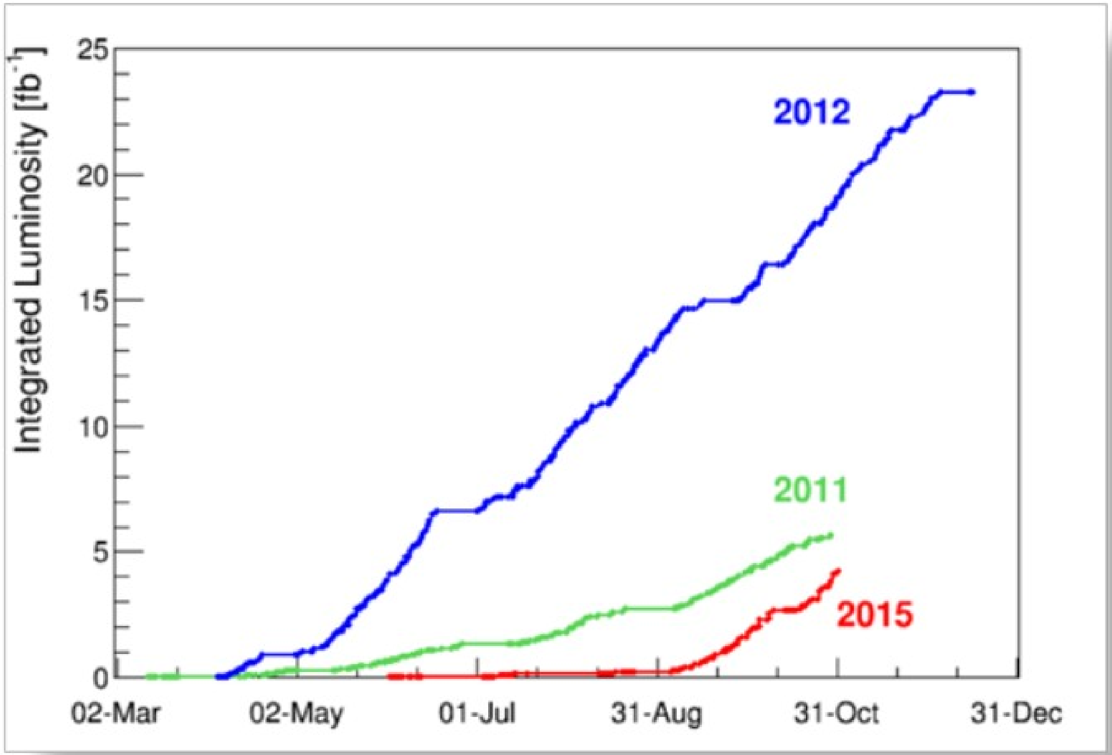
- B hadrons lifetime $10^{-12}$ s → can travel few mm in the detector before decaying into a jet
- B-jets have a secondary vertex
- Tracks coming from a secondary vertex have a large impact parameter
- In 20% of events a b-jet contains a lepton coming from the semi-leptonic decay of the B hadron

These features are used to build the method, which gives a single discriminator value for each jet



# LHC LUMINOSITY 2015

- The initial projections of integrated luminosity for 2015 were ~5-15 $fb^{-1}$.
- We finally achieved ~ 4 $fb^{-1}$.
- The main reasons for the lower value:
  - Start-up delays (~6 weeks),
  - Availability issues,
  - Progress slowed down by electron cloud conditioning.




*The production slope at the end of the year was almost as high as in 2012*

# CONFERENCES AND PUBLICATIONS

**$H \to \gamma\gamma$ analysis for in Run II** ( Higgs boson rediscovery) :

- Primary vertex identification algorithm is crucial for diphoton mass resolution

**$\mathbf{ttH}$ , $\mathbf{H} \to \gamma\gamma$ analysis** is a part of $H \to \gamma\gamma$ :

- Selection cuts implementation and optimization

## Conferences:

- Both results $H \to \gamma\gamma$ and $\mathrm{ttH}$, $\mathrm{H} \to \gamma\gamma$ were presented at Moriond conference, March 2016
- I gave a dedicated talk on vertex identification algorithm at the same conference

## Publications:

- Results of both analysis described in the conference paper **CMS PAS HIG-15-005**
- I am one of the authors of 2 internal CMS documents describing $H \to \gamma\gamma$ analysis and vertex identification algorithm in details