Inna Kucher : CMS group, SPP, IRFU

Thesis subject: 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

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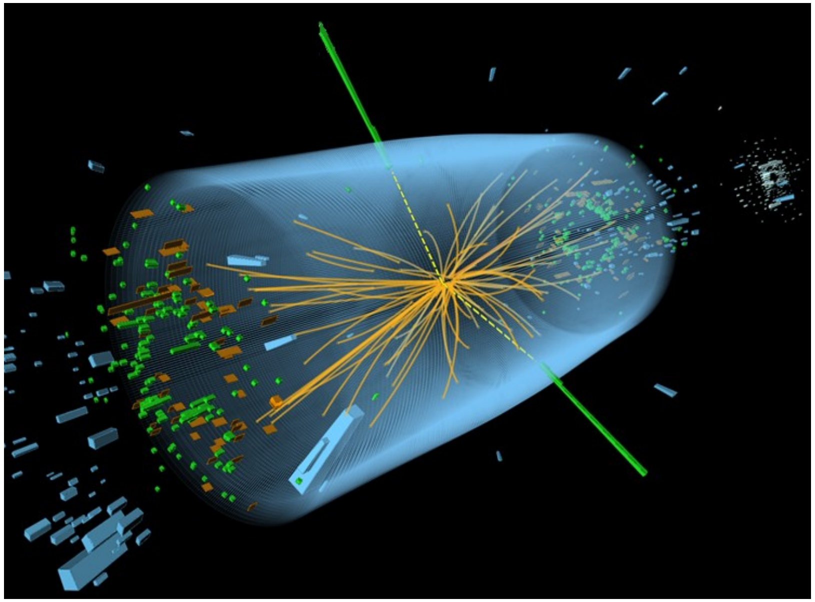
Université d'inscription - Ecole doctorale : Paris 11 – Pheniics

Partenaire académique/industriel : CERN

Référence THOT : SL-DSM-14-048



Key words: CMS, SM, Higgs boson, vertex identification, associated production with a pair of top quarks

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 (EM and Weak): all gauge bosons should be massless to preserve gauge invariance

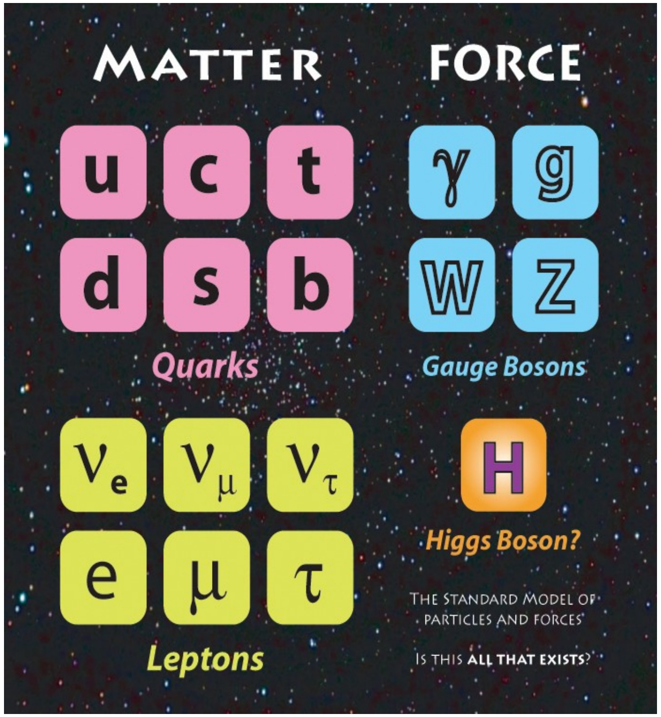
BUT : W and Z bosons are carriers of weak force (short range interaction), they are massive

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)
- This mechanism also gives a mass to the SM fermions
- 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)



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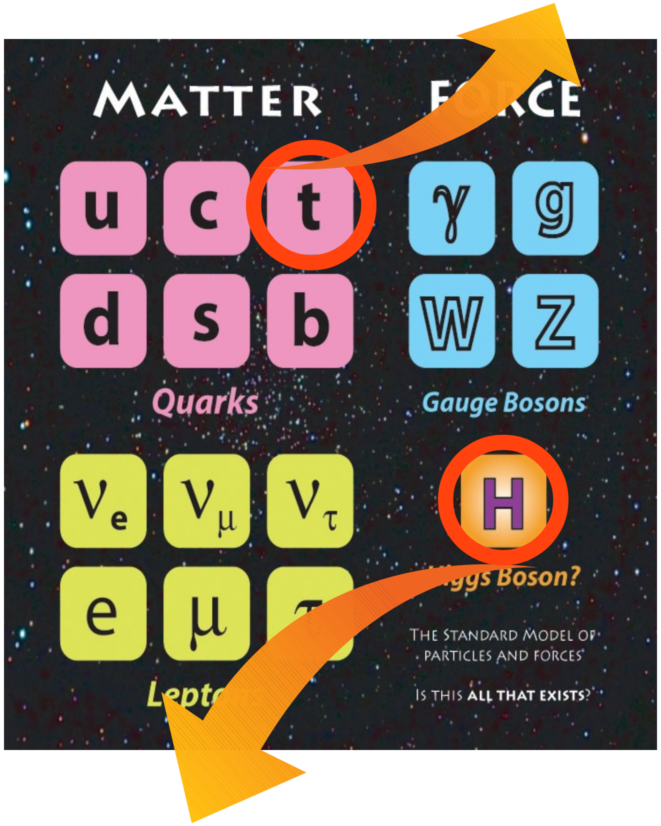
Most massive SM particle



Responsible for "giving the mass" to the SM particles

Standard model

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}

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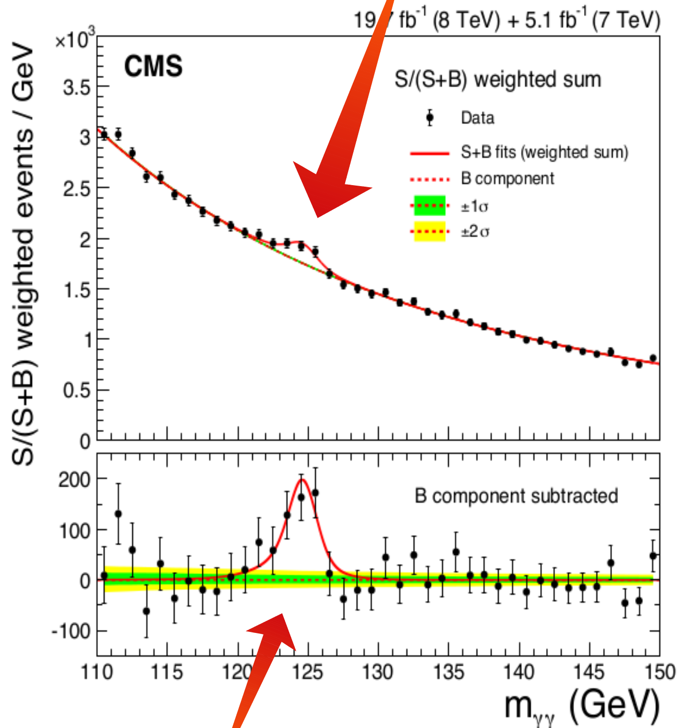
Clear signal peak on the falling background



The width of the peak = resolution. The less it is the better S/B ratio

Higgs mechanism

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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**

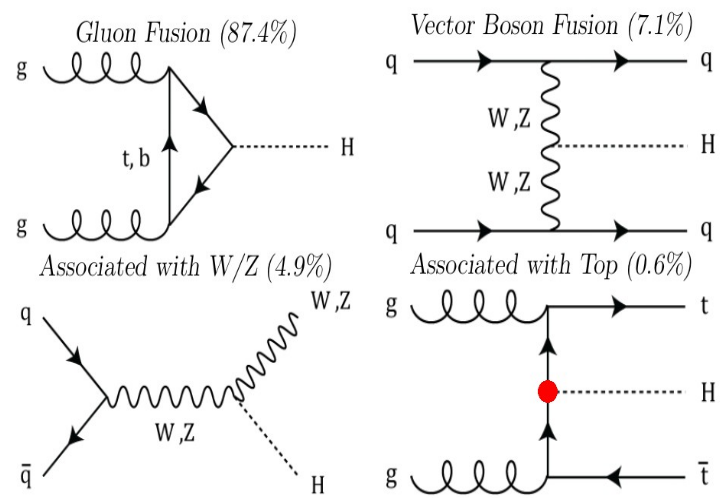
Most promising channel for long-term

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

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

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

Higgs production and decay modes at LHC:



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

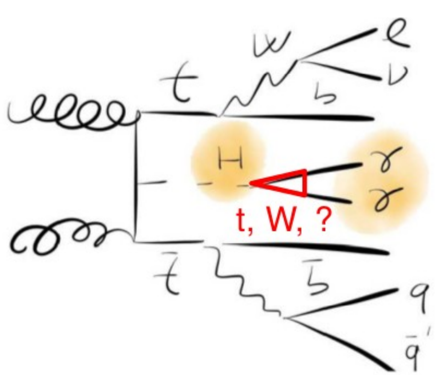
ttH, $H \to \gamma\gamma$ is very rare process

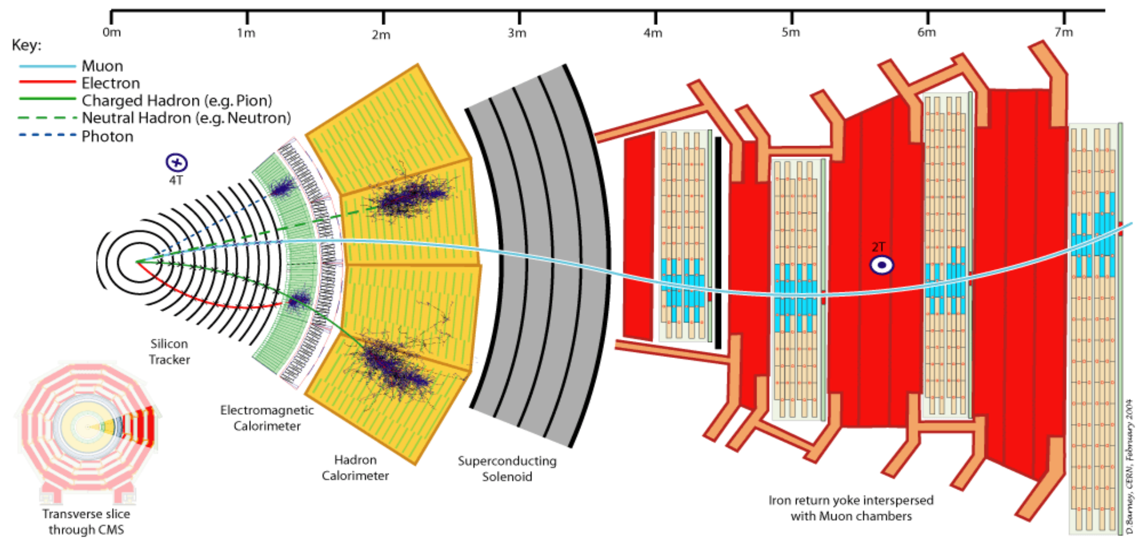
ttH cross-section is 4 times higher wrt Run I

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 is going on 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 $H \rightarrow \gamma\gamma$ 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 in Run II (Higgs boson rediscovery) :

- Identification of primary vertex, which is crucial for diphoton mass resolution
- Identification of prompt photons (work is ongoing for ICHEP conference in August)

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

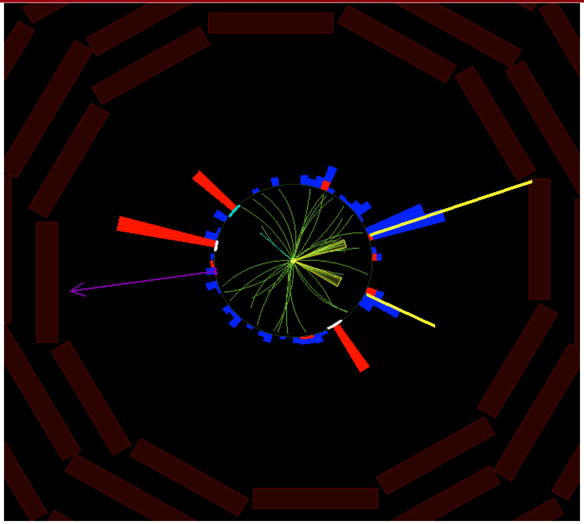
- Optimization and implementation of selection cuts

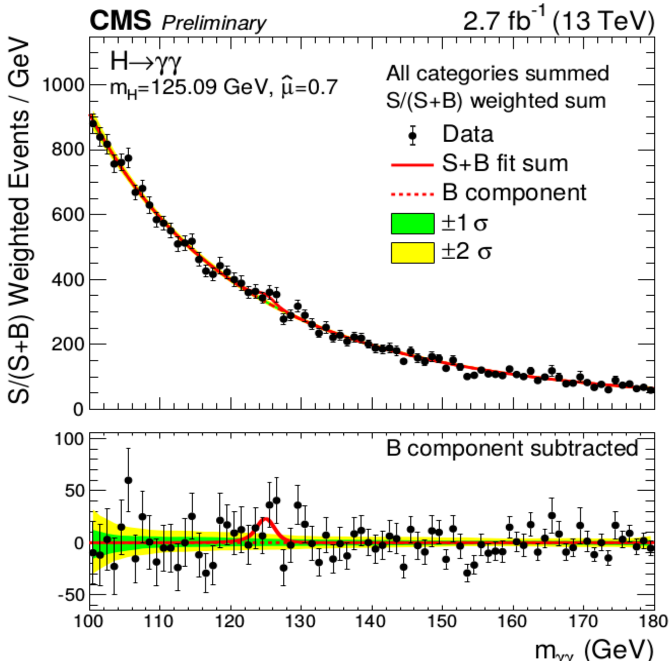
ECAL Laser monitoring system upgrade for LHC Phase II :
(not described in this talk)

- 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

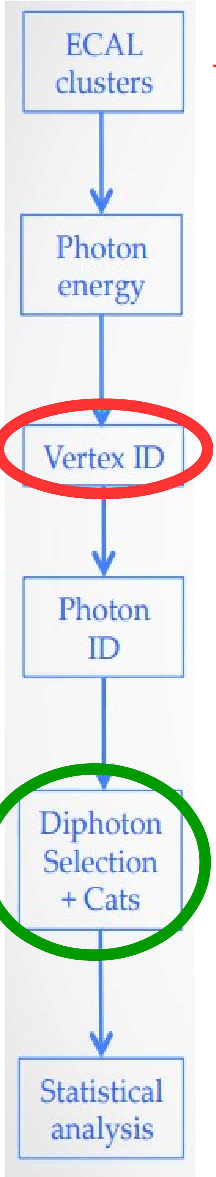
$H \rightarrow \gamma\gamma$ ANALYSIS WORKFLOW

- Select events with two well-identified and 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





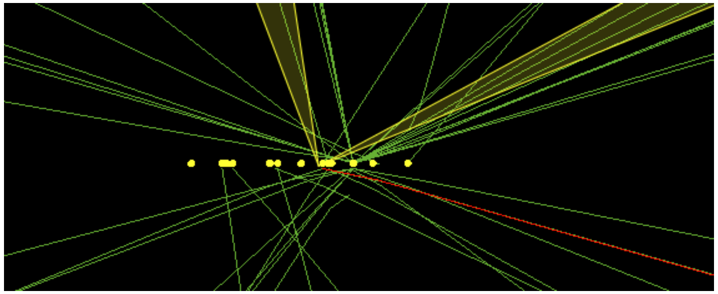
VERTEX IDENTIFICATION : MOTIVATION

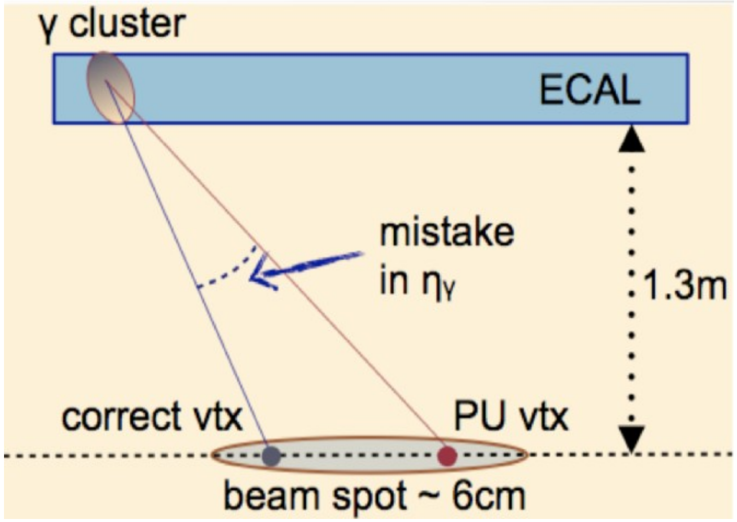


Vertex identification

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

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





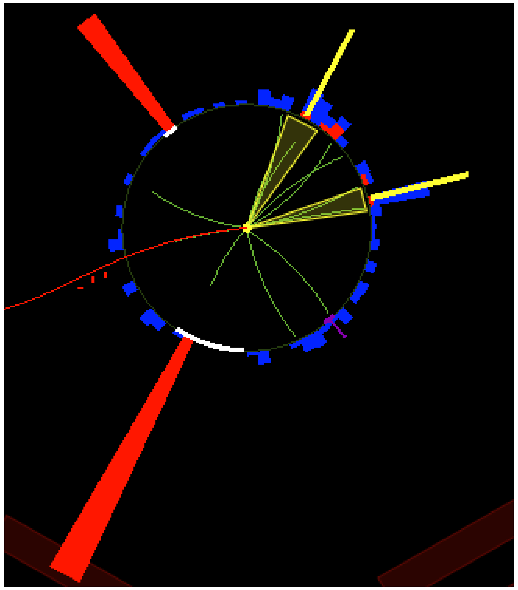
A wrong vertex choice implies a mistake in the angle θ between two photons → worsen mass resolution

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

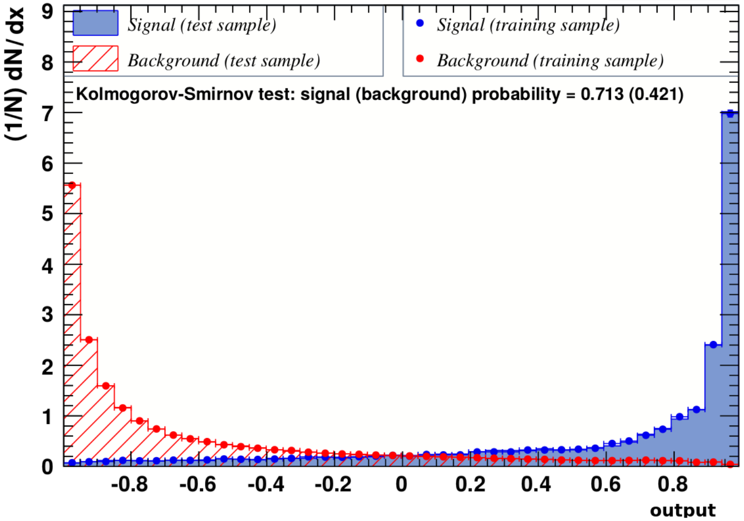
- Optimized on Higgs simulation
- The vertex with the most signal-like output is chosen

Performance : Efficiency - fraction of events with

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

Because in this case the photons opening angle makes a negligible contribution to the diphoton mass resolution

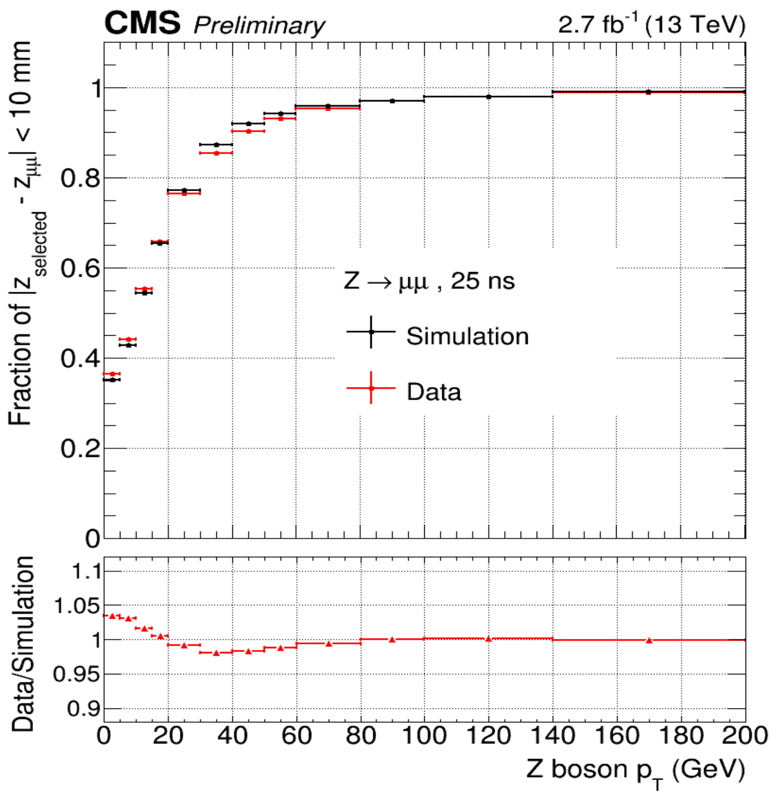
The efficiency $\sim$ 83% for 2015 data



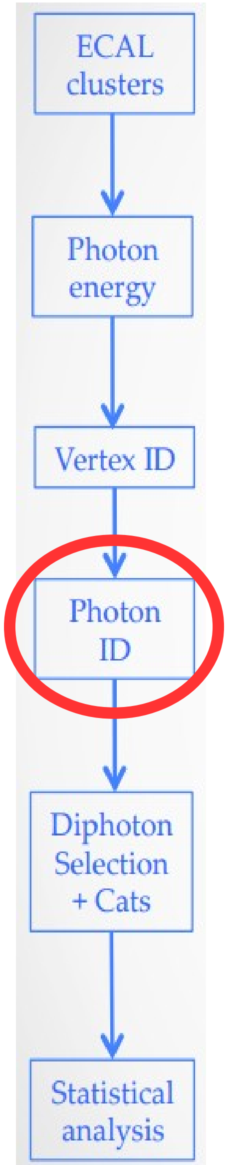
VERTEX IDENTIFICATION : VALIDATION

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

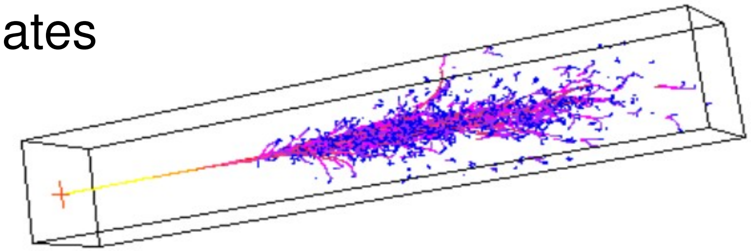
→ remove muon tracks and re-reco vertices in order to mimic the diphoton system
→ choose the primary vertex with vertex ID algorithm



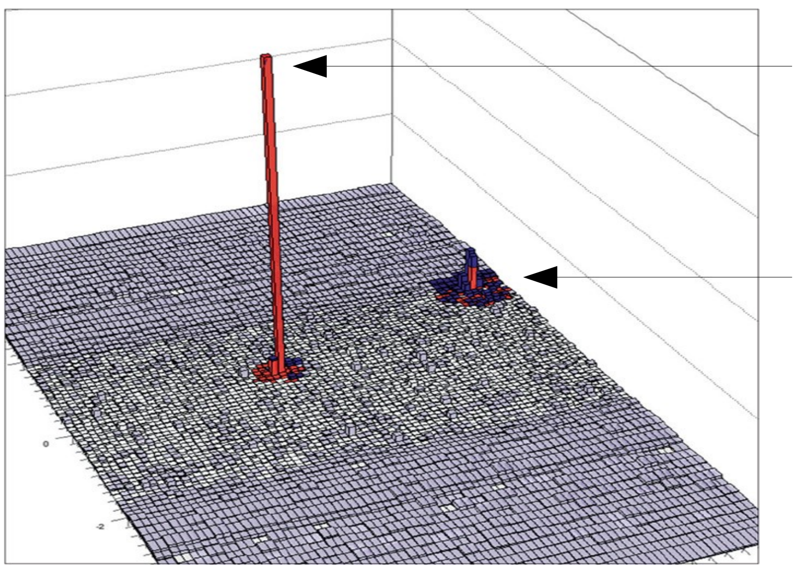
$Z \to \mu\mu$ data/simulation vs p_T used to correct simulation and compute systematic uncertainty



Photon interacting with ECAL crystal creates electromagnetic shower



The goal : distinguish prompt photons from fake ones.



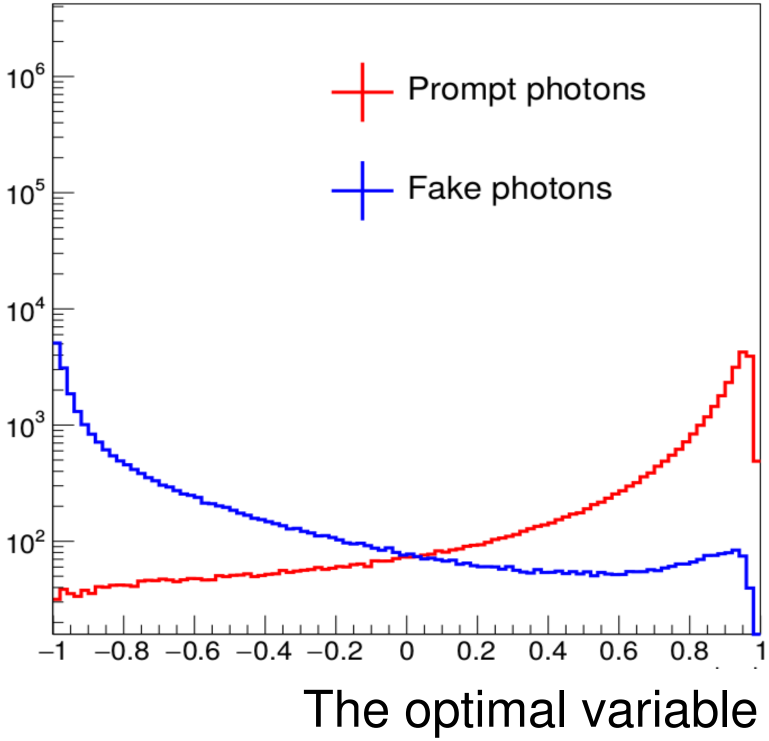
Prompt photons (signal) :
coming from hard scatter vertex
Compact shower

Fake photons (background) :
mostly jets, like $\pi^0 \to \gamma\gamma$

Broader shower

Information : the electromagnetic shower description and energy deposits features

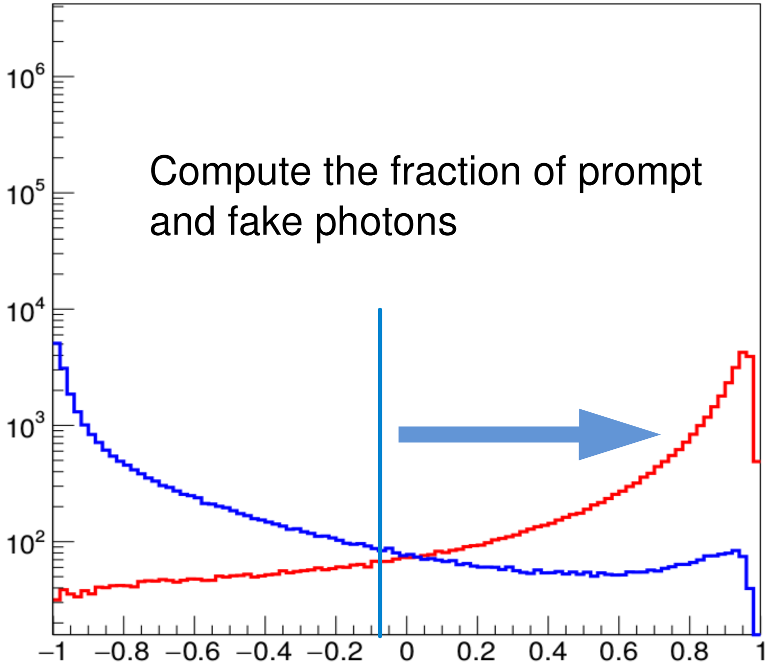
Method : combine discriminating variables in one optimal variable



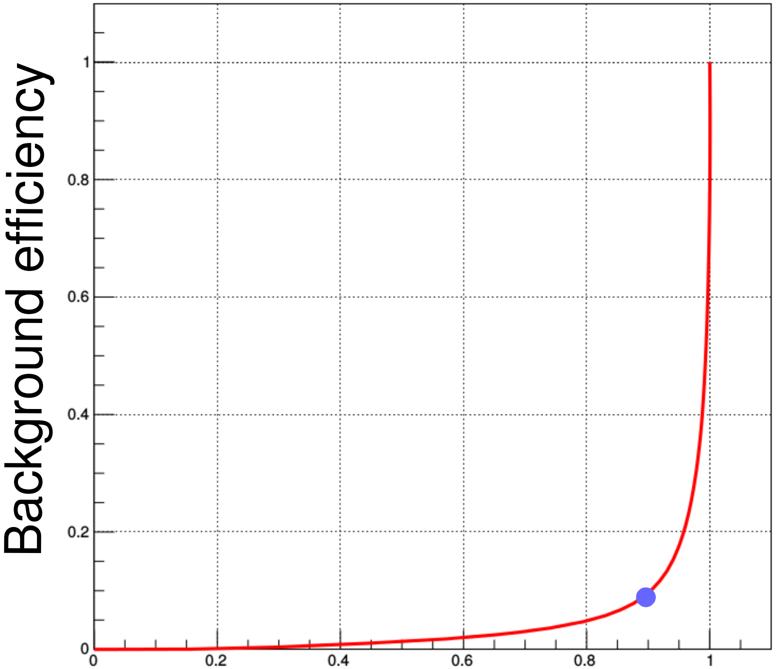
PHOTON IDENTIFICATION

Information : the electromagnetic shower description and energy deposits features

Method : combine discriminating variables in one optimal variable



The optimal variable



Signal efficiency

PHOTON IDENTIFICATION

Information : the electromagnetic shower description and energy deposits features

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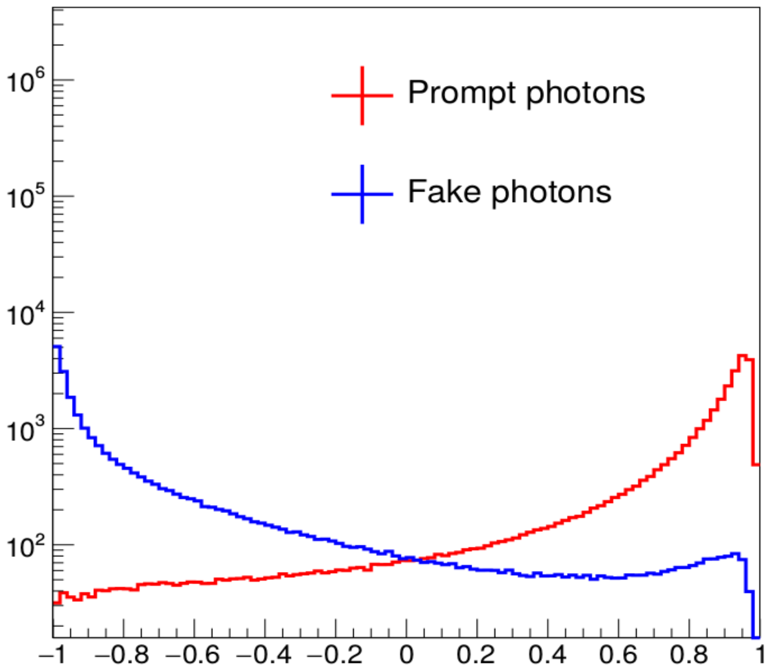
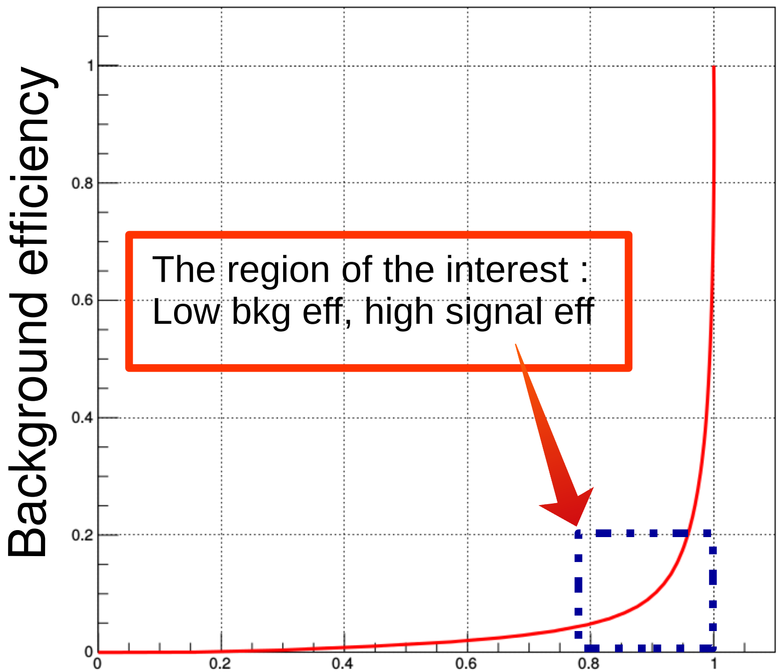


The optimal variable



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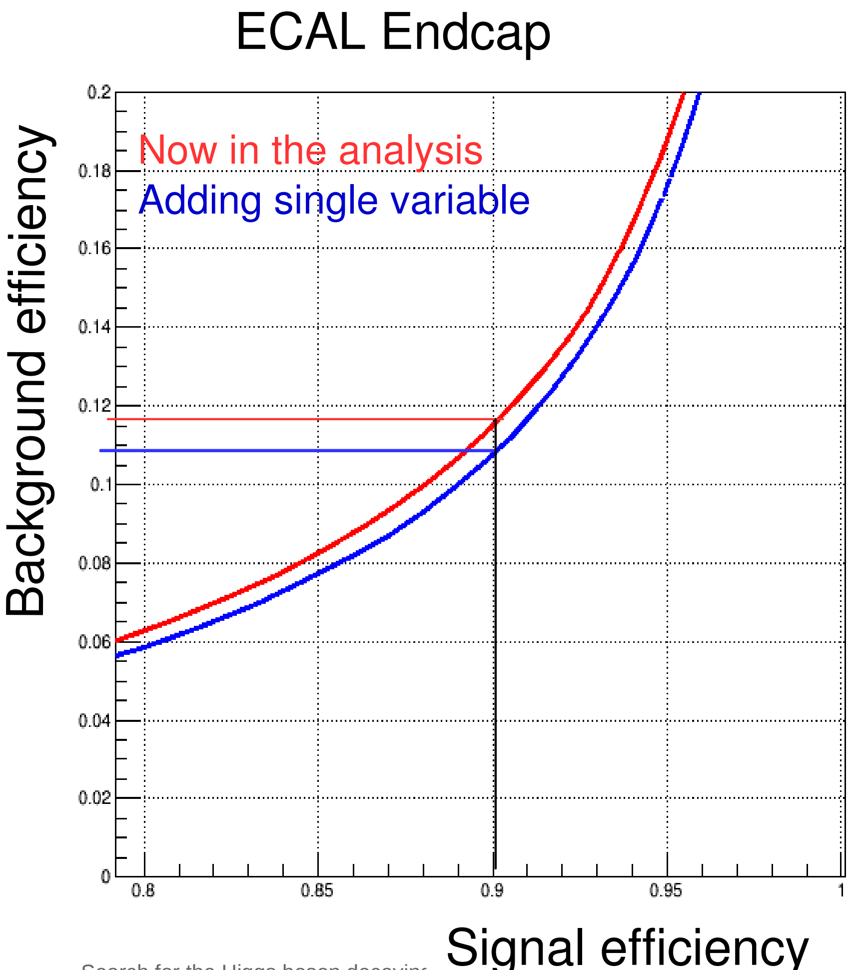


- The photon identification is being updated for ICHEP
- The improvement for ECAL endcap was found by adding single variable

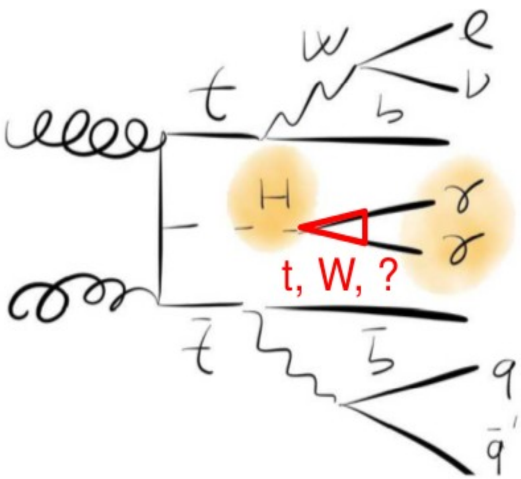
Adding single variable we reject ~10% more background at signal efficiency = 90%

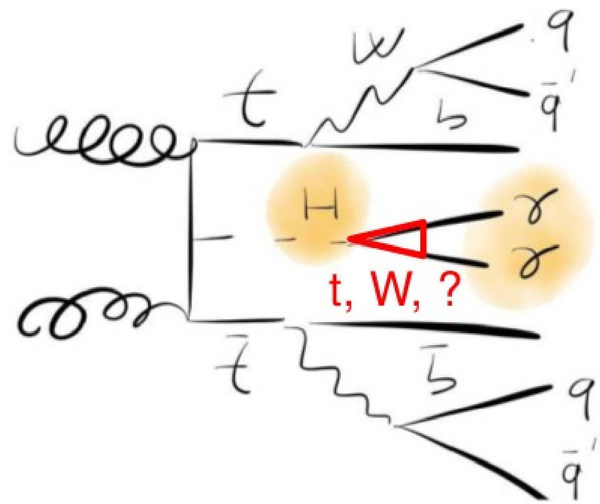
- It will be implemented in the analysis at the next iteration

TTH ANALYSIS : SELECTIONS

Leptonic: $t\bar{t} \rightarrow bl\nu_l\bar{b}q\bar{q}^{'}\ t\bar{t} \rightarrow bl\nu_l\bar{b}l^{'}\nu_{l^{'}}$

Hadronic: $t\bar{t} \rightarrow bq\bar{q}^{'}\bar{b}q\bar{q}^{'}$





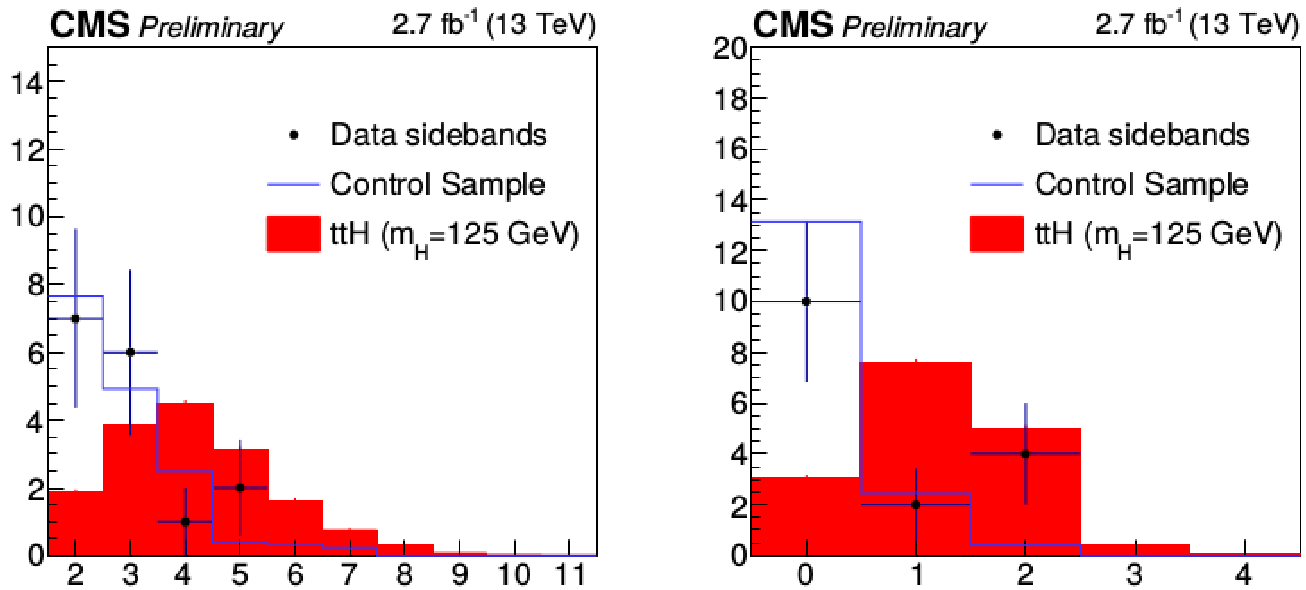
- at least one isolated lepton
- at least 2 jets
- at least one b-tagged jet

- no leptons
- at least 5 jets
- at least one b-tagged jet

b-tagged jet : jet identified as originating from a b quark

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

- at least one isolated lepton
- at least 2 jets
- at least one b-tagged jet



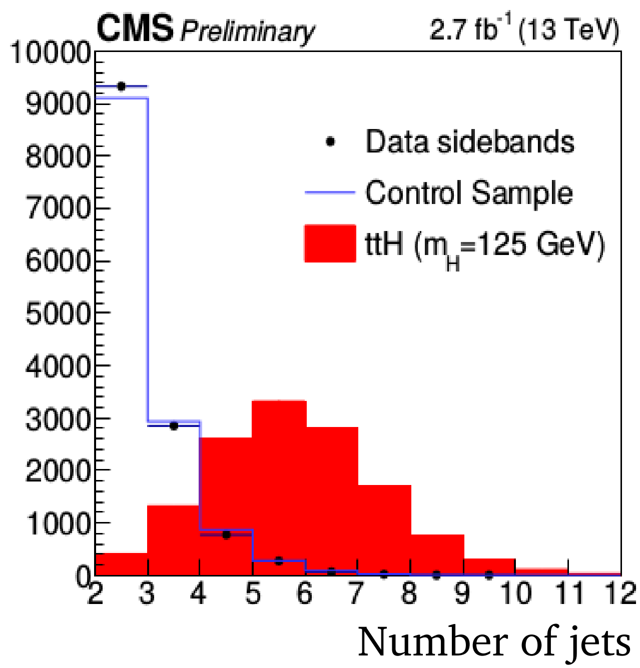
Signal - simulation, background - data :

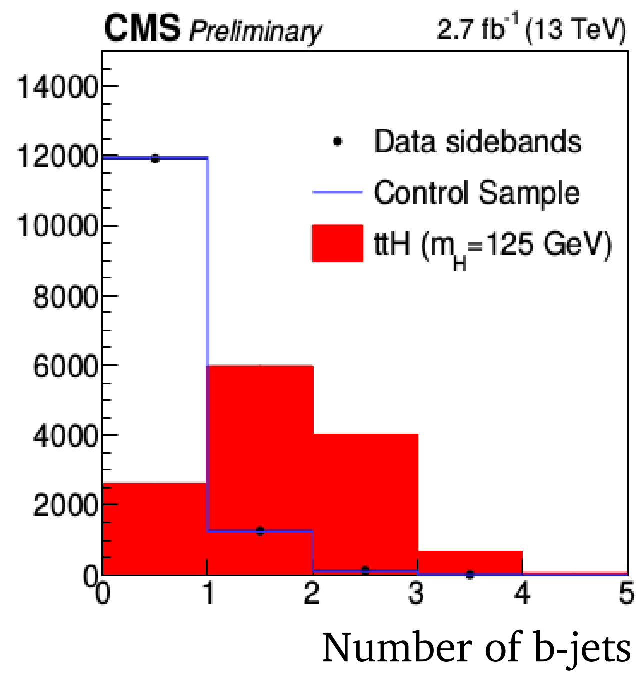
- Data sidebands: data events with $m_{\gamma\gamma}$ range 100-115 and 135-180 GeV
- Control sample: data events with one photon ID requirement inverted → one photon - fake

TTH ANALYSIS : HADRONIC CHANNEL

Hadronic: $t\bar{t} \rightarrow bq\bar{q}^{'}\bar{b}q\bar{q}^{'}$

- no leptons
- at least 5 jets
- at least one b-tagged jet





Signal - simulation, background - data :

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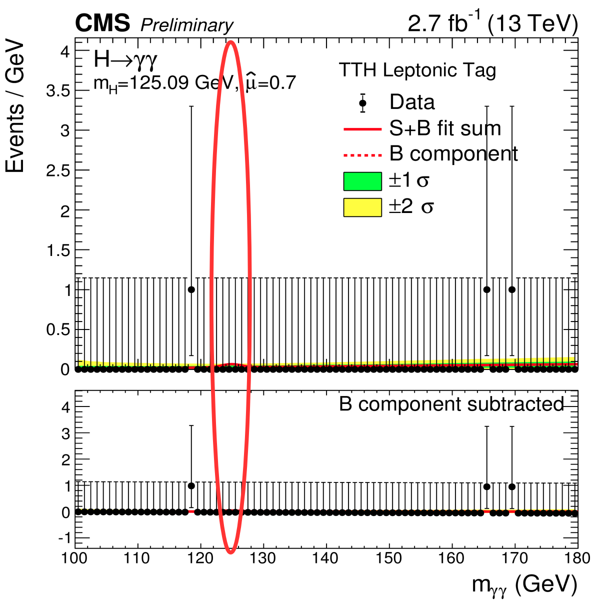
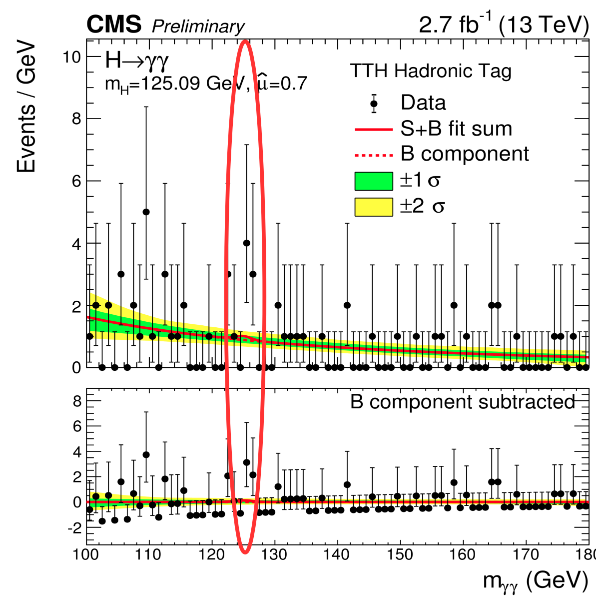
TTH FIRST RESULTS AT 13 TEV

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 (σ/σ_{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

- $H\to\gamma\gamma$ analysis was presented at 13 TeV with Run II 2015 data
- Vertex identification studies were presented at 13 TeV for $H\to\gamma\gamma$ analysis
- First ttH results in Run II were shown

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

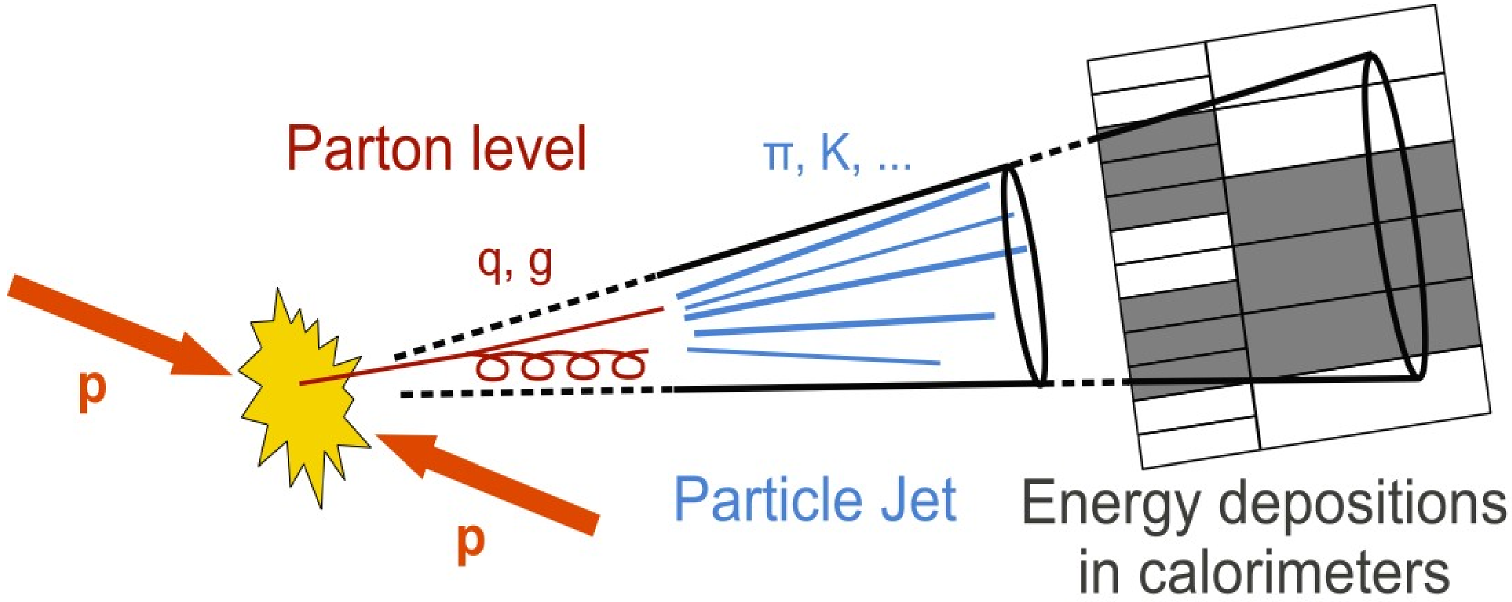
- Statistics is too low to be sensitive now to ttH
- Work is ongoing to improve ttH sensitivity
- The analysis is being updated for ICHEP conference with expected luminosity $\sim 10\ fb^{-1}$
- We expect to have 30 fb^{-1} by the end of 2016, which should allow us to have first constraint on the ttH cross-section

THANK YOU!

BACKUP SLIDES

JETS

<u>Jets:</u> experimental signature of quarks and gluons



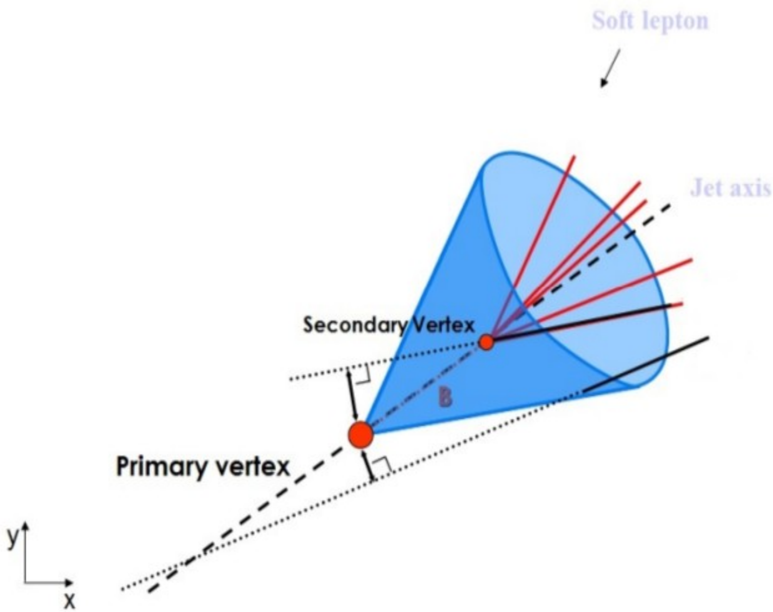
- Jet - collimated cone of particles associated with a final state parton (gluon or quark)
- Fragmentation - process of producing final state particles from the parton
- The hard scatter - initial scattering between partons

B-JETS

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

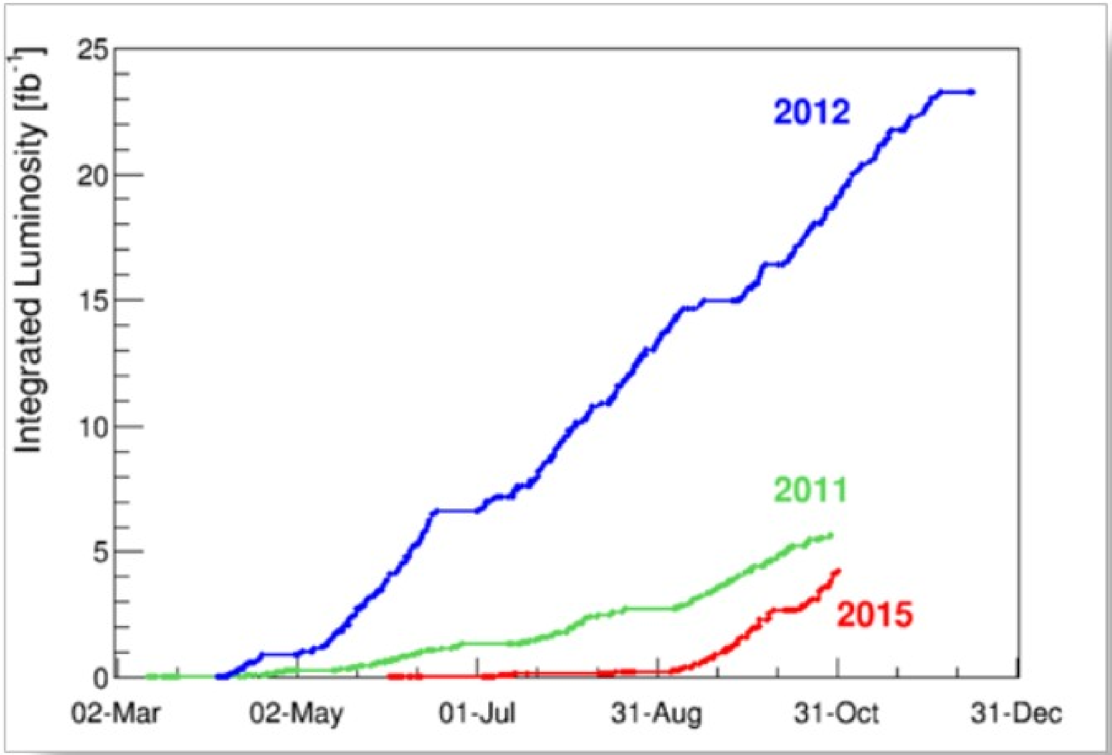
- B hadrons lifetime 10^{-12} s → can travel few mm in the detector before decaying into a jet
- B-jets have a secondary vertex
- Tracks coming from a secondary vertex have a large impact parameter
- In 20% of events a b-jet contains a lepton coming from the semi-leptonic decay of the B hadron

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