# Modeling of Diboson+jets and Higgs+jets at CMS

**8/12/2014 - Higgs+Jets 2014 workshop, IPPP Durham**

**Nicolas Chanon - IPHC Strasbourg**
on behalf of the CMS collaboration

# Introduction

- **This workshop**: aims at reviewing state of the art Higgs and Higgs+jet kinematics in theoretical predictions and data measurement
  - see previous talks from ATLAS on Higgs differential measurement

- **V+jets** can be seen as a **benchmark for Higgs jet multiplicities modeling**
  - see V+jets talk later this afternoon

- **VV+jets** is an **irreducible background to H→VV decays and also an interesting benchmark** for NNLO and multijet computations

- In this talk I will focus on jet modeling in **H→γγ, H→ZZ and H→WW** analyses, and what we learned about jets with γγ, ZZ, WW measurements, that may be useful for the Higgs.

# H→VV summary

## PAS HIG-14-009

**Higgs boson signal strength μ=σ/σ_SM**

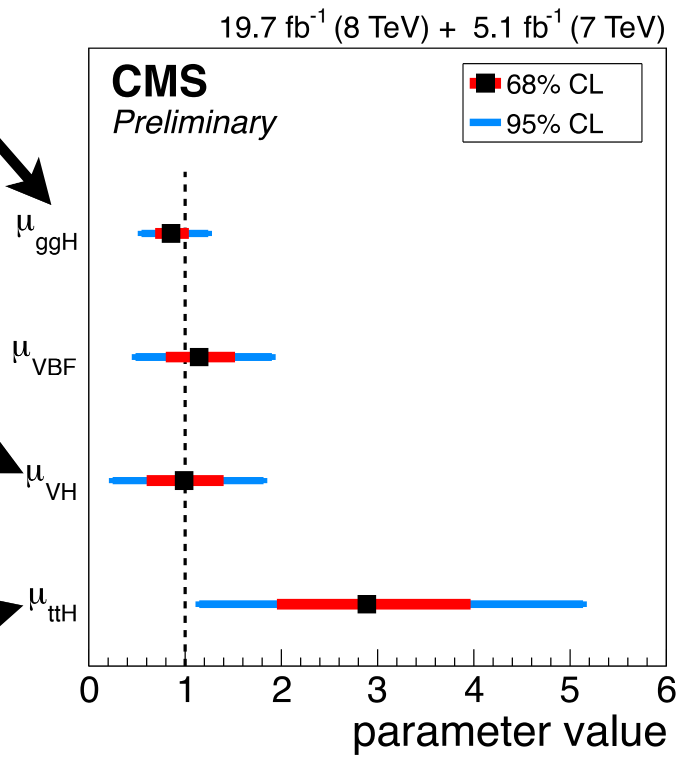
**ggH**:
- NNLO normalization
- Shape from Powheg

**VBF**:
- NNLO normalization
- Shape from Powheg

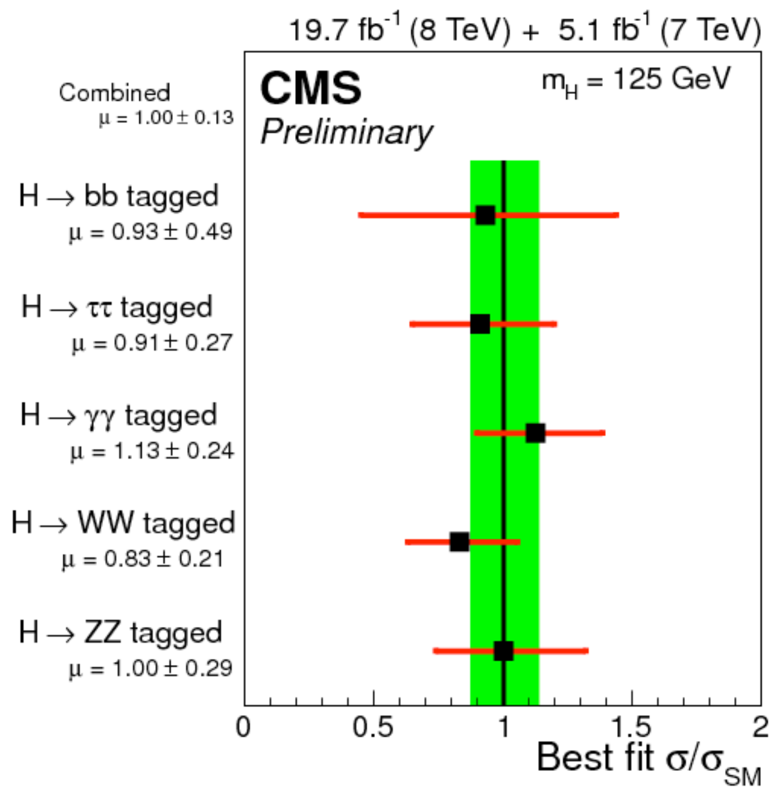
**VH**:
- NNLO normalization
- Shape from Pythia

**ttH**:
- NLO normalization
- Shape from Pythia

**by production mechanism**




**and final state tag**

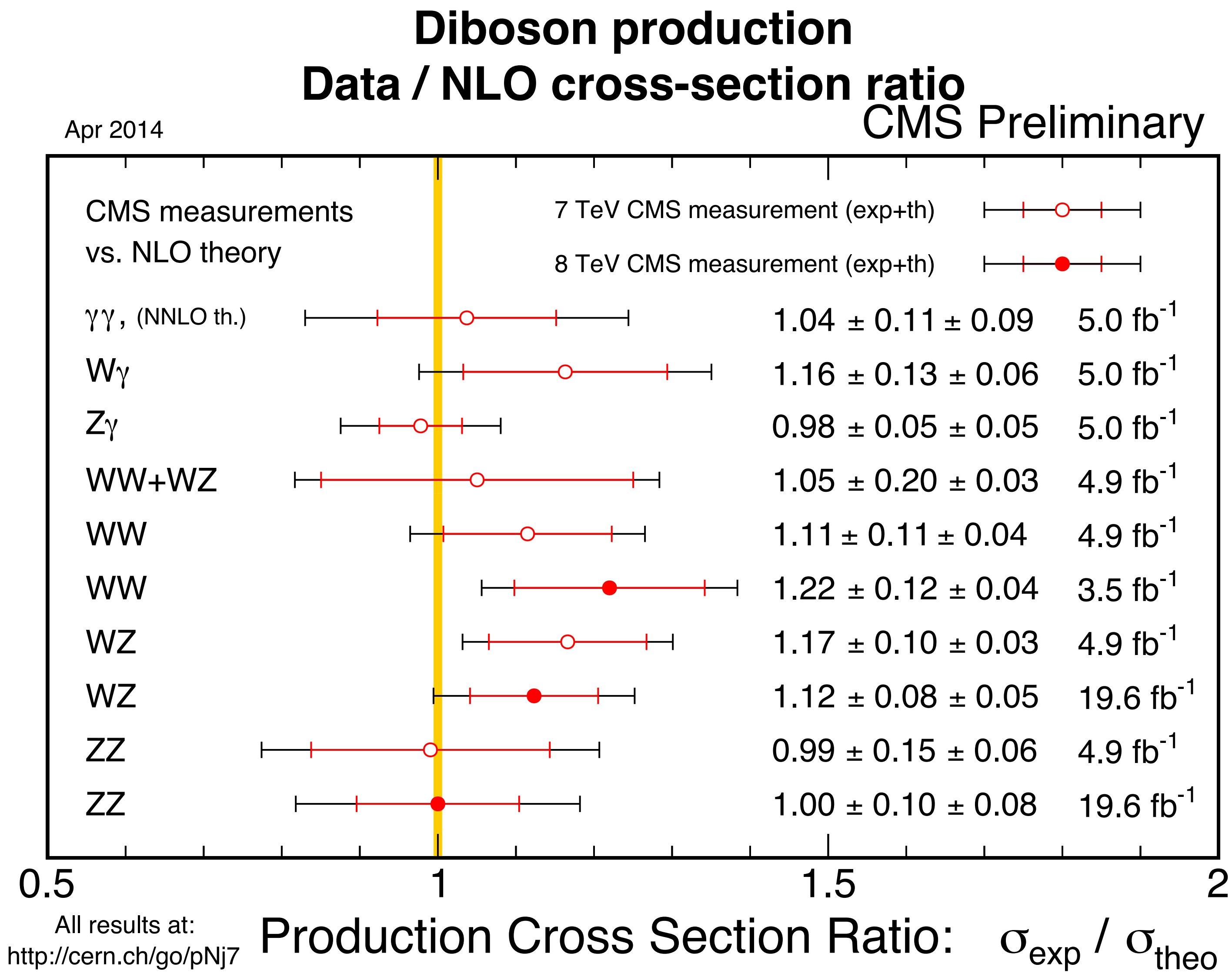


# VV summary

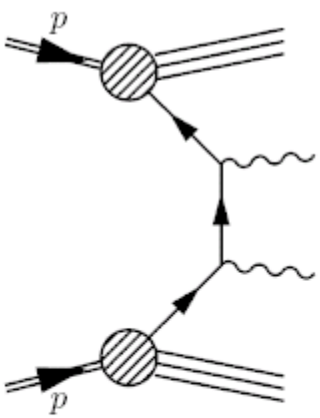
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

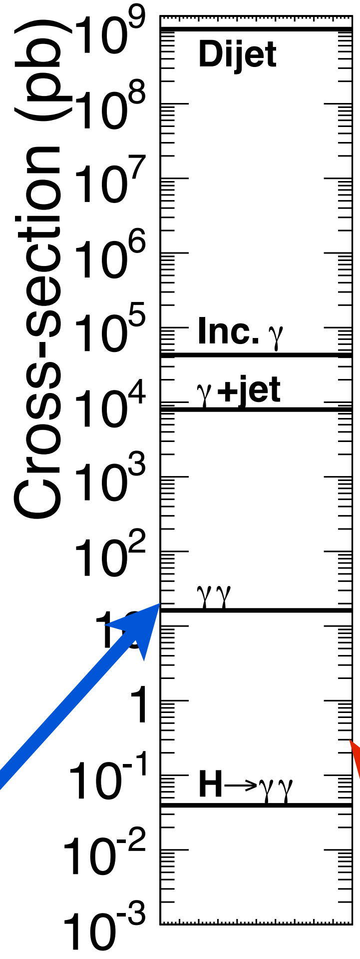
**Recent progress in NNLO computation:**

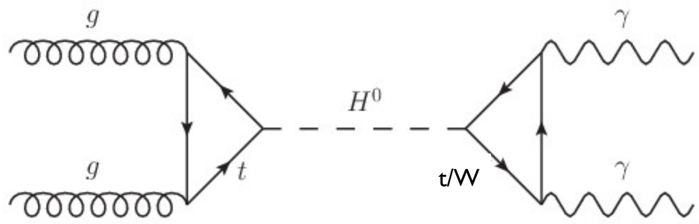
- Diphoton, Zγ, Wγ differential available
- WW, ZZ inclusive cross-section available
- Only WZ is missing !

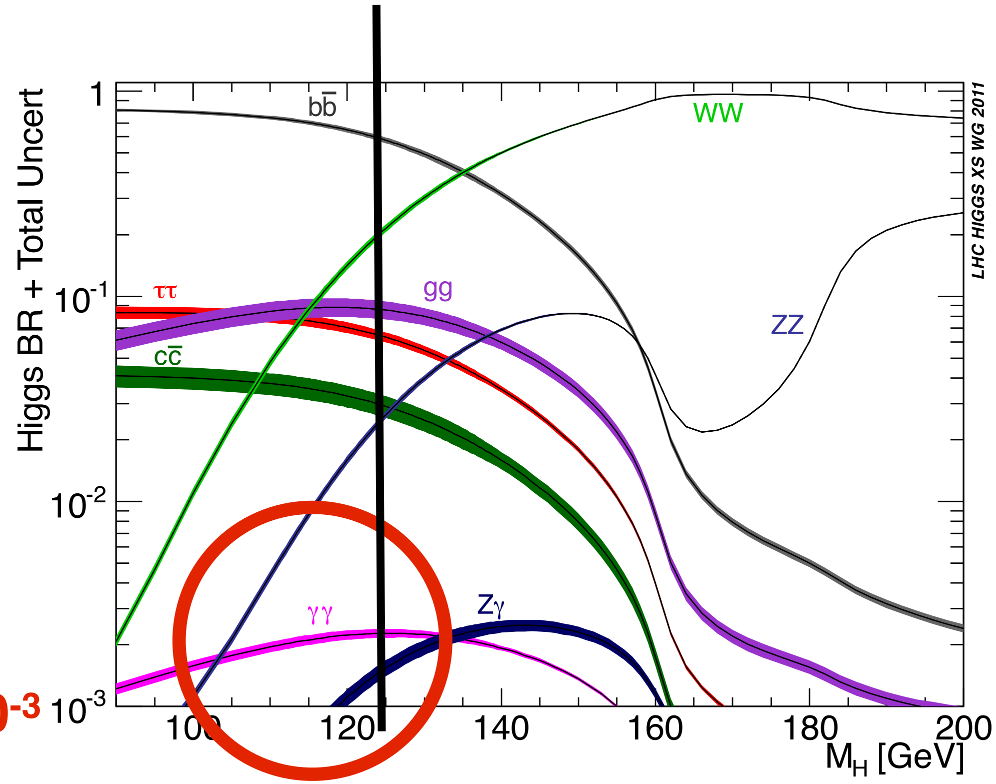


# H→γγ



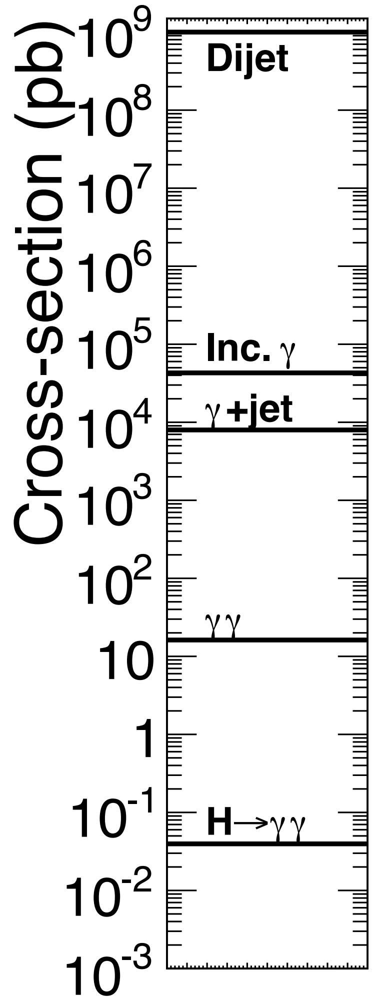

**Diphoton production**

**BR(H→γγ)~2.10$^{-3}$**

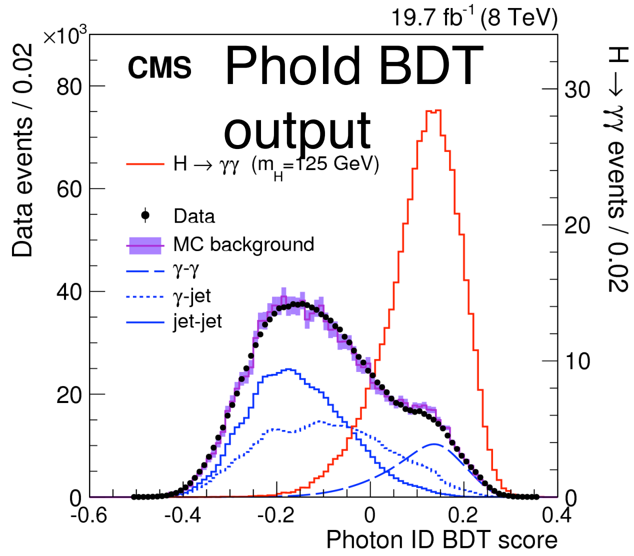
# H→γγ analysis

## EPJC 74 (2014) 3076

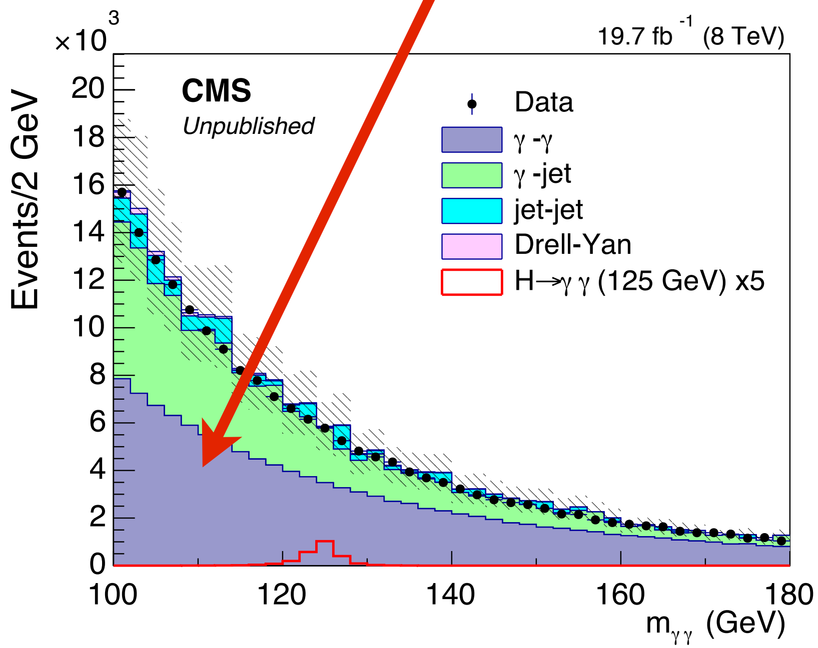
- **Look for small signal peak (small BR) over large background**
- **Main analysis is MVA - cut-based analysis and 2nd MVA analyses as cross-checks**
- Select **two high pt isolated photons** from the same **vertex**




- **Photon identification BDT** to reject jets faking photons: shower shape and isolation



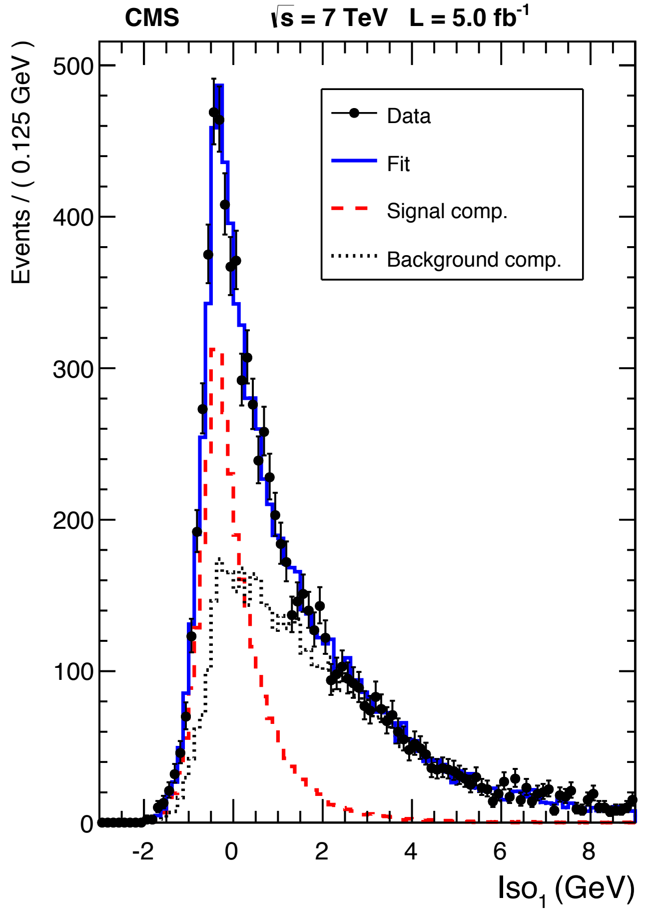

**Large background from diphoton continuum (~70%)** (after photon Id)

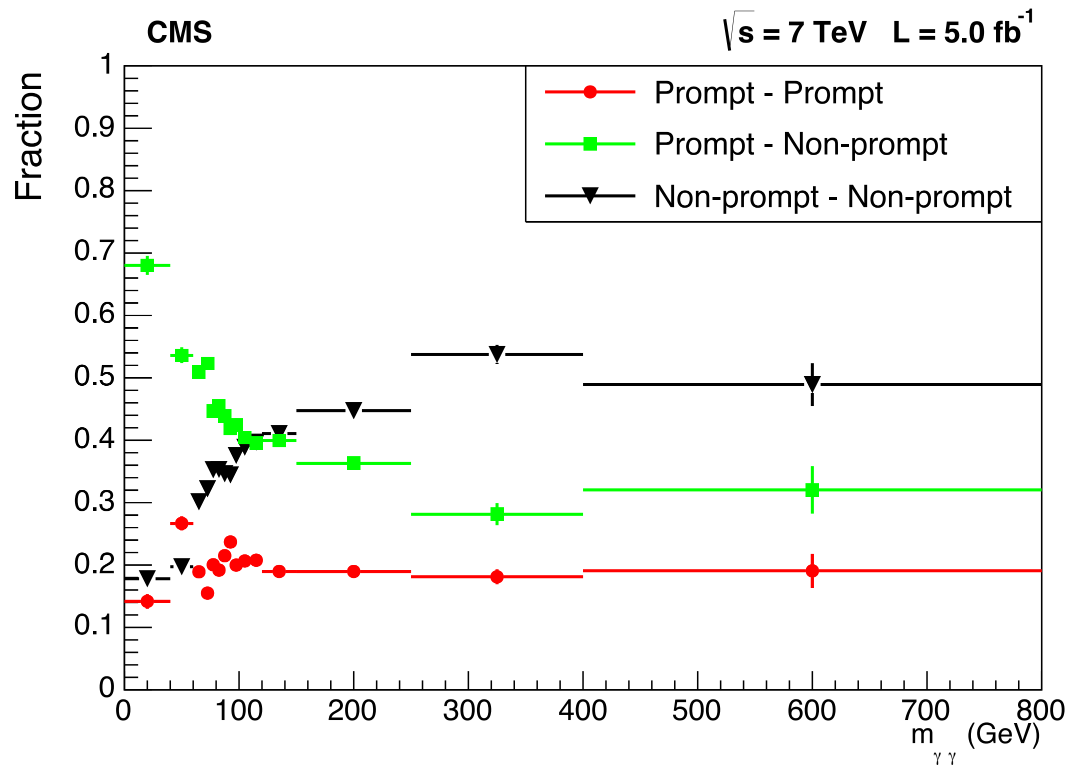


# Diphoton cross-section (7 TeV)

## EPJC 74 (2014) 3129

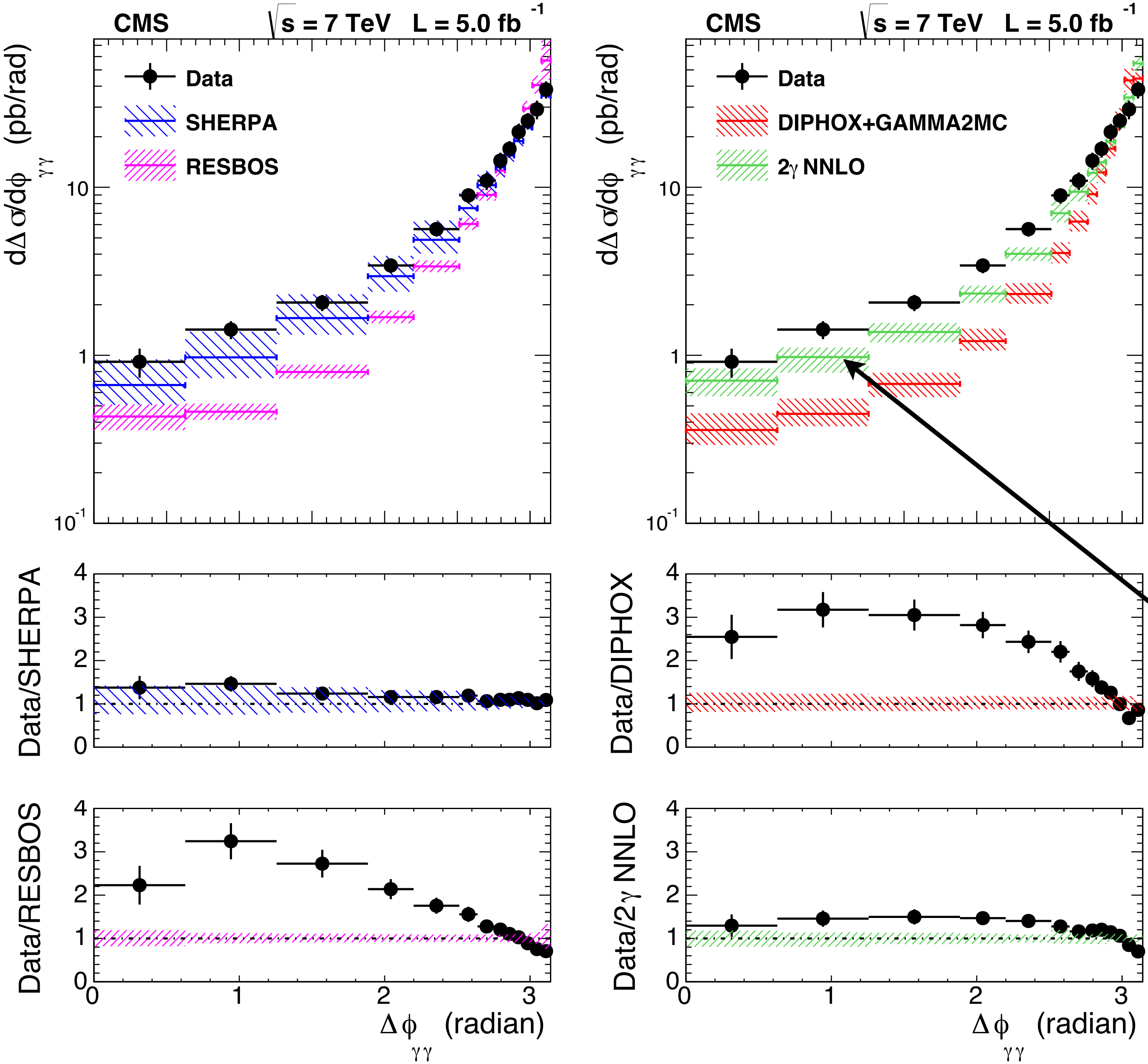
- **Kinematical range:** $|\eta_\gamma|<2.5$, $E_{T,\gamma1}>40$, $E_{T,\gamma2}>25$ GeV, $\Delta R(\gamma_1,\gamma_2)>0.45$
- **Differential cross-section** measured as a function of $M_{\gamma\gamma}$, $P_{T,\gamma\gamma}$, $\Delta\Phi(\gamma_1,\gamma_2)$, $\cos(\theta^*)$
- **Background**: boosted neutral mesons ($\pi^0\rightarrow\gamma\gamma$) reconstructed as a single $\gamma$ (fake)
- **Method**: particle-flow photon isolation template to subtract statistically the background
- Purely data-driven: ~10% systematic uncertainties



# Diphoton cross-section (7 TeV)

## EPJC 74 (2014) 3129




- **NNLO** predictions improve a lot the data/MC agreement

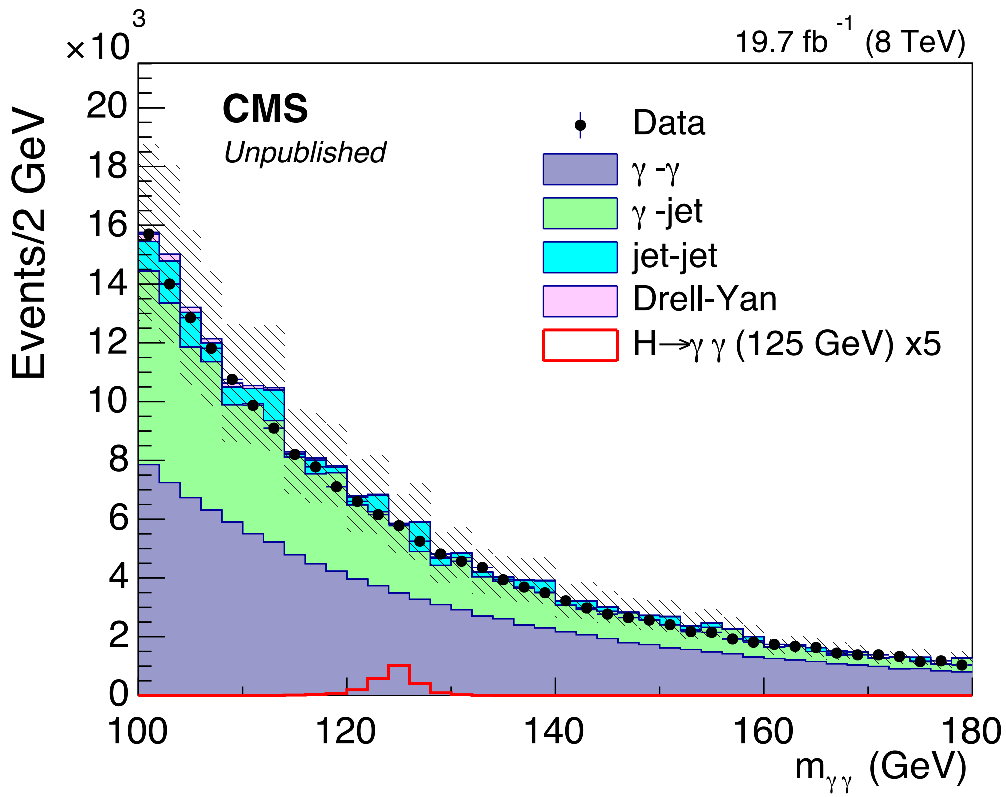
- **Sherpa** (up to 3 ME extra-jets) shows also a good agreement

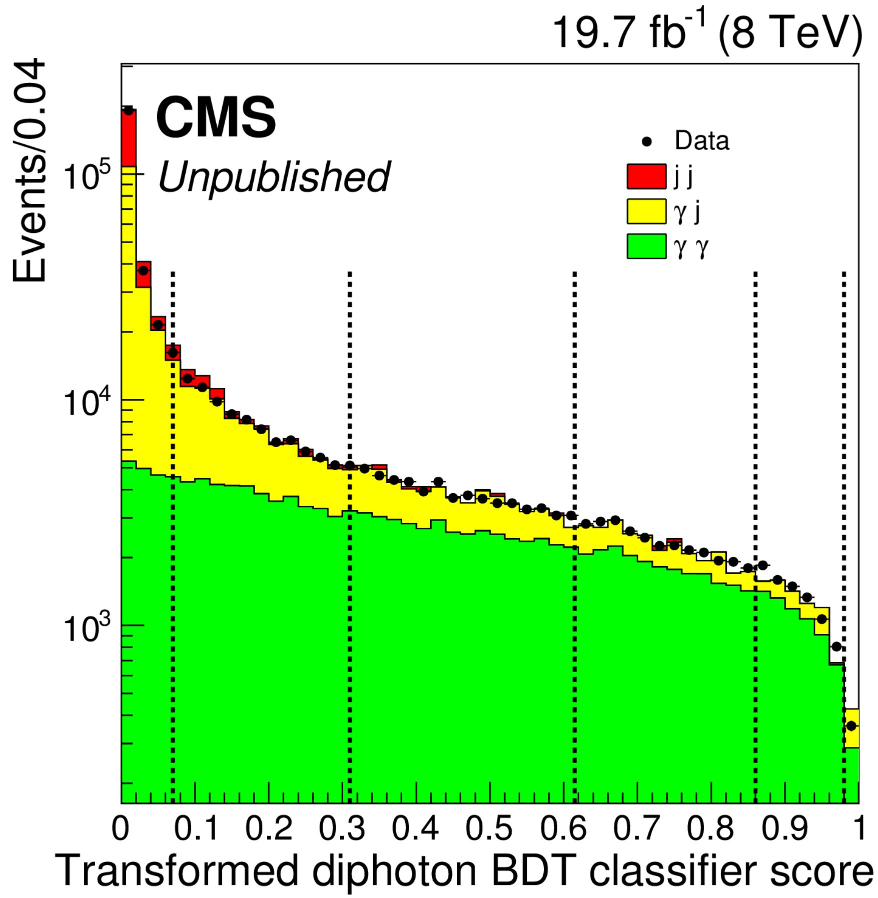
- Still an **excess in data at low ΔΦ** (sensitive to missing higher order QCD effects)

# Backgrounds in H→γγ

## EPJC 74 (2014) 3076

- Excellent agreement of diphoton sherpa with data also in H→γγ searches
- Gamma+jet and dijet with Pythia and k-factor estimated from XS measurements
- Models adequately difficult observables like diphoton mass and diphoton BDT output
- But MC is not used to evaluate the background, only to train the BDTs



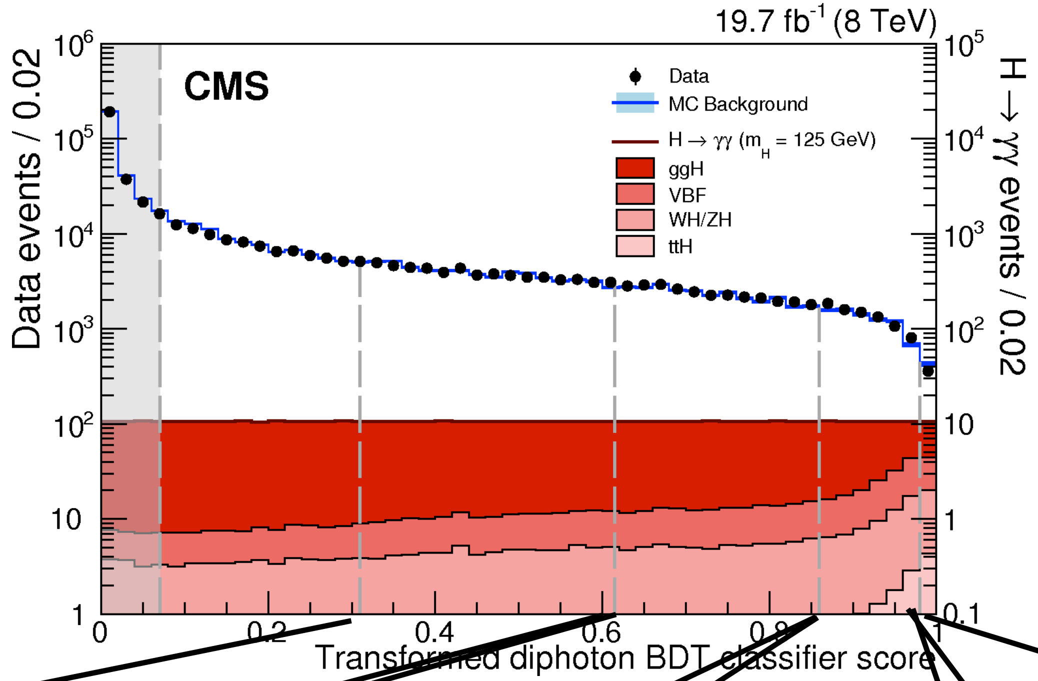



# H→γγ: categories

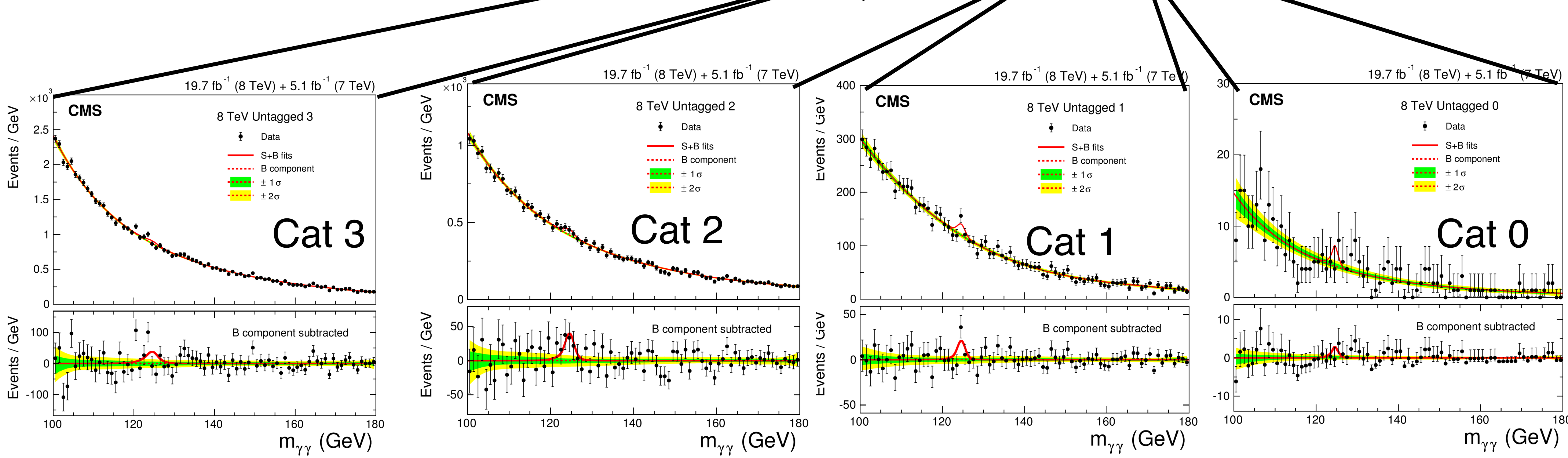
## EPJC 74 (2014) 3076

**Diphoton BDT**

- Mass independant
- Kinematics, vertexing, PhotonId output, energy resolution variables




**Sensitivity from mass fit**. Bkgd: Bernstein polynomial (bias <20% stat uncertainty)



# H→γγ: VBF categories

## EPJC 74 (2014) 3076

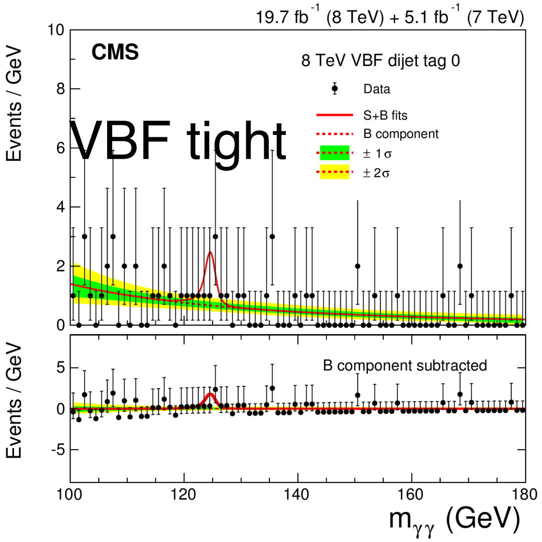
**VBF tags:**

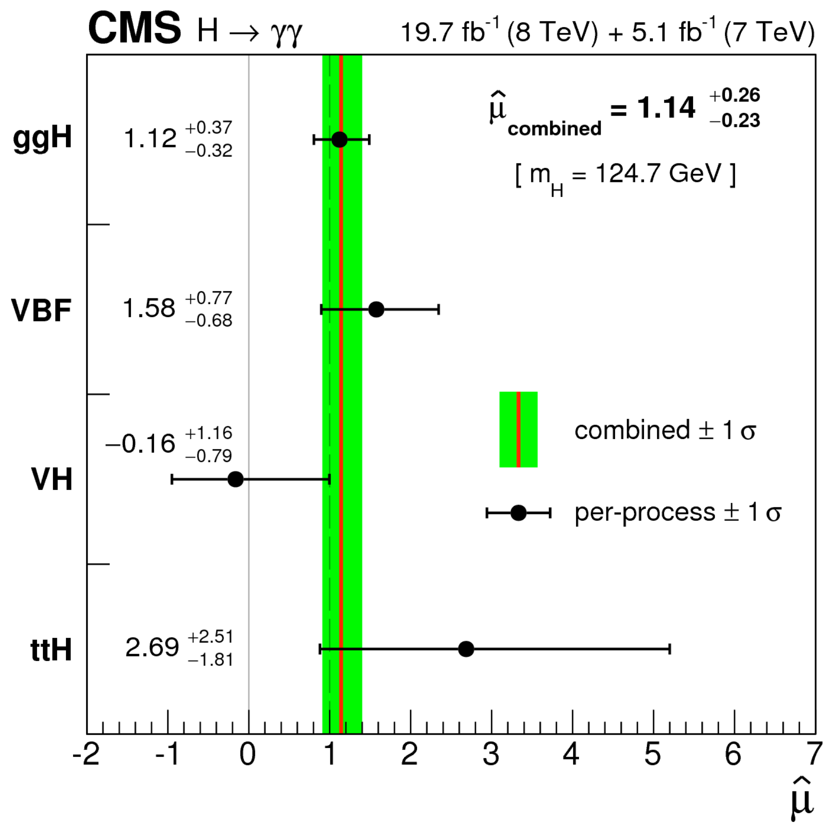
- VBF is higher γγ $p_T$, two forward jets
- **Dijet BDT** using γγ, jets kinematics
- Define two categories: s/b~0.5 and s/b~0.2

**Gluon-gluon fusion contamination** in VBF categories ~20-50%

**Uncertainty:**

- Stewart-Tackmann procedure: QCD scale uncertainty from $\mathbf{\Delta\sigma = \Delta\sigma_1 \oplus \Delta\sigma_2}$



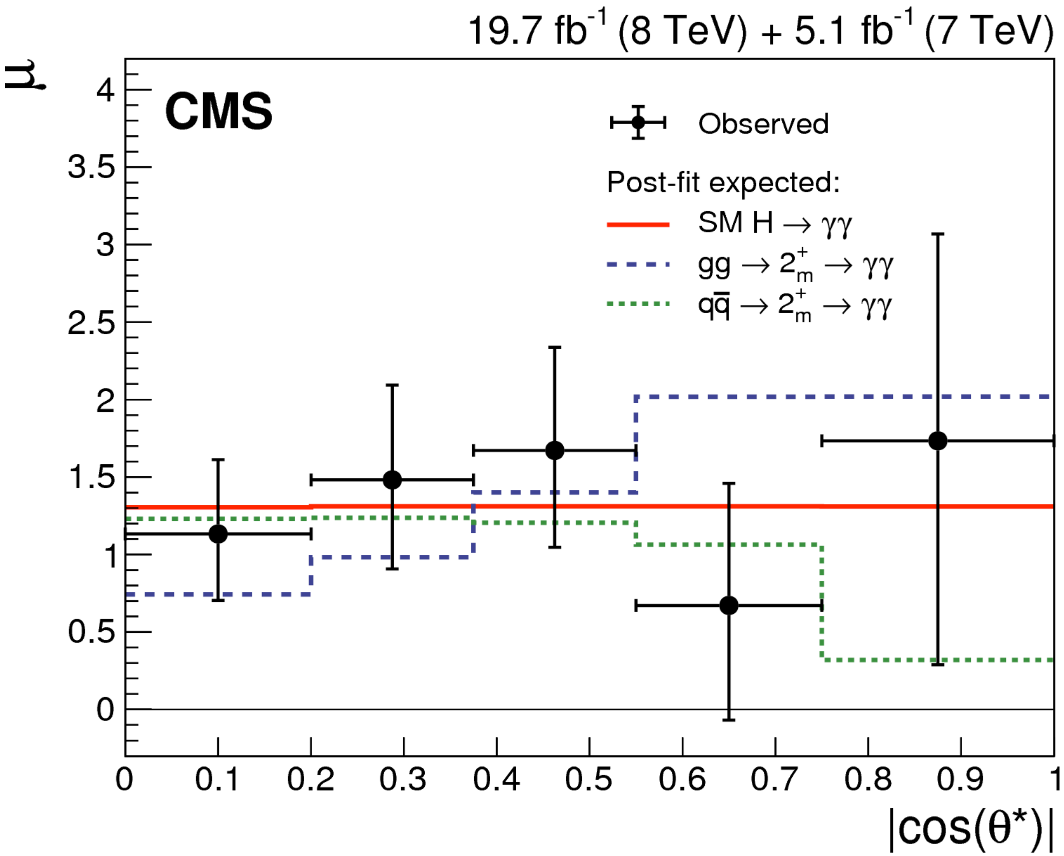

**Categories:**

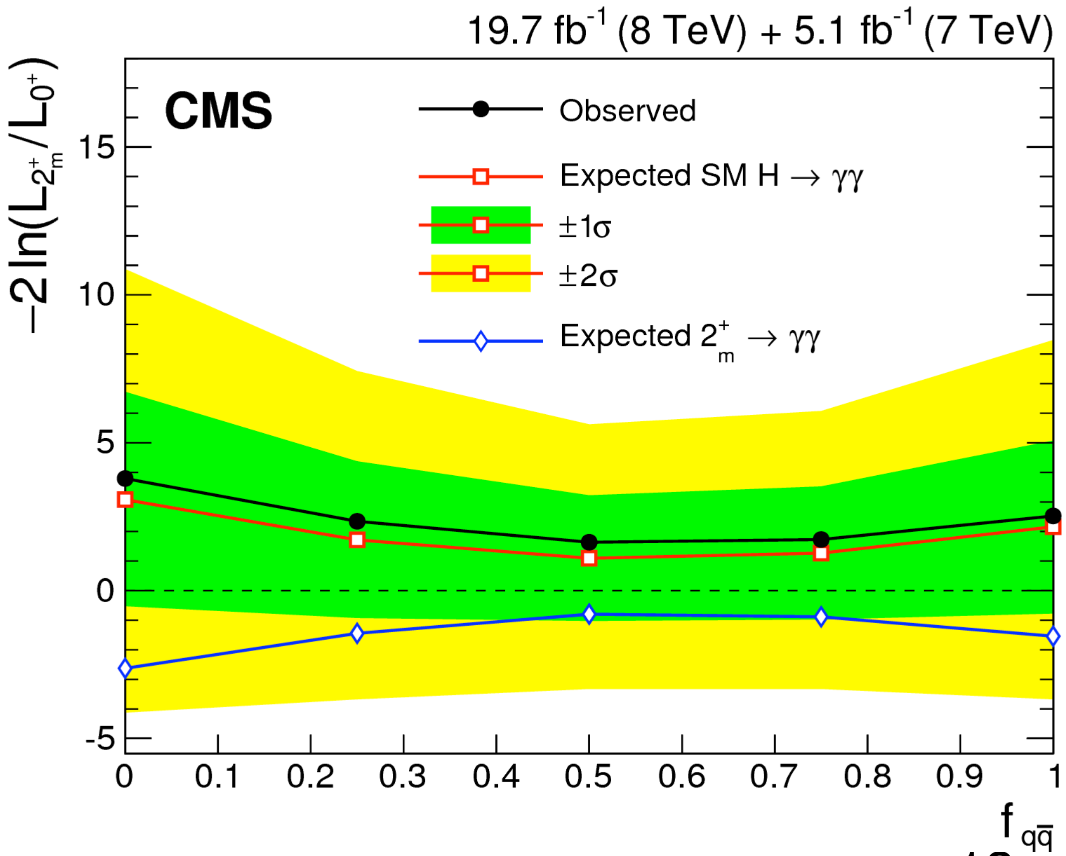
- Defined with s/b and resolution level
- 5 **untagged**, 3 **VBF categories,** 3 VH cat, 2 ttH

# Spin measurement with H→γγ

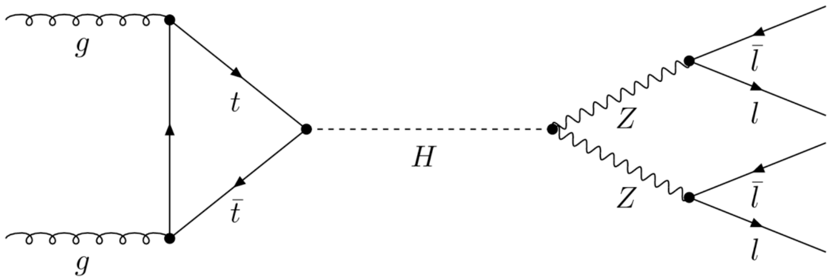
**EPJC 74 (2014) 3076**

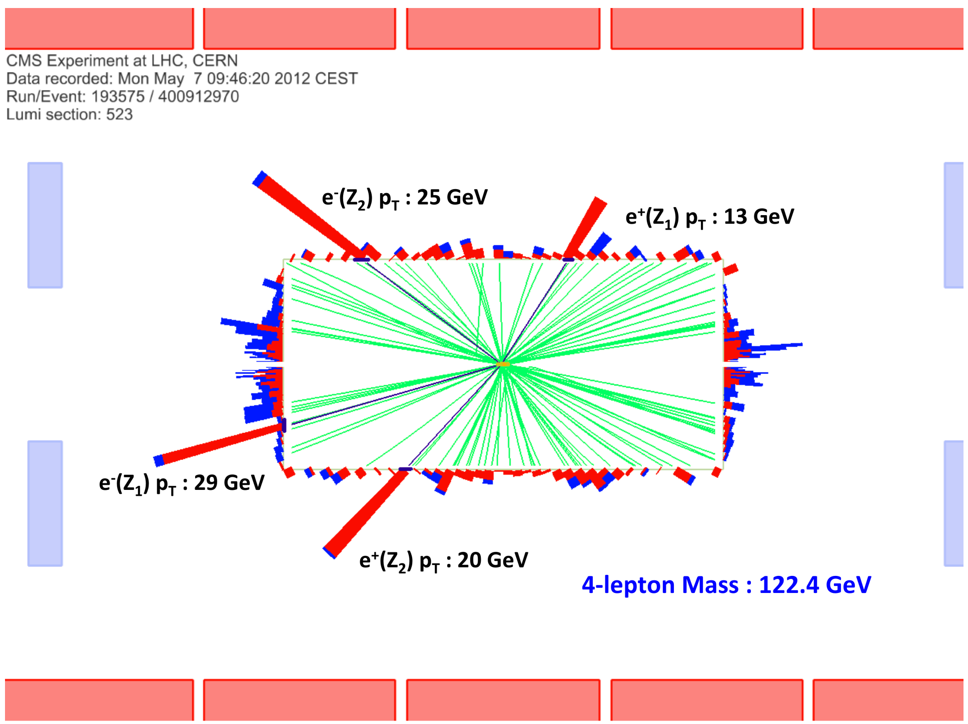
- Cut-based analysis to minimize model-dependence
- Measurement of signal yield in bins of **cos(θ*): μ differential measurement**
- **No unfolding**
- Testing minimal graviton couplings, spin **2+** gluon fusion or qqbar initiated

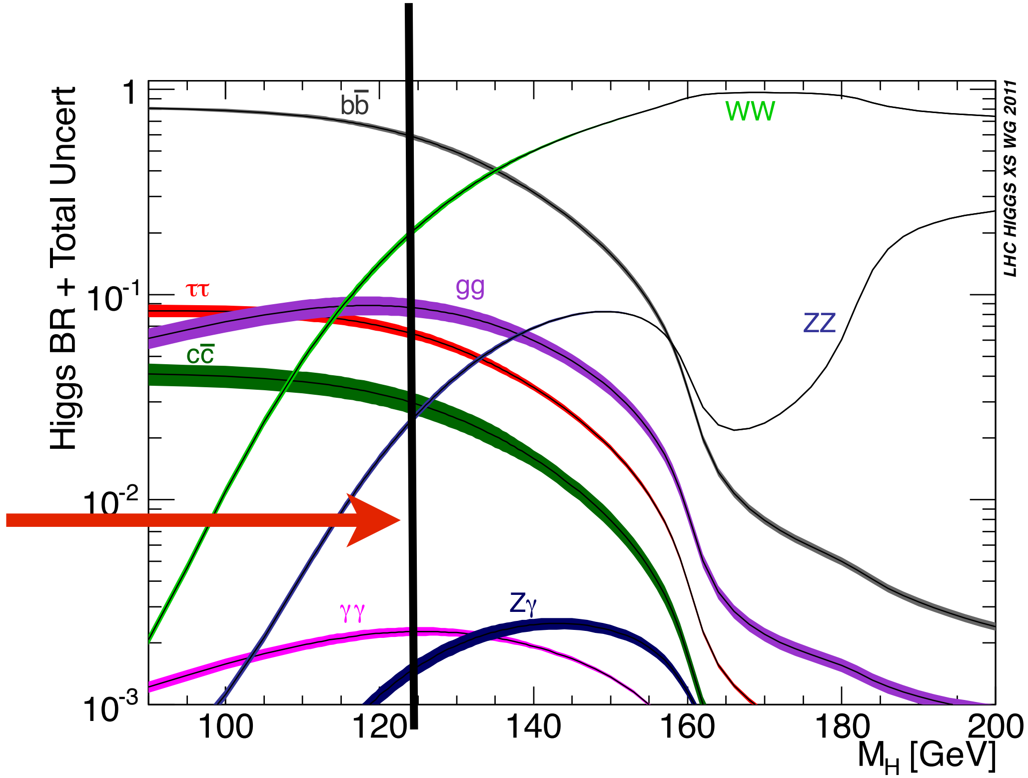


# $H \rightarrow ZZ \rightarrow 4l$

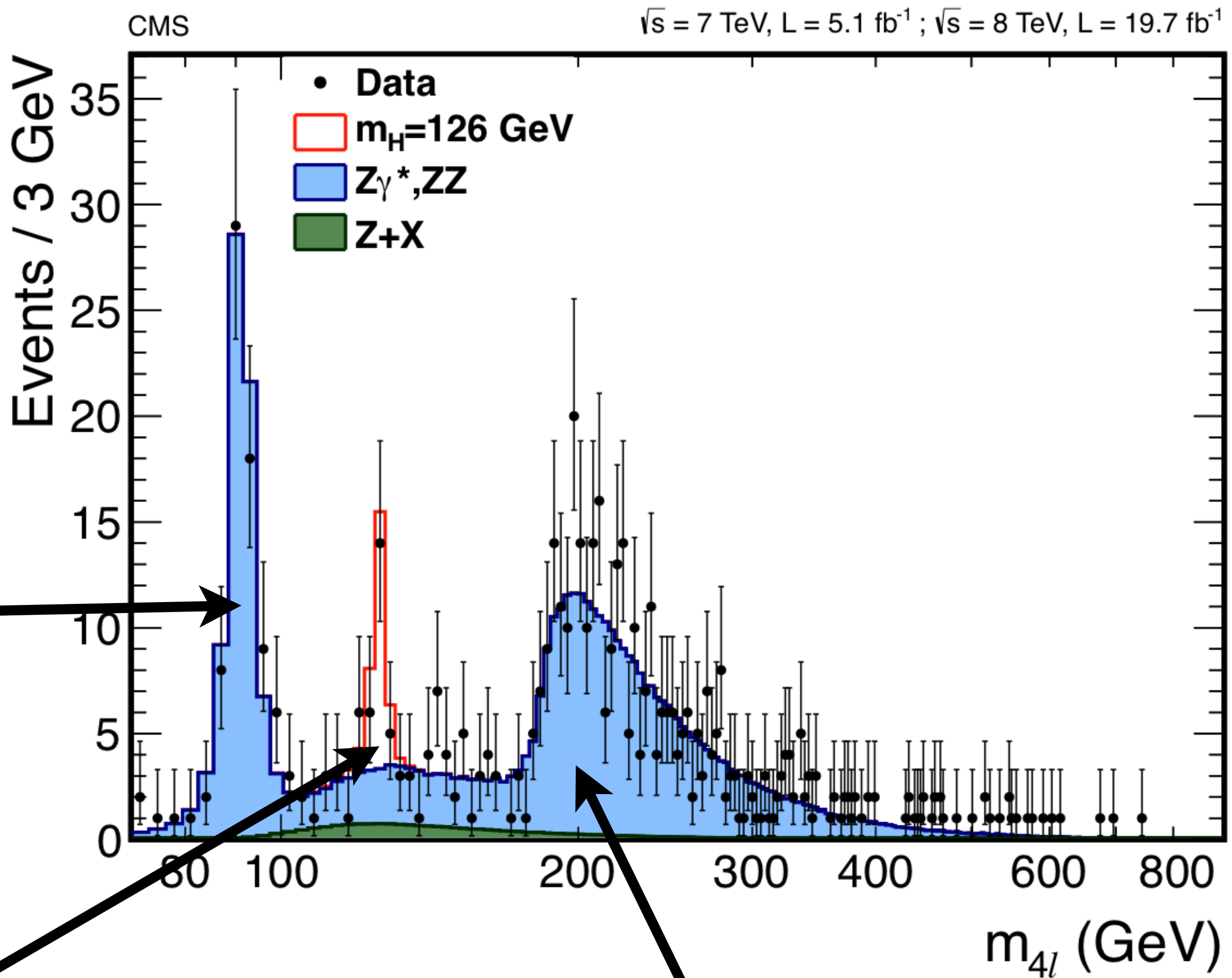


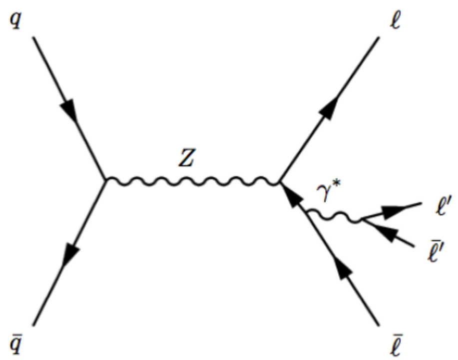



# ZZ→4l and H→ZZ$^{(*)}$→4l

**Signature:**
2 pair of opposite sign isolated leptons (4e, 2e2μ, 4μ) consistent with the same vertex




**Z→4l:**
- XS x BR measurement




**H→ZZ*→4l:**
- **Very good s/b~2**
- **3D analysis**

- **ZZ→4l**: onshell Z's
- differential cross-section
- aTGC

# ZZ→4l cross-section

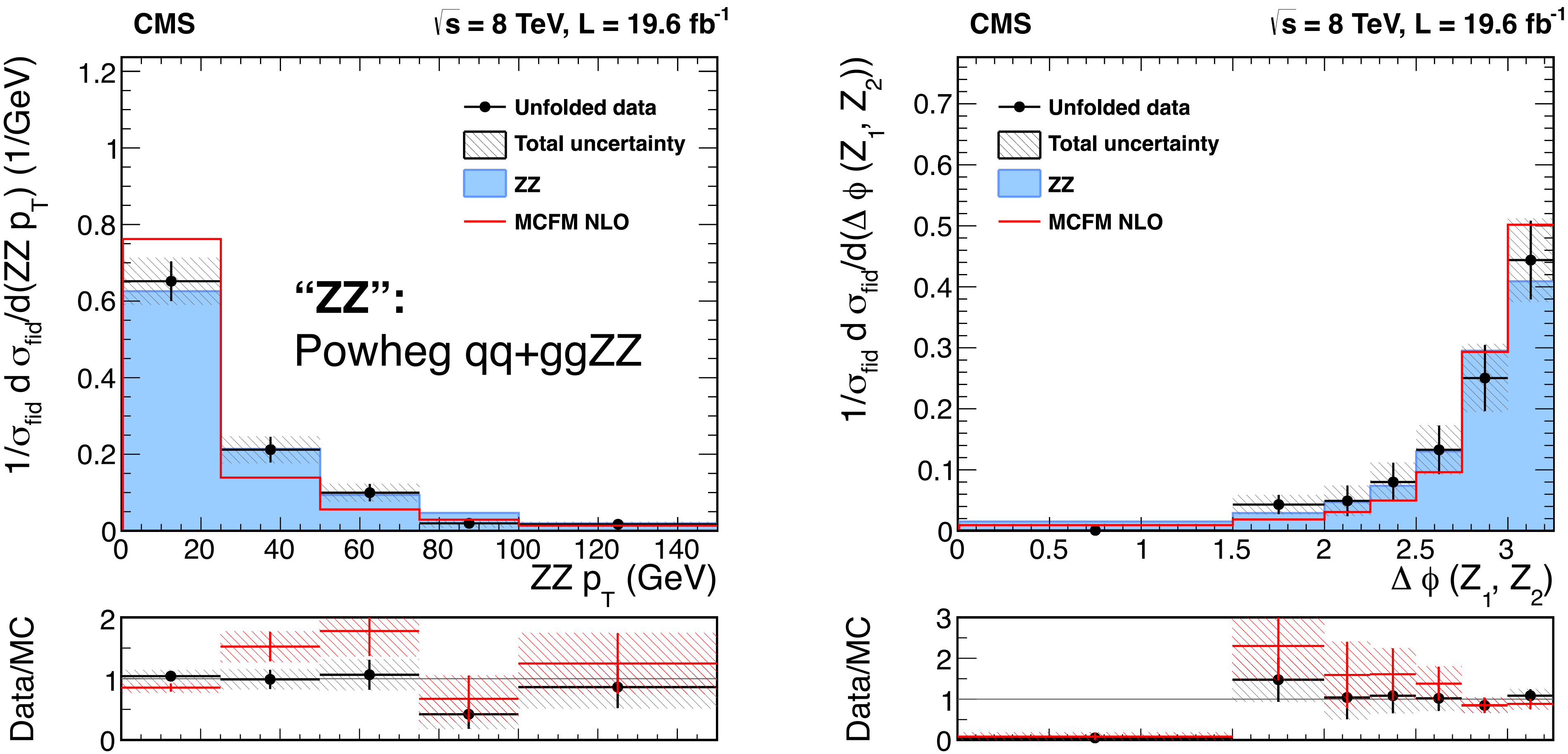
## arxiv:1406.0113 (accepted by PLB)

- Background subtraction: Z+jets (estimated with inverted isolation), ttbar
- **Inclusive** and **differential cross-sections**

$$\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 7.7 \pm 0.5\,(\mathrm{stat.})\,^{+0.5}_{-0.4}\,(\mathrm{syst.}) \pm 0.4\,(\mathrm{th.}) \pm 0.2\,(\mathrm{lum.})\,\mathrm{pb}$$

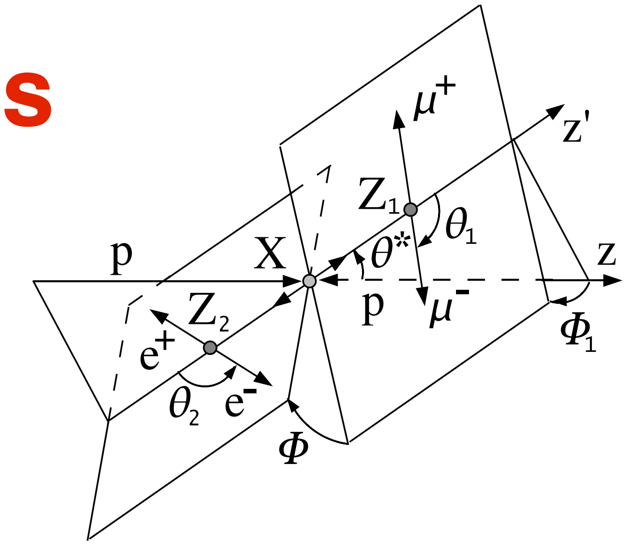
- New **NNLO** total cross-section [hep-ph:1405.2219]

| $\sigma_{NLO}$ (pb) | $\sigma_{NNLO}$ (pb) |
|---|---|
| $7.369^{+2.8\%}_{-2.3\%}$ | $8.284^{+3.0\%}_{-2.3\%}$ |



# H→ZZ$^{(*)}$→4l analysis

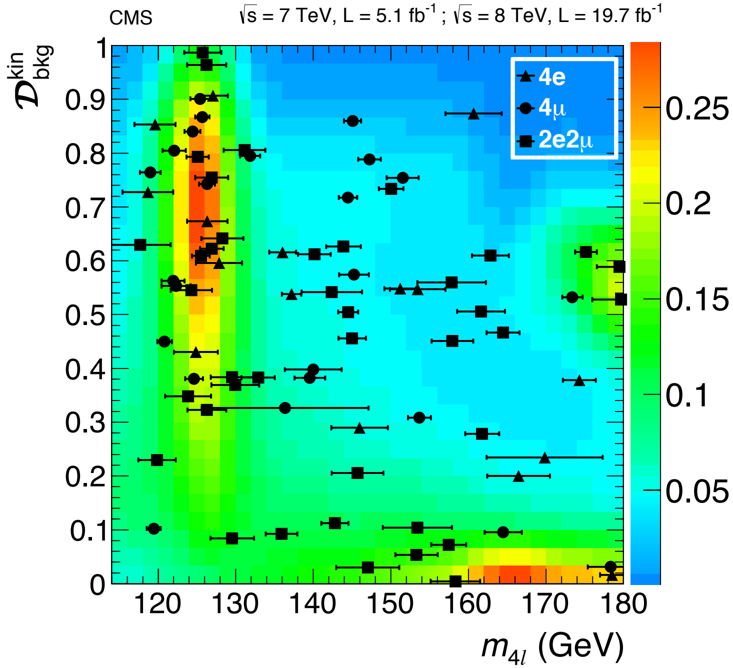
## PRD 89 (2014) 092007



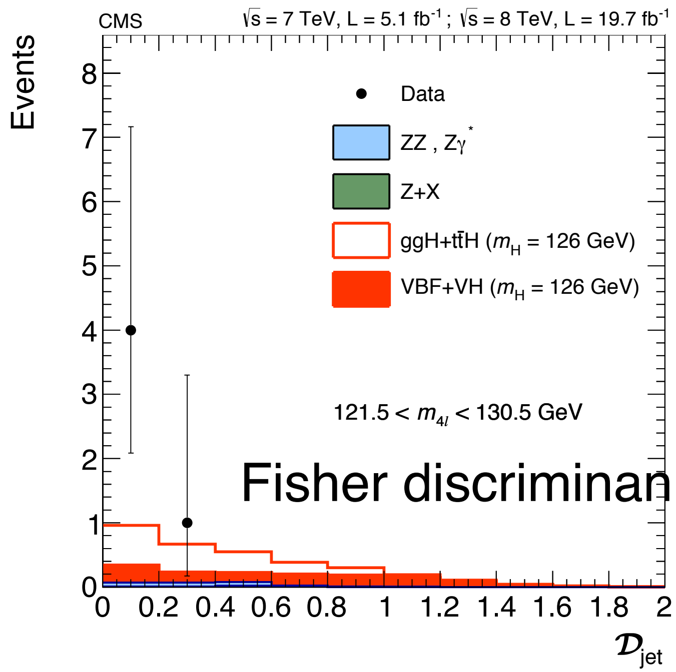

- **3D analysis** in Mass, KD, and pT(H) (**untagged**), and Mass, KD, Fischer discriminant (**dijet tag**)

**- 0,1jet Kinematic discriminant (KD):** Matrix element method using invariant mass of Z1 and Z2 and 5 angular variables.

**KD in Signal MC**

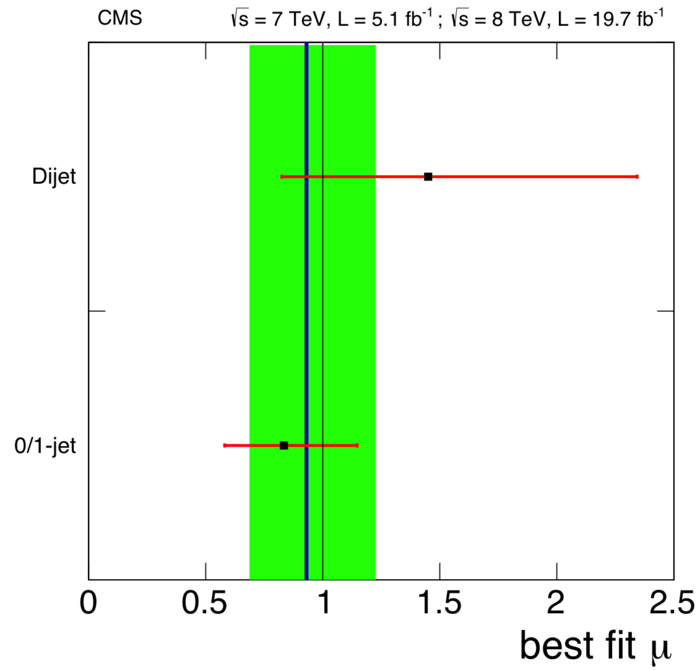



**2-jets:** Fischer discriminant with jet information




- Sizeable guon fusion contamination in 2jet bin

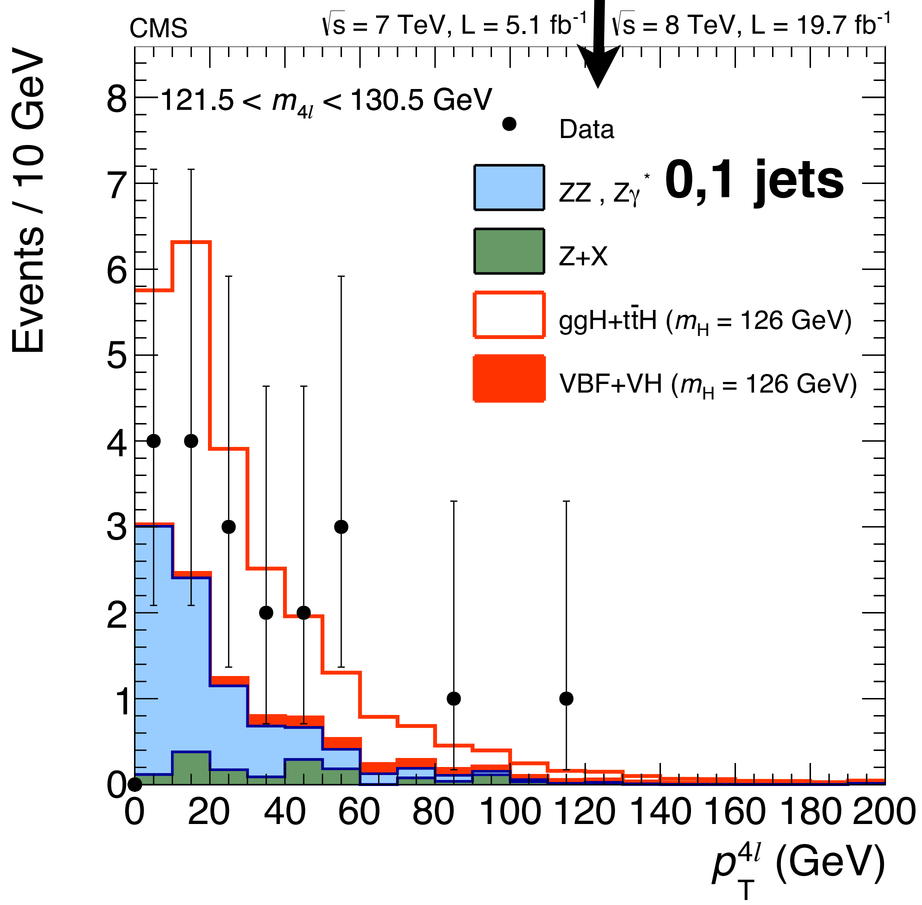
**Results:**



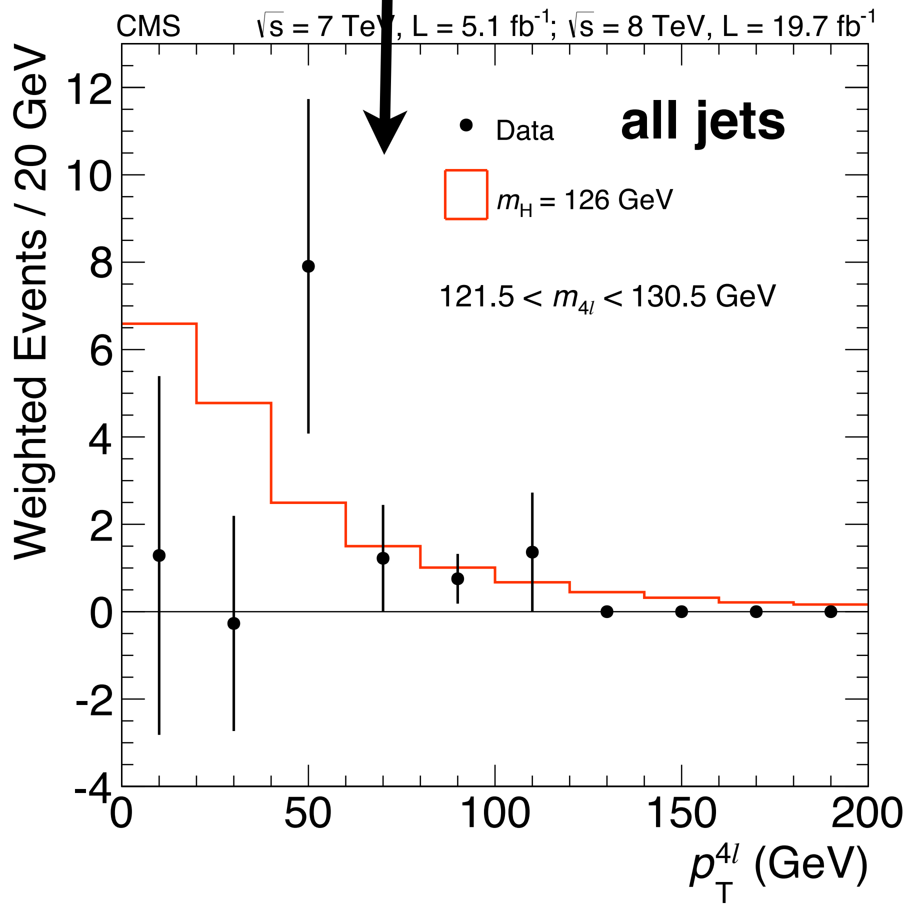
# H→ZZ(*)→4l: Higgs pT

**PRD 89 (2014) 092007**

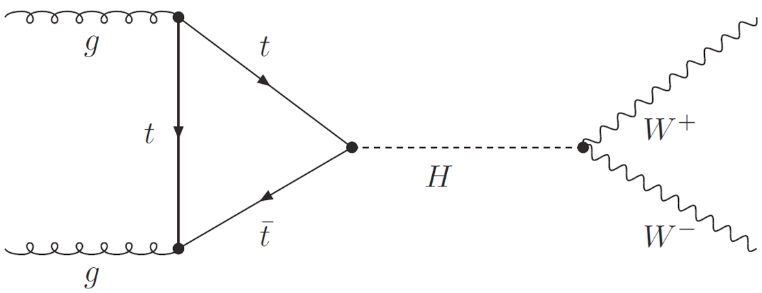
- **4l pT** without background subtraction, in Higgs mass window:



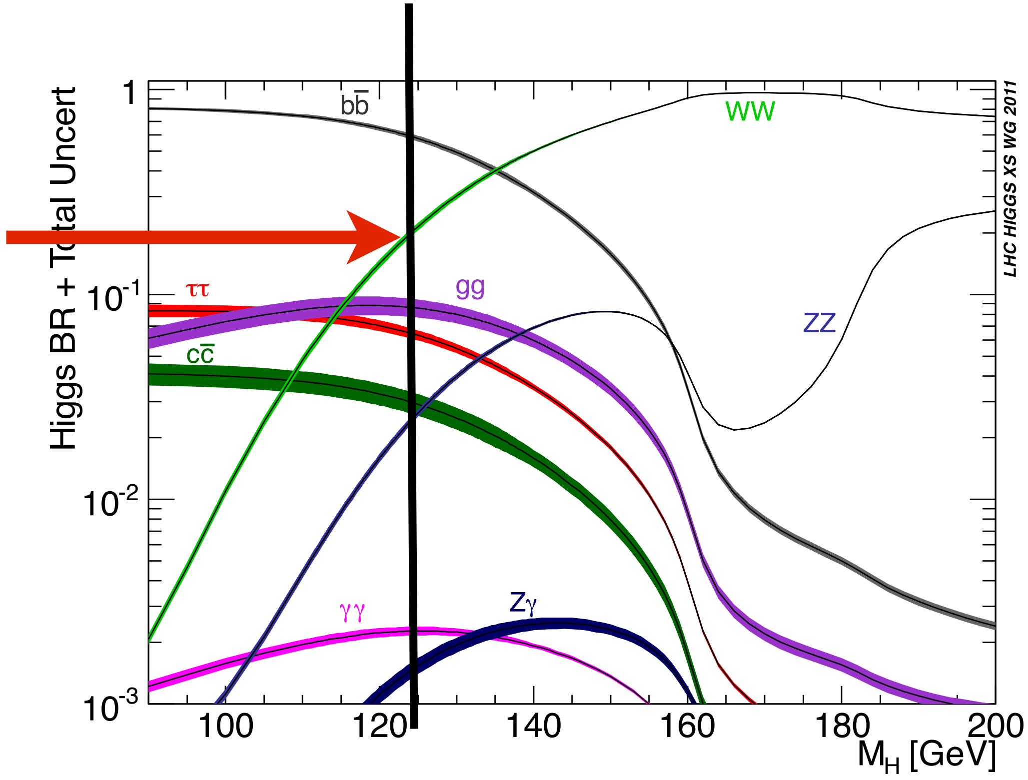

- **Higgs pT** measured using s-plot method, using m4l only for background weights estimation



# H→WW



g
t
t
$\bar{t}$
g
H
$W^+$
$W^-$

Higgs BR + Total Uncert
LHC HIGGS XS WG 2011
$b\bar{b}$
WW
ττ
gg
ZZ
$c\bar{c}$
γγ
Zγ
1
$10^{-1}$
$10^{-2}$
$10^{-3}$
100
120
140
160
180
200
$M_H$ [GeV]

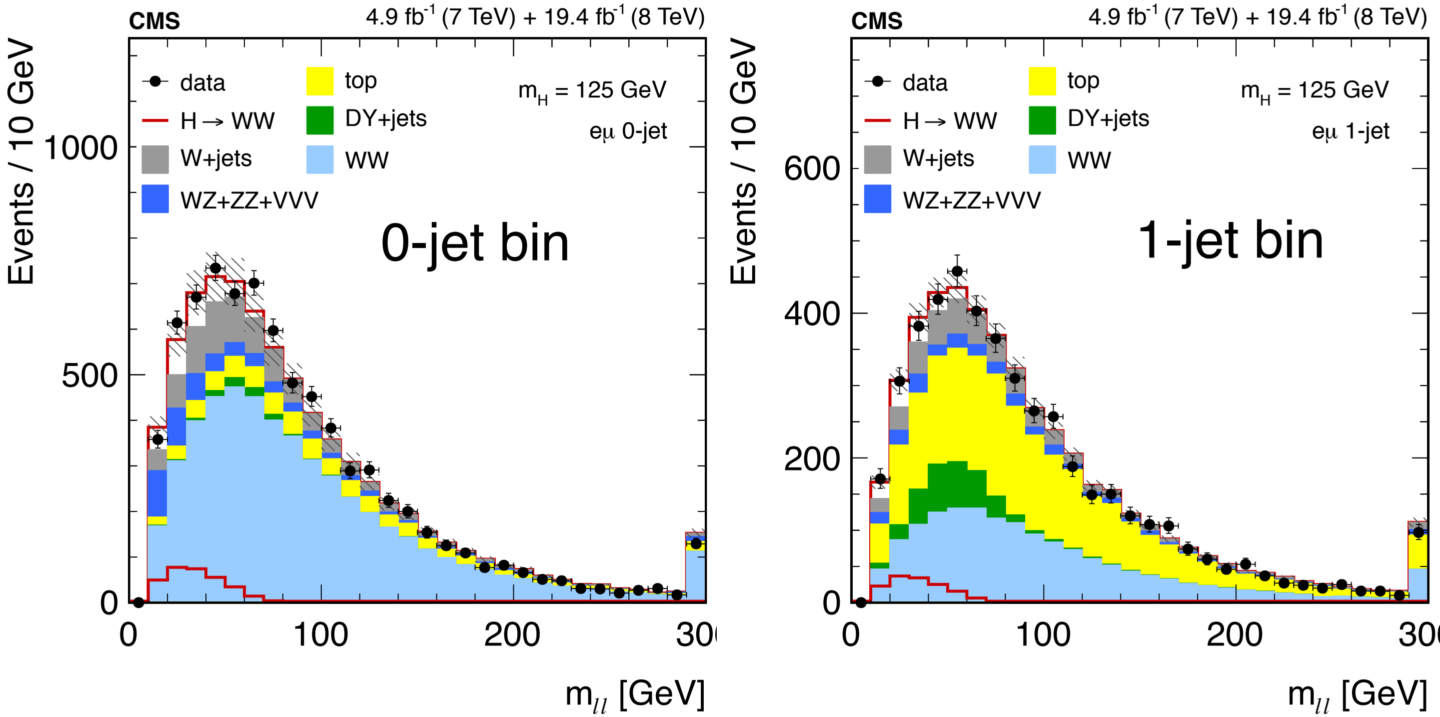
# H→W+W- analysis

## JHEP 01 (2014) 096

**H→WW→2l2v analysis:** High BR, but no mass peak (resolution is ~20%)

- Two isolated leptons with pT>20,10 GeV and mET>20 GeV
- CategorIES: **0-jet, 1-jet, 2-jet bins**, then **ee,μμ,eμ** with opposite charge
- Main backgrounds: WW, top (1,2jet bins), W+jets (estimated from control regions in data)

**2D analysis** in **($m_T$, $m_{ll}$)** for the opposite flavor 0-jet and 1-jet bins (cross-check with a 2nd 2D analysis)




| $q\bar{q} \to WW$ generator | 95% CL limits on $\sigma/\sigma_{SM}$ expected / observed | Significance expected / observed | $\sigma/\sigma_{SM}$ observed |
|---|---|---|---|
| MADGRAPH (default) | 0.4 / 1.2 | 5.2 / 4.0 sd | $0.76 \pm 0.21$ |
| MC@NLO | 0.4 / 1.2 | 5.3 / 4.2 sd | $0.82 \pm 0.24$ |
| POWHEG | 0.4 / 1.2 | 5.1 / 3.9 sd | $0.74 \pm 0.21$ |

qq→WW background modeling is crucial !

# WW cross-section

## EPJC 73 (2013) 2610

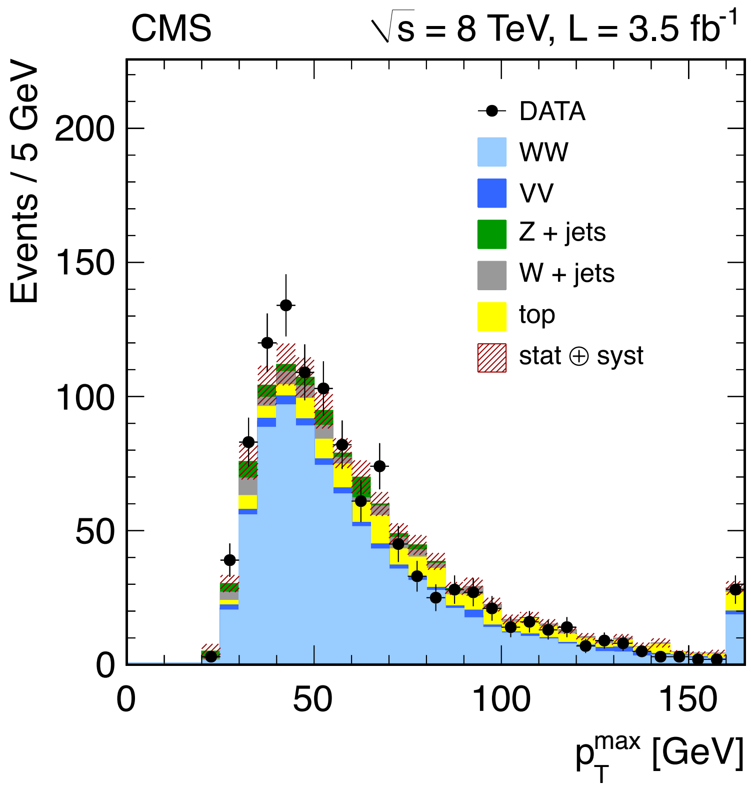
**Inclusive WW cross-section**

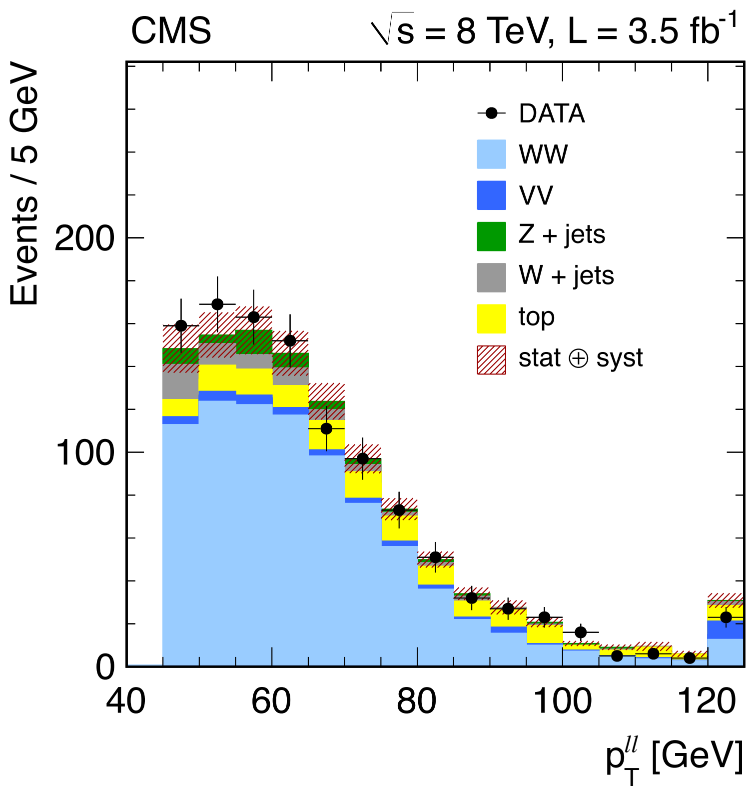
- Fakes from inverted isolation
- Measurement performed in **0-jet bin** (so far)
- Jet veto QCD scale uncertainty 4.6%
- Unfolding to inclusive cross-section

$$69.9 \pm 2.8\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 3.1\,(\text{lum.})\ \text{pb}$$

- New **NNLO** cross-section is available [hep-ph:1408.5243], in better agreement with data

| $\sigma_{NLO}$ | $\sigma_{NNLO}$ |
|---|---|
| $54.77^{+3.7\%}_{-2.9\%}$ | $59.84^{+2.2\%}_{-1.9\%}$ |




For the future: moving to differential measurement

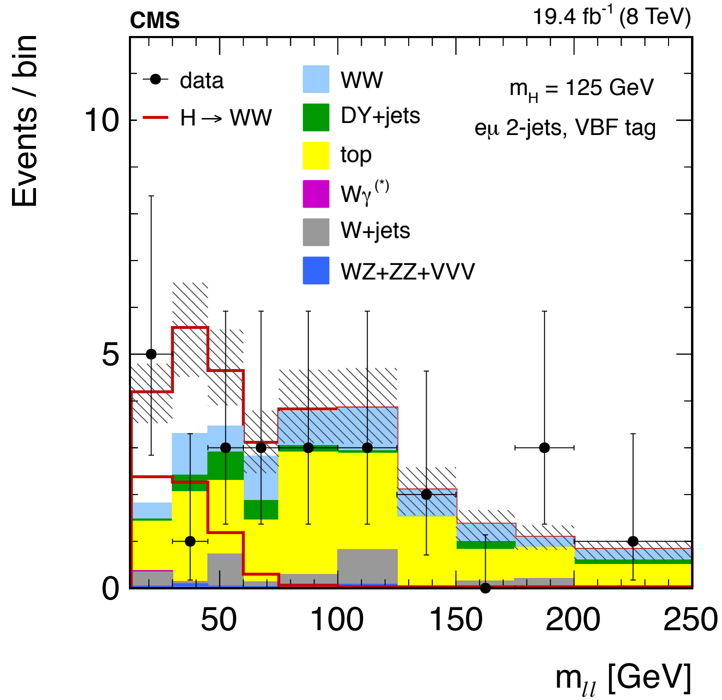
# H→W⁺W⁻ dijet and results

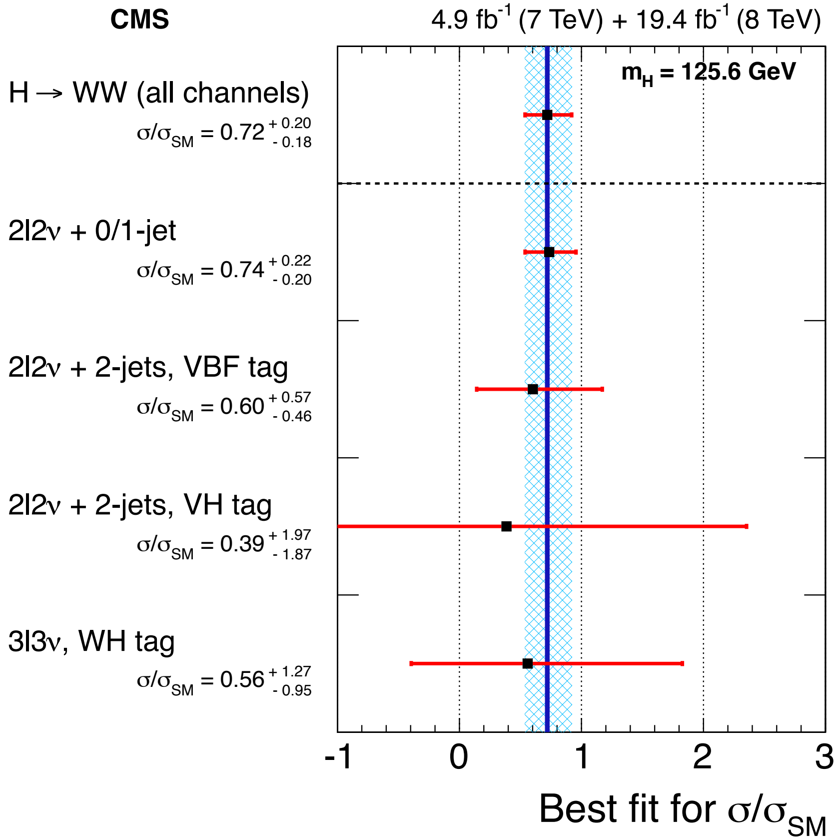
## JHEP 01 (2014) 096

VBF tag

$|\Delta\eta_{jj}| > 3.5$

$m_{jj} > 500\,\mathrm{GeV}$



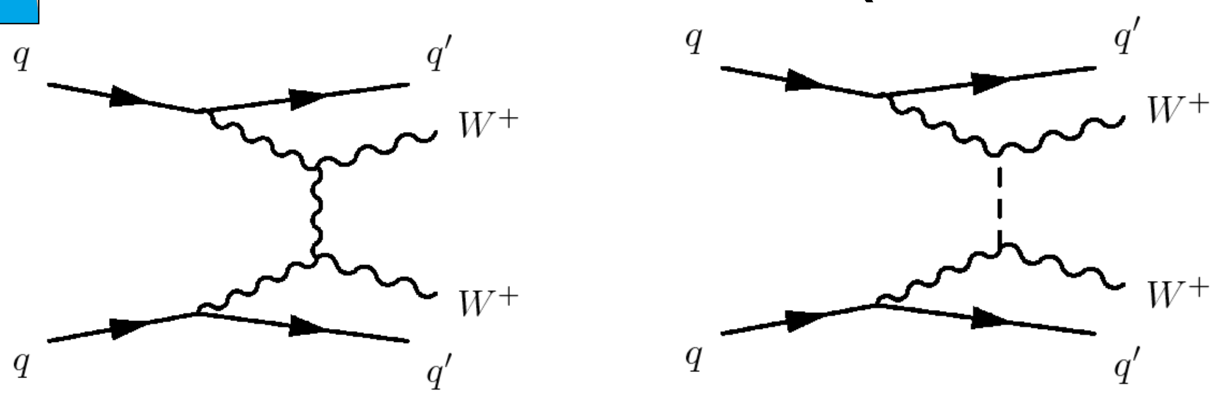

- **2jets: VBF-tag and VH tag** use a fit to mll distribution
- Stewart-Tackmann procedure used for gluon fusion uncertainty

- Trilepton final state also used: WH→3l3ν, ZH→3lν+2jets

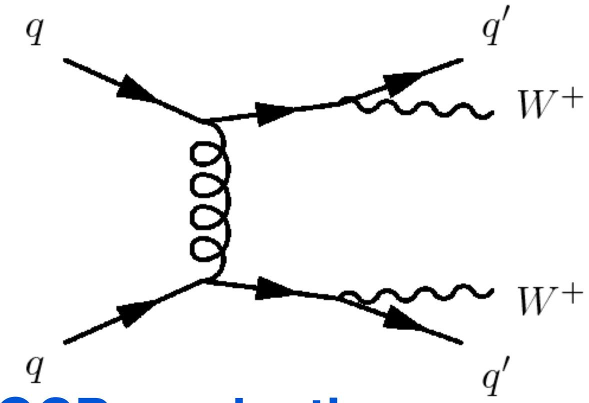
- **Best fit** signal strength **$\mu=0.72^{+0.20}_{-0.18}$ at 125.6 GeV**
- **Local significance: expected 5.8σ, observed 4.3σ**

# Same sign WW scattering

## arxiv:1410.6315 (submitted to PRL)




**Electroweak production**

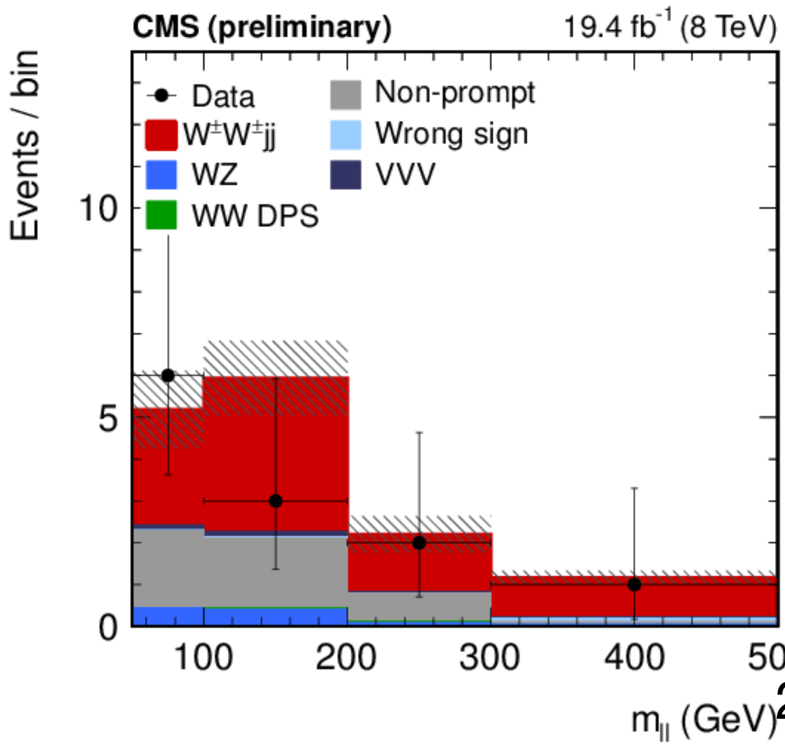



**QCD production**

Electroweak WW production can help us understanding how Higgs is involved in unitarization.

**Signal definition:** EWK+QCD with interference
**Fiducial region:**
**$M_{jj}$>500 GeV** and dijet rapidity difference **$|\Delta\eta_{jj}|$>2.5**

**Backgrounds:**
**- Jets faking electrons (non-prompt):** estimated from loosely isolated leptons
- **WZ:** estimated from data 3 leptons control region



# Same sign WW scattering

**arxiv:1410.6315 (submitted to PRL)**

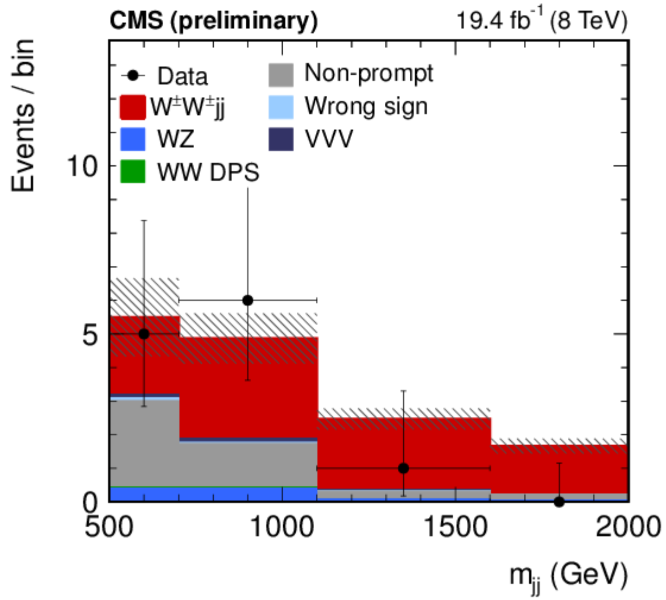
**EWK / QCD contamination:**

- CMS defines signal as EWK+QCD (interference compatible with 0 within scale uncertainty)

**Signal extraction:**

- Use **dijet mass shape** (4 bins x positive and negative signs)
- **Significance**: expected 3.1σ, observed 2.0σ

$4.0^{+2.4}_{-2.0}\,(\mathrm{stat})^{+1.1}_{-1.0}\,(\mathrm{syst})$ fb with an expectation of $5.8 \pm 1.2$ fb.




**Also measure WZjj cross-section:**

$\sigma(\mathrm{WZ}jj) = 10.8 \pm 4.0\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})$ fb with an expectation of $14.4 \pm 4.0$ fb

# Conclusions

- Diboson cross-sections: excess seems reduced by comparing to newly available NNLO cross-sections
- Accurate description of differential distributions needs NNLO differential or multijet ME+PS

- Higgs differential measurement at CMS is ongoing work, stay tuned...

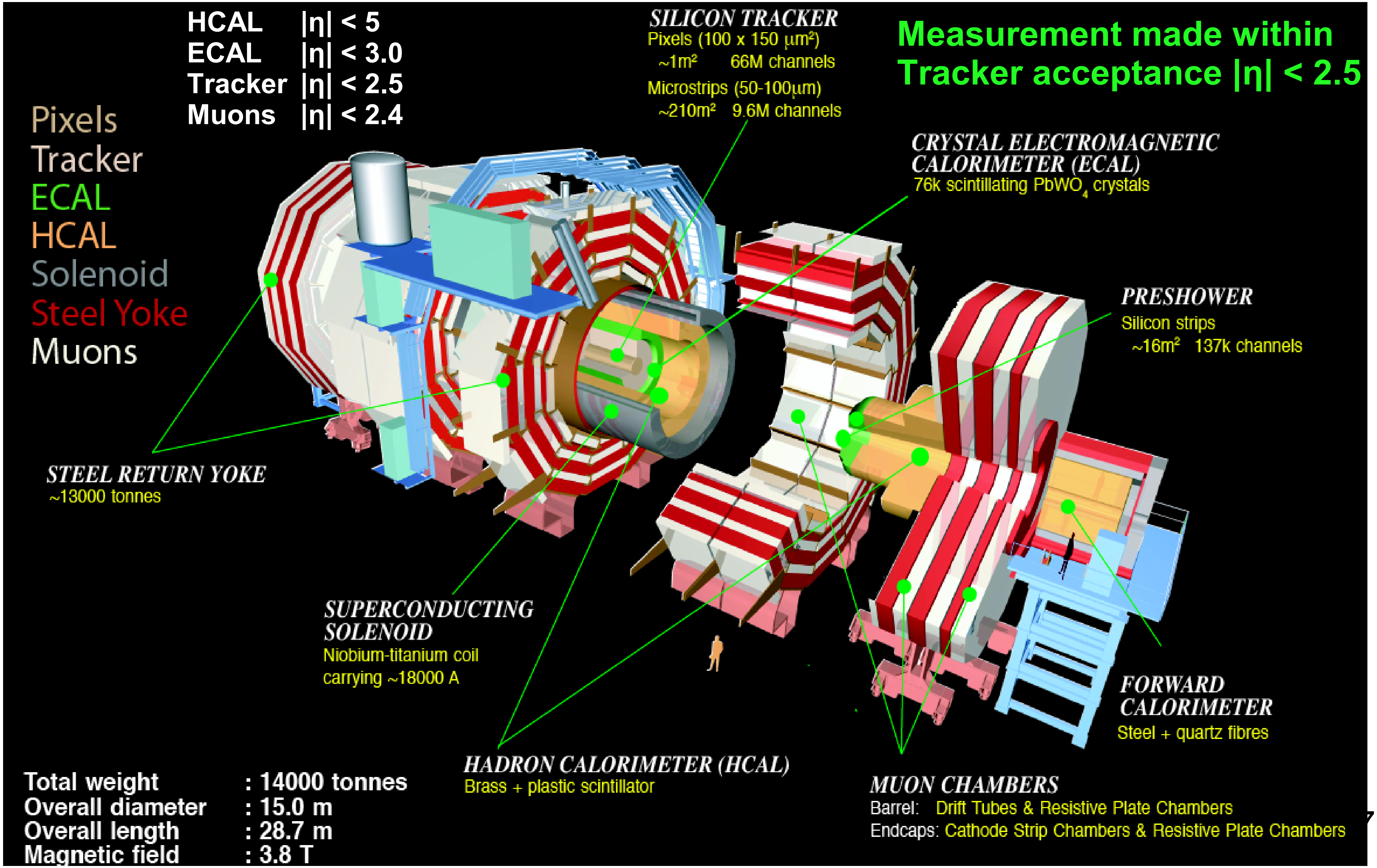
- Higgs measurement rely on adequate MC for gluon fusion contamination in VBF

- WW scattering: first measurements performed. Needs more data for 5σ. Measuring interference with Higgs needs more data.

**Thank you!**

# BACK-UP SLIDES

# CMS detector

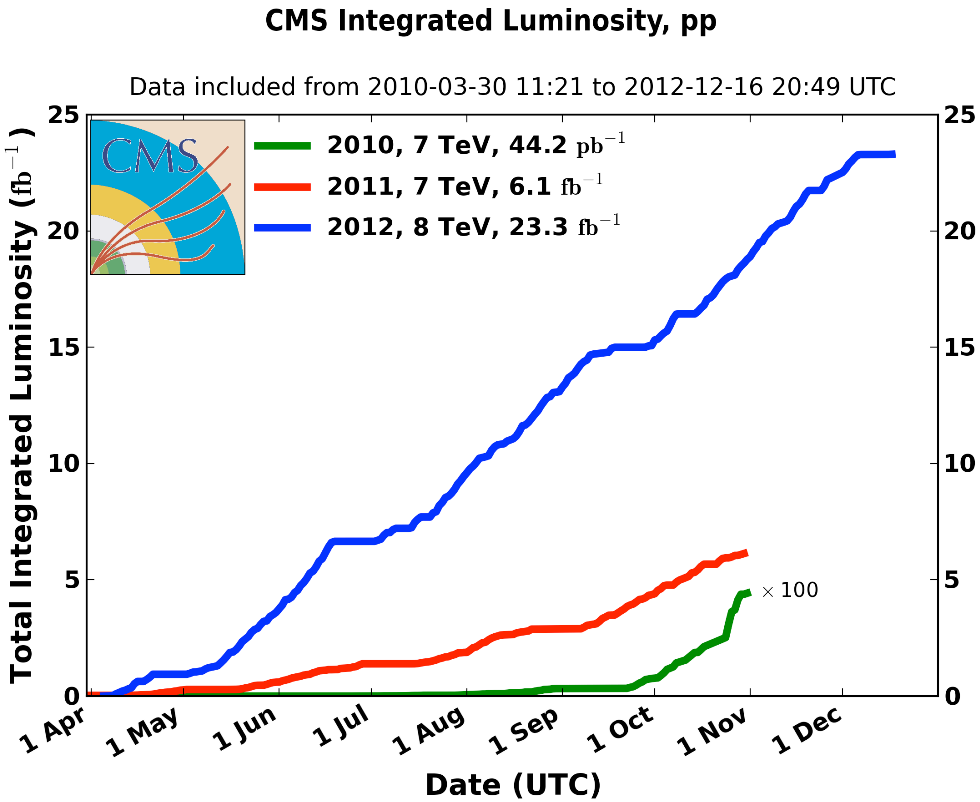


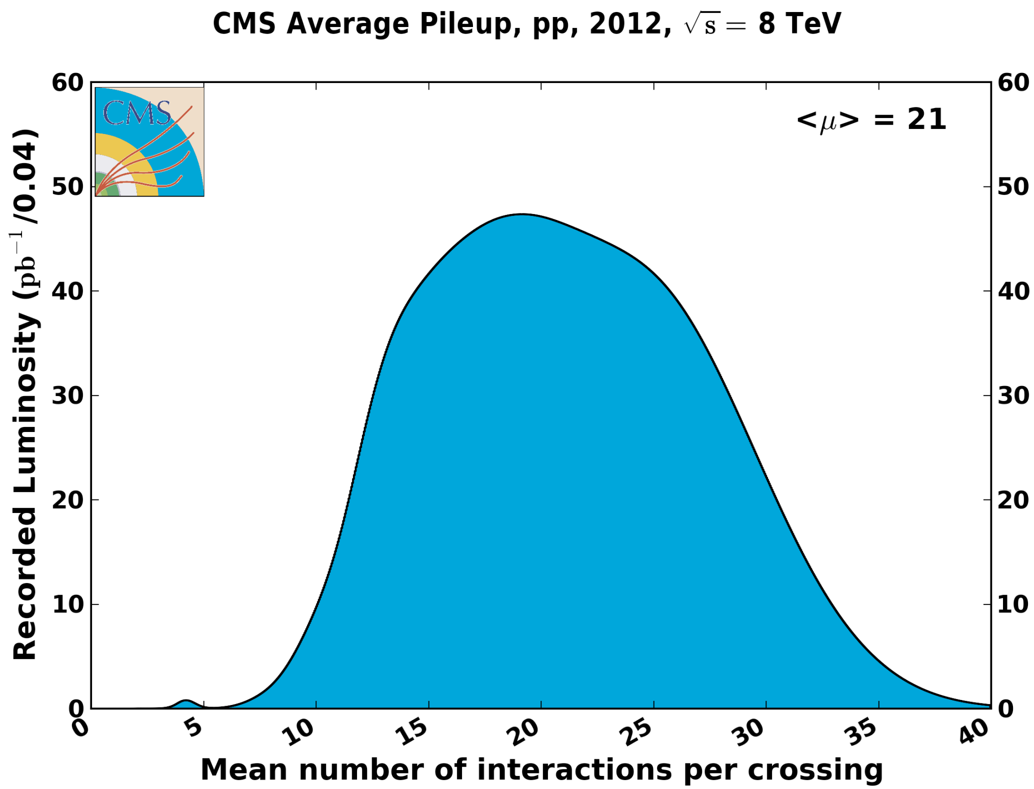
# Luminosity conditions

**Analyses presented in this talk are using:**

- **5.1 fb-1 of 7 TeV data** in 2011
- **Up to 20 fb-1 of 8 TeV data in 2012**

**Pileup mean interaction ~21 in 2012 (~10 in 2011)**



# CMS electromagnetic calorimeter(ECAL)

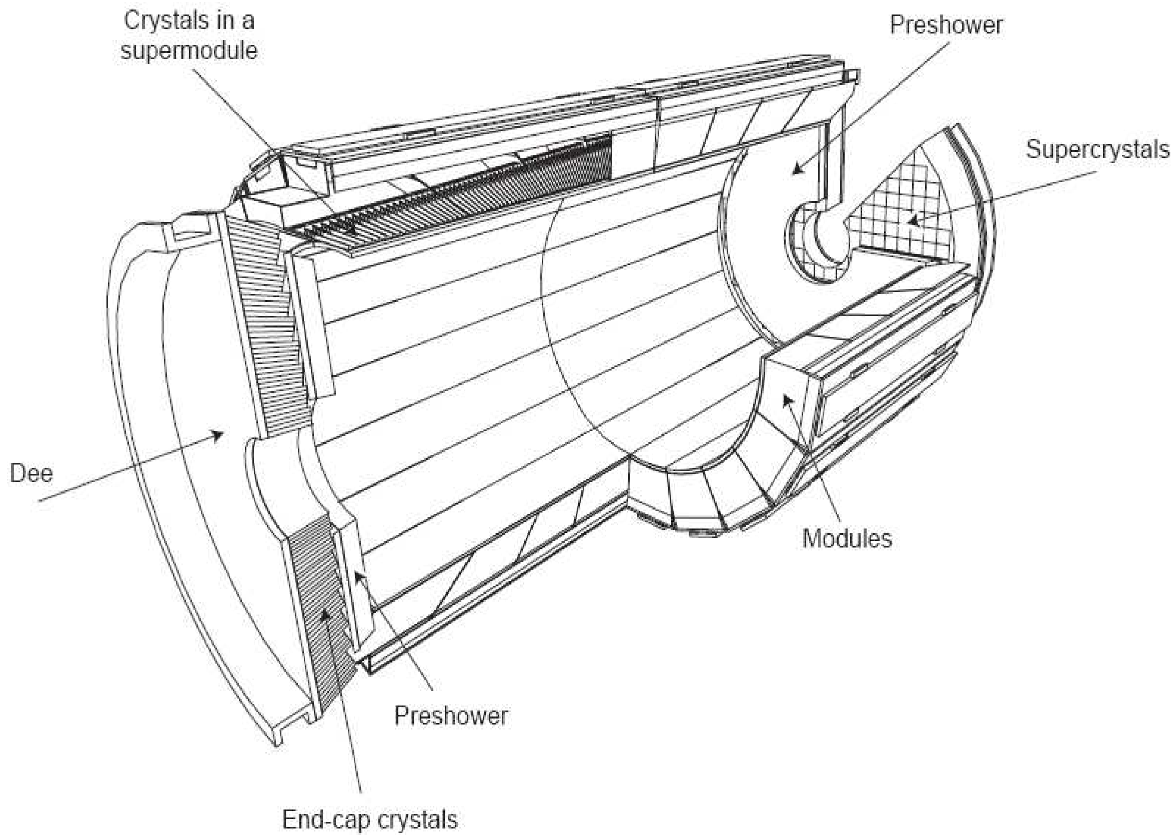
The **ECAL** is made of scintillating crystals of PbWO4 :
- **Barrel** : 36 “supermodules” with 1700 crystals each (coverage $|\eta|<1.48$)
- **Endcaps** : 268 “supercrystals” with 25 crystals each (coverage $1.48<|\eta|<3.0$)

Furthermore, a **preshower** made of silicon strip sensors is located in front of the endcaps ($1.65<|\eta|<2.6$)

**Energy resolution** (measured in electron test beam) :

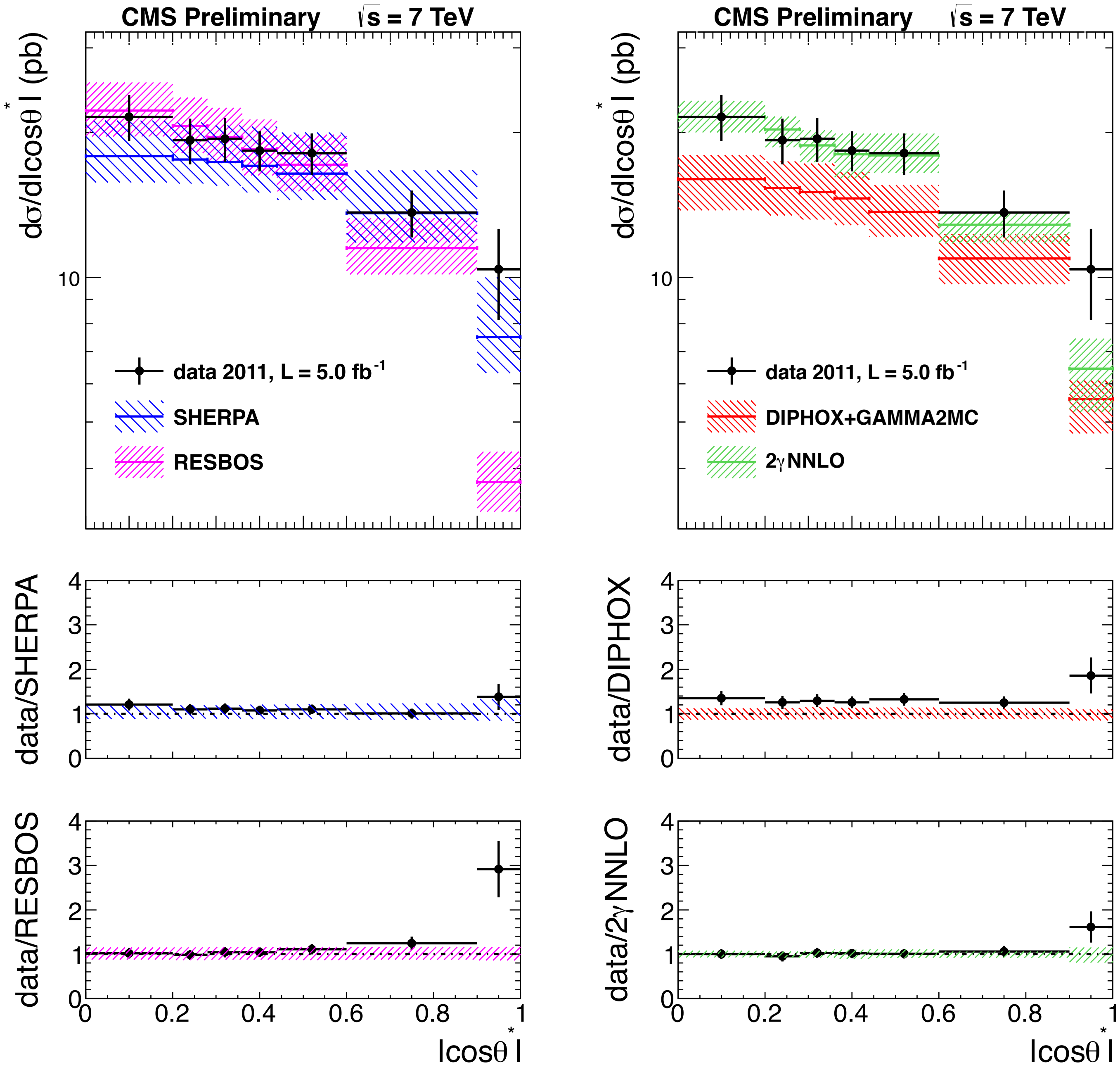
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E(GeV)}} \oplus \frac{b}{E(GeV)} \oplus c$$

a = 2.8% stochastic term
b = 12% noise term
c = 0.3% constant tern



# Diphoton cross-section at 7 TeV

## SMP-13-001, 4.7fb$^{-1}$ at 7 TeV



# $Z\gamma \rightarrow ll\gamma$ cross-section

**NEW**

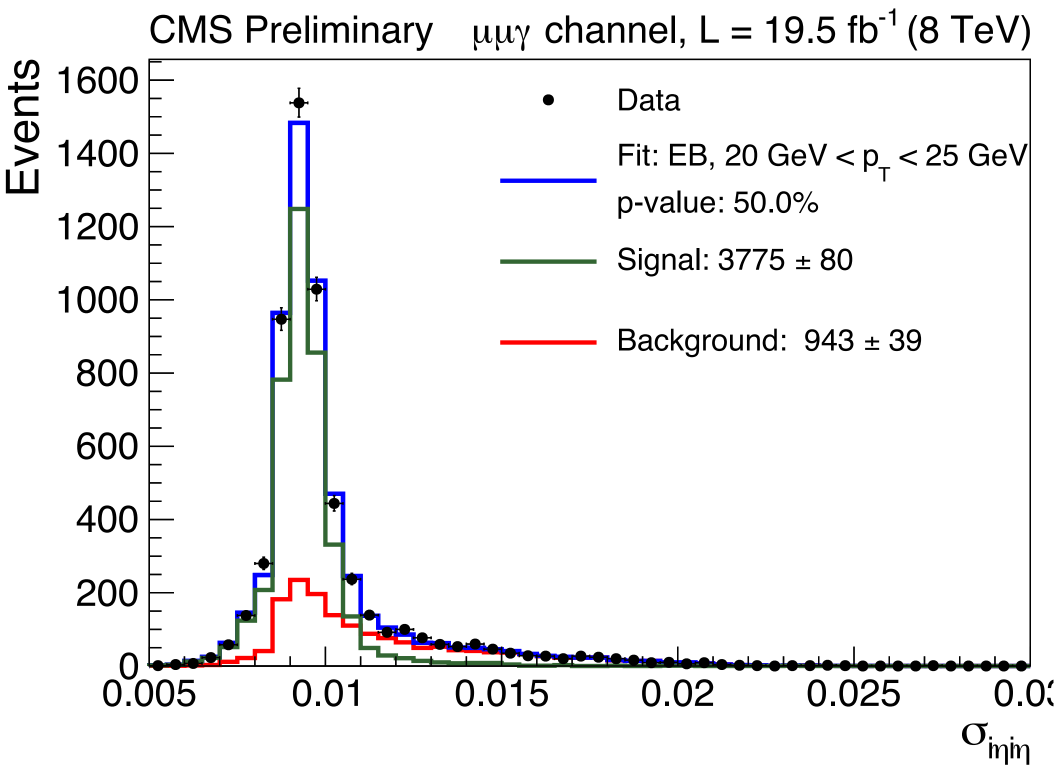
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13014

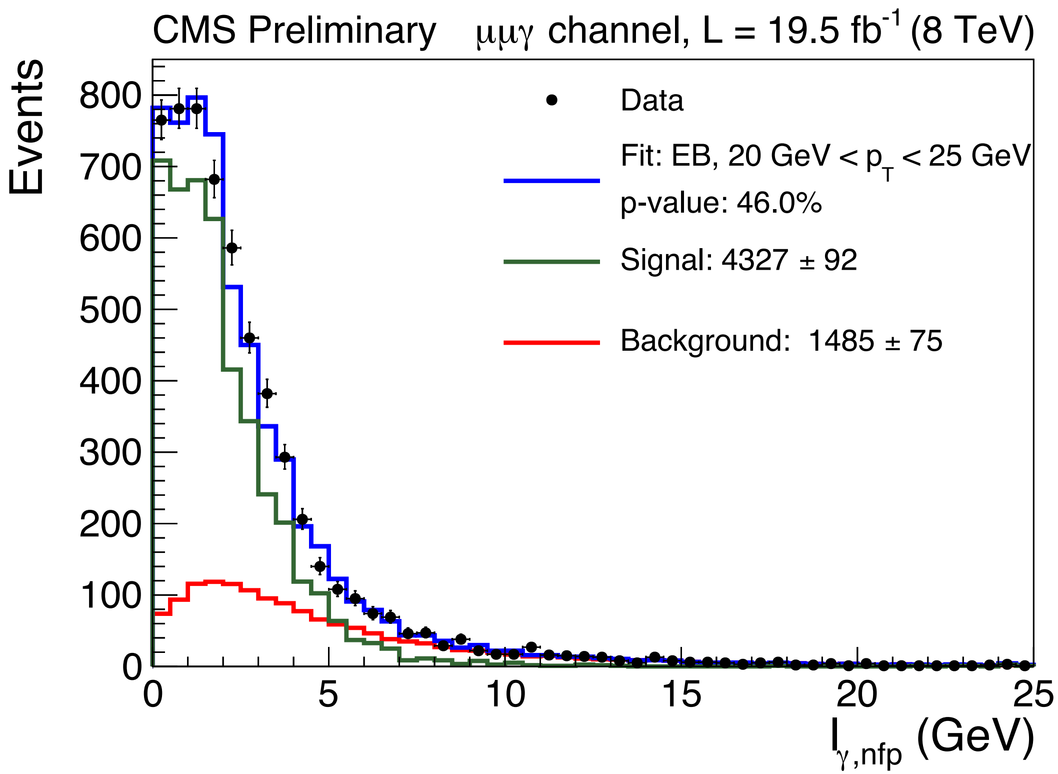
**Kinematical range:**

- Leptons $M_{ll}$>50 GeV, $p_{T,l}$>20 GeV, photons $|\eta_\gamma|$<2.5, $E_{T,\gamma}$>15 GeV, $\Delta R(\gamma,l)$>0.7 (selects ISR)

**Two methods are combined to estimate jets faking photons background**:

- Particle-flow photon isolation template
- $\eta$ width of the energy deposit ("$\sigma_{i\eta i\eta}$")
- Sideband regions tuned to minimize bias in MC



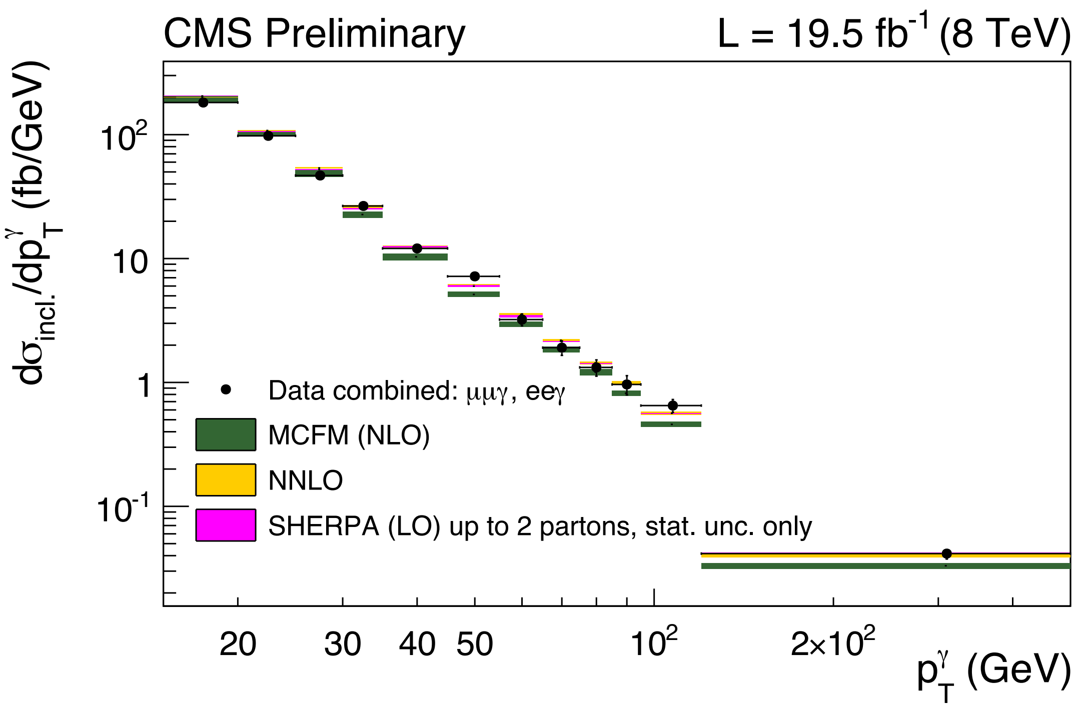
# $Z\gamma \rightarrow ll\gamma$ cross-section

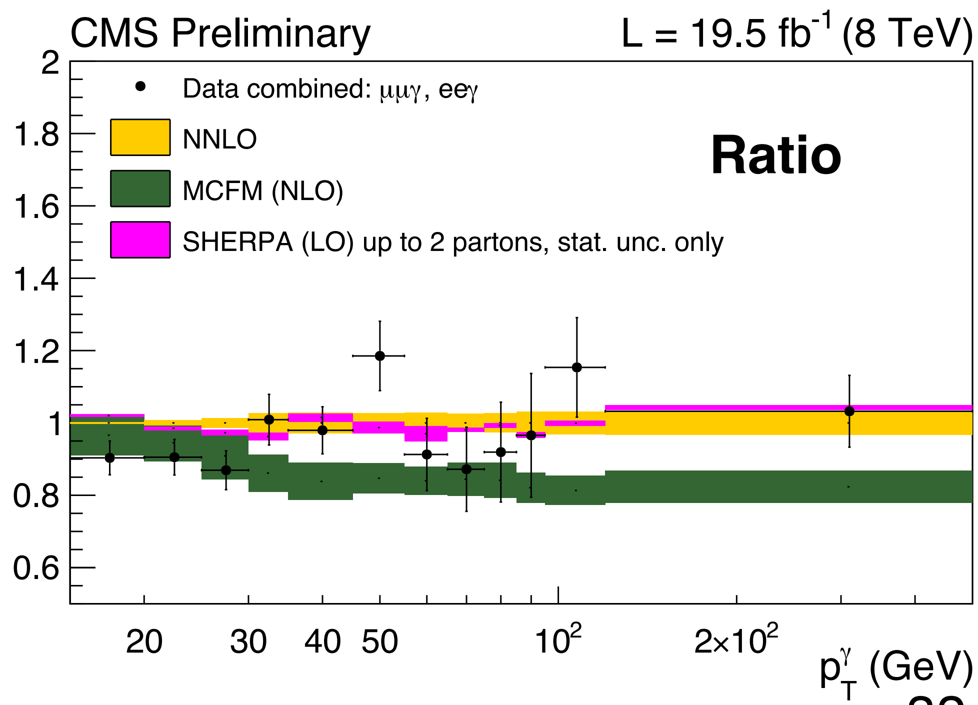
**NEW**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13014

## Inclusive cross section measured vs photon pT

- For the first time **comparison with NNLO** [Grazzini, Kallweit, Rathlev, Torre, hep-ph:1309.7000]: **good agreement**
- **Kinematical range:** Leptons $M_{ll}$>50 GeV, $p_{T,l}$>20 GeV, $|\eta_l|<2.5$, photons $|\eta_\gamma|<2.5$, $E_{T,\gamma}$>15 GeV, $\Delta R(\gamma,l)>0.7$



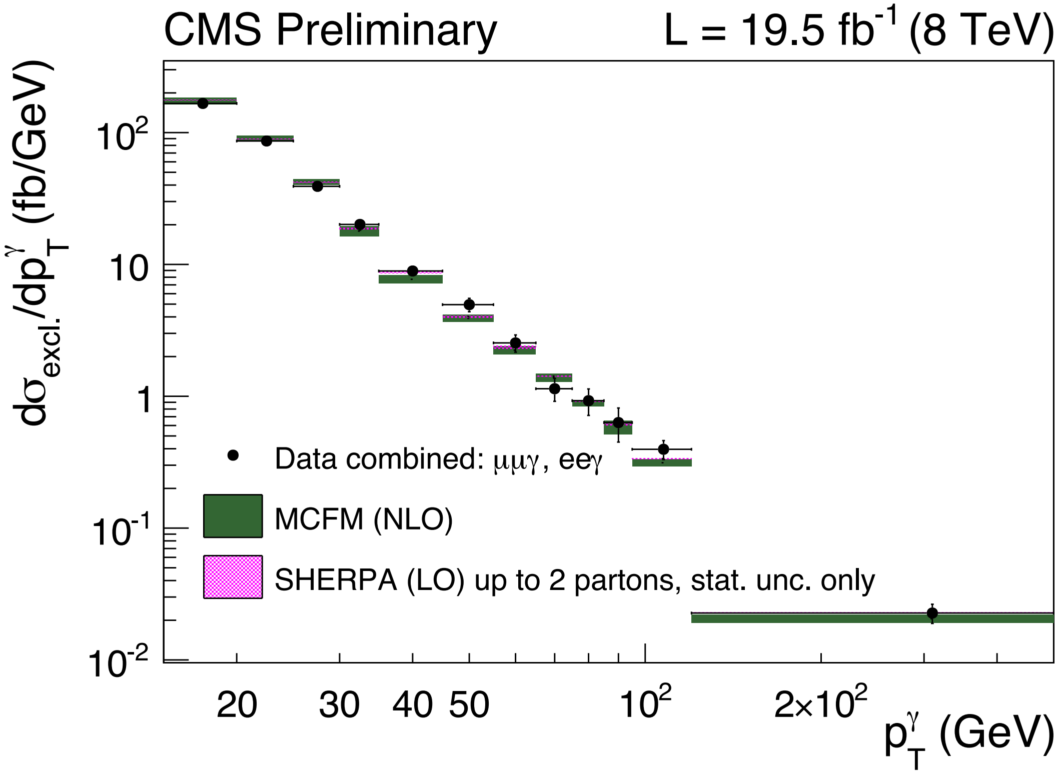
# Zγ→llγ cross-section

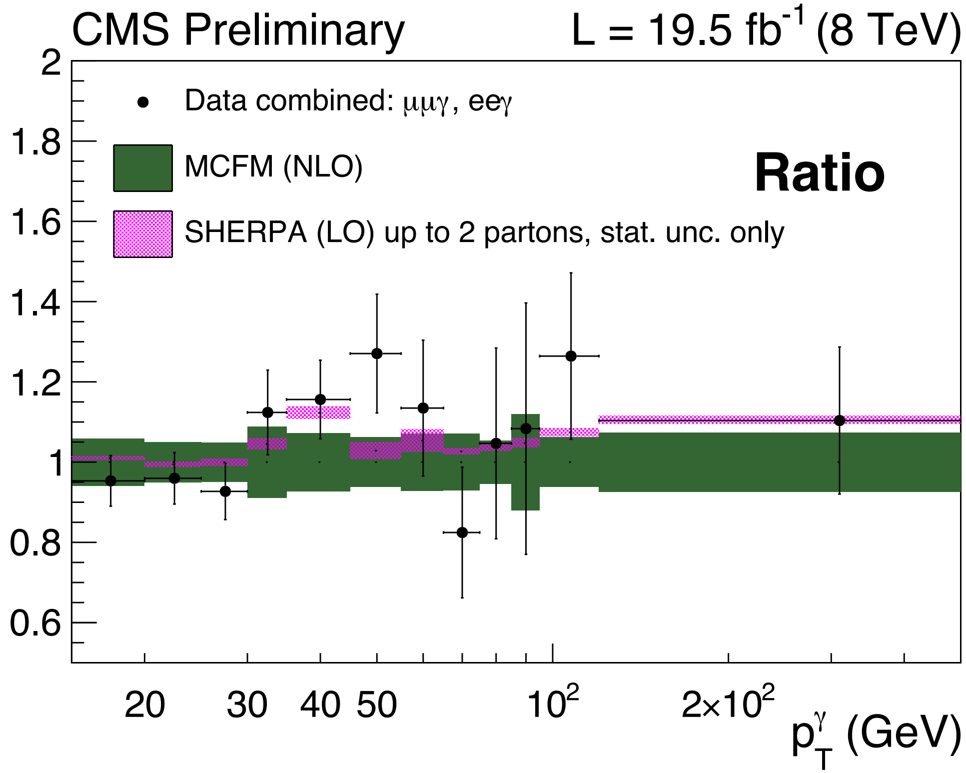
**NEW**

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13014

**Exclusive cross-section with jet veto:**

- Comparison with MCFM (NLO) and Sherpa with jet-veto: good agreement also with NLO because of softer phase-space
- **No jet with pT>30 GeV in $|\eta_j|<2.4$**



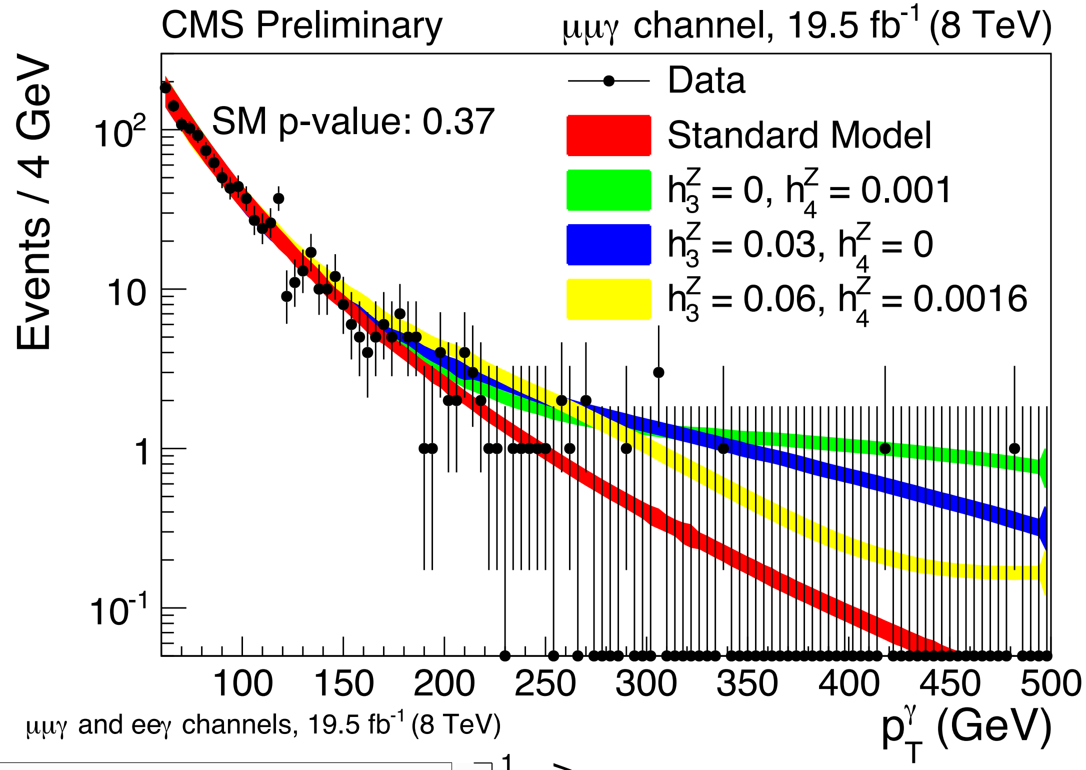
# Zγ→llγ cross-section

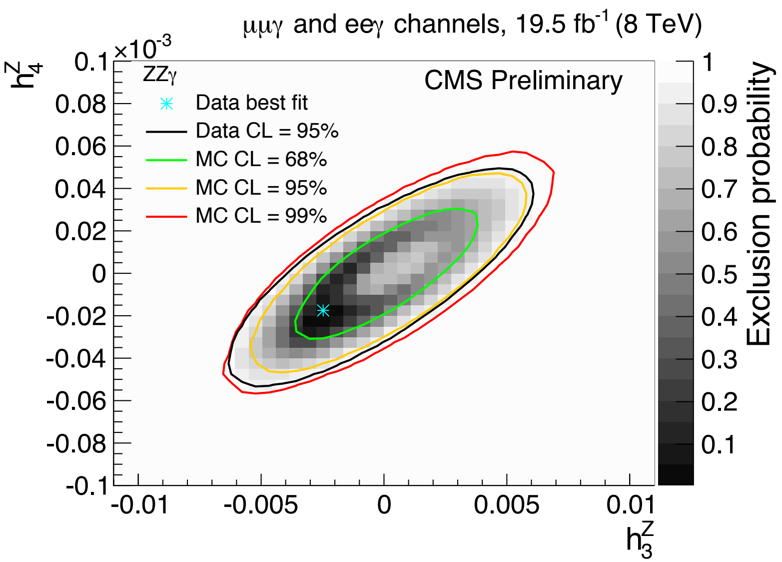
NEW

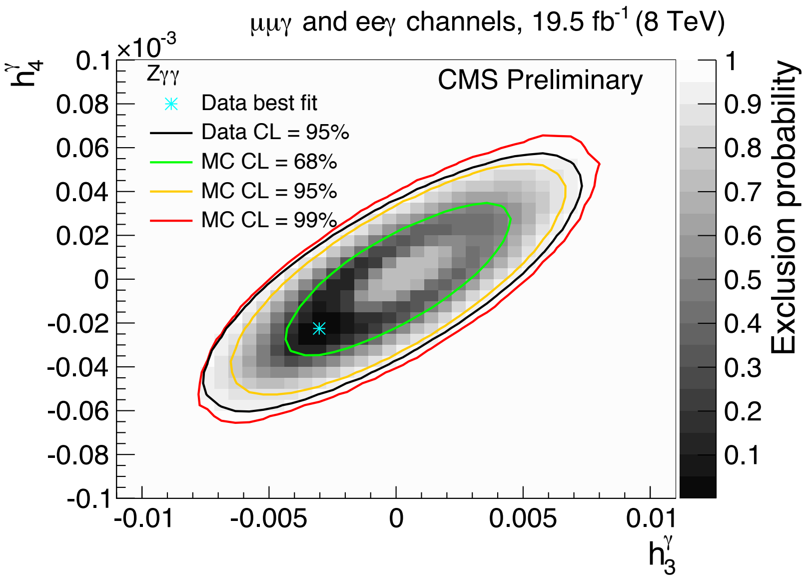
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13014

**aTGC measurement:**

- Limits set using **photon pT**
- Limits on **ZZγ, Zγγ** vertices
- Improvement by a factor 2.5-3 over the previous 7 TeV measurement



# Zγ→llγ cross-section

NEW

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP13014

**Behavior using a form factor and unitarity bounds**

- The non-unitarized limit can be recovered with a infinity form factor
- Unitarity bound (computed with VBFNLO website) crossed for a form factor of around 6 TeV (h3Z) or 3.5 TeV (h4Z)
- Below, the measurement probes aTGC in the unitarity region