LATEST SM STUDIES, HIGGS AND BEYOND SM SEARCHES AT CMS

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on behalf of CMS collaboration

Colloquium on "Latest results from the LHC" - 12 July 2012 - CERN

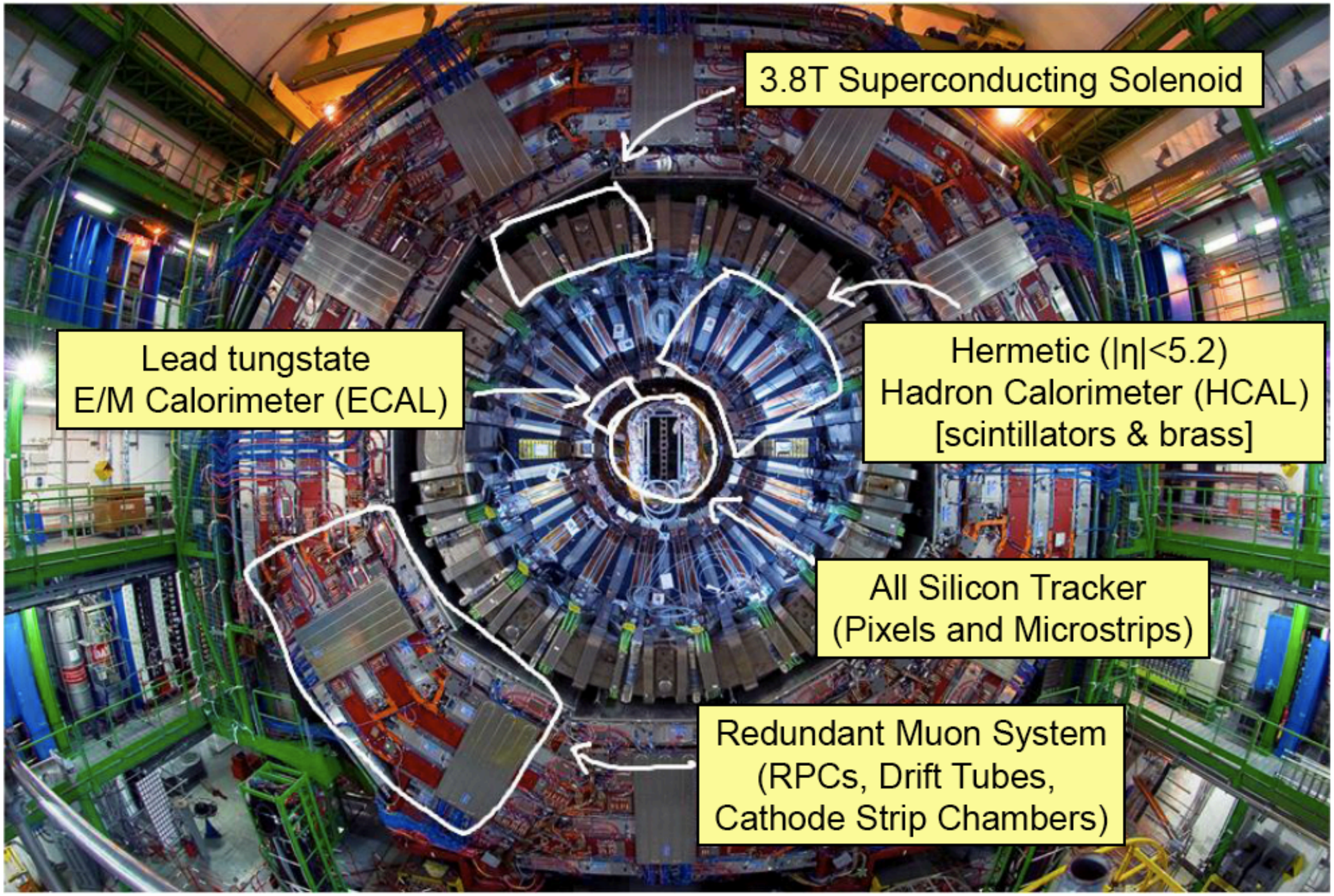
Summary of results presented at

ICHEP2012 Melbourne

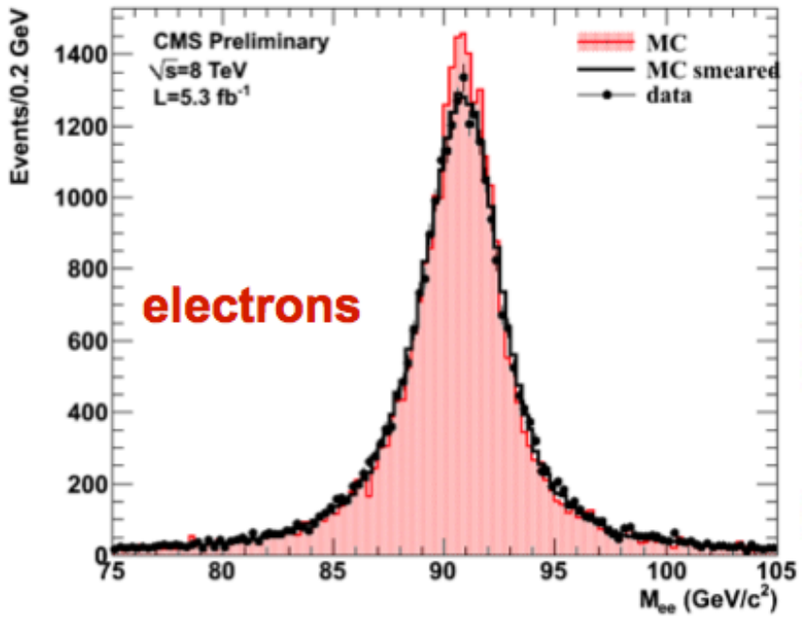
CONTENTS (AND DISCLAIMER)

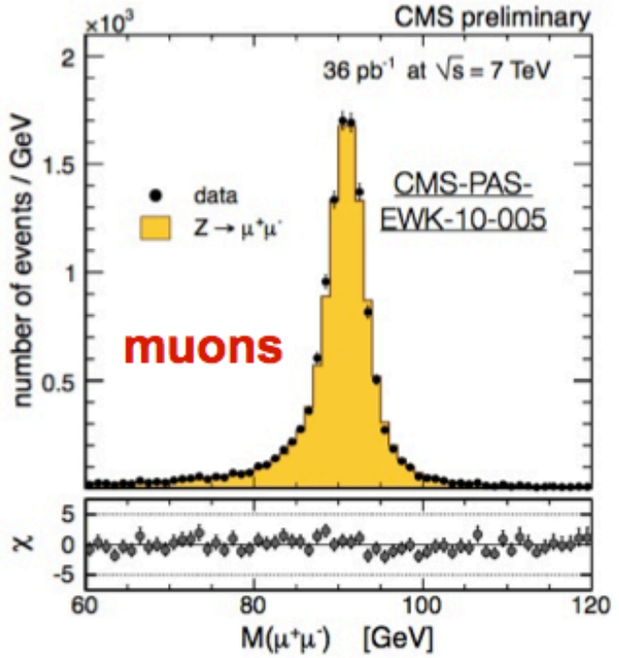
- CMS presented many new results at ICHEP
- Here presenting a selected list of results
  - Focussing mostly on new results on 8 TeV 2012 dataset
- **Standard Model Physics**
  - W/Z cross section @ 8 TeV and differential distributions @ 7 TeV
  - Di boson cross sections (WW/ZZ) @ 8 TeV & TGC
  - Top cross sections @ 8 TeV, combined top mass measurement, first observation of tt+V
- **Higgs search**
  - Observation of a new boson around 125 GeV
- **Beyond the SM**
  - New recent results from searches
- **All physics results can be found @**
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

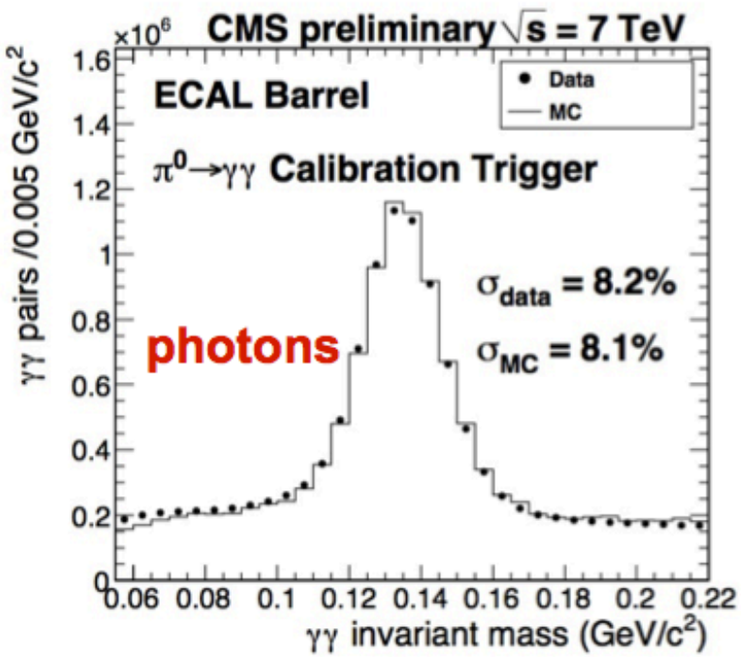
CMS IN A NUTSHELL

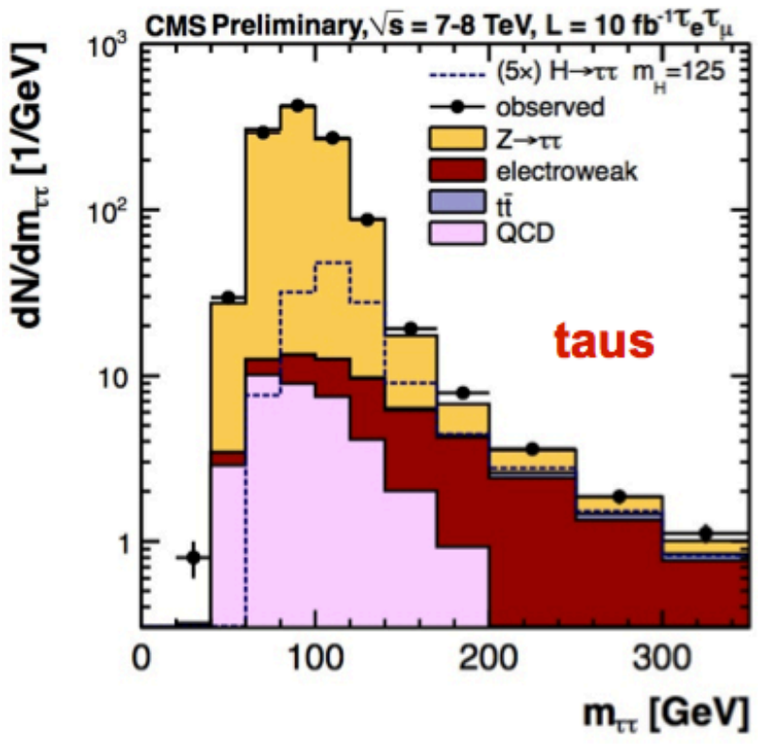


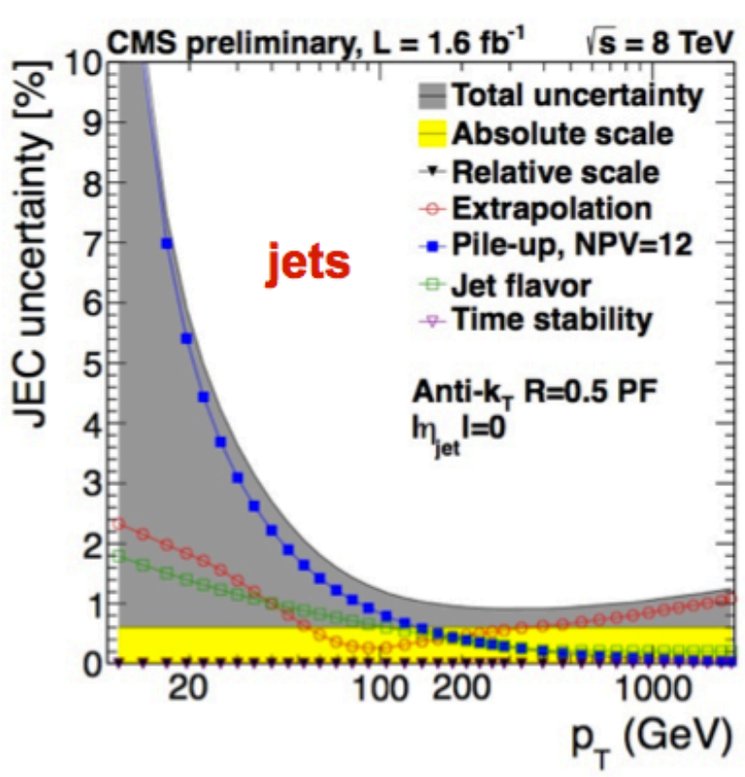
VERY GOOD UNDERSTANDING OF PHYSICS OBJECTS

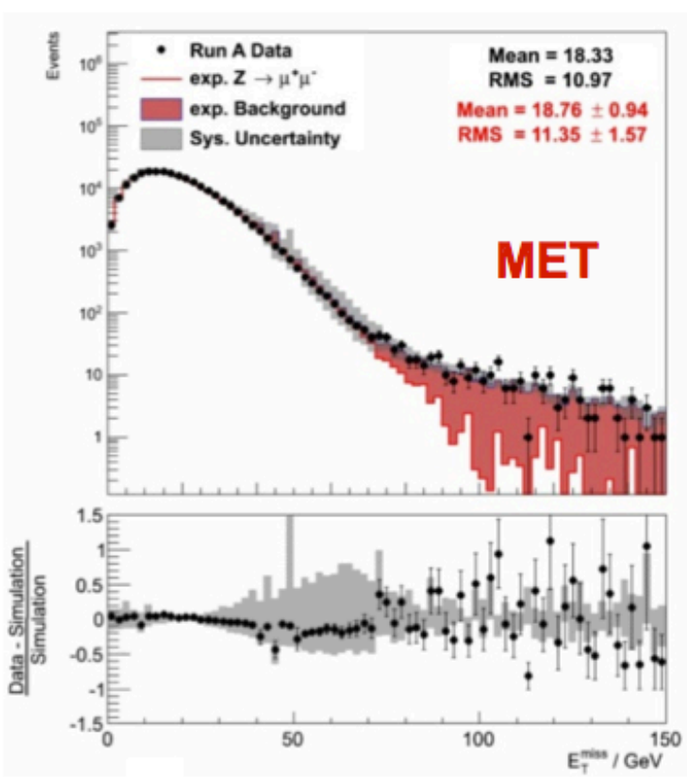






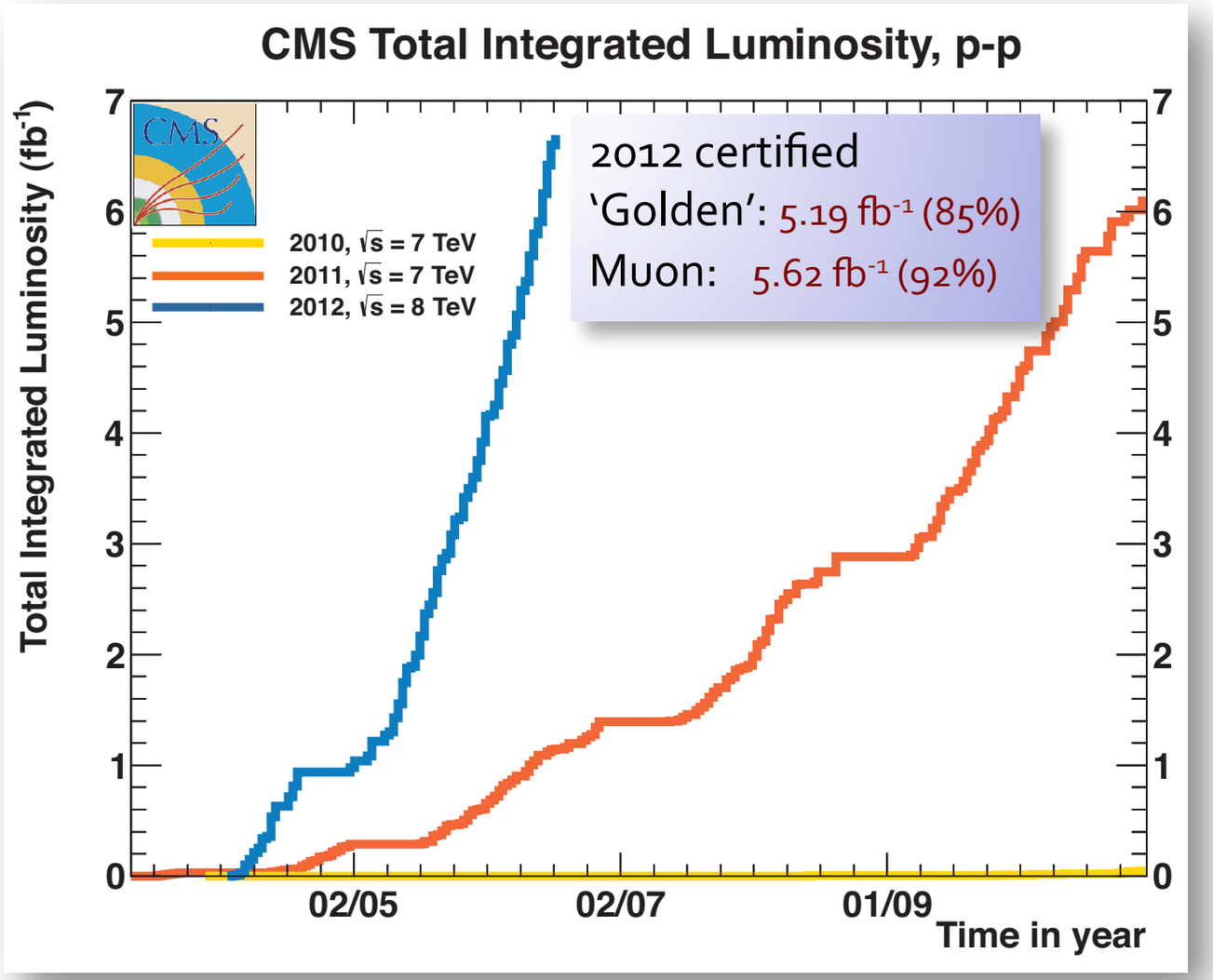




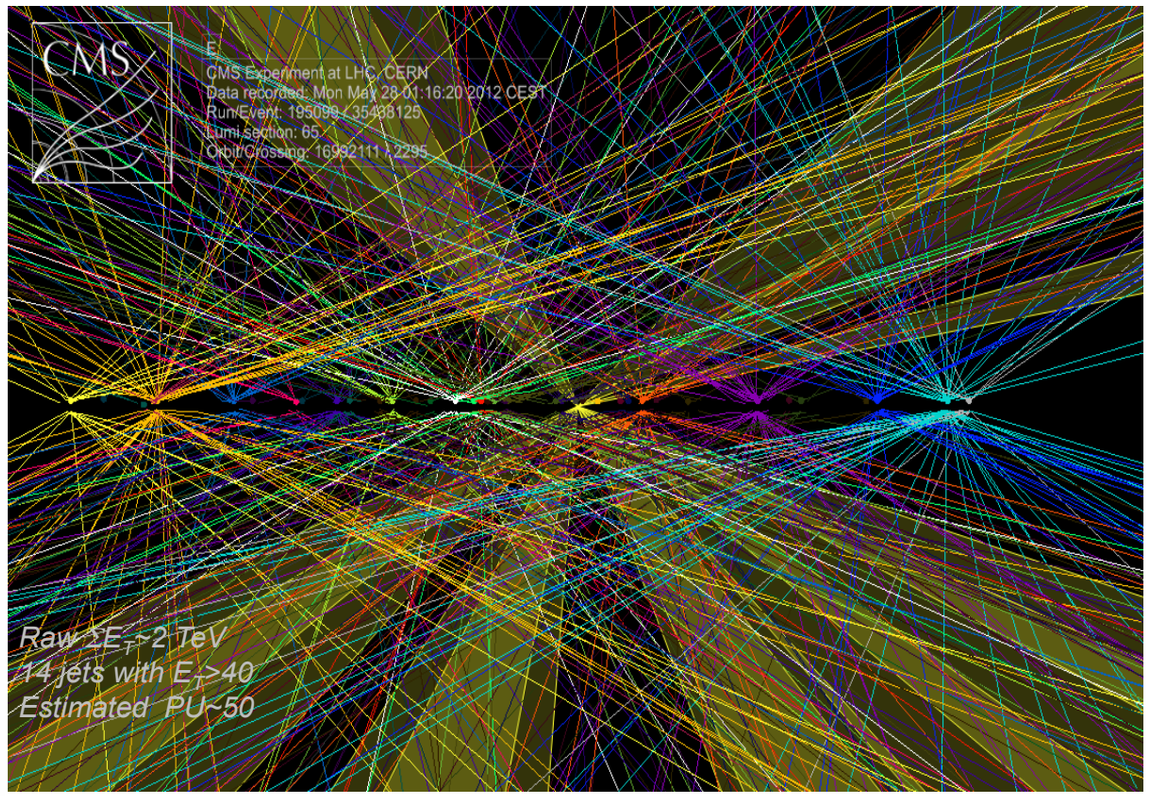


REMARKABLE LHC & CMS OPERATIONS

Expected size of 2012 dataset >15fb^{-1}



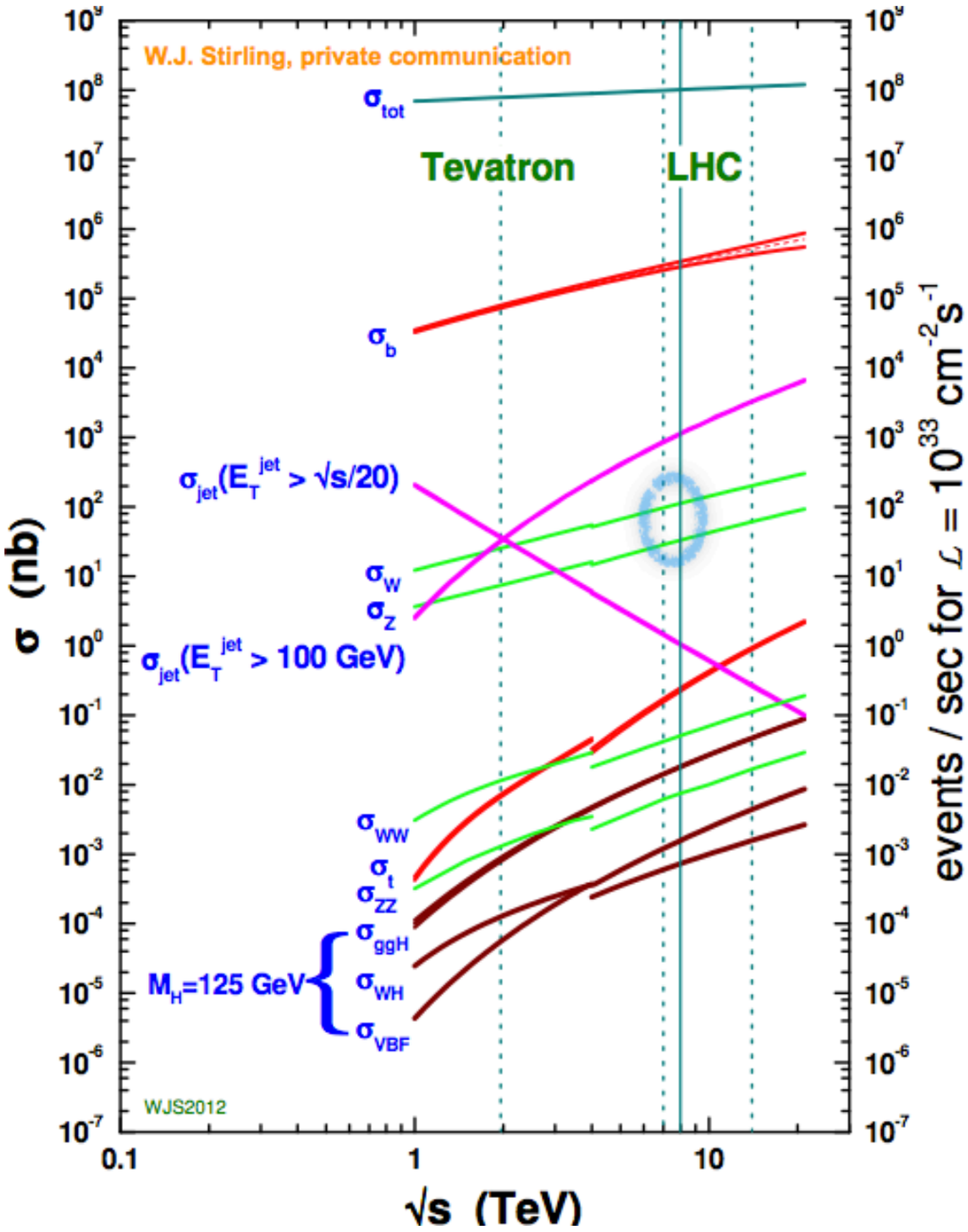
High lumi comes at a cost: in 2012 already exceeding detectors design capabilities for pile-up



2012: on average O(20) pile-up events
50 ns inter-bunch spacing

ELECTROWEAK STUDIES

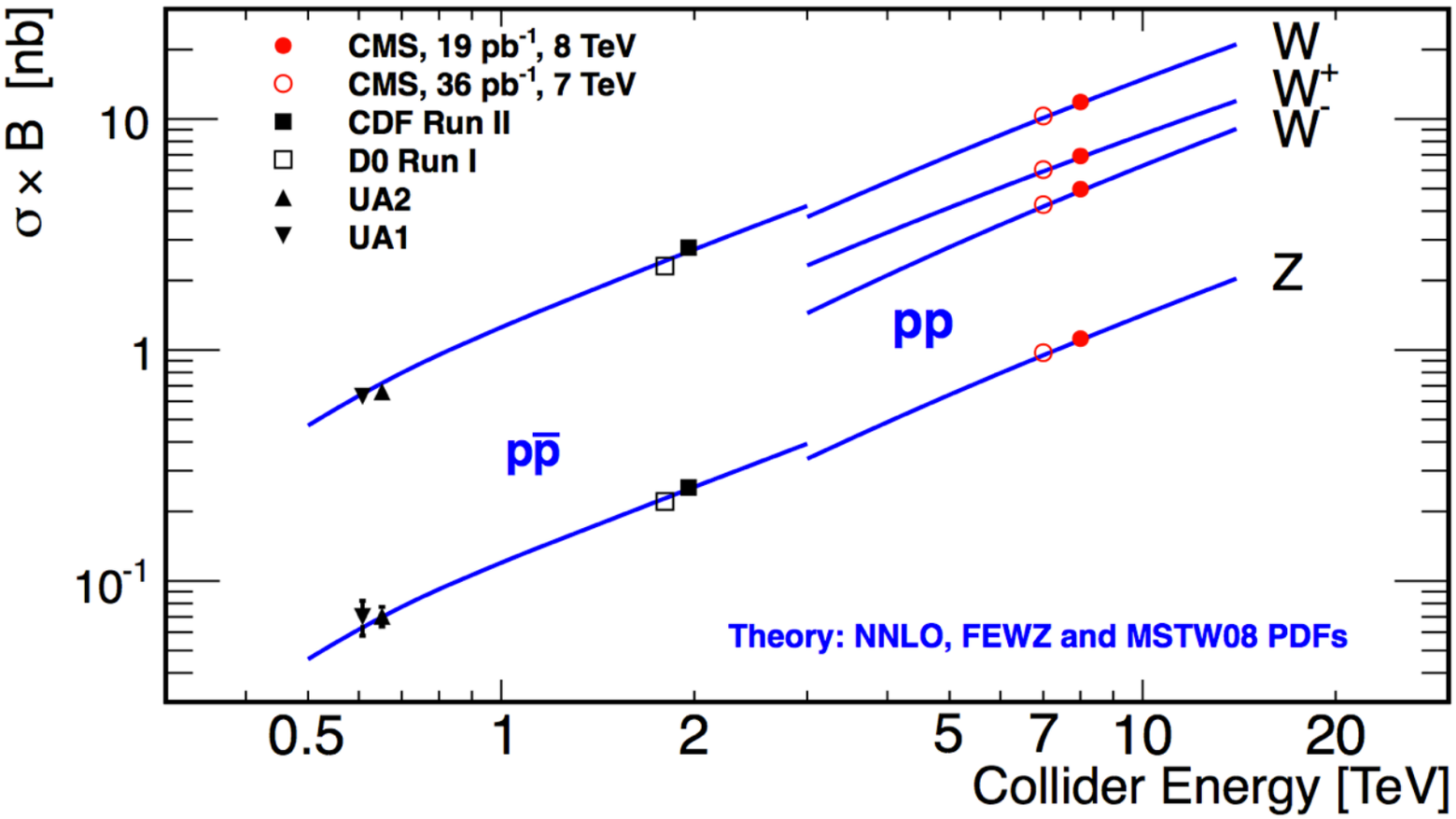
- **W and Z production at LHC**
  - Precise test of the SM
  - Help to improve understanding of proton **P**arton **D**ensity **F**unctions (PDF)
  - Candles used to calibrate our detector (trigger, energy scale, efficiencies...)
  - They are bkg for many searches
- **New studies presented @ ICHEP**
  - First inclusive W/Z and WW/ZZ xsec @ 8 TeV
  - Detailed differential distributions in Z+jets events



W AND Z INCLUSIVE @ 8 TEV

- **In 2012 performed using special low pile-up runs**
- Looking also at absolute inclusive xsec and ratio (W/Z, W^+/W^-) with reduced theoretical and experimental systematic errors
- Good agreement with predictions

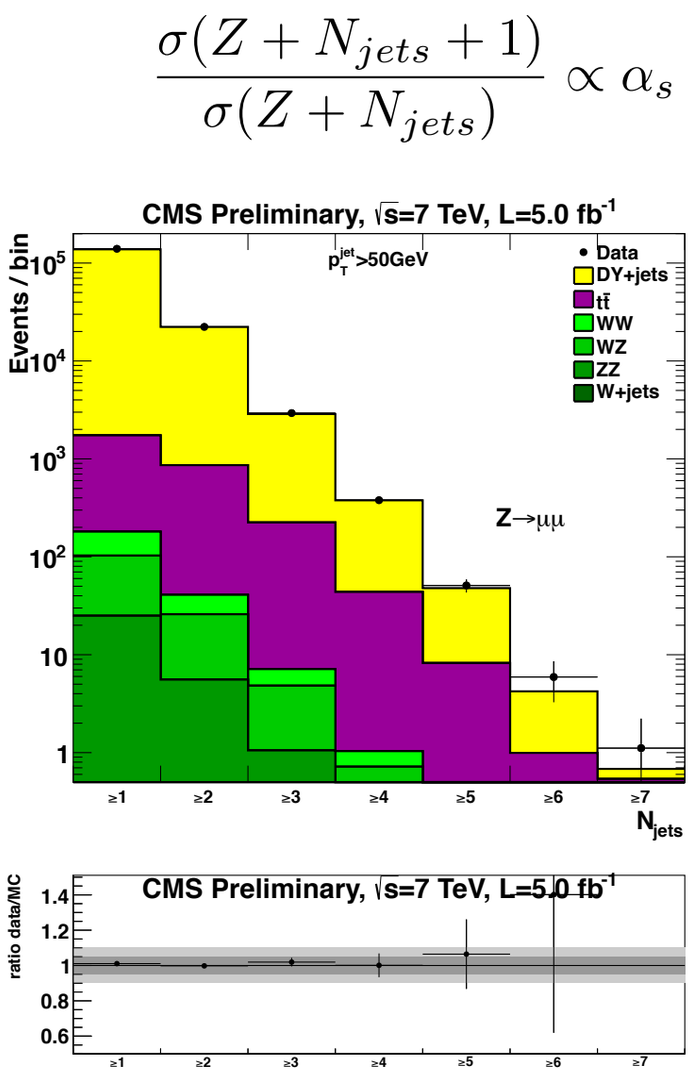
CMS-SMP-12-011

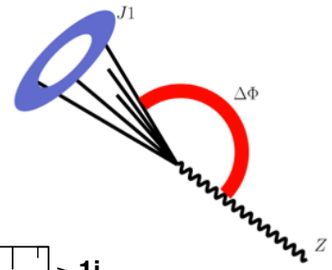


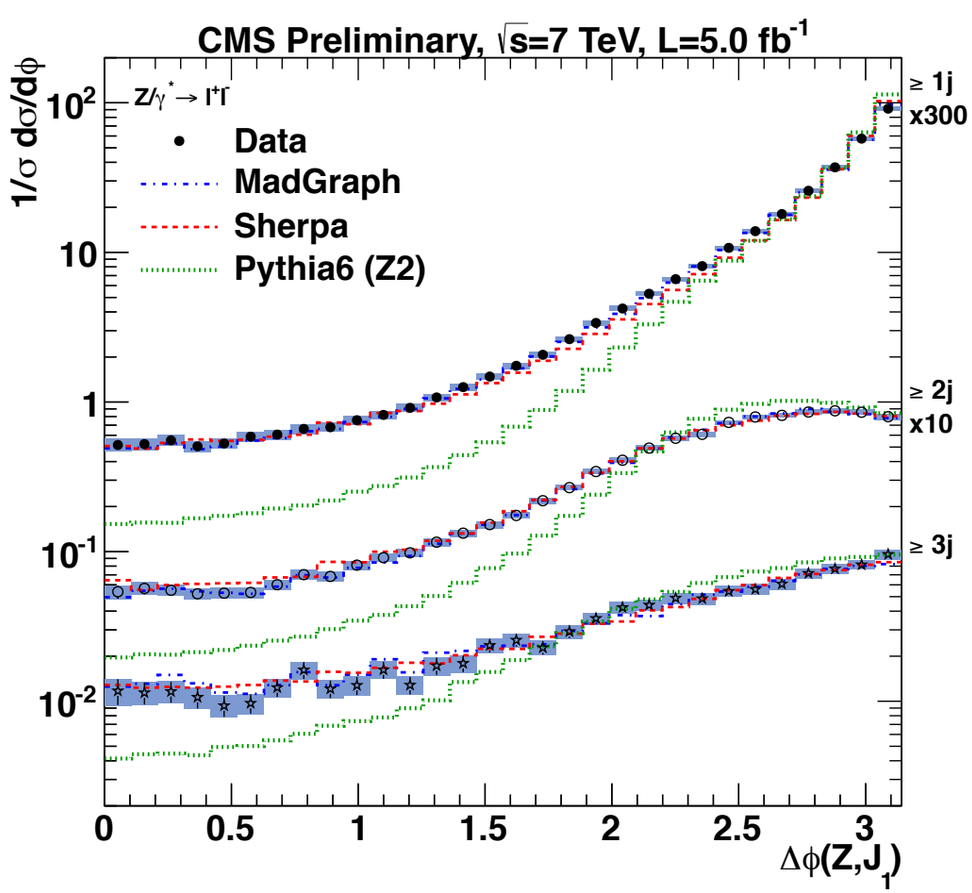
Z+JETS DIFFERENTIAL DISTRIBUTIONS

- **Critical test of pQCD at unprecedented level**
  - Background to a plethora of searches
- Now studying differential cross-sections and event shapes in Z+jets events
- **LO matrix element (many legs) + matched parton showering accurately describing data in all regions of analyzed phase space**

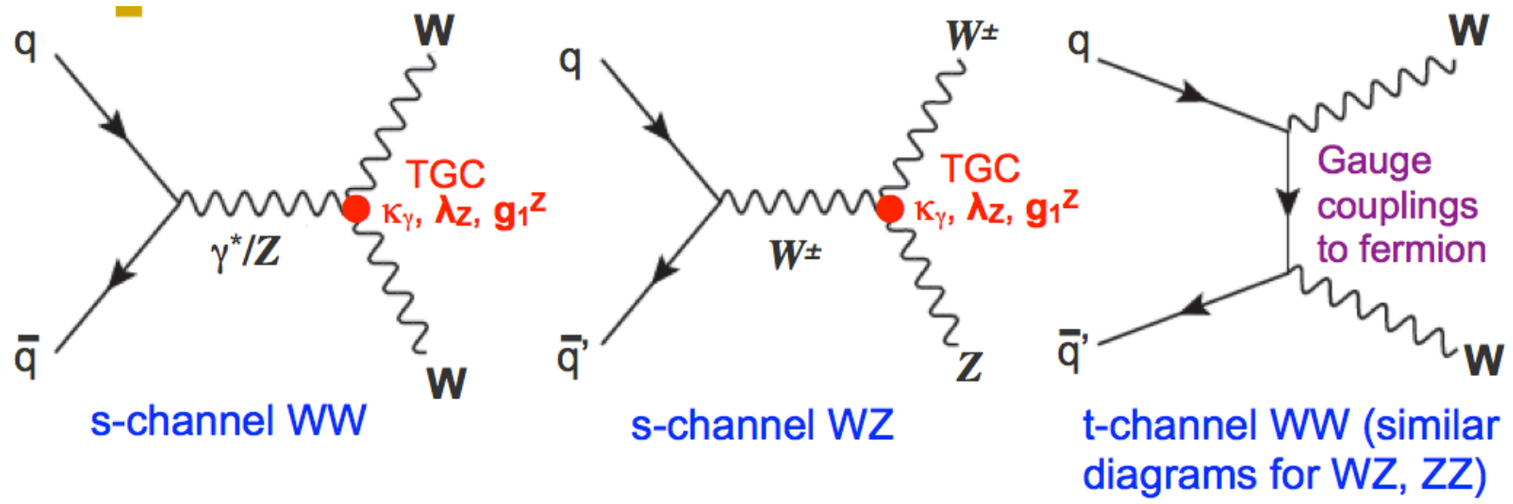
$$\frac{\sigma(Z + N_{jets} + 1)}{\sigma(Z + N_{jets})} \propto \alpha_s$$







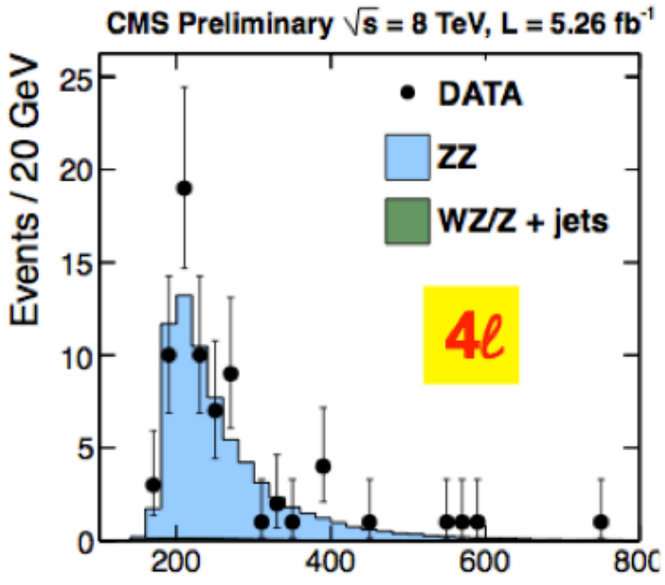
DIBOSON PRODUCTION

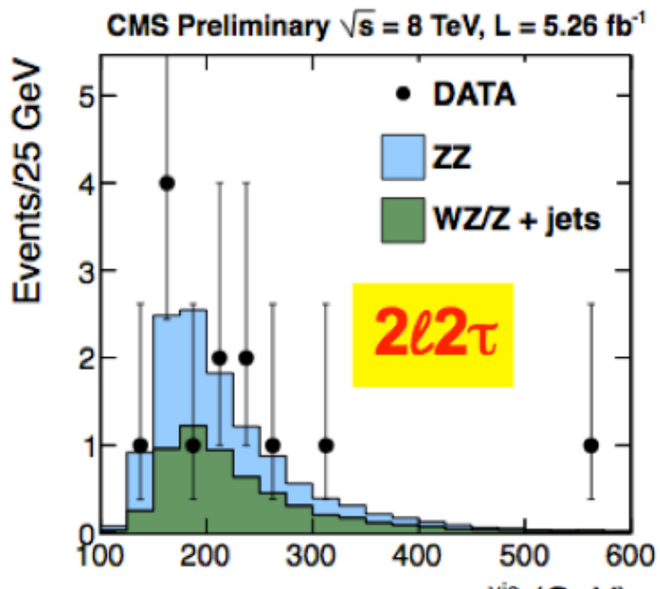


- **Critical test of the gauge structure of the SM**
  - Allows to search for anomalous Triple Gauge Couplings (TGC)
- **Mandatory preliminary study for Higgs searches**: irreducible background for Higgs searches in WW and ZZ modes
- Probe for new physics
  - Resonances with diboson final states
- WW/WZ/ZZ cross section already measured @ 7 TeV and found in agreement with predictions

WW & ZZ @ 8 TeV

CMS-SMP-12-014





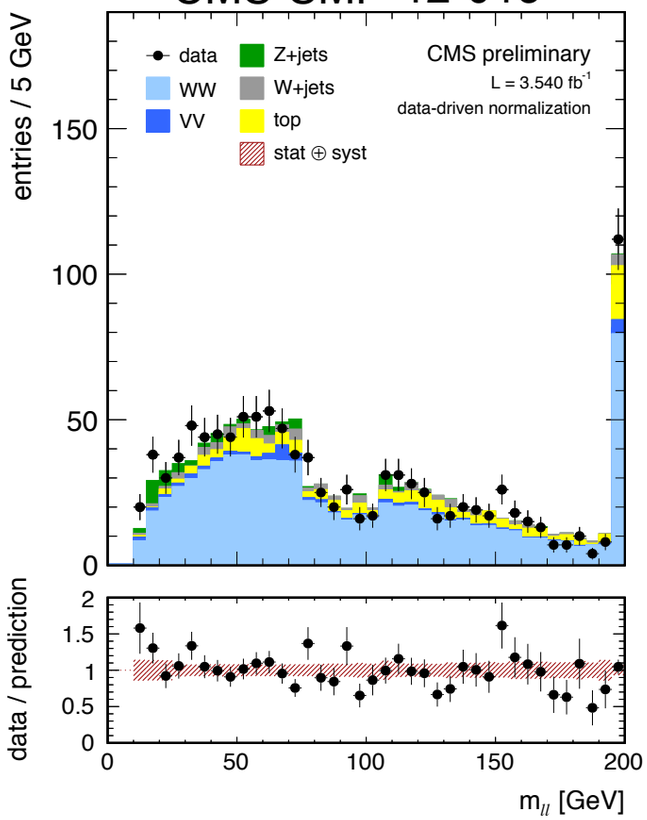
ZZ

σ = 8.4 ± 1.0 (stat) ± 0.7 (sys) ± 0.4 (lum) pb

NLO (MCFM 6.0): 7.7 ± 0.4 pb

(NLO for qq→ZZ and LO for gg→ZZ, MSTW 2008 PDF)

CMS-SMP-12-013



WW: 2 opposite sign leptons (e,μ) + MET + jet veto
All backgrounds are estimated from data

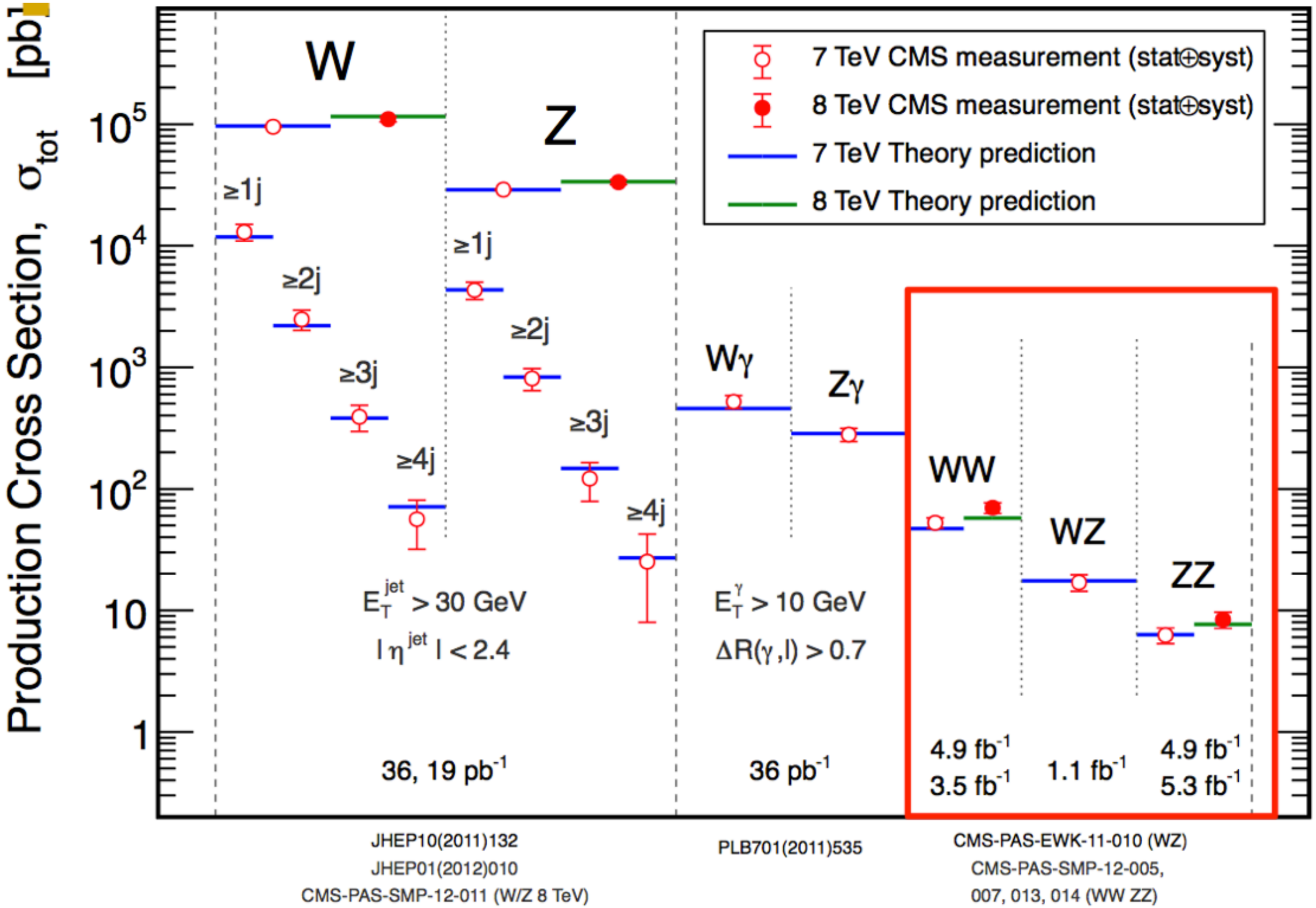
σ = 69.9 ± 2.8 (stat) ± 5.6 (sys) ± 3.1 (lum) pb

NLO prediction:

$$\sigma^{\mathrm{NLO}}(\mathrm{gg} \to \mathrm{W^+W^-} + \mathrm{qq} \to \mathrm{W^+W^-}) = 57.25\,(^{+2.35}_{-1.60})\ \mathrm{pb}$$

Campbell, Ellis, Williams. JHEP 07 (2011), 018. arXiv:1105.0020. MCFM.

EWK: Grand Summary



JHEP10(2011)132
JHEP01(2012)010
CMS-PAS-SMP-12-011 (W/Z 8 TeV)

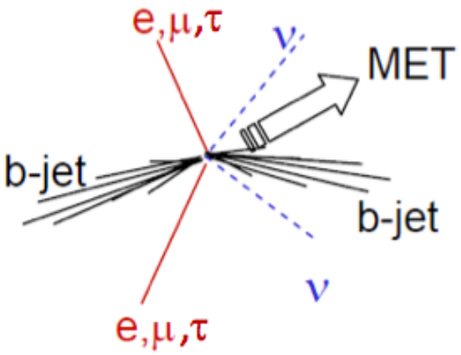
PLB701(2011)535

CMS-PAS-EWK-11-010 (WZ)
CMS-PAS-SMP-12-005,
007, 013, 014 (WW ZZ)

TOP PHYSICS @ CMS

- **Another pillar of the physics programme at the LHC**
  - A very special particle ($Y_t \sim 1$), the only "free" quark
  - LHC a top factory. ttbar cross-section @ 8TeV ~230pb
  - Possibility to do precise measurements of important parameters of the SM (m_t, V_{tb})
  - Critical from the experimental point of view: all sub-detectors are involved in top reconstrucion
- **Top sector also interesting to search for new physics**
  - New particles decaying in top quarks or associated production with top quarks.

Top Pair Cross Section @ 8 TeV



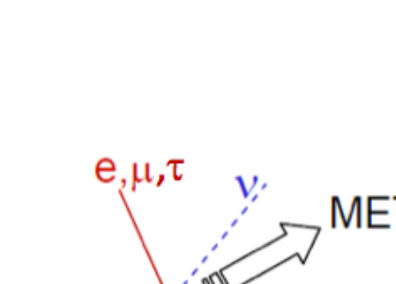
dileptons

BR ~ 10%

CMS-TOP-12-007

di-lepton channel

- very clean channel
- counting experiment with increasing number of b-tagged jets
- e-mu channel particularly clean: driving the xsec measurement



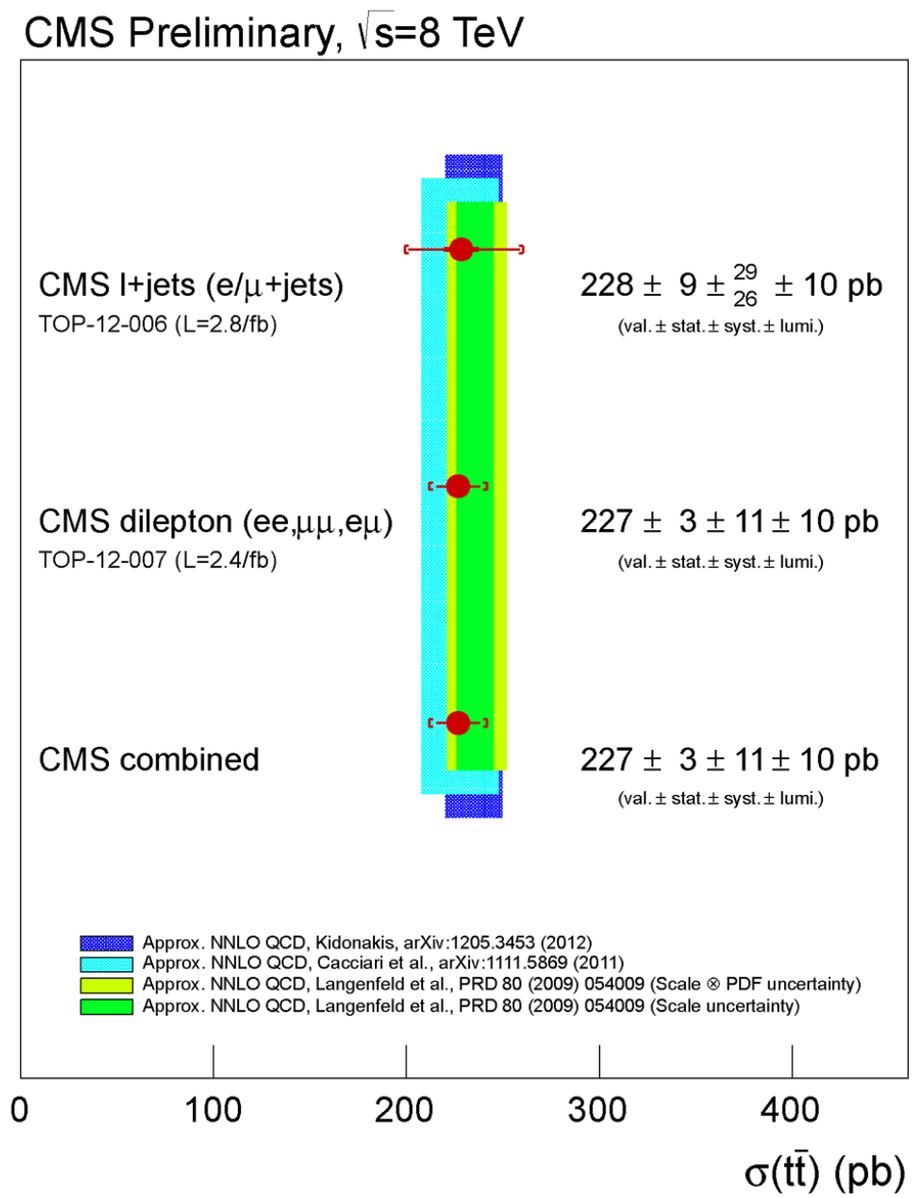
lepton + jets

BR ~ 44%

CMS-TOP-12-006

lepton + jets channel

- good compromise between purity and statistics
- Cross section extracted from a fit to the invariant mass of lepton and b-jet

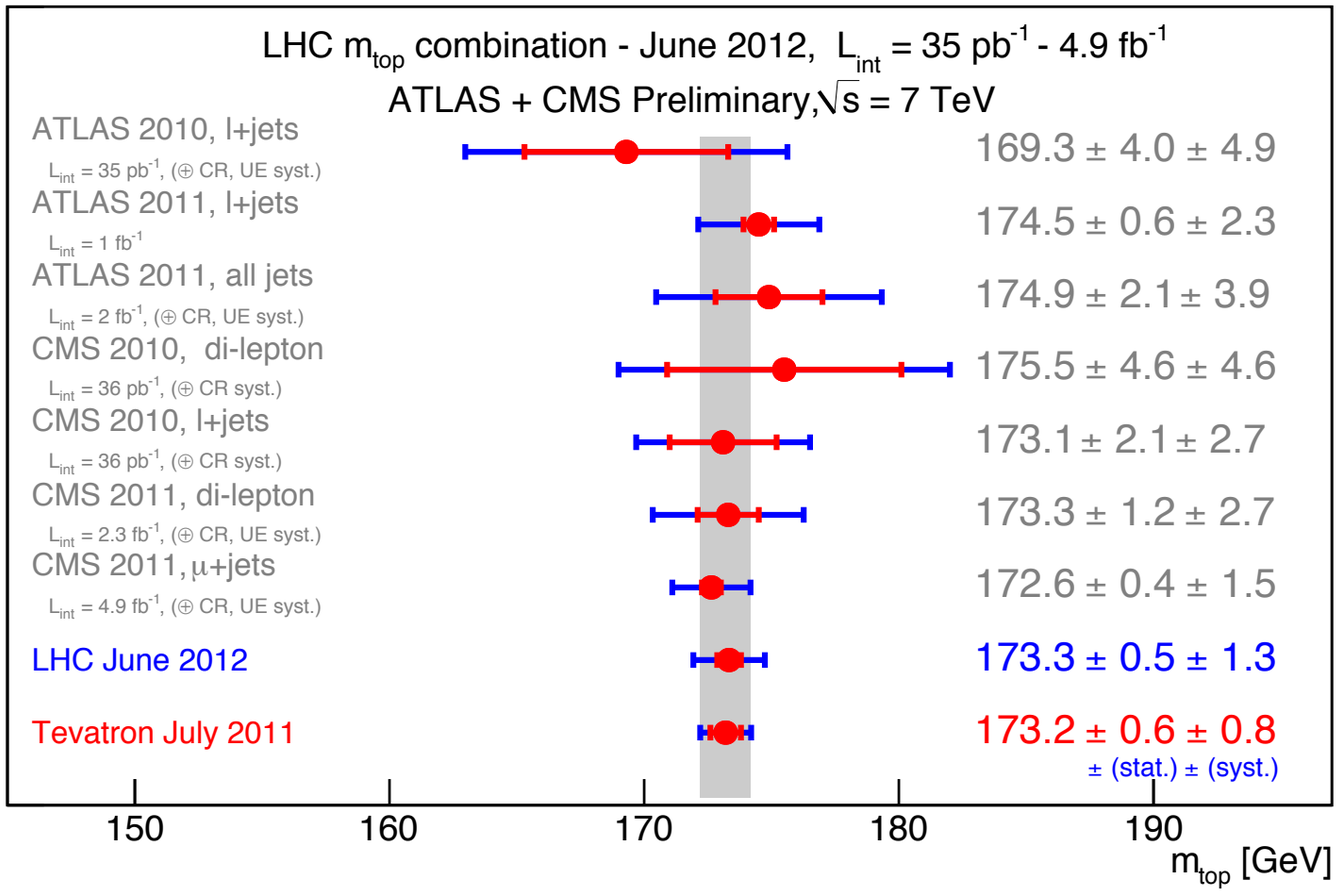


Precision is challenging NNLO predictions

TOP MASS MEASUREMENT

ATLAS-CONF-2012-095

CMS PAS TOP-12-001



- Top mass measurement performed both in the di-lepton and in the l+jets channels
- **Dominant systematic from Jet Energy Scale**
  - Recently added the systematics error due to color reconnection and UE (increase the systematics error by about 20%).
- Systematic error at the moment ~50% worse then Tevatron

MEASUREMENT OF TOP SPIN CORRELATION AND POLARIZATION

Top decays before hadronization: polarization or spin information is transferred to decay products

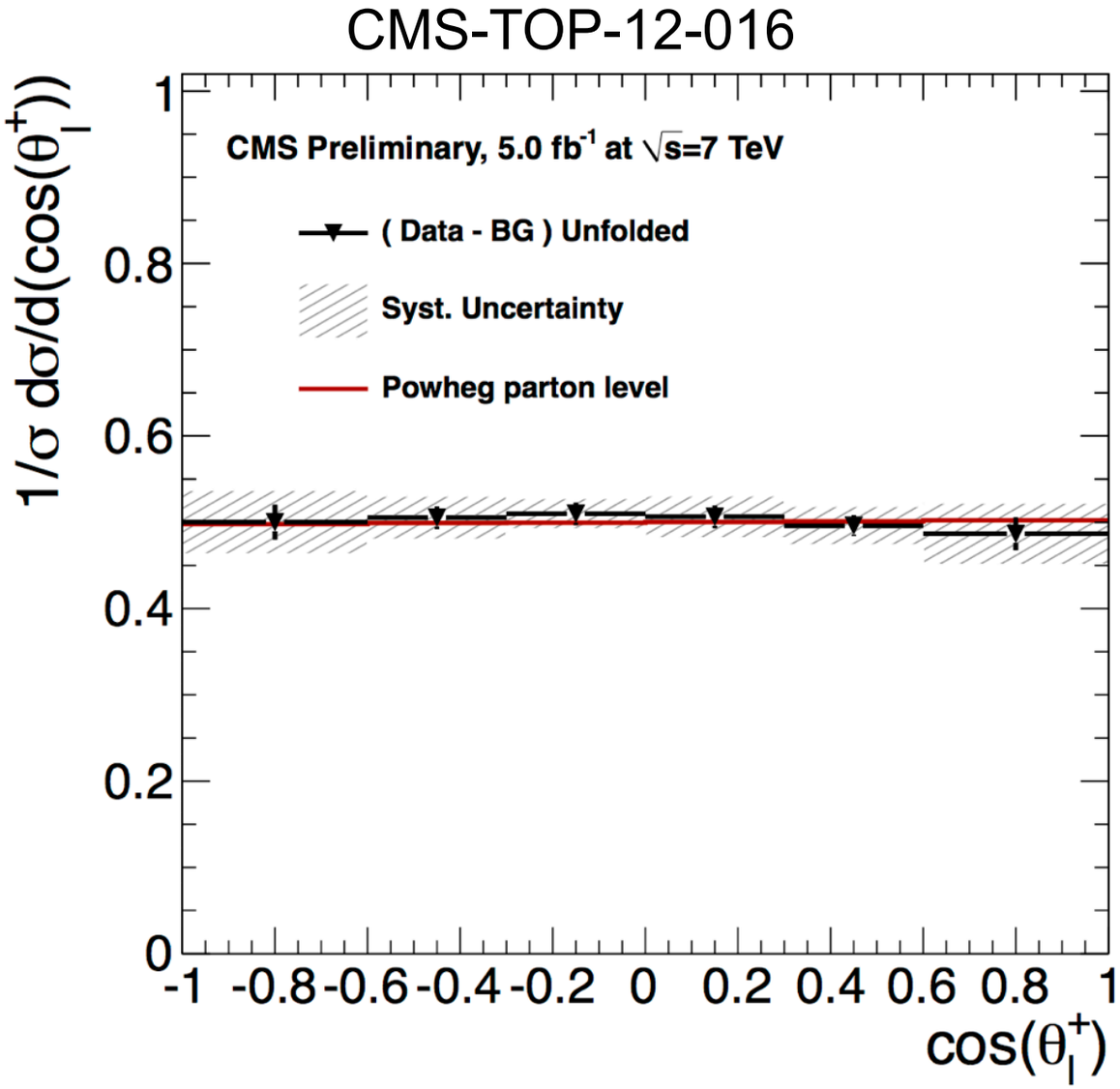
Studying in detail ttbar production can help revealing physics beyond SM

In SM top is produced unpolarized (polarization only coming through EWK corrections)

Measurement done looking at distribution of the angle between lepton and top direction in ttbar rest frame in di-lepton events

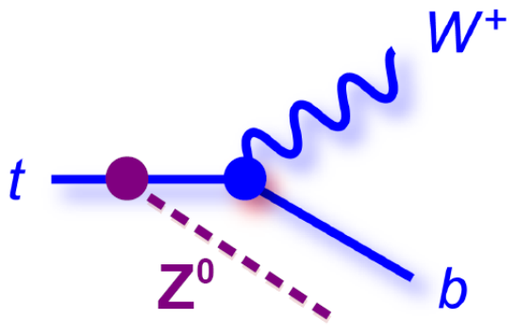
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{l,n}} = \frac{1}{2}(1 + 2\kappa_l P_n \cos\theta_{l,n})$$

$P_n = -0.009 \pm 0.029 \pm 0.041$



TTBAR+V PRODUCTION

Starting to observe associated production of top pairs with W or Z

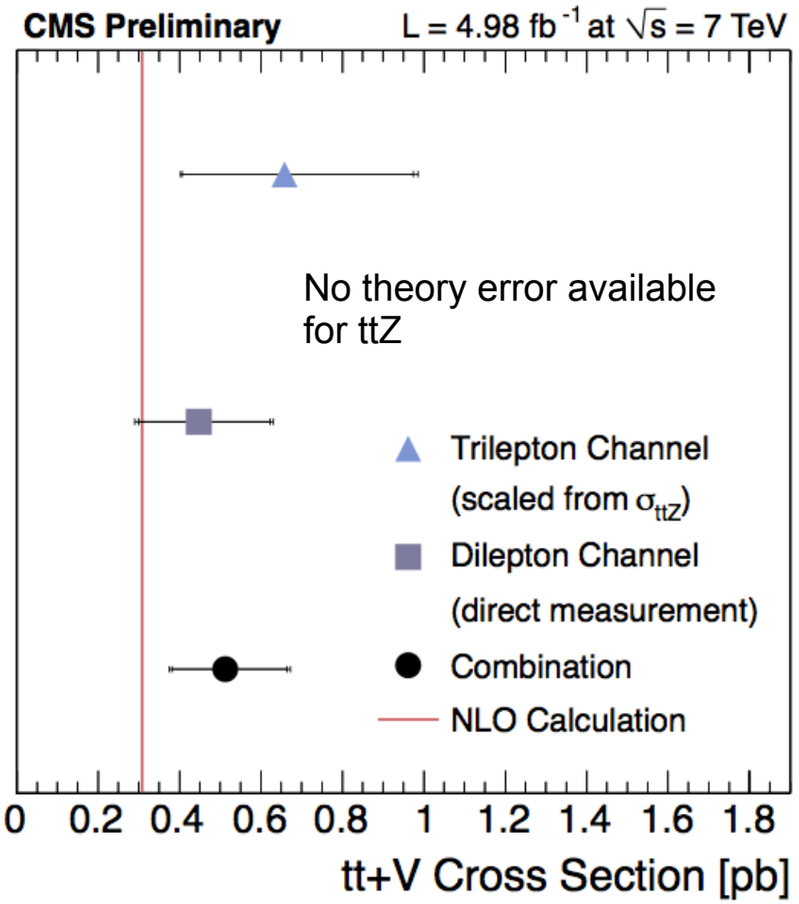


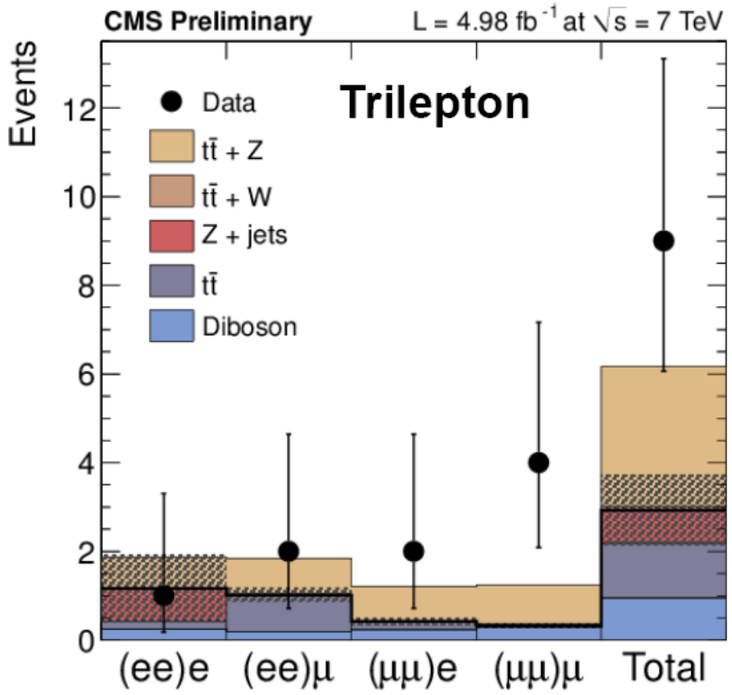
$$\frac{\sigma(t\bar{t})}{\sigma(t\bar{t}+V)} \approx 500$$

Trilepton channel: $\sigma(t\bar{t}Z \to l + \text{jets} + (Z \to l\,l))$

Same-sign dilepton channel: $\sigma(t\bar{t}V \to l + \text{jets} + (W \to l\,\nu) \text{ or } (Z \to l\,l))$

CMS-TOP-12-014





First measurement of *ttV*:

- Result combining all 7 channels:

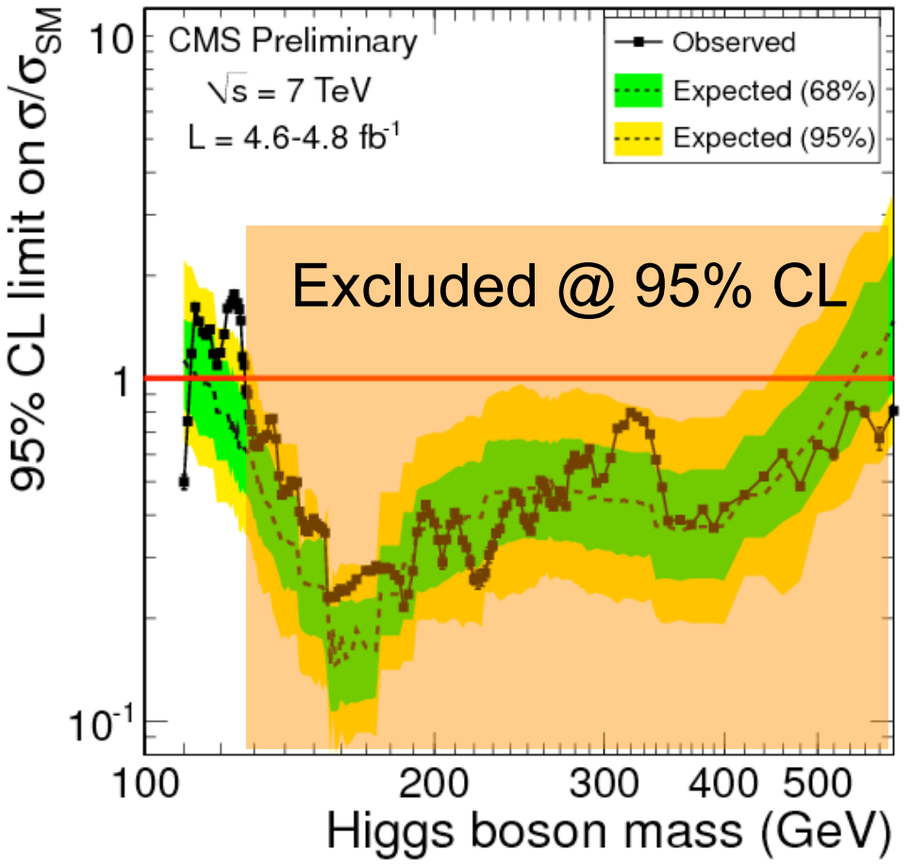
$$\sigma(t\bar{t}V) = 0.51^{+0.15}_{-0.13}(\text{stat.})^{+0.04}_{-0.02}(\text{syst.})\ \text{pb}$$

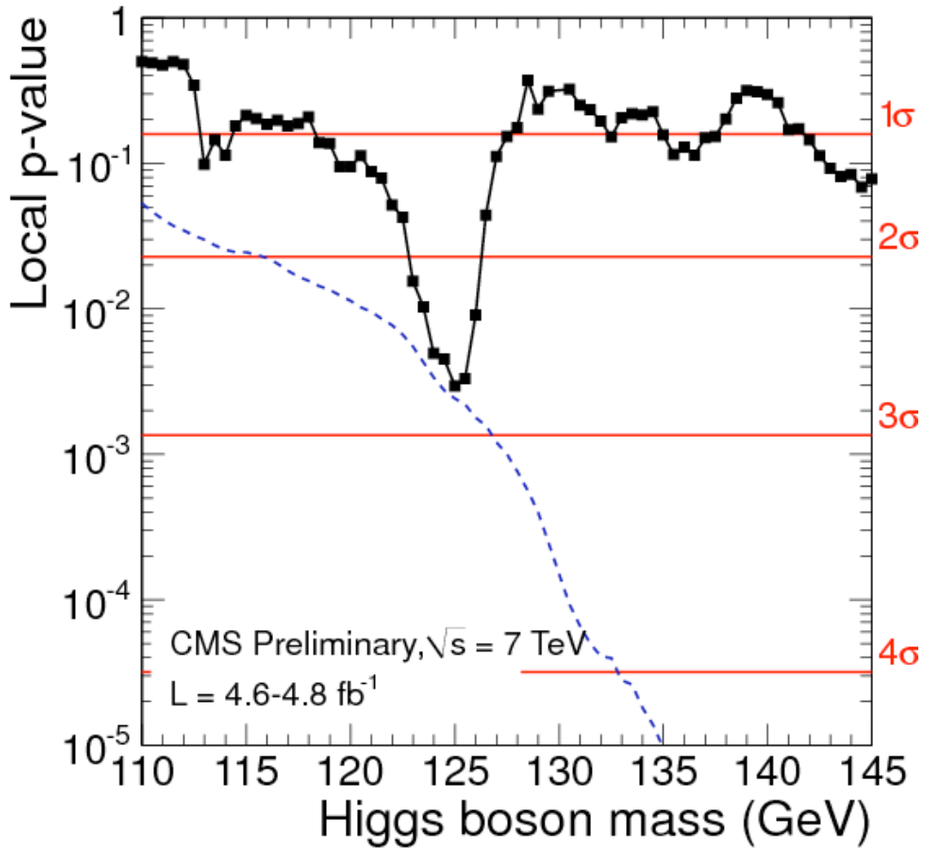
➔ Significance of 4.67 σ

HIGGS SEARCH: SITUATION @ MARCH 2012

Excluded SM higgs in 127.5-600 GeV range @ 95% CL

Close to 2.8σ excess at ~ 125 GeV (similar for ATLAS), 2.1σ after look else-where correction (110-145 GeV)



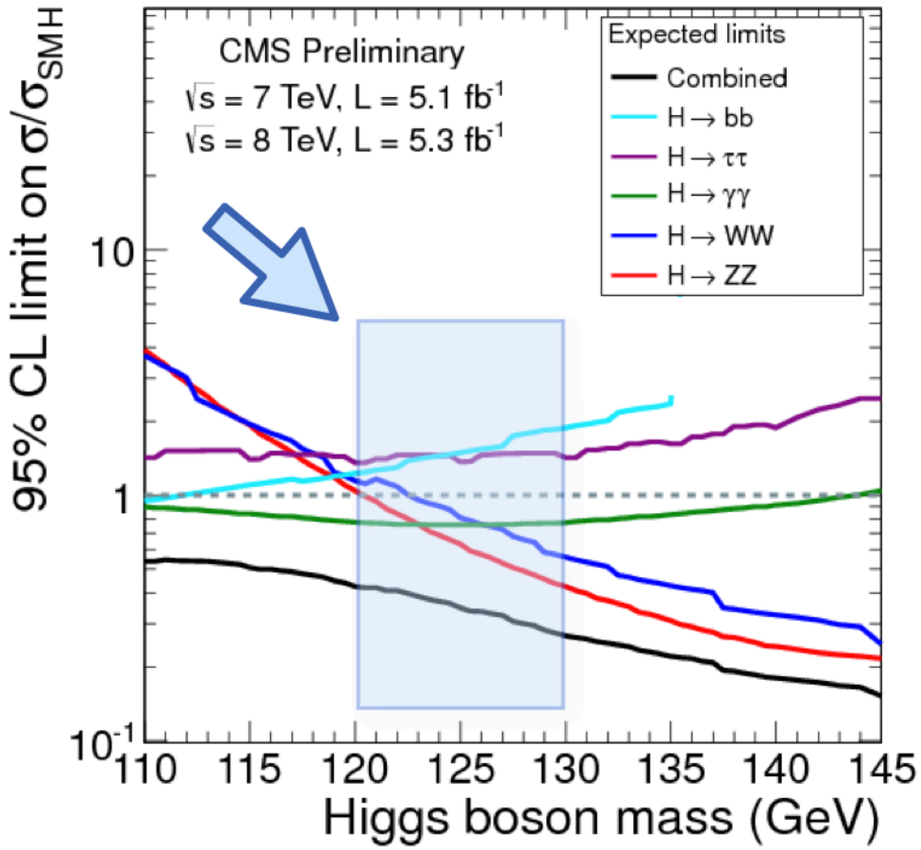


- After March analysis were blinded
  - Re-optimization performed only using simulation
  - Analysis validated in data using control regions

HIGGS ANALYSIS IN A NUTSHELL

Higgs search strategy designed to cover the full mass range

mode	signature	S/B	Mass Resol.	N events in 10fb^{-1}	Good For
H→bb	two b-jets, Z or W, bb inv. mass	low O(0.1)	10%	~10^5 ~30 (sel)	couplings to fermions
H→ττ	had tau, leptons, MET	low O(0.1)	15%	~10^4 ~20 (sel)	couplings to fermions
H→WW	two leptons with opposite charge MET	medium O(1)	-	~10^3 ~60 (sel)	cross section, BR, couplings to V
H→γγ	two photons peak in inv. mass	low O(0.1)	2%	400 ~200 (sel)	H mass, couplings $C_V C_F$, discovery
H→ZZ	four leptons with right charge peaks in inv. mass (Z_1 and Higgs)	high >1	1-2%	20 ~6 (sel)	H mass, discovery



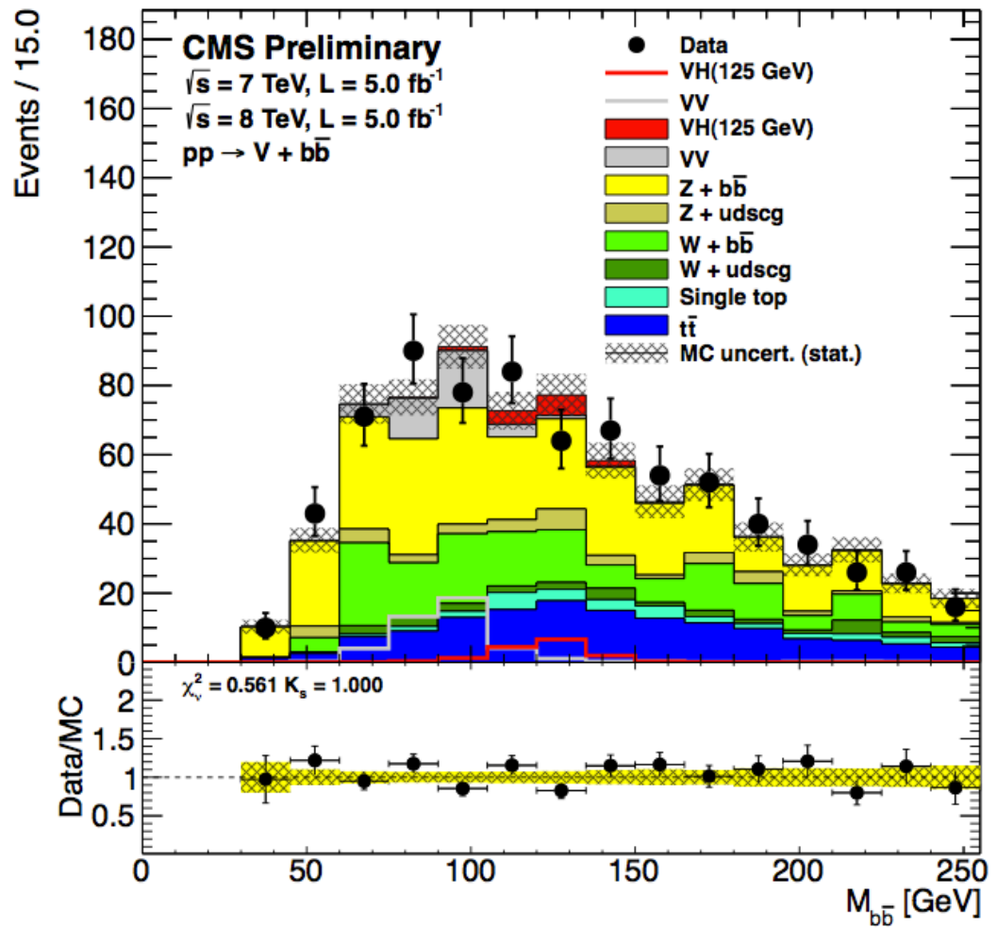
@125 GeV all analysis shows very good sensitivity

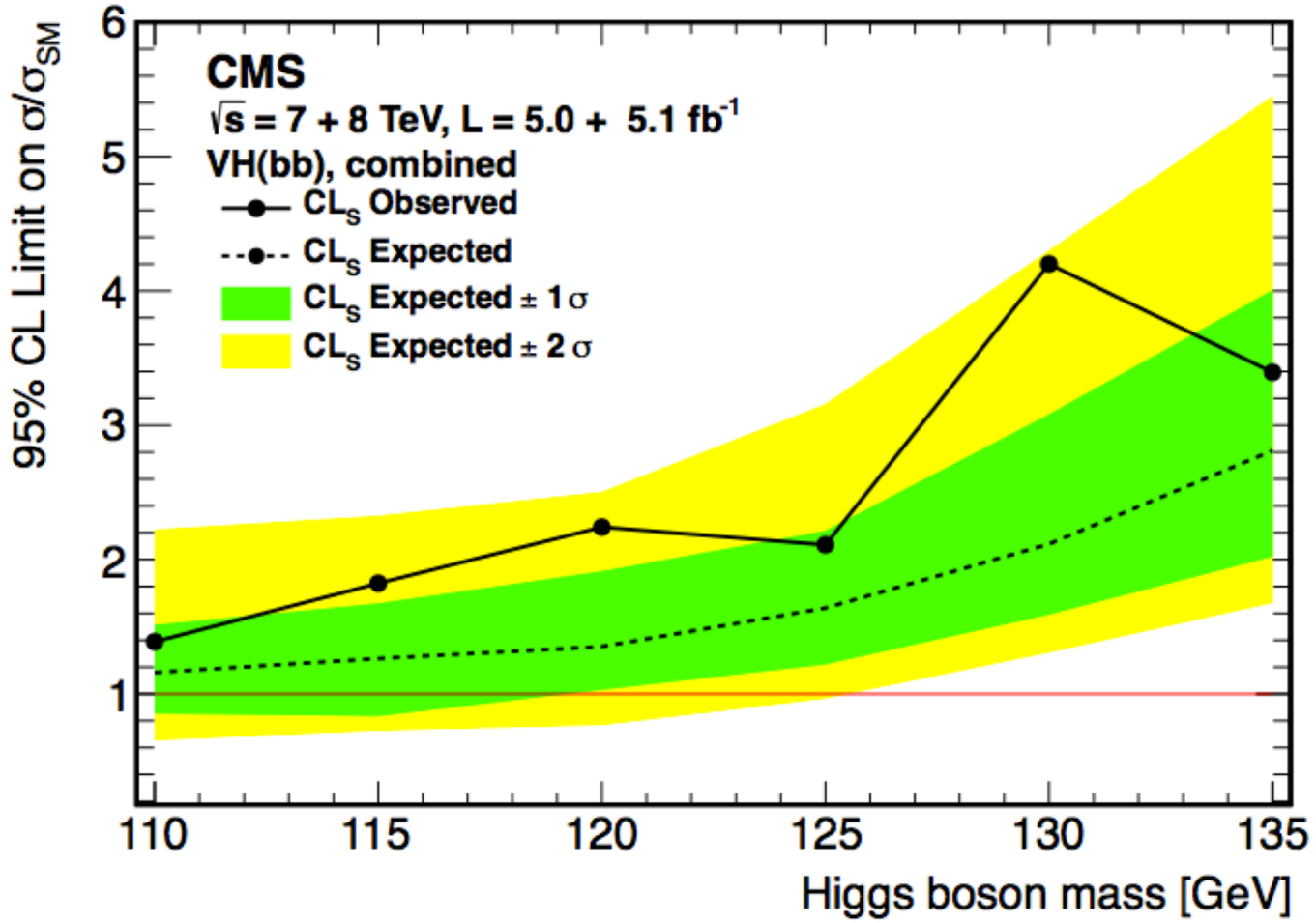
- redundant measurement, possibility to compare different decay modes
- allows measurement of Higgs properties

H → bb

- **Two b-jets** with high pT
- Overwhelming background reduced **requiring associated Z,W**
- Analysis improvements wrt 2011 ~ 50% in sensitivity
- Results: **broad excess compatible with presence of 1xSM Higgs**

CMS-HIG-12-019

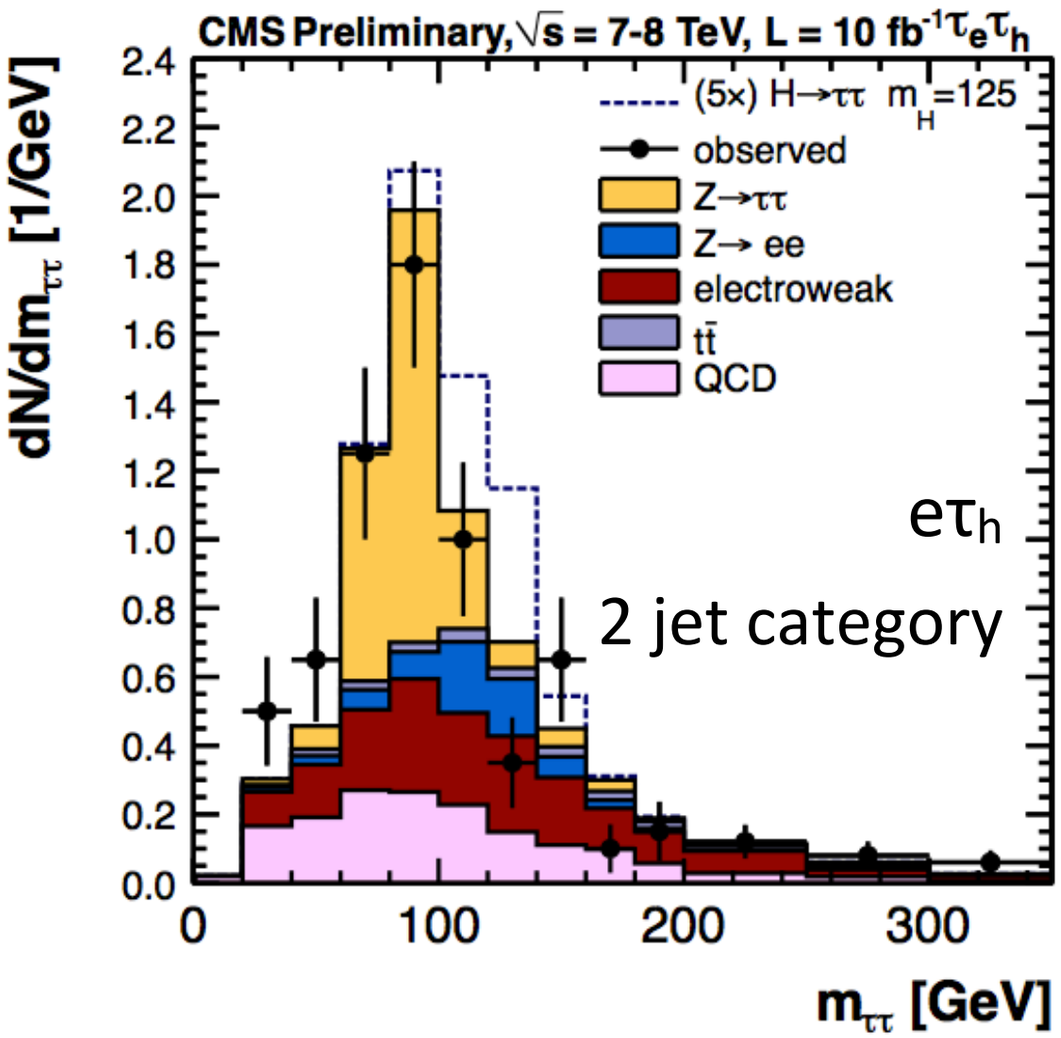


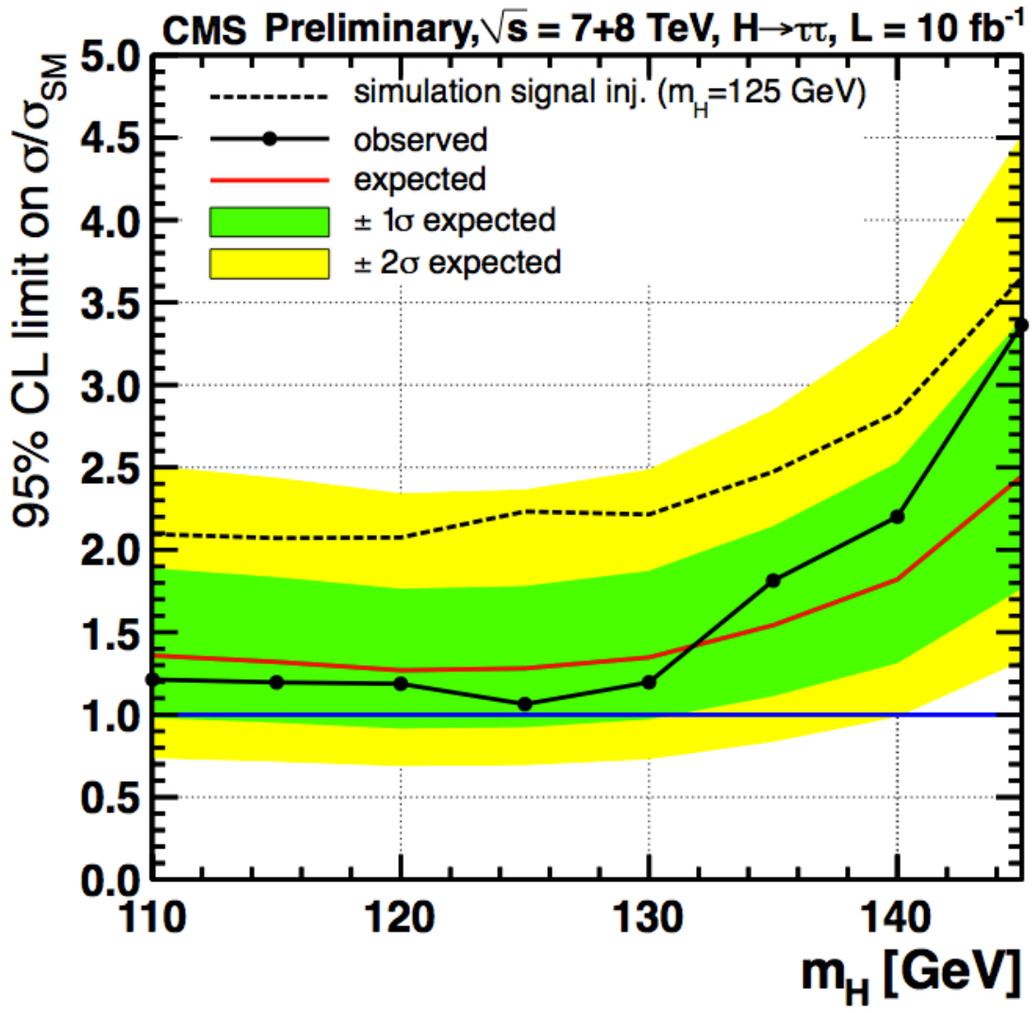


$H \rightarrow \tau\tau$

- **No significant excess** wrt SM background
  - very broad excess expected
- **Sensitivity close to 1xSM Higgs** (improved by about 70% wrt 2011)

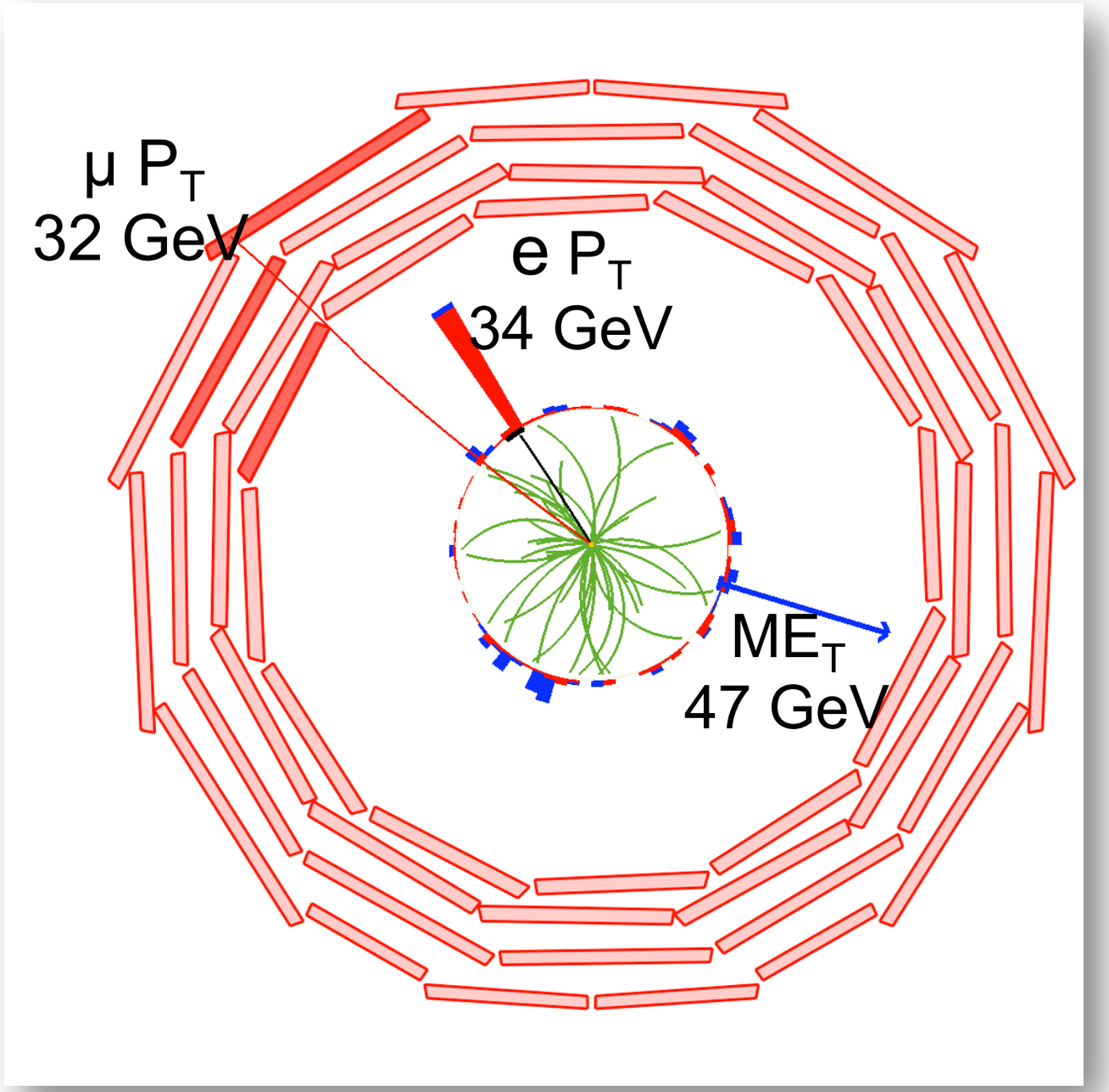
CMS-HIG-12-018





H → WW

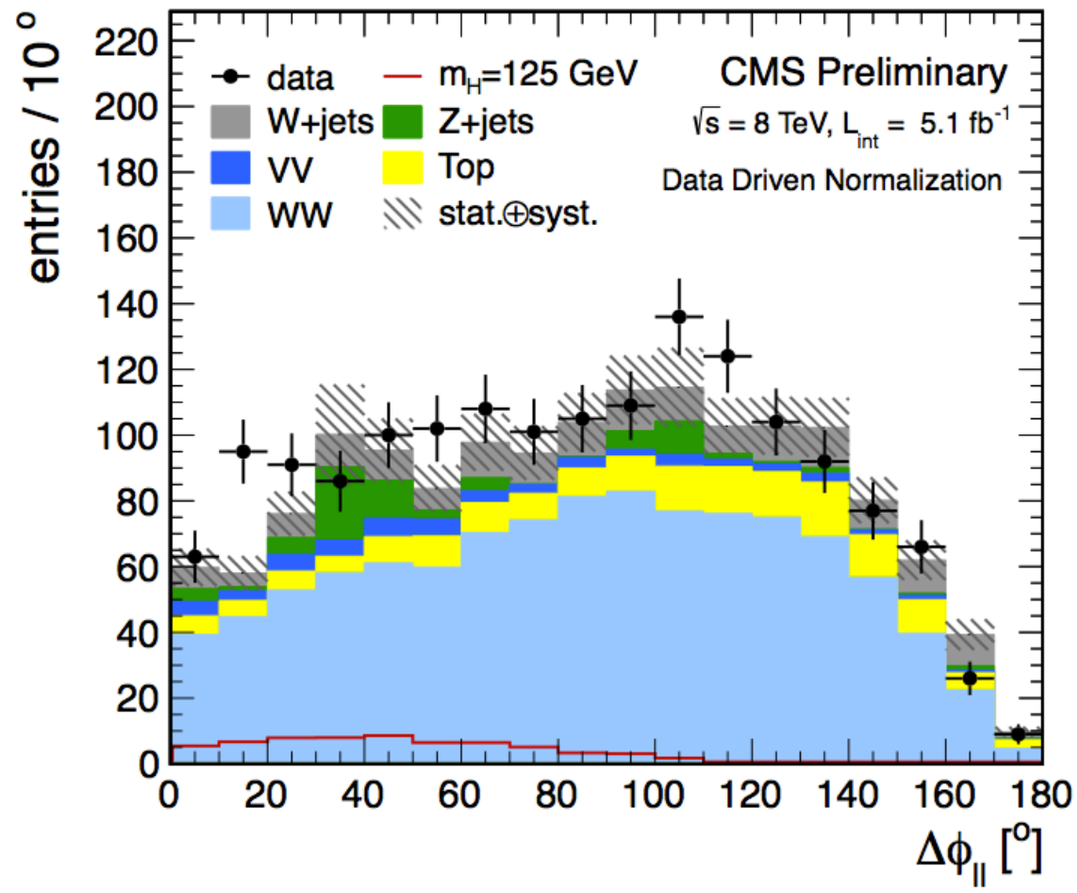
- **Two leptons with opposite charge**
- **Large missing ET**
- **6 categories**
  - 0 jet, 1 jet and 2 jet (VBF)
  - same and different flavor
- **Kinematic variables** to reject background (most discriminant $\Delta\phi_{ll}$ and m_{ll})
- Main background is **ttbar and irreducible WW** (from control samples)

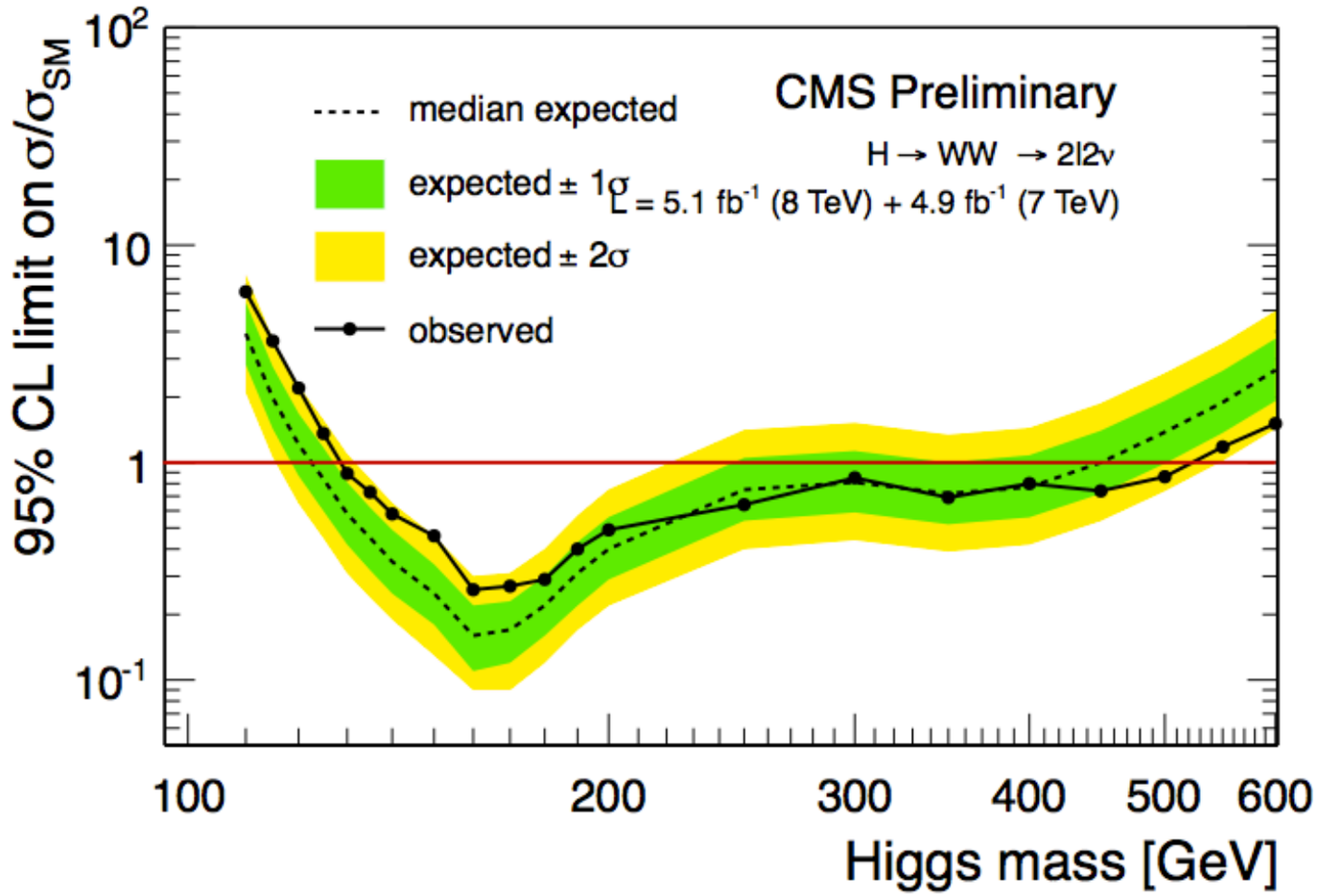


H → WW: RESULTS

- **Broad excess compatible with presence of 1xSM Higgs**

CMS-HIG-12-017

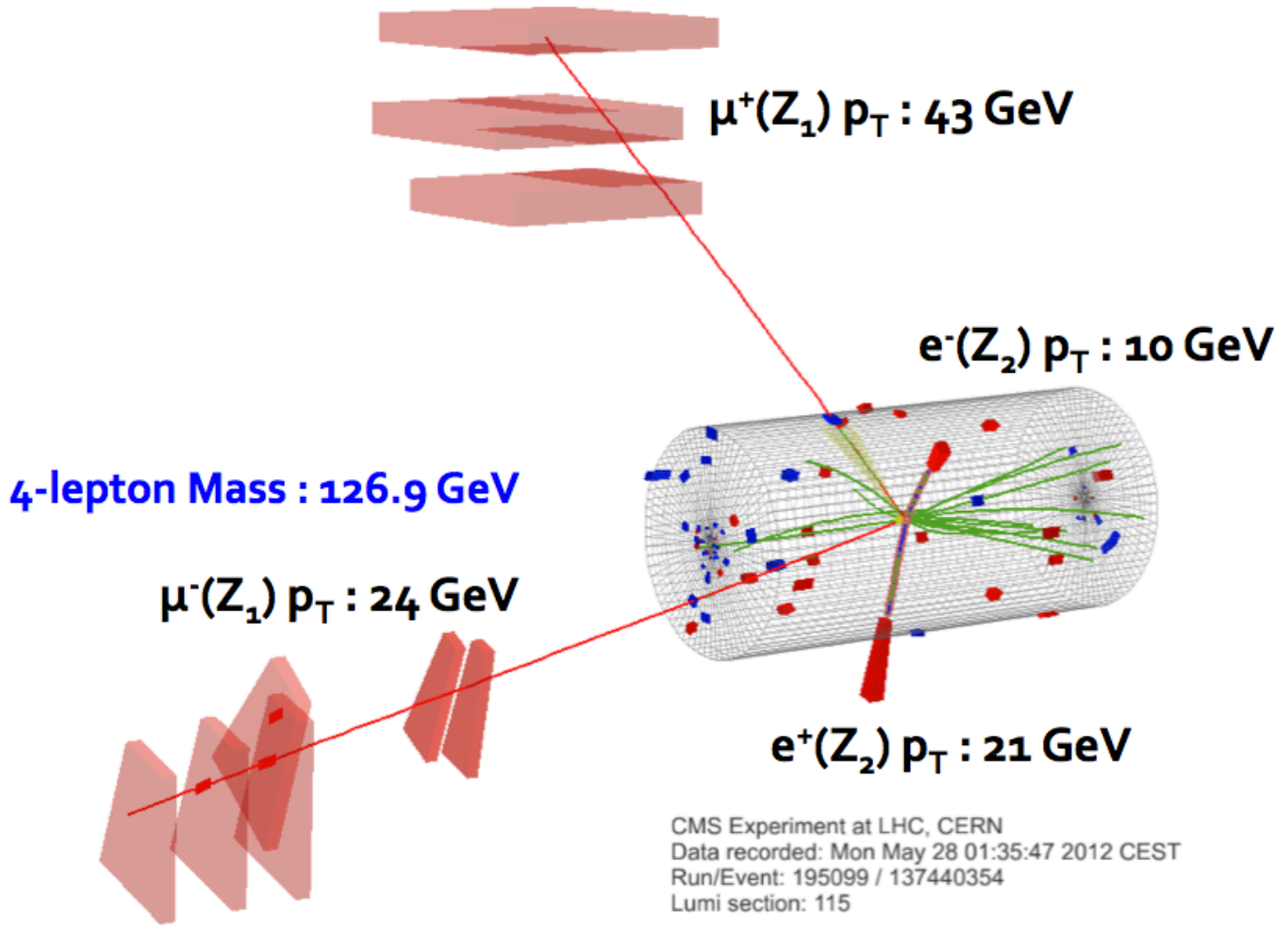




H → ZZ

- **Extremely clean analysis**
  - four leptons with proper flavor, tiny contamination from jets
  - **Three modes** eeee, eeμμ, μμμμ

>20% improvement for wrt 2011 analysis

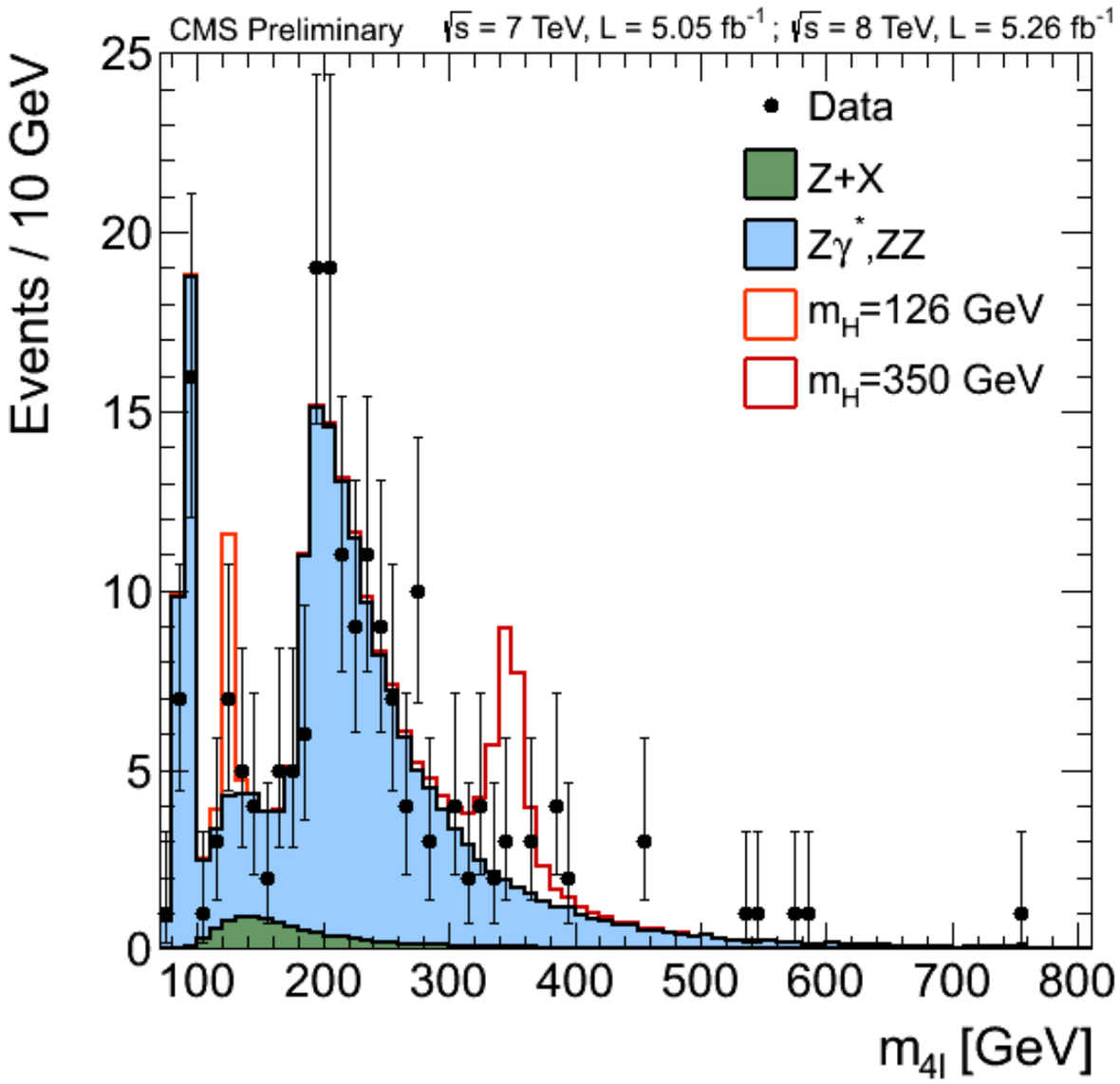


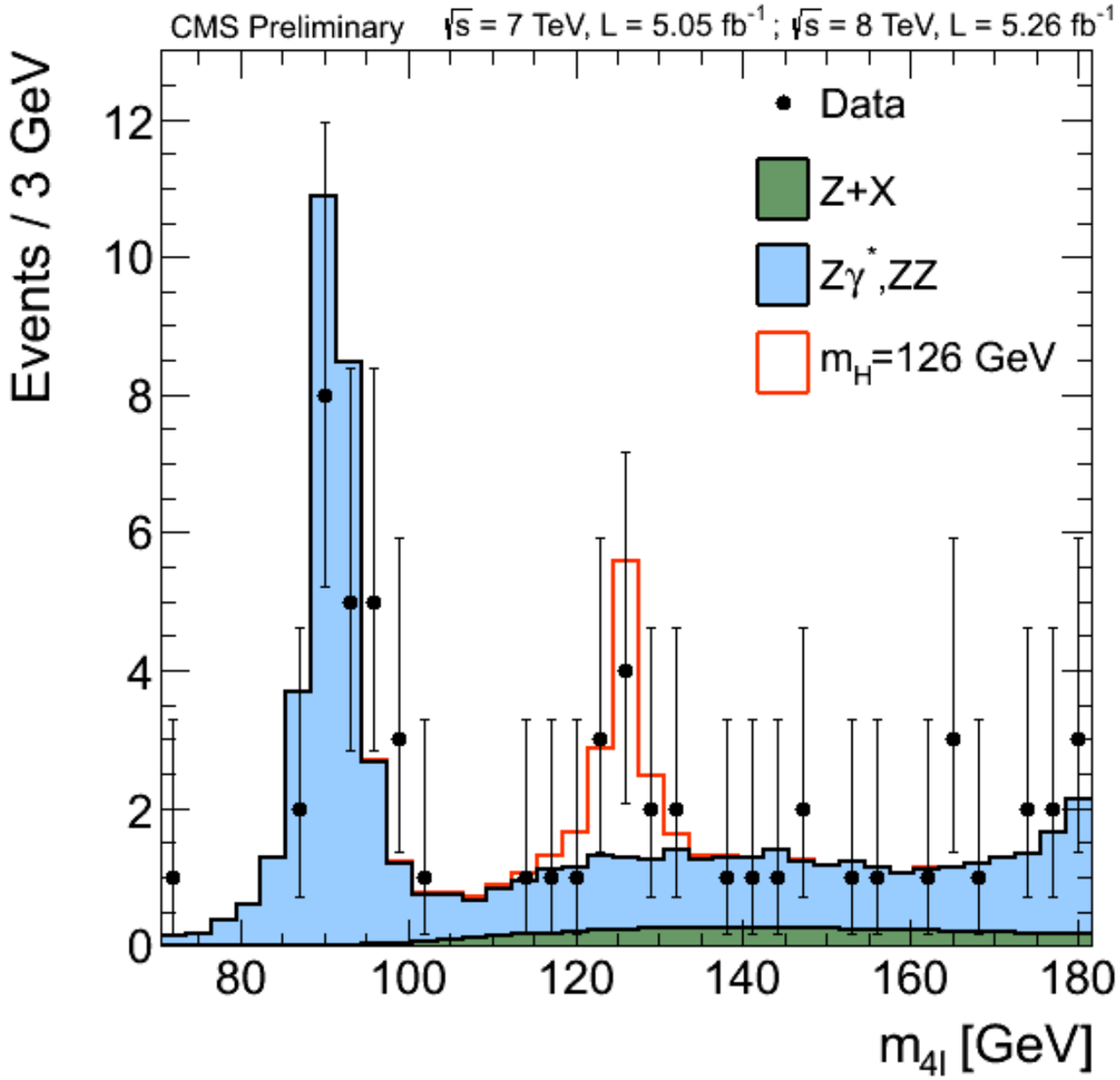
MASS SPECTRUM

Normalization and background shape ok

Excess at ~126GeV

A bit less abundant than SM prediction (ok within errors)

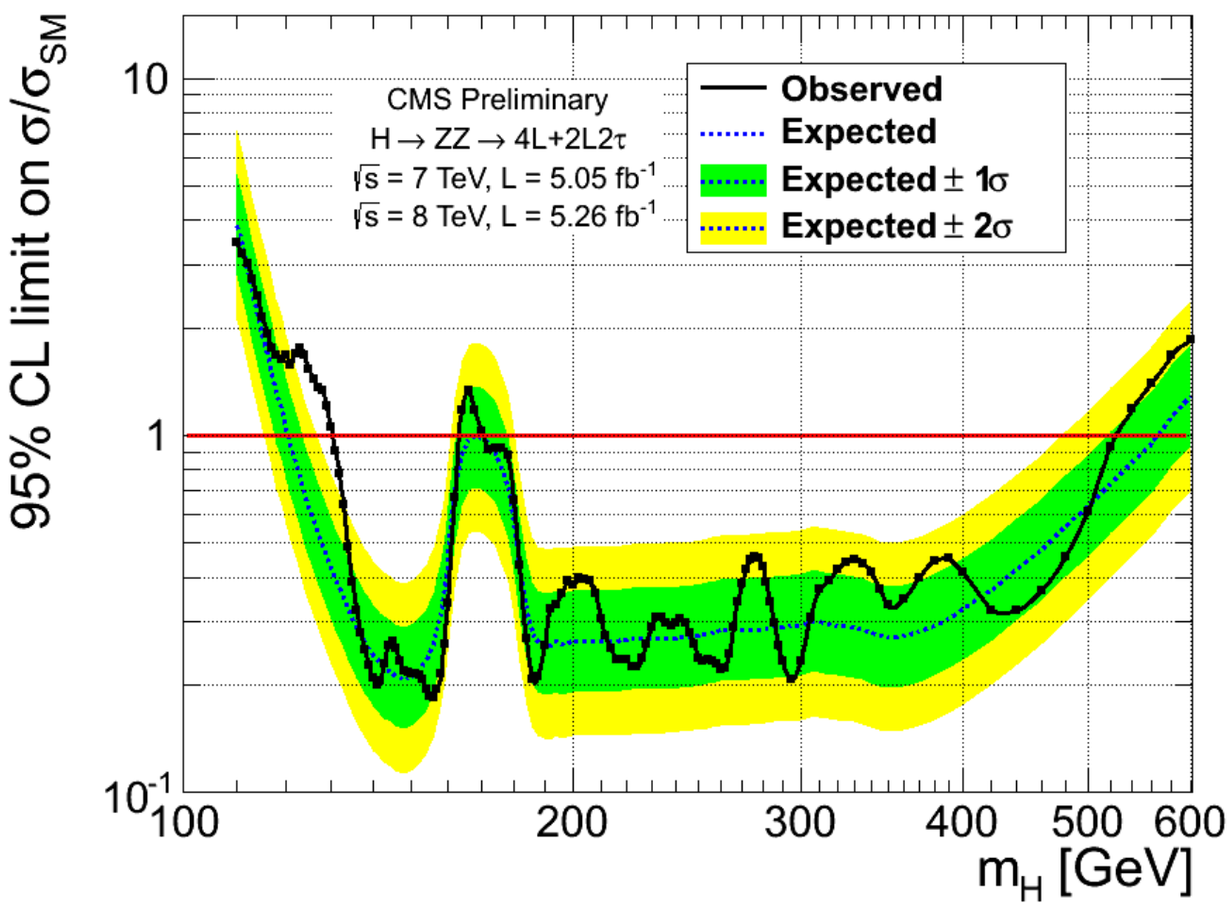


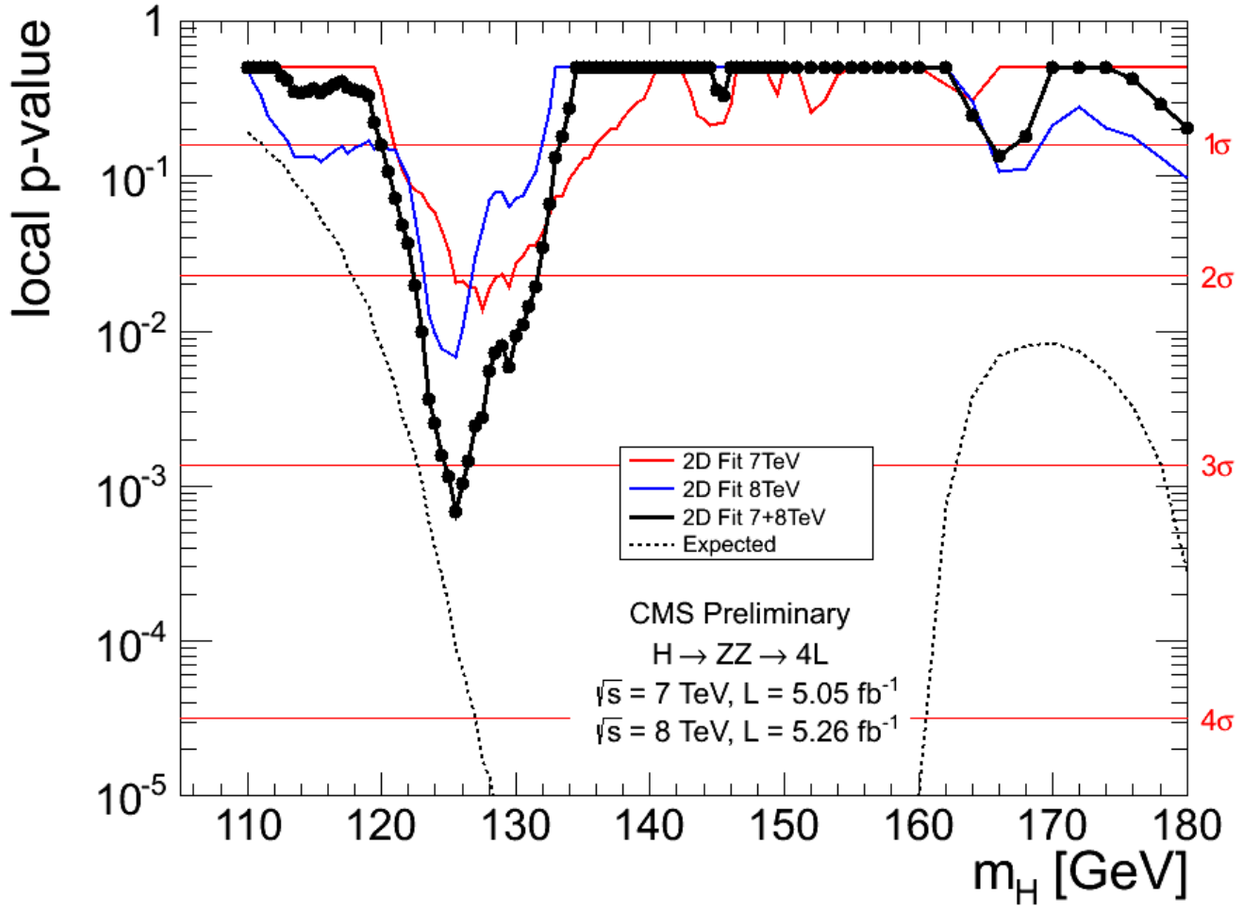


H → ZZ: Resulting Limit and P-Value

- **Excess at ~125.6 GeV**
  - **observed 3.2σ, expected 3.8σ**
- **Resulting strength at 125.6 GeV: $\mu = \sigma/\sigma_{SM} \sim 0.7$**
- ZZ alone excludes almost full mass region

CMS-HIG-12-016





$H \rightarrow \gamma\gamma$

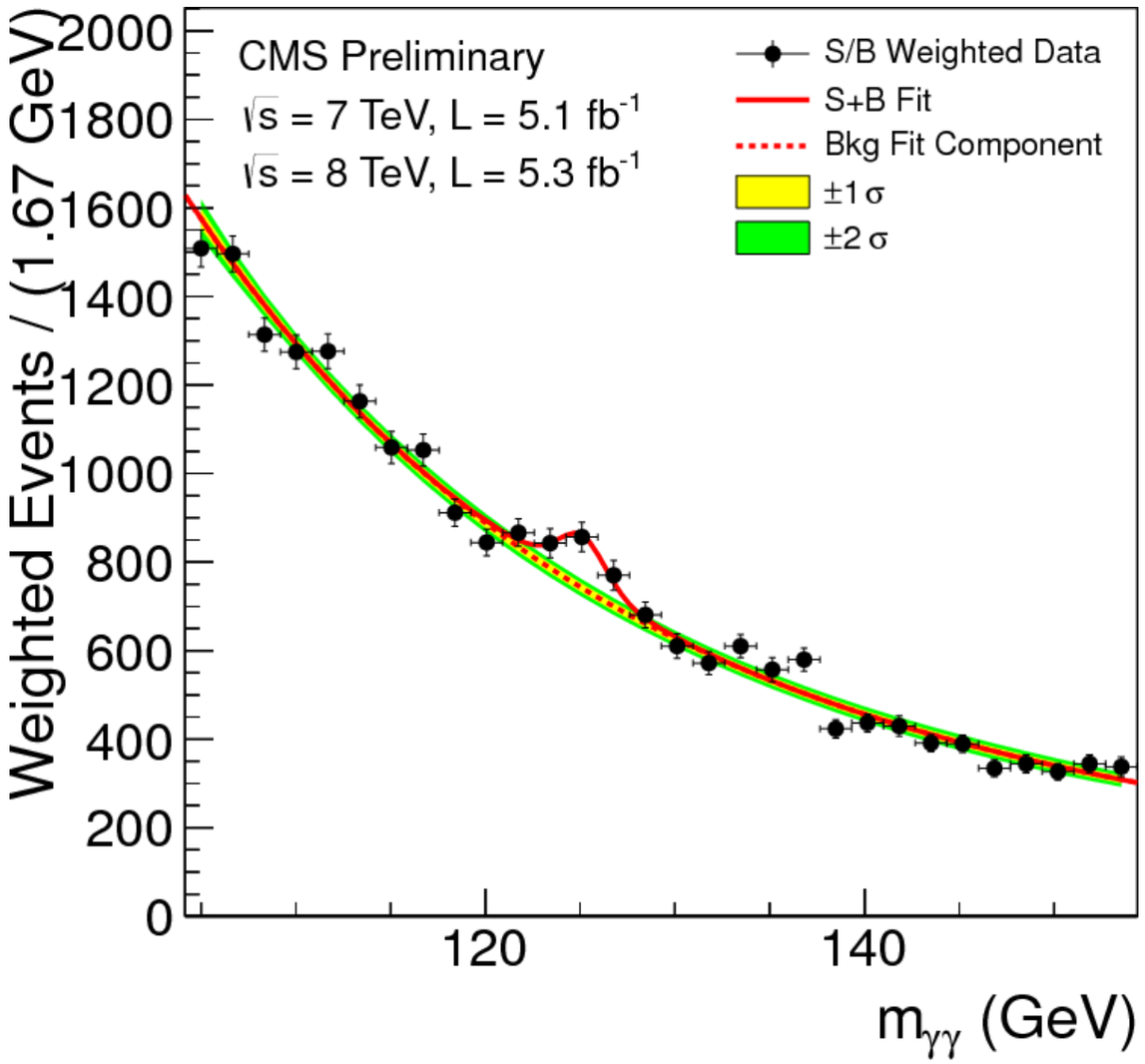
Analysis very advanced: makes use of several multivariate techniques to enhance the small S/B signal

STEP	CRITICAL ISSUES
1) two isolated photons with large transverse momentum	• isolation to reject γ+jet and QCD background
2) di-photon mass reconstruction $m_H^2 = 2E_1E_2(1-cos\theta)$	• vertex determination in presence of multiple interactions pile-up (PU) • energy scale and resolution
3) signal extraction	• event categories to maximize sensitivity: MVA categories + di-jet (VBF enriched) • background shape

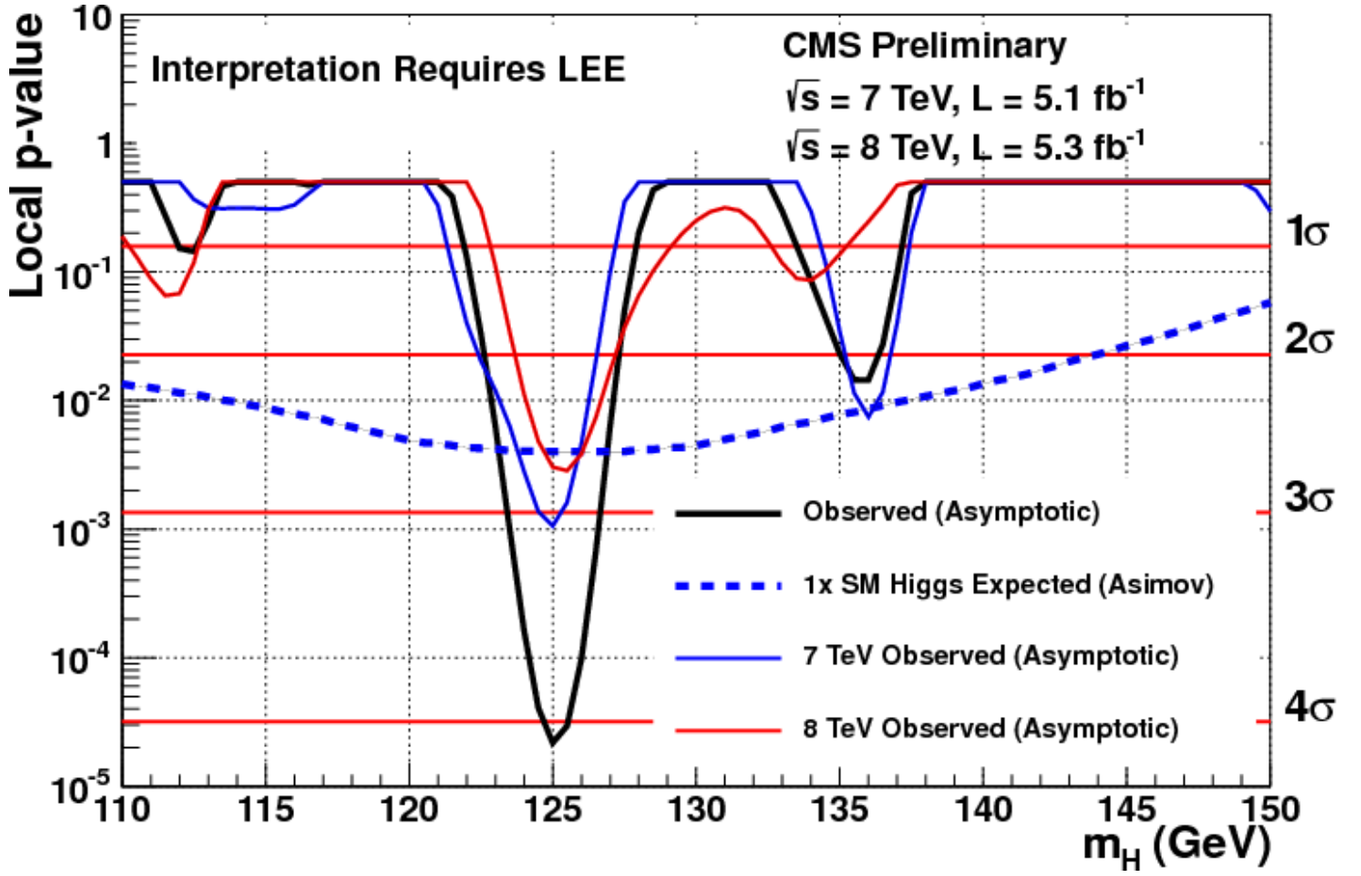
H → γγ: RESULTS

- **4.1 σ** excess at **125 GeV**
- **Very consistent between 2011 and 2012**
- Cross-checked with two alternative analyses (including fully cut based). Compatible results

events weighted by expected S/B



CMS-HIG-12-015

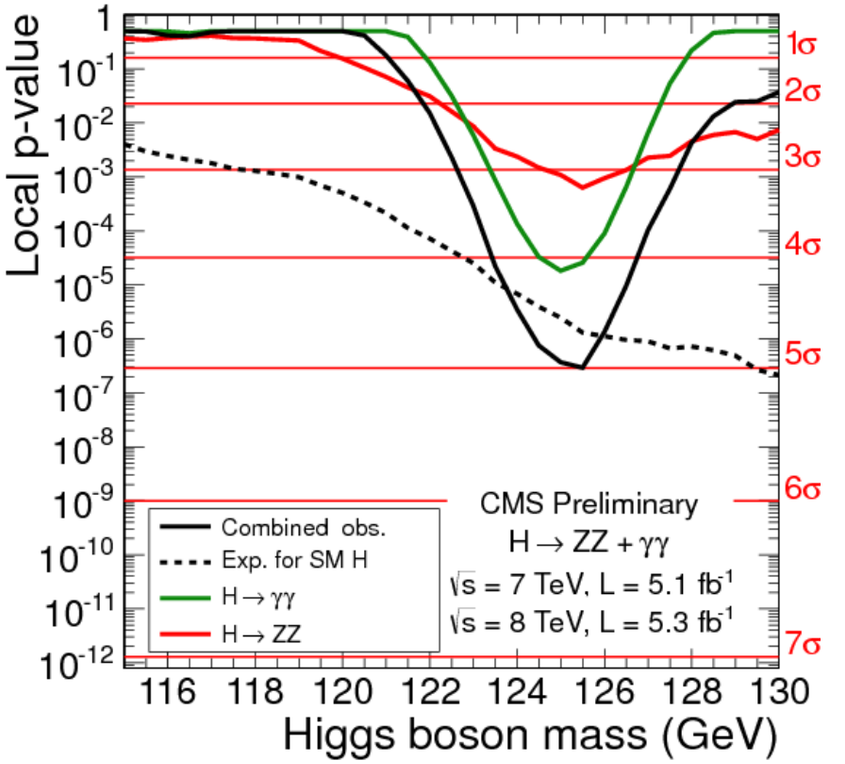


Questions on the Excess

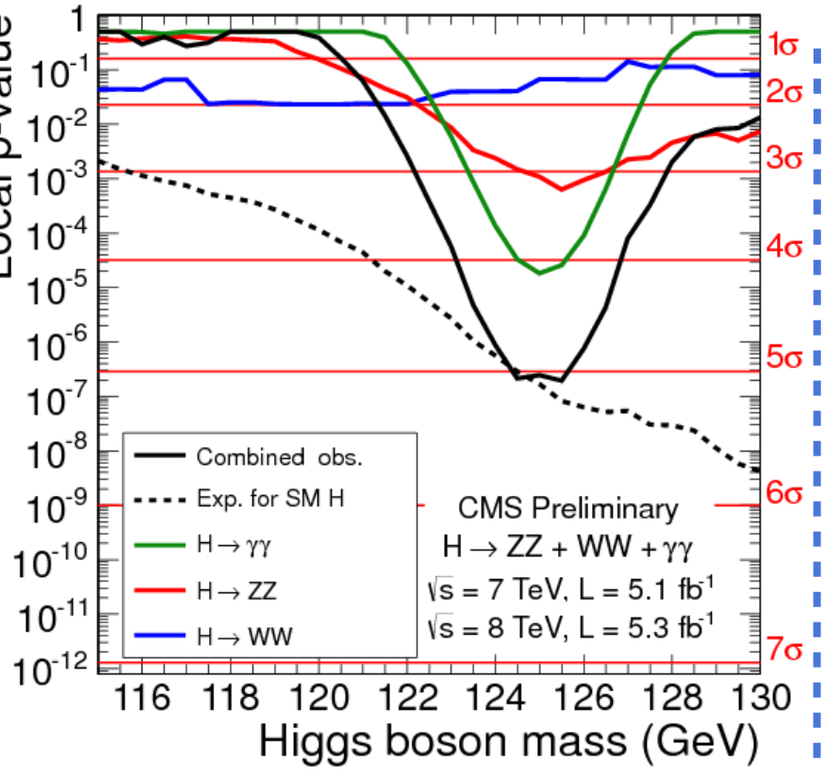
- **Is it statistically significant?**
- **Is it a boson?**
- **Which is the mass?**
- **Is it "the" SM Higgs boson?**
- **Is it "a" Higgs boson?**

P-Value Evolution Adding Modes

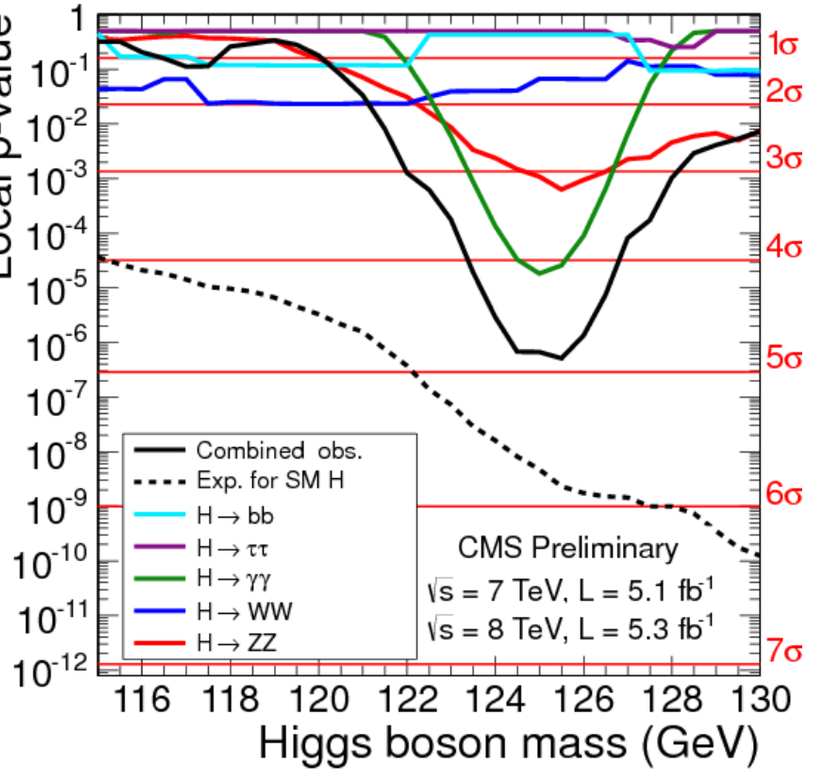
CMS-HIG-12-020



- **γγ and ZZ combo only**
- 5σ excess (exp. 4.7σ)
- Is it a boson?
  - Yes, for instance significance from di-photon channel



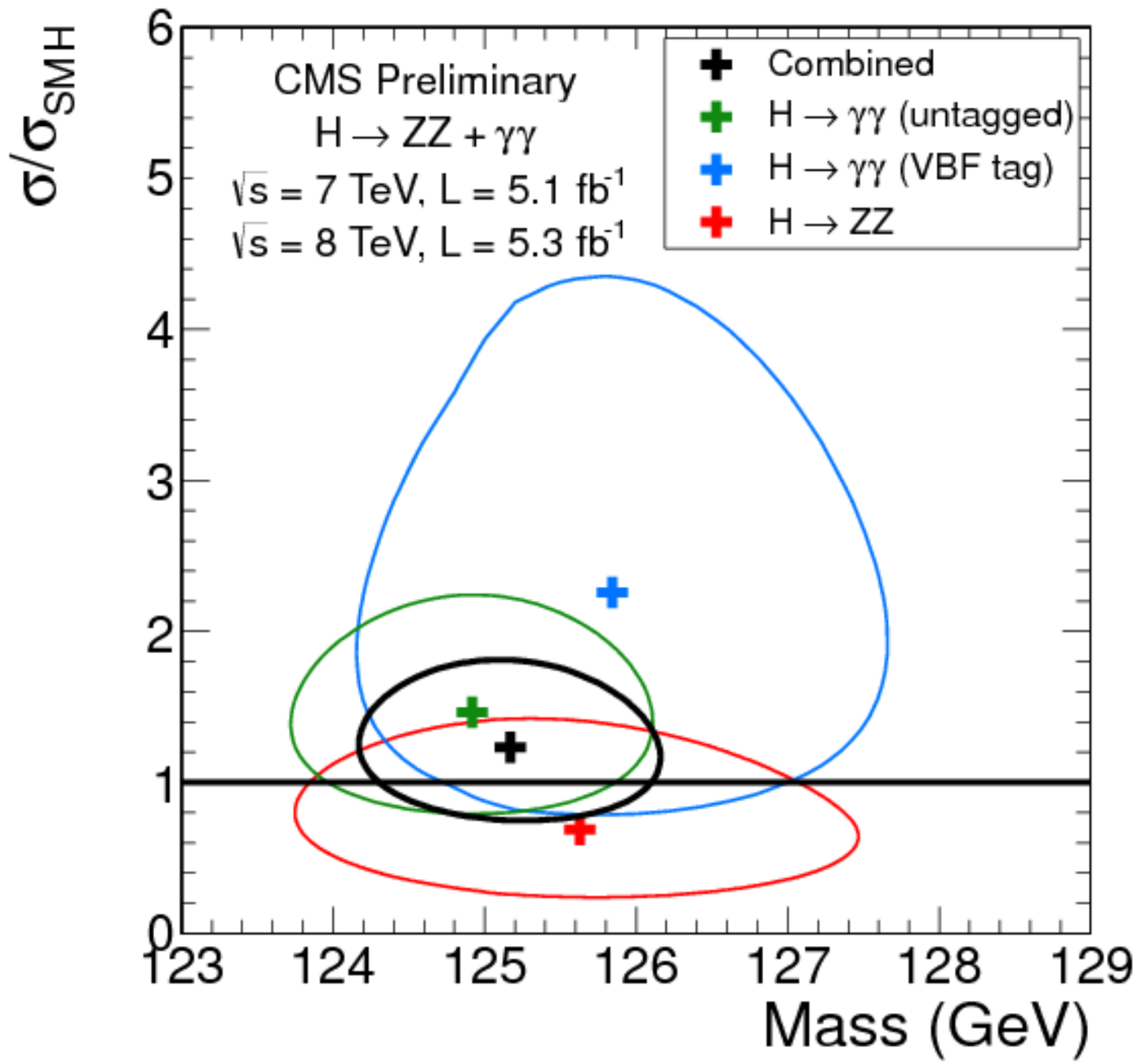
- **adding WW**
- 5.1σ excess (exp. 5.2σ)



- **all channels together**
- 4.9σ excess (exp. 5.9σ)

STARTING TO MEASURE PROPERTIES: MASS OF THE BOSON

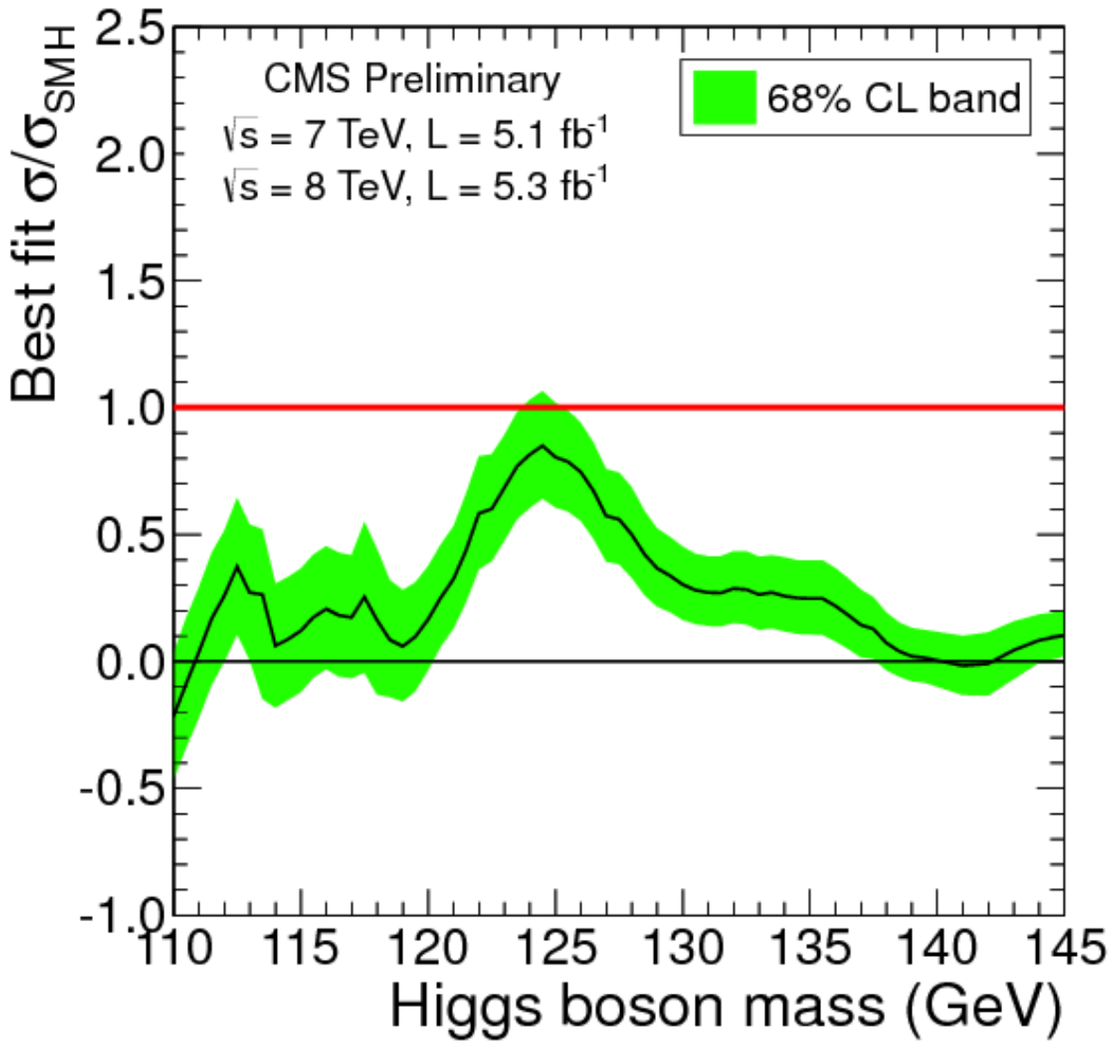
- Mass derived from **most sensitive channels** (best resolution)
  - H→γγ
  - H→γγ dijet (VBF enriched)
  - H→ZZ
- Likelihood scan (mass vs σ)
- Systematics mainly from **ECAL energy scale**

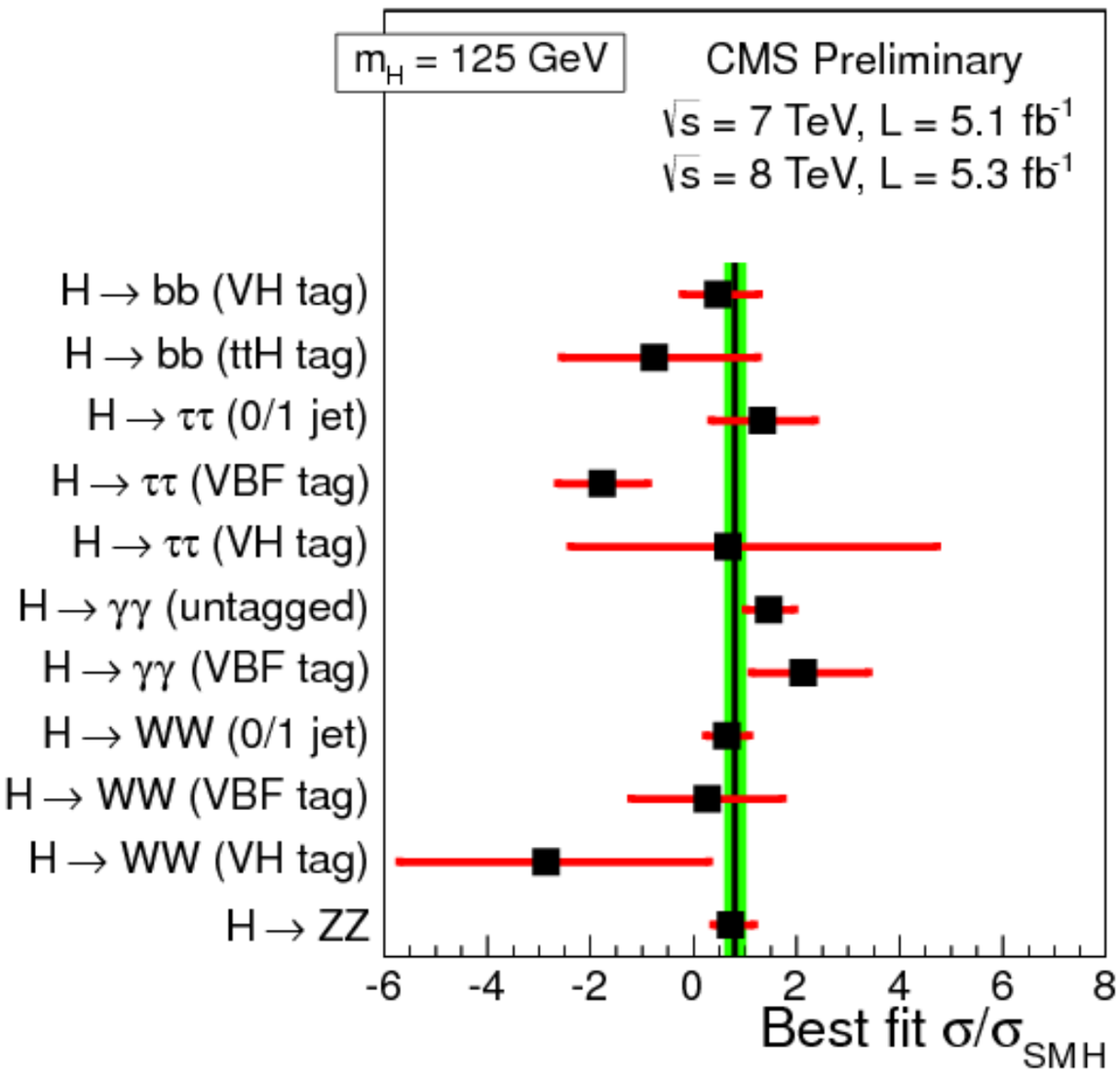


m = 125.3 ± 0.4 (stat) ±0.5 (syst) GeV

COMPATIBILITY WITH SM HIGGS

- Best fit SM **strength at 125GeV: $\mu = \sigma/\sigma_{SM} = 0.80 \pm 0.22$**
- **Good agreement among modes**
  - **exceptions**: $\tau\tau$ (small), $\gamma\gamma$ (large, about 1.6xSM)

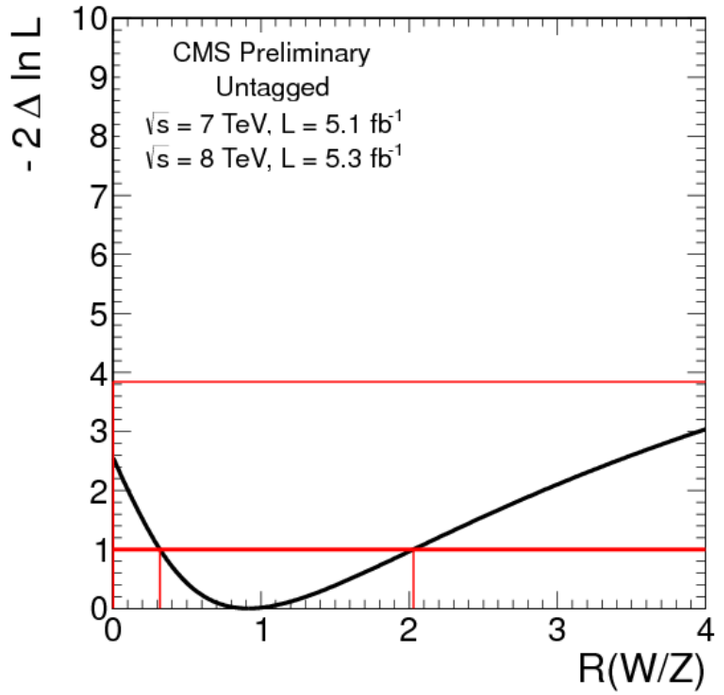




Is It the SM Higgs?

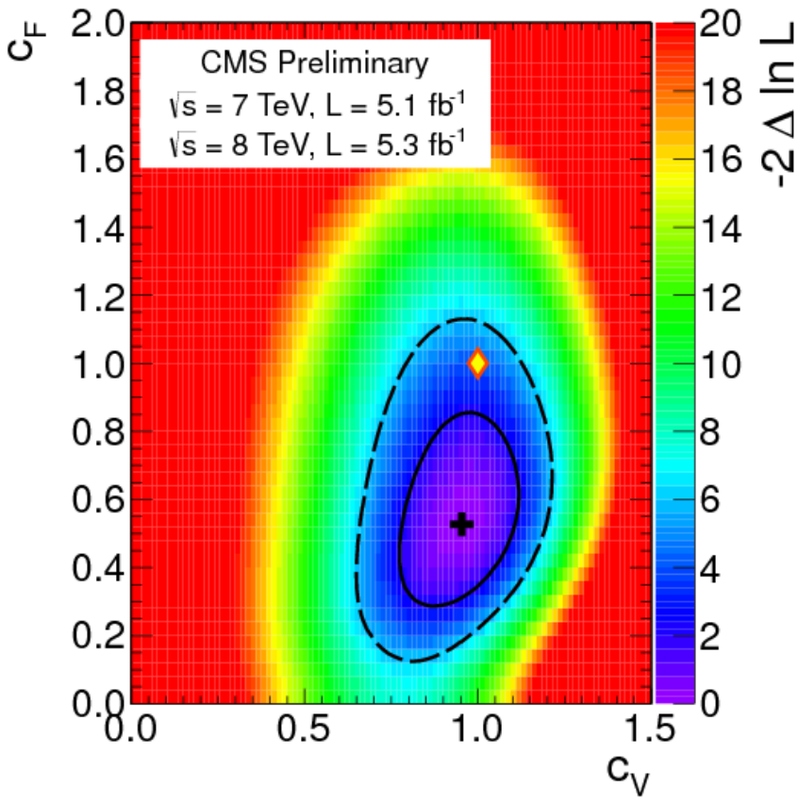
Ratio sensitive to coupling to W and Z bosons (g_{HWW}/g_{HZZ}) protected by gauge custodial symmetry

$$R_{WZ} = \mu_{WW}/\mu_{ZZ} = 0.9\ ^{+\ 1.1}_{-\ 0.6}$$



Another exercise: group couplings in fermionic and vectorial ones (C_F, C_V)

- Use LO prediction for loops in H→γγ and H→gg couplings
- In **agreement with SM within 95% CL**
- **Some tension** to be studied with more exclusive channels and data



BEYOND STANDARD MODEL SEARCHES

- **We believe SM is not the ultimate theory. LHC was built to understand if there is new physics at the TeV scale**
- **Does nature have any additional symmetry? SuperSymmetry (SUSY) is a very appealing theory**
  - Light Higgs: Higgs mass is protected in SUSY
  - Dark Matter: SUSY has the possibility to generate DM candidates
- **Is there any new force? Is there a new generation of particle? Are there extra-dimensions?**

- Broad CMS program for searches
  - **I will just show few results from analysis already updated with 8 TeV datasets**

SUSY SEARCHES @ 8 TEV

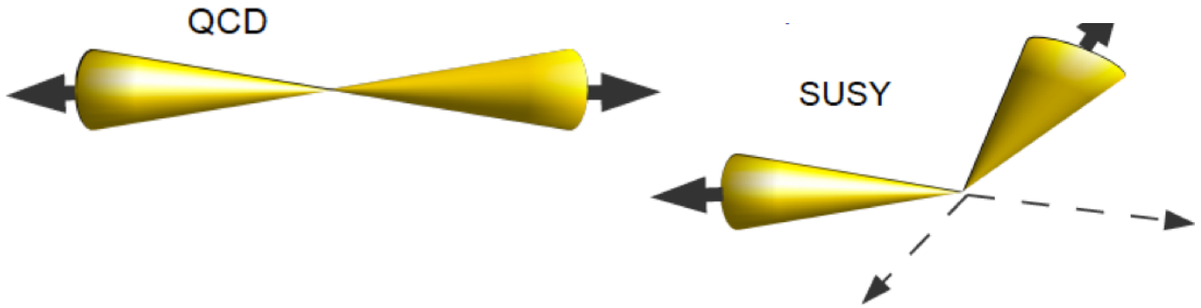
>=2 jets + MET using α_T

$$\alpha_T = \frac{E_T^{j2}}{M_T}$$

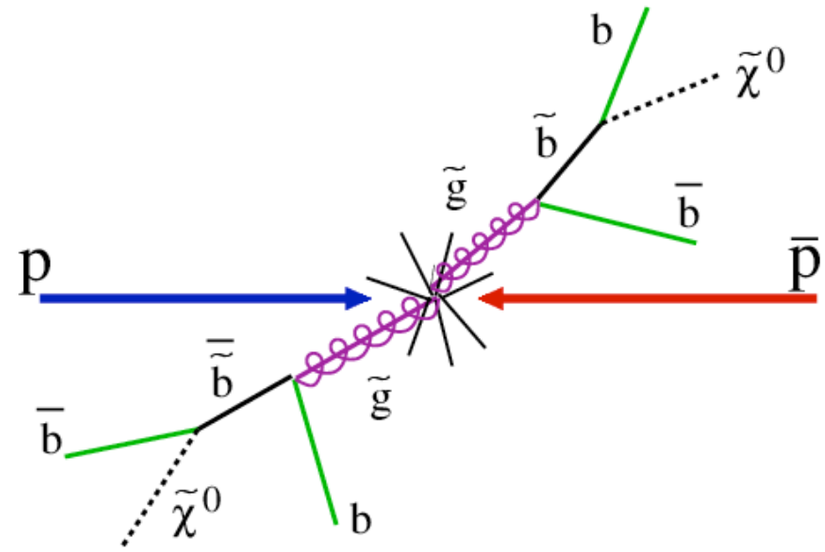
For well balanced dijet systems, $\alpha_T = 0.5$

For an multi-jet system, jets are merged to make an equivalent dijet system such that difference in E_T of two systems (ΔH_T) is minimum.

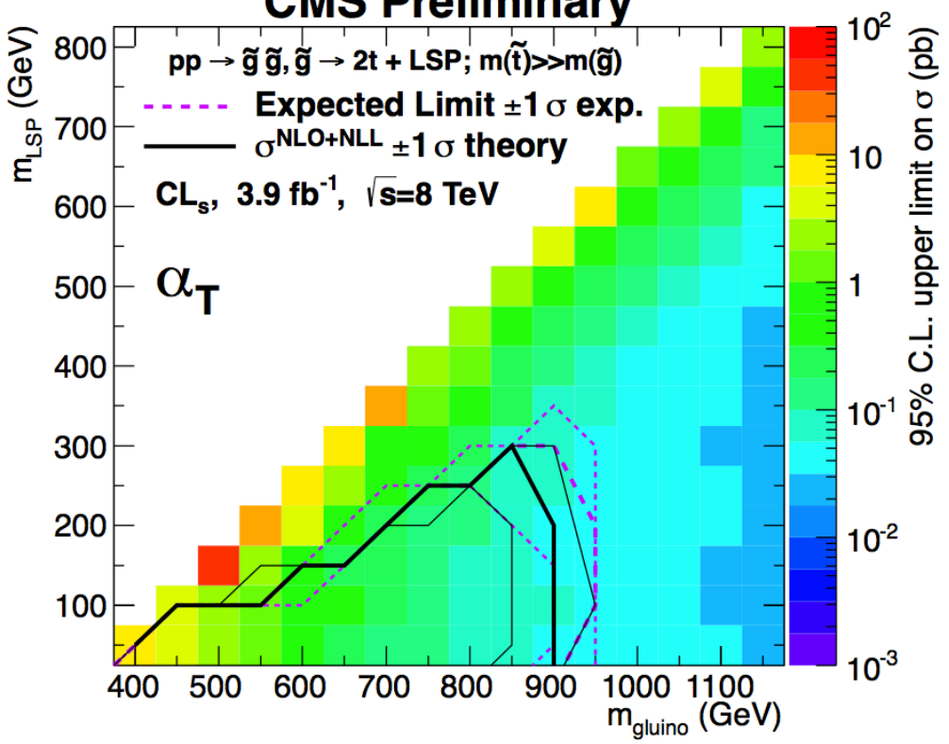
$$\alpha_T = \frac{1}{2} \cdot \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \not{H}_T^2}}$$



General purpose search for SUSY, use α_T and bins in H_T to reduce QCD
Enhancing the sensitivity to third generation squarks introducing b-tag categories
Bkg is data driven from control regions (μ+jets, μμ +jets,γ+jets)



CMS-SUS-12-016



Interpretation in simplified model where

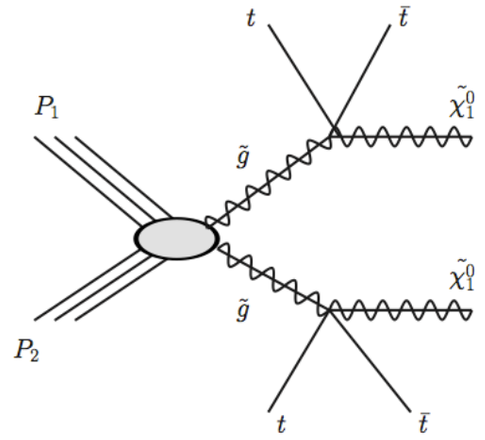
$$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$$

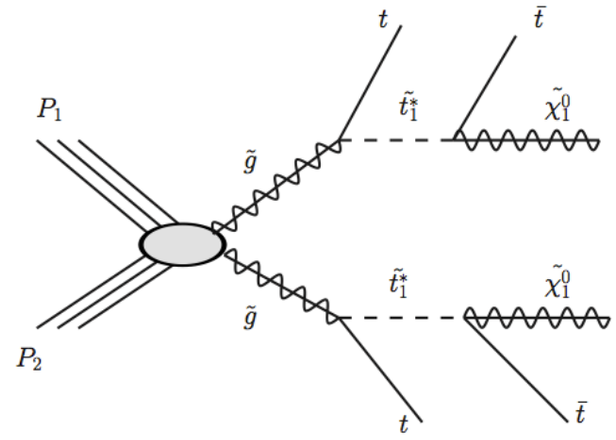
SUSY SEARCHES @ 8 TEV

2 Same sign leptons + b-jets + MET

Rare process in SM
Sensitive to many SUSY models.
Sensitivity to 3rd generation sparticles via b-tagging.

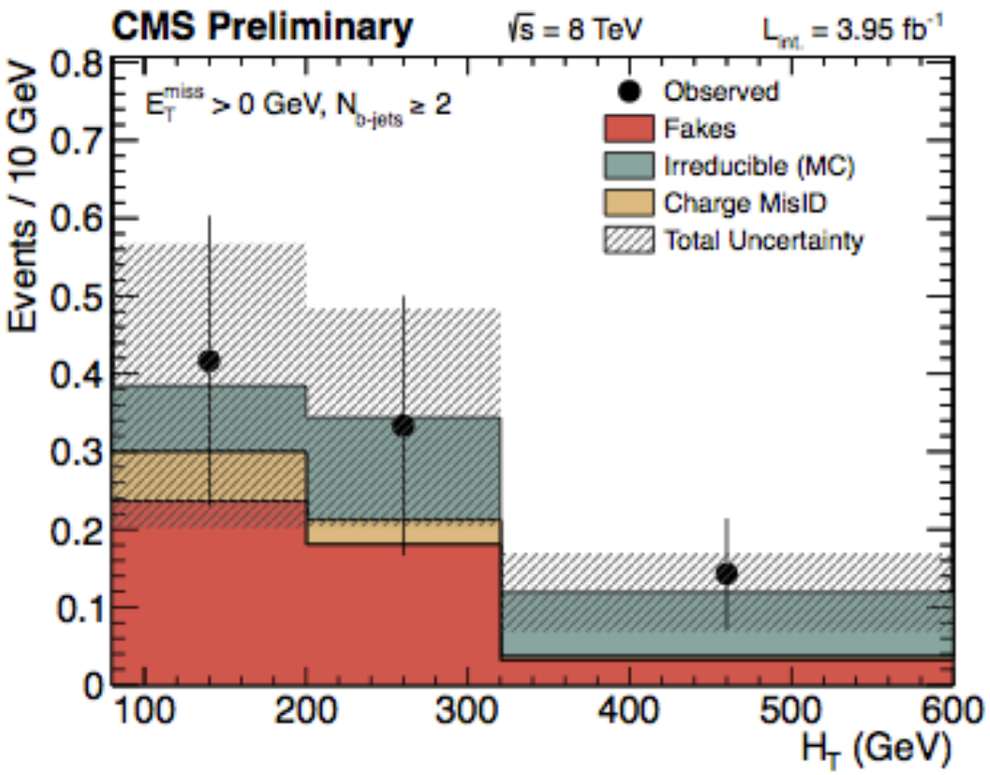
Also sensitive to anomalous uu→tt via Z' (proposed to explain forward-backward ttbar production asymmetry @ Tevatron)





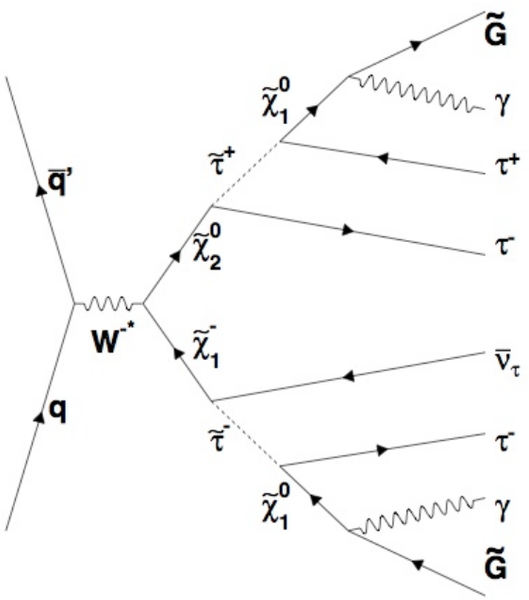
Exclusion for various SUSY simplified models
Limits in the stop-gluino mass plane up to m(stop)>700 GeV

CMS-SUS-12-017



13 events observed with H_T>80 GeV
Consistent with SM expectation

Gauge Mediated SUSY breaking: γ+2-jets+MET; γγ+jet+MET



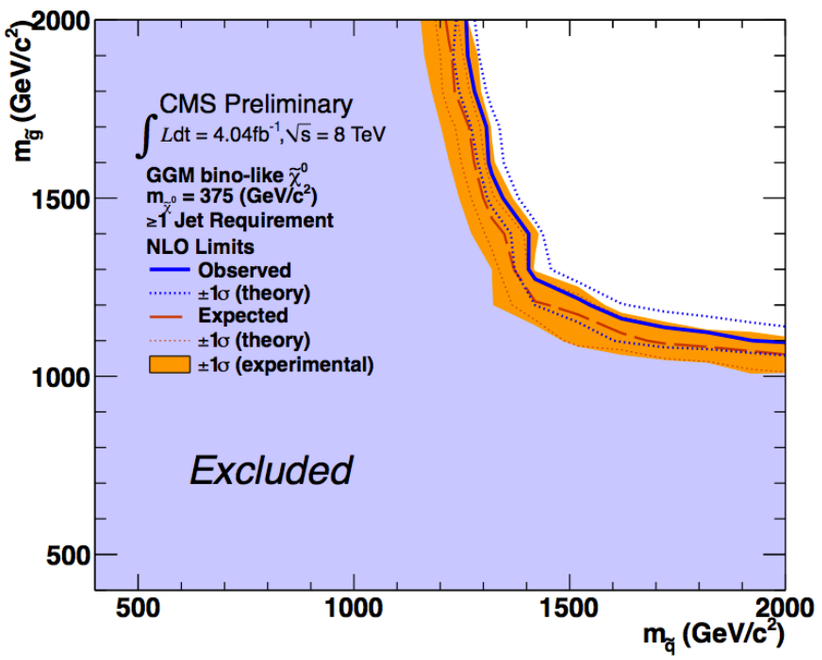
Gravitino is the LSP
Signatures with 1 or more photons

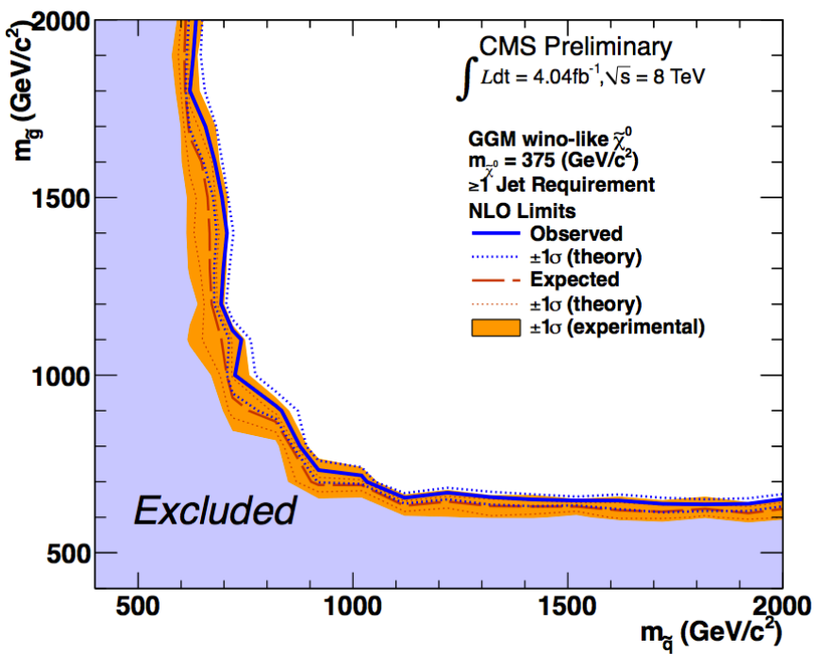
Exclusion is model dependent: in Wino-LSP scenario, chargino decays without photons suppress signal

$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + X \qquad \tilde{\chi}_1^0 \to \gamma \tilde{G}$ Photon

$\tilde{\chi}_1^\pm \to W + X \qquad M(\tilde{\chi}_1^\pm) \approx M(\tilde{\chi}_1^0)$ No photon

CMS-SUS-12-018



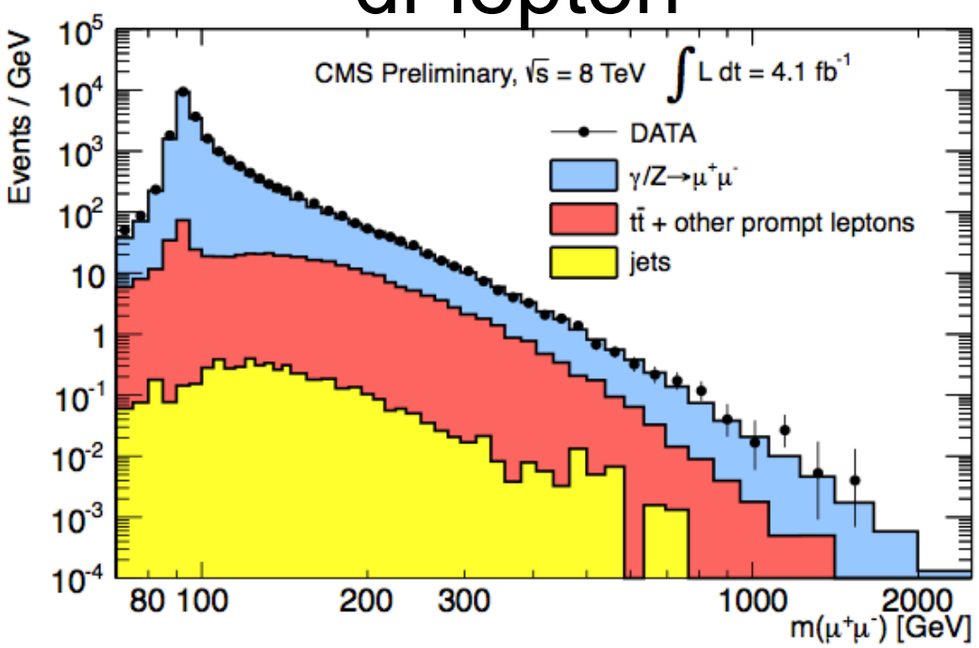


NEW RESONANCES @ 8 TEV

8 TeV data extends the reach in the current searches for a possible new resonance

- **x10 qq parton luminosity @ 4 TeV mass**

di-lepton

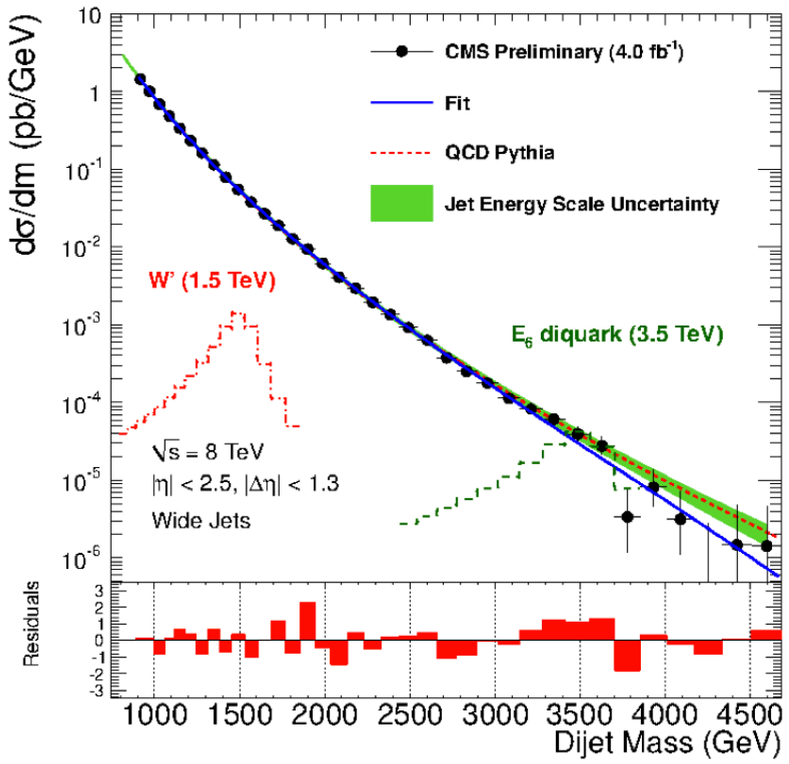


CMS-EXO-12-010
CMS-EXO-12-015
CMS-EXO-12-016

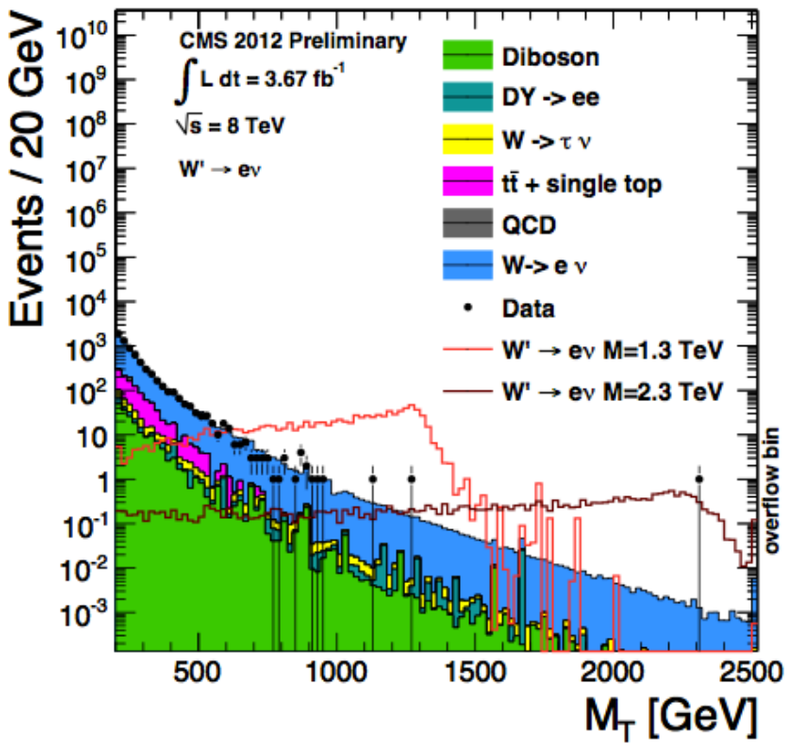
No excess seen... Setting limits

Z' (SSM)	2.5 TeV
W' (SSM)	2.8 TeV
E6 (qq)	4.2 TeV
S8 (gg)	2.5 TeV
String resonance (qg)	4.7 TeV
Λ (contact interactions)	9-12 TeV

di-jet (qq,qg, gg)



W' (lν)

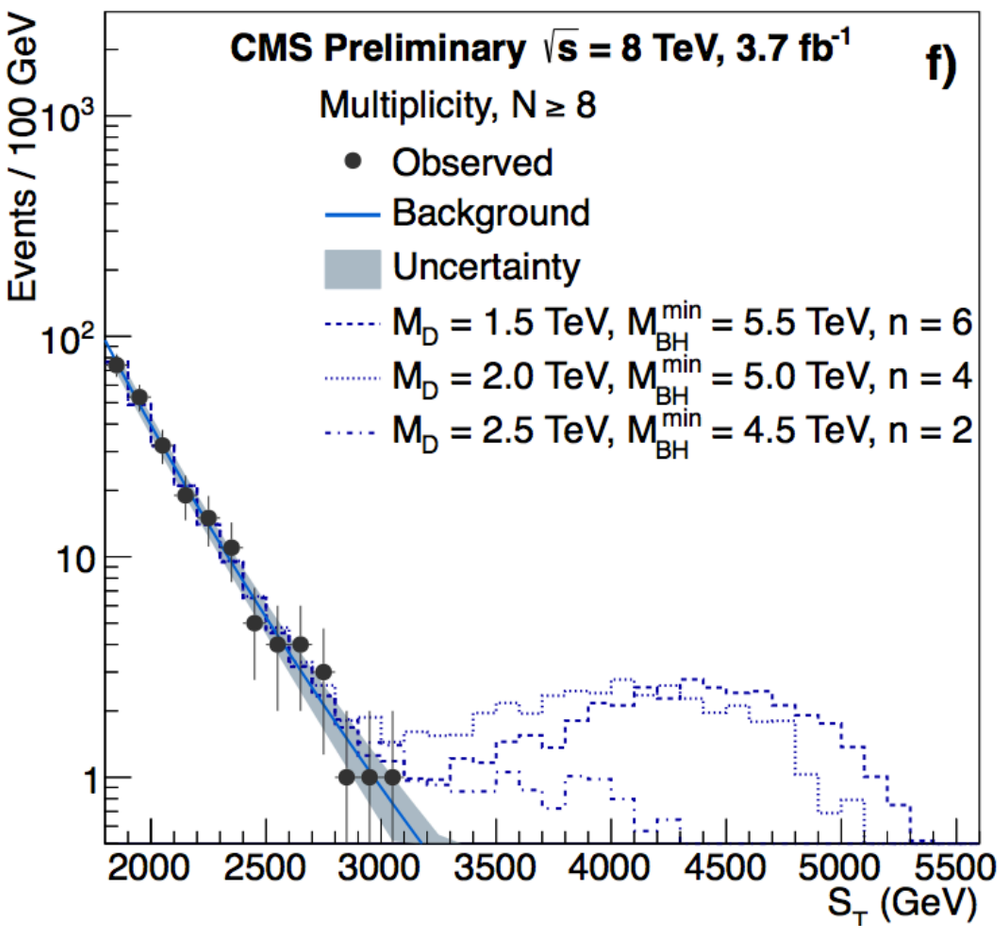


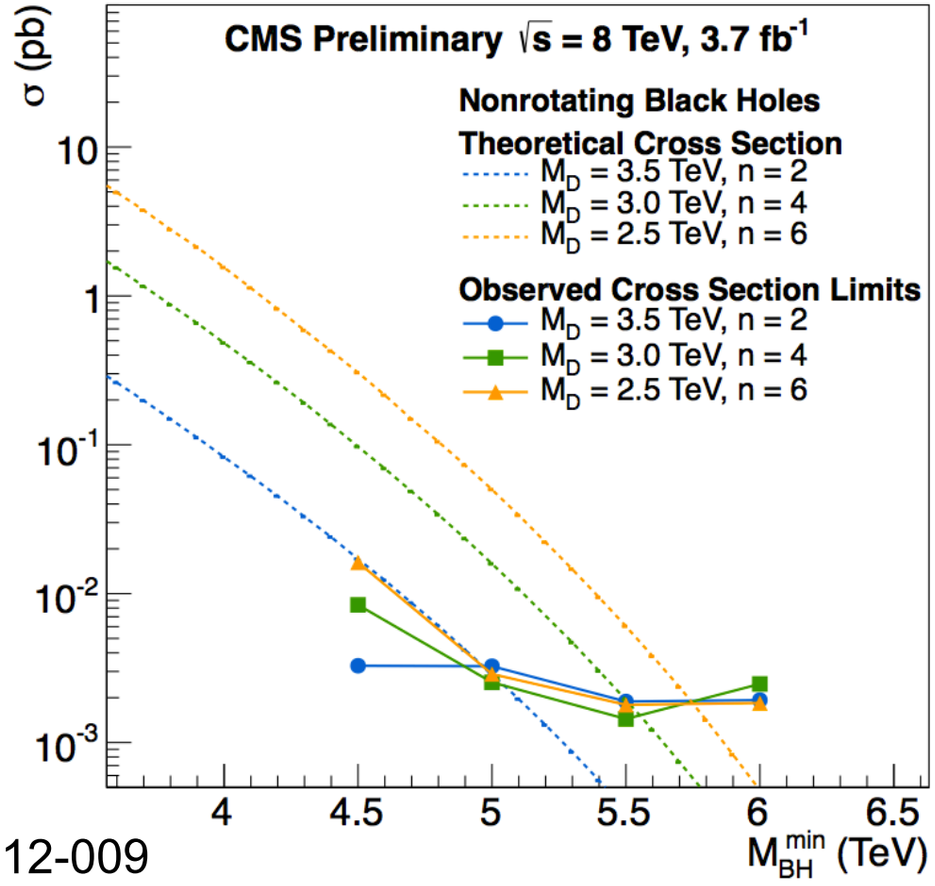
MICROSCOPIC BLACK HOLES @ 8 TEV

- Updated also the search for microscopic black holes @ 8 TeV
- Microscopic black holes production possible if Planck scale moved @ O(TeV) (need extra dimensions!)

BH decays very quickly (~10^{-27}s)
Searching for events with high multiplitity of e,γ,μ,jets characterized by large scalar sum p_T (S_T)

Limits between 4 and 6 TeV on the black-hole mass



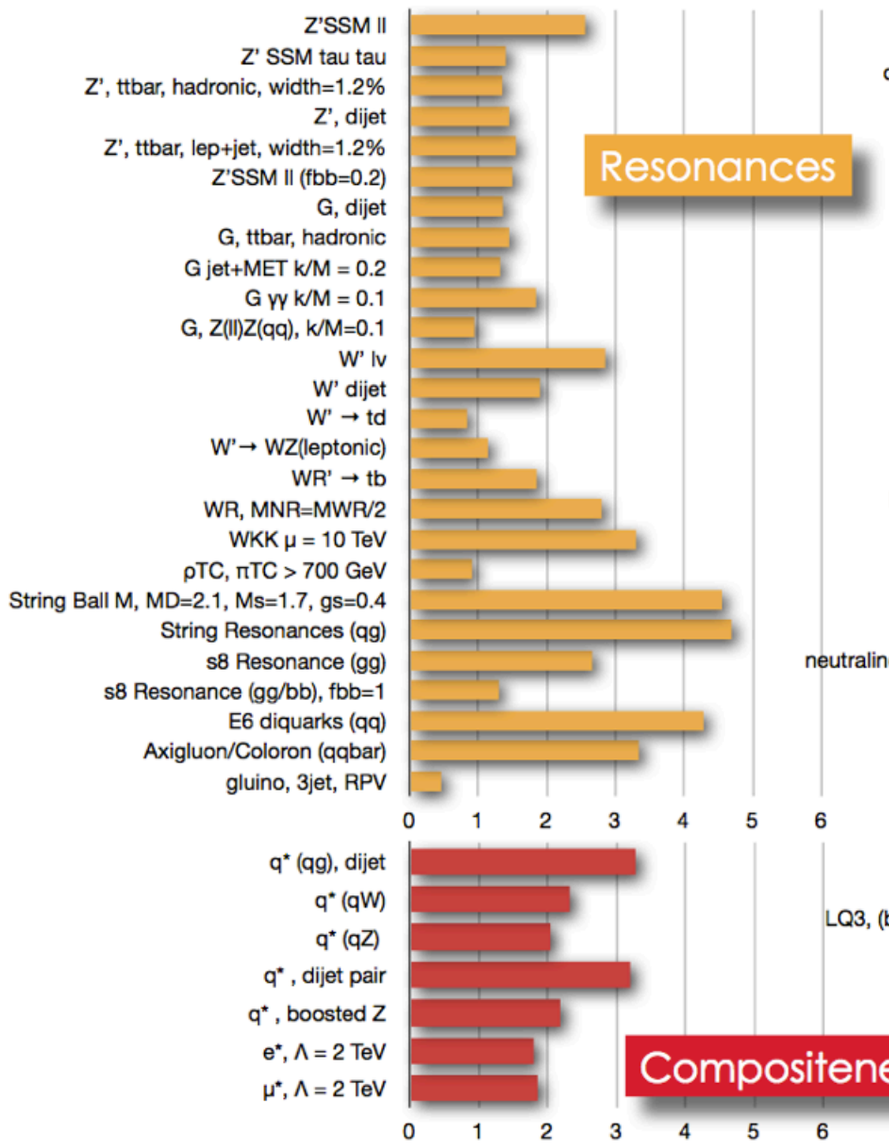


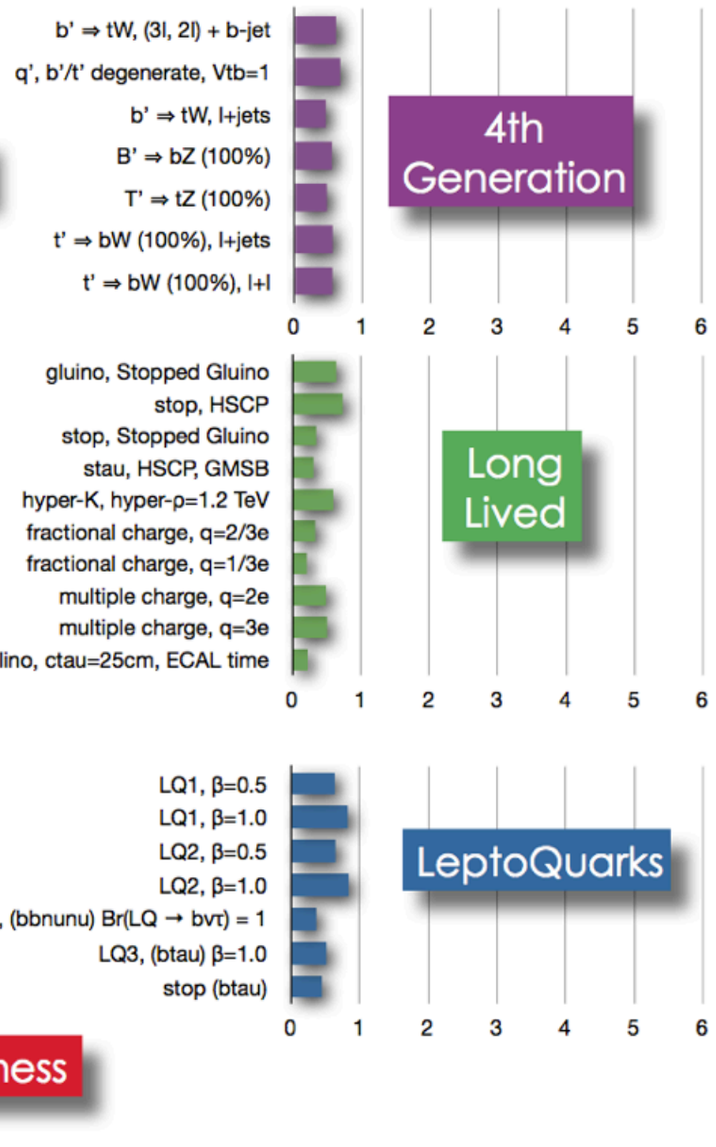
CMS-EXO-12-009

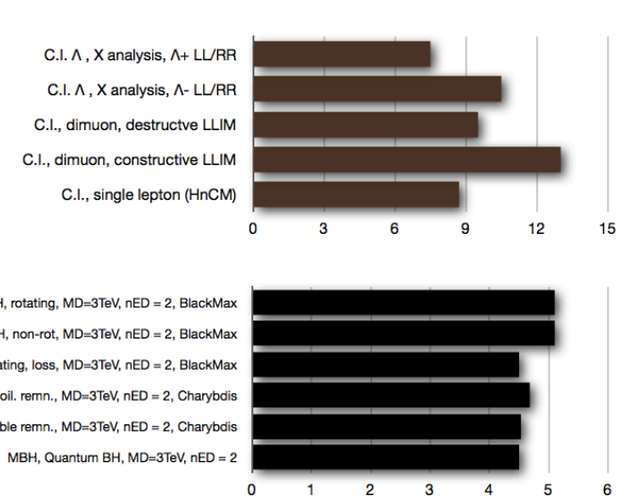
SUMMARY

- **CMS is producing new results at very high rate. Looking forward to full 2012 dataset >20fb^{-1}**
- **SM is behaving as better then ever ;-)**
  - Impressive agreement in all corners of phase space which have been studied
  - We have finally observed a new boson at around 125 GeV compatible with the SM Higgs
  - Is it really "the" SM Higgs? We need more data to start assessing its properties.
- **No sign of new physics at the horizon, yet :-(**
  - Tremendous effort to search in many different directions
  - Most obvious SUSY models are becoming unnatural
  - Many BSM models are being challenged

EXOTICS 95% CL LIMITS







Anomalous Triple Gauge Couplings (ZZZ and ZZγ)

- **Possible vertices using an effective Lagragian**

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2}\left[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta\right]$$

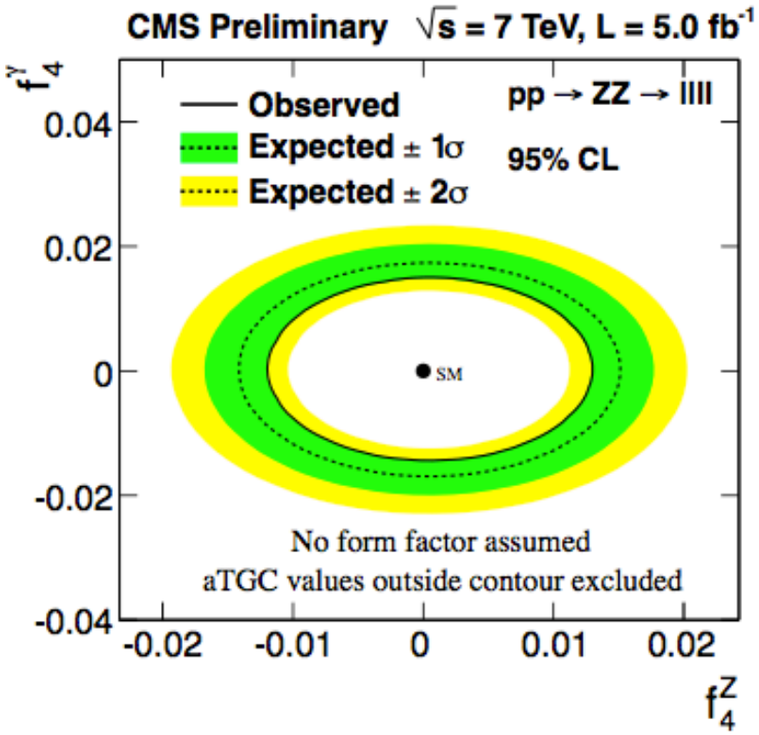
ZZZ, ZZγ

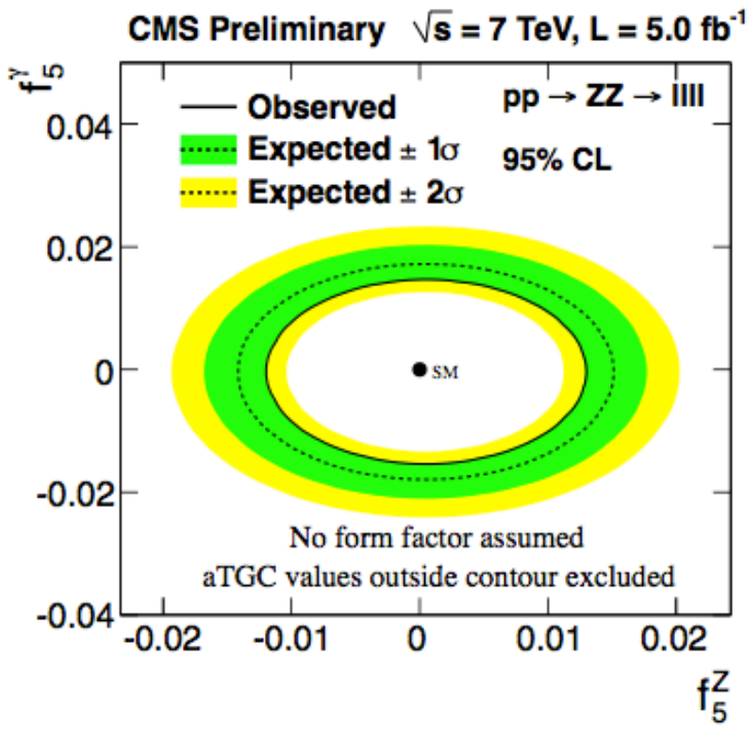
$(f_4^Z, f_4^\gamma, f_5^Z, f_5^\gamma) = (0,0,0,0)_{SM}$

Scale dependent form-factors

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^2}$$

with cutoff scale Λ





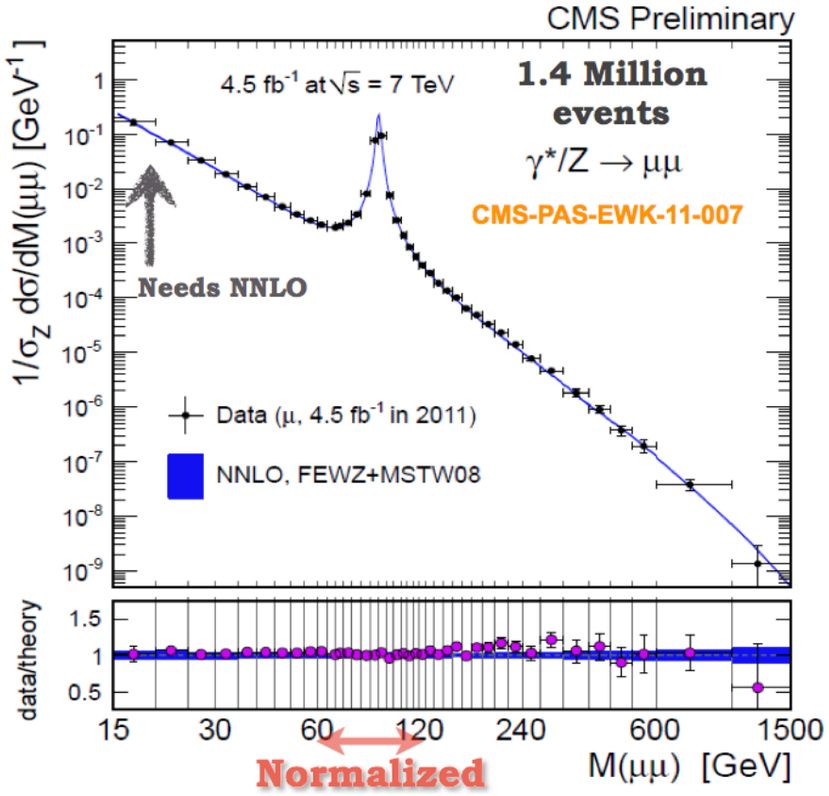
Use no form factors, i.e., $\Lambda = \infty$

$$-0.012 < f_4^Z < 0.013$$
$$-0.012 < f_5^Z < 0.013$$
$$-0.014 < f_4^\gamma < 0.014$$
$$-0.015 < f_5^\gamma < 0.015$$

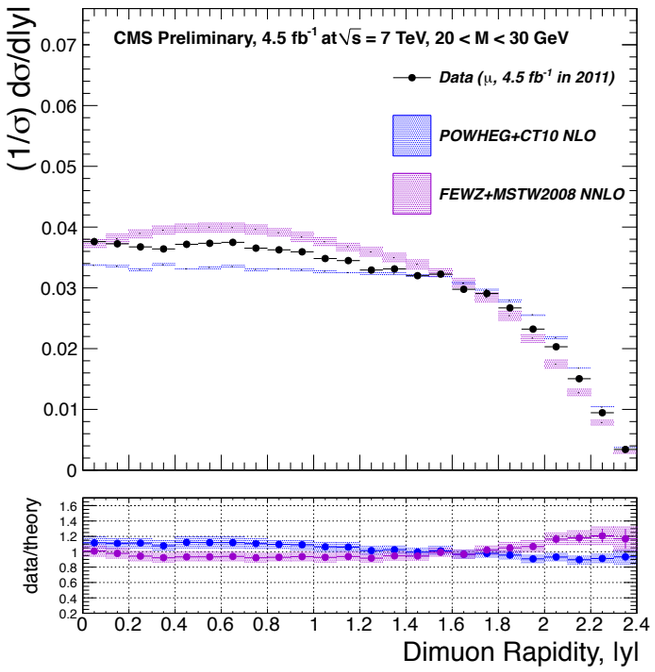
at 95% CL, the strongest limit to-date

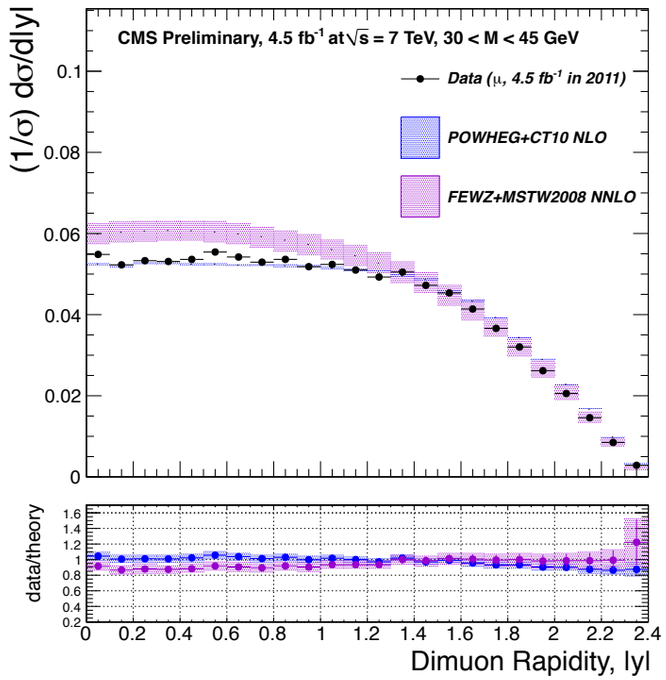
Using m_{4l} as discriminating variable

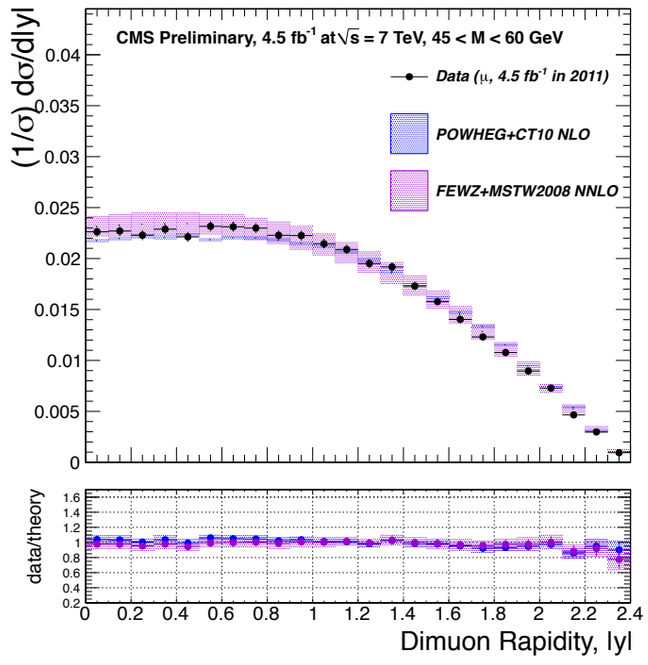
DRELL YAN DOUBLE DIFFERENTIAL



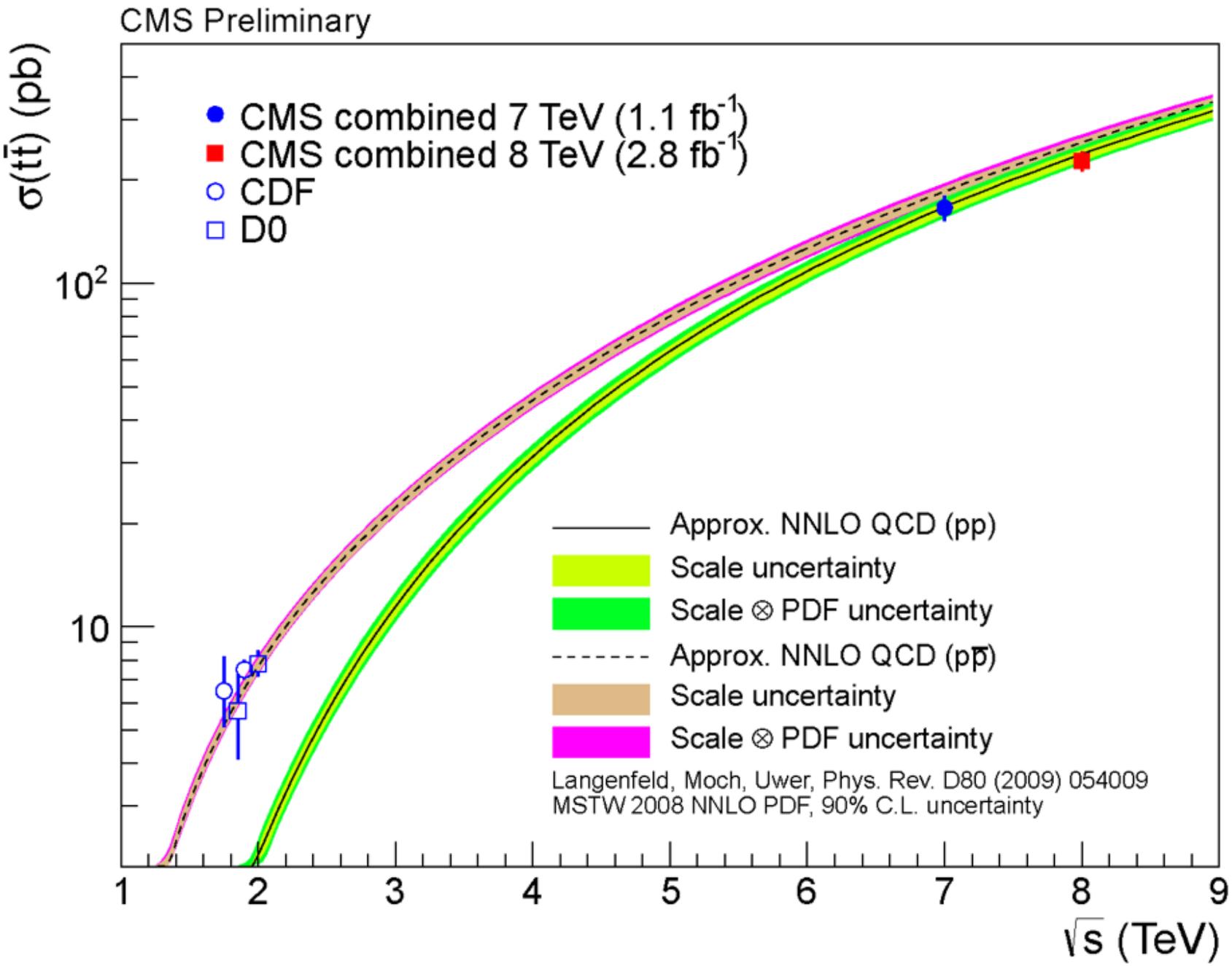
- **Going double differential**
  - Measured DY cross-sections vs mass of the di-muon system and also vs rapidity in 6 mass bins
- **Some discrepancies observed for low mass bins**
  - interesting input for PDF fits







TTBAR CROSS SECTION 7&8 TEV

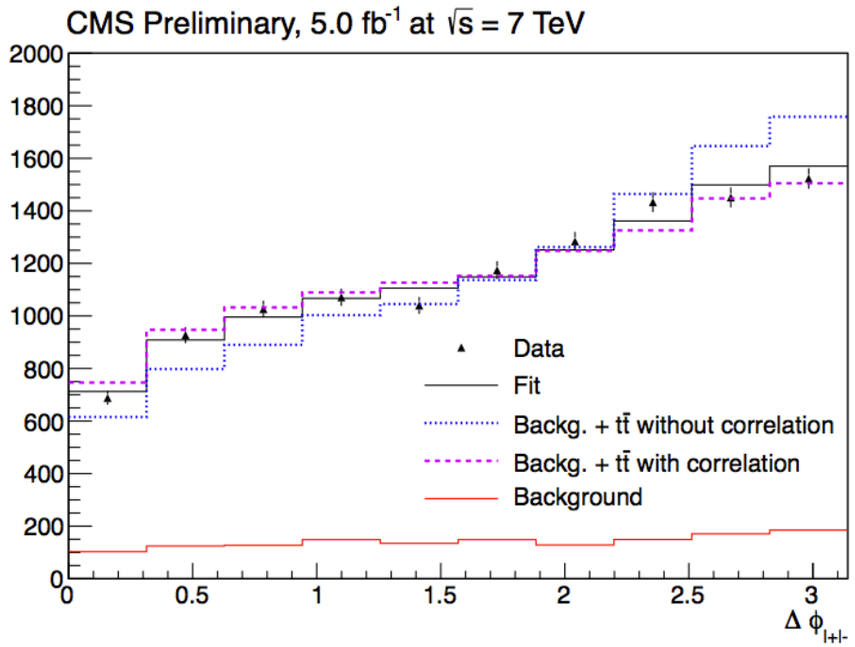


TTBAR SPIN CORRELATION

Spin correlation in SM: low m_{ttbar} prefers aligned orientation, high m_{ttbar} prefers opposite

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\downarrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\downarrow\uparrow) + N(\uparrow\downarrow)}$$

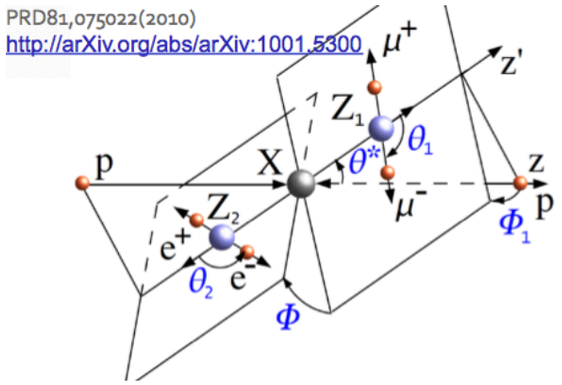
Measurement performed from a fit to the $\Delta\varphi_{l+l-}$ distribution



A = 0.24 ± 0.02 (stat) ± 0.08 (syst)

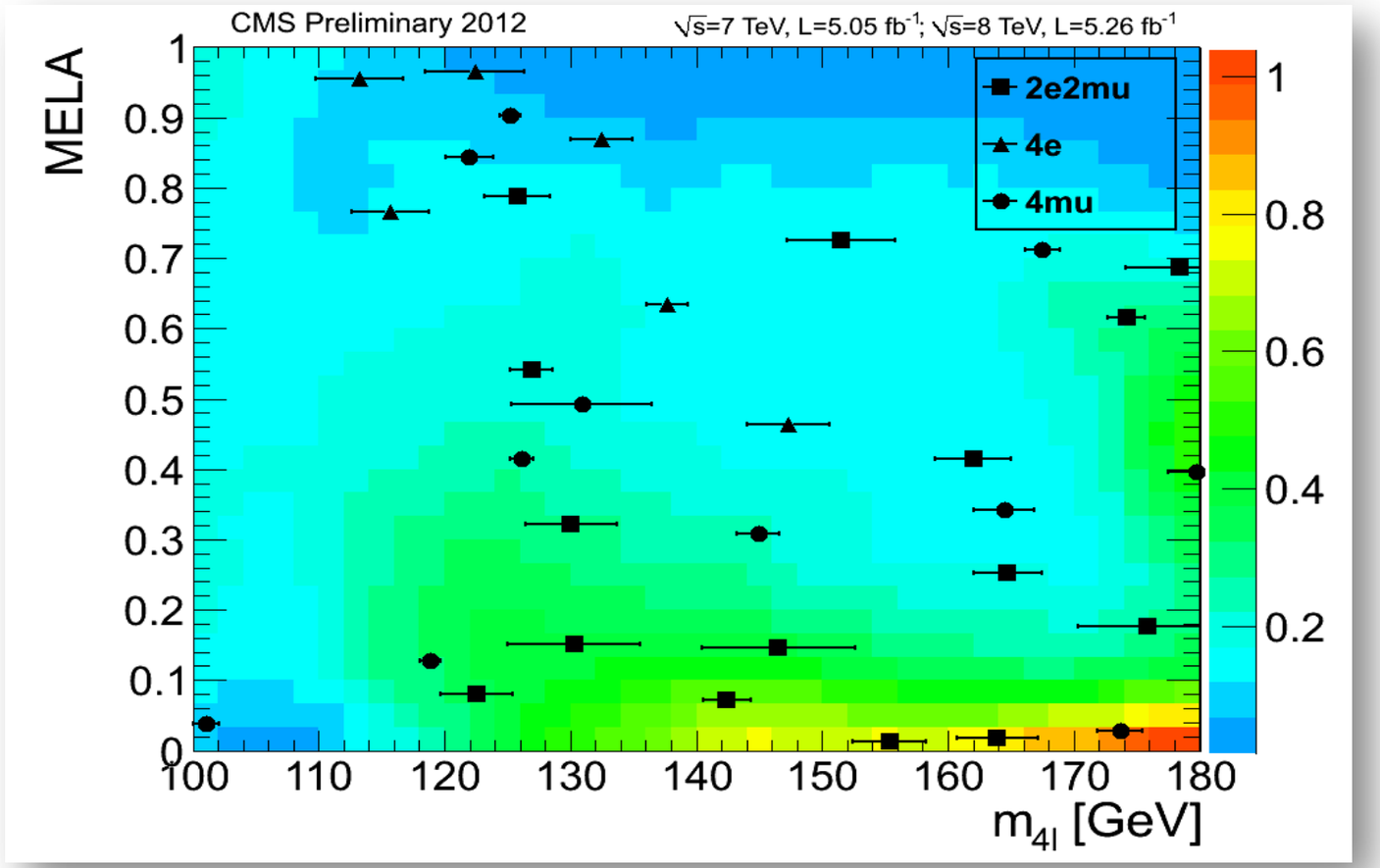
Nice agreement with SM expectation 0.31

HZZ Spin-0 Discriminator



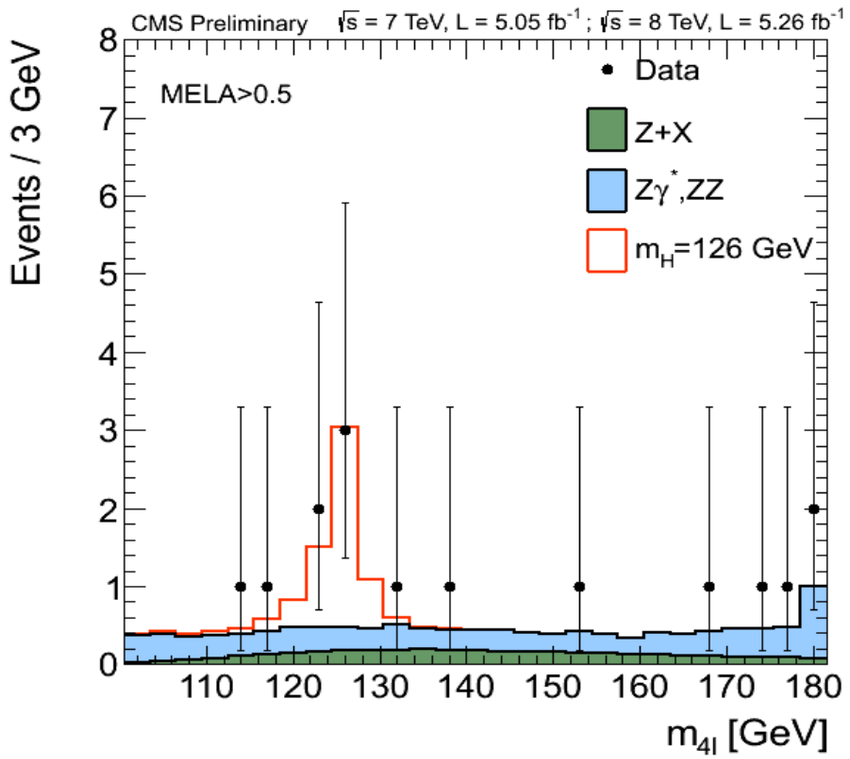
Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$



Selecting events with
MELA>0.5 makes excess more evident

Final discrimination using 2D likelihood approach



Data w.r.t 126 GeV Higgs Expectation