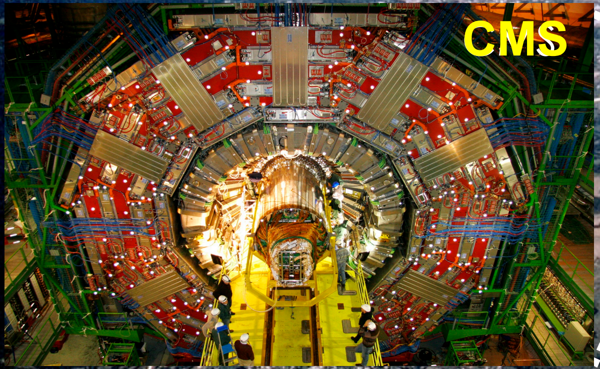
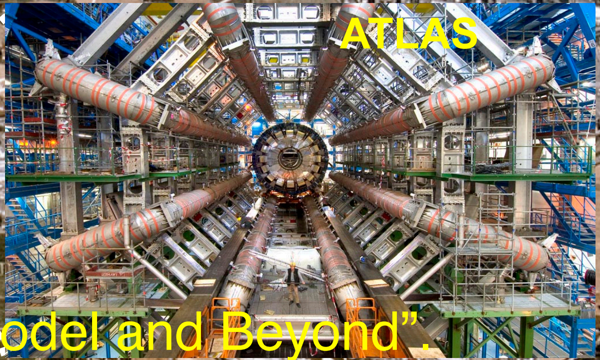
CMS results.
Where are we? What's next?



Guido Tonelli
(CERN, INFN&University of Pisa)



"Summer School and Workshop on the Standard Model and Beyond".
(CORFU2012) September 08-16, Corfu (Greece)

Design and Physics Goals.

The design of CMS was driven by the very ambitious goals of the experiment.

1) Sort out the mechanism responsible of the Electroweak Symmetry Breaking: discover the Higgs boson or find an alternative mechanism.
2) Discover SUSY if super-symmetry is a symmetry of nature.
3) Try to discover new physics in general using a large variety of different signatures.

Design specifications

|η|<2.5 : Tracker

$$\sigma / p_T \approx 10^{-4} p_T \oplus 0.005$$

|η|<4.9 : EM Calorimeter

$$\sigma / E \approx 0.03 / \sqrt{E} + 0.003$$

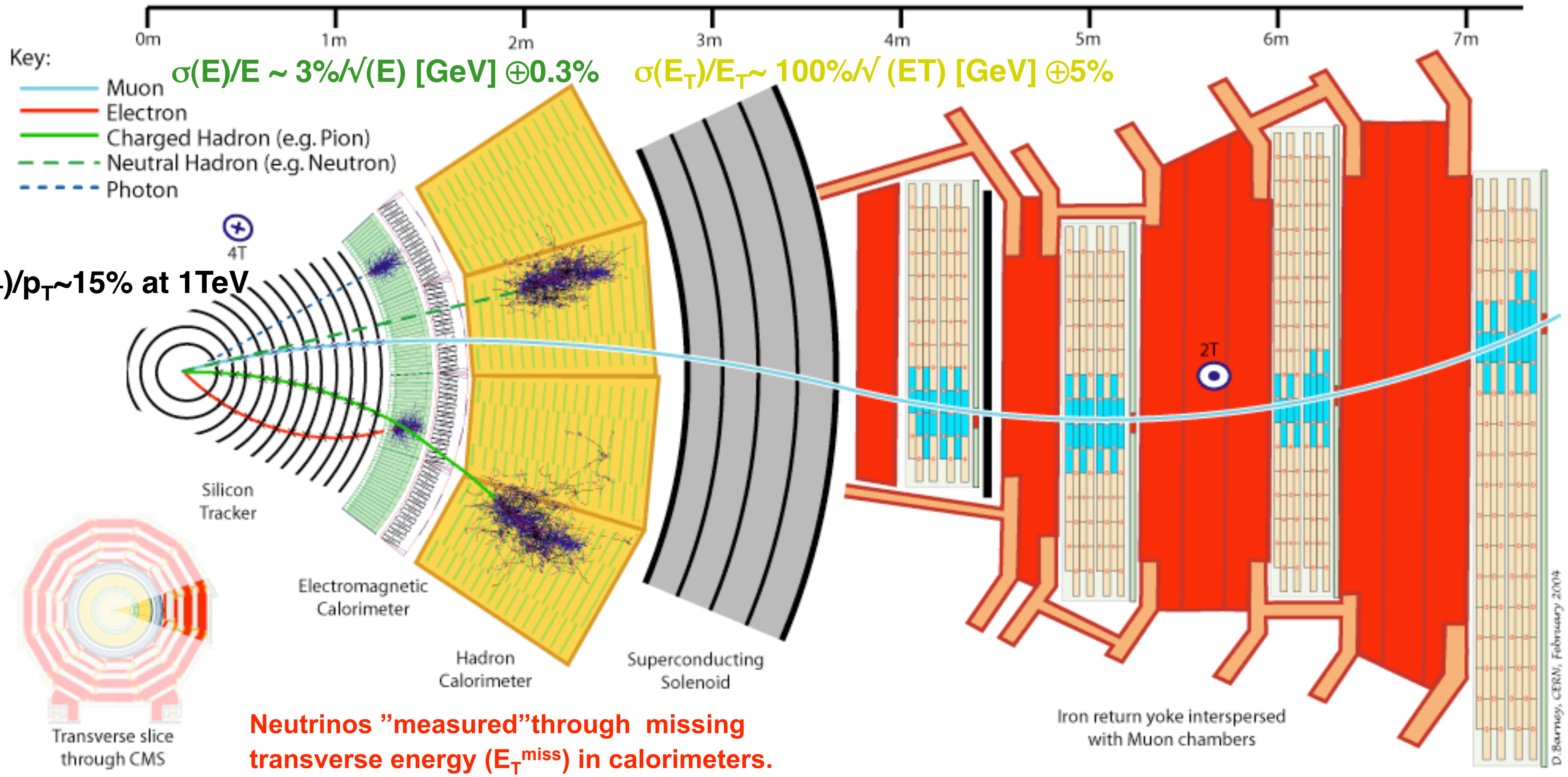
|η|<4.9 : Had Calorimeter

$$\sigma / E \approx 1.0 / \sqrt{E} + 0.05$$

|η|<2.6 : Muon spectrometer

$\sigma / p_T \approx 0.10$ *(1TeV muons)*

A simple and elegant concept.



$\sigma(E)/E \sim 3\%/\sqrt{(E)}$ [GeV] $\oplus 0.3\%$

$\sigma(E_T)/E_T \sim 100\%/\sqrt{}$ (ET) [GeV] $\oplus 5\%$

$\sigma(p_T)/p_T \sim 15\%$ at 1TeV

Neutrinos "measured" through missing transverse energy (E_T^{miss}) in calorimeters.

Fast detectors: 25-50ns bunch crossing

High granularity: 20-40 overlapping complex events

High radiation resistance: >10 years of operation

$\sigma(p_T)/p_T < 1\%$ @ 100GeV

$\sigma(p_T)/p_T < 10\%$@1 TeV

Redundancy and Flexibility

But on top of the "standard" design parameters a key component of CMS, which is rarely highlighted, is its high level of

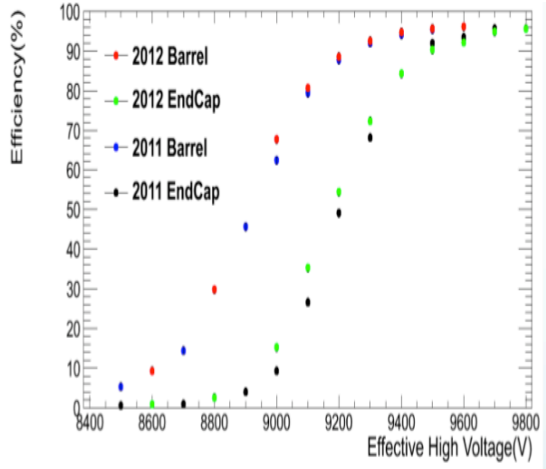
Redundancy and Flexibility

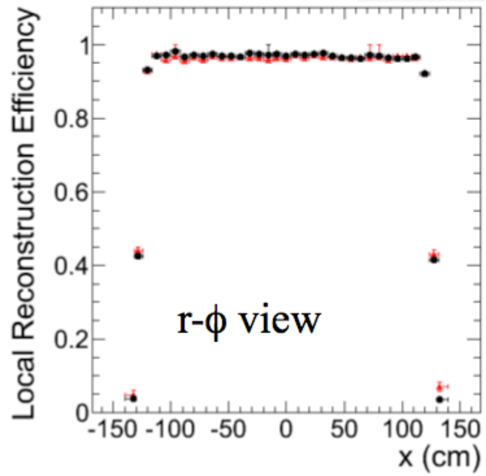
Redundancy was considered mandatory since no major discovery would have been fully trusted if based only on an excess in a single channel or in a physics object crucially dependent on a single detector. In addition the environment of the LHC high energy collisions was completely unknown and we expected it to be very challenging

Flexibility was another important choice; we didn't know exactly in which form New Physics would have appeared, therefore we designed a detector able to identify as many particles and signatures as possible (e, μ, τ, ν, γ, jets, b-quarks, ….) and as hermetic as possible.

Examples of Redundancy and Flexibility

The muon system: we decided to have two independent and fully complementary muon systems (DT/CSC and RPC). Today we measure an average efficiency >97% and > 95% respectively.

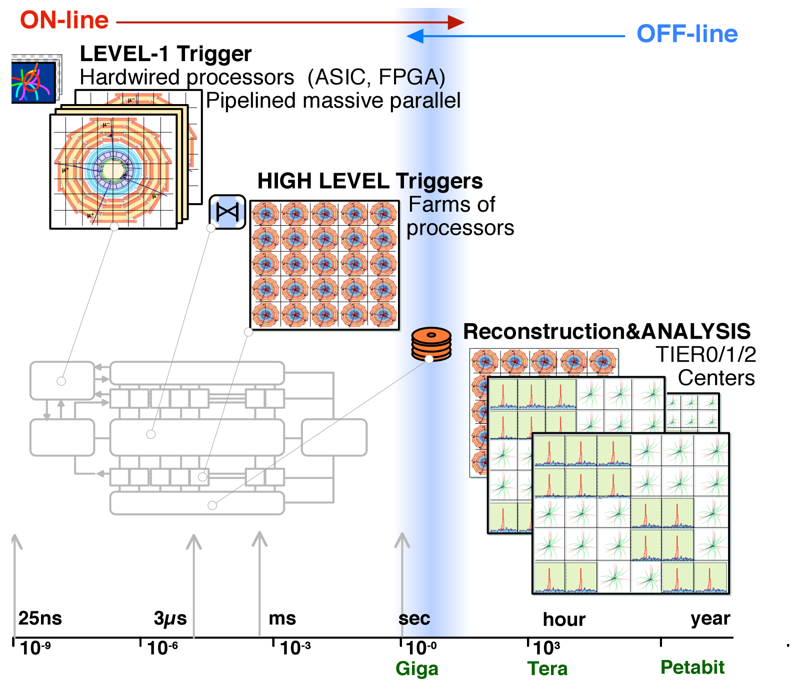




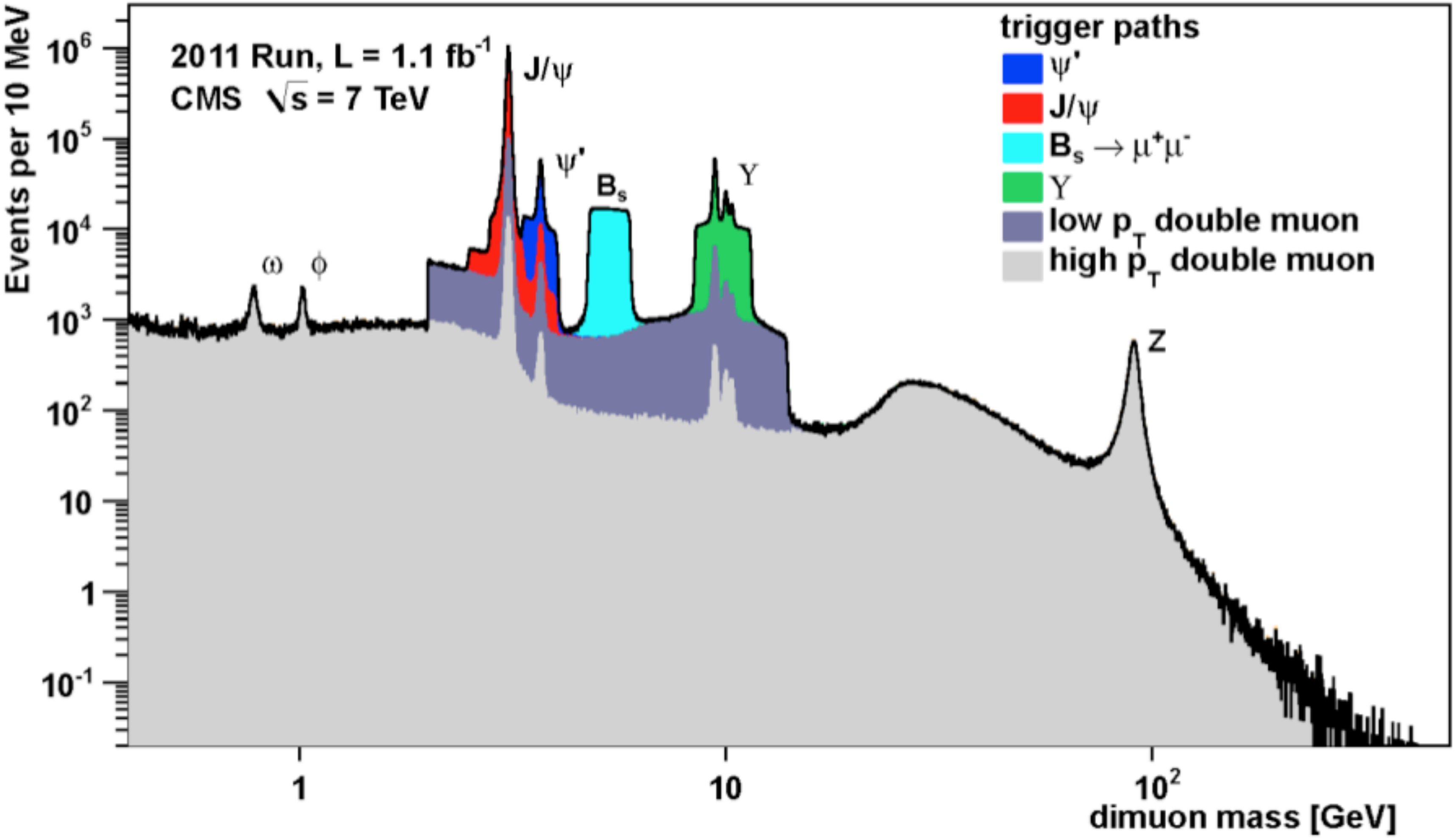
The trigger system: a very simple concept.

Two levels only:

A hardwired L1 Trigger coupled to a highly flexible and fully programmable High Level Trigger. A good new idea→ a new trigger path If compatible with the available bandwidth.

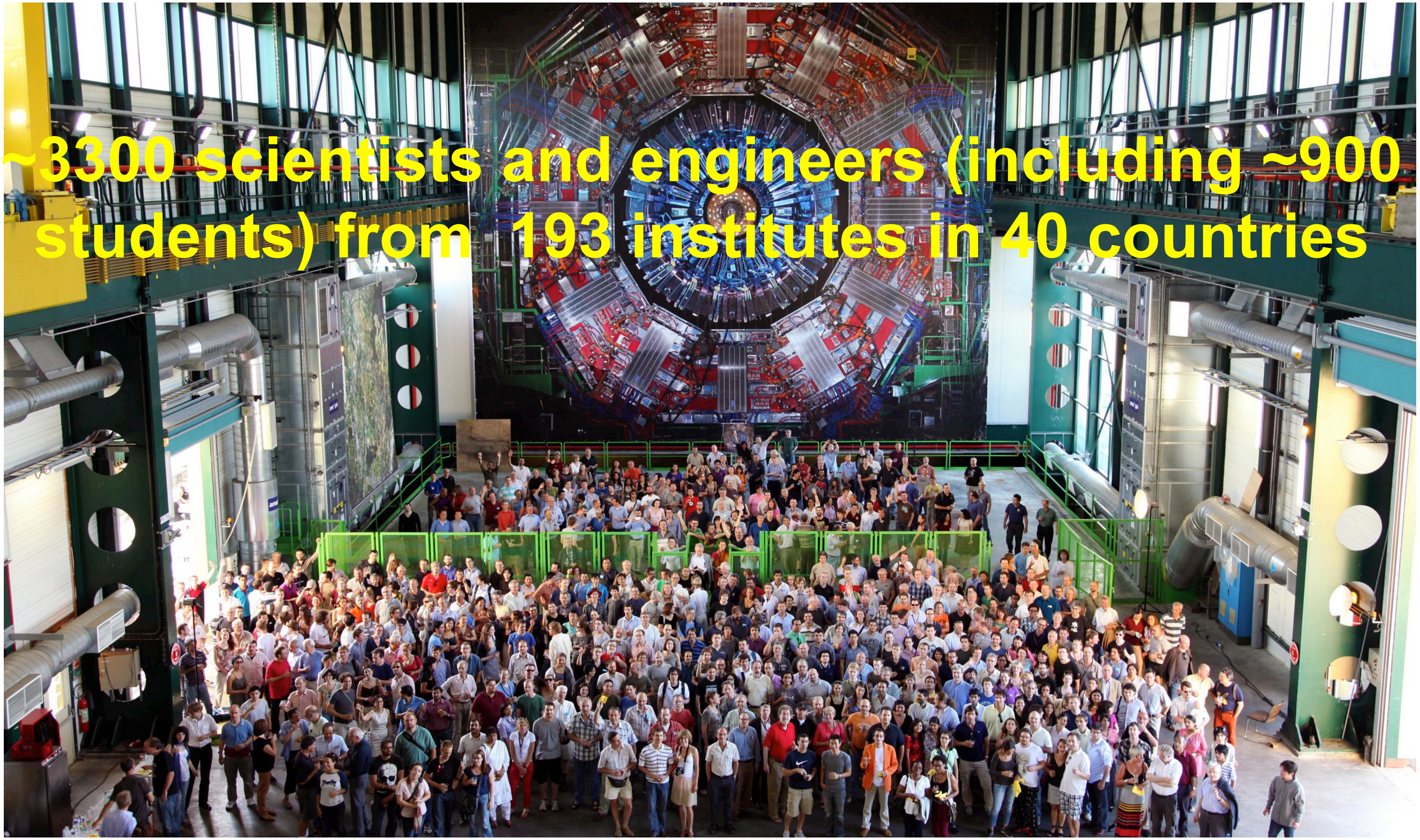


The Power of Flexibility at the Trigger Level



Dimuon mass distribution obtained from overlapping several trigger paths. Dimuon triggers are fundamental for searches but used also for studying quarkonia and for calibrations purposes.

Another key component: the people



Collaborations strong of ~1000 students and post-doc can do incredible things facing challenges that were once considered "mission impossible".

Two examples of “mission impossible”

1. Hunting the Higgs at 7-8 TeV

After the terrible incident of LHC and the decision **to run at 7 TeV** in 2010 nobody really believed that we could have seriously addressed the discovery of the Higgs boson before the repair of the splices of LHC to **run at 14TeV**.

If we are here today it is just because, in the last two years, an incredible effort has been put together basically from scratch (if you want to have fun just compare the actual Higgs analyses with the very naïve approach described in the Higgs section of our Physics TDR). New ideas, completely new approaches, very aggressive and modern analysis tools.

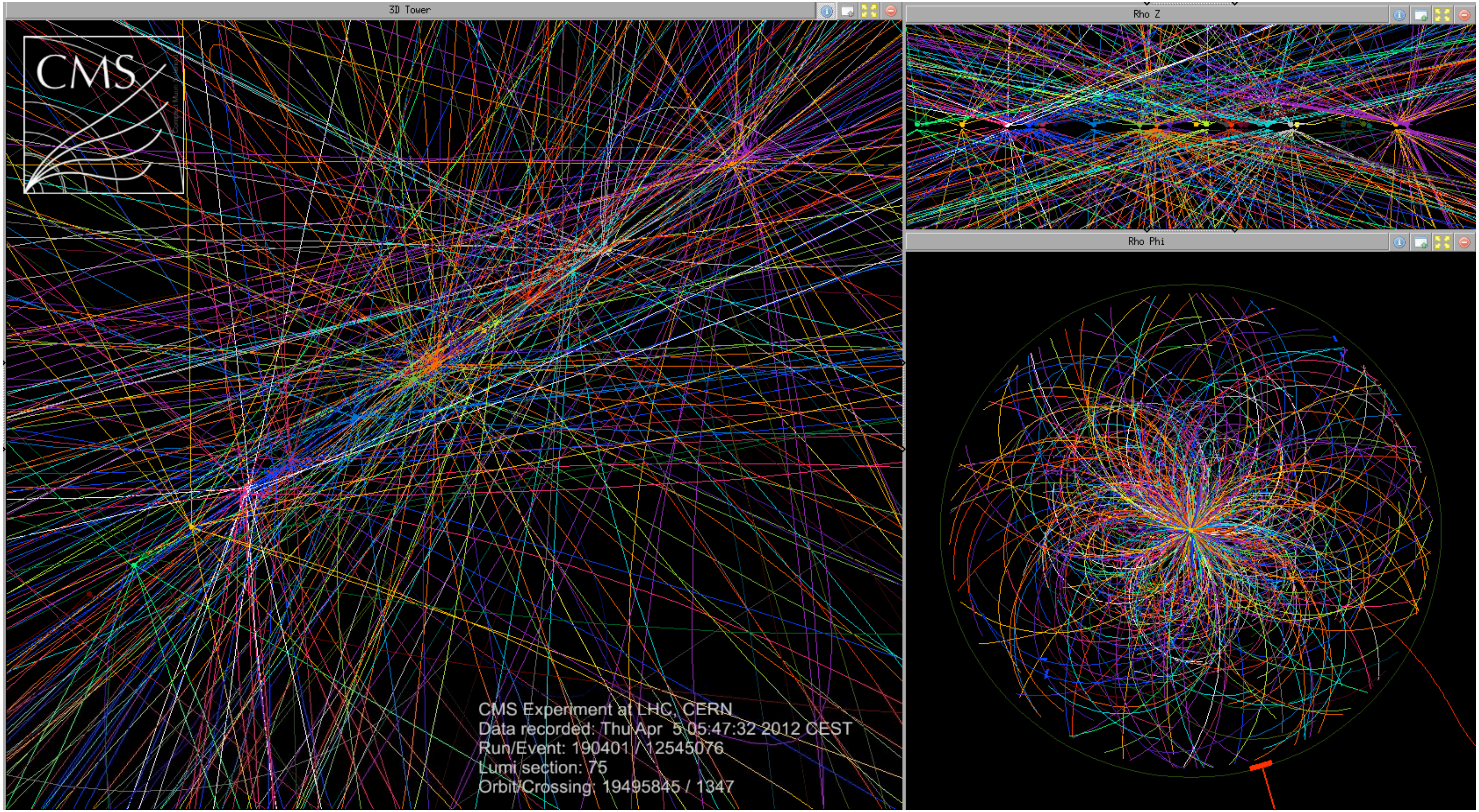
2. Tackling the high pile-up conditions:

Just one year ago, I remember very hot discussions, within CMS and ATLAS, on the pile-up. The machine was planning to reach an **average pile-up around 7** in september 2011 and many people were afraid that in these conditions the $H \rightarrow \gamma\gamma$ and $H \rightarrow WW$ searches would have been completely jeopardized.

Now that we have been able to manage **average pile-up in excess of 14** with tails up to 30 you can realize how much effort and ingenuity has been put together.

I’ll come back to this point when discussing the new challenges

The challenge of 2012: 8 TeV and high pile-up.



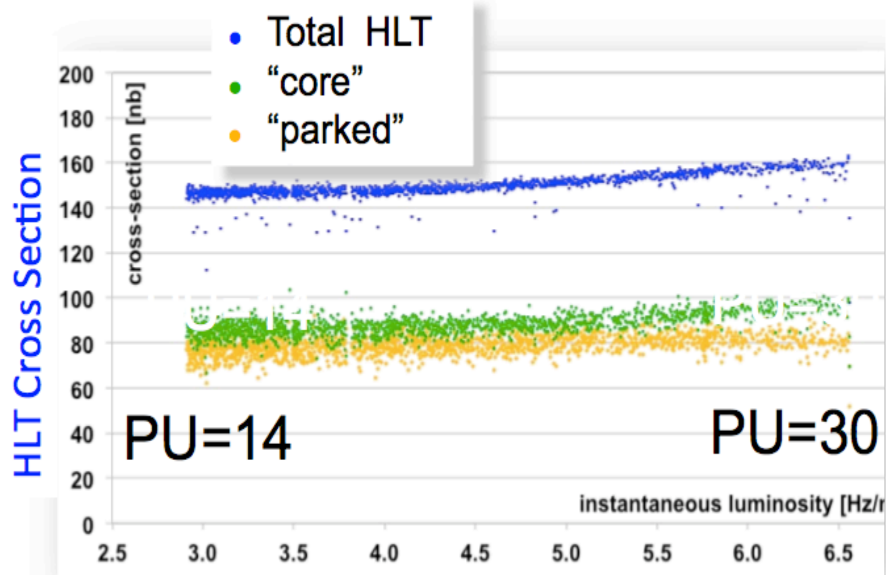
Trigger

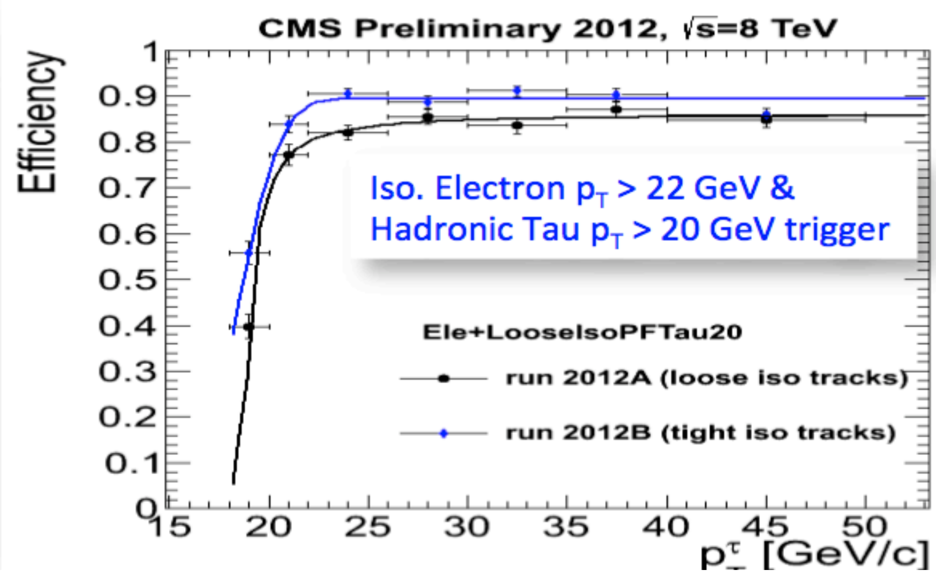
The challenge is to keep a constant cross-section- with varying pile-up conditions without sacrificing physics.

Full use of the high flexibility of our HLT system.

Continuous deployment of new ideas leading to faster and safer algorithms.

Some of the offline features (Particle Flow reconstruction and PU corrections) are basically implemeted on-line.





Tracking

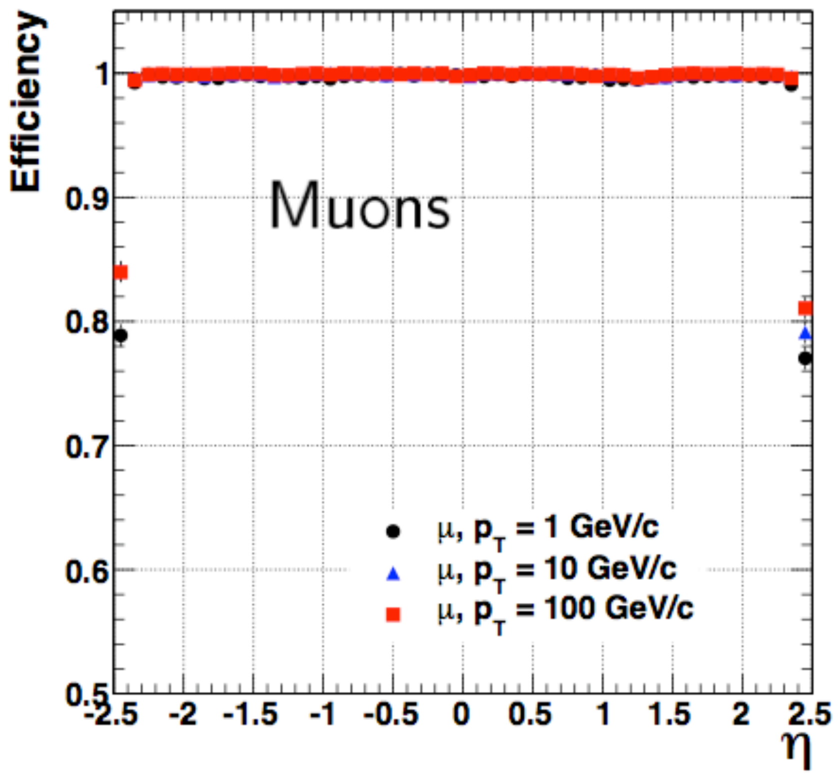
- CMS uses multi-stage iterative tracking
- subsequent steps with typically looser seeding

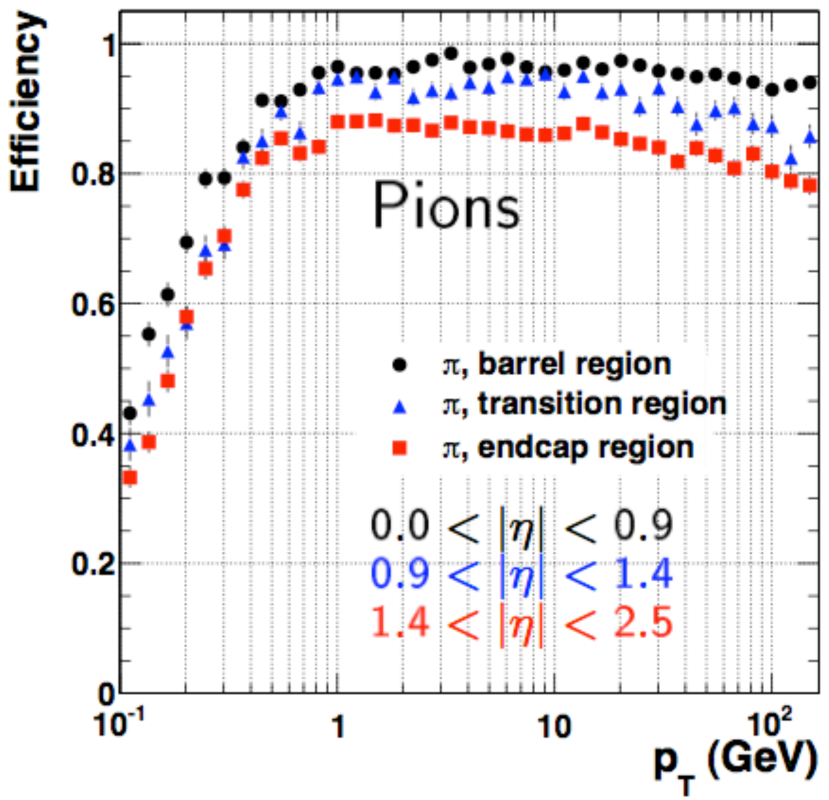
→ recovering inefficiencies from earlier iterations

→ removing hits on tracks earlier iterations reduces combinatorics at each step

- later iterations are looking for more complicated tracks (lower p_T, displaced tracks, less strict seeding requirements)
- seeds are constructed from
  - pixel triplets
  - mixed pairs (pixel || strips) + vertex
  - mixed triplets
  - strip pairs
- The main tracking algorithm is based on pixel seeds and uses a Kalman filter.

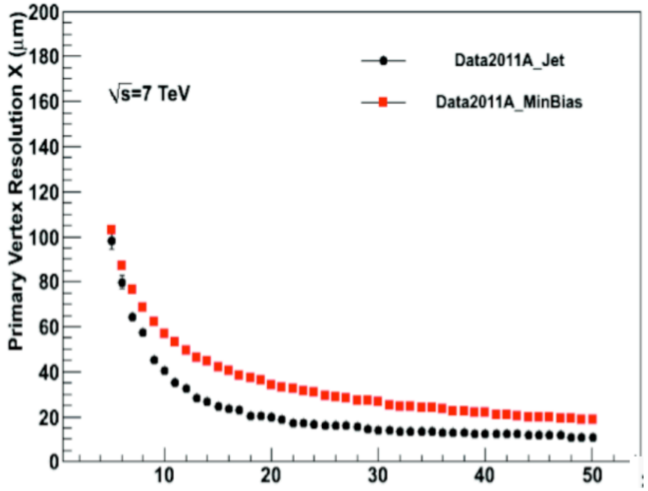
Tracking efficiency



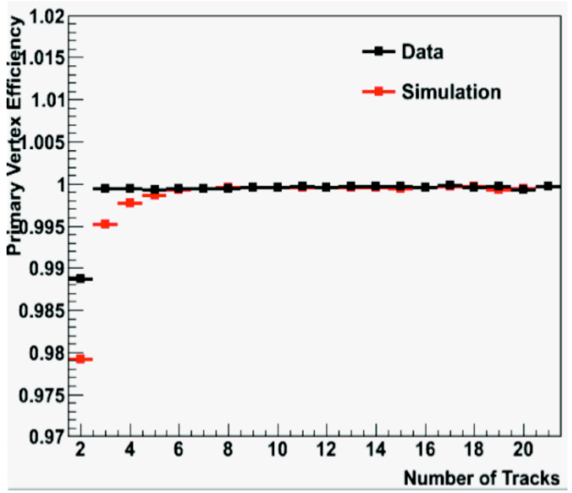


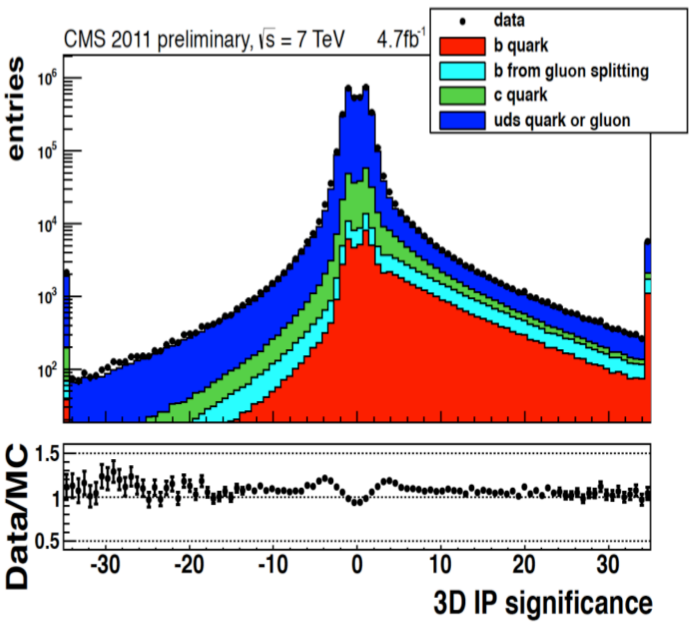
- efficiency for isolated muons very close to 100% for $|\eta| < 2.4$
- single pions with efficiencies above 90 (80)% in the barrel (endcap) region for $p_T > 500$ MeV

Vertexing and b-tagging



Vertex resolution << average vertex separation. (Asymptotic value for the resolution ~10μm for high number of tracks). No surprise to get efficiency close to 100% for N_{tracks}>2.





Several algorithms using different combinations of the impact parameter information on tracks and of secondary vertices have been developed for b-tagging purposes.

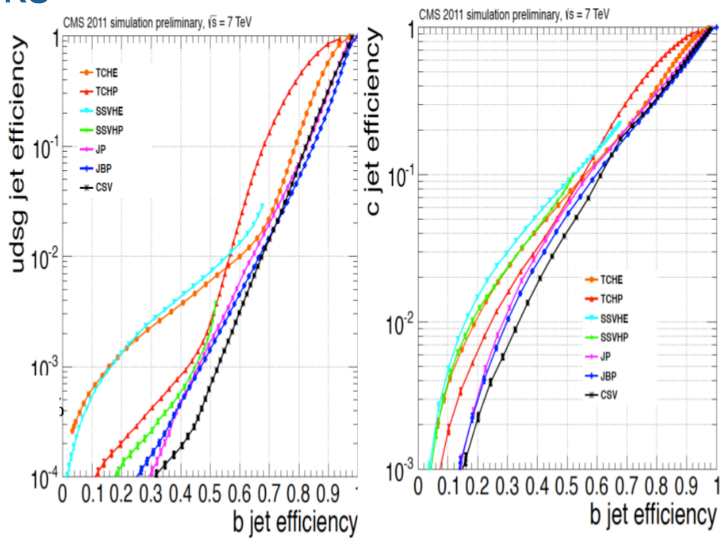
Track Counting (TC)

Jet Probability (JP)

Jet B probability (JBP)

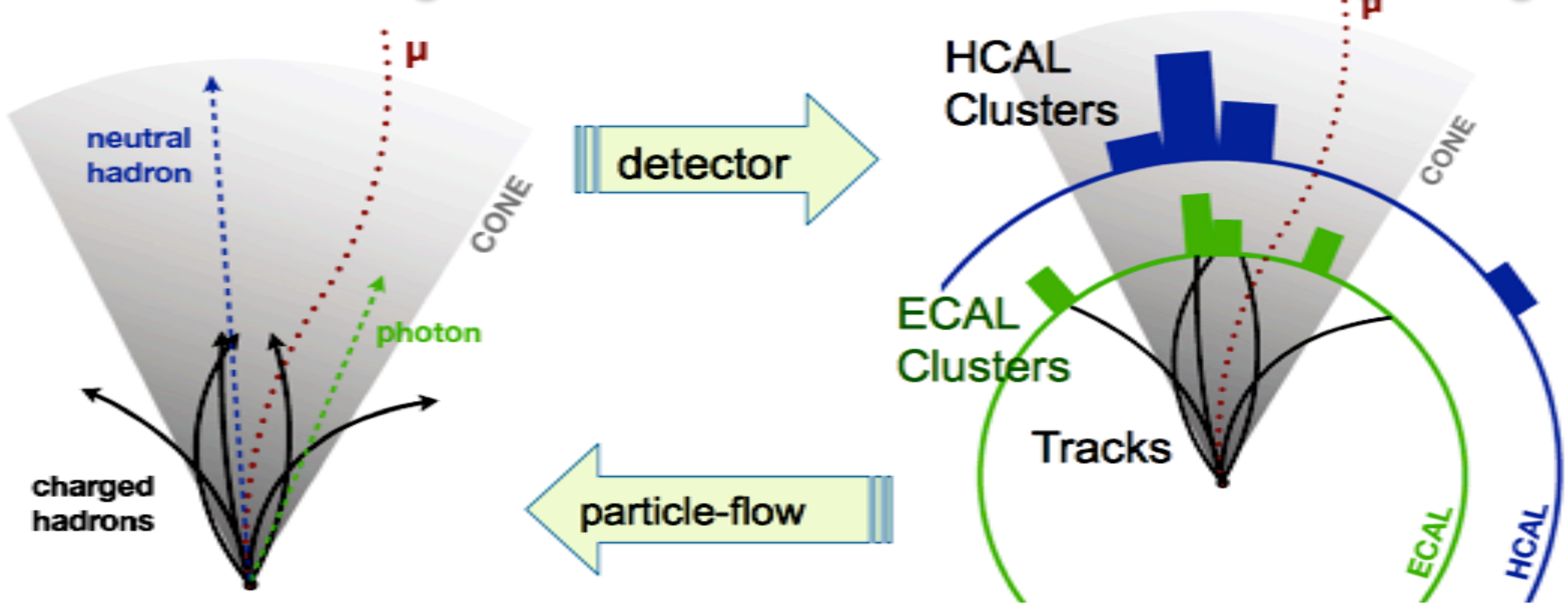
Simple Secondary Vertex (SSV)

Combined Secondary Vertex (CSV)



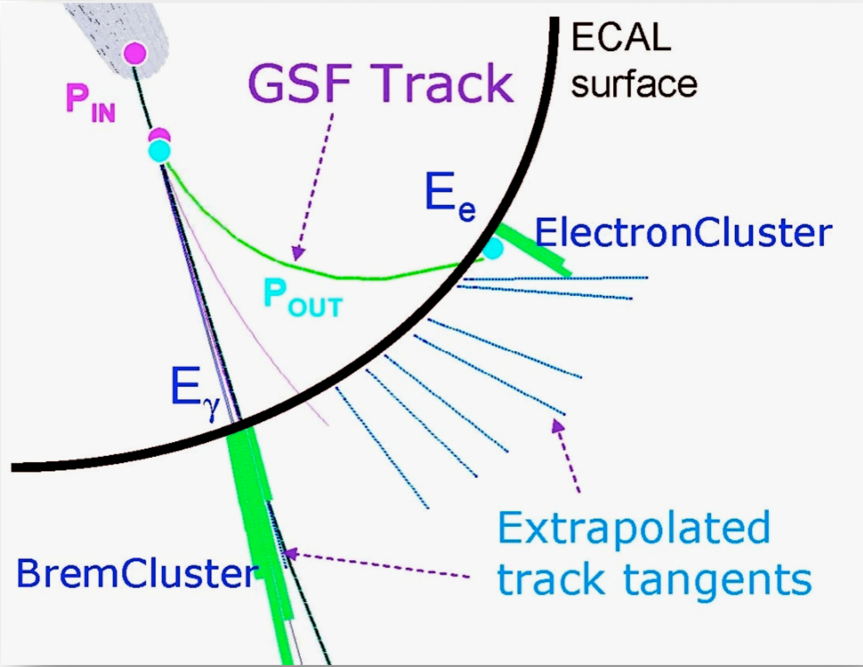
Particle Flow Reconstruction

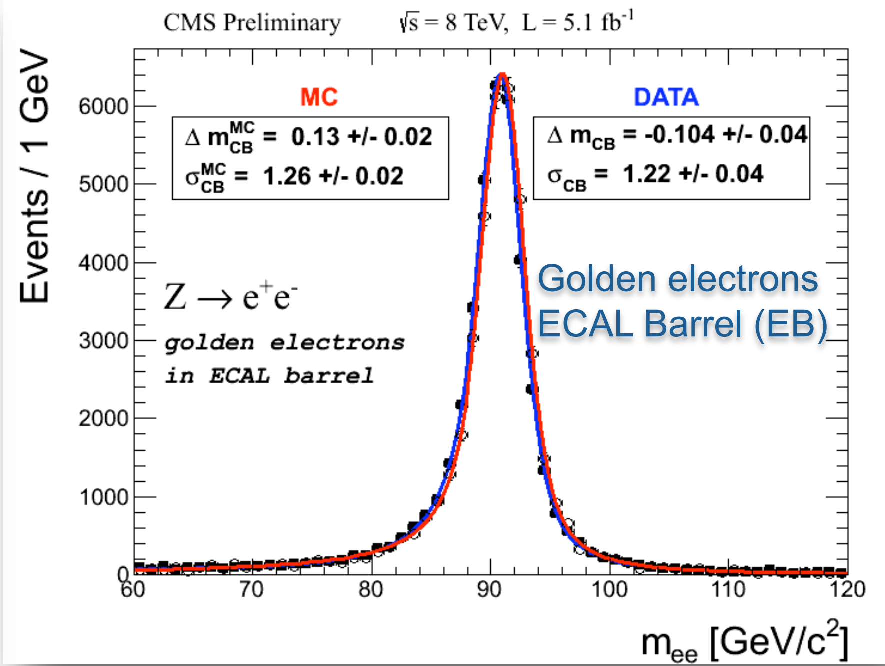
Possible in CMS for its redundancy, for the excellent granularity of Tracker and Electromagnetic Calorimeter and for the strong magnetic field



- Optimal combination of information from all subdetectors
- Returns a list of reconstructed "particles"
  ➡ **Electrons, Muons, Photons, Charged and Neutral Hadrons**
- **Used as building blocks for jets, taus, missing ET, lepton isolation**
- Allows tagging of charged particles from pile-up: minimizes impact of PU on jet reconstruction, and lepton or photon isolation

Electron/photon reconstruction and identification

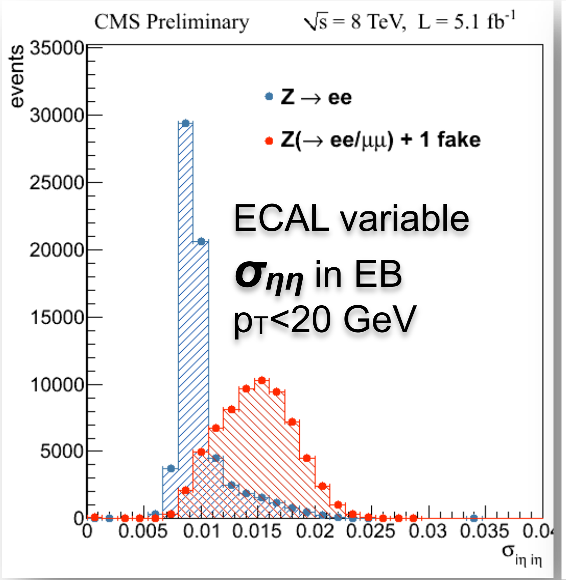


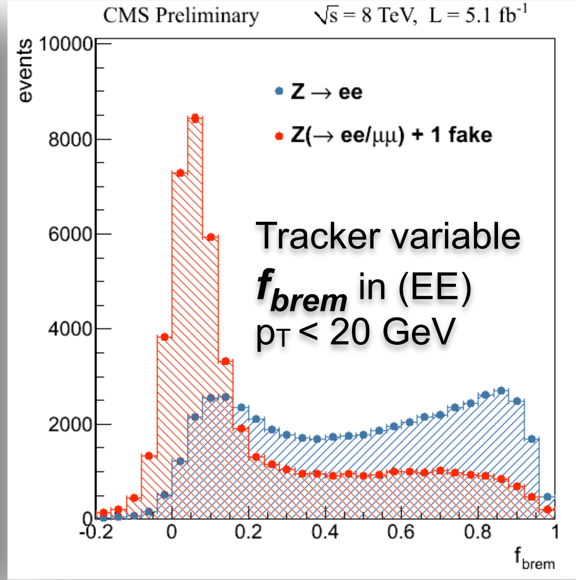


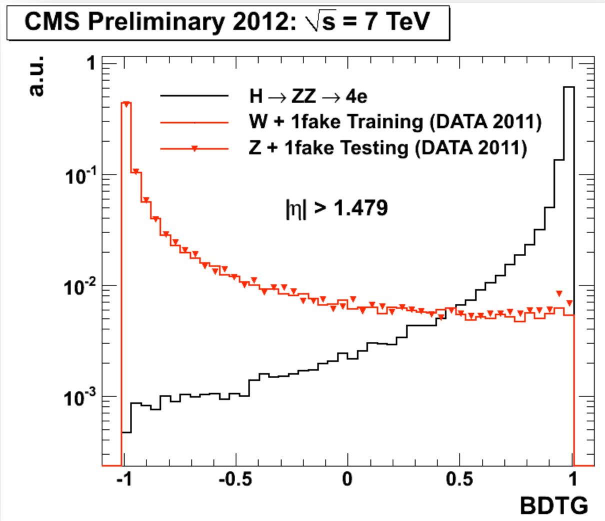
- **Cluster reconstruction in ECAL Common for both electrons & photons. Designed to collect bremsstrahlung and conversions in an extended phi region.** Energy spread in ϕ due to brems (E_T>4 GeV)
- **Dedicated track reconstruction for electrons Gaussian Sum Filter allows for tracks with large curvature due to brems and** enables hit collection up to ECAL; ECAL-seeded reconstruction complemented by a tracker-seeded reconstruction to gain efficiency at low p_T
- **Energy scale and resolution**
  - **Extensive control at the Z peak (and at the J/ψ➔ee for low p_T electrons)**

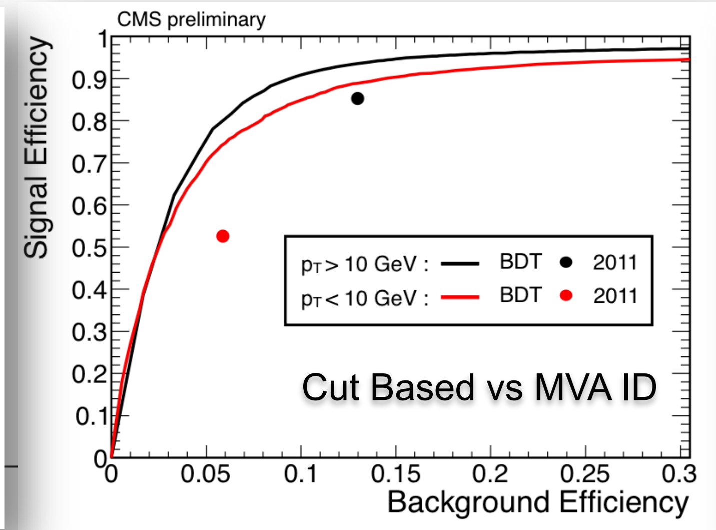
Electron reconstruction and identification

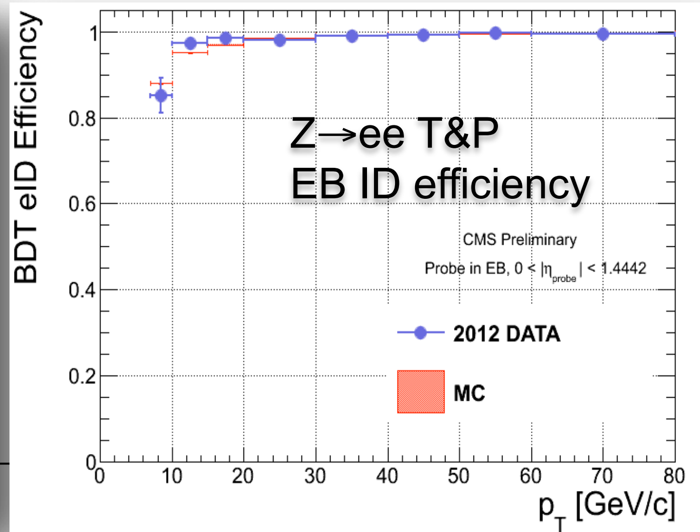
- Multivariate electron identification in 2012
  - ECAL, tracker, ECAL-tracker-HCAL matching and impact parameter (IP) observables
- Background from data samples
  - W+jet for training
  - Z+jet for testing
- Performance
  - 30% efficiency improvement in H->ZZ->4e wrt cut based ID
- Efficiencies
  - Via tag-and-probe at the Z->ee peak





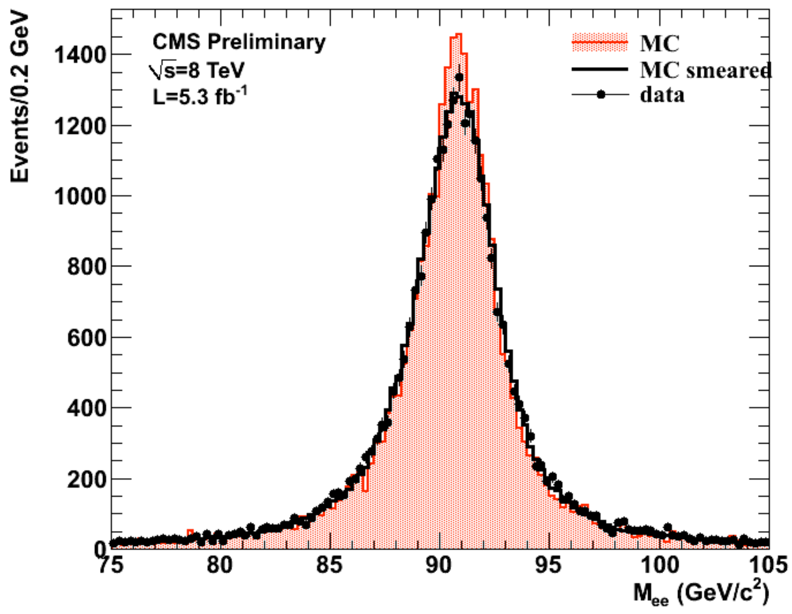




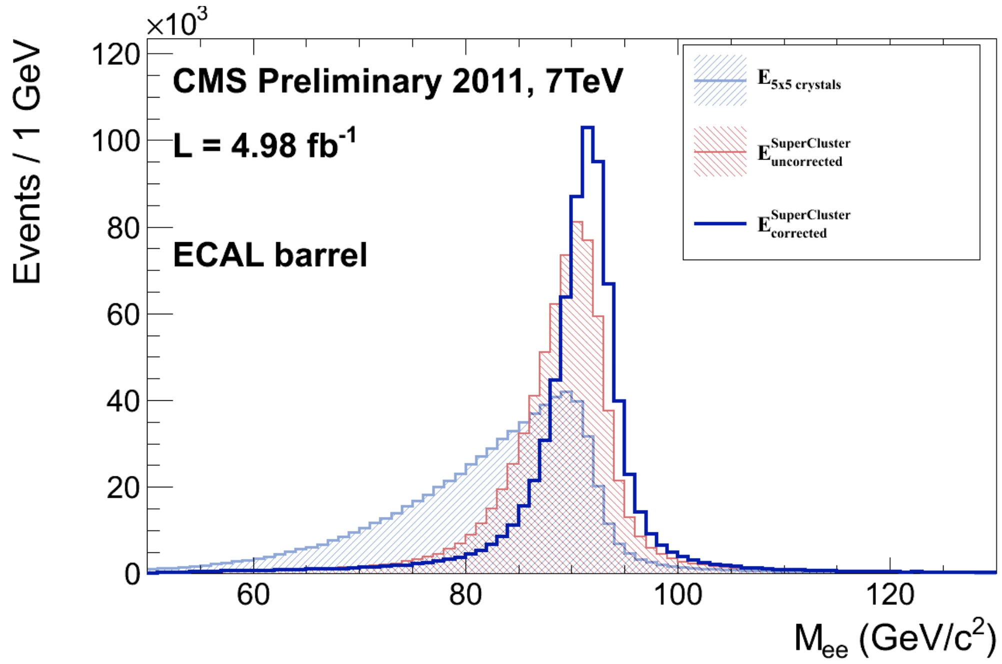


Photon Energy Corrections, Scale and Resolution

- ECAL cluster energies corrected using a MC trained multivariate regression
  - Improves resolution and restores flat response of energy scale versus pileup
  - Inputs: Raw cluster energies and positions, lateral and longitudinal shower shape variables, local shower positions w.r.t. crystal geometry, pileup estimators
- Regression also used to provide a per photon energy resolution estimate
- **Energy Scale and resolution:** use $Z \to e^+e^-$



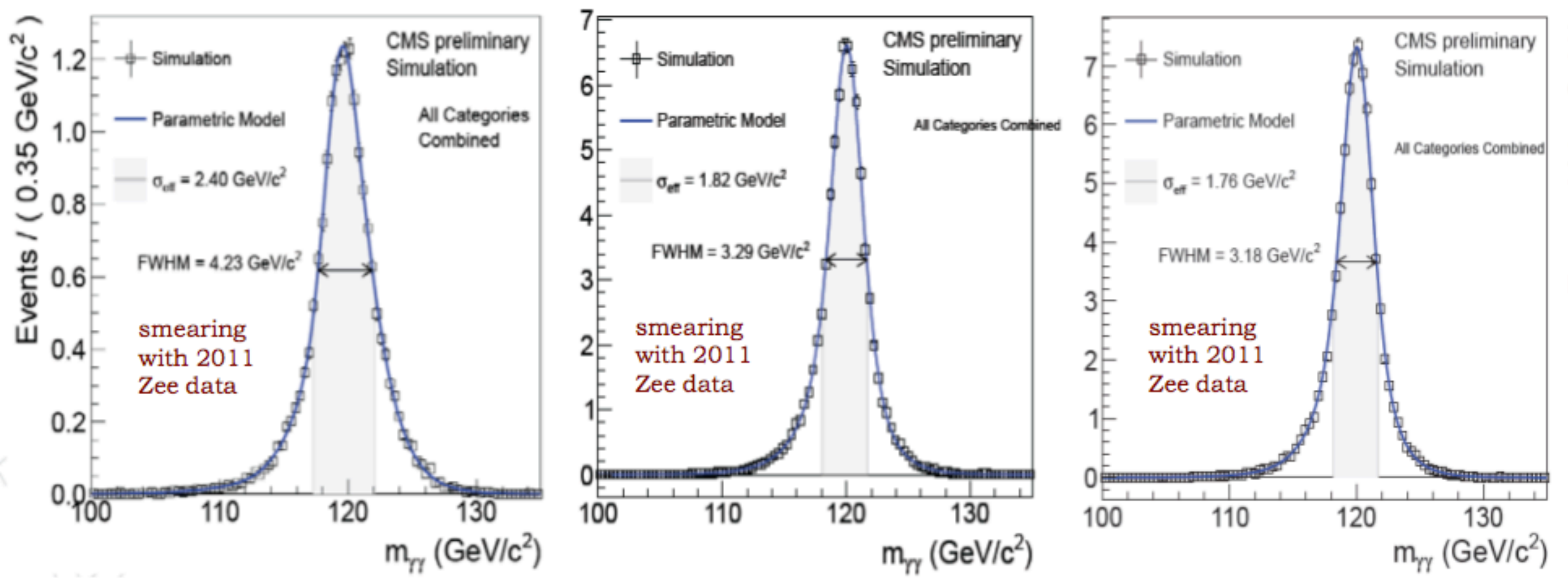
Non converted photons in the barrel $|\eta|<1$



Effect of the regression on the $Z \to e^+e^-$ peak

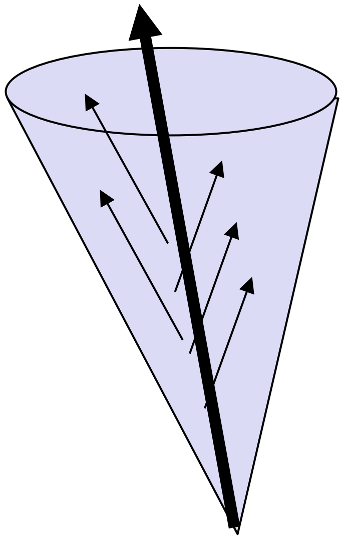
Progress in ECAL calibration

July 2011 EPS	March 2012 Moriond	July 2012 ICHEP
FWHM/2.35 = 1.80 GeV (1.50%)	FWHM/2.35 = 1.40 GeV (1.17%)	FWHM/2.35 = 1.35 GeV (1.13%)

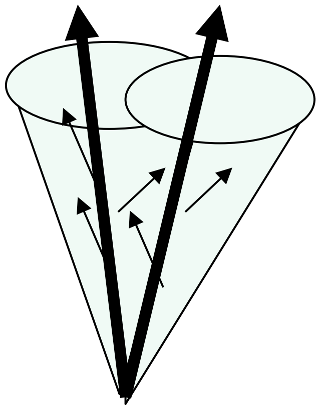


For the golden categories, both photons in the barrel and no conversions: FWHM/2.35=1.04GeV (0.87%) approaching the nominal value. Still room for improvement.

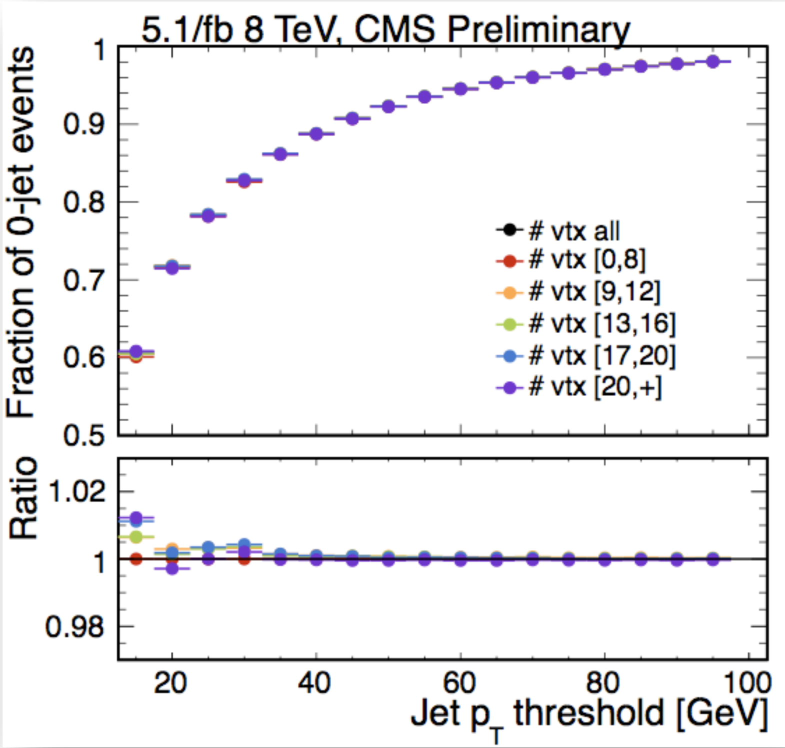
Jet Identification



Typical regular jet

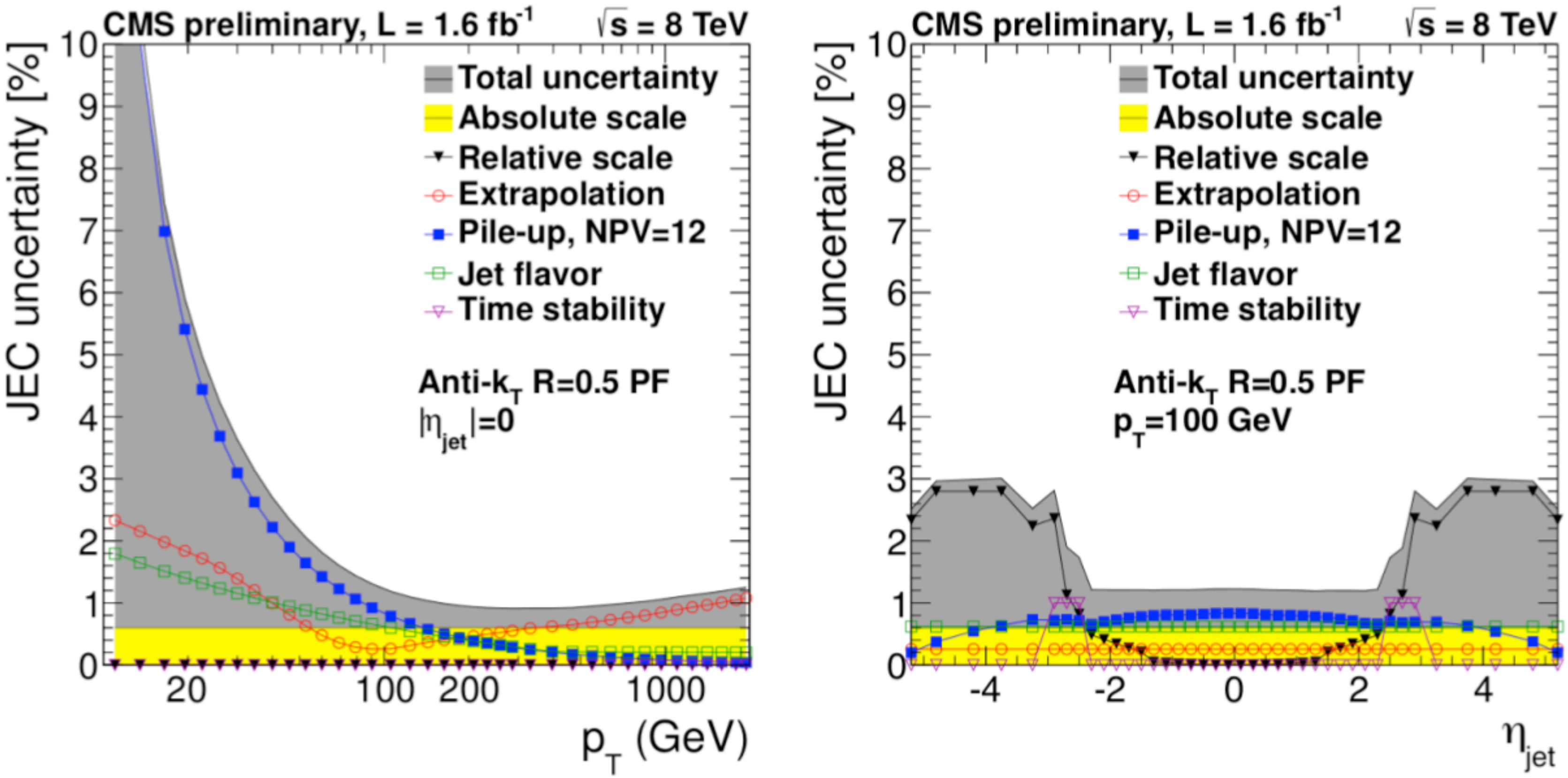


Typical Pileup jet



- Pileup jets structure differs wrt regular jets:
  - Pileup jets originate from several overlapping jets which merge together
  - Likelihood grows rapidly with high pileup
  - discriminant exploits shape and tracking variables
    - discrimination both inside and outside tracker acceptance

Jet Energy Correction Uncertainties



- the contribution of different uncertainty sources depends on p_T and η
- total uncertainty of the jet energy scale is close to 1% for $|\eta|$ < 2.4

Missing Energy Resolution and PU

- MET resolution for different N_{PV} is fitted with:

$$\sigma_{\rm tot} = \sqrt{c^2 + \frac{N_{\rm PV}}{0.7} \cdot \sigma_{\rm PU}}$$

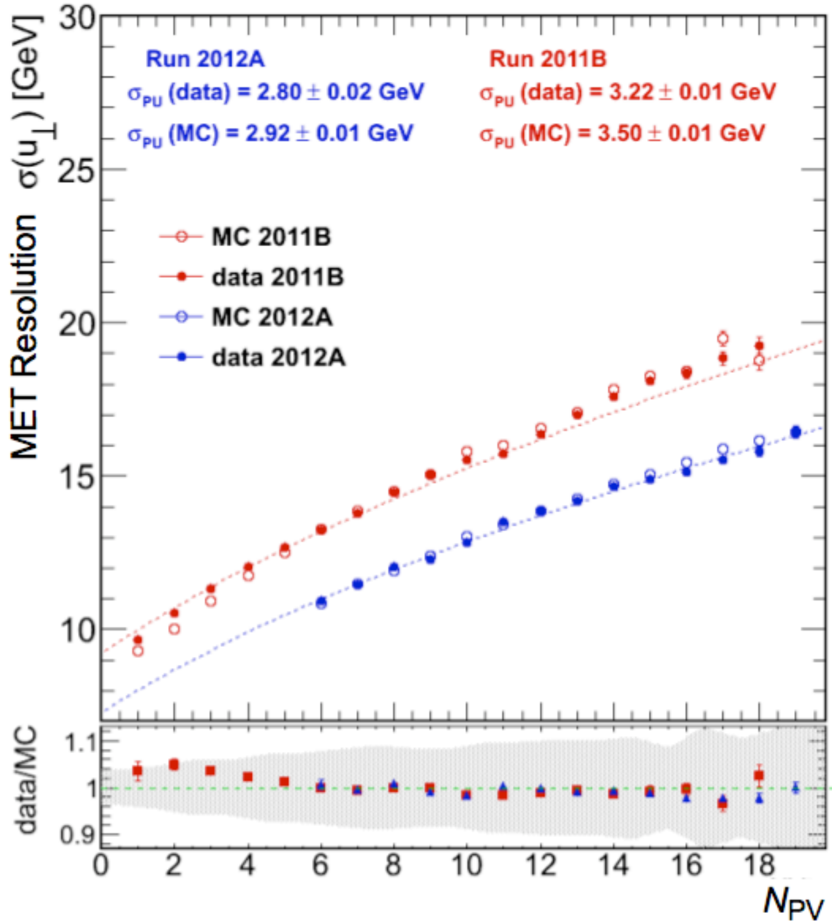
- the fit yields:

  c : average resolution without PU

  σ_{PU} : degradation in resolution caused by PU

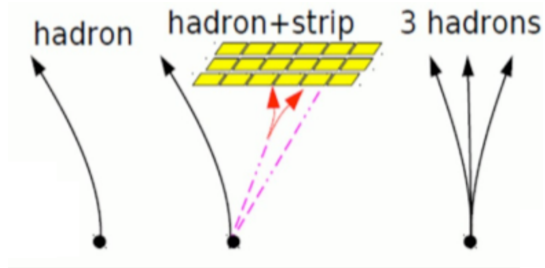
- improved resolution in 2012 for fixed N_{PV}
  - improved ECAL/HCAL energy reconstruction

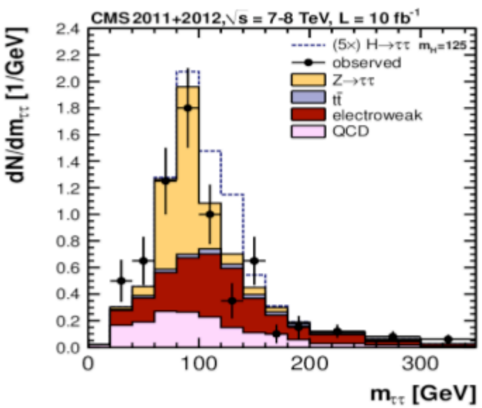
    ⇒ reduces out-of-time pileup effects
  - MET pile-up corrections applied
- pile-up introduces an additional smearing of ~ 3 GeV on MET resolution σ_{PU} (in quadrature)



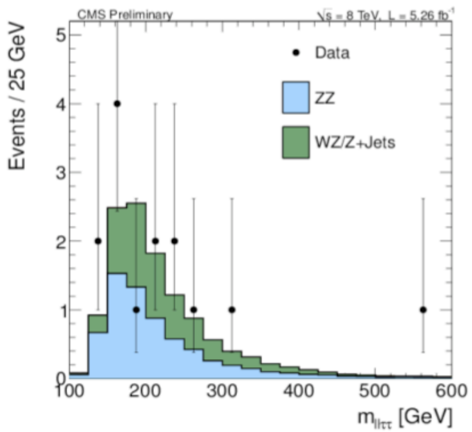
Tau Identification

- **Tau identification**:
  - Searches for major τ decay modes within PF jets. Mainly τ decaying to 1 or 3 charged hadrons.
  - Photons/Electrons clustered in strips to reconstruct π^0
  - Discriminating variables computed on reconstructed τ object.
- **Tau isolation**:
  - Multivariate discriminator using sum of energy deposits in dR rings around the τ.



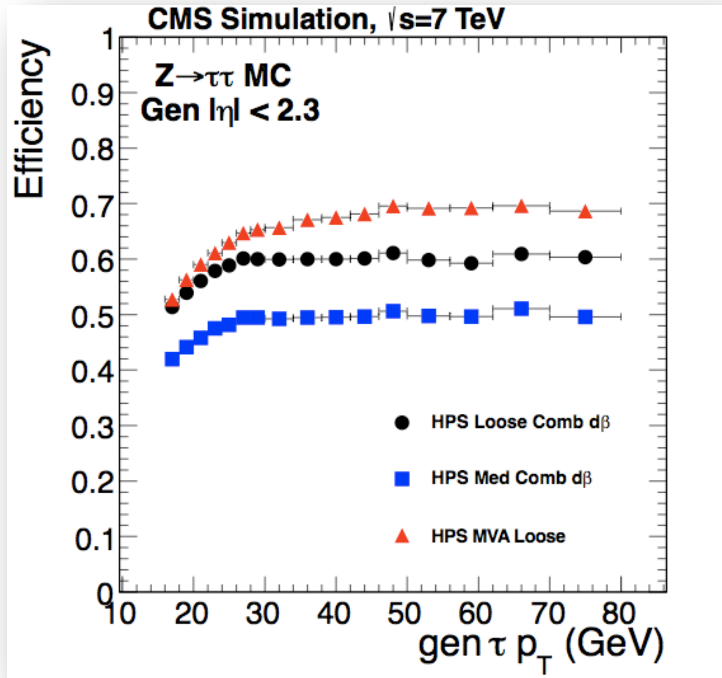


e-τ_h visible Mass



ZZ→ ll$\tau\tau$ invariant Mass

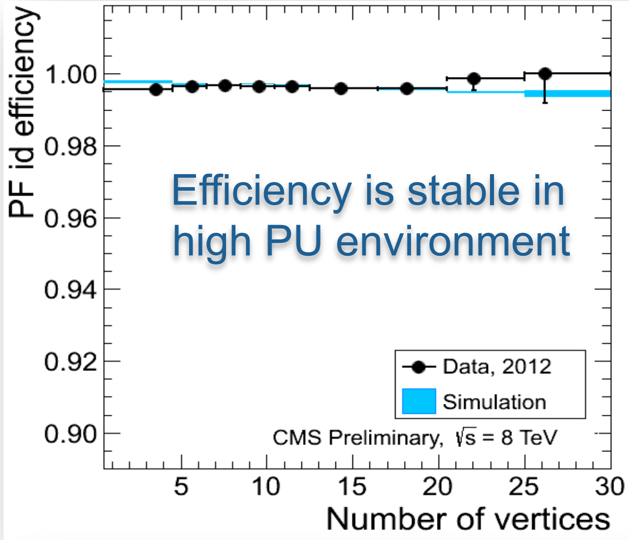
Tau ID + Isolation efficiency



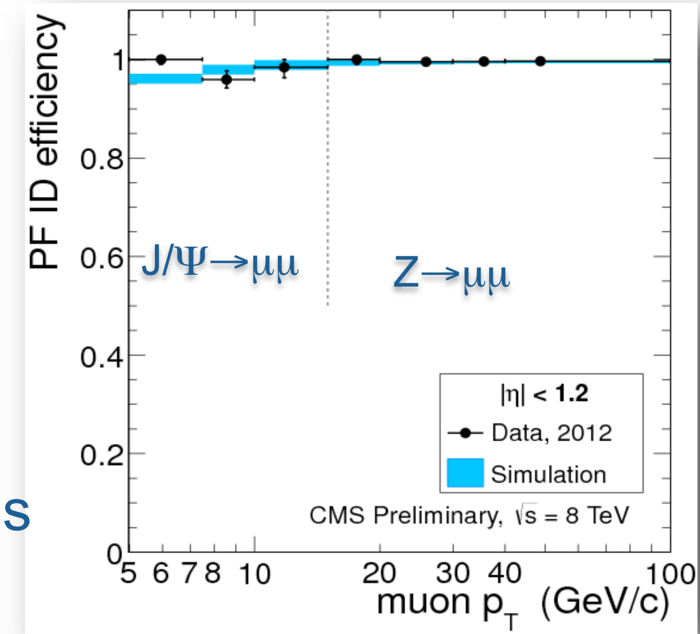
70% efficiency with 5% fake!
τ's in CMS have become "normal" leptons.

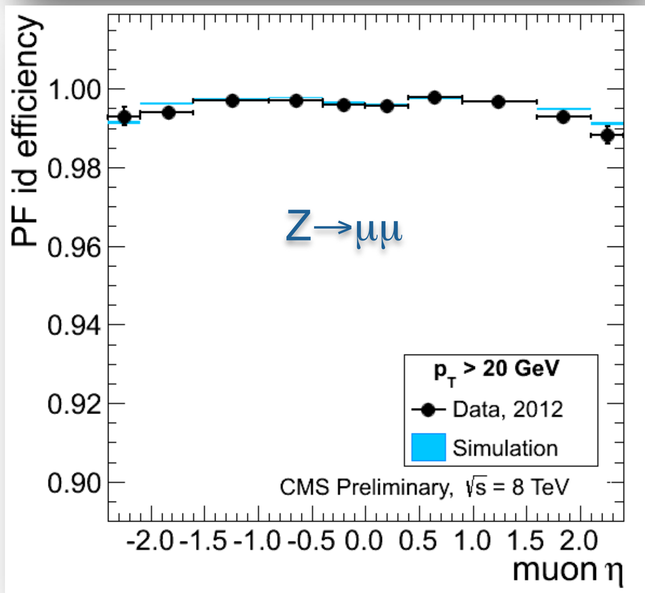
Muon reconstruction and identification

- PF Muon Identification in 2012
  - Exploit information from all subdetectors
- High efficiency **>96% for p_T=5 GeV; >99% for p_T=10 GeV;**
  - Exploit also tracker-based muon ID
  - Important for H->ZZ->4l
  - Efficiency controlled in data with J/Ψ and Z T&P



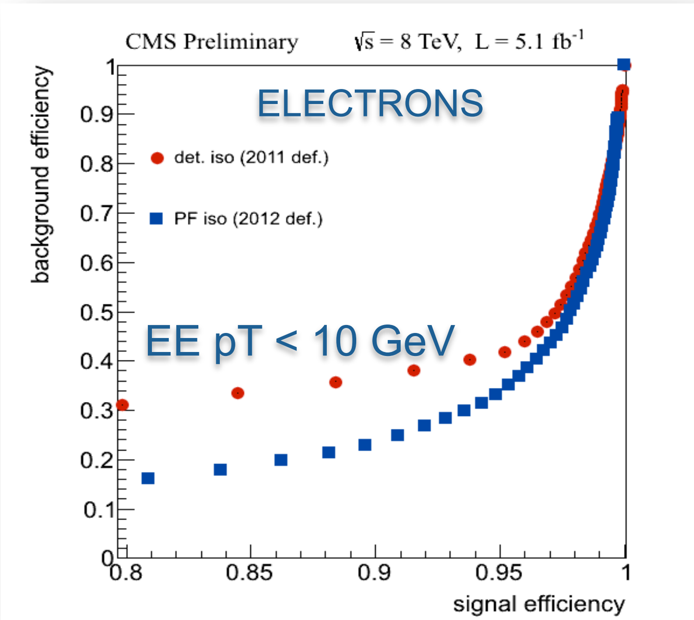
Tighter quality criteria applied in some analyses to further suppress reducible backgrounds





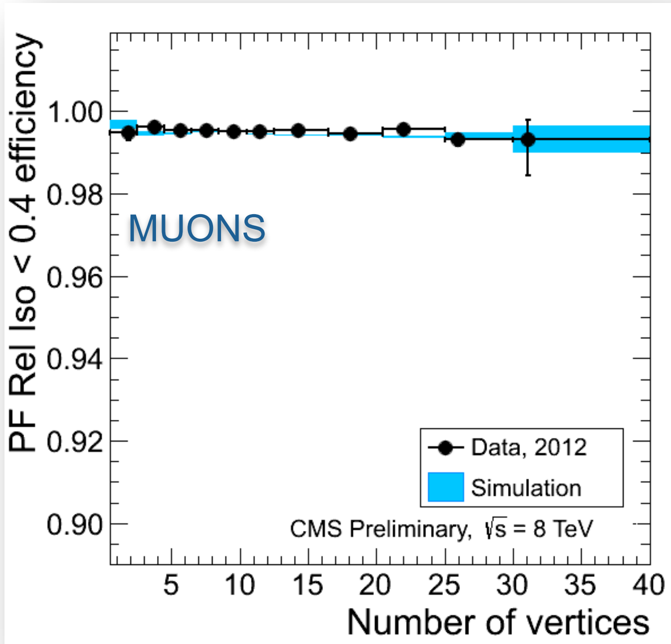
Particle-based isolation

- Created by summing energy deposits from individual particles in ΔR=0.4 cone around the lepton
    - Avoids double counting of the energy deposits in the calorimeters from charged particles
- Pile-up contribution:
    - Negligible for charged hadrons from vertex
    - Neutral contribution corrected using the average energy density, ρ, from the pile-up and underlying event.



Det Based vs PF Based

Isolation Efficiency is stable in high PU environment

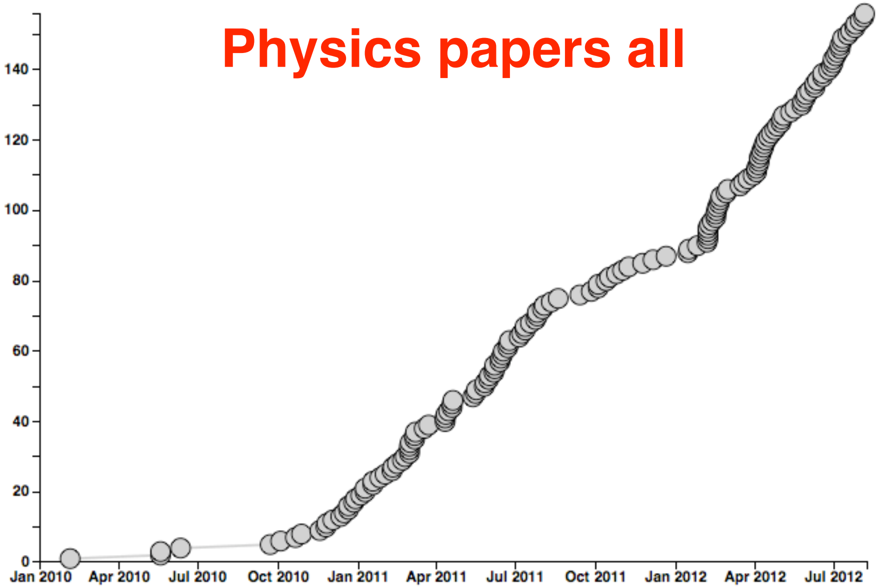


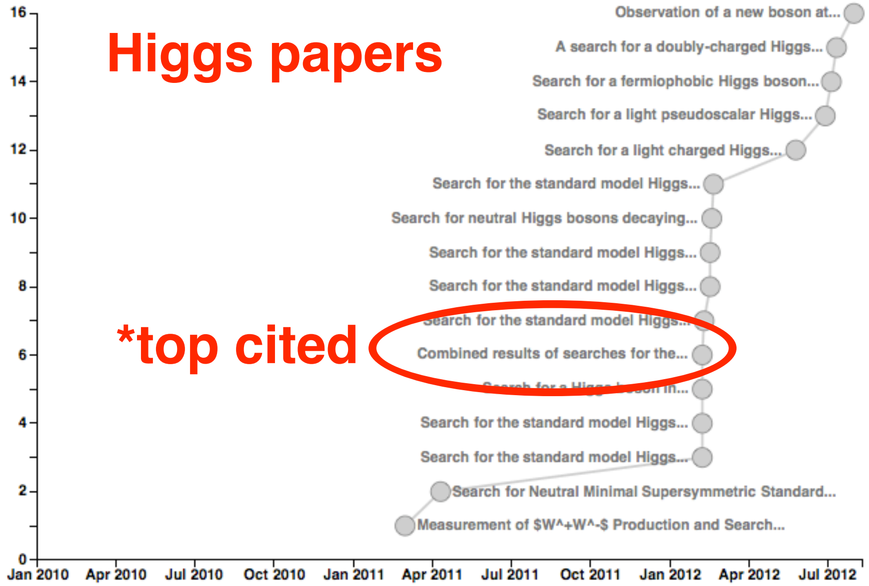
CMS Publications

156 physics papers+24 detector papers+ 5 performance papers

8 papers >100 citations

top cited paper >340 cit.*





406 Physics Analysis Summaries

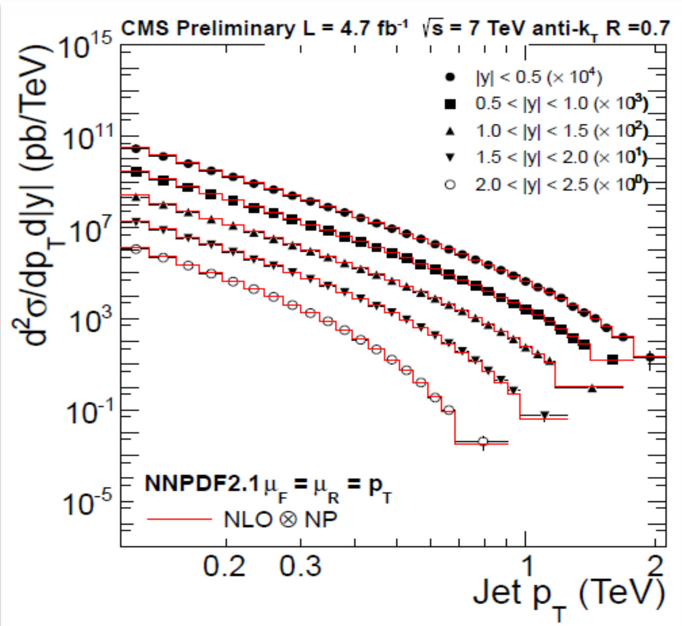
1597 Conference Reports

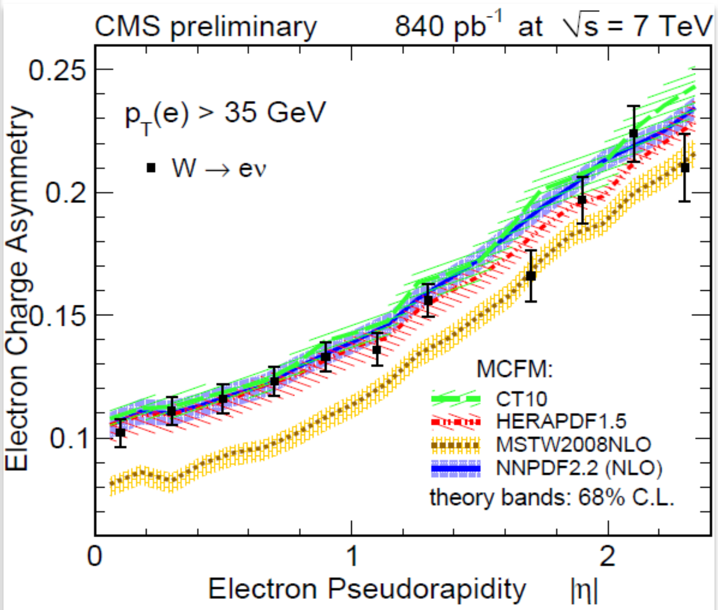
QCD and Standard Model processes.

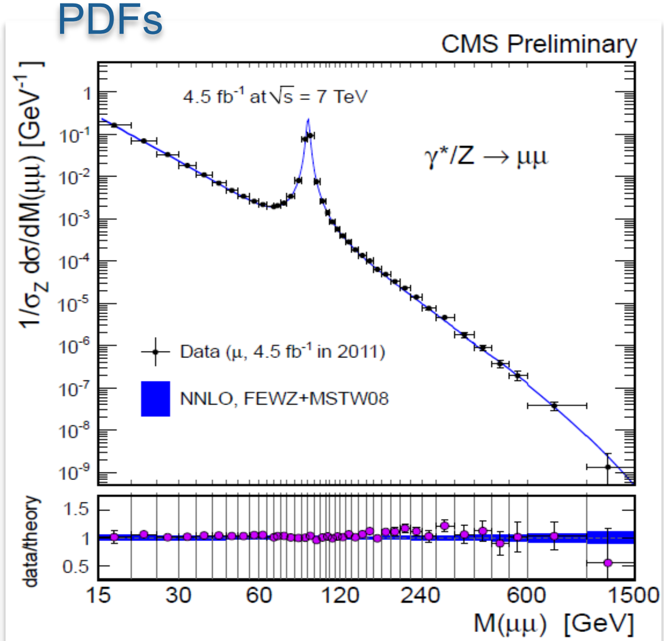
Inclusive jet and dijets. 2-4% JES. Constrains gluon PDF up to x=0.6

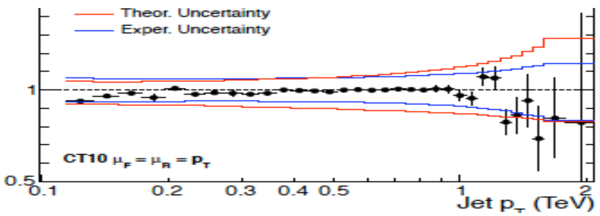
W electron charge asymmetry measured to 0.5-1% per bin of 0.1 in $\Delta\eta$. Constrains u/d PDF ratio

Differential Drell-Yan cross section: 2.5M $Z\rightarrow\mu\mu$ pairs test NNLO cross sections and PDFs









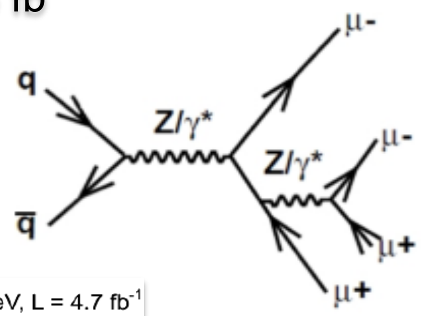
$$A(\eta) = \frac{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) - d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \rightarrow \ell^+\nu) + d\sigma/d\eta(W^- \rightarrow \ell^-\bar{\nu})}$$

CMS-PAS-QCD-11-004 *CMS-PAS-SMP-12-001* *CMS-PAS-EWK-11-007*

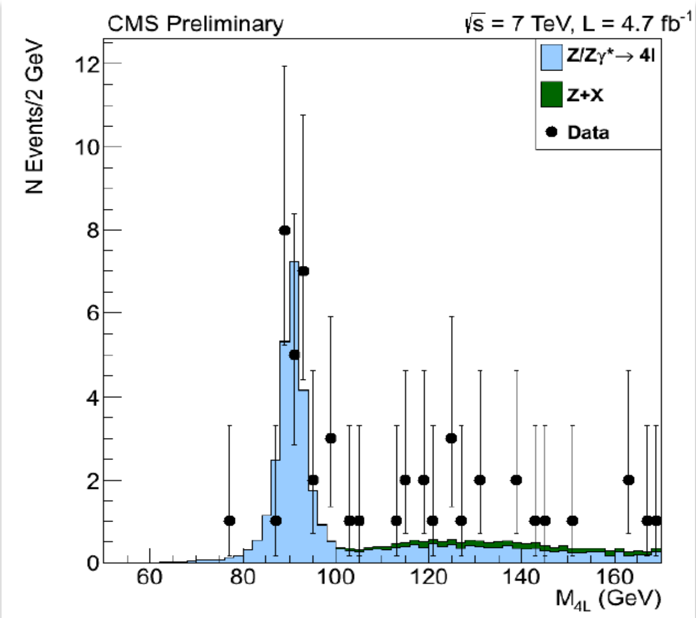
Standard Model rare processes.

4-fermion $Z\rightarrow llll$ decays observed at a hadron collider! (BR = $4.4\cdot10^{-6}$), $\sigma \approx 125\pm26$ fb

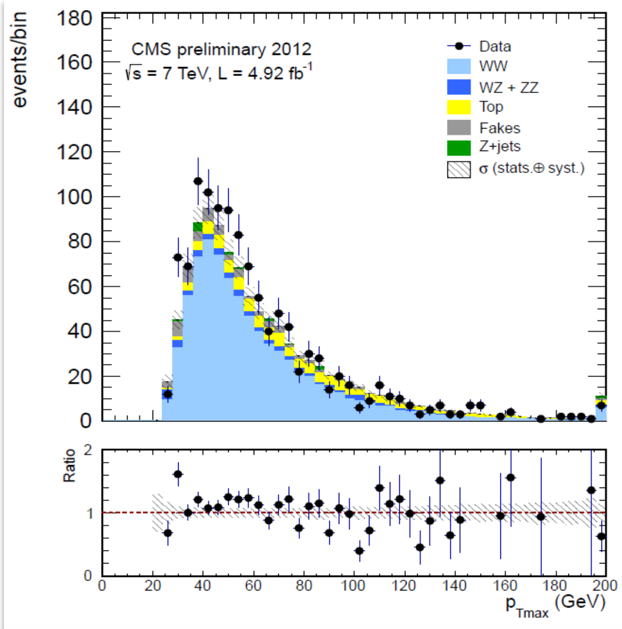
$$Z\rightarrow \mu^+\mu^-\mu^+\mu^-$$



800 $WW\rightarrow l\nu l\nu$ events observed in 2011, ±10% xsec precision. It constrains Higgs backgrounds and anomalous trilinear couplings.

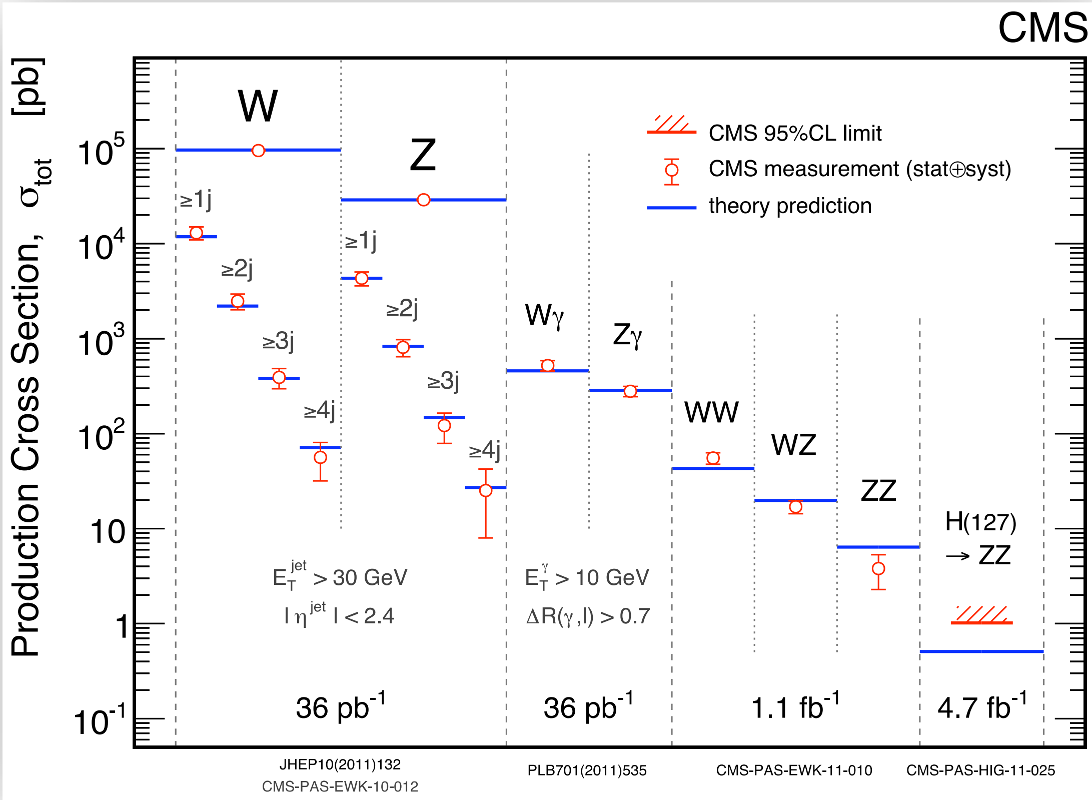


CMS-PAS-SMP-12-009



CMS-PAS-SMP-12-005

Standard Model at 7TeV (2010-11)



Excellent agreement with NLO (or approx. NNLO) predictions.
Key ingredients for Higgs hunting.
$\sigma(pp)\rightarrow H+X$ (for m_H=125GeV)=17.5pb same order of magnitude of the diboson (WW, WZ, ZZ production).

Where are we today

A lot of beautiful results but…

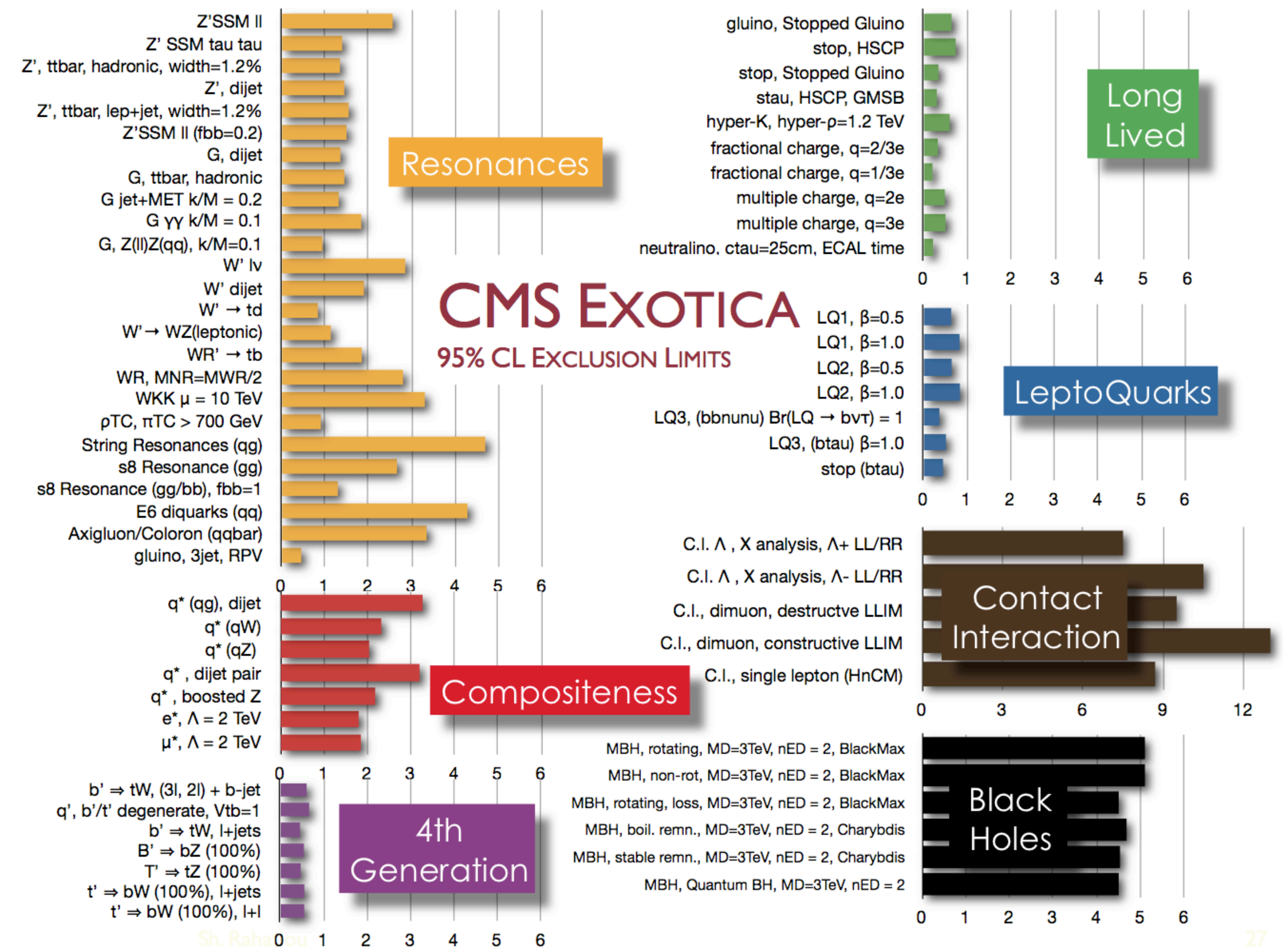
Where are we today with respect to our initial ambitious goals?

1) Sort out the mechanism responsible of the Electroweak Symmetry Breaking: discover the Higgs boson or find an alternative mechanism.

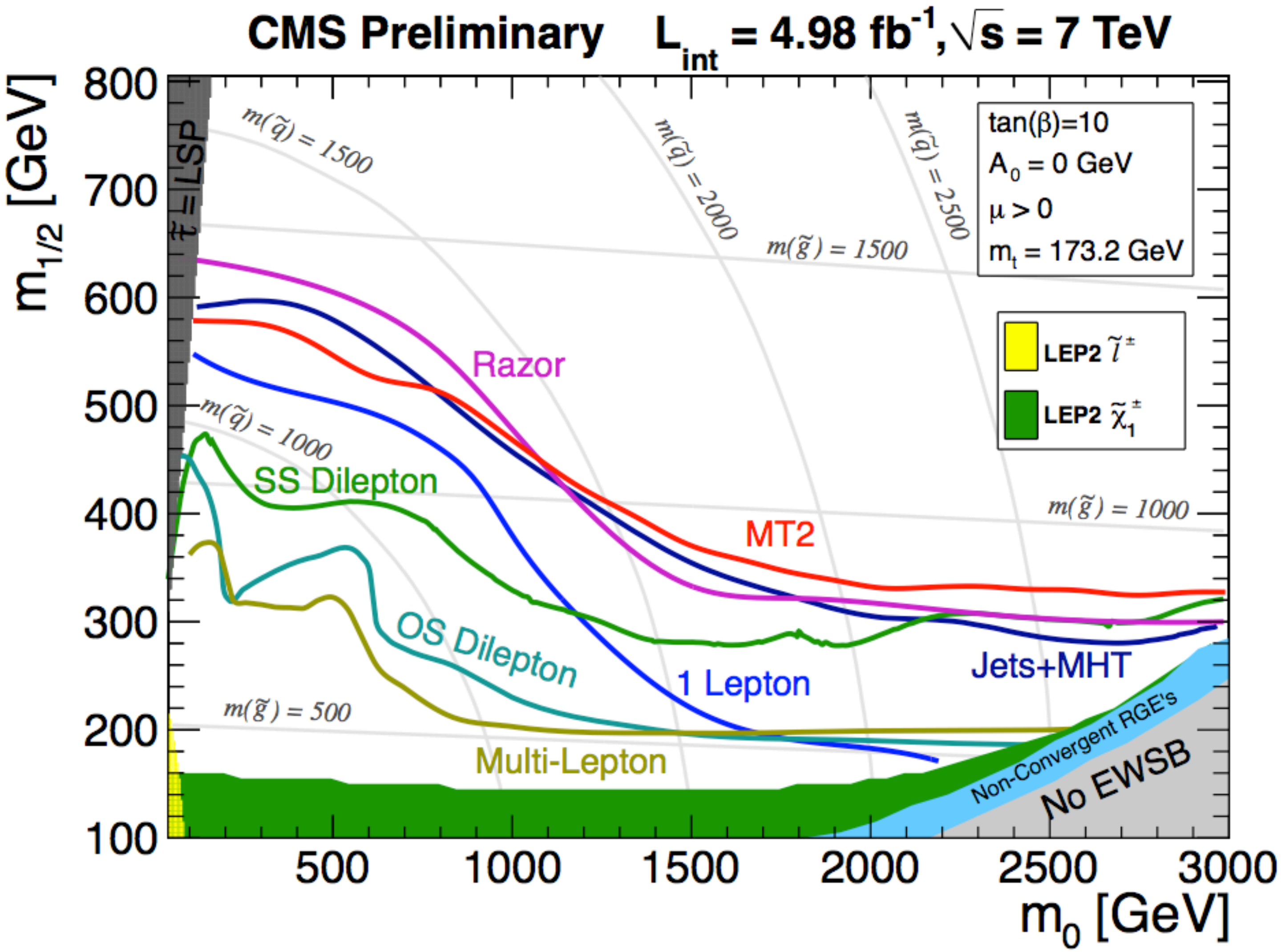
2) Discover SUSY if super-symmetry is a symmetry of nature.

3) Try to discover new physics in general using a large variety of different signatures.

No new physics(so far)

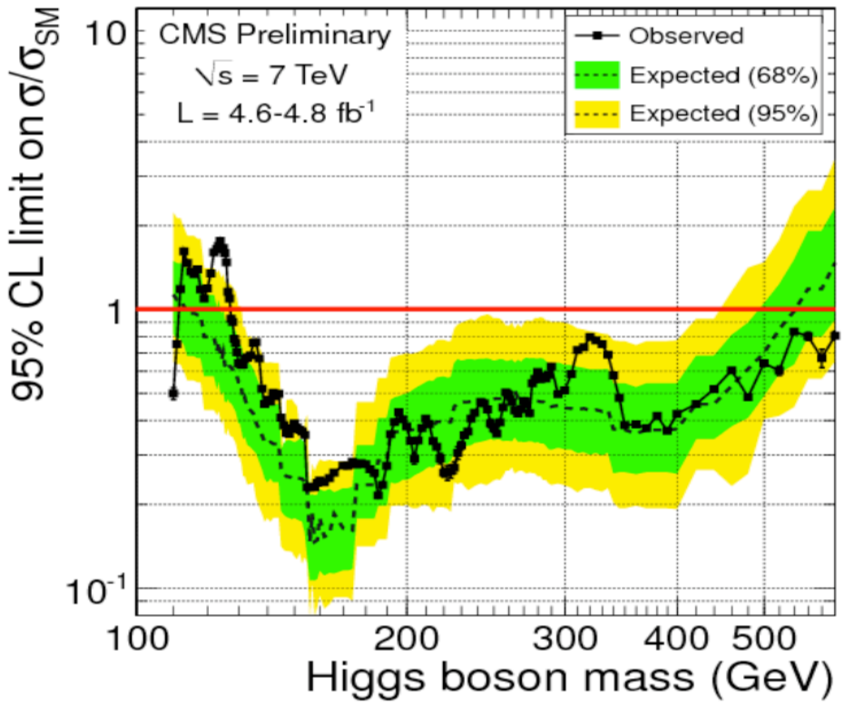


No SUSY (so far).



At least within constrained MSS models.

But on Dec 13th 2011….

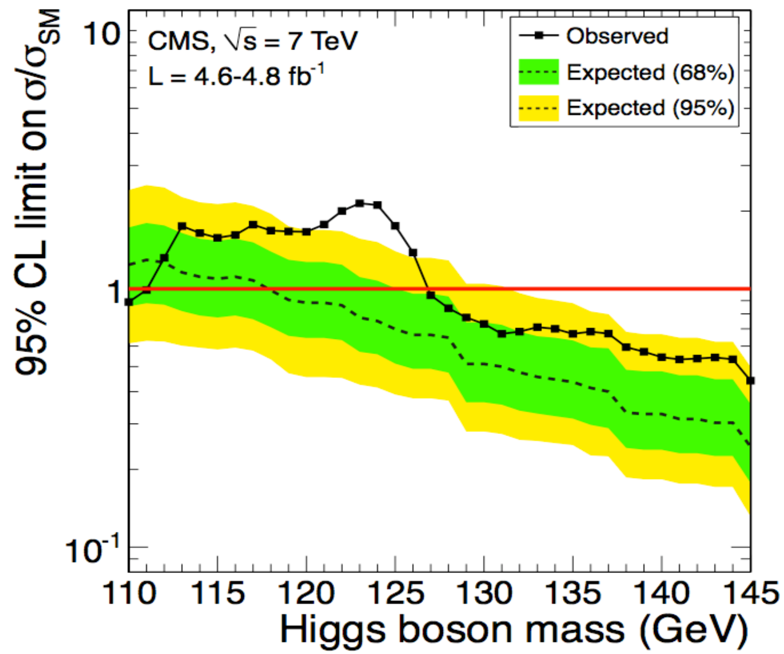


Expected exclusion 114.5 - 543 GeV

Observed exclusion 127.5 - 600 GeV.

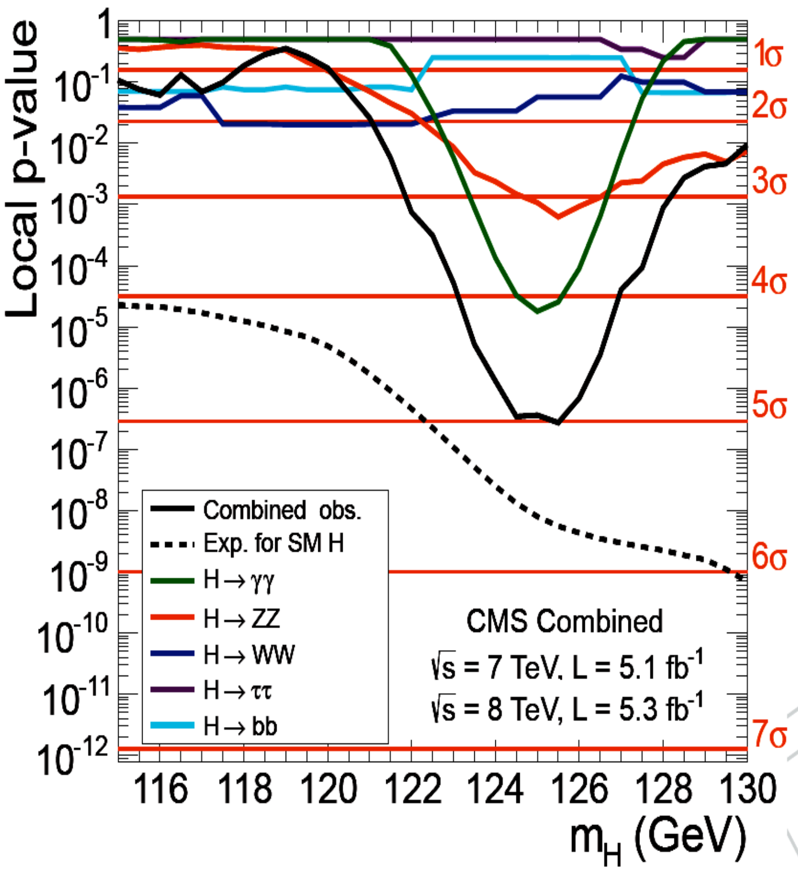
We cannot exclude the presence of the SM Higgs boson below **127.5 GeV** due to the presence of an excess of events in the low mass region around **125GeV.**

"We observe an excess of events which is most compatible with a SM Higgs hypothesis in the vicinity of **m_H~ 124 GeV**, but the statistical significance (**2.6σ** local and 1.9σ global after correcting for the LEE in the low mass region) is not large enough to say anything conclusive. **Additional data will ascertain the origin of the excess**



July 4th 2012.

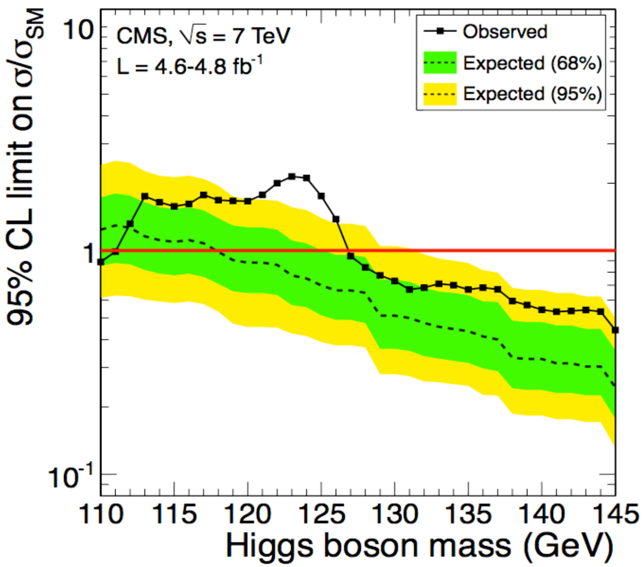
Discovery of a Higgs-like boson in CMS.



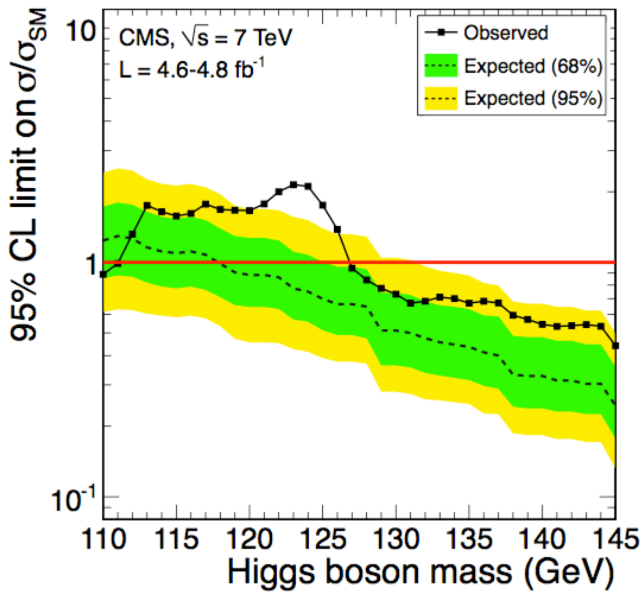
- **5 Modes combined significance 5.0 σ**
- **mass: 125.3±0.6GeV; σ/σ_{SM} = 0.87±0.23;**
- **July 4th Seminar at CERN**
  https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=6125
- **Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at LHC**
- arXiv:1207.7235v1
  http://cdsweb.cern.ch/record/1470975
- **Many details in Albert's talk at this school.**

We are on track to understand better EWSB.

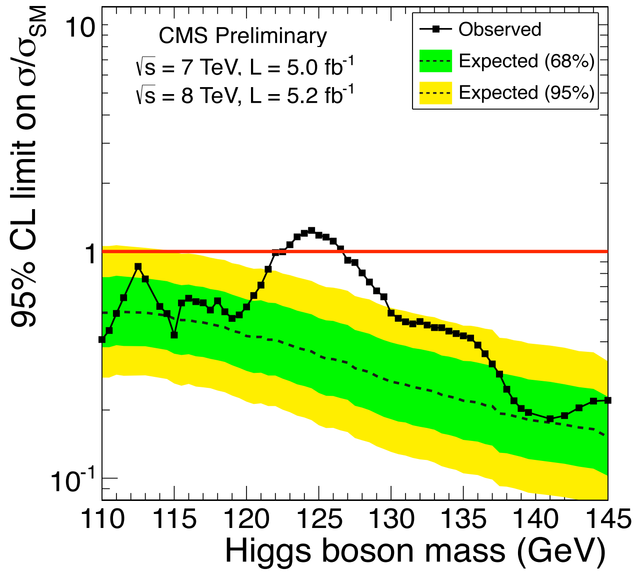
7 months that changed physics



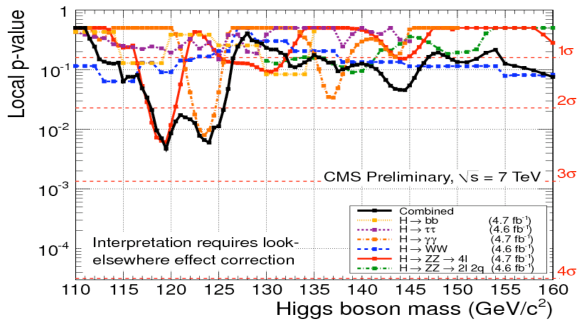
13 Dec 2011 **2.6σ**
CERN 1st Seminar

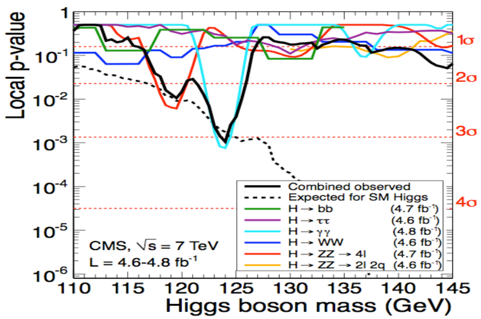


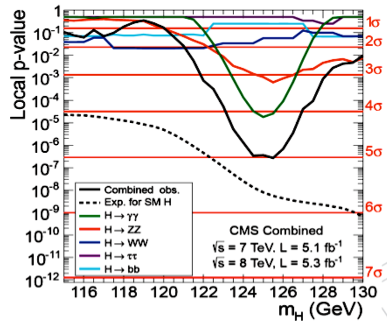
7 Feb. 2012 **3.1σ**
arXiv:1202.1488v1



4 Lug 2012 **5.0σ**
CERN 2nd Seminar







To be noted

•This discovery has arrived with LHC running at **7/8 TeV: 1/2 of its design energy !!!**

•The discovery was announced when ATLAS and CMS had collected **~10fb^{-1}: 1/3 of the minimal amount considered necessary at the time of our Physics TDR 2007!!!**

This is the result of the 'mission impossible" set-up just in July 2010:

"We'll discover the SM higgs boson-or exclude it forever- before entering the long shut-down needed to run LHC at 14TeV"

Key components: a beautifully working detector, a reliable accelerator and hundreds of enthusiastic young physicists willing to take the challenge.

First implications of the discovery

Is it really the SM Higgs or do we see already deviations from the SM?

The strength of its interactions with all other particles and with itself are precisely the ones predicted by the SM?

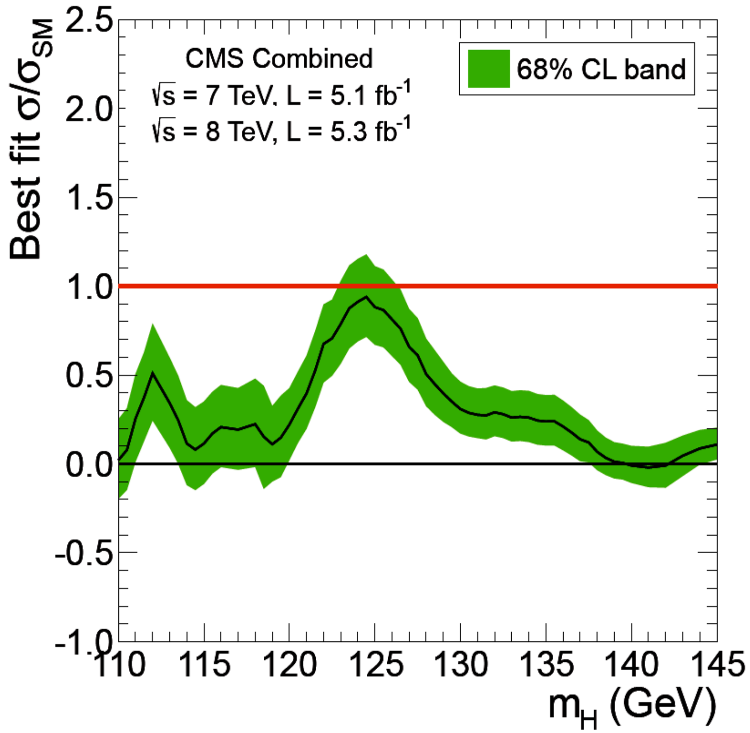
Is it alone or accompanied? Is it "elementary" or "composite"?

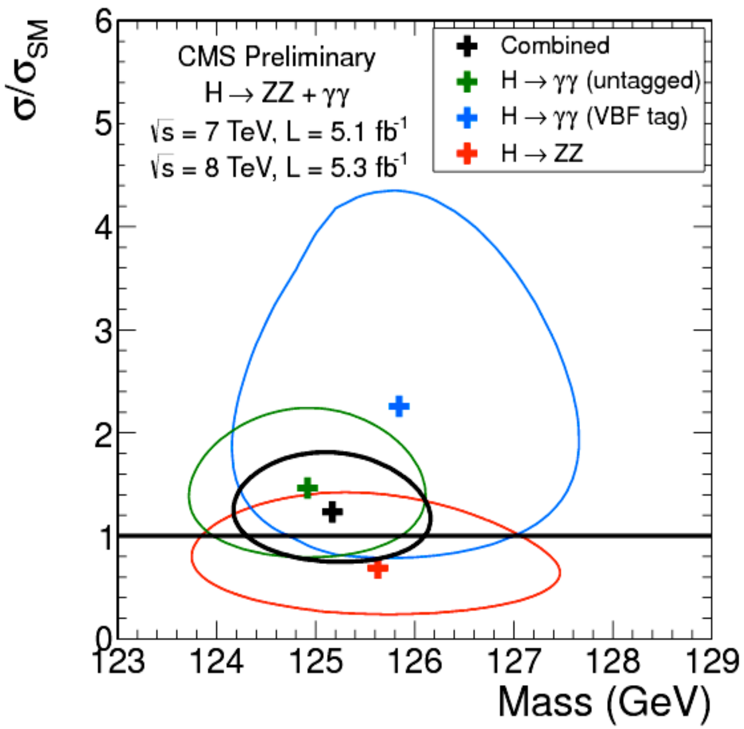
What are the implications for the search for new physics?

A new field has been opened by the discovery: precision measurement of the "Higgs-like particle" properties as a possible path to BSM physics.

Measuring the mass.

We could use μ but the achievable accuracy is not very high. Better results are obtained by measuring independently the mass using the high resolution channels: H→γγ and H→ZZ→4leptons. Fit a peak with a freely floating cross section.





Mass fits with H→γγ and H→ZZ→4leptons on 2011/2012data.

Precision measurement of m_H

Likelihood scan for Mass and Signal strength in three high mass resolution channels. Results are self-consistent:

- $\gamma\gamma$: 125.1 ± 0.7 (± 0.4 stat ± 0.6 sys) GeV
- ZZ: 125.6 ± 1.2 (± 0.9 stat ± 0.8 sys) GeV

m_H=125.3±0.4(stat)±0.5(syst)GeV

- We are already ~600MeV but many improvements are possible.
- $H \rightarrow \gamma\gamma$ could hopefully give the best performance. It will be only limited by statistics and by our capability to reach the ultimate performance in the calibration of ECAL.
- Possible improvements: use of di-jet tagged channels, single crystal calibration using the large statistics of π^o, η, W and Z, better understanding of the tracker material, better understanding of the clusters variables.
- Prospects for the accuracy on the mass ~300MeV with >30fb^{-1} and combination of ATLAS and CMS; (~100MeV?? with >300fb^{-1}.) Systematics to be better understood.
- To go below lepton colliders will be needed.

Have we observed a scalar?

Spin ⇆ angular distribution of final decay products

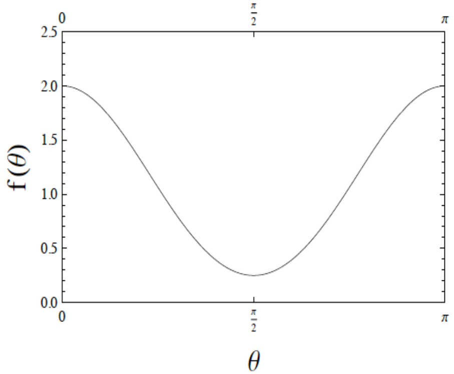
Since it decays to two photons: spin 1 is forbidden by Bose symmetry (Landau-Yang theorem).

1) gg →X→γγ qq →X→γγ   Gao et al. 2010

spin-0: flat in cosθ*

spin-2: quartic in cosθ*

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$$

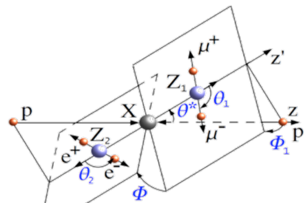


2) gg →X→ZZ*→4ℓ Choi et al. 2002, De Rujula et al 2010

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

arXiv:1001.5300

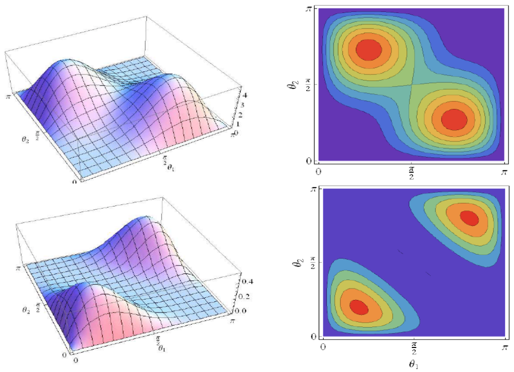
3) gg →X→W⁻W⁺ →ℓ⁻ℓ⁺νν Ellis et al. 2012

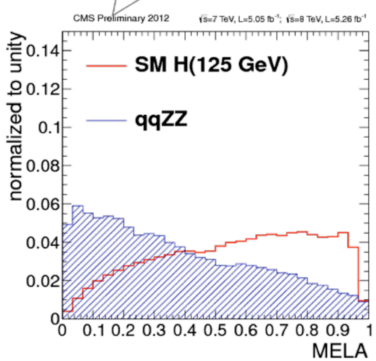


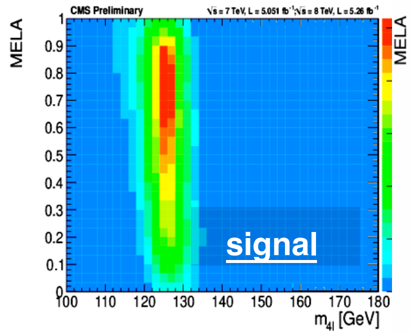
Polar angle distribution for X_2→W^+W^-

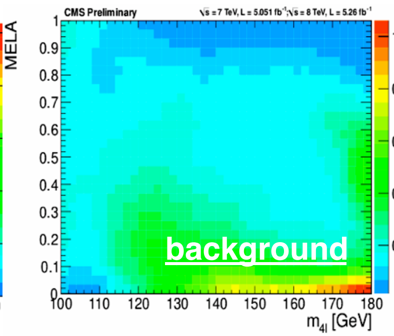
Polar angle distribution for X_0→W^+W^-

(for $\phi = \pi$)









Have we observed a scalar?

Parity ⇆ angular distribution of final decay products
CP-odd: couplings to WW are loop-induced only!
Hard to explain data

1) **Angular distribution of leptons in gg →H→ZZ*→4ℓ**
   work ongoing

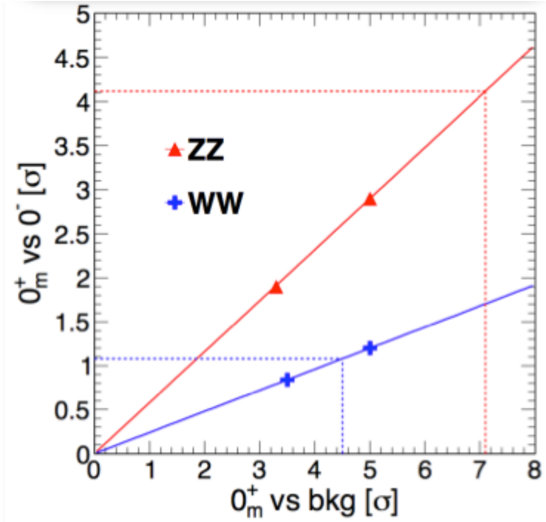
2) **Angular distribution of jets produced in VBF** Plehn et al 2001
   studies ongoing

3) **Spin correlations in X →ττ** Berge et al '2008
   hard for the moment since we don't have a signal yet

Quantum numbers of the new particle

Spin and parity J^P

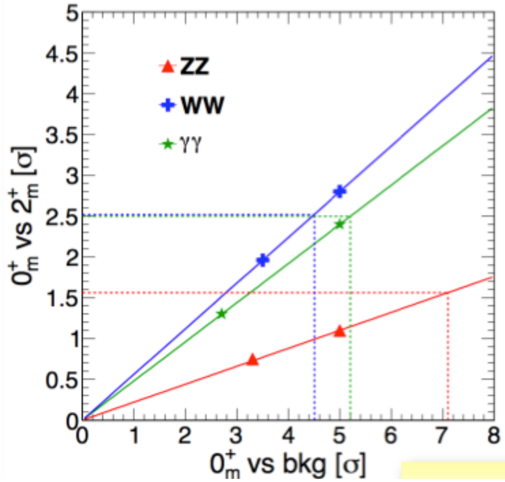
J^P: currently using angular correlations in ZZ*, WW* and $\gamma\gamma$. By the end of 8 TeV run, assuming a total of $35 fb^{-1}$ per experiment.
~4σ separation of 0^+ vs 0^- and 0^+ vs 2^+



Expected hypothesis separation Significance vs signal observation. arXiv:1208.4018v1, Bolognesi et al.

CP: even, odd or a mixture? More tricky.
If focus at LHC stays on WW*, ZZ* and VBF: limited sensitivity to distinguish pure CP-even state from a mixture of CP-even and CP-odd components.

Linear collider: threshold behaviour of e+e-→ttH gives precision measurement of CP mixing.



A SM Higgs at 125GeV is a very special object

A light mass scalar, could in principle rule its self-interaction and the Yukawa interactions with fermions in such a way that the theory could remain weakly coupled up to the Planck scale without any dynamics appearing beyond the EWK scale.

This would be in itself an outstanding discovery: for the first time we would have seen a phenomenon that could be described by the same theory over 15 orders of magnitude in energy.

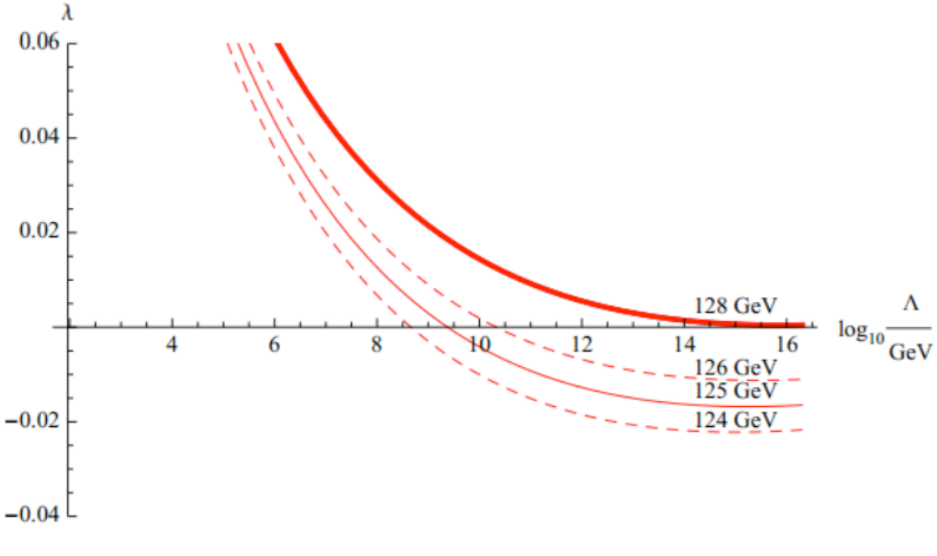
Although possible, this scenario would be severely constrained by the need that the couplings of the Higgs boson must be finely tuned to very well predicted values.

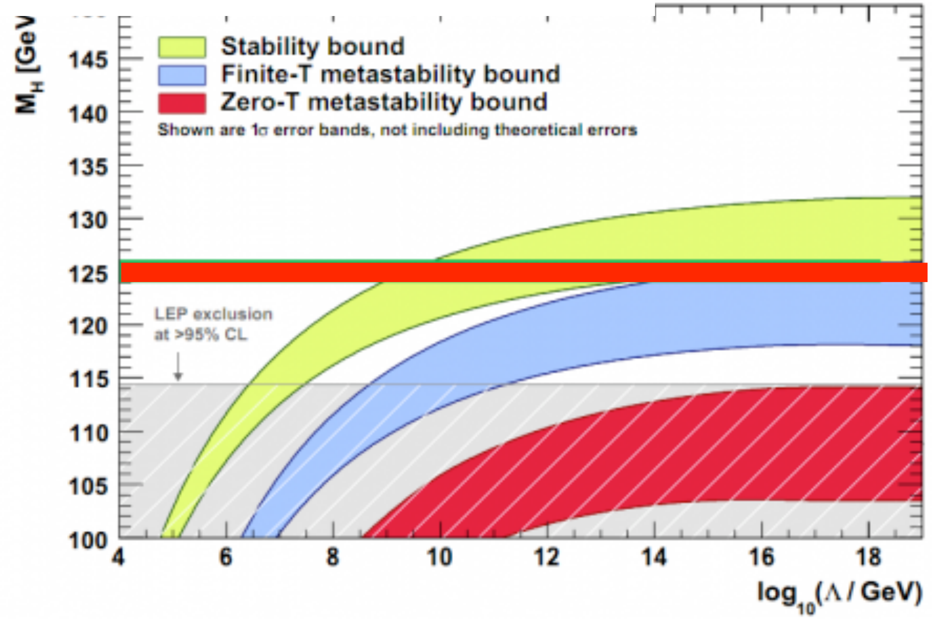
Precision measurements of the Higgs coupling could lead to unambiguous hints of the presence of New Physics beyond the EWK symmetry breaking scale.

A SM Higgs at 125GeV might have profund implications.

Is the Higgs potential vanishing at M_{Pl} ?

$$\lambda(M_{\rm Pl}) = -0.0144 + 0.0028\left(\frac{M_h}{\rm GeV} - 125\right) \pm 0.0047_{M_t} \pm 0.0018_{\alpha_s} \pm 0.0028_{\rm th}$$





arXiv:1112.3647

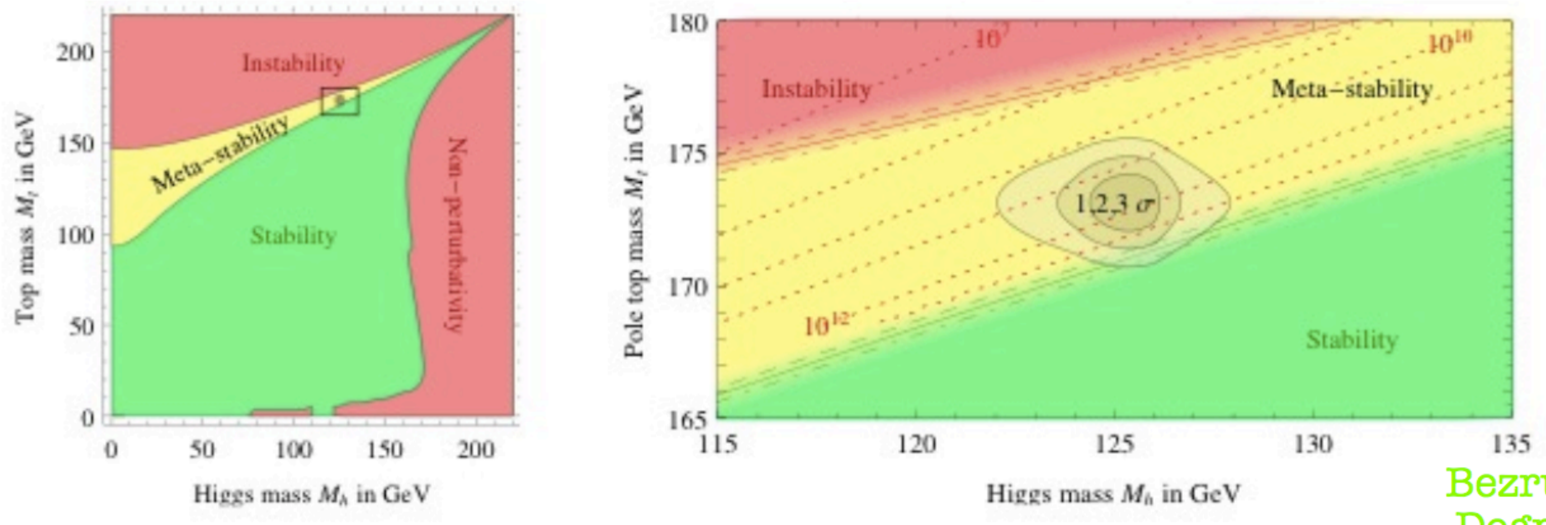
Implications of the 125 GeV Higgs boson for scalar dark matter and for the CMSSM phenomenology

M. Kadastik, K. Kannike, A. Racioppi, M. Raidal

EWSB determined by Planck physics? absence of new energy scale between the Fermi and the Planck scale? Anthropic or natural EWSB?

Vacuum Stability and a Light Higgs Boson

With a heavy top quark and a 125GeV Higgs the EWK vacuum in our Universe appears to be in a meta-stable state. The Higgs potential could develop an instability around **$10^{11\text{-}12}$ GeV**, with a lifetime still much longer than the age of the Universe. However, taking into account theoretical and experimental errors, stability up to the Planck scale cannot be excluded.



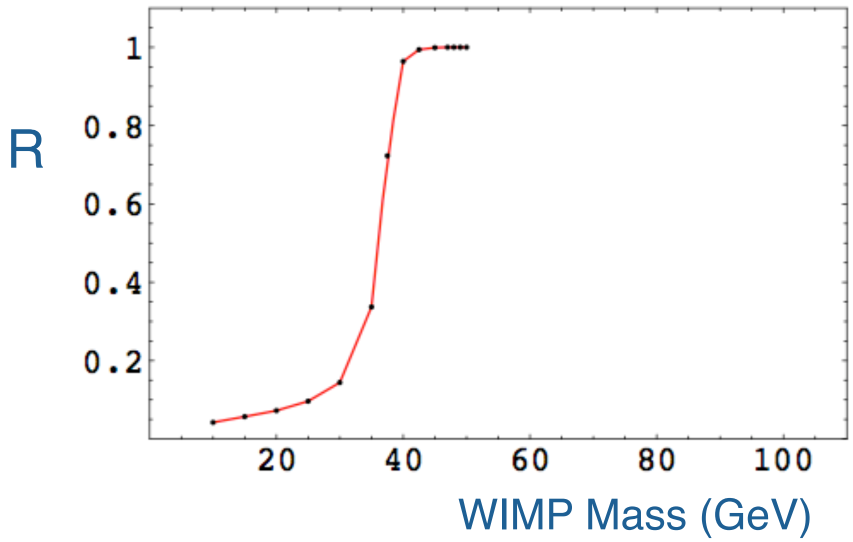
Bezrukov et al '12
Degrassi et al '12

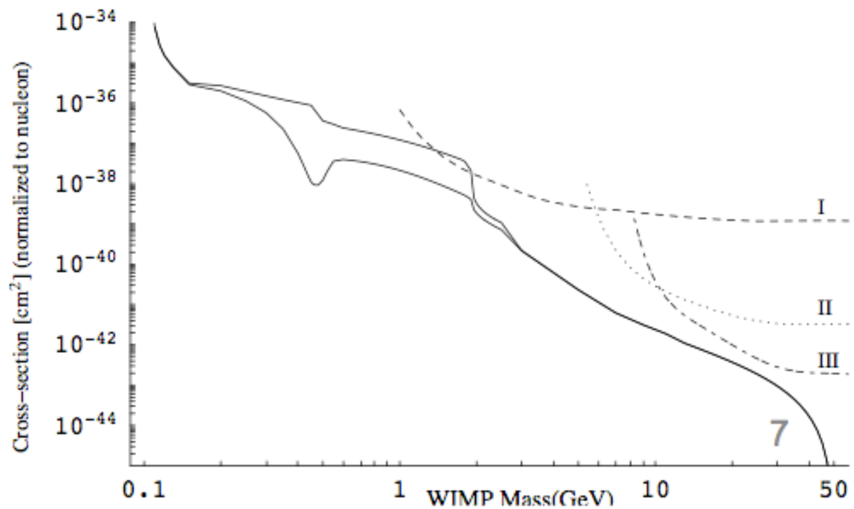
if $m_H > M_{stability}$, the Higgs could serve as an inflaton
if $m_H = M_{stability}$ the SM is asymptotically safe, ie consistent up to arbitrary high energy

Precise determination of the Higgs mass as well as a new round of measurements of the top mass will be key ingredients of this game. Implications on the mass of RH neutrinos, temperature reheating after the inflation, leptogenesis etc.

Dark Matter and a 125GeV scalar

- The main motivation for an invisible Higgs boson decay width comes from the existence of Dark Matter (DM) of the Universe. Because Higgs boson decays to fermion dark matter are essentially ruled out by direct detection constraints, in this scenario the dark matter is naturally scalar. **If the dark matter particles are two times lighter than the Higgs boson, they can lead to invisible Higgs boson width.**
- A 125GeV/c^2 Higgs is a "very fragile" object since its width is very small and there is no much room left for invisible decays. Through a rough measurement of **R = (SM modes)/(SM modes+DM modes)** many models based on scalar particles of masses <50GeV could be immediately ruled out.





Direct access to invisible width only at lepton colliders

SUSY and a 125GeV scalar

In the SM, the Higgs mass is essentially a free parameter.
In the MSSM, the lightest CP-even Higgs particle is bounded from above:
$M_h^{max} \approx M_Z |\cos 2\beta| +$ radiative corrections $\leq$110–135 GeV

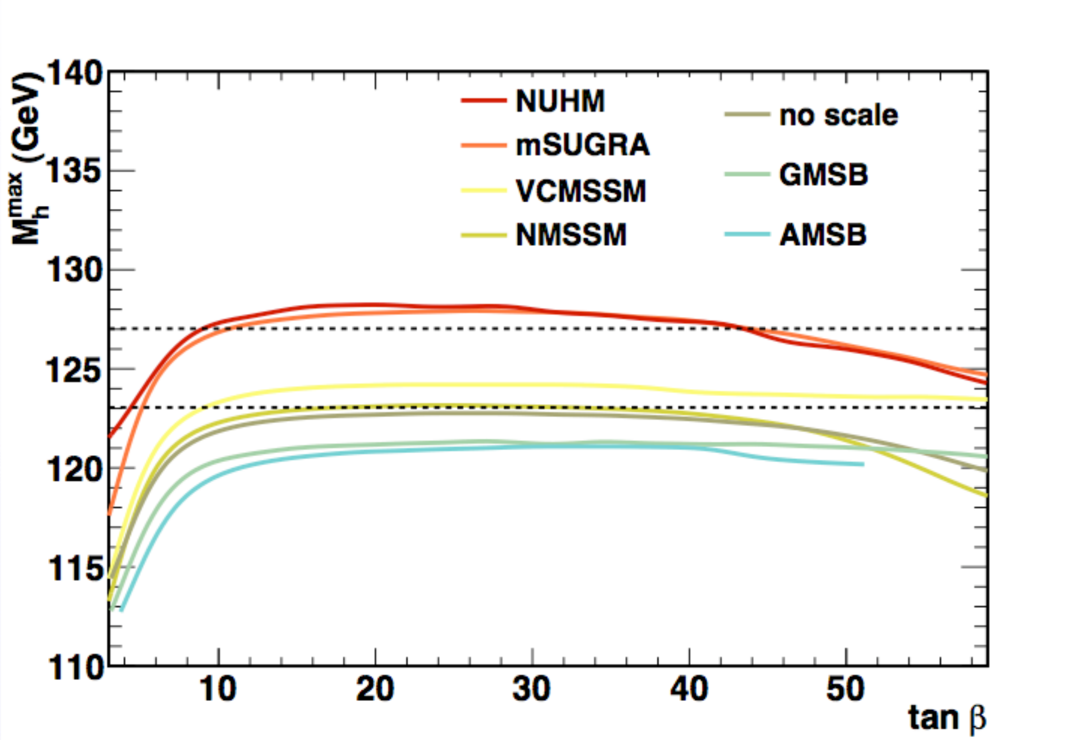
Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections.

$$M_h^2 \overset{M_A \gg M_Z}{\approx} M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\log\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu \cot\beta$

SUSY models compatible with a 125GeV scalar

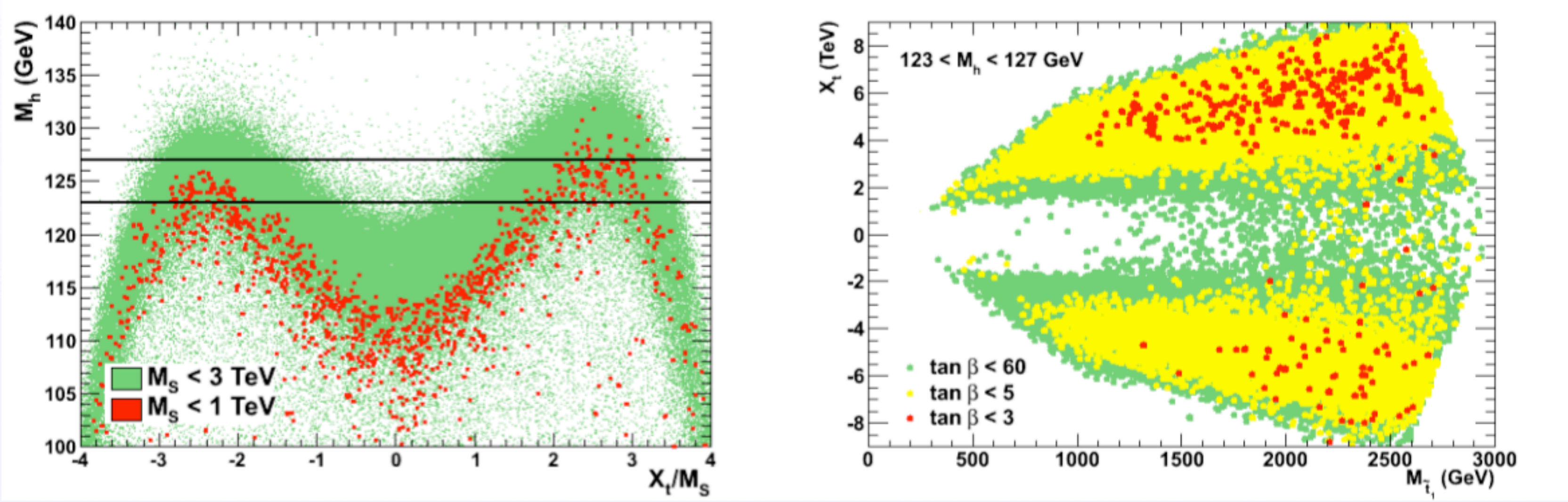
Maximal Higgs masses



A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

model	AMSB	GMSB	mSUGRA	no-scale	cNMSSM	VCMSSM	NUHM
$M_h^{\max}$	121.0	121.5	128.0	123.0	123.5	124.5	128.5

Still a not negligible part of pMSSM survives



A. Arbey, M. Battaglia, A. Djouadi, F.M., J. Quevillon, Phys.Lett. B708 (2012) 162

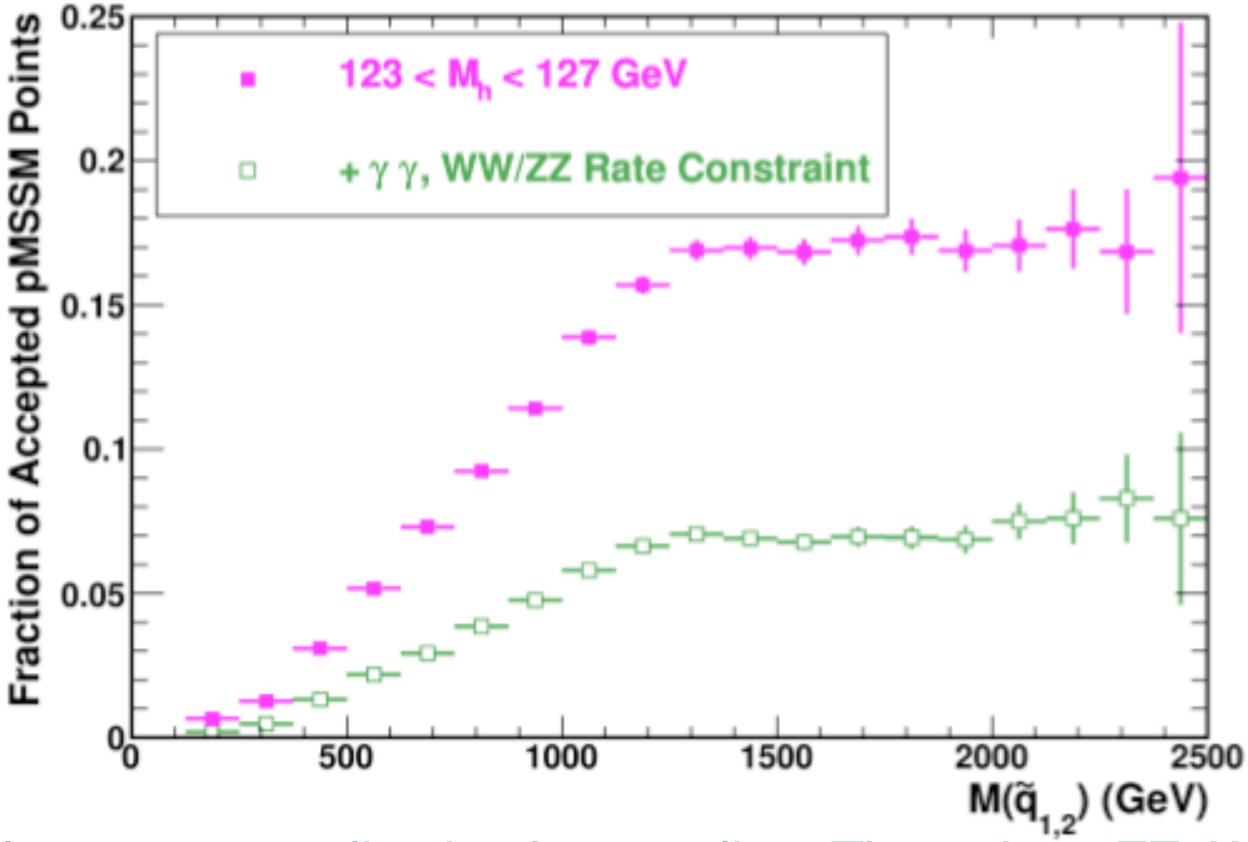
A large part of the pMSSM still survives

No mixing cases ($X_t \approx 0$) excluded for $M_S < 1$ TeV

Small stop masses still allowed

20 % of the points passing all constraints are compatible with a 123GeV<M_H <127GeV

...but using couplings...

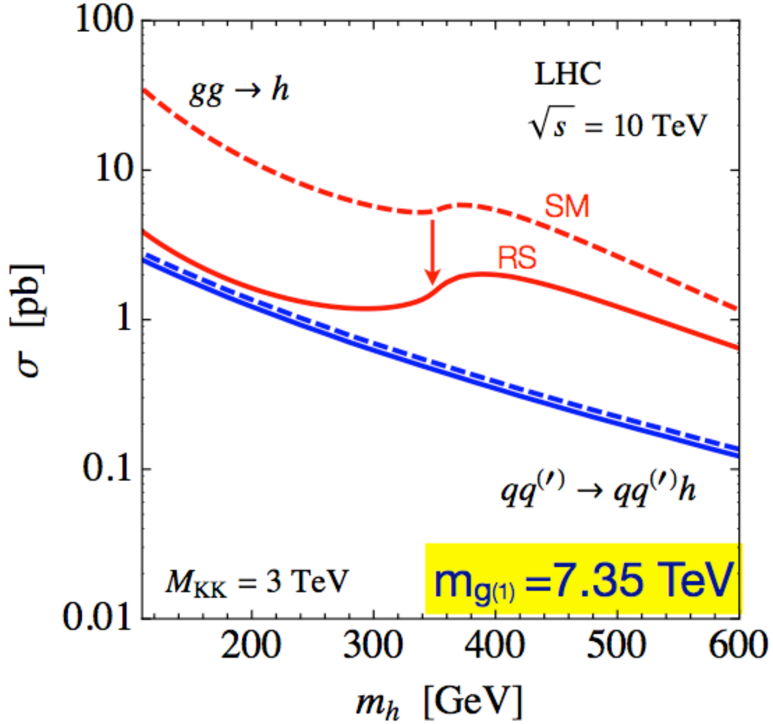


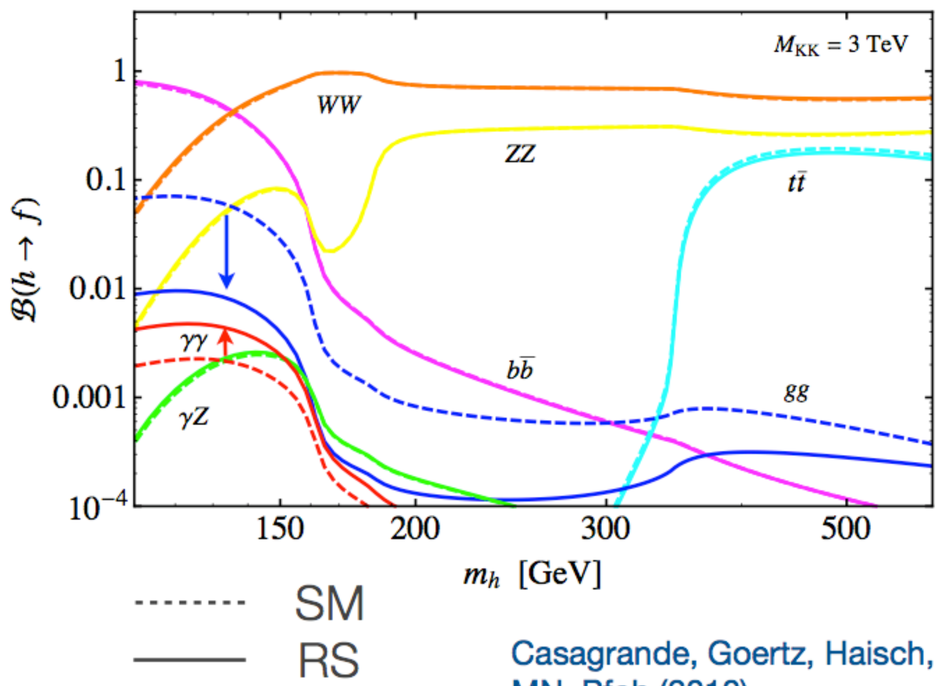
We should also see anomalies in the coupling. The ratio γγ/ZZ, WW/ZZ constrains the fraction of models to 5-6%. Additional constraints from a precise measurement of the mass (124 or 125GeV does matter).

A 125GeV scalar and extradimensions.

Much like rare FCNC processes, Higgs production in gluon-gluon fusion and Higgs decays into the di-photon final state are loop-suppressed processes, which are very sensitive to new heavy particles.

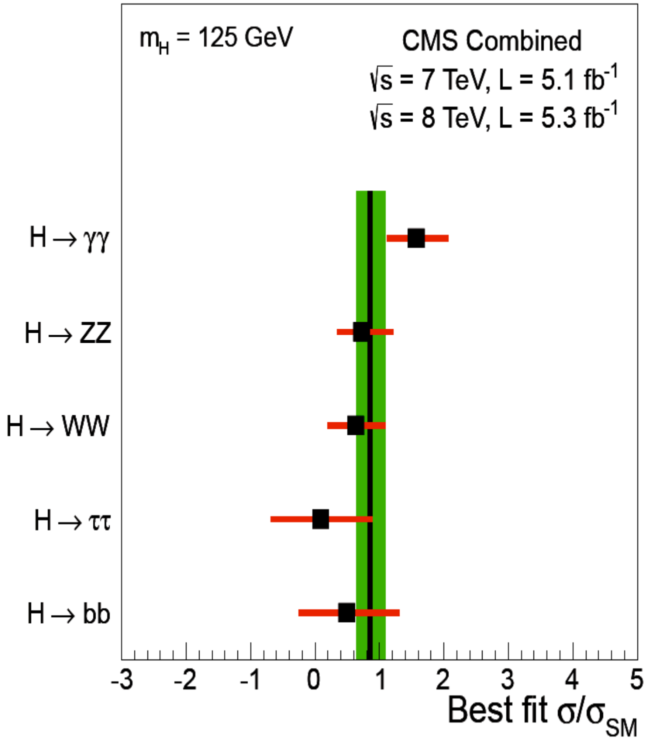
We could see spectacular effects on Higgs production via gluon fusion, even for KK masses out of reach at LHC ($m_{g(1)} \sim 2.45 M_{KK}$). **Correspondingly, we could find significant enhancement (suppression) of the $h \rightarrow \gamma\gamma$ ($h \rightarrow gg$) branching ratios. Importance of using clean dijet tagging to disentangle VBF.**

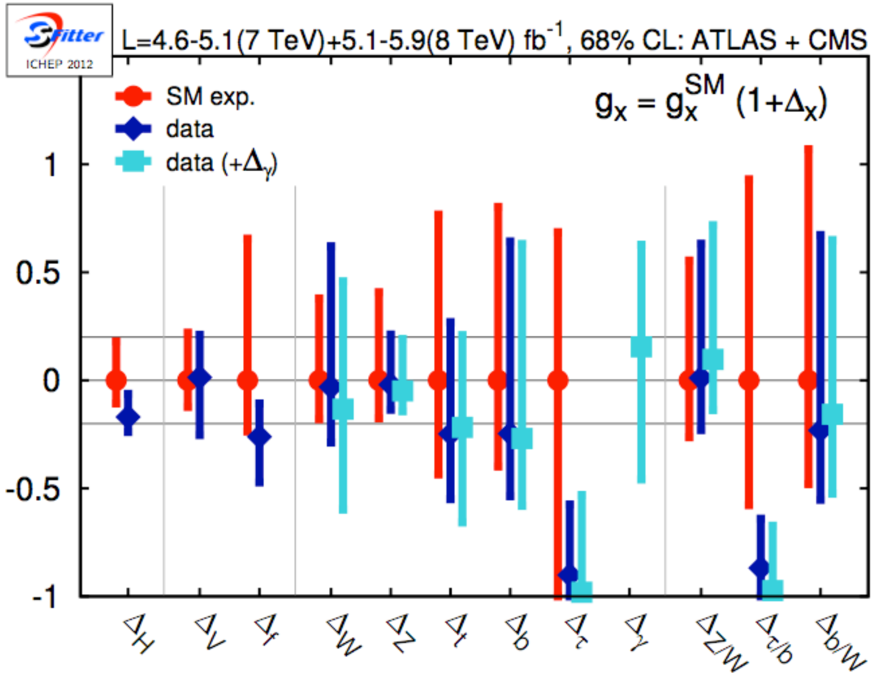




Casagrande, Goertz, Haisch, MN, Pfoh (2010)

“It walks like a duck, it quacks like a duck, but…”





arXiv:1207.6108

Signal strength σ/σ_{SM} in different modes is self-consistent, but…

• Some modes (i.e. $\tau\tau$, bb) would require more data to distinguish a SM signal from background.

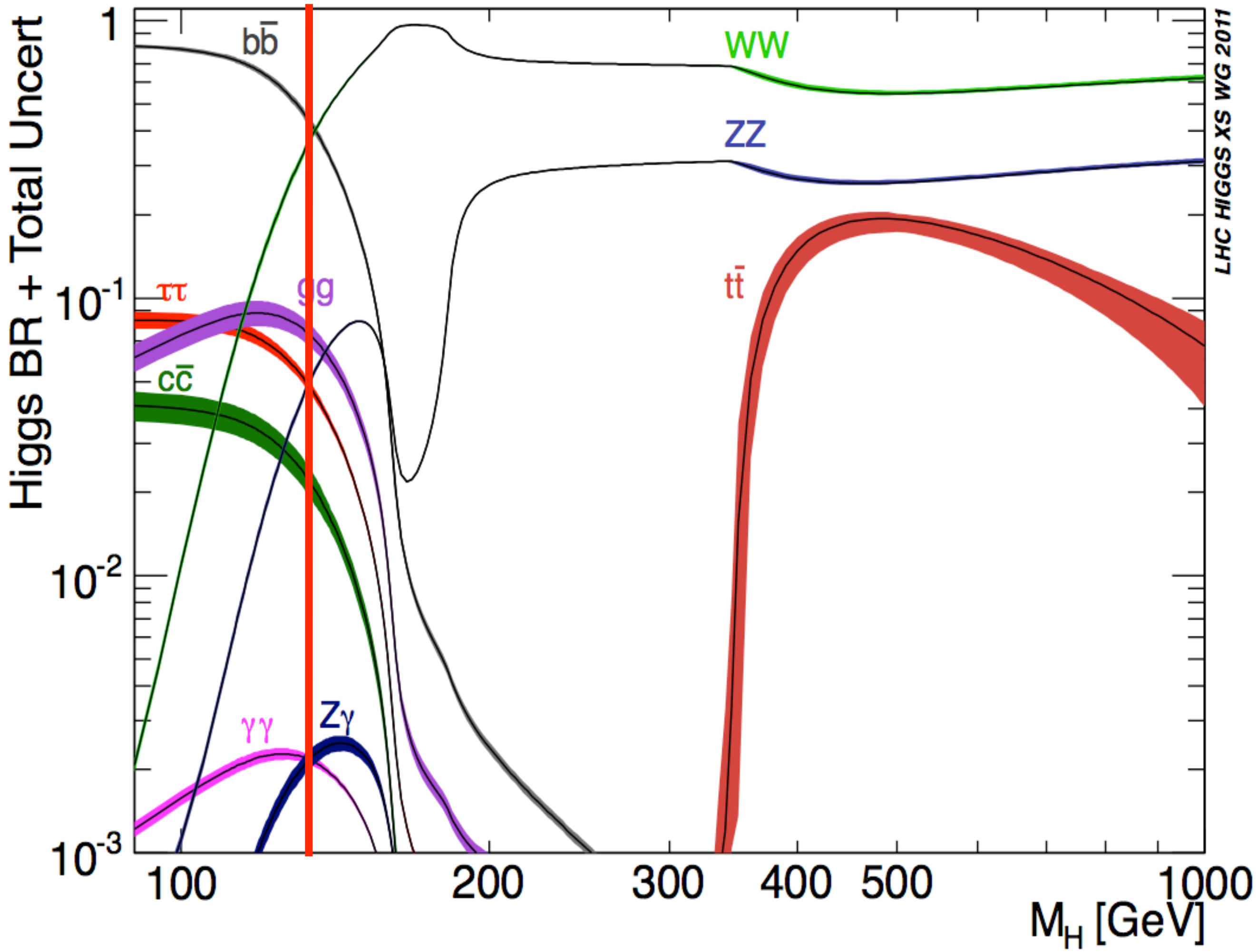
• **There is a hint of an excess in H2GG both in ATLAS and CMS.** Additional data will tell us if it will fade away or there is something happening there.

•**The crucial importance of measuring the couplings.**

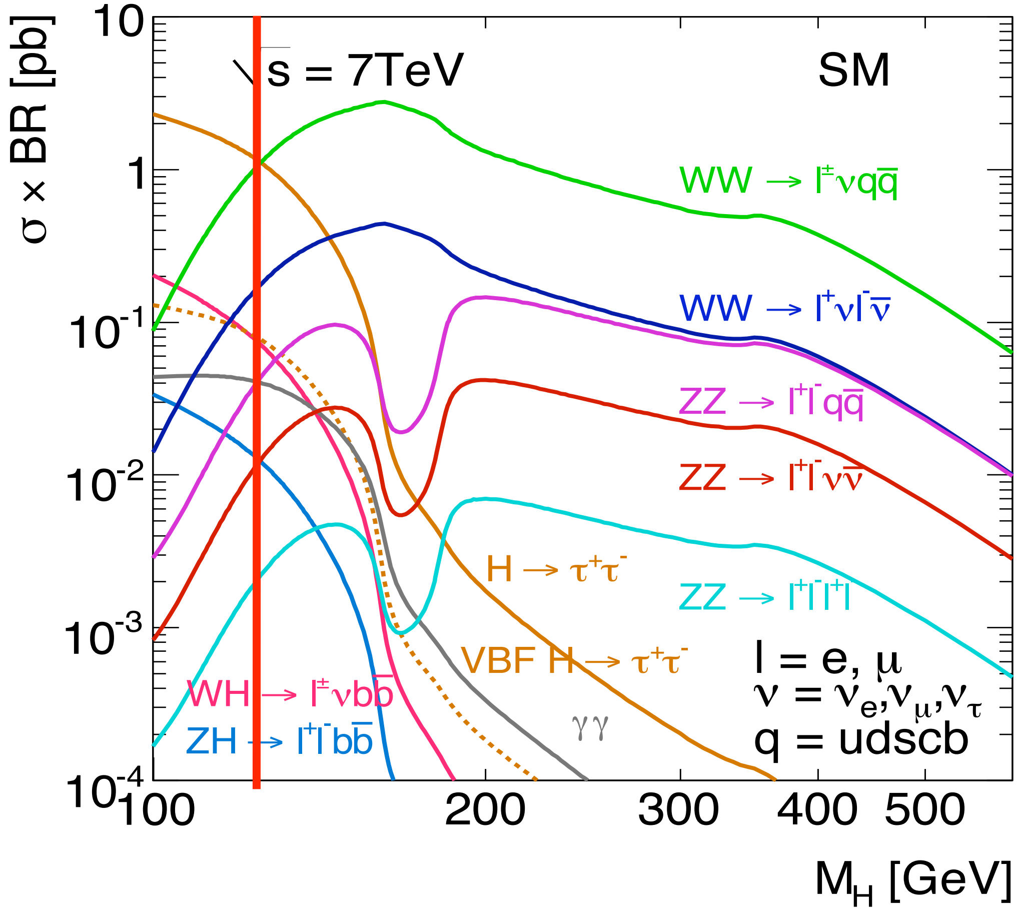
125GeV is a very special mass

The Higgs boson of the Standard Model with a mass of 125GeV/c^2 sits in a very special place.

It looks like magically placed exactly in the mass range in which we could directly access a large amount of its decay modes.



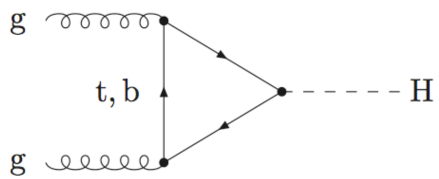
.....and CMS is very effective there

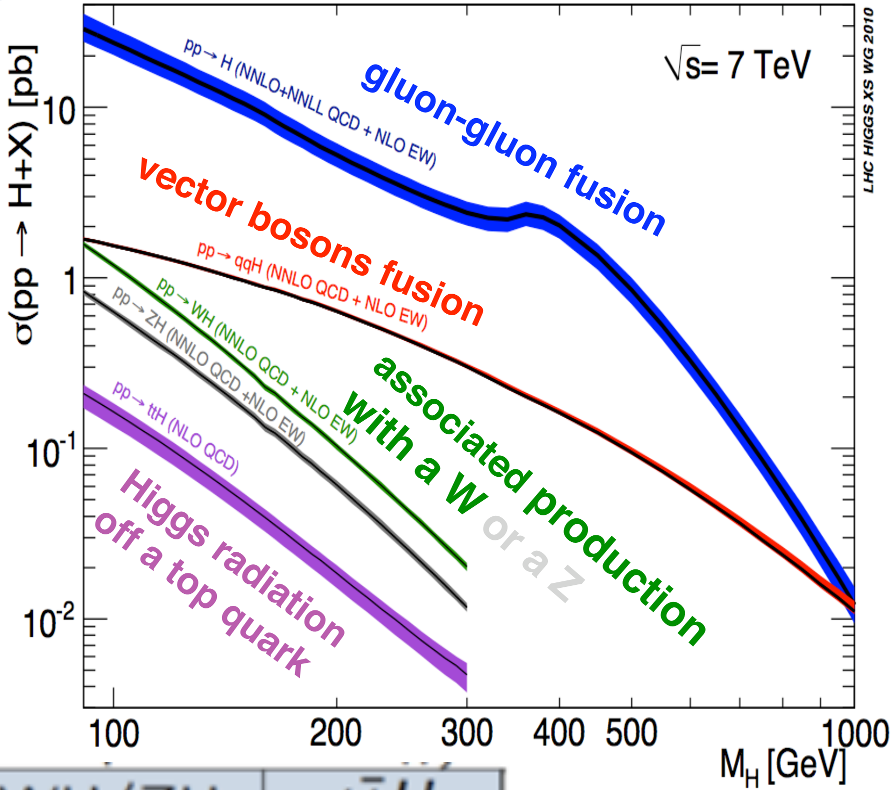


Additional channels and new decay modes are being added in the low mass region (i.e. H→Zγ et al); very important the new exclusive modes in associated production, in particular ttH→ttbb, that have been recently developed within CMS.

Better theoretical predictions on $\sigma_{(gg \to H)}$

Gluon-gluon fusion, the dominant production mechanism at LHC, is still affected by a significative uncertainty





We need more accurate theoretical predictions of the SM Higgs cross section at $125 GeV/c^2$.

Typical size of the uncertainty (there is also a dependance on the mass)

	ggF	VBF	WH/ZH	$t\bar{t}H$
QCD scale:	$^{+12\%}_{-8\%}$	$\pm1\%$	$\pm1\%$	$^{+3\%}_{-9\%}$
PDF + α_s:	$\pm8\%$	$\pm4\%$	$\pm4\%$	$\pm8\%$
Mass line shape:	$(150\%) \times \left(\frac{M_H}{TeV}\right)^3$			

Couplings from rescaling LO SM

C_g

$$\sigma(gg \to h) = c^2 \sigma(gg \to h)_{SM}$$

$$\sigma(qq \to qqh) = a^2 \sigma(qq \to qqh)_{SM}$$

$$\sigma(q\bar{q} \to Vh) = a^2 \sigma(q\bar{q} \to Vh)_{SM}$$

$$\sigma(gg, q\bar{q} \to t\bar{t}h) = c^2 \sigma(gg, q\bar{q} \to t\bar{t}h)_{SM}$$

C_W, C_Z

C_b, C_τ

C_γ

$$\Gamma(h \to VV) = a^2 \Gamma(h \to VV)_{SM}$$

$$\Gamma(h \to f\bar{f}) = c^2 \Gamma(h \to f\bar{f})_{SM}$$

$$\Gamma(h \to gg) = c^2 \Gamma(h \to gg)_{SM}$$

$$\Gamma(h \to \gamma\gamma) = \frac{|c\, A_f(m_h) + a\, A_W(m_h)|^2}{|A_f(m_h) + A_W(m_h)|^2} \Gamma(h \to \gamma\gamma)_{SM}$$

$$\Gamma(h \to Z\gamma) = \frac{|c\, B_f(m_h) + a\, B_W(m_h)|^2}{|B_f(m_h) + B_W(m_h)|^2} \Gamma(h \to Z\gamma)_{SM}$$

- For SM, all parameters known (for fixed m_H).
- Progressively relax SM constraints:
  1. Float couplings to W/Z (**c** = **C_V**) and fermions (**a** = **C_F**), get gluon and photon couplings from SM loops.
  2. Float couplings to W/Z (**C_V**), b, tau (**C_b**, **C_τ**) and also (effective) couplings to gluons and photons (**C_γ**, **C_g**).

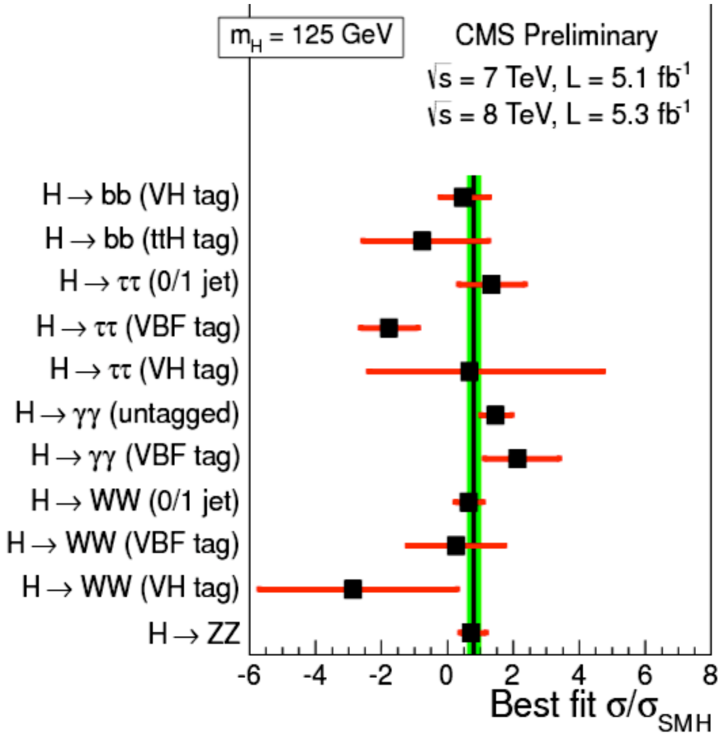
arxiv :1204.4817, arxiv:1202.3144, etc

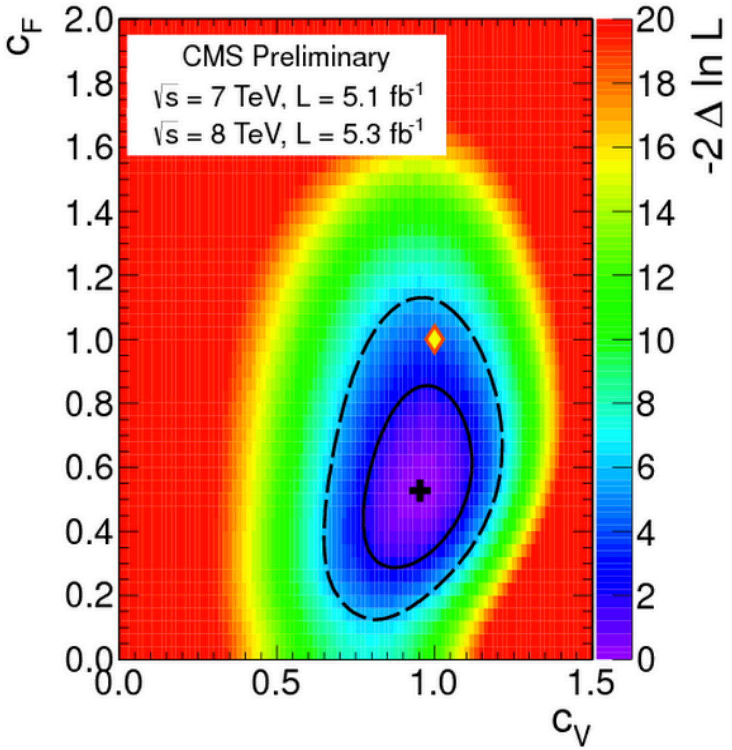
Measurements to disentangle couplings

<table>
<tr><th></th><th></th><th>BR(ττ)</th><th>BR(bb)</th><th>BR(WW)</th><th>BR(ZZ)</th><th>BR(γγ)</th><th>BR(Zγ)</th></tr>
<tr><td></td><td></td><td>$C_F \rightsquigarrow C_\tau$</td><td>$C_F \rightsquigarrow C_b$</td><td>$C_V$</td><td>$C_V$</td><td>$f(C_V, C_F) \rightsquigarrow C_\gamma$</td><td>$f(C_V, C_F)$</td></tr>
<tr><td>σ(gg)</td><td>$C_F \rightsquigarrow C_g$</td><td>☑</td><td></td><td>☑</td><td rowspan="5">☑</td><td>☑</td><td rowspan="5">☐</td></tr>
<tr><td>σ(VBF)</td><td>C_V</td><td>☑</td><td>☐</td><td>☑</td><td>☑</td></tr>
<tr><td>σ(WH)</td><td>C_V</td><td rowspan="2">☐</td><td>☑</td><td rowspan="2">☑</td><td rowspan="2">☐</td></tr>
<tr><td>σ(ZH)</td><td>C_V</td><td>☑</td></tr>
<tr><td>σ(ttH)</td><td>$C_F \rightsquigarrow C_t$</td><td></td><td>☑</td><td></td><td></td></tr>
</table>

- ✓ NB - experimental channels mix:
- ✓ different productions modes (di-jet = gg ⊕ VBF)
- ✓ different branching modes (2l+MET = WW ⊕ ττ).

Preliminary measurements on the couplings





Group Higgs couplings into "Vector" and "Fermion" sets.

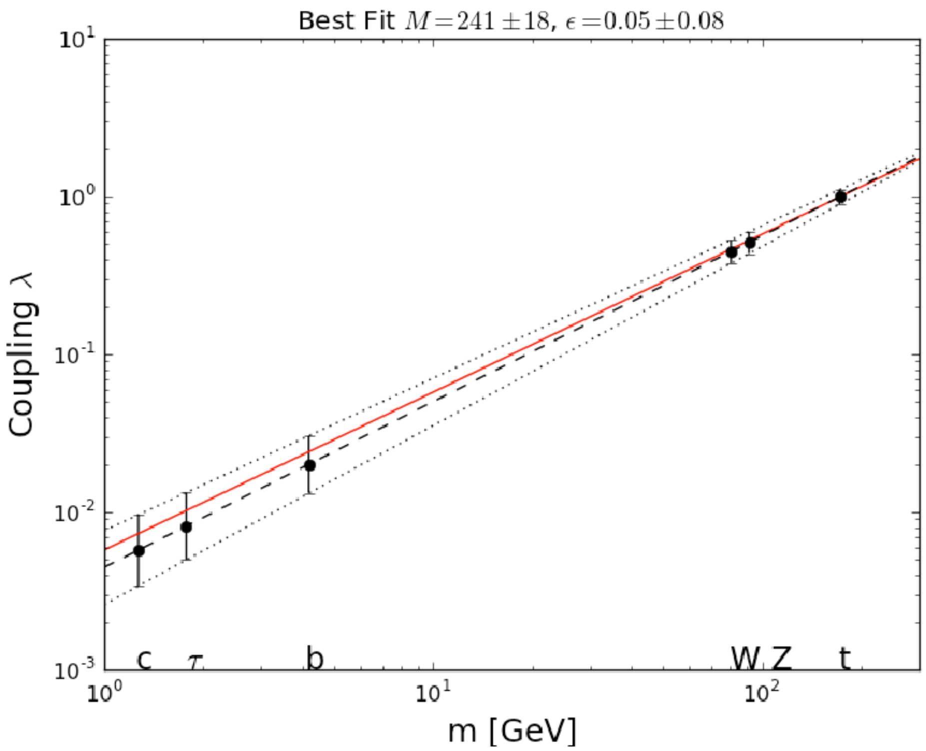
Attach a modifier to the SM prediction for each set: C_V and C_F LO theoretical prediction for loop-induced $H \to \gamma\gamma$, $H \to gg$ couplings

In agreement with the SM within the 95% CL range

More data needed to draw any definite conclusion.

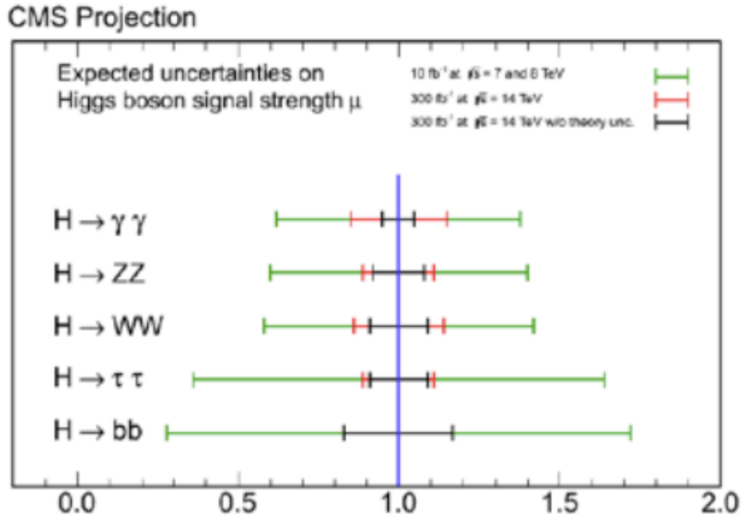
Couplings

- **Coupling to vector bosons:**
- Is this boson related to EWSB, and how much does it contribute to restoring unitarity in $W_L W_L$ scattering
- **Couplings to fermions** - is Yukawa interaction at work? - contribution to restoring unitarity? couplings proportional to mass ?



Projections on the couplings

5-10%@LHC 14TeV and 300fb^{-1}.



for luminosities up to 3ab^{-1} very rare channels such as H→μμ will be accessible at the 20% level; Higgs self-coupling (double-Higgs production) can also be targeted: most promising channels, such as bbγγ, currently under study.

If you want to do better you must build a lepton collider BUT… beware that the thousands of CMS (and ATLAS) young scientists will continue to produce new ideas and LHC will likely continue to exceed even the most optimistic expectations.

There is some risk that these estimates will be considered very conservative within a few years.

SUSY at a cross-road.

A 125 GeV Higgs is challenging to accommodate in constrained versions of SUSY, particularly for "natural" superpartner masses.

If SUSY exists, can still be "natural" with "stop" and "sbottom" in the 4-500GeV mass range. We have retuned our strategy to implement a systematic search for 3rd generation SUSY signatures. Redefinition of the trigger paths and analysis largely done. First results appearing.

More challenging case if SUSY is fine-tuned. Very different mass spectrum and un-conventional signatures. Look for long-lived particle in various decay modes. A lot of work ongoing. Room for new ideas.

Again another area in which the CMS flexibility, particularly at the trigger level will be a very important asset.

Next stops

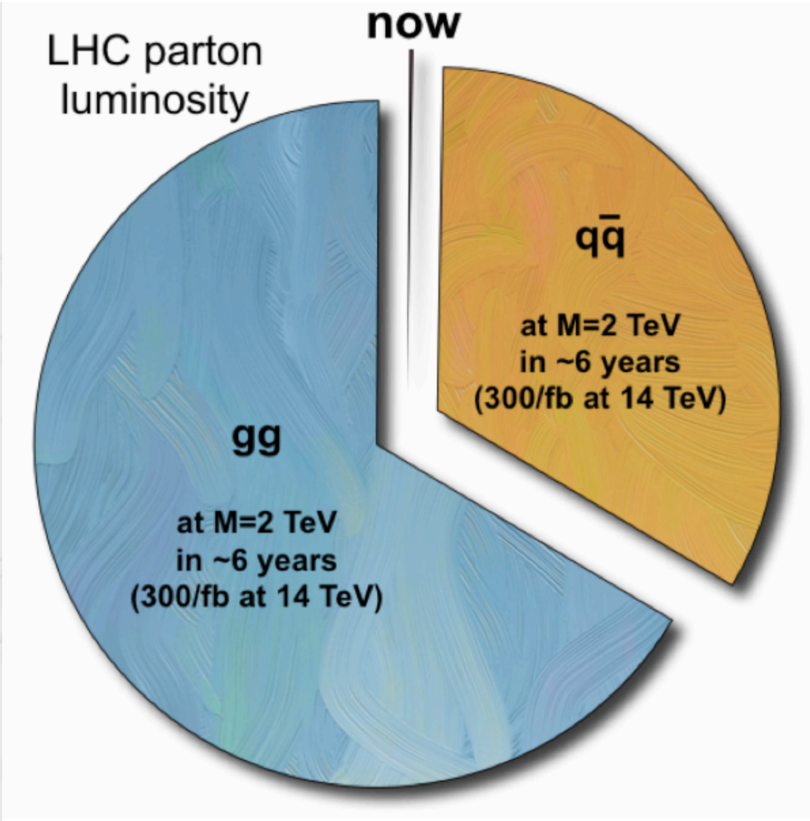
HCP Kyoto November 2012
Higgs: updated results with the full statistics available up to mid september (~20fb^{-1})
New results on $B_s \rightarrow \mu\mu$ expected
Natural SUSY, 3rd generation: new results coming.

Winter Conferences February 2013
Preliminary results with full statistics 2011+2012

LP and EPS July 2013
Final results with full statistics 2011+2012.

Be ready for any scenario and even for additional suprises.

GD plot



G. Dissertori Crakow 2012

Conclusion.

- By analysing the 2011 and 2012 data, we have discovered a new boson around a mass of 125GeV/c^2. The result is consistent, within uncertainties, with expectations for a standard model Higgs boson. The collection of further data will enable a more rigorous test of this conclusion and an investigation of whether the properties of the new particle imply physics beyond the standard model.

- As a consequence of this observation a significant re-tuning of our search strategies for new physics is ongoing.

We are just at the beginning of the exploration of the TeV region. Stay tuned!