Κολυμπάρι, June 12th 2012

The Compact Muon Solenoid at the CERN LHC: **Recent results**

Tommaso Dorigo

INFN Padova

On Behalf of the CMS Collaboration

Overview

- The LHC and its Scientific Goals
- The CMS Detector
- B physics highlights
- The search for the Higgs boson
- Top physics highlights
- New Physics Searches
- Conclusions

Note: this will only be a summary of selected recent results.
CMS Higgs searches have been discussed in detail by S. Choudgury in plenary session yesterday.

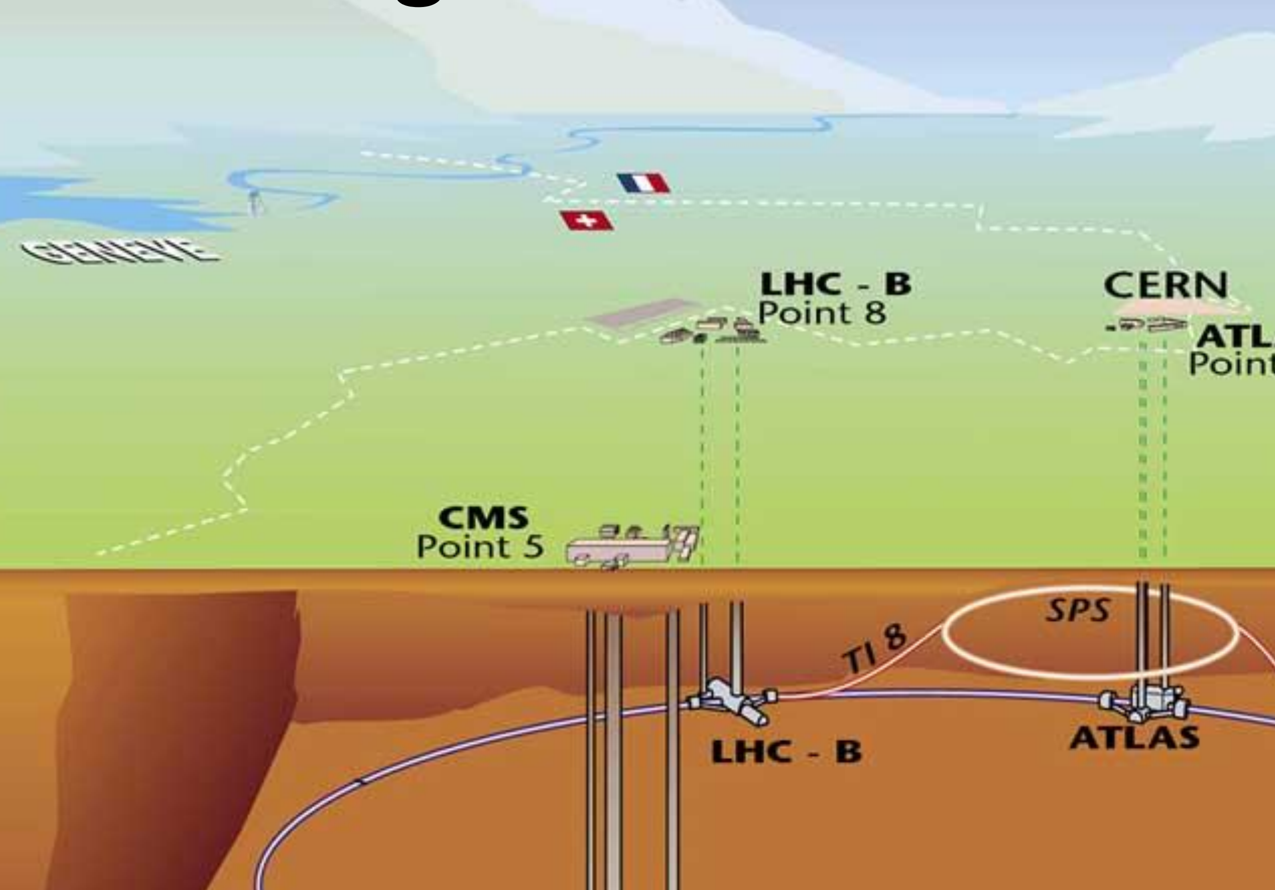
For detailed information on all CMS analyses please refer to the following presentations:

- N. Saoulidou, SUSY searches (Monday, in "Higgs boson" p.s.)
- M. Meneghelli, H→ZZ→4 leptons (Monday, in "Higgs boson p.s.)
- M. Gouzevich, QCD results (Tuesday, 7.25PM in "experiments, detector performances" p.s.)
- T.J. Kim, Top physics results (Friday, 3.55PM in "particle physics" p.s.)
- C. Grab, B physics results (Friday 5.05PM in "particle physics" p.s.)

and also:

- A. Penzo, CMS Upgrades (Friday, 5.55PM in "perspectives" p.s.)

The Large Hadron Collider



CMS

LHC

The LHC And Its Scientific Goals

- Original goal: discover the mechanism of EWSB;
  extend our knowledge in the High-Energy frontier
  → Find the Higgs boson!!

!

- Also targeting heavy ion physics (ALICE) and precision B physics and CP violation (LHCb)

- Many other targets of exceptional interest:
  - Supersymmetry
  - Dark Matter particles
  - Large Extra Dimensions
  - Microscopic Black Holes
  - New particles ? New forces ?

  (Note: as B.Anastasiou put it yesterday: "**Anything beyond the Higgs boson is a present of Nature we haven't paid the bill for.**" But Nature is a bitch !)

?

- Plus the potential to improve by one order of magnitude the precision of our SM measurements
  - W mass, diboson physics, QCD measurements
  - Rare decays

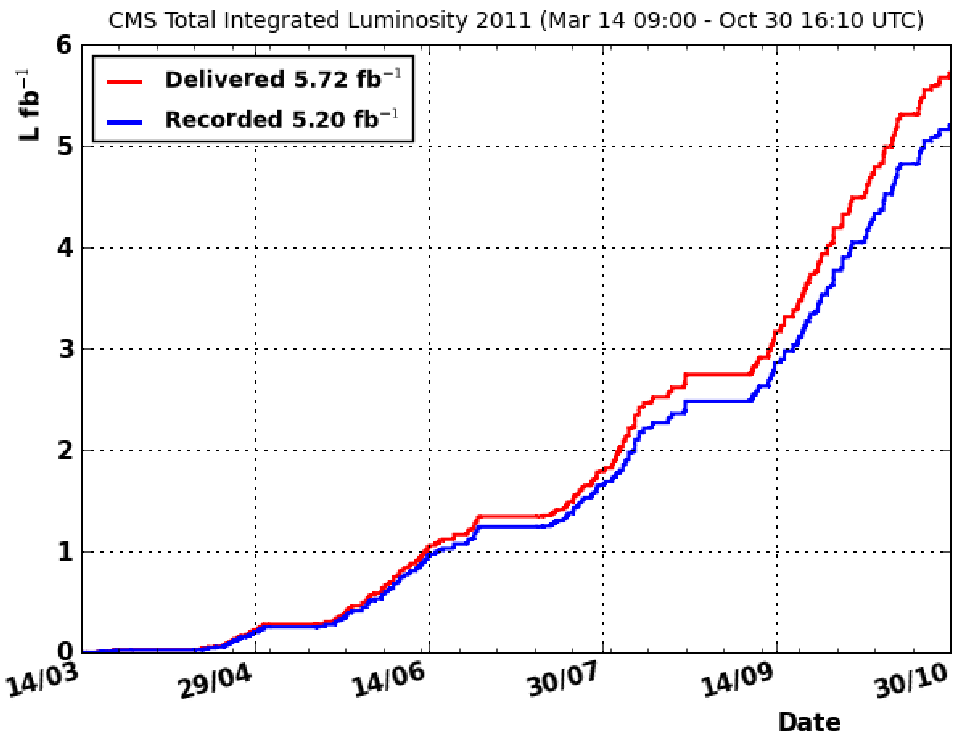
→ ←

Review of the 2011 Run

- LHC delivered high-quality, high-intensity data in 2011
  - surpassed by x5 the goals for integrated luminosity delivered to experiments
- Smooth running conditions, smooth curve in instantaneous luminosity
  - Allowed experiments to gradually understand triggers / tune them / tighten thresholds
  - Optimal turnaround in terms of studies of high-xs phenomena, then "rediscovery" of known EW physics, and finally searches of rare processes
  - Also collected small dataset of pp collisions at 2.76 TeV for xs comparisons to PbPb data
  - End-of-year heavy-ion running (Pb-Pb, 2.76 TeV/nucleon) allows to extend measurements in high-energy nuclear collisions
    - 150/μb: x20 statistics wrt2010

5.72 fb^{-1} delivered by LHC
5.2 fb^{-1} recorded by CMS.
→ 140 times more data than 2010

Average fraction of operational channels per subsystem >98.5% in CMS



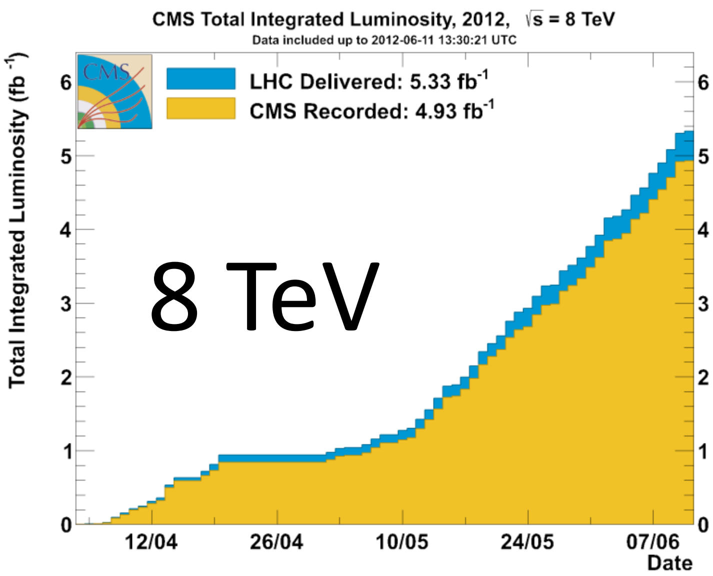
The 2012 Run so far

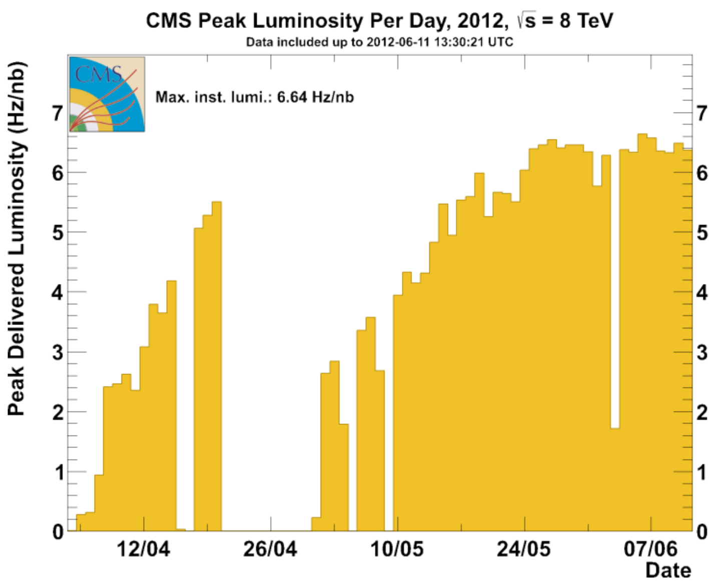
- In 2012 the LHC is running with 4-TeV beams → 8-TeV collisions
  - higher reach to high-mass resonances
  - sizable increase in Higgs and top cross sections
- The goal is to deliver 15/fb to ATLAS and CMS

- Run started in April, performance as expected; collected 5/fb until 6/12.

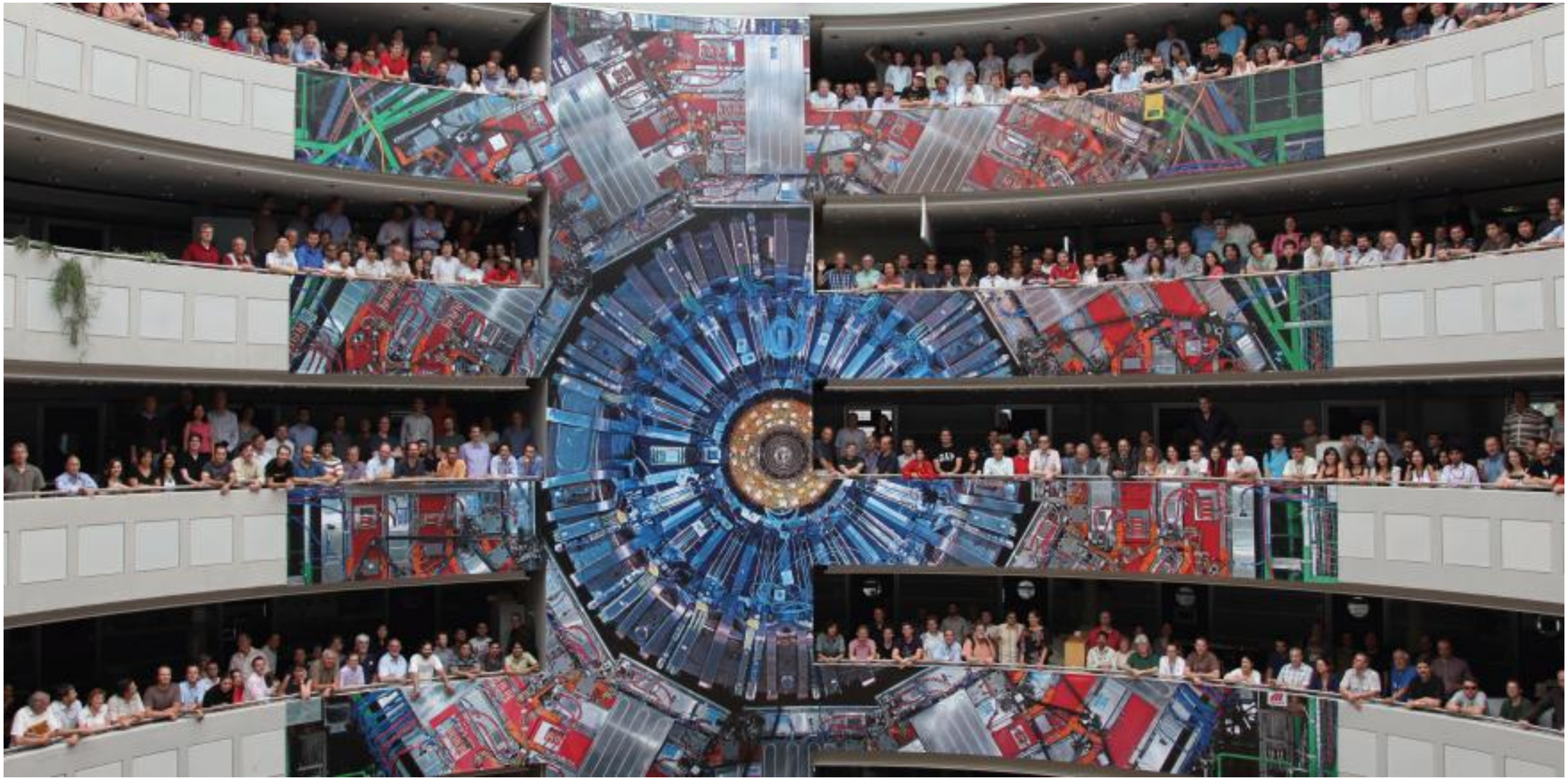
- Peak luminosity reached 6.8E33 $cm^{-2}\ s^{-1}$
  - running with max number of filled bunches (1380) at 50 ns spacing
  - only minor further rate increases possible

- Pileup is higher than in 2011 → slight worsening of per-femtobarn sensitivity on experimental signatures, largely addressed by improvements in software reconstruction algorithms





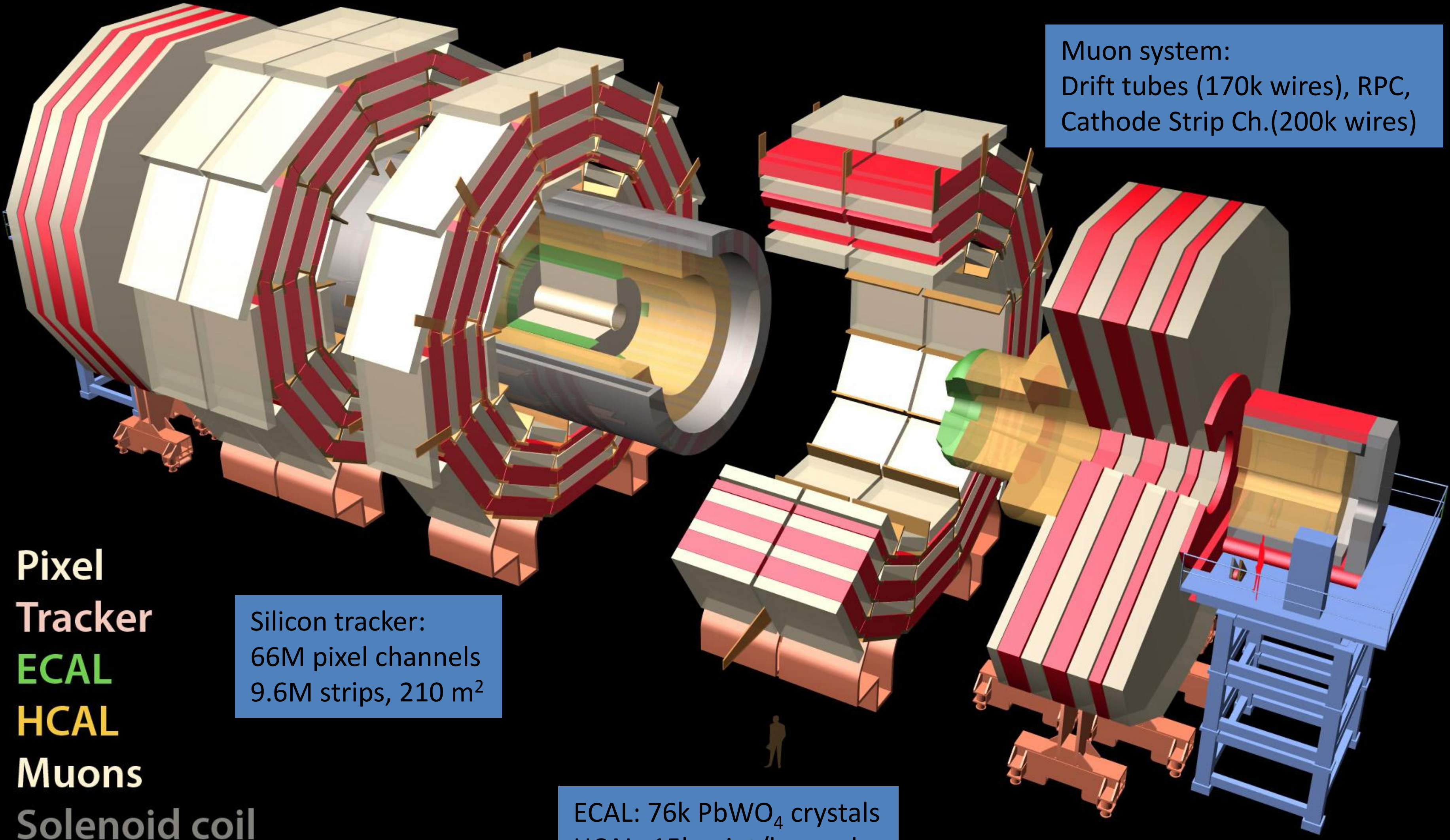
The CMS Collaboration



3381 scientists and engineers (including ~840 students) from 173 institutes in 40 countries

The CMS Detector

10k CPU cores,
2M lines of code



Muon system:
Drift tubes (170k wires), RPC,
Cathode Strip Ch.(200k wires)

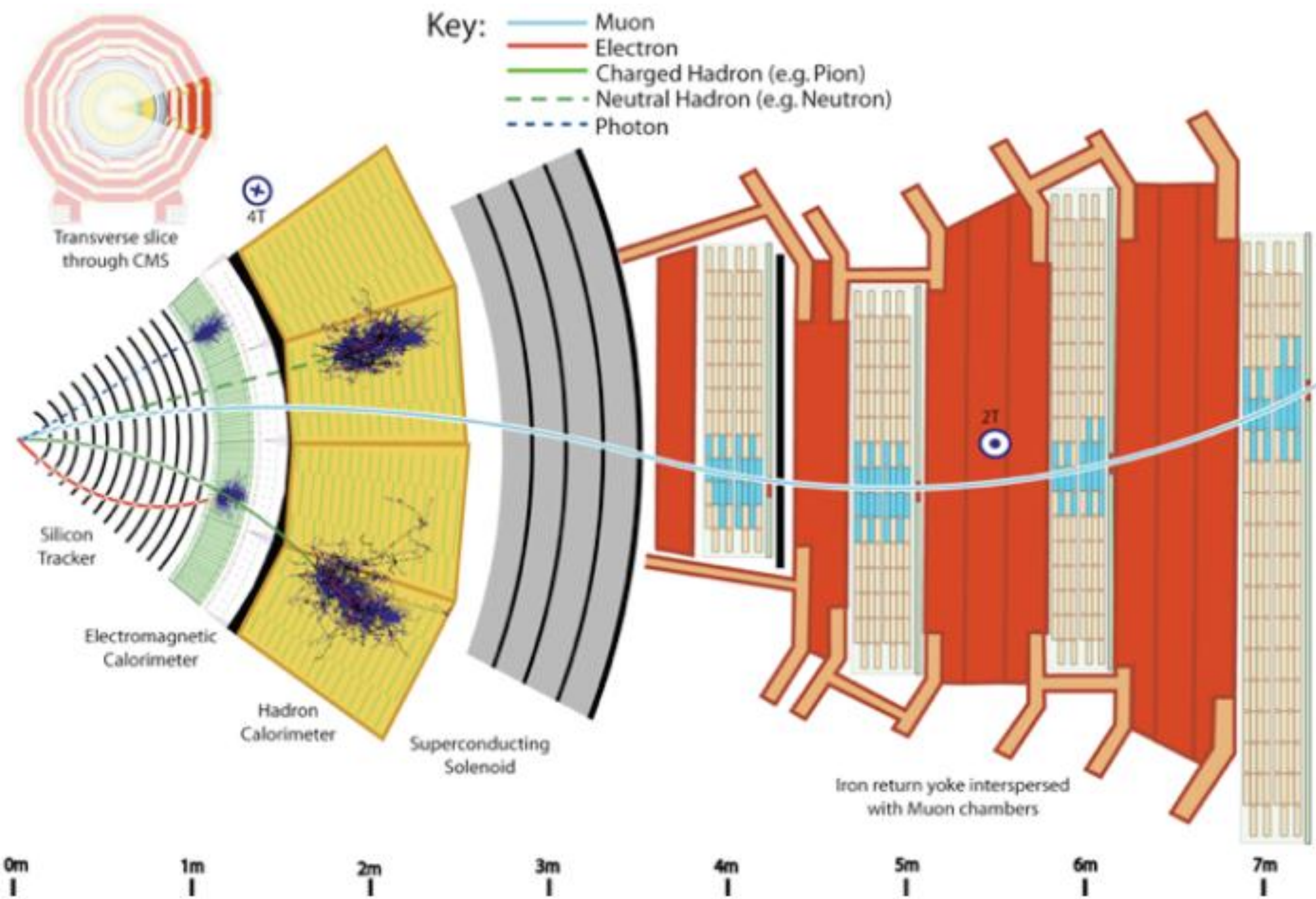
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Silicon tracker:
66M pixel channels
9.6M strips, 210 m^2

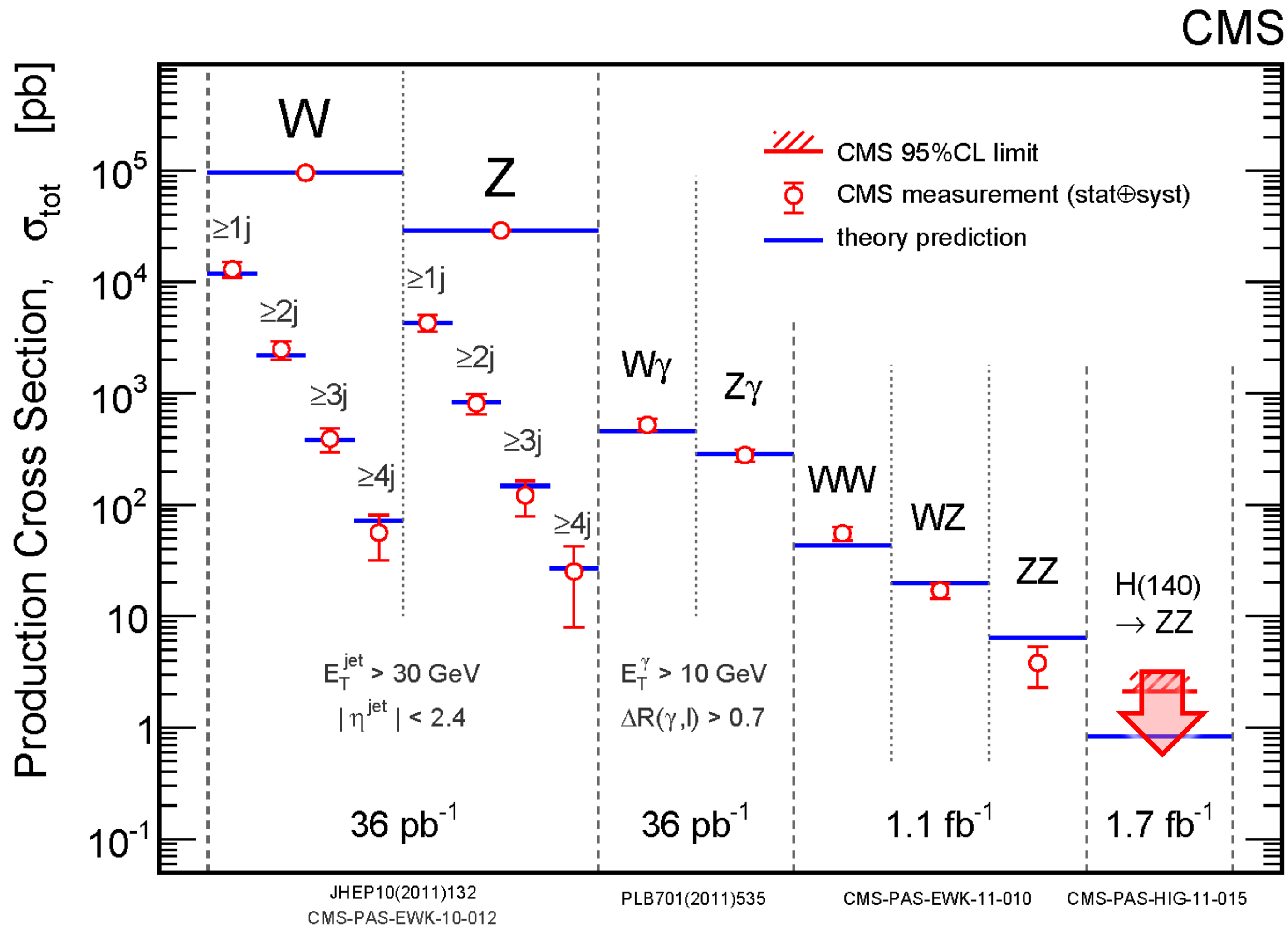
ECAL: 76k $PbWO_4$ crystals
HCAL: 15k scint/brass ch.

Total weight 12500 t, Overall diameter 15 m, Overall length 21.6 m, Magnetic field 4 Tesla

Particle Detection in CMS

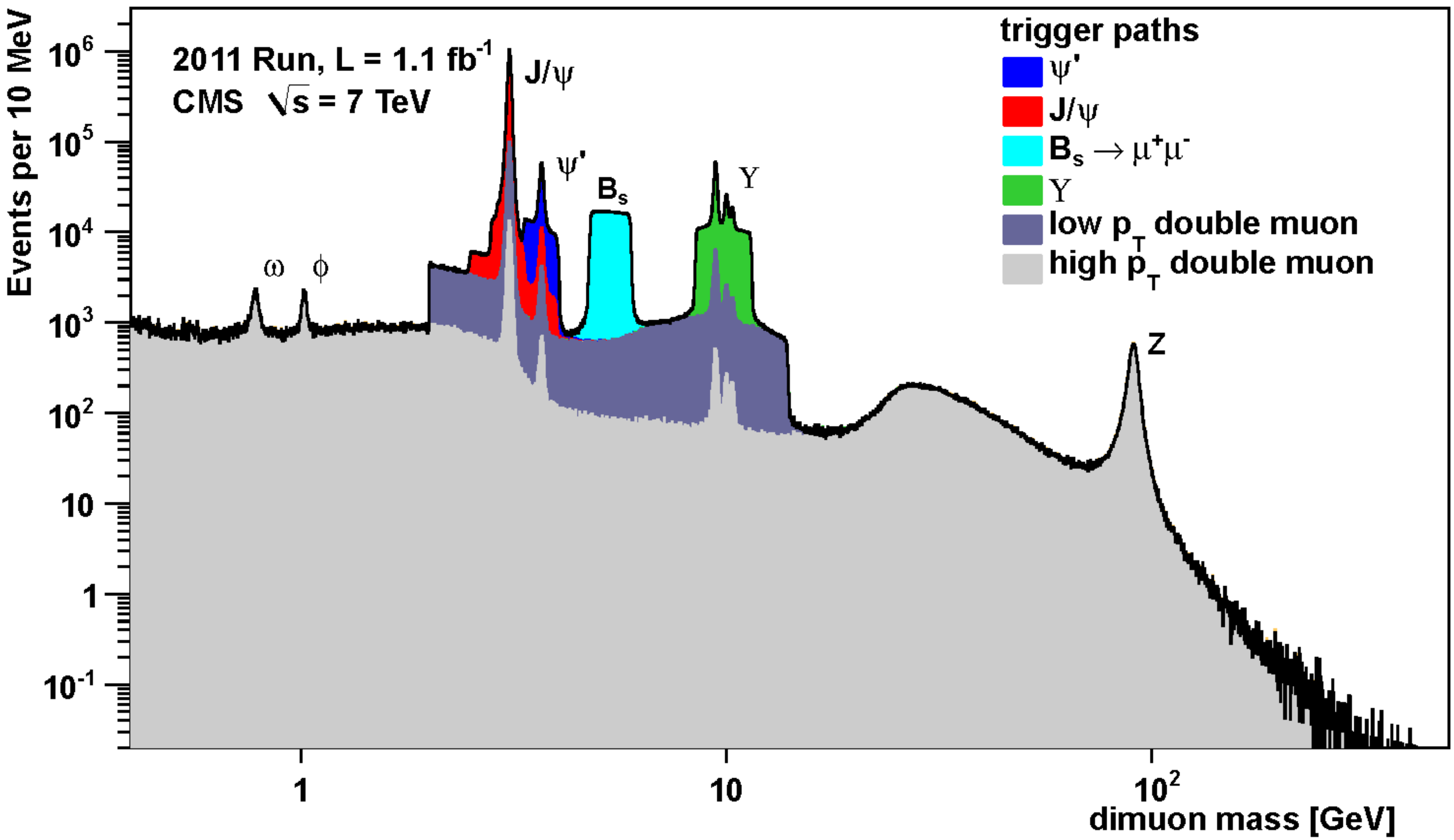


Rates of Electroweak processes



Measurements of V+jets and diboson yields in excellent agreement with theory predictions at NLO and NNLO → backgrounds to rare physics searches well under control

40 Years of Physics In One Spectrum



- CMS is a superb muon detector → muon triggers yield important signals for calibration as well as for searches
- Dedicated dimuon trigger paths further increase acceptance to specific resonances

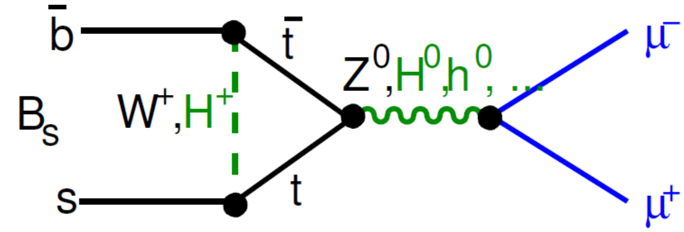
Search for $B_{s(d)} \rightarrow \mu\mu$

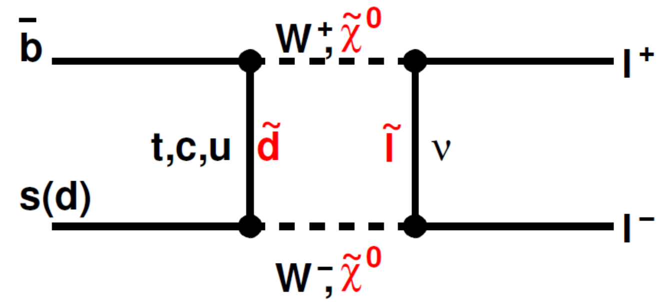
Highly suppressed decays in the SM: no FCNC; helicity suppression $(m_\mu/m_B)^2$; form-factor reductions from annihilation $(f_b/m_b)^2$

- The search for these rare decays to muon pairs is close to become sensitive to SM box diagrams, and might hit enhancements due to loop of heavy SUSY particles. The SM predicts:

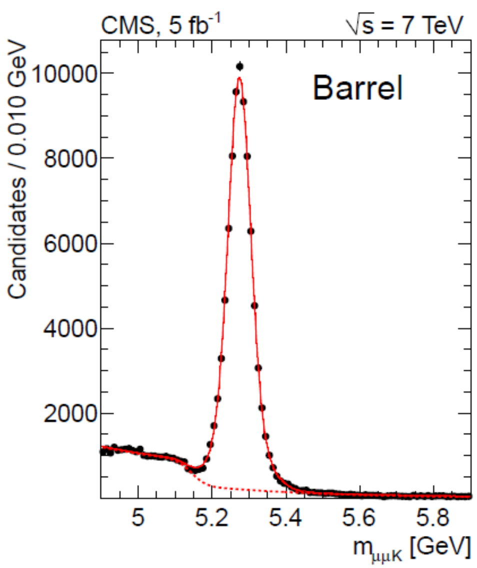
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

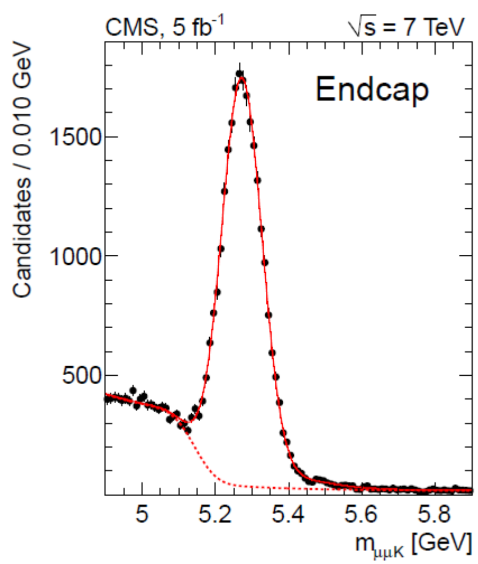
(Buras 2010)

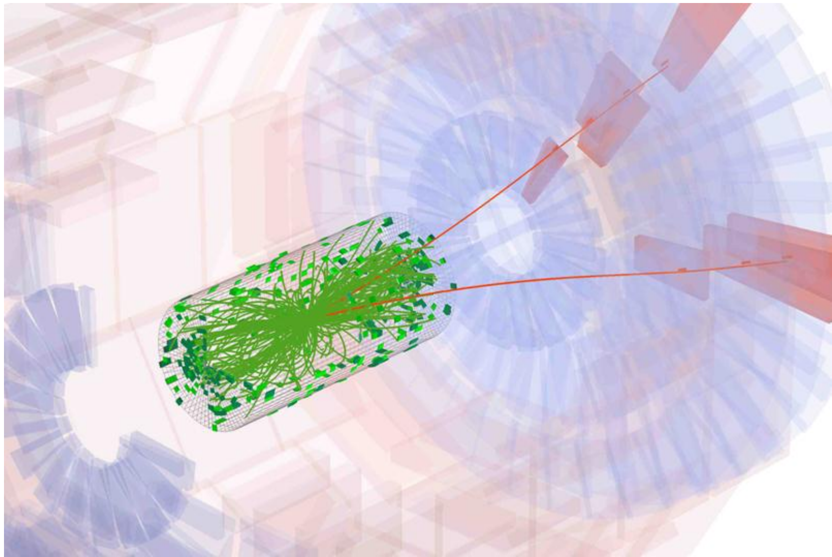




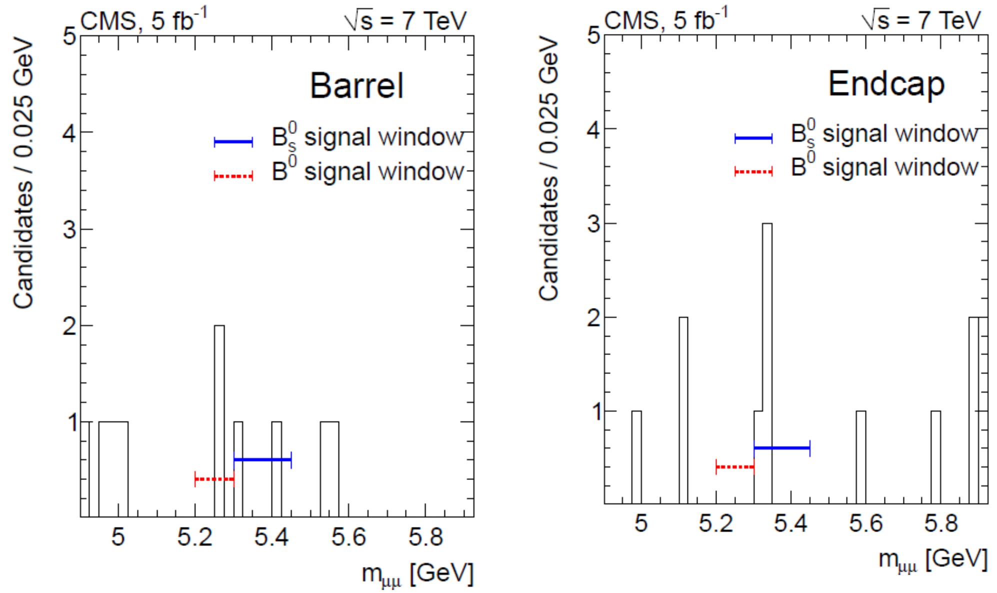
- Sensitivity to SUSY is proportional to powers of tanβ
- Analysis technique:
  - Use muon isolation, L_{xy} of decay vertex, kinematics to improve S/N
  - Normalization to unsuppressed decay channel $B^+ \rightarrow J/\psi\, K^+$
  - MC modeling tested in orthogonal sample $B \rightarrow J/\psi\phi$







5/fb Results



The search is **blind** and simultaneous for the two decay signals; in part one is in the sidebands of the other so each may contribute to the background expectation of the other

The results of the search in the full 2011 dataset allow to set very stringent upper limits – World's best until LHCb produced their result

Variable	$B^0 \to \mu^+\mu^-$ Barrel	$B_s^0 \to \mu^+\mu^-$ Barrel	$B^0 \to \mu^+\mu^-$ Endcap	$B_s^0 \to \mu^+\mu^-$ Endcap
Signal	0.24 ± 0.02	2.70 ± 0.41	0.10 ± 0.01	1.23 ± 0.18
Combinatorial bg	0.40 ± 0.34	0.59 ± 0.50	0.76 ± 0.35	1.14 ± 0.53
Peaking bg	0.33 ± 0.07	0.18 ± 0.06	0.15 ± 0.03	0.08 ± 0.02
Sum	0.97 ± 0.35	3.47 ± 0.65	1.01 ± 0.35	2.45 ± 0.56
Observed	2	2	0	4

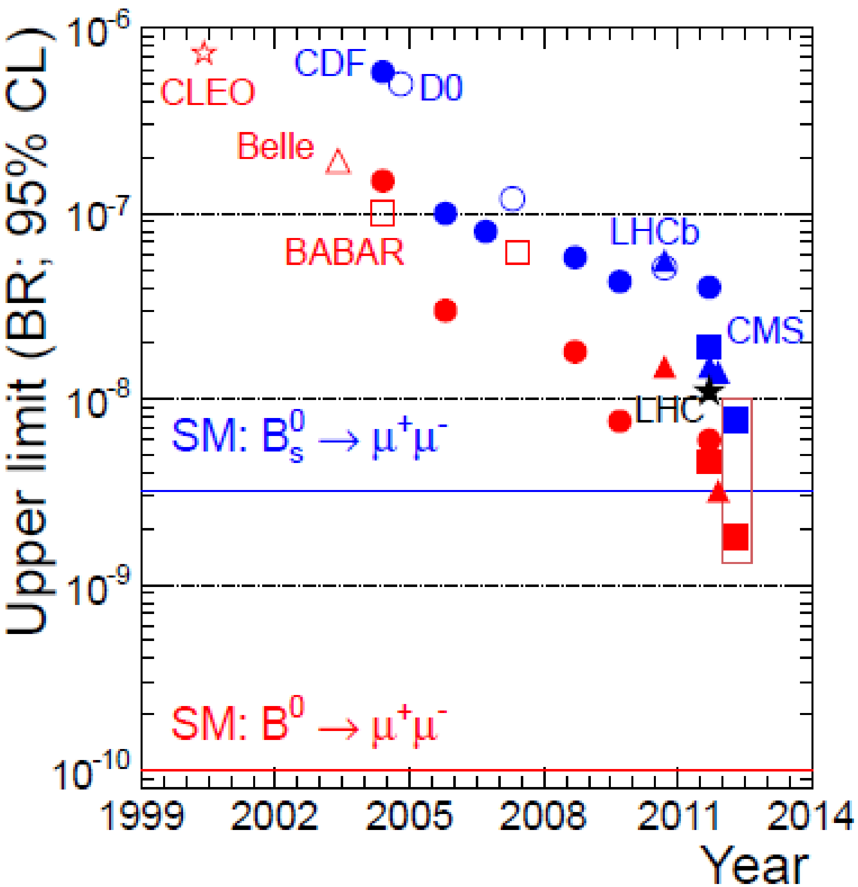
upper limit (95%CL)	observed	expected
$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	7.7×10^{-9}	8.4×10^{-9}
$\mathcal{B}(B^0 \to \mu^+\mu^-)$	1.8×10^{-9}	1.6×10^{-9}

CMS has bright prospects on these signals due to **small backgrounds**: more luminosity will improve significantly the reach

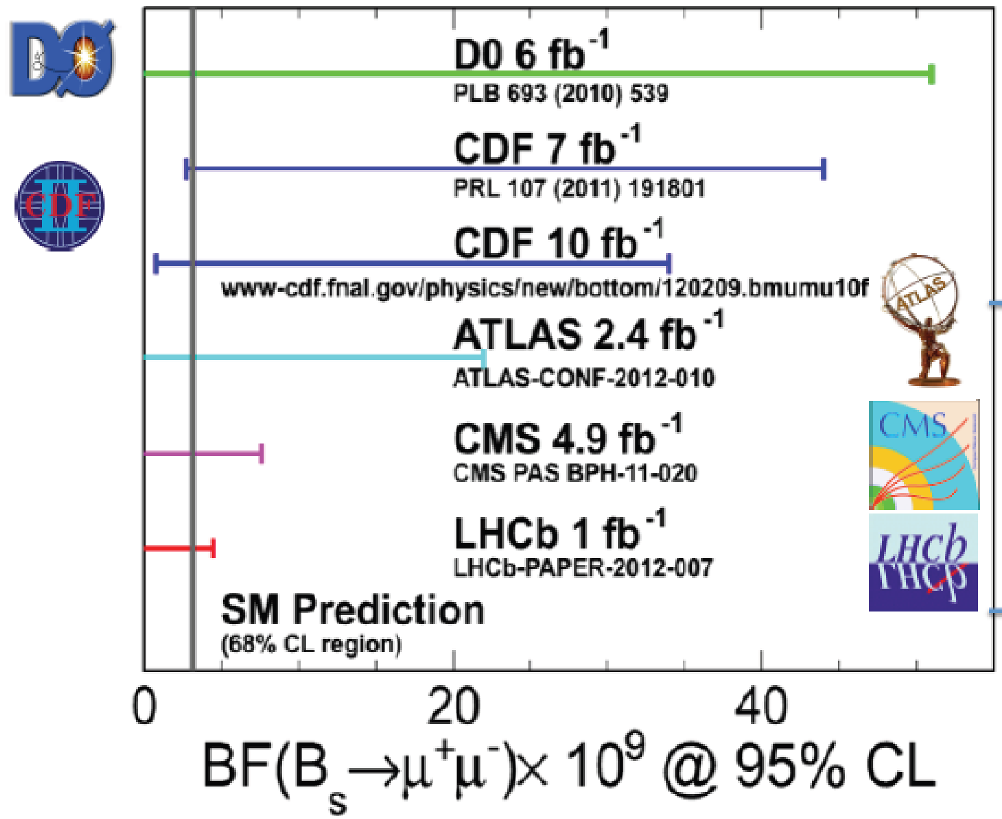
p-values for Bs->mu mu result	
0.06	p-value for background only hypothesis
0.07	p-value with background + SM-expectation for B0 -> mu mu
0.11	p-value with background + floating B0 -> mu mu
0.71	p-value for SM hypothesis (background and signals)

p-values for B0->mu mu result	
0.11	p-value for background only hypothesis
0.29	p-value with background + SM-expectation for Bs -> mu mu
0.24	p-value with background + floating Bs -> mu mu
0.86	p-value for SM hypothesis (background and signals)

Summaries of the chase



A decade-long search is coming to a close !!



The best result is now the one obtained by LHCb (1/fb of data) (but CMS has brighter prospects !)

Combination with LHCb and ATLAS

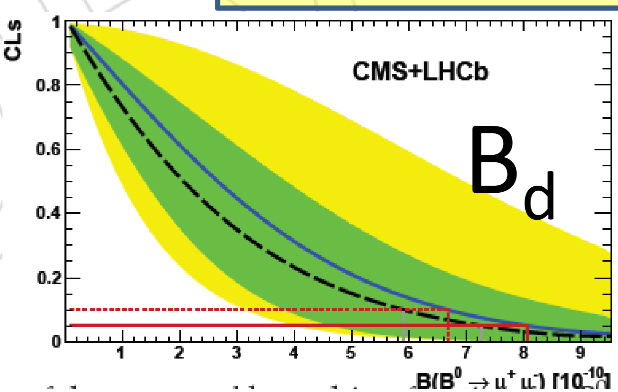
The 2012 combination of CMS search results of the B_s meson with the ATLAS and LHCb results is performed using a likelihood ratio test statistic,

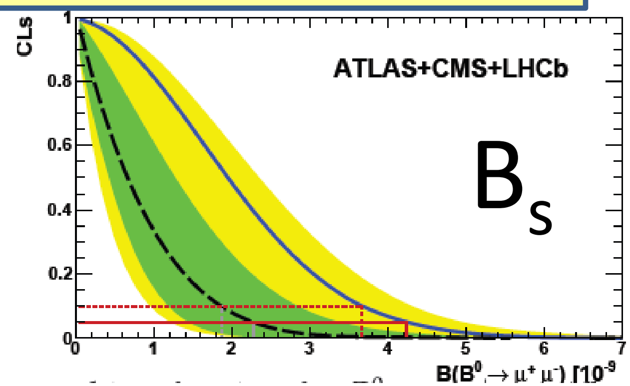
$$Q = \mathcal{L}_{s+b} / \mathcal{L}_{b} = \prod_i \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}/d_i!}{e^{-(b_i)}(b_i)^{d_i}/d_i!}$$

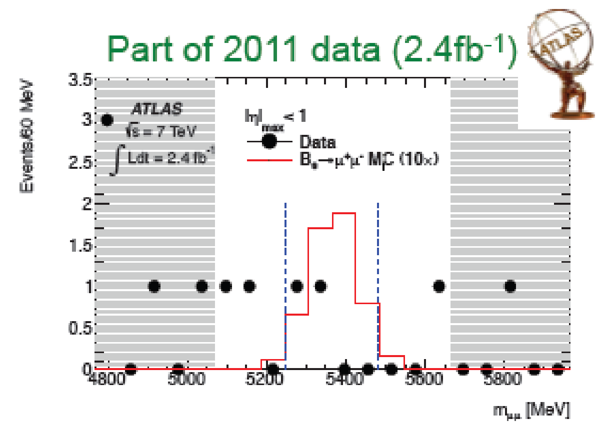
with integration over nuisances. The resulting CL_s values are used to set the upper limit.

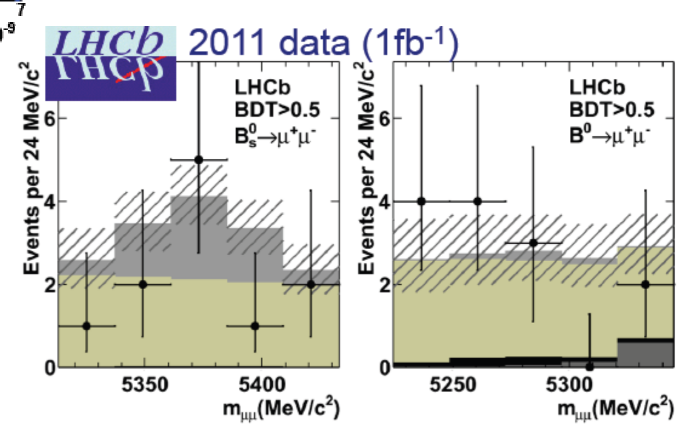
$B_s \to \mu^+\mu^- = 4.2(3.7)\times10^{-9}$ at 95%(90%) CL

$B_d \to \mu^+\mu^- = 0.81(0.67)\times10^{-9}$ at 95%(90%) CL









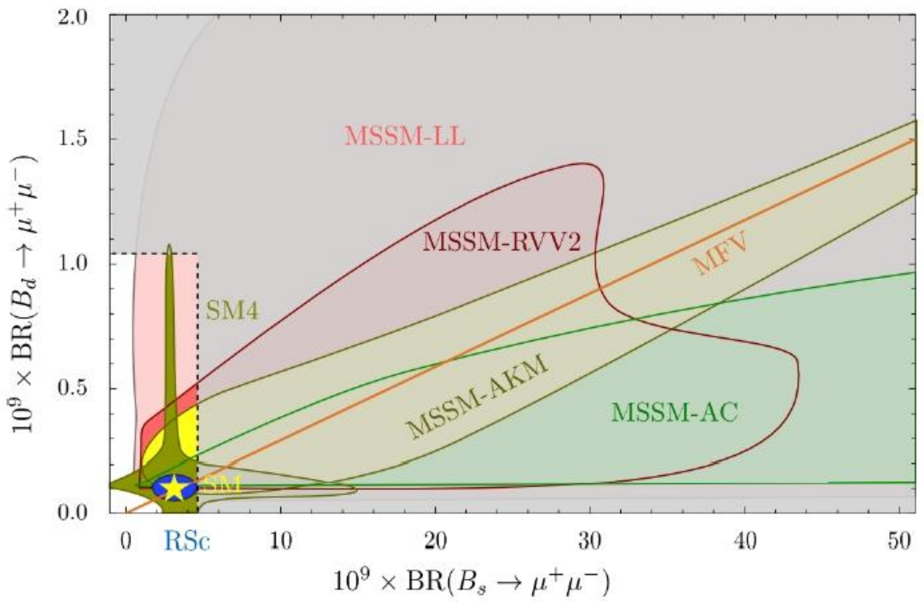
The B_s limit is affected by the possible presence of real SM decays in the experimental samples.
The SM contribution is providing an "excess" over backgrounds at the 2σ level, while the compatibility with the SM is at the 84% level.

What does that mean for NP models ?

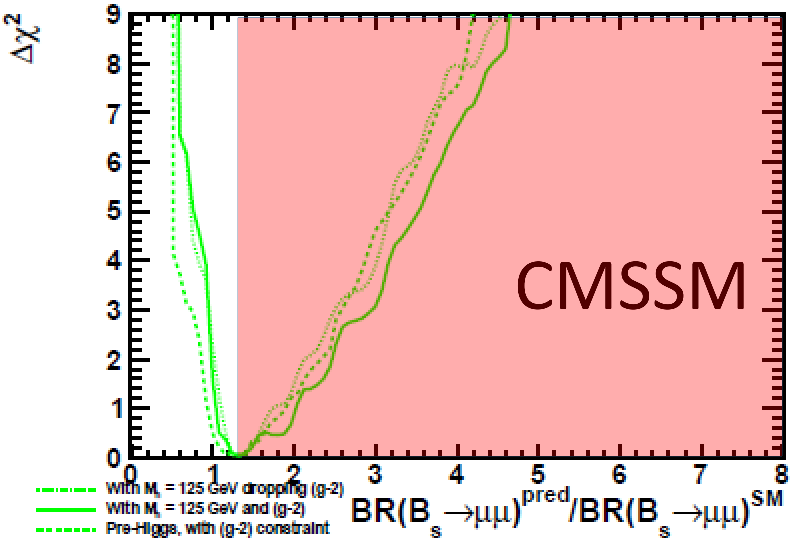
The new constraints can be used to place tighter constraints on the allowed regions of parameter space of SUSY and other theories.

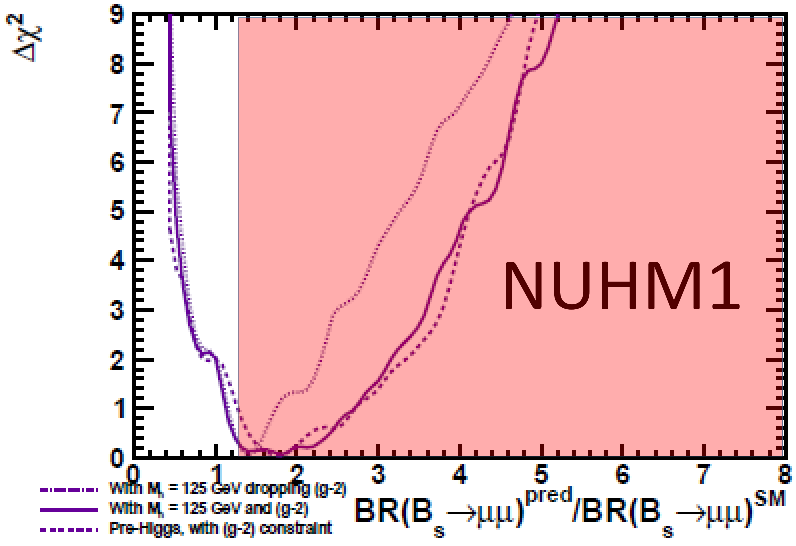
Some results are already available:

- D. Straub (arxiv:1205.6094) takes the LHCb and CMS limits and compares them to range of BR allowed by open parameter space of NP models affecting them
- One may also compare limits to e.g. S. Heinemeyer et al. (arxiv:1112.3564)'s $\Delta\chi^2$ curves vs $B(B_s \rightarrow \mu\mu)$ (see bottom)

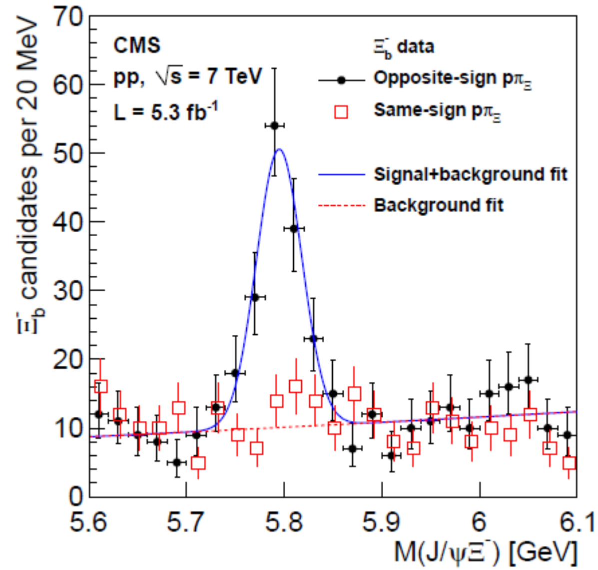


Most models compatible with no enhancing the BR of B mesons, yet the view is striking – new physics could have well shown up here already !





A Discovery!
The new Ξ_b^* Baryon



Outstanding CMS tracking capabilities allow the full reconstruction of decays of Ξ^-_b baryons through the chain $\Xi^-_b \rightarrow J/\psi \Xi^-$ followed by $J/\psi \rightarrow \mu\mu$ and $\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\pi^-\pi^-$

One can then search for excited states with decay $\Xi_b^* \rightarrow \Xi^-_b \pi^+$

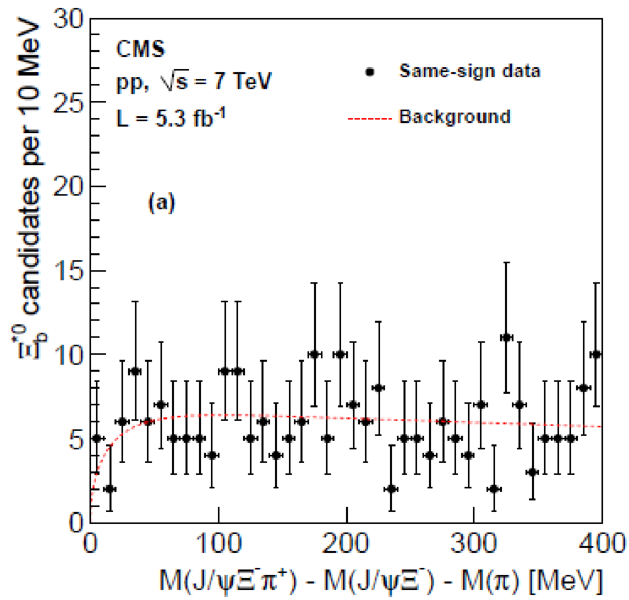
The signal of the excited new state is found in the distribution of the mass difference between the $J/\psi \Xi_b \pi$ system and the two supposed products of the two-body decay. The background shape is a phase space model checked in data with same-sign pions.

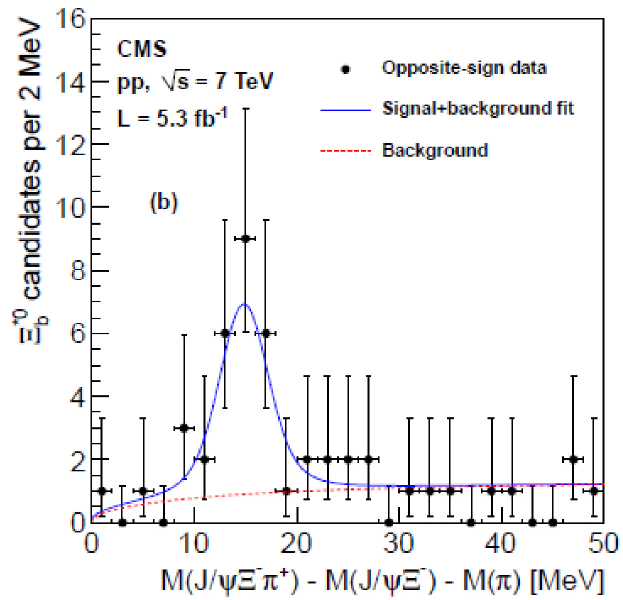
http://arxiv.org/pdf/1204.5955.pdf

The significance of the observed signal is much larger than 5σ even accounting for the trials factor

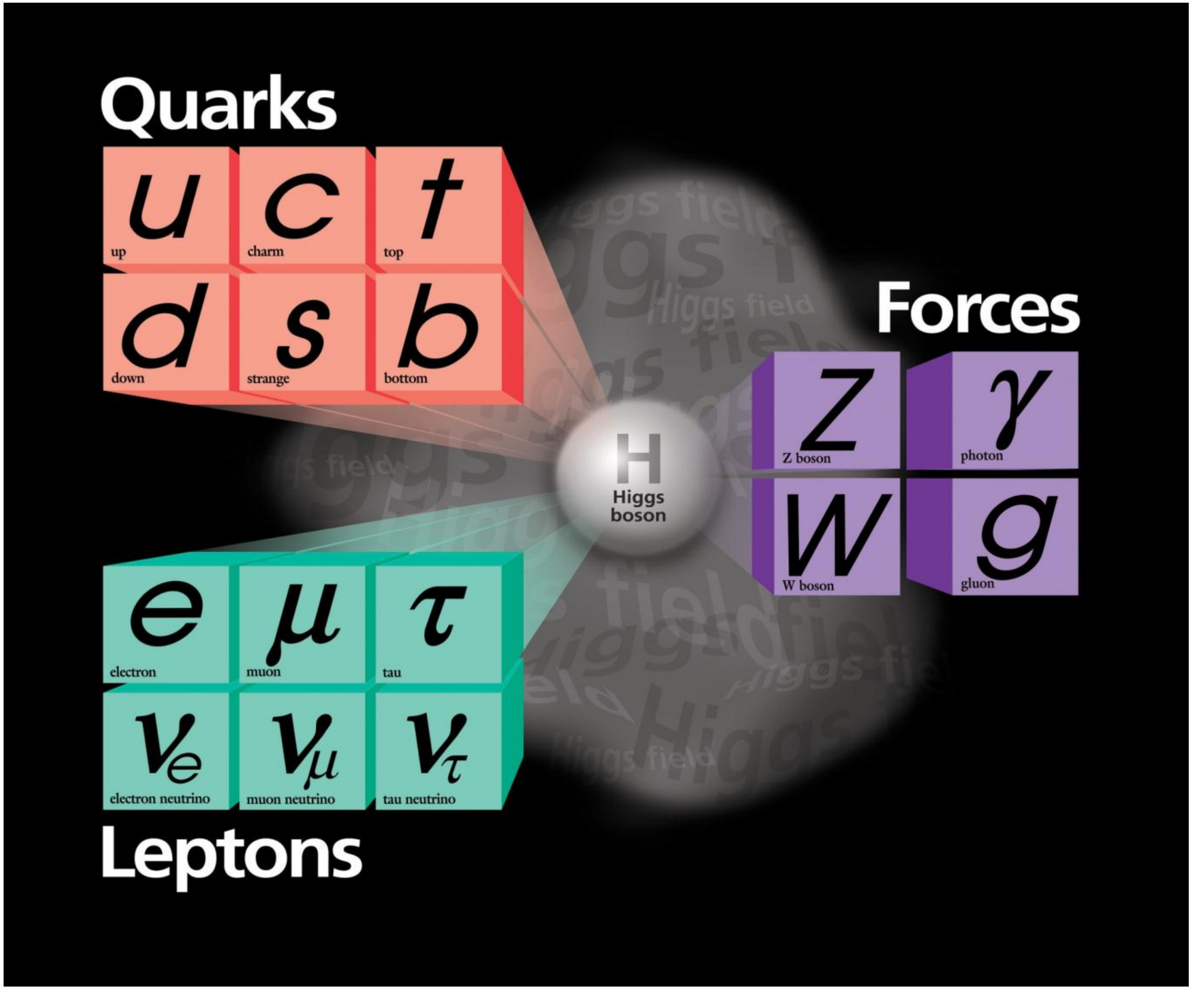
The mass of the new state is measured to be

M_{Ξ_b*}=5945+-0.3+-0.7+-2.3 MeV





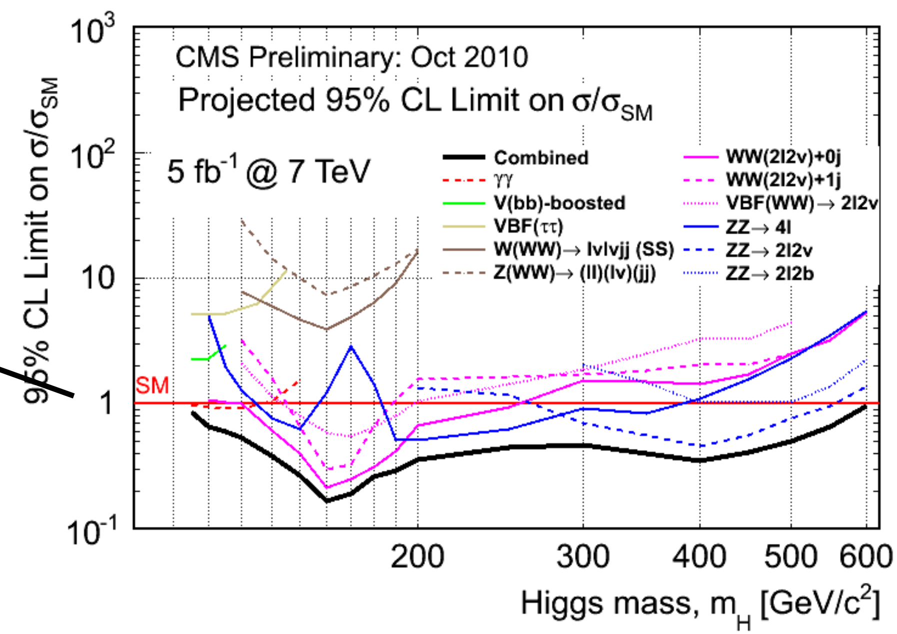
Higgs Boson Searches

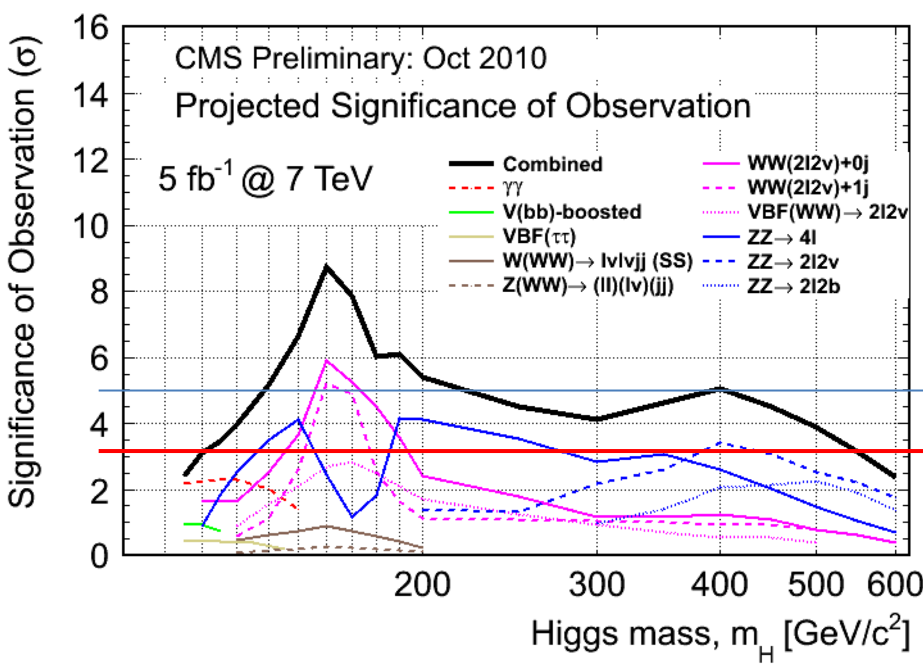


Fall 2010 forecasts

- One of the main goals of LHC
- In 2010, CMS predicted that 5/fb of 7-TeV data would provide:
  - a 95% exclusion across the full mass range, if the Higgs is not there

    At low mass, reliance on γγ decay mode found crucial for this





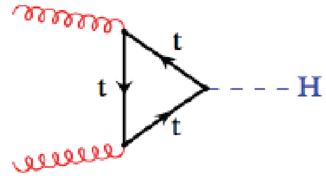
✓ Or a discovery, for 137<M_H<220 GeV

At low mass, γγ and ZZ decay modes both necessary to achieve that goal

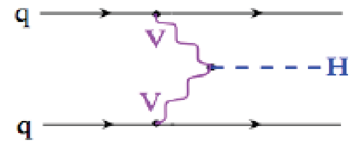
✓ Or at least firm (>3σ) evidence, for all other mass values below 600 GeV…

Higgs Production in pp Collisions

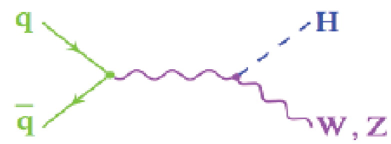
- In 7-TeV pp collisions the Higgs boson has a significant production cross section via several production mechanisms
- Gluon-gluon fusion is the dominant one, but VBF processes are also above 1pb and less dependent on M_H.
- Bremsstrahlung from EW bosons possible but huge rate of QCD backgrounds make it less profitable WRT Tevatron
- The spectacular production in association to top pairs is small and not pursued yet



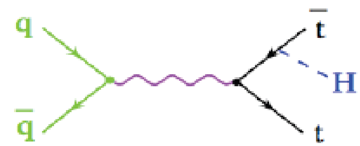
Direct production by gluon fusion



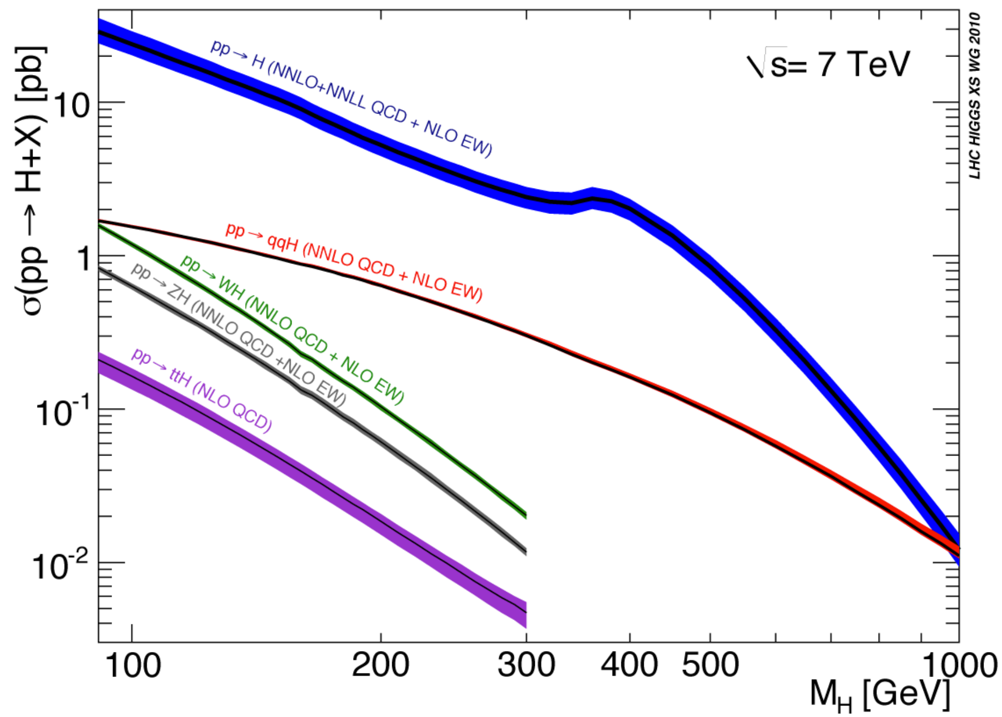
VBF: fusion of vector bosons



Higgsstrahlung from off-mass-shell vector bosons

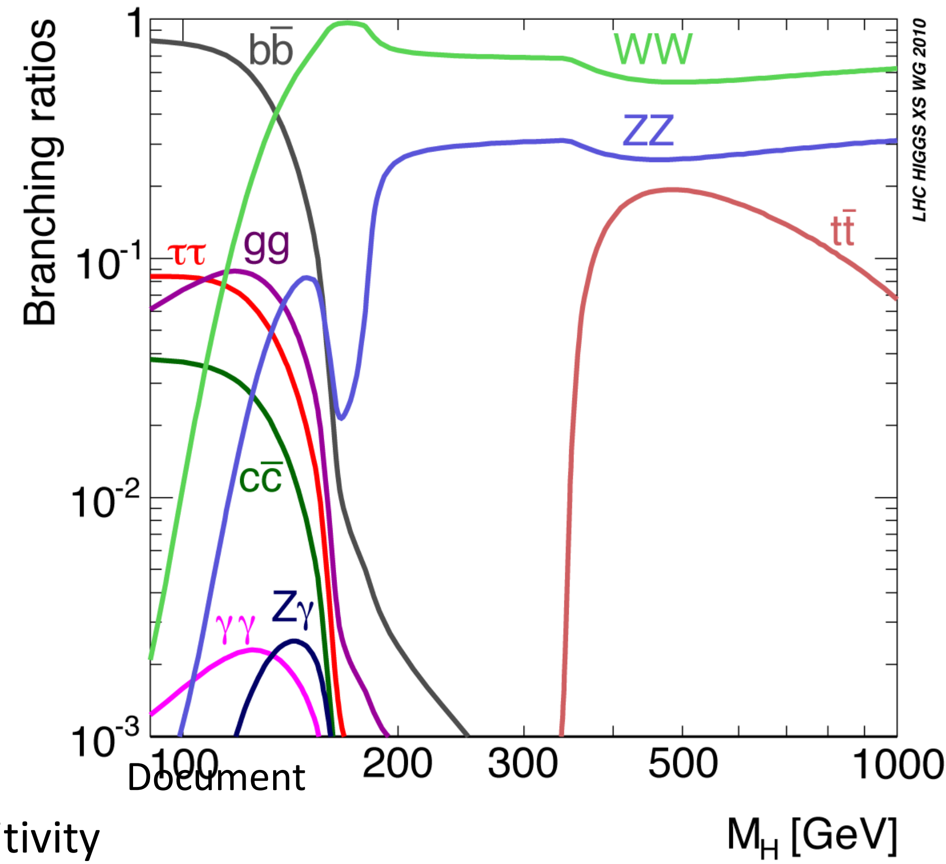


Higgsstrahlung from top quarks



Higgs decays

- H couples to all massive particles directly, plus to photons indirectly
  → rich decay phenomenology!
- The value of branching ratios depend on Higgs mass. All open decays fight each other
  - WW "peak" suppresses everything else at 165 GeV
  - clear division between "low-mass" and "high-mass" regimes at 135 GeV
  - Note "lucky" M_H=125 GeV point gives sizable BR to many interesting accessible final states !



CMS pursued most decay modes in 2011.

The further division in sub-classes improves sensitivity

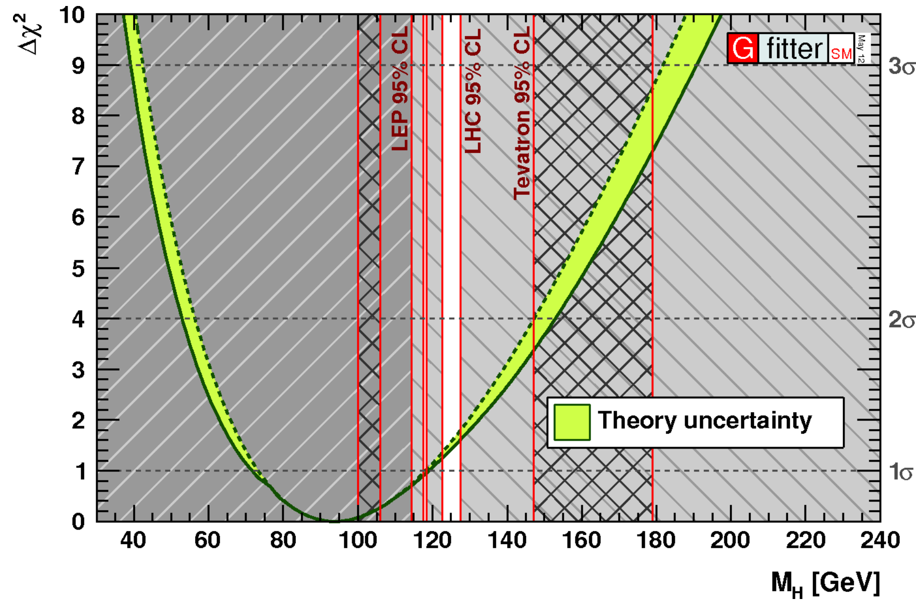
Mode	Mass Range	Data Used (fb^{-1})	Categories	Mass Resolution (%)	Document
H → γγ	110-150	4.7	4	1.2-2.7	HIG-11-030
H → bb	110-135	4.7	5	10	HIG-11-031
H → ττ	110-145	4.6	9	20	HIG-11-029
H →WW →2l 2ν	110-600	4.6	5	20	HIG-11-024
H → ZZ →4l	110-600	4.7	3	1-2	HIG-11-025
H → ZZ →2l2τ	180-600	4.7	8	10-15	HIG-11-028
H → ZZ →2l2j	130-165/200-600	4.6	6	3	HIG-11-027
H → ZZ →2l2ν	250-600	4.6	2	7	HIG-11-026

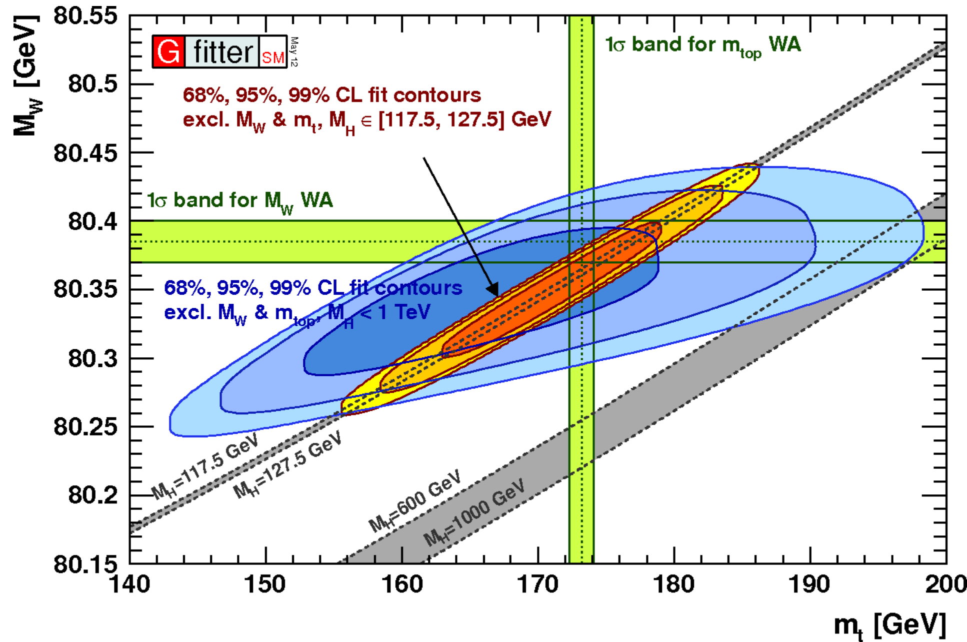
What do Electroweak fits say ?

- Radiative corrections to electroweak parameters values provide a means of inferring the unknown mass of the Higgs boson with the precise measurements of EW observables at LEP/SLD and the Tevatron

- Particularly sensitive: top and W masses
  - M_t now known to 0.9 GeV accuracy (CDF, DZERO) → not going to change much in near future
  - M_W known to 15 MeV accuracy

- The fits to all information are consistent with a low-mass Higgs boson. Now, however, direct searches are leaving only a tiny window for the possible mass range.





Nuts and Bolts of Higgs results

All Higgs searches from CMS follow the recipe of a joint working group with ATLAS. The method is CL_s and the test statistics is a profile log-likelihood ratio. The recipe is as follows:

1) One writes a global likelihood function, whose parameter of interest is the "signal strength modifier" $\mu=\sigma/\sigma_{SM}$. If **s** and **b** denote signal and background, and **θ** is a vector of systematic uncertainties, one can generically write for a single channel:

$$\mathcal{L}(\mathrm{data}\,|\,\mu,\theta) = \mathrm{Poisson}\left(\,\mathrm{data}\,|\,\mu\cdot s(\theta)+b(\theta)\,\right)\cdot p(\tilde{\theta}|\theta)$$

Note that θ has a "prior" coming from (sometimes hypothetical) auxiliary measurements.

In L one may combine many different search channels; e.g., where counting experiments are performed one includes the product of the Poisson factors:

$$\prod_i \frac{(\mu s_i + b_i)^{n_i}}{n_i!}\; e^{-\mu s_i - b_i}$$

2) A profile likelihood test statistics q_μ is defined as $$\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$$

A constraint is posed on the MLE $\mu^\wedge$ to be confined in $0<=\mu^\wedge<=\mu$, which avoids negative solutions and ensures that best-fit values *above* the signal hypothesis μ are not counted as evidence against it.

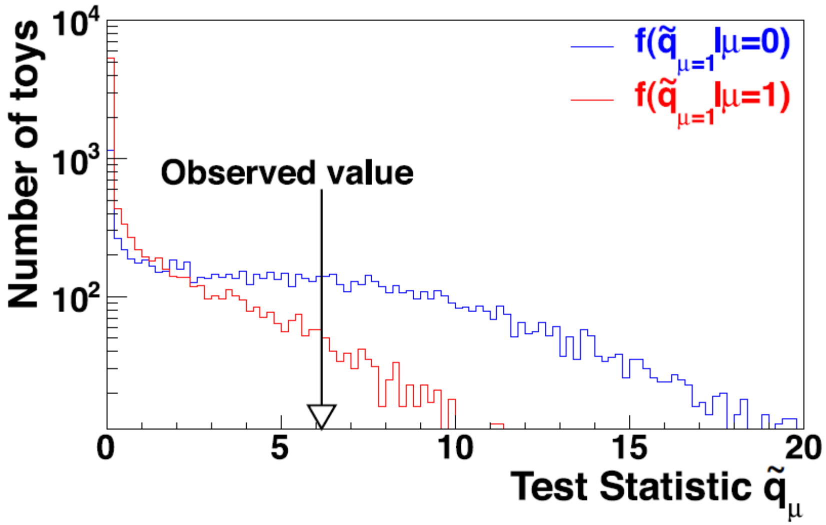
3) ML estimates θ_μ for H_1 and θ_0 for H_0 are then computed, given the data

4) Pseudo-data is then generated for the two hypotheses, using the above MLE of the nuisance parameters. With the pseudo-data, one constructs the pdf of the test statistics given a signal of strength μ (H_1) and $\mu=0$ (H_0).

5) One can then compute the integrals defining p-values for the two hypotheses:

$$p_\mu = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs}\,|\,\text{signal+background}) = \int_{\tilde{q}_\mu^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|\mu,\hat{\theta}_\mu^{\text{obs}})\,d\tilde{q}_\mu$$

$$1-p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs}\,|\,\text{background-only}) = \int_{q_0^{\text{obs}}}^{\infty} f(\tilde{q}_\mu|0,\hat{\theta}_0^{\text{obs}})\,d\tilde{q}_\mu$$



6) Finally one obtains:

$CL_s = p_\mu/(1-p_b)$

→Mass hypotheses are excluded if $CL_s < 0.05$

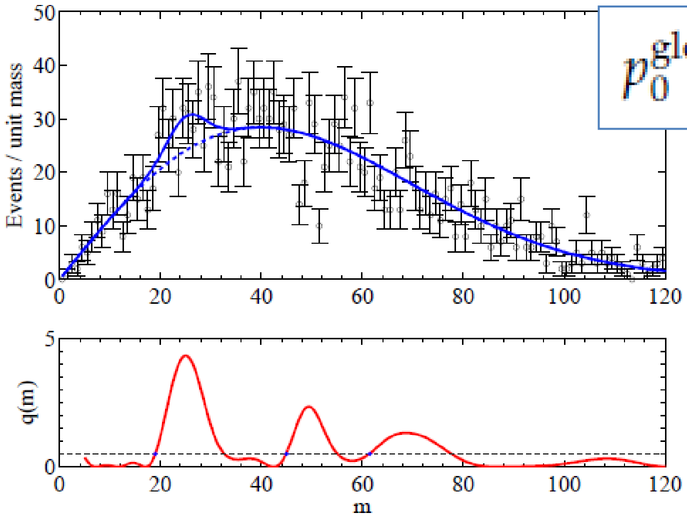
Significance: LEE and upcrossings

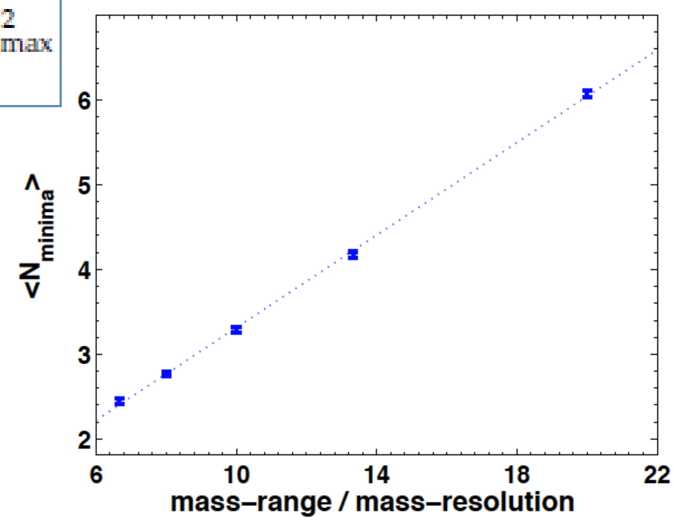
The look-elsewhere effect is well-known and rules of thumb or toys are often used to "rescale" the significance of a background fluctuation.

In complex cases such as the Higgs combination the above are insufficient or cumbersome measures. At the LHC we count the number of "upcrossings" of the distribution of p-value (or the value of the test statistics itself) above some reference value, as a function of mass. Its wiggling tells one how many places one has been searching in

The number of times that the test statistics crosses some reference point is a **measure of the trials factor**. One estimates the global p-value with the number N_0 of upcrossings from a minimal value of the q_0 test statistics (for which $p=p_0$) by the formula

$$p_0^{\mathrm{global}} \sim p_0^{\mathrm{min}} + N_0\, e^{-\frac{1}{2} Z_{\mathrm{max}}^2}$$





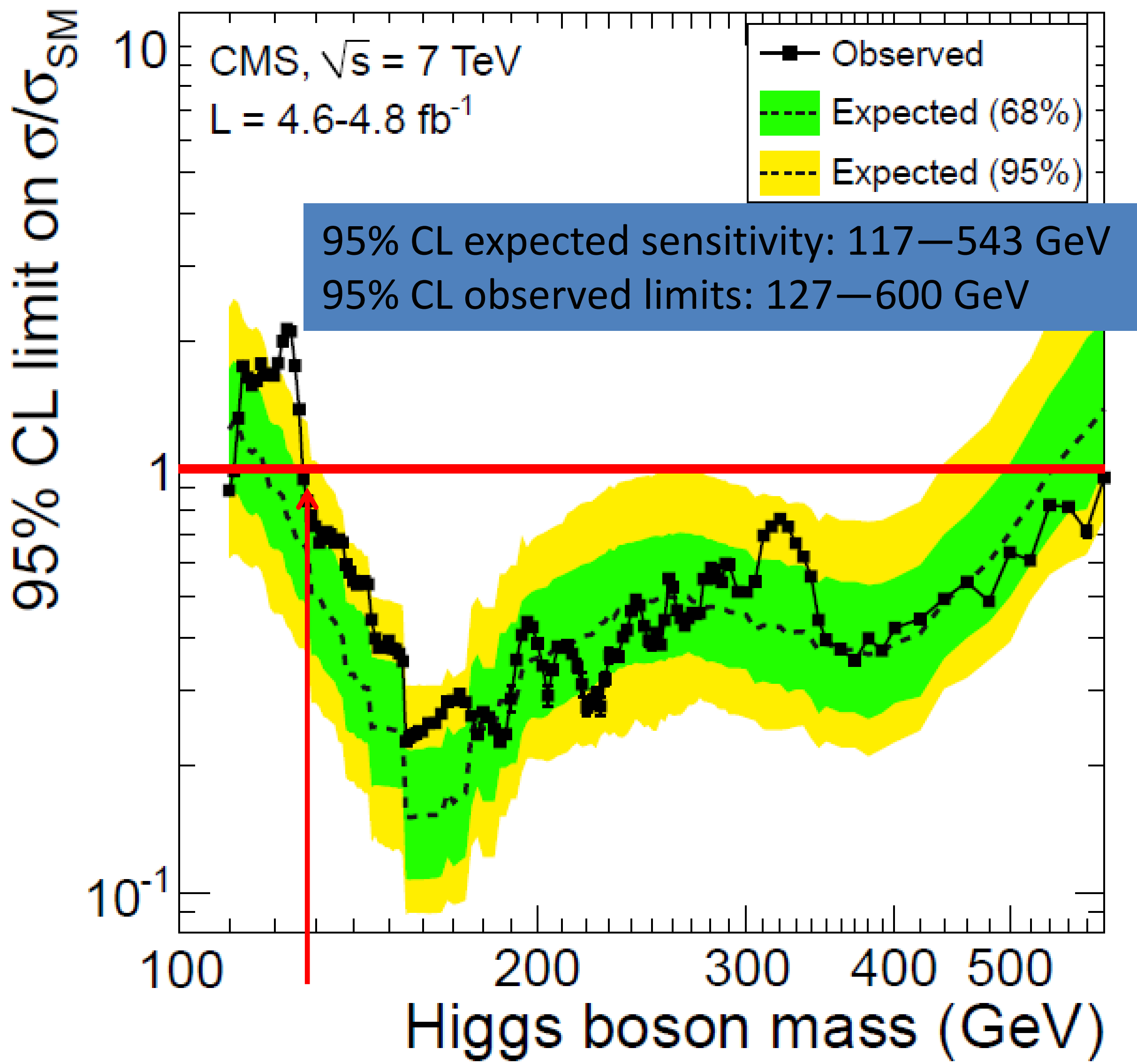
E. Gross and O. Vitells, "Trials factors for the look elsewhere effects in High-Energy Physics", Eur.Phys.J.C70:525-530 (2010)

The number of local minima is closely connected to the freedom of the fit to pick signal-like fluctuations in the investigated range

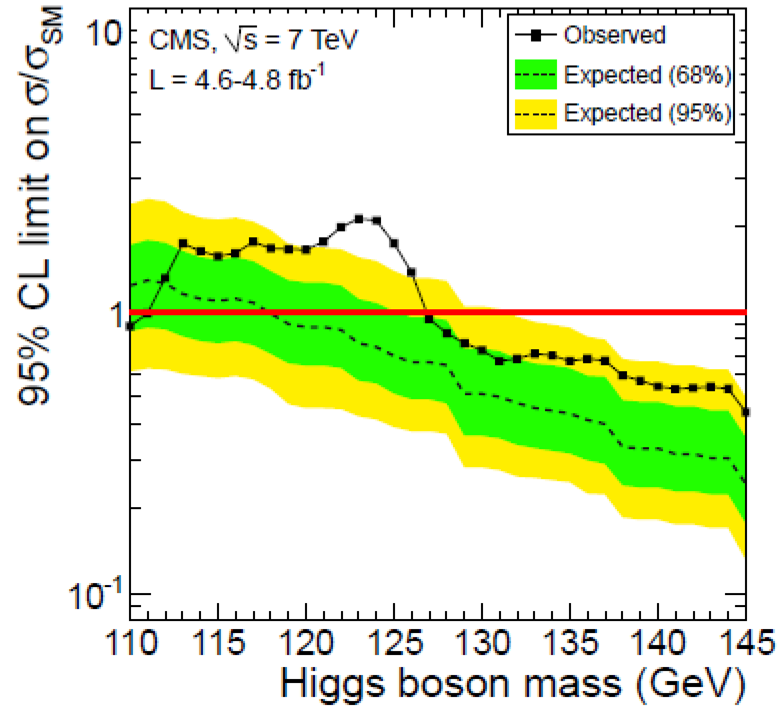
Combination of Higgs Search Results

The combination of the eight sets of upper limits on the ratio $\mu=\sigma/\sigma_{SM}$ is performed with the same technique used for the summer 2011 ATLAS-CMS combination

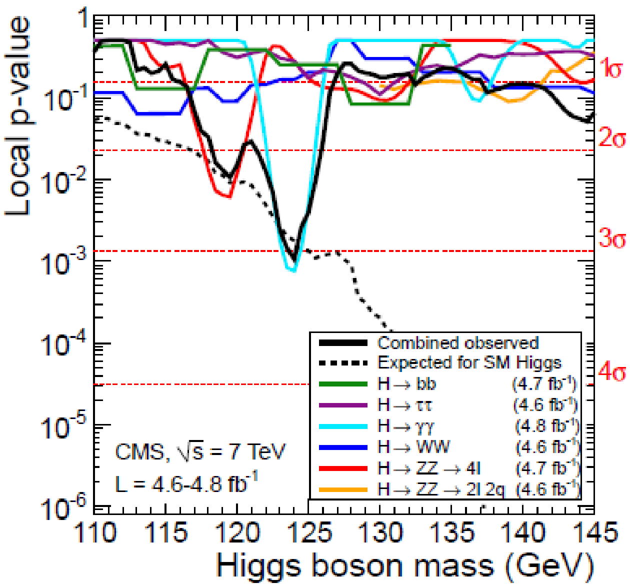
The result is a full exclusion of the high-mass range: CMS data is only compatible with the existence of a Higgs boson if its mass is in the narrow window between the LEP II limit and 127 GeV

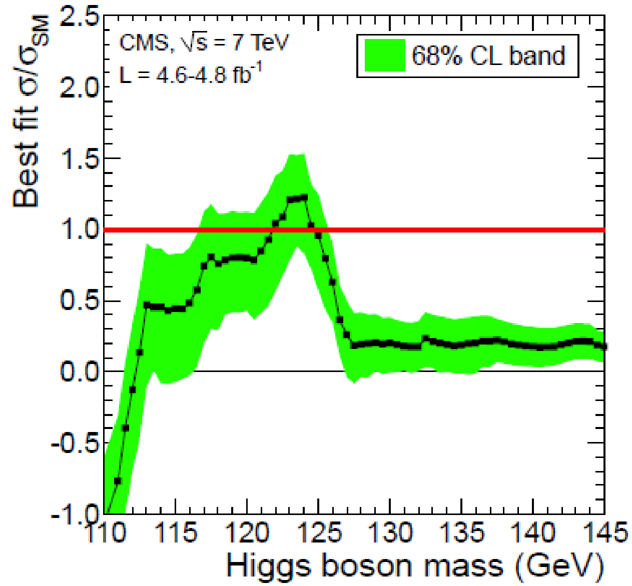


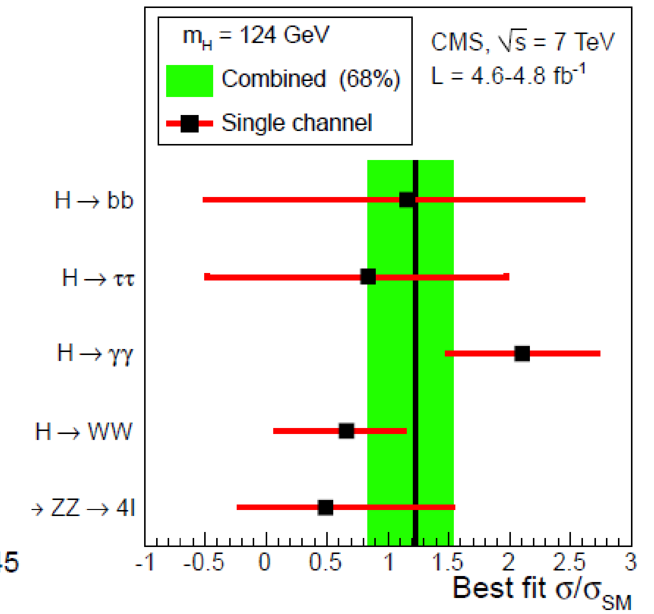
Compatibility with a Higgs signal



- The 124-GeV effect is compatible with a SM Higgs boson – the p-value and best-fit cross section agree with predictions
  - CMS finds globally a local significance of 3.1σ; a trials-factor corrected one is 2.1σ when considering the search range 110/145 GeV
  - More data is necessary to ascertain the origin of the effect → <u>2012 data will tell !</u>



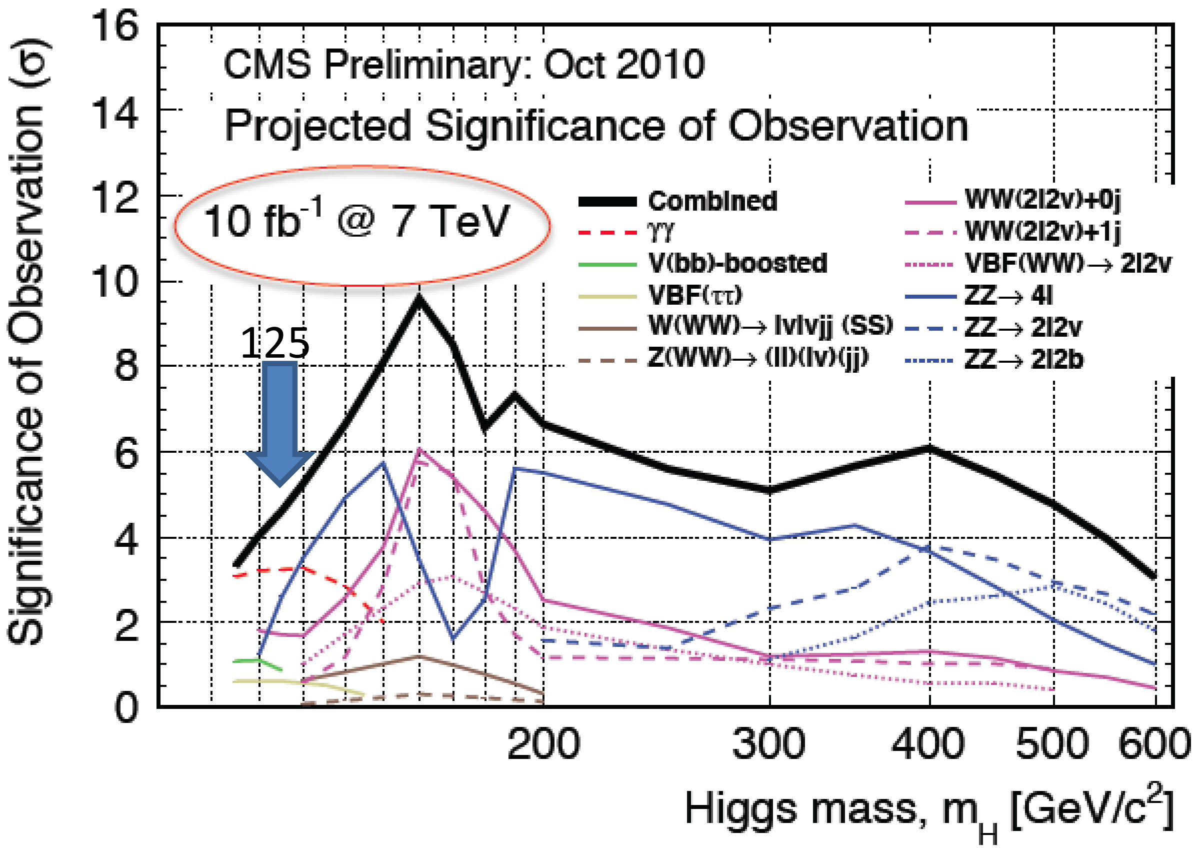




Forecast for 2012

The October 2010 predictions for the sensitivity to a SM Higgs boson were on par with results, given 5/fb of data

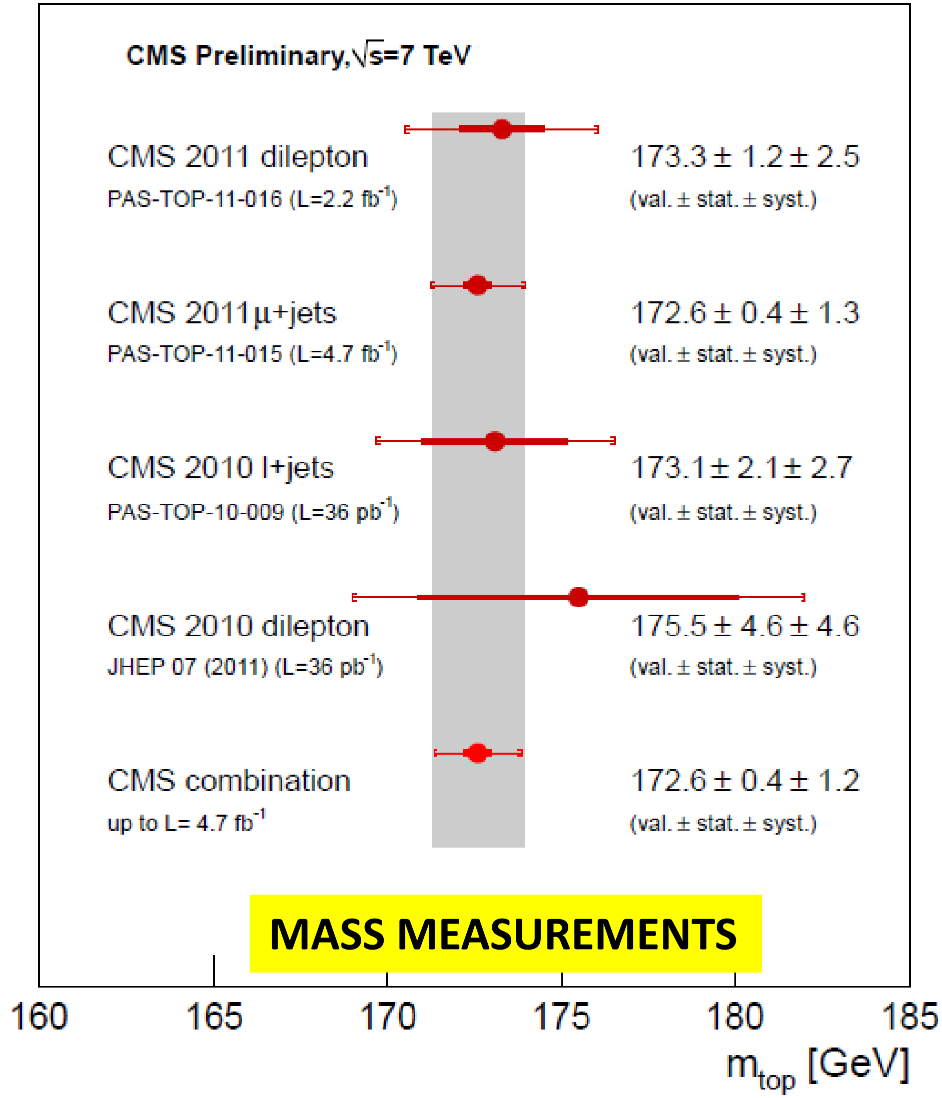
→ We may turn to the 10/fb 7-TeV prediction to have a rough idea of what CMS might be able to produce for summer conferences (eg. ICHEP) with 2012 8-TeV data already in hand

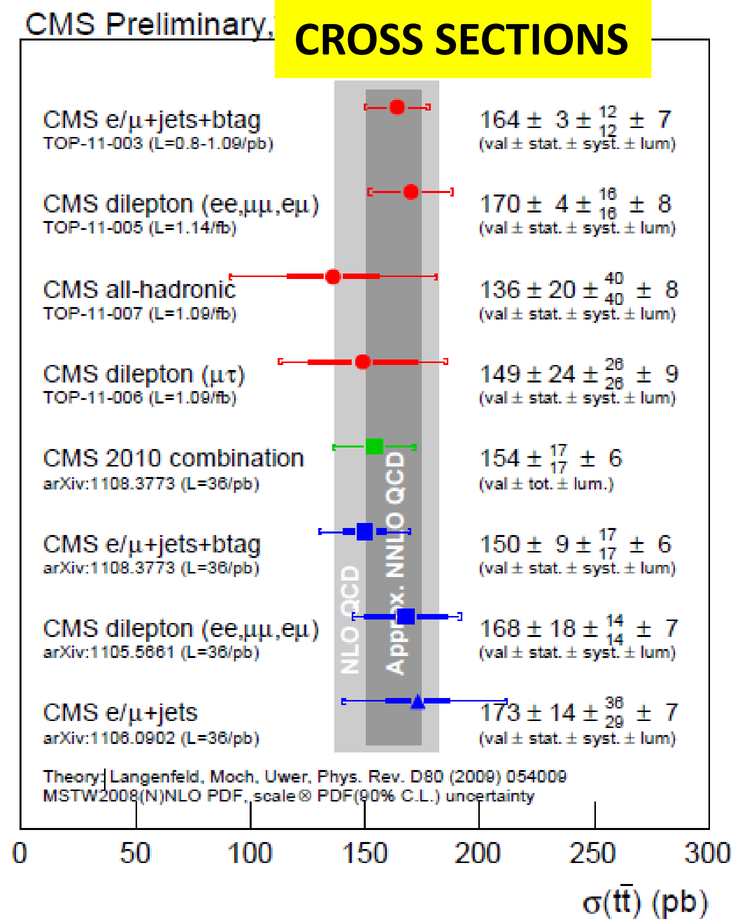


In the 125 GeV region the local significance should be close to 5 standard deviations with 10/fb

→Very likely crossing the 5σ mark by combining with ATLAS or by just collecting some additional few/fb.

Top Physics Results



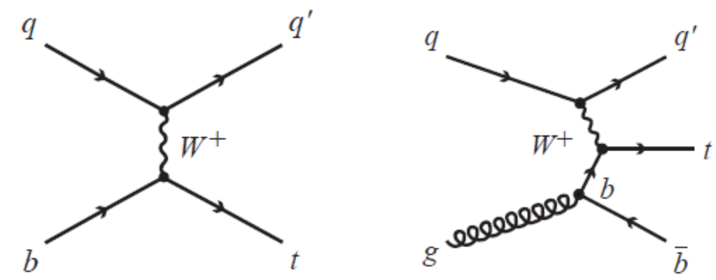


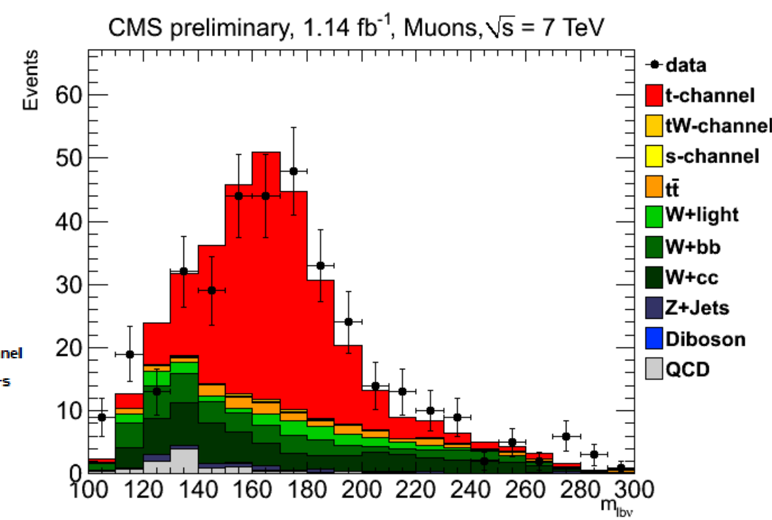
- Top pair production cross sections are measured in all main decay channels
- Results agree well with NLO QCD and approximate NNLO calculations
- Top mass measurements not yet matching the precision of excellent Tevatron results (Δm=0.9 GeV) but the CMS average is getting very close (Δm=1.25 GeV!)

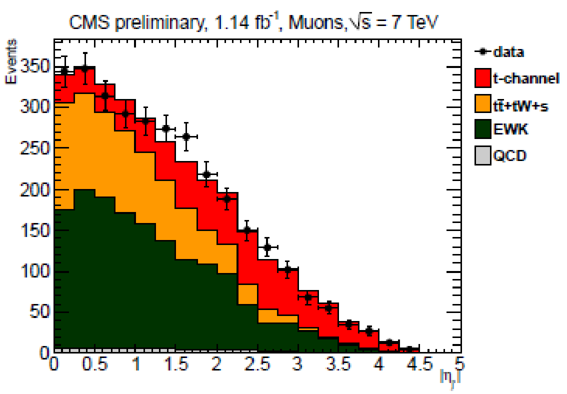
Single top t-channel production

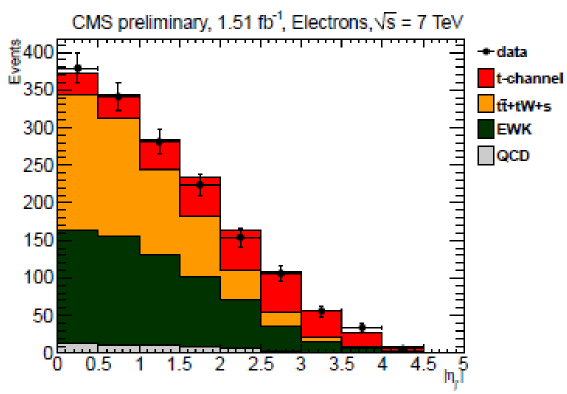
- Events with a high-p_T lepton (e or μ), two jets (one of them b-tagged) and missing E_T are selected for this measurement
- The top mass is reconstructed using the b-tagged jet and the W candidate
  - A signal region is defined to include events with $130 < M_{bl\nu} < 220$ GeV
- The pseudorapidity of the untagged jet is used in a combined fit to the e and μ samples (see below) to extract the signal contribution
- Result:

  σ(t)=70.2+-5.2(stat)+-10.4(syst)+3.4(lum) pb





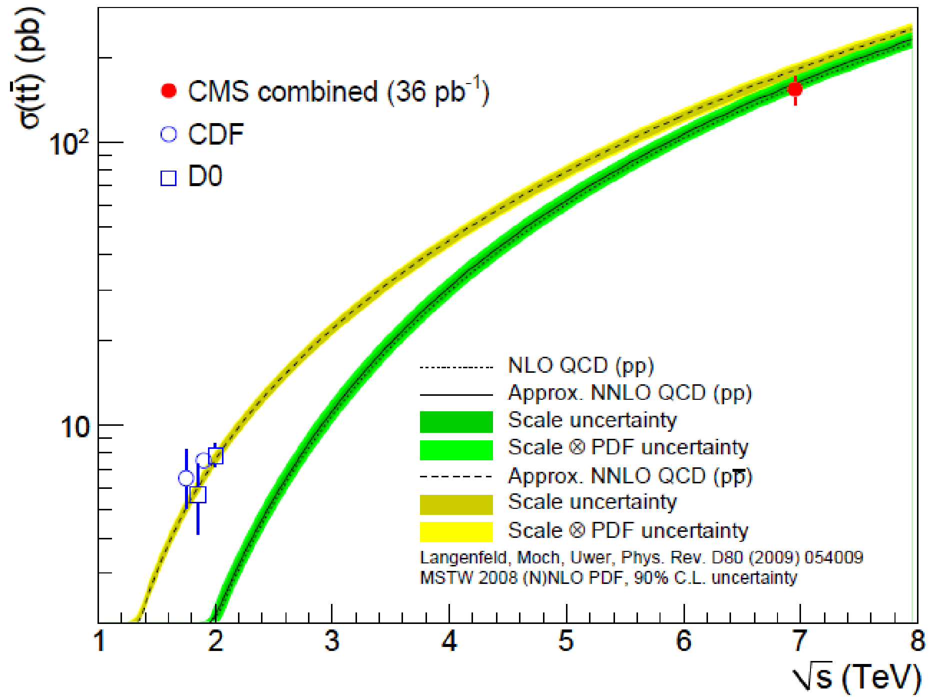


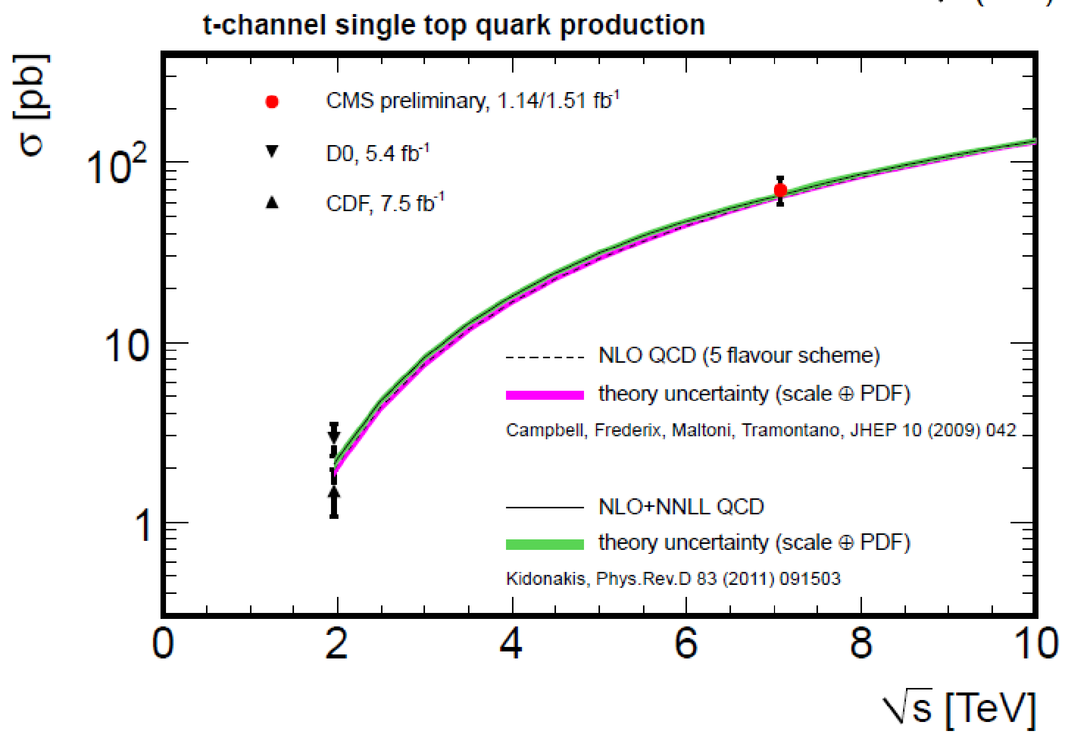


At high light-jet rapidity (|η|>2.8) the signal contribution is dominant

Cross sections vs energy plots

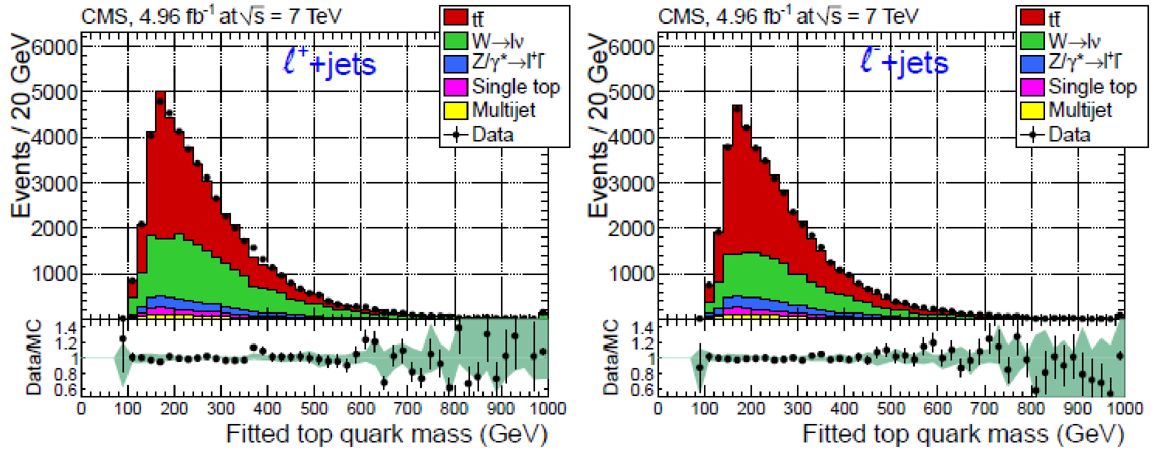
The cross section is perfectly in line with predictions at NNLO for both top quark pairs (right) and t-channel single top production (below)





Two More Recent Top Results

Top-antitop mass difference: measured in 5/fb of l+jets events by looking at lepton charge. Many systematics cancel in difference; the result is a three-times more precise measurement than previous determinations. See arxiv:1204.2807.



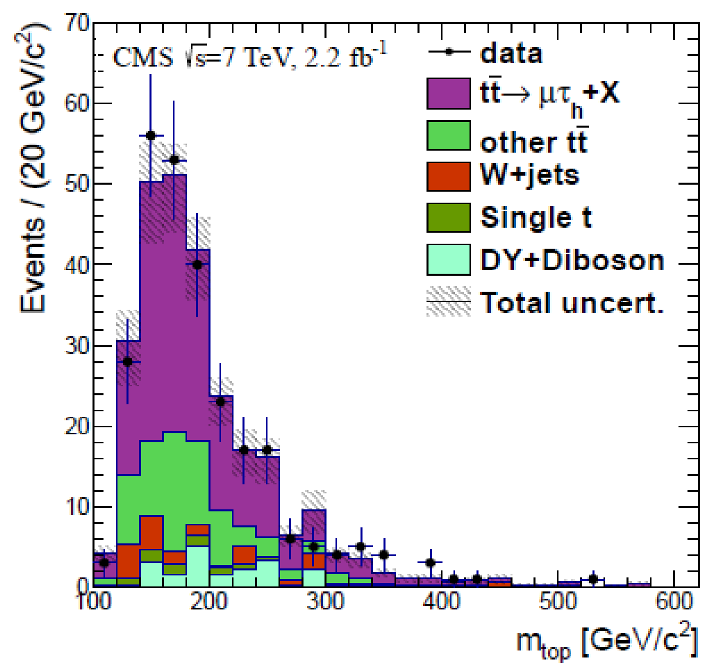
Δm=-0.44+-0.46 (stat)+-0.27(syst) GeV

The top cross section has been measured using 2.2/fb in the “tau-dilepton” final state (which includes one e or μ and one hadronically-decaying tau lepton).

Result:

σ(tt) = 143+-14+-22+-3 pb ,

in agrement with SM prediction. See arxiv:1203.6810.



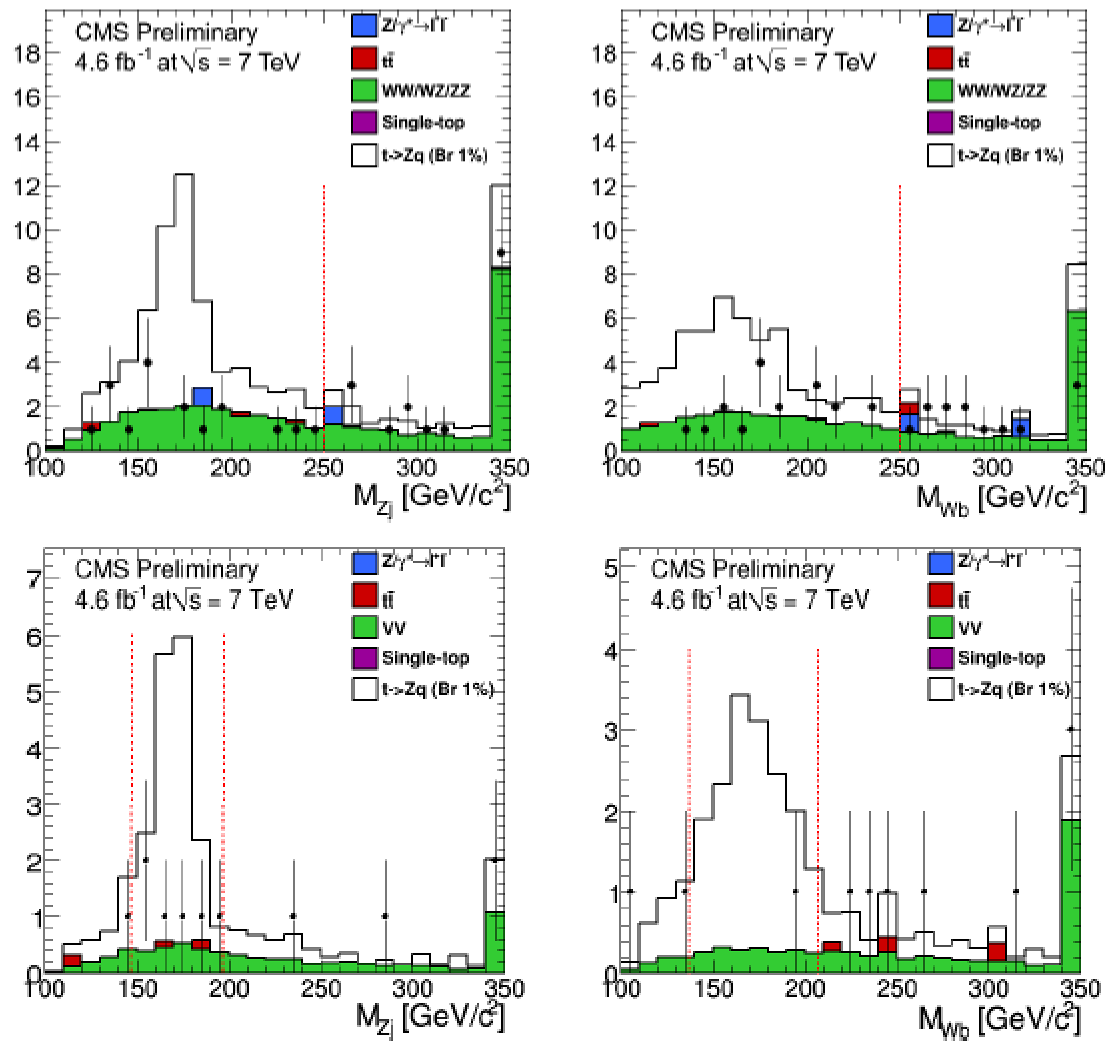
Search for FCNC top decays

- FCNC top decays are very rare in the SM: $O(10^{-14})$
- NP models (topcolor-assisted technicolor, RPV SUSY) predict enhancements up to $O(10^{-4})$
- CMS searched for neutral-current decays of top quarks in tt→WbZj→3l+jets events

  The signature is very clean, with only electroweak backgrounds to fight against
- The mass of top candidate combinations is used to search for candidates
- 95% CL upper limits are placed on the branching fraction of t→Zj at **B<0.34%**

  This is three times more precise than existing limits

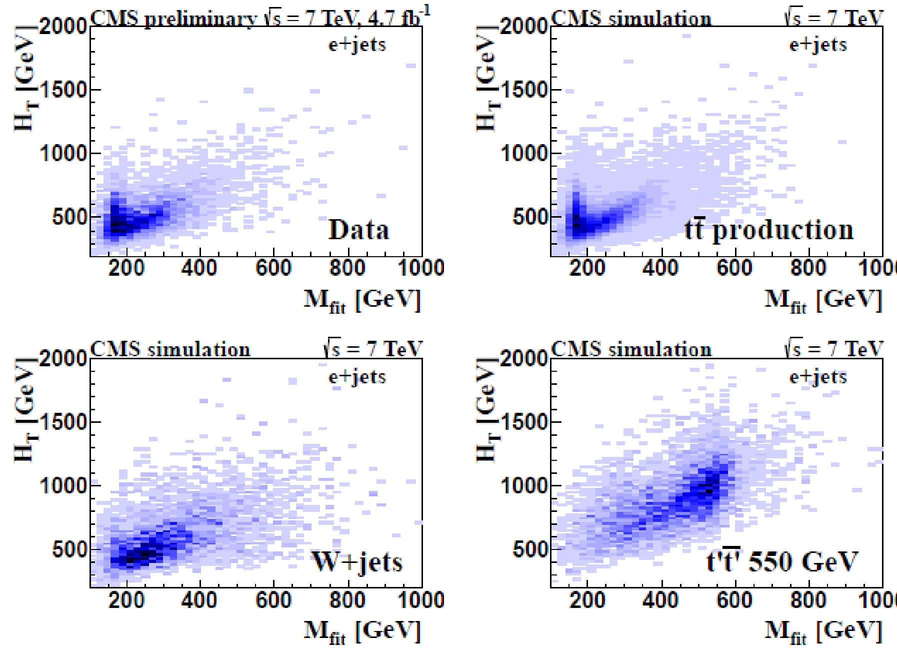
Top row: HT-based selection; bottom: b-tagged events

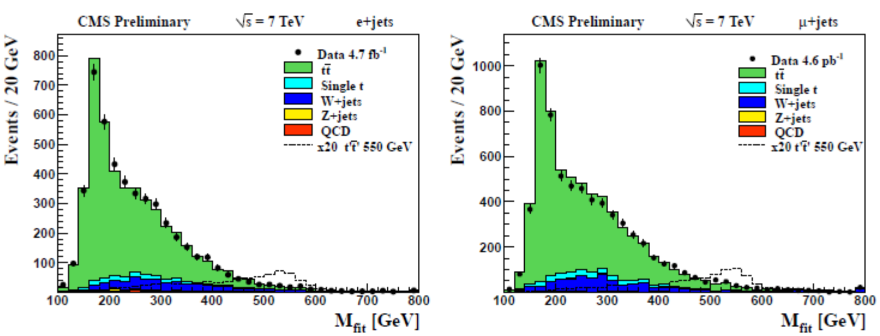


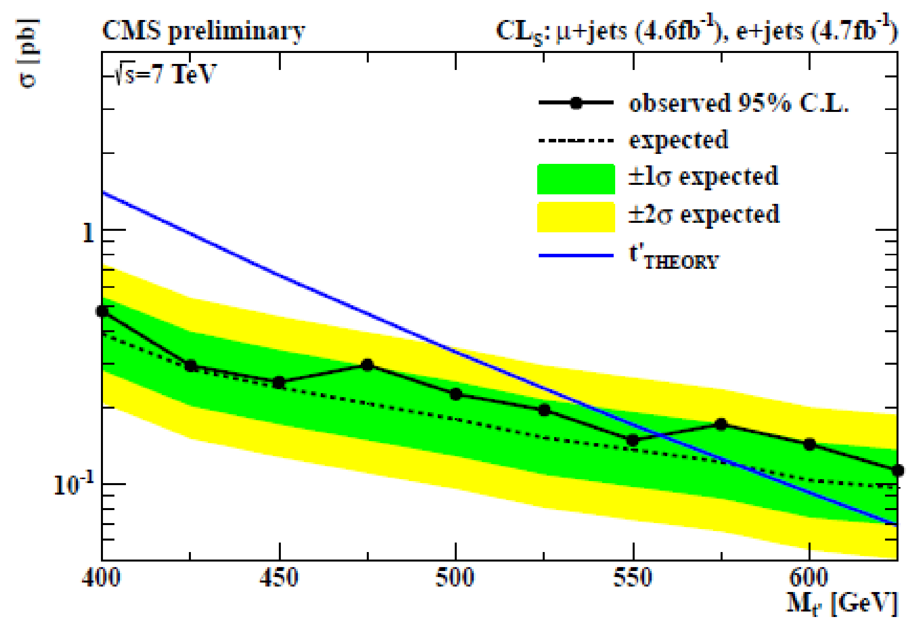
Search for t' quarks

- A fourth generation of matter fields is not inconsistent with precision EW data; quark masses are experimentally constrained to be above 358 GeV
- The mass splitting between fourth-generation quarks t', b' is expected to be smaller than m_W → the t' is assumed to decay to Wb
- A search for pair-production of fourth generation quarks was made in 4.6/fb of lepton+jets events
- The three-body mass and the H_T are fit simultaneously to search for a t' component
- Limits are set with CLs:

  $M_{t'} > 560$ GeV at 95% CL

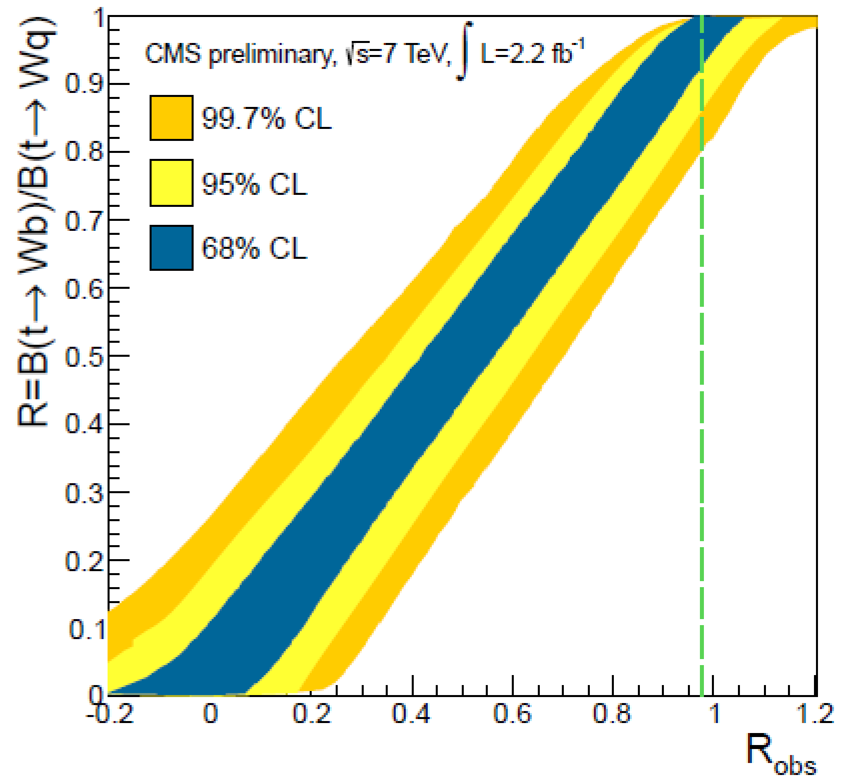




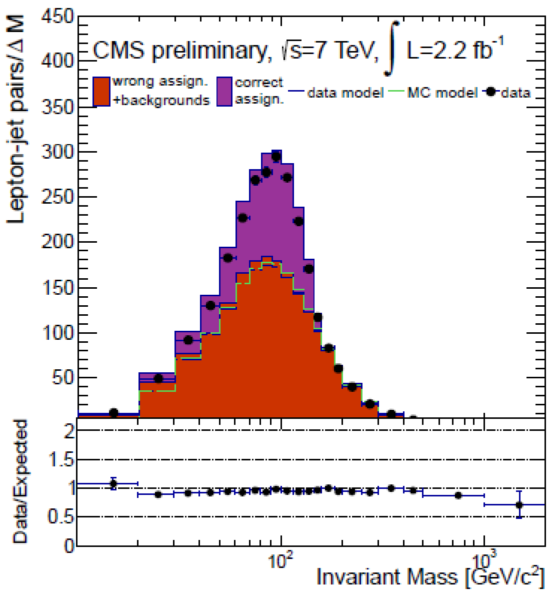


Measurement of R=B(Wb)/B(Wq)

The analysis studies the fraction of jets from top decay that contain b-quarks, a number which is >99% according to present knowledge of the CKM matrix

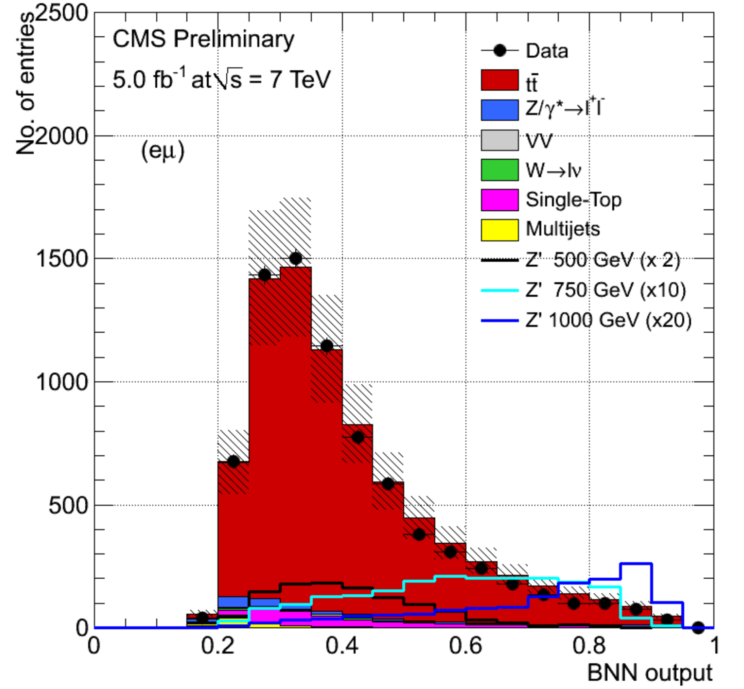


A very pure sample of candidate top quark pairs are selected in the dilepton topology (ee, eμ, or μμ) with missing E_T>30 GeV for the same-lepton category, and two jets. The three-body masses are used to verify the hypothesis that jets come from the top decay



The b-content of the jet is determined looking at the impact parameter significance of the tracks in the jet
The observed ratio of events with identified b-jets allows to set a lower limit R>0.85 at 95% CL using the Feldman-Cousins unified approach

Search for Z'→tt

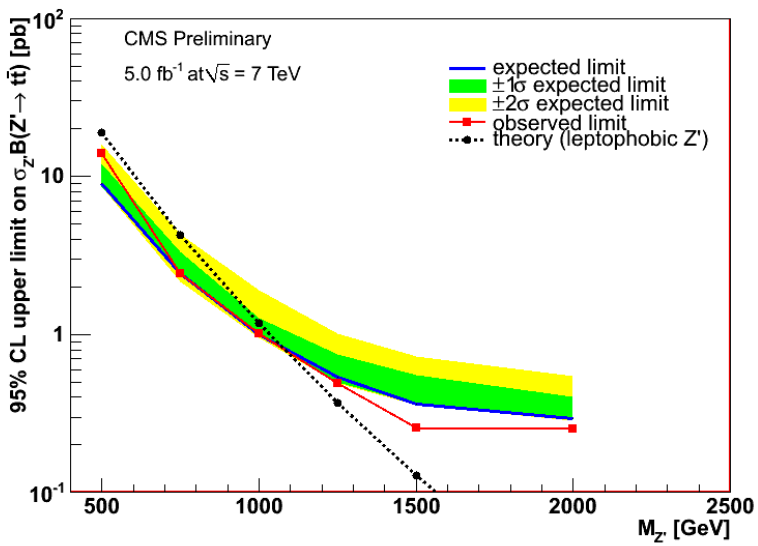


In topcolor-assisted technicolor models a dynamical mechanism for electroweak symmetry breaking is generated. A prediction of the model is the existence of a Z' boson with preferential coupling to 3rd generation fermions

Events with two charged leptons, two jets (one of which b-tagged) and missing E_T are selected.
The top mass is reconstructed in the ttbar hypothesis by setting neutrino longitudinal momenta to zero.

17 variables are used in a Bayesian Neural Network to discriminate the Z'(750) signal from backgrounds

The resulting limits in the signal cross section allow to exclude a leptophobic Z' boson with mass below 1.1 TeV (for width 0.012 $M_{Z'}$)



Search for Boosted Z bosons

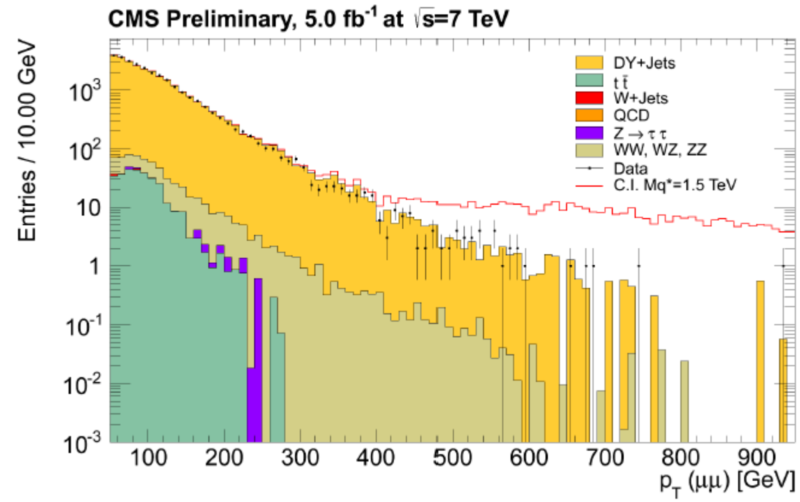
- Boosted Z bosons are a signature of contact interactions, as well as other models of BSM physics

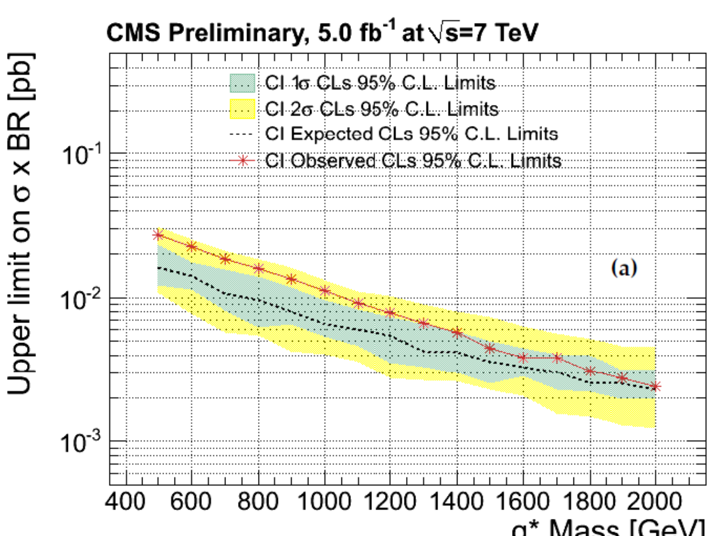
  CMS studied the signature of high-P_T $Z \rightarrow \mu\mu$ pairs, optimizing the search for $q^* \rightarrow qZ$ decays. This signature is practically background-free given the very clean Z signal

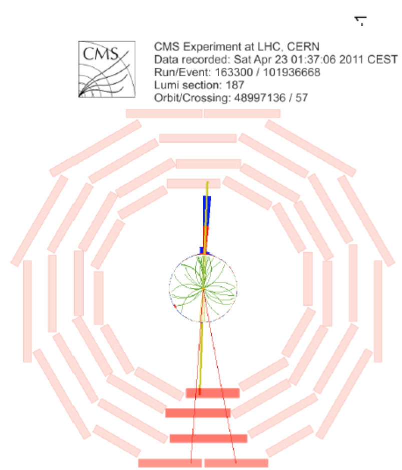
  The $1/p_T$ distribution of the muon pair is studied, looking for enhancements at the low end

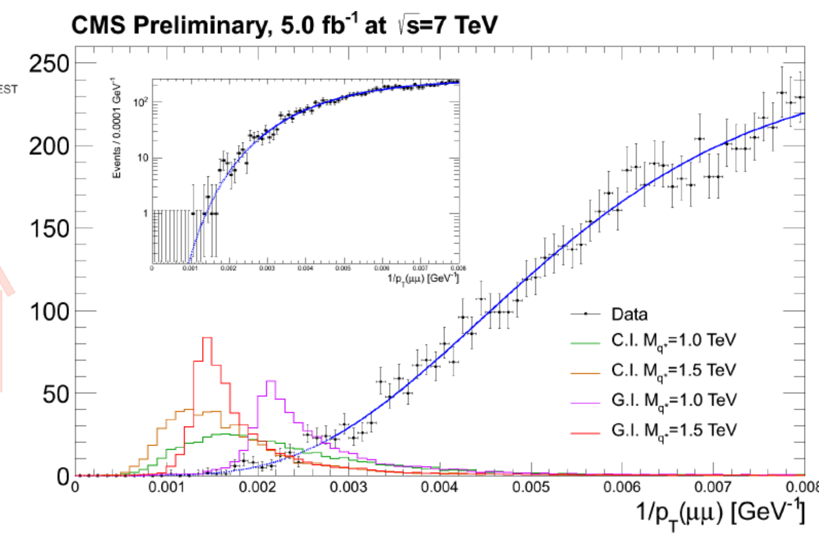
- Cross section limits are obtained for several classes of models predicting high-P_T enhancements – See [EXO-11-025-PAS] for details

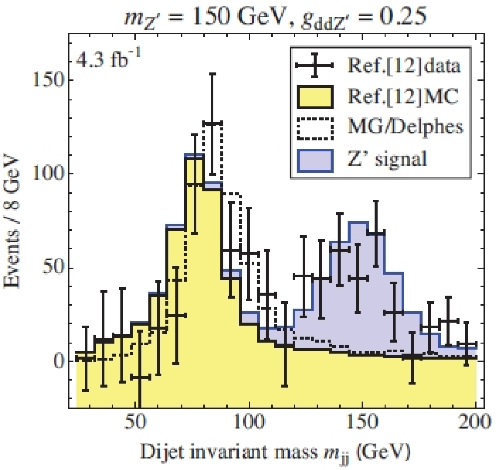
  95% CL limits: m_{q^*}>1.94 (2.14) TeV for new gauge interactions (contact interactions)



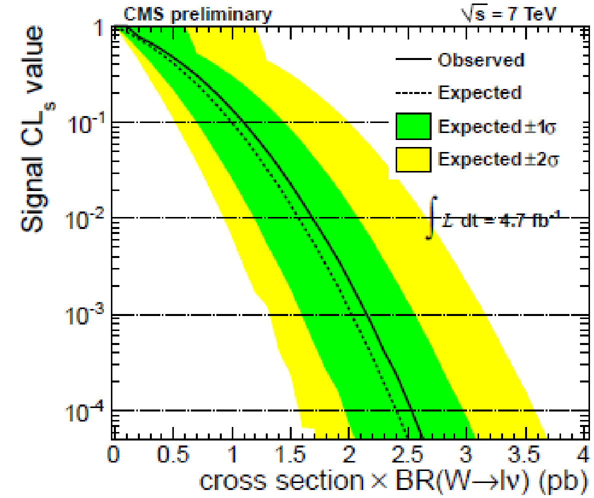








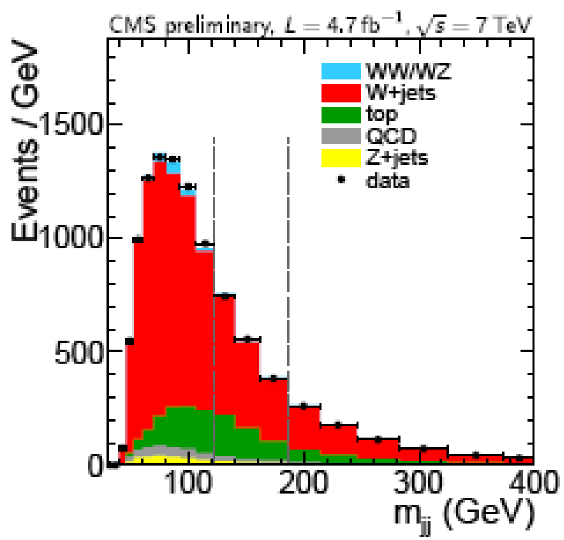
Search for V+jj Bumps

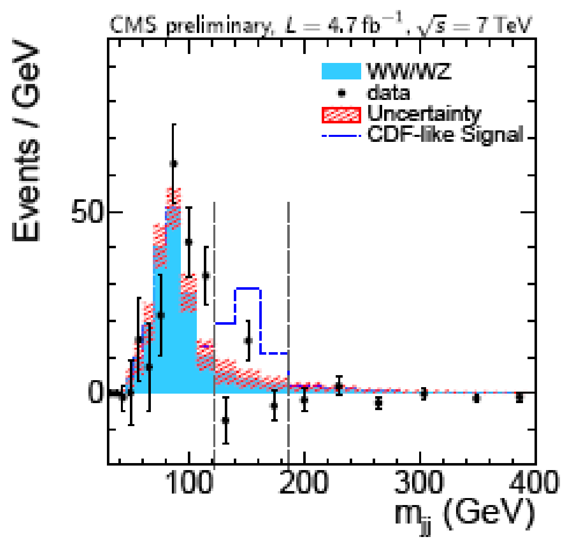


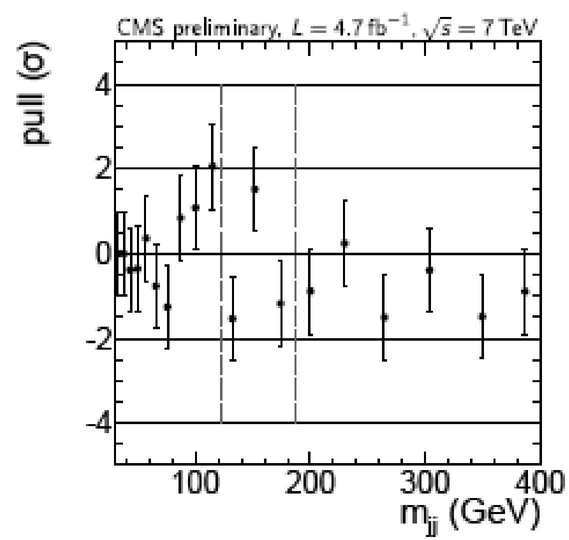
Two years ago CDF published a >4σ evidence of a structure in the mass distribution of jet pairs produced with a W or Z boson (the "**Vivianonium**"), see top left

CMS looked for this dijet resonance with 2011 data (e/μ with missing E_T and two jets)

No signal is observed above W+jets/top background→ 95% CL upper limits exclude the CDF effect and place constraints on similar models (see arxiv:1107.4771)

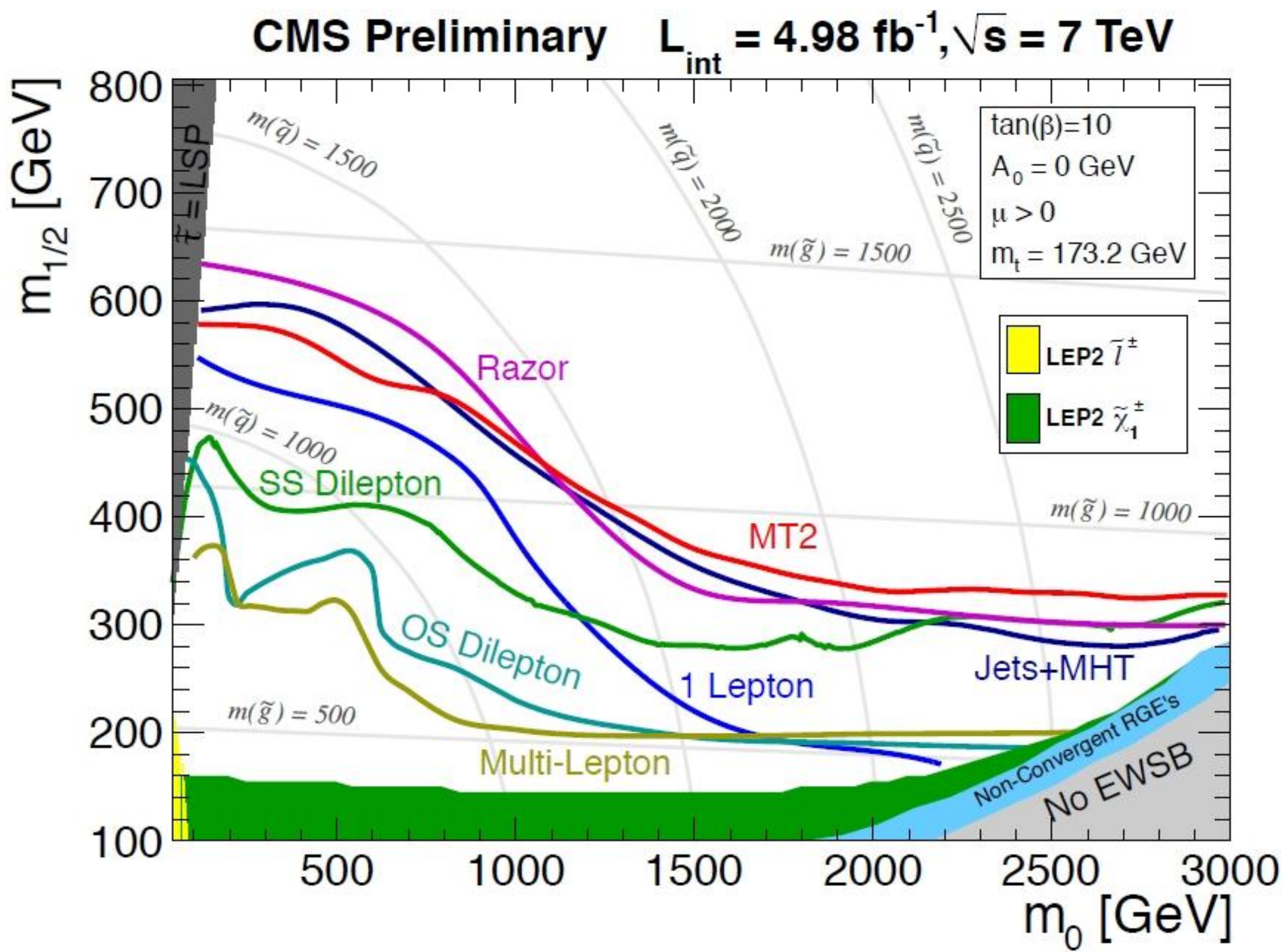






SUSY searches

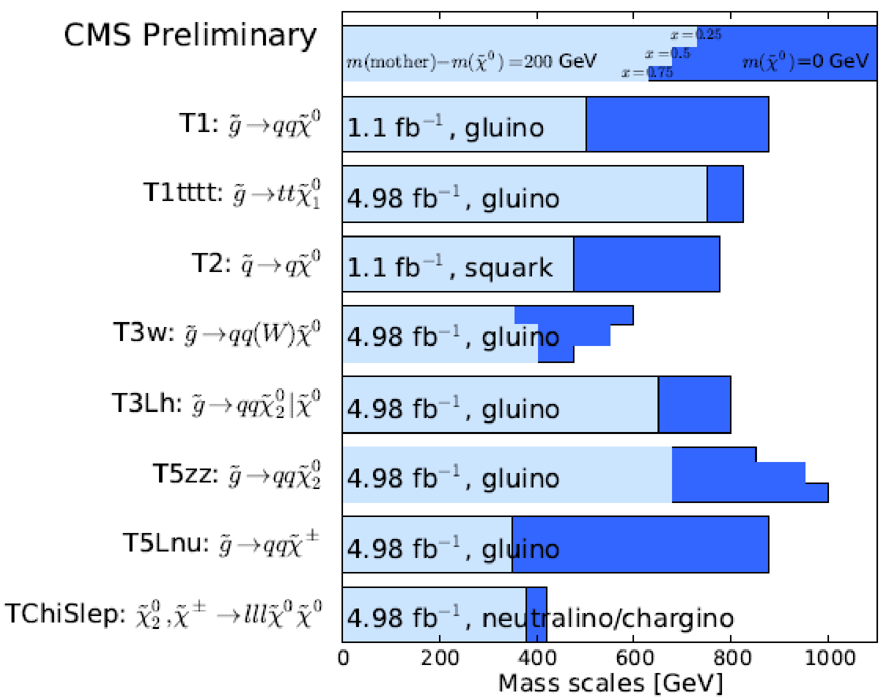
CMSSM limits extracted by many different searches highlight the absence of any new signal of SUSY particles in the many pursued signatures
For more details and channel-by-channel results please see the slides of yesterday's talk by N. Saolidou, or visit the [CMS SUSY public page]()

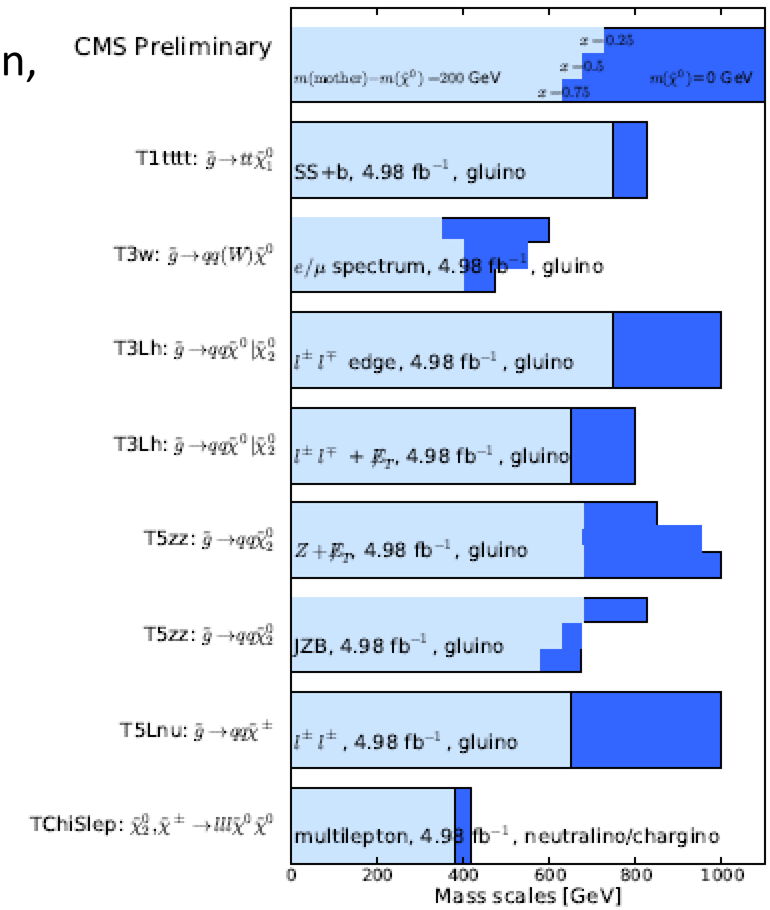


SUSY Limits in simplified models

- A summary of the limits on the mass of gluinos and squarks can be obtained in simplified scenarios.
  - These predict specific mass spectra for superpartners, so they cannot be taken to represent the full range of SUSY theories

The produced "limits" are indicative of the current reach of the CMS analyses considered in the combination, given the production modes and decay signatures

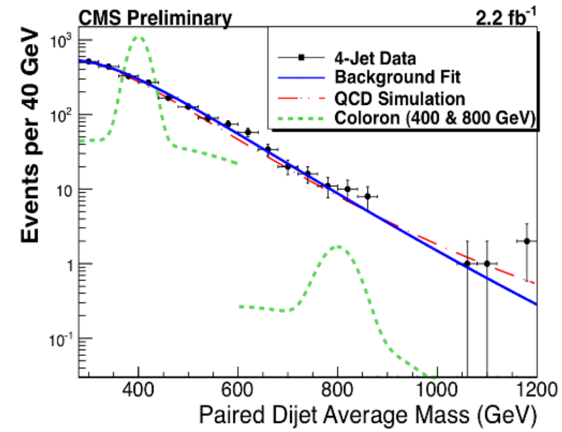


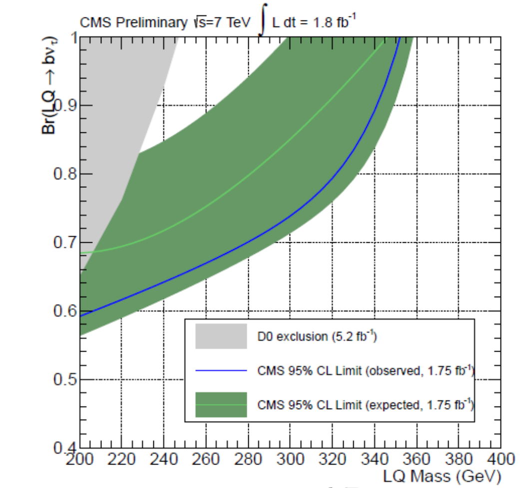


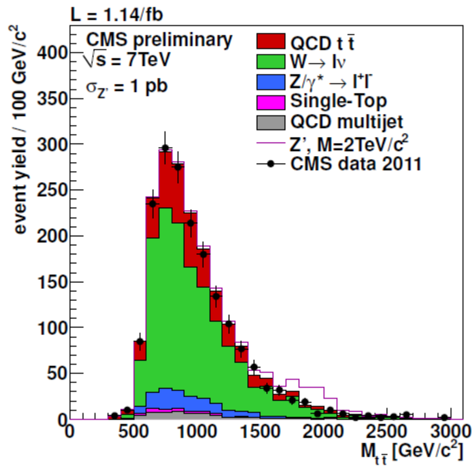
Other Exotics Searches

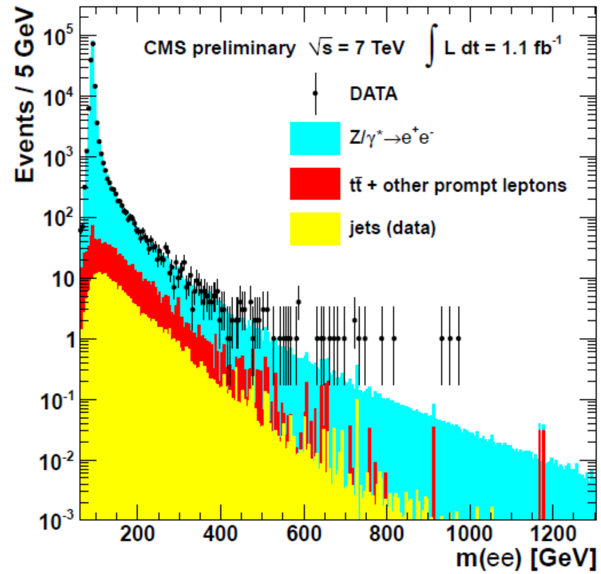
- So much to discuss, so little time...
- **Executive summary**: Many new physics signatures sought, none found
- Please visit the CMS public web pages of Exotics results for information on searches for
  - Large extra dimensions (limits from searches in $\gamma\gamma$, jet plus MET, dileptons...)
  - vector-like quarks
  - dijet mass resonances
  - leptoquarks (first,second,third generation)
  - microscopic black holes
  - W', Z' bosons
  - heavy stable charged particles
  - fourth generation quarks
  - colorons, and similar jet resonances
  - etcetera

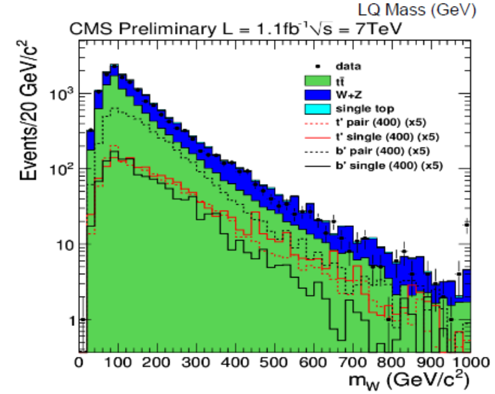
An invitation to give a look at CMS results on Exotica

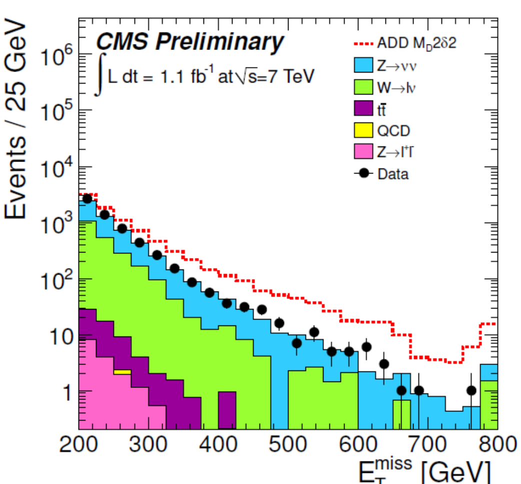


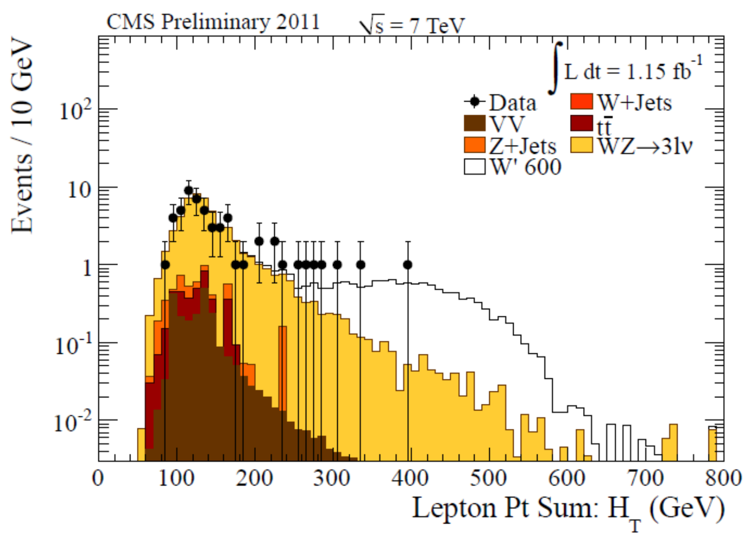


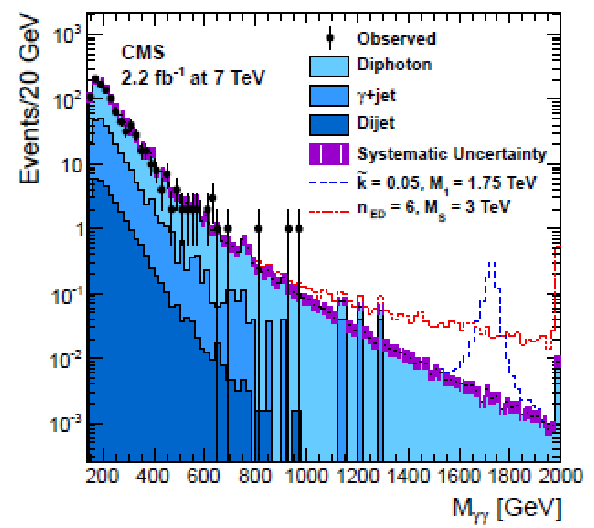










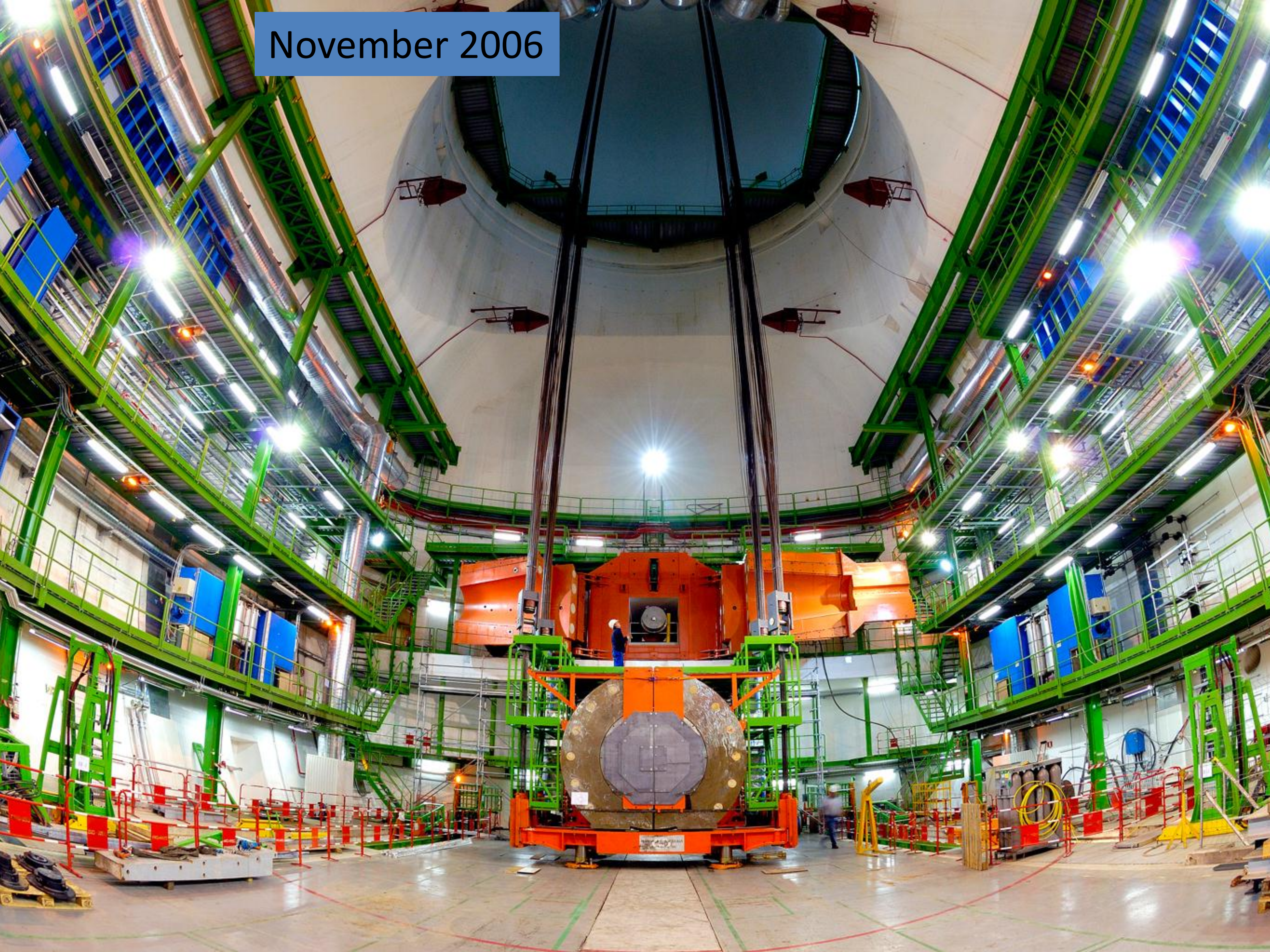


Conclusions

- The CMS experiment used over 5/fb of pp collisions delivered in 2011 by the LHC at 7 TeV cm energy for a large number of physics measurements and searches
  - The new limits on rare B meson decays strongly constrain the parameter space of SUSY models
  - the Higgs boson has been sought in 8 different final states (for a total of 42 independent sub-channels)
    - **Excluded mass hypotheses from 127 GeV to 600 GeV at 95% CL**
    - Observed slight excesses at low mass (119-125 GeV) not significant but compatible with signal hypothesis
  - Electroweak measurements provide precision probes of the SM in 7 TeV collisions
  - A new hadron resonance, the Ξ_b^*, has been discovered by CMS
  - Large swaths of SUSY parameter space have been excluded by inclusive and exclusive searches
  - Produced limits on Large Extra Dimensions, new resonances, and other exotica models vastly improve over previous knowledge
- The LHC physics program is continuing in 2012 with the goal of tripling the 2011 data at 8 TeV
  - This will give the final word on the existence of a light Higgs boson
  - Expect to soon reach the sensitivity to SM $B_S \rightarrow \mu\mu$ production

BACKUP

- 1994: LHC project approved
- 1999: CMS MoU signed
- 2004: The CMS Cavern is read
- 2009: First Physics !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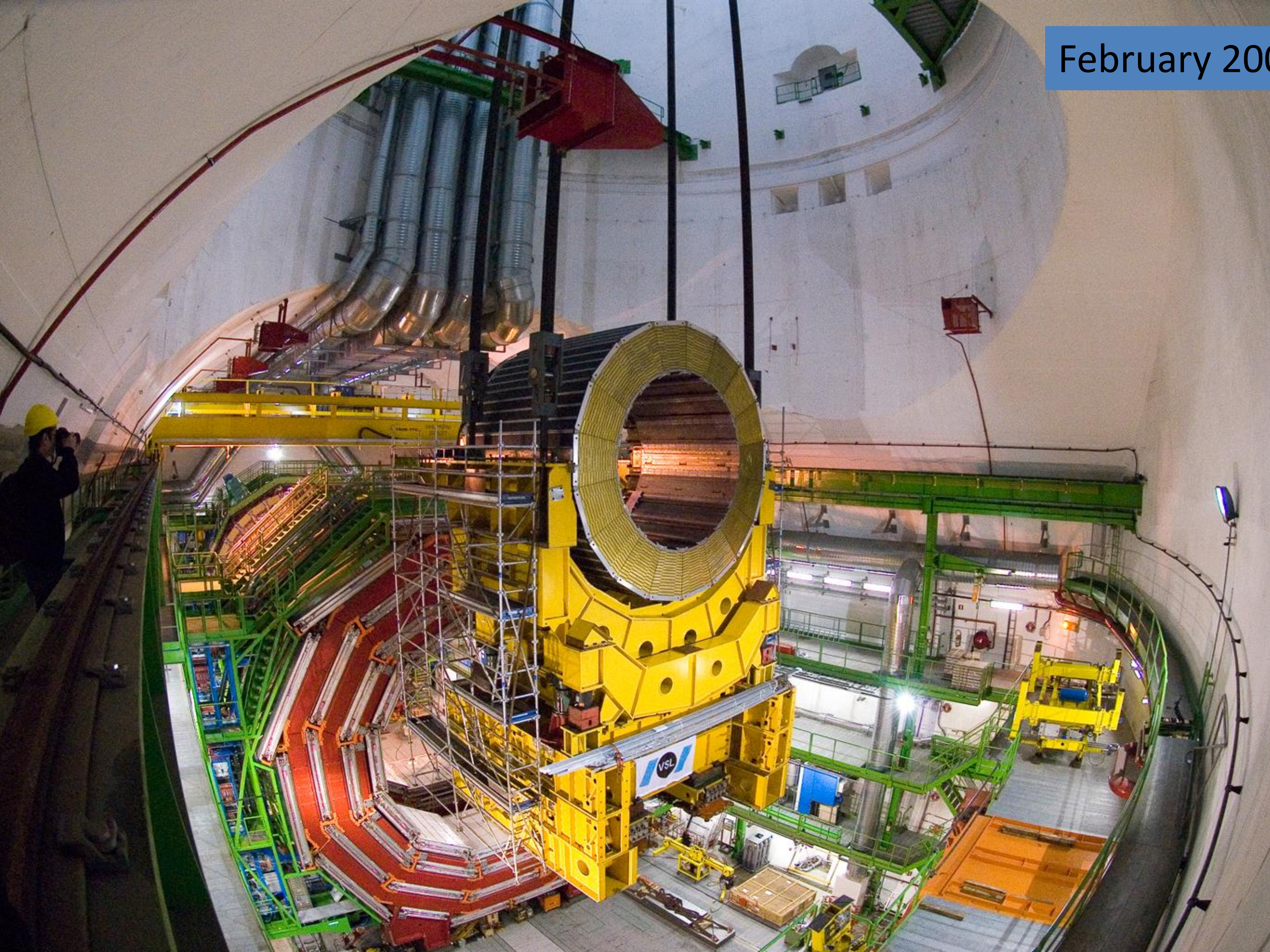

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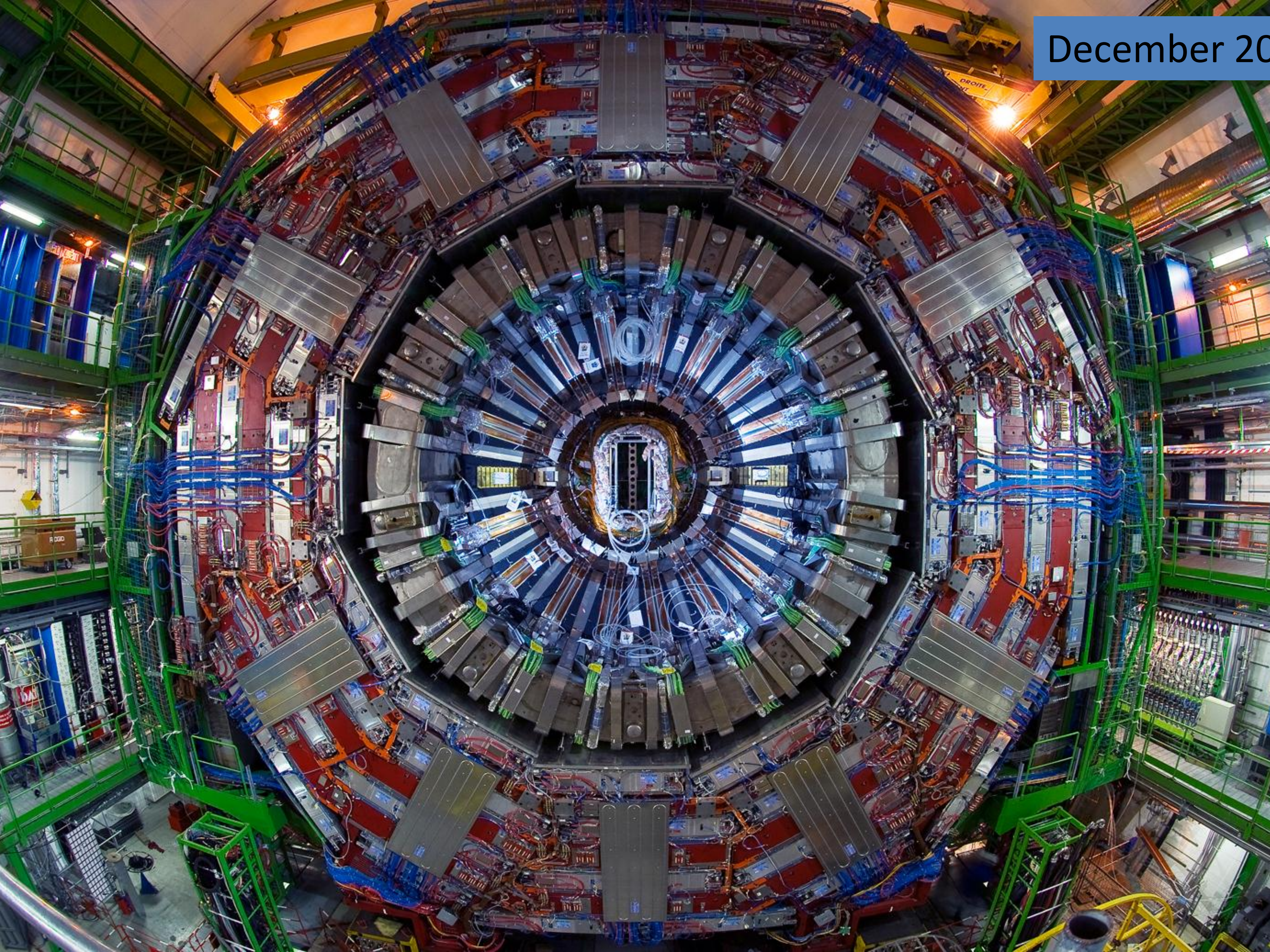
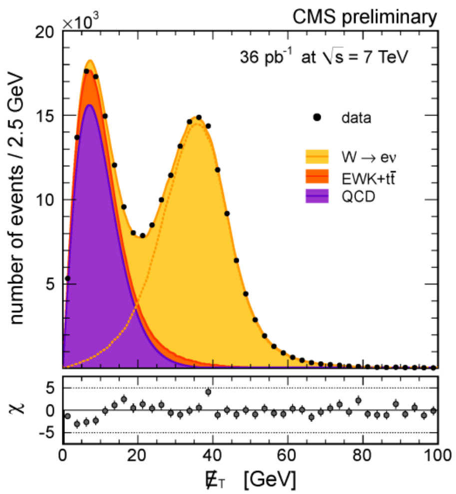
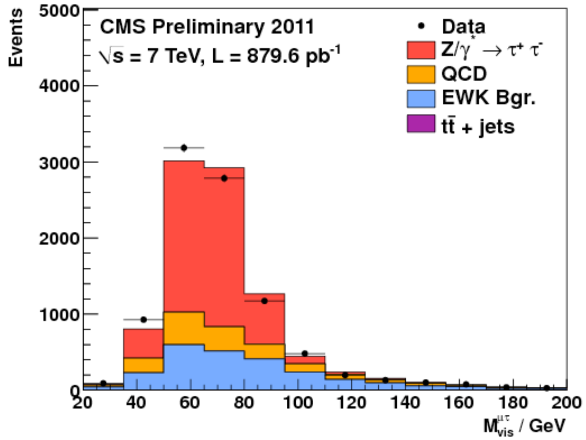
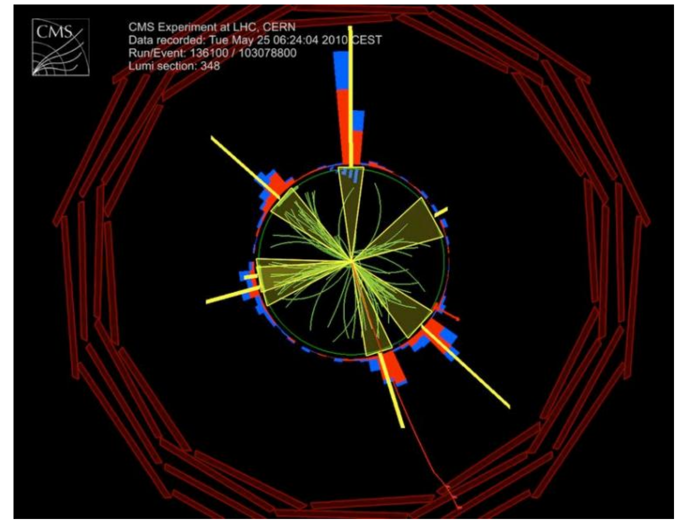


Physics Objects Reconstruction





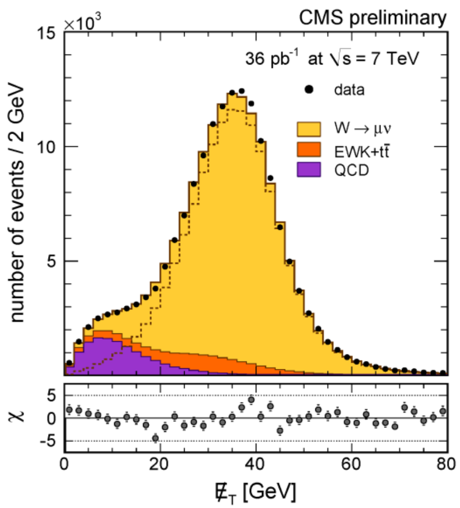
Jets are reconstructed with anti-kT clustering and corrected with Particle-flow algorithm

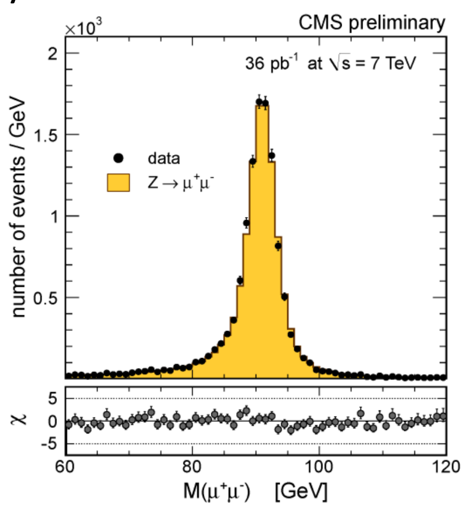


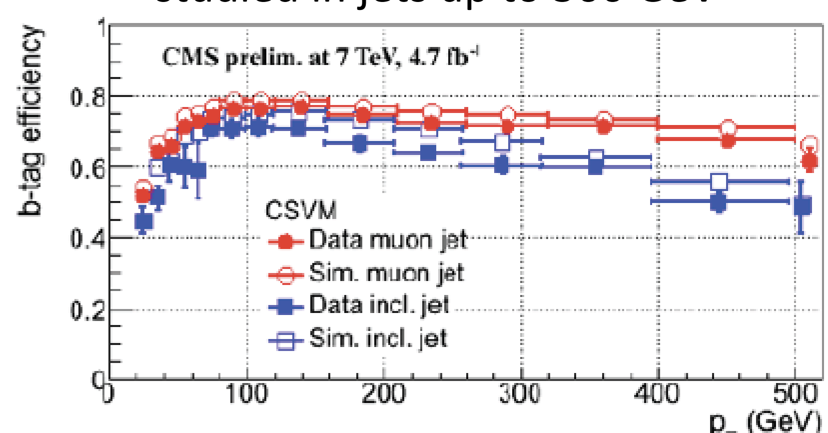
W and Z decays to leptons provide calibration of the reconstruction of electrons, muons, taus, and missing energy from neutrinos

Tag-and-probe techniques using Z decays allow to reduce systematics on efficiency estimates

B-tagging well understood – studied in jets up to 500 GeV





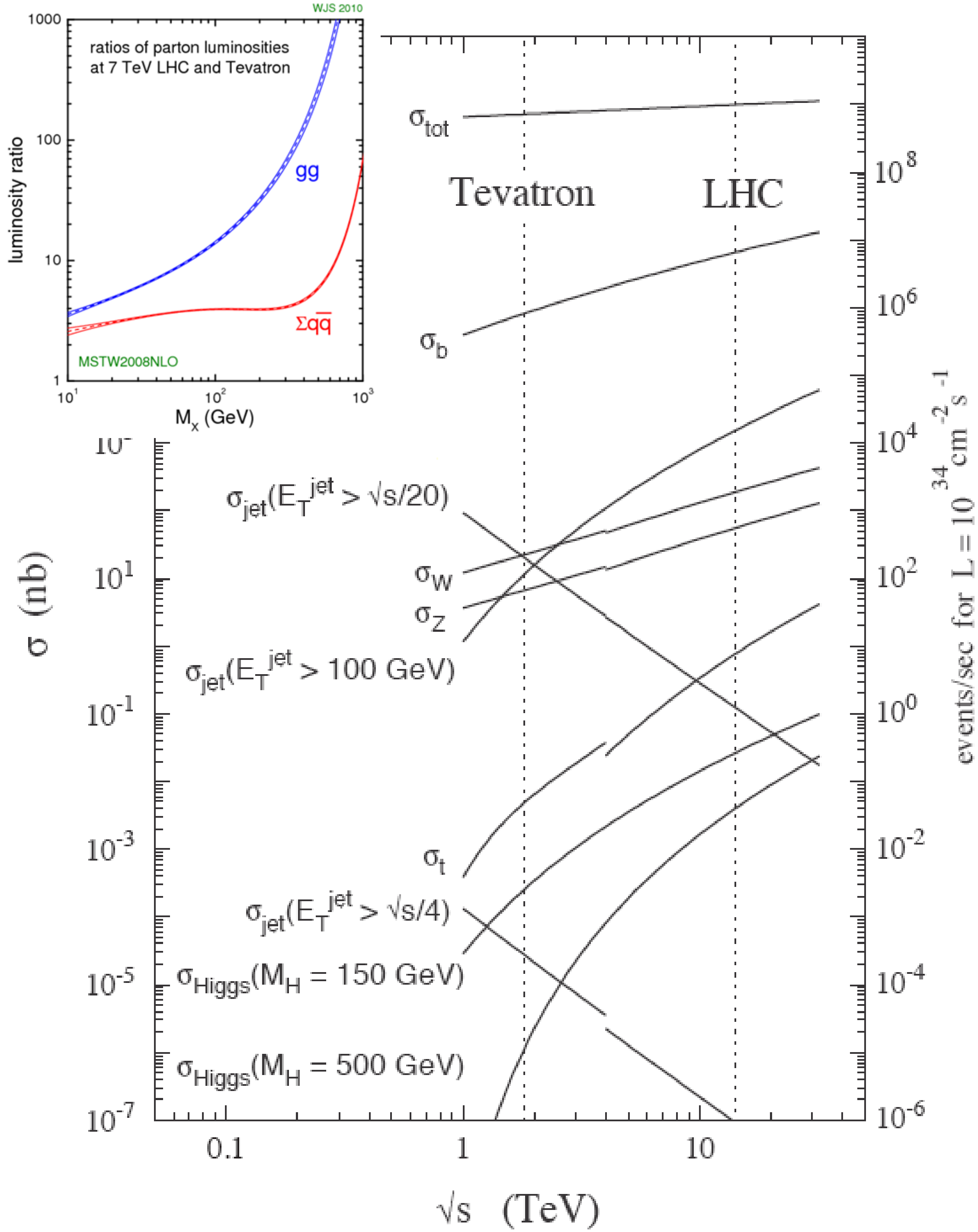


Cross Sections at a glance

The increase in centre-of-mass energy causes all cross sections to grow

Rare, high-energy phenomena grow faster
- e.g. top quark pair production: x25 WRT Tevatron

Some backgrounds also grow bigger and nastier, e.g.
- b cross section grows by x10
- large growth in jet and multijet cross sections



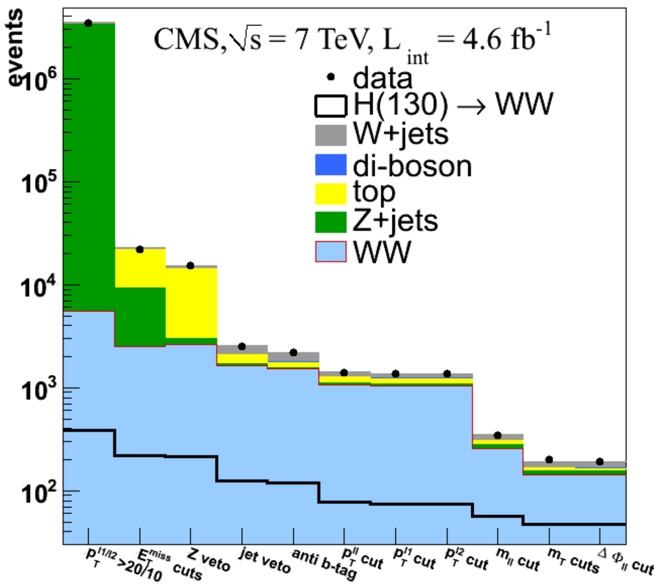
Sample Searches: H→WW

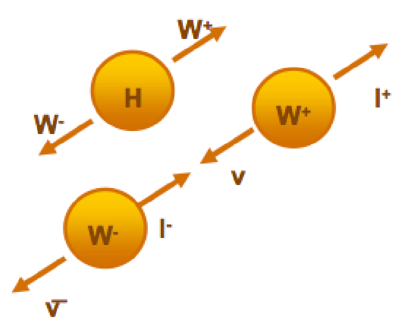
- The WW channel is the one with highest rate for masses around $2M_W$
- Backgrounds are essentially due to SM WW production
- Mass resolution is poor → use kinematics to discriminate from irreducible backgrounds
  - Use zero spin of H → charged leptons correlated in azimuth
  - Anti-btag /SL veto to remove top-pair background; veto Z-peak candidates
  - Classify by jet multiplicity (sensitive to VBF topologies)
  - Classify by lepton flavor (DY contributes more to OF)

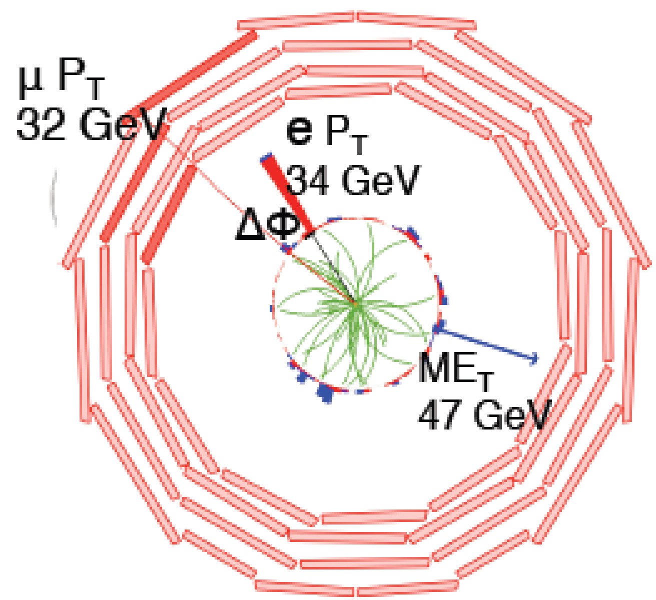
Two strategies:

- Counting experiment: five categories (N_j=0, SF/OF; N_j=1, SF/OF; N_j=2)
- BDT classifier (ignores low-sensitivity N_j=2 category)

Most backgrounds estimated with data (except WZ,ZZ, high-mass WW)

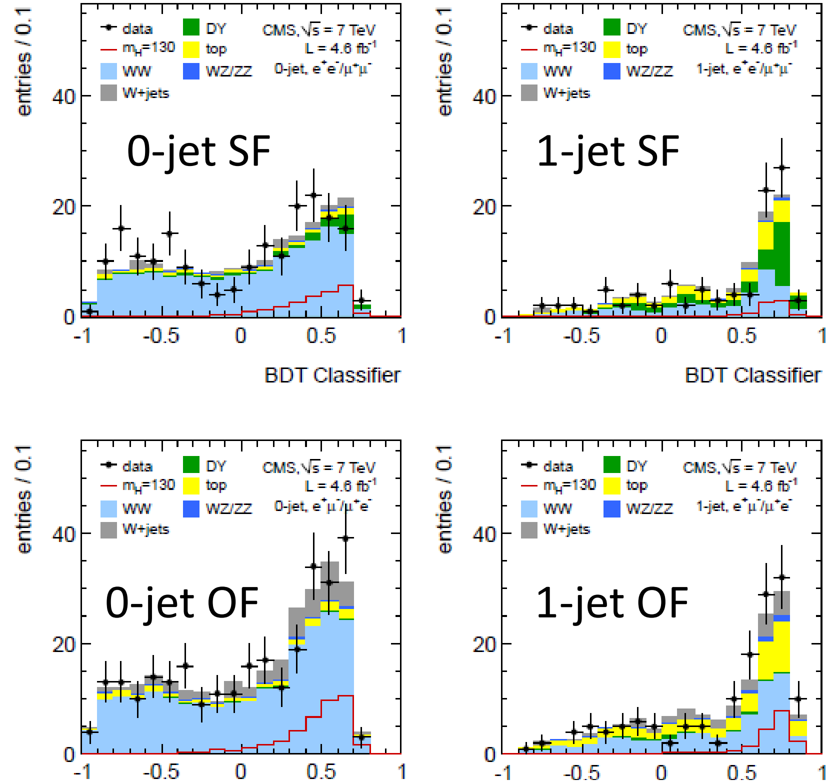


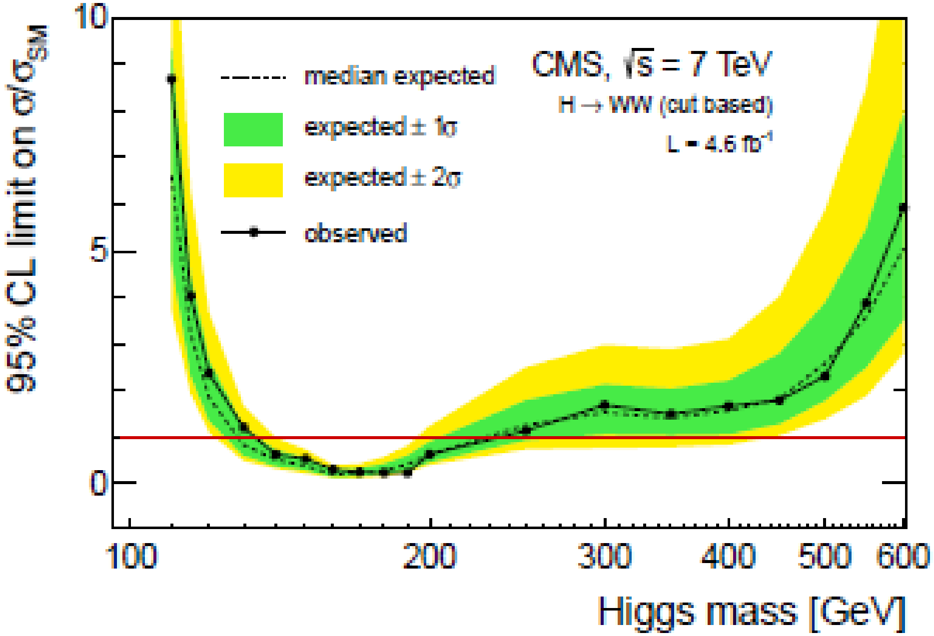


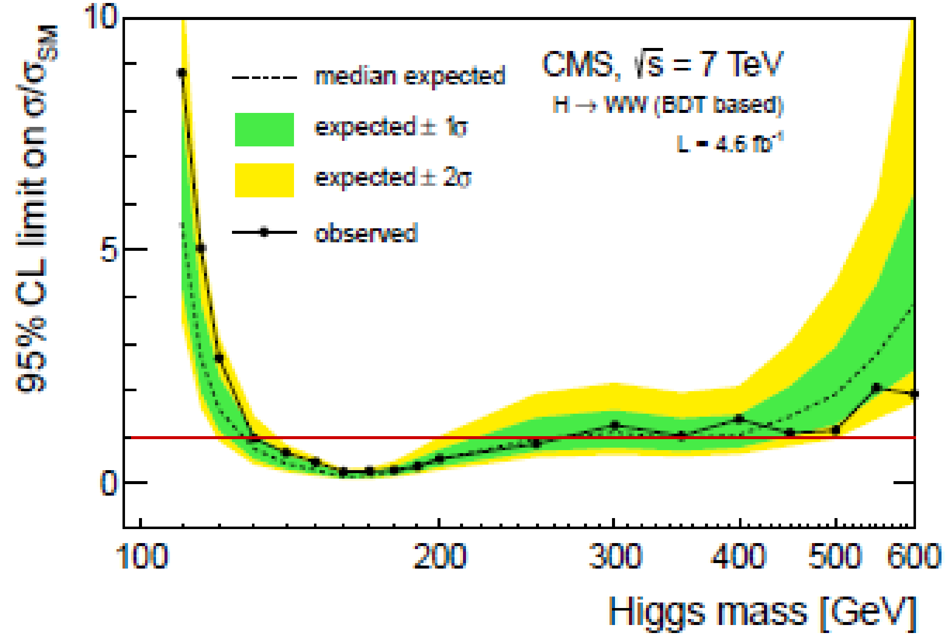


H→WW results

- Division in categories allows to tailor selection to the different characteristics of signal wrt background – e.g. ME_T criteria are optimized class by class
- Further cuts are optimized differently for each mass point
- The BDT method is found to be marginally more sensitive
- Backgrounds are well modeled in all categories; most are estimated from the data in control samples
- Upper 95% CL limits: $132<M_H<238$ GeV (cut-based), $128<M_H<300$ GeV (BDT)

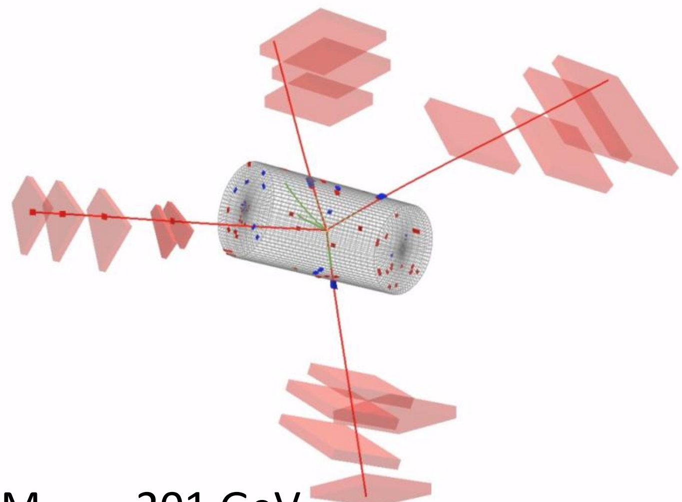




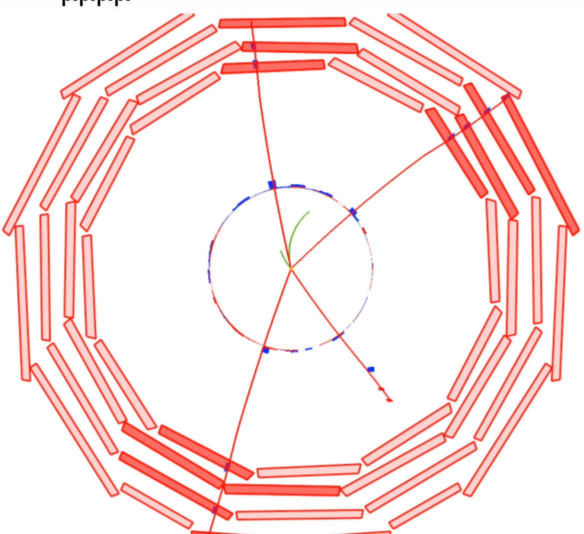


H→ZZ→4 leptons: the golden channel

This search is discussed in M.Meneghelli's parallel session talk in more detail.



$M_{\mu\mu\mu\mu}$=201 GeV



The four-lepton final state is one of the two targets driving the design of CMS

We can study high-mass Higgs production with excellent mass resolution

We can also search for M<180 GeV when one Z is off-mass shell → very significant sensitivity down to 110 GeV!

Three topologies: 4e, 4μ, 2e2μ

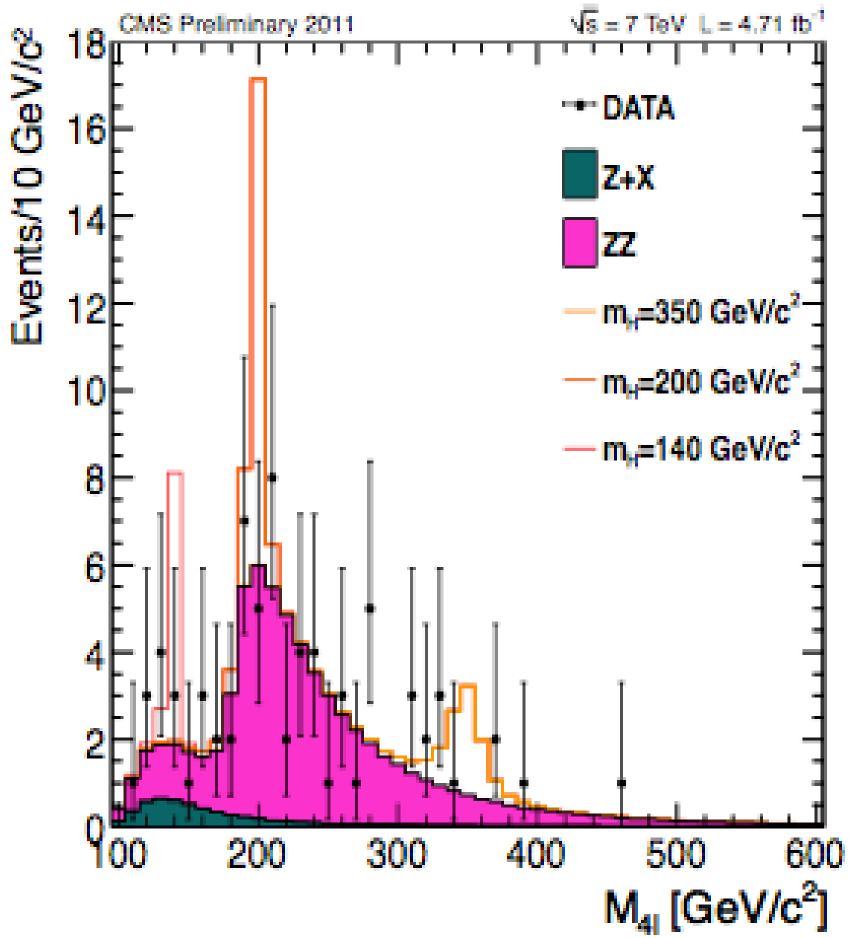
Only require well-identified, isolated leptons

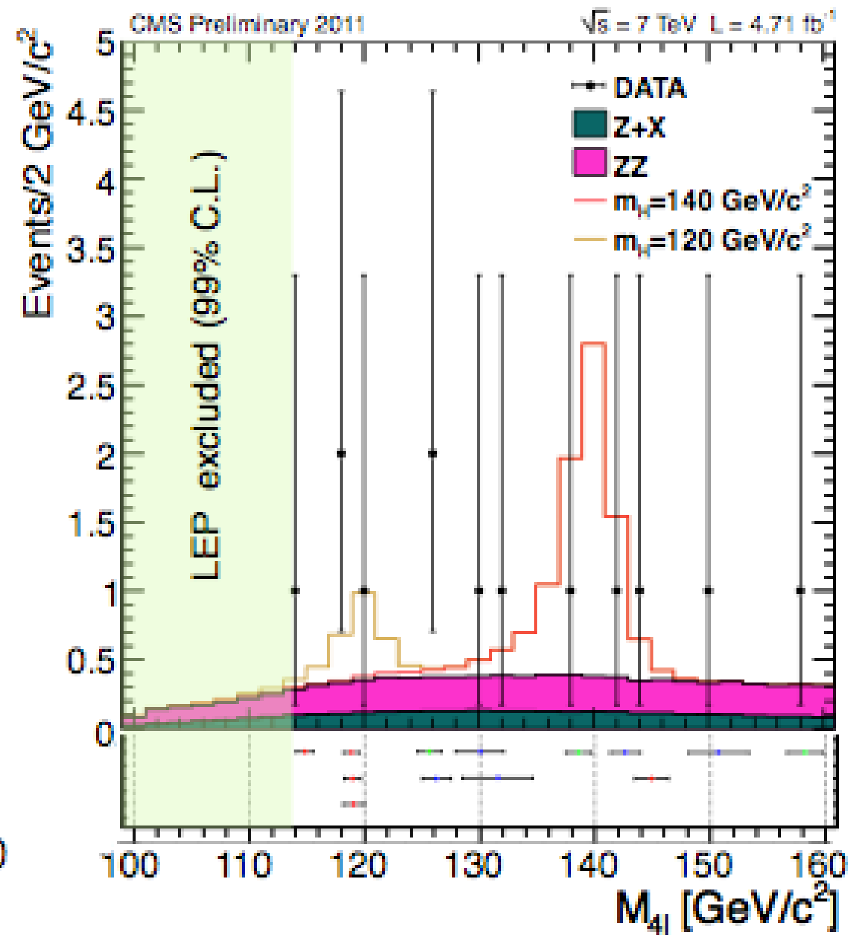
Baseline	$4e$	4μ	$2e2\mu$
ZZ	12.27 ± 1.16	19.11 ± 1.75	30.25 ± 2.78
Z+X	1.67 ± 0.55	1.13 ± 0.55	2.71 ± 0.96
All background	13.94 ± 1.28	20.24 ± 1.83	32.96 ± 2.94
$m_H = 120\ \mathrm{GeV}/c^2$	0.25	0.62	0.68
$m_H = 140\ \mathrm{GeV}/c^2$	1.32	2.48	3.37
$m_H = 350\ \mathrm{GeV}/c^2$	1.95	2.61	4.64
Observed	12	23	37

CMS collectively observes 72 events, expects 67.1 from known backgrounds (ZZ, Z+bb)

Mass distributions

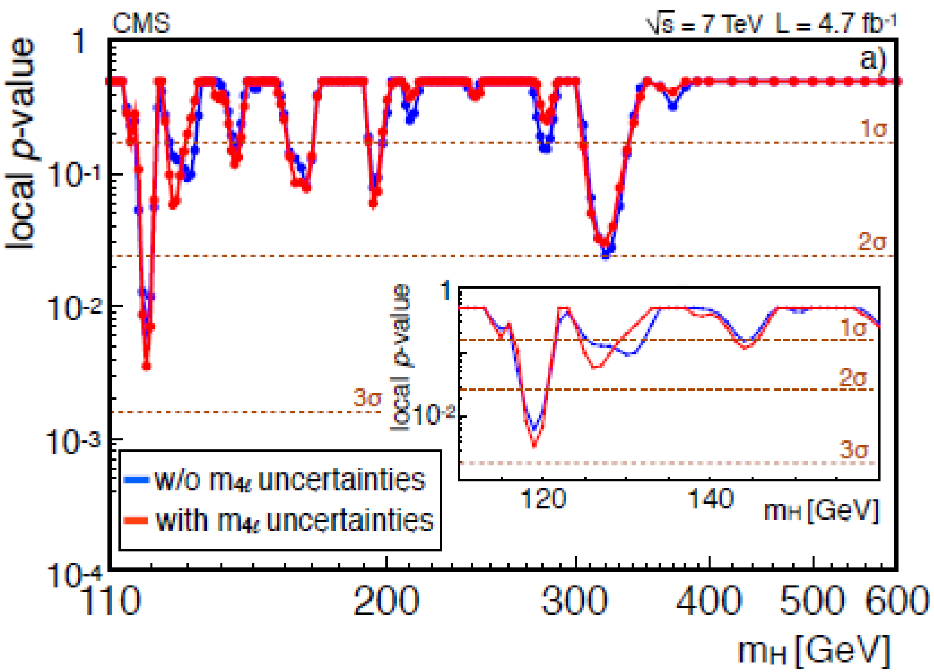
- The search exploits the fine mass resolution of the 4l final state
- At low mass O(few) event signals are expected. CMS observes 13, expects 9.5+-1.3 in [100,160] GeV region
- Three 4μ events are seen with mass around 119 GeV, two more at 126 GeV

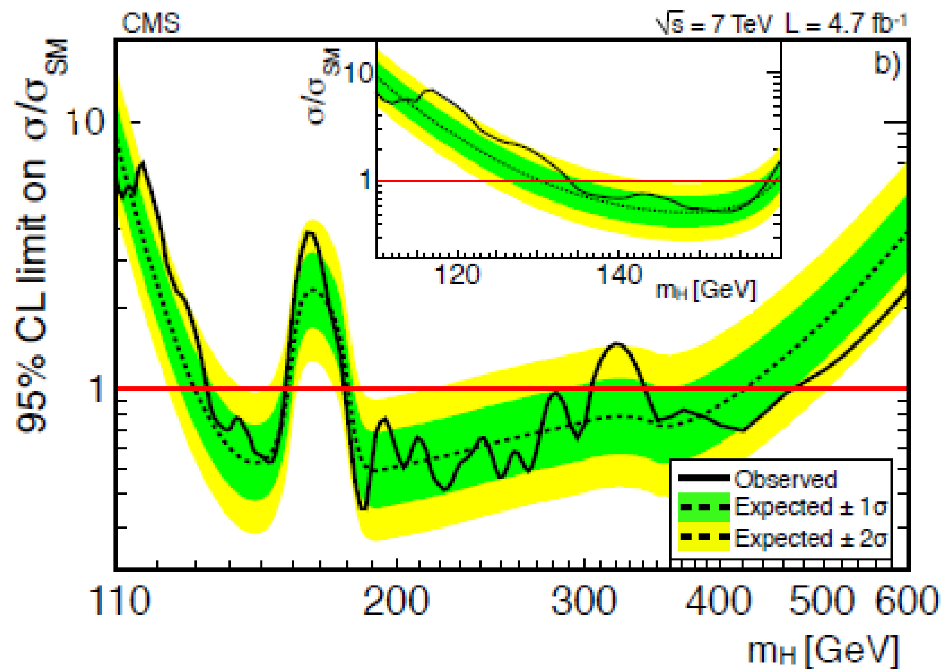




H→ZZ→4l results

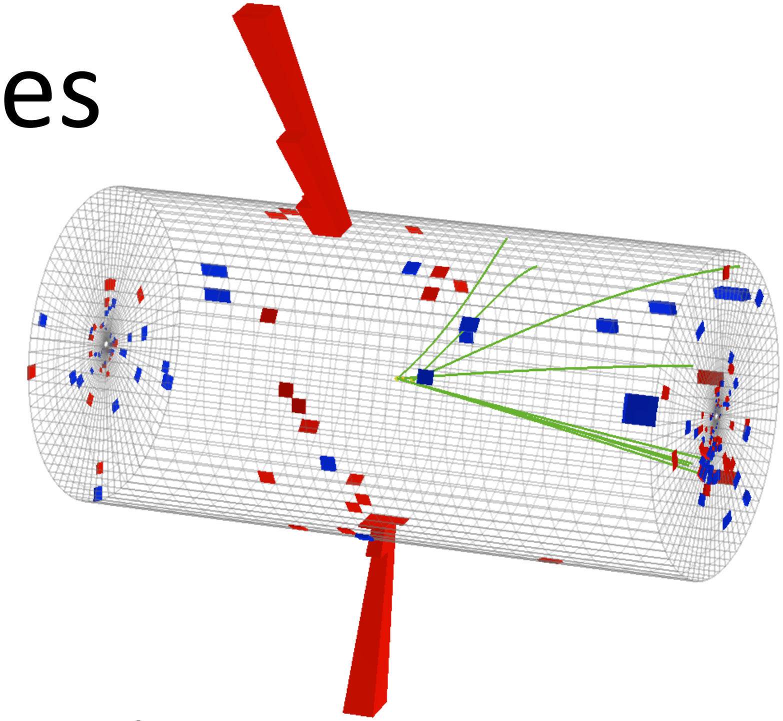
- The ZZ→4l channel alone allows to exclude most of the M_H>180 GeV region at 95%CL:
  - Expected exclusion: 130 < M_H < 160 GeV; 182 < M_H < 420 GeV
  - Observed exclusion: 134 < M_H < 158 GeV; 180 < M_H < 305 GeV; 340 < M_H < 465 GeV
- The *local* p-value of background-only hypothesis show a 2.7σ dip at 119 GeV, a smaller 1.5σ dip at 125 GeV





8 - H→γγ searches

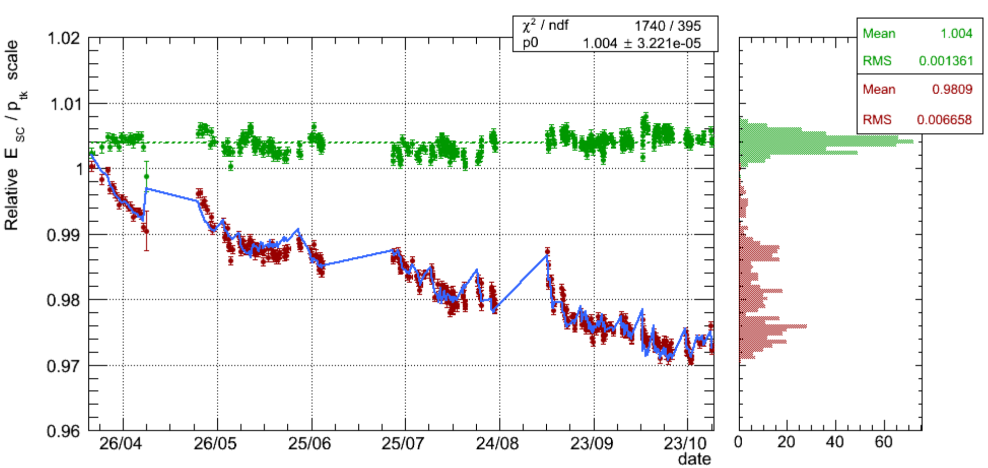
The signal of H→γγ decays is a pair of isolated photons with little additional energetic activity

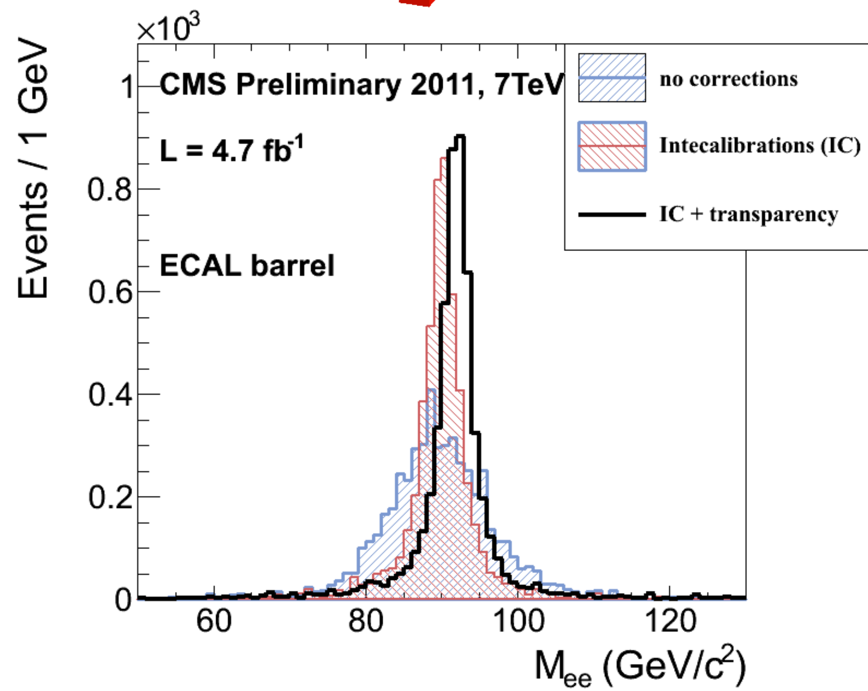


The electromagnetic calorimeter plays a crucial role in the search

Energy resolution and scale studies are made with Z→ee, W→eν, π^0 and E/p as well as laser signals for transparency corrections.

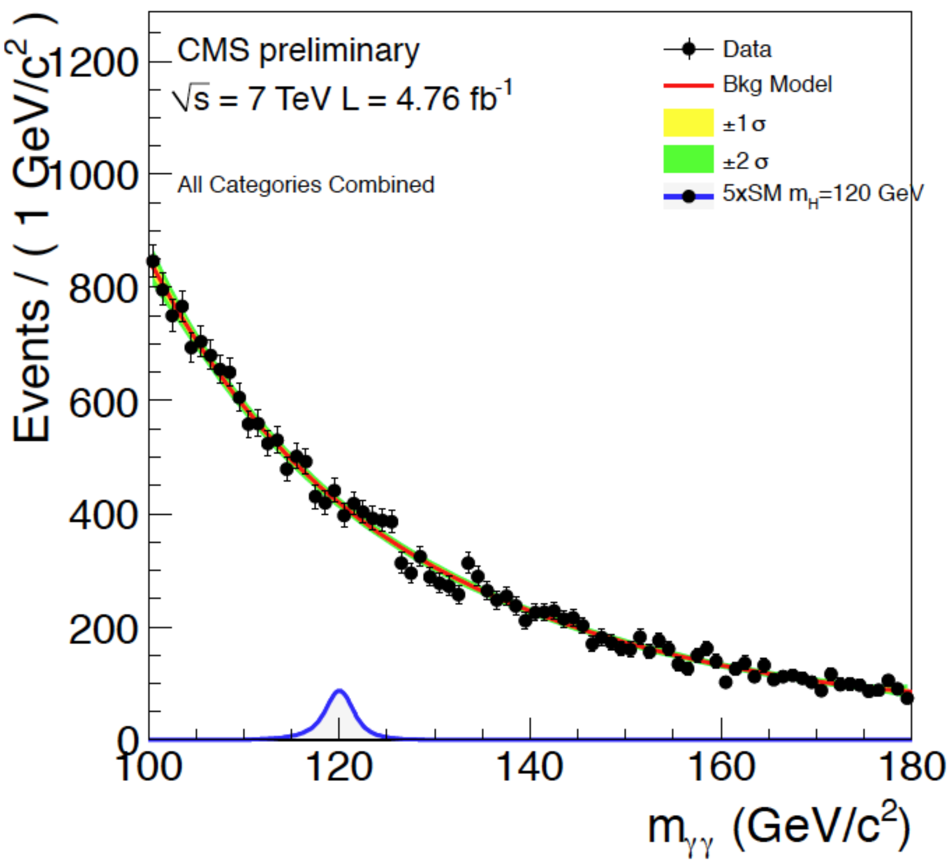
After corrections, the energy scale is stable to a 0.1% level in 2011.





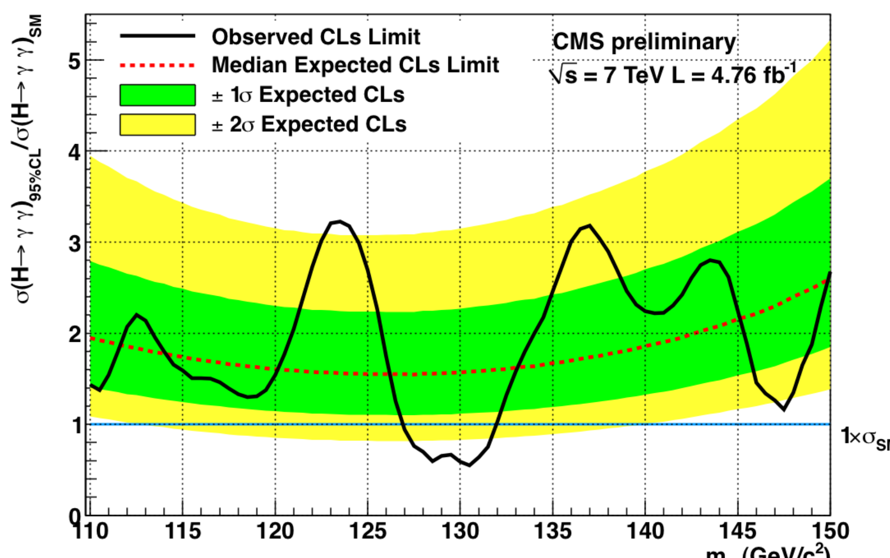
Mass distribution and limit

- Events are classified according to the way photons are detected, to exploit the different resolutions and background contaminations
- Each category is fit separately and results are then combined. Shown below is the total dataset for illustrative purpose only



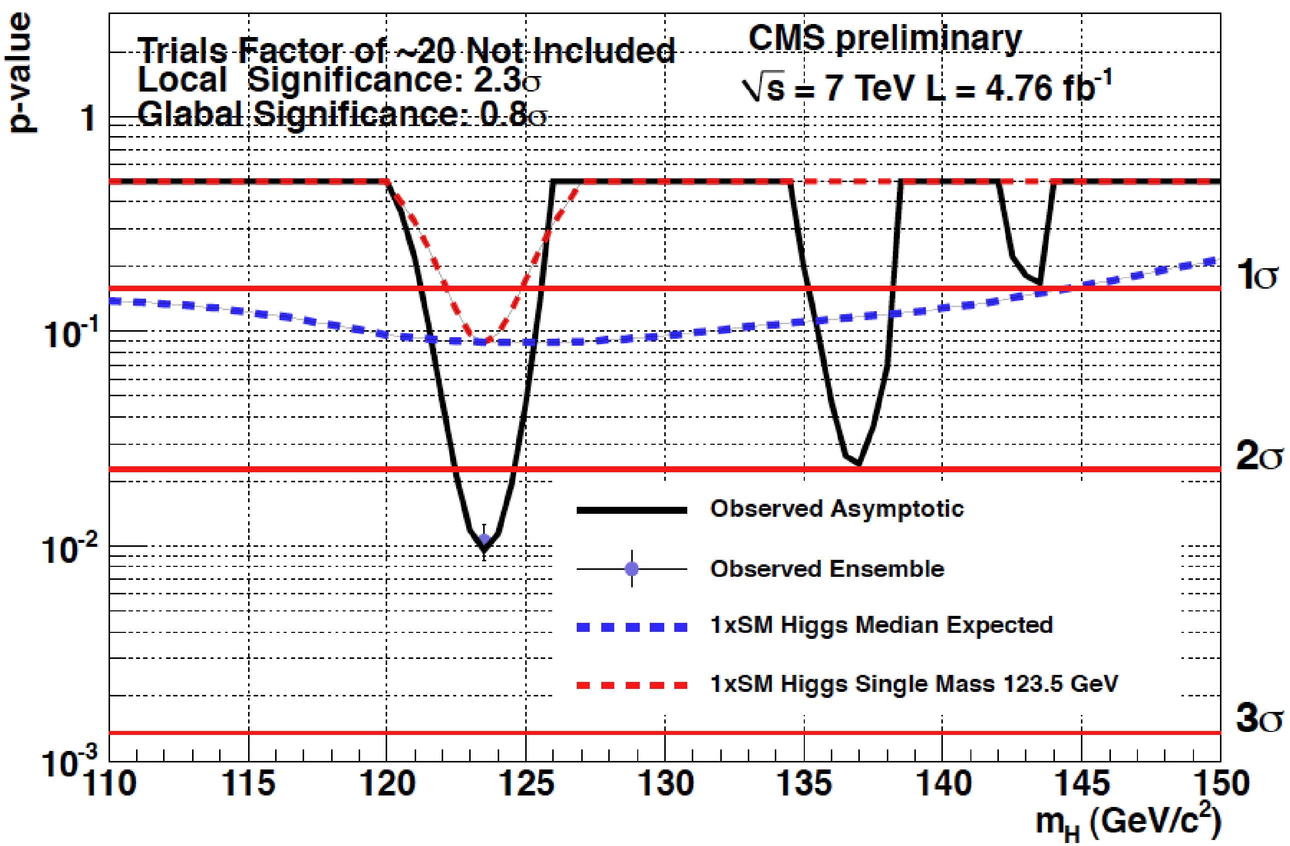
The resulting observed upper limit shows a 2-sigma fluctuation at 124 GeV

Quantified in next slide



H→γγ p-value

- Probability of 124-GeV fluctuation in γγ final state can be quantified at the 1% level
- Accounting for LEE trials factor this is not significant



Observation of Z→4l decays

As a "sideline" of the search for H→ZZ decays, the four-lepton final state provides a chance to observe the peculiar decay of a single Z boson to four leptons.

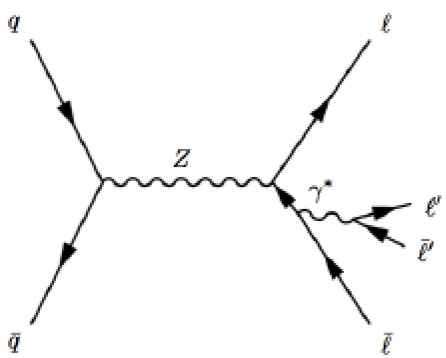
Note: the (4e), (4μ),and (2e2μ) final states are not in a 1:1:2 proportion for this decay as would happen to uncorrelated pairs, due to additional Feynman diagrams contributing to the same-flavour final states

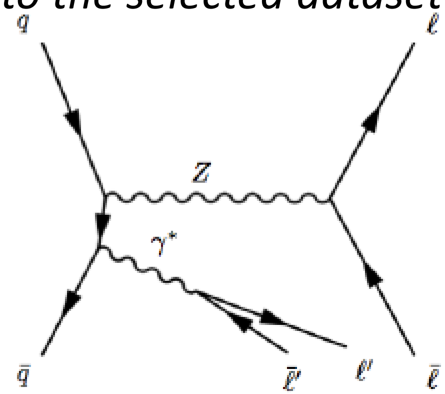
CMS observes a large peak (8.9σ significance) due to the radiative decay

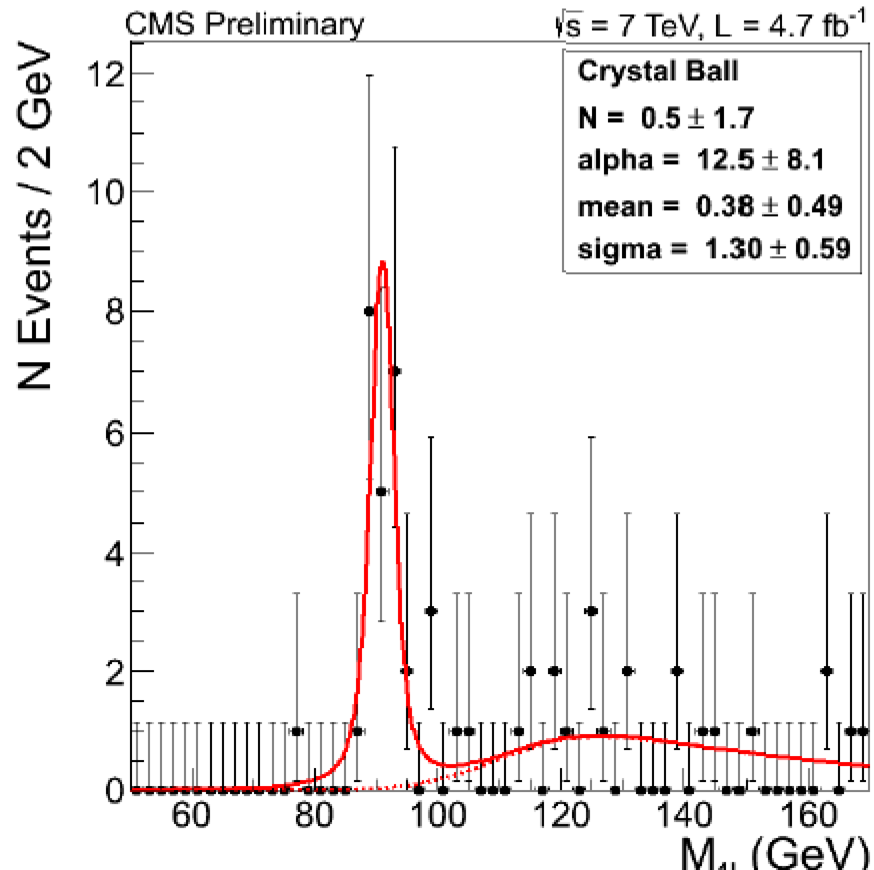
The branching ratio B(Z→4l) is measured at

$B = (4.4^{+1.0}_{-0.8} \pm 0.2)\ 10^{-6}$

Below: signal (left) and background (right) processes contributing to the selected dataset







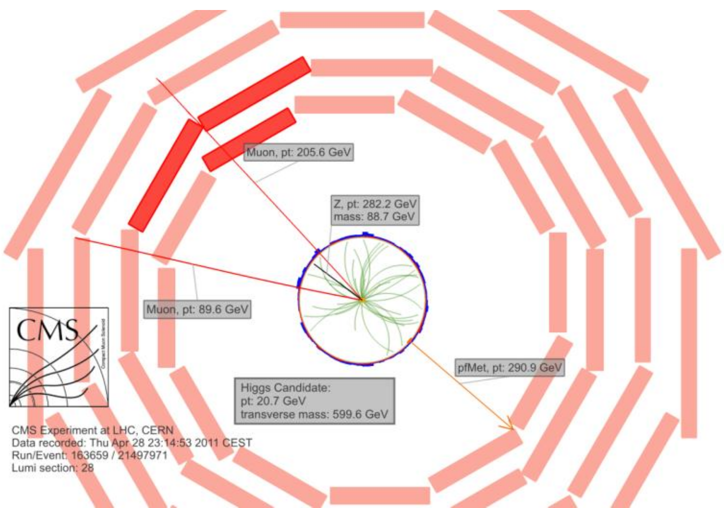
2 – H→ZZ→llνν

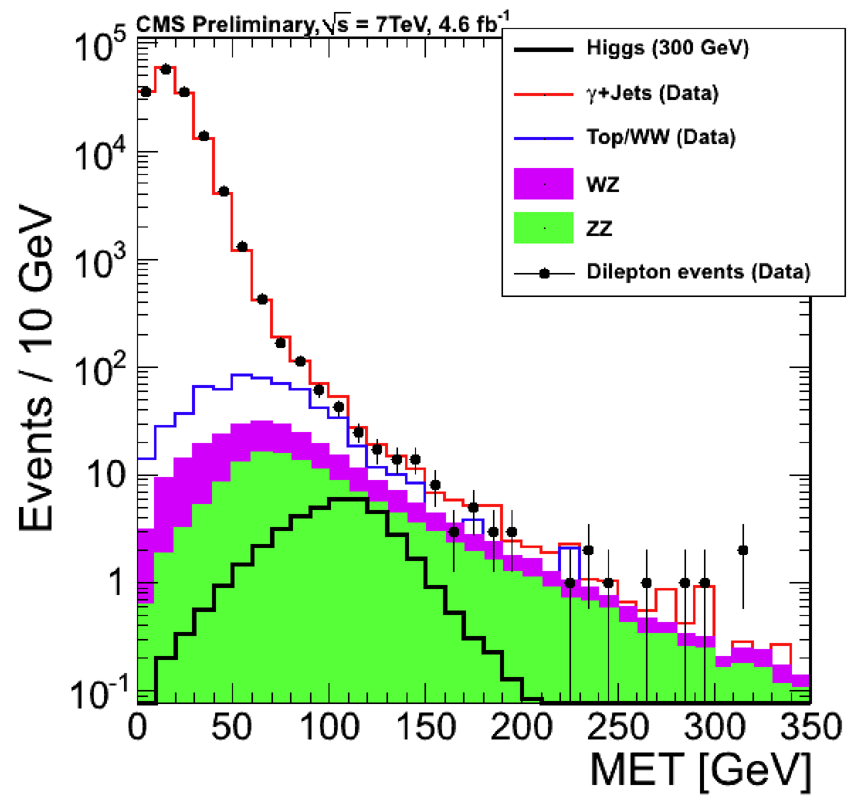
- The final state including a Z→ll signal and large missing transverse energy is hard to mimic by backgrounds. Main contributions: Z+jets, tt, WZ/ZZ SM production
- Compute a “transverse mass” (7% resolution) by assuming ME_T due to neutrinos:

$$M_T{}^2 = \left(\sqrt{P_{TZ}{}^2 + M_Z{}^2} + \sqrt{MET^2 + M_Z{}^2}\right)^2 - (\vec{P_{TZ}} + \vec{MET})^2$$

Two categories: Z→ee, Z→μμ; both a cut-based and a M_T-shape analysis are performed

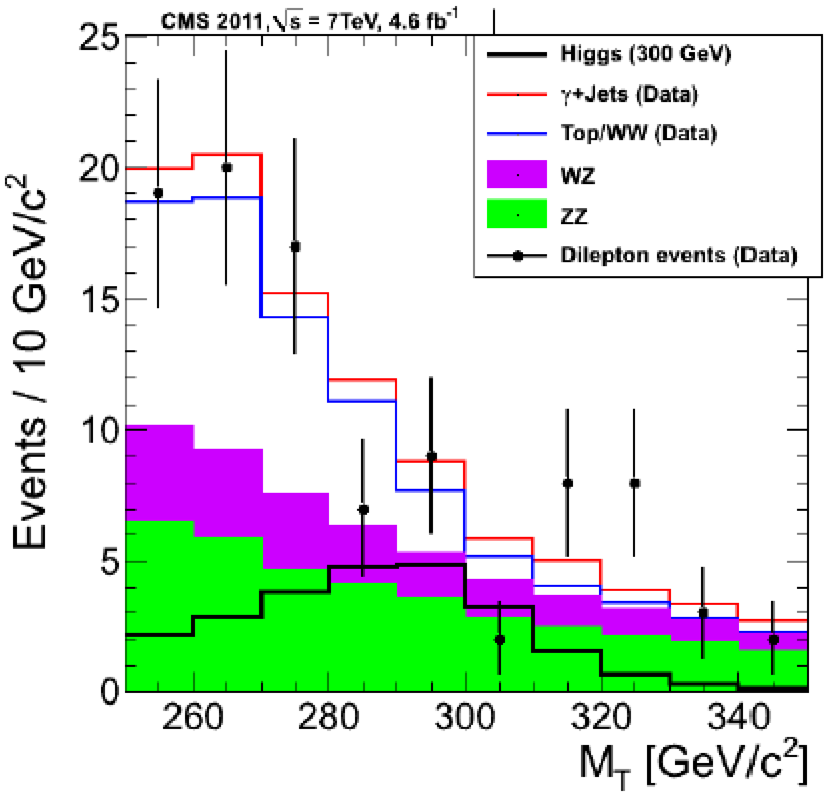
- Events are selected with a M_{ll} cut and $p_T{}^{ll} > 25$ GeV.
- Require large ME_T, not aligned with jets (ΔR>0.5) or leptons (>70->150 GeV cut-based, >80 GeV M_T shape) → reduce Z+jets by 10^5
- Anti-b-tag suppresses top production



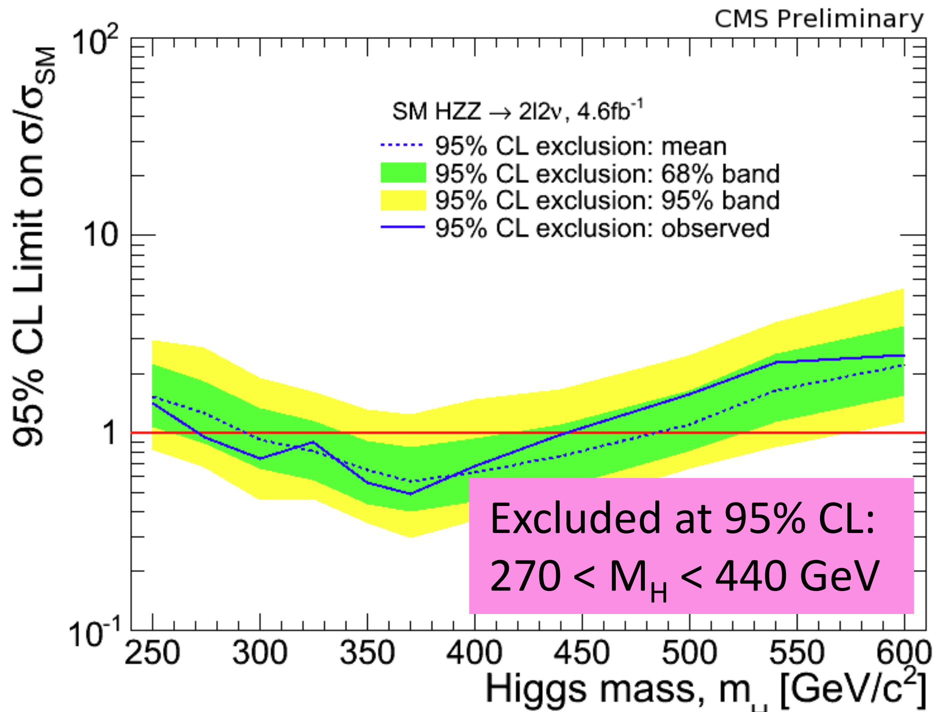


H→ZZ→llνν results

- The search has good sensitivity in the high-mass region, particularly for M_H>350 (where the expected limit is lower than that of the ZZ→4-lepton analysis, due to the larger branching fraction of the mixed decay)

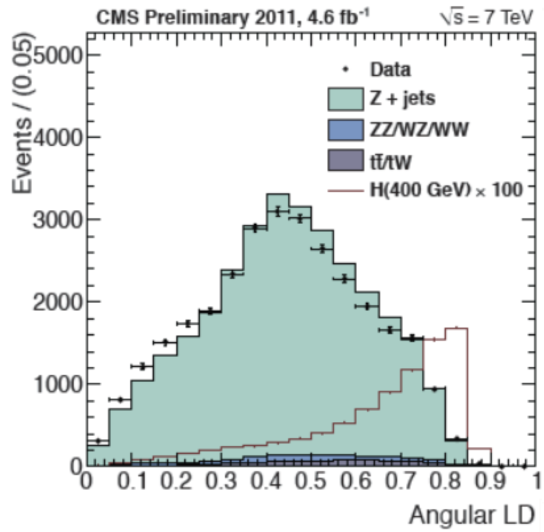


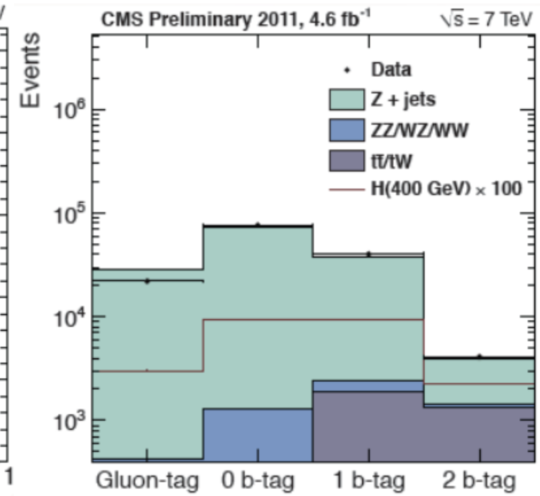
Transverse mass spectrum for events accepted by M_H=300 GeV selection

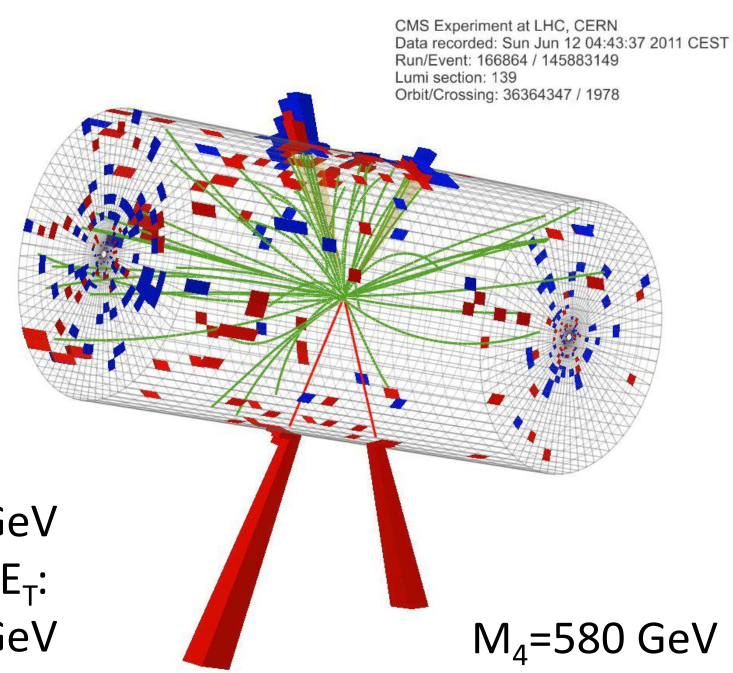


3 – H→ZZ→llqq search

- Less sensitive despite higher BR, because of huge Z+jets background
- 6 categories: Z→ee,μμ and 0,1,2 b-tags
- Good mass resolution (3%) thanks to Z-mass constraints
- To select the data, use an angular discriminant based on 5 production and decay angles
- Backgrounds mainly due to Z+jets, top production, and dibosons

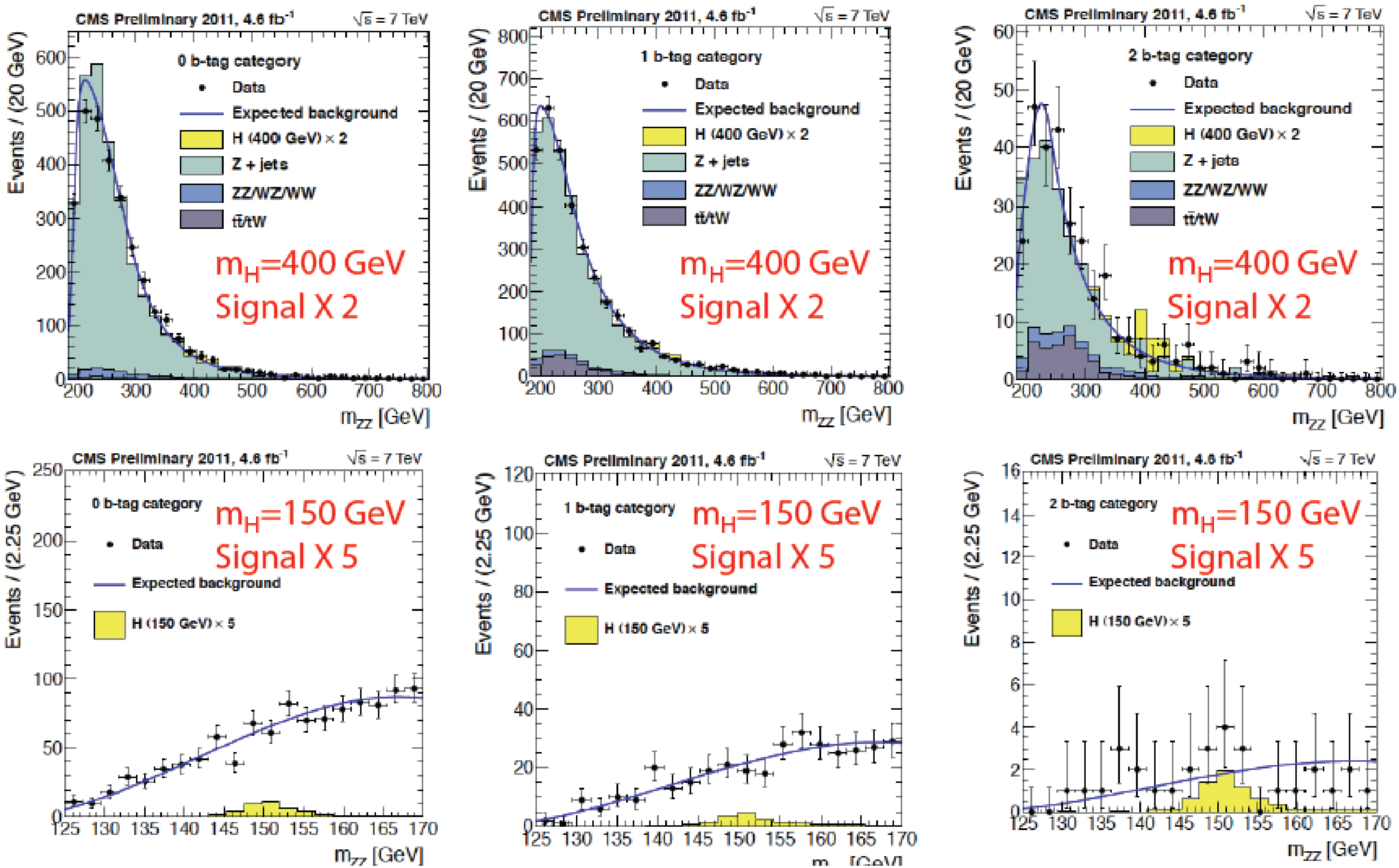




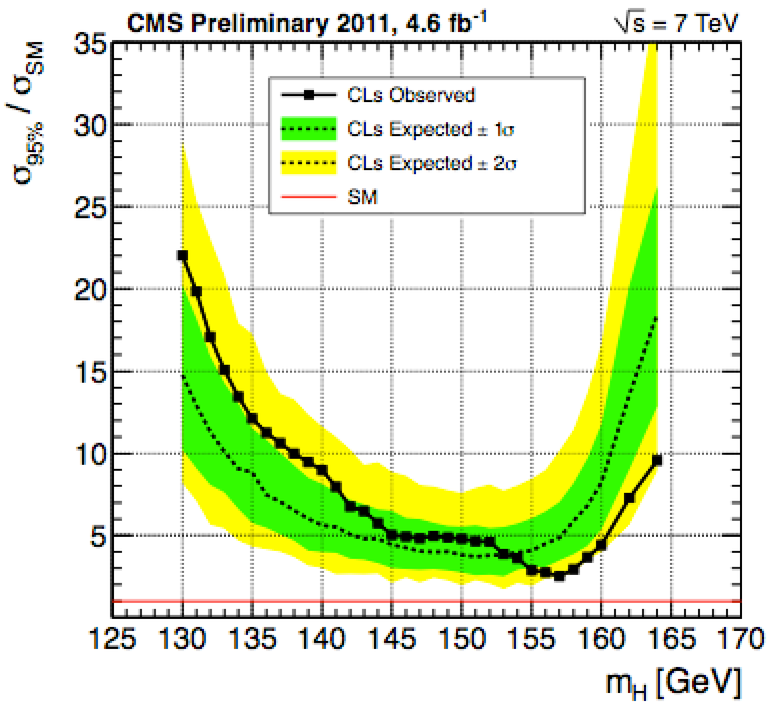


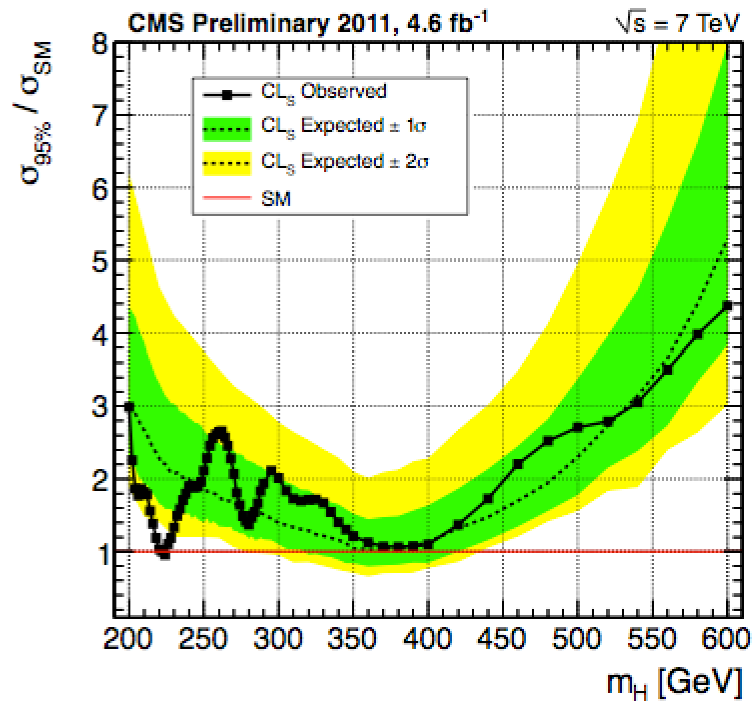
Jets E_T:
207,114 GeV
electrons E_T:
177,114 GeV

H→ZZ→llqq: mass distributions



H→ZZ→llqq Upper Limits

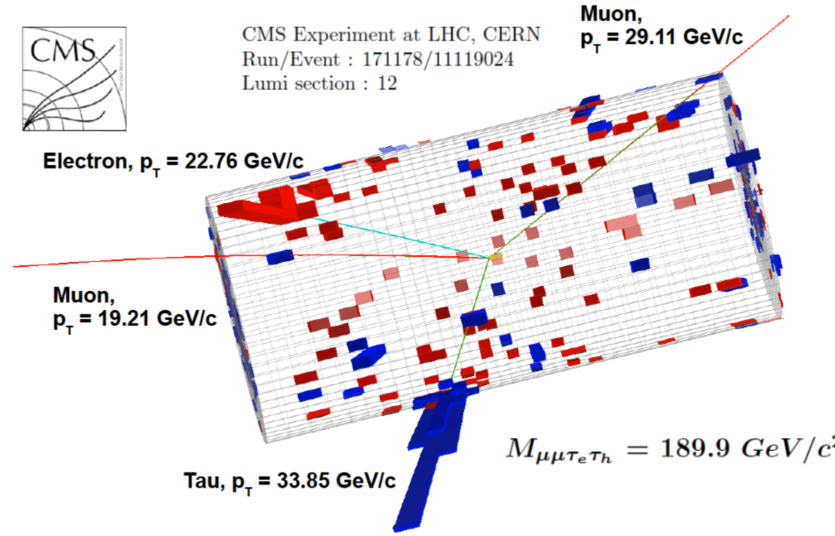


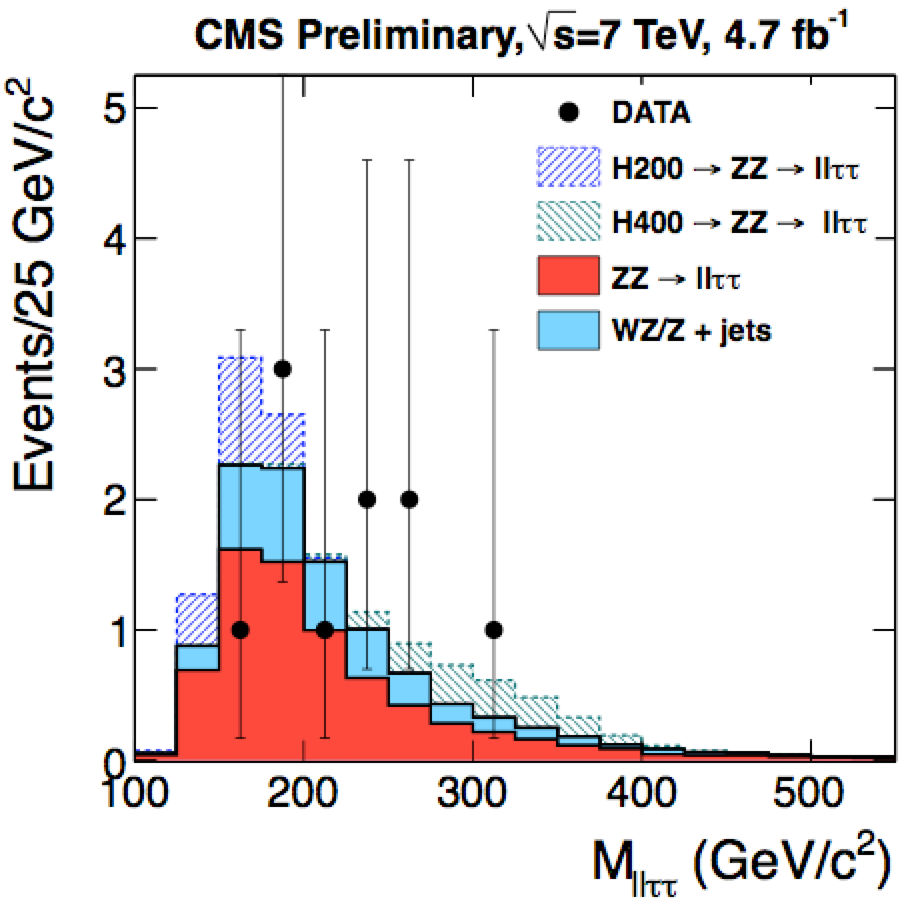


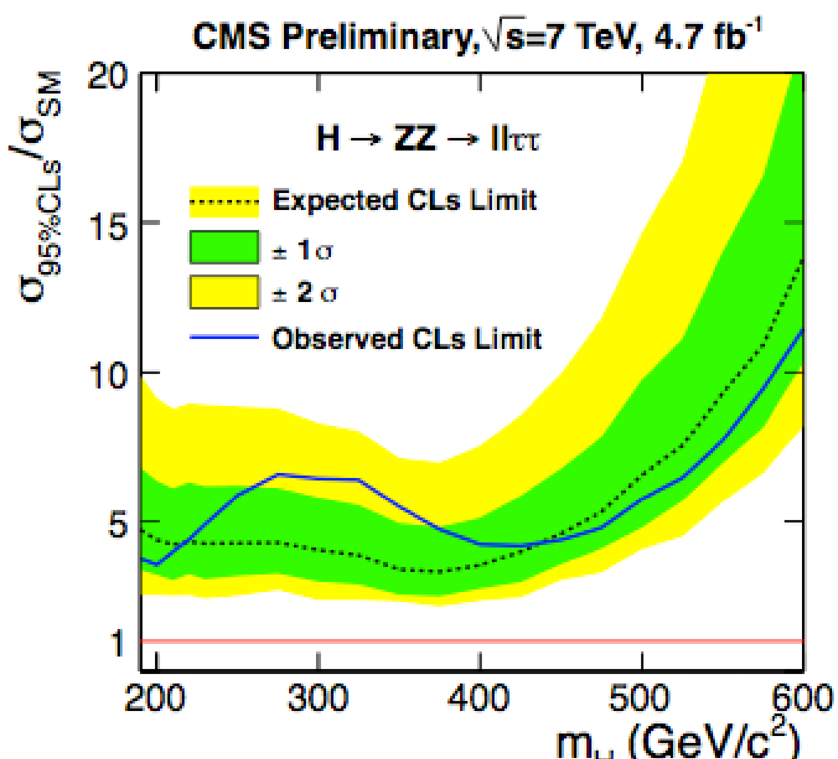
Results by themselves insensitive to SM Higgs with 5/fb – but help the combination, particularly at high mass

4 - H→ZZ→llττ

- Search only performed in high-mass region
- **10 observed events, 10.3 expected background**
  Background shapes are taken from MC simulation and normalized to the values obtained using data-driven techniques.

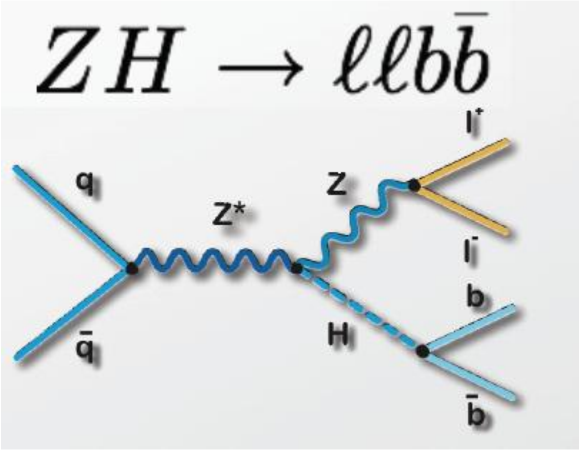






5 – H→bb search in Higgsstrahlung

- H→bb decay mode is impossible to extract from huge QCD background in the absence of other features
- Only searchable in association with vector boson (W,Z) – even then, at a disadvantage WRT Tevatron due to large increase in V+jet background



- Use back-to-back topology: $\Delta\phi_{VH}>3$, large boost (p_T^V>100-160 GeV)
- Tight b-tagging, ME_T cut
- Search in 5 sub-channels: Z→ee, μμ; W→eν, μν; Z→νν
- Backgrounds estimated from control regions

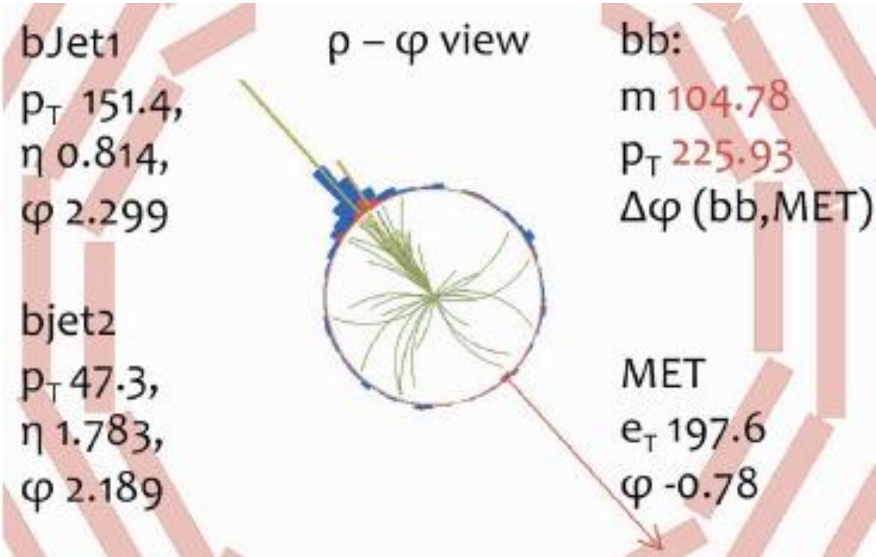
  Vbb: estimated from data

  V+jets: from data, inverting b-tag requirement

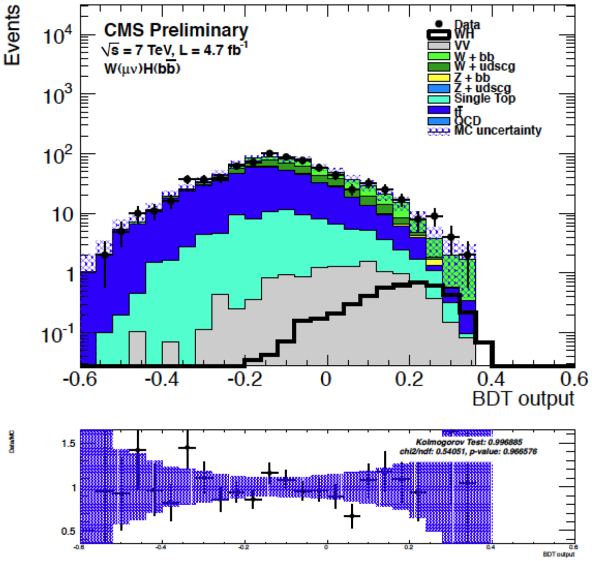
  top pairs: from data, requiring extra jet

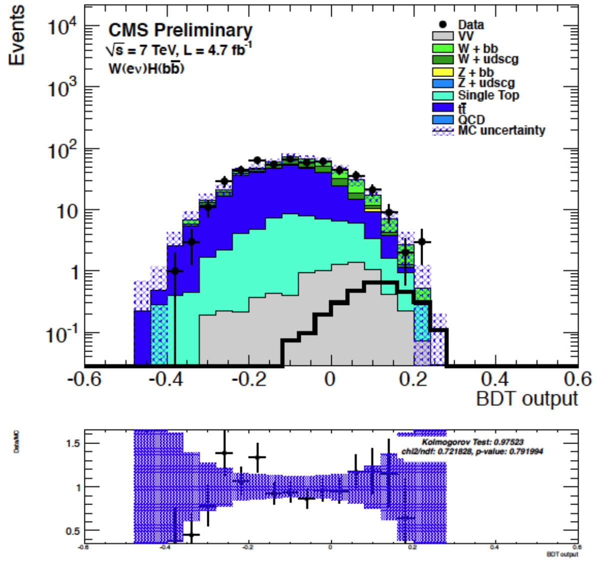
  QCD: from data, requiring small $\Delta\varphi$ (ME_T, j)

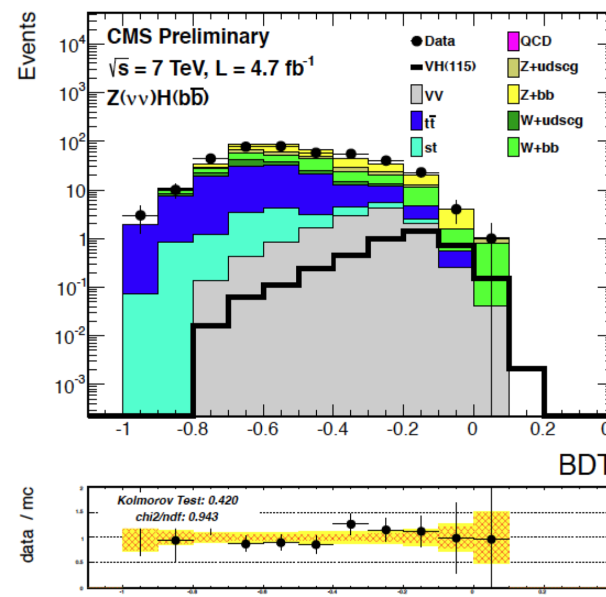
  W+Z(bb) and Z+Z(bb): estimated from MC
- The dijet mass resolution is 10%

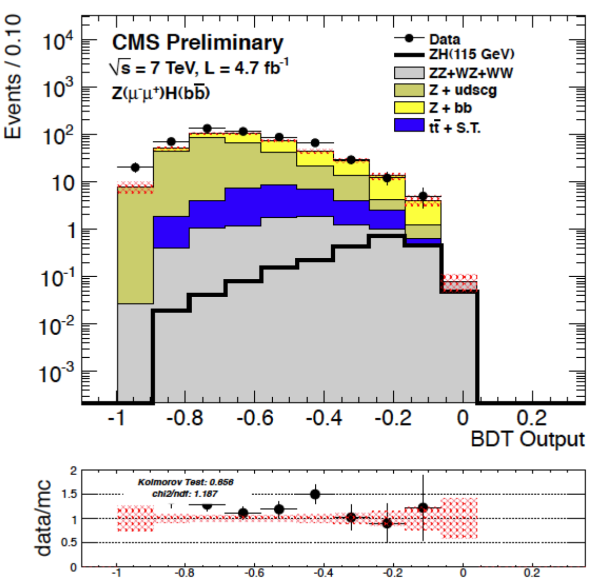


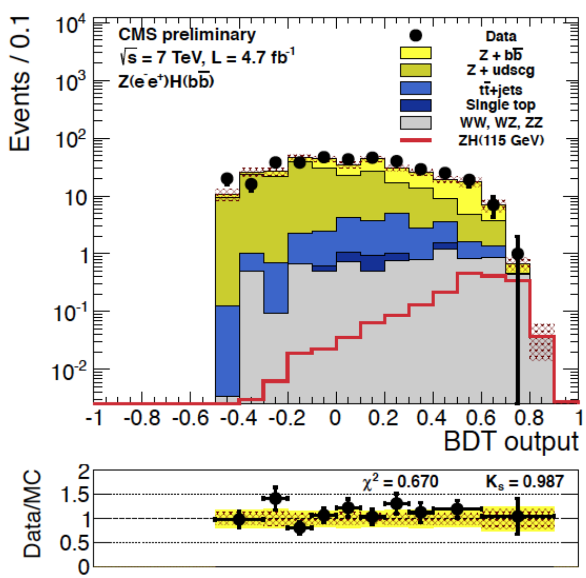
WH,ZH BDT Distributions





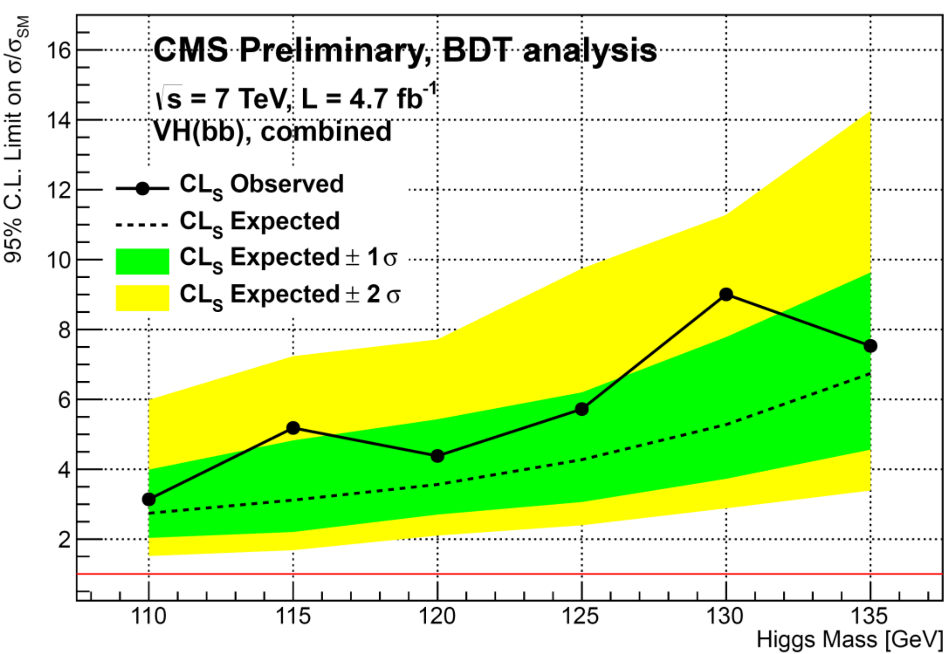


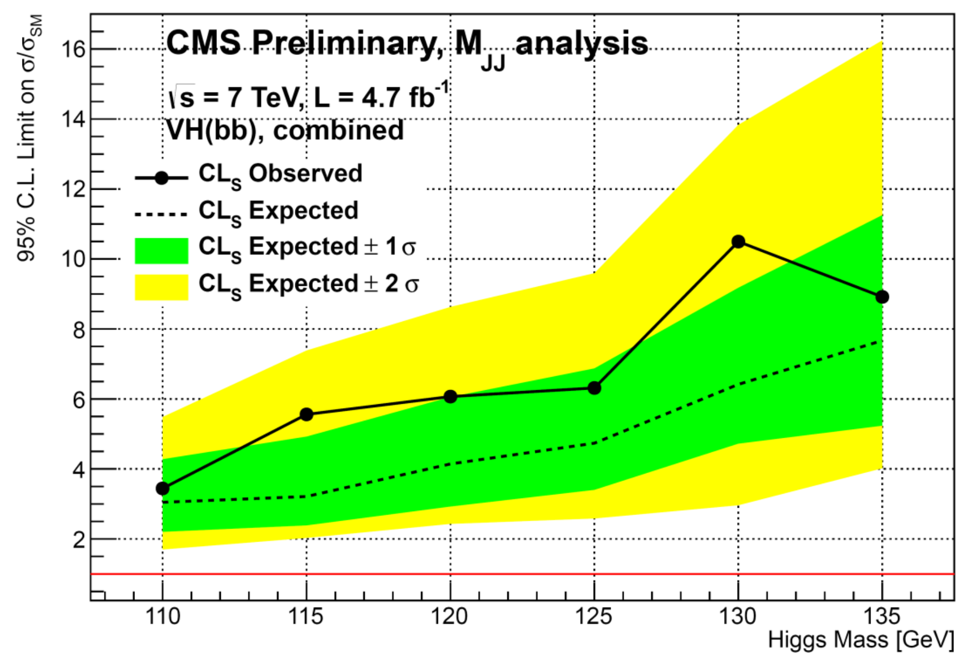




H→bb Results

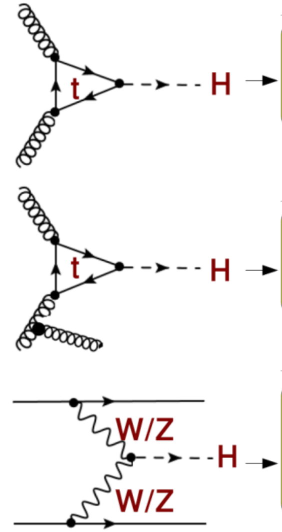
- The BDT analysis is found marginally superior to the mass shape analysis (expected limits slightly lower)
- Results not jet binding SM cross section at low mass, but surprisingly close to do so





6 - H→ττ searches

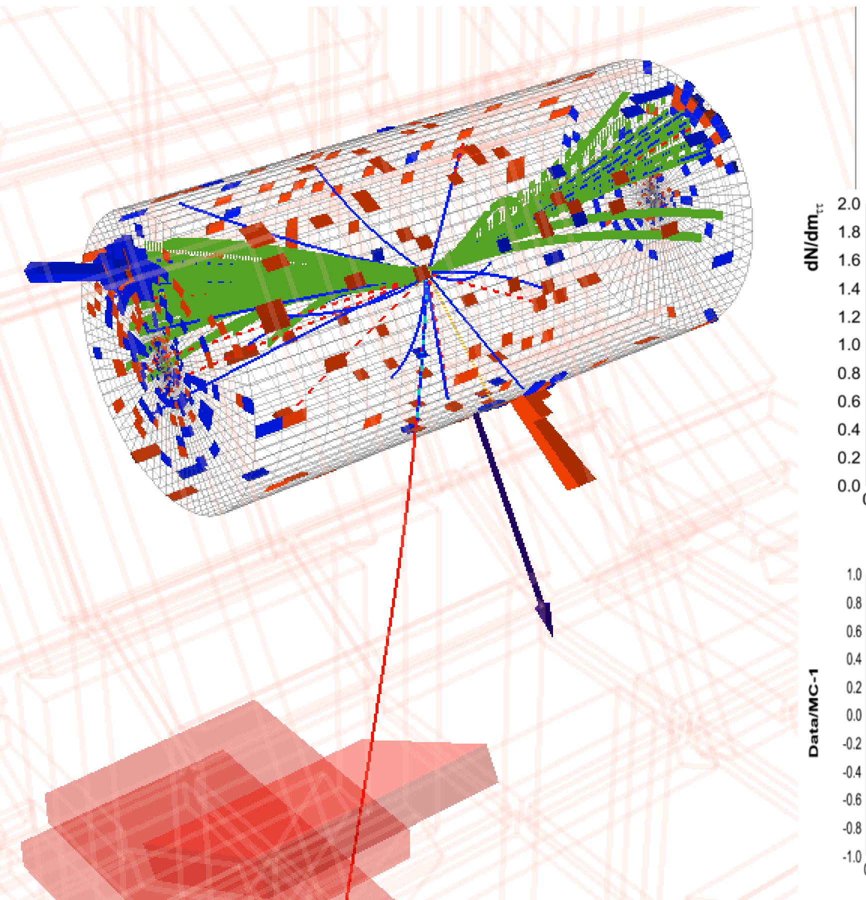
- H→ττ decays can be searched both in direct H production, and in VBF qqH→qqττ final states
- In direct production more kinematic handles are needed to separate from DY → require large boost of H candidate
- Three ττ topologies: $\mu+\tau_{had}$, $e+\tau_{had}$, μe



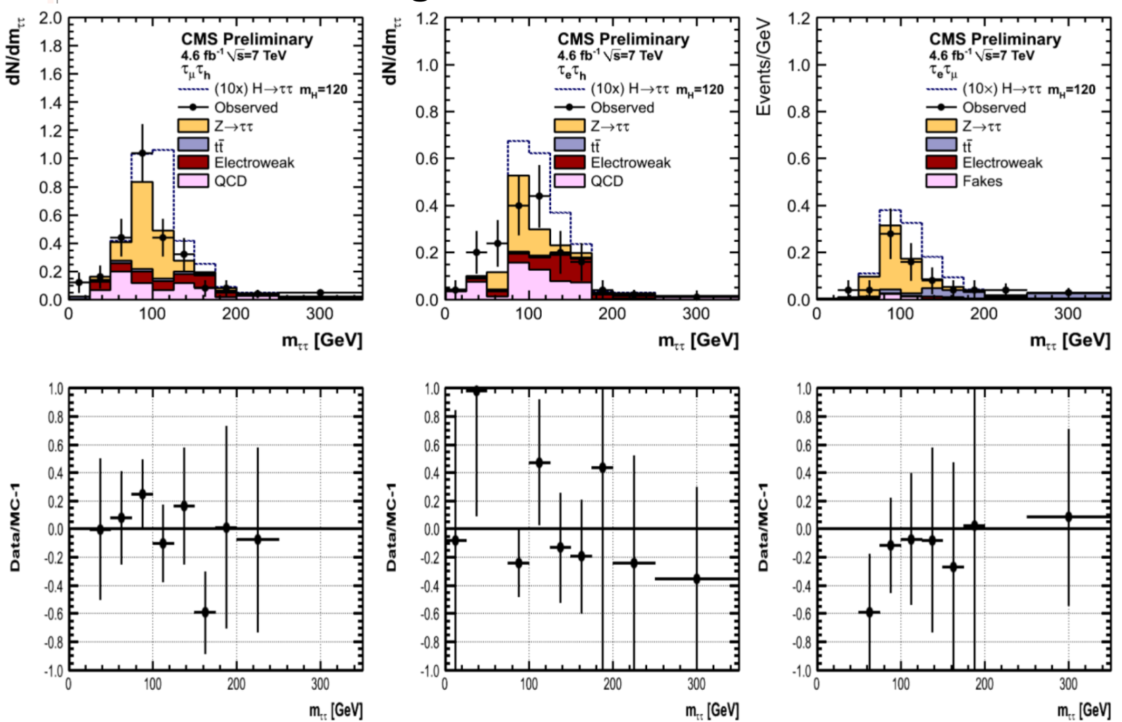
SM-0/1 jet
0 jets >30 GeV or 1 jet<150 GeV

SM-Boosted
One jet Pt>150 GeV
No other jets>30 GeV

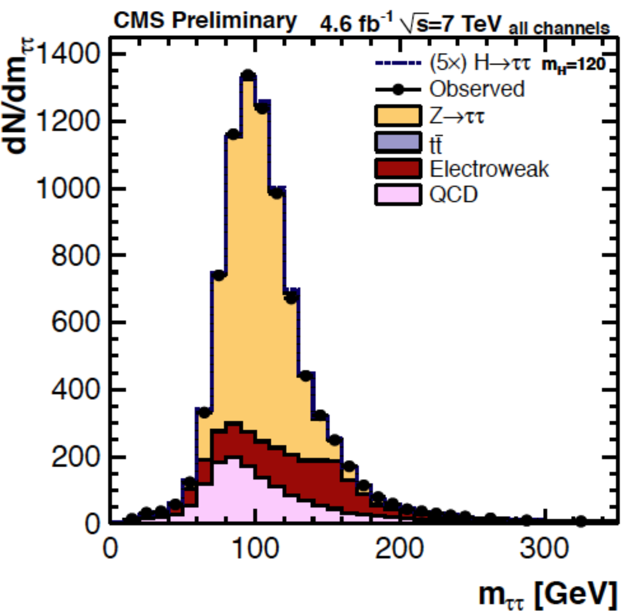
SM-VBF
>=2 Jets >30 GeV
Δη>4 , Mjj>400 GeV
No additional jets with Pt>30 in the rapidity gap

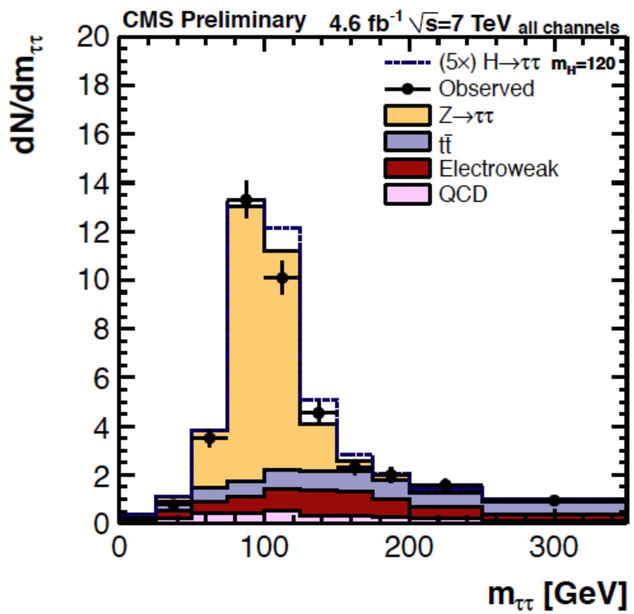


BDT mass distributions are divided for the three categories of ττ candidates

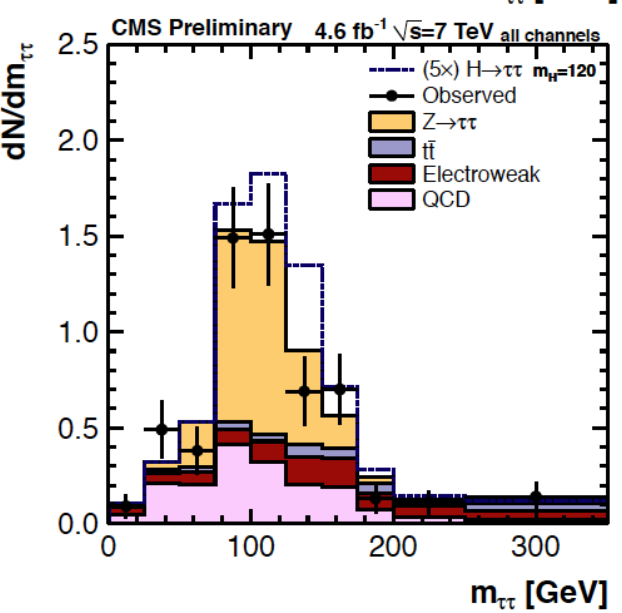


H→ττ results



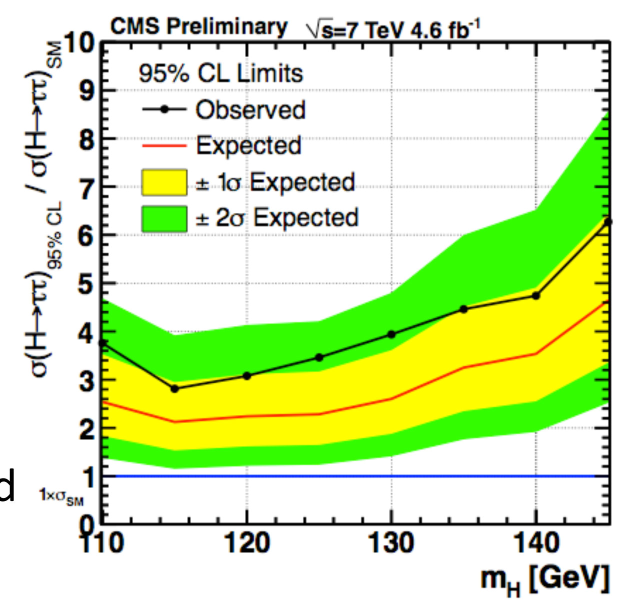


The three final states have different sensitivities – the first one is a "proof of principle" and is sensitive to MSSM H→ττ signals (see later).



The channel has best sensitivity for M_H=120 GeV

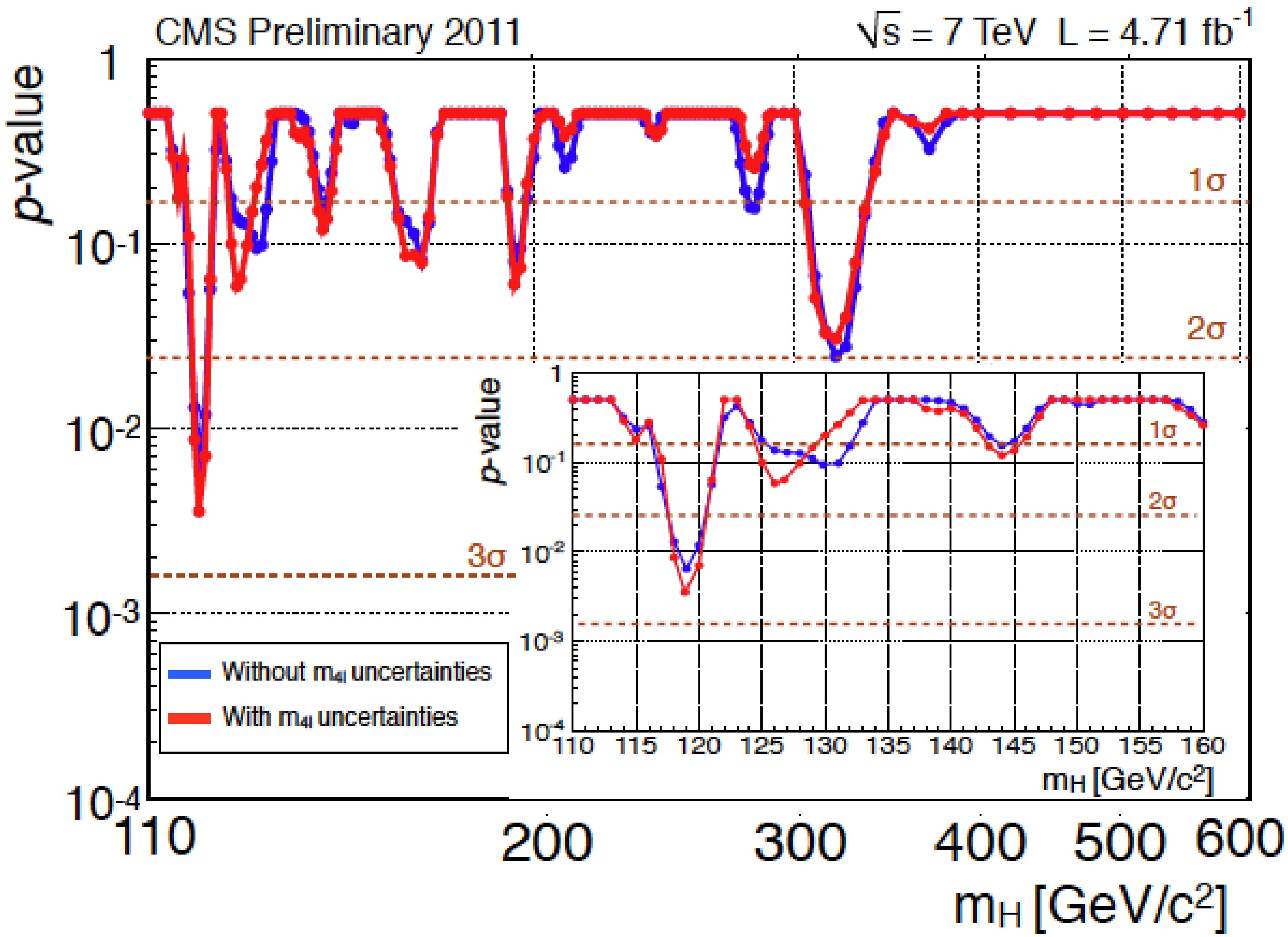
The mass resolution of ττ channels is poor
A 1-σ excess is observed throughout the investigated mass range



H→ZZ→4l: Excess and p-value

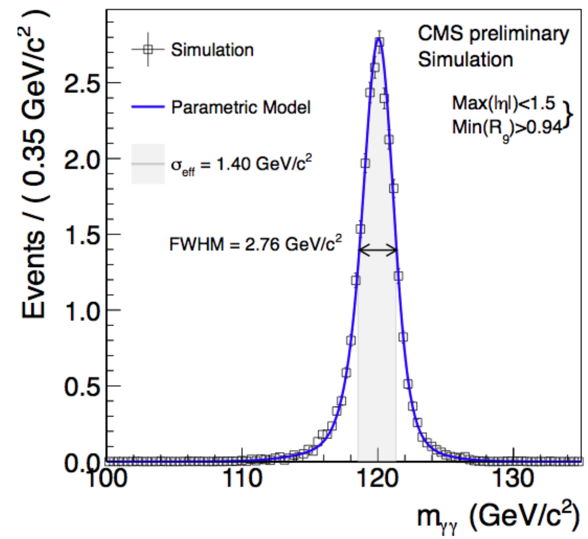
- By itself, the local p-value of the 119 GeV mass hypothesis corresponds to a 2.4 standard deviations effect

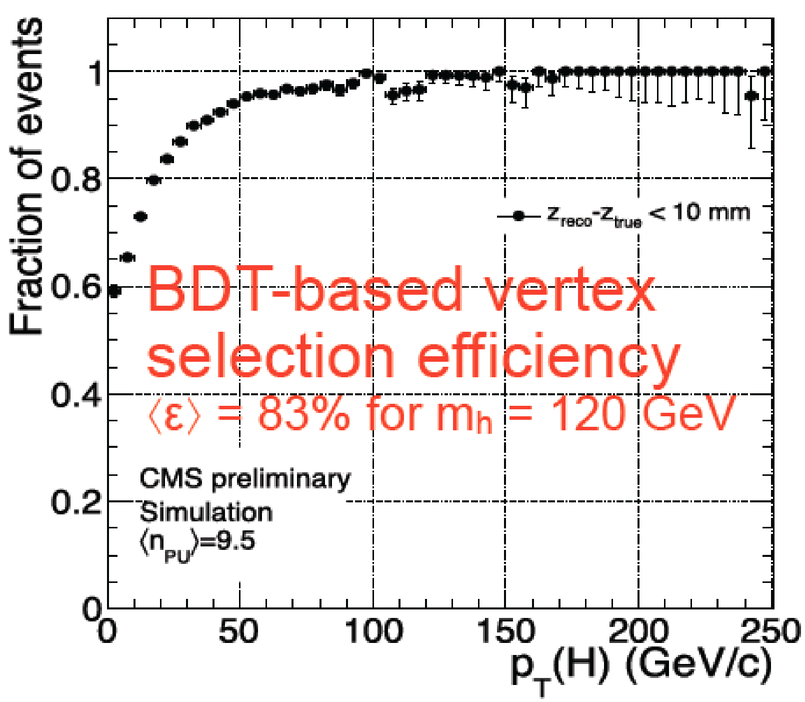
- But trial factor for full-mass search is ~40

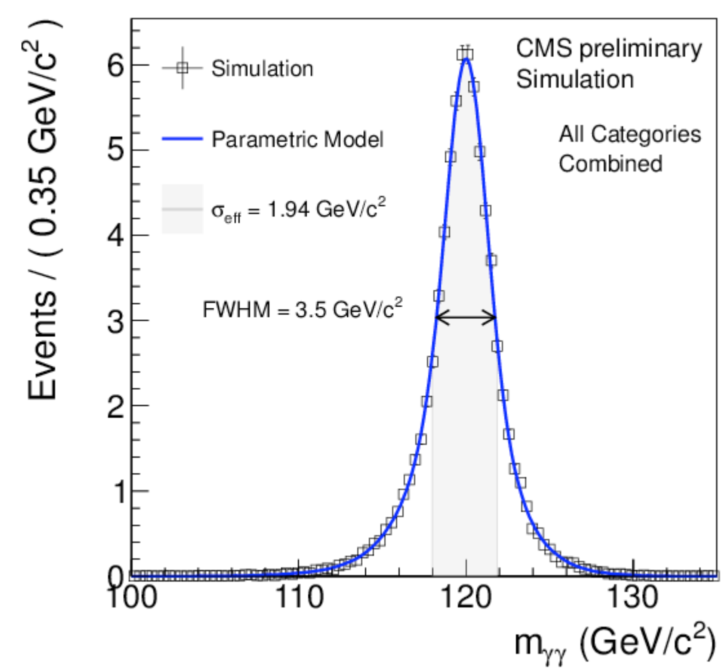


More detail in H→γγ reconstruction

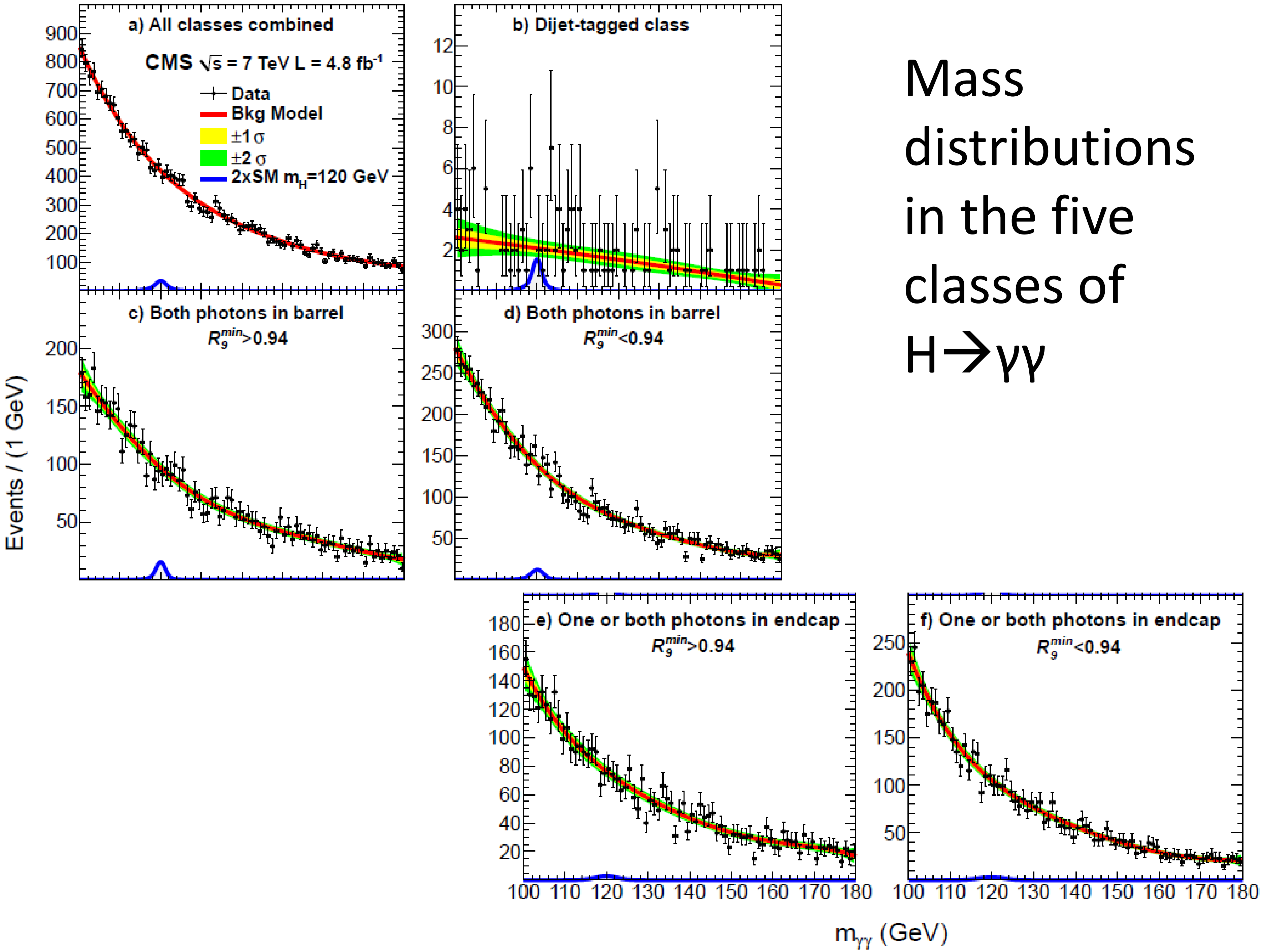
- Photon-photon mass for central-central pairs has resolution close to 1 GeV
- Primary vertex is chosen with BDT discriminant – performance improves with diphoton p_T
- Four categories kept separate to profit from differences in signal and background shapes and normalizations



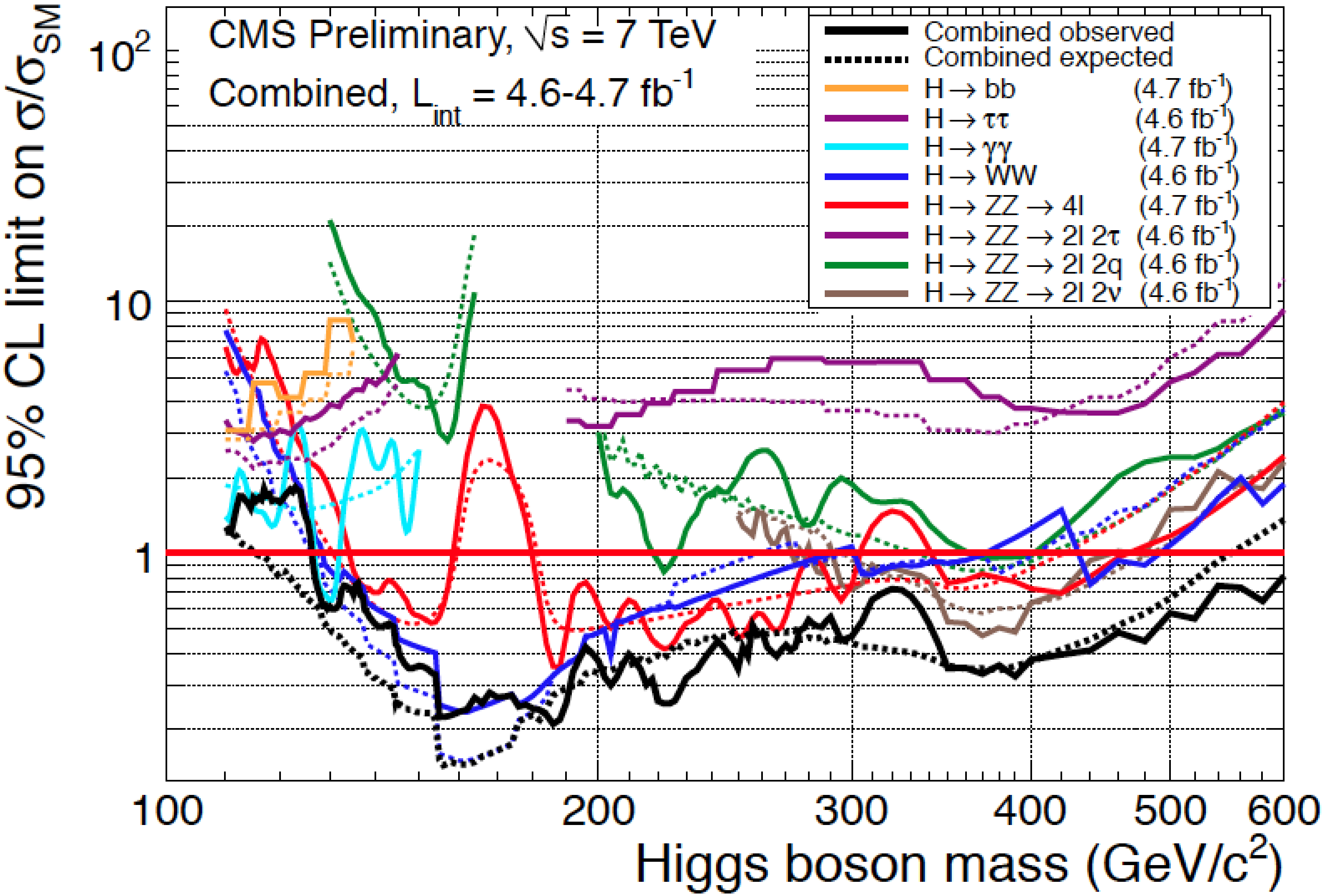




Mass distributions in the five classes of $H \rightarrow \gamma\gamma$

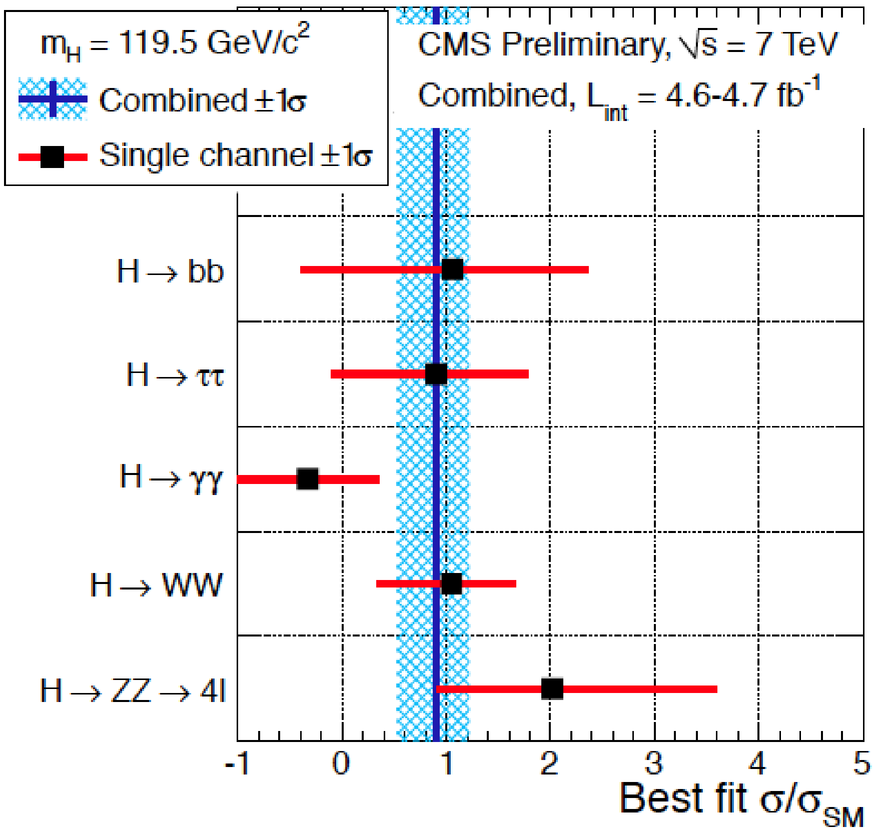


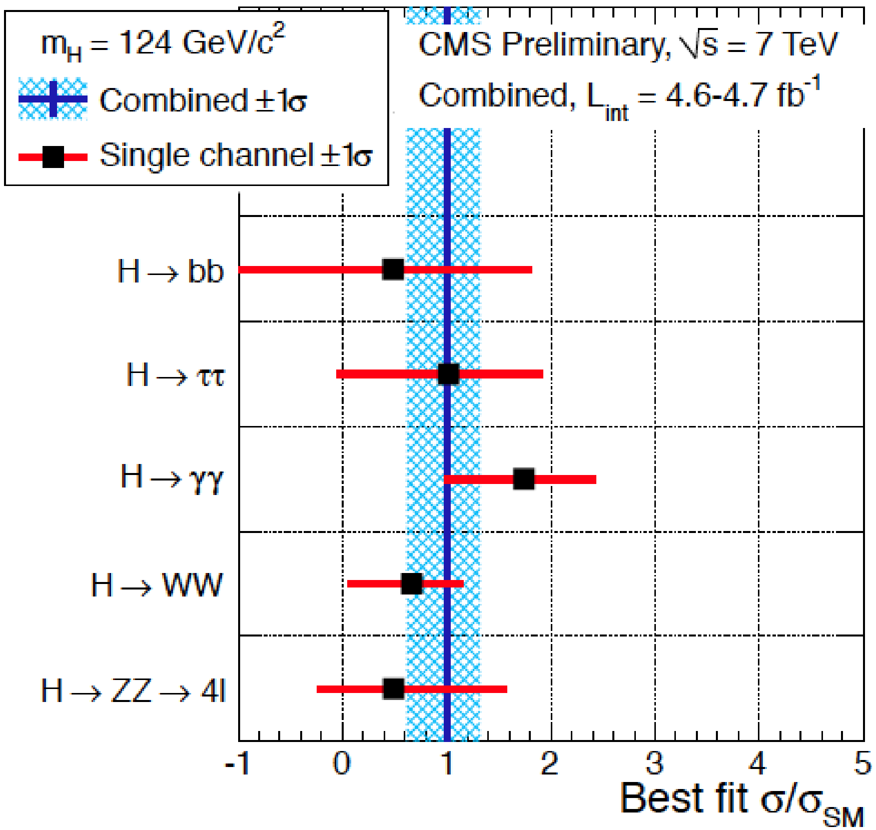
Channel-by-channel view



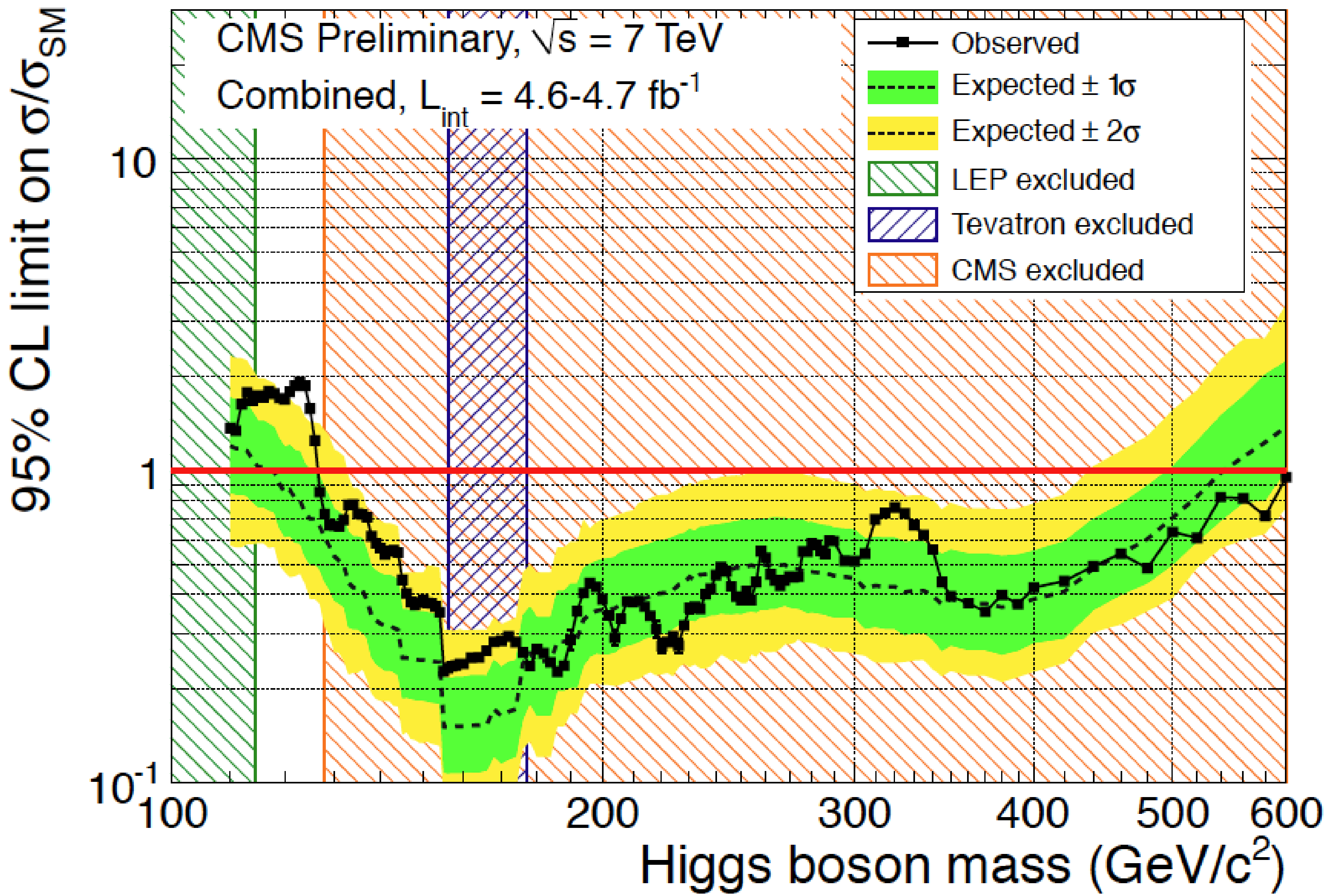
Best fit cross section, channel by channel

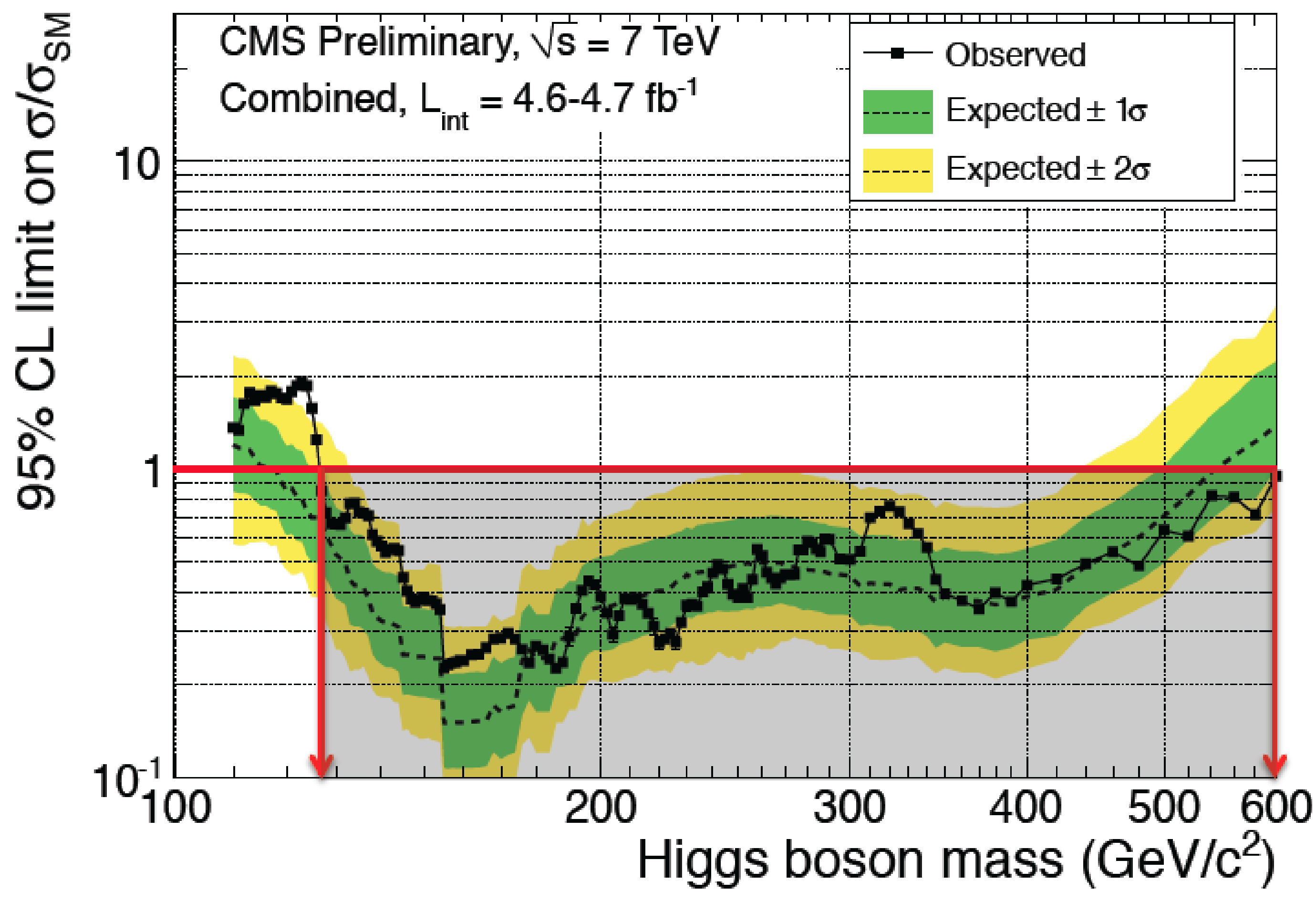
Although not significant, the slight excesses observed in most search channels appear compatible with the expected contribution from SM Higgs production, both for M_H=119.5 and for M_H=124 GeV





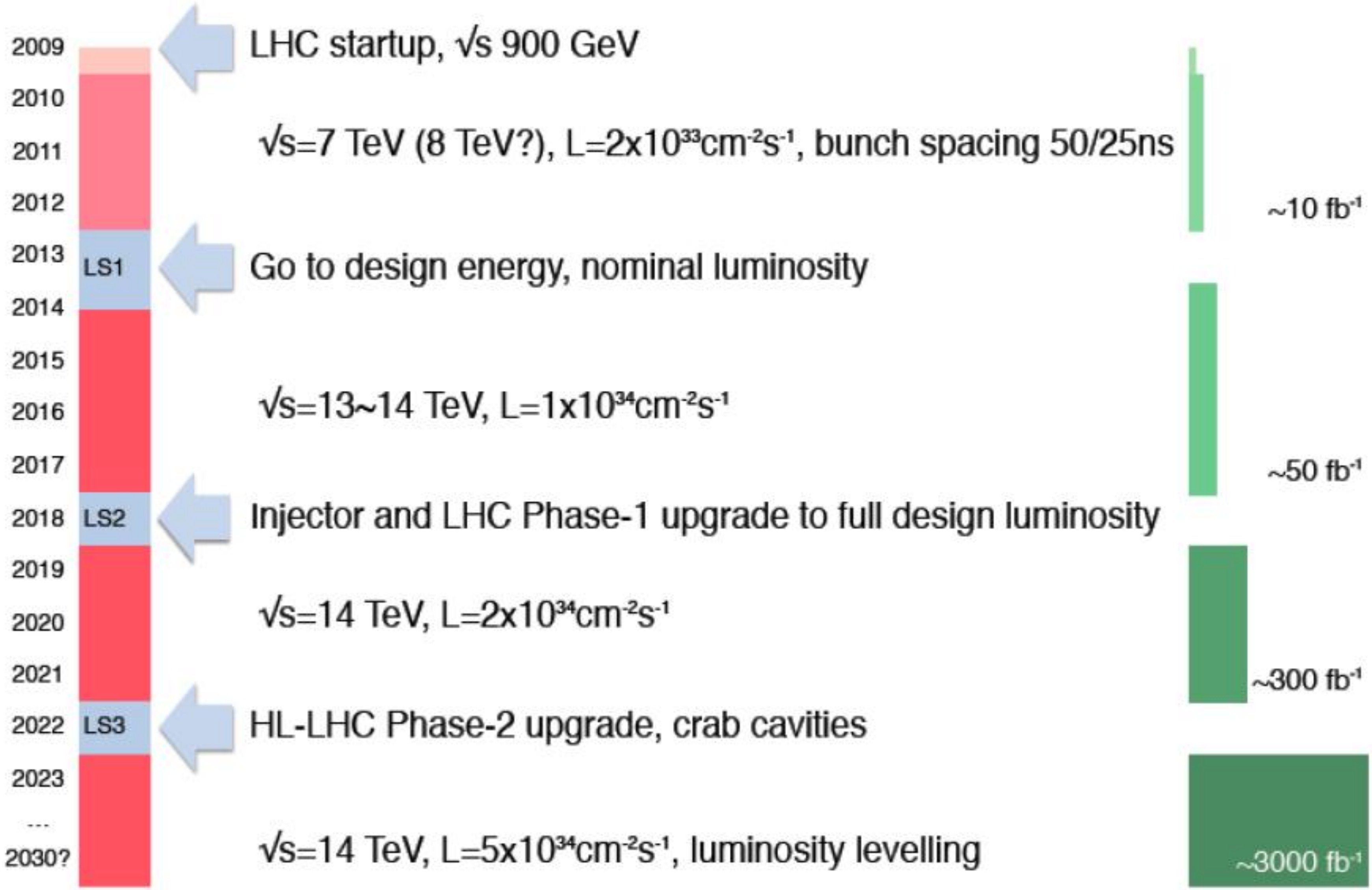
Summary of Higgs Searches: Where are we ?





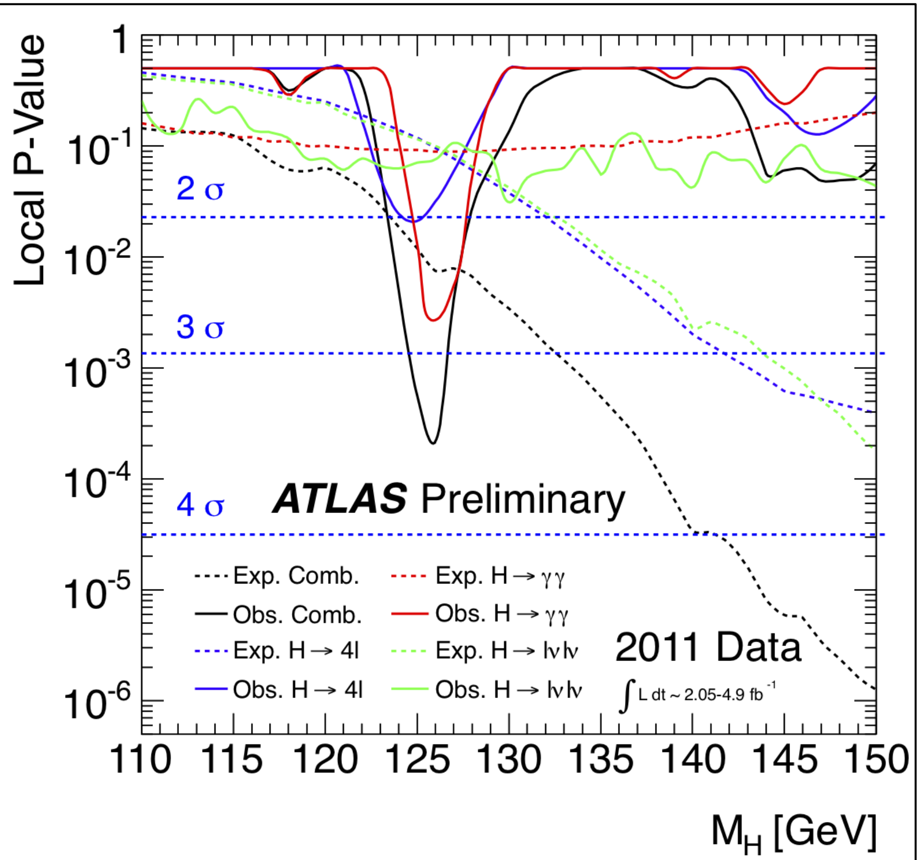
CMS Preliminary, √s = 7 TeV
Combined, L_int = 4.6-4.7 fb^-1
Observed
Expected ± 1σ
Expected ± 2σ
95% CL limit on σ/σ_SM
10
1
10^-1
100
200
300
400
500
600
Higgs boson mass (GeV/c^2)

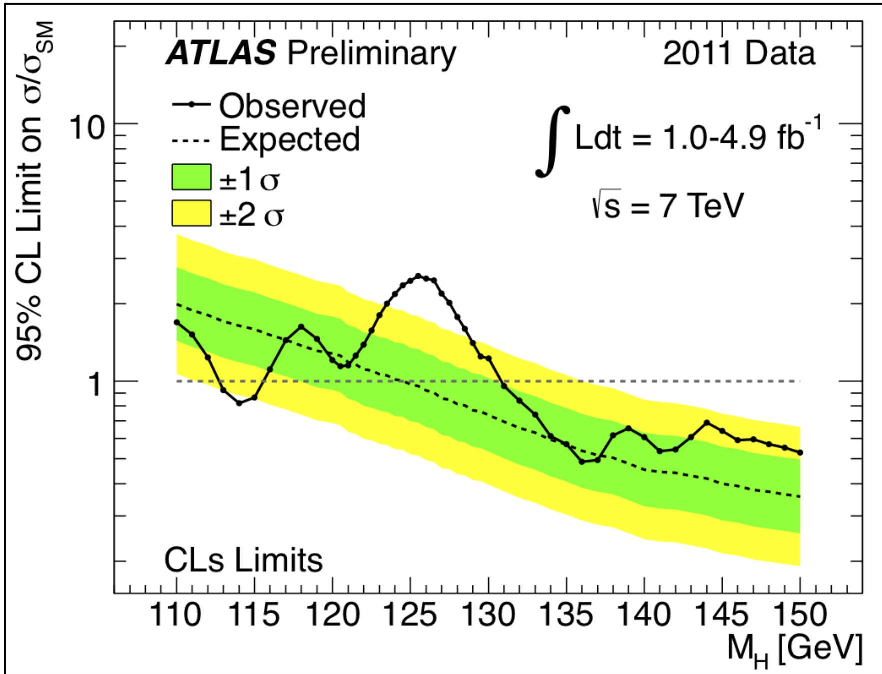
The Future of the LHC



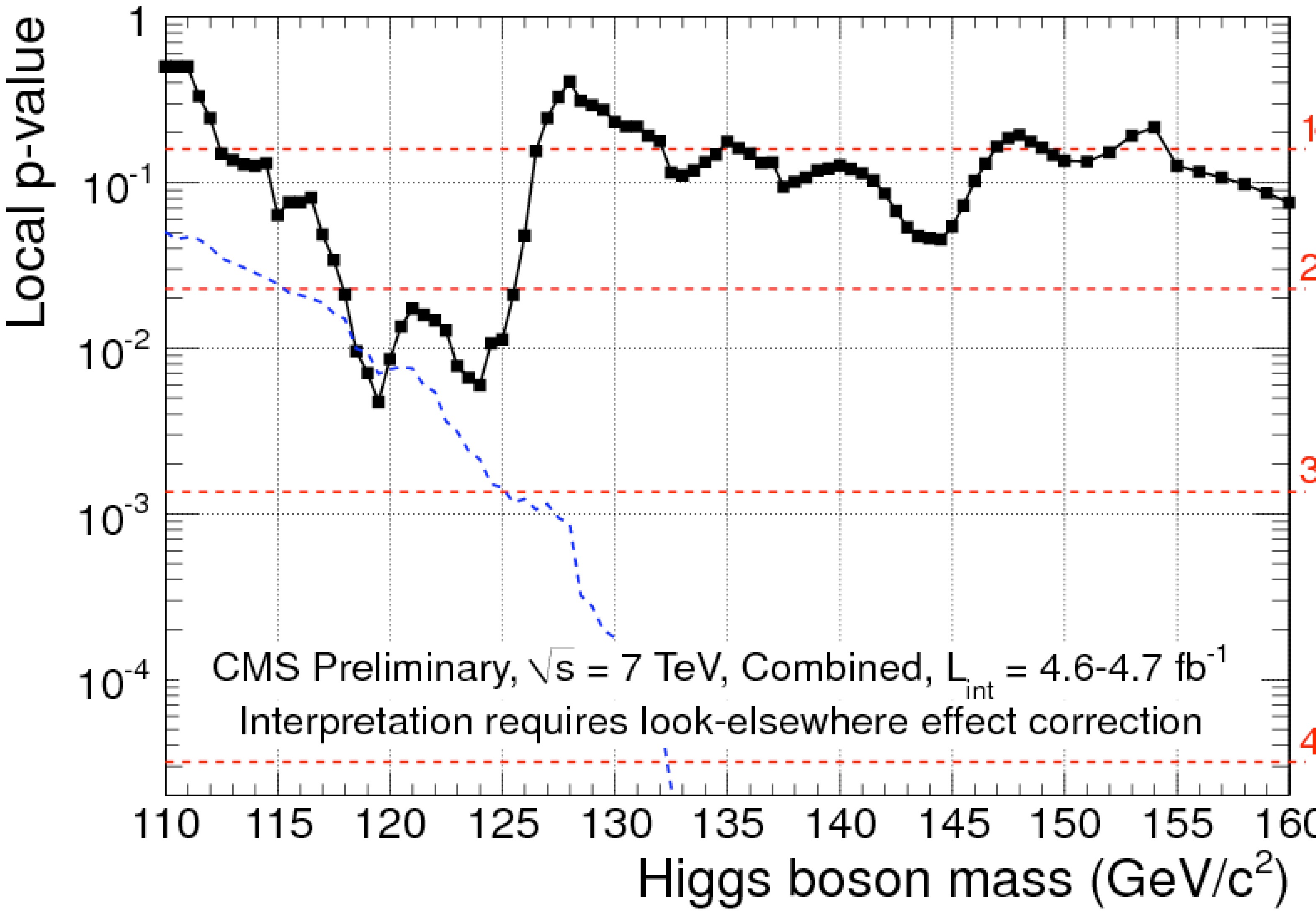
ATLAS Higgs Results

Atlas observes a 3.5 standard deviation effect at MH=126 GeV (local significance)

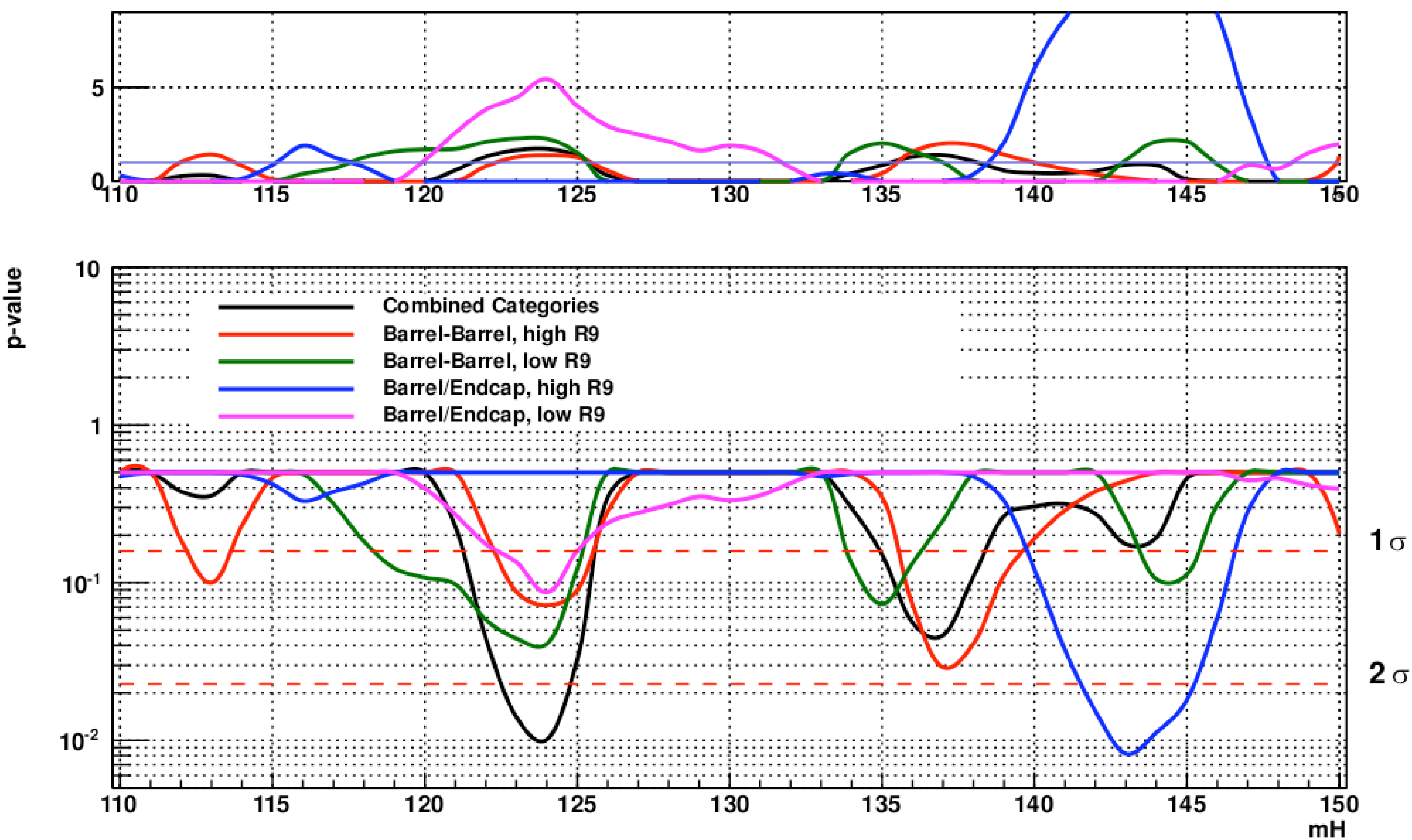




p-value compared with H hypothesis

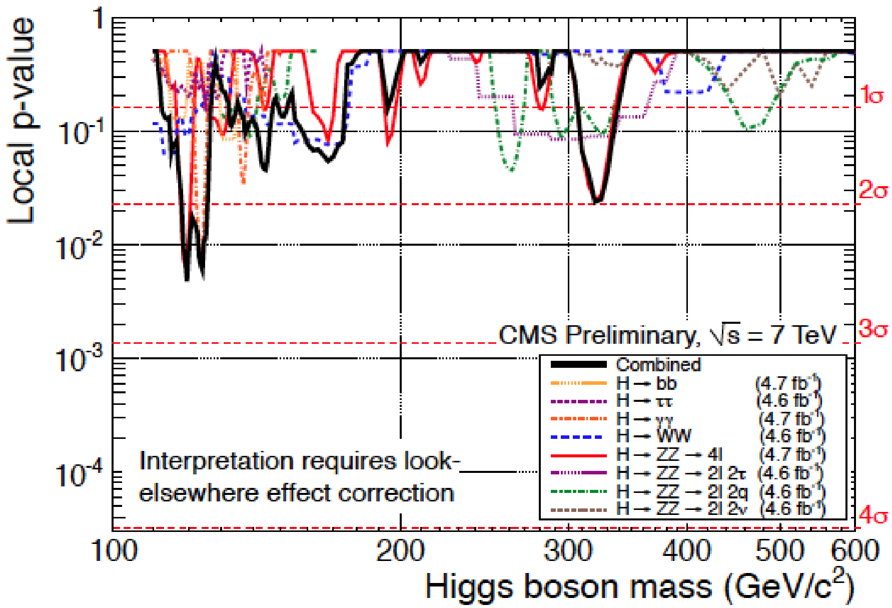


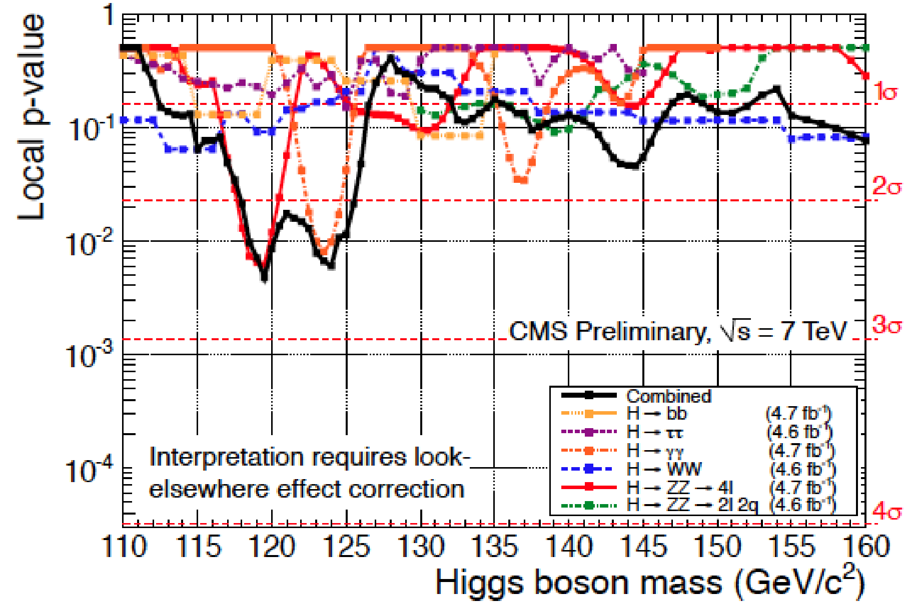
H→γγ p-values

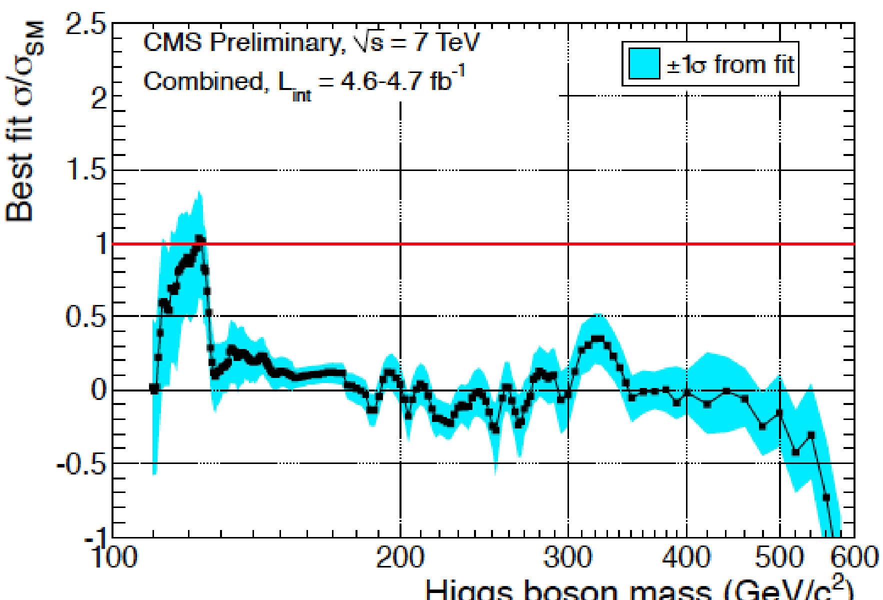


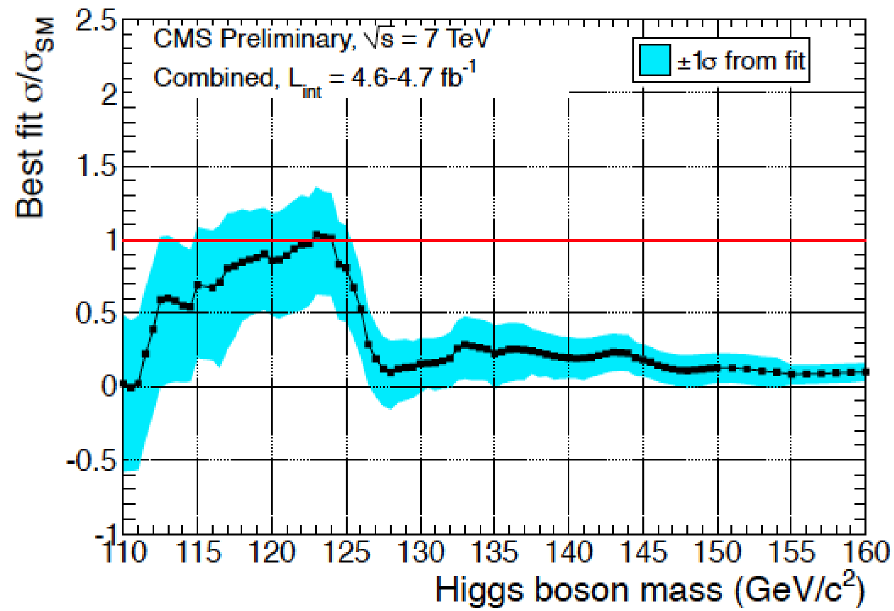
5
0
110
115
120
125
130
135
140
145
150
p-value
10
1
10^{-1}
10^{-2}
Combined Categories
Barrel-Barrel, high R9
Barrel-Barrel, low R9
Barrel/Endcap, high R9
Barrel/Endcap, low R9
1 σ
2 σ
mH

p-values and best-fit cross section



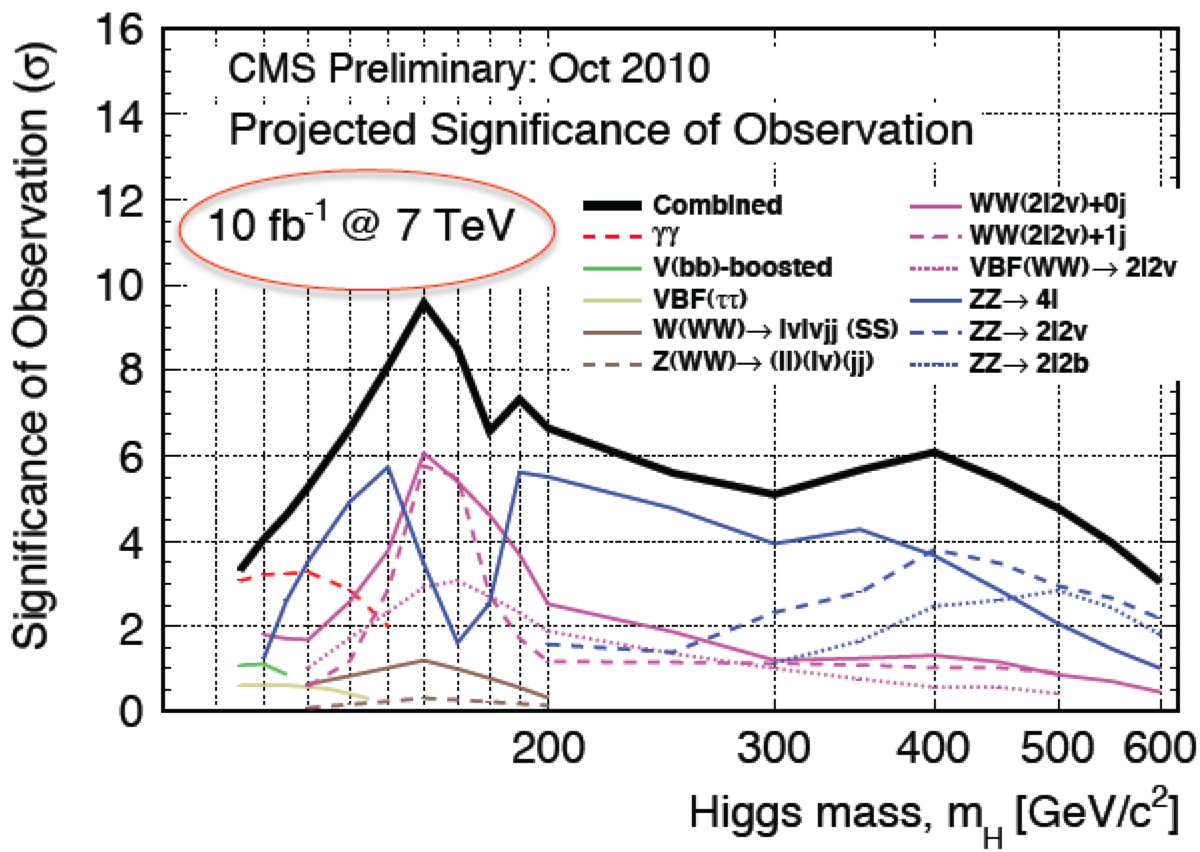






Forecast for 2012

The October 2010 predictions for the sensitivity to a SM Higgs boson were on par with results, given 5/fb of data → high reliance on results achievable with doubled statistics

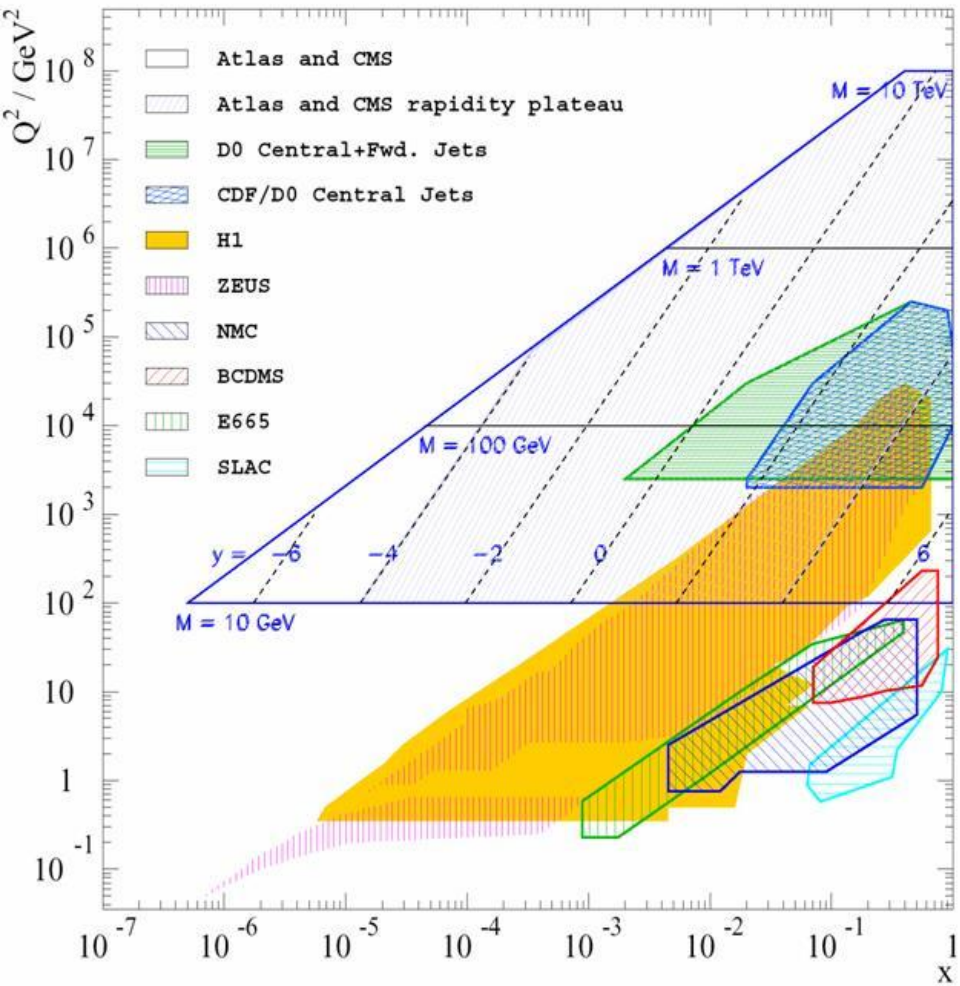


In the 120-125 GeV region the local significance should exceed 4 standard deviations with 10/fb at 7 TeV

Likely crossing 5σ mark by combining with ATLAS or if delivered luminosity reaches 15/fb

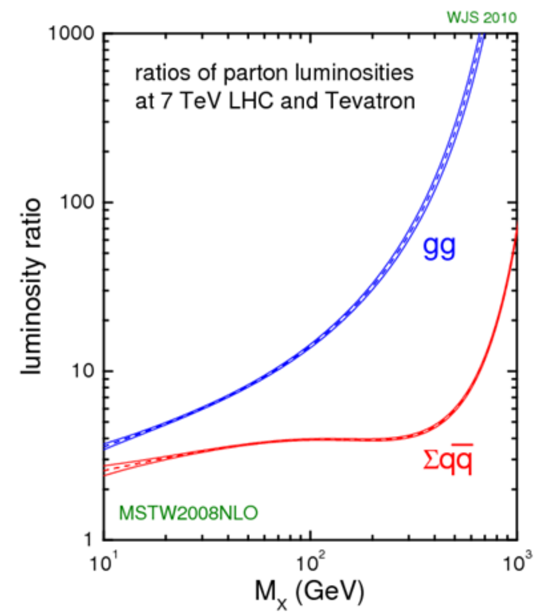
PDF and Parton Luminosities

Kinematical range spans largely unknown regions of (x,Q^2) → PDF uncertainties



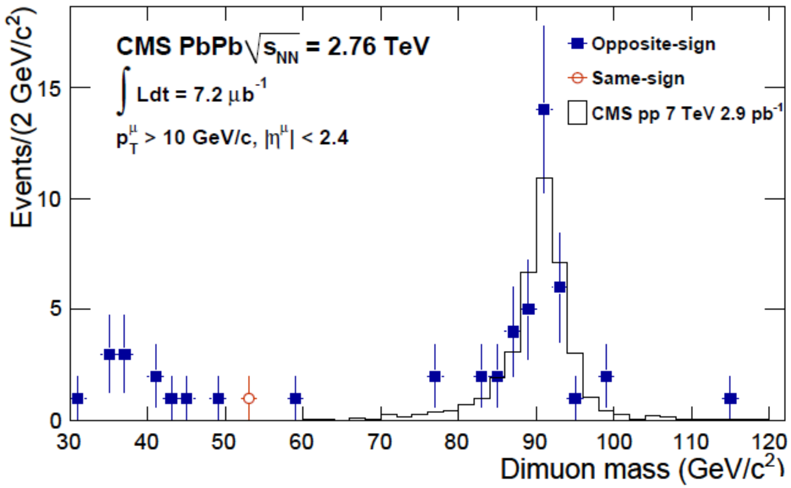
Gluon luminosity grows much faster than quark luminosity below effective masses of 500 GeV

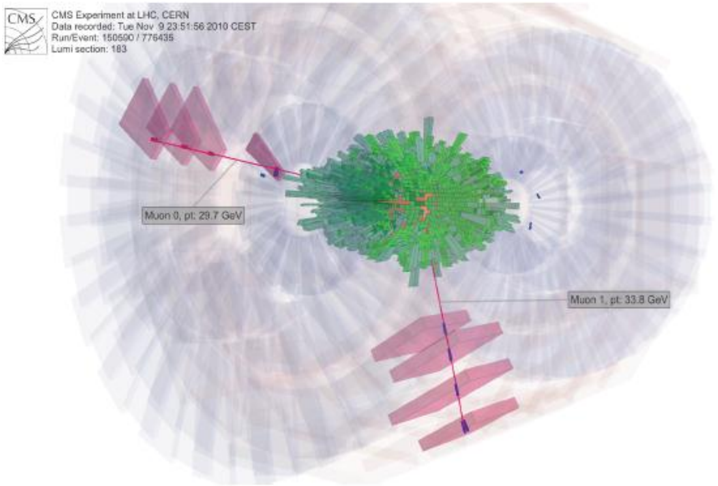
The implication for searches is generally a strong advantage WRT lower-energy machines (TeVatron) in production of massive particles, particularly at high end



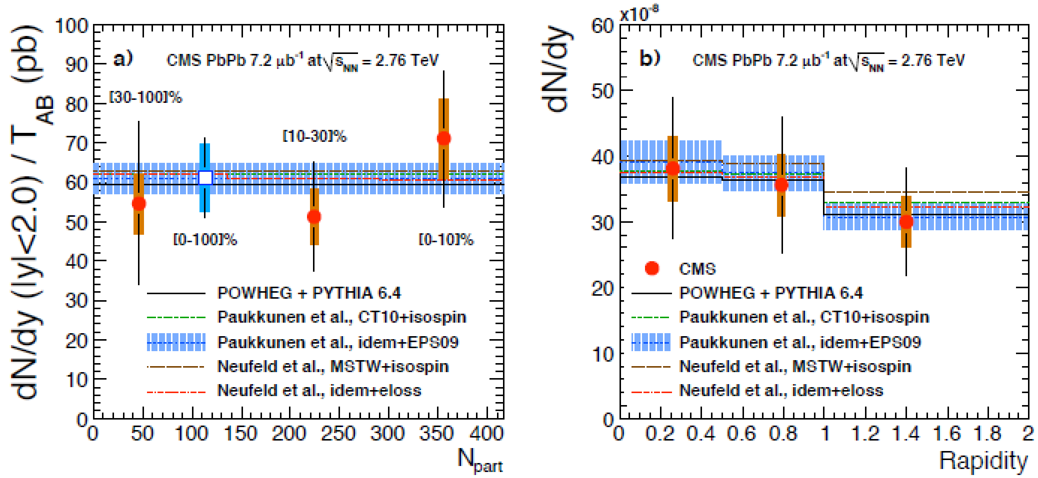
Z production in HI collisions

Z production is a useful benchmark at the LHC, not accessible to lower energies (where direct γ production is studied, but is plagued by π^0 backgrounds and contributed by fragmentation processes also affected by the environment)





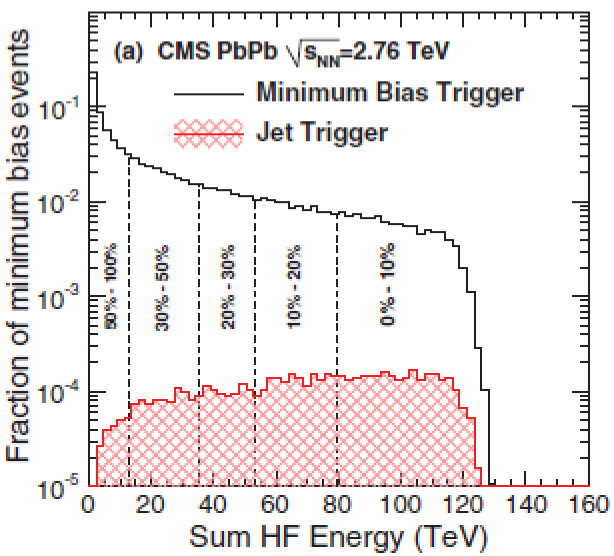
The yields, scaled by the number of participating nucleons, are observed to be in agreement with NLO calculations This also confirms the validity of the Glauber scaling

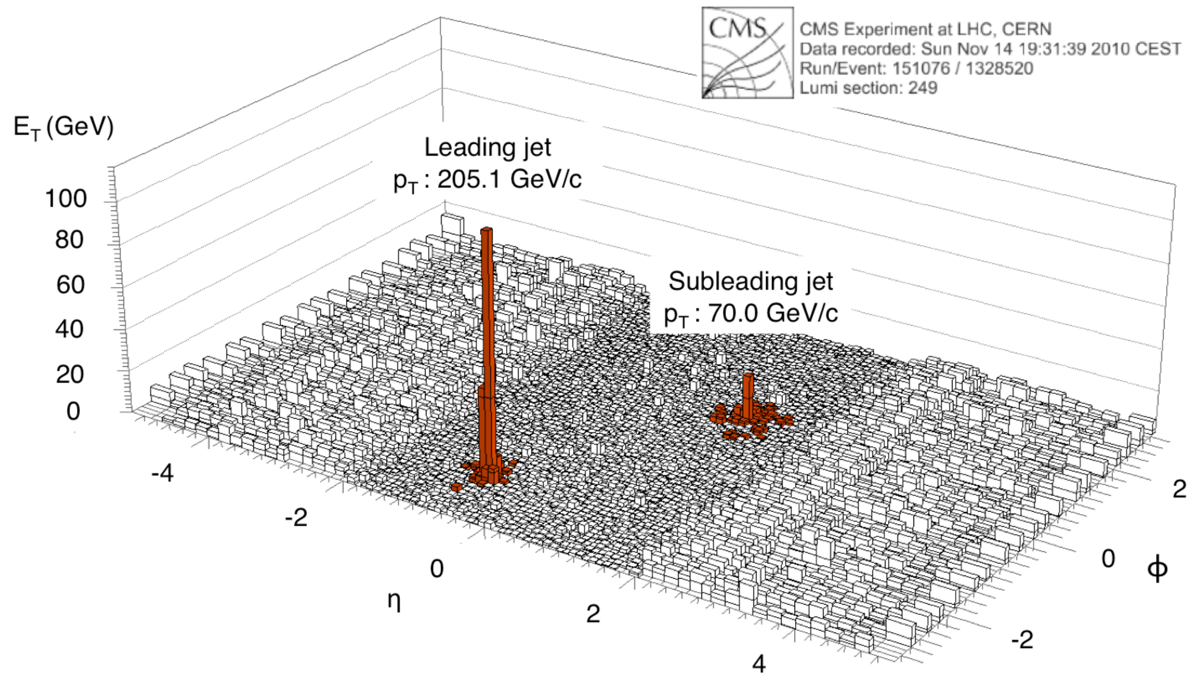


Heavy Ion Results: 1 – Jet Quenching

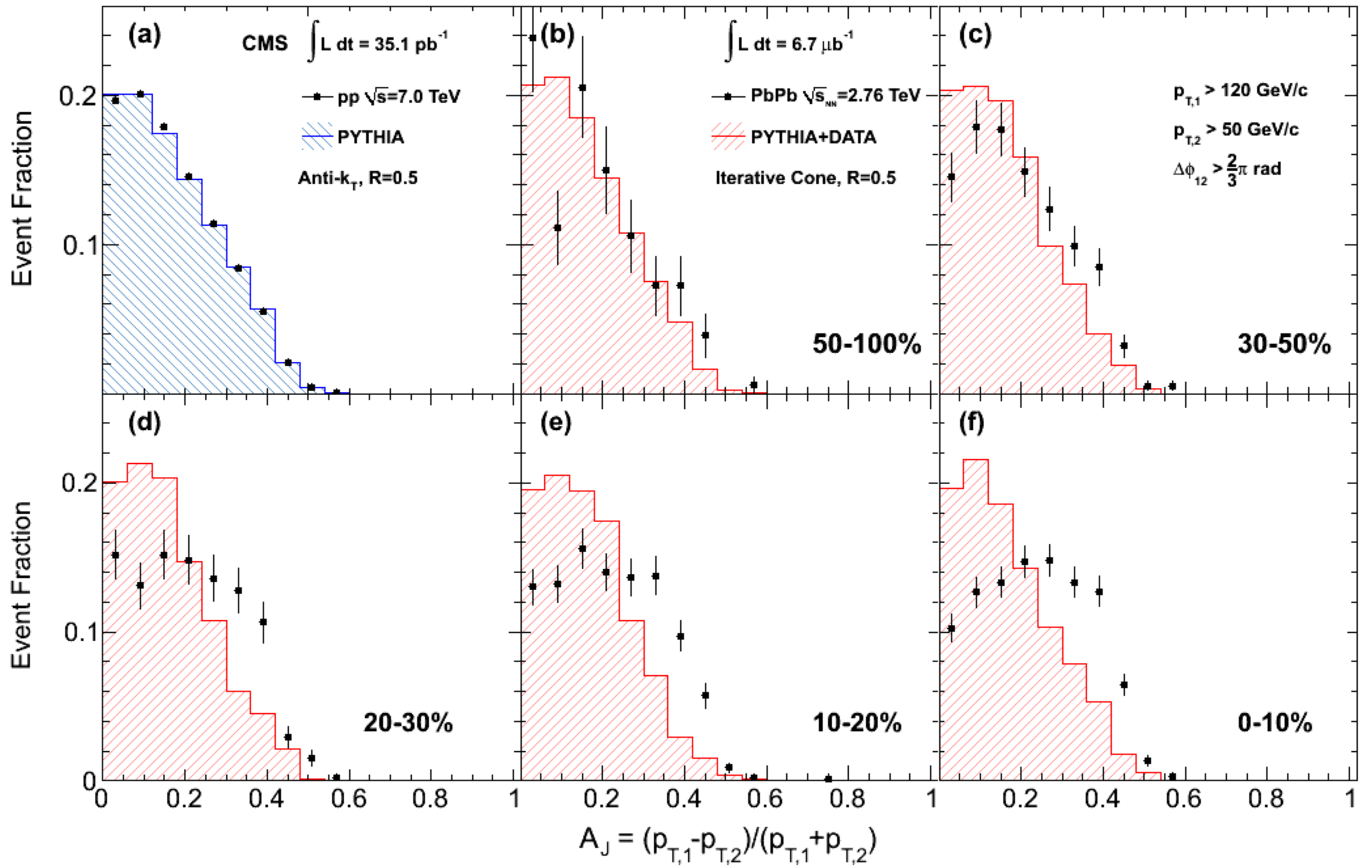
- A study of jet quenching was performed on 6.7/μb of PbPb data at cm energy of 2.76 TeV/nucleon

Events are selected with a jet of p_T>120 GeV in |η|<2.0; their correlation with a second jet with p_T>50 GeV, |η|<2 is studied as a function of the *centrality of the collision*
The latter quantity is determined from the energy deposited in the forward calorimeters



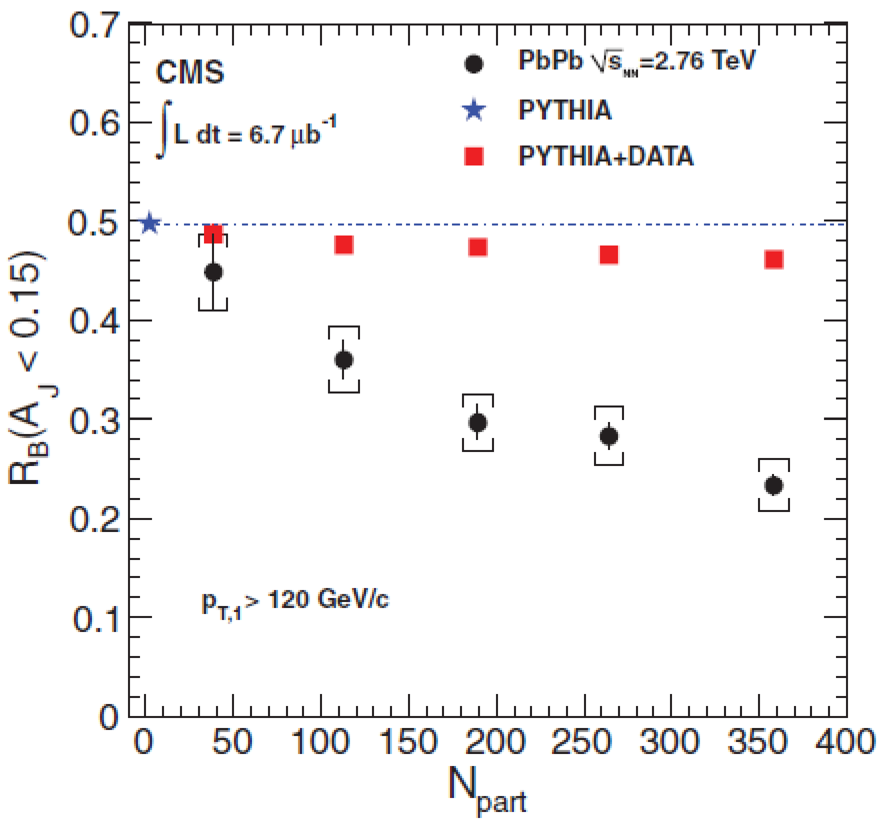


Imbalance growing with centrality



Dijet asymmetry ratio *for leading jets of* $p_{T,1}$ *> 120 GeV/c, subleading jets of* $p_{T,2}$ *>50 GeV/c, and* φ_{12} *>2π/3 for 7 TeV pp collisions (a) and 2.76 TeV PbPb collisions in several centrality bins*
Data are shown as black points, while the histograms show (a) PYTHIA events and (b)–(f) PYTHIA events embedded into PbPb data.

Summary of Jet quenching studies

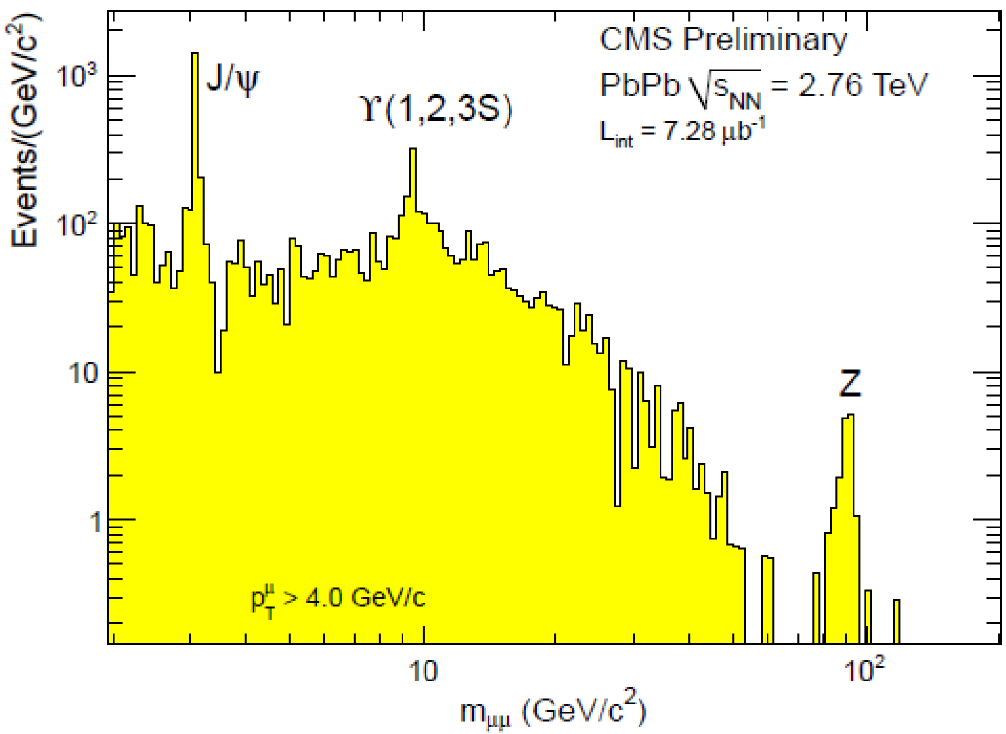


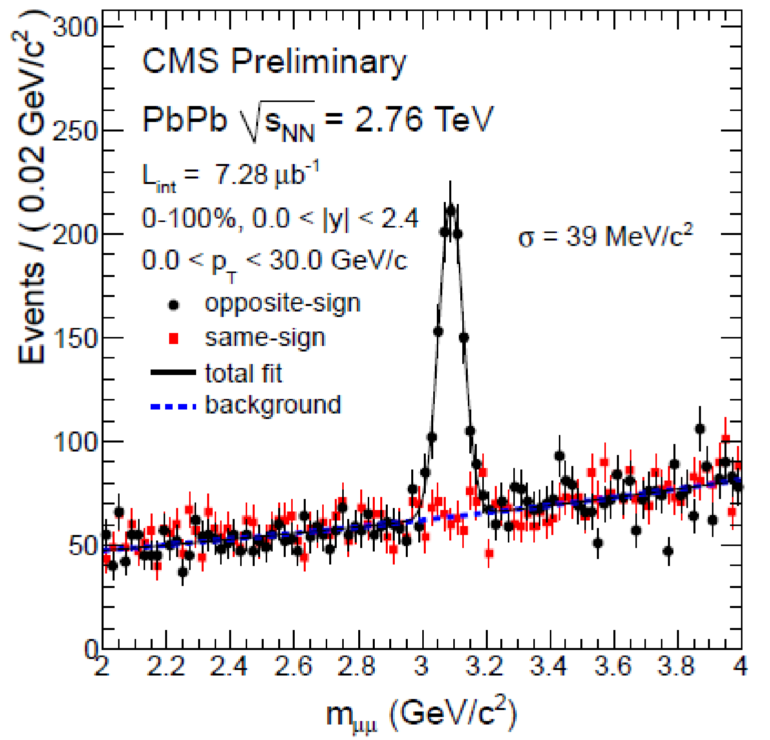
Above: fraction of events with a leading jet with *$p_{T,1}$ > 120 GeV for which a subleading jet with A_J < 0.15* and *φ_{12} > 2π/3 was found, as a function of N_{part}*

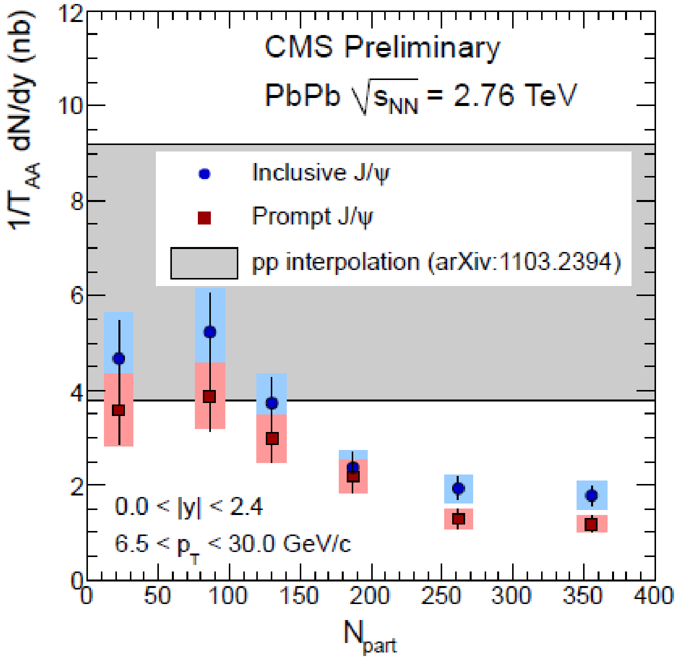
- The observed strong quenching of jets probes QCD dynamics at high temperature and density
- Energy is transferred to low p_T particles emitted at large angle, challenging traditional energy loss models.
- Quenching found independent on leading jet p_T
- For more details see Phys. Rev. C84: 024906, 2011

Quarkonium and Z production

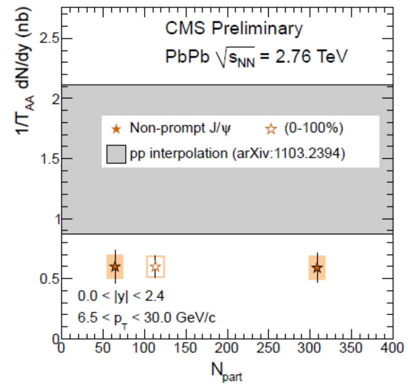
- With single muon triggers sizable signals of J/Psi, Y, and Z decays have been collected in the PbPb run
- Comparisons of the yields with pp collisions exposes the suppression of quarkonium production
- Studies are performed on the variation of yields with the number of nucleons participating in the collisions. The latter allows to compare to pp collisions by acting as a normalization factor: $T_{AA}=N_{part}/\sigma_{pp}$. It is determined from the centrality of the event as in the Jet Quenching analysis



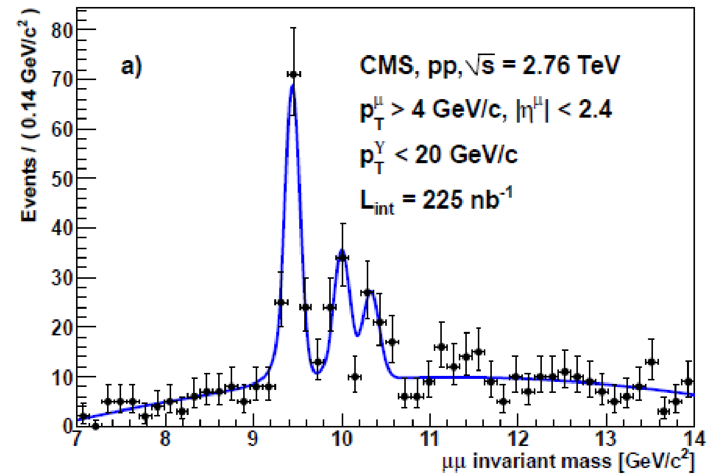




Left: T_{AA}-normalized yield of J/Psi decays (inclusive and prompt, left; non-prompt, right) as a function of the number of participants in the collision, N_{part}



Below:
Y signals in pp and PbPb collisions

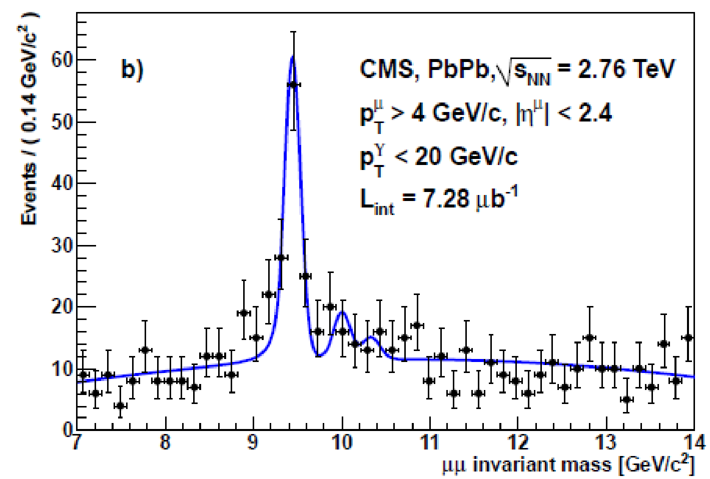


pp yield extrapolated- large uncertainty due to lack of high-p_T data
The yield drops by a factor 2.6 for the most central collisions.
The yield of the non-prompt component is not showing apparent variation with N_{part}

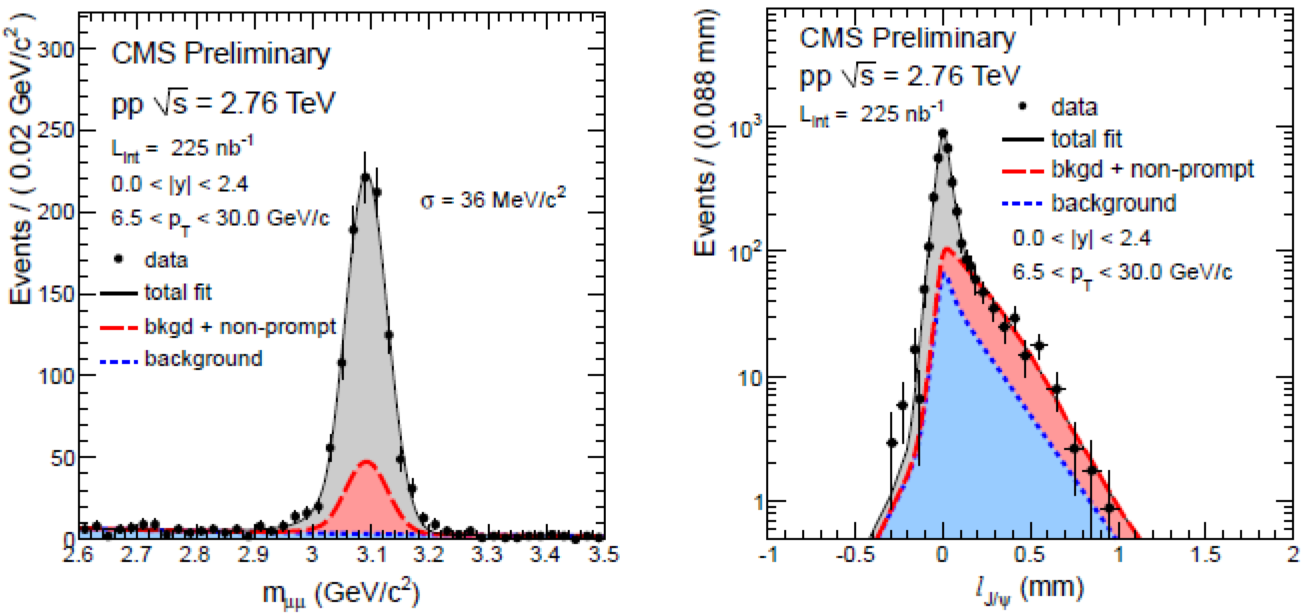
The suppression of 2S and 3S states with respect to the 1S is quantified by comparing the yields to those of pp interactions

$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{PbPb}}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{\mathrm{pp}}} = 0.31^{+0.19}_{-0.15}\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{syst.})$$

The probability to observe a double ratio as low or lower than this, if the true value is unity, is less than 1%
The Y(1S) is also found to be suppressed by 40% with respect to pp collisions

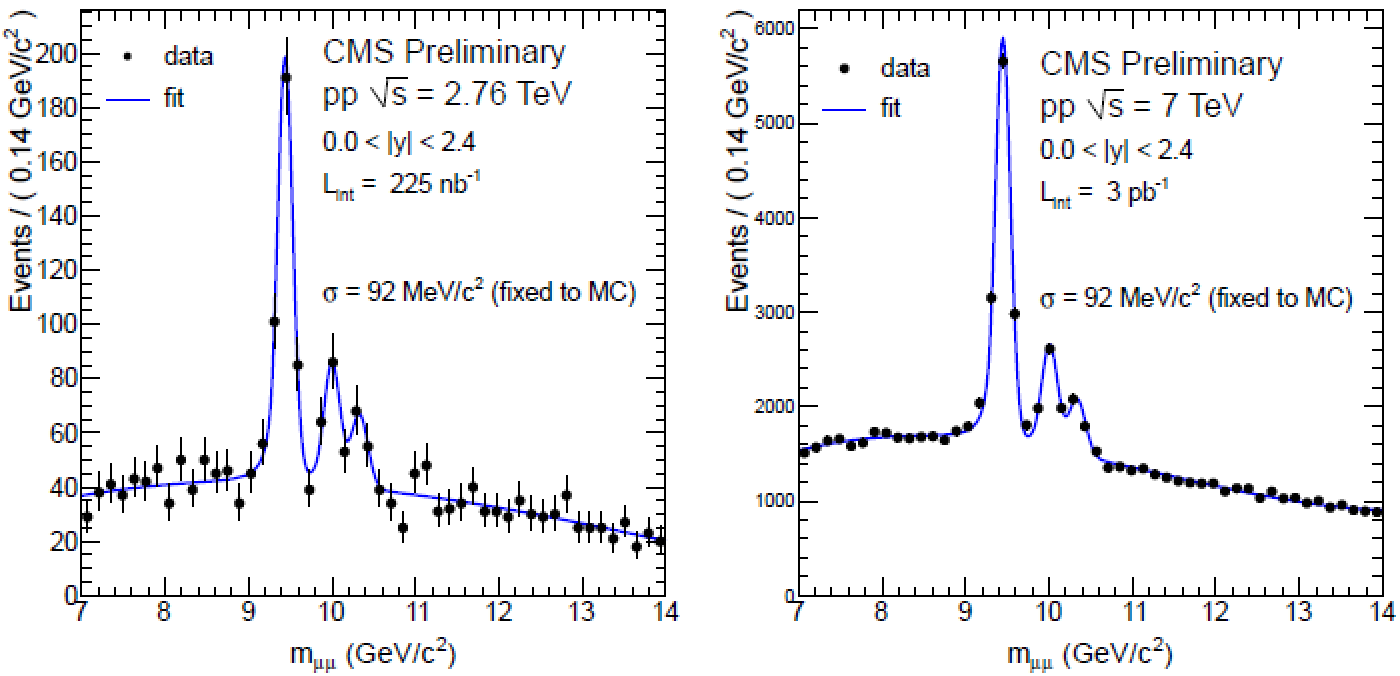


Quarkonium production in HI: details

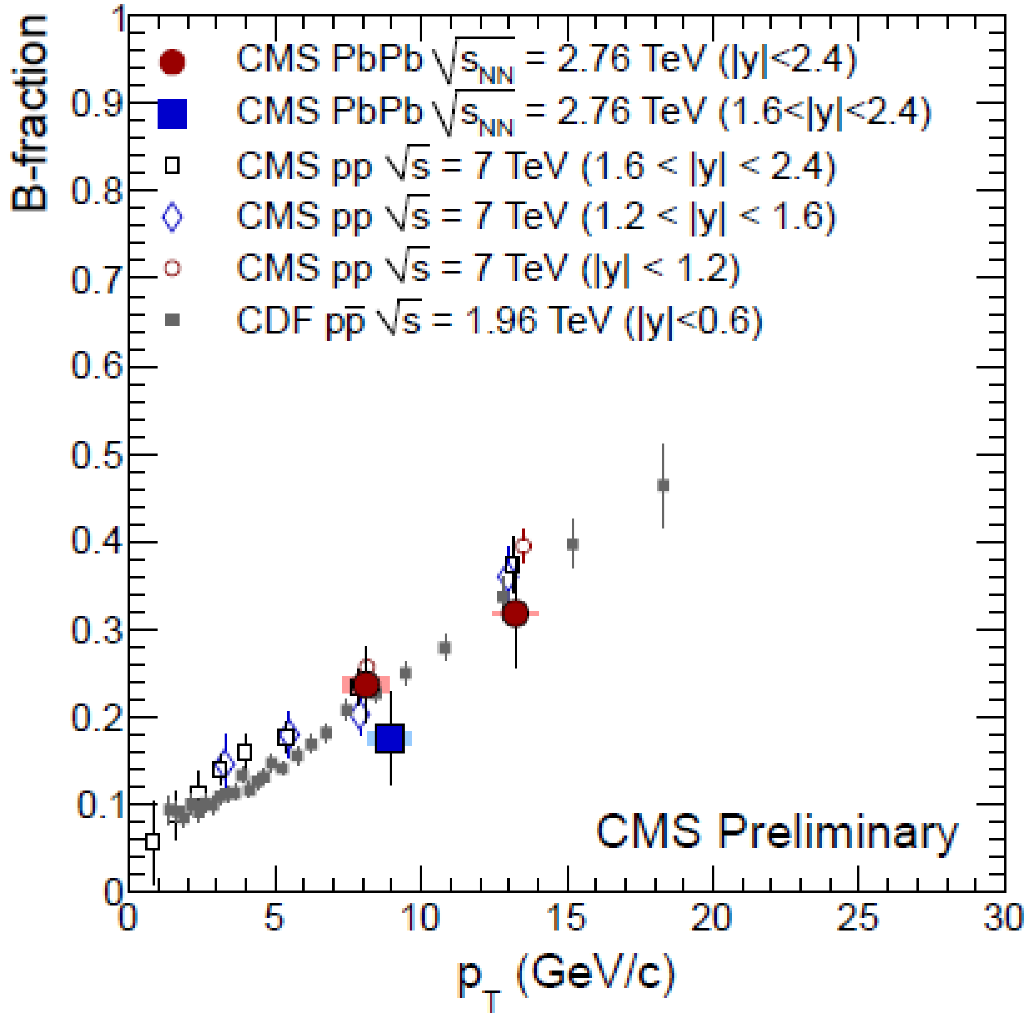


- The figure shows the extraction of the non-prompt component of J/ψ decays to dimuon pairs in pp collisions using the HI algorithm

- The figure illustrates the Y yields in pp collisions at 2.76 and 7 TeV center-of-mass energy

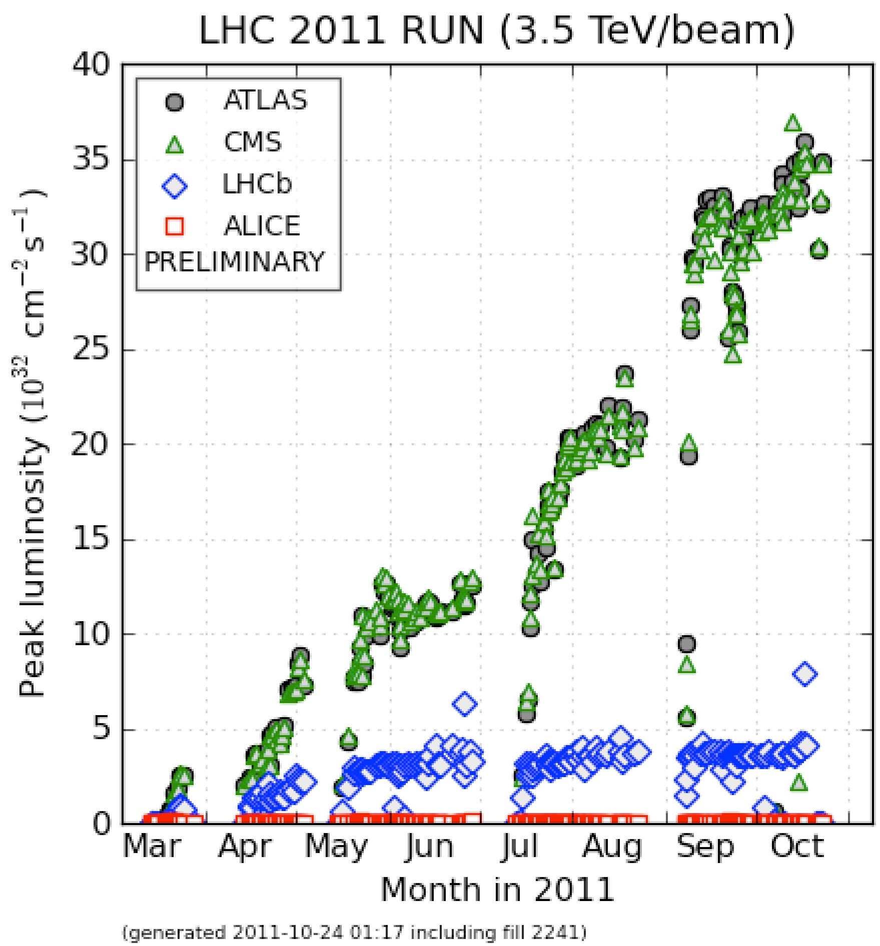


- The figure shows the fraction of J/Psi decays to dimuon pairs attributed to B meson decays for different data samples, and compared to CDF measurements of the same quantity



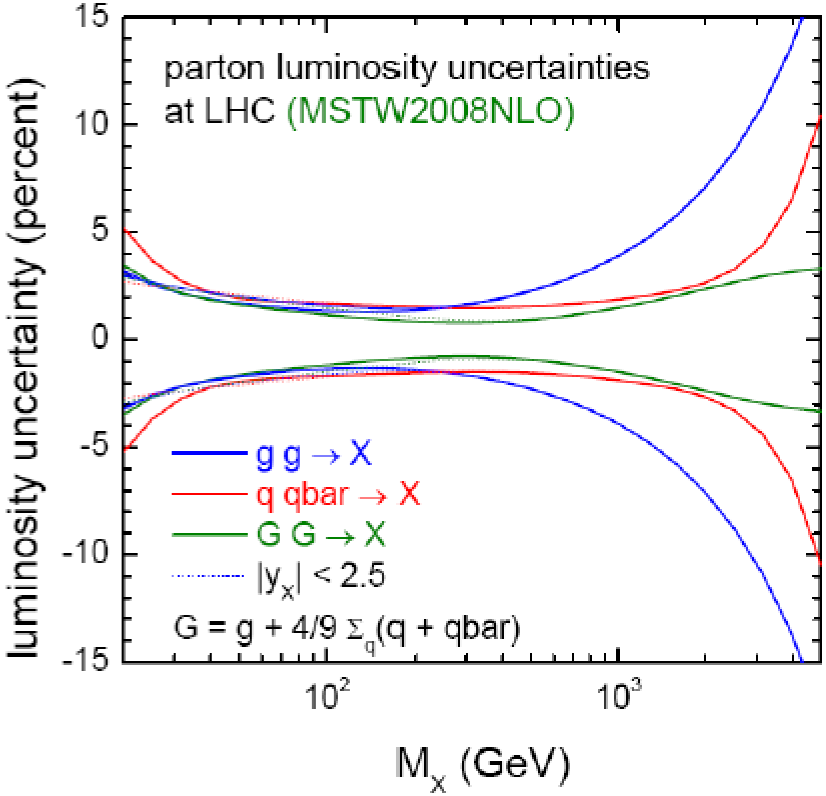
Details of 2011 running

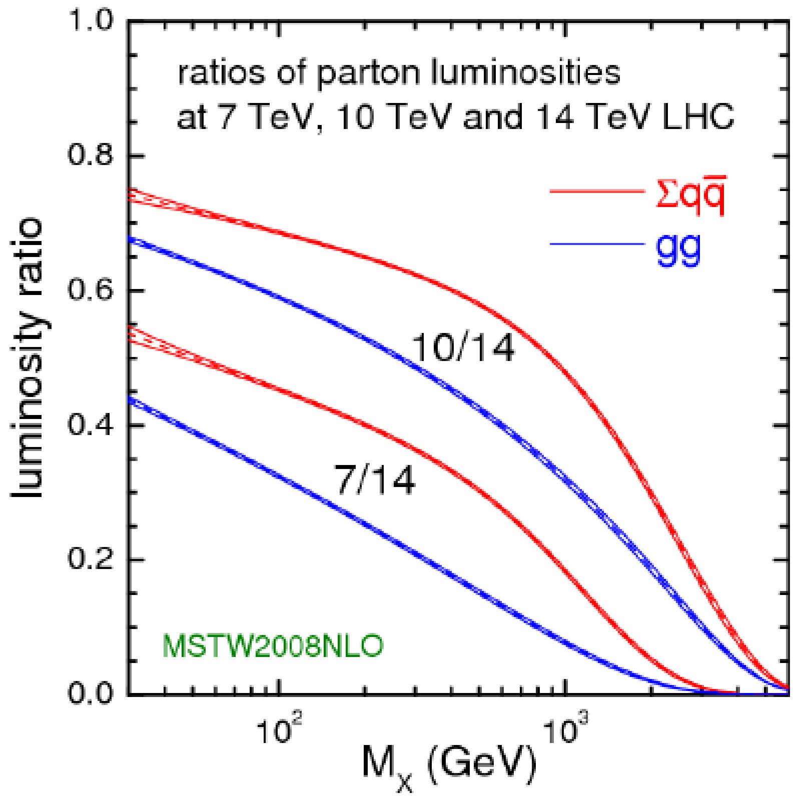
- Large, but smooth growth in instantaneous luminosity
- 50ns bunches → already explored pileup conditions with <n> up to 15-20



Parton Luminosities

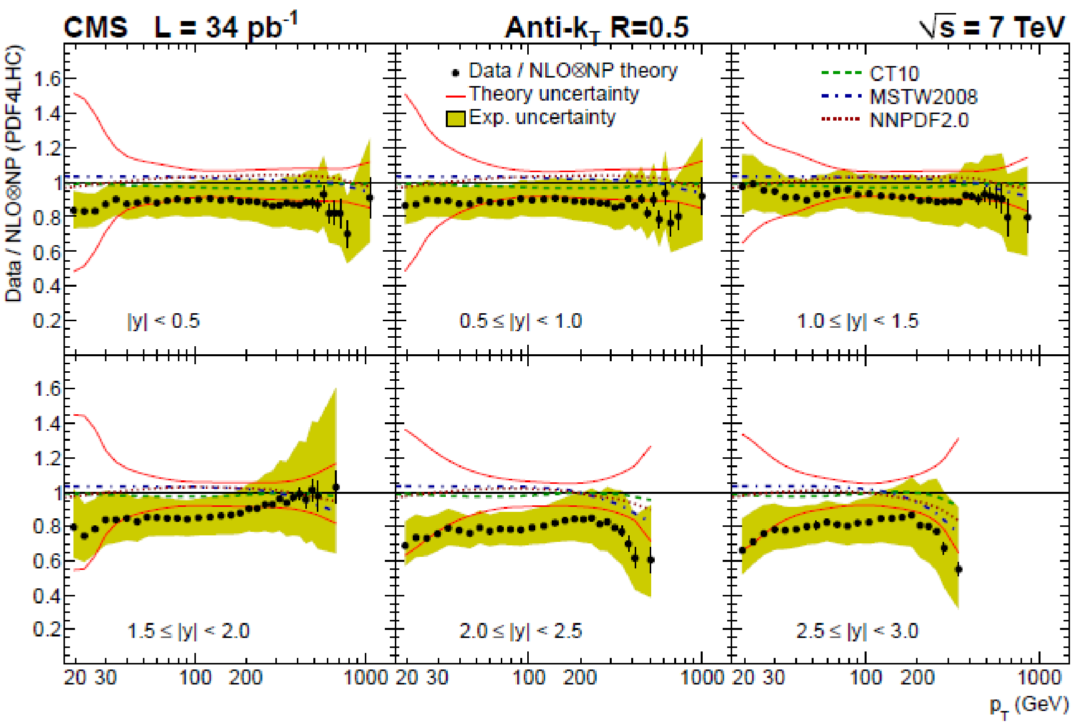
- The PDF uncertainties have a large impact in the prediction of cross sections in the low- and high- "effective mass" domains
- Running at higher energy rapidly improves the reach – at M=1 TeV the improvement of 10 over 7 TeV cms energy is already a factor of two for q-qbar annihilation processes

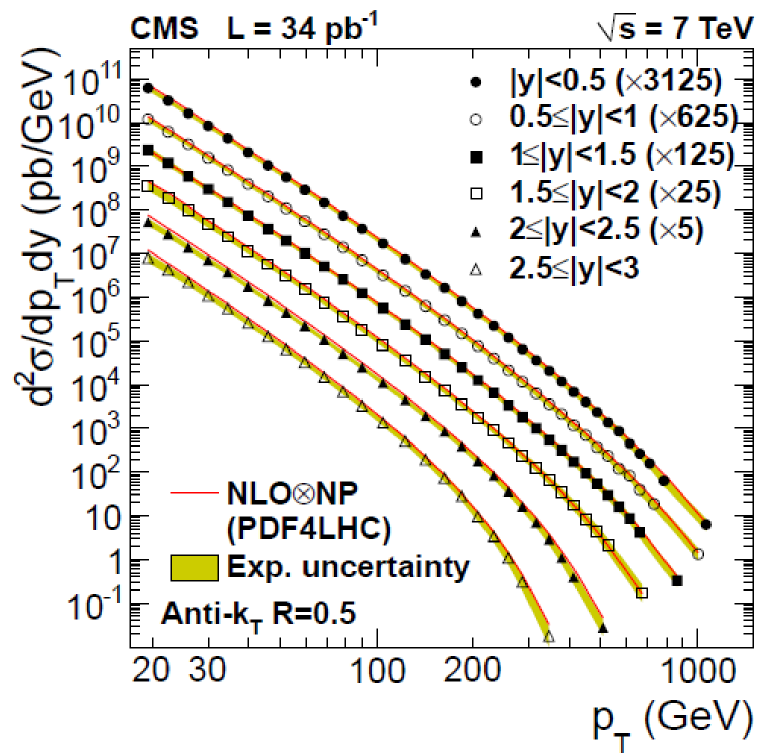


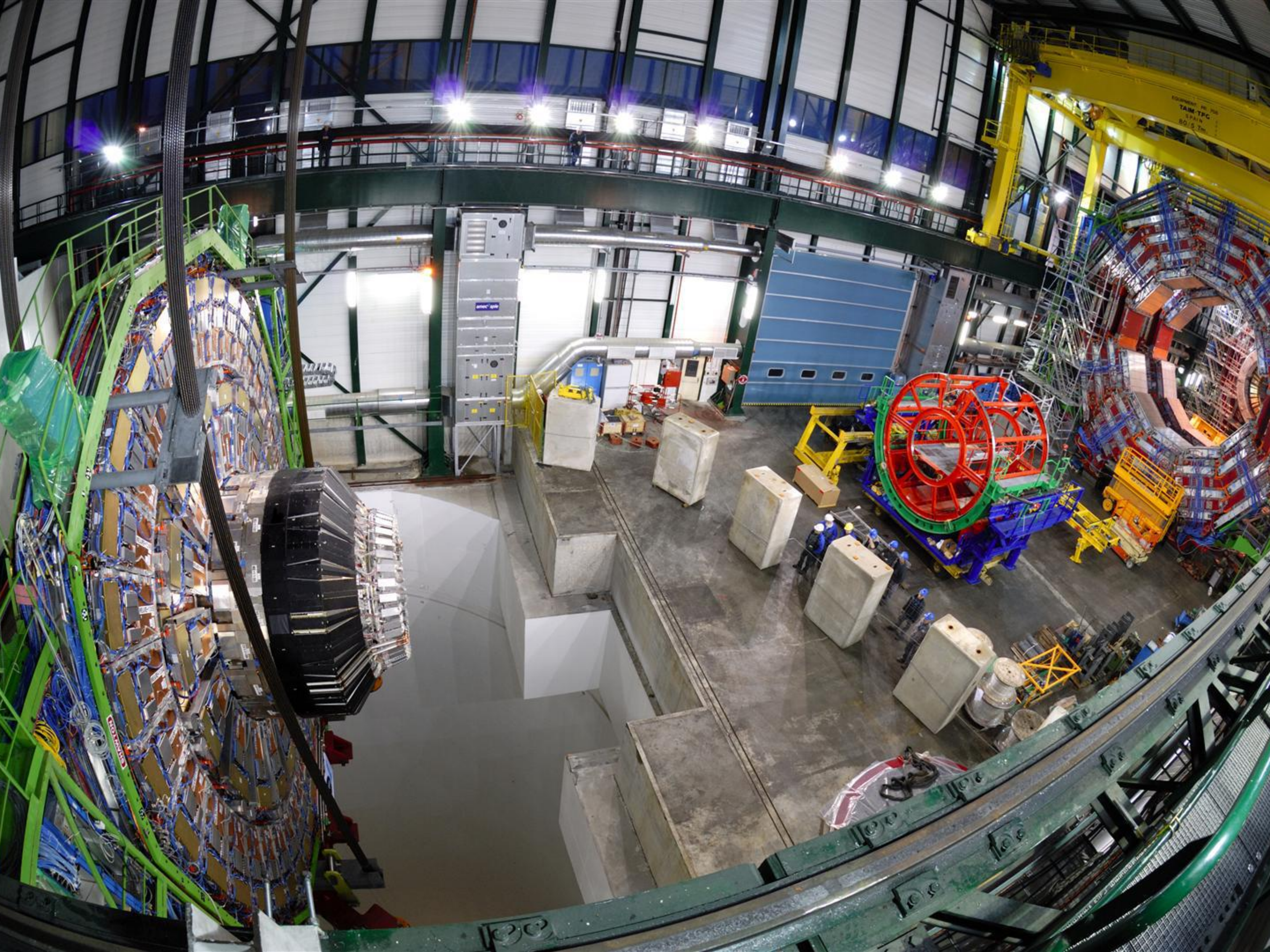


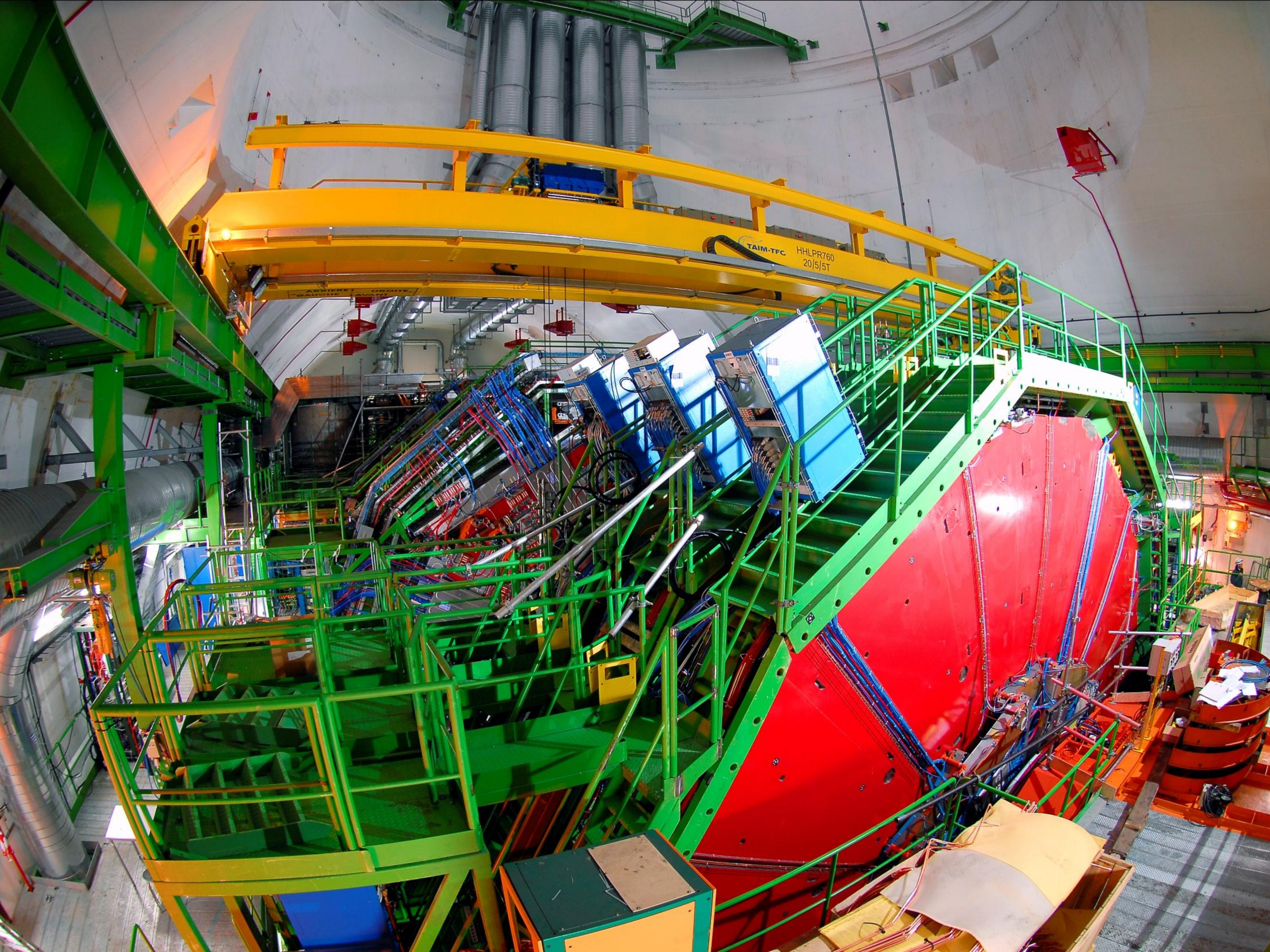
QCD: Jet Cross Sections

- 2010 data was used for a double-differential cross section for inclusive-jet production
- Jets are clustered with the Anti-K_T calgorithm (R=0.5)
- Momentum scale and resolution dominate total uncertainty
- Results agree very well – over 12 orders of magnitude! - with NLO predictions corrected for non-perturbative effects (hadronization, multiple-parton interaction effects: Pythia 6.422, Herwig++ 2.4.2) and using the PDF4LHC recommendations






TAIM-TFG
SPAIN
80/5 Tm.


TAIM-TFC
HHLPR760
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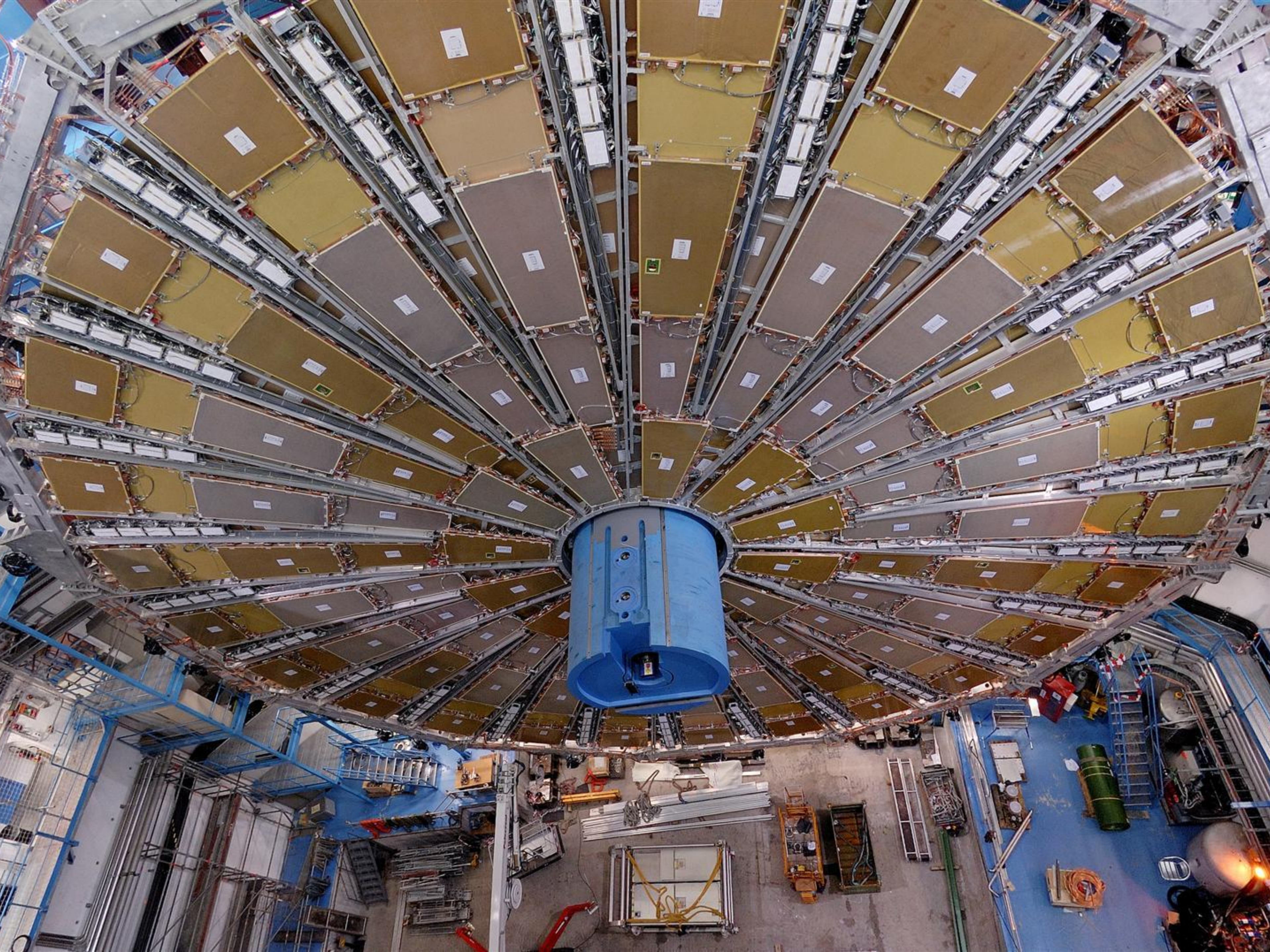
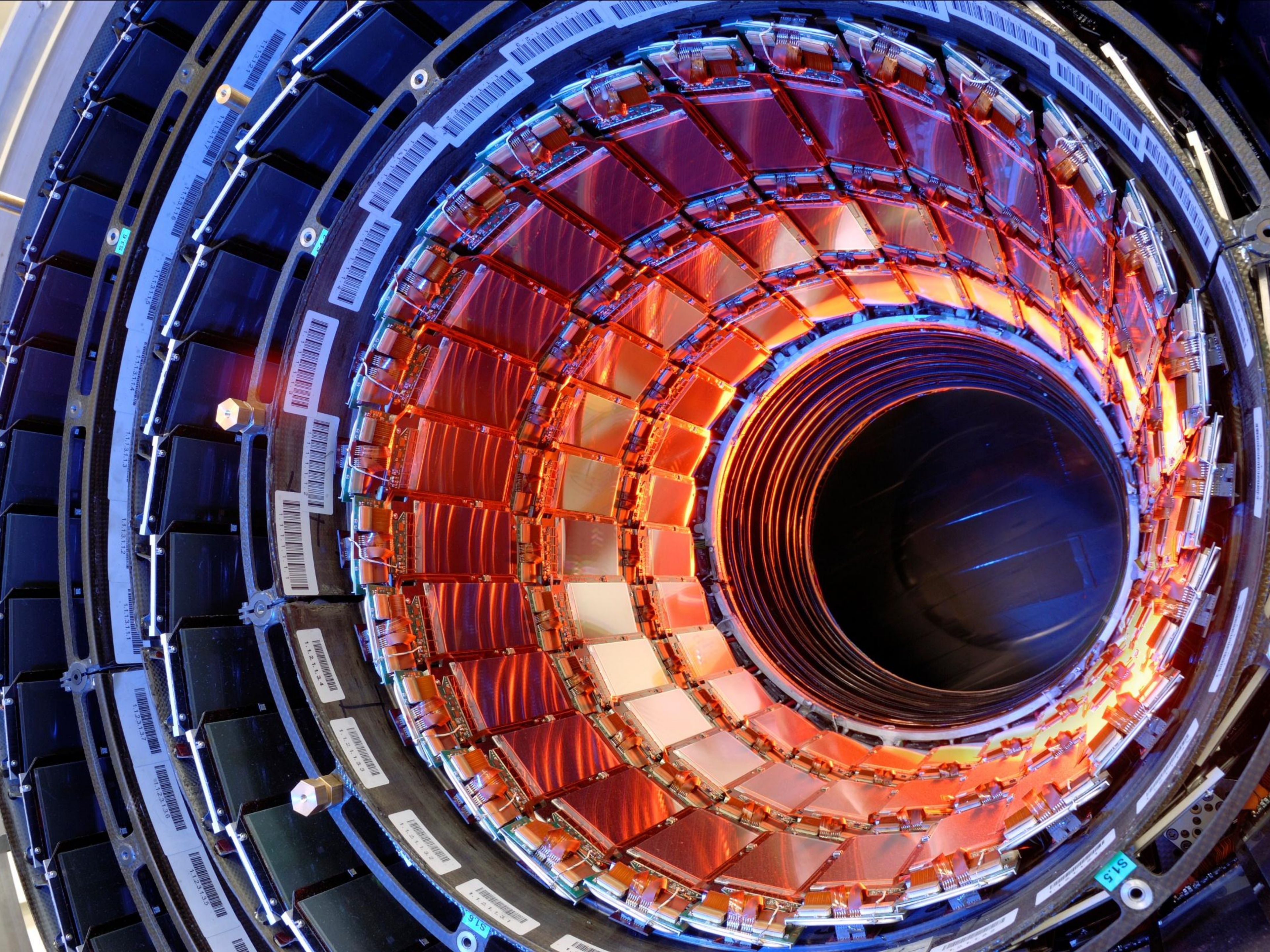
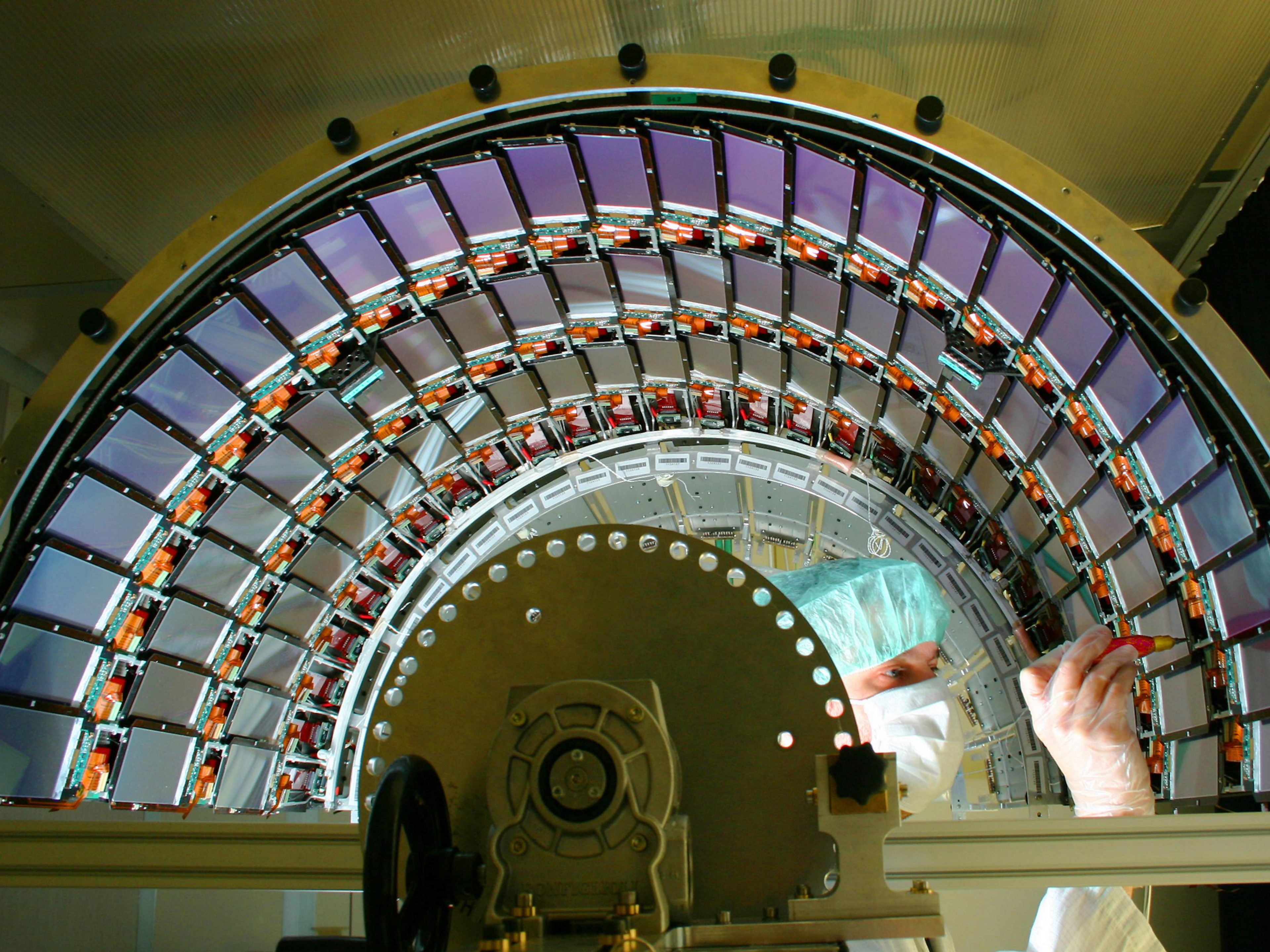
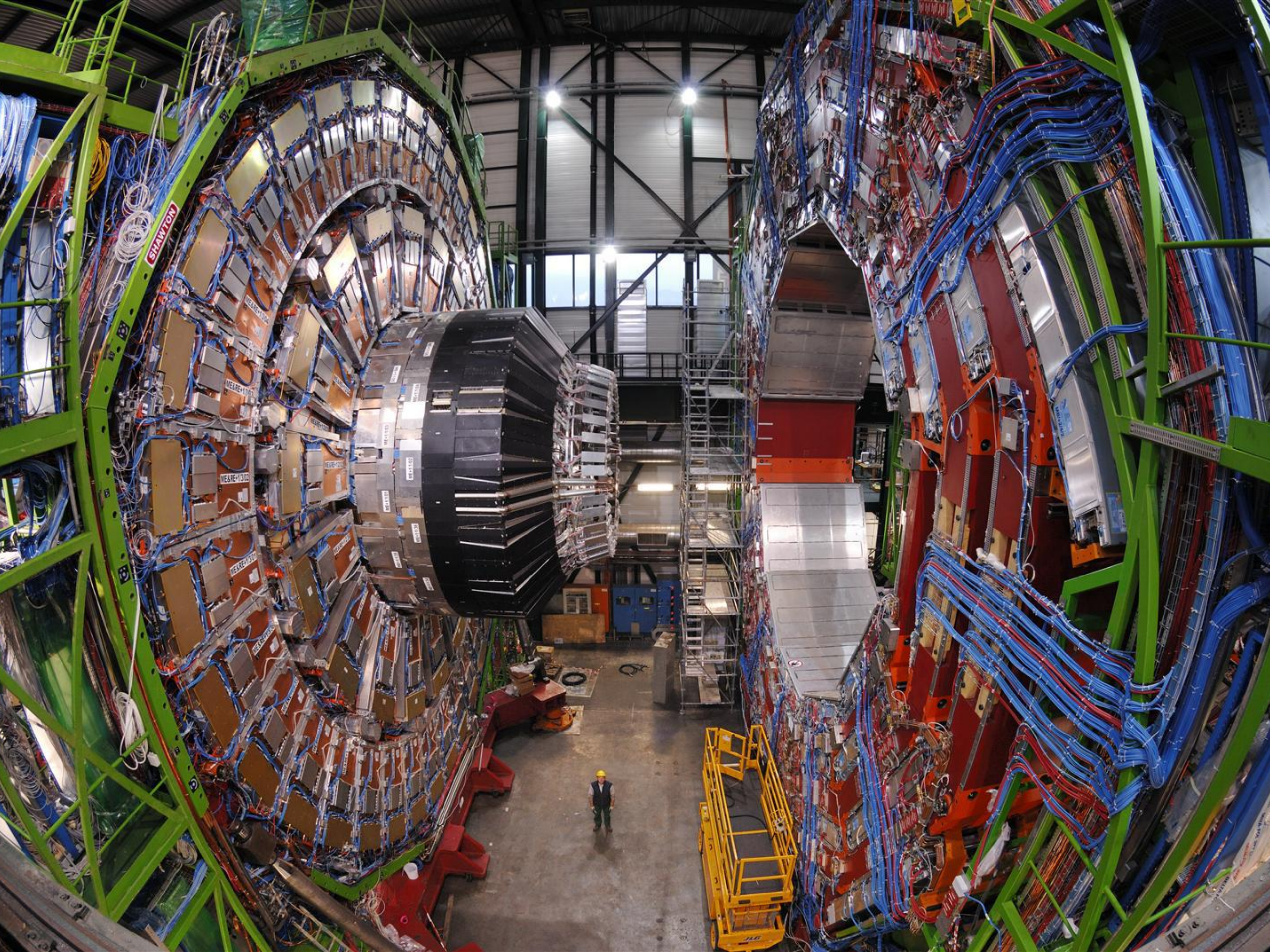



S15
S16




SHAWTON