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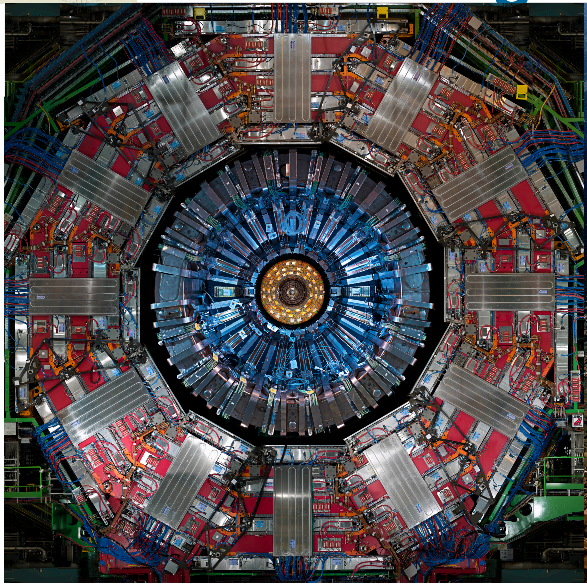
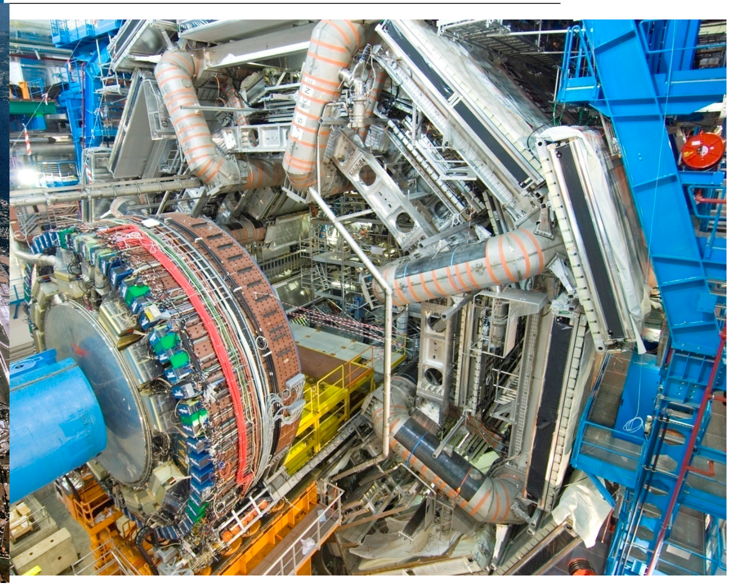
The Quest for the Higgs boson at the LHC
Highlights and Future Perspectives

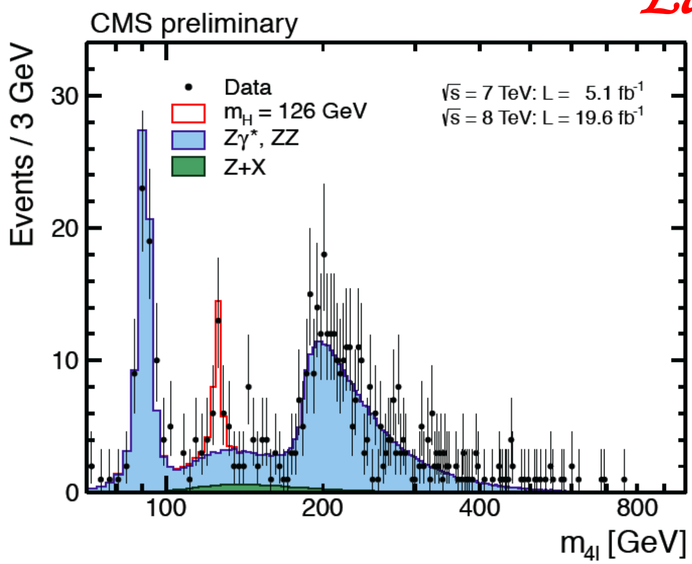


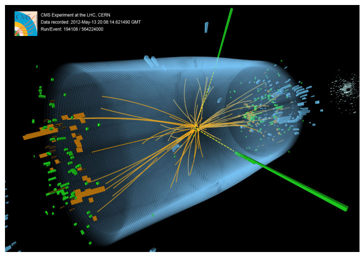


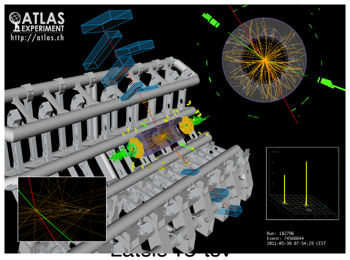
Nature at the Energy Frontier

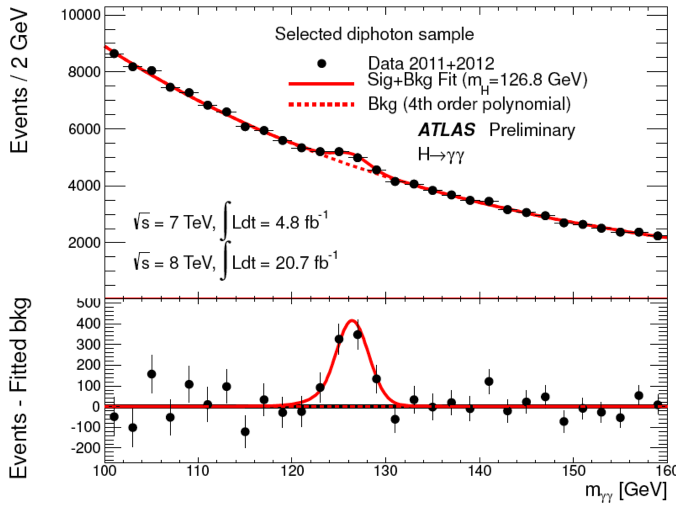
Latsis Symposium

ETH Zurich, 3rd June 2013







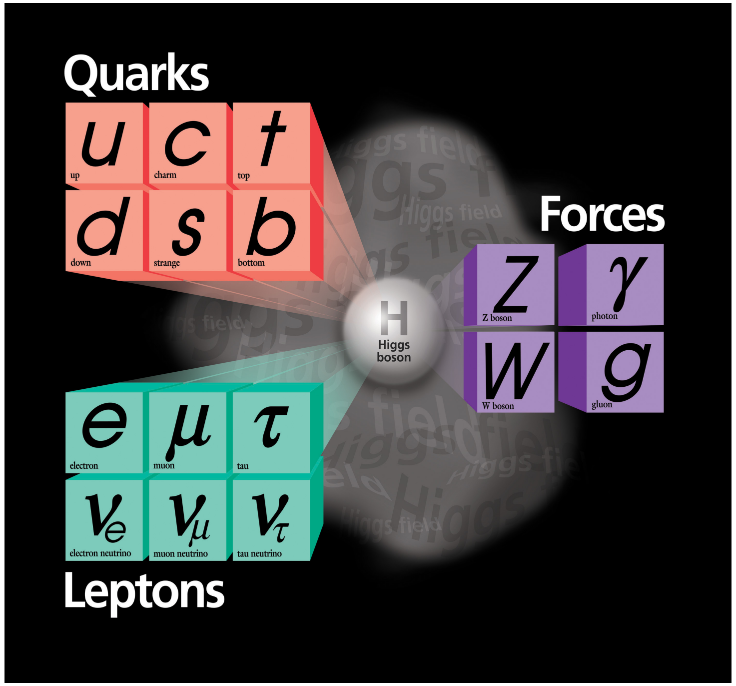


T. S.Virdee, Imperial College

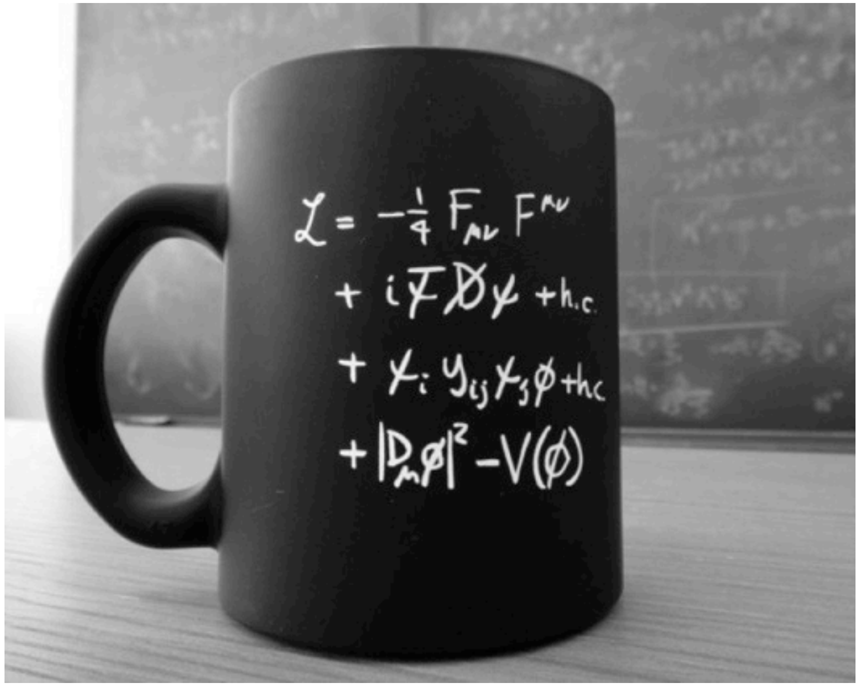
The Standard Model of Particle Physics

A crowning achievement of 20th Century Science

Matter particles



Force particles



The SM has been tested thousands of times, to excellent precision.
Its most basic mechanism, that of granting mass to particles, needed elucidation, => the Higgs boson?

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Physics Outlook: Questions

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector

SM has an unproven element: the generation of mass

Higgs mechanism ->? or other physics ?

Answer will be found at **LHC energies**

e.g. why $M_{\gamma} = 0$

M_W, $M_Z \sim 100,000$ MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs exists all is not well with SM alone: next question is "why is (Higgs) mass so low"?

*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV)**

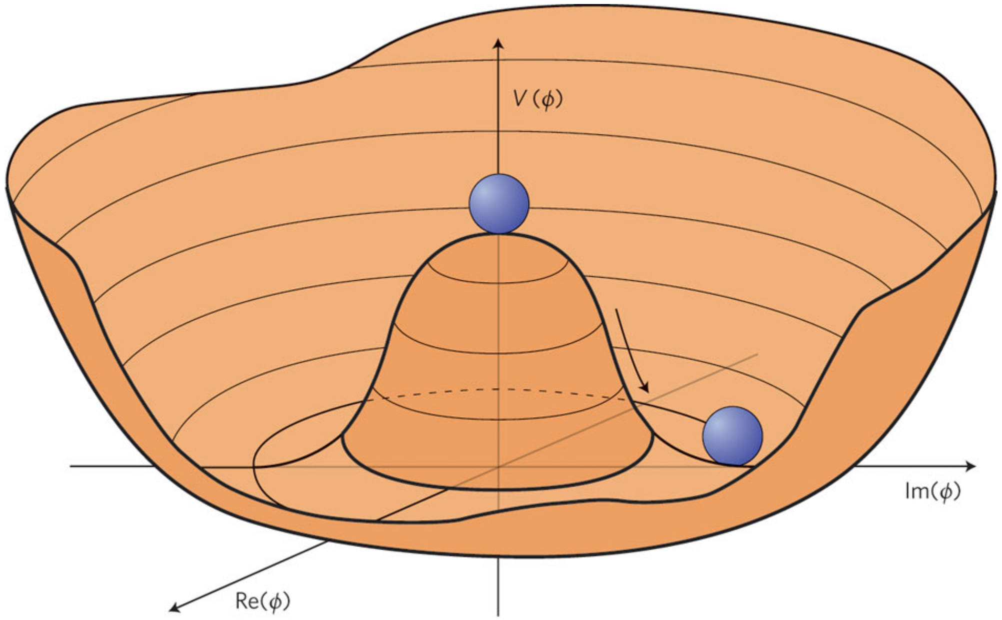
5. Search for new physics at the TeV scale

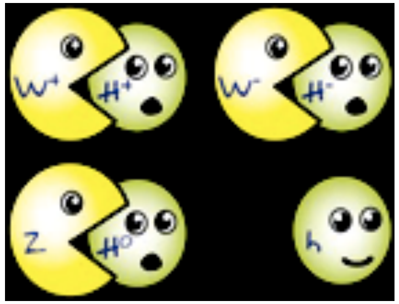
SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

Spontaneous Symmetry Breaking

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda^2 \left(\Phi^\dagger \Phi\right)^2$$





Unbroken Gauge Theory
Massless Gauge Bosons

SSB

EW Theory
Massive $W^\pm$, Z
Massless γ

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Almost 50 years ago – the seminal papers

Higgs

An Intellectual Conjecture: The 1st references in ATLAS/CMS Discovery papers

[1] F. Englert and R. Brout, "Broken symmetry and the mass of gauge vector mesons", *Phys. Rev. Lett.* **13** (1964) 321, doi:10.1103/PhysRevLett.13.321.

[2] P. W. Higgs, "Broken symmetries, massless particles and gauge fields", *Phys. Lett.* **12** (1964) 132, doi:10.1016/0031-9163(64)91136-9.

[3] P. W. Higgs, "Broken symmetries and the masses of gauge bosons", *Phys. Rev. Lett.* **13** (1964) 508, doi:10.1103/PhysRevLett.13.508.

[4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, "Global conservation laws and massless particles", *Phys. Rev. Lett.* **13** (1964) 585, doi:10.1103/PhysRevLett.13.585.

These papers on the *spontaneous symmetry breaking mechanism* attracted very little attention at the time. The *boson* attracted even less interest (T. Kibble, 2011)

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Nature at the energy frontier

Almost 50 years ago – the seminal papers

References in ATLAS/CMS Discovery papers

[6] T. W. B. Kibble, "Symmetry breaking in non-Abelian gauge theories", *Phys. Rev.* **155** (1967) 1554, doi:10.1103/PhysRev.155.1554.

Further work on the detailed application of the SSB mechanism to non-abelian theories. This work helped in getting to electroweak unification.

Describes the real world: photon massless, W/Z massive"
F. Close, "Infinity Puzzle"

[7] S. L. Glashow, "Partial-symmetries of weak interactions", *Nucl. Phys.* **22** (1961) 579, doi:10.1016/0029-5582(61)90469-2.

[8] S. Weinberg, "A Model of Leptons", *Phys. Rev. Lett.* **19** (1967) 1264, doi:10.1103/PhysRevLett.19.1264.

[9] A. Salam, "Weak and electromagnetic interactions", in *Elementary particle physics: relativistic groups and analyticity*, N. Svartholm, ed., p. 367. Almqvist & Wiskell, 1968. Proceedings of the eighth Nobel symposium.

SU(2)XU(1): Unified model of weak and electromagnetic interactions of leptons proposed by Weinberg (1967), and independently by Salam (1968).
Labeled electroweak theory by Salam

Electro-weak Unification: seminal papers

A Model of leptons (S. Weinberg, 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

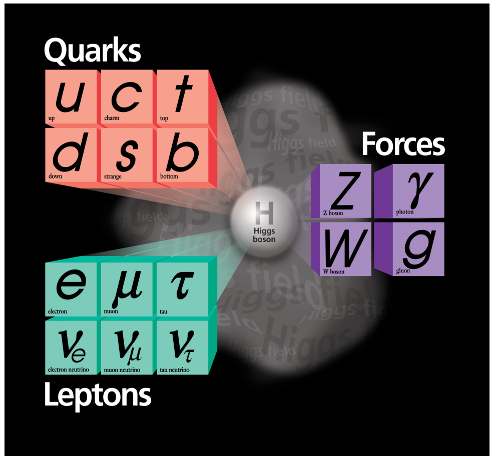
[3]P. W. Higgs, Phys. Letters 12, 132 (1964), Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964).

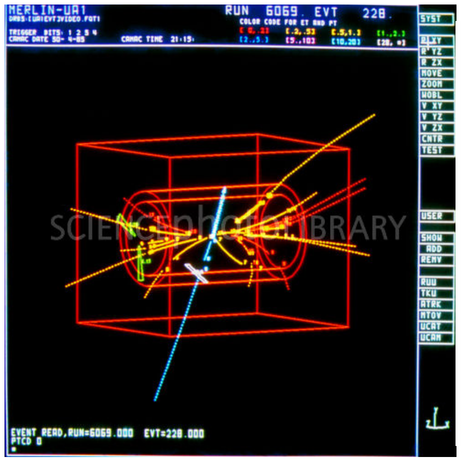
Further Theoretical and Experimental Developments

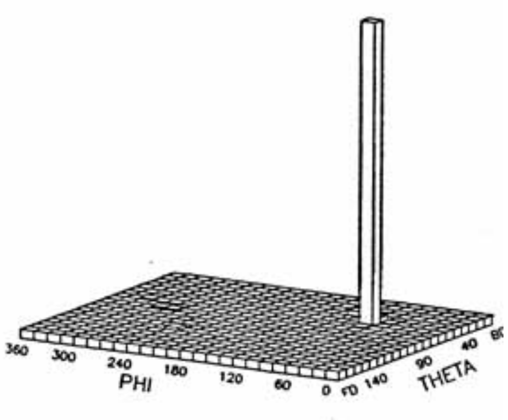
Salam and Weinberg speculated that their theory was renormalizable
This was proven in 1971 (by Gerard ’t Hooft & Tini Veltman)

In 1973 a key prediction of the e-w theory, the existence of neutral current interactions — those mediated by Z^0 — was confirmed at CERN.

In 1983 the *W* and *Z* particles were discovered at CERN (UA1 and UA2)
***then* the Higgs boson became the last important missing piece of SM!**







A Phenomenological Profile of the Higgs Boson

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

Reviewed Higgs decay modes and status of the searches in 1975

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

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Timeline of the LHC Project

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia "**Long-Range Planning Committee**" recommends Large Hadron Collider as the right choice for CERN's future

1990 ECFA LHC Workshop, Aachen

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 **Letters of Intent** (ATLAS and CMS selected by LHCC)

1994 Technical Proposals Approved

1997 Approval to move to **Construction** (materials cost of 475 MCHF)

1998 Memorandum of Understanding for Construction Signed

1998 Construction Begins (after approval of Technical Design Reports)

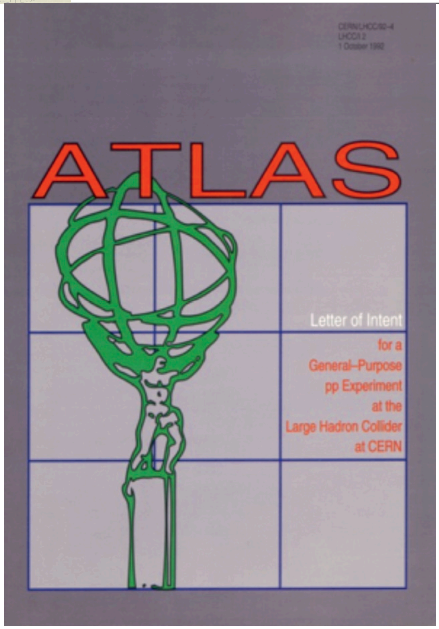
2000 ATLAS and CMS assembly begins above ground. LEP closes

2008 **ATLAS & CMS ready for First LHC Beams**

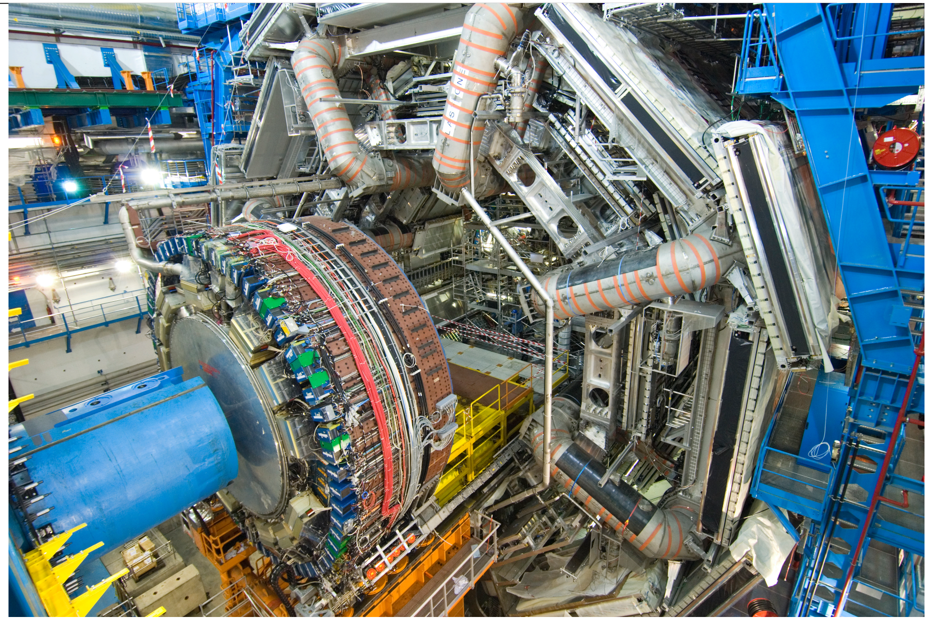
2009 First proton-proton collisions

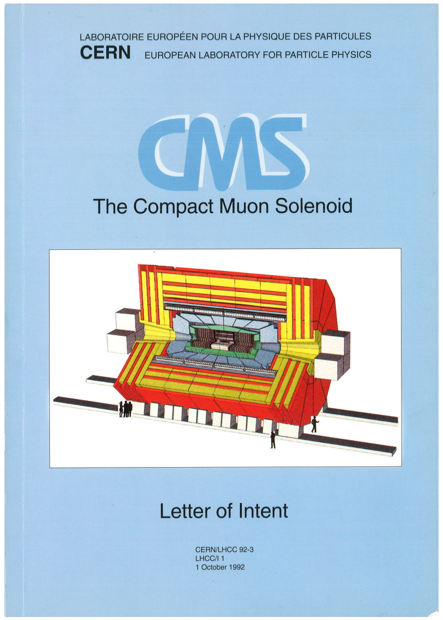
2012 A new heavy boson discovered with mass ~125 × mass of proton

20 Years Ago: Approval of ATLAS and CMS LoI

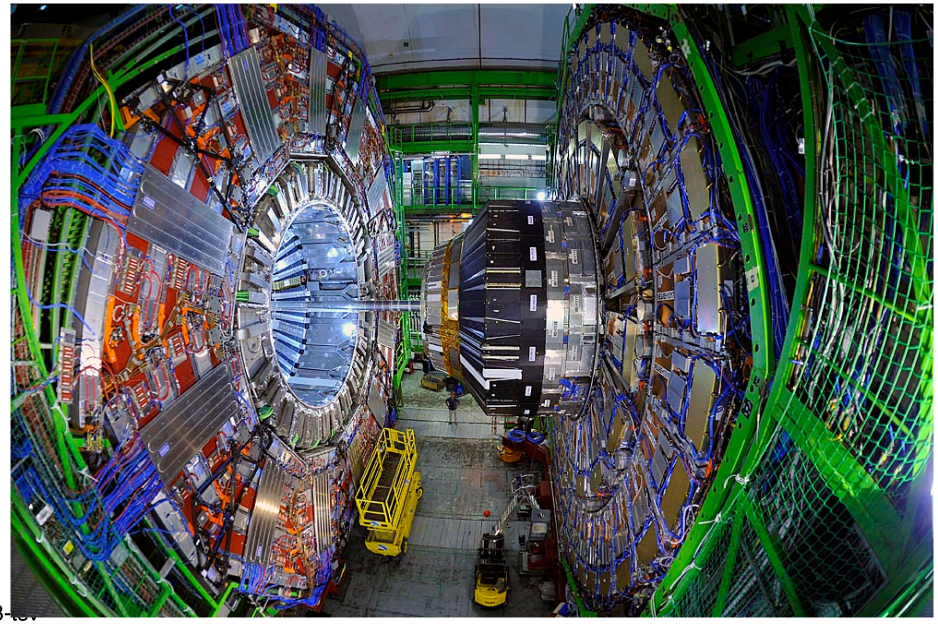


LHCC
June 1993





15 Years Later



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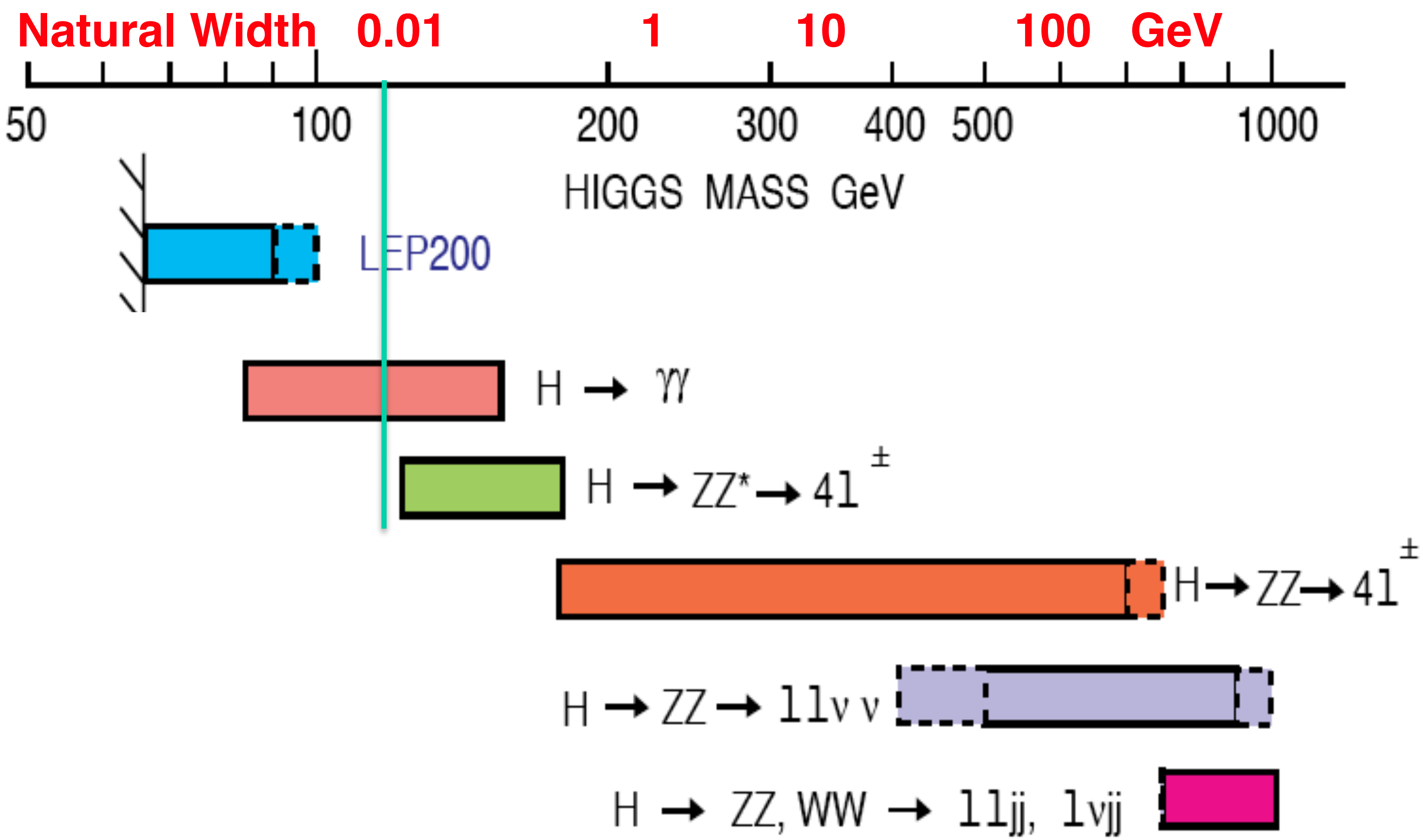
SM Higgs Boson as a Physics Benchmark For Detector Design



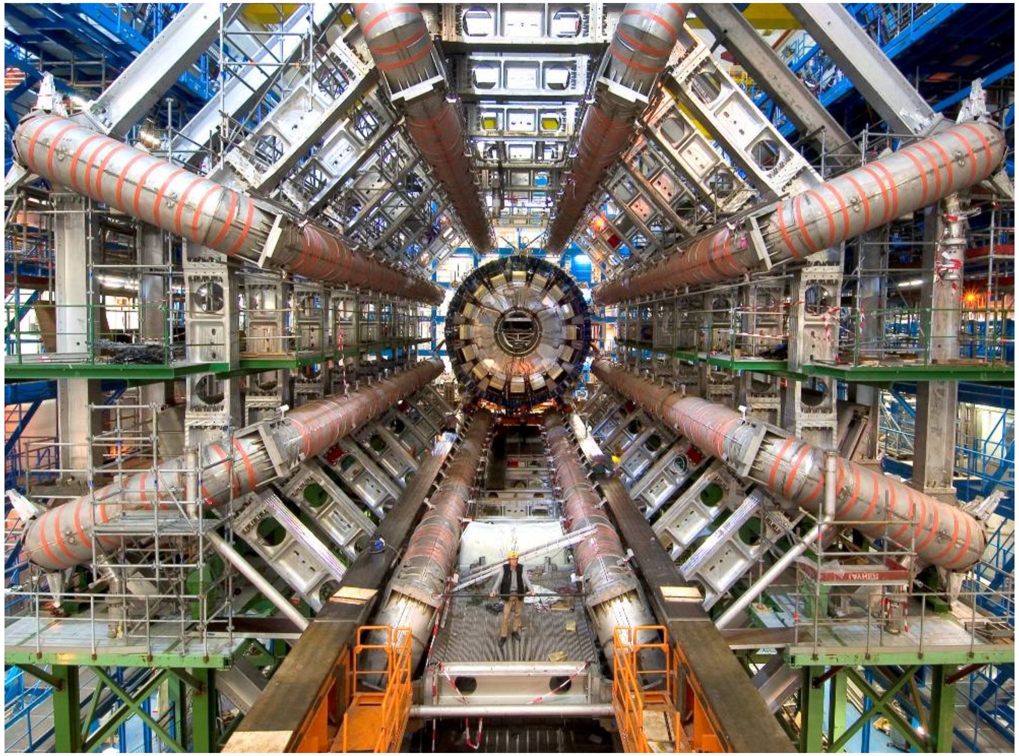
Theory does not predict m_H

The favourable decay modes change with mass

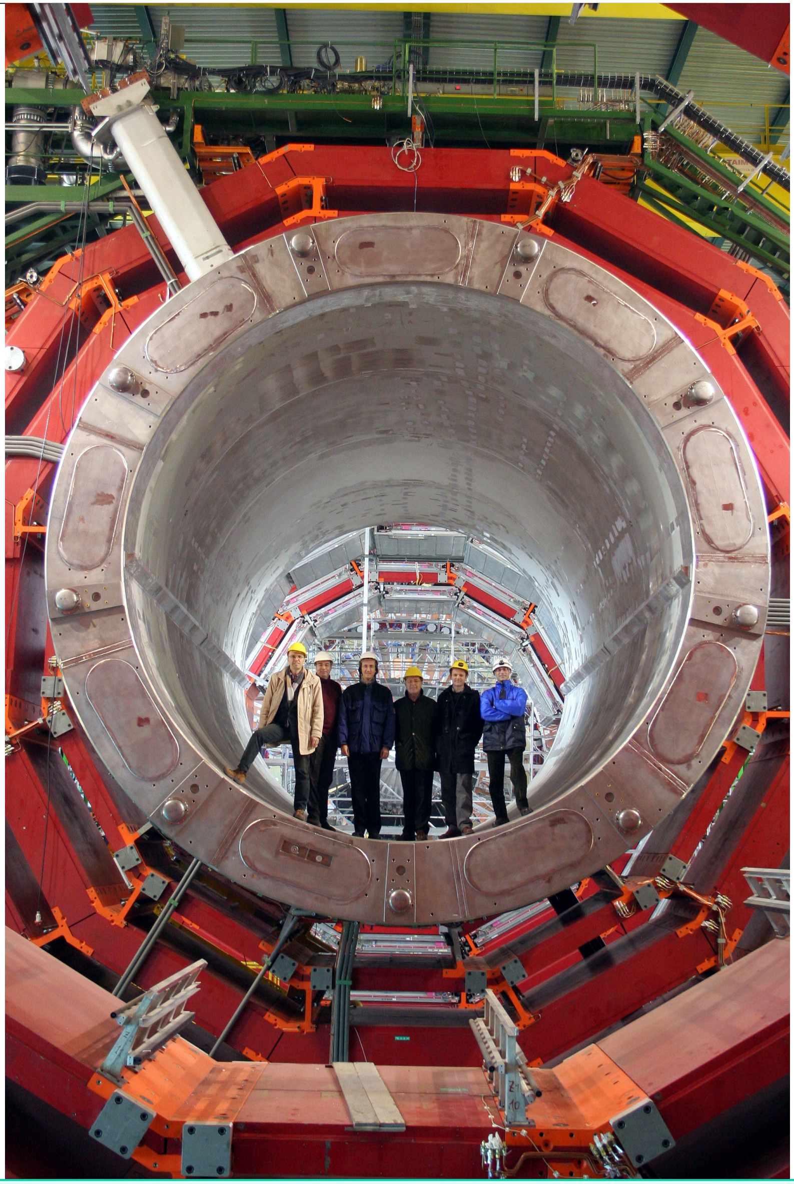
Transparency from the 90's

Designs of LHC-GPDs

Designs determined by the choice of magnet field configuration for the measurement of muons



ATLAS Superconducting Air-core Toroid



CMS Superconducting Solenoid

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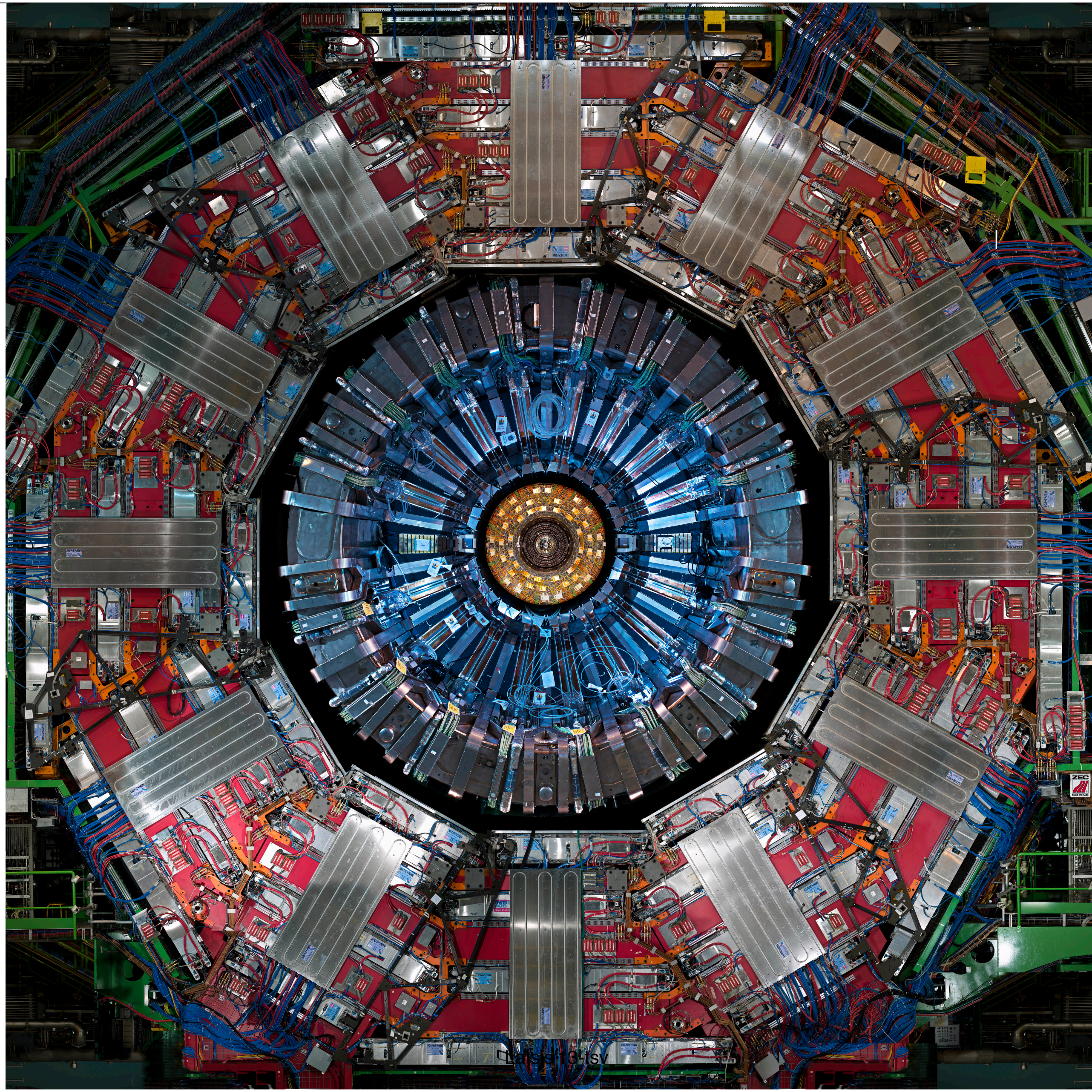
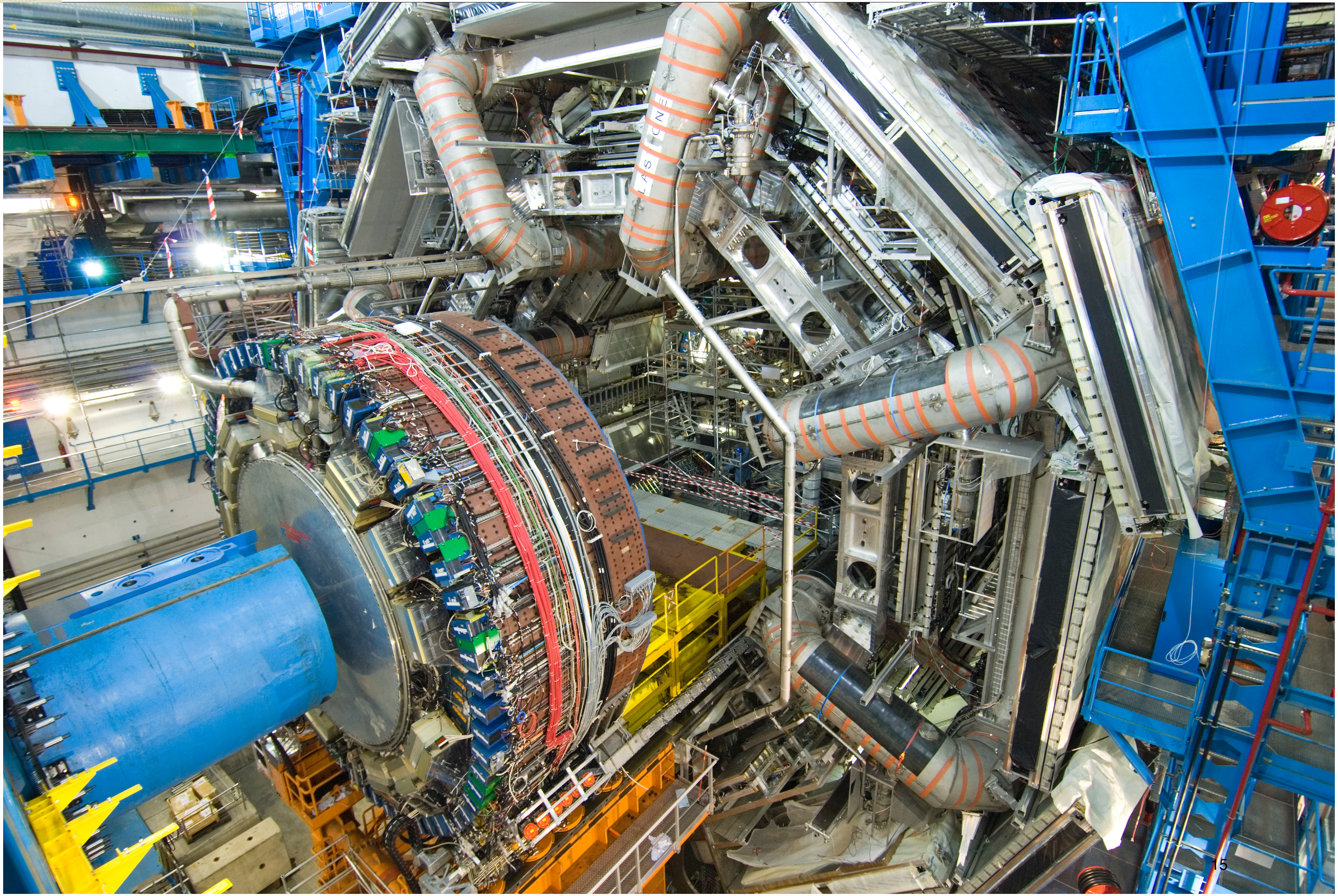
CMS Concept to Data Taking – took 18 Years!



Construction of the ATLAS Detector



An Example from the Construction of ATLAS and CMS

The Electromagnetic Calorimeters

Physics Drove the Design

Measure the energies of photons from
a decay of the Higgs boson
to a precision of ~ 0.5%
and mass to a precision of < 1%.

ATLAS Electromagnetic Calorimeter

From Concept to the Liquid Argon Calorimeter

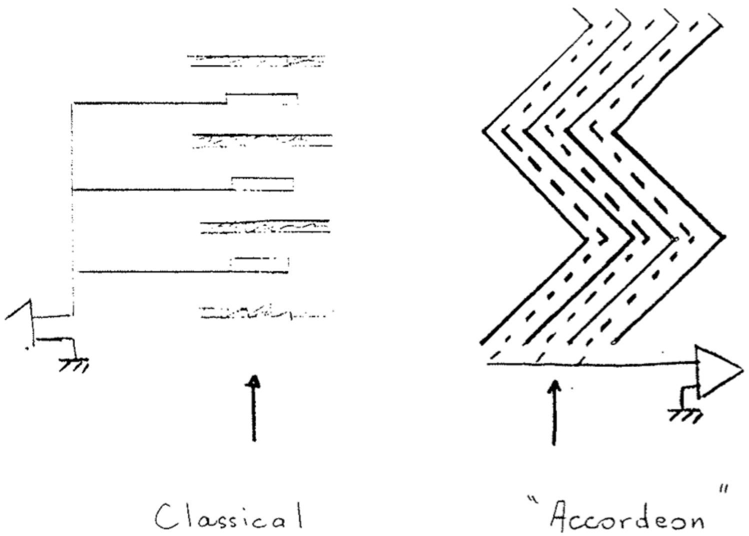
D.Fournier 5-jan-90

An approach to high granularity,fast Liq Ar calorimetry

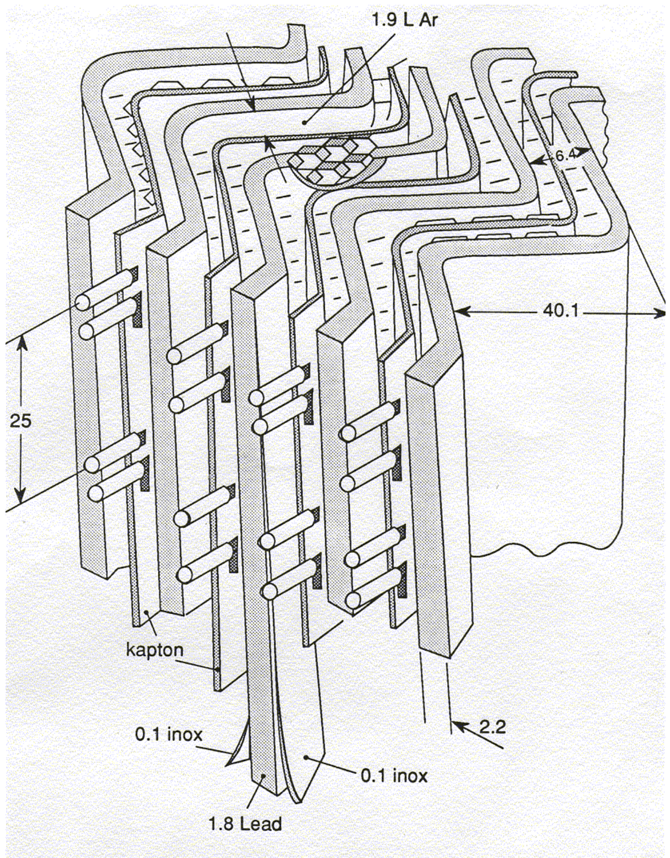
using an "accordeon" structure

1)BASIC IDEA

In the conventionnal approach of liquid argon calorimetry parallel electrodes are connected in parallel(or in serie in the ES transformer approach) to form a tower. Instead one consider here a scheme in which the converter plates and electrodes are at +- 45 degrees ,thus making an "automatic" connection of the elements forming a tower.
In this situation the incident particle makes an angle of 45 degrees with the converter plates.To first order resolution similar to the standard case is recovered by choosing converter plates thinner by sqrt(2).

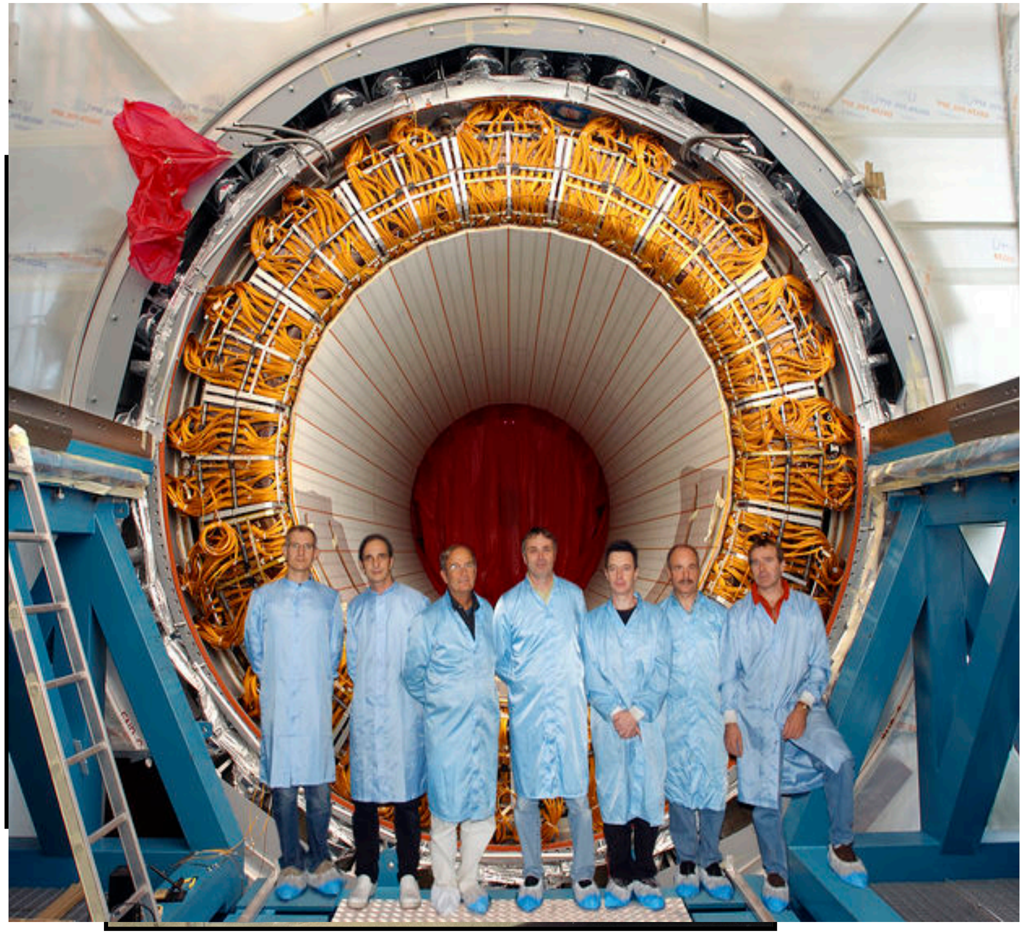


- a very stable and radiation hard detector
- easy to calibrate
- a lot of freedom in spatial granularity
- difficult to construct… cryogenics

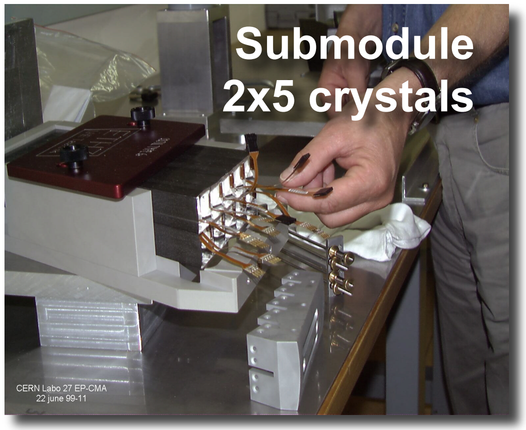


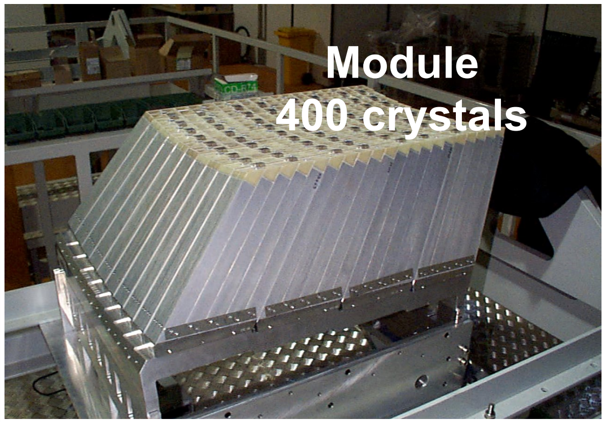
ATLAS Electromagnetic Calorimeter

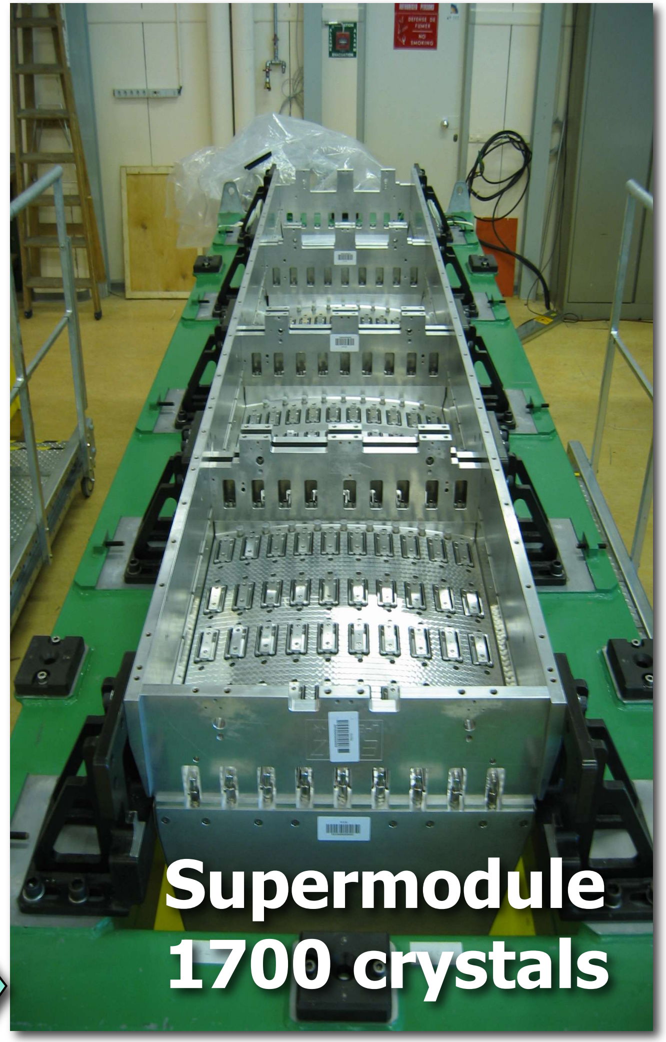
From Concept to the Liquid Argon Calorimeter



CMS Electromagnetic Calorimeter:
Lead Tungstate Scintillating Crystals



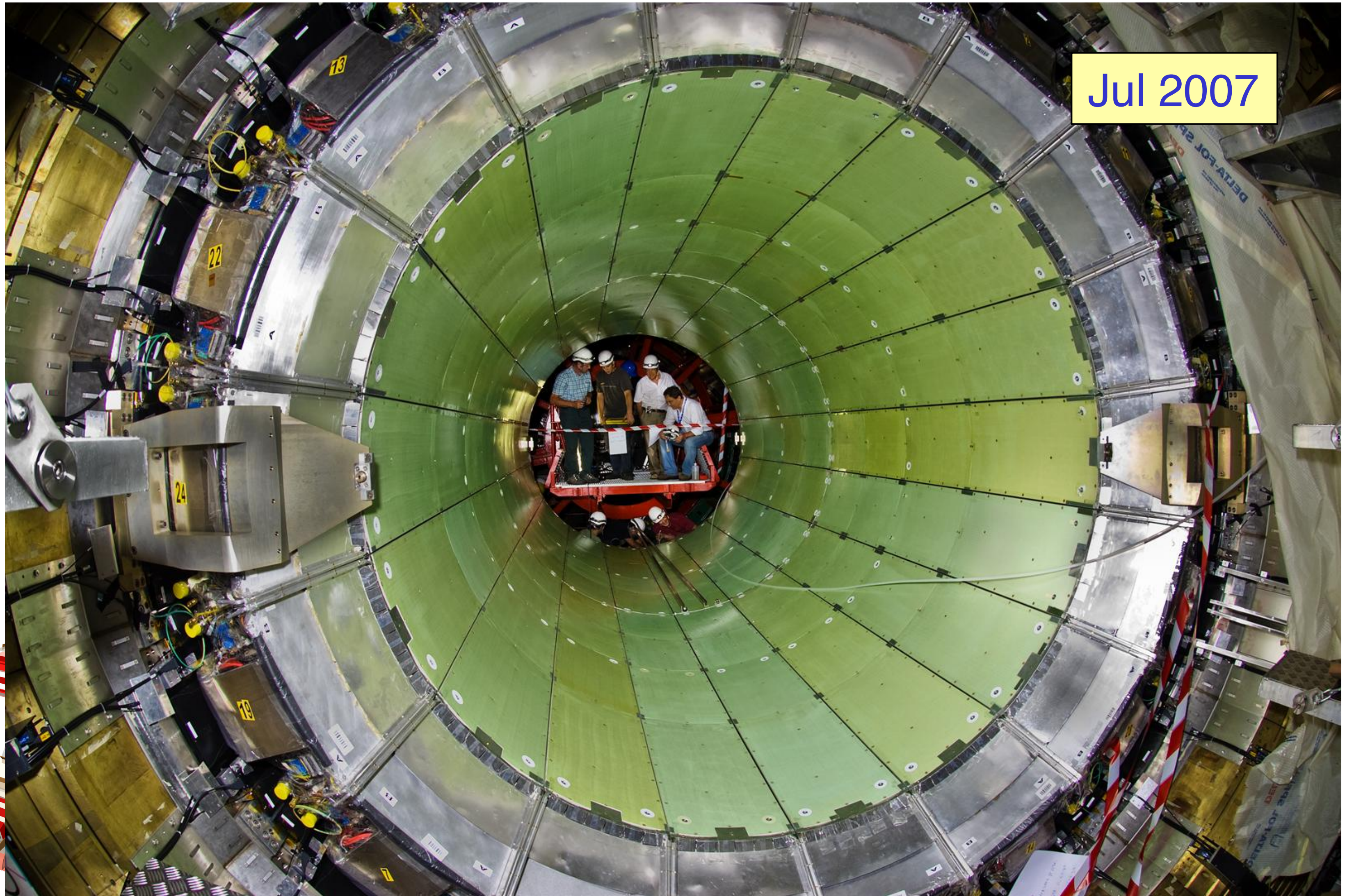


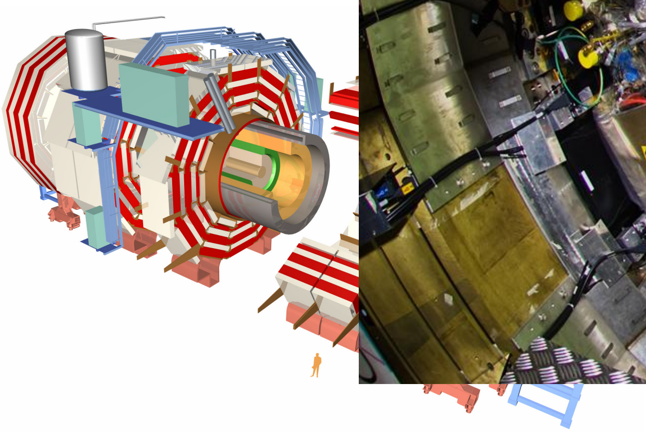


Total 36 Supermodules

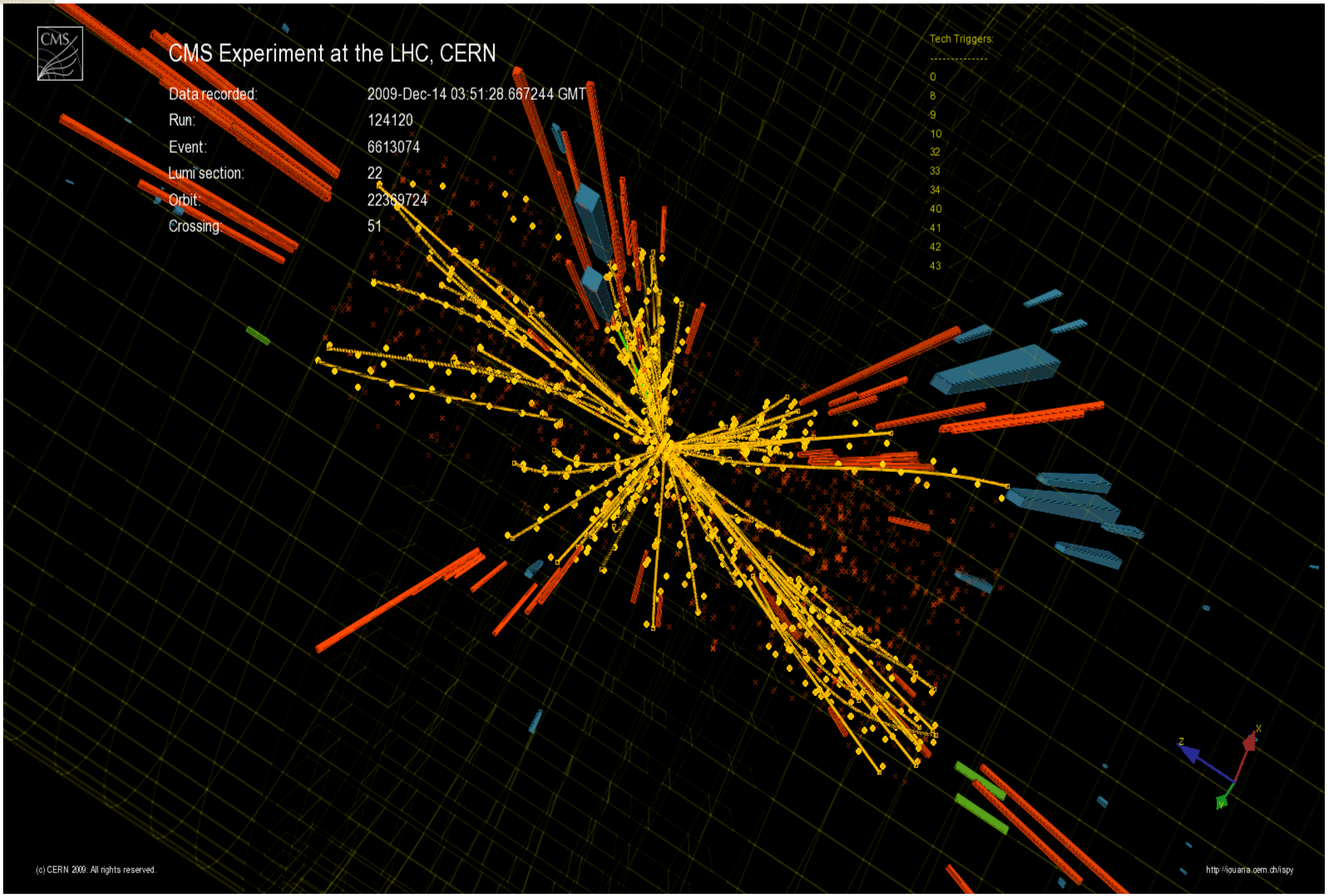
CMS Electromagnetic Calorimeter:

15 years from Concept - Installation

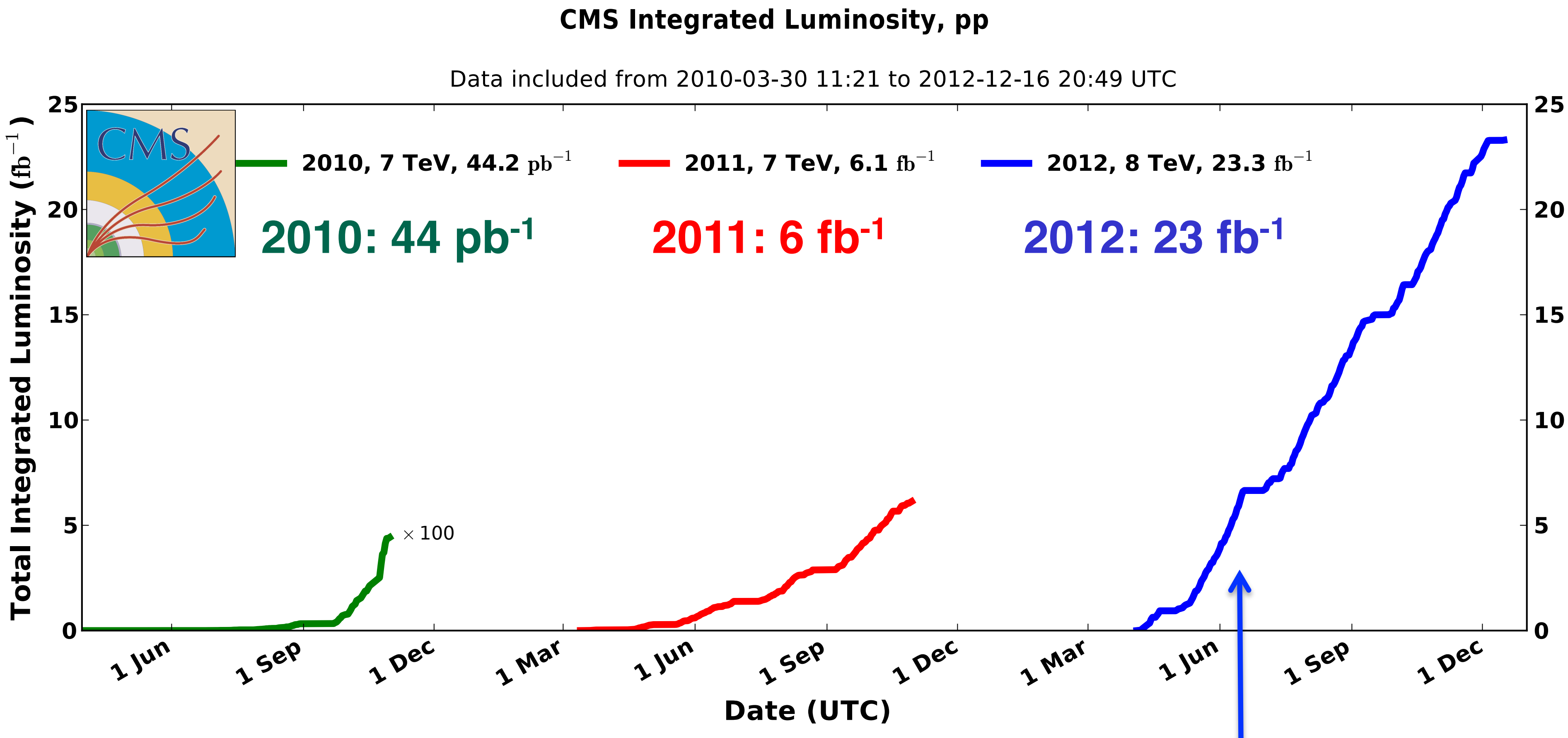




A proton-proton Collision at the LHC



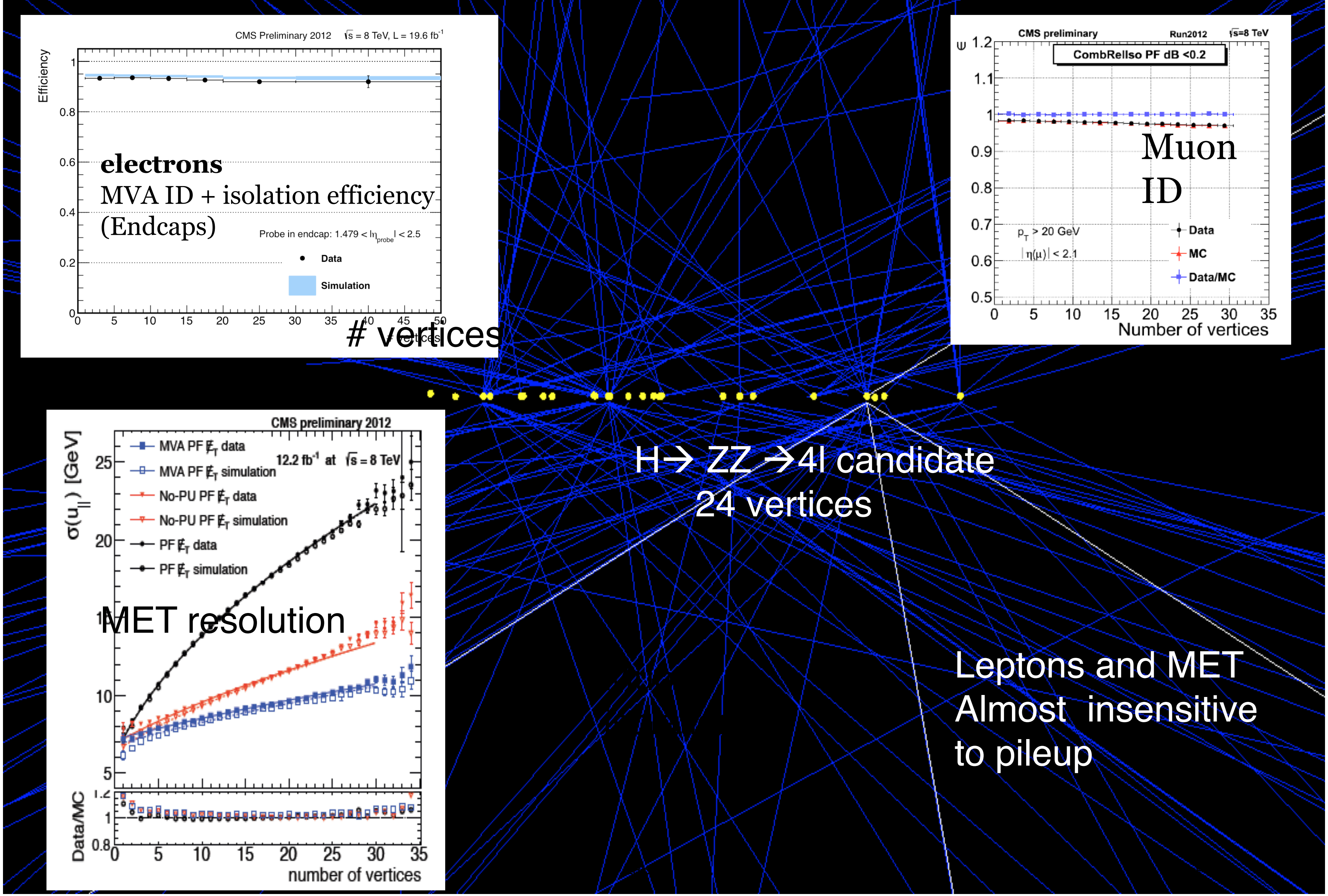
Run 1: The LHC has performed marvelously well!



Discovery of a new boson

$1 fb^{-1}$ equivalent to study of 80 trillion pp interactions

Performance under Pileup

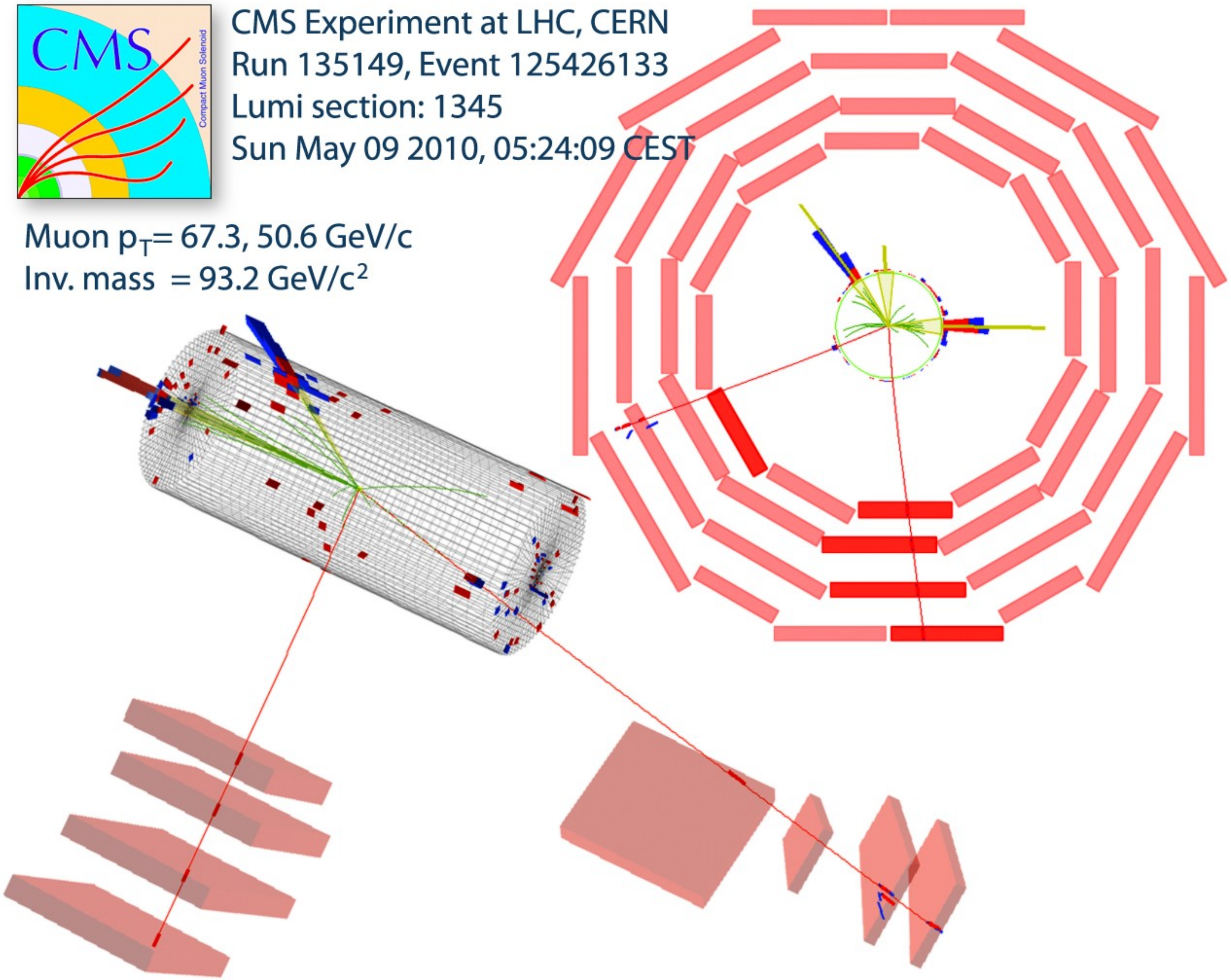


Going to the Science

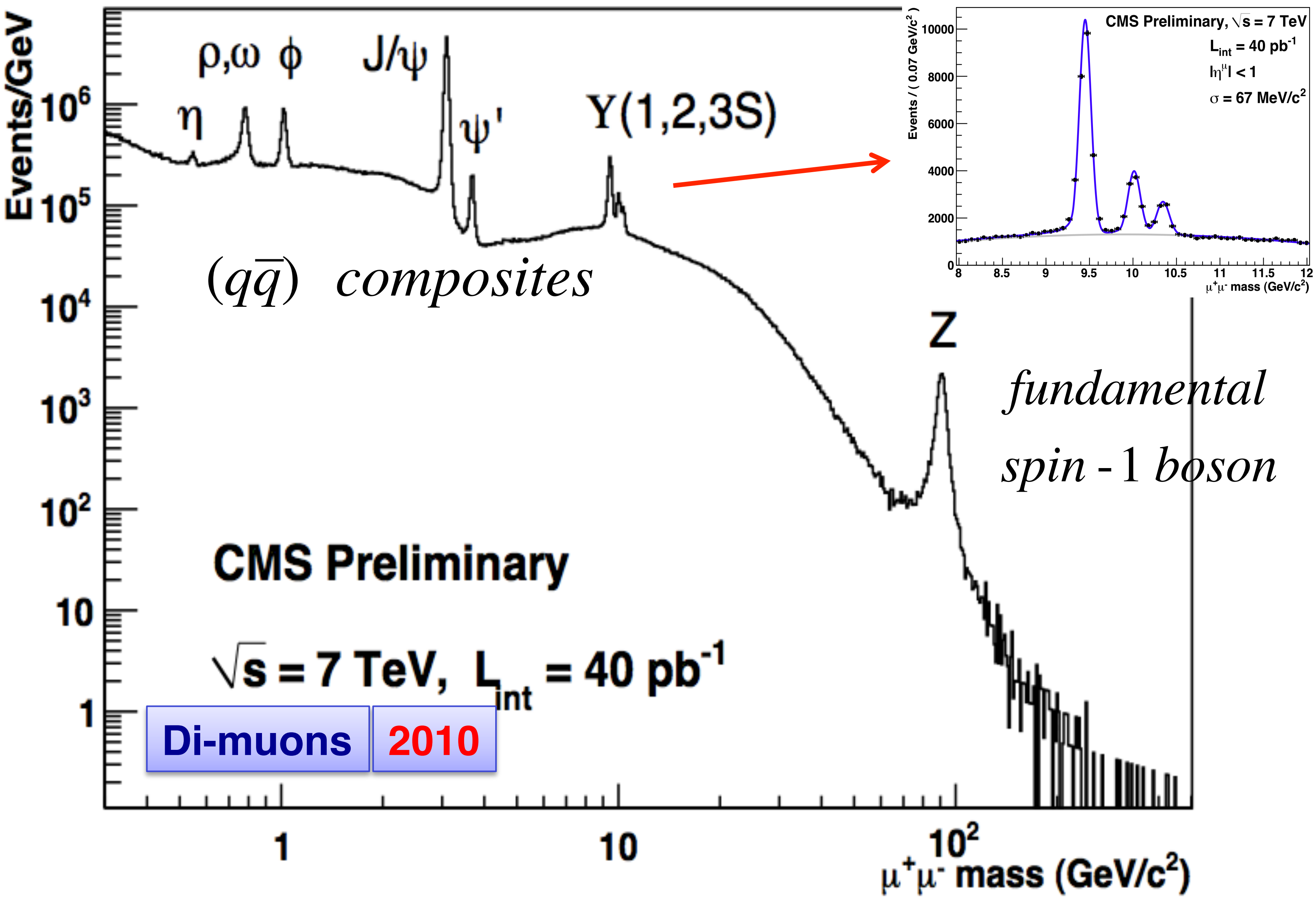
1. Do the experiments perform as designed?
2. Is known physics correctly observed?
3. Then look for new physics

We can only claim signals of new physics after having made measurements of already known physics that are consistent with the precise predictions of the Standard Model.

1. A Z boson decaying into $\mu^+ \mu^-$ pair

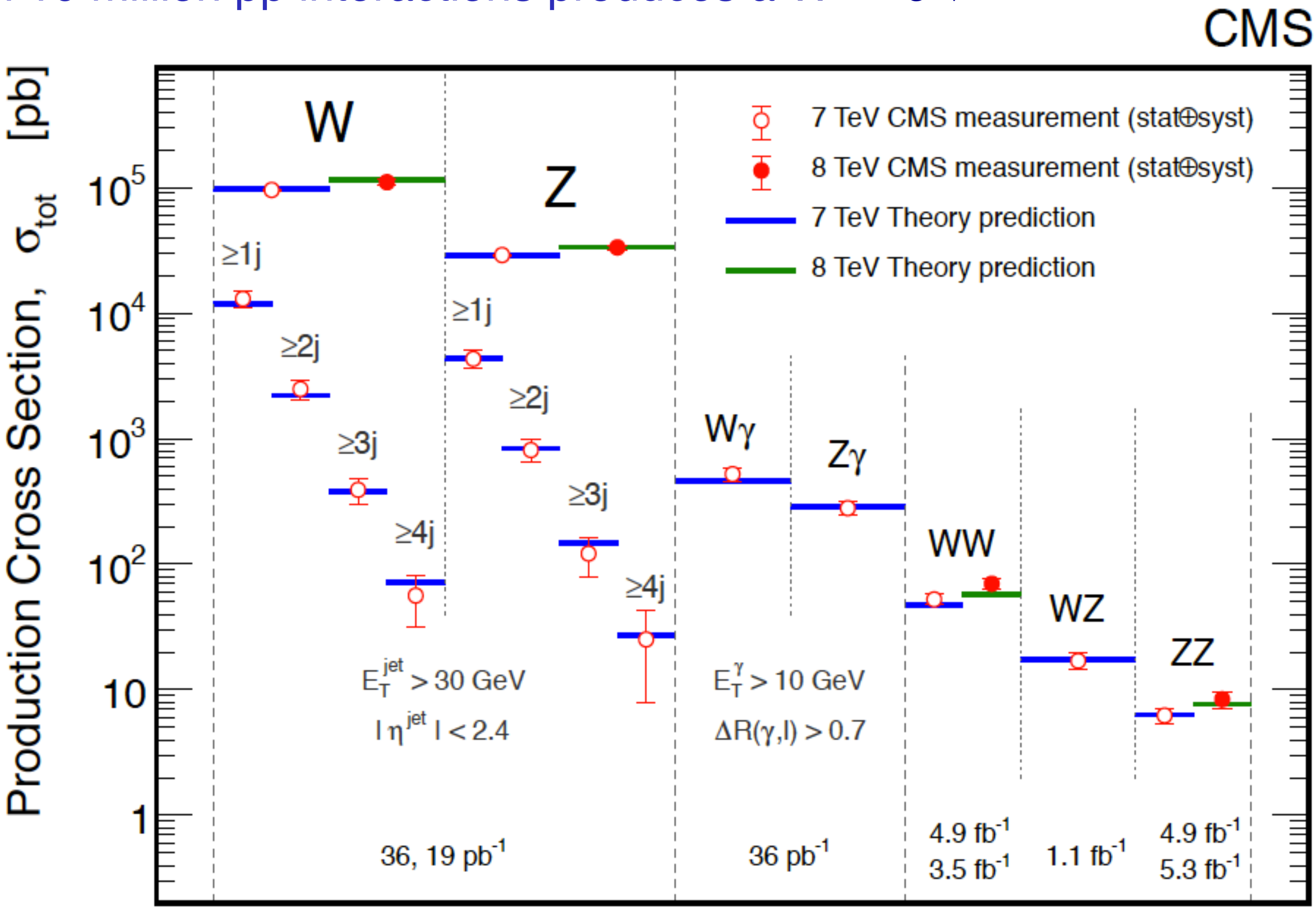


1. Performance of Experiment: e.g. CMS



2. SM Electroweak Measurements

1 in 10 million pp interactions produces a W → e ν



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

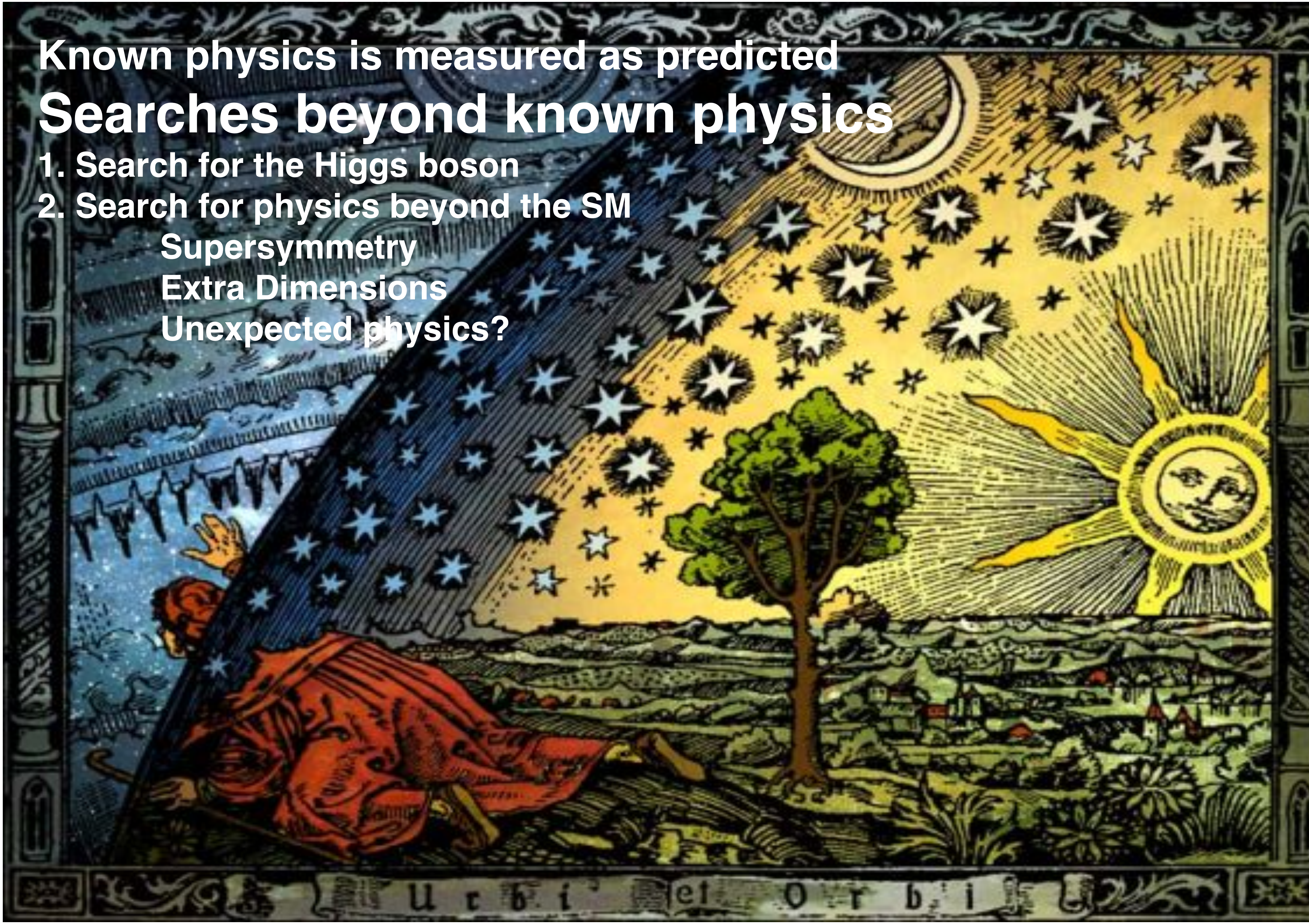
PLB701(2011)535

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

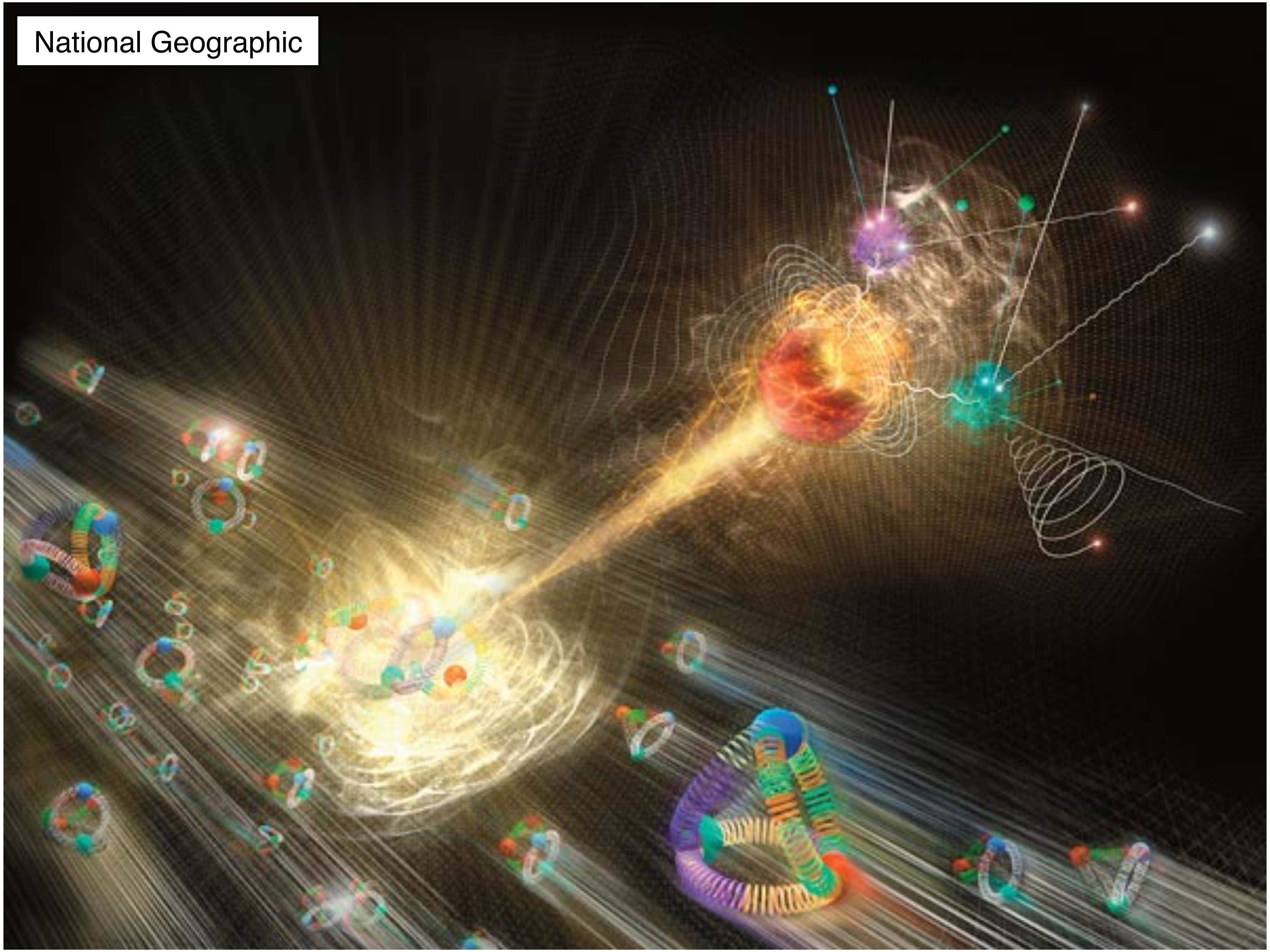
Known physics is measured as predicted

Searches beyond known physics

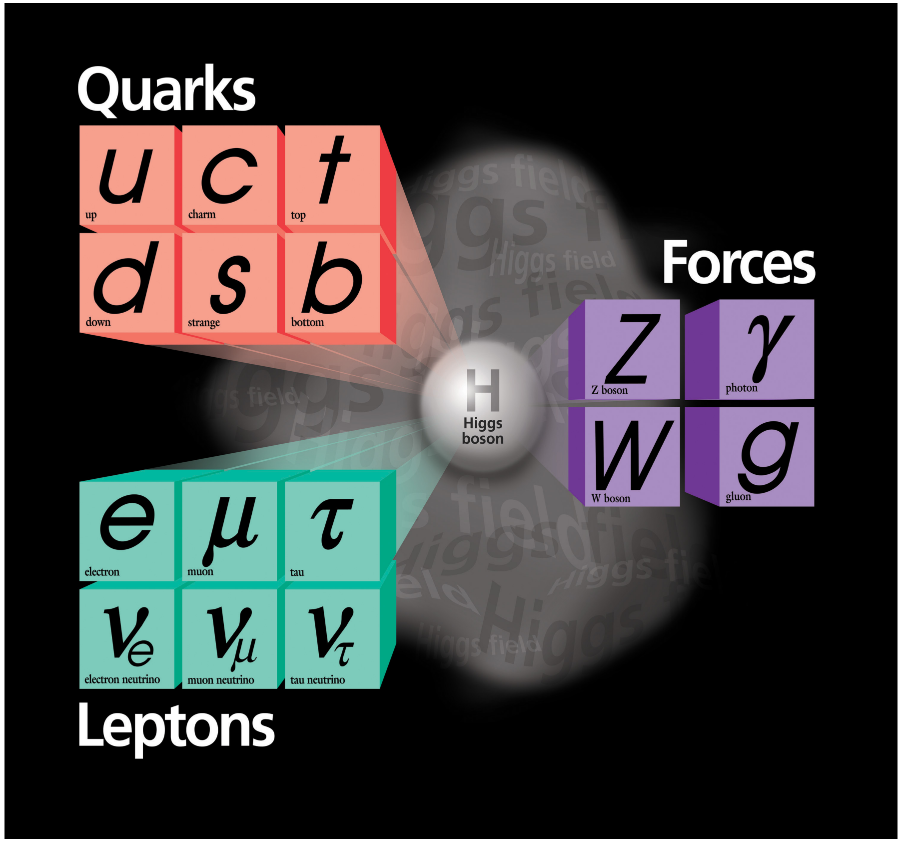
1. Search for the Higgs boson
2. Search for physics beyond the SM
    - Supersymmetry
    - Extra Dimensions
    - Unexpected physics?



Seeking the Higgs Boson



Search for the SM Higgs Boson



Higgs lifetime (125 GeV): 10^{-22} s

Will only see decay products

Higgs couples to mass:

Coupling to fermions ~ $(M_f/v)^2$

Suitable at LHC $H \to b\bar{b}$, $H \to \tau^+\tau^-$

Coupling to bosons ~ $(M_V/v)^4$

Suitable at LHC: $H \to ZZ$, $H \to W^+W^-$

Special Case: $H \to \gamma\gamma$

Search for the SM Higgs Boson

For a given Higgs boson mass hypothesis, the sensitivity of the search depends on:

-the mass of the Higgs boson

-Higgs boson production cross section,

- the decay branching fraction into the chosen final state,

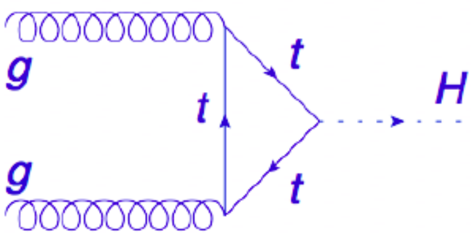
- the signal selection efficiency,

- the Higgs boson mass resolution, and

- the level of backgrounds with the same or a similar final state.

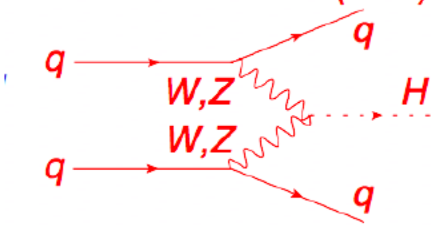
SM Higgs Boson: Production Cross-section

gluon fusion

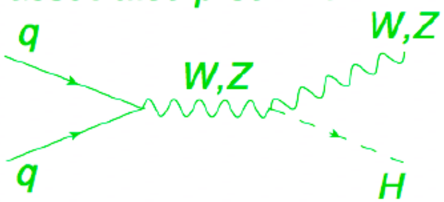


Main production via a quantum loop!

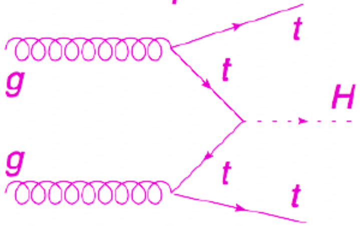
vector boson fusion (VBF)

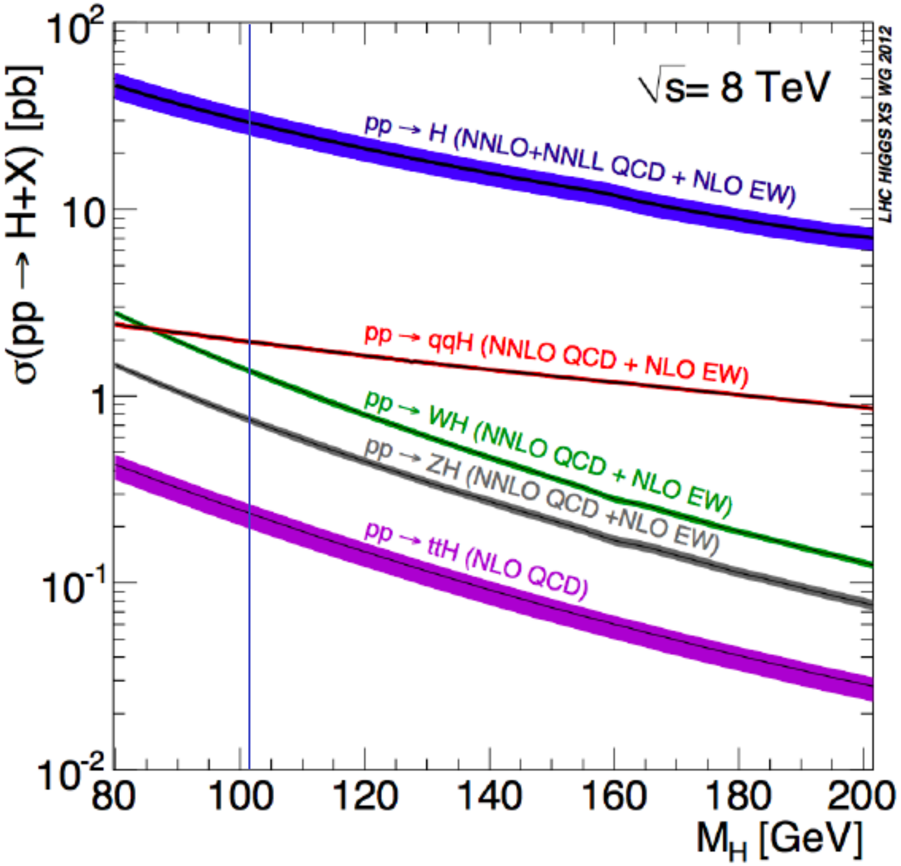


associated prod. with W/Z



associated prod. with tt





Integrated Luminosity

~5 fb^{-1} at $\sqrt{s}$=7TeV and ~ 20fb^{-1} at $\sqrt{s}$=8TeV

2000 trillion pp collisions examined

And potentially produced

~ 700k SM Higgs bosons (m_H=125 GeV)

SM Higgs Boson: Decay Modes

Natural Width: Γ_{H_125} ~ few MeV

The best instrumental mass resolution achievable is ~1GeV

Only two channels have such a resolution

$$H \to ZZ \to 4l,\ H \to \gamma\gamma$$

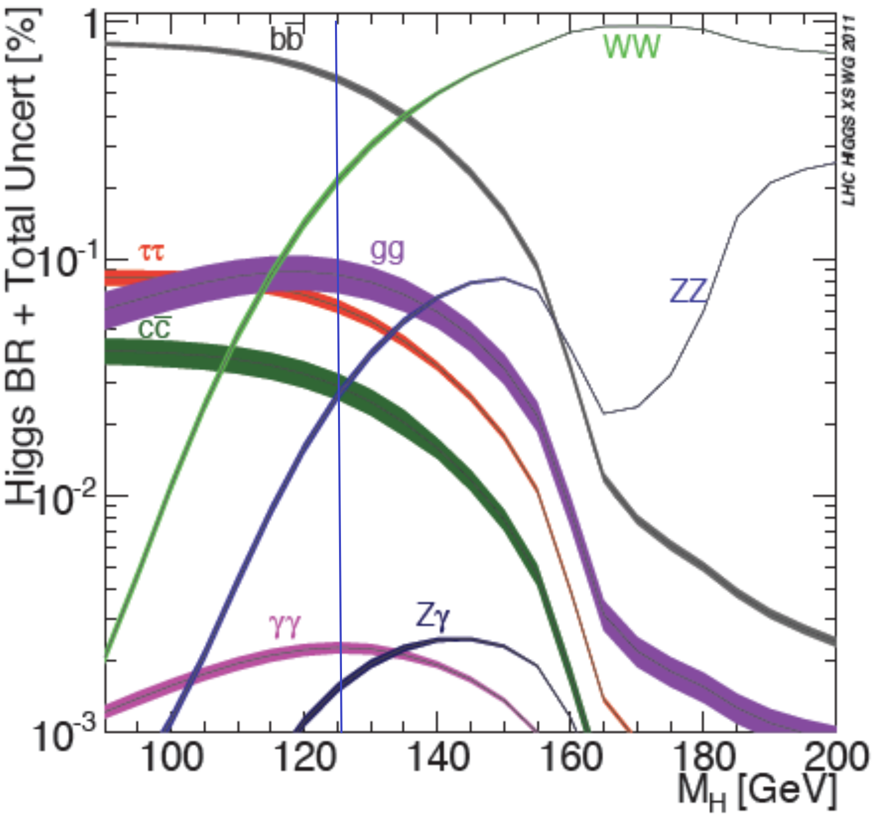
with decay Branching Fractions:

γγ is 2 per mille

ZZ → 4l is $\sim 10^{-4}$

m_H= 125	Exp Sig	σ_M/M
• bb	2.2σ	10%
• ττ	2.6σ	10%
• WW	5.3σ	20%
• ZZ	7.1σ	1-2%
• γγ	3.9σ	1-2%

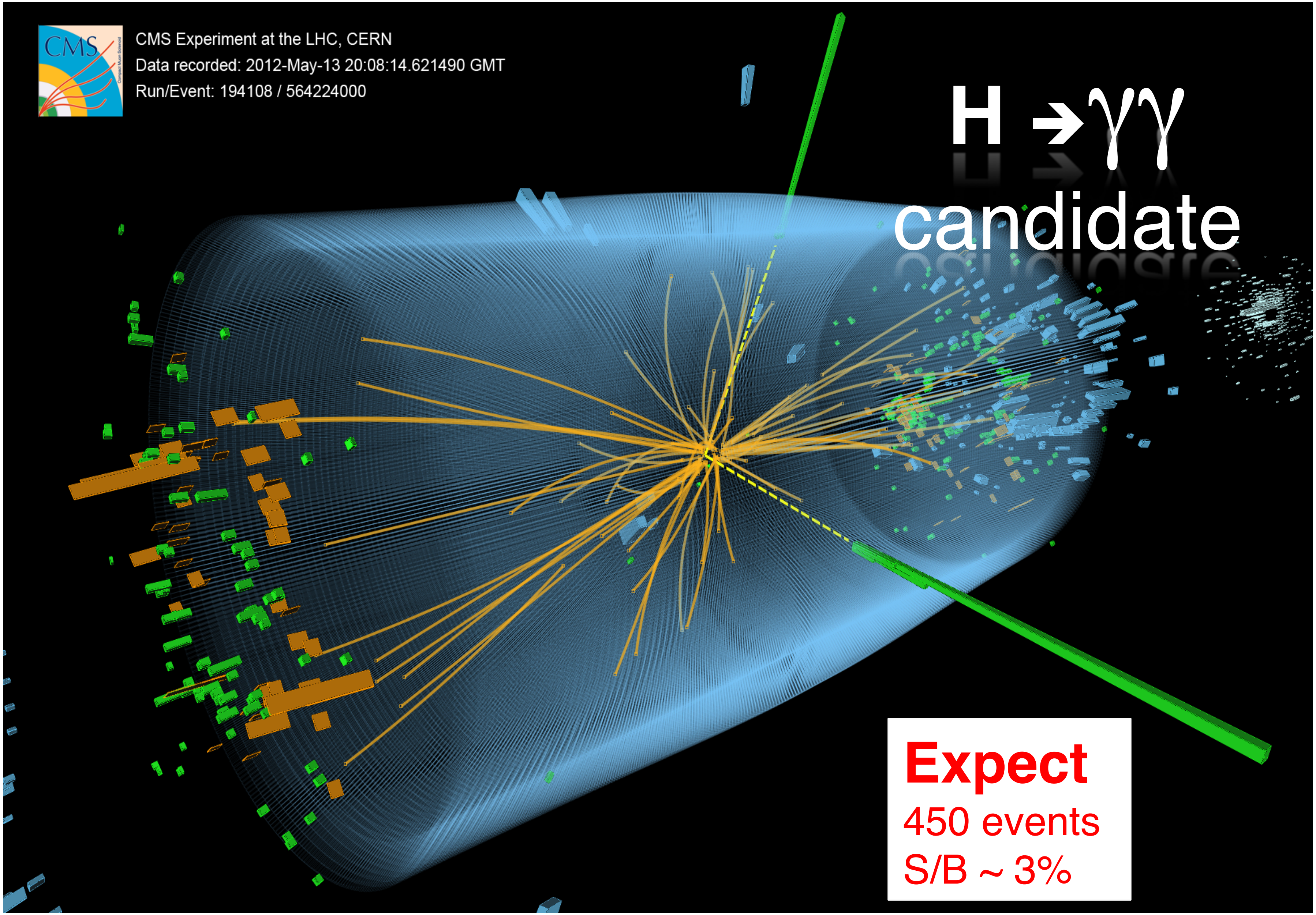
decay branching fraction



At m_H ~125 GeV many decay modes are detectable

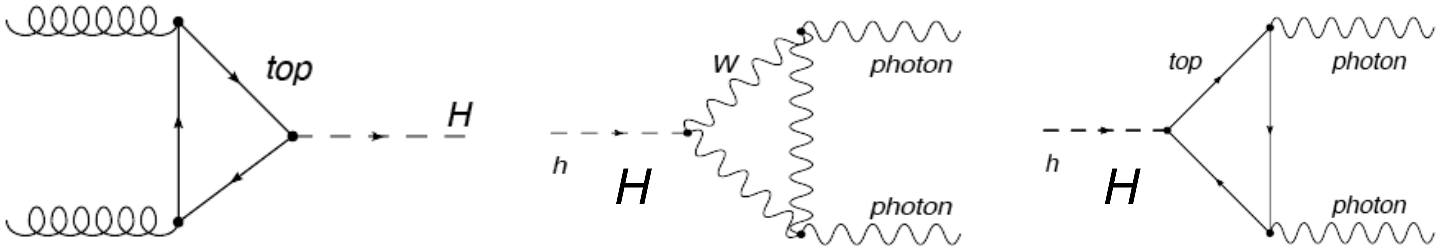
Makes it easier to establish whether it is a SM Higgs boson or not

H→ 2γ Channel


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate
Expect
450 events
S/B ~ 3%

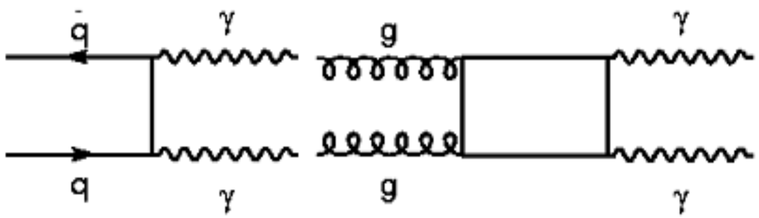
Search for the SM Higgs boson in the γγ channel

Signal:

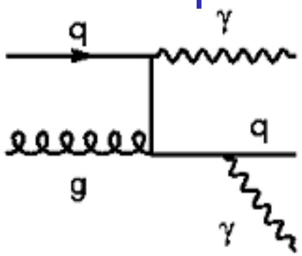


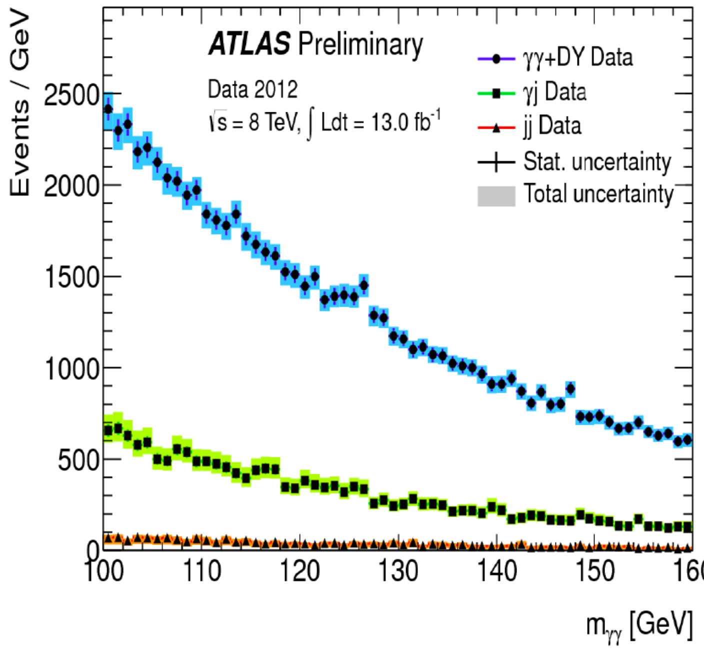
Background: essentially from QCD processes

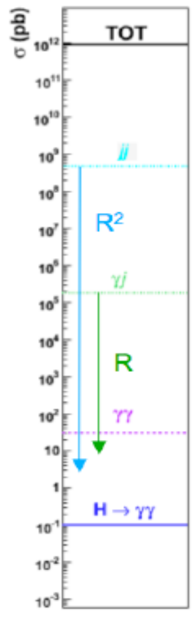
Irreducible: QCD processes



Reducible: Compton (gq→γq, q(jet)→γ)



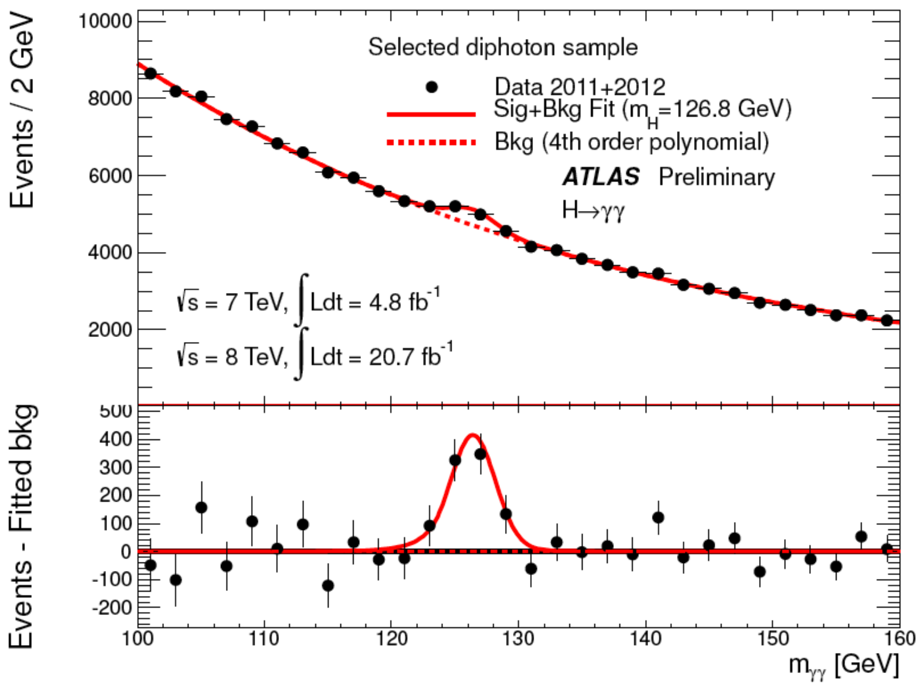




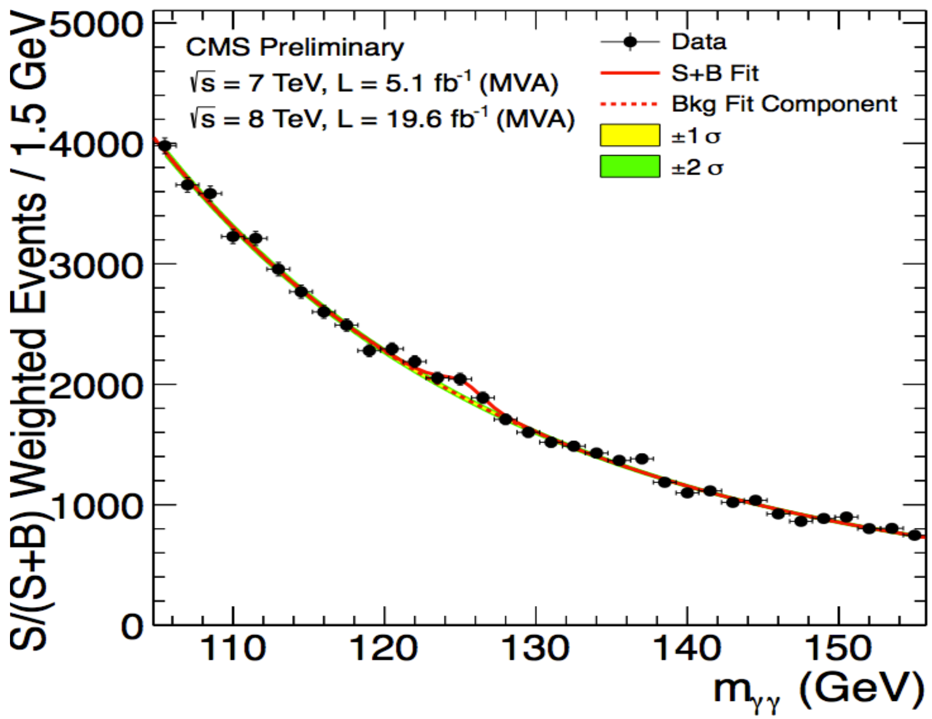
R ~ O(8000)

Preliminary Results from the Full Dataset

ATLAS: H→ 2γ Channel

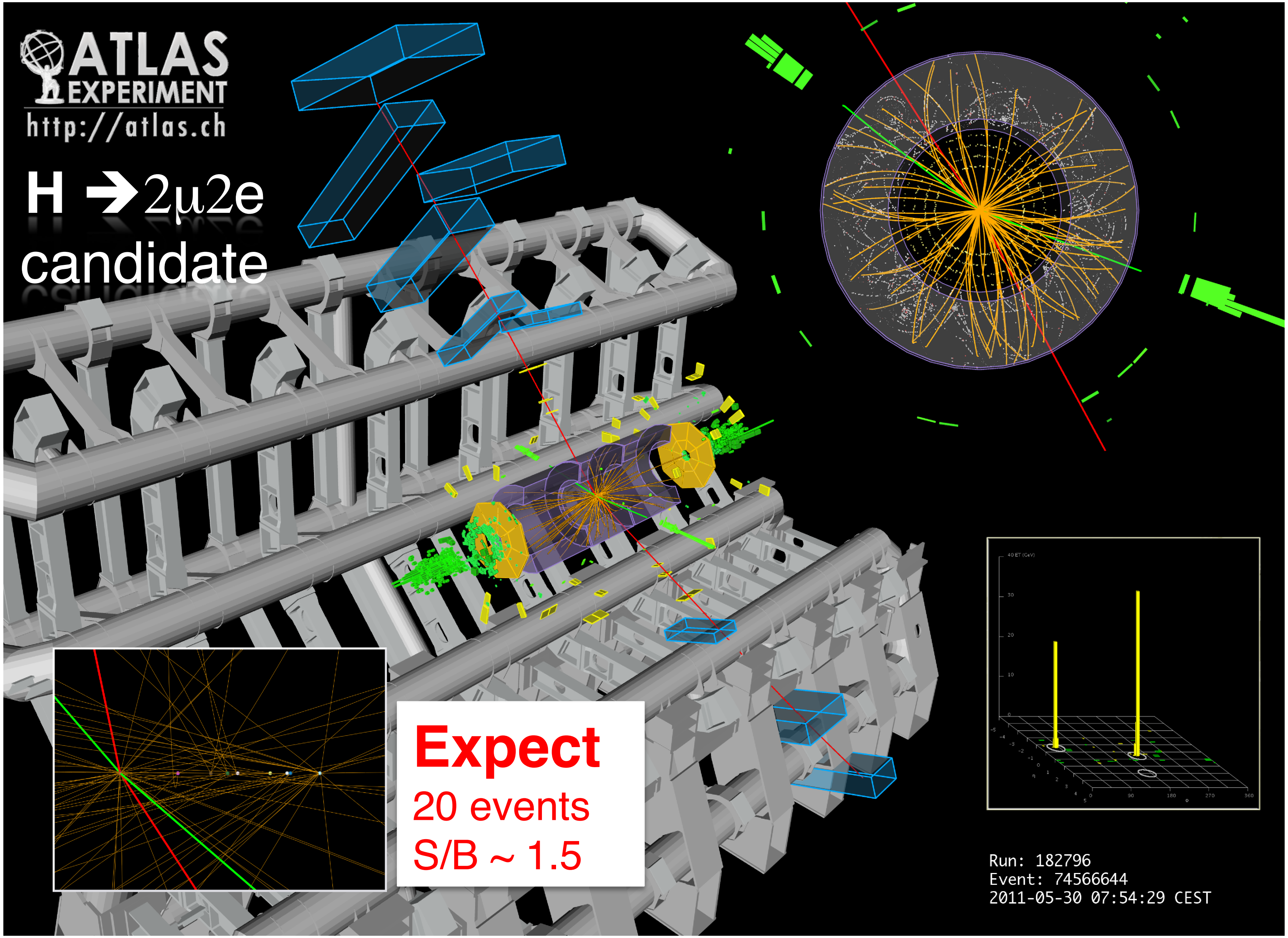


CMS: H→ 2γ Channel



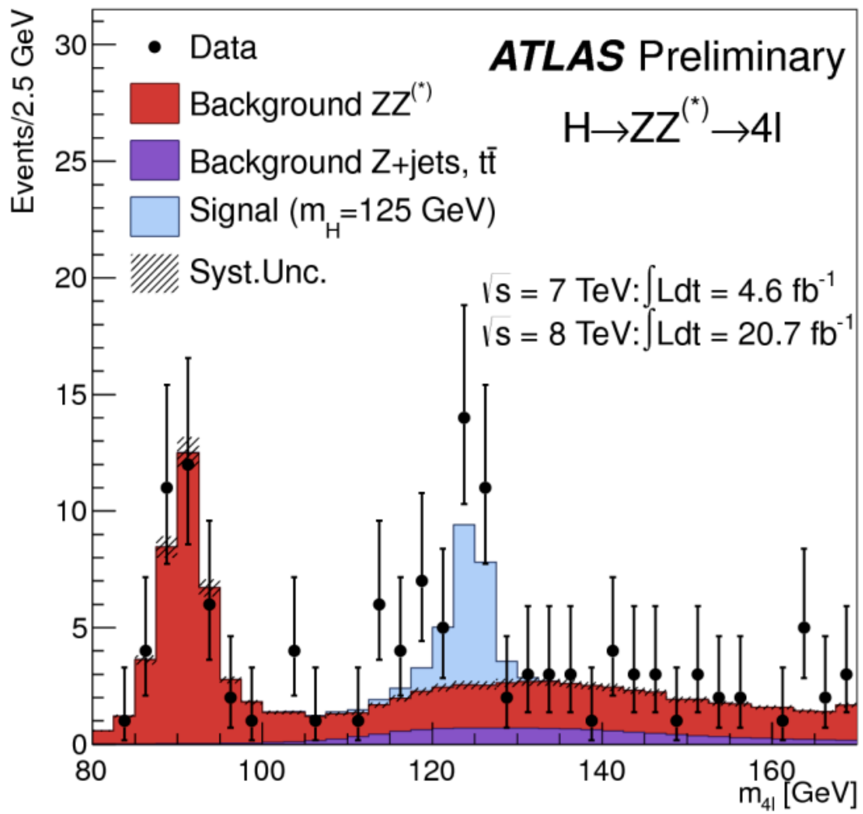
Sign/Exp	Exp	Obs
ATLAS	4.1 σ	7.1 σ
CMS	4.2 σ	3.2 σ

$H \to ZZ^{(*)} \to 2\mu 2e$ Channel

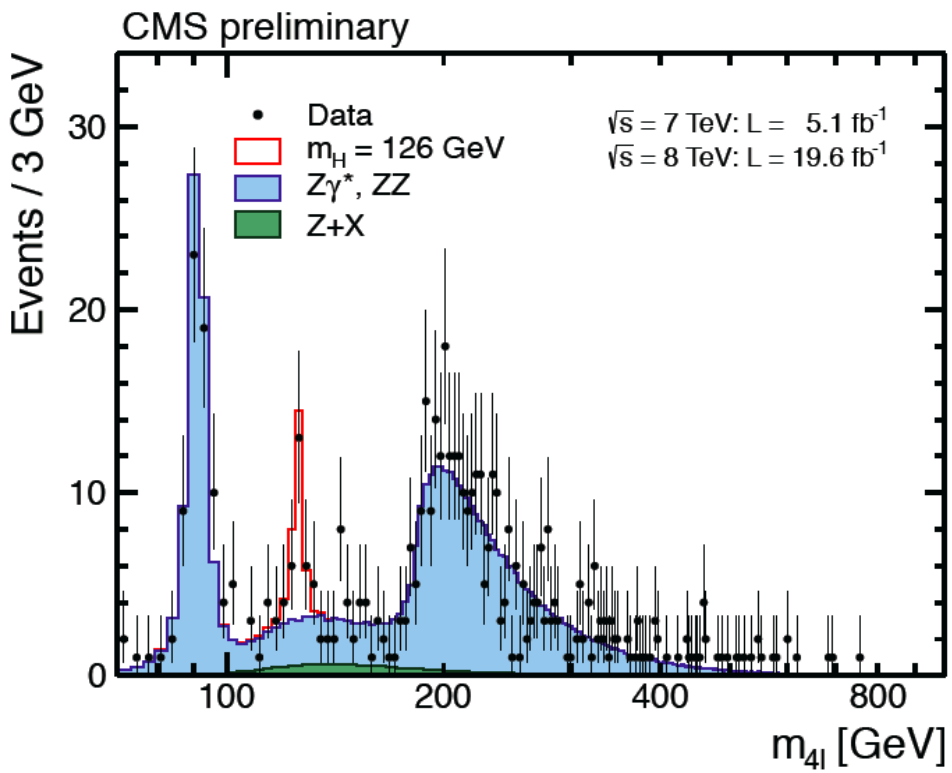


Preliminary Results from the Full Dataset

ATLAS: H→ 4*l* Channel



CMS: H→ 4*l* Channel



Significance	Exp	Obs
ATLAS	4.4 σ	6.6 σ
CMS	6.7 σ	7.2 σ

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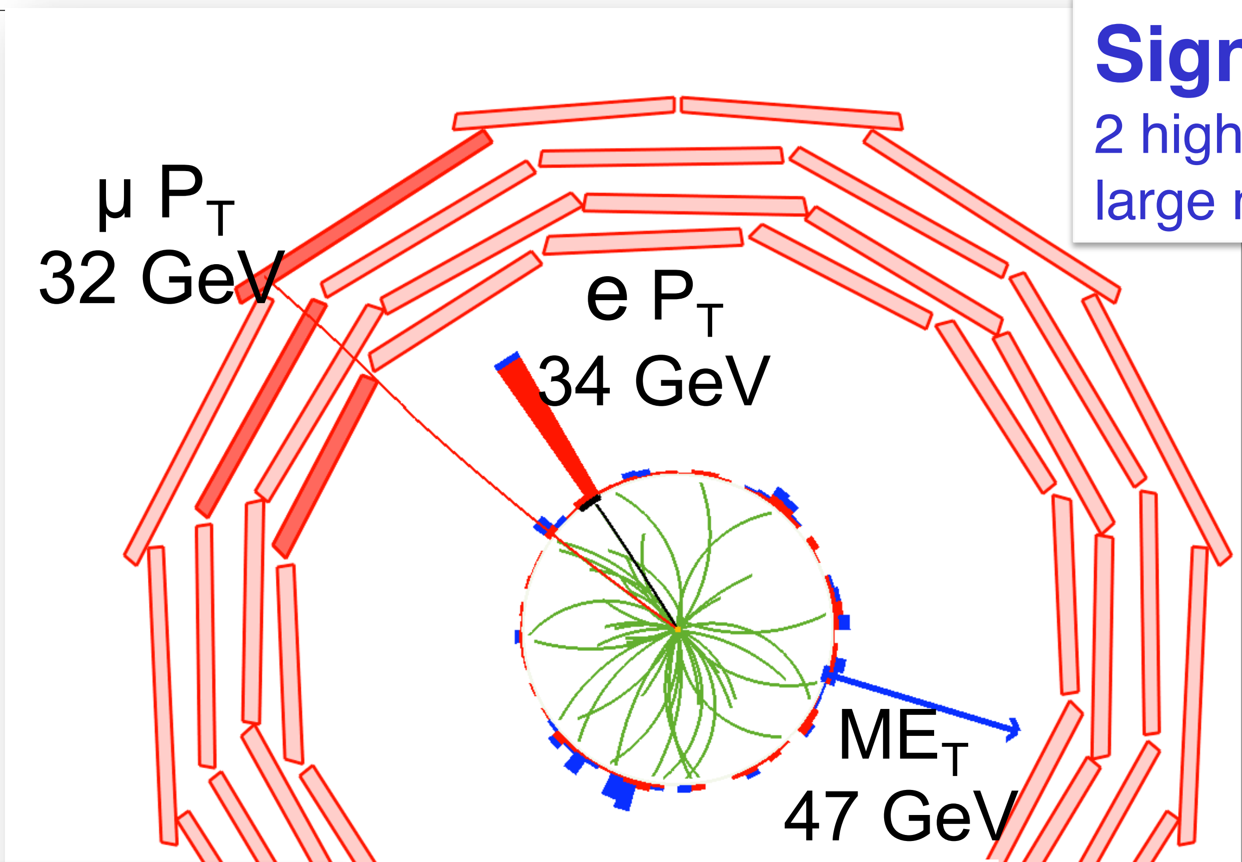
Nature at the energy frontier

H → WW → 2l2ν channel

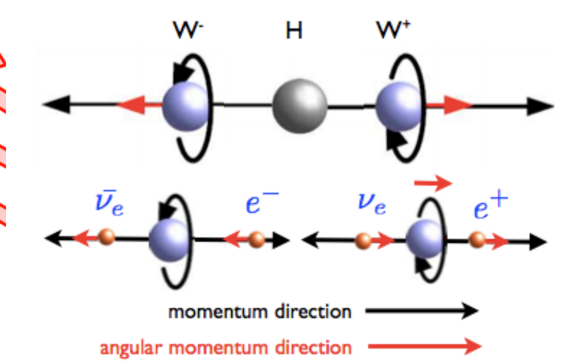


Signature:
2 high p_T leptons
large missing E_T

Expect
200 events
S/B ~ 15%

qq→WW + gg→WW
- Non-resonant

H→WW
- Large BR
- Small Δϕ(ll)

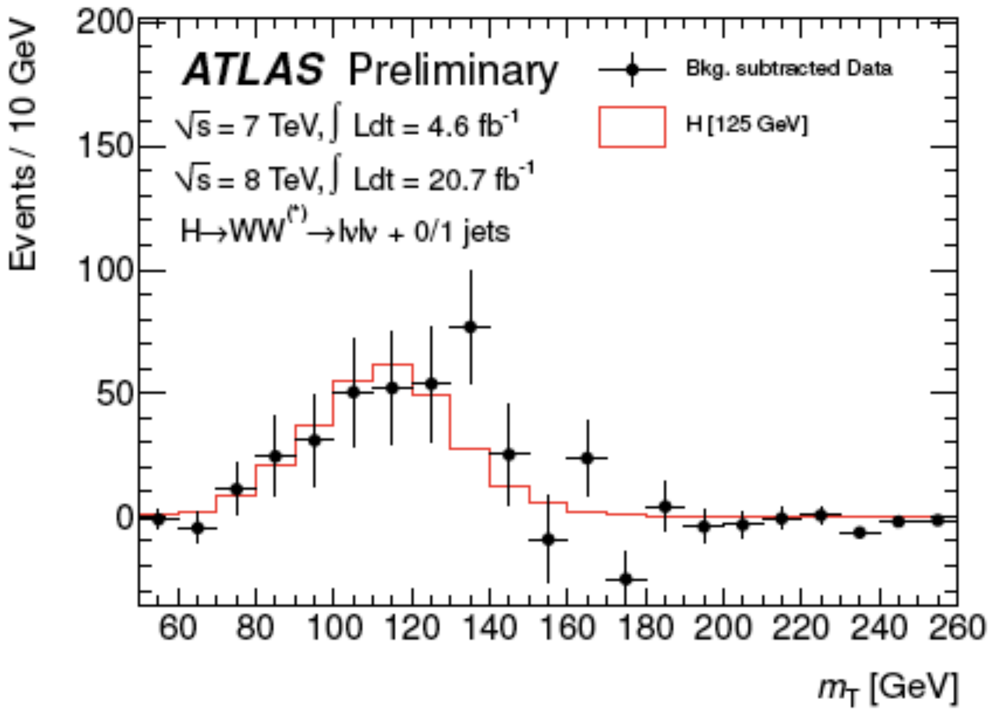


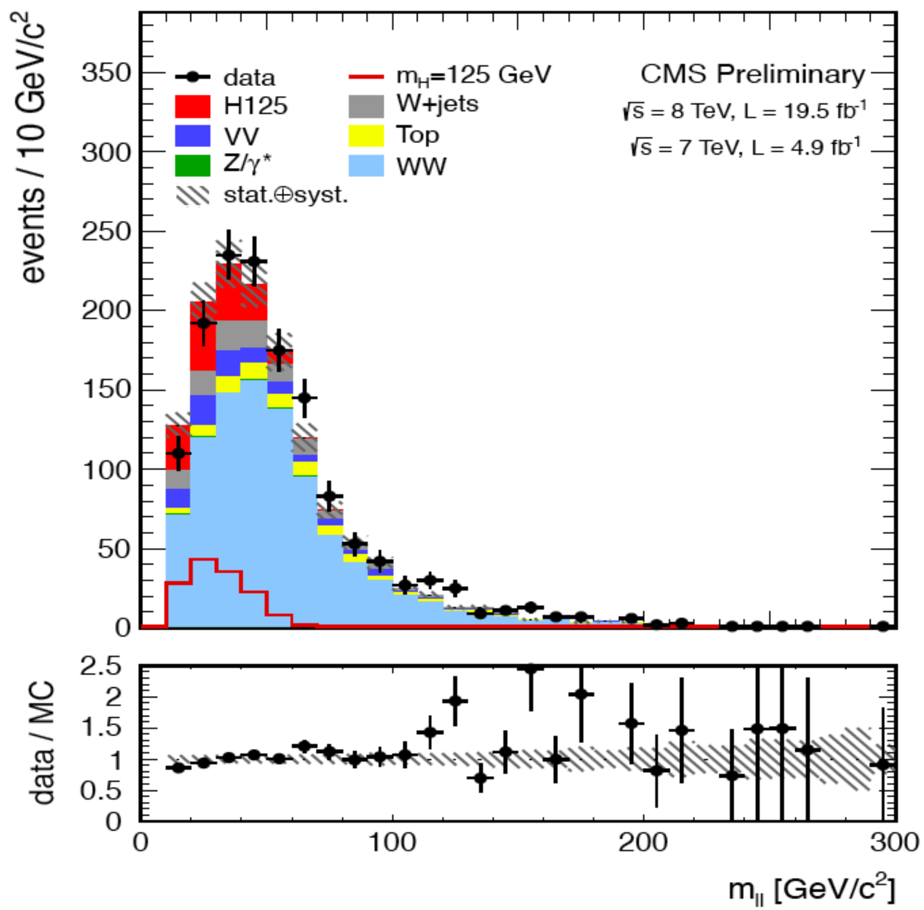
Main backgrounds:
WW, top
Other backgrounds:
W+jet, Z/γ*, WZ, ZZ, Wγ

Preliminary Results from the Full Dataset

ATLAS: H→ WW→2l 2ν Channel Full Dataset

CMS: H→ WW→2l 2ν Channel Full Dataset



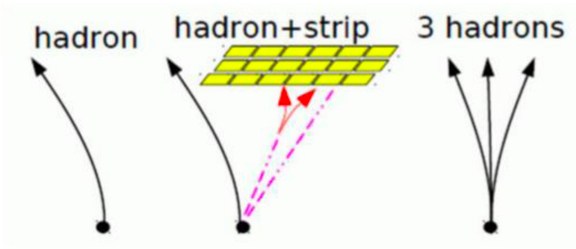


Sign/Exp	Exp	Obs
ATLAS$_{full}$	3.7 σ	3.8 σ
CMS$_{full}$	5.1 σ	4.0 σ

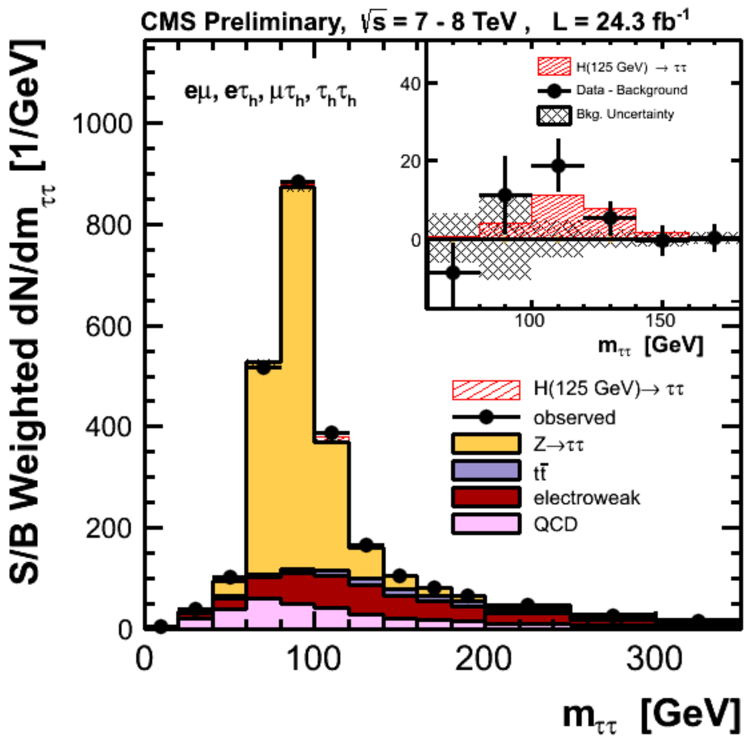
at 125 GeV

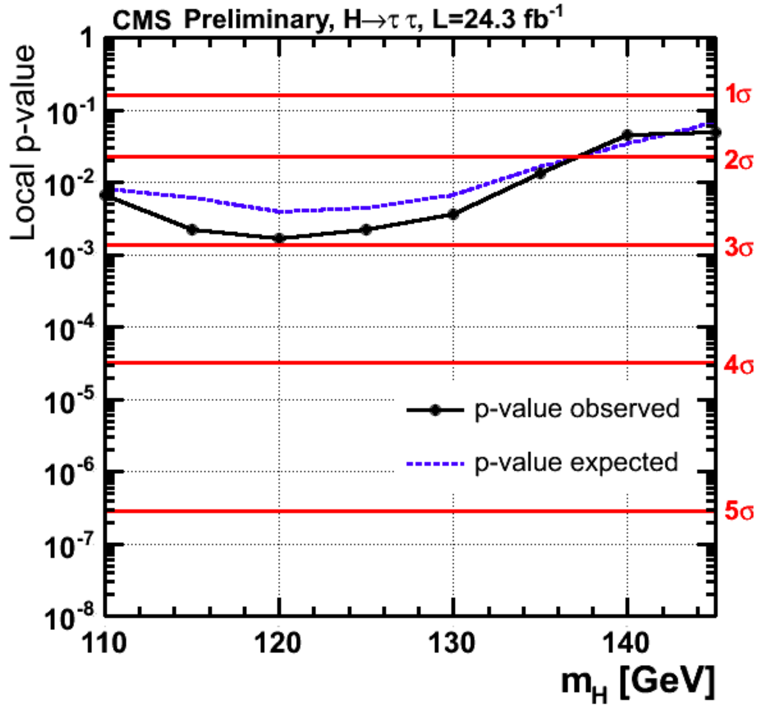
W/Z + H, H→ττ

CMS Preliminary results from Full Dataset



$e\tau_h$, $m\tau_h$, $e\mu$, $\tau_h\tau_h$



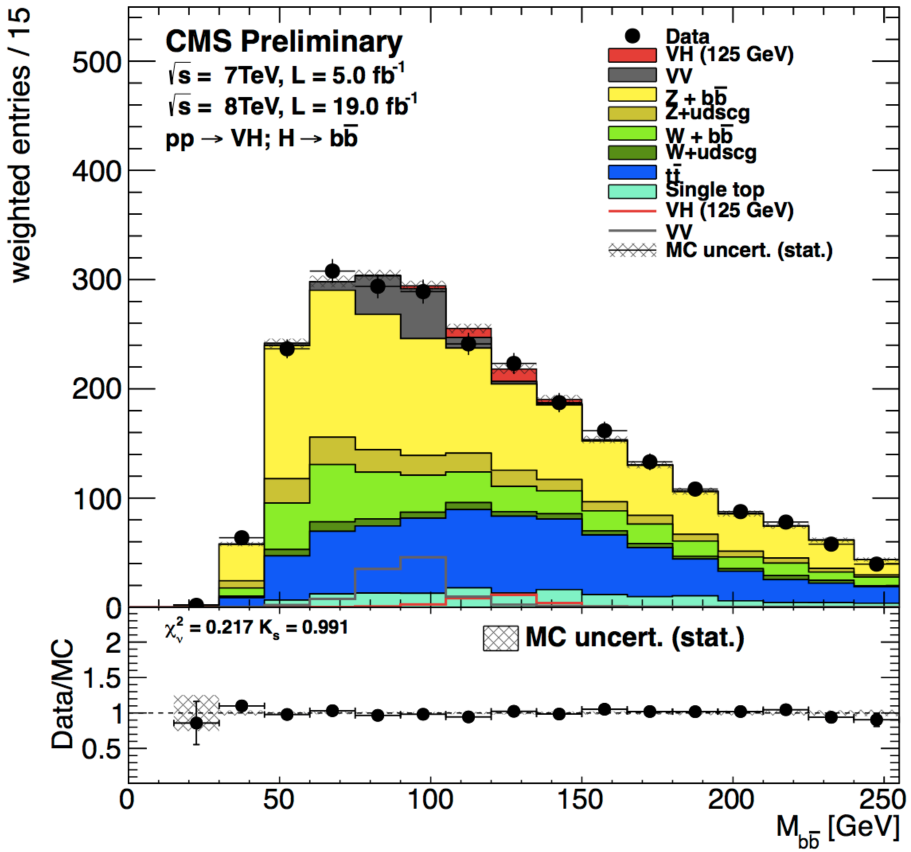


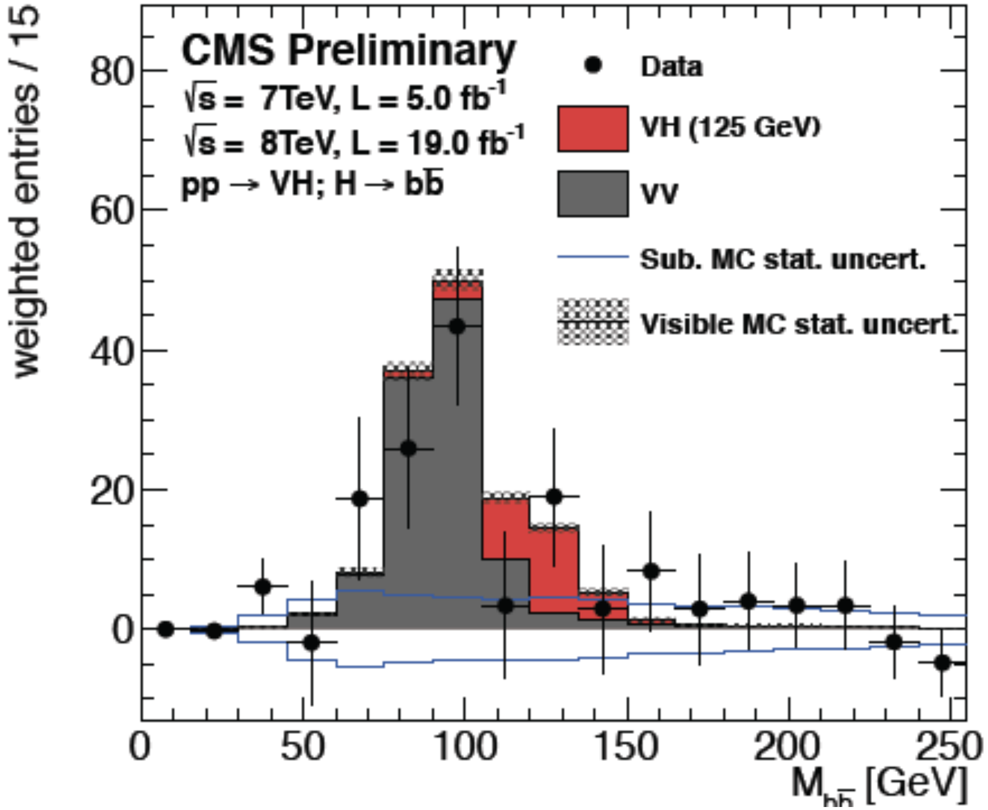
Signif.	Exp	Obs
CMS	2.6 σ	2.9 σ

at 125 GeV

It decays to taus (and thus to fermions)

Search for SM VH (H → 2b): CMS Full Dataset



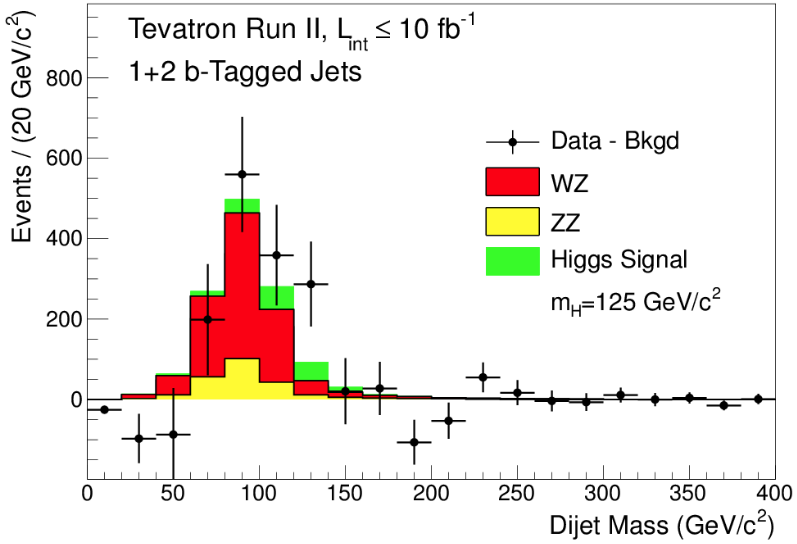


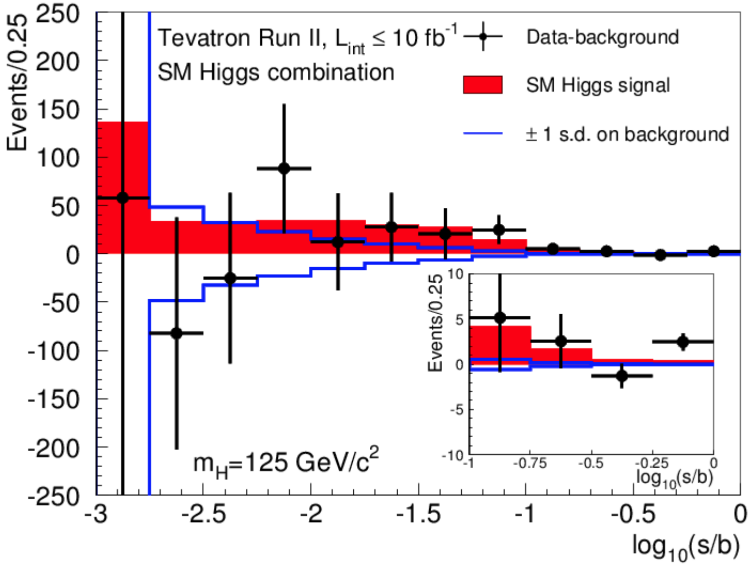
Significance	Exp	Obs
CMS	21 σ	2.1 σ

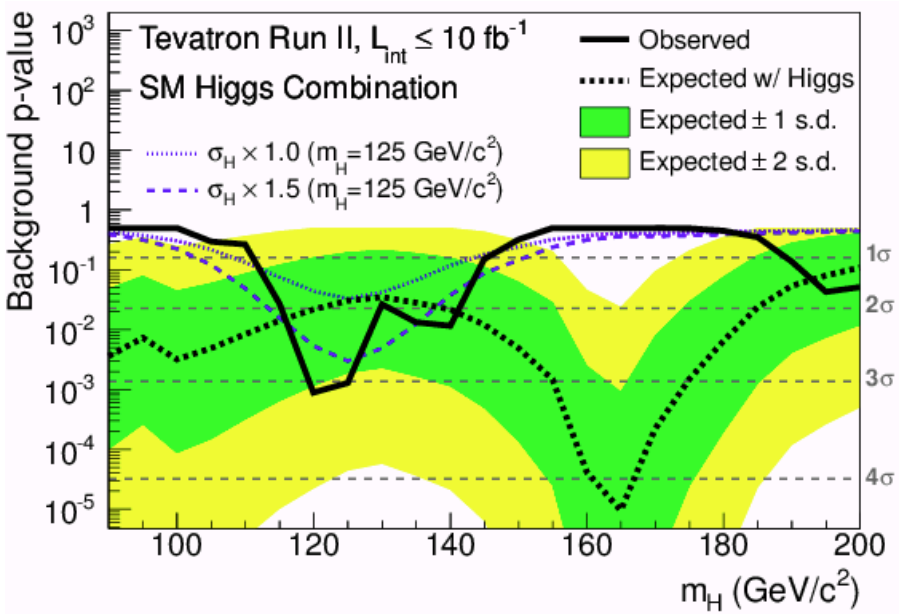
at 125 GeV

σ/σ_{SM} = 1.0±0.5

Search for SM VH ($H \rightarrow b\bar{b}$) (Tevatron)







Sign/Exp	Exp	Obs
Tevatron	2.1 σ	3.0 σ

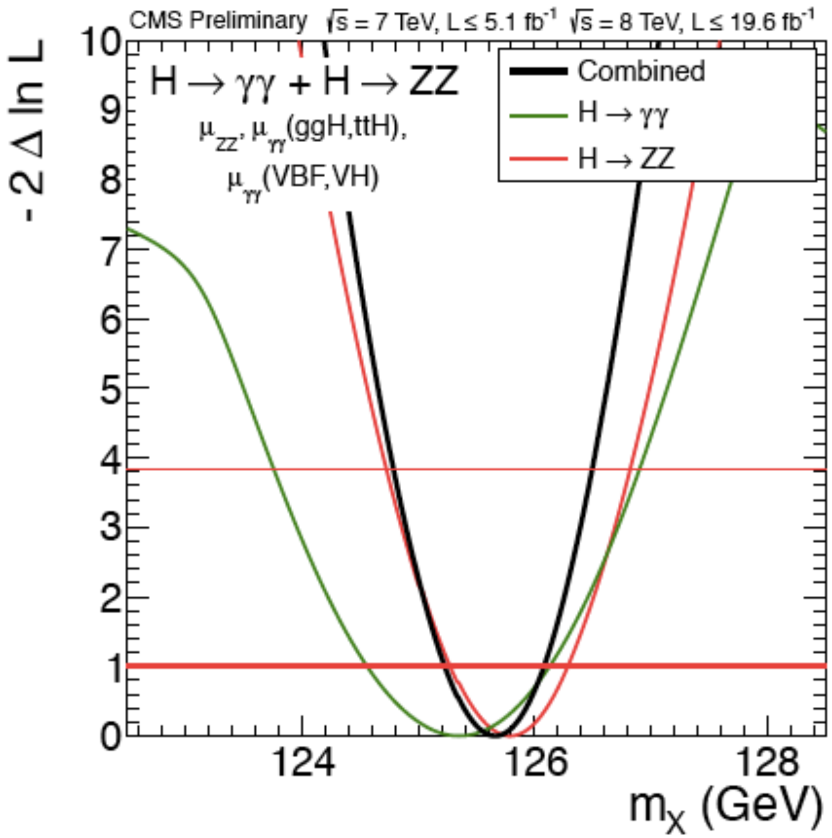
at 125 GeV

σ/σ_{SM} = 1.4± 0.6

Putting It All Together

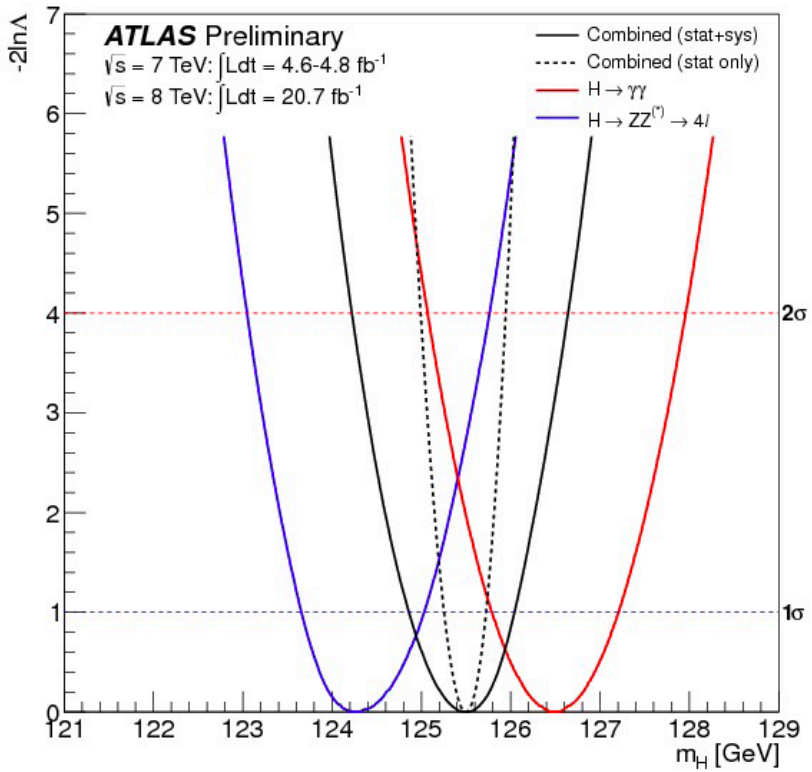
Mass

CMS



125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

ATLAS



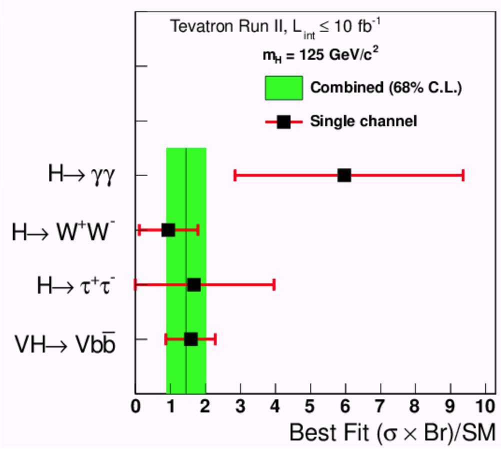
125.5 $^{+0.5}_{-0.6}$ (stat) ± 0.2 (syst) GeV

M_t (Tevatron) = 173.18 ± 0.94 GeV

M_t (LHC) = 173.36 ± 1.10 GeV

Couplings

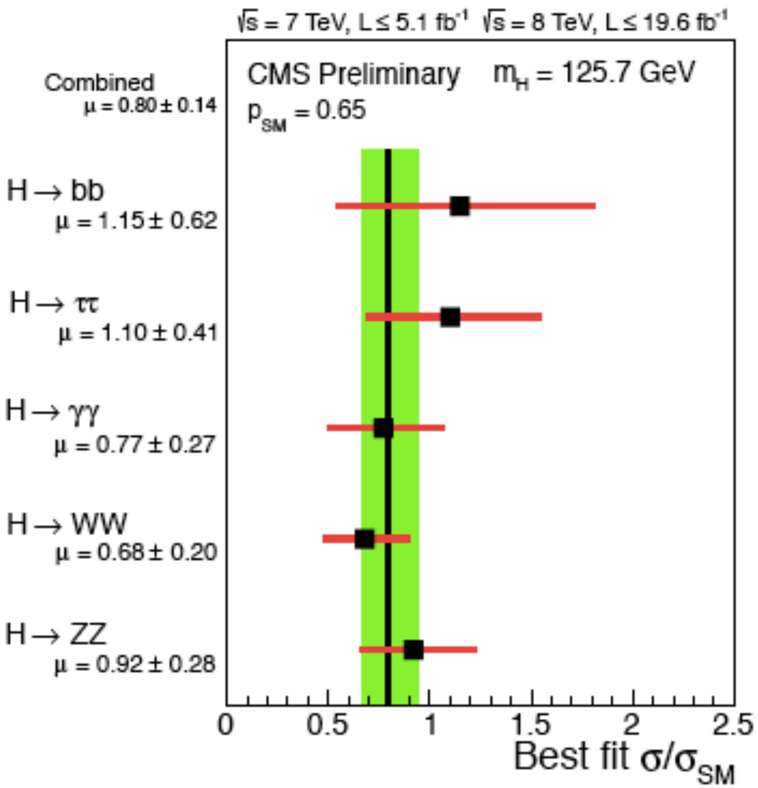
Signal strength and comparison to SM Higgs boson:
$\mu = \sigma/\sigma_{SM}$

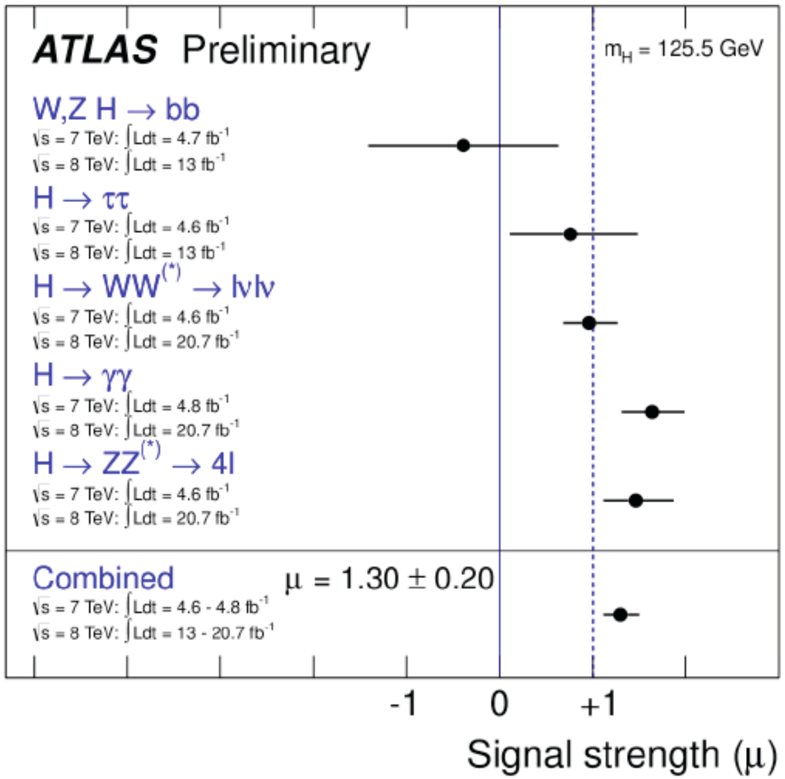


CMS : 0.80 ± 0.14

ATLAS: 1.30 ± 0.20

Tevatron
1.40 ± 0.60





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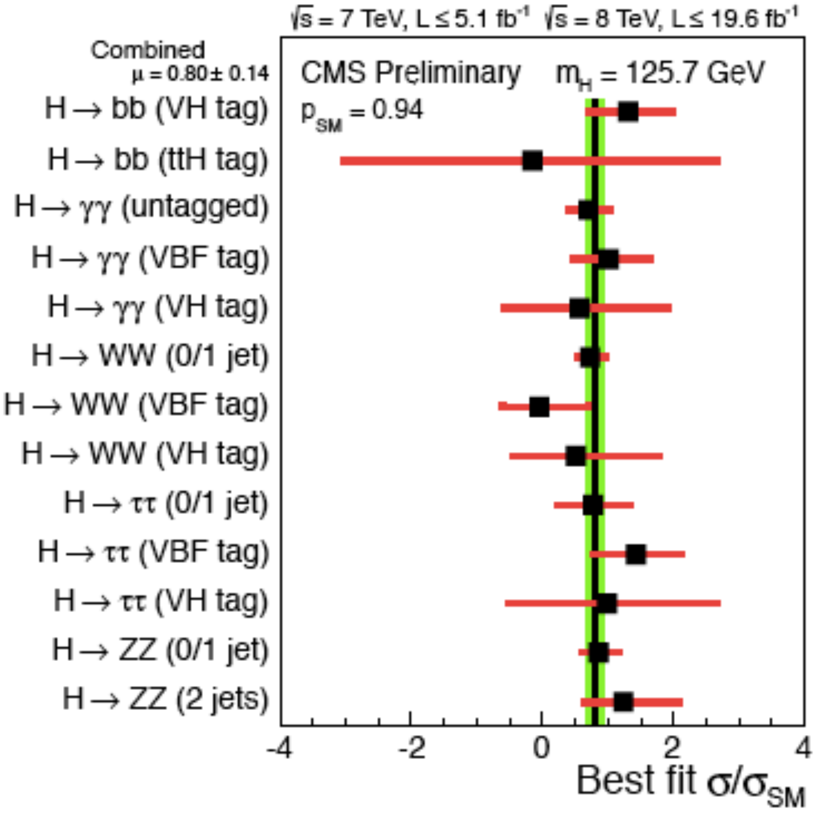
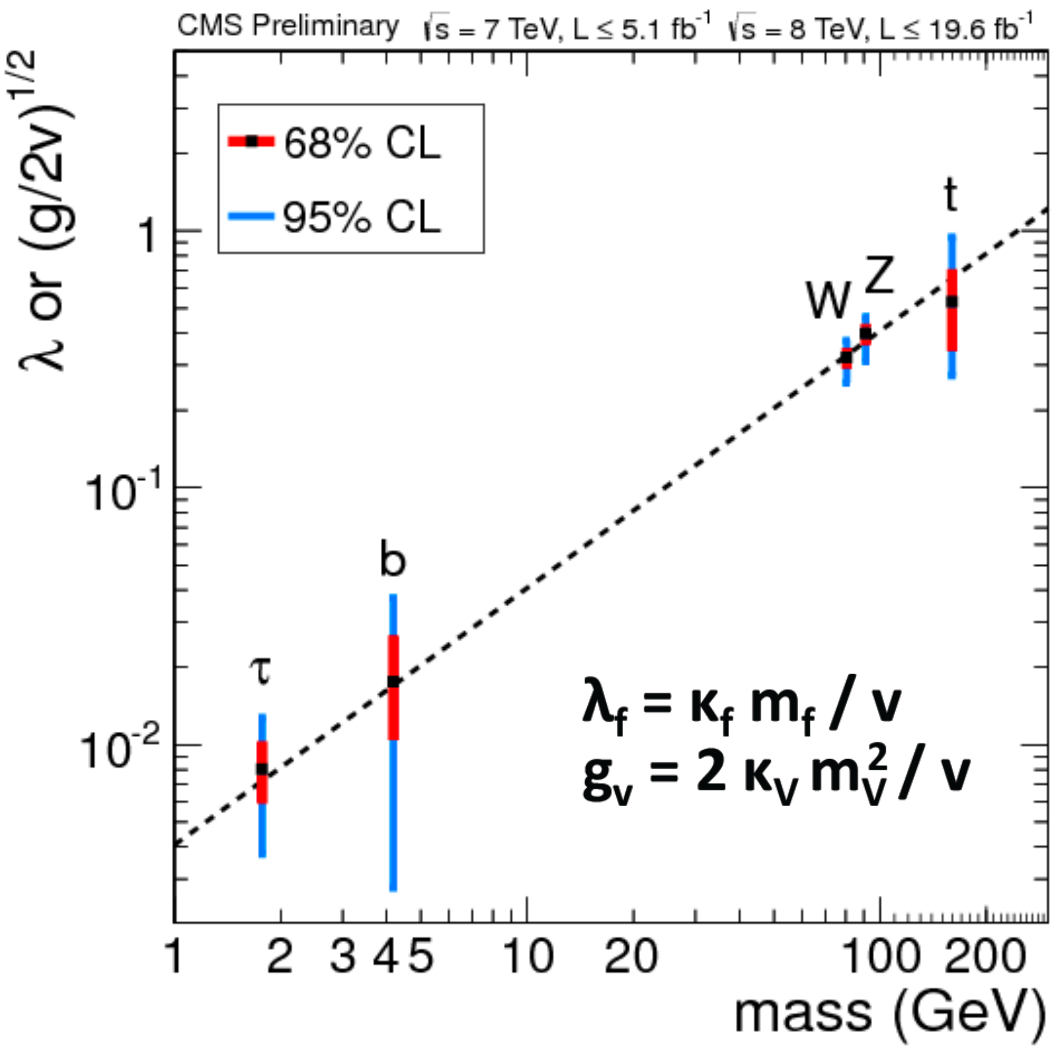
Do Couplings Scale as Expected in the SM?

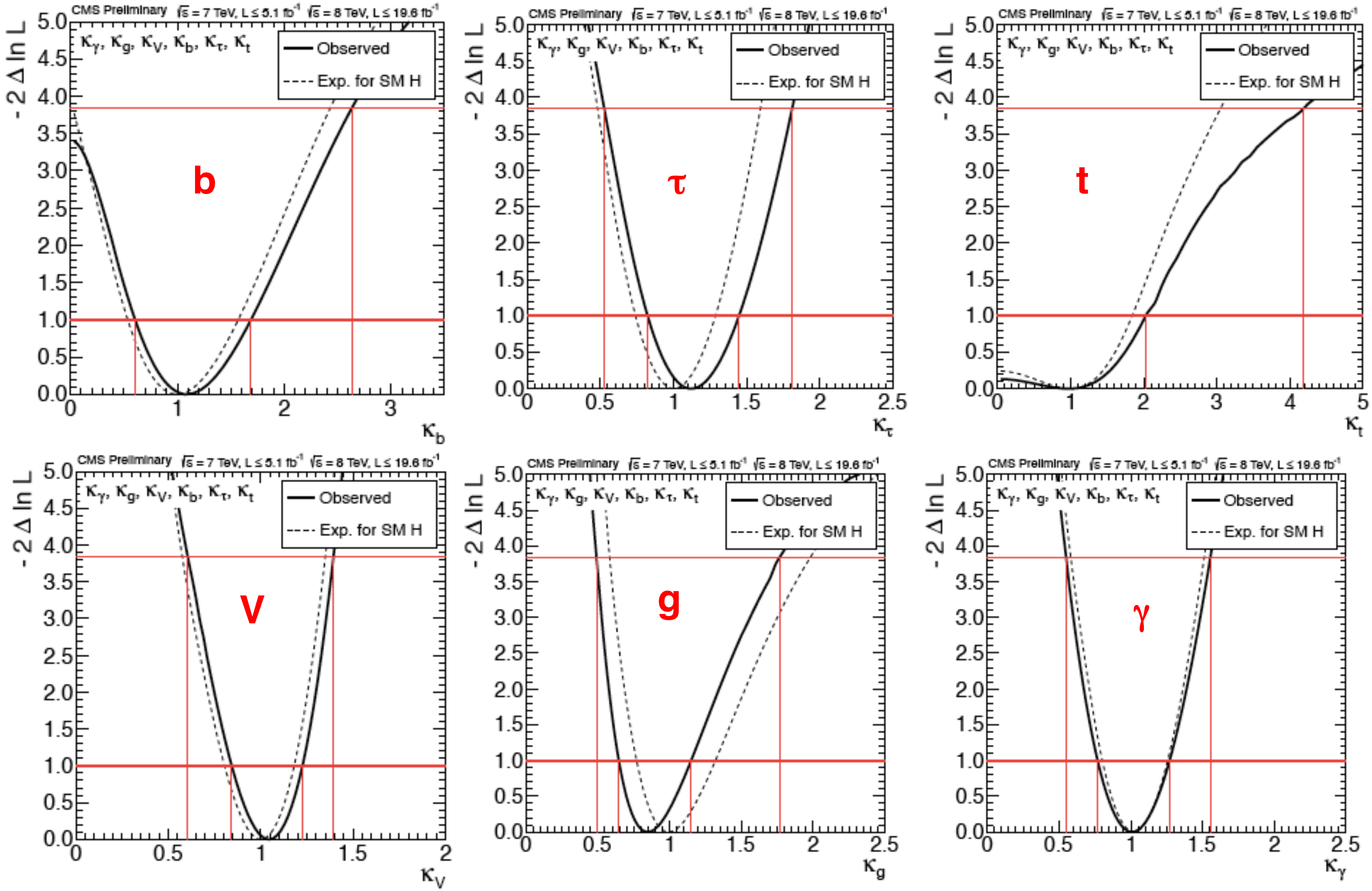




σ.BR/(σ.BR)$_{SM}$
is consistent with 1

Higgs couplings are proportional to masses

Do Couplings Scale as Expected in the SM?



Spin

Prediction for SM Higgs boson is $J^P = 0^+$

It decays into two photons so not spin-1 (Landau-Yang theorem)

Use angular distributions of the decay products in H rest frame
Construct BDT variables out of distinguishing information

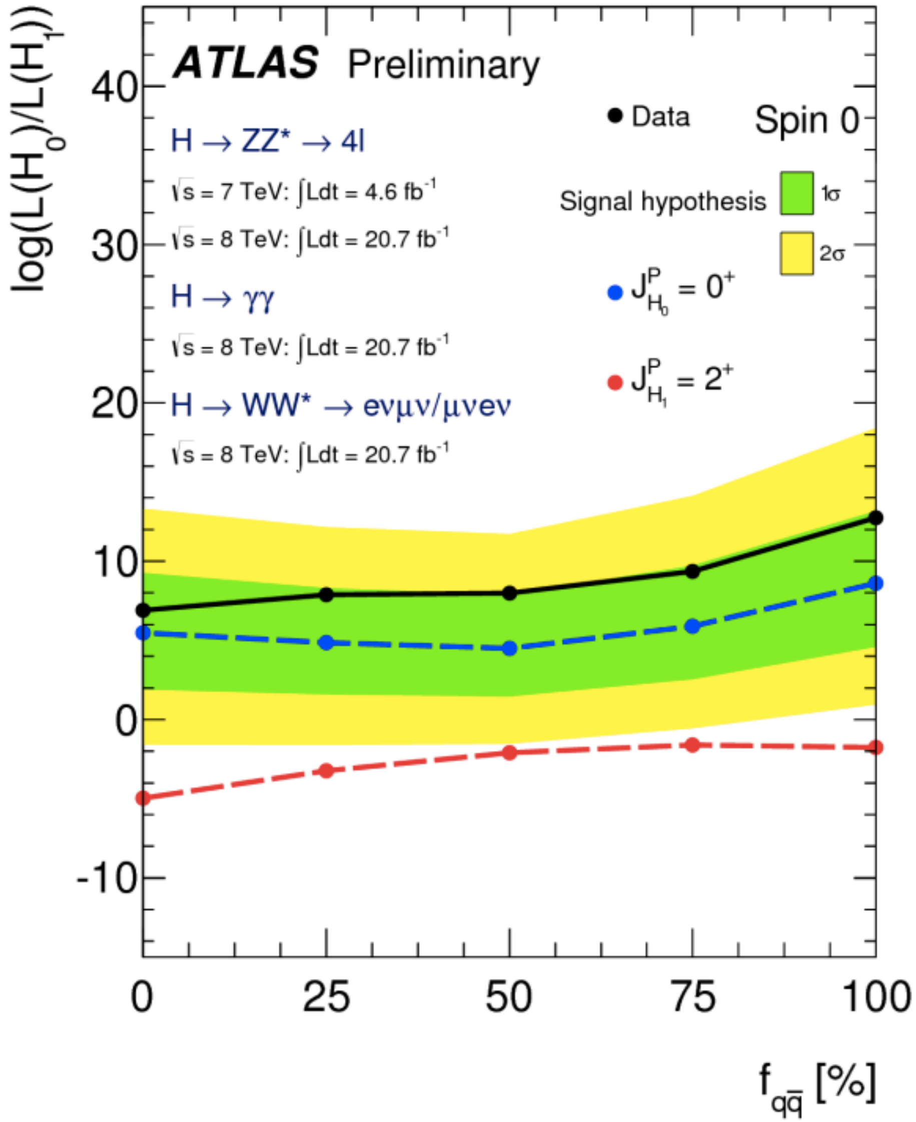
$H\rightarrow\gamma\gamma$,H $\rightarrow$ZZ and H$\rightarrow$WW

H$\rightarrow$ZZ used to test 0^- and 1^+ scenarios

Spin 2^+ hypothesis tested in all channels*

*Graviton inspired model - production mechanism is unknown so present results as fraction of qq to gg

ATLAS Summary: Spin

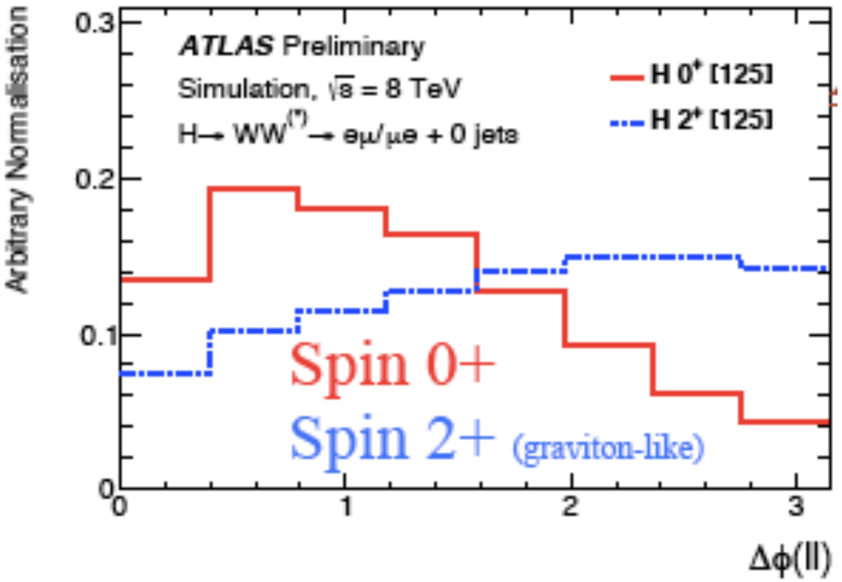


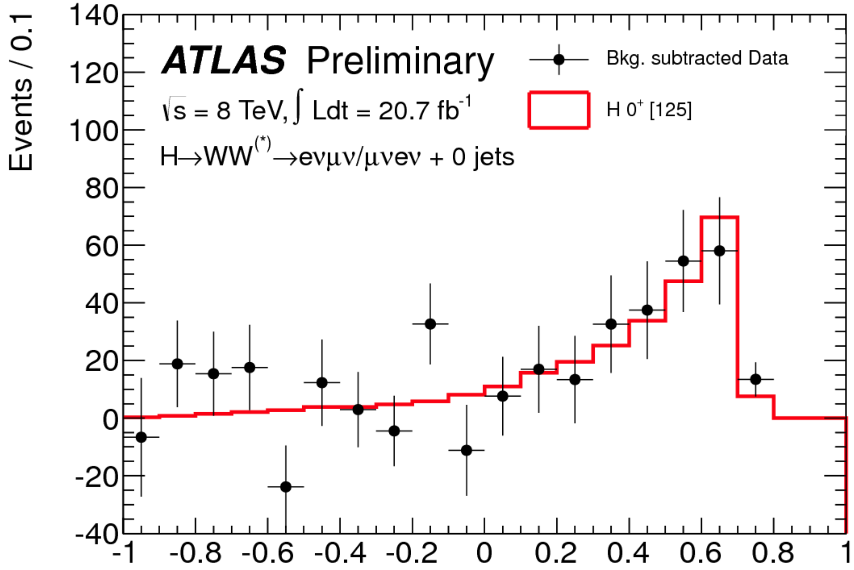
3 channels combined exclude 2^+ at 99.9% CL independent of production mode

H→ZZ excludes 0^-, 1^+ and (1^-) at >95% (94%) CL.

Spin 0 or 2? ATLAS: H→ WW→2*l* 2ν

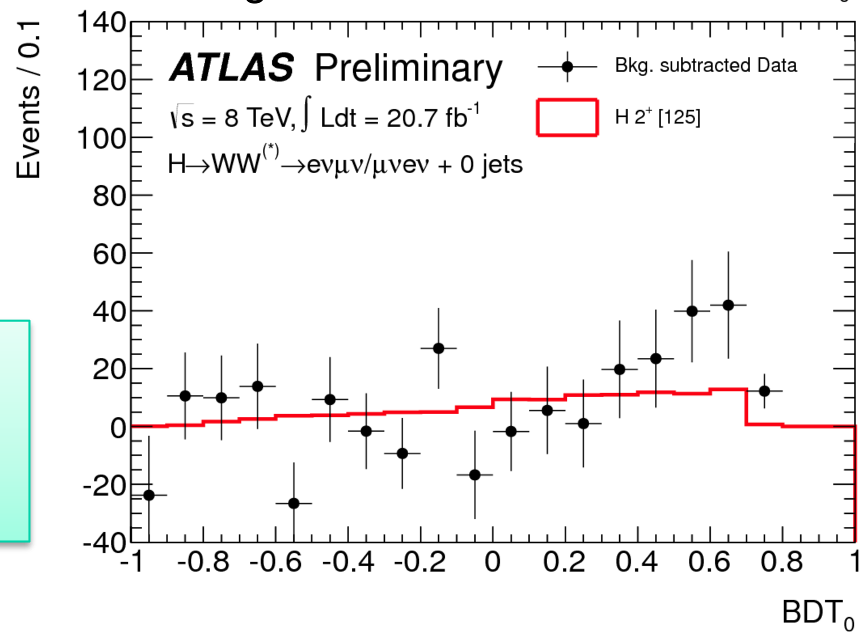
Combine several variables in a multivariate discriminant (BDT)
Variables used: m_{ll}, P_T^{ll}, $\Delta\phi_{ll}$, m_T





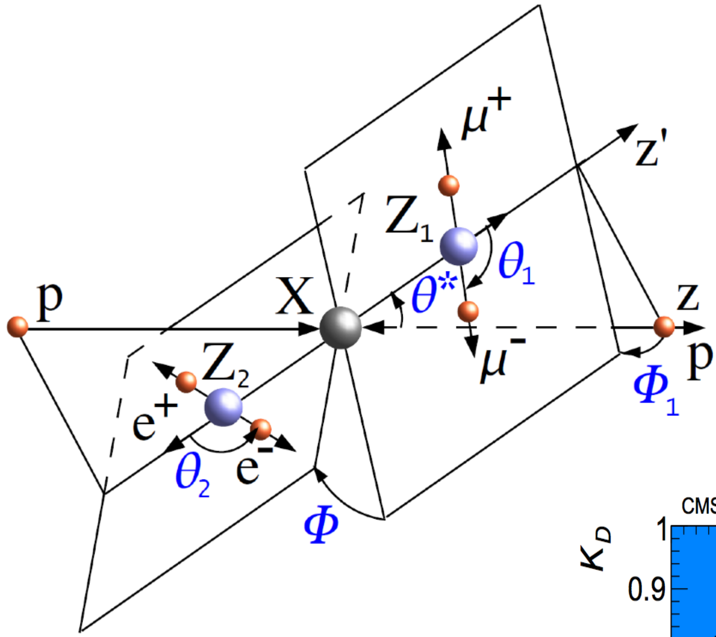
Background subtracted BDT

BDT0



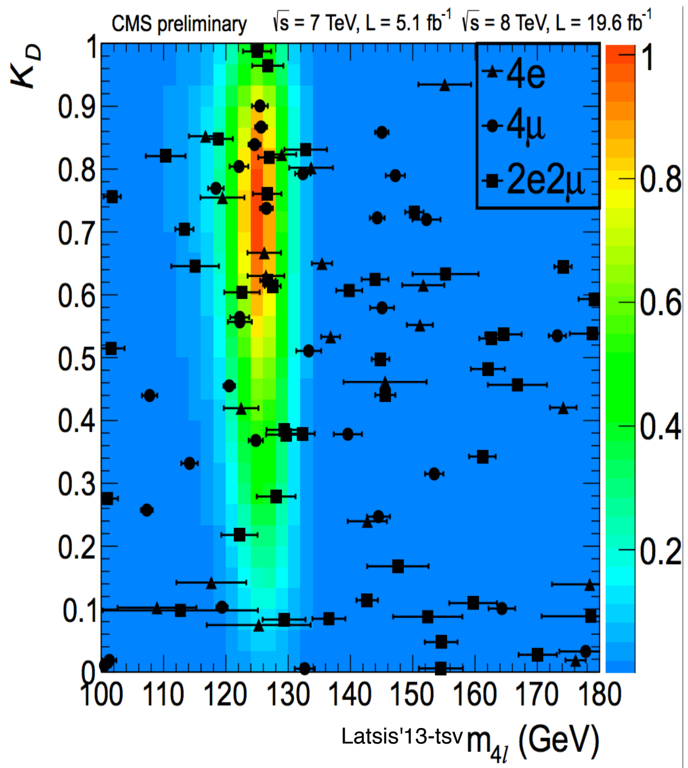
Data compatible with 0^+ hypothesis
2^+ (graviton-like) scenario excluded at: 99% CL if qq, 95% if gg production

CMS: H→ ZZ(*) → 4l Kinematic Discriminant

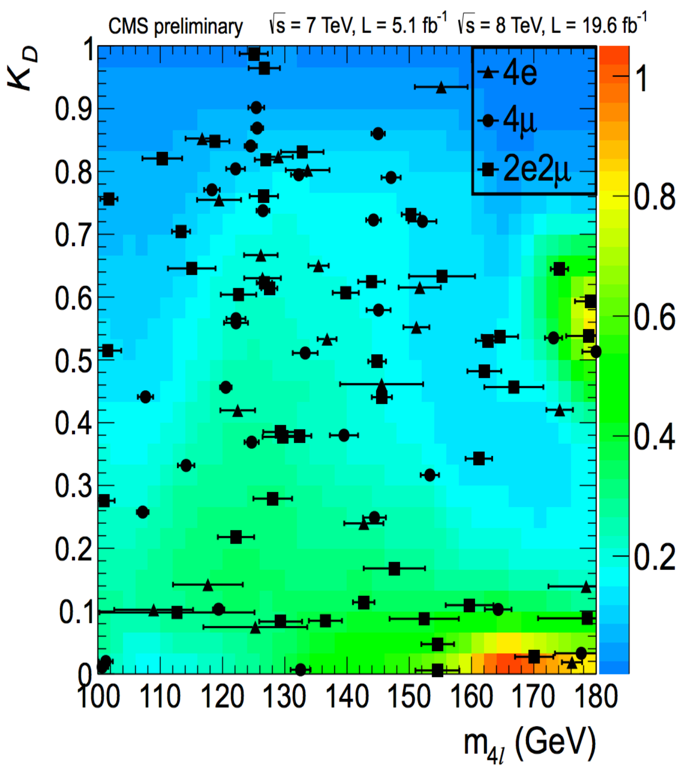


Matrix **E**lement **L**ikelihood **A**nalysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

SIGNAL

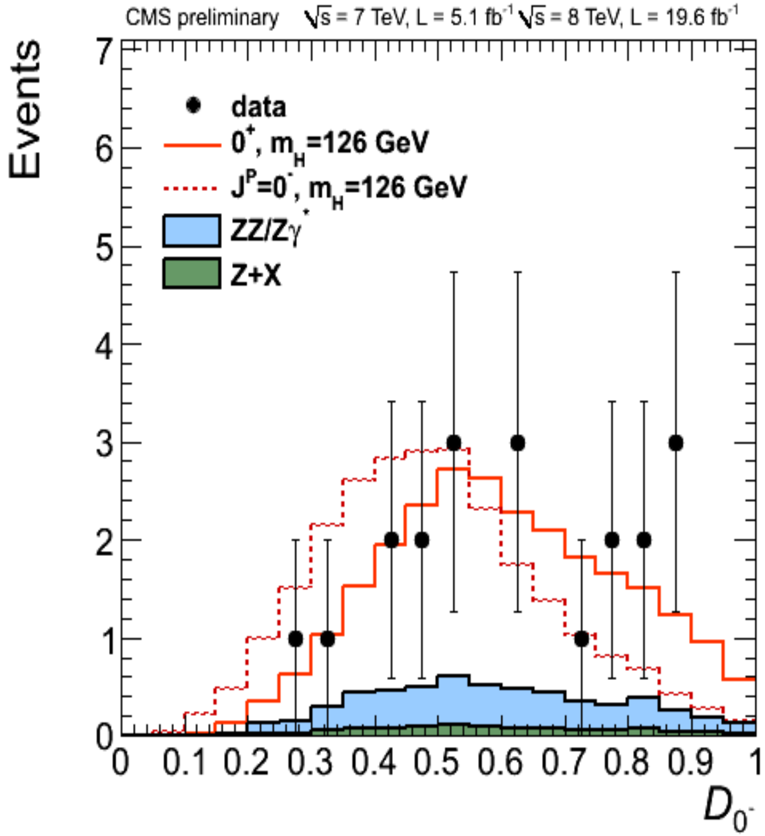


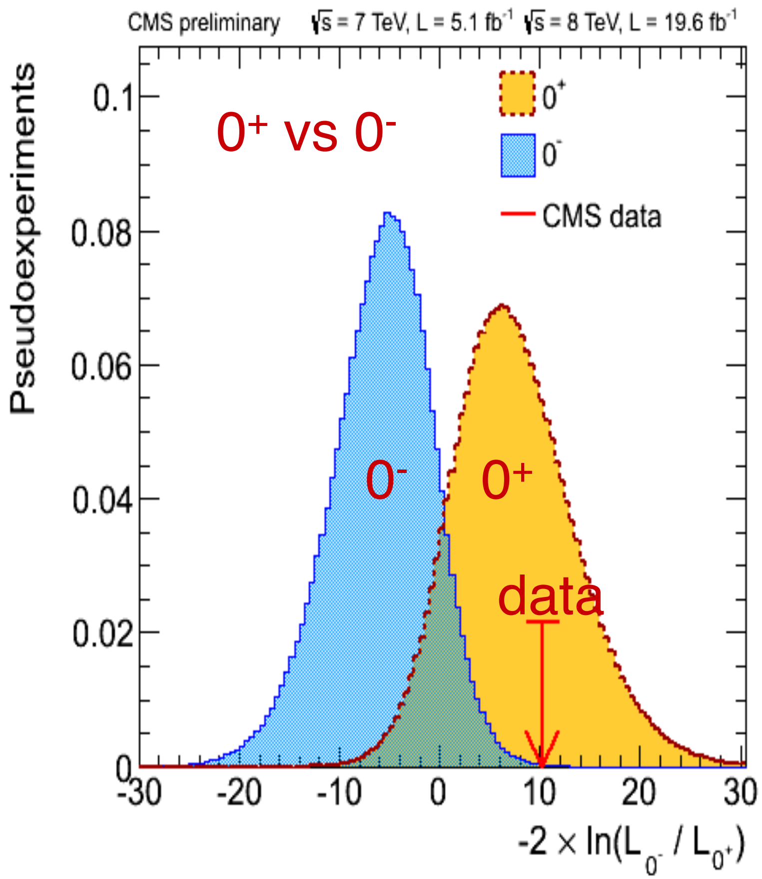
BACKGROUND



CMS: H→ ZZ$^{(*)}$ → 4l: Spin 0$^+$ v/s 0$^-$

CMS data consistent with scalar (0$^+$)

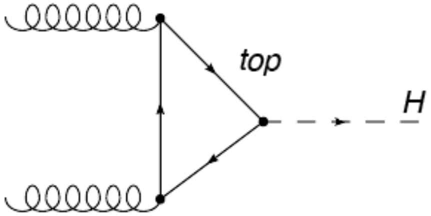




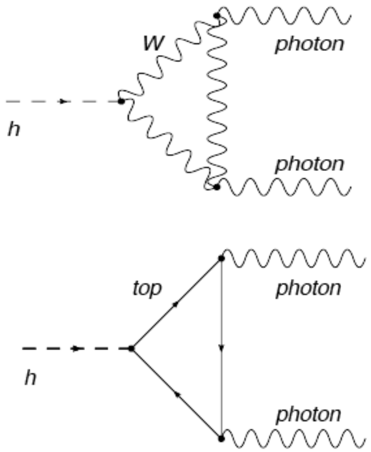
CL_s=0.16%

Influence of Undiscovered Heavy Charged Particles?

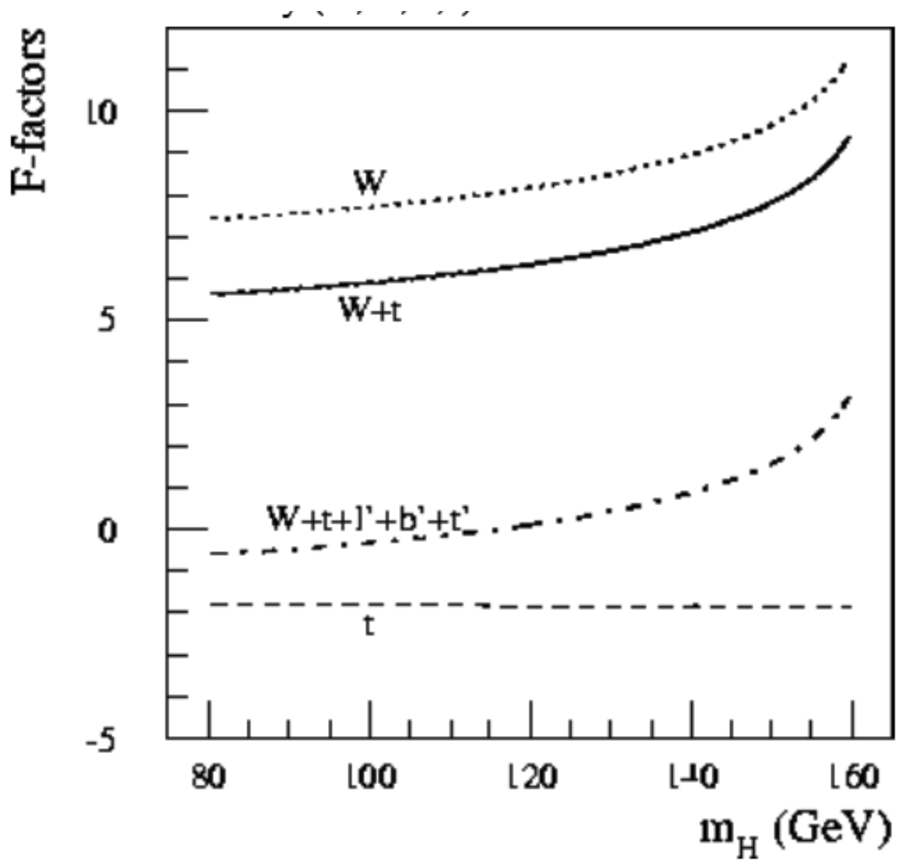
e.g. H → γγ



Dominant production mechanism



SM decay to 2γ

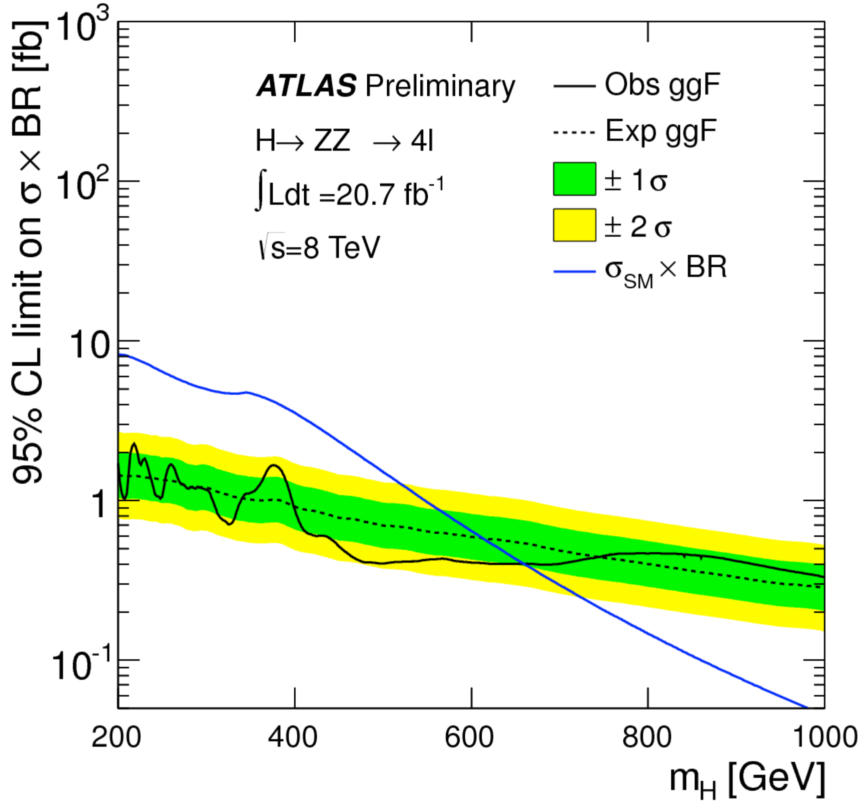


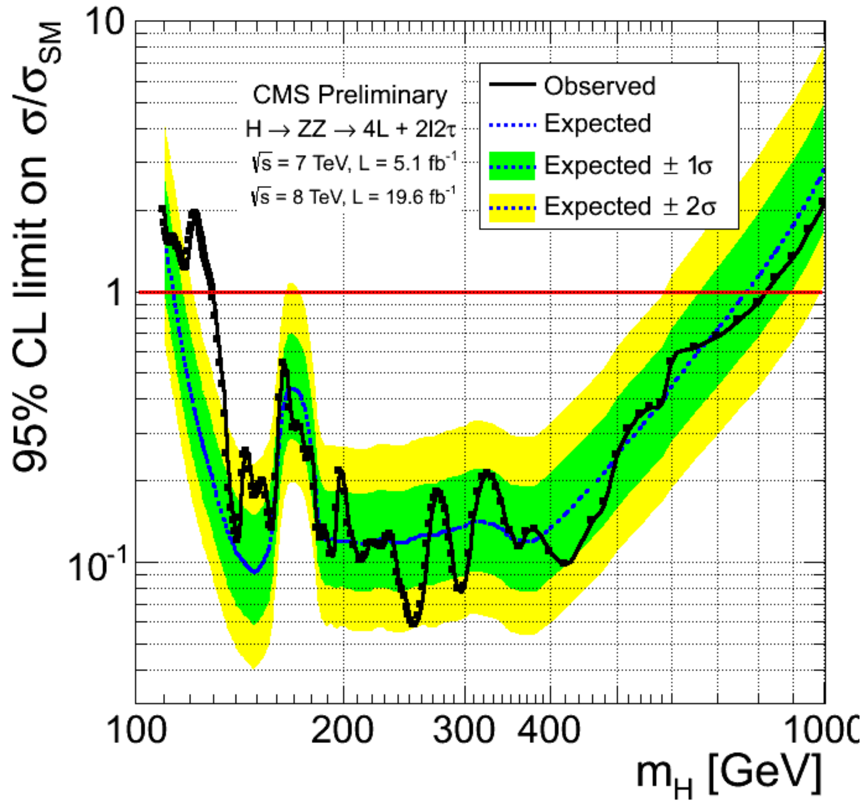
$$|M|^2 = \frac{g^2 m_H^4}{32\pi^2 m_W^2}\left|\sum_i \alpha N_c e_i^2 F_i\right|^2$$

Importance of H → γγ channel
A signal strength different from SM would indicate new physics

ATLAS: $\mu = 1.65^{+0.34}_{-0.30}$ CMS: $\mu = 0.78^{+0.28}_{-0.26}$

Any other Higgs bosons?





σ x BR limit for an additional gluon-gluon fusion produced Higgs boson with SM-like width decaying to ZZ → 4l

H to ZZ → 4l

Exclude M_H<800 GeV (95% CL)

What makes a SM Higgs boson?

Does it have spin 0 or 2? What is its parity (SM H → 0^+)
Data consistent with 0^+, excluding 0^- at >95% CL

Is it elementary or composite? (SM H is elementary)
No significant deviations from Standard Model

Couples to particle masses in proportion to their masses ($\sim M_f^2/v^2$, $\sim M_V^4/v^2$) ?
Evidence that it does

Couples to massless photon (gluons) trhrough loops of virtual charged/coloured particles (t, W,…)?
$\gamma\gamma$ coupling > Standard Model? Average appears consistent with SM.

What are its self-couplings? HL–LHC (>2025)
Is it alone? No evidence for another one but still looking

Is there any room for new physics?

Imperial College London

Physics of the LHC: Questions from the 1990's

1. SM contains too many apparently arbitrary features – *presumably should become clearer as we make progress towards a unified theory.*

2. Clarify the origin of mass (e-w symmetry breaking sector)

SM has an unproven element: the generation of mass

The SSB mechanism ? or other physics ?

✔Answer may have been found

e.g. why $M_{\gamma} = 0$

M_W, M_Z ~ 100,000 MeV!

3. SM gives nonsense at LHC energies

Probability of $W_L W_L$ scattering becomes greater than 1 !! Nature's slap on the wrist!

✔Answer may have been found. Next: measure WW scattering at √s>1 TeV.

4. Identify particles that make up Dark Matter

Even if the Higgs exists, all is not well with SM alone: next question is "why is its mass so low"? *If a new symmetry (Supersymmetry) is the answer, it must show up at O*(**1TeV).** Lightest of the species is a candidate for dark matter

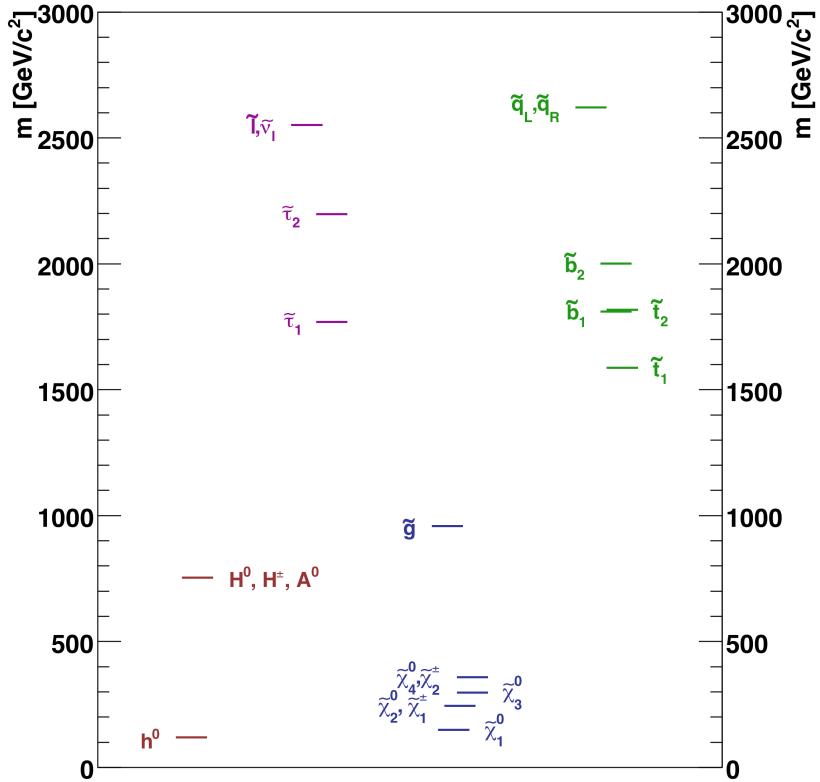
5. Search for new physics at the TeV scale

SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨ dramatic concepts: extra space-time dimensions, supersymmetry ?

Any other Higgs bosons? SUSY Higgs?

Here consider only Higgs' in MSSM
- **5 Higgs bosons h/H/A, H^+, H^-**
- At tree level, determined by two additional parameters: $\tan\beta = v_1/v_2$ and m_A (or m_{H+})



Major Higgs production modes:
- h/H/A: gg-fusion, associated b-production
- Light H^+: top quark decays
- *[Heavy H^+: gg/gb-fusion]*

Dominant decay modes
- **h/H/A** → bb, **ττ**
- Light **H^+ → τν**, small $\tan\beta$: $H^+ \rightarrow cs$

Couplings to b, τ enhanced wrt SM for large tan β

Any other Higgs bosons? SUSY Higgs?

Here consider only Higgs' in MSSM
- 5 Higgs bosons h/H/A, H^+, H^-
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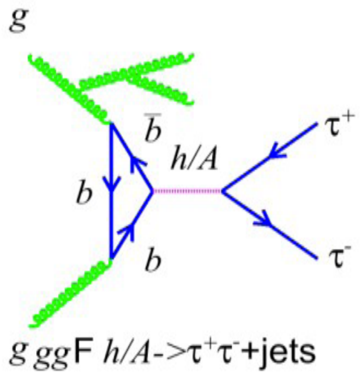
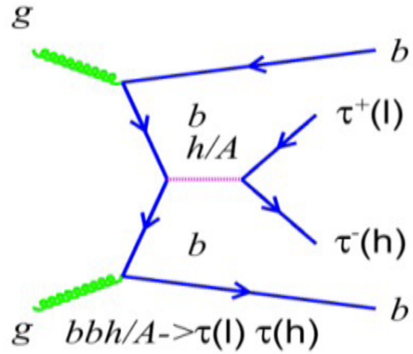
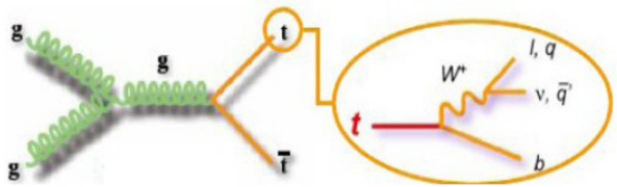
Major Higgs production modes:
- h/H/A: gg-fusion, associated b-production
- Light H^+: top quark decays
- *[Heavy H^+: gg/gb-fusion]*

Dominant decay modes
- h/H/A → bb, ττ
- Light $H^+ \to \tau\nu$, small $\tan\beta$: $H^+ \to cs$

Couplings to b, τ enhanced wrt SM for large tan β

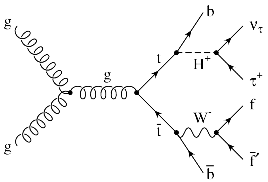


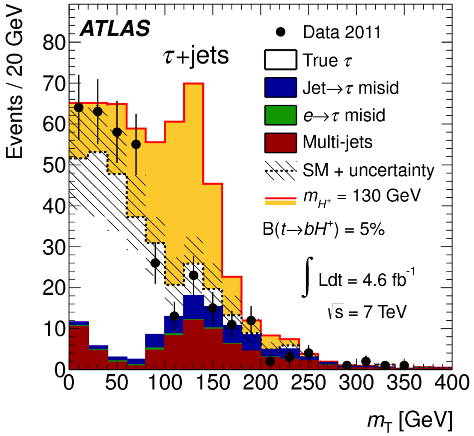


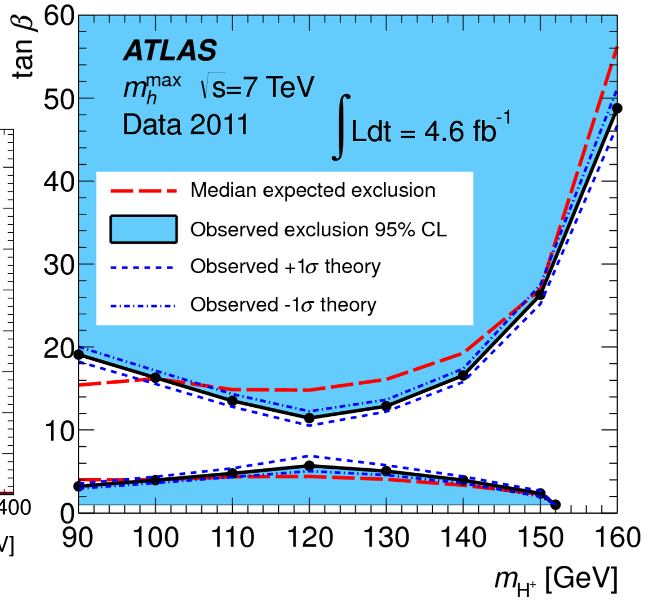


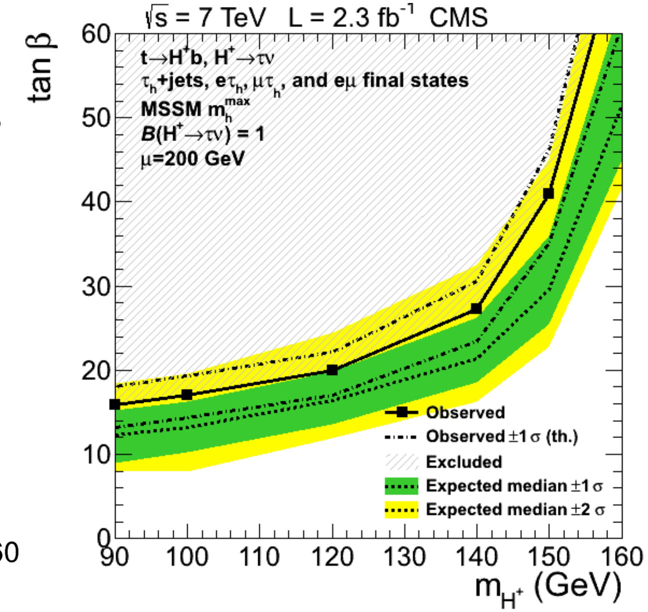
SUSY Higgs bosons: MSSM Inspired

$H^+ \rightarrow \tau^+\nu$

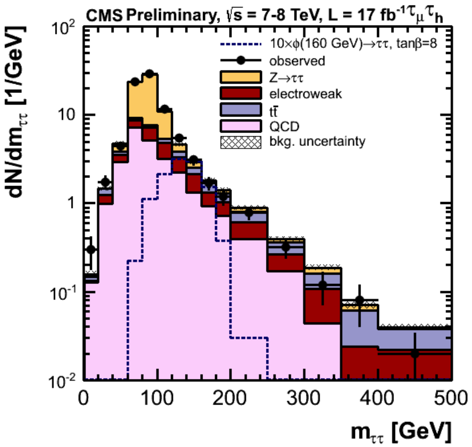


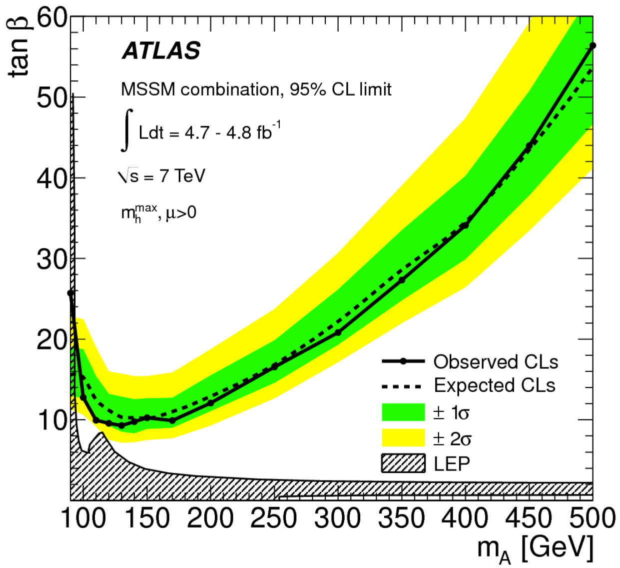


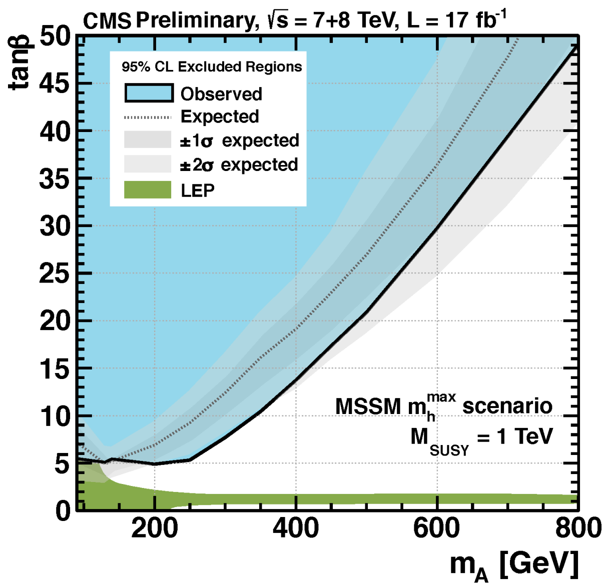




$h/H/A \rightarrow \tau\tau$

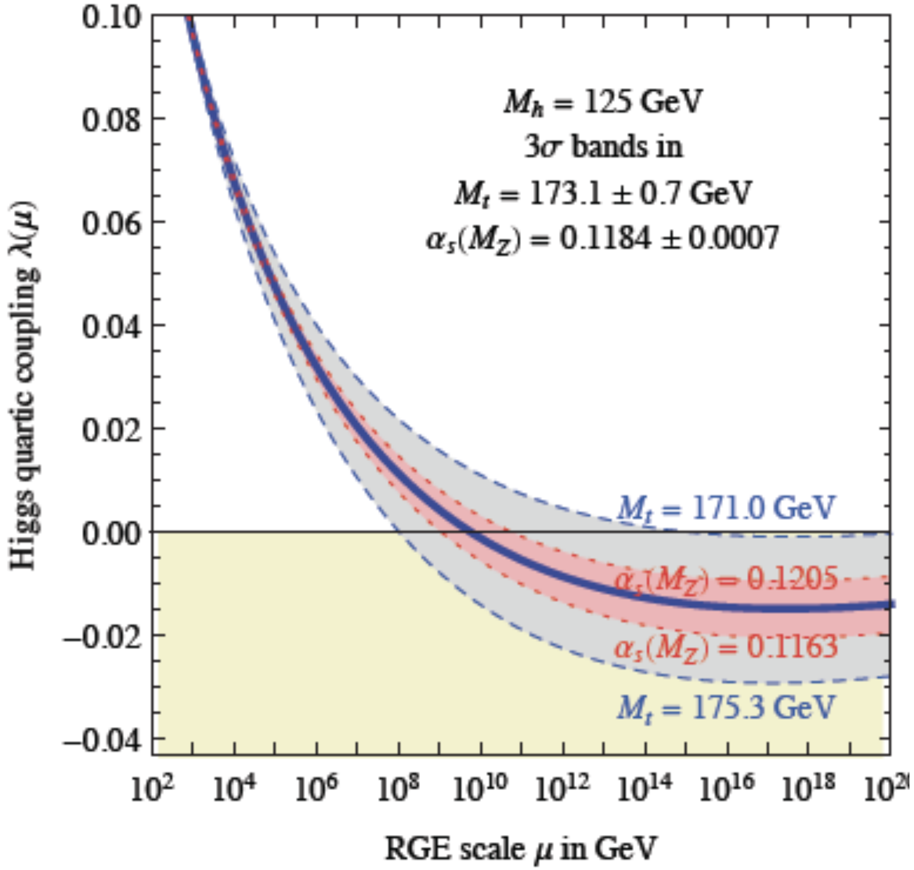


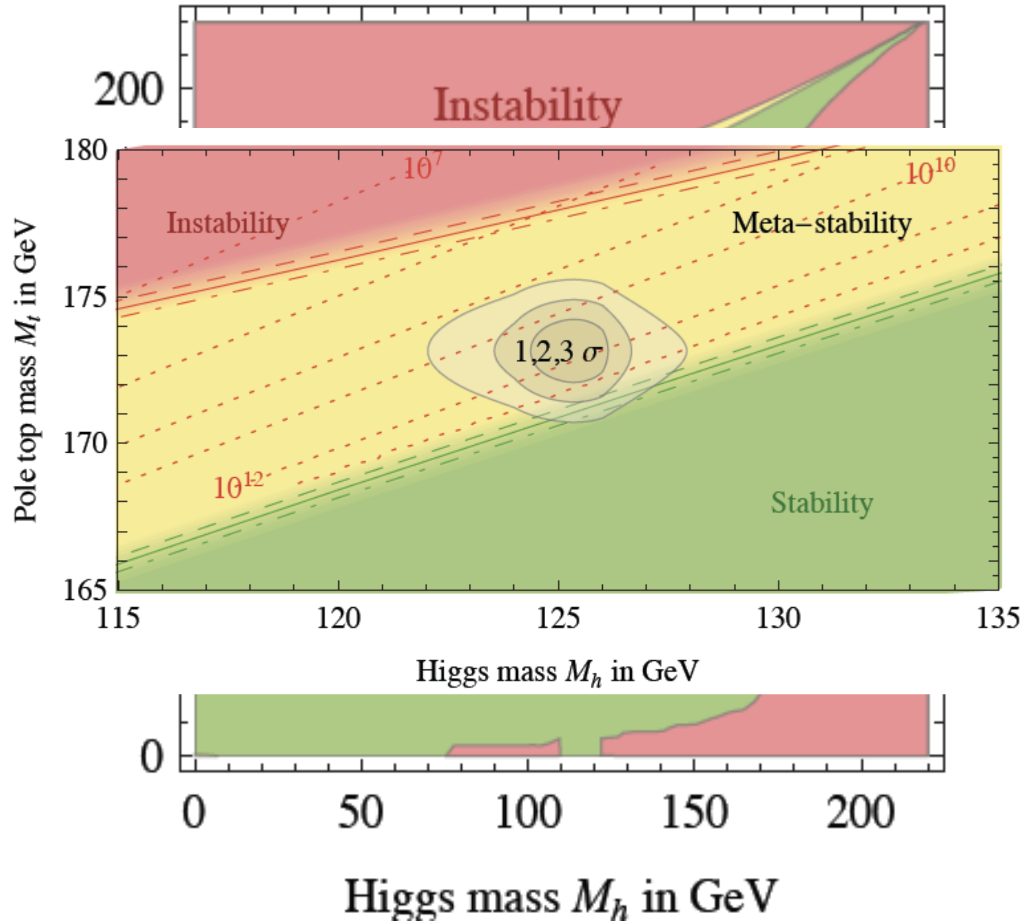




Vacuum Stability in the SM

Vacuum stability of the SM up to Planck scale is excluded at 2σ level (98% one sided) for m_H<126 GeV





Both λ and $\beta(\lambda)$ nearly vanish at the Planck Scale
Is it accidental or is it something deep?

G. Degrassi et al arXiv 1205.6497

Outlook for the LHC

Increase the Energy (√s)
Increase the Rate of Useful Integrated Luminosity

14 TeV vs 8 TeV – Gain Factors

Use parton luminosties to illustrate the gain of 14 vs 8 TeV

Higgs:
pp → H, H→WW, ZZ and γγ
mainly gg: Factor **~2**

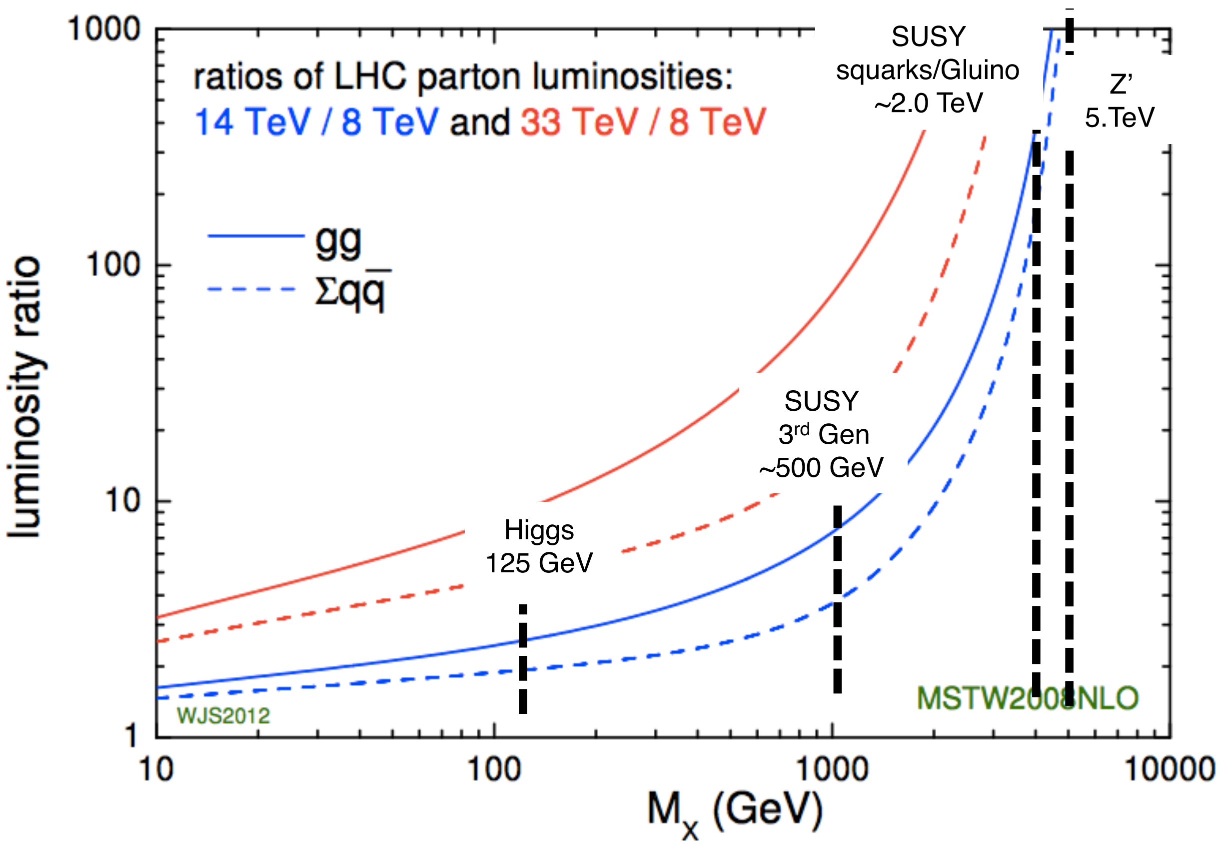
SUSY – 3rd Generation:
Mass scale ~ 500 GeV
qq and gg: Factor **~8**

SUSY – Squarks/Gluino:
Mass scale ~ 2.0 TeV
qq,gg,qg: Factor **~300**

Z' :
Mass scale ~ 5 TeV
qq: Factor **~1000**

O. Buchmuller

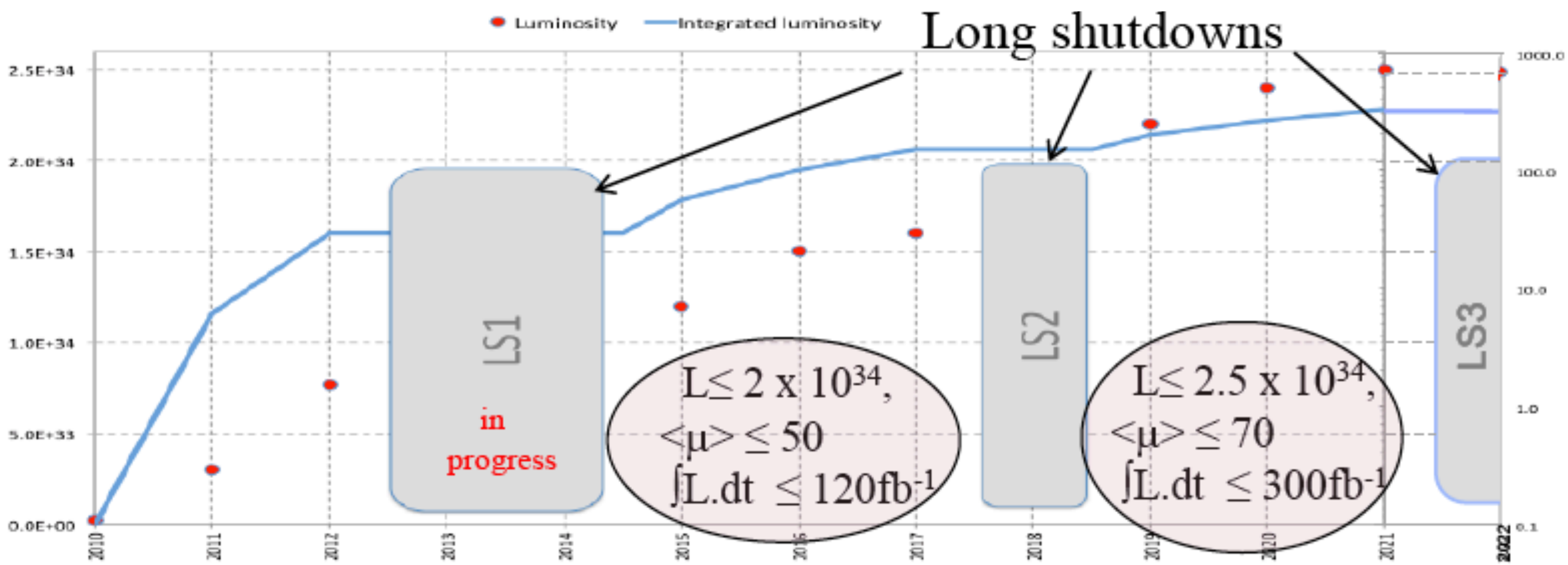
J. Stirling



For the searches increase in energy will help a lot!

Looking Ahead: Run II, III at LHC

LHC is outperforming its design performance on the way to 300fb^{-1} will exceed nominal



2013 2015 2020

√s > 13 TeV

Short-term Outlook

2012-2013:

Measurement of the properties of the new boson

Final "legacy" results from the full dataset – 2nd half-2013

2015 and beyond ($\sqrt{s}$ > 13 TeV)

Elucidate the detailed nature of the new boson

Does it really behave like the SM Higgs boson? Is it alone?

Search for Dark Matter (SUSY) (mass scale up to 3.0 TeV)

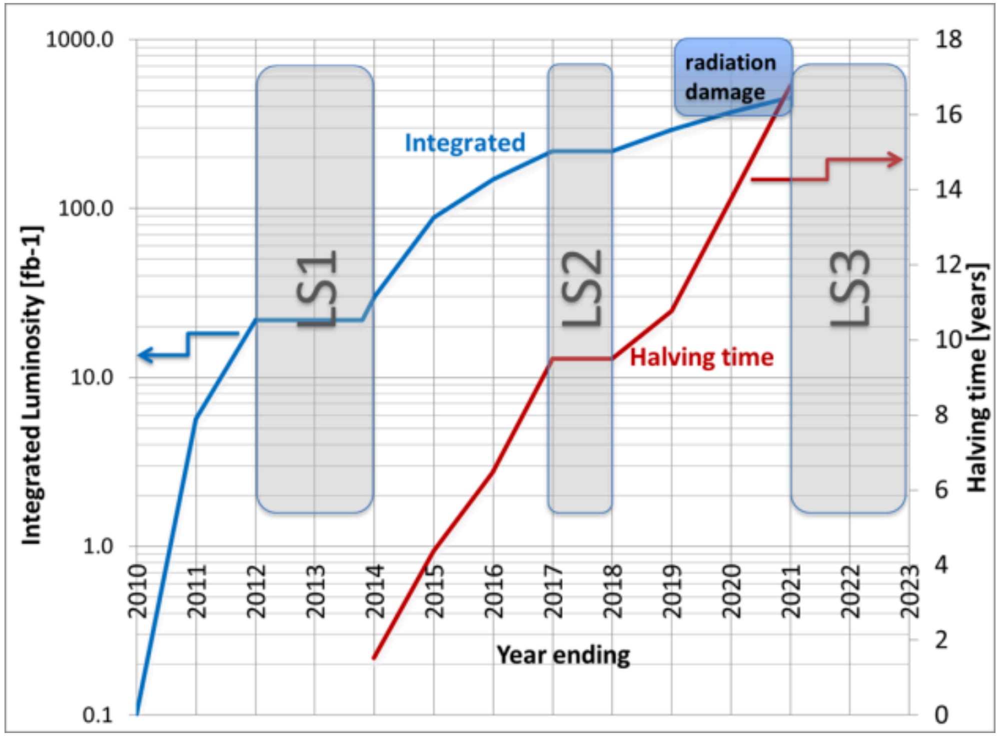
Search for conjectured new physics

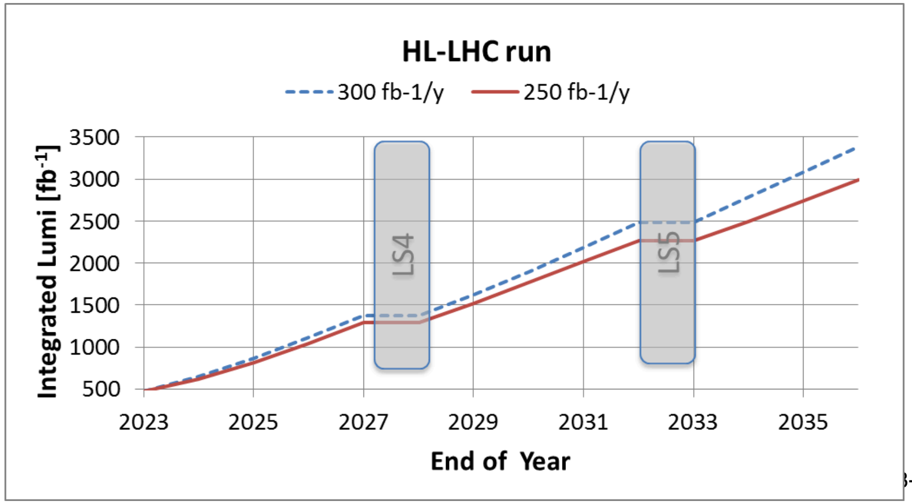
Why is m_H so low? Supersymmetry? Extra Dimensions?

Mass reach for objects with mass up to 4.0 TeV

Look for the unexpected

Looking Further Ahead: HL-LHC





"Halving-time" for statistical errors becomes very long after LS3.

Increase substantially the annual useful integrated luminosity

Need to upgrade LHC→ HL-LHC
Aim to integrate 3000fb^{-1},

Long Term Outlook: The Physics

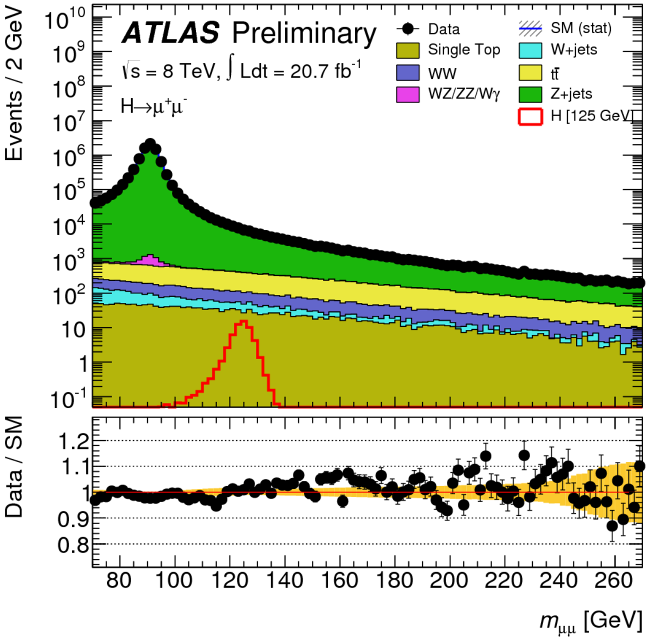
A clear priority: In depth studies of the found Higgs boson
Improved measurements of: i) mass, spin, signal strengths and couplings

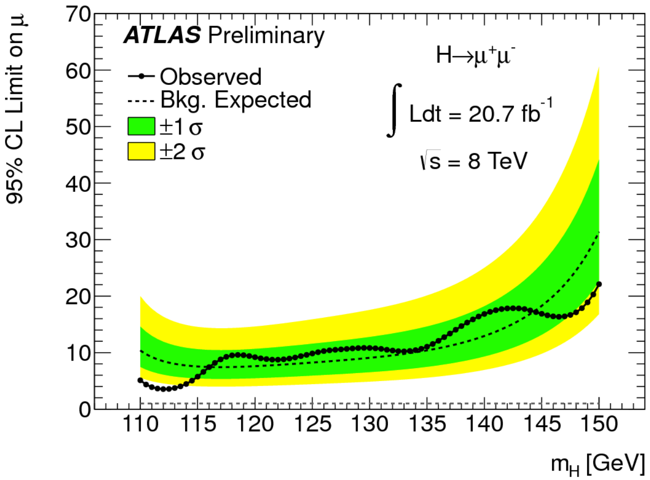
With increasing integrated luminosity search for rare decay modes and make increasingly precise measurements of the couplings, self-interaction, is it alone?, is it elementary or composite?, how much does it contribute to restoring unitarity in VBF
LHC → HL-LHC (HL-LHC will be a Higgs factory! 100M produced $3ab^{-1}$)

Another clear priority
i) Search for new physics: resonances, supersymmetry, exotica, yet unknown.
ii) Probe possible new physics through more precise SM measurements e.g.:
- top physics → study rare decays & measure couplings (LHC as top factory)
- search for anomalous TGC's).
- study of new physics via vector boson fusion

Detector Challenge: Must maintain/improve on detector performance as in Run I, in more hostile conditions

Rare Decays of Higgs boson





In the search for new physics we should also look at rare or exotic Higgs boson decays?

In Run II each experiment will produce ~ 10M H bosons

For 3 ab^{-1} ~ 100M H boson

e.g. Flavour Changing Decays?

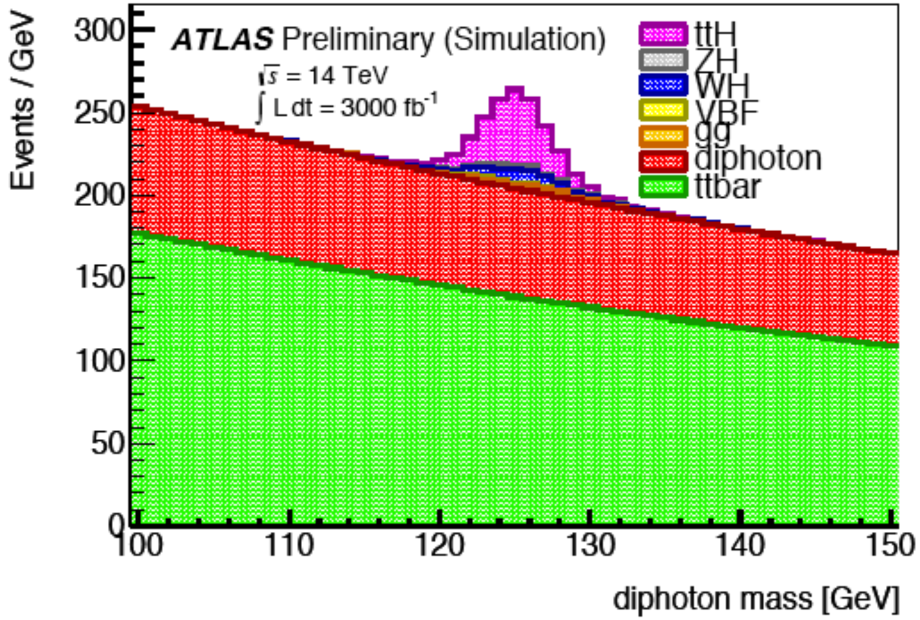
(consistent with current limits) H→ τe, τμ !

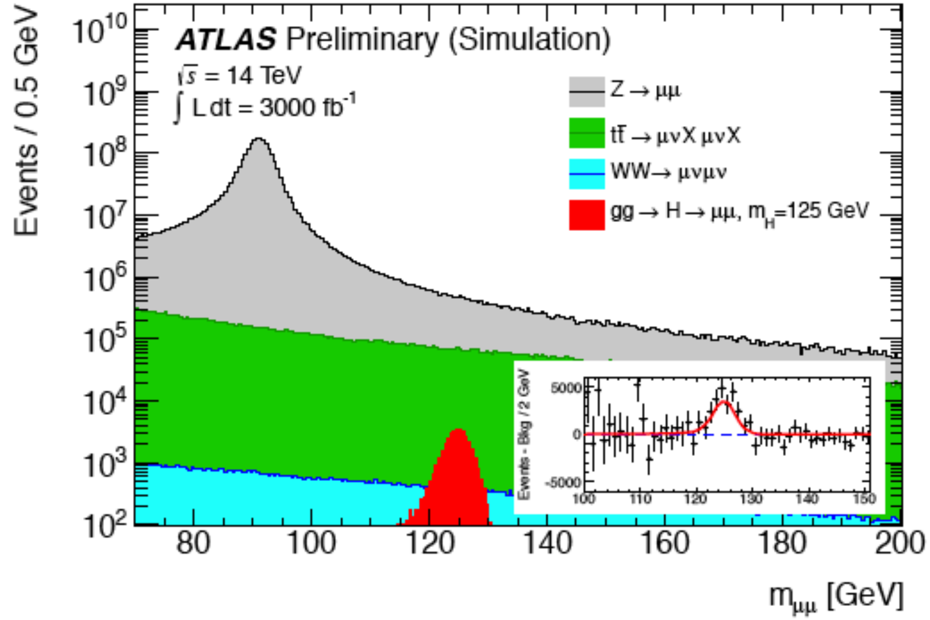
G. Blankenburg, J.E. Ellis, G. Isidori arXiv 1202.5704

Imperial College London

Some of the Physics of the HL-LHC

European Strategy Group CERN-ESG-005 Jan13





CMS

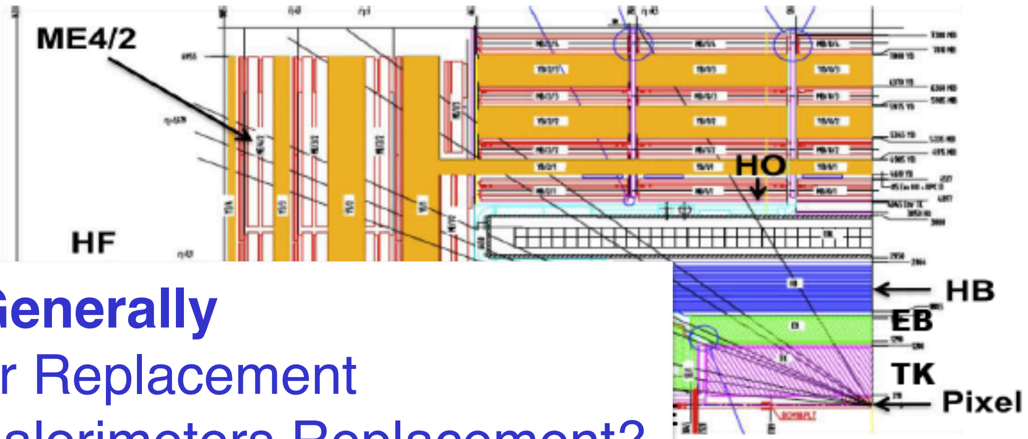
Coupling	300 fb^{-1} syst. (%) actual	300 fb^{-1} syst. (%) scaled	3000 fb^{-1} syst. (%) actual	3000 fb^{-1} syst. (%) scaled
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

What accuracy is needed and why?

HL-LHC: What does it mean for the Detectors?

CMS detector upgrades summary

Phase 1: in production for LS1
- Complete muon coverage (4'th endcap layer)
- Improve muon operation (1'st endcap layer), and barrel drift tube electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and (
- DAQ1 → DAQ 2
- Consolidate comm



LS1(22mo)

Generally
Tracker Replacement
Endcap/Forward Calorimeters Replacement?
Level-1 Trigger: Increase in Accept Rate?
Front-end Electronics?

Phase 1: up to (
- TDR's approved:4 layer Pixel tracker (install in YEETS 2016-17), HCAL electronics/granularity
- TDR in 2013: L1-Trigger
- Preparatory work during LS1
  - New beam pipe (for 4 layer pixel tracker)
  - Test slices: *Pixel(CO2 cooling), HCAL, L1-trig*
  - Install ECAL optical splitters
    - *L1-trigger upgrade in parallel with run.*

posal in 2014)
- Tracker Replacement, Track Trigger
- Endcap/Forward region improvements : Calorimetry, Muon system and tracking
- Further Trigger upgrade
- Further DAQ upgrade
- Many obsolescence/lifetime replacements
- Shielding/beampipe for higher LHC aperture

Summary

- After twenty years of design, construction we are in the 2nd half of the journey - that of extraction of the science.

- The accelerator and the experiments have operated very well.
- The LHC experiments are physics producing engines!

- A "massive" discovery has been made – A Higgs boson.
The boson discovered appears just to be the one predicted by the SM.
- The Standard Model with a single "elementary" scalar doublet seems to work well (too well)
- No evidence found yet of physics BSM

- The discovery of Higgs boson is just the start of a major programme at the LHC. In equal parts:
  - Precision measurements (not only of the new boson)
  - Searches for new particles and phenomena

Summary II

The discovery is a triumph for science and tribute has to be paid to

- **all the theorists** who built the SM, those who carried out detailed calculations of the many processes (including precise predictions for known physics),
- **all the accelerator builders and operations teams,**
- **all the technicians, engineers and the experimental physicists,**

who had the vision and tenacity to build and operate the superb accelerator and the experiments

We seem to have discovered a particle *sans precedent*

Likely to have far-reaching consequences on our thinking about Nature.

Must exploit the FULL potential of the LHC

“this includes the high luminosity upgrade of the accelerator and the experiments with a view to collecting ten times more data than in the initial design by around 2030”

European Strategy Group 2013