SM and BSM: experimental techniques and results

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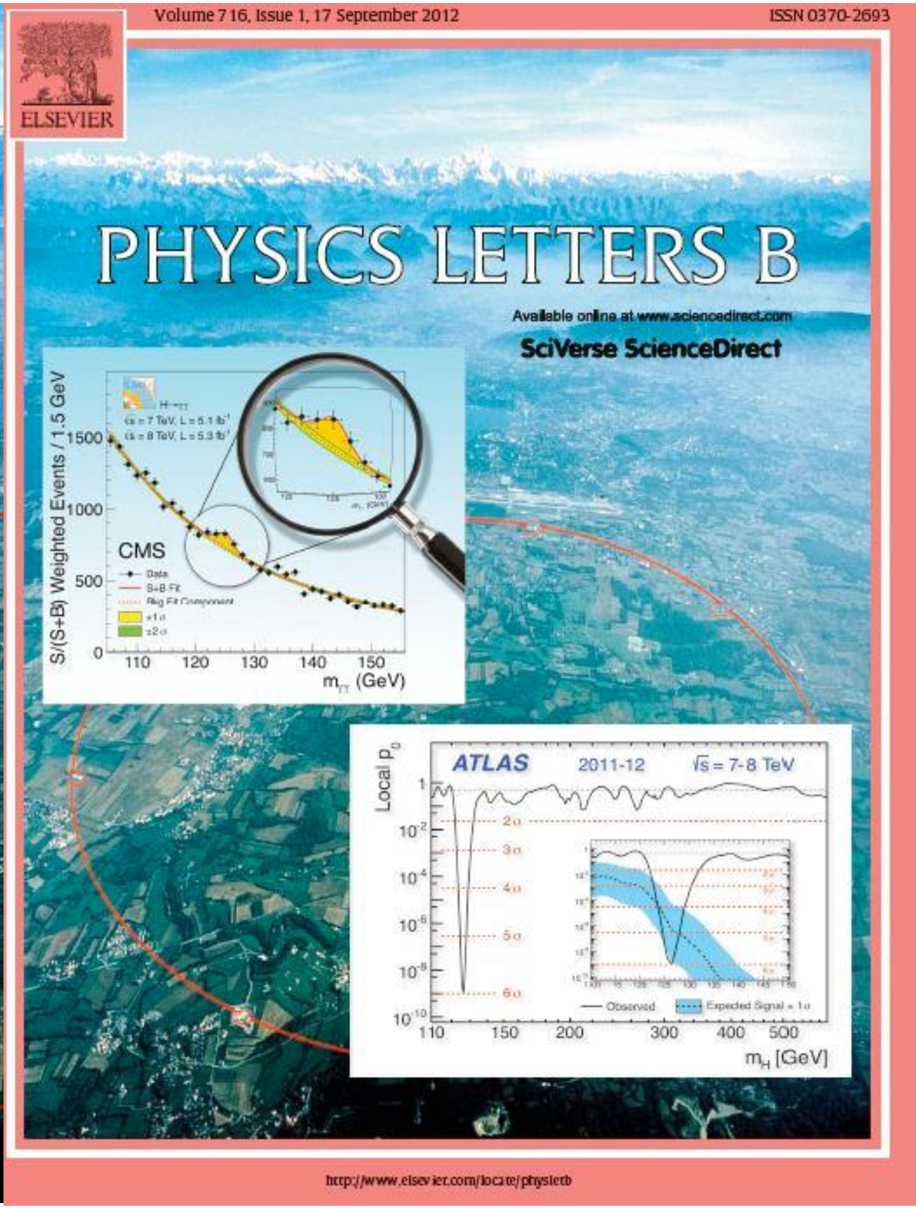
TAE 2015,
22th – 26th Sep 2015, Benasque



Outline

- **SM measurements at the LHC**
  - Status of the SM
    - EWK measurements
    - top-quark related measurements
  - Results at 7,8 and some new at 13 TeV
- **BSM at LHC**
  - Lessons from RUN 1
  - What to expect at RUN2 at 13 TeV and with 100 fb^{-1} / experiment

Four main results from LHC Run-1

1) We have **consolidated** the Standard Model

(wealth of measurements at 7-8 TeV, including the rare $B_s \rightarrow \mu\mu$ decay, very sensitive to New Physics)

→ it works BEAUTIFULLY …

2) We have **completed** the Standard Model: Discovery of the messenger of the BEH-field, the Higgs boson discovery

(over 50 years of theoretical and experimental efforts !)

3) We found interesting properties of the hot dense matter

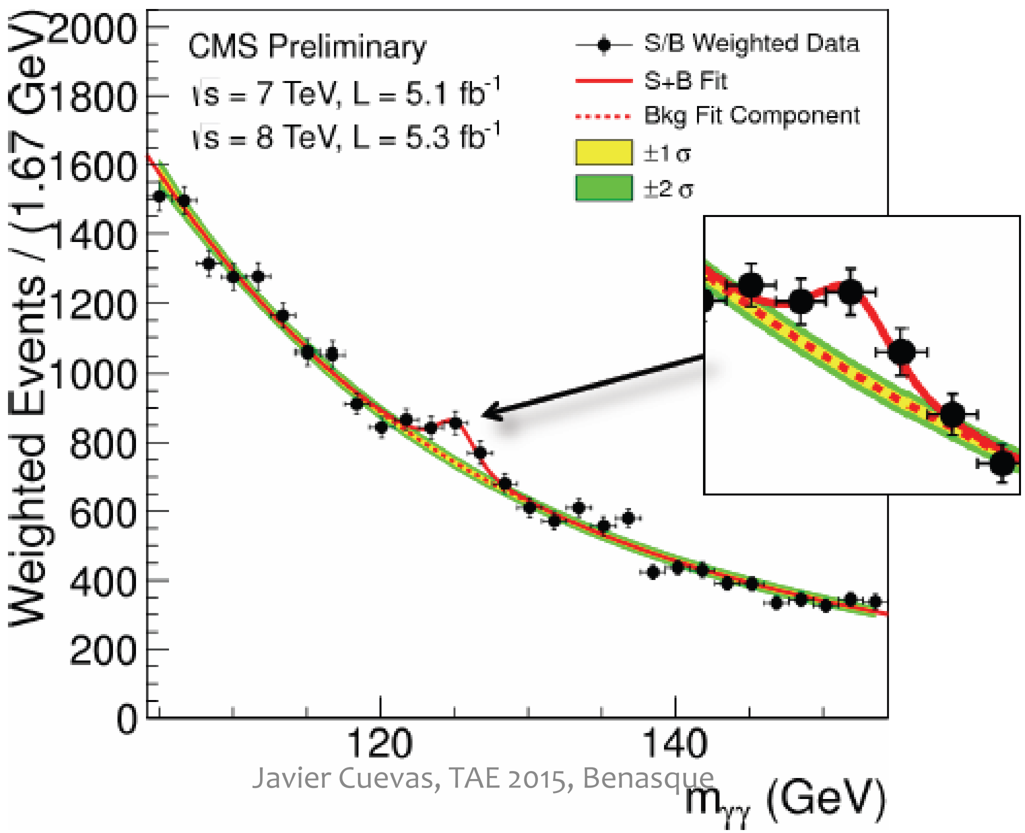
4) We have no evidence of new physics (YET)

R. Heuer, CERN school last week.

July 14th Seminar

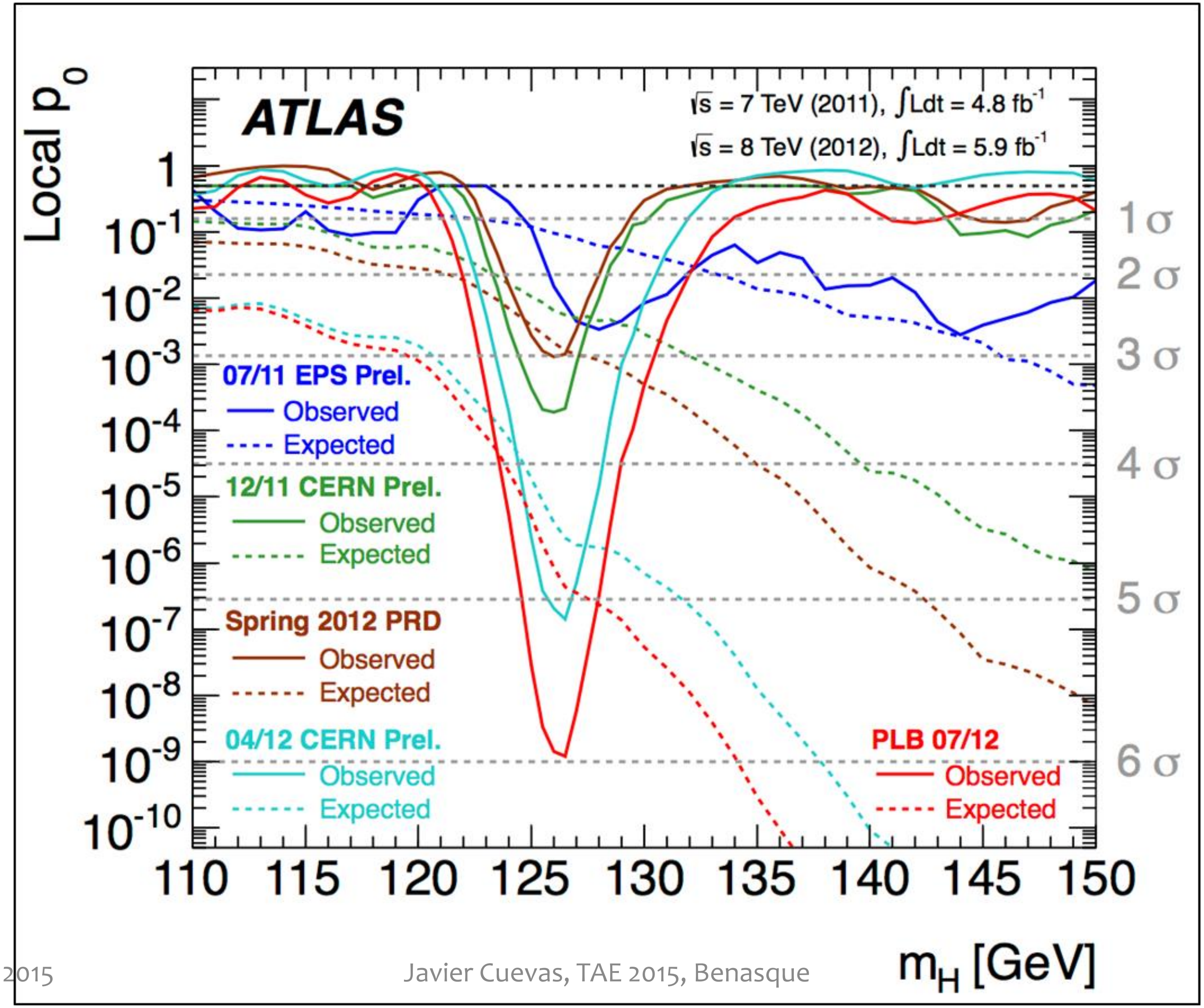
S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval

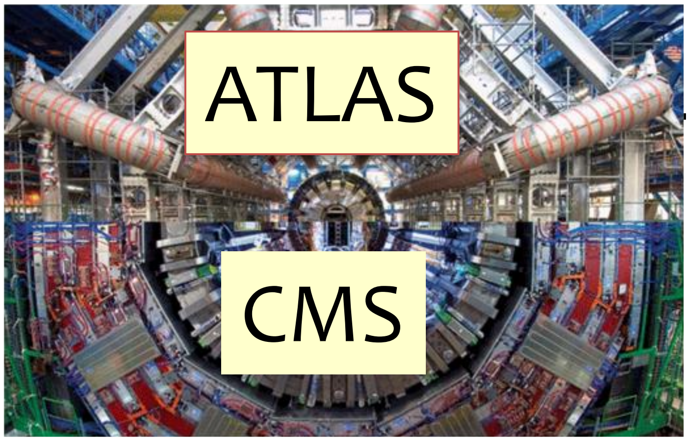


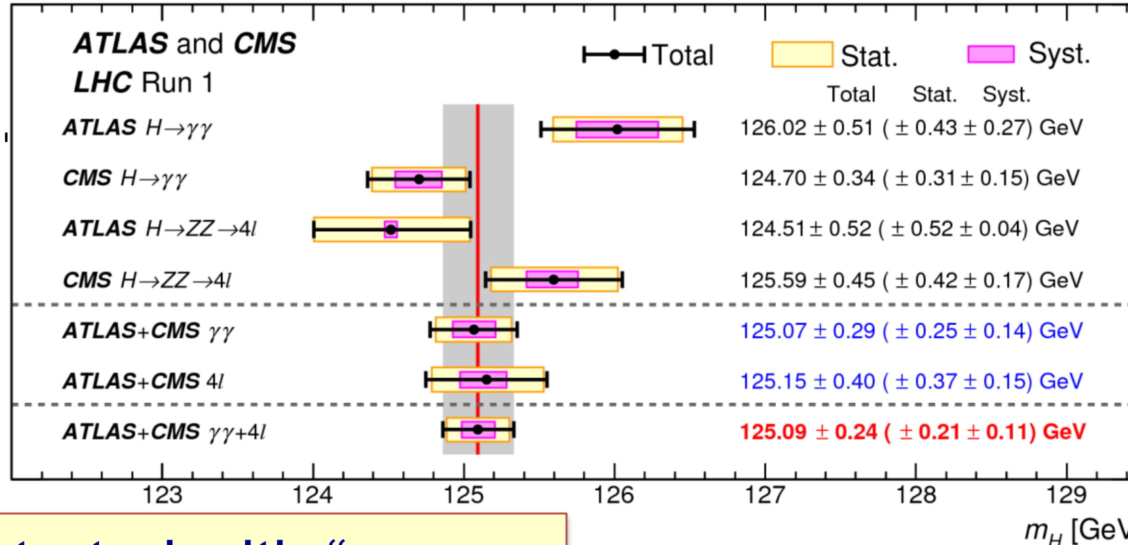
July 4th 2012 The Status of the Higgs Search J. Incandela for the CMS COLLABORATION

Evolution of the excess with time

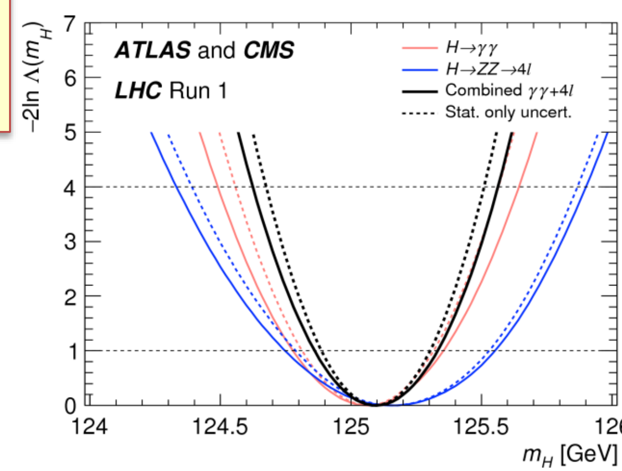


The BEH scalar (aka "Higgs boson")





90's, 00's, 10,11: talks started with "… we know everything … except its mass…"

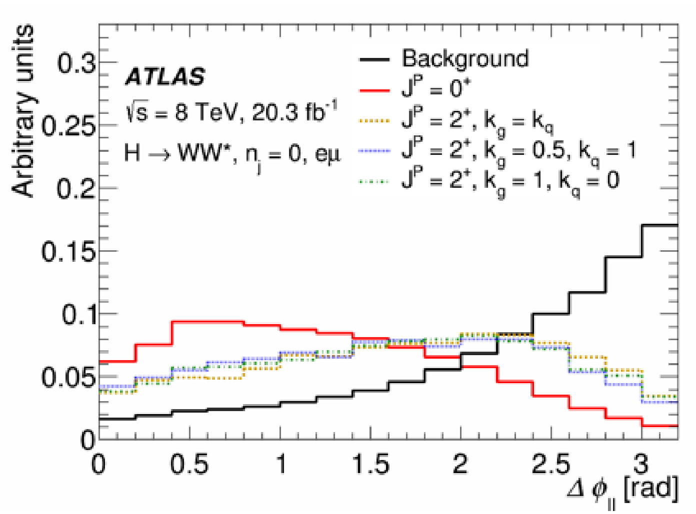


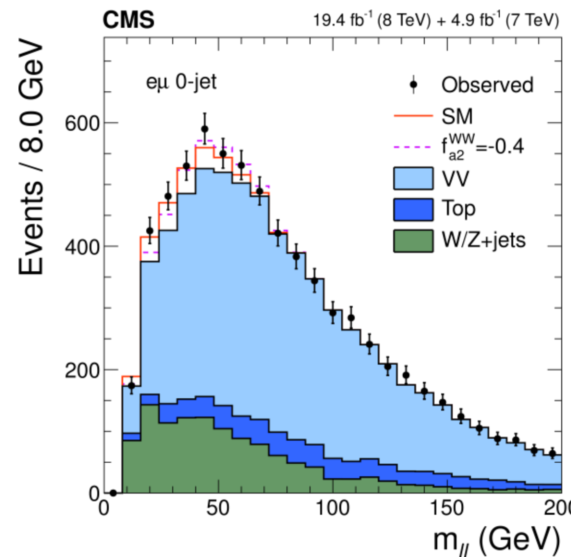
$M_H = 125.09 \pm 0.24$ GeV
$= 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})$ GeV

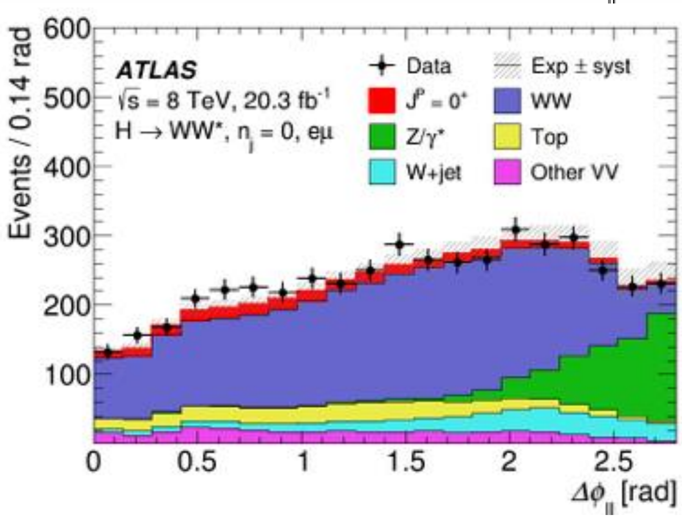
$\Delta m_H/m_H = 0.2\%$

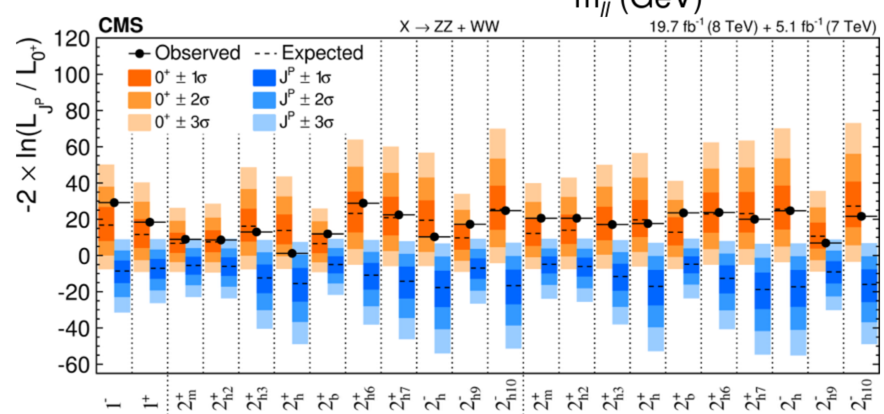
A scalar, beyond "reasonable" doubts

γγ, WW, ZZ modes







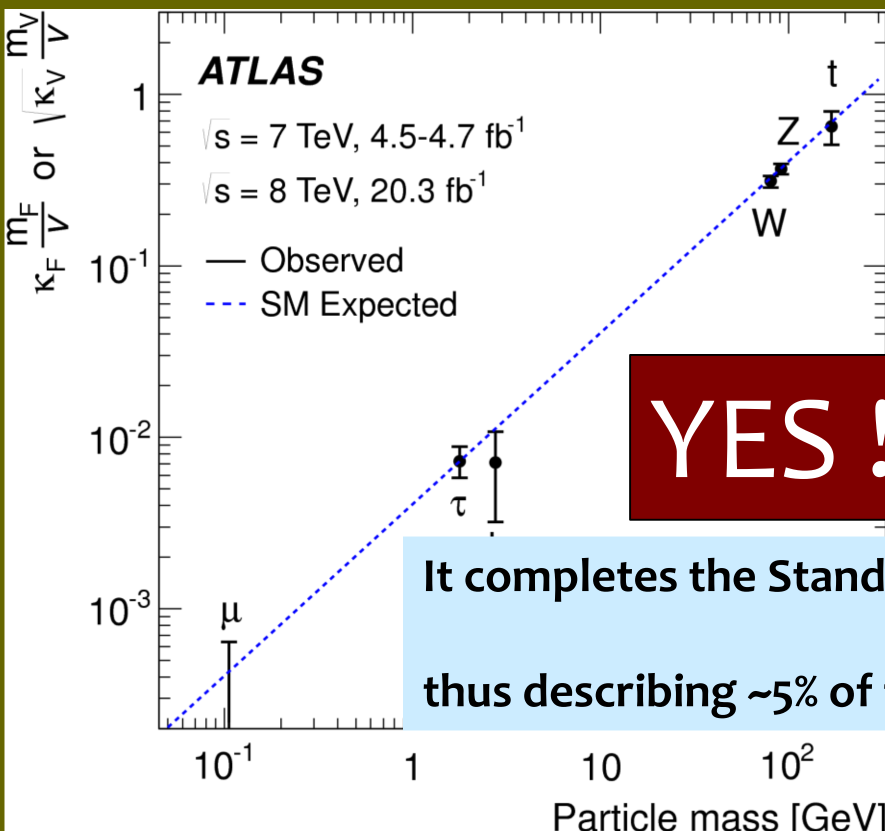


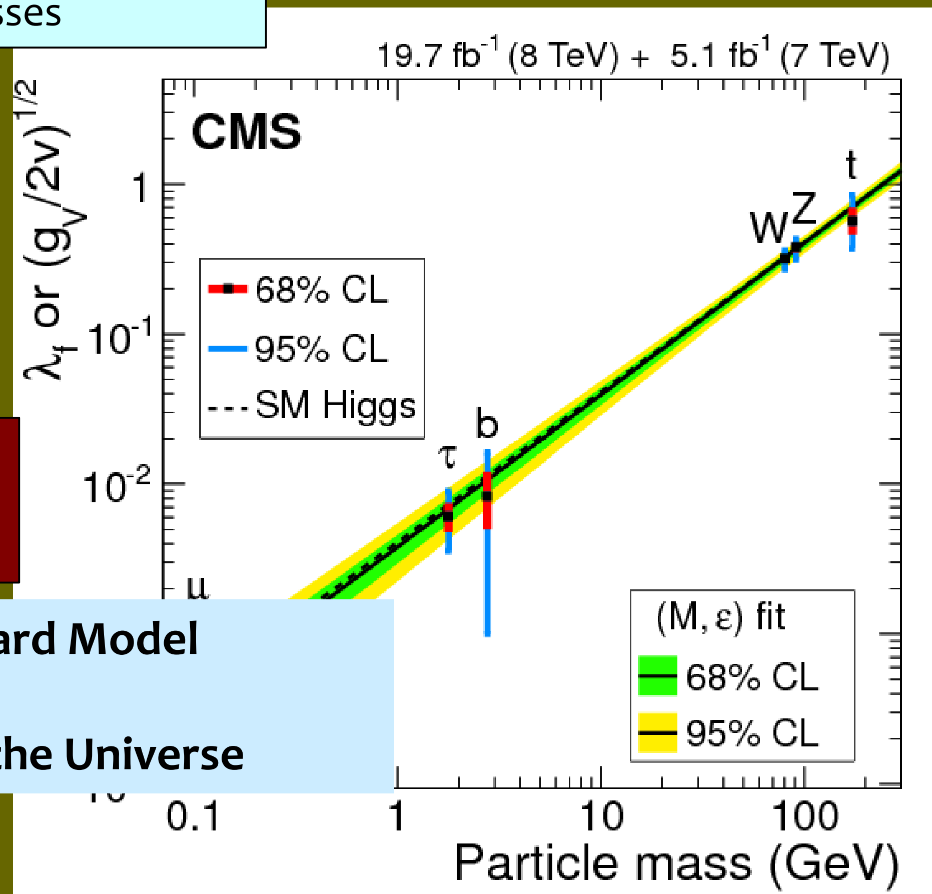
Alternatives tested: $0^{\pm}$, $1^{\pm}$ and $2^{\pm}$;
Excluded at >99% CL

Is the new particle a Higgs boson ?

ATLAS and CMS have verified the two "fingerprints"

1) To accomplish its job (providing mass)
it interacts with other particles (in particular W, Z)
with strength proportional to their masses





YES !

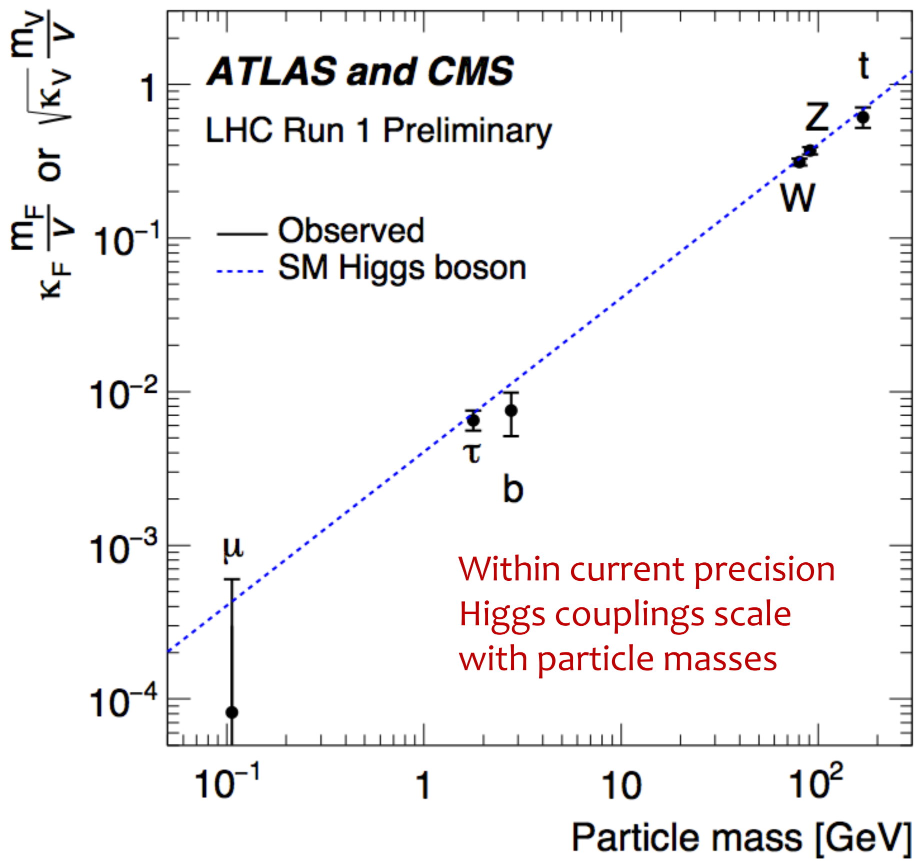
It completes the Standard Model

thus describing ~5% of the Universe

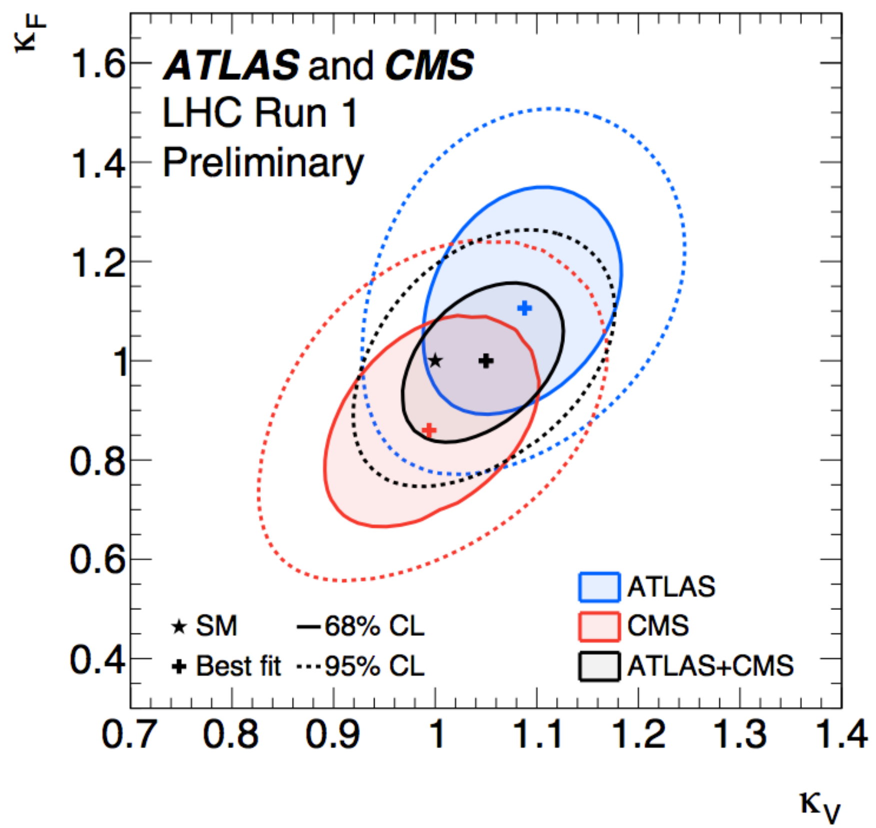
2) It has spin 0, it is representing a scalar field

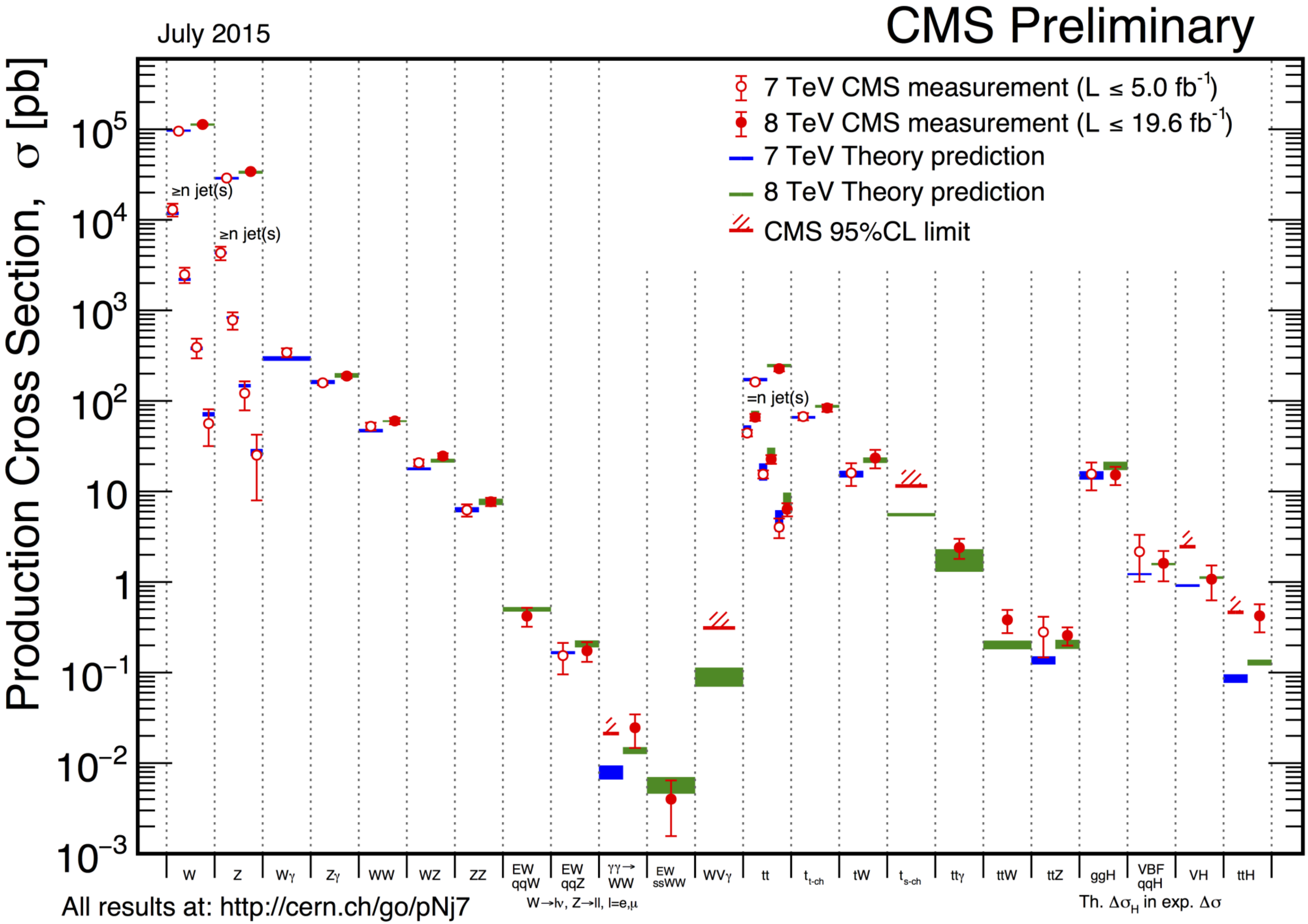
All results in agreement with SM

Fitting the 5 main tree level coupling modifiers + κ_μ and resolving all the loops.

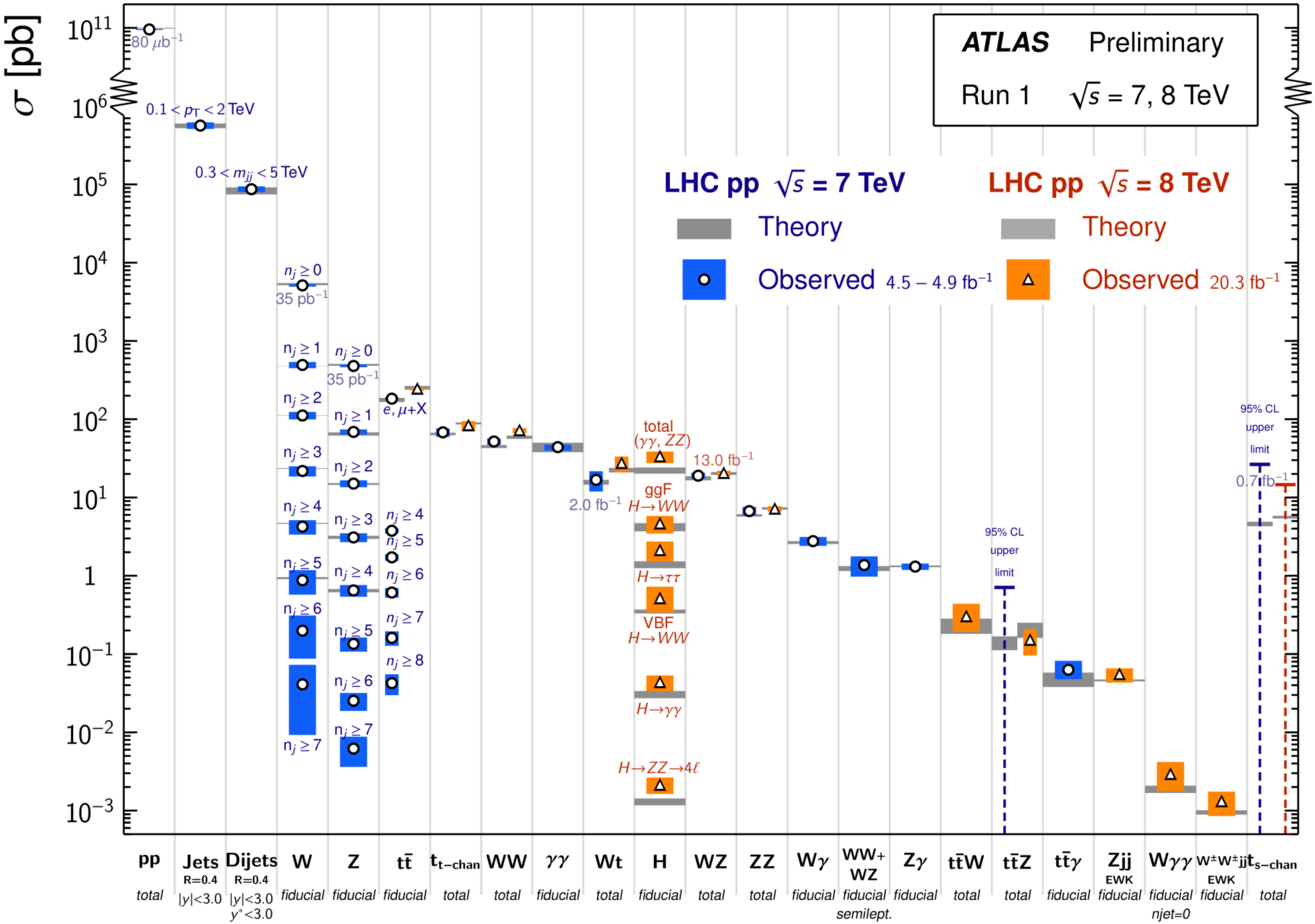


All vector and fermion couplings scaled by κ_V and κ_F




CMS Preliminary
July 2015
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb-1)
8 TeV CMS measurement (L ≤ 19.6 fb-1)
7 TeV Theory prediction
8 TeV Theory prediction
CMS 95%CL limit
≥n jet(s)
≥n jet(s)
=n jet(s)
W
Z
Wγ
Zγ
WW
WZ
ZZ
EW qqW
EW qqZ
γγ→ WW
EW ssWW
WVγ
tt
t t-ch
tW
t s-ch
ttγ
ttW
ttZ
ggH
VBF qqH
VH
ttH
W→lν, Z→ll, l=e,μ
Th. ΔσH in exp. Δσ
All results at: http://cern.ch/go/pNj7

Standard Model Production Cross Section Measurements



Where have all the New Physics signatures gone?

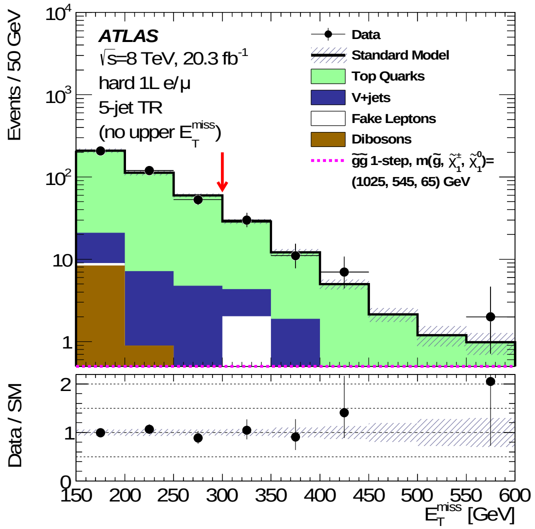
- Solutions to the h-problem -> signatures
- All solutions demand the presence of new particles
  - More Higgs bosons; SUSY partners; New W/Z bosons; new T, B
  - Once we speak of the "allowable": even "Vector-Like Quarks"
- Searches for new physics: main path has been the search for these (higher-mass) states
  - In the beginning inclusively; as time goes by and searches come in empty-handed, ask "what/how" would have escaped?
    - And then tune analyses and go after specific signatures
- **Broadly speaking, five categories of searches:**
  - **Searches for new resonances**
  - **Non-resonant: searches for SUSY (exemplified by MET)**
  - **Extending SUSY-like signatures: Dark Matter searches**
  - **Deviations from the QCD+EWK predictions (compositeness)**
  - **Exotica (e.g. long-lived "stuff")**

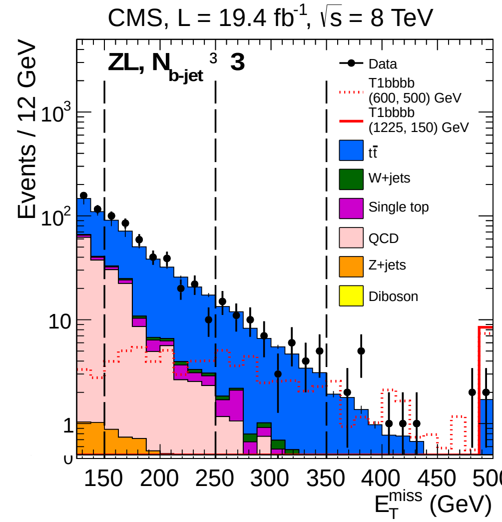
SUSY: the (19)90's–(20)00's view

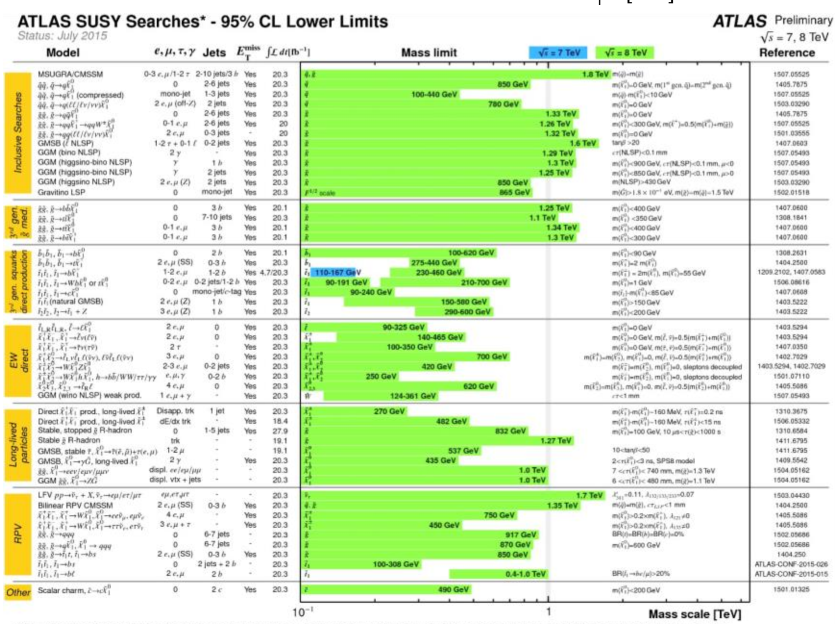
SUSY Summary

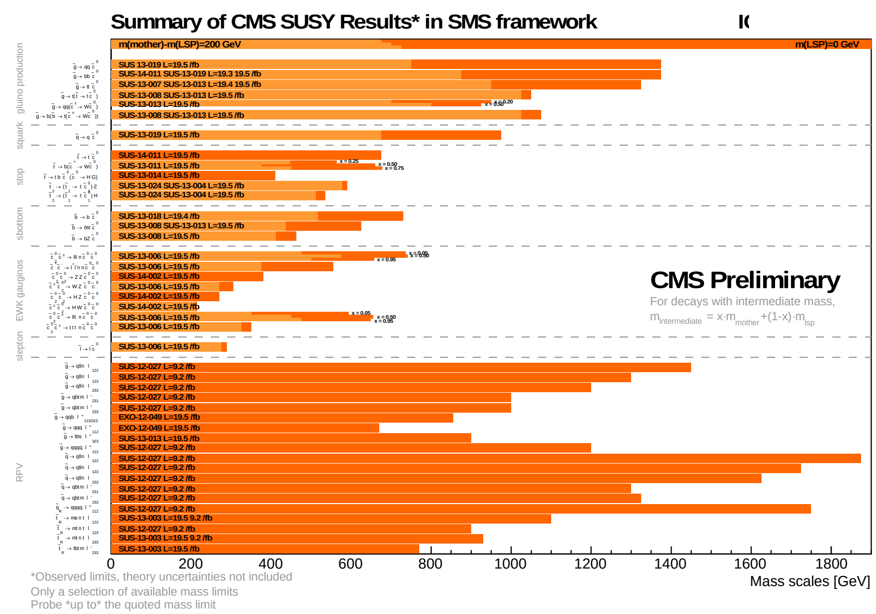
- SUSY discovery (should be) easy and fast
  - Expect very large yield of events in clean signatures (dilepton, diphoton).
    - Establishing mass scale is also easy (M_{eff})
- Squarks and gluinos can be discovered over very large range in SUGRA space (M_0,$M_{1/2}$)~(2,1)TeV
  - Discovery of charginos/neutralinos depends on model
  - Sleptons difficult if mass > 300 GeV
  - Evaluation of new benchmarks (given LEP, cosmology etc) in progress
- Measurements: mass differences from edges, squark and gluino masses from combinatorics
- Can extract SYSY parameters with ~(1-10)% accuracy

Run1 Results







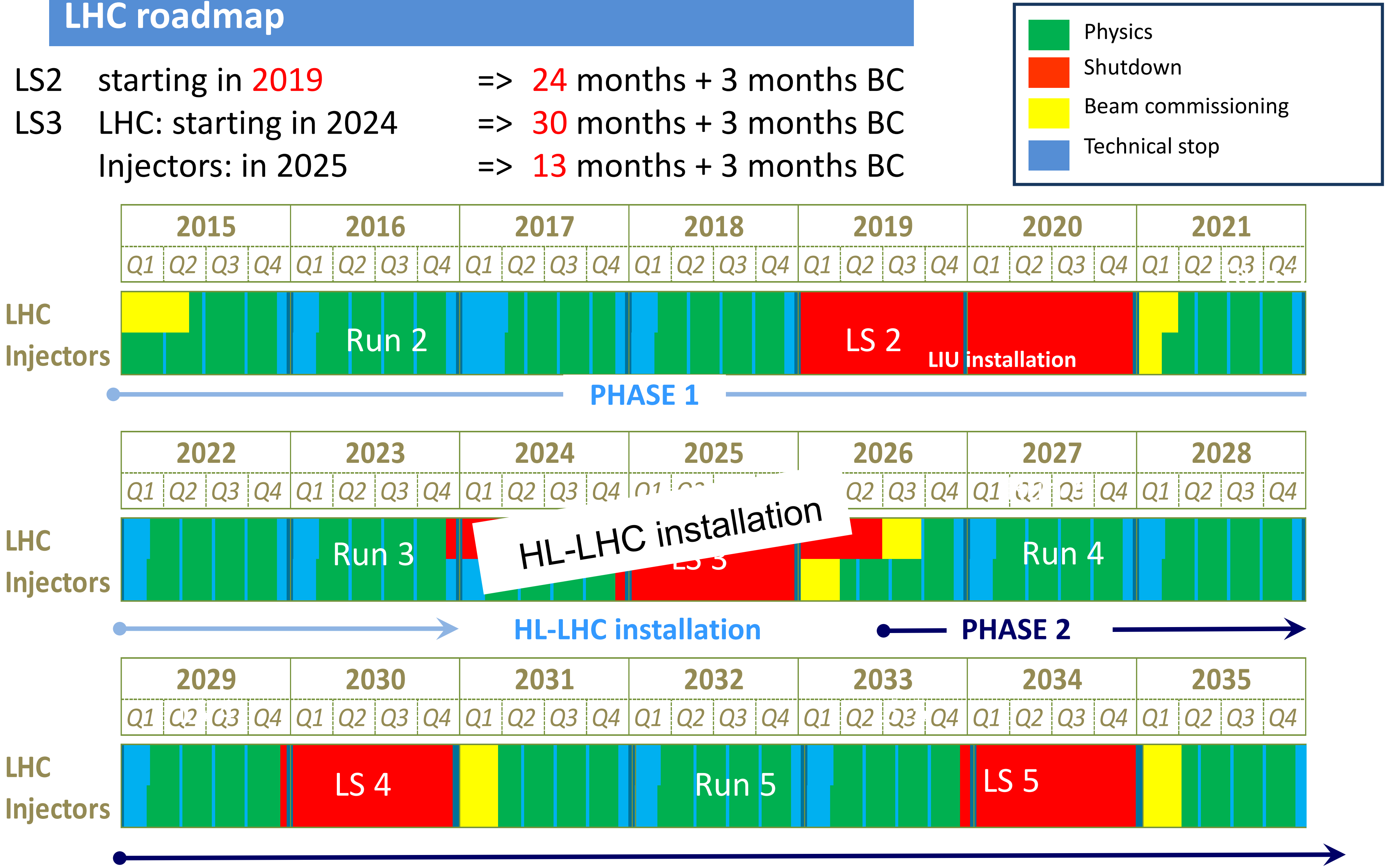


Post- Higgs-discovery -> LHC run 2

- Good reasons to expect more
  - **We have really just begun the searches**
  - **Much space has yet to be accessed**
  - **And there are important new physics models yet-to-be invented**
- Precision and rare physics
  - Beyond our direct production reach
    - LHC is also a superb **intensity** frontier machine
- Investment is critical
  - Powerful detectors, triggers, computing
    - A sustained period of important results
    - And practical applications
- **The LHC is the only Higgs, and top, Z, W… factory on the planet for many years to come!**

LHC roadmap

LS2	starting in 2019	=>	24 months + 3 months BC
LS3	LHC: starting in 2024	=>	30 months + 3 months BC
	Injectors: in 2025	=>	13 months + 3 months BC



Some of the physicists' jargon

- **Cross section (σ)**
  - A measure of 'frequency' of the physical process
  - Units: barns (10^{-28} m^2)
  - Typical values: femtobarns (fb), picobarns (pb)
- **Luminosity (L)**
  - Or instantaneous luminosity
  - A measure of collisions 'frequency'
  - Typical at LHC: $L = 10^{34}$ $cm^{-2}s^{-1}$
- **Integrated luminosity ($L = \int L dt$)**
  - A measure of number of accumulated collisions after a certain time period
  - Units: (cross section)$^{-1}$.... E.g. 1 fb^{-1} = 1000 pb^{-1}
  - Typical at LHC: few fb^{-1}
- **Number of events (N)**
  - Number of (expected) events (N) after a certain time of running
  - $N = \sigma \cdot L$

Uncertainties in physics measurements

The sources of uncertainty in measurement[9]:

- **Incomplete definition** of the measurand; or its imperfect realization
- **Non-representative sampling**
- inadequate knowledge of the effects of environmental conditions; or imperfect measurements of these conditions
- **Personal bias** in reading instruments
- **Finite instrument resolution**
- Inexact values of measurement standards and reference materials
- **Inexact values of constants** and other parameters obtained from external sources and used in the data-reduction algorithm
- **Approximations and assumptions** incorporated in the measurement procedure
- **Variations of repeated observations** of the measurand under apparently identical conditions

[9] Adapted from the The International Organization for Standardization (ISO) Guide to the Expression of Uncertainty in Measurement.

“Optimal” presentation of (search) results

Optimal presentation of search results has some desired properties[10]:

- **Uncertainties due to systematic effects should be included in a clear and consistent way.**
  - Often it is useful to quote the statistical and systematical error separately, e.g. $\sigma = 45 \pm 4 \pm 1\ mb$.
- The result should summarize completely the experiment; so that no extra information should be required for further analysis.
- Results should be easily turned into probabilistic statements.
- Analysis should be transparent, and result should be stated in such a way that it cannot be misleading. The presentation of the result should not depend on the particular application.
- **If possible full pdf-distributions and even data sets can be attached into analysis results**.
- In **unified approach to data analysis**, the transitions between exclusion, observation, discovery, and measurement are kept as small as possible.

[10] Adapted from F. James, *Workshop on Confidence Limits*, CERN-2000-005, 2000.

Measurements vs predictions

Predictions/Simulation

Event Generation

Tools: **MC** generators (PYTHIA, …)

Output: final state particles

Detector simulation

Tools: **MC** simulators (GEANT)

Output: simulated detector response

Measurements

Collisions

Tools: Accelerator (LHC, Tevatron…)

Output: final state particles

Data acquisition

Tools: Detectors (CMS, ATLAS,…)

Output: detector response

Event reconstruction

Tools: Detectors' software packages (custom made; **MC** used in algorithms)

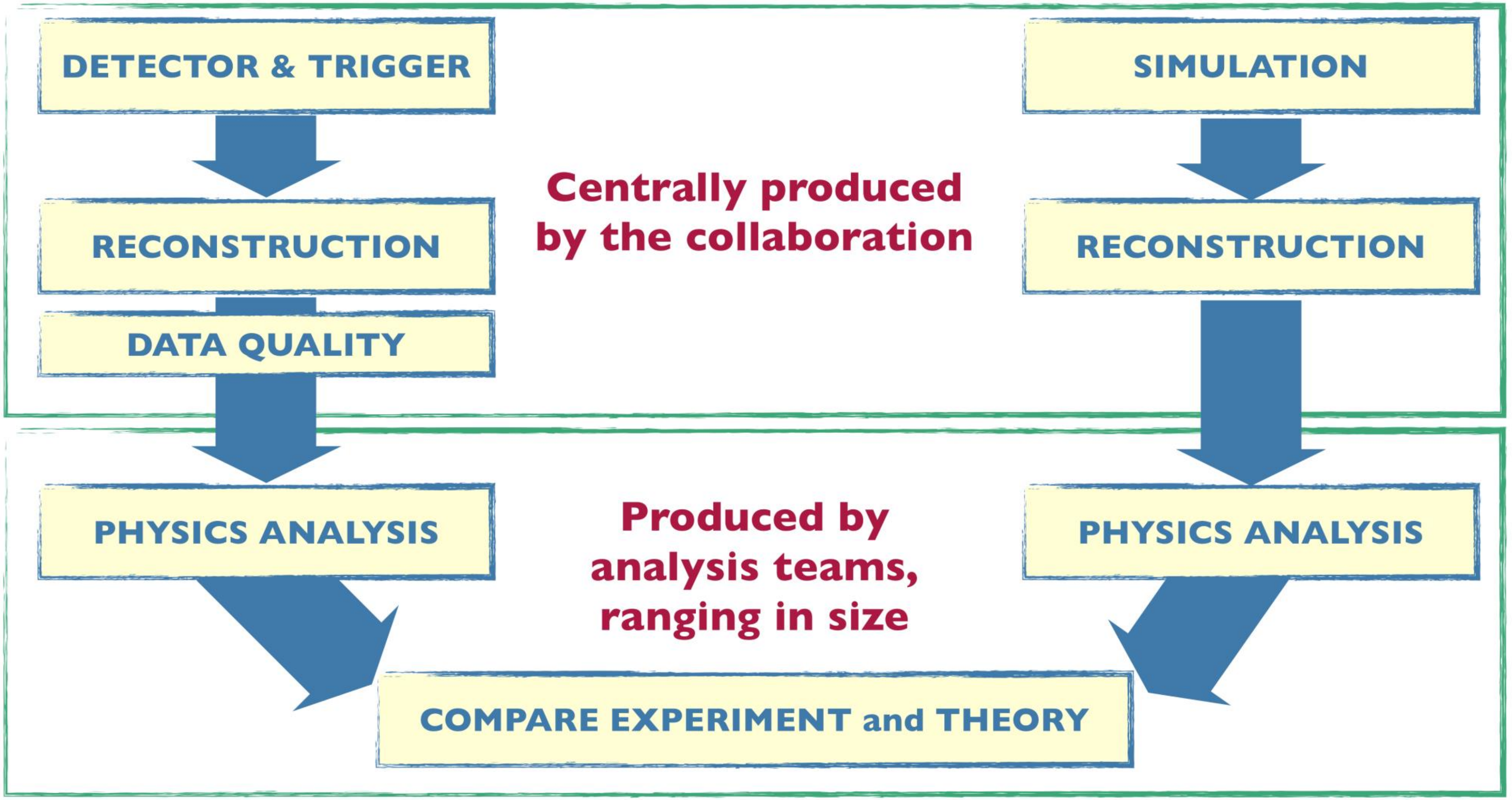
Output: reconstructed physical objects (electrons, muons, jets …)

Data analysis

Tools: Statistics (ROOT, …; **MC** used in algorithms; f.g. **Toy MC**)

Output: new knowledge (parameter/interval estimates, hypothesis tests, article, talks …)

GENERAL ANALYSIS FLOW



Reality → Experiment

```
0x01e84c10:  0x01e8 0x8848 0x01e8 0x83d8 0x6c73 0x6f72 0x7400 0x0000
0x01e84c20:  0x0000 0x0019 0x0000 0x0000 0x01e8 0x4d08 0x01e8 0x5b7c
0x01e84c30:  0x01e8 0x87e8 0x01e8 0x8458 0x7061 0x636b 0x6167 0x6500
0x01e84c40:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c50:  0x01e8 0x8788 0x01e8 0x8498 0x7072 0x6f63 0x0000 0x0000
0x01e84c60:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c70:  0x01e8 0x8824 0x01e8 0x84d8 0x7265 0x6765 0x7870 0x0000
0x01e84c80:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84c90:  0x01e8 0x8838 0x01e8 0x8518 0x7265 0x6773 0x7562 0x0000
0x01e84ca0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
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0x01e84ce0:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
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0x01e84d30:  0x01e8 0x87a8 0x01e8 0x8658 0x7370 0x6c69 0x7400 0x0000
0x01e84d40:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d50:  0x01e8 0x8854 0x01e8 0x8698 0x7374 0x7269 0x6e67 0x0000
0x01e84d60:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d70:  0x01e8 0x875c 0x01e8 0x86d8 0x7375 0x6273 0x7400 0x0000
0x01e84d80:  0x0000 0x0019 0x0000 0x0000 0x0000 0x0000 0x01e8 0x5b7c
0x01e84d90:  0x01e8 0x87c0 0x01e8 0x8718 0x7377 0x6974 0x6368 0x0000
```

Make sense of these numbers through data abstraction based on physics

Theory

$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$W^{\pm}, Z, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R$$

lepton and quark kinetic energies and their interactions with $W^{\pm}, Z, \gamma$

$$+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2} - V(\phi)$$

$W^{\pm}, Z, \gamma$ and Higgs masses and couplings

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)$$

lepton and quark masses and coupling to Higgs

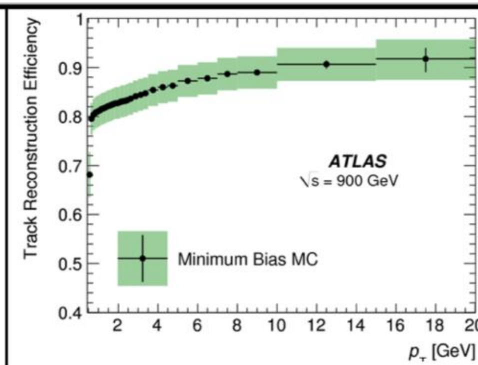
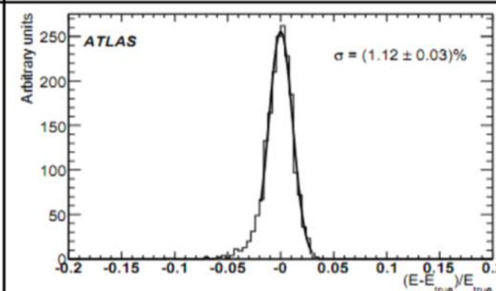
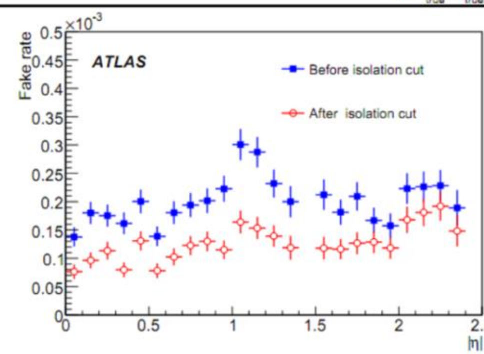
L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

$\mathcal{L}$ from QCD:

$$\mathcal{L} = \underbrace{\bar{q}\,(i\gamma^{\mu}\partial_{\mu} - m)\,q}_{E_{kin}(q)} - \underbrace{g\,(\bar{q}\gamma^{\mu}T_a q)G^a_{\mu}}_{\text{Interaction } q,\, g} - \underbrace{\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{E_{kin}(g)}$$

$E_{kin}(q)$ — Interaction q, g — $E_{kin}(g)$ includes self-interaction between gluons

IMPORTANT FIGURES OF MERIT:

Efficiency	how often do we reconstruct the object	tracking efficiency = (number of reconstructed tracks) / (number of true tracks)		High
Resolution	how accurately do we reconstruct the quantity	energy resolution = (measured energy – true energy) / (true energy)		Good
Fake rate	how often we reconstruct a different object as the object we are interested in	a jet faking an electron, fake rate = (Number of jets reconstructed as an electron) / (Number of jets)		Low

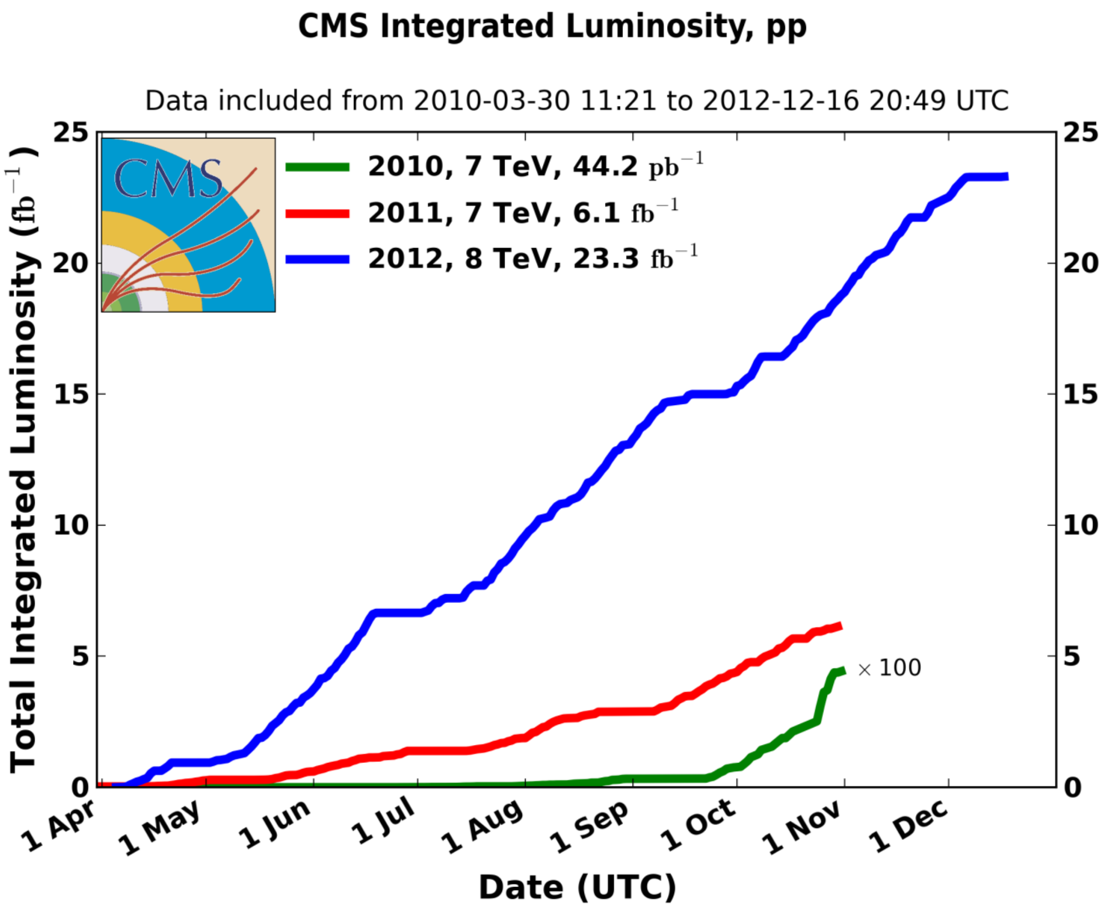
When wee see something interesting

- Is it something new?
- Or it can be explained with what we already know ?
- What does it mean for our instruments?
  - We need to calibrate them
    - By measuring something we know very well
  - Then when we see something interesting ->chances that it is something new are much larger
    - With respect to chances that it's a simple bug
- Be aware:
  - we will never be absolutely sure
  - But we can be **pretty** sure
  - What does the "pretty" really mean?

The boson

- Landmark discovery of boson X(125) marks the start of long-awaited new research line in the field of particle physics.
  - A good candidate for the first fundamental scalar!
  - Is it the long-sought Higgs boson of the (minimal) Standard Model?
  - Is it responsible for EWSB? (i.e. is it the excitation of a scalar field with $v \neq 0$?
  - Does it cure the divergence of SM amplitudes at high E ($W_L W_L \to W_L W_L$ …)
  - Is it embedded into a larger non-SM Higgs sector?
  - Does it provide a window to BSM physics?
- Study the particle with all possible means at LHC

Integrated Luminosity 2010-2012

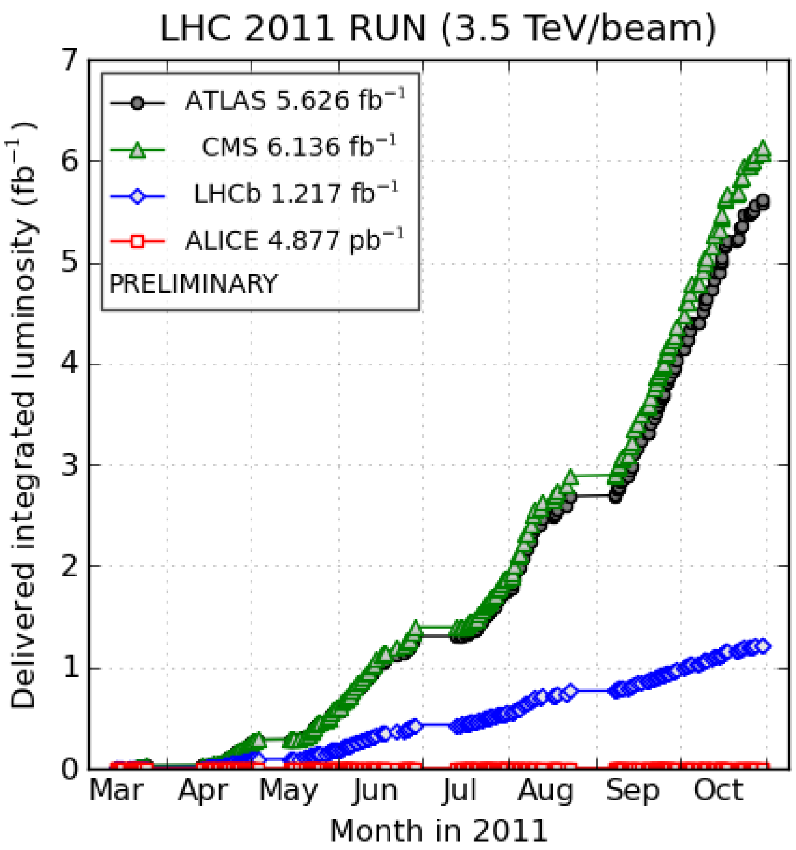


- 2010: **0.04 fb^{-1}**
  - $\sqrt{s}$ = 7 TeV
  - Commissioning
- 2011: **6.1 fb^{-1}**
  - $\sqrt{s}$ = 7 TeV
  - … exploring the limits
- 2012: **23 fb^{-1}**
  - $\sqrt{s}$ = 8 TeV
  - … production

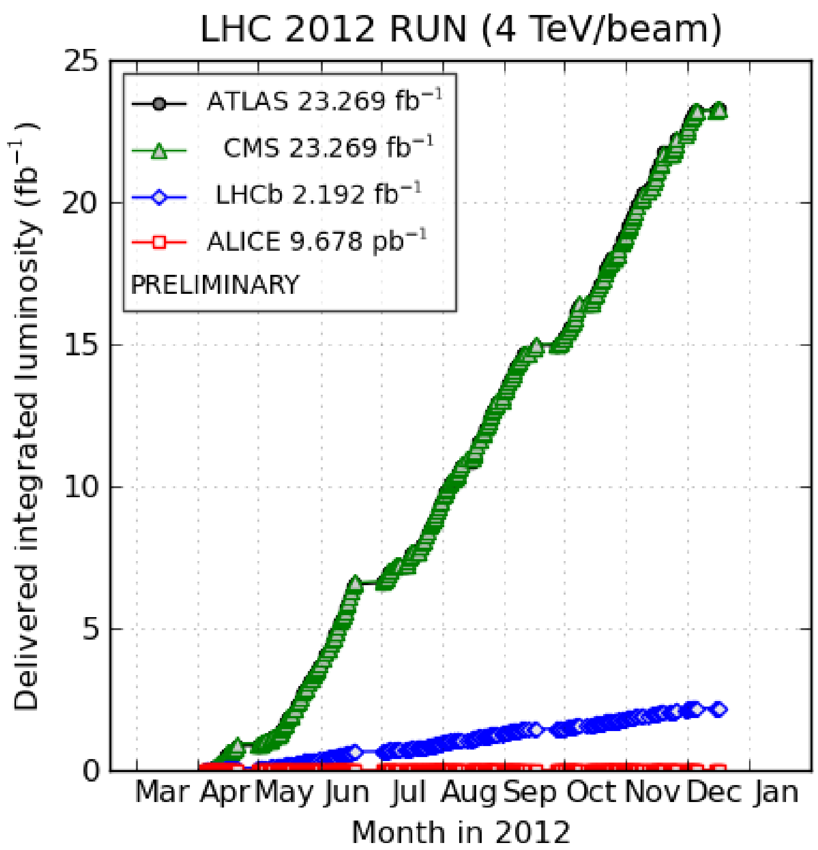
The LHC performed incredibly well (even better than expected) an this is possible thanks to the quality of the design, construction and installation and to the thorough preparation in the injectors which were delivering beams well beyond nominal parameters

Integrated luminosity for all: 2012 vs 2011

2011: target was 1 fb^{-1}; ~6 obtained



2012: target was 15-20 fb^{-1}; ~23 obtained

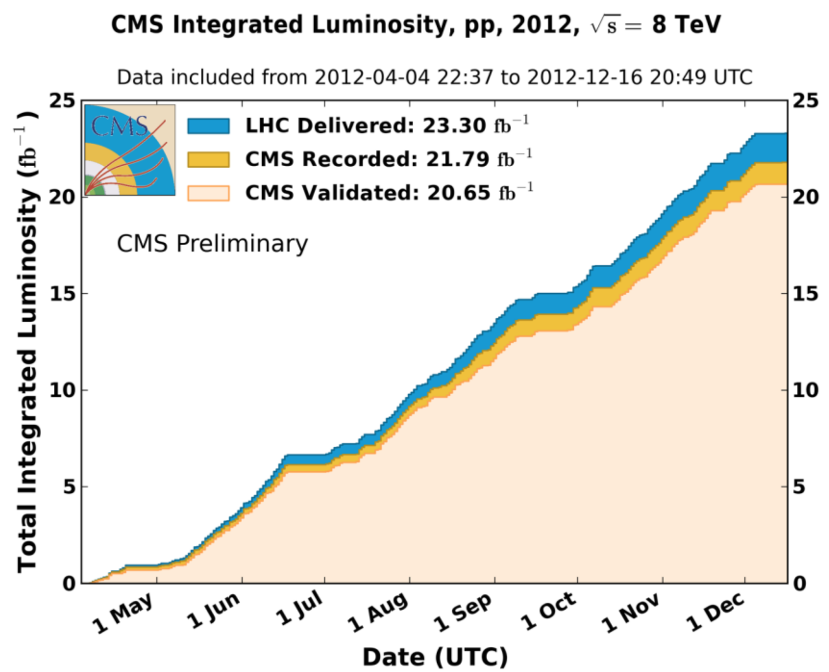


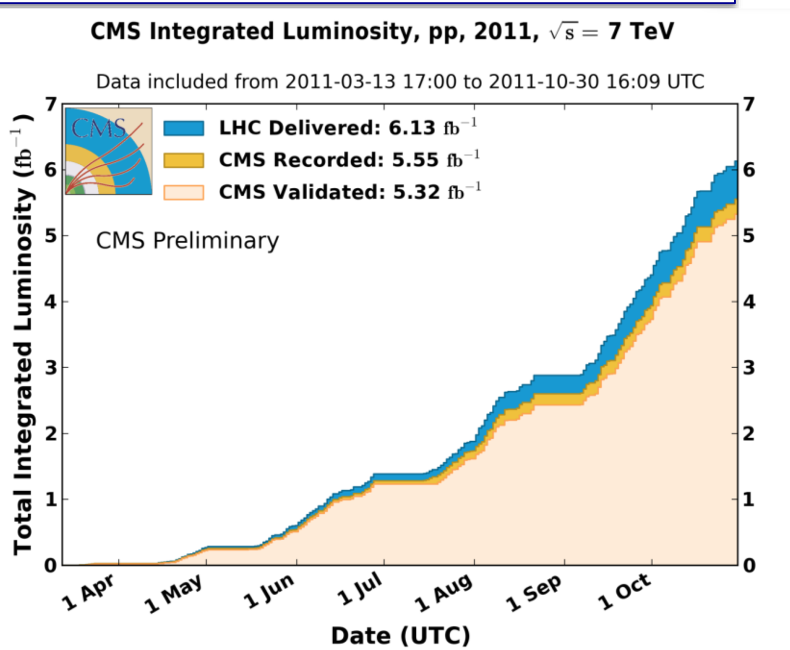
LHC in 2010-2011-2012

Fraction of delivered data used for physics

pp 2011: 87%

pp 2012: 89%





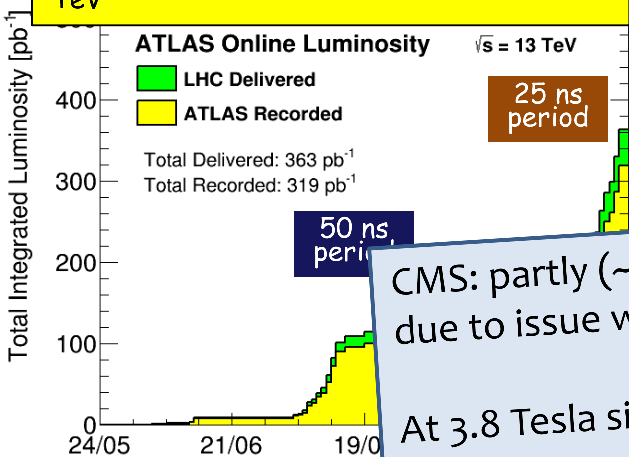
Analyses presented in this talk:

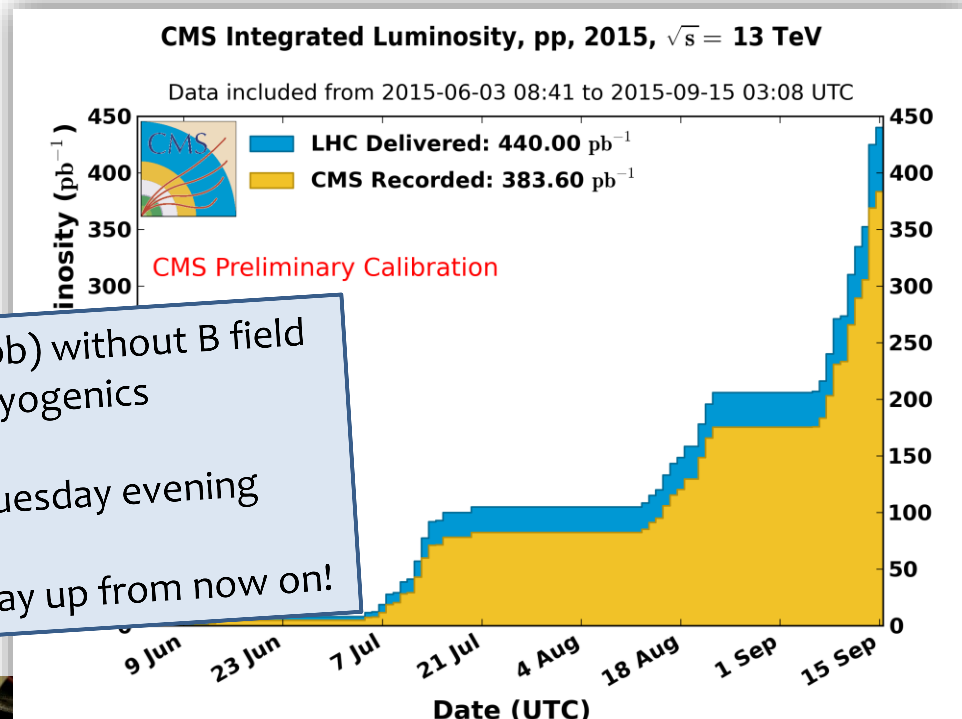
$L < 5.1 fb^{-1}$ at 7 TeV

$L < 19.6 fb^{-1}$ at 8 TeV

13 TeV data

ATLAS integrated luminosity at √s = 13 TeV



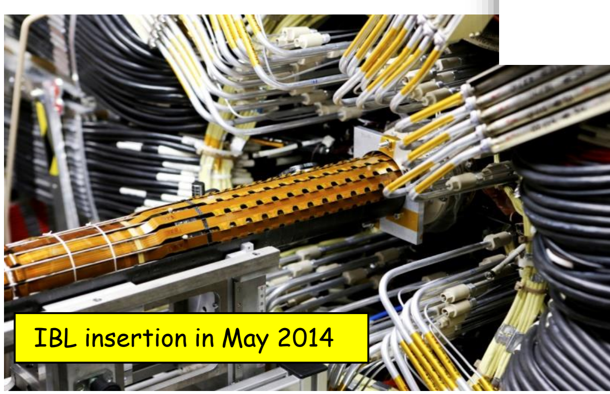


CMS: partly (~250 /pb) without B field due to issue with cryogenics

At 3.8 Tesla since Tuesday evening

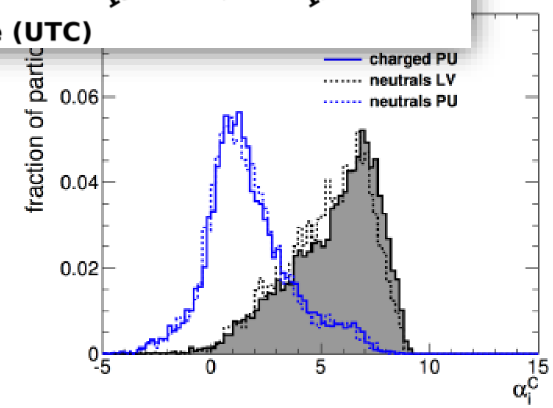
Let's hope it will stay up from now on!

Detector Improvements:



IBL insertion in May 2014

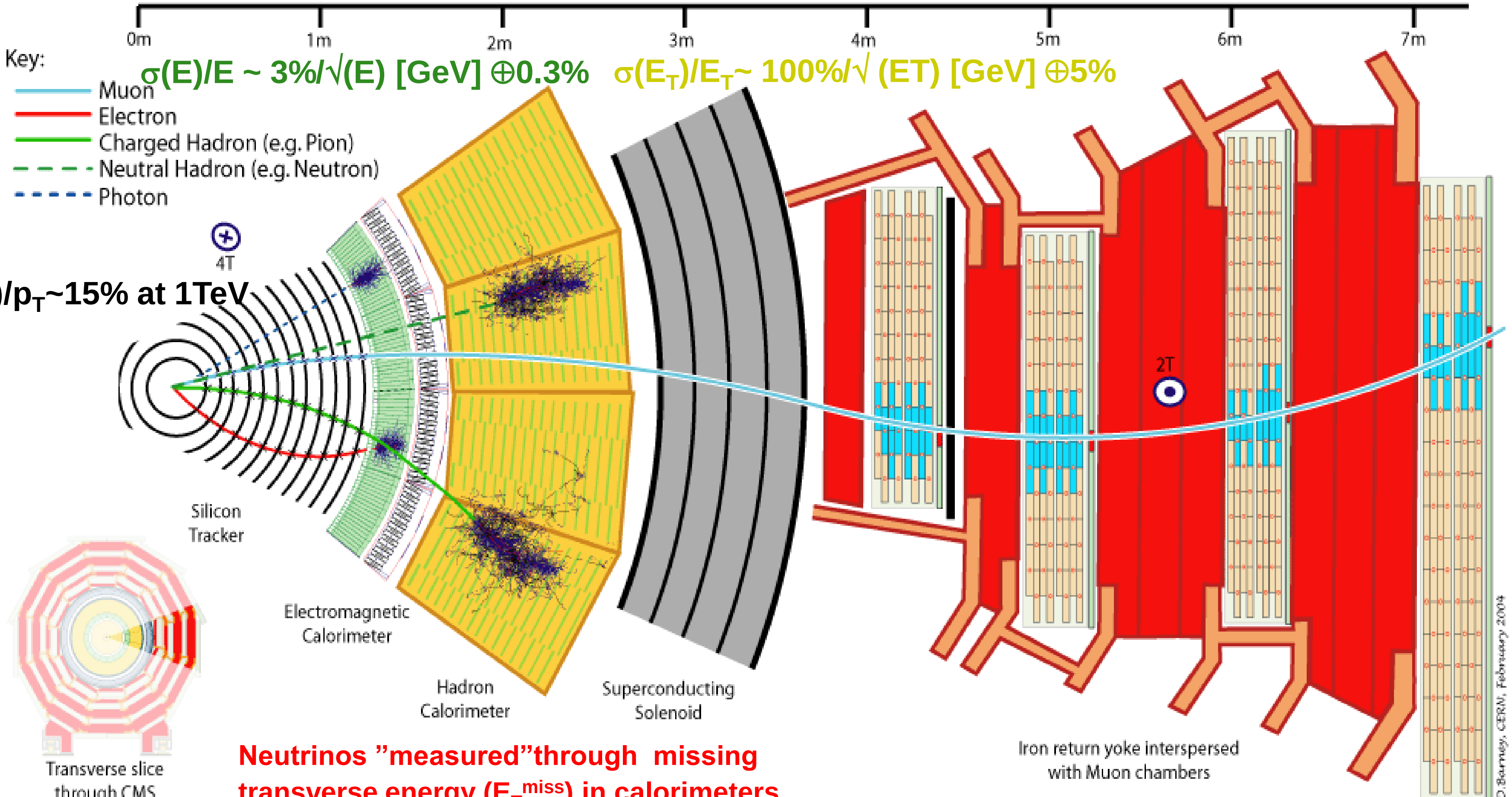
Reconstruction Improvements, Eg PUPPI (pile-up per particle identification):



CMS: a simple and elegant concept

$\sigma(E)/E \sim 3\%/\sqrt{(E)}$ [GeV] $\oplus 0.3\%$ **$\sigma(E_T)/E_T \sim 100\%/\sqrt{(ET)}$ [GeV] $\oplus 5\%$**

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



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

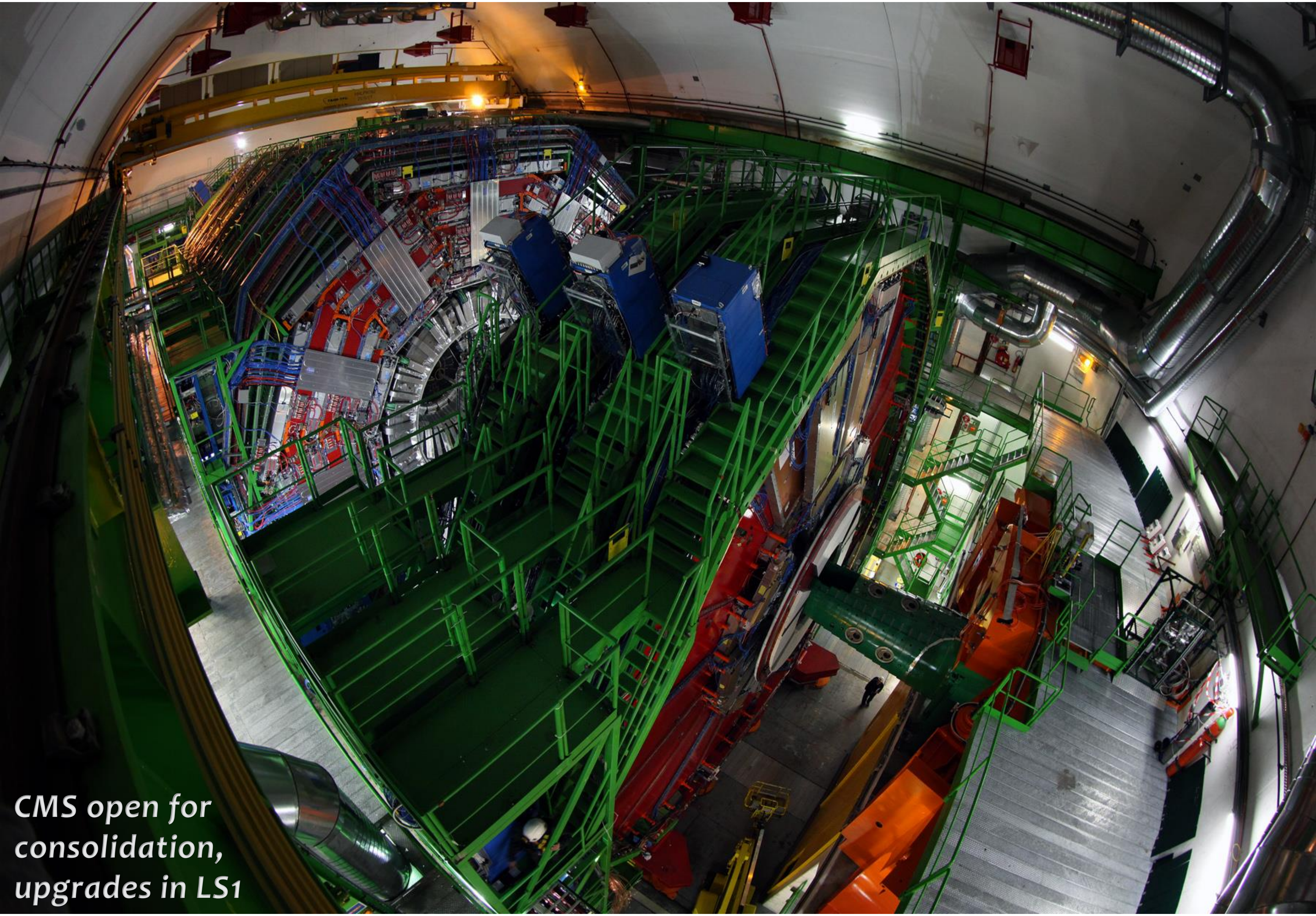
No particle should go undetected

Fast detectors: 25-50ns bunch crossing

High granularity: 20-40 overlapping complex events

High radiation resistance: >10 years of operation

$\sigma(p_T)/p_T < 1\%$ @ 100GeV
$\sigma(p_T)/p_T < 10\%$@1 TeV



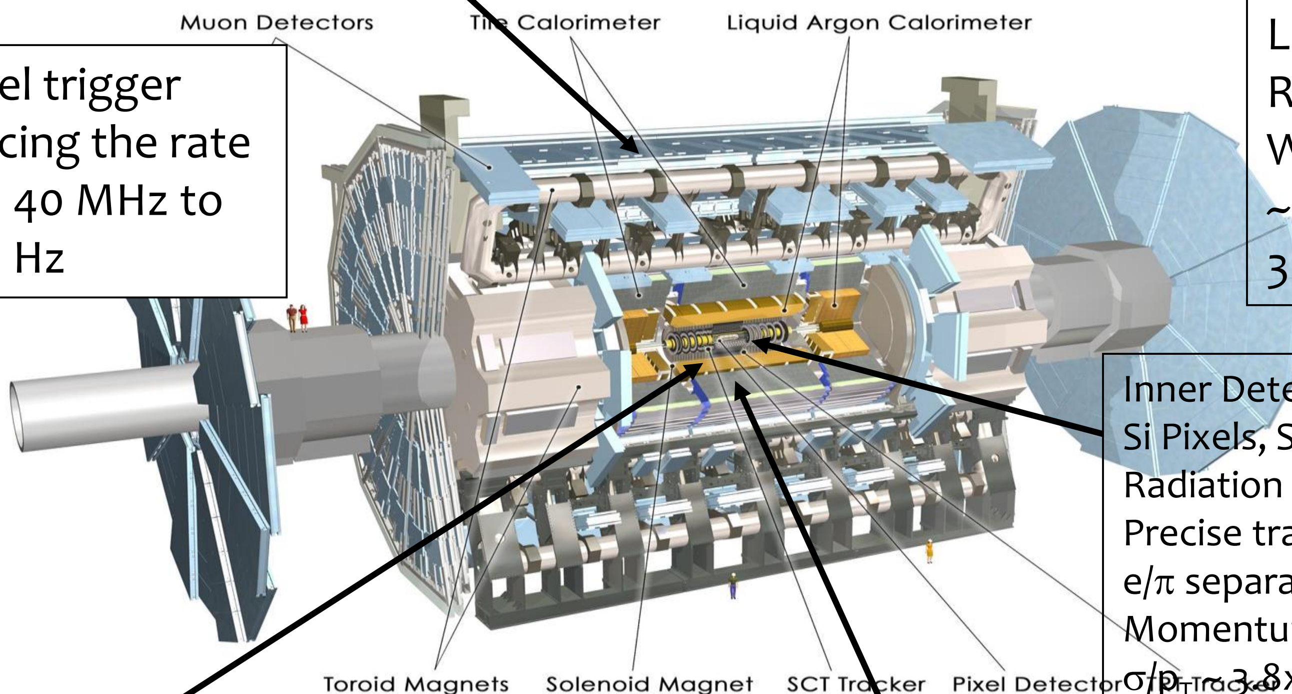
CMS open for consolidation, upgrades in LS1

The experiments: ATLAS

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to $E_\mu \sim 1$ TeV

3-level trigger reducing the rate from 40 MHz to ~200 Hz

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables



Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and ,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\text{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

The experimental conditions at the LHC

- **The LHC is a discovery machine: the ultimate goal is to experimentally find the answers to the open questions about fundamental particles and interactions.**

- The big challenge at the LHC is the huge range of cross sections that needs to be understood:
  - Huge cross section for "uninteresting" processes
  - Large cross sections for previously known processes
  - Medium cross section for not so-well studied processes
  - Low cross section for discovery processes
- It should be noted that all challenges at LHC are produced exactly for this reason:
  - Large backgrounds: interesting physics swamped by known processes.
  - Large Pile-Up: to be able to produce some small number of very interesting events, need to produce so many of unintereseing ones that they even happen in the same crossing!
  - Large available energy implies the chance to produce a lot of soft or medium-pT stuff affecting the reconstruction

Production rates at LHC

> "At LEP every event is signal.
> At LHC every event is background."
> Sam Ting, LEPC, Sept-2000

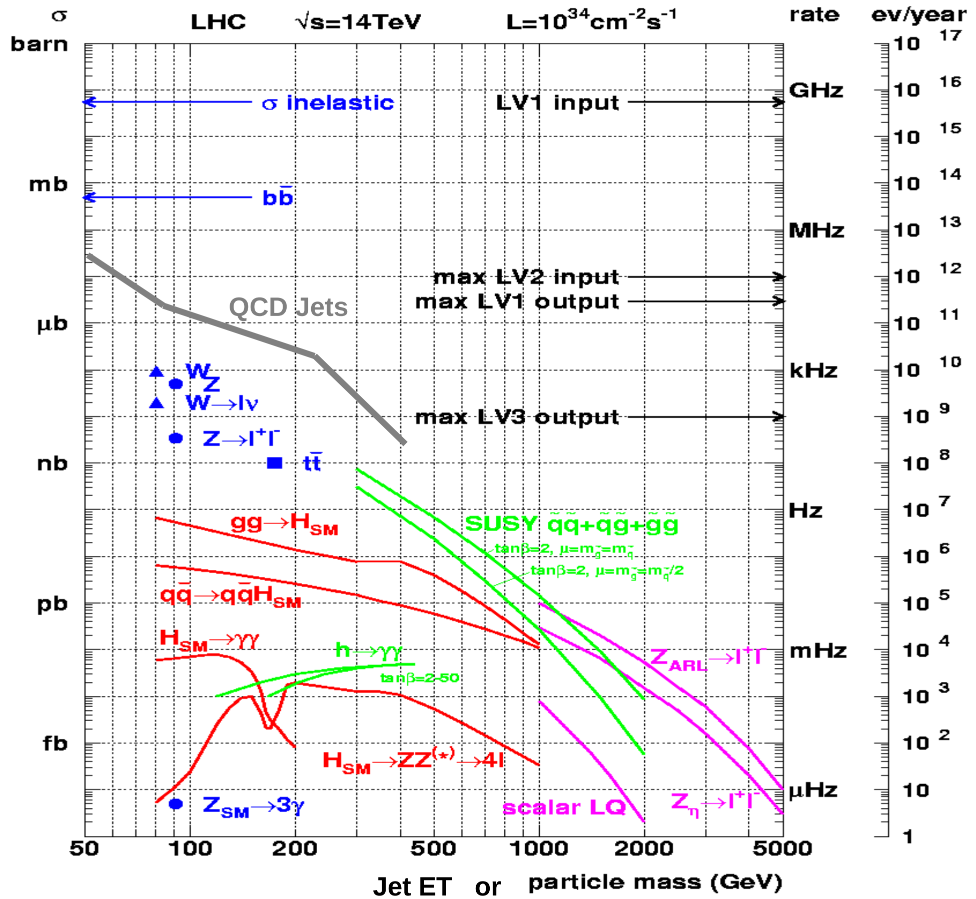
At sqrt(s)=14 TeV

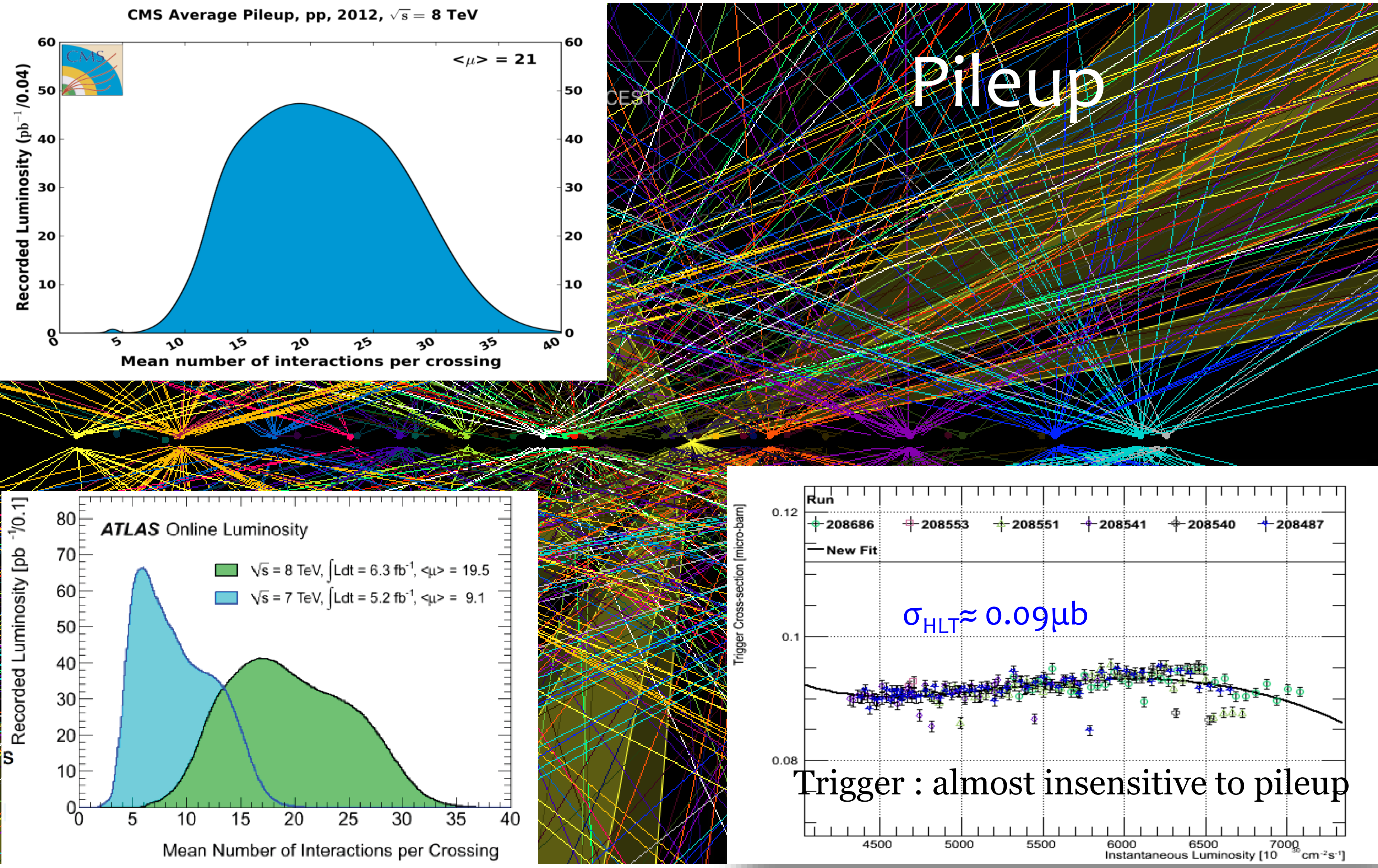
σ_{tot} ~ 105 mb
$\sigma_{elastic}$ ~ 28 mb
σ_{inel} ~ 65 mb

Evt rate = $L.\sigma = 10^{34} \times 65\ 10^{-27}$ /s
= 6.5×10^{8} /s

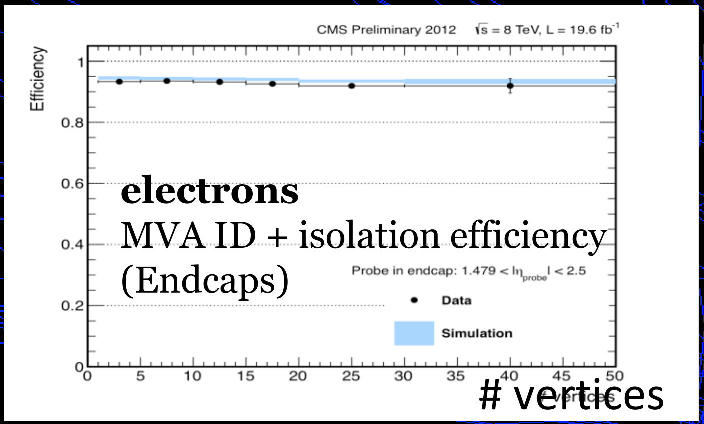
W→ev	15 events/second
Z→ee	1.5
tt	0.8
bb	10^5
H(200 GeV)	0.001

- General event properties
- Heavy flavour physics
- Standard Model physics
- including QCD jets
- Higgs searches
- Searches for SUSY
- Examples of searches
- for 'exotic' new physics



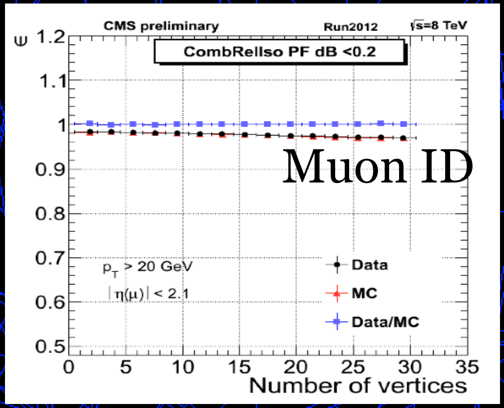

Pileup
CMS Average Pileup, pp, 2012, √s = 8 TeV
<μ> = 21
Recorded Luminosity (pb⁻¹/0.04)
Mean number of interactions per crossing
ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 6.3 fb⁻¹, <μ> = 19.5
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing
Run
208686
208553
208551
208541
208540
208487
New Fit
Trigger Cross-section [micro-barn]
Instantaneous Luminosity [10³⁰ cm⁻²s⁻¹]
σHLT≈ 0.09μb
Trigger : almost insensitive to pileup

PU control

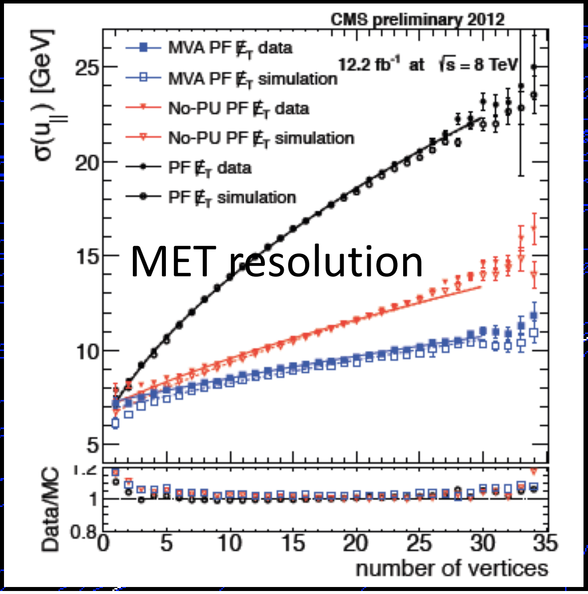


electrons
MVA ID + isolation efficiency (Endcaps)

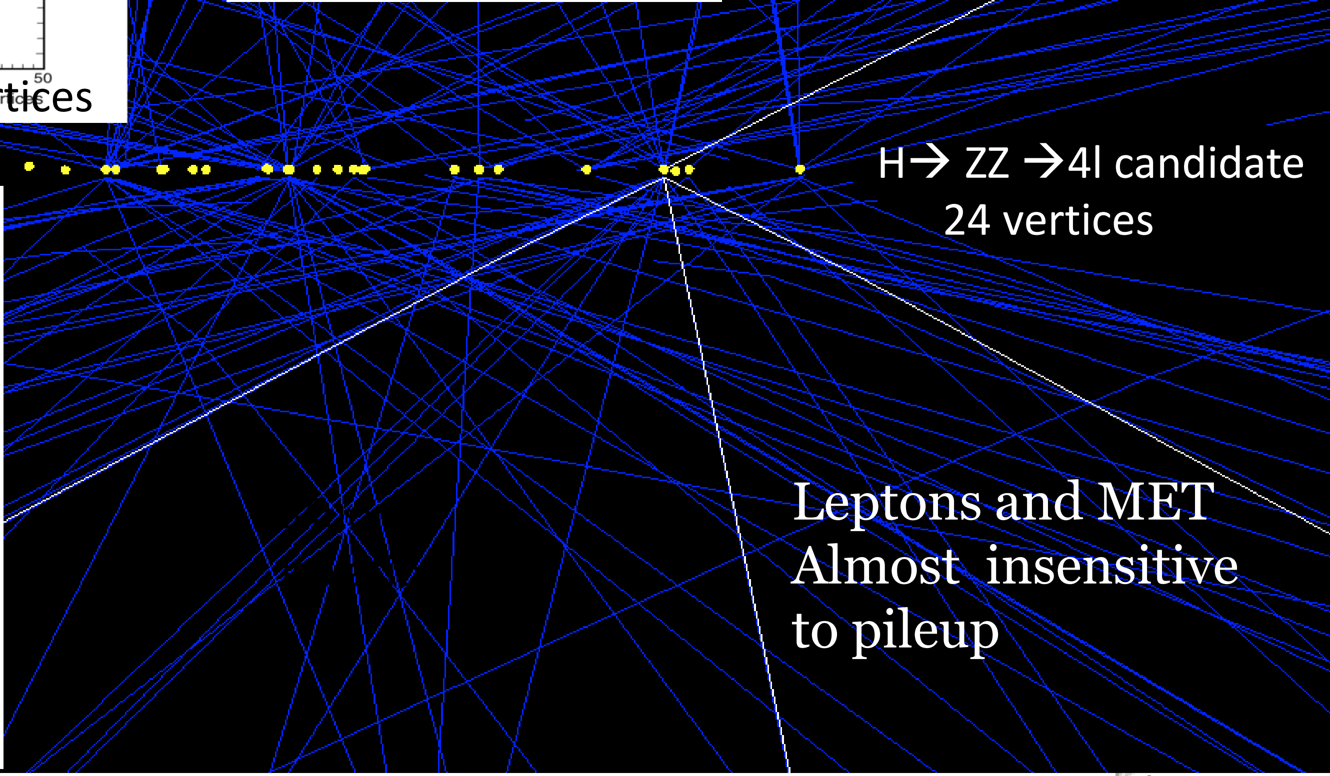
vertices



Muon ID



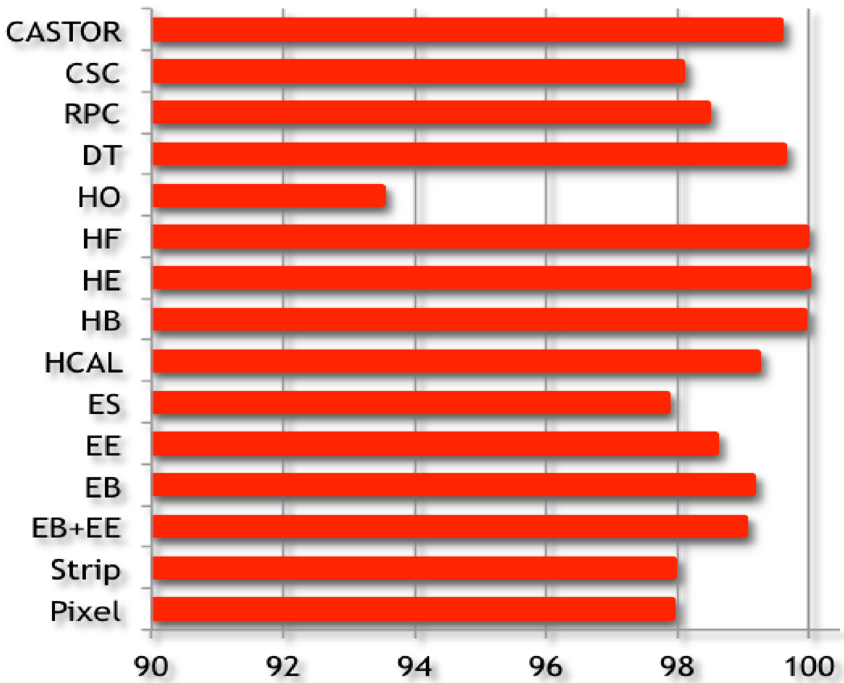
MET resolution



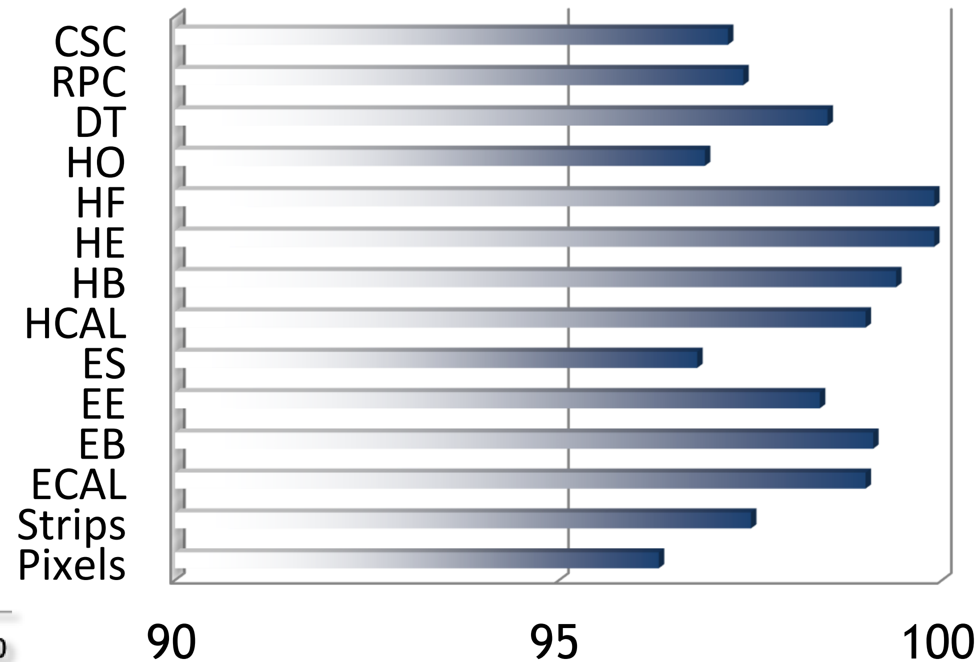
H→ ZZ →4l candidate
24 vertices

Leptons and MET
Almost insensitive
to pileup

Detector status

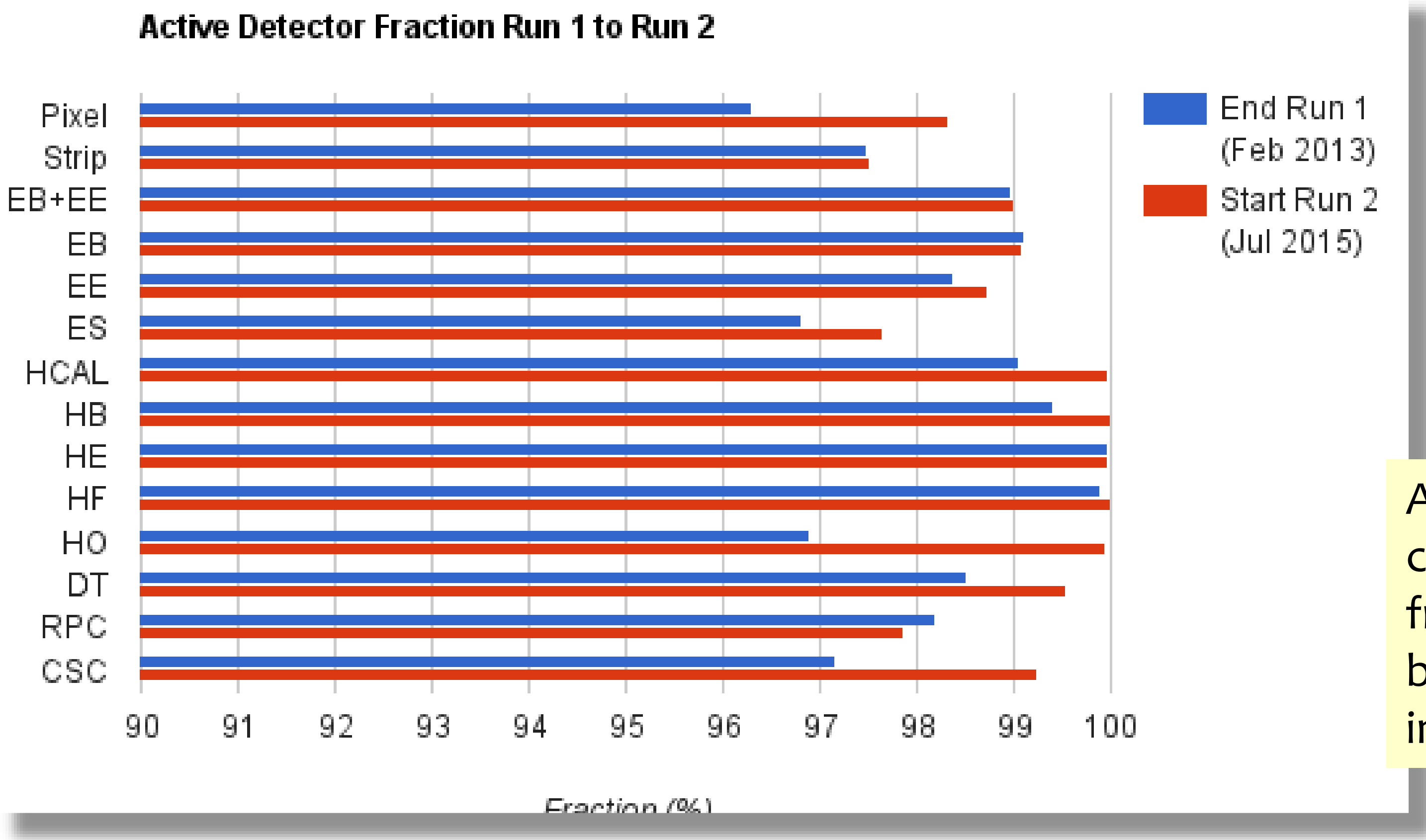


the first runs in 2010



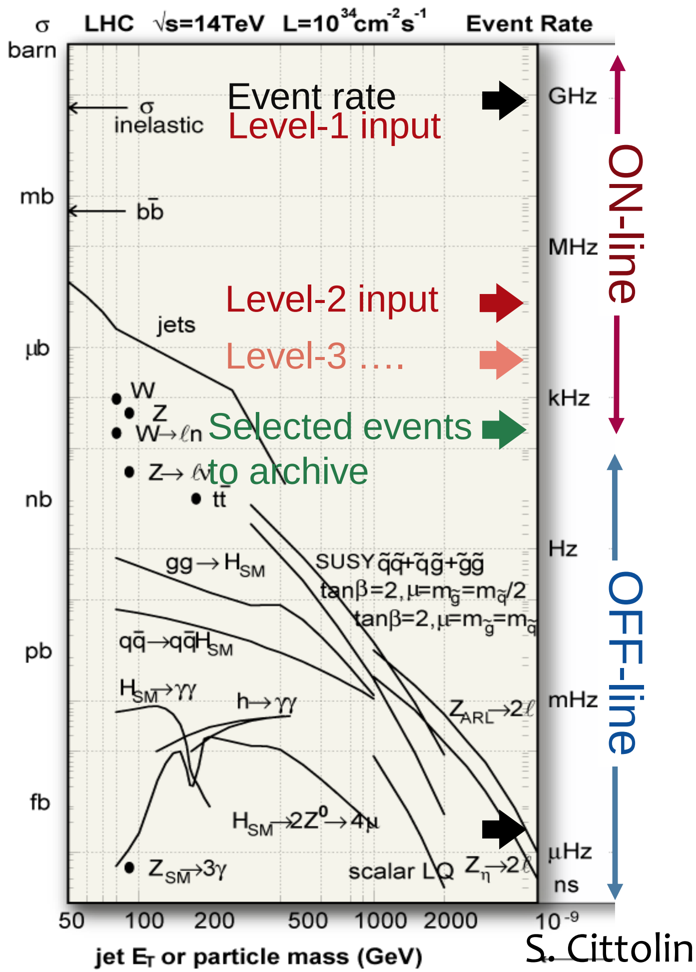
the last runs in 2013

(RUN 2): Detector and SW in great shape



Active channel fraction better than in Run1

Trigger



S. Cittolin

- At LHC the collision rate is 20-40 MHz
  The Event size ~1 Mbyte

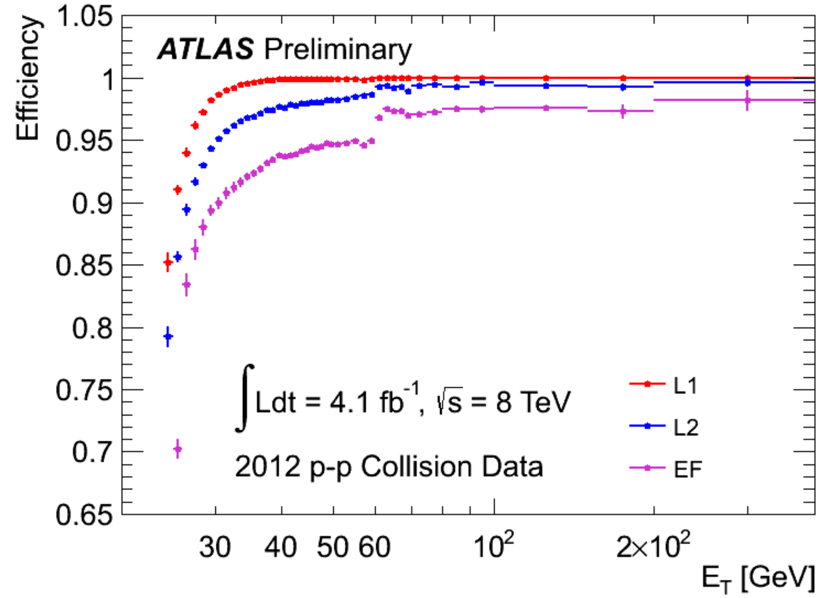
  Band width limit ~ 100 Gbyte →
  Mass storage rate ~100 Hz

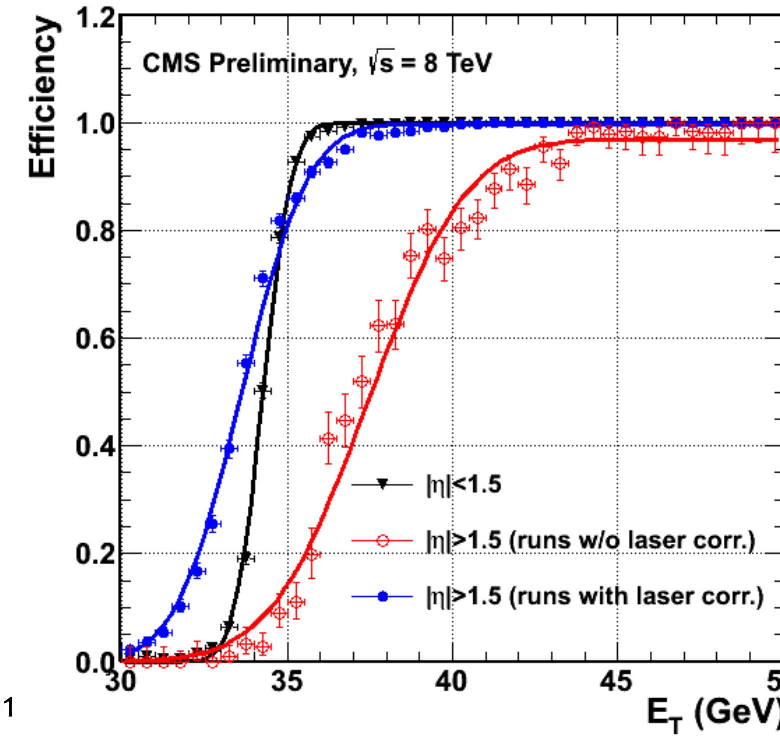
Thus we should select the events with "the Trigger"

- Level-1 Trigger input 40 MHz
- Level-2 Trigger input 100 kHz (HLT for CMS)
- Level-3 Trigger input xx kHz (HLT for Atlas)

Electron Triggers

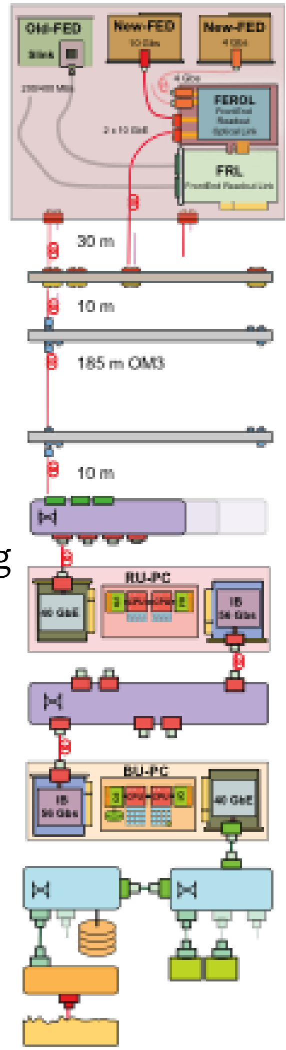
- **L1:** based mainly on ECAL deposit
- **L2/L3/HLT/EF:** full reconstruction and ECAL/Tracker isolation (a must to keep sustainable rate!!)
- **Large eta acceptance but larger ET threshold**
- **Efficiencies** close to 95%
- **Lowest unprescaled bit:**
  - **ATLAS** SingleIsoEle24 (OR Ele60 + Dilepton Triggers)
  - **CMS** SingleIsoEle27 (+ DiEle17_8 + EleMu17_8 + Lower CrossTriggers)
  - **Tevatron** SingleEle18 (+ DiElectron)





High data taking eff: non trivial
Improvements wrt to run 1

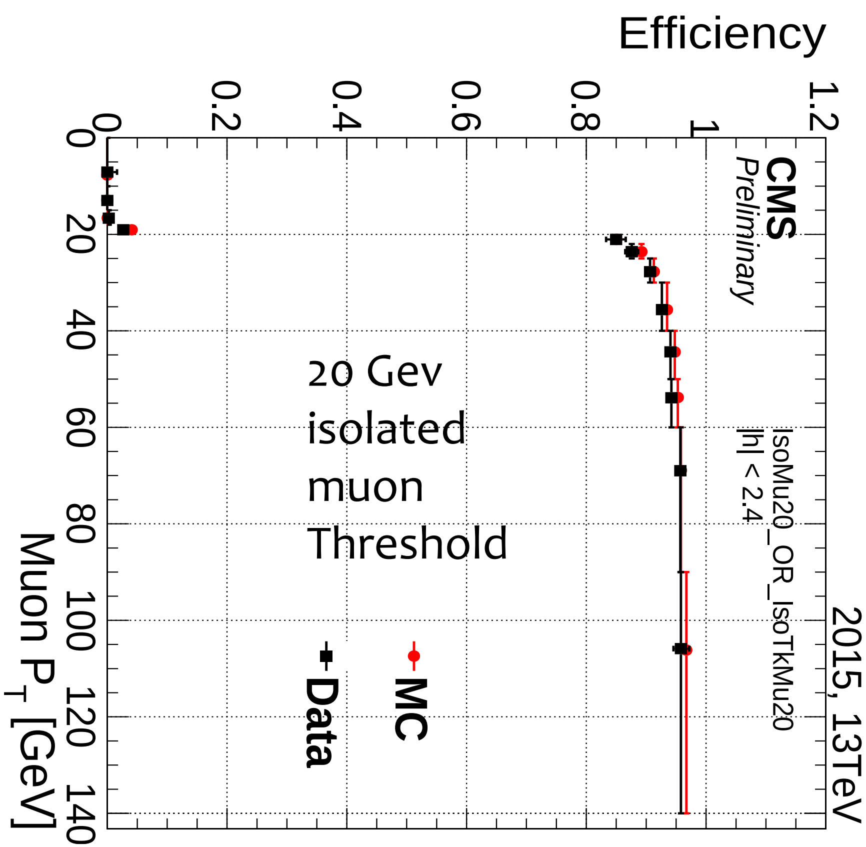
- Updated online cluster
  - Replaced obsolete hardware, new OS, new sysadmin tool, etc
- New TCDS (Trigger Control and Distribution System)
  - Combines TTC, TCS (Trigger Control System), TTS (Trigger throttling system)
  - Provides additional TTC partitions for new Trigger and detector systems installed in LS1
- Update of Detector Control System
  - New OS, SCADA and enhanced CMS applications
- Entirely new DAQ system (DAQ2)
  - New PC server nodes and event building with TCP/IP in FPGA, 40 GbE / 56 Gbps IB networking
  - Support for legacy and new (uTCA based) back-end electronics of L1 trigger upgrade and HF
  - File based HLT, monitoring with Elastic data analytics tool (File system LUSTRE)
- Extended the HLT farm
  - Replaced obsolete (2011) nodes with new Haswell based nodes.
- Running with new CALO trigger (stage 1 of Phase 1 upgr.)

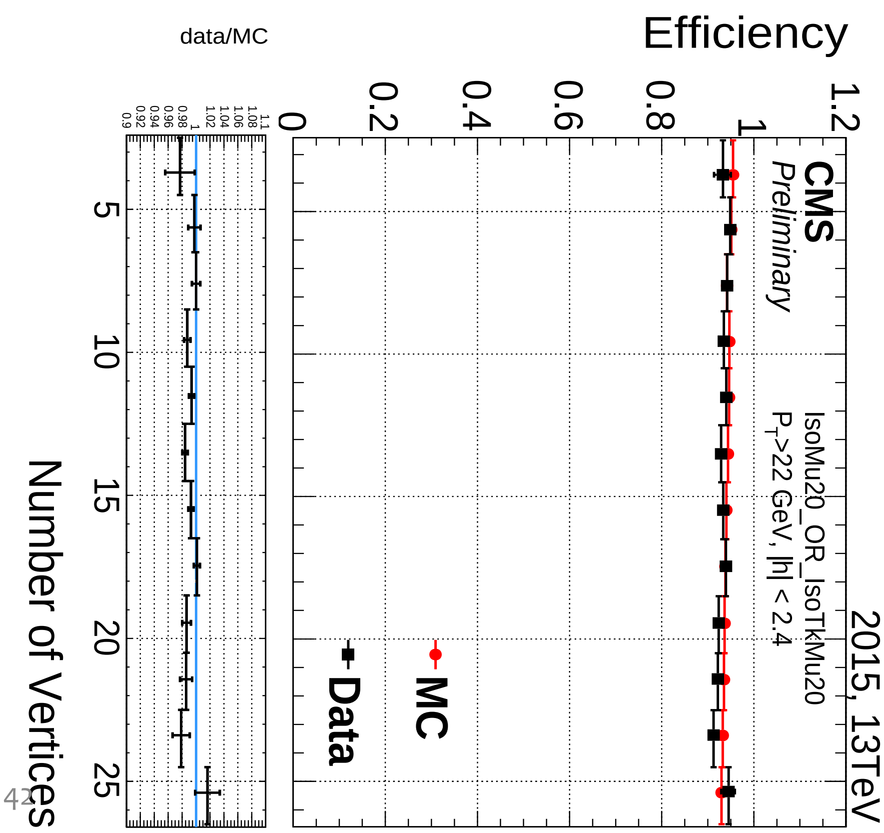


HLT (13 TeV)

Isolated muon efficency

- Successful commissioning of improvements in HLT algorithms
  - Including HLT specific pileup mitigation





Role of LHC in EWK landcape

- LHC is not a machine designed a priori for ElectroWeak (EWK) physics: large Pile-Up.
- But general purpose detectors were carefully designed to discover Higgs bosons with leptons/photon probes: e, μ, γ.
  - Efficient (> 80-90%)
  - Good separation of "isolated" leptons from EWK decays and in-jet leptons.
  - Trigger systems were optimized for probes with $p_T < M_W/2$.
- EWK physics is a very important "by-product" of the LHC design:
  - W is produced in s-channel in DY at Tevatron/LHC but not in ee collisions at LEP: large statistical sample to study W properties – mass/width.
  - VV production have to be well understood/measured: To support Higgs discovery. It is an (interfering) background for Higgs decays in VV final state.
  - High mass VV production and VV scattering are sensitive to the terms of SM/BSM Lagrangian well beyond LEP reach.