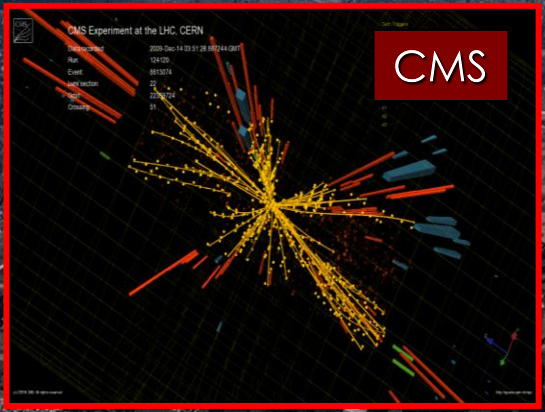
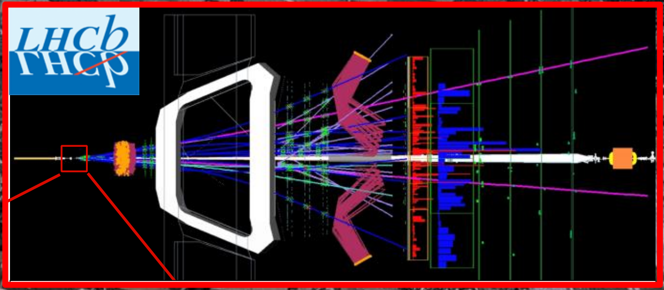
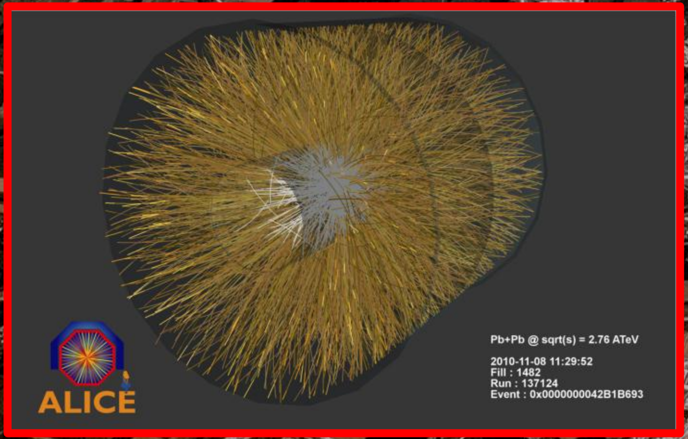
Highlights of LHC physics results

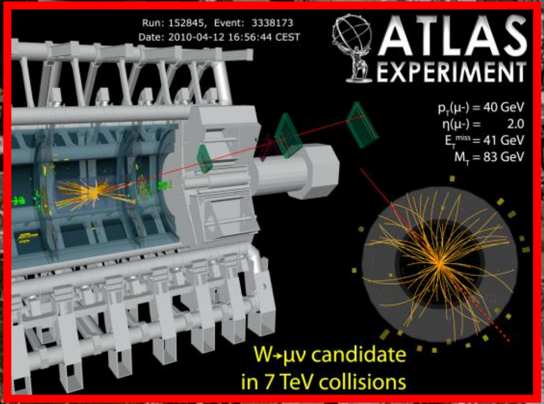
Fabiola Gianotti (CERN, Physics Department)

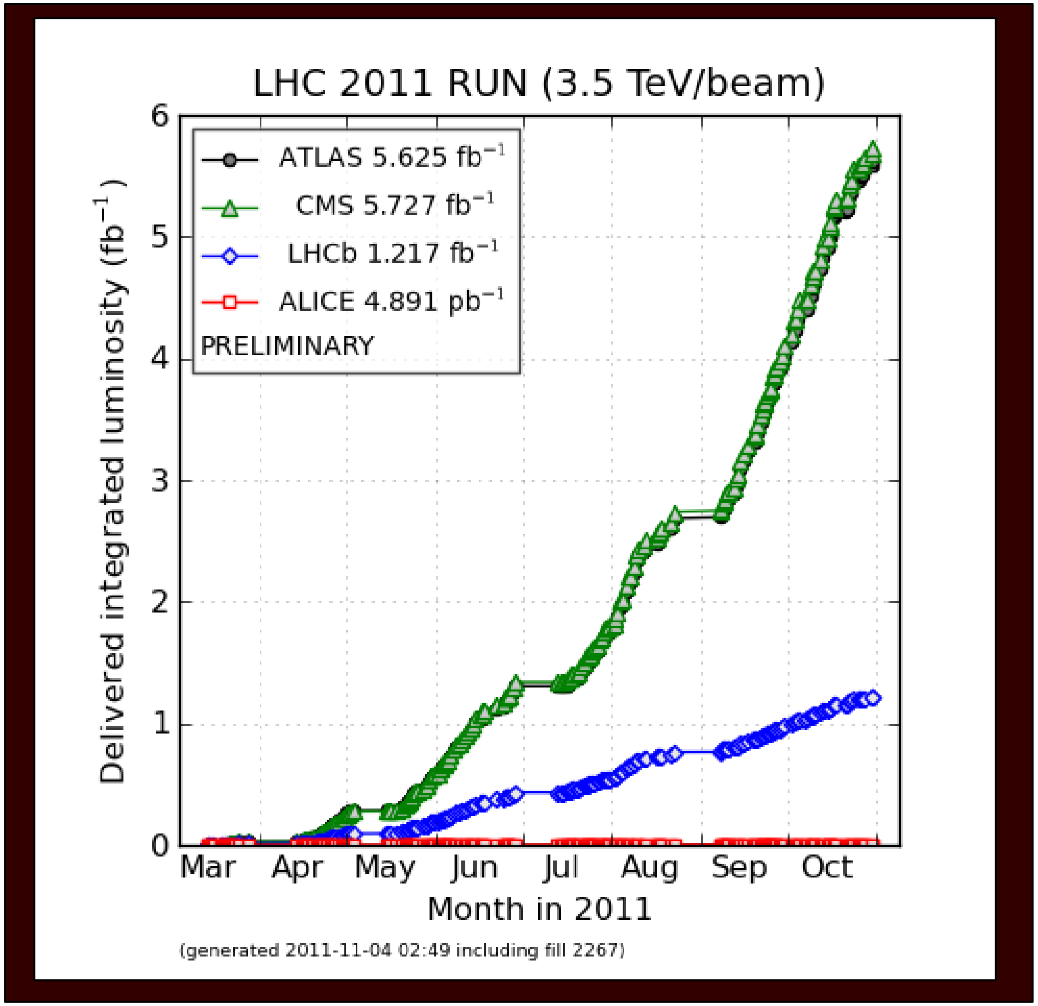
2011: Annus Mirabilis !



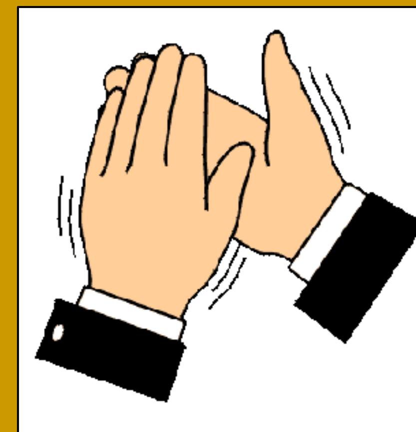




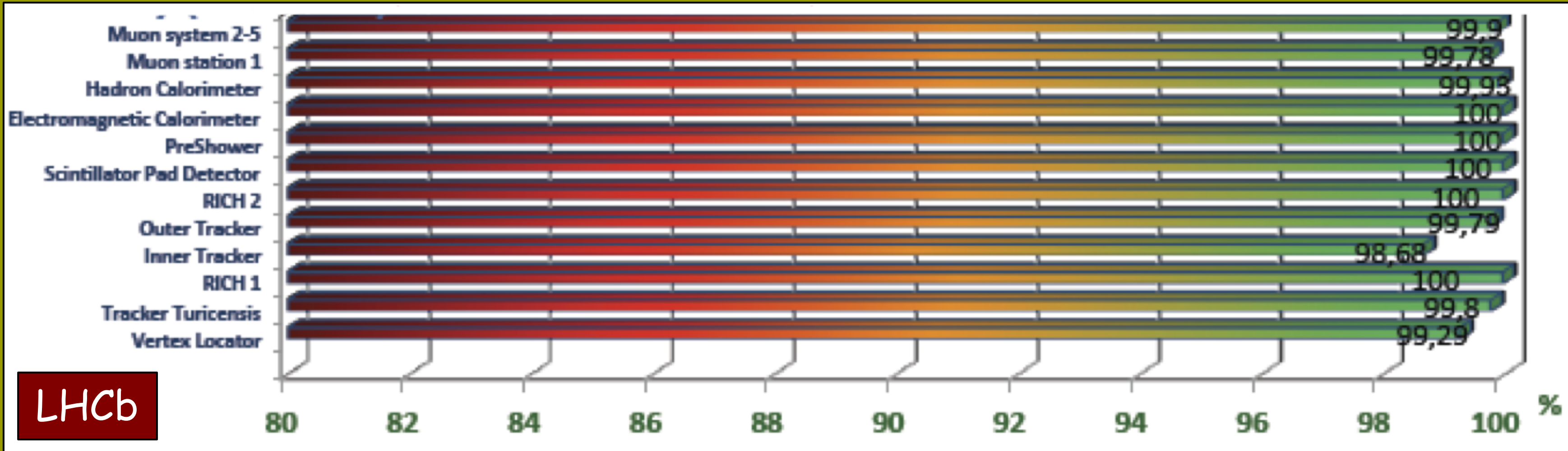




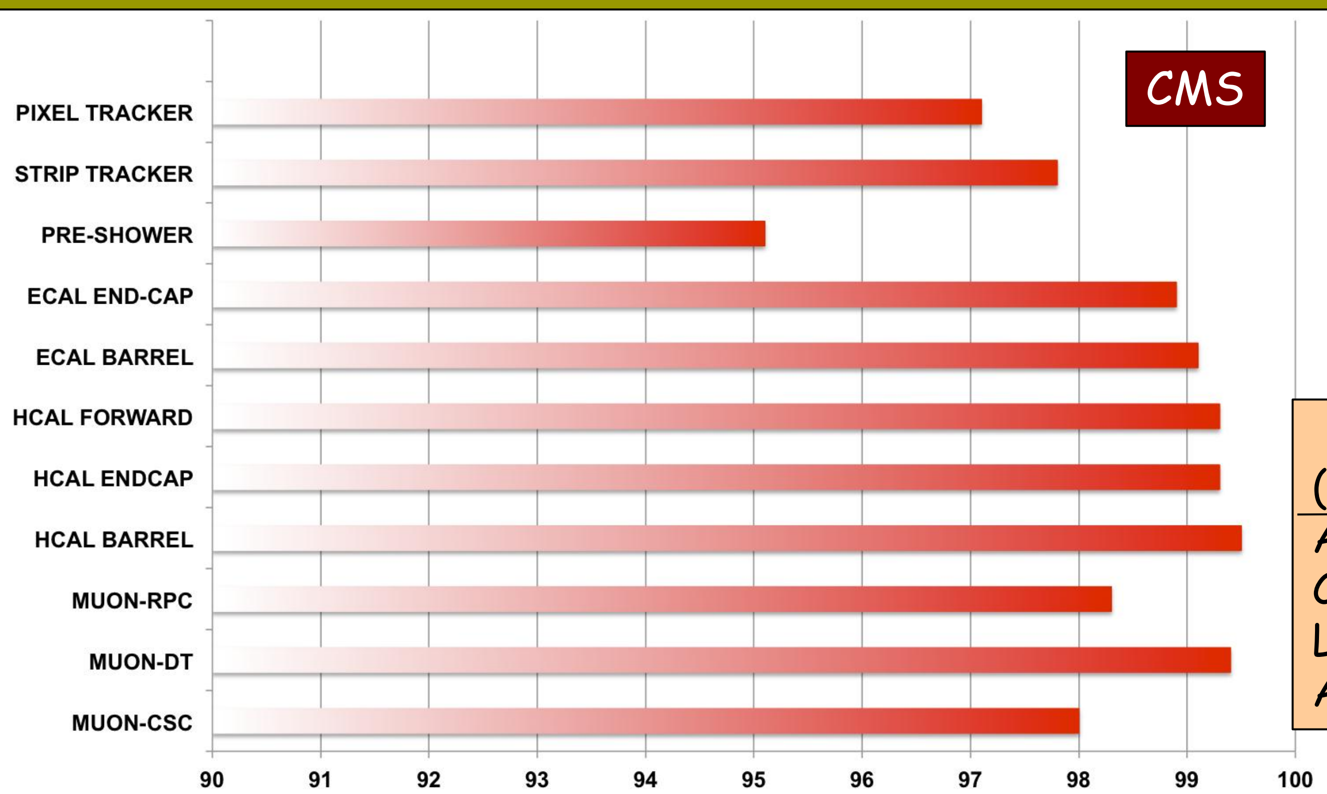
Many thanks to the LHC team for such a superb performance !



	ATLAS	CMS	LHCb	ALICE (Pb-Pb)
Delivered integrated luminosity (fb^{-1})	5.6	5.7	1.2	9 μb^{-1}
Max peak luminosity (10^{33} cm^{-2} s^{-1})	3.7	3.7	0.35 (leveling)	3×10^{25} cm^{-2} s^{-1}
N. of pp collisions/xing: up to	~ 24	~ 24	~2.5	--



Fraction of non-operational channels: few permil to few percent in all experiments

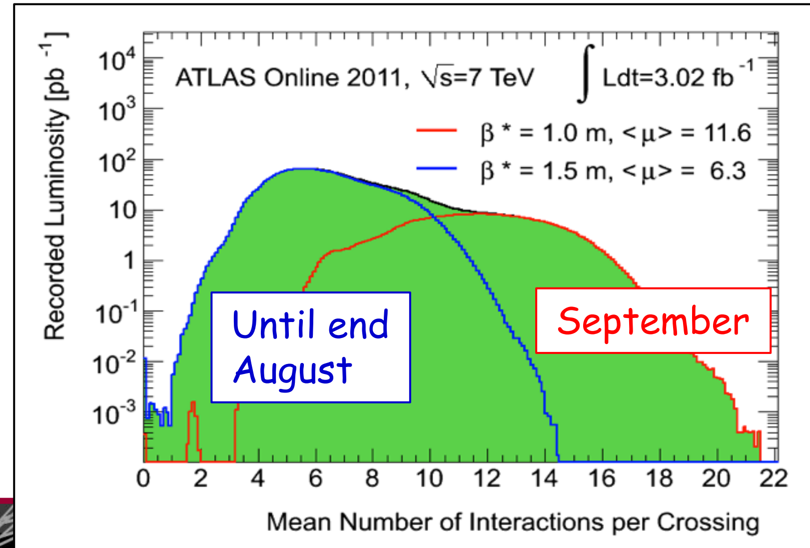


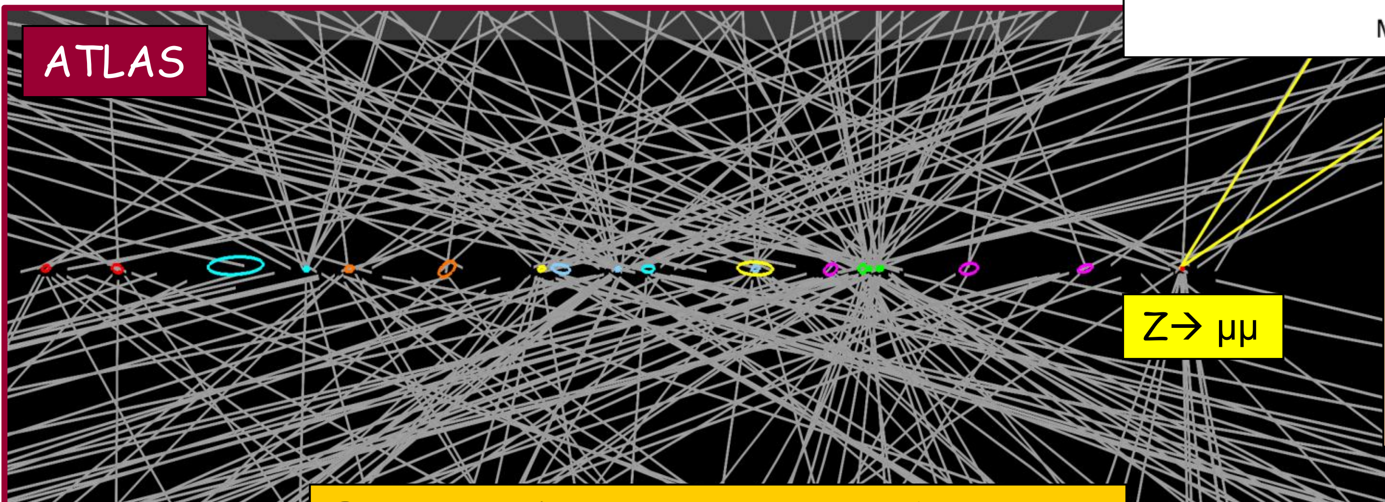
Data-taking efficiency (recorded/delivered lumi)	
ATLAS	93.5%
CMS	91%
LHCb	91%
ALICE	94% (Pb-Pb)

Data quality (good-for-analysis/recorded)	
ATLAS	~ 90 %
CMS	~ 90 %
LHCb	99 %
ALICE	~ 95 %

Price to pay for high luminosity: higher-than-expected pile-up

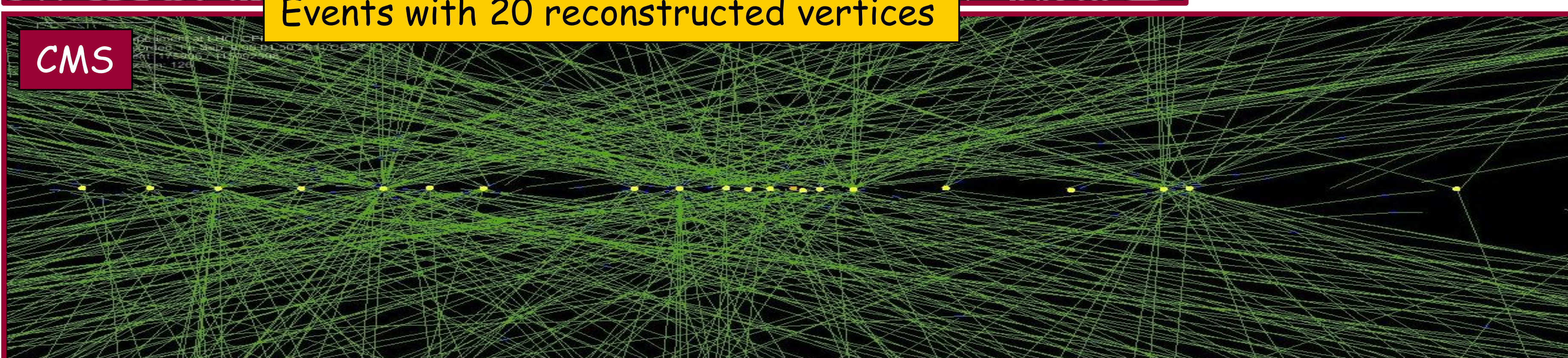
High L achieved through parameters maximizing pile-up (number of interactions per crossing):
bunch charge (up to 1.5 10^{11} p → beyond design)
transverse emittance (~ 2μm → beyond design)
β^* = 1.5 → 1 m





- Also sensitive to bunch-by-bunch and bunch-train effects
- Pile-up could increase by up to ~2 in 2012

Events with 20 reconstructed vertices



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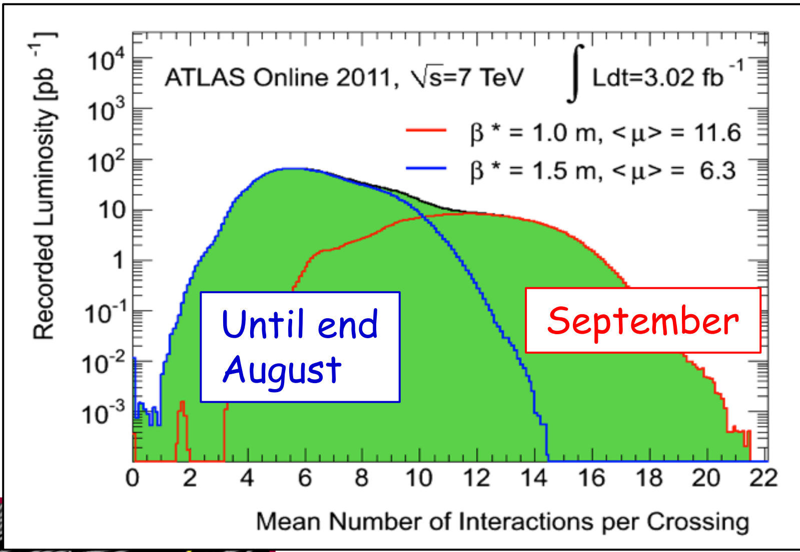
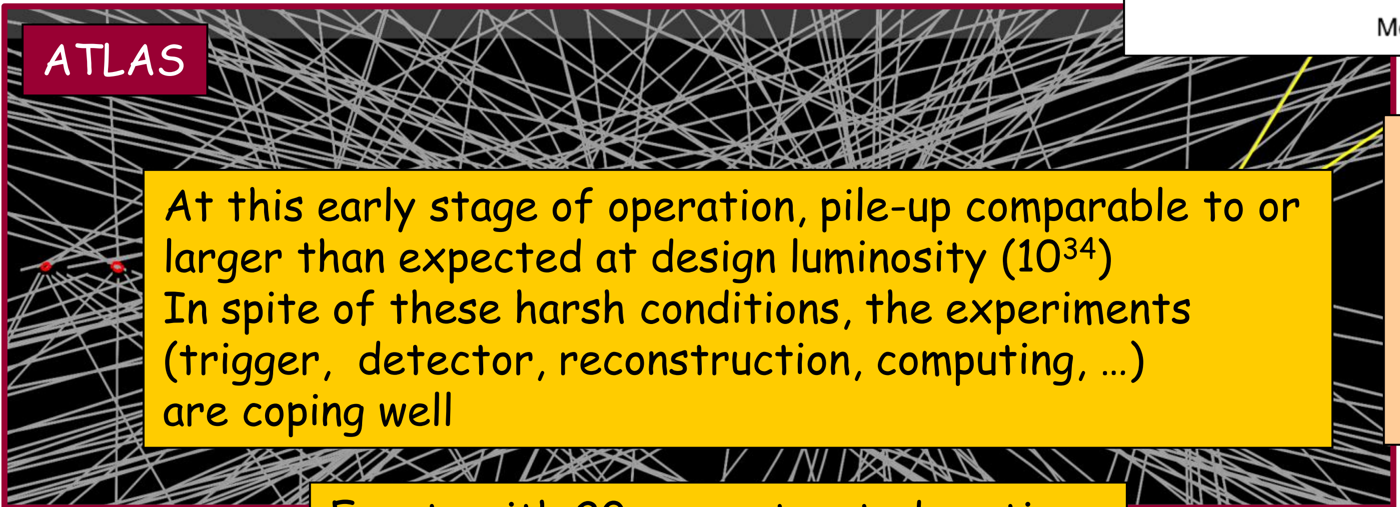
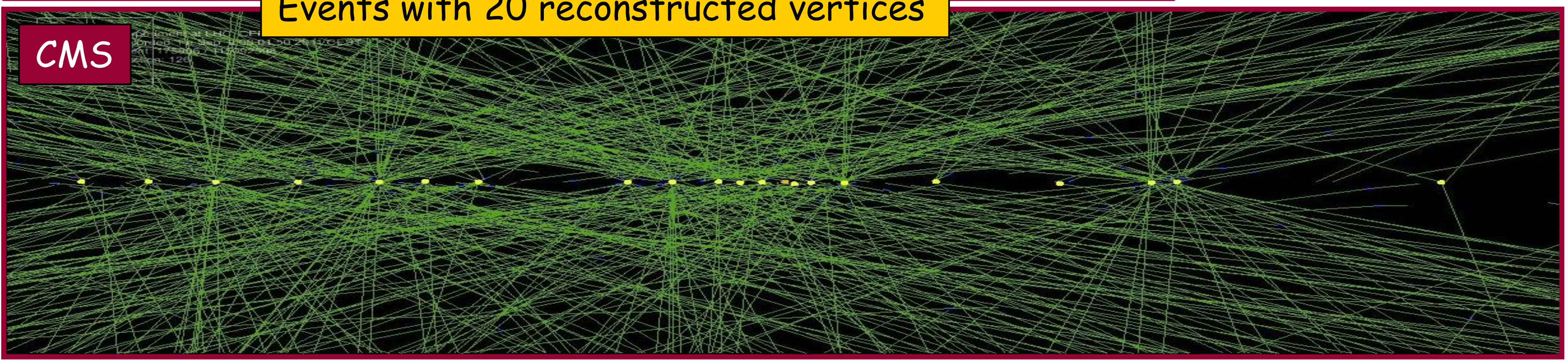




At this early stage of operation, pile-up comparable to or larger than expected at design luminosity (10^{34})
In spite of these harsh conditions, the experiments (trigger, detector, reconstruction, computing, …) are coping well

- ❑ Also sensitive to bunch-by-bunch and bunch-train effects
- ❑ Pile-up could increase by up to ~2 in 2012

Events with 20 reconstructed vertices



As the accelerator, the LHC experiments are also instruments of unprecedented technology, complexity and performance:

- technical requirements: speed (25-50 ns), radiation hardness, strong magnetic fields, granularity (ATLAS: ~ 100 M readout channels, 3000 km of cables), < 100 μm detector alignment over big volumes, etc.
- performance: particle identification (in particular LHCb, ALICE), precise measurements from few GeV to few TeV, energy resolution, very selective trigger systems, etc.

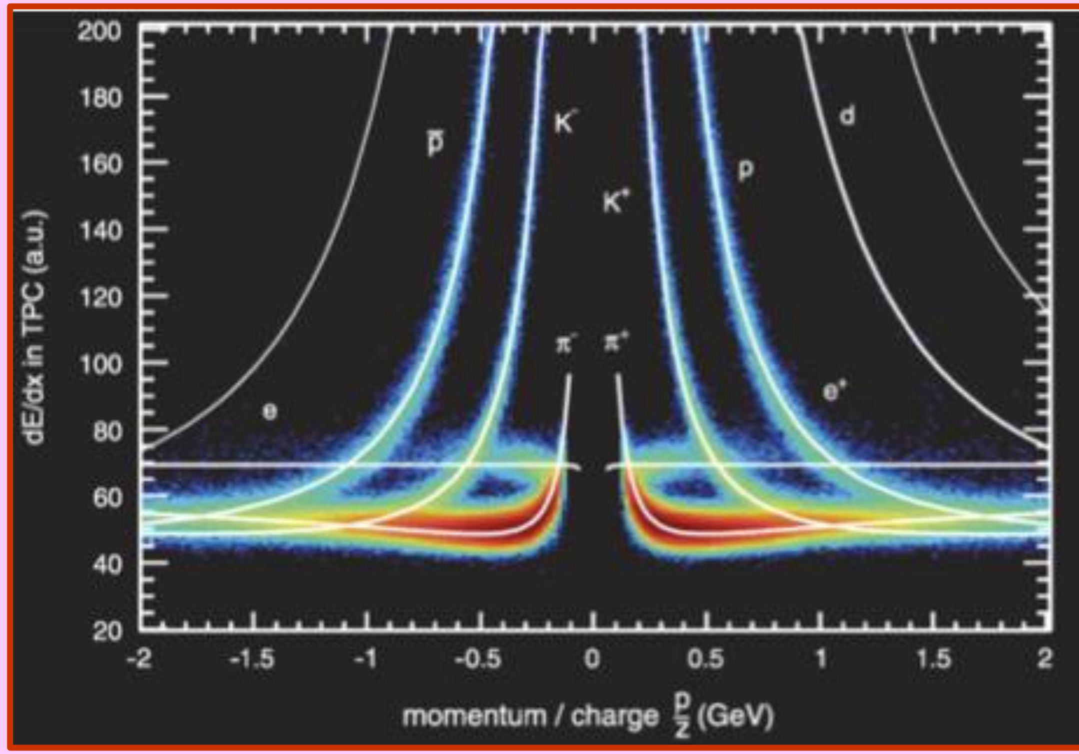
As for the accelerator, also for the experiments:

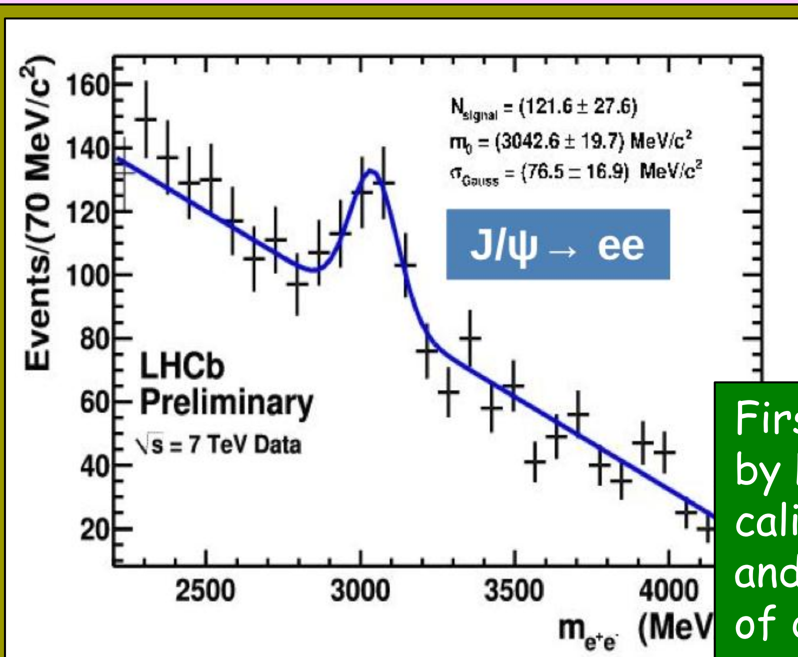
- the commissioning went much faster than expected
- excellent performance → right technological choices, tight specs, meticulous quality controls, …
- had to face big challenges much earlier than expected (e.g. pile-up)

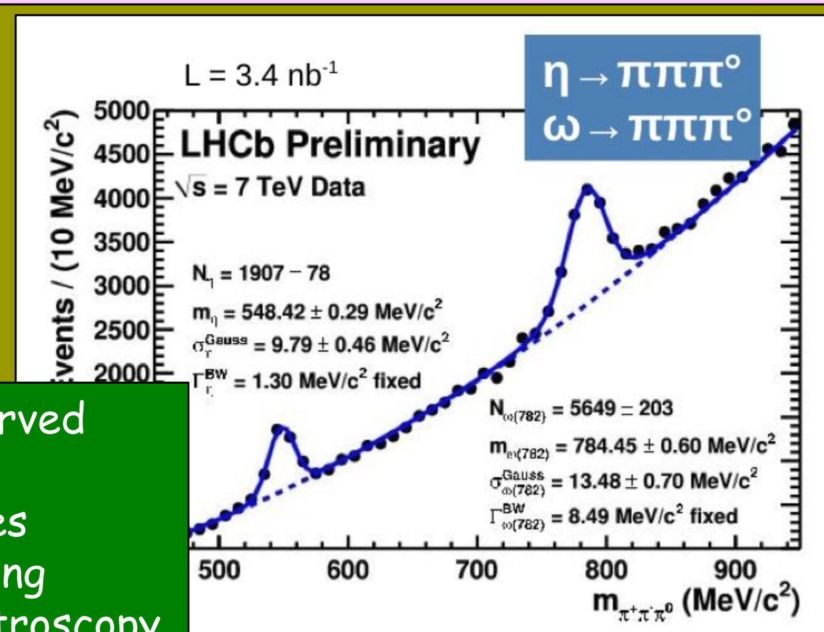
Work plan since first collisions in November 2009:

- commission the experiments (detector, trigger, data processing, computing) with physics data
- understand and calibrate the detectors using well known final states: e.g. Z → ll
- "rediscover" the Standard Model at $\sqrt{s}$=7 TeV : W, Z, top-quark … (important per se but also as background to searches for New Physics)
- undertake searches for New Physics → discovery phase

Particle identification in the ALICE TPC using specific energy loss (dE/dx) vs momentum



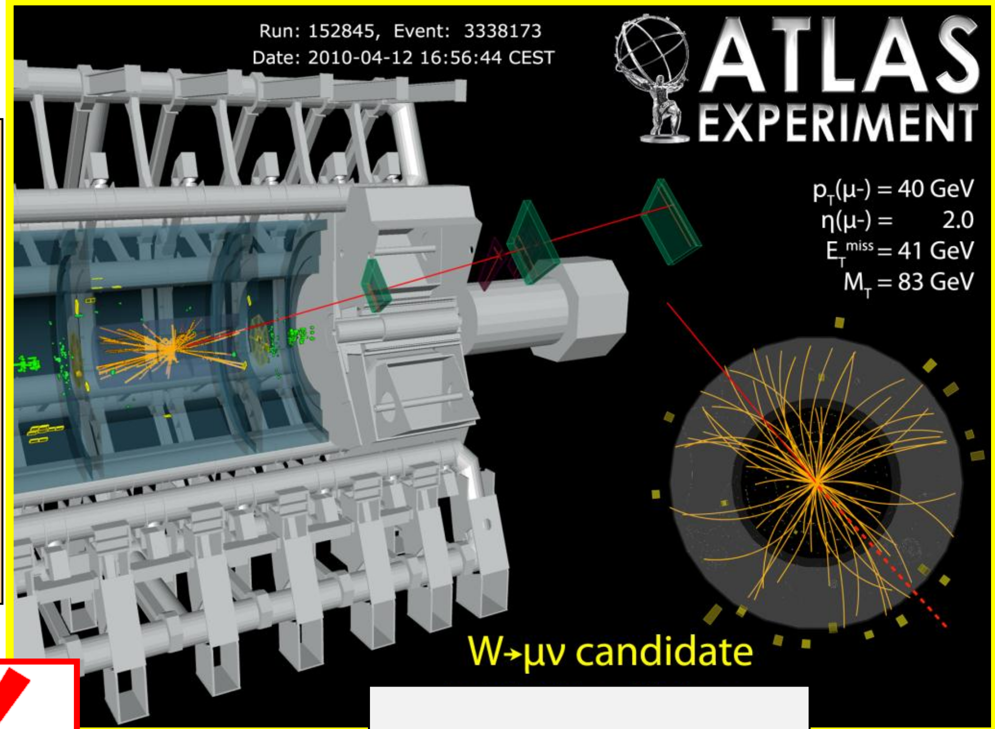


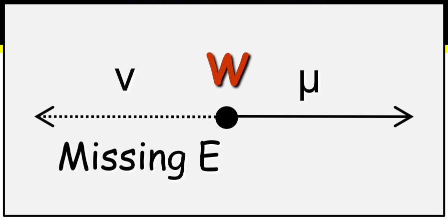


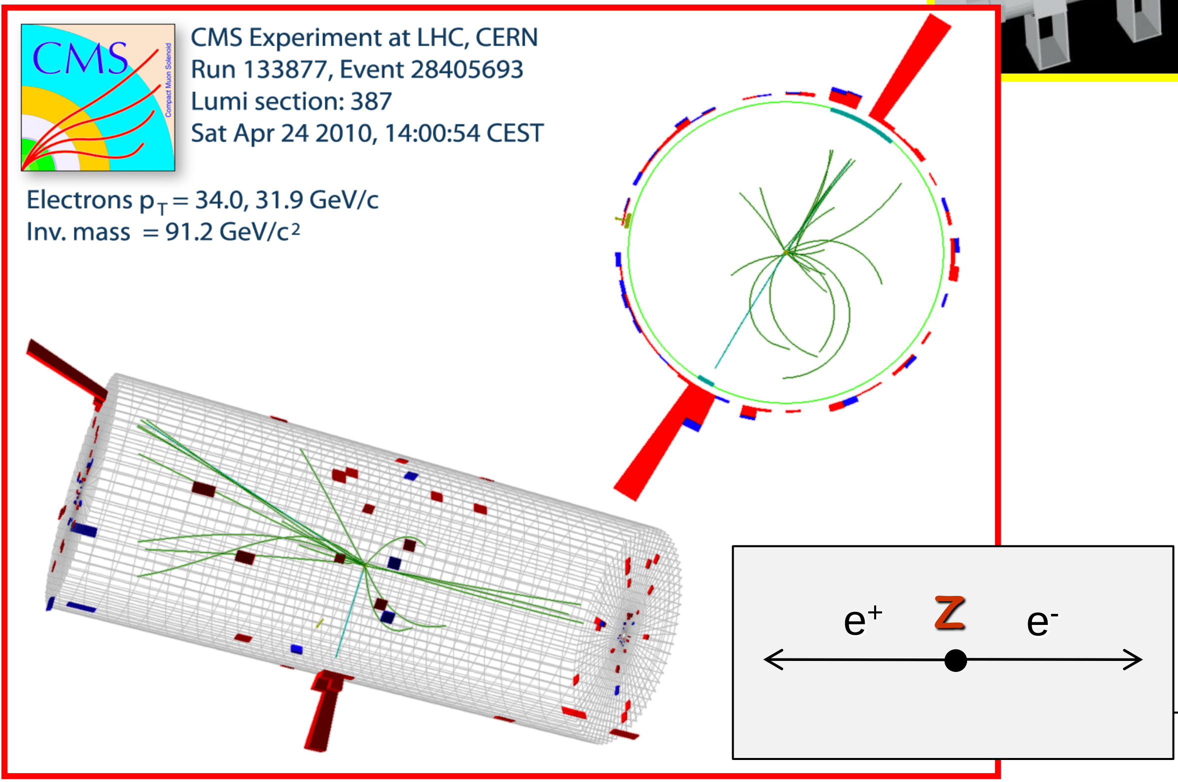
First peaks observed by LHCb provide calibration probes and mark beginning of detailed spectroscopy

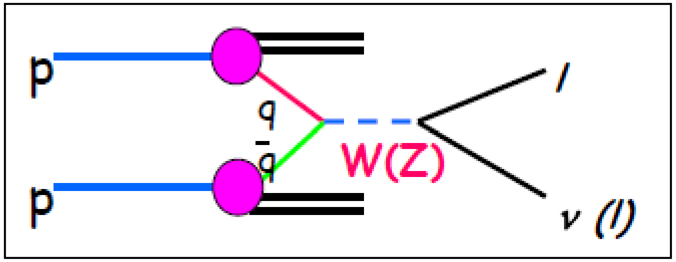
W and Z bosons

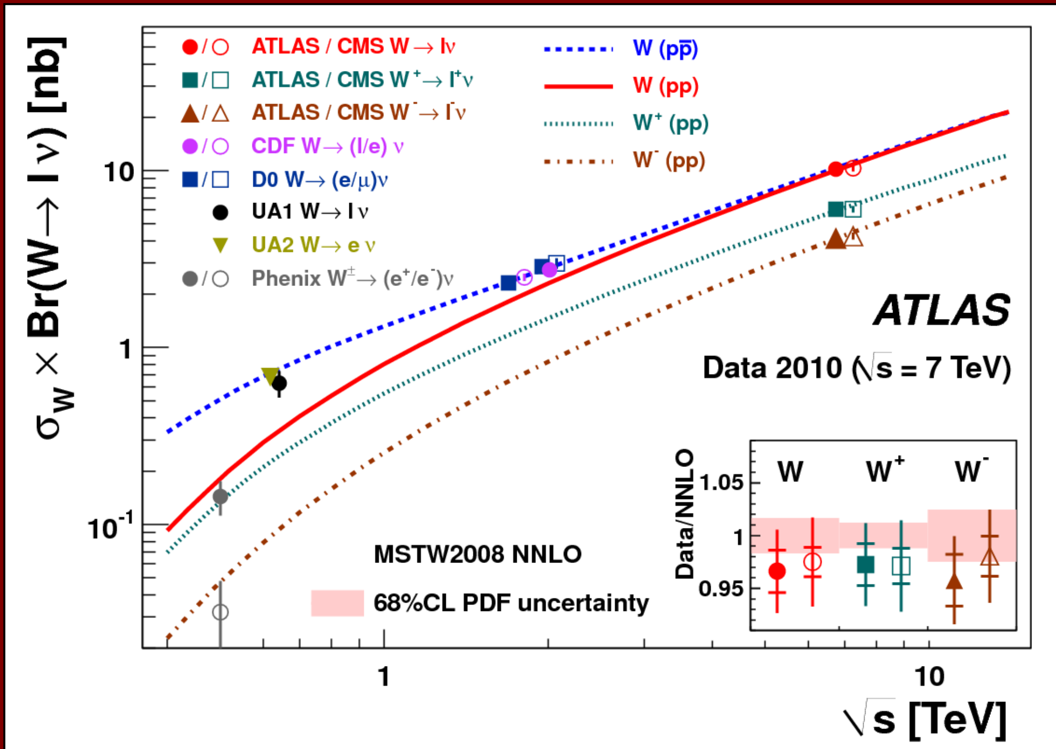
- Fundamental milestones in the "rediscovery" of the Standard Model at $\sqrt{s}$ = 7 TeV
- Carriers of weak interactions
- Provide several tests of SM
- Among dominant backgrounds to searches for New Physics
- Z → ll is gold-plated process to calibrate detectors to ultimate precision



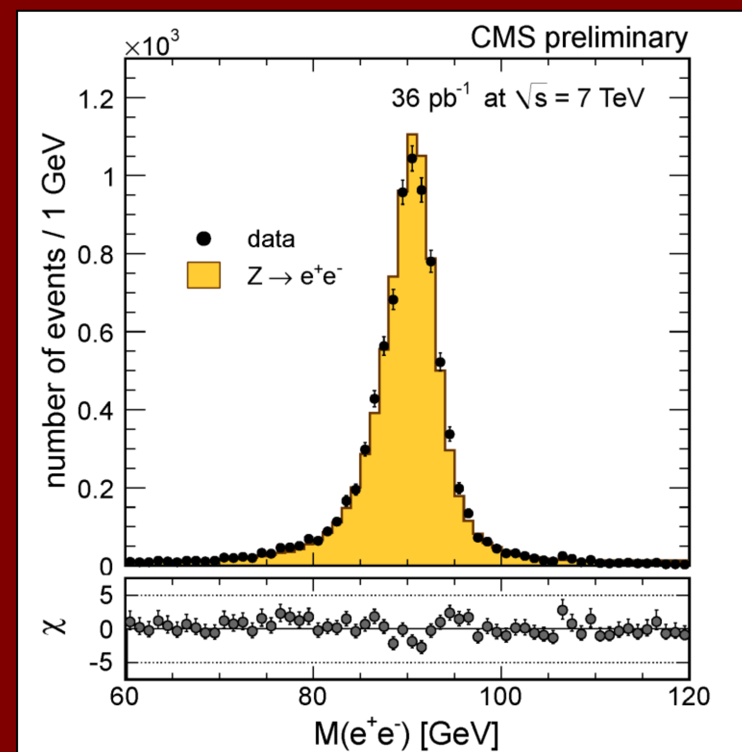






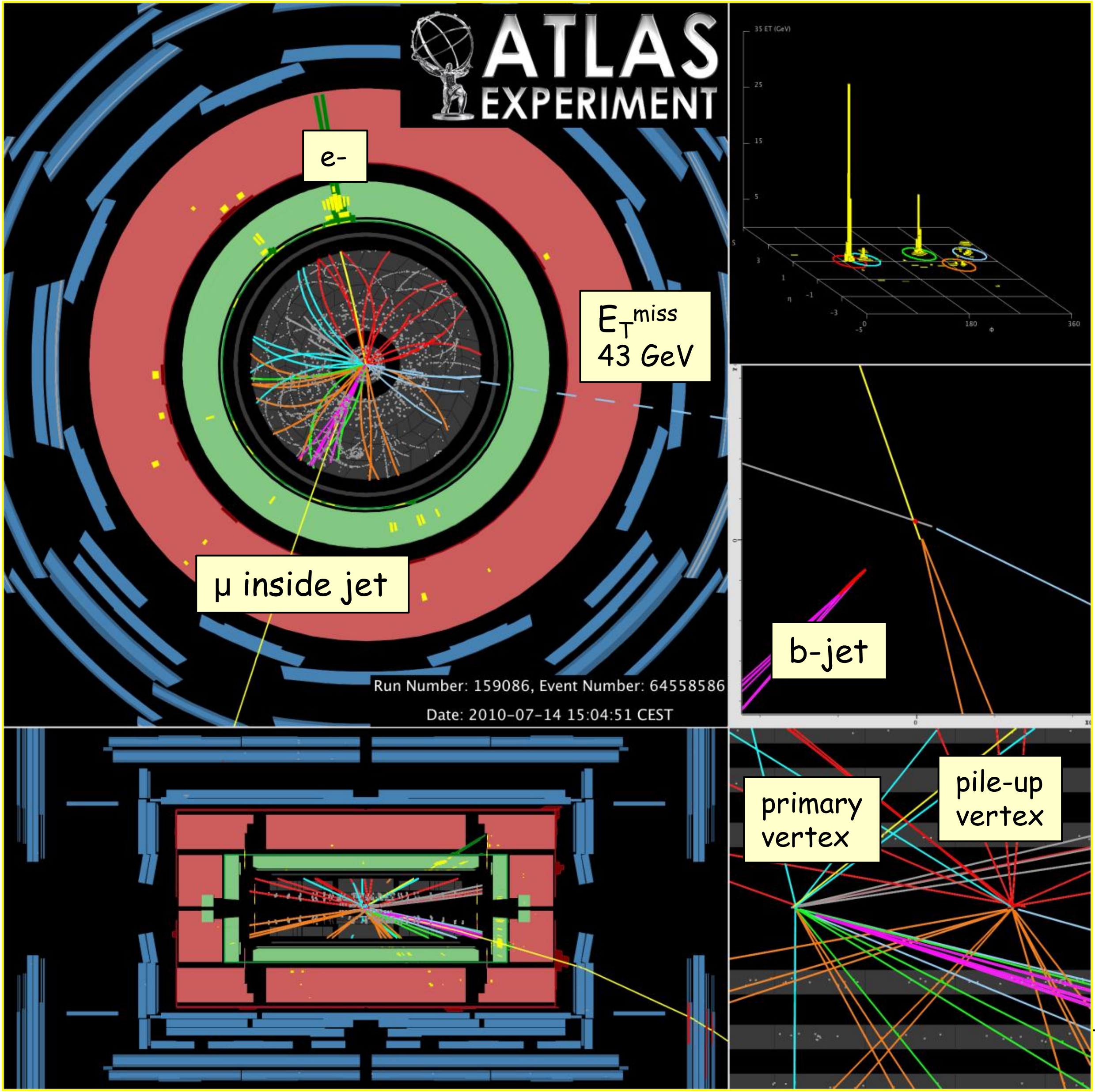


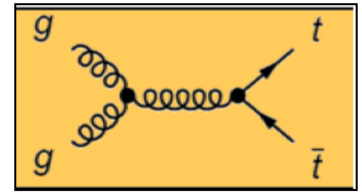
In their present datasets (~ 5 fb^{-1})
ATLAS and CMS have
~ 30 M W→ μν, eν events
~ 3 M Z → μμ, ee events
after selection cuts
→ factor ~ 2 more than CDF and D0

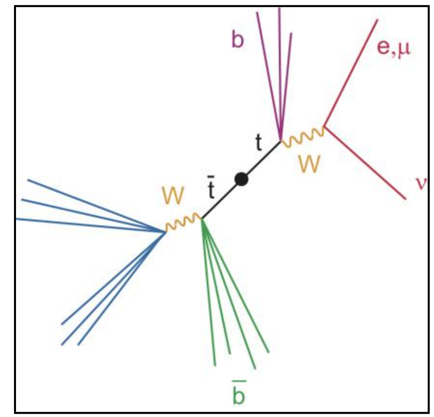


Top quark

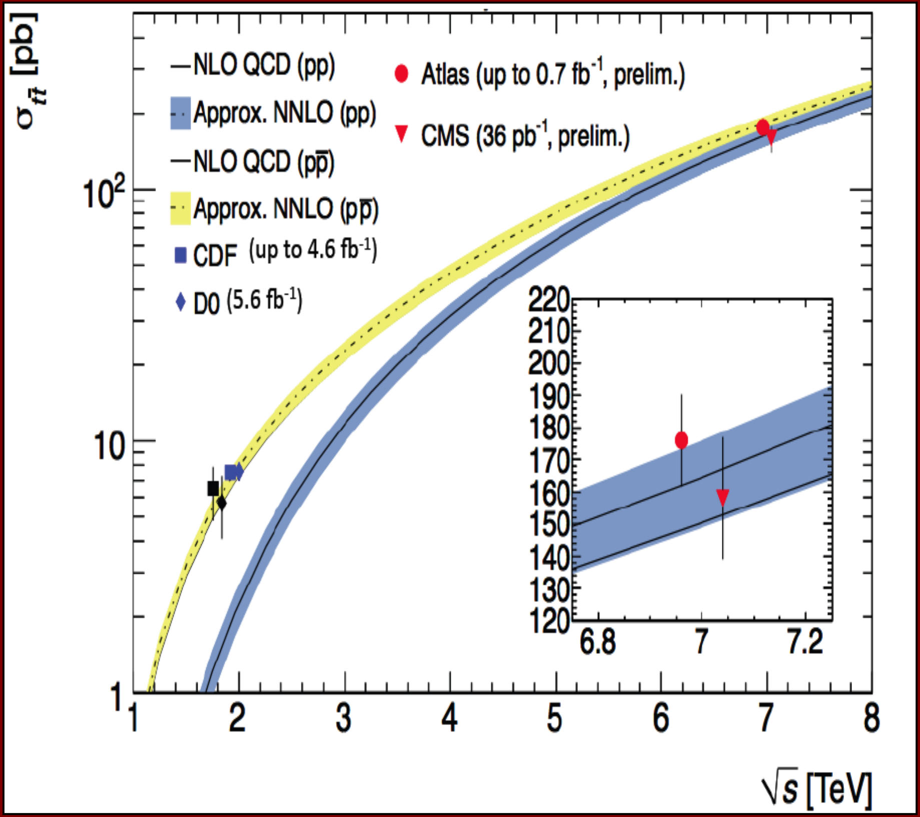
The heaviest (m_t=172 GeV) and most intriguing elementary particle observed so far



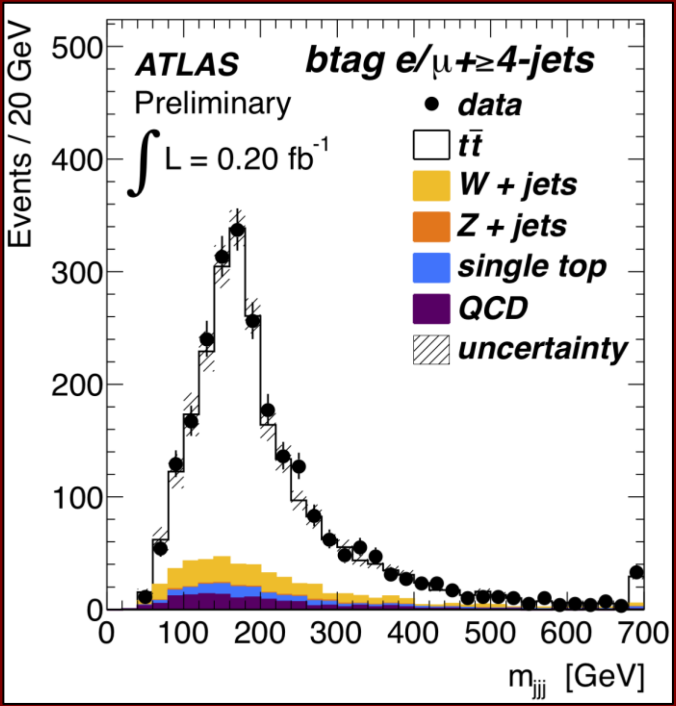




Top events contain all main physics objects (l, jets, missing energy, b-quark jets) → top-quark measurements demonstrate detector performance, as well as good maturity of reconstruction algorithms and modeling of main physics objects

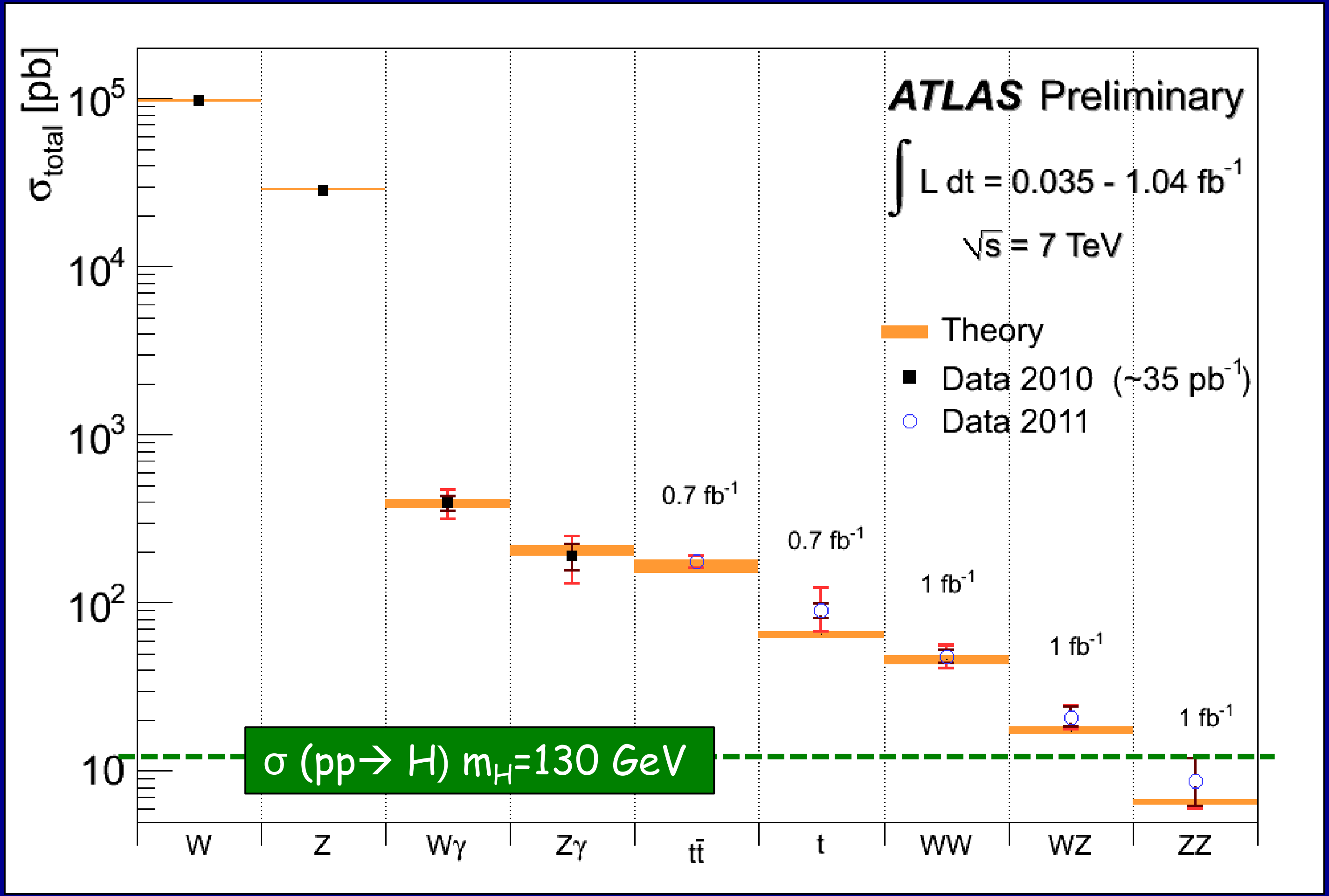


ATLAS: σ_{tt}= 179.0 ± 11.8 pb
→ 6.6% uncertainty → smaller than theoretical error (10%) and comparabale to Tevatron (6.5%)



In their present datasets (~5 fb^{-1}) ATLAS and CMS have ~ 60000 top-pair events each (after selection cuts), factor ~ 10 more than CDF and D0
→ LHC is a "top-quark factory"

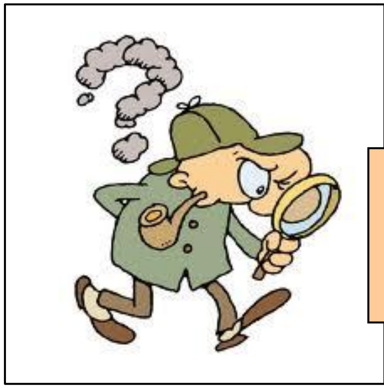
Summary of main cross-section measurements



Good agreement with SM expectations (within present uncertainties)

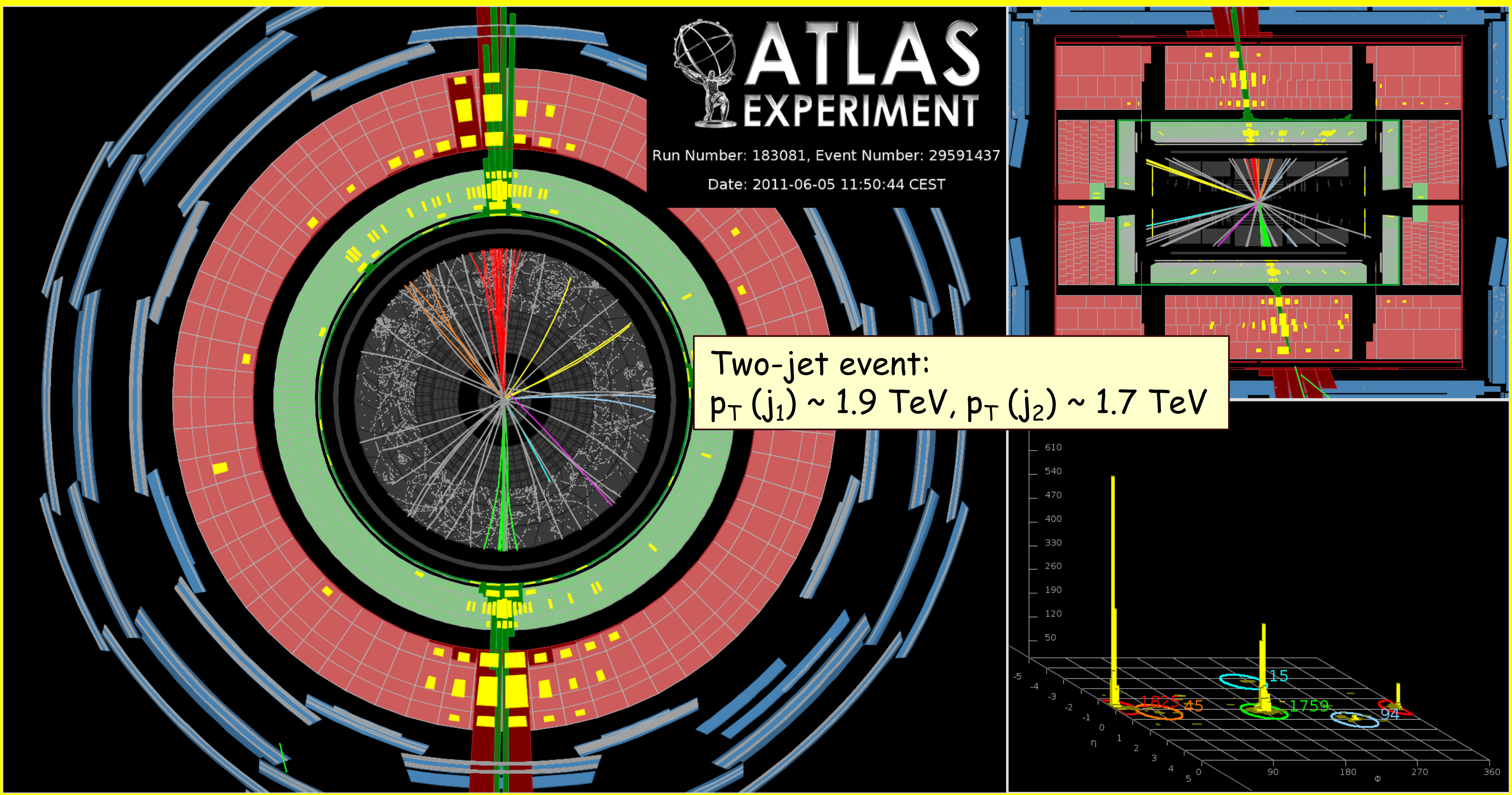
Sensitive to cross-sections comparable to or smaller than SM Higgs cross-section

Most backgrounds to searches for Higgs and New Physics measured



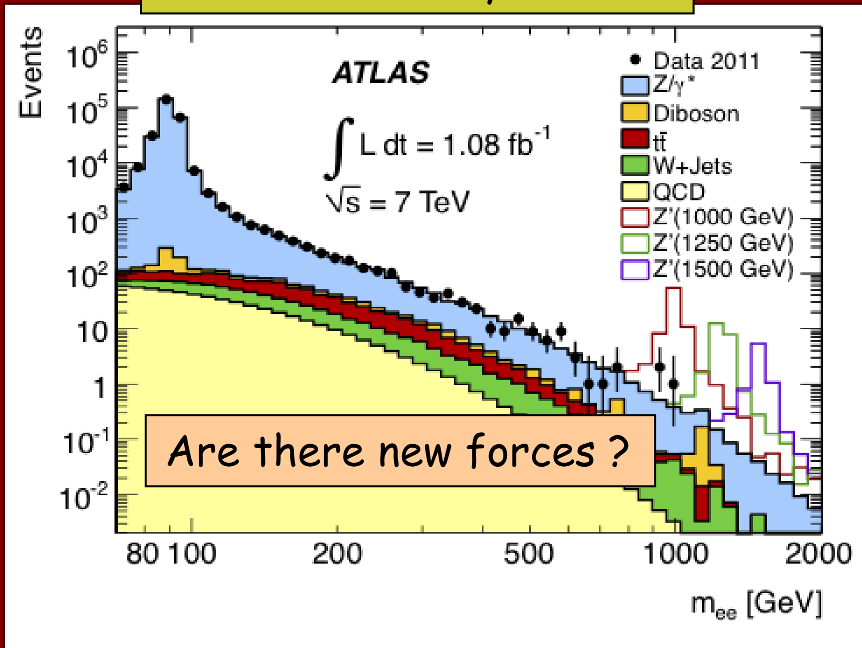
Searches for New Physics

- Huge number of scenarios and topologies investigated
- Extending the kinematic reach further and further into the TeV region
- Larger sensitivity than Tevatron in most cases



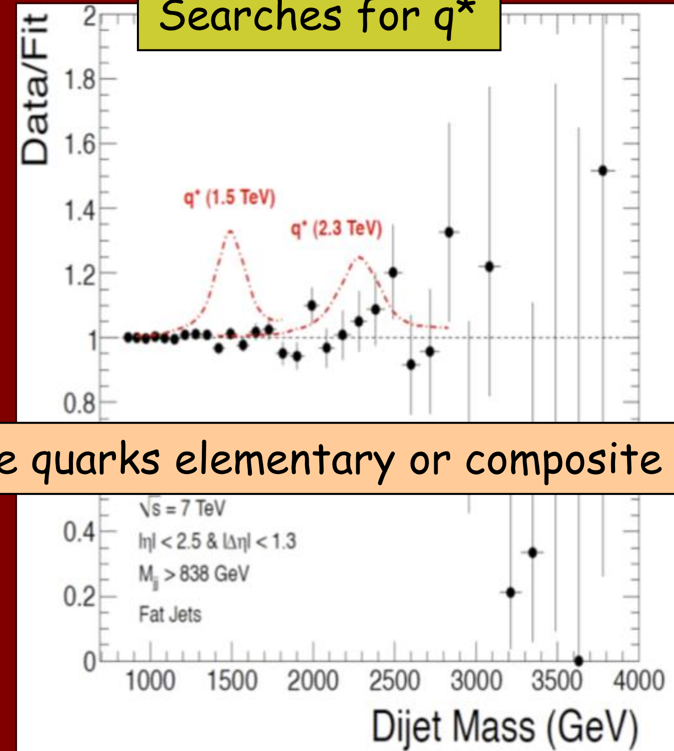
Two-jet event:
$p_T (j_1) \sim 1.9$ TeV, $p_T (j_2) \sim 1.7$ TeV

Search for heavy Z' → ee



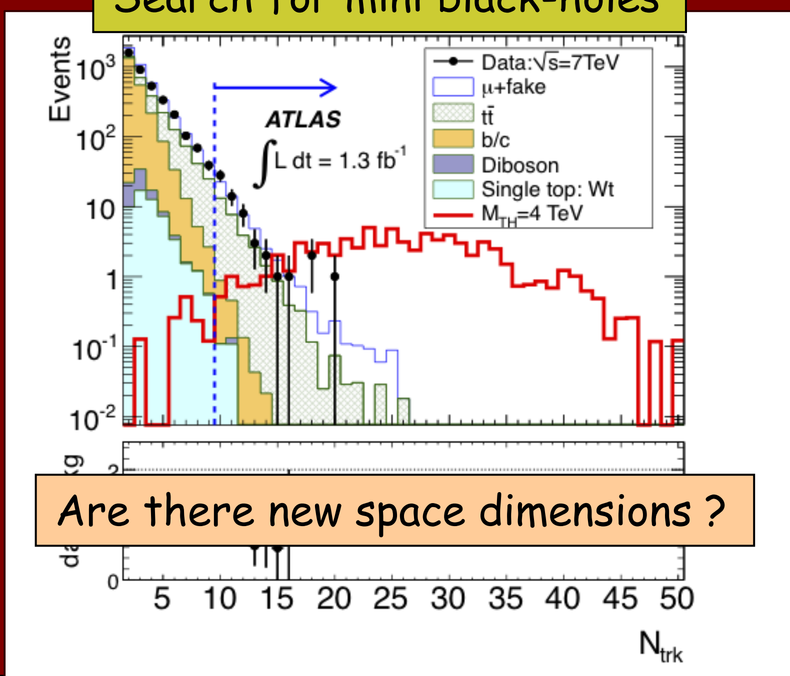
Are there new forces ?

Searches for q*



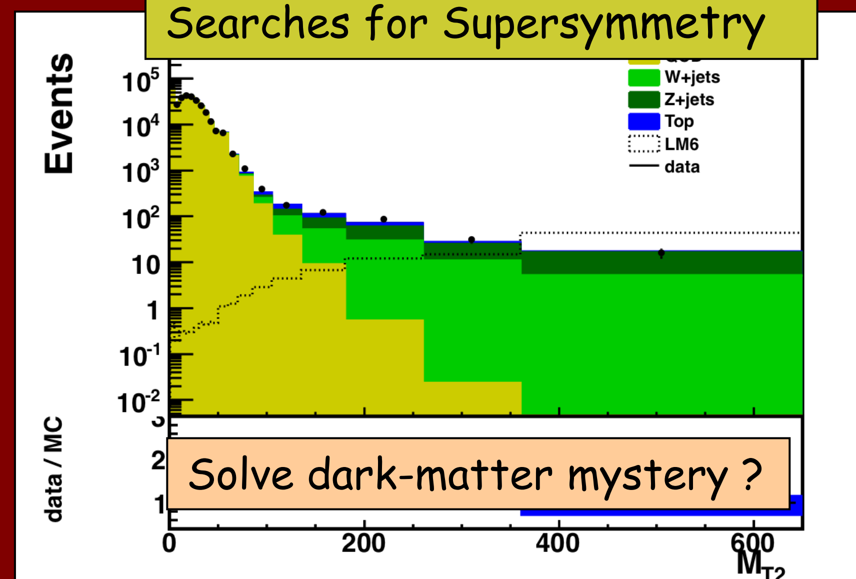
Are quarks elementary or composite ?

Search for mini black-holes



Are there new space dimensions ?

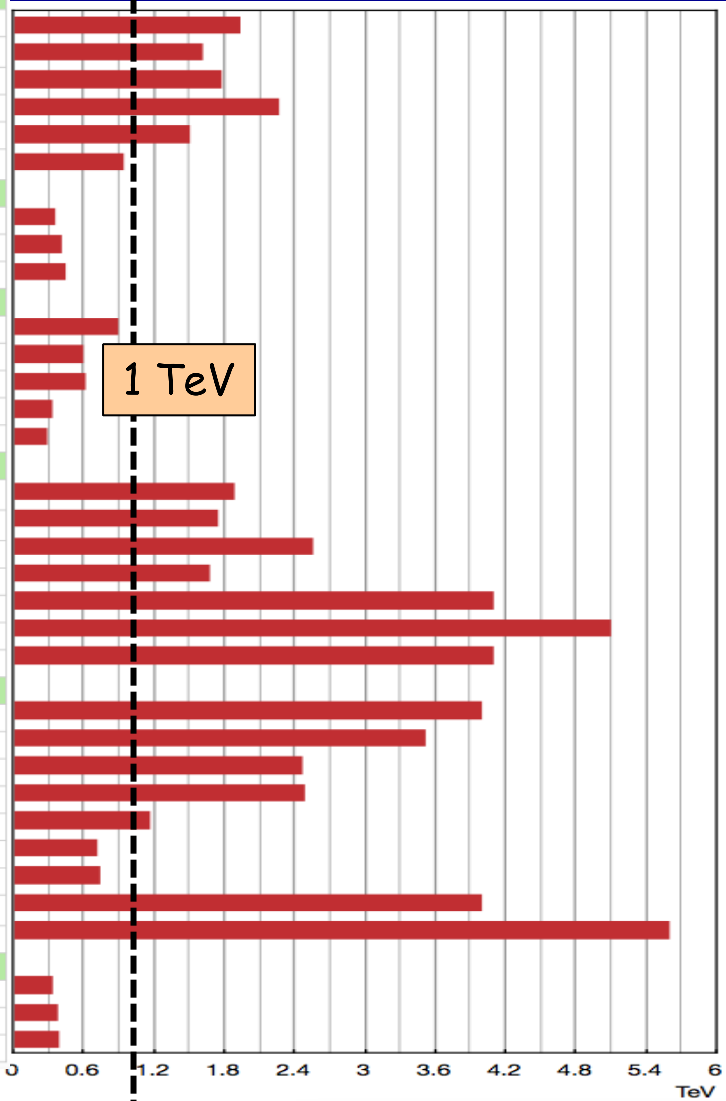
Searches for Supersymmetry



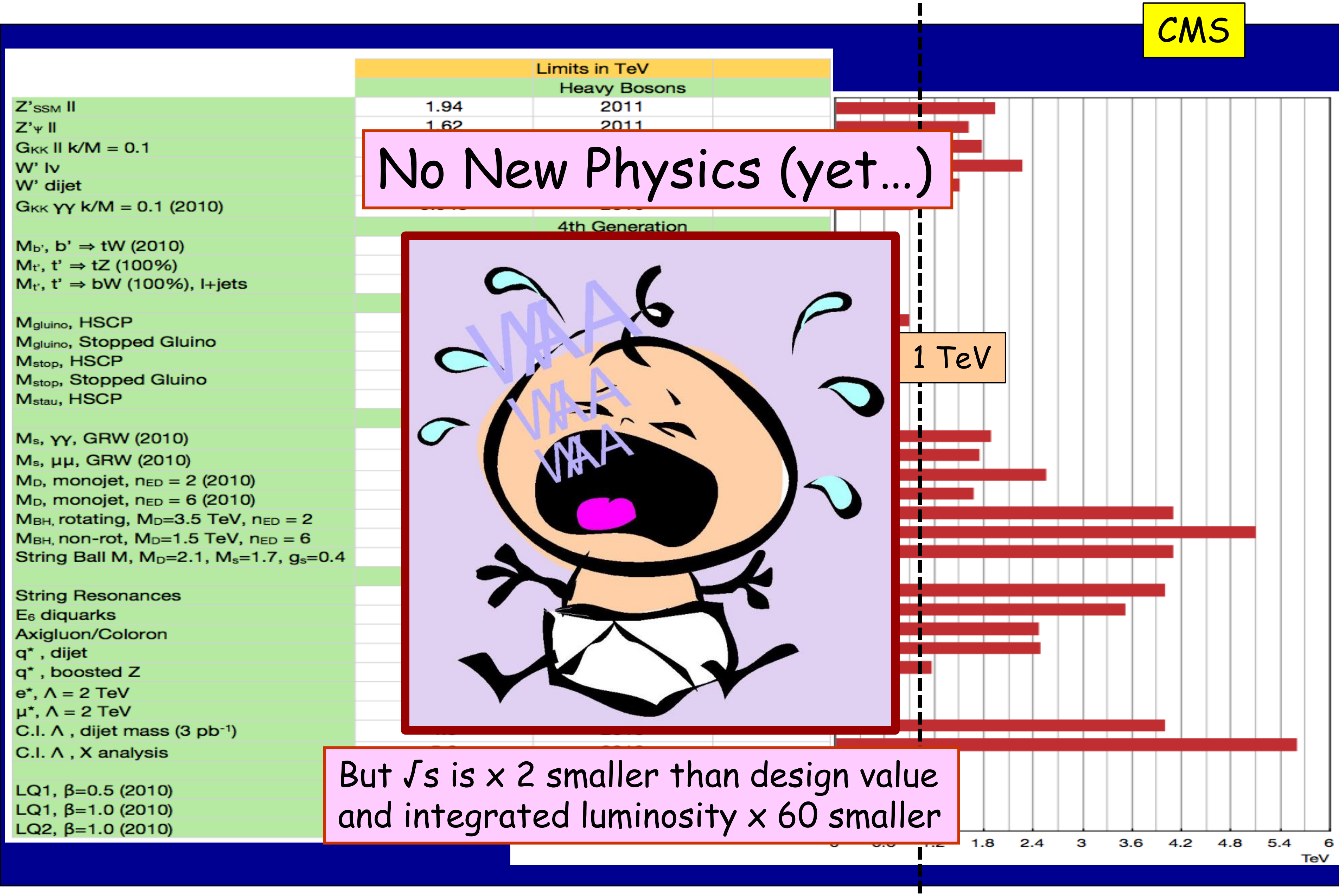
Solve dark-matter mystery ?

CMS

	Limits in TeV	
	Heavy Bosons	
Z'_{SSM} ll	1.94	2011
Z'_{Ψ} ll	1.62	2011
G_{KK} ll k/M = 0.1	1.78	2011
W' lν	2.27	2011
W' dijet	1.51	2011
G_{KK} γγ k/M = 0.1 (2010)	0.945	2010
	4th Generation	
$M_{b'}$, b' ⇒ tW (2010)	0.361	2010
$M_{t'}$, t' ⇒ tZ (100%)	0.417	2011
$M_{t'}$, t' ⇒ bW (100%), l+jets	0.45	2011
	Heavy Stable Particles	
M_{gluino}, HSCP	0.899	2011
M_{gluino}, Stopped Gluino	0.601	2011
M_{stop}, HSCP	0.620	2011
M_{stop}, Stopped Gluino	0.337	2011
M_{stau}, HSCP	0.293	2011
	Large Extra Dimensions	
M_s, γγ, GRW (2010)	1.89	2010
M_s, μμ, GRW (2010)	1.75	2010
M_D, monojet, n_{ED} = 2 (2010)	2.56	2010
M_D, monojet, n_{ED} = 6 (2010)	1.68	2010
M_{BH}, rotating, M_D=3.5 TeV, n_{ED} = 2	4.1	2011
M_{BH}, non-rot, M_D=1.5 TeV, n_{ED} = 6	5.1	2011
String Ball M, M_D=2.1, M_s=1.7, g_s=0.4	4.1	2011
	Compositeness and Contact Interactions	
String Resonances	4.0	2011
E_6 diquarks	3.52	2011
Axigluon/Coloron	2.47	2011
q* , dijet	2.49	2011
q* , boosted Z	1.17	2010
e*, Λ = 2 TeV	0.720	2010
μ*, Λ = 2 TeV	0.745	2010
C.I. Λ , dijet mass (3 pb^{-1})	4.0	2010
C.I. Λ , X analysis	5.6	2010
	LeptoQuark	
LQ1, β=0.5 (2010)	0.340	2010
LQ1, β=1.0 (2010)	0.384	2010
LQ2, β=1.0 (2010)	0.394	2010

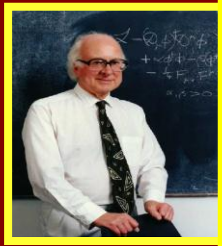


No New Physics (yet…)



But $\sqrt{s}$ is x 2 smaller than design value and integrated luminosity x 60 smaller

Searches for a Standard Model Higgs boson



Higgs searches are among the most challenging studies at the LHC because of the huge backgrounds from other Standard Model processes, especially in the low-mass region between 114.4 GeV (LEP limit) and 200 GeV

Therefore, they have driven the conception, design and technological choices of ATLAS and CMS, and set some of the most stringent performance (→ technical) requirements: lepton identification, lepton energy/momentum resolution, b-tagging, E_T^{miss} measurement, forward-jet tagging, etc.

In the past, most studies assumed $\sqrt{s}$ = 14 TeV, 30-100 fb^{-1}

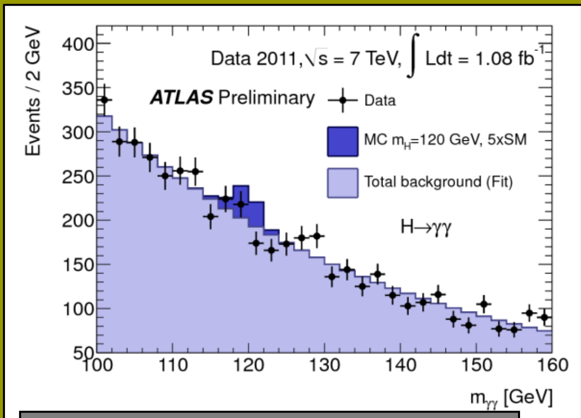
After < 2 years of LHC operation, ATLAS and CMS has achieved sensitivity over most of the still-allowed mass range, thanks to:

- excellent LHC performance → 5 fb^{-1} per experiment
- detector operational efficiency, data-taking efficiency, data quality: 90-100%
- (understanding of) detector performance better than expected at this stage and improving fast → approaching final goals in several cases
- fast understanding and measurements of the Standard Model processes, in particular the main backgrounds to Higgs searches

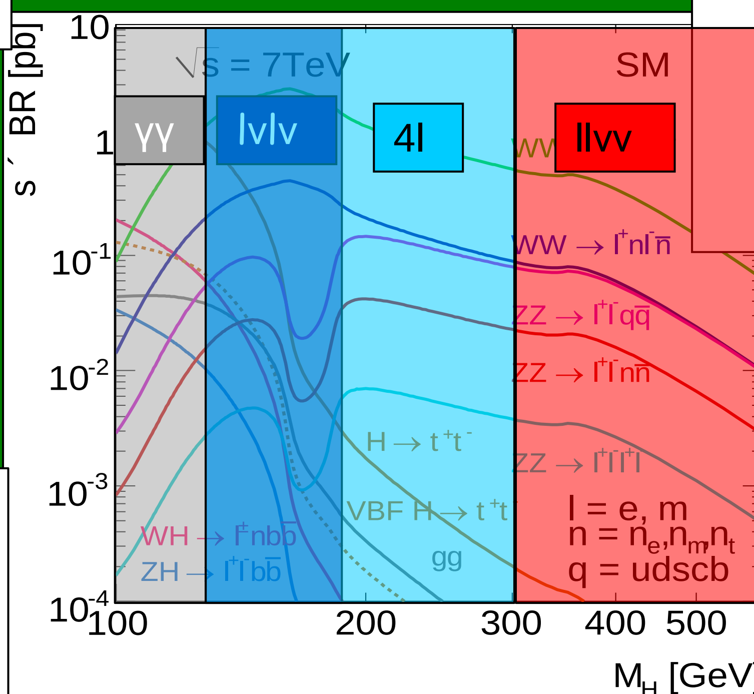
Today we expect the SM Higgs question to be settled by end 2012, at $\sqrt{s}$ ~ 7 TeV and ~ 10 fb^{-1}

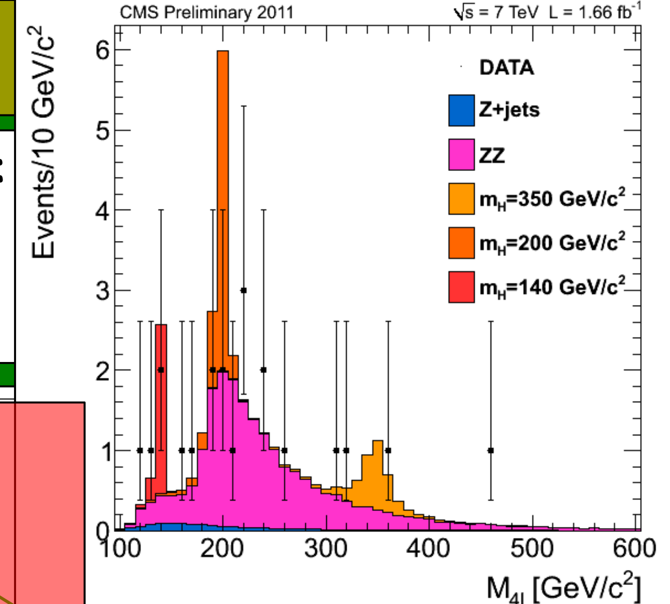
Main search channels at LHC:

Higgs cross-section for observable decay modes vs mass



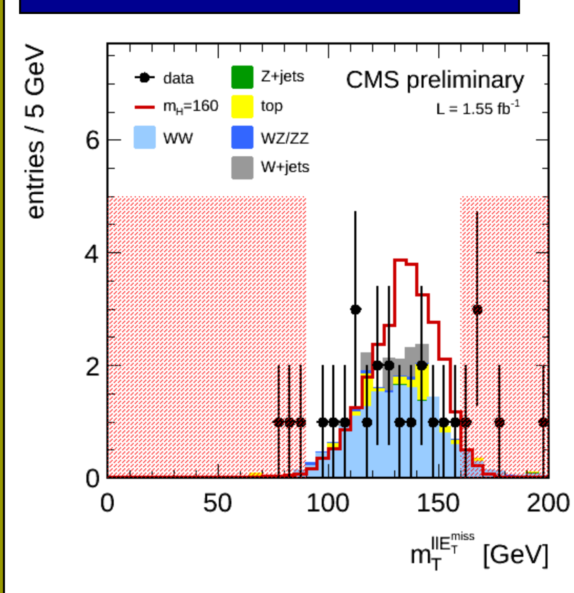
Most sensitive channel
$m_H \leq 120$ GeV: $H \rightarrow \gamma\gamma$



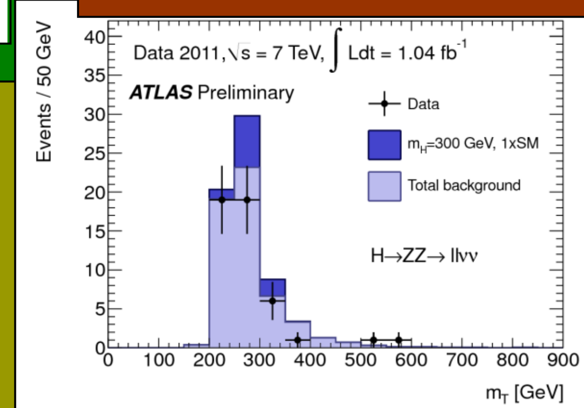


Most sensitive channel
$180 \leq m_H \leq 300$ GeV and most convincing one down to ~ 130 GeV: $H \rightarrow ZZ^{(*)} \rightarrow 4l$

Most sensitive channel
$130 \leq m_H < 180$ GeV:
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

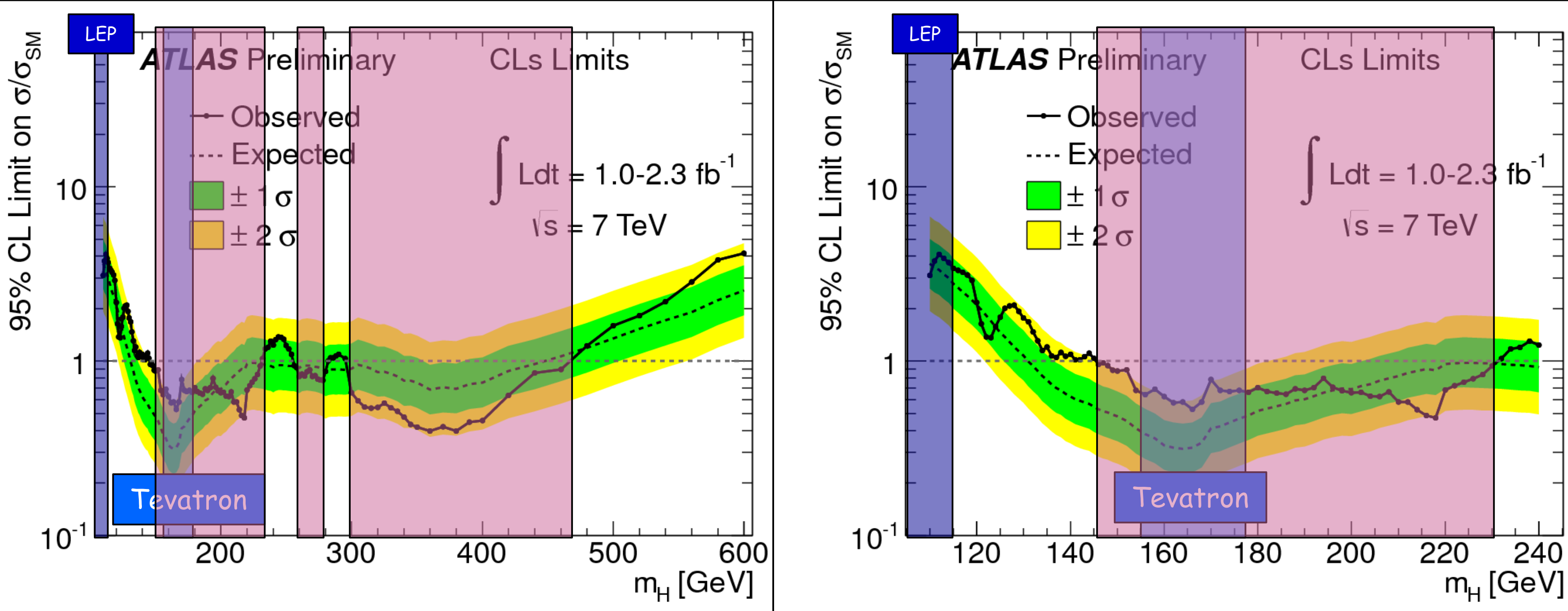


Most sensitive channel
$300 < m_H \leq 600$ GeV:
$H \rightarrow ZZ \rightarrow ll\nu\nu$



In total, 13 different channels studied by ATLAS and CMS

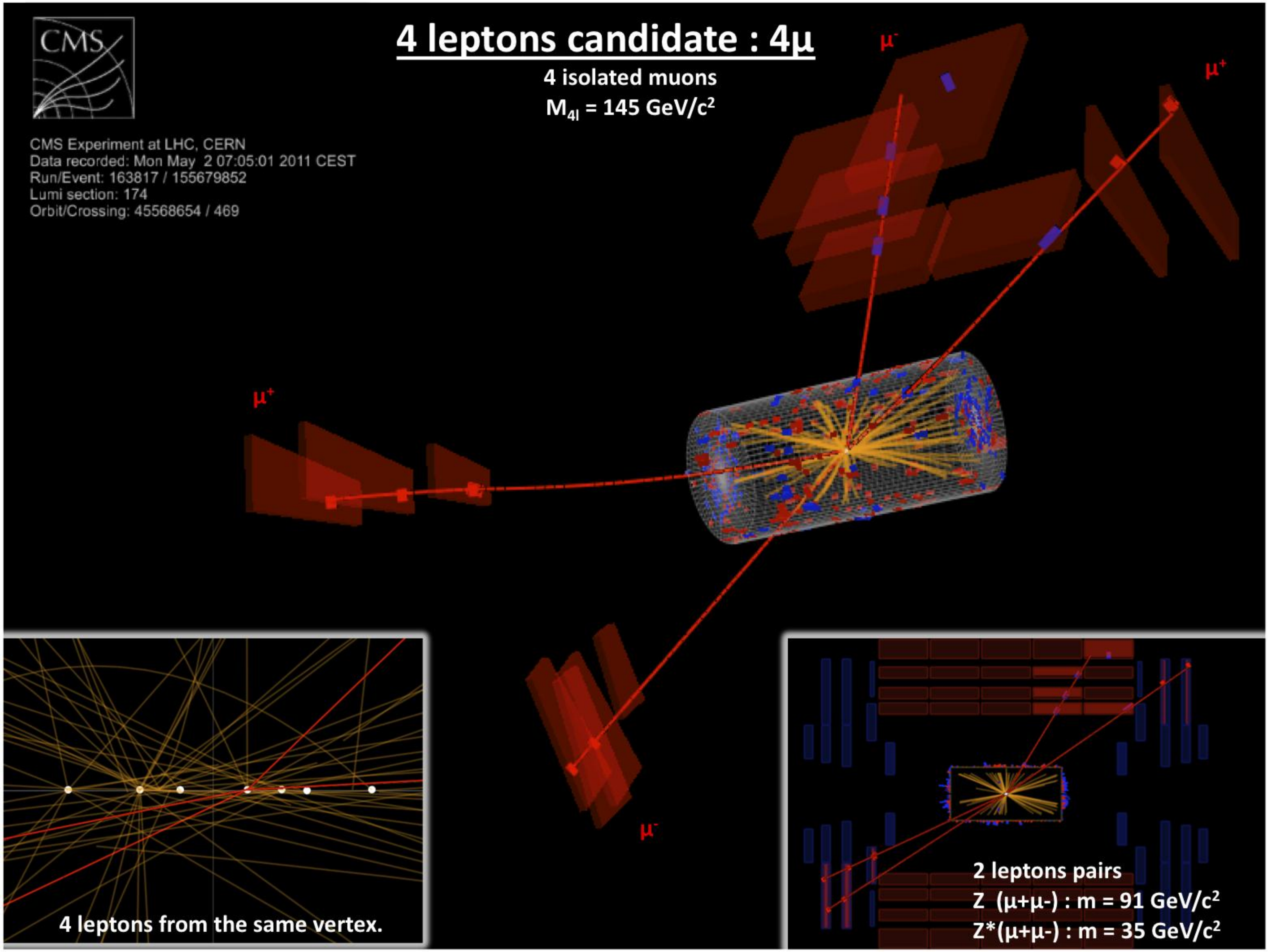
Present status
(all channels together, results based on up to ~ 2 fb^{-1})



Excluded by ATLAS at 95% CL : 146-466 GeV, except 232-256, 282-296 GeV
Excluded by CMS at 95% CL : 145-400 GeV, except 216-226, 288-310 GeV
Expected if no signal : exclusion down to ~ 130 GeV

- LHC provides direct exclusion (95% CL) of a large mass range until now unexplored
- Data are within ±2σ of expectation for no signal → no significant excess
- The best-motivated low-mass region (114.4 < m_H < 161 GeV), favoured by the fit of the SM to existing experimental measurements (LEP, Tevatron, …), still open to exploration

H→ 4l: the gold-plated channel for Higgs searches at the LHC: the rarest (a handful of events expected with few fb^{-1}), the purest (narrow mass peak, $S/B \geq 1$)



Higgs: la suite …

The experiments will update their results based on up to ~5 fb^{-1} by end of the year

2012 will be "the year of the Higgs": the LHC can say the final word about the SM Higgs mechanism:

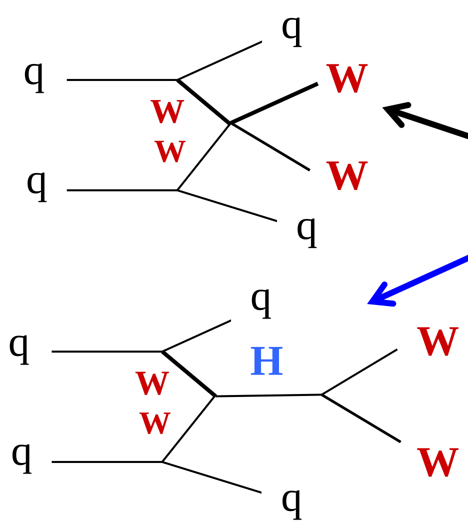
- exclude it over the full allowed mass range (at > 95% C.L.)
- discover it (5σ) over the full allowed mass range
  (requires at least 10 fb^{-1} per experiment)

What if a SM Higgs exist ?
And what if it doesn't ?

If the SM Higgs does not exist ….

We will have to find another explanation for the so-called "electroweak symmetry breaking"
i.e. why the carriers of the electromagnetic force (γ) and of the weak force (W, Z)
do not have the same mass.

More urgent: the SM without Higgs is expected to break down at high energy

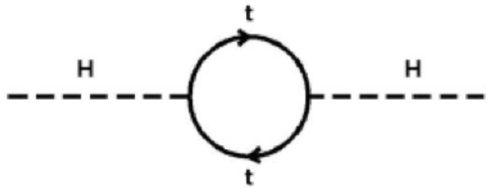


This process becomes unphysical (cross section diverges) at high m (WW)
if this process does not exist

→ If no Higgs → expect weird behaviour of WW scattering at high-E (or new physics ..)
Need $\sqrt{s}$=14 TeV for first observation and luminosity upgrade for more detailed understanding of underlying dynamics

If the SM Higgs exists ….

Why is its mass so light ? → Need new physics (close-by, ~TeV scale) to "stabilize" the divergent Higgs mass



In the SM, this correction to m_H diverges as ~ Λ^2 (energy scale up to which the SM is valid)

E.g. Supersymmetry: the supersymmetric partner of the top (the stop) gives rise to the same diagram with opposite sign → cancellation
However: cancellation only works if mass difference between stop-top is small (few hundreds GeV) → motivation for supersymmetry at the ~ TeV scale

Furthermore, precise measurements of the Higgs couplings requires $\sqrt{s}$ =14 TeV and LHC luminosity upgrade

Conclusion: whether or not the SM Higgs boson exists, new physics (to fix problems) and an exciting programme of discoveries and measurements are expected at the LHC and its upgrade

The first two years of LHC operation have been …. SUPERB !
Thanks to the outstanding performance of machine and experiments, far beyond expectation

The four experiments work extremely well, from smooth and efficient operation of the detector, trigger, data processing, computing, to the (fast) delivery of physics results
(~ 90 papers each published/submitted by ATLAS and CMS, ~ 20 each by ALICE and LHCb)

Excellent physics achievements:

- "Rediscovery of the Standard Model" completed; precise measurements of various processes start to challenge the theory predictions and previous machines
- Searches for new physics extend well into the few-TeV region for many scenarios
- Pb-Pb collision data produced exciting results, from jet quenching to J/ψ suppression, and detailed study of the quark-gluon plasma → with the new data being collected now we will soon be able to do more quantitative measurements also in this field

ATLAS and CMS have looked for a SM Higgs boson over the mass region 100-600 GeV, using 13 distinct channels and up to 2.3 fb^{-1} of data:
→ We have excluded most of the mass region 145-470 GeV
→ If a SM Higgs exists, it is most likely in the region ~ 114-145 GeV

2012 will most likely be "the year of the Higgs" (discover or rule out definitely)

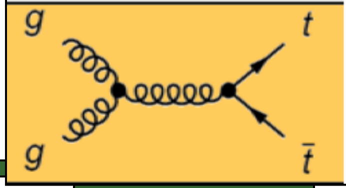
The success of the LHC demonstrates the importance of designing, optimizing and operating accelerator and experiments together, as the two must live in full symbiosis

The LHC will (hopefully !) discover many things, but it will not be the end of the story.
<u>Most importantly</u>, it will tell us what are the right questions to ask and how to continue

SPARES

Top-quark measurements

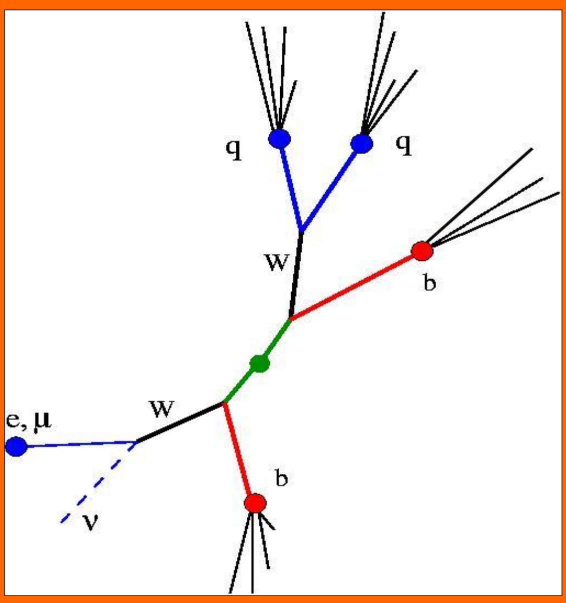
s (t$\bar{\text{t}}$) @160 pb at $\sqrt{s} = 7$ TeV



lepton + jets channel
tt → bW bW → blν bjj
σ ~ 70 pb

1 isolated lepton p_T > 20 GeV
E_T^{miss} > 20 GeV, E_T^{miss} + m_T > 60 GeV
≥ 4 jets p_T > 25 GeV
≥ 1 b-tag jet

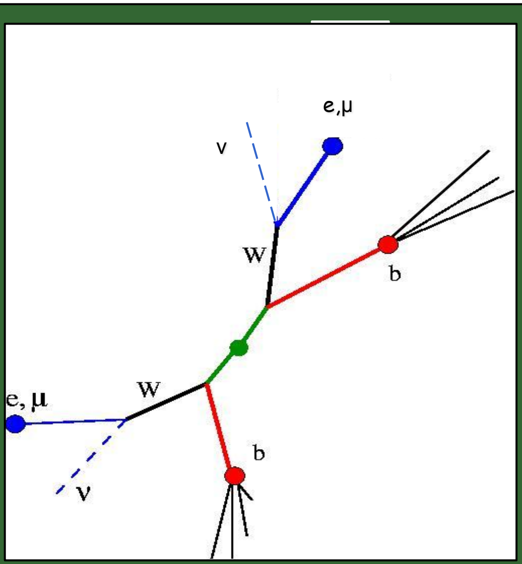
Acceptance x efficiency ~ 15%

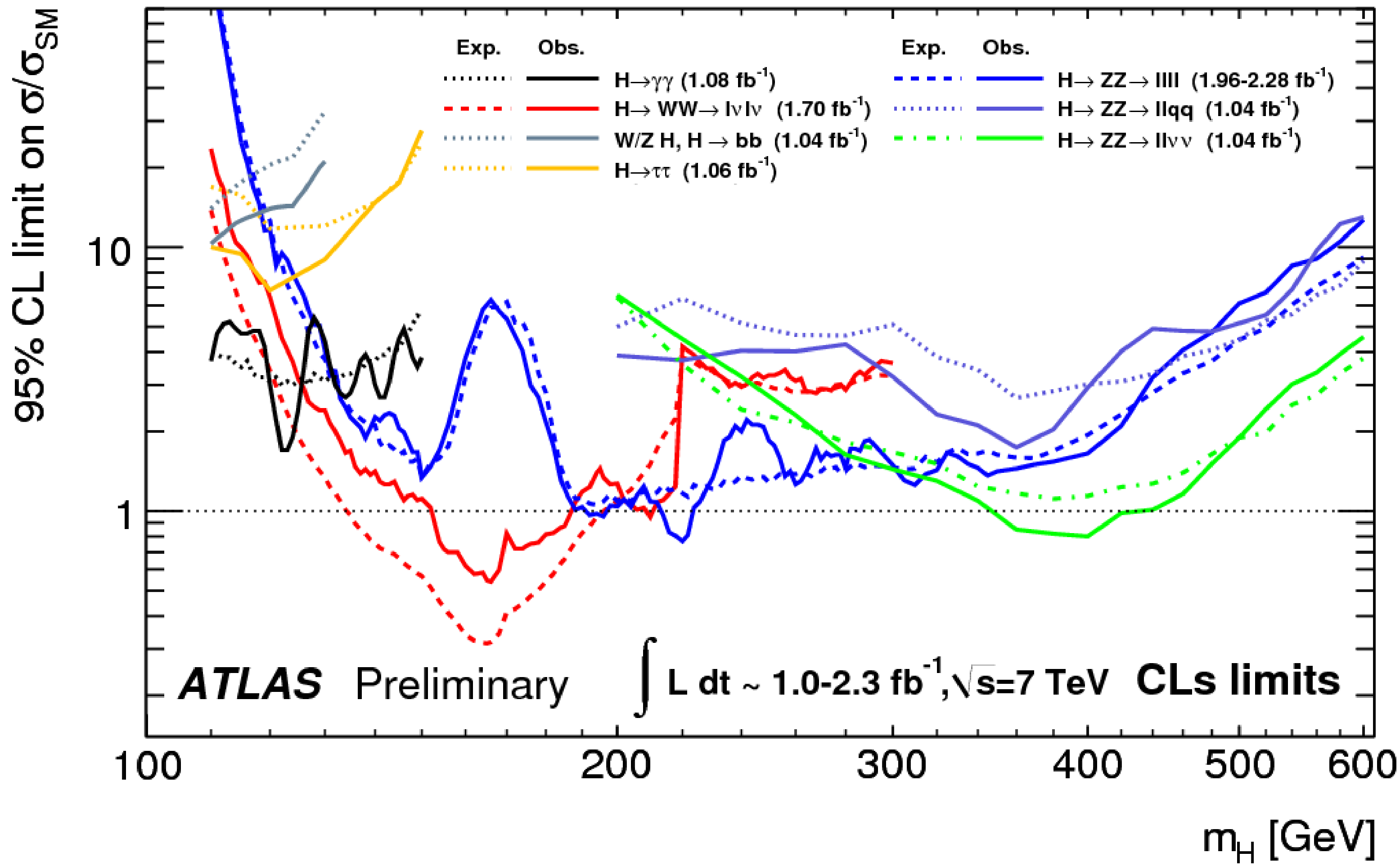


2-lepton channel
tt → bW bW → blν blν
σ ~ 10 pb

2 opposite-sign leptons: ee, eμ, μμ
both leptons p_T > 20 GeV
≥ 2 jets p_T > 20 GeV
ee: E_T^{miss} > 40 GeV $|M(ee)-M_Z|$ > 5 GeV
μμ: E_T^{miss} > 30 GeV $|M(\mu\mu)-M_Z|$ > 10 GeV
eμ: $H_T = \Sigma E_T$ (leptons, jets) > 150 GeV

Acceptance x efficiency ~ 25%





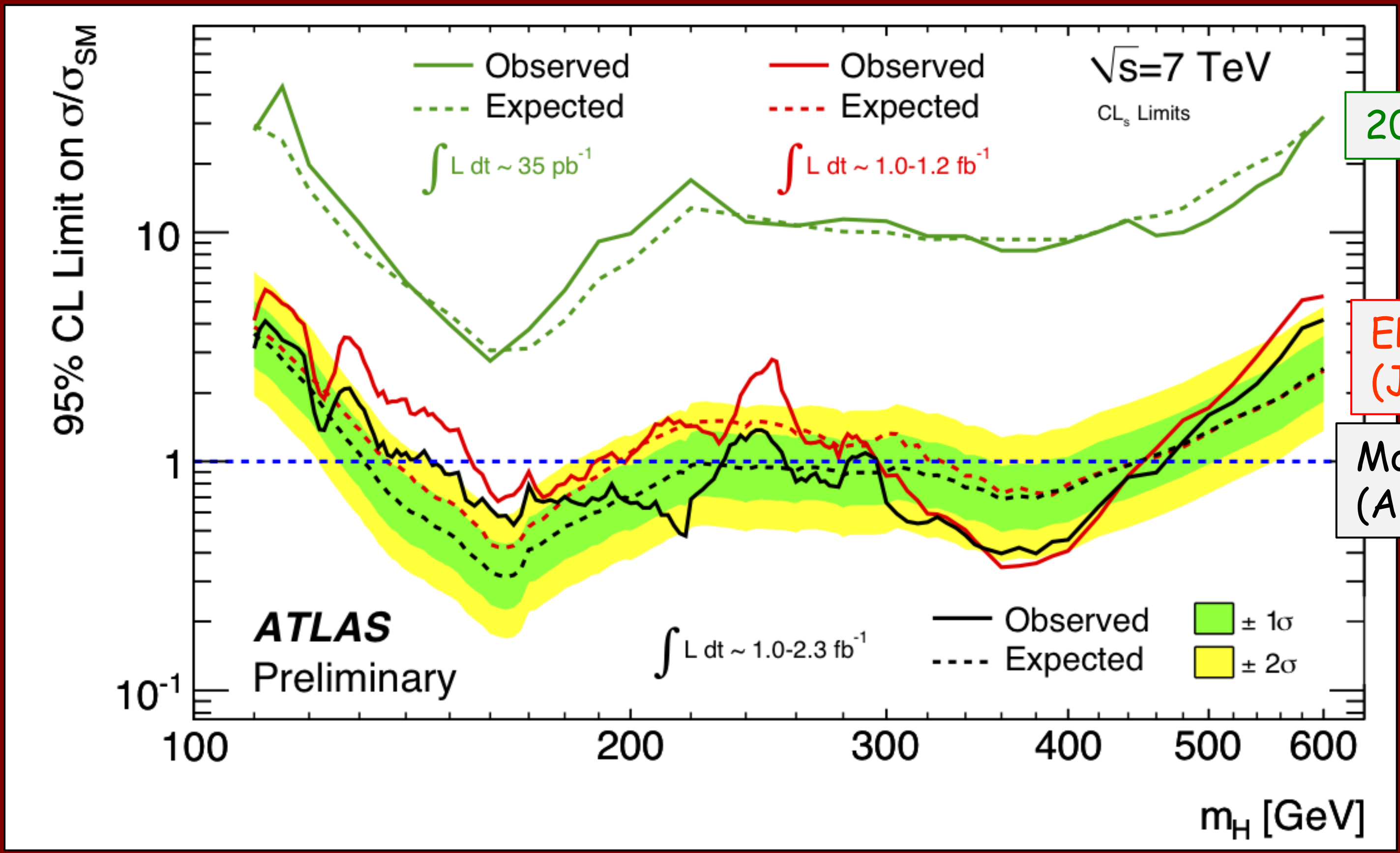
$H \to \gamma\gamma$	: most sensitive channel $m_H \leq 120$ GeV
$H \to WW^{(*)} \to l\nu l\nu$	: most sensitive channel $130 \leq m_H < 180$ GeV
$H \to ZZ^{(*)} \to 4l$	: most sensitive channel $180 \leq m_H \leq 300$ GeV and most convincing channel down to ~ 130 GeV
$H \to ZZ \to ll\nu\nu$	: most sensitive channel $300 < m_H \leq 600$ GeV

Femto-summary of present Higgs searches in ATLAS

Channel	m_H range (GeV)	Int. lumi fb^{-1}	Main backgrounds	Number of signal events after cuts	S/B after cuts	Excluded σ/σ_{SM} and m_H range
$H \to \gamma\gamma$	110-150	1.08	$\gamma\gamma$, γj, jj	~ 15	~ 0.02	~ 4
$H \to \tau\tau \to ll+\nu$	110-140	1.06	$Z \to \tau\tau$, top	~ 0.8	~ 0.02	30-60
$H \to \tau\tau \to l\tau_{had}$	100-150	1.06	$Z \to \tau\tau$	~ 10	~ 5 10^{-3}	6-25
$W/ZH \to bbl(l)$	110-130	1.04	W/Z+jets, top	~6	~ 5 10^{-3}	10-20
$H \to WW \to l\nu l\nu$	110-300	1.7	WW, top, Z+jet	~ 50 (150 GeV)	~ 0.6	0.3-10 154-186 GeV
$H \to ZZ^* \to 4l$	110-600	up to 2.3	ZZ*, top, Zbb	~ 1 (130 GeV)	~ 1	1-10 190-200 GeV
$H \to ZZ \to ll\,\nu\nu$	200-600	1.04	ZZ, top, Z+jets	~ 10 (400 GeV)	~ 0.3	1-5 340-450 GeV
$H \to ZZ \to ll\,qq$	200-600	1.04	Z+jets, top	~ 5	~0.05	2-13
$H \to WW \to l\nu qq$	240-600	1.04	W+jets,top,jets	~ 60	10^{-3}	~ 3-20

- Based so far on (conservative) cut-based analyses
- Large and sometimes not well-known backgrounds estimated mostly with data-driven techniques using signal-free control regions

Improvements with time



2010 data (35 pb^{-1})

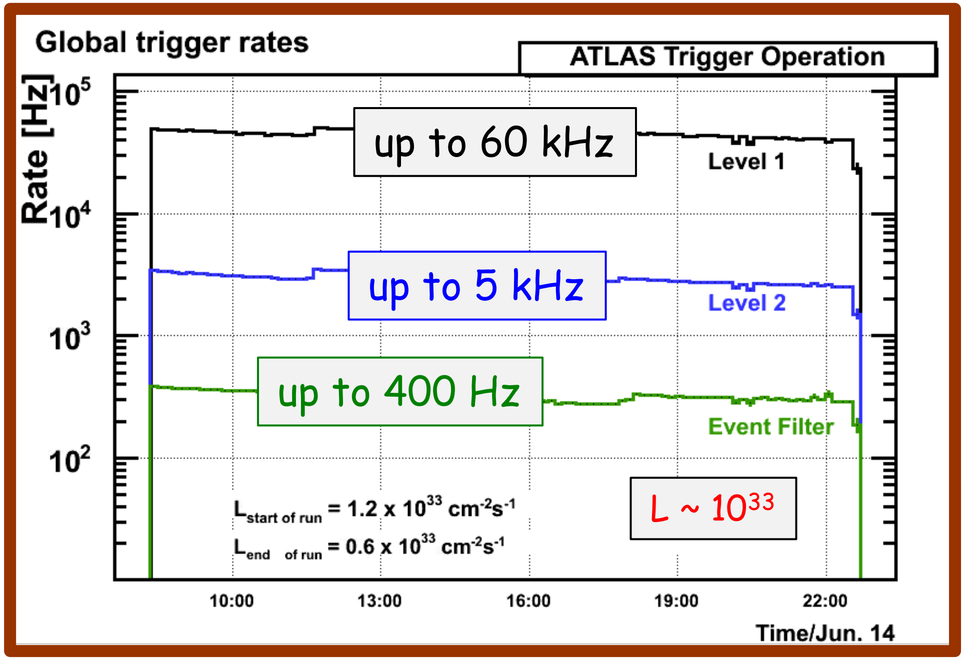
EPS results (July, 1-1.2 fb^{-1})

Most recent results (August, 1-2.3 fb^{-1})

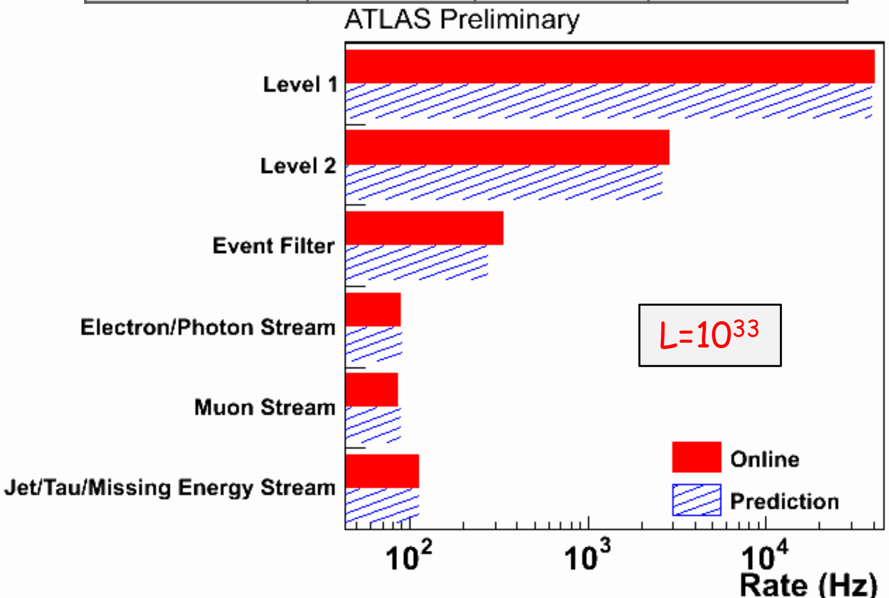
Most of 200-300 GeV region excluded in August

Trigger

- 3 levels: L1 (hardware), L2, Event Filter
- Very good performance (operation, efficiency, …)
- Coping very well with rapidly-increasing luminosity (6 orders of magnitudes during 2010-2011) by adapting prescales, thresholds, menu

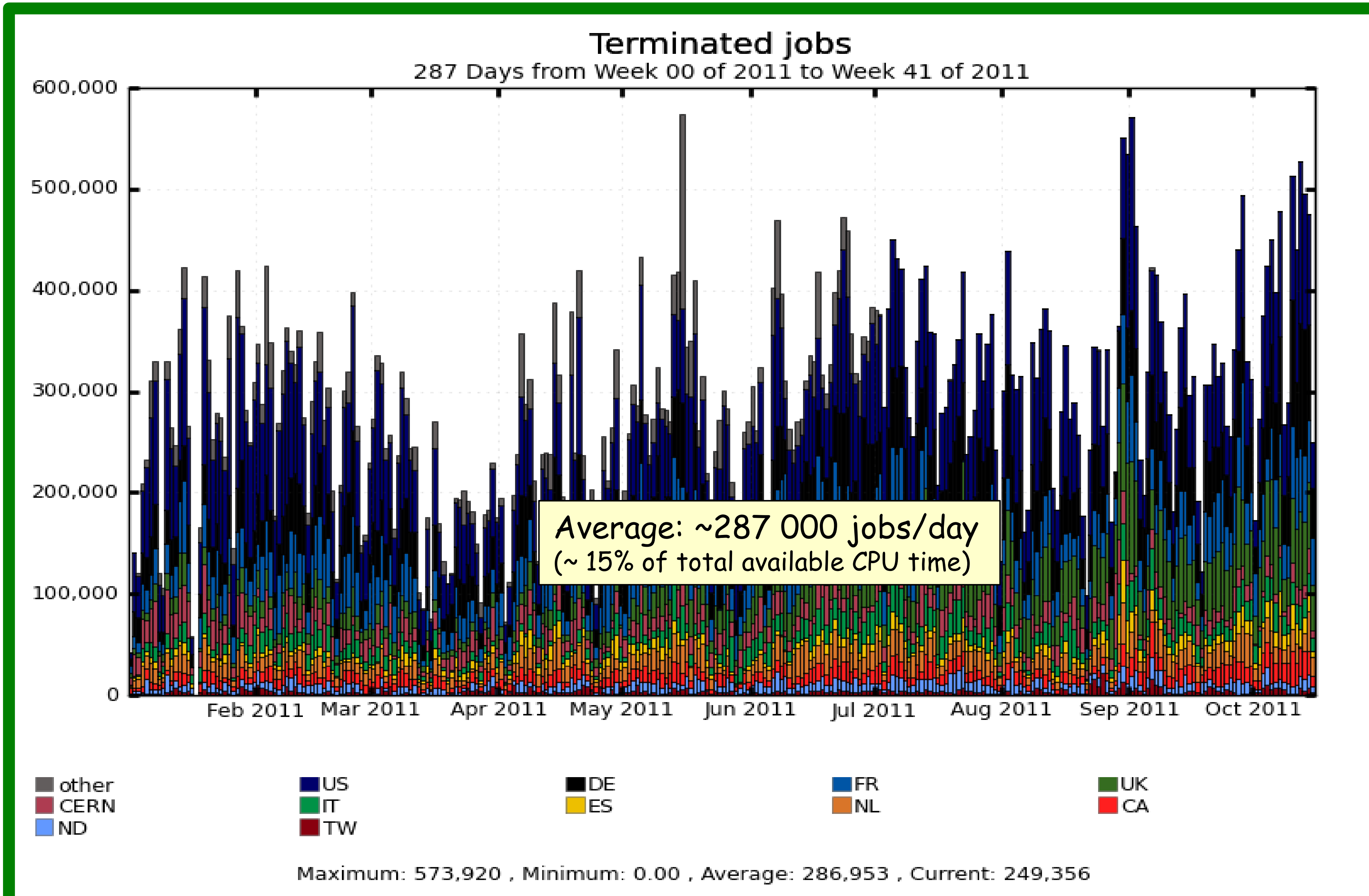


trigger	L1 item	L1 Rate (Hz)	EF Rate (Hz)
E20_medium	EM14	8500	50
2e12_medium	2EM7	5700	1
g80_loose	EM30	700	3
2g20_loose	2EM14	750	2
mu18	MU10	5300	40
2mu10	2MU10	100	1
xe60	XE40	300	4
J180	J75	200	6
Tau29medium_xe35	TAU11_XE20	3800	6
Tau16_e15	TAU6_EM10	7500	6
J75_xe45	J50_XE20	500	10



Trigger rates at a given luminosity estimated from dedicated samples recorded at lower luminosity with L1 only and low thresholds
→ good agreement between predicted and observed rates → method used to define trigger settings ahead of time
Performance well understood: can predict rates to better than 20%

Analysis jobs running on ATLAS Grid every day



Grid-based analysis in 2011 : > 1500 different users, ~ 83M analysis jobs