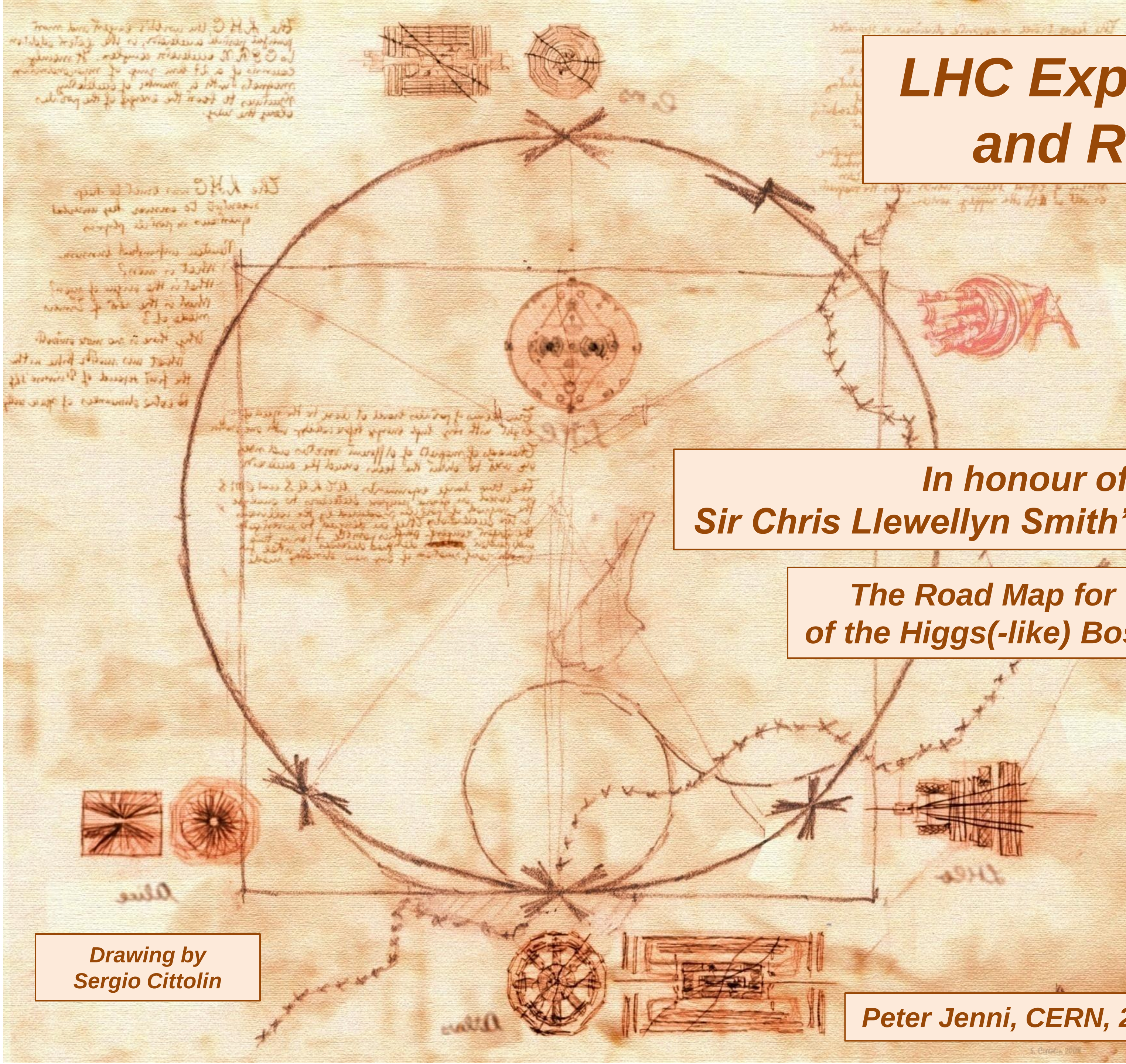
LHC Experiments and Results

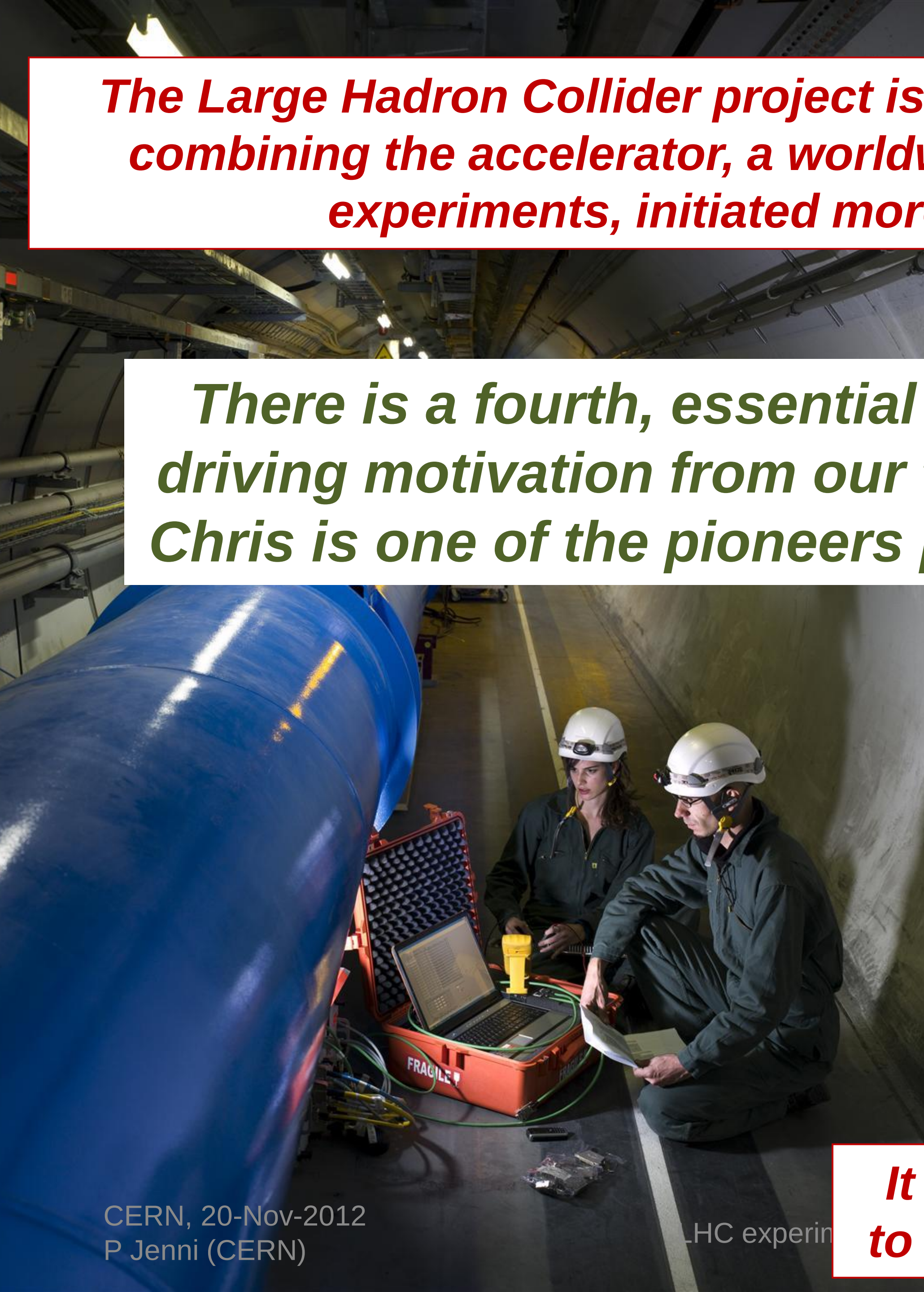


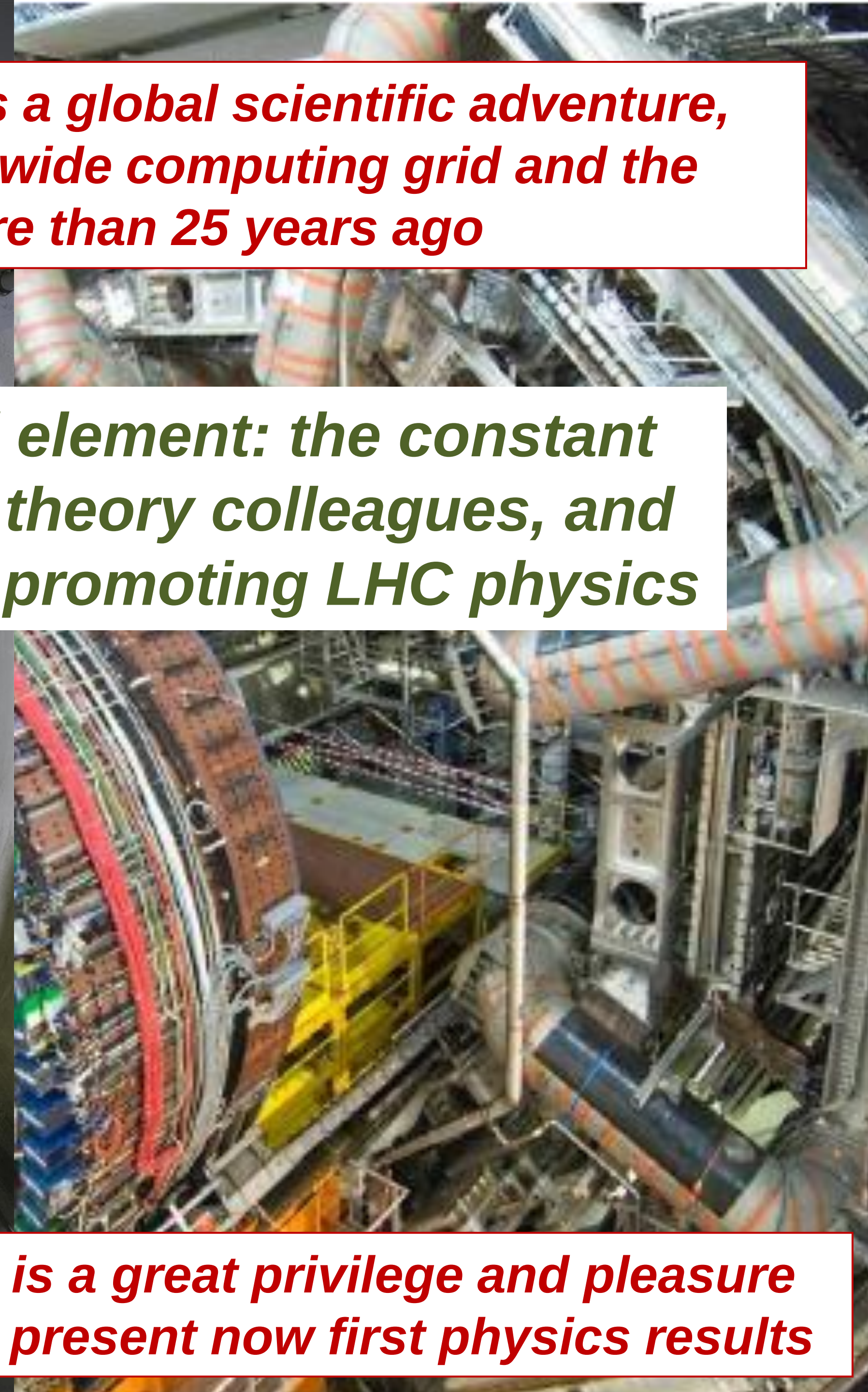
In honour of
Sir Chris Llewellyn Smith's 70th birthday

The Road Map for the Discovery of the Higgs(-like) Boson and Beyond

Drawing by Sergio Cittolin

Peter Jenni, CERN, 20th November 2012

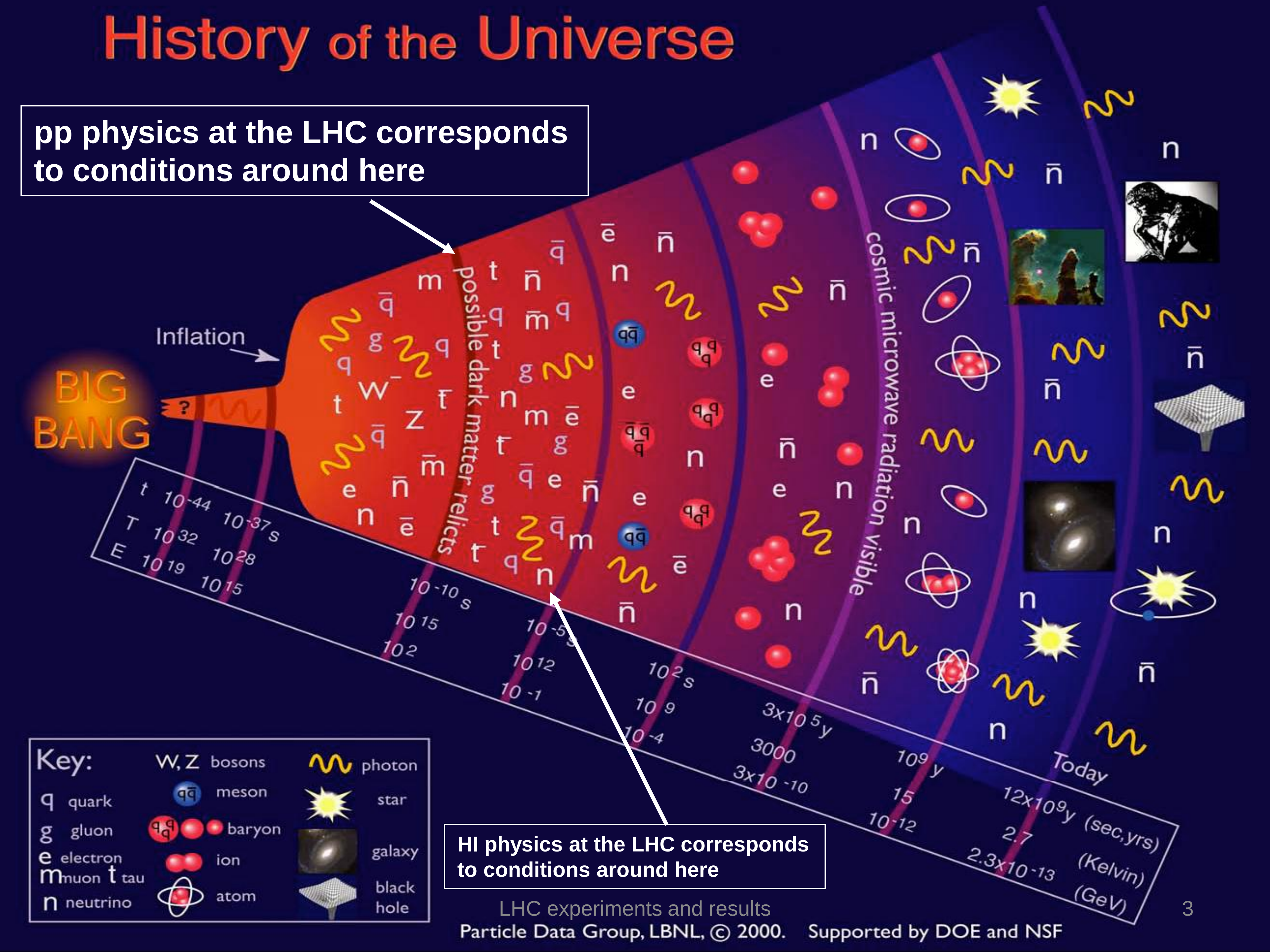




The Large Hadron Collider project is a global scientific adventure, combining the accelerator, a worldwide computing grid and the experiments, initiated more than 25 years ago

There is a fourth, essential element: the constant driving motivation from our theory colleagues, and Chris is one of the pioneers promoting LHC physics

It is a great privilege and pleasure to present now first physics results



pp physics at the LHC corresponds to conditions around here

HI physics at the LHC corresponds to conditions around here

How the LHC came to be …

(see a nice article by Chris Llewellyn Smith in Nature 448, p281)

Some early key dates

1977 **The community talked about the LEP project, and it was already mentioned that a new tunnel could also house a hadron collider in the far future**

1981 **LEP was approved with a large and long (27 km) tunnel**

1983 **The early 1980s were crucial:**

The real belief that a 'dirty' hadron collider can actually do great discovery physics came from UA1 and UA2 with their W and Z boson discoveries at CERN

This also triggered a famous quote from a 1983 New York Times editorial:

'Europe: 3 - US Not Even Z-Zero'

A very early Z → ee online display from one of the detectors (UA2)

Chris on an SPC Visit to UA2 in June 1981

1984 For the community it all started with the CERN – ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel

CHAPTER I

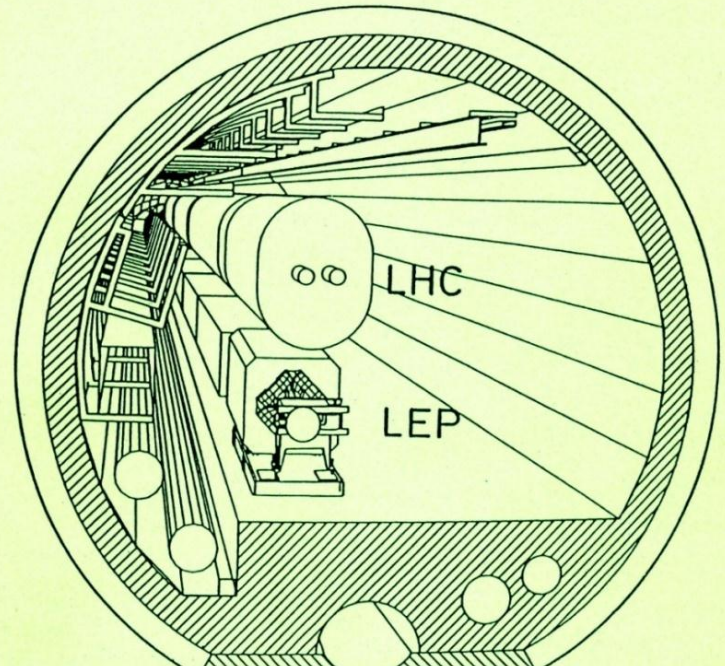
THE PHYSICS CASE

Physics with a Multi-TeV Hadron Collider

C.H. Llewellyn Smith

P. Jenni

ECFA 84/85
CERN 84-10
5 September 1984

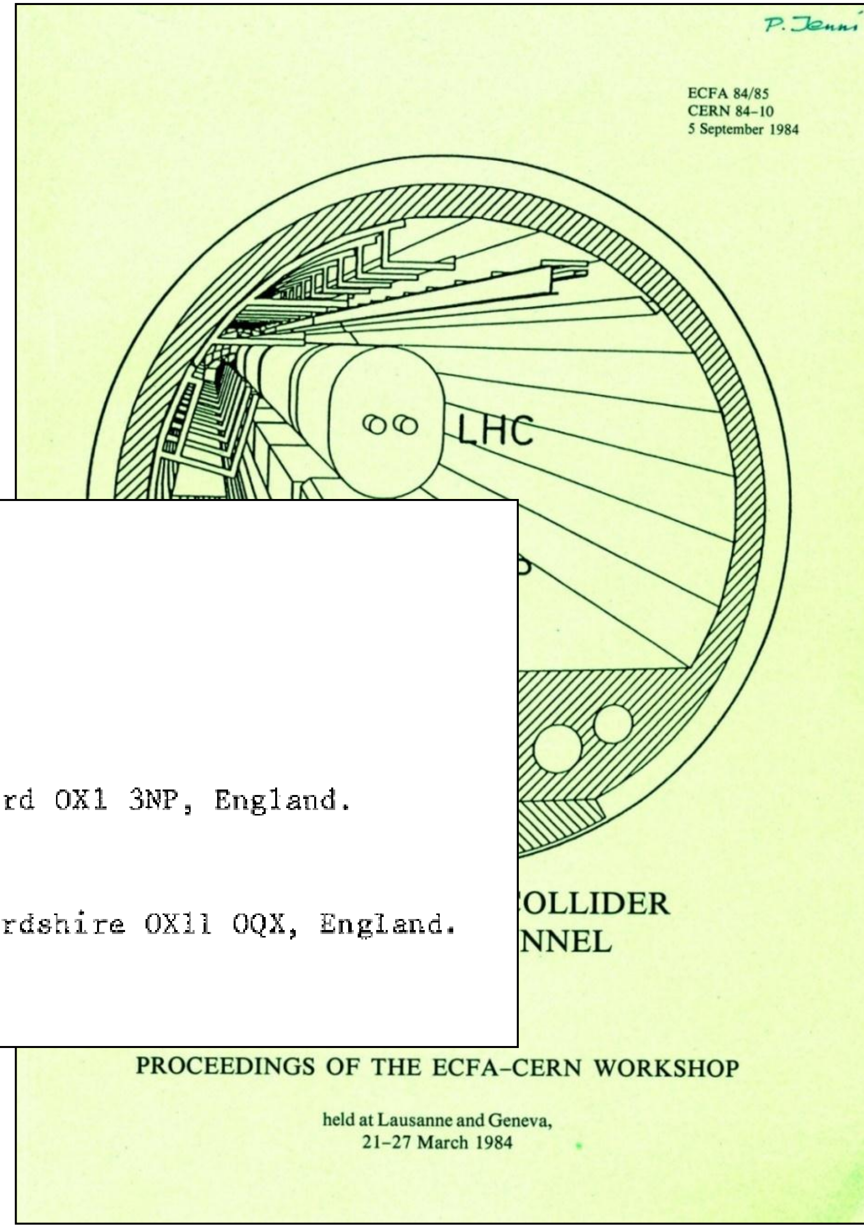


OP

11. SUMMARY AND CONCLUSIONS

A theoretical consensus is emerging that new phenomena will be discovered at or below 1 TeV. There is no consensus about the nature of these phenomena but it is interesting that many of the ideas which have been suggested can be tested in experiments at an LHC. Although many, if not all, of these ideas will doubtless have been discarded, disproved or established by the time an LHC is built, this demonstrates the potential virtues of such a machine.

1984 For the community it all started with the CERN – ECFA Workshop in Lausanne on the feasibility of a hadron collider in the future LEP tunnel



\- 543 -

HEAVY VECTOR BOSONS AND SUPER COLLIDERS

C.H. Llewellyn Smith and J.F. Wheater

Department of Theoretical Physics, 1 Keble Road, Oxford OX1 3NP, England.

R.J.N. Phillips

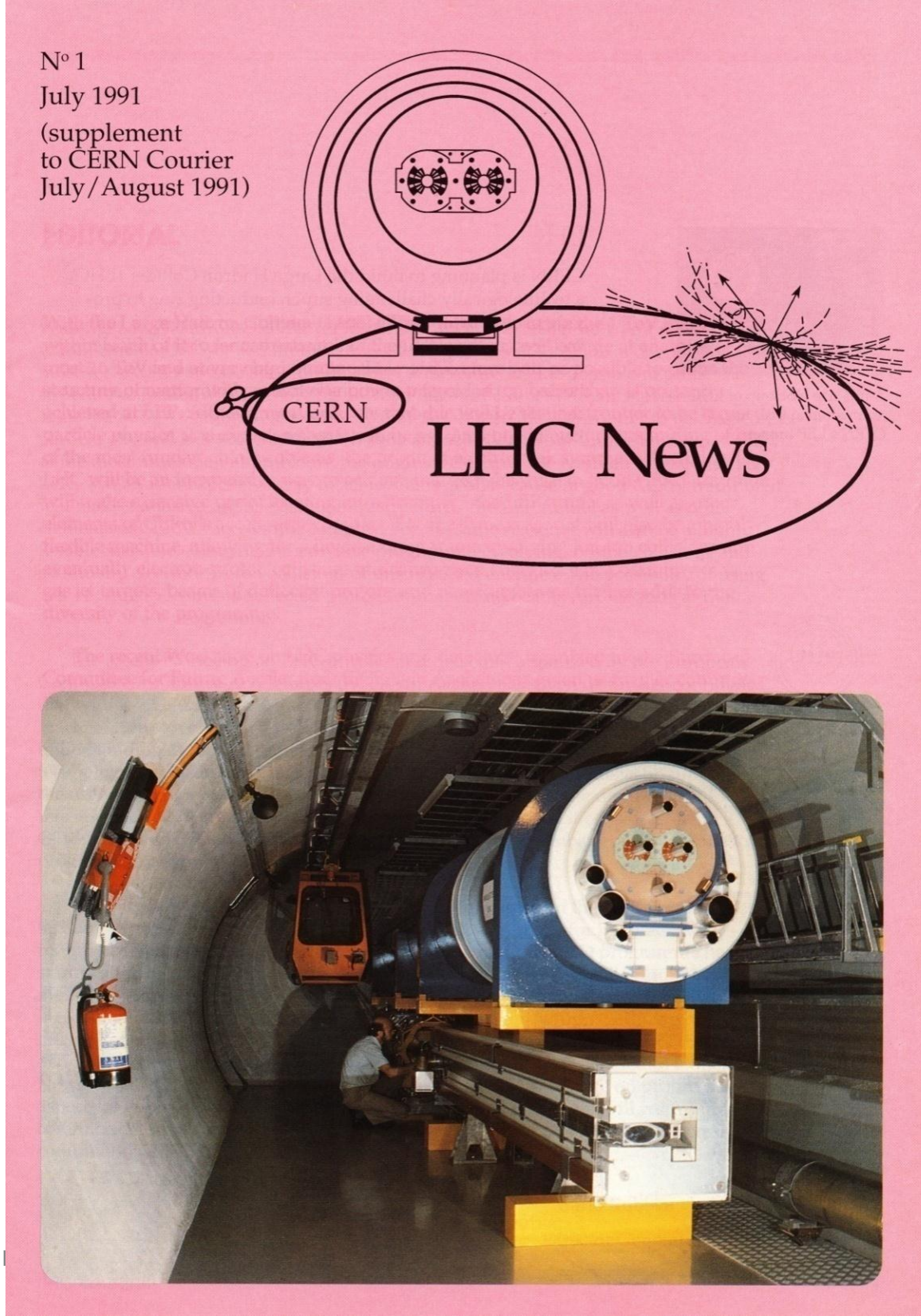
Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, England.

Spokesperson Fabiola Gianotti, celebrating 20 years of ATLAS on 1st October 2012

ATLAS and CMS were born with Letters of Intent (LoI), submitted on 1st October 1992, 20 years ago

1991 December CERN Council:
'LHC is the right machine for advance of the subject and the future of CERN' (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002



1991 December CERN Council:
‘LHC is the right machine for advance of the subject and the future of CERN’ (thanks to the great push by DG C Rubbia)

1993 December proposal of LHC with commissioning in 2002

1994 June Council:

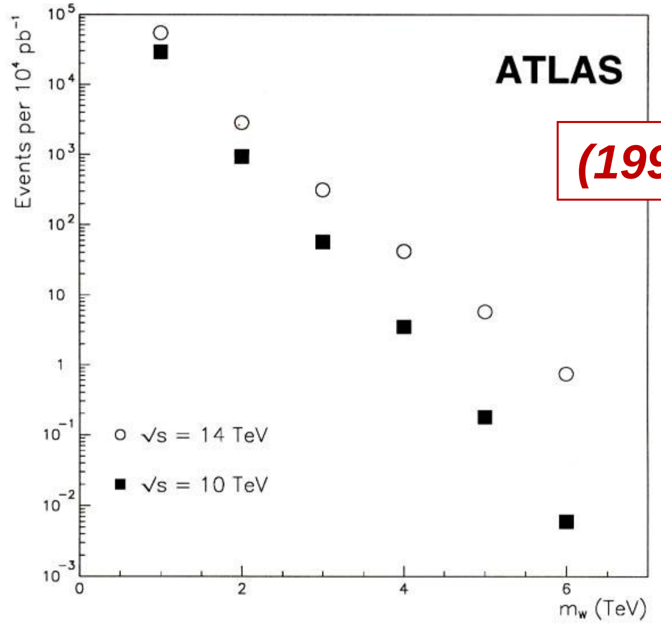
Staged construction was proposed by DG Chris Llewellyn Smith, but some countries could not yet agree, so the Council session vote was suspended until

16 December 1994 Council:

(Two-stage) construction of LHC was approved

Search for new, heavy, gauge bosons

Number of W' decays into eν or μν for 10^4 pb^{-1}



(1994 !)

The accessible mass range is affected by both the lower energy and luminosity

The two-stage approval of LHC was understood to be modified in case sufficient CERN non-member state contributions would become available

A lot of LHC campaigns and negotiations took place in the years 1995 - 1997, including also the experiments

Japan, Russia, India, Canada and the USA were agreeing in that phase to contribute to the LHC

(Israel contributed all along to the full CERN programme and LHC)

1997

December Council approved finally the single-stage 14 TeV LHC for completion in 2005

Delivery of the last dipole for the LHC injection lines from Russia (15th June 2001), with L Maiani and A Skrinsky in the centre

Here two more 'souvenir pictures' from these times…

Daruma doll ceremony to mark the start of the Japanese – CERN LHC cooperation), June 1995

(K Yosano – Minister, Japan, H Curien – Council President, C Llewellyn Smith – CERN DG)

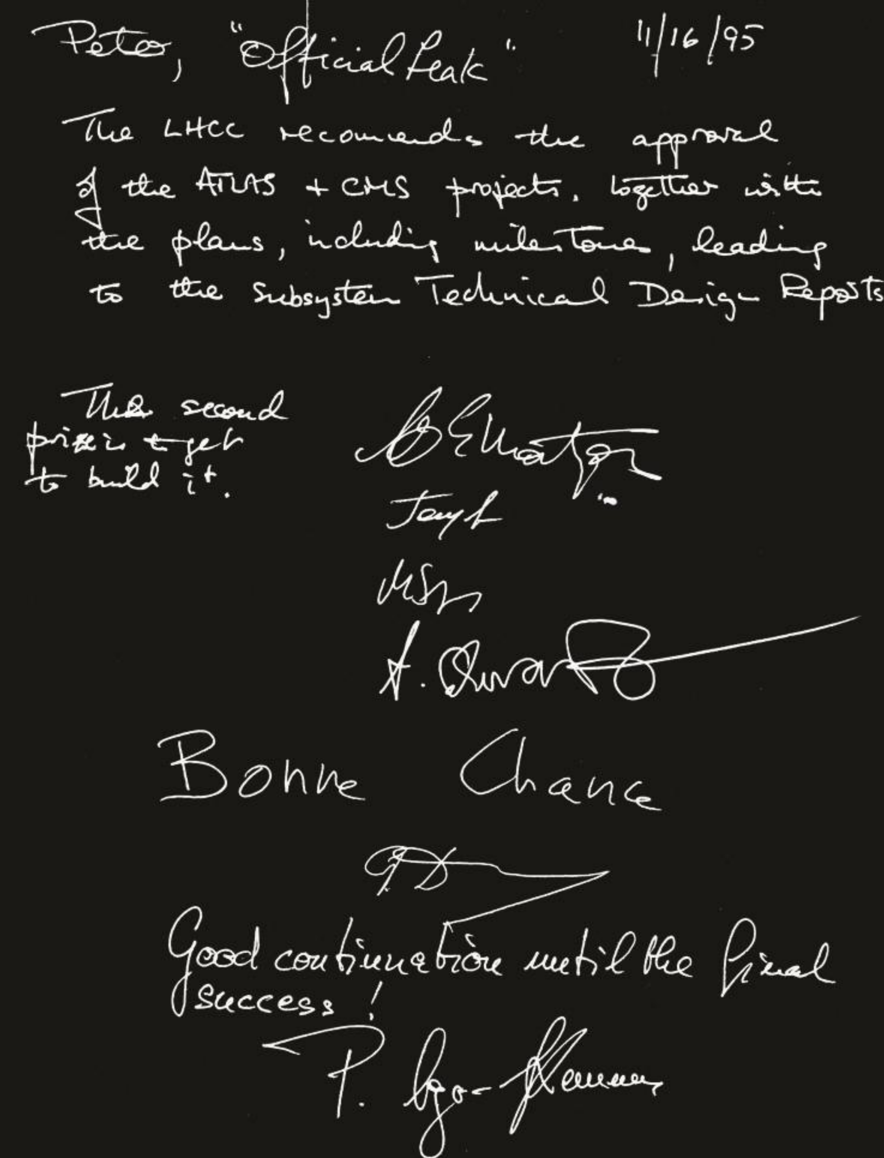
Signature of the US-CERN agreement in December 1997

(R Eisenstein – NSF, C Llewellyn Smith – CERN DG, M Krebs – DOE)

Thank you, Chris, for having made the LHC become a reality!

For the experiments it was a long way convincing the LHCC, but finally, on 16th November 1995, our referees were happy, and Hugh Montgomery, ATLAS main referee at that time, gave us the following 'official leak' from the committee…

The LHCC recommendations meant in particular that ATLAS and CMS could now proceed in developing their series of Technical Design Reports


Peter, "Official leak" 11/16/95

The LHCC recommends the approval of the ATLAS + CMS projects, together with the plans, including milestones, leading to the Subsystem Technical Design Reports

The second prize is to get to build it.

Bonne Chance

Good continuation until the final success!

The formal construction approval was then given with the approval of the first TDRs

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
Laboratoire Européen pour la Physique des Particules
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Fax: (41.22) 767 89 95
E-mail: Christopher.Llewellyn.Smith@cern.ch

Our Ref. DG/mnd/2540

Dr Peter Jenni
PPE Division
CERN

Geneva, 1st July 1997

Dear Peter,

Following the thorough discussion of the status of ATLAS and CMS by Council and its Committees two weeks ago, the way is now open for construction to begin. I am therefore pleased to inform you that I have decided to *i)* set the cost ceiling for ATLAS at 475 MCHF (1995 prices), and *ii)* approve the TDR of the ATLAS calorimeters on the following basis formulated by the LHCC and endorsed by the Research Board at its meeting on 12th June:

*"The LHCC **recommends general approval** of the ATLAS Calorimetry Technical Design Report describing design, performance, construction, and installation in 2004. The review **identified some concerns** in limited areas, which require resolution (LHCC 97–27). The LHCC considers that the schedules and milestones given in the TDR are reasonable, and these will be used by the committee to measure and regulate the future progress of the project."*

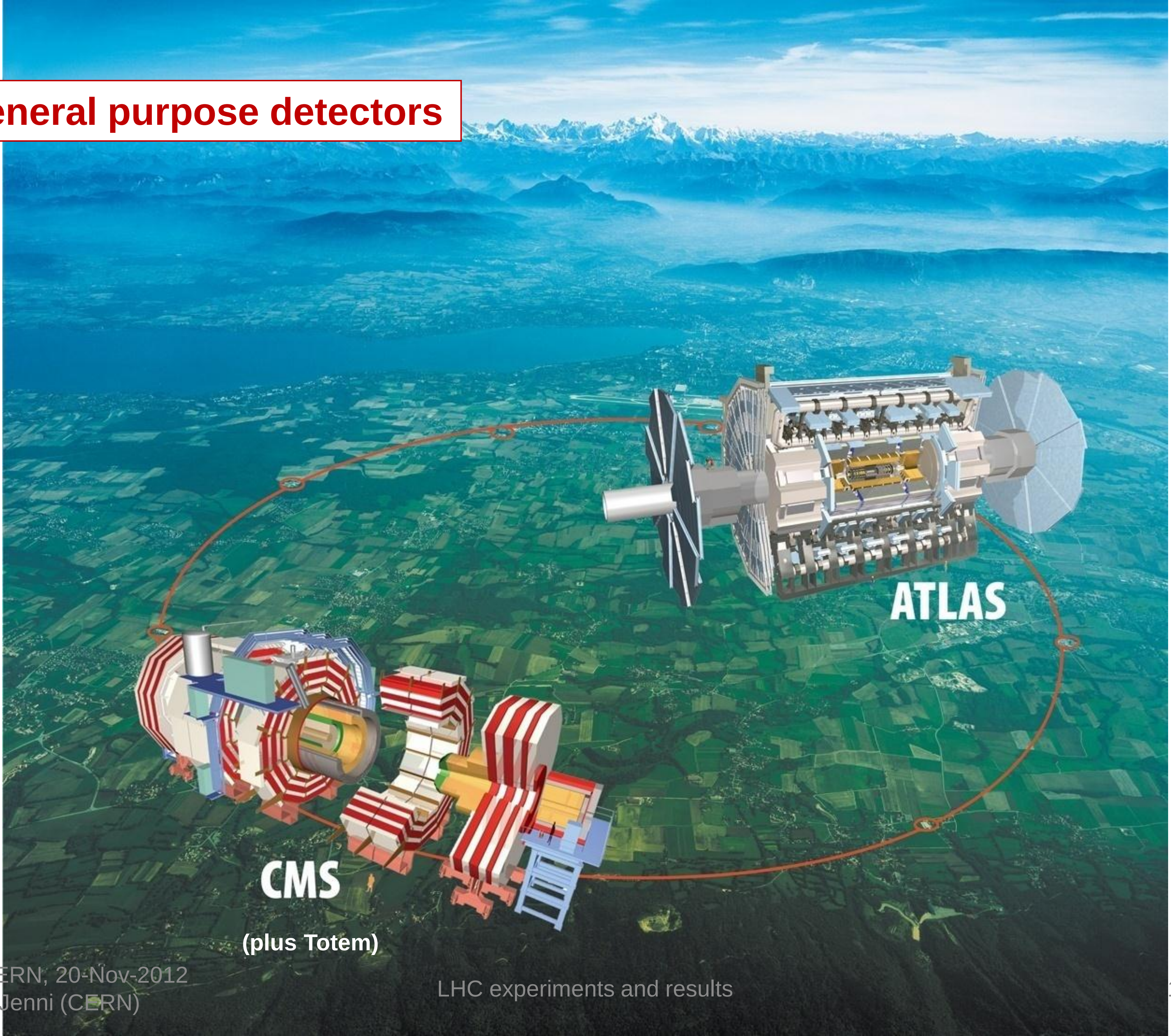
Yours sincerely,

Chris

Chris Llewellyn Smith

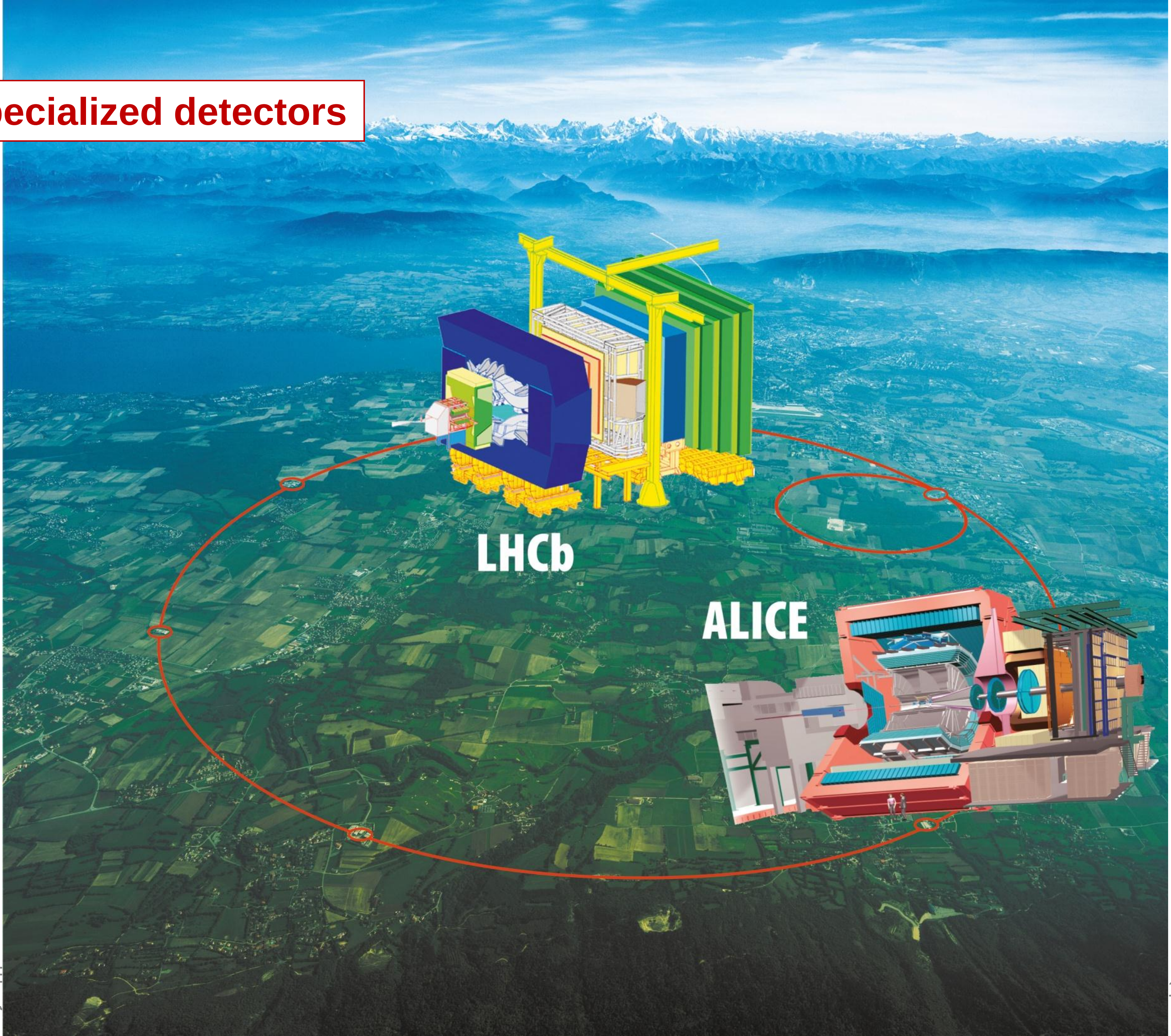
cc: L Foà
E Iarocci

General purpose detectors



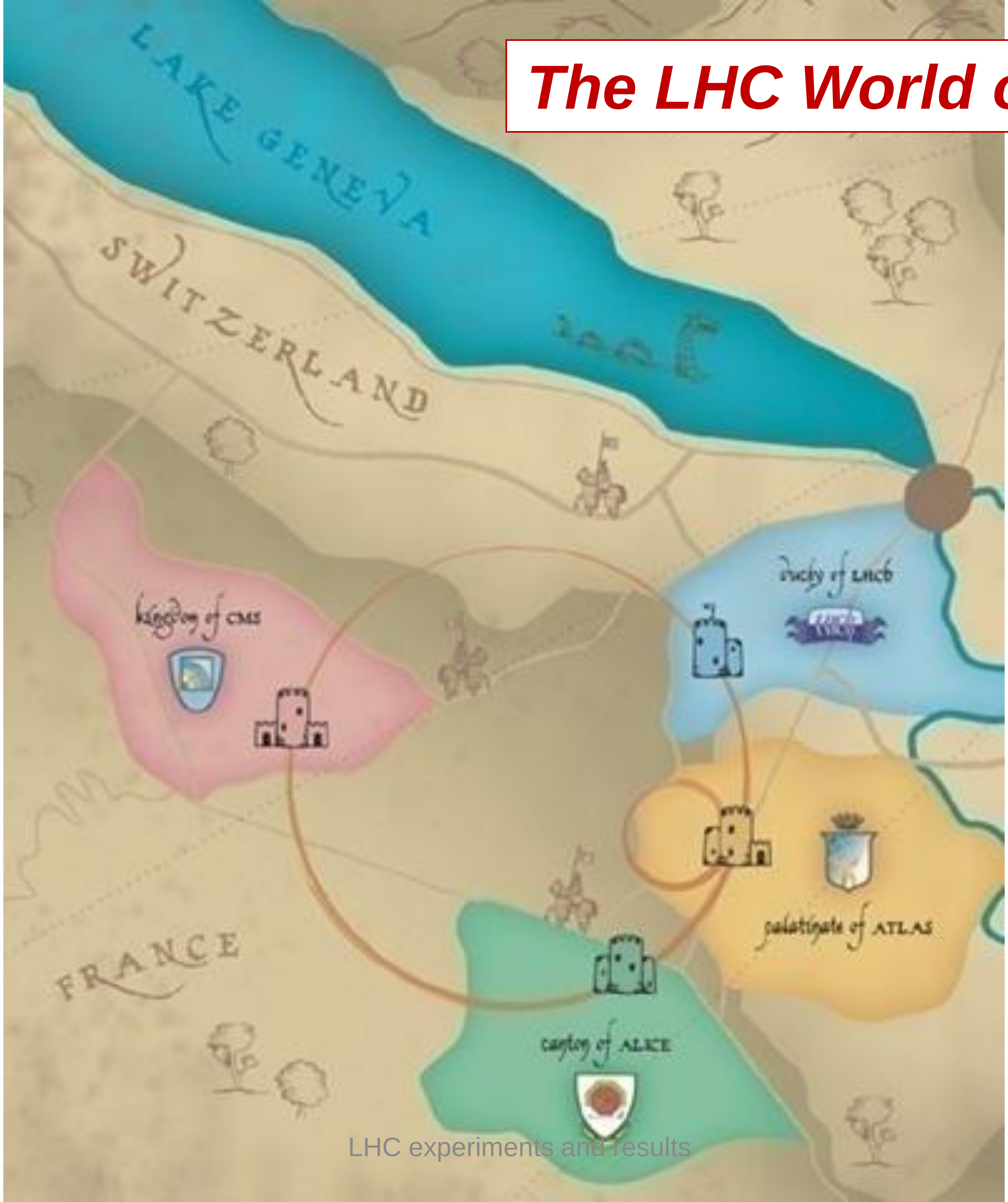
(plus Totem)

Specialized detectors



The LHC World of CERN

Plus smaller local earldoms
LHCf (point-1)
TOTEM (point-5)
Moedal (point-8)

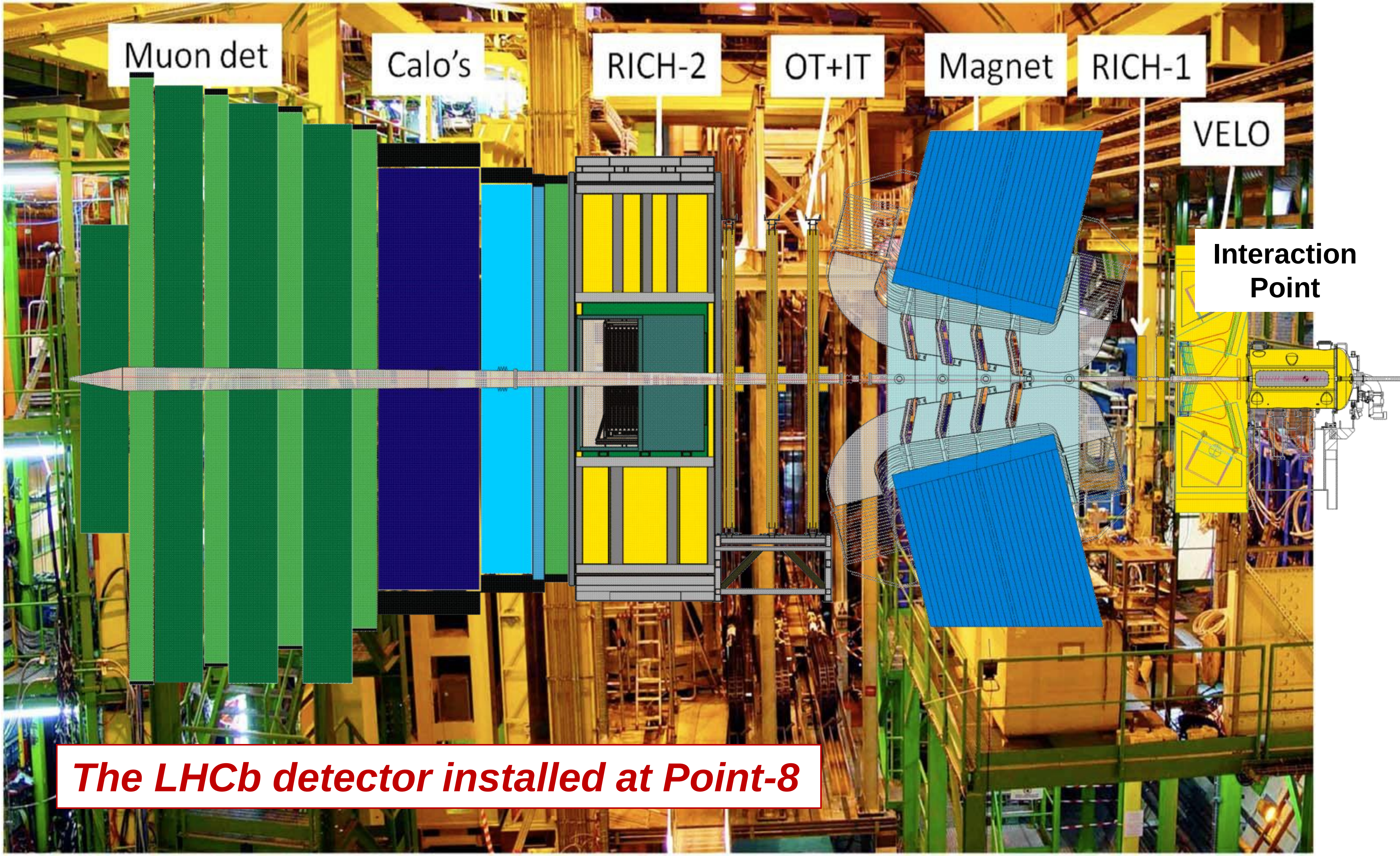


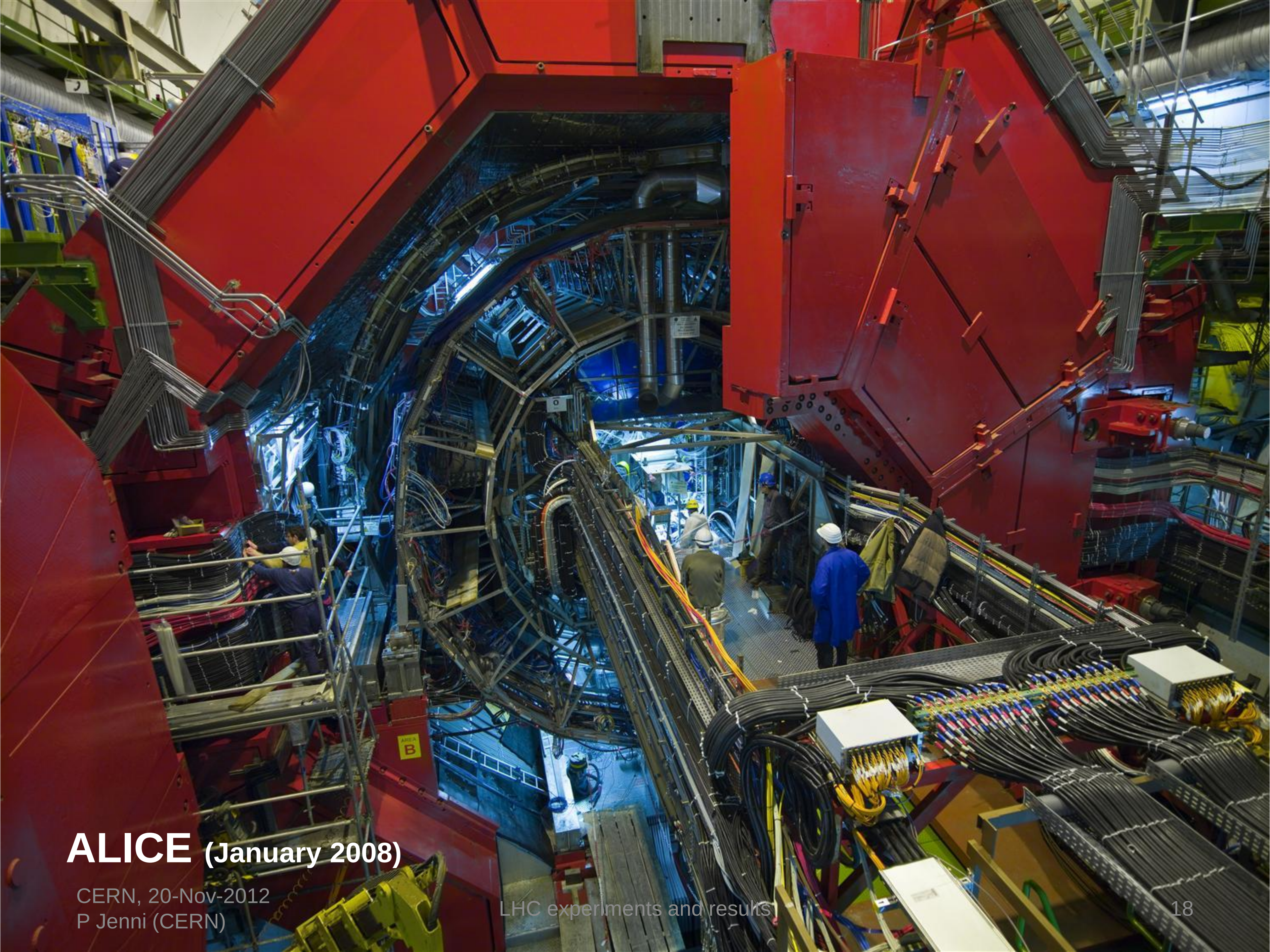
CMS
3000 Physicists
184 Institutions
38 countries
550 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

ATLAS
3000 Physicists
176 Institutions
38 countries
550 MCHF

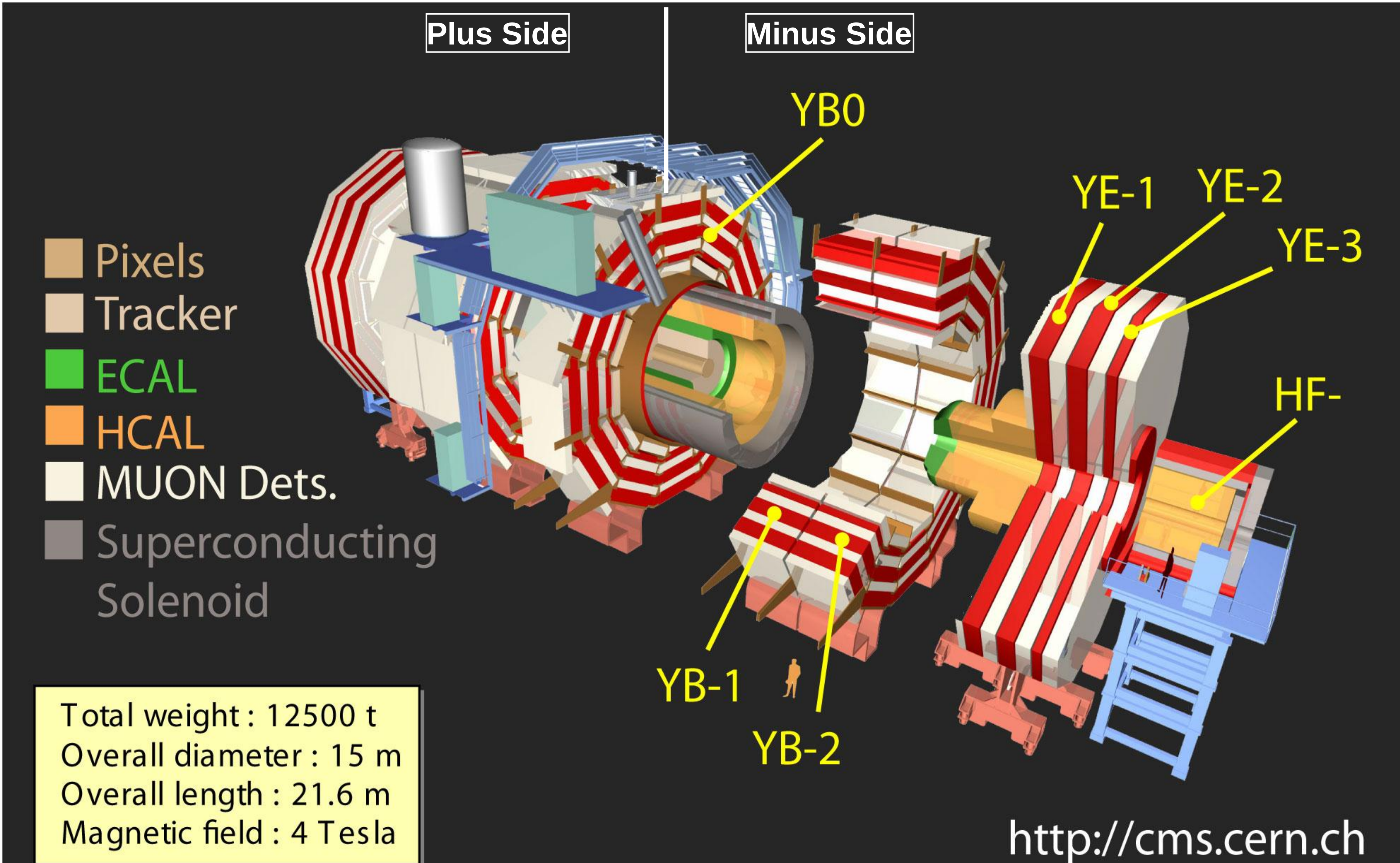
ALICE
1300 Physicists
130 Institutions
35 countries
160 MCHF


Muon det
Calo's
RICH-2
OT+IT
Magnet
RICH-1
VELO
Interaction Point
The LHCb detector installed at Point-8



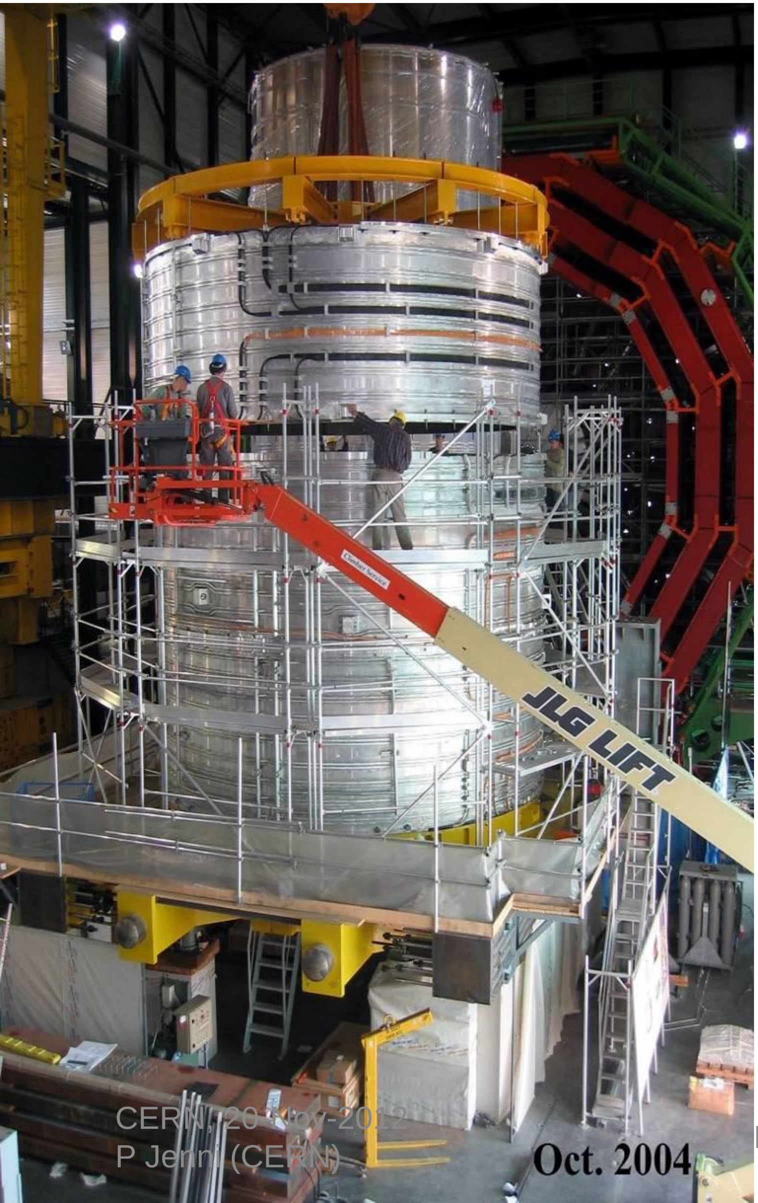
ALICE **(January 2008)**

Exploded View of CMS

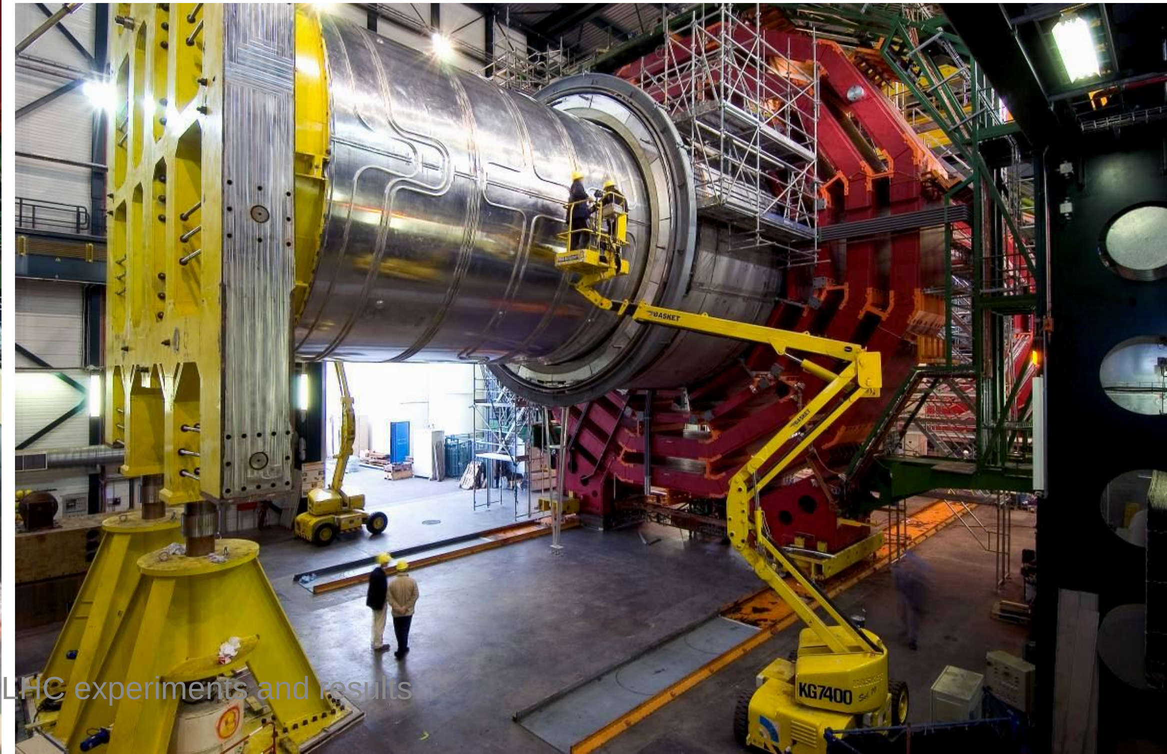


Chris enjoying the CMS design, Dec 1997

An Example of an Engineering Challenge: CMS Solenoid



CMS solenoid:	
Magnetic length	**12.5 m**
Diameter	**6 m**
Magnetic field	**4 T**
Nominal current	**20 kA**
Stored energy	**2.7 GJ**
Tested at full current in Summer 2006	

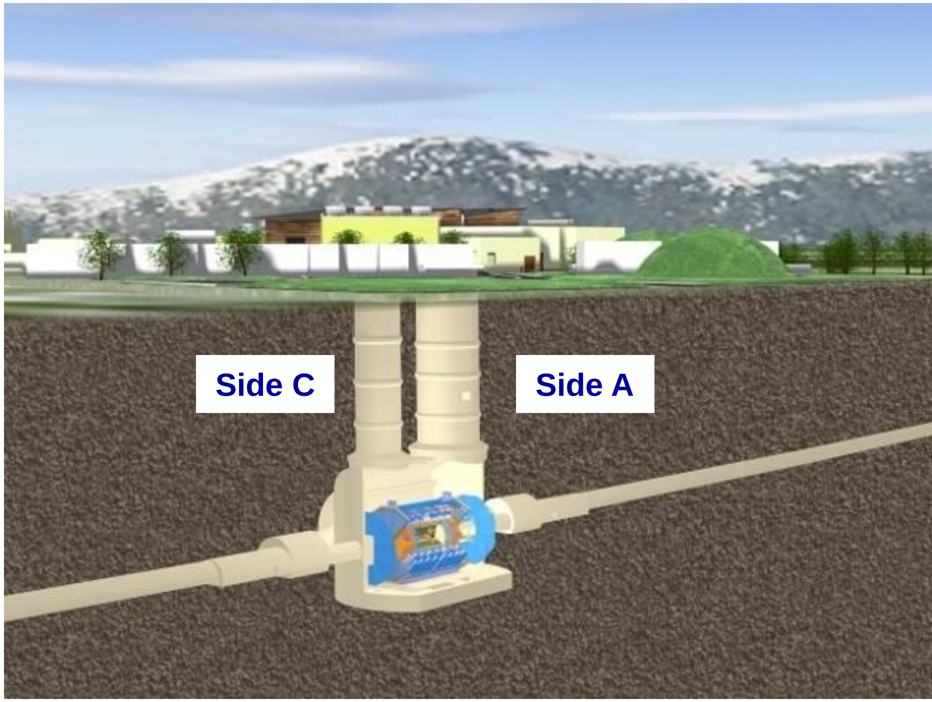


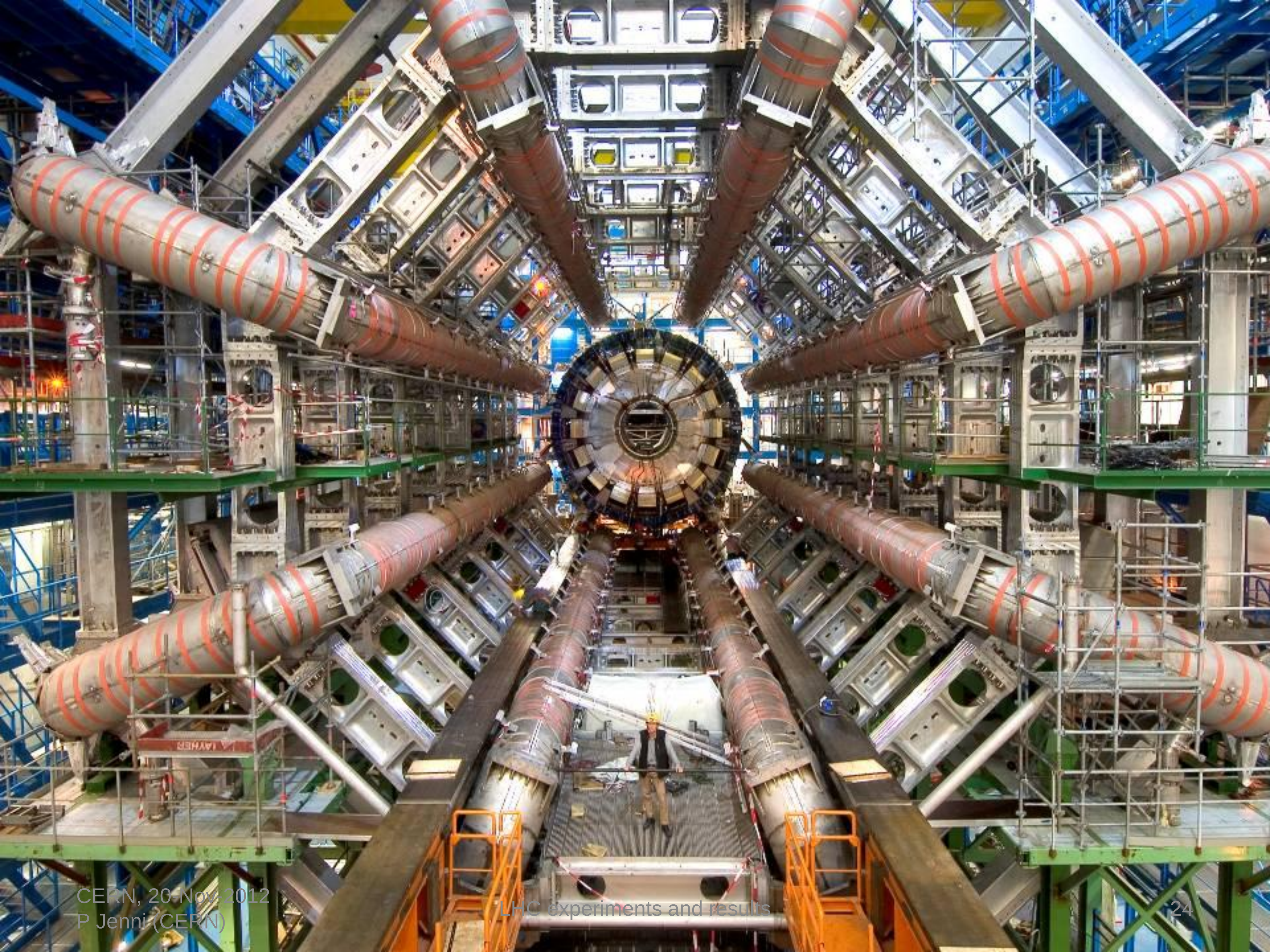
CMS before closure 2008

The Underground Cavern at Point-1 for the ATLAS Detector

Chris and Lyn inspecting civil engineering progress at Point-1 on 15 Oct 1998

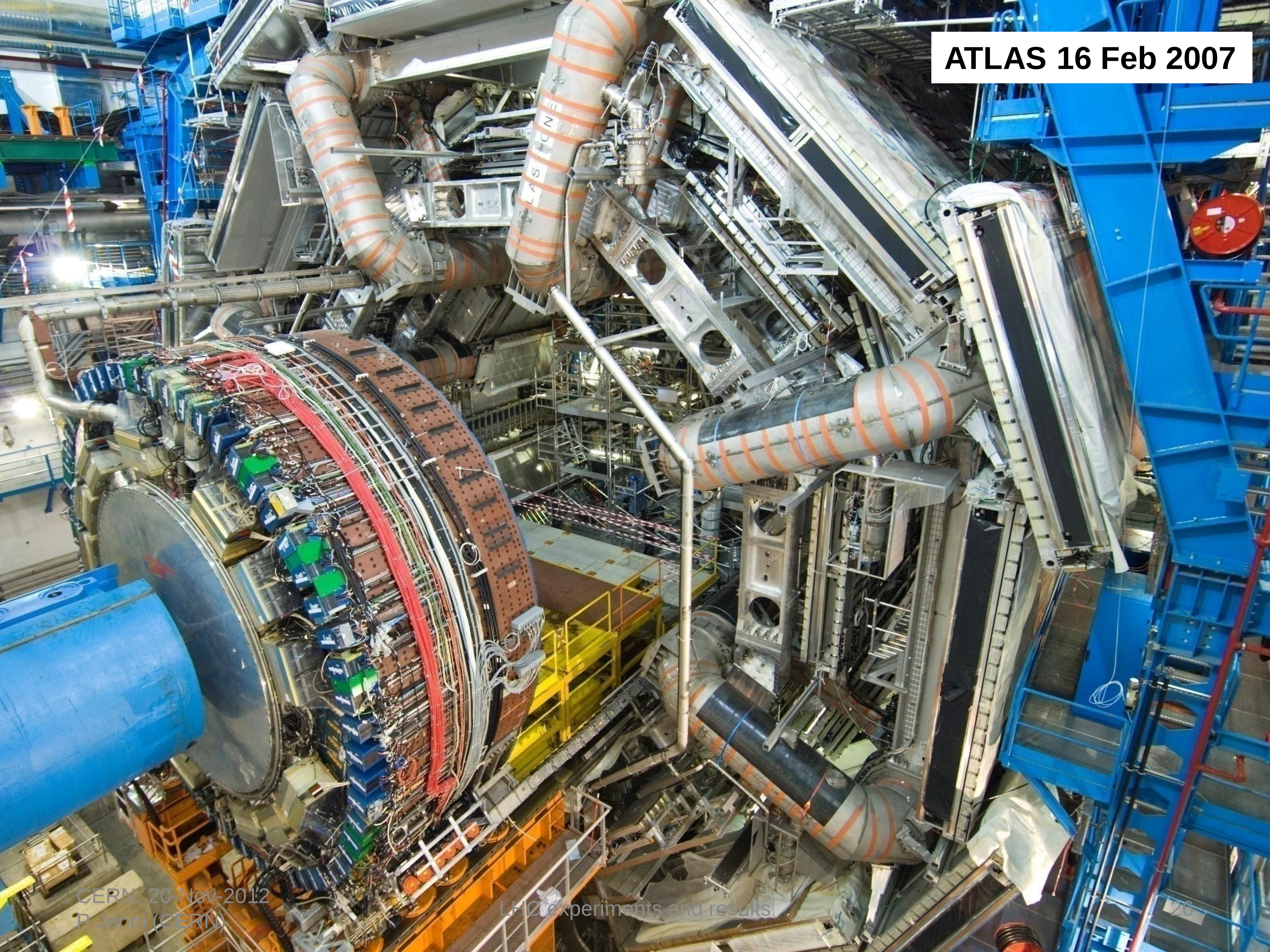
Length = 55 m
Width = 32 m
Height = 35 m





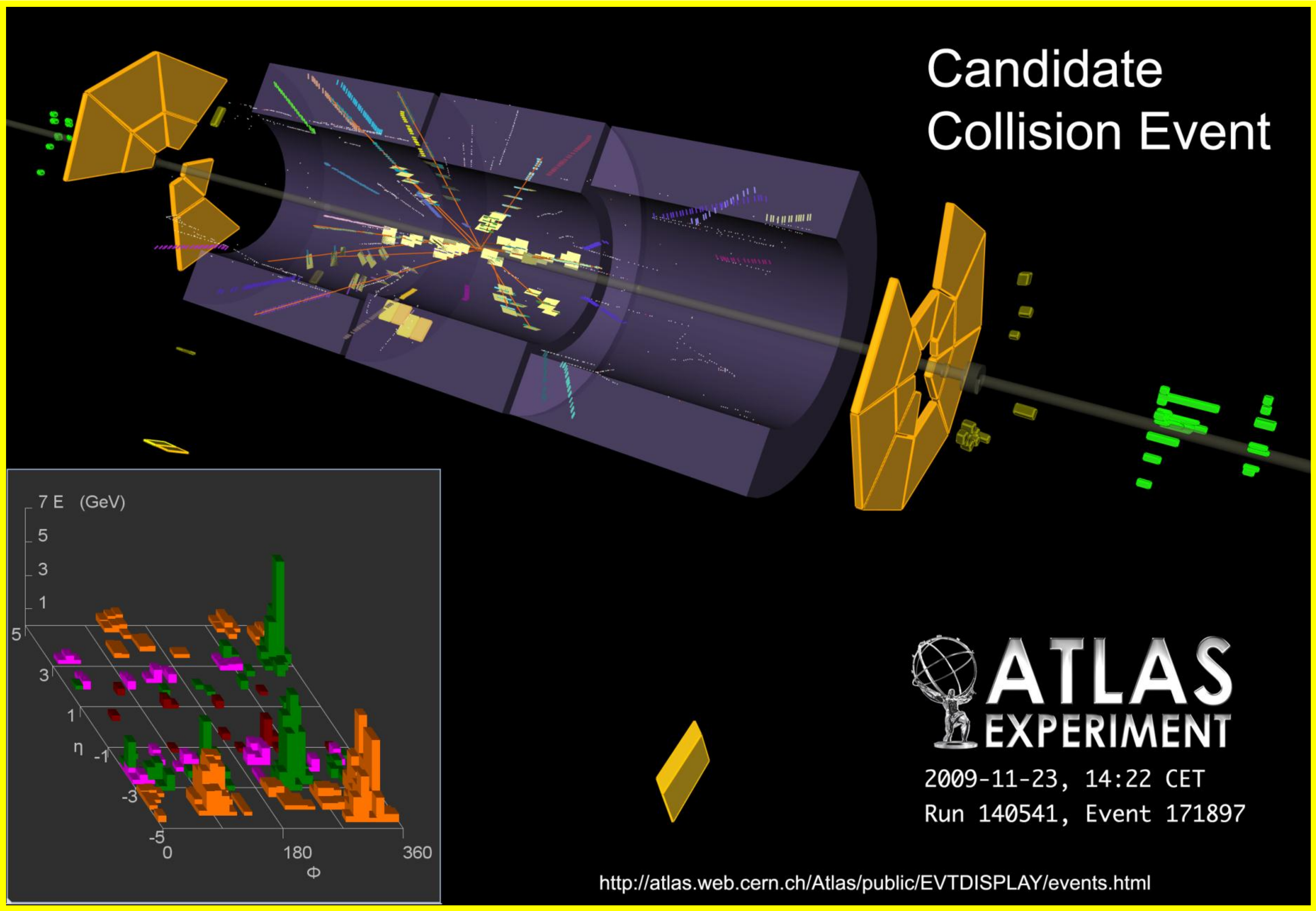
Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009

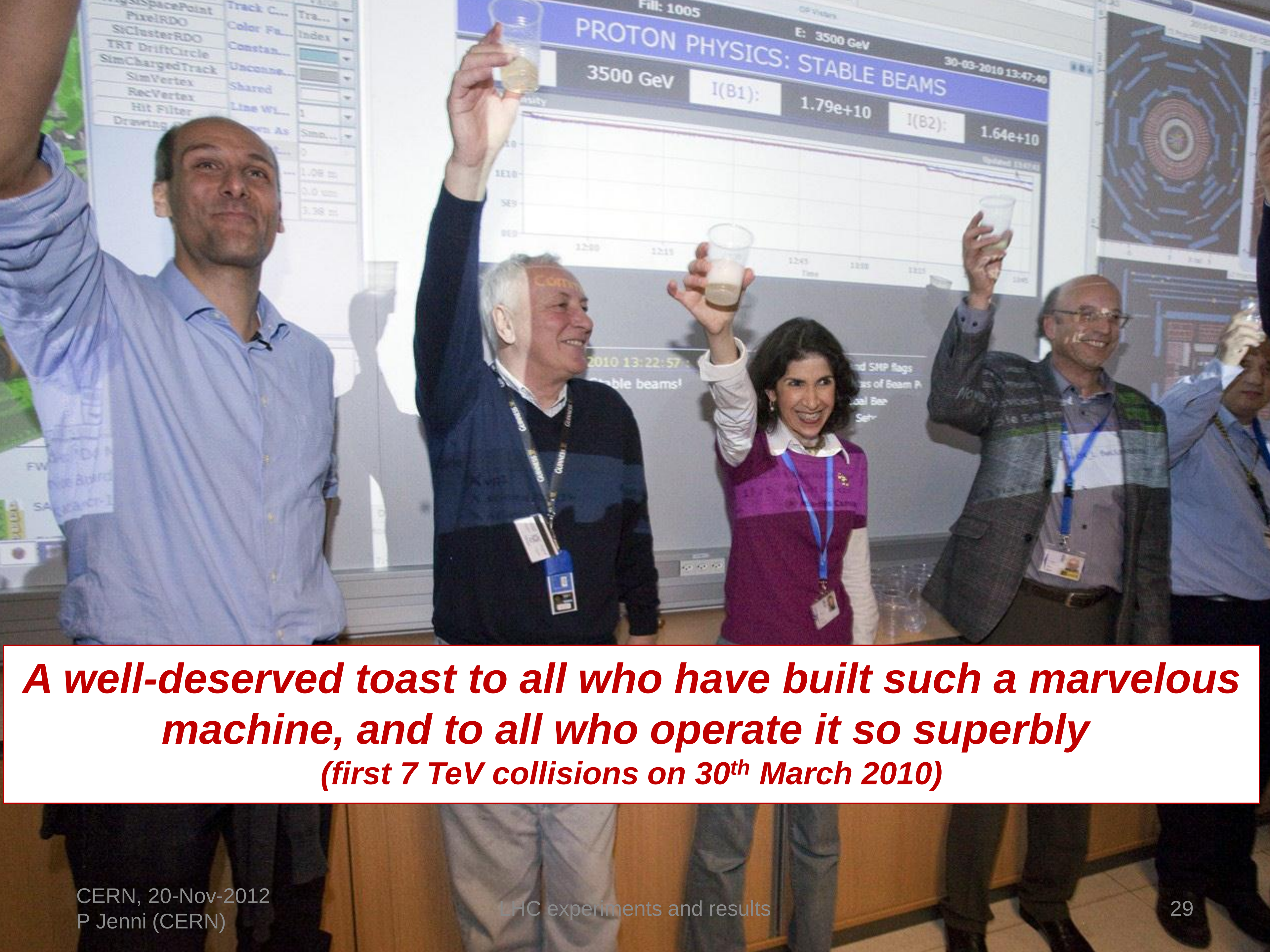
ATLAS 16 Feb 2007



The joy in the ATLAS Control Room when the first LHC beam collided on November 23rd, 2009....

First collisions at the LHC end of November 2009 with beams at the injection energy of 450 GeV

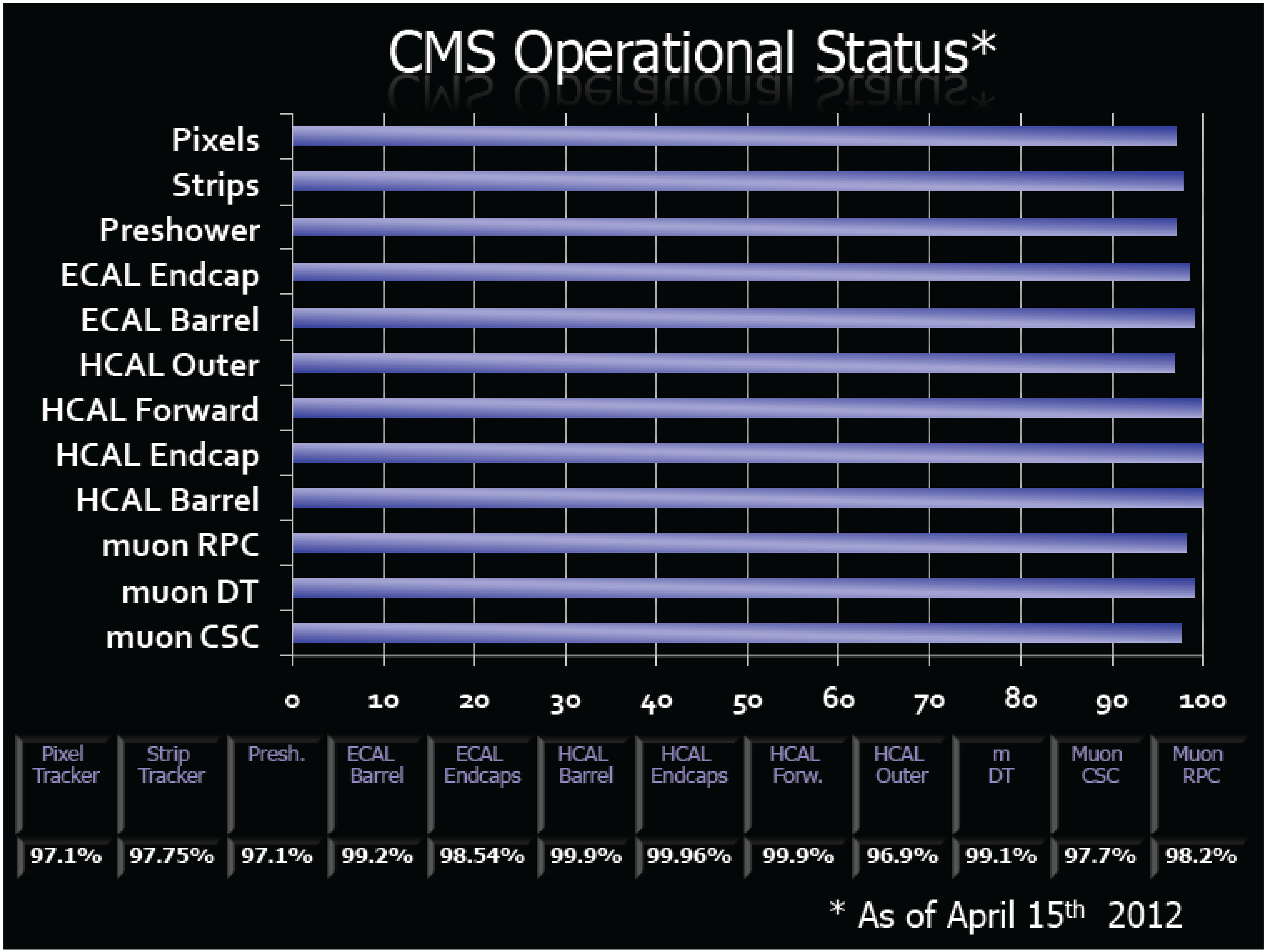




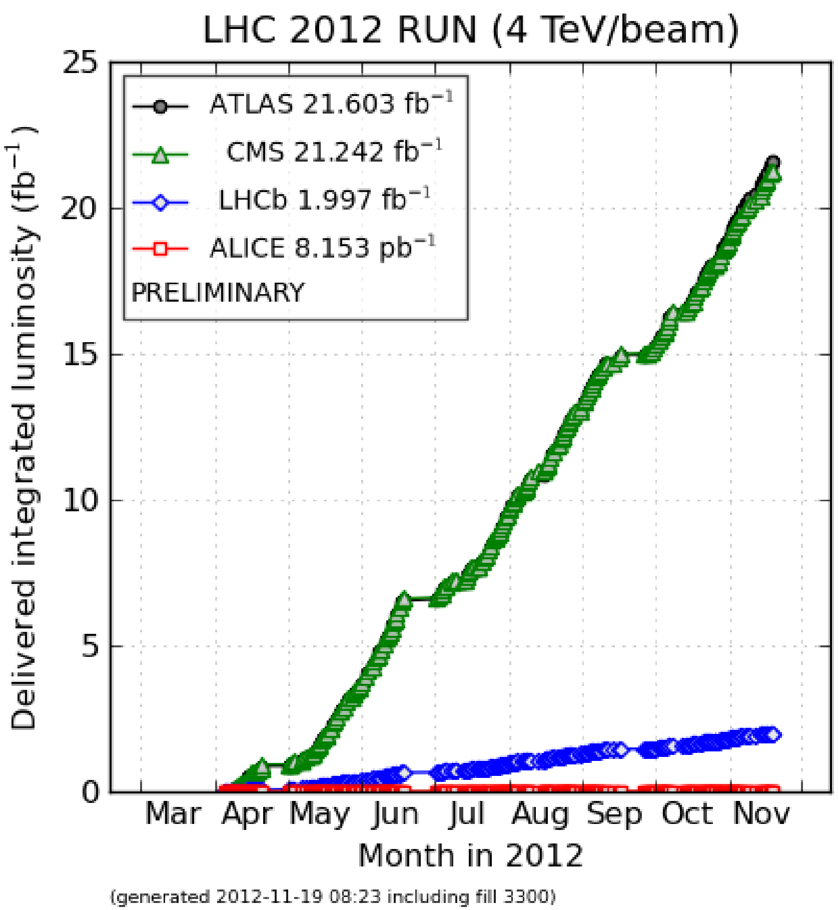
A well-deserved toast to all who have built such a marvelous machine, and to all who operate it so superbly

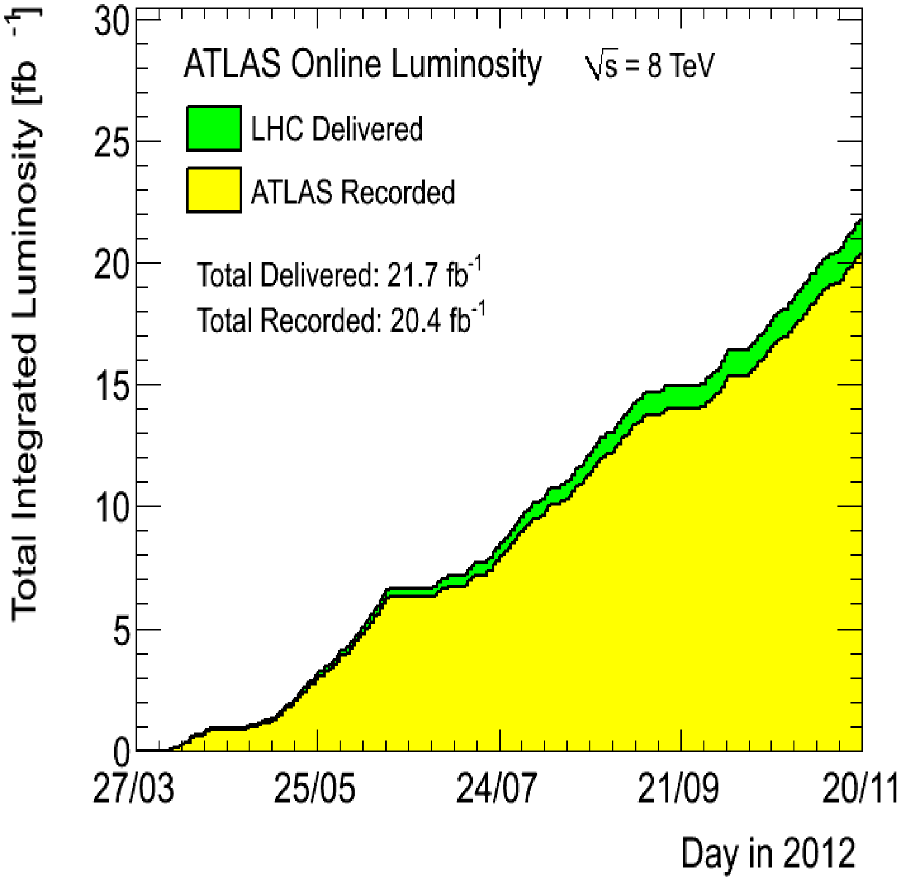
(first 7 TeV collisions on 30th March 2010)

Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	95.9%
SCT Silicon Str		
TRT Transition		
LAr EM Calorin		
Tile calorimeter		
Hadronic endca		
Forward LAr ca		
LVL1 Calo trigg		
LVL1 Muon RP		
LVL1 Muon TG		
MDT Muon Drif		
CSC Cathode S		
RPC Barrel Mu		
TGC Endcap M		

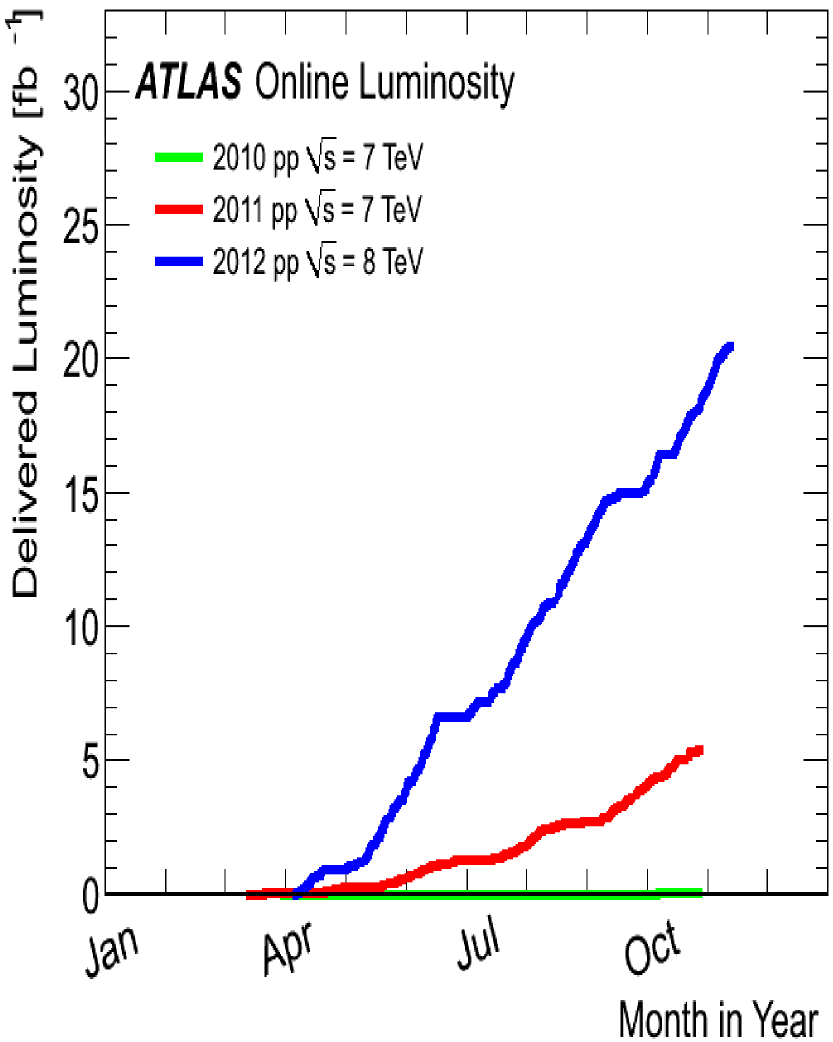


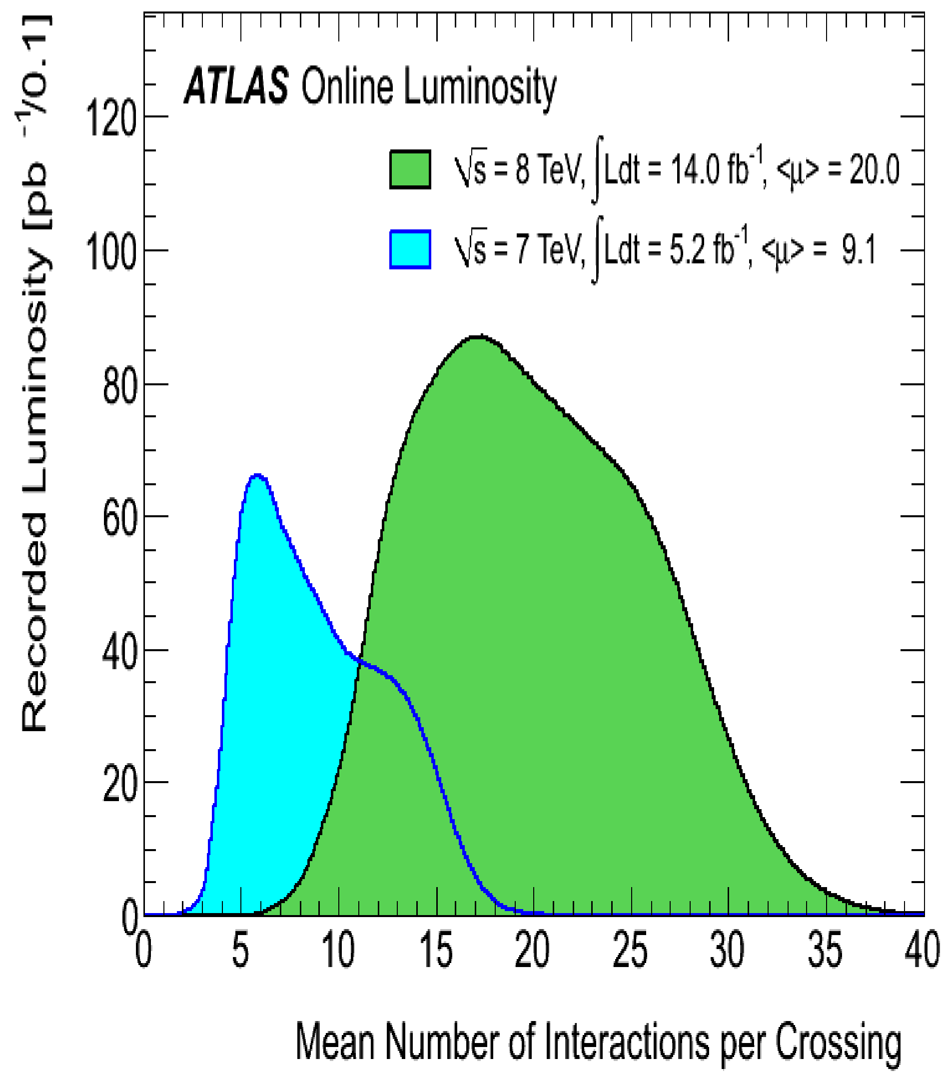
The LHC and experiments performances are simply again fantastic this year





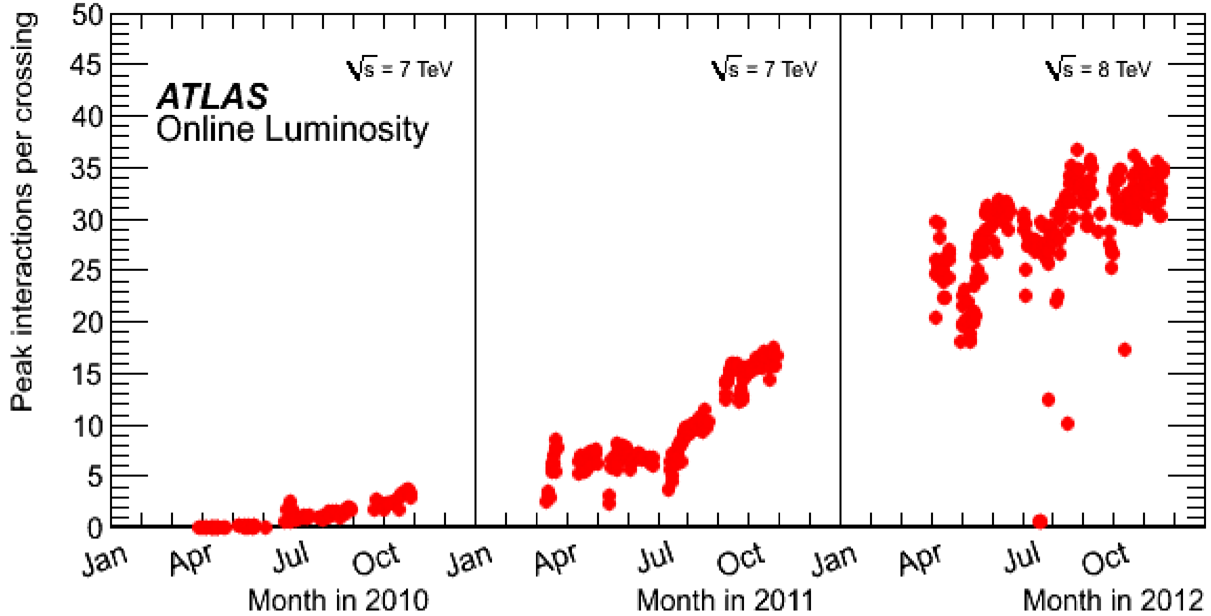
The experiments record typically 94% of the stably delivered luminosity, and use up to 90% of the LHC luminosity in the final analyses!

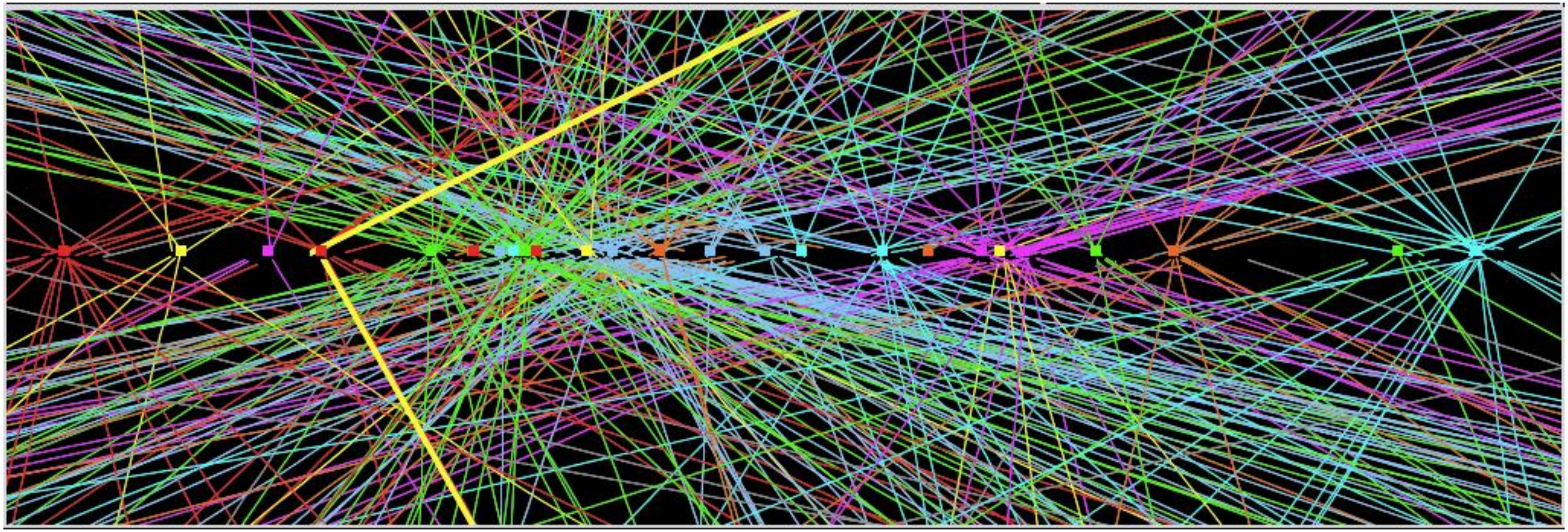

Delivered Luminosity [fb $^{-1}$]
ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
30
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Month in Year


Recorded Luminosity [pb $^{-1}$/0.1]
ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 14.0 fb^{-1}, <μ> = 20.0
√s = 7 TeV, ∫Ldt = 5.2 fb^{-1}, <μ> = 9.1
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
Mean Number of Interactions per Crossing

Excellent LHC performance is a (nice) challenge for the experiment:

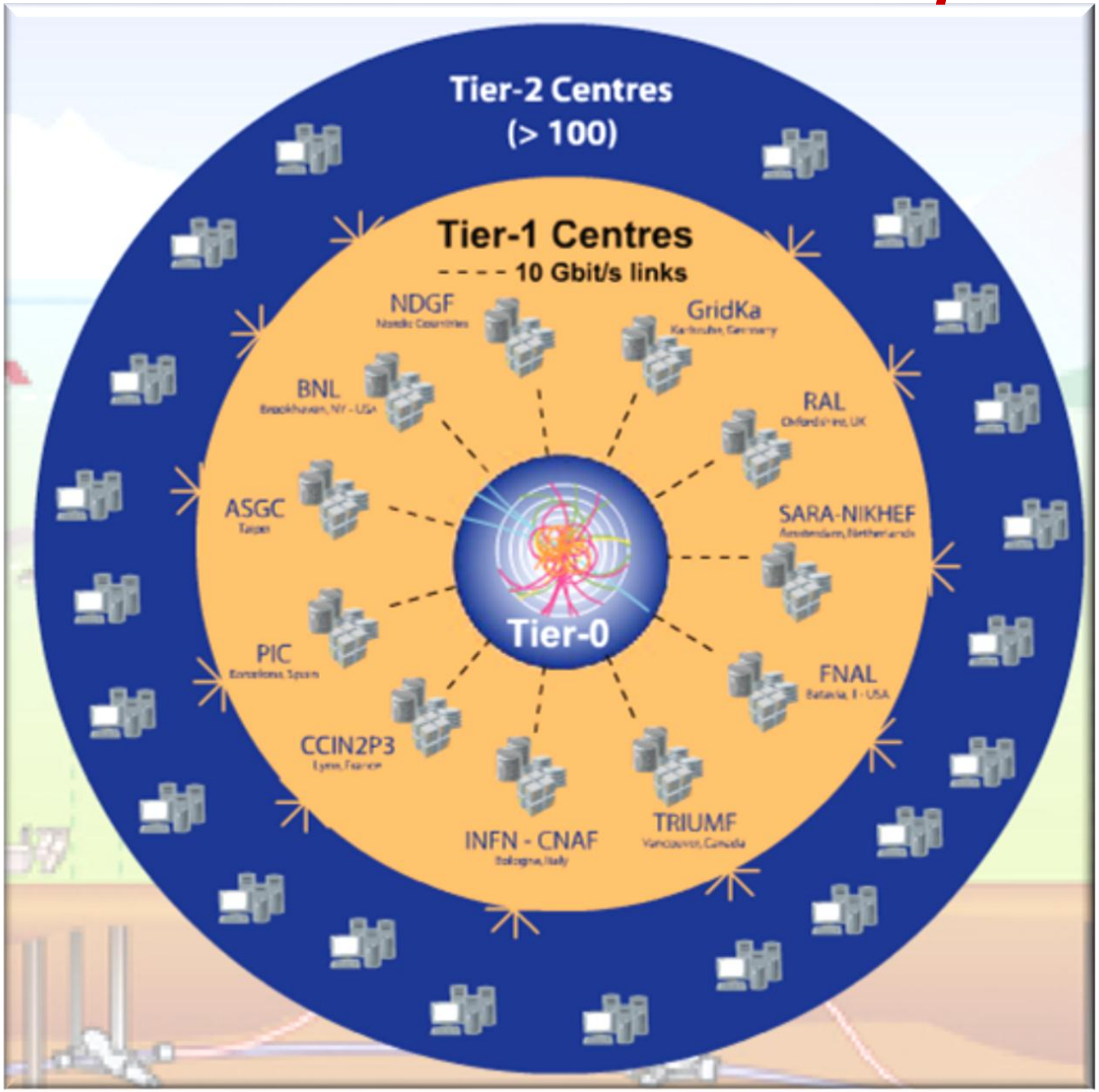
- **Trigger**
- **Pile-up**
- **Maintain accuracy of the the measurements in this environment**





Inner Detector for a Z → μμ event with 25 primary vertices

The Worldwide LHC Computing Grid (wLCG)

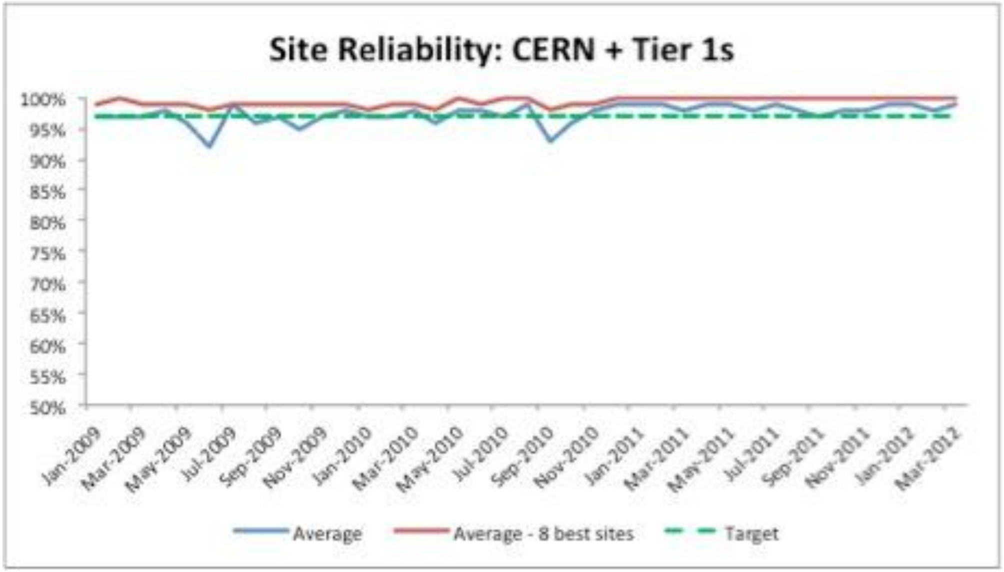


Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (12 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

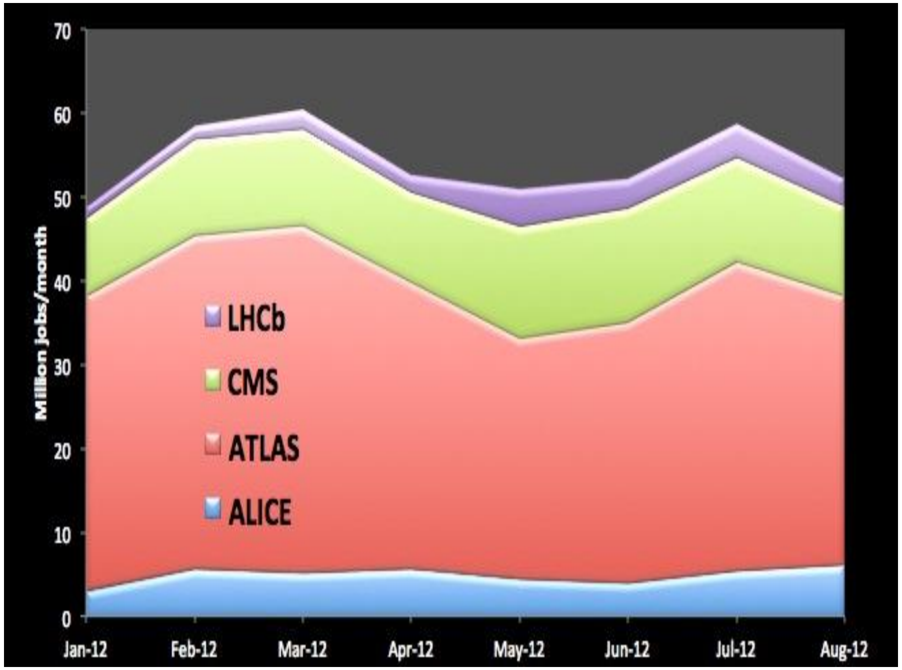
Tier-2 (68 federations of >100 centres):
- Simulation
- End-user analysis

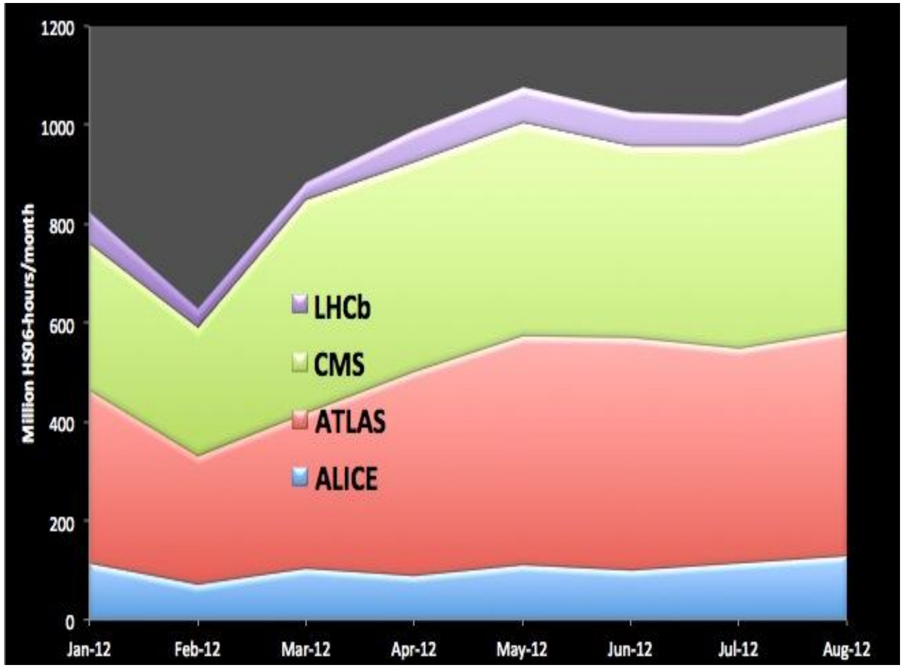
The high quality of the WLCG computing system allows LHC experiments to show results from data taken just few weeks before



Data preparation (ATLAS):

- **First-pass reconstruction at Tier-0 within ~2 days**
- **Calibration good for physics analysis on Grid within ~1 week**





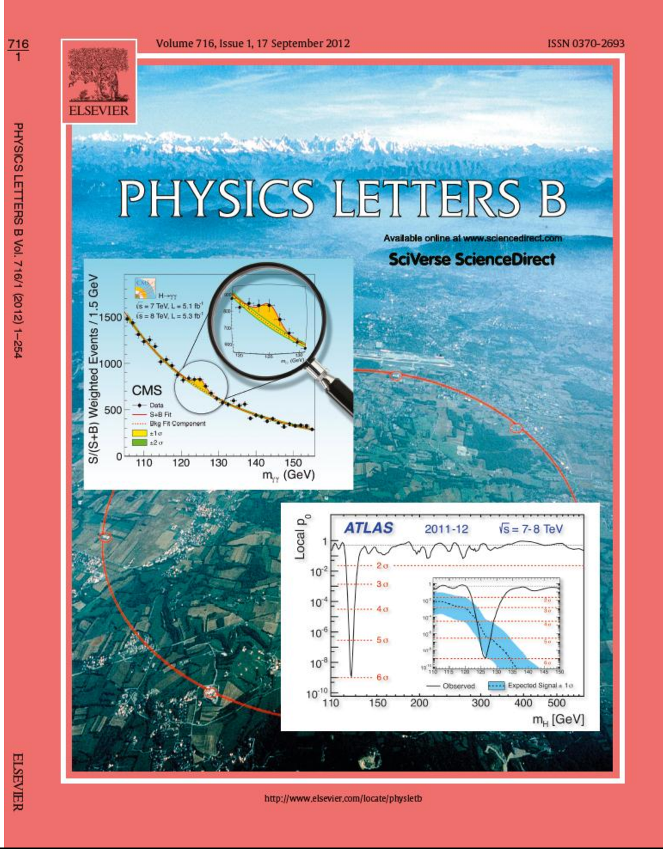
Physics Highlights

ATLAS and CMS have already published together more than 400 papers in scientific journals (and many more as public conference notes…)

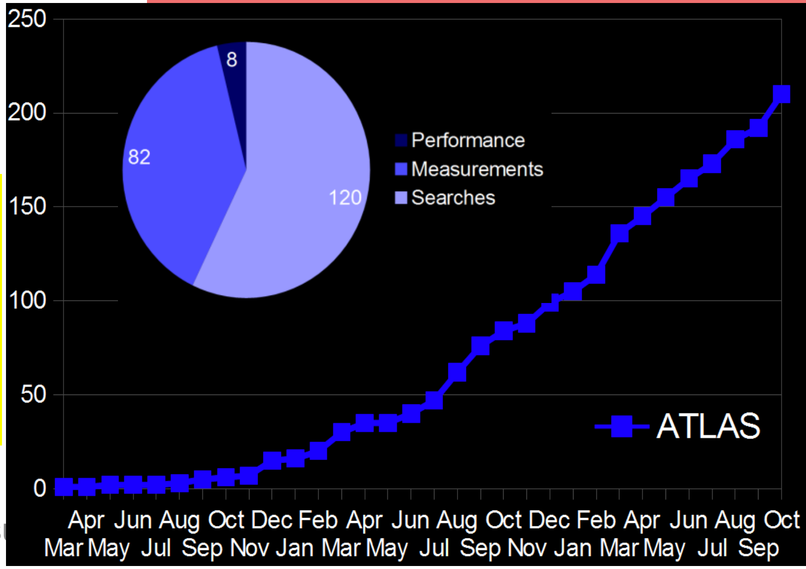
The other experiments, ALICE, LHCb, LHCf, and TOTEM total another 150 journal publications together

It is clearly not possible to cover all these results…

No attempt is made to show in a democratic way, for example, CMS and ATLAS results, but examples are given that are meant to represent the others as well where applicable...



Note that all public results are available from the experiments Web pages, and from the CERN Document Server
http://cdsweb.cern.ch/collection/LHC%20Experiments?ln=en



Physics Highlights:

General event properties

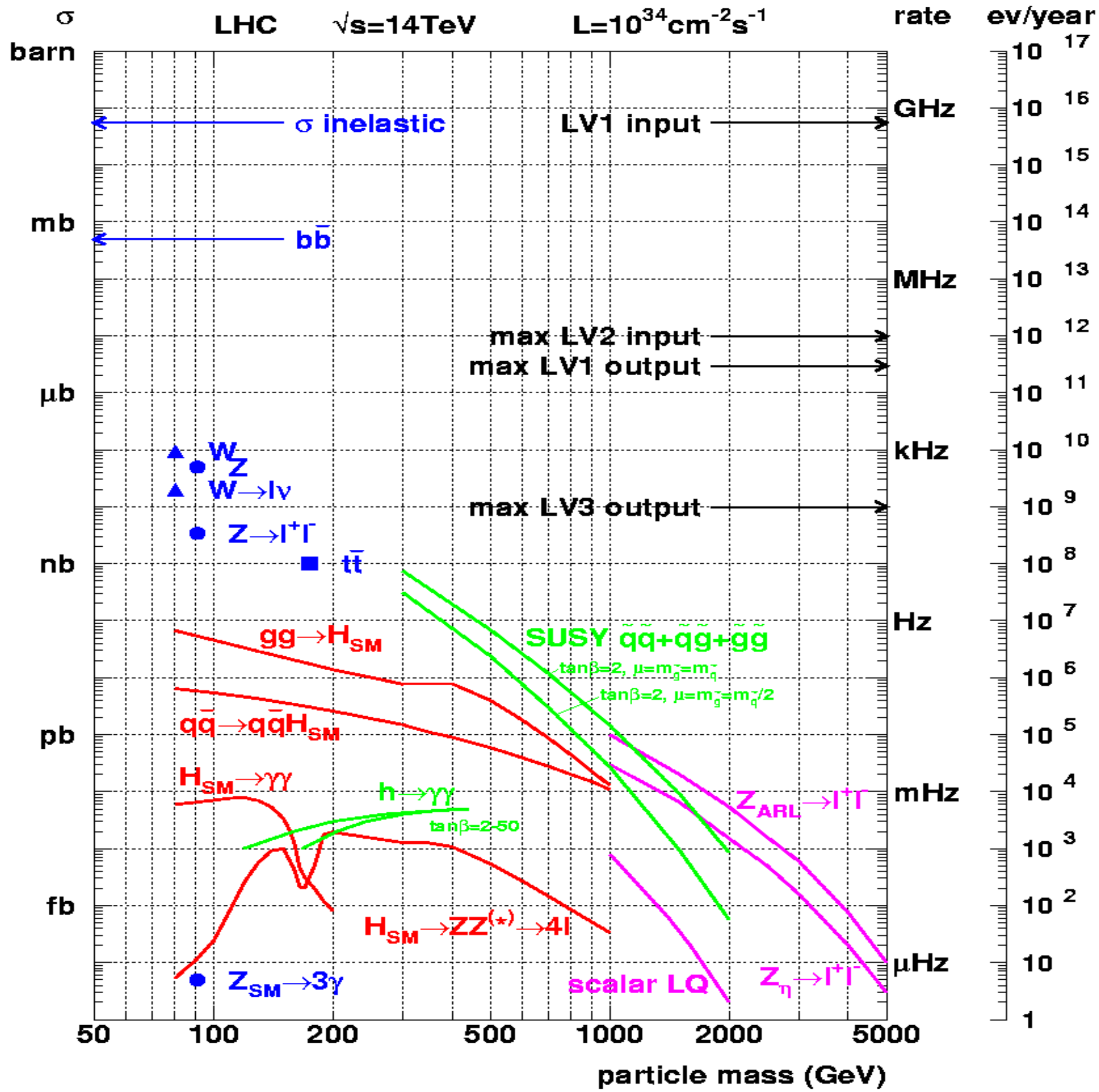
Heavy flavour physics

Standard Model physics including QCD jets

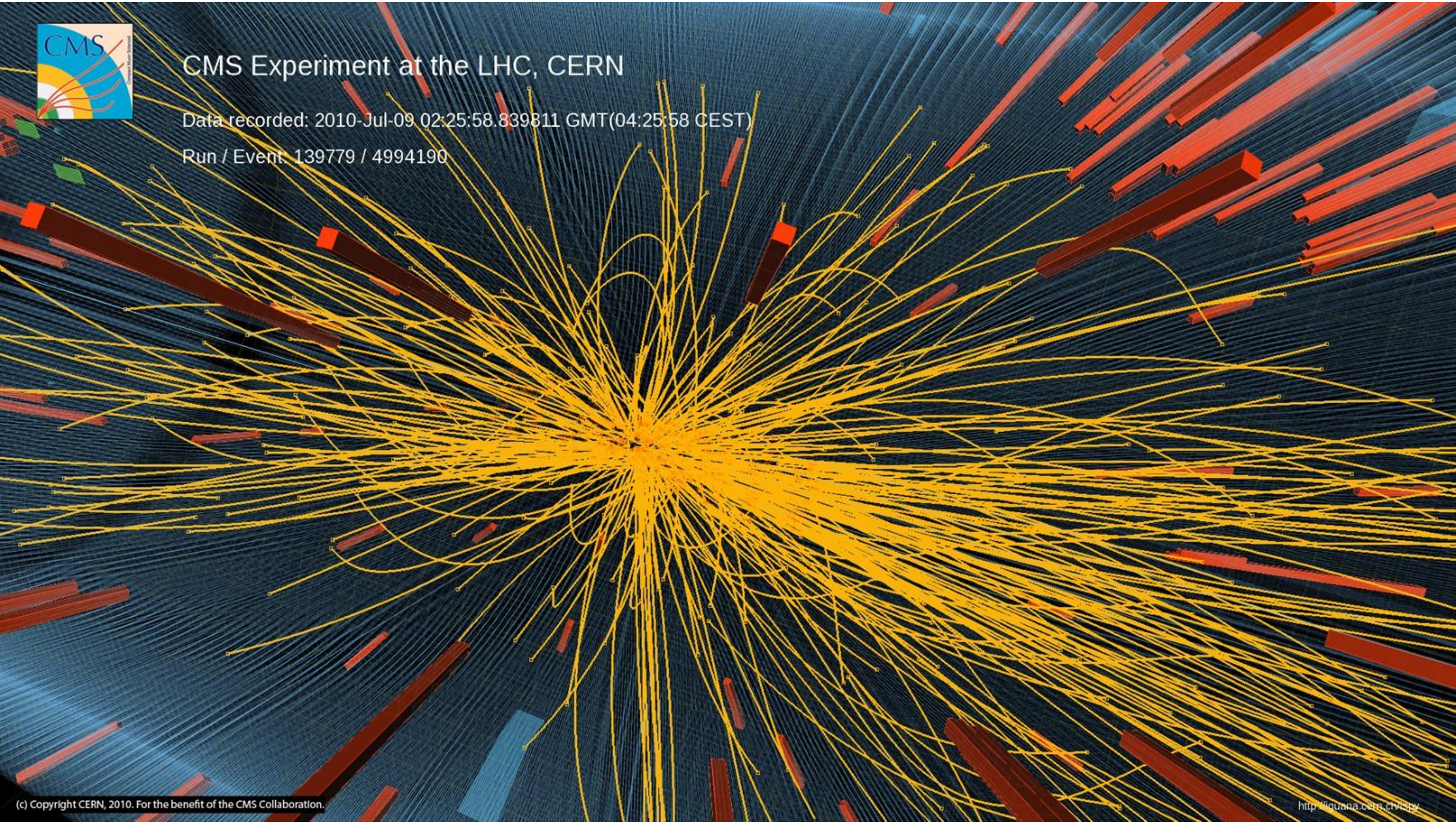
Higgs searches

Searches for SUSY

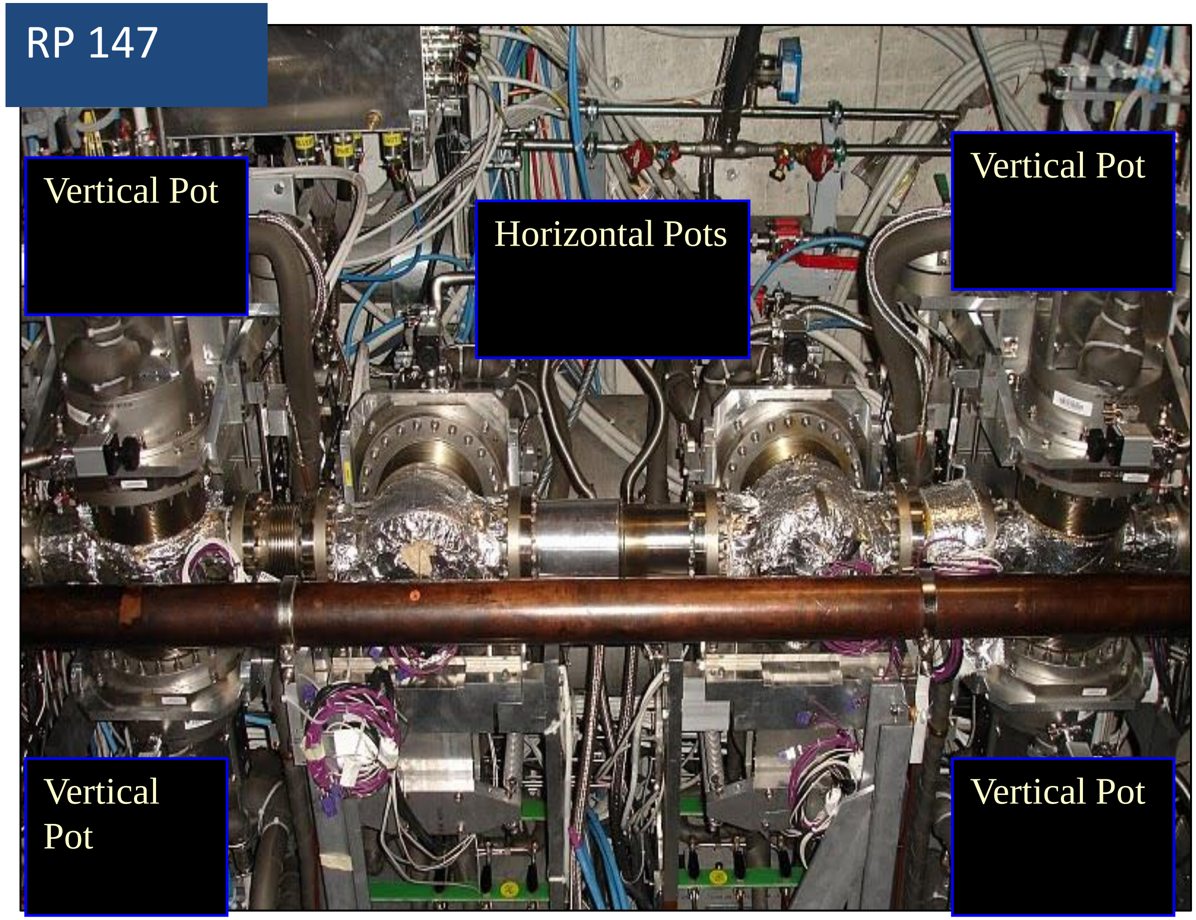
Examples of searches for 'exotic' new physics



General Event Properties and Resonances

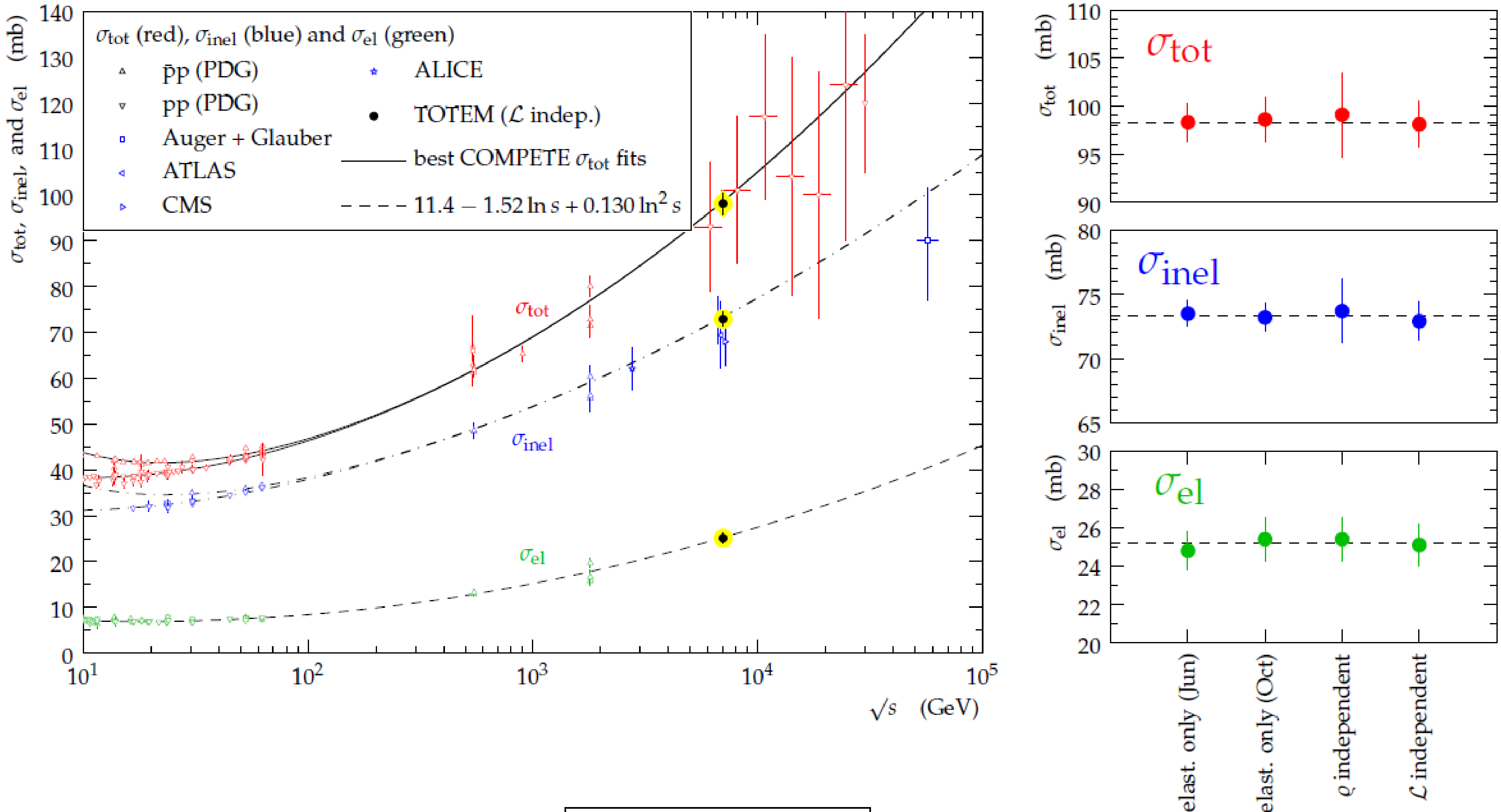


Total cross-section measurement by TOTEM



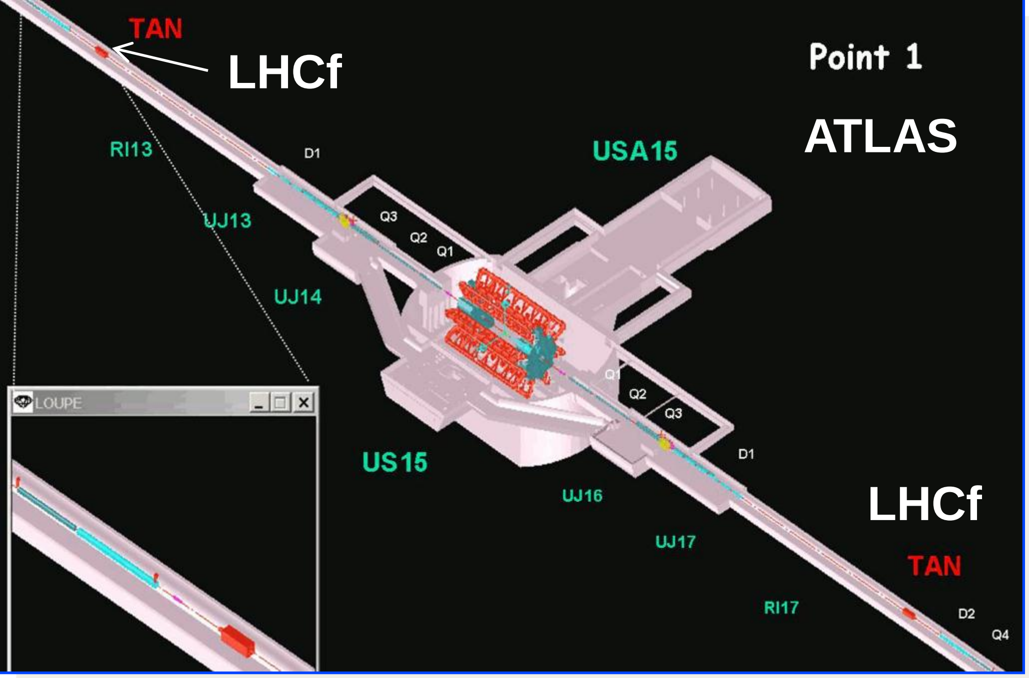
Example: Roman Pots at 147 m from interaction point

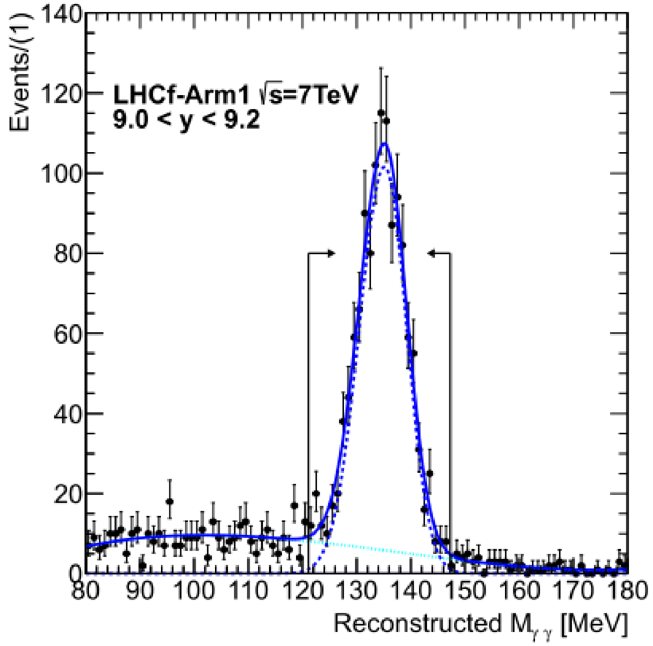
Total cross-section measurement by TOTEM

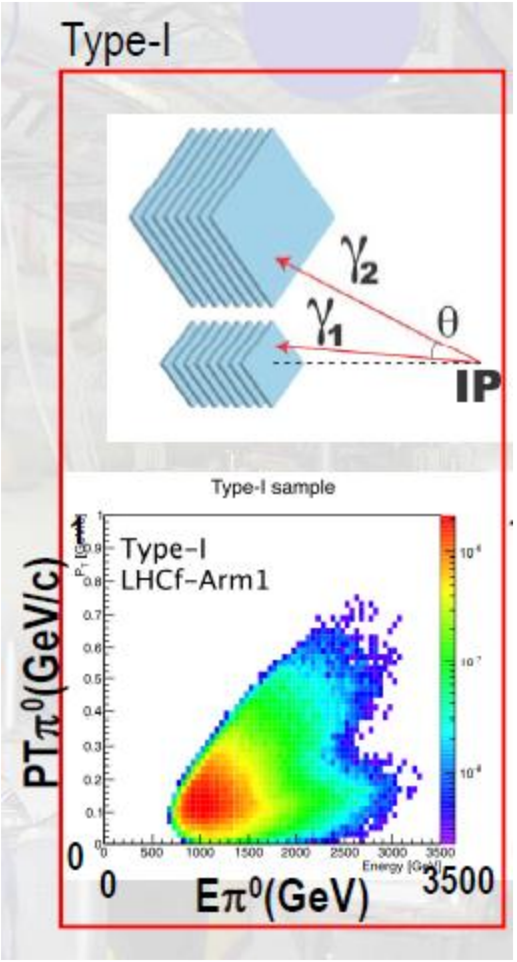


Presented at HCP2012

LHCf 7 TeV π^0 signal



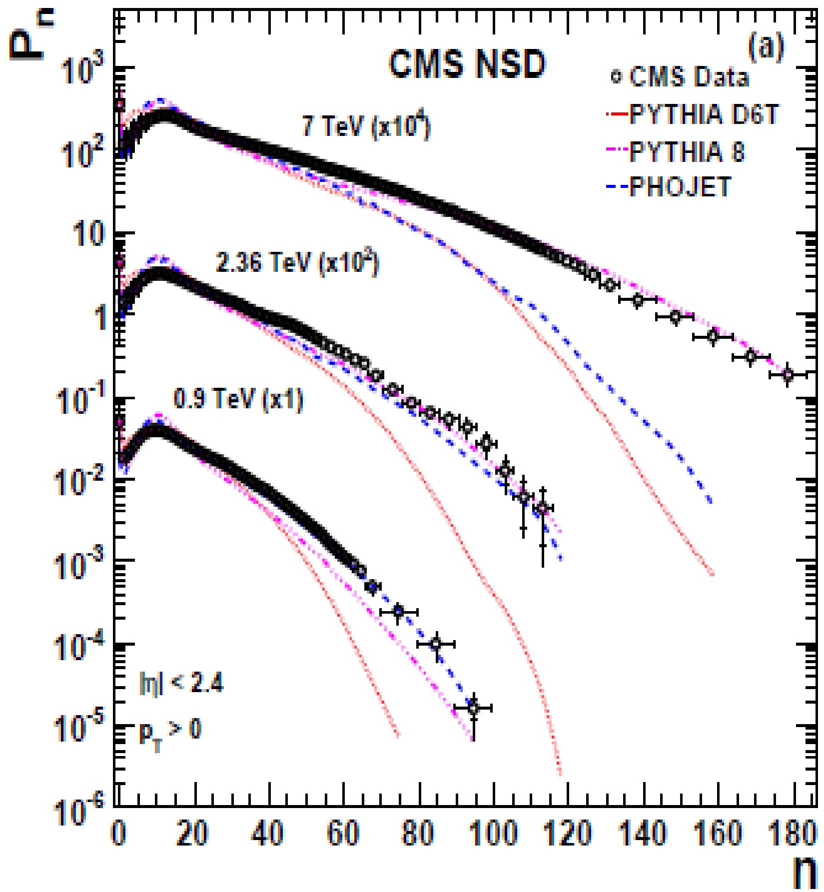




Feedback to modeling of Ultra High Energy Cosmic Rays (UHERCs)

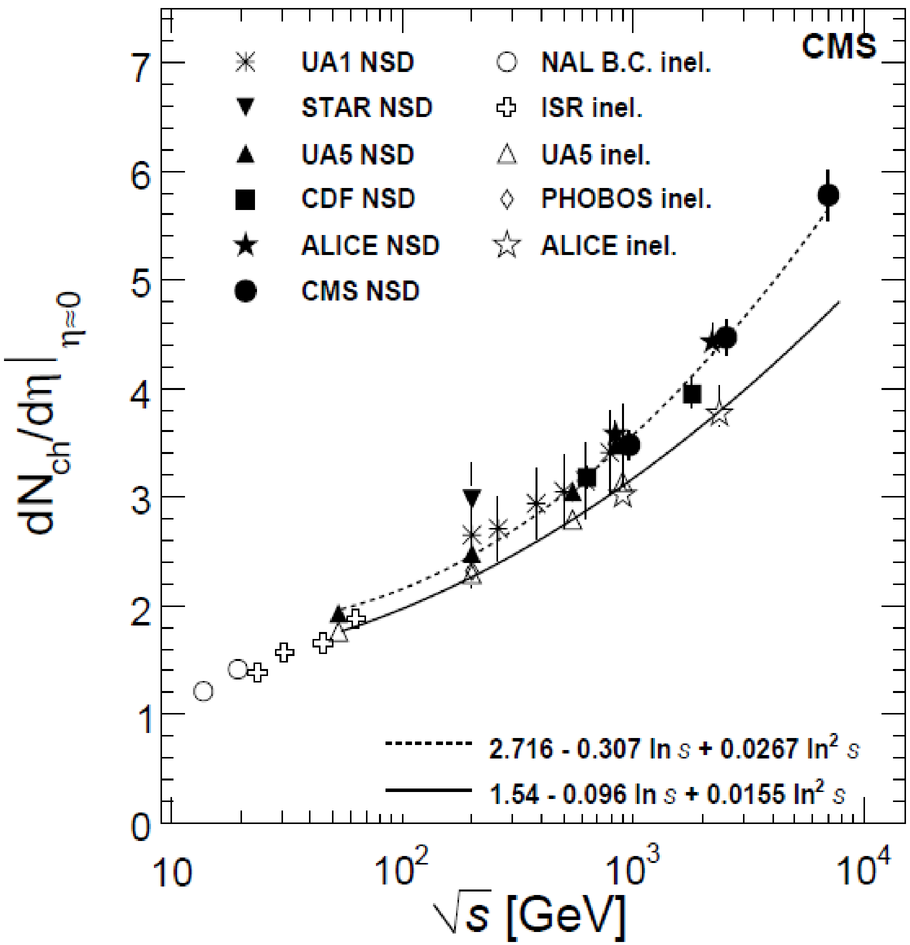
Presented at HCP2012

Charged hadron multiplicities at the three different √s



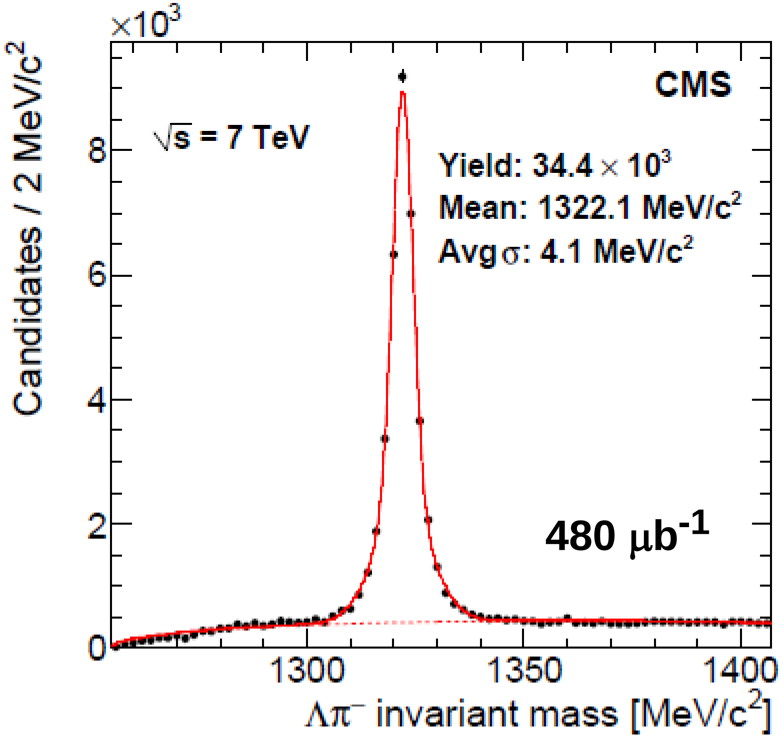
JHEP 01 (2011) 079

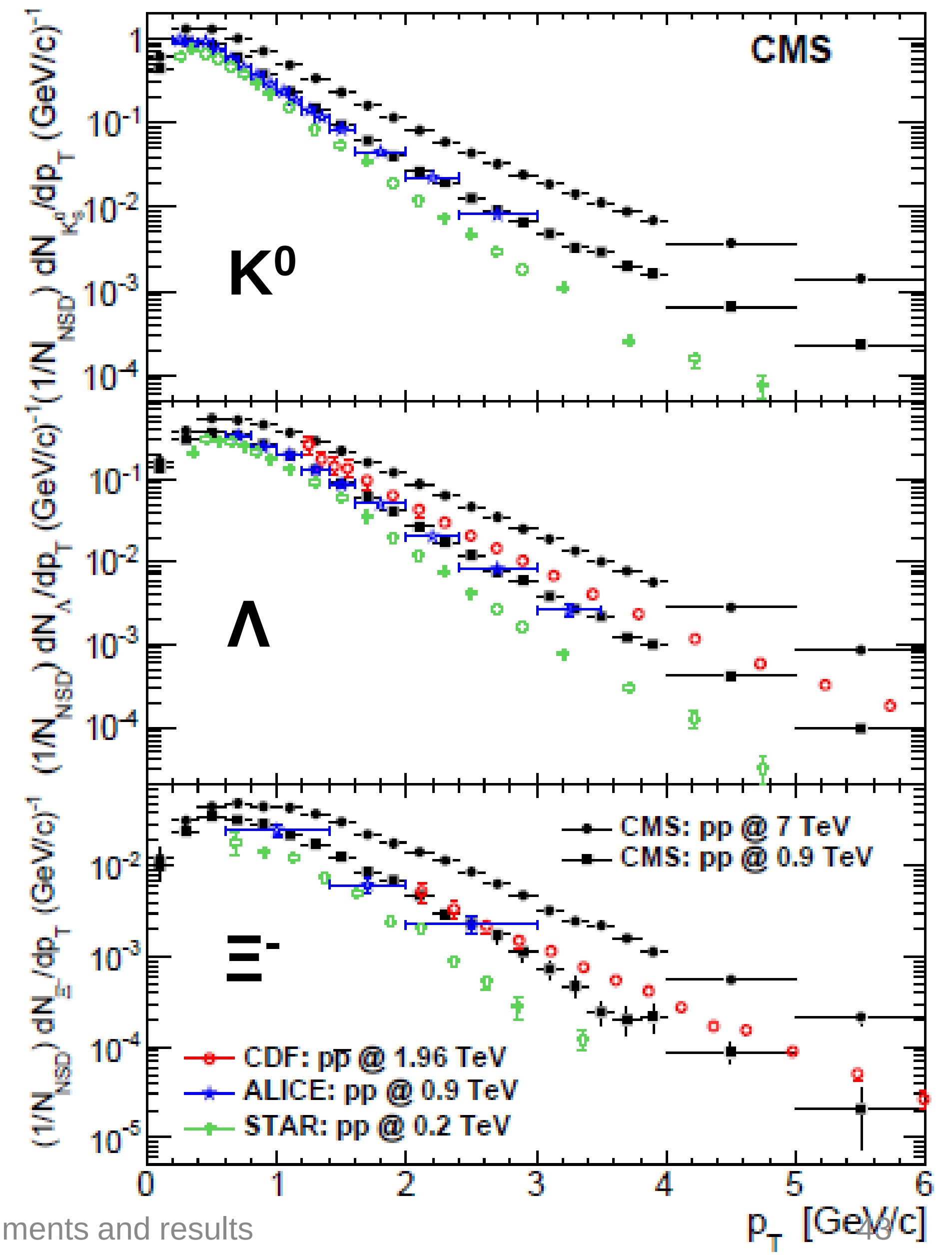
Average charged particle density for the central η region (pp and p̄p)



Phys. Rev. Lett. 105 (2010) 022002

Strange particle production spectra



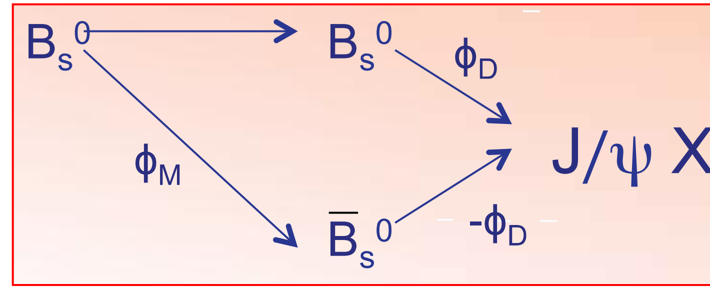


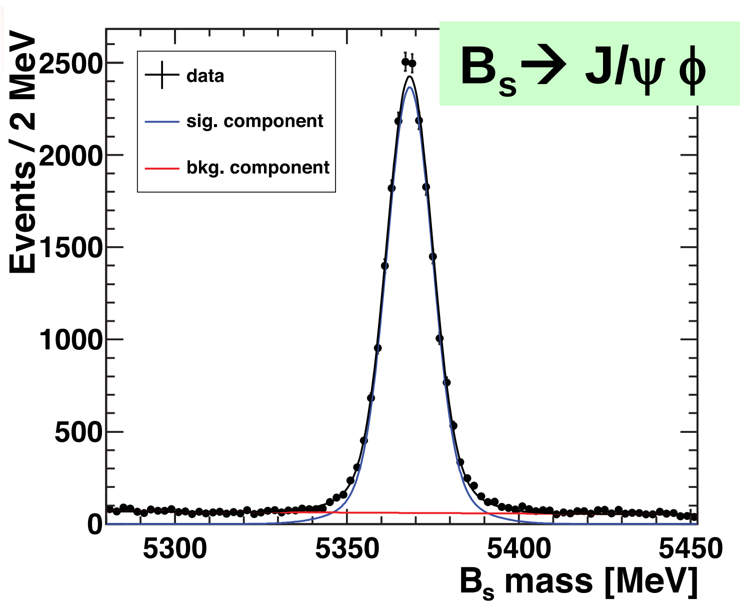
Example $\Xi^- \rightarrow \Lambda\pi^-$

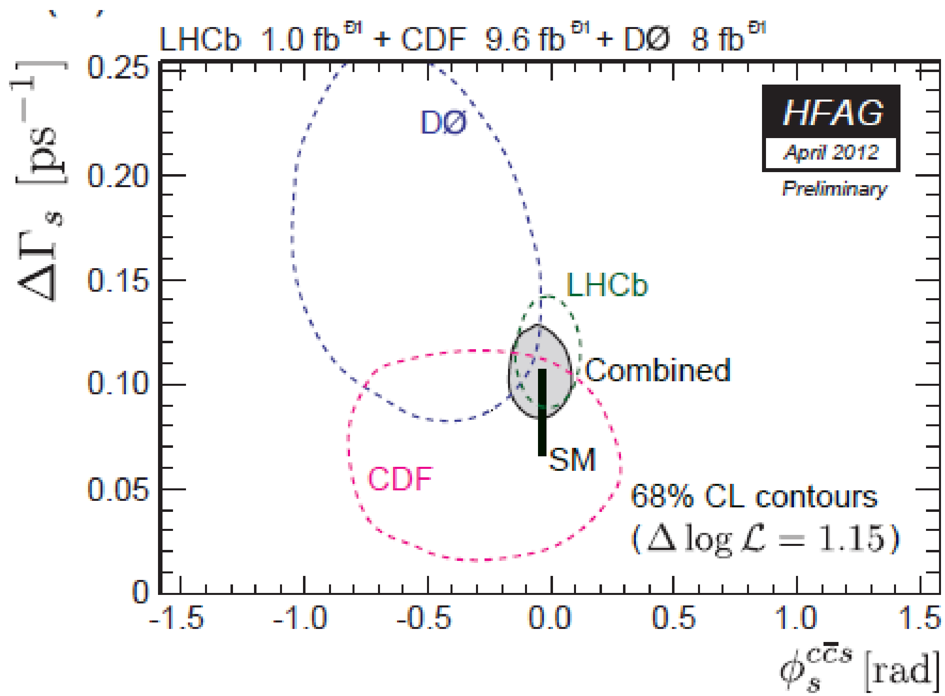
JHEP 05 (2011) 064

CP violation in B_s mixing (ϕ_s and $\Delta\Gamma_s$)

Measure relative phase difference between "two legs" of $B_s \rightarrow J/\psi\ \phi$ decay
Looking for effects of NP in ϕ_s (~0 in SM)







First determination of sign of $\Delta\Gamma_s$ (removal of ϕ_s ambiguity)

ϕ_s= -0.002 ± 0.083 ± 0.027 rad

CP violation in B_s mixing (semileptonic decay asymmetries)

Measured by D0 (FNAL) with semileptonic events (μ and di-μ)

$A_{sl}^{\mu\mu}$ = (-0.79 ± 0.20)% (mix of a_{sl}^d and a_{sl}^s) ~ 4 σ tension (in SM ~0)

Difficult to reconcile with ϕ_s LHCb data

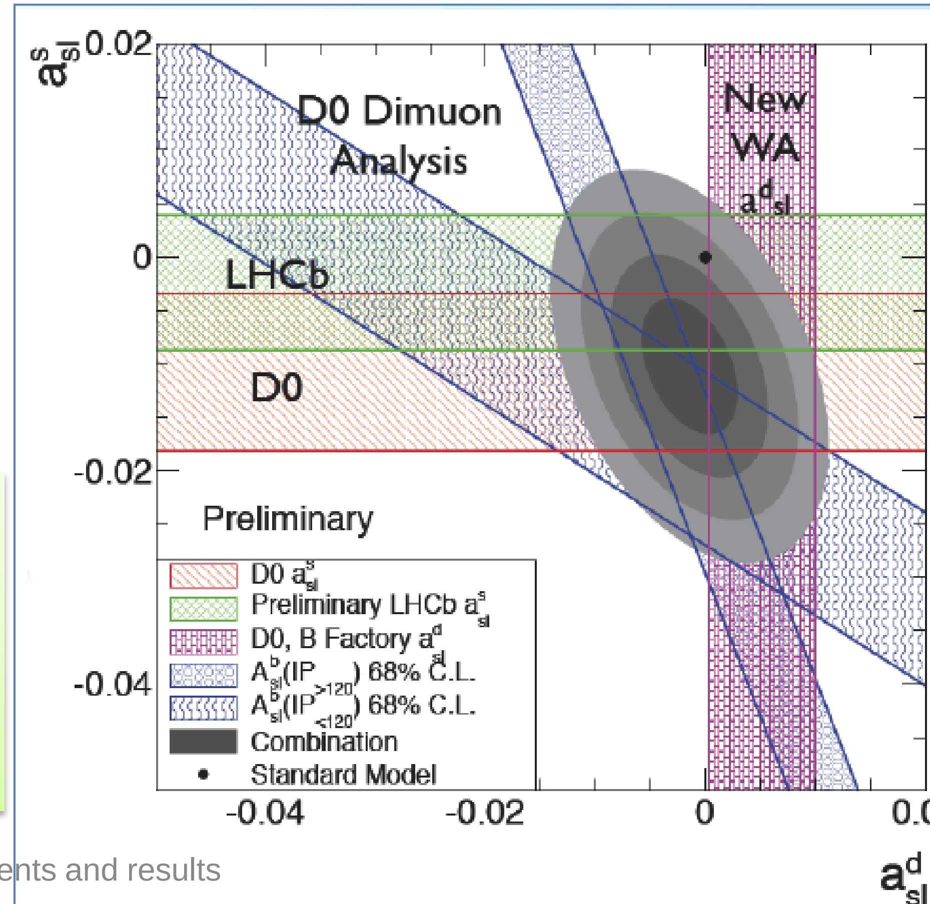
$$a_{sl}^s = \frac{\Gamma(\overline{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \overline{f})}{\Gamma(\overline{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \overline{f})}$$

LHCb measurement:

$$a_{sl}^s = (-0.24 \pm 0.54 \pm 0.33)\%$$

Fitting $a_{SL}(B_s)$ (D0-B fact.-LHCb):
~ 2.5 σ from SM

Less tension but still more data needed from LHCb to solve a_{SL} D0 discrepancy (if any…)



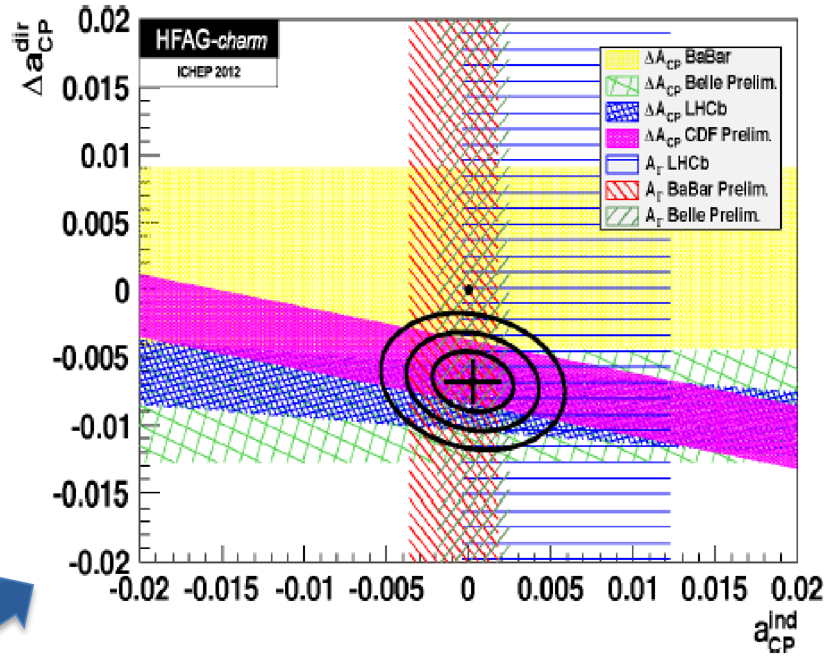
Charm physics

LHCb has the world's largest sample of c-hadron decays
Rich program: mixing, CP asymmetries, branching fractions

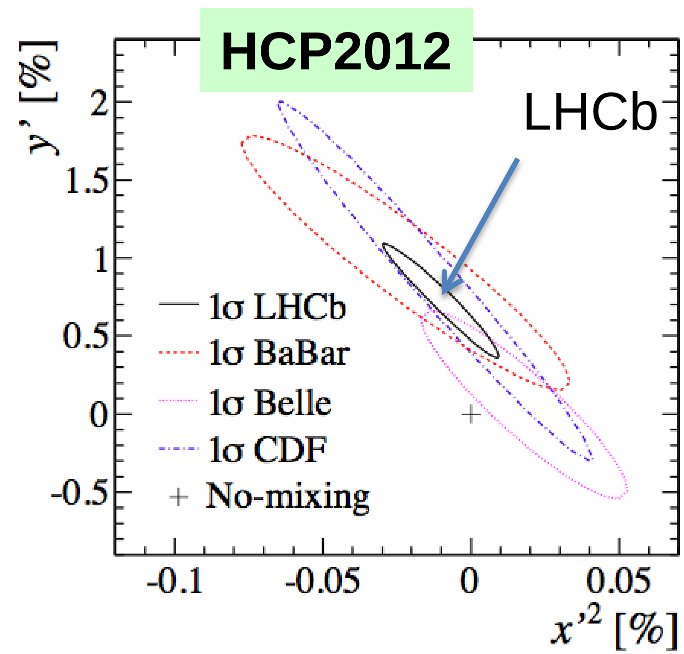
CPV in charm decays **($D^0 \rightarrow KK$ or $\pi\pi$)**

Hint of CPV≠0 from LHCb, CDF, Belle
$A^{CP}_{dir} = (-0.68 \pm 0.15)$ %

NP or explicable within SM ?
More data & confirmation in other D channels needed

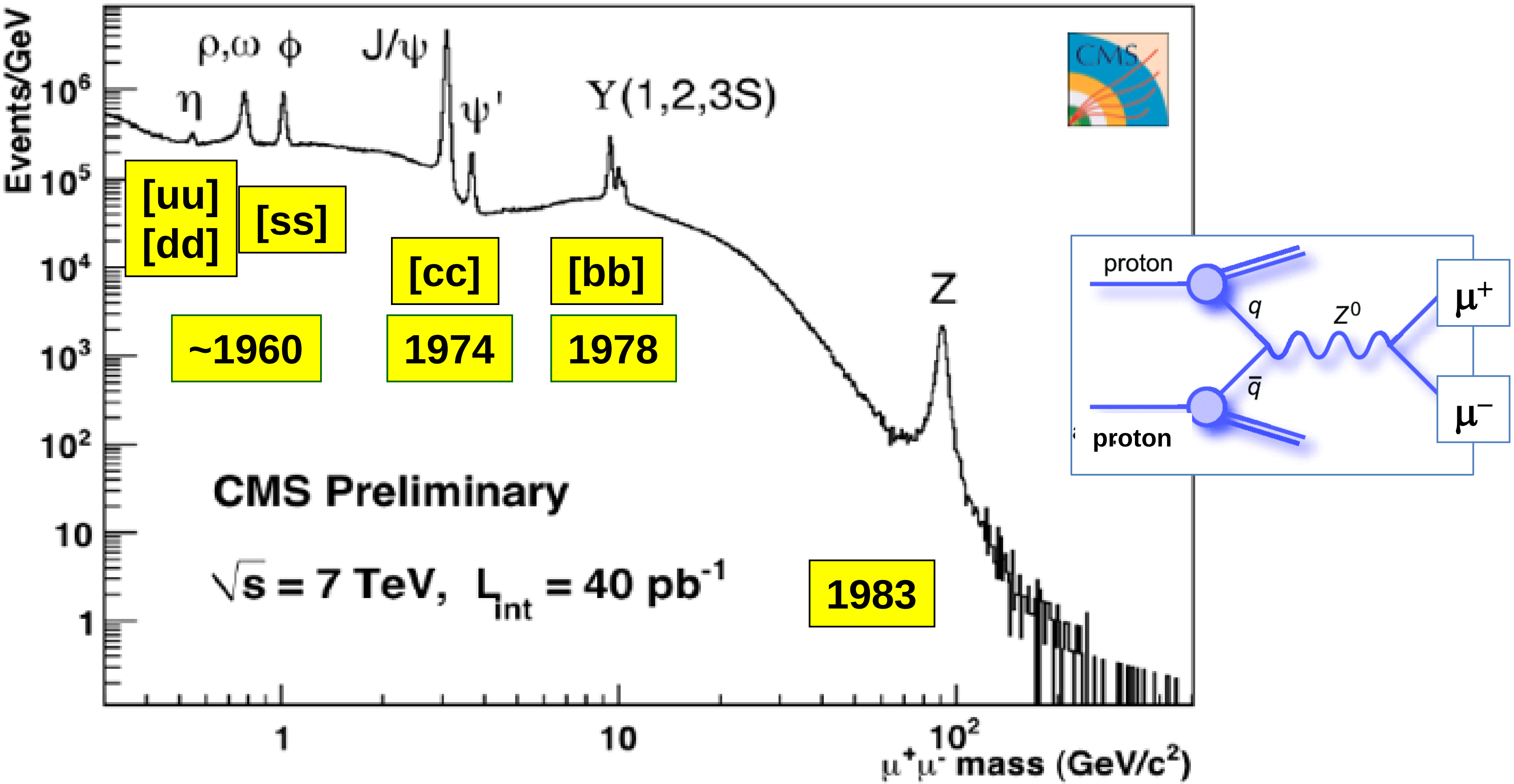


First observation of charm mixing in $D^0 \rightarrow K\pi$ by a single measurement (9σ)



2010

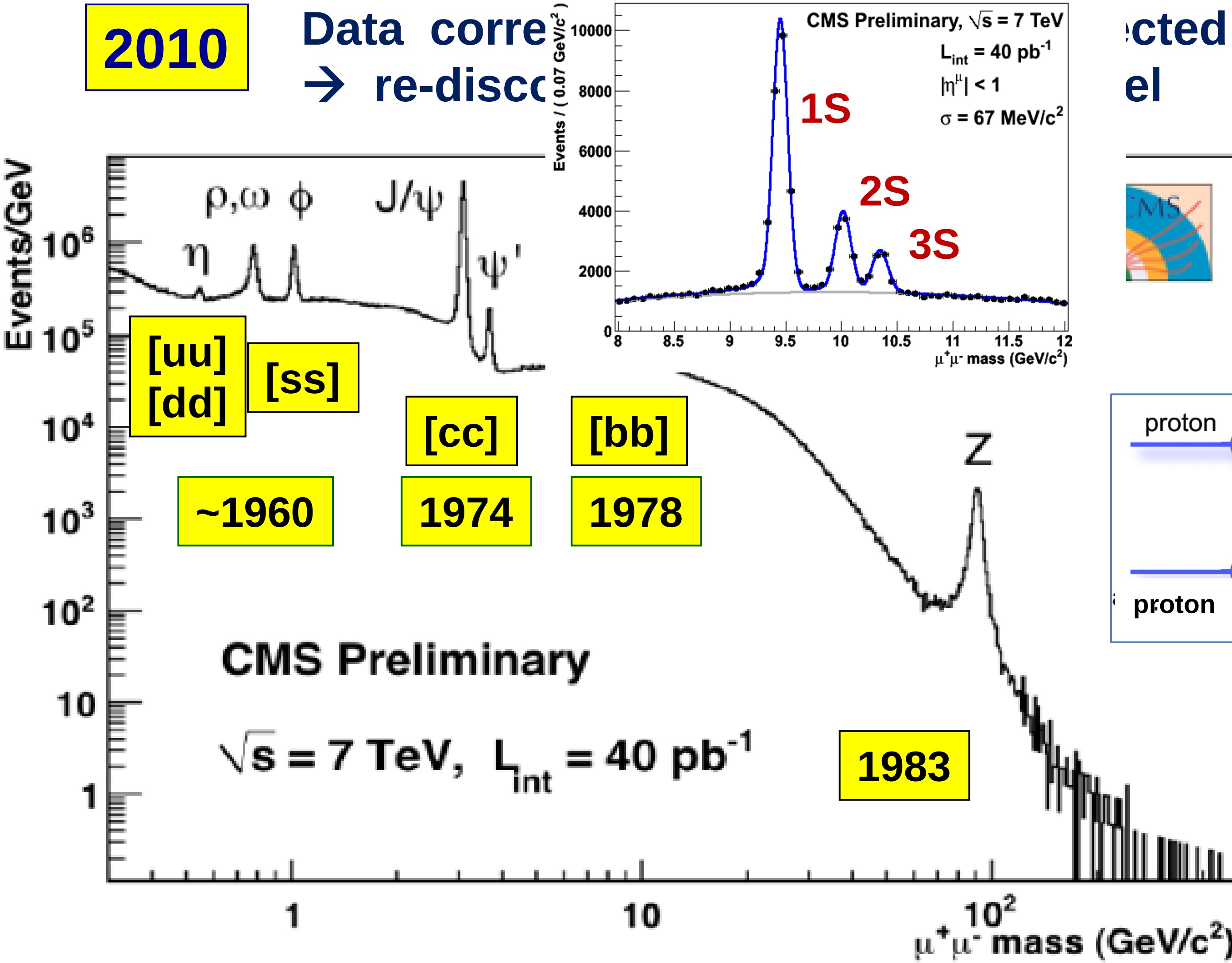
Data corresponding to ~40 pb^{-1} collected → re-discovery of the Standard Model

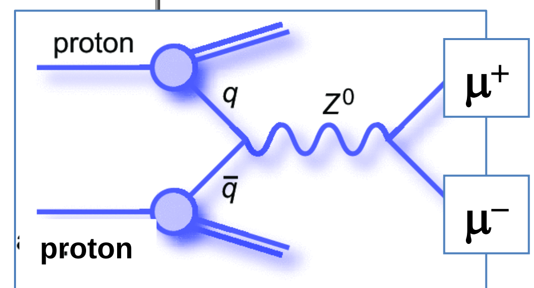


The di-muon spectrum recalls a long period of particle physics: Well known quark-antiquark resonances (bound states) appear "online"

2010

Data corre… …cted
→ re-discc… …el



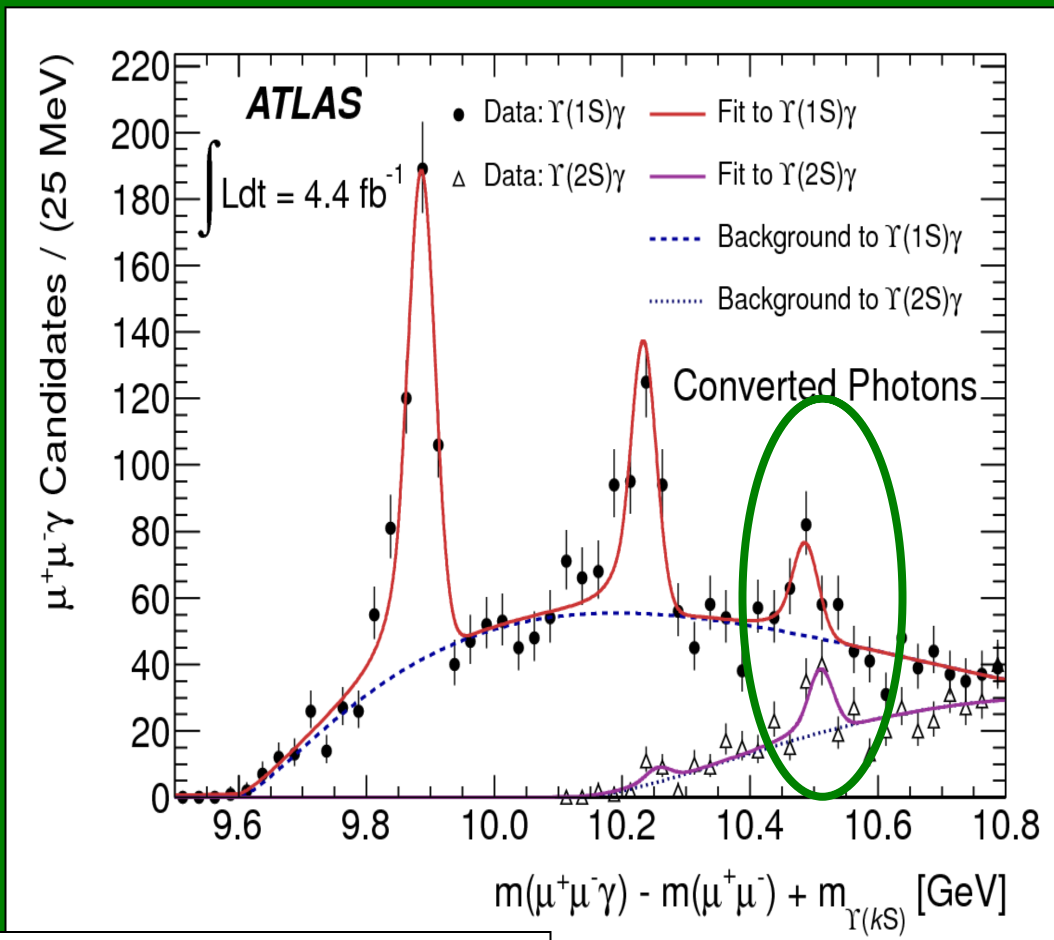


The di-muon spectrum recalls a long period of particle physics:
Well known quark-antiquark resonances (bound states) appear "online"

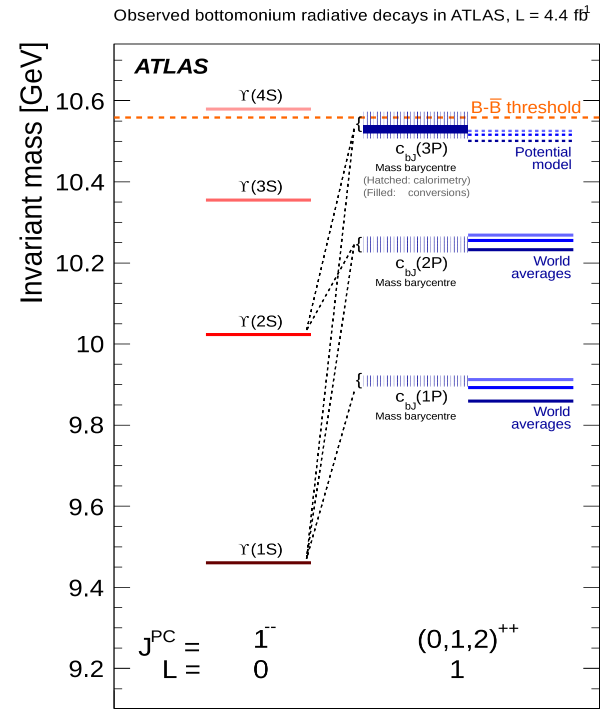
The first new particles 'discovered' at LHC

$\chi_b(3P) \rightarrow \Upsilon(1s,2s)\ \gamma$

$m\ [\chi_b(3P)] = 10.530 \pm 0.005\ (stat) \pm 0.009\ (syst)$ GeV

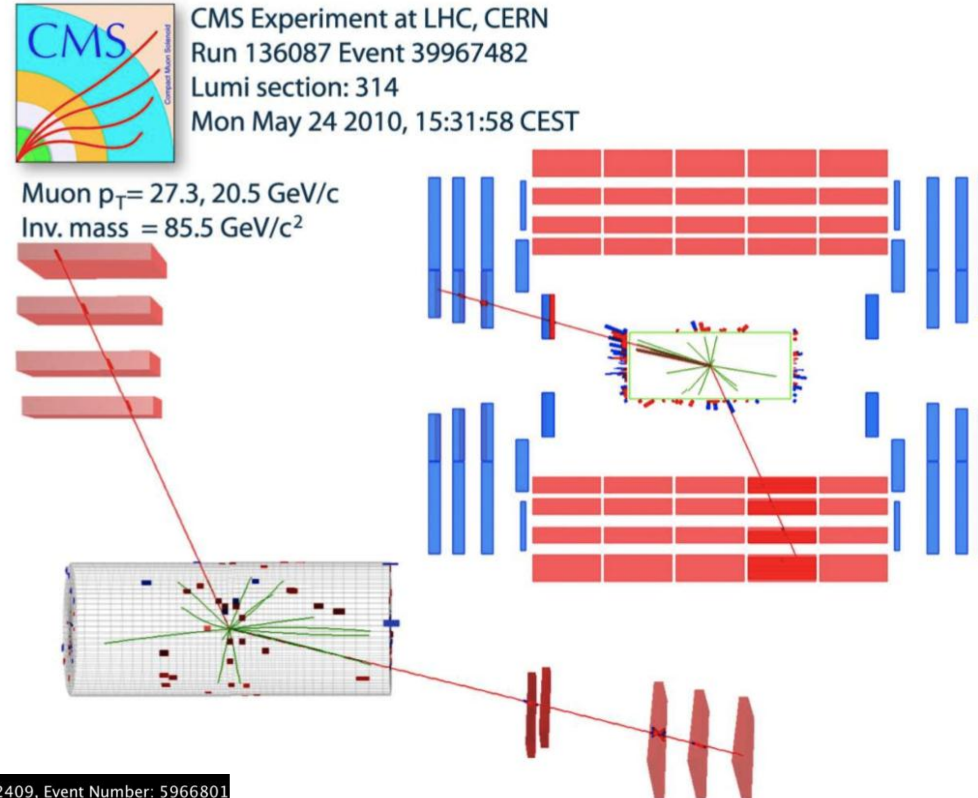


Phys. Rev. Lett. 108 (2012) 152001



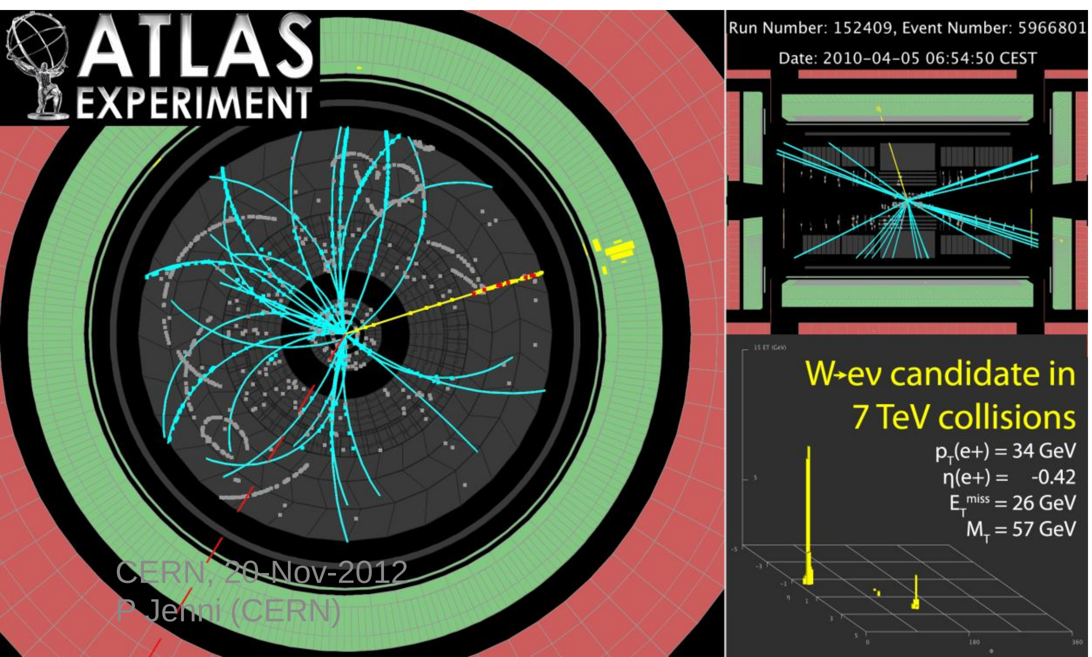
- ❑ **$\chi_b(nP) \rightarrow \Upsilon(1s,2s)\ \gamma \rightarrow \mu\mu\ \gamma$**
- ❑ **$X_b(1P)$ m= 9.9 GeV and $X_b(2P)$ m= 10.2 GeV states clearly visible**
- ❑ **New structure at 10.5 GeV → $X_b(3P)$**
- ❑ **Significance > 6 σ**
- ❑ **As theoretically predicted**

Standard Model Physics



Candidate Z → $\mu^+\mu^-$

W → eν candidate



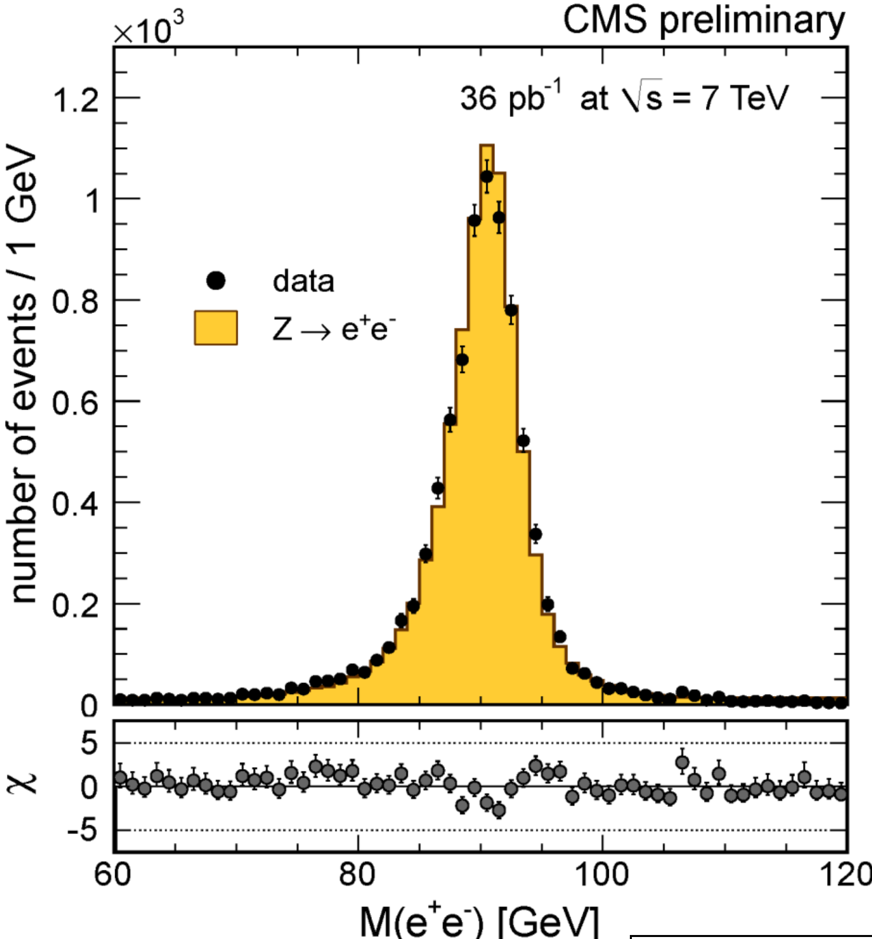
Today each ATLAS and CMS have in their data more than:

100 M W→ μν, eν events
10 M Z → μμ, ee events

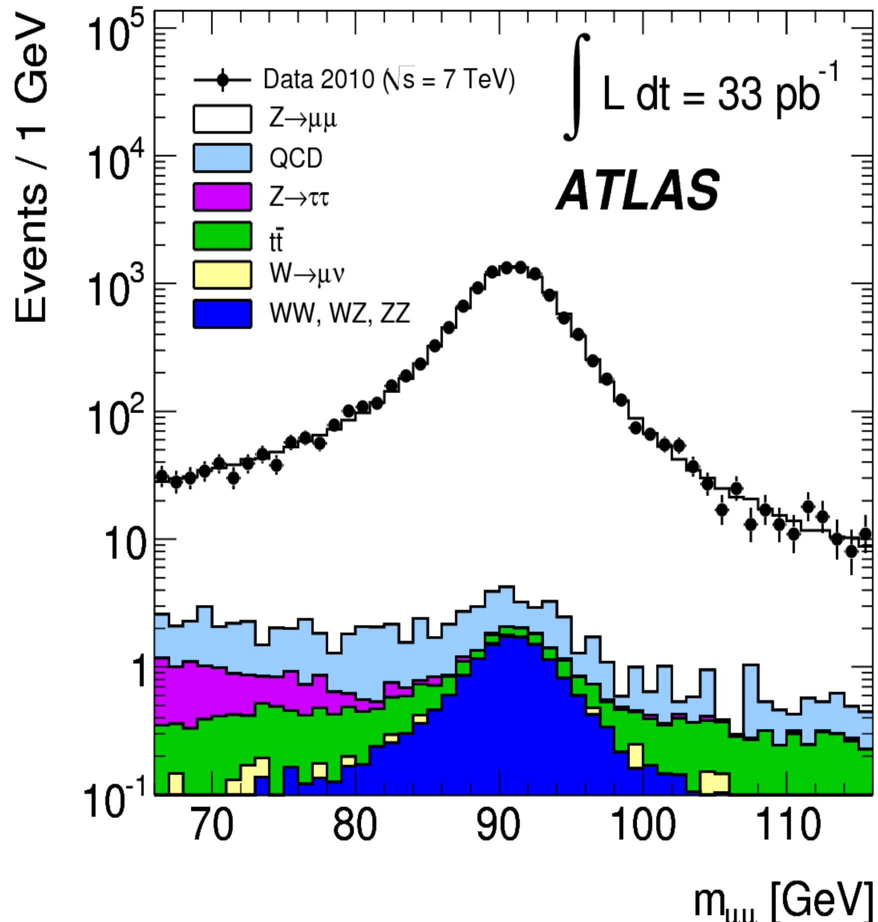
after all selection cuts

Z and W production

Phys Rev D85 (2012) 072004



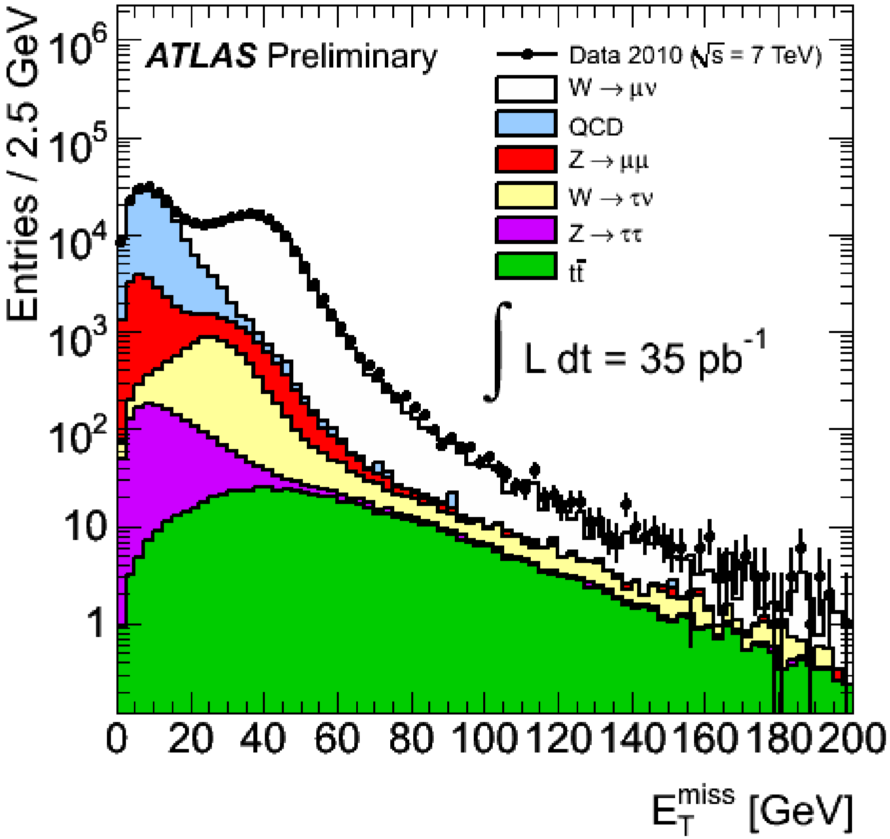
JHEP 10 (2011) 132



Z peak (di-lepton pair mass distributions, can be extracted essentially background-free)

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

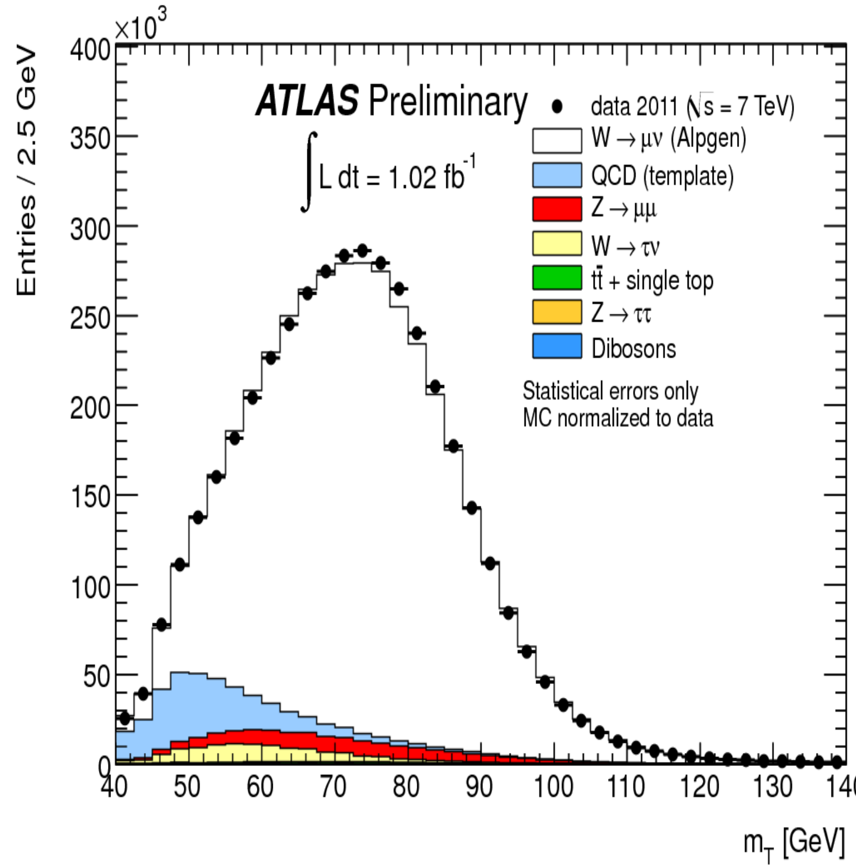
W transverse mass



Missing transverse energy from the W → μ + ν decays

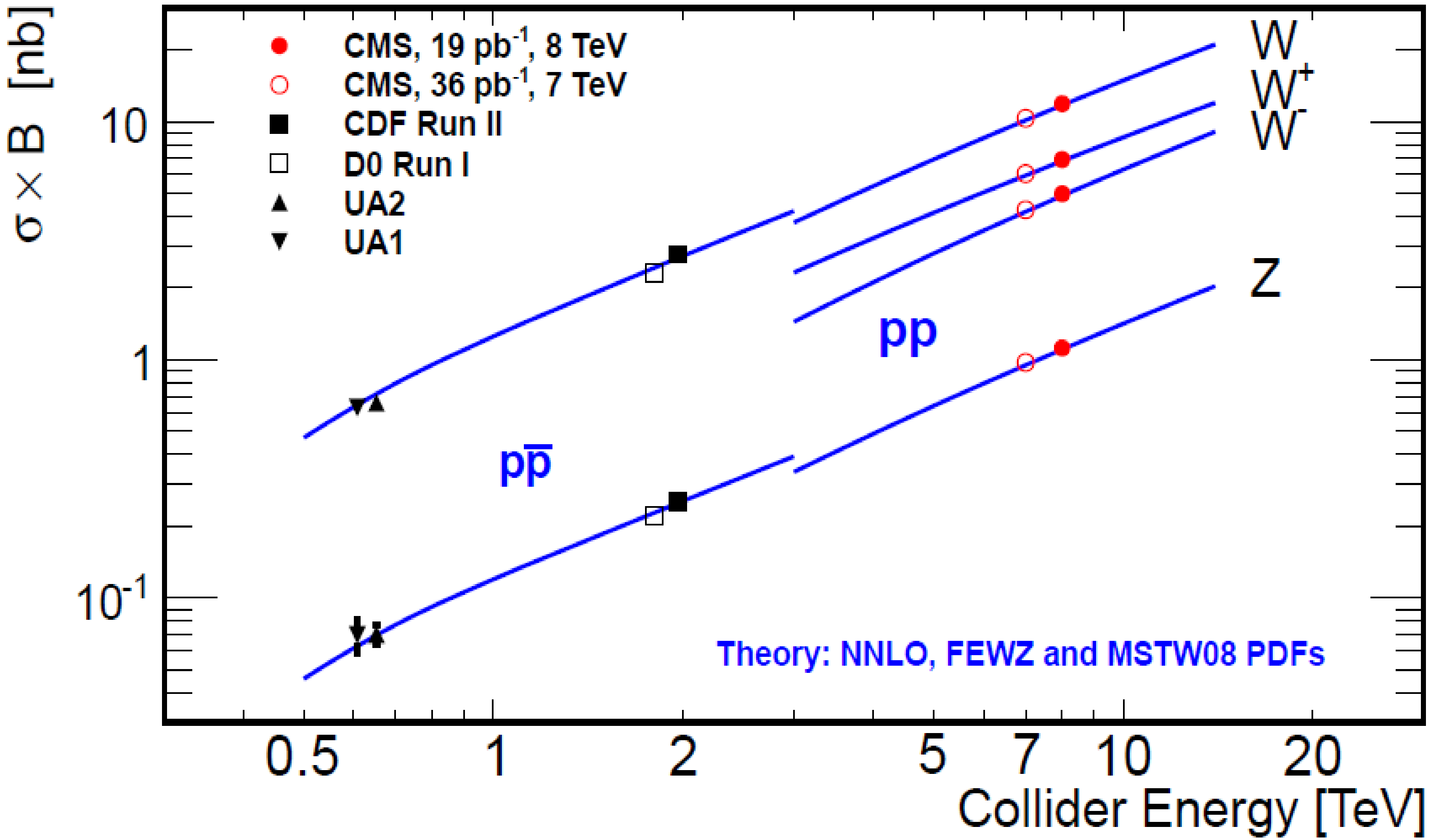
ATLAS-CONF-2011-041

μ with p_T>20 GeV, E_T^{miss}>25 GeV



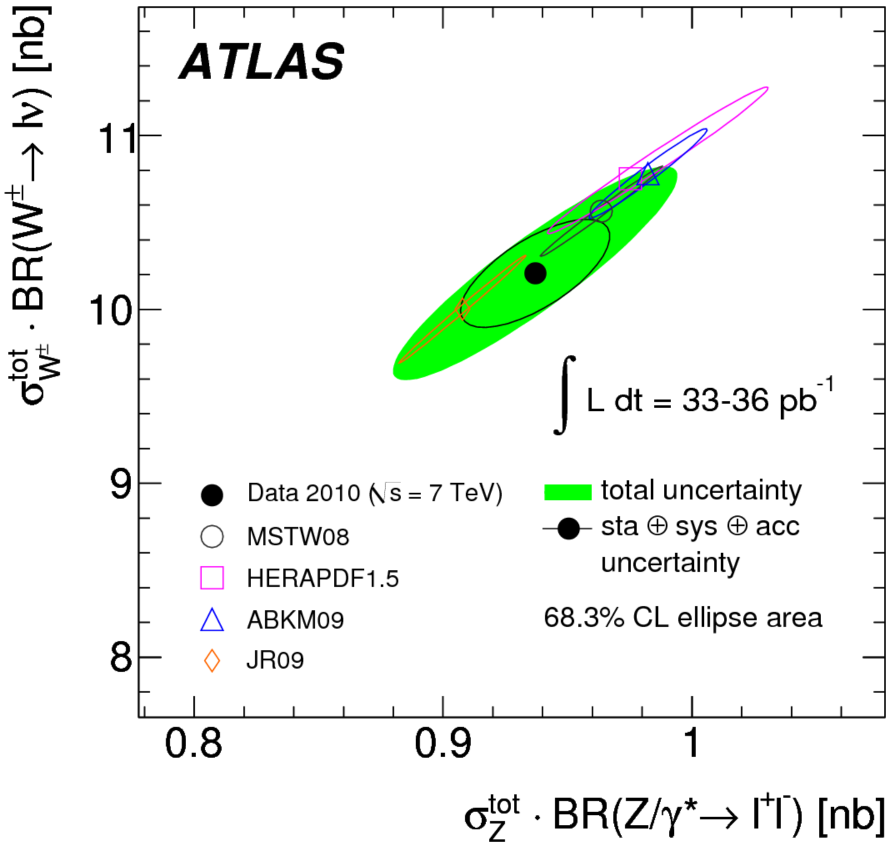
$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

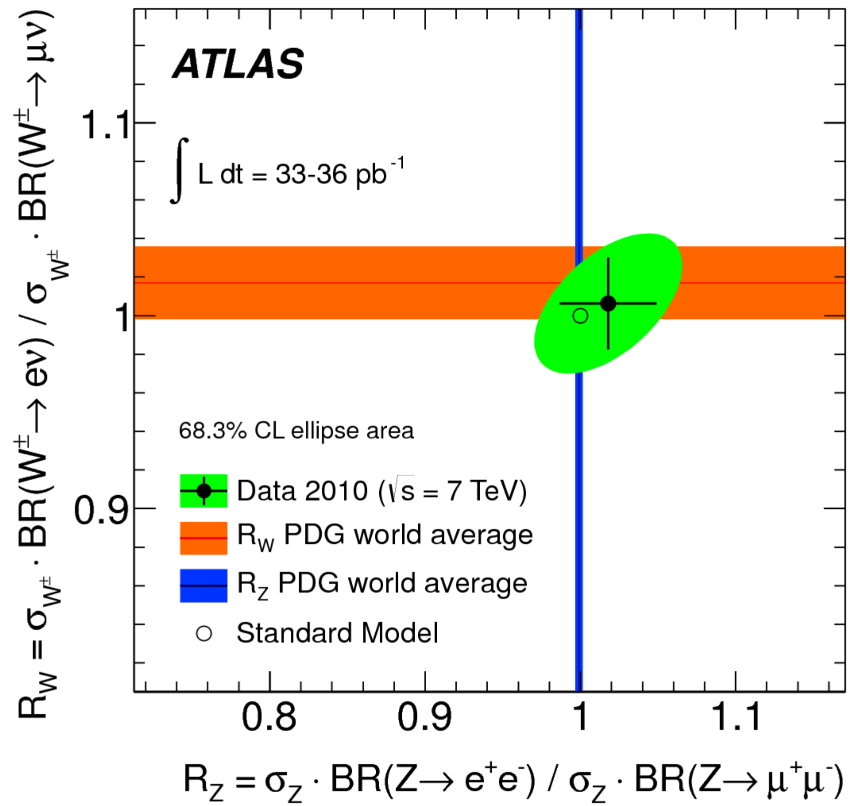
Cross section measurements



CMS-PAS-SMP-12-011

Two examples of confronting the 2010 data with SM theory

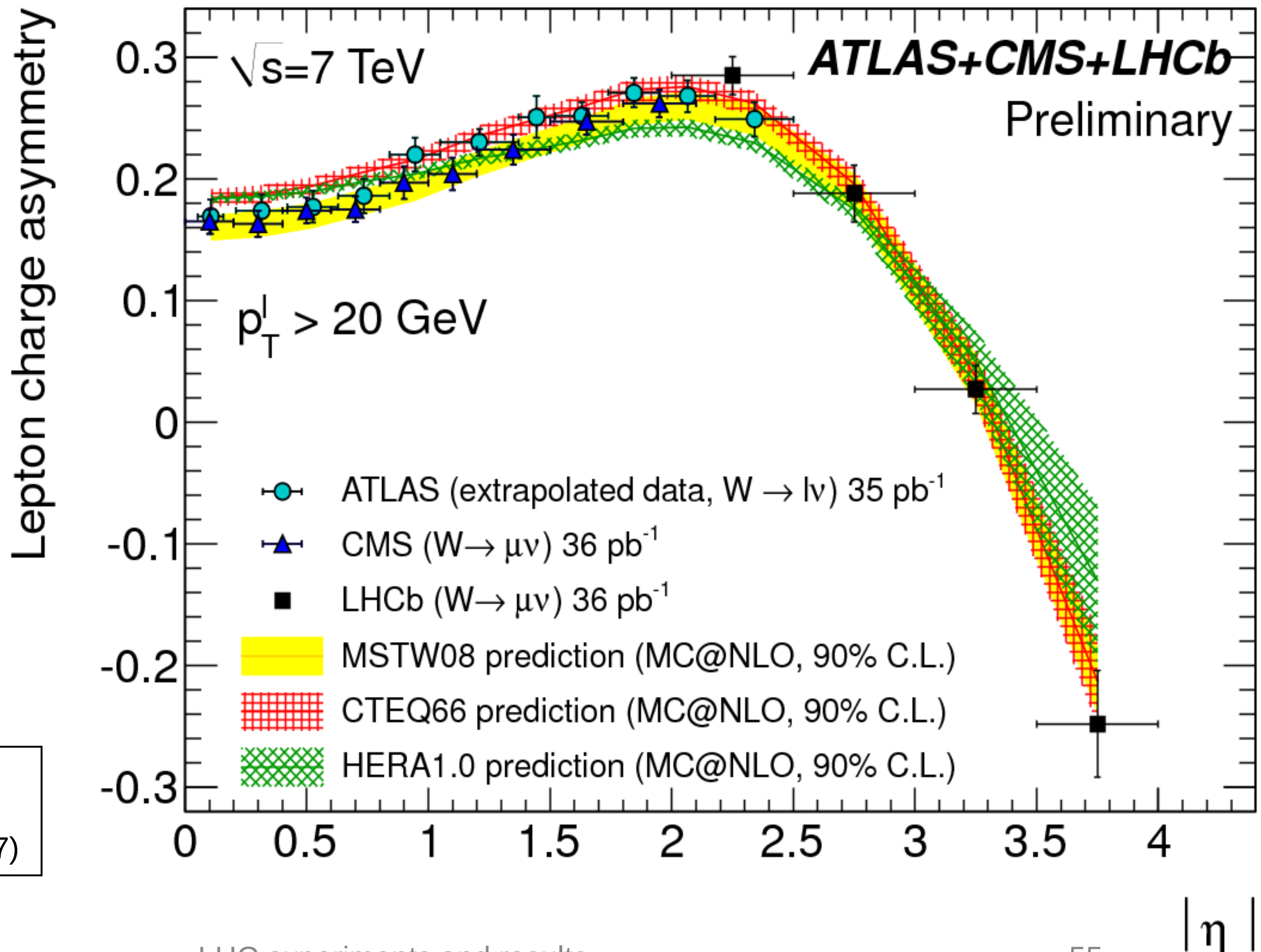




Phys Rev D85 (2012) 072004

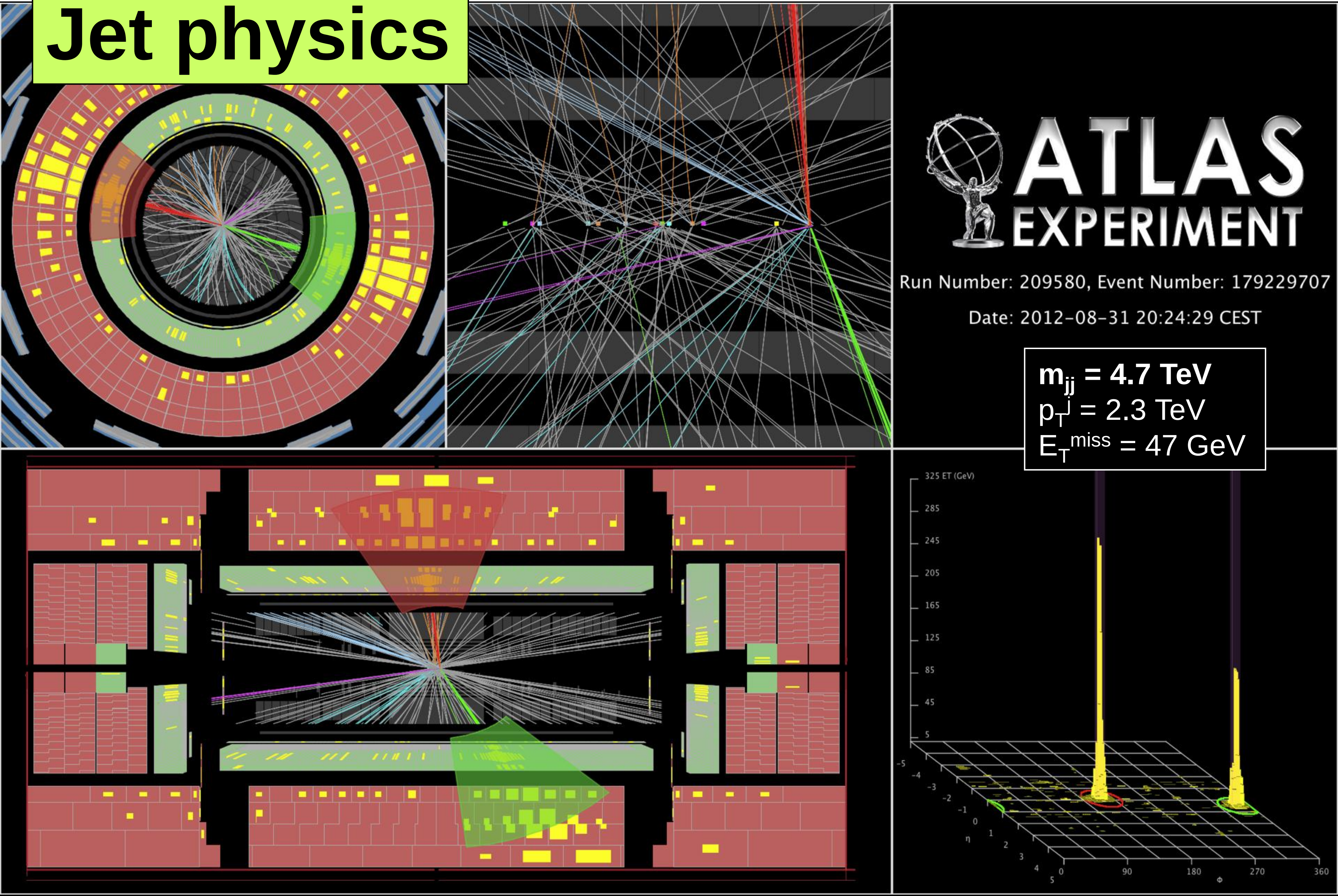
Lepton charge asymmetry from W decays in pp collisions at 7 TeV

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

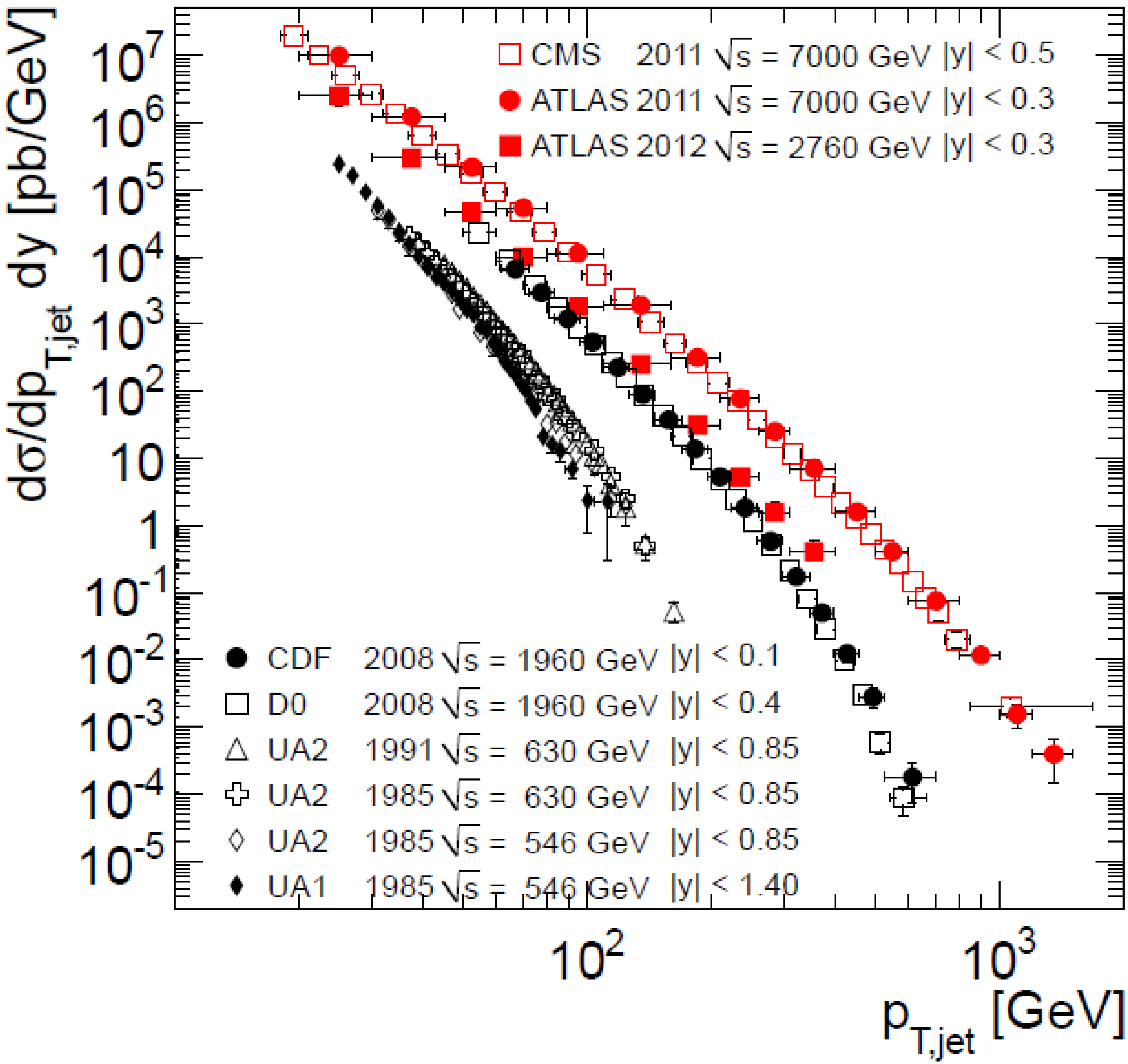


ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

Jet physics



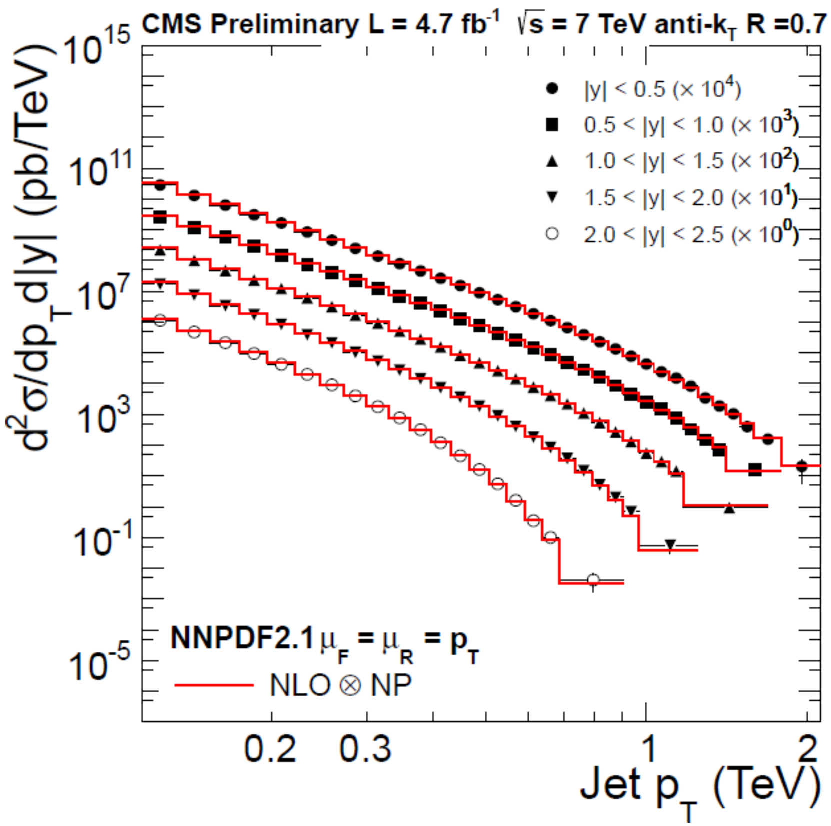
m_{jj} = 4.7 TeV
p_T^j = 2.3 TeV
E_T^{miss} = 47 GeV

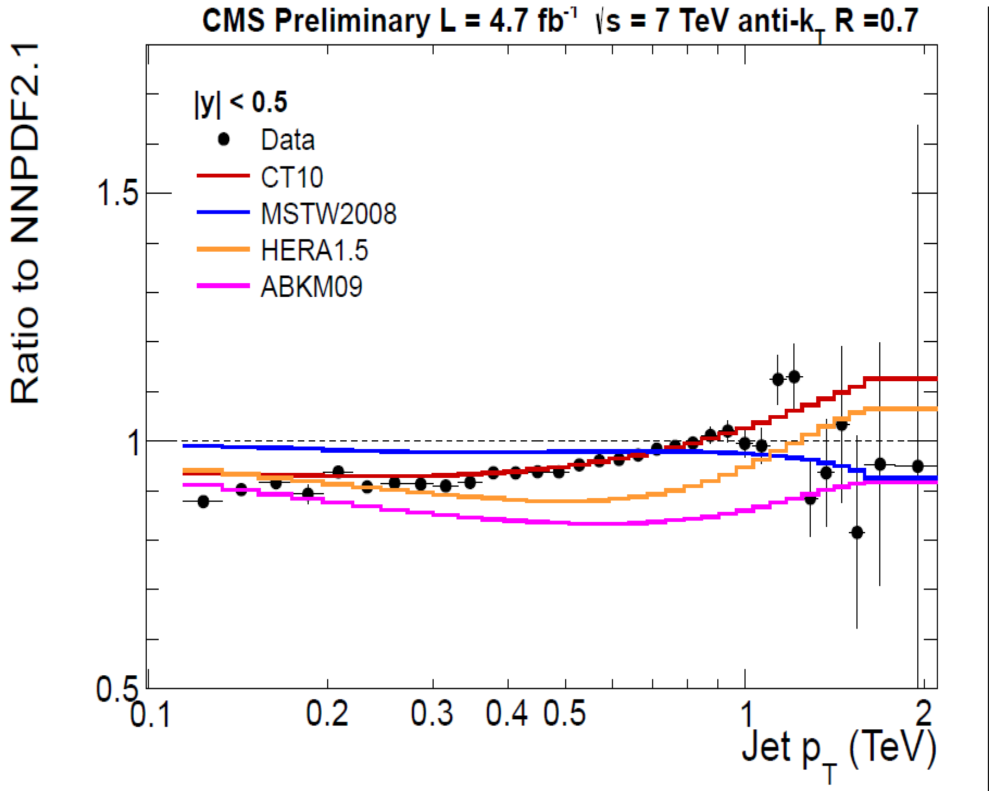


CMS 2011 √s = 7000 GeV |y| < 0.5
ATLAS 2011 √s = 7000 GeV |y| < 0.3
ATLAS 2012 √s = 2760 GeV |y| < 0.3
CDF 2008 √s = 1960 GeV |y| < 0.1
D0 2008 √s = 1960 GeV |y| < 0.4
UA2 1991 √s = 630 GeV |y| < 0.85
UA2 1985 √s = 630 GeV |y| < 0.85
UA2 1985 √s = 546 GeV |y| < 0.85
UA1 1985 √s = 546 GeV |y| < 1.40
dσ/dp_T,jet dy [pb/GeV]
p_T,jet [GeV]

Very detailed jet measurements are now available from LHC that can be compared with QCD calculations …

Example: The inclusive jet cross sections as a function of the jet P_T in rapidity bins

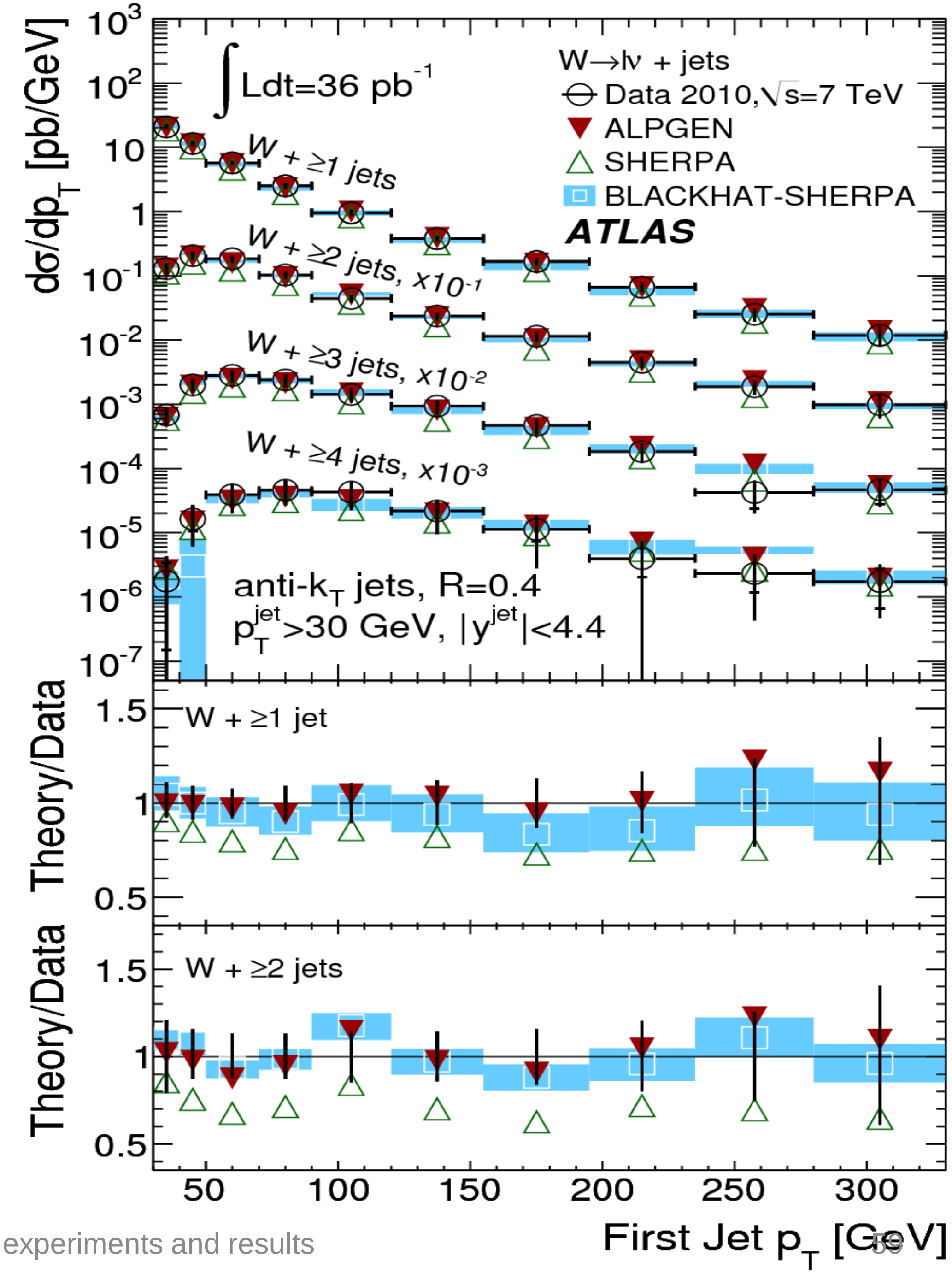




CMS-PAS-QCD-11-004

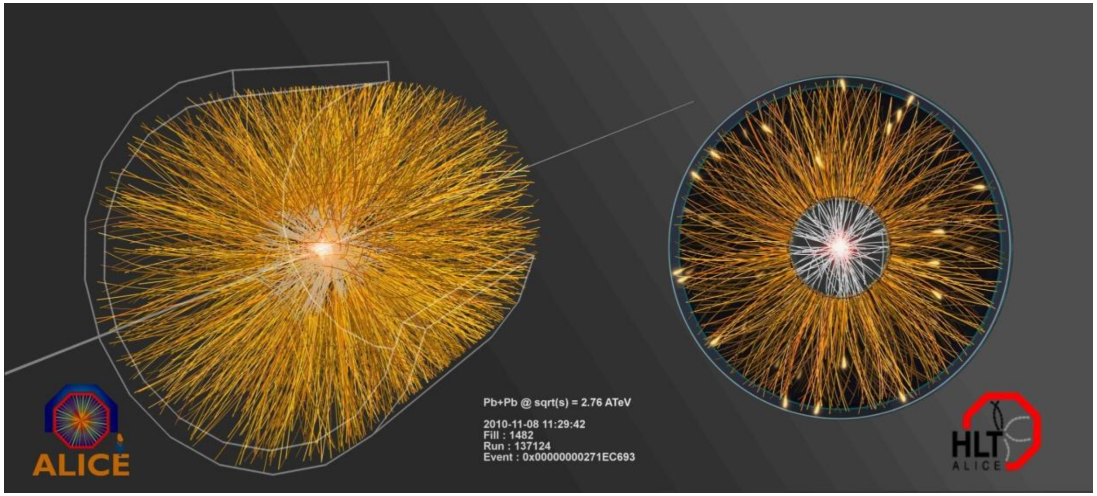
W + jet(s) production

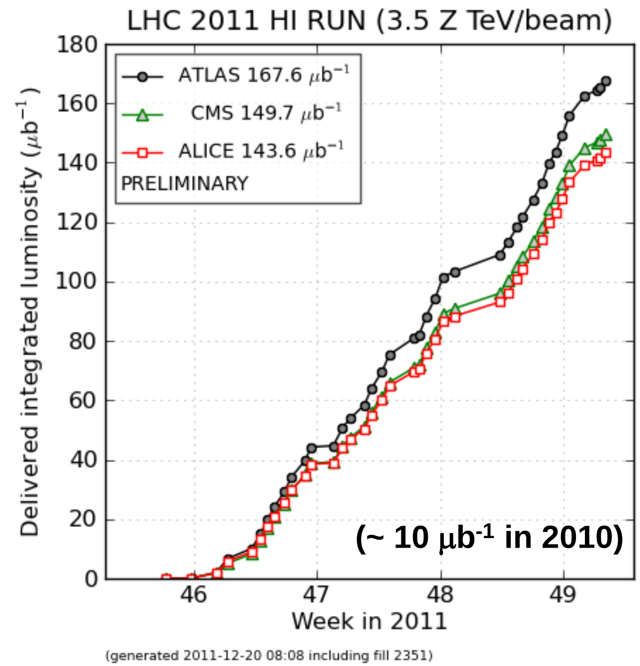
Both an interesting QCD measurement as well as a dominant background to many searches

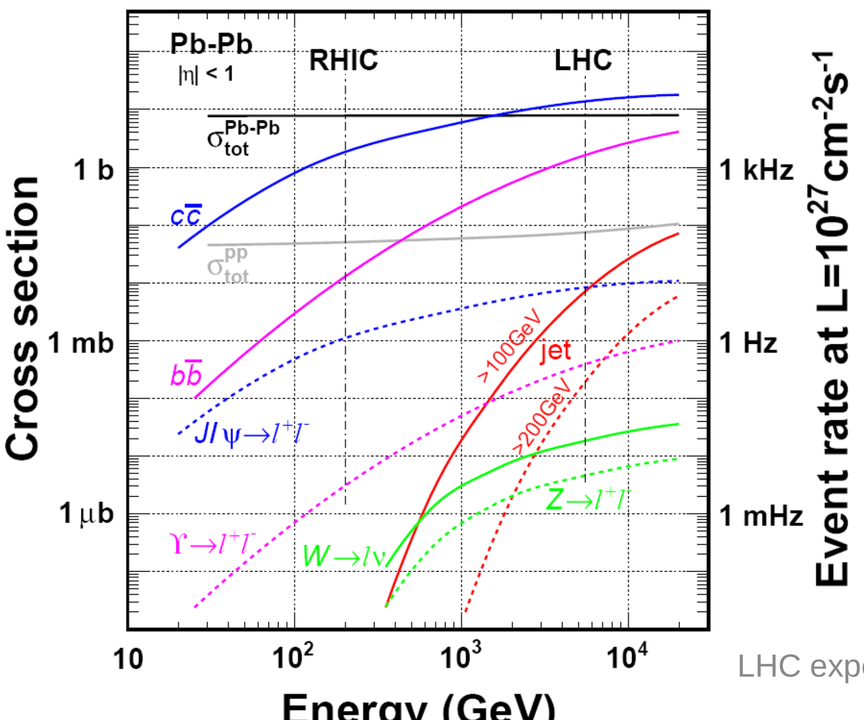


Phys. Rev. D85 (2012) 092002

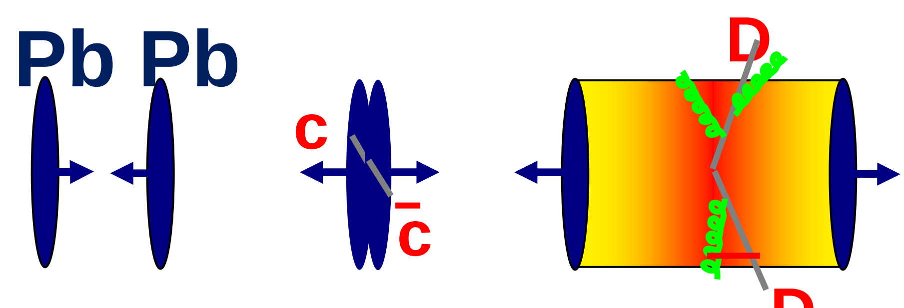
Another view on QCD: Pb - Pb collisions



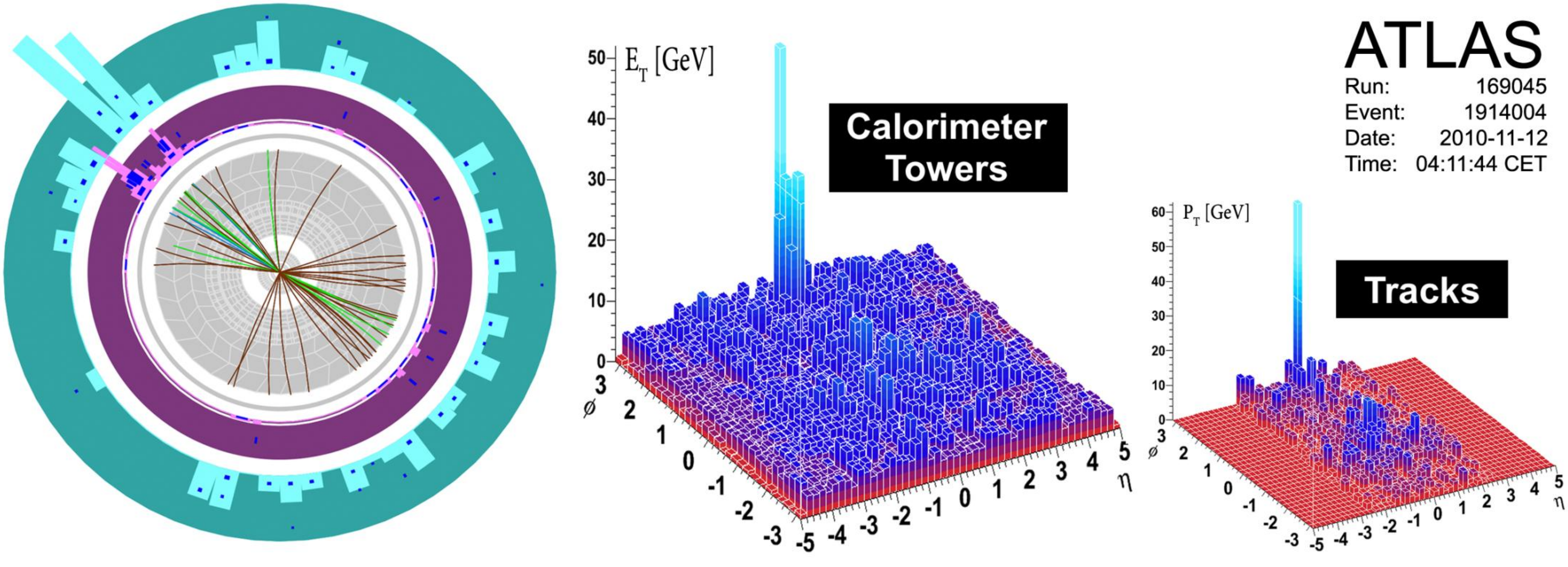




→ **large cross-sections for "hard probes" of the QCD medium (e.g. heavy quarks):**



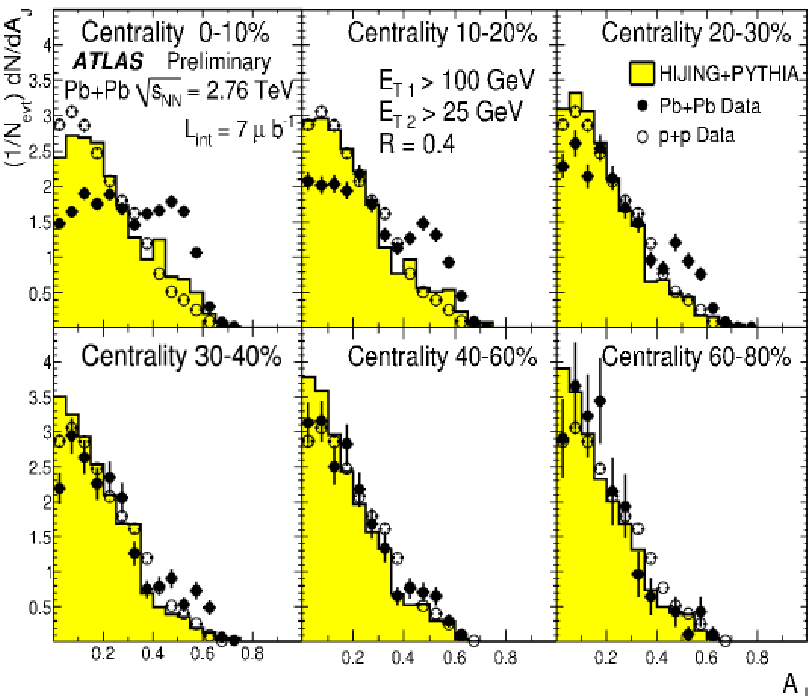
Jet quenching was observed right away in the first Pb-Pb run of the LHC in 2010

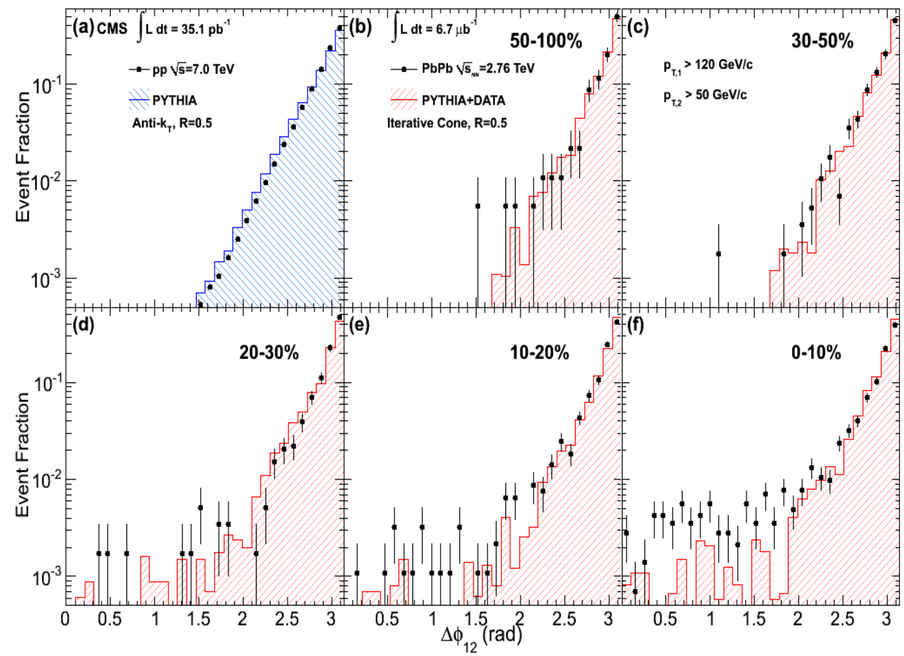


Phys. Rev. Lett. 105 (2010) 252303

The Di-jet imbalance has since be studied in great details by ATLAS and CMS

substantial imbalance in central Pb-Pb… …but no visible angular decorrelation





$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \qquad E_{T1} > 100\,GeV \qquad E_{T2} > 25\,GeV$$

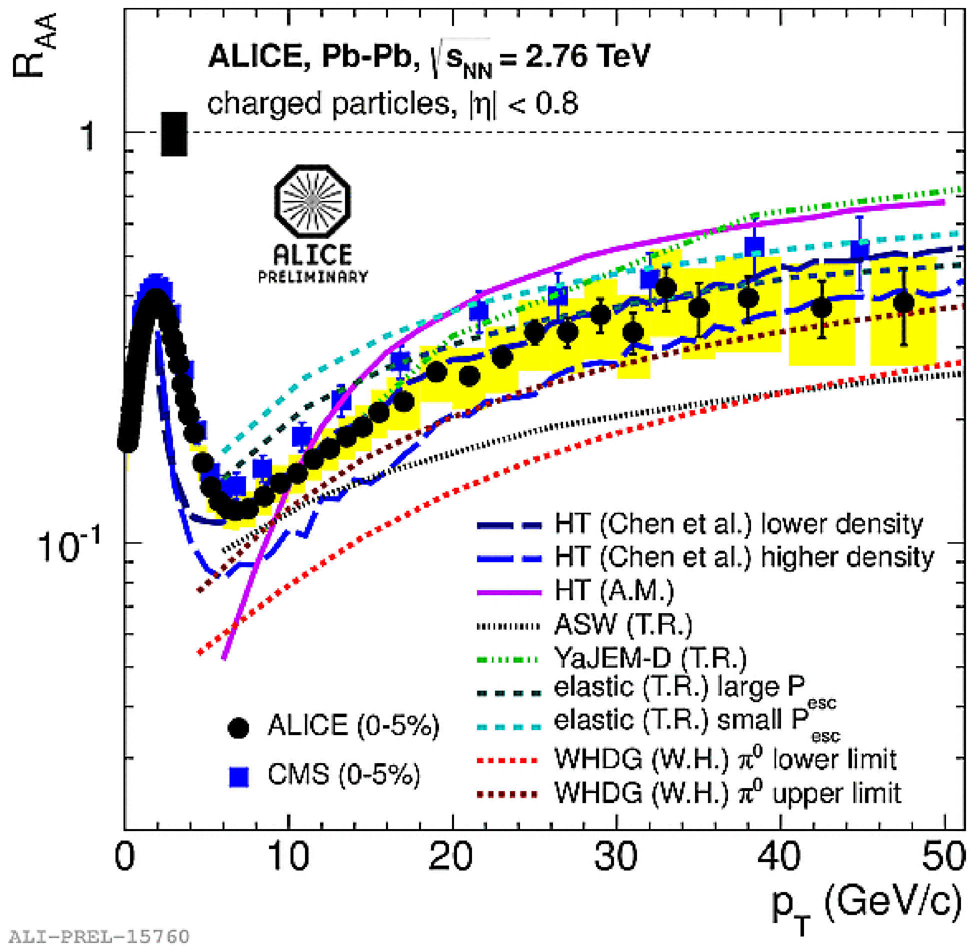
In-medium energy loss

- **Nuclear Modification Factor R_{AA}:**

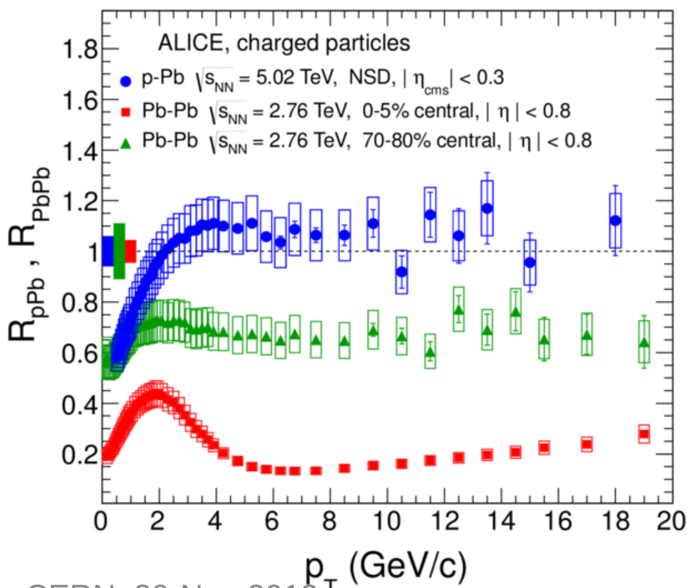
$$R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\langle N_{COLL}\rangle_{AA}\,\text{Yield}_{pp}(p_T)}$$

in the absence of nuclear modifications, N_{COLL} scaling → $R_{AA} = 1$

- **substantial suppression for hadrons**

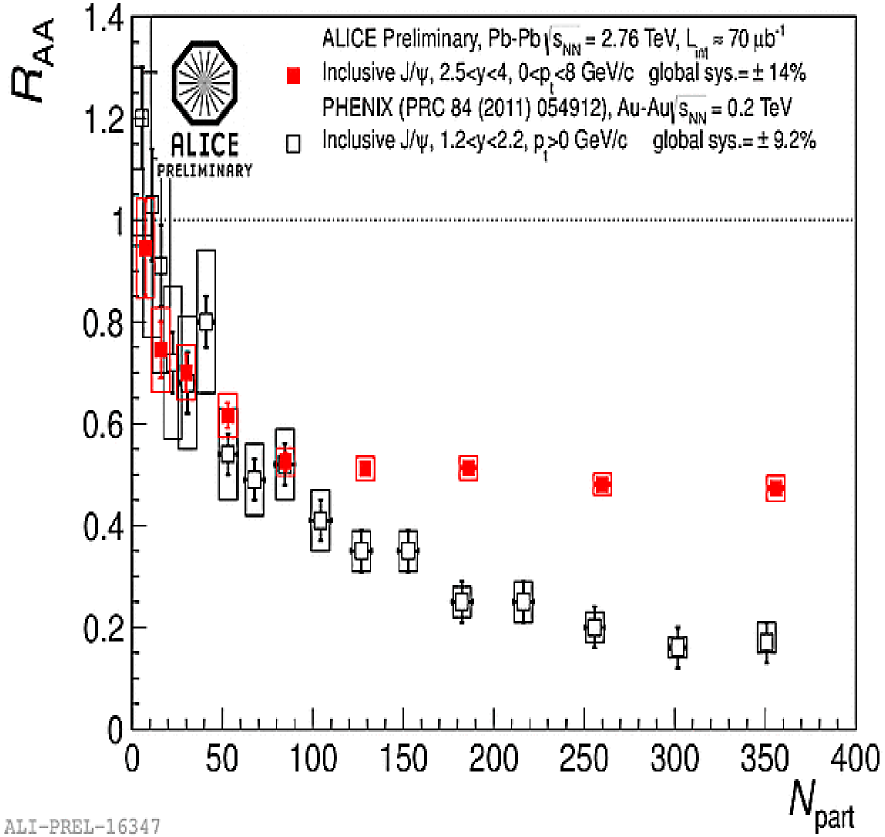


- **no suppression in p-Pb (very recent test run in preparation for 2013**

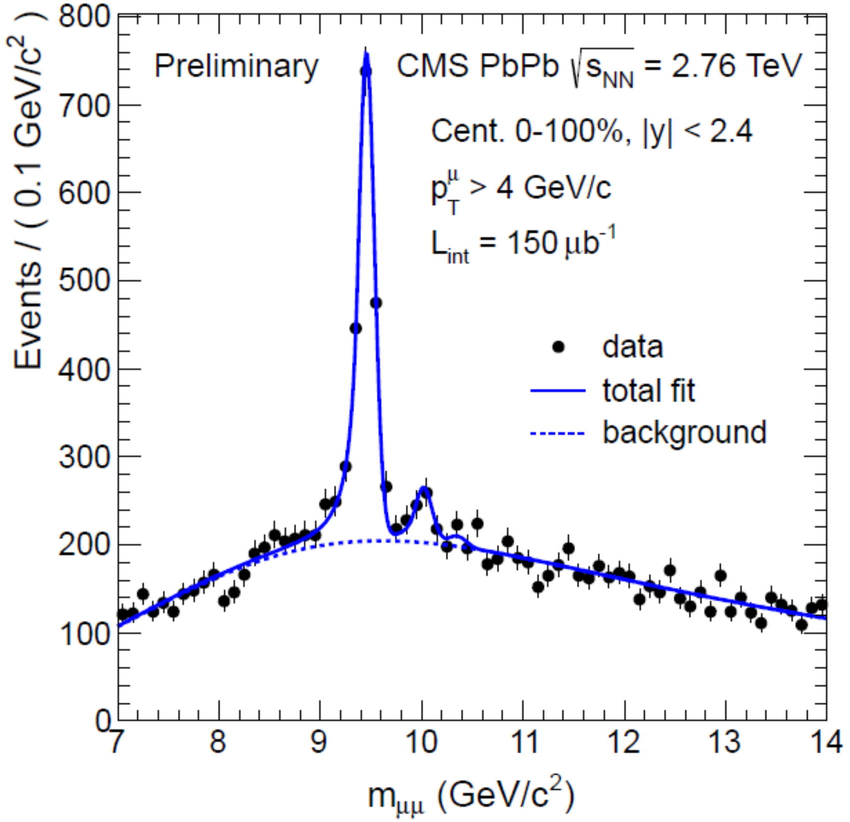


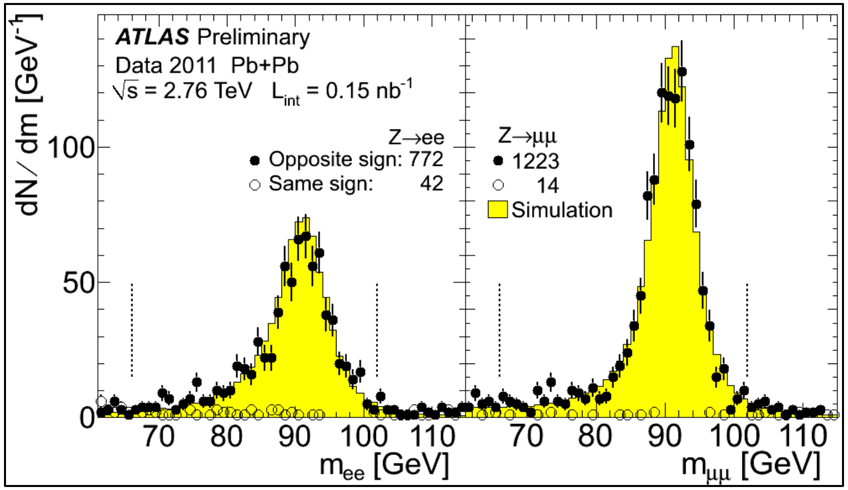
Suppression of Quarkonia

- **J/ψ: less suppressed than at RHIC**
  + very weak centrality dependence…

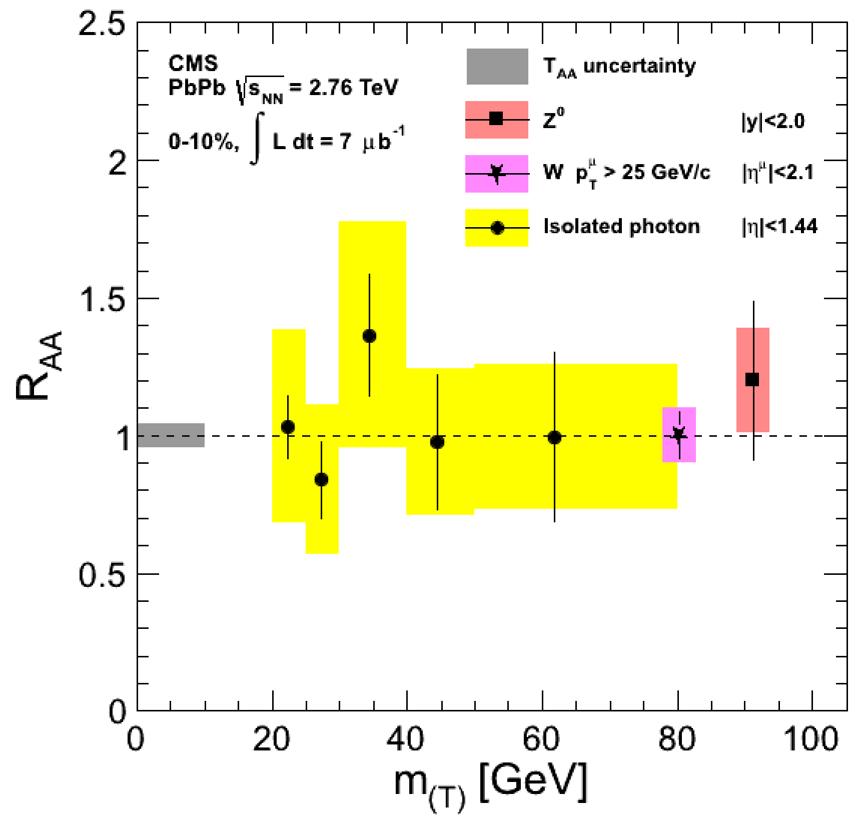


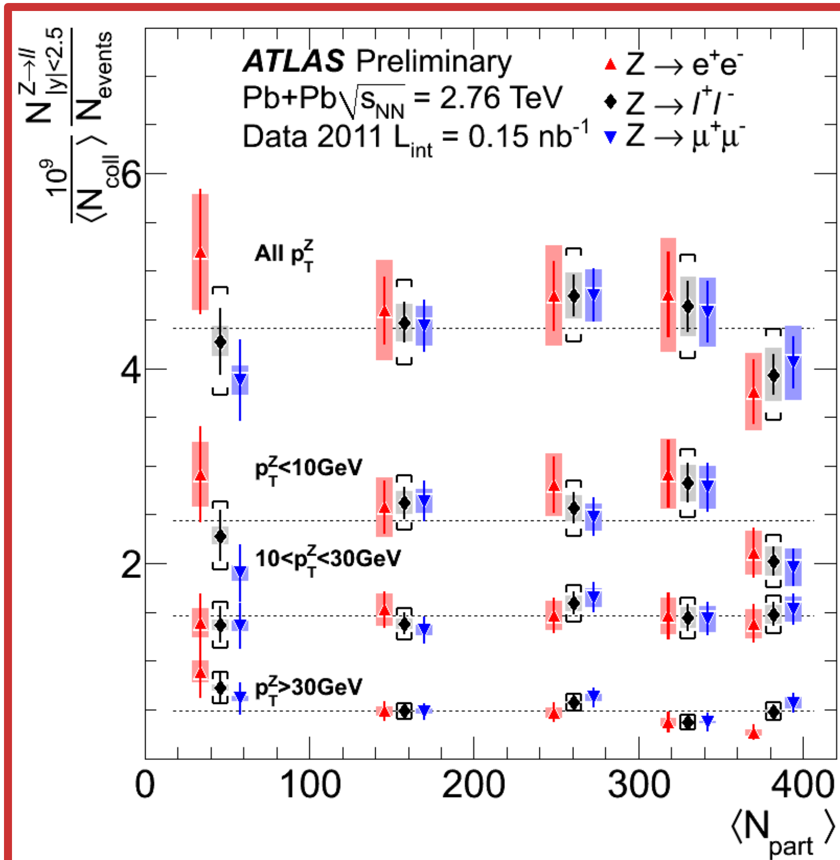
- **Υ family strongly suppressed**





No suppression for vector bosons in Pb-Pb

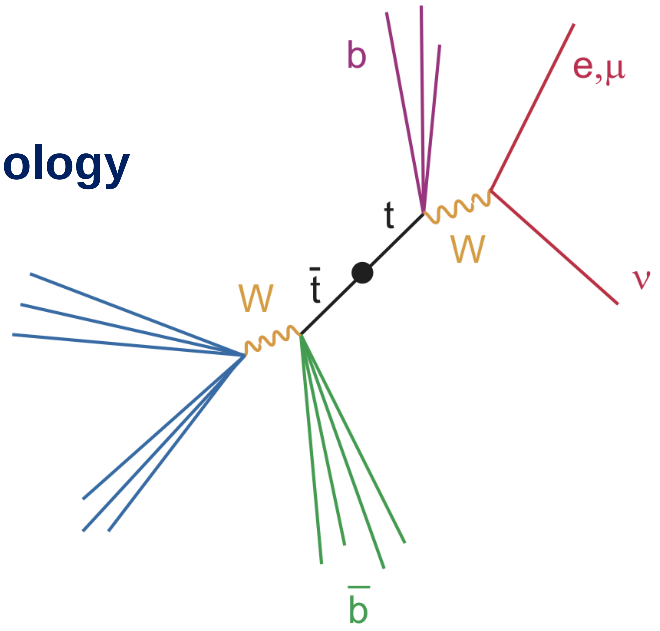




Sorry, specially to ALICE, I skip a rich harvest of detailed 'classical' studies of the LHC Heavy Ion Physics agenda

Top measurements

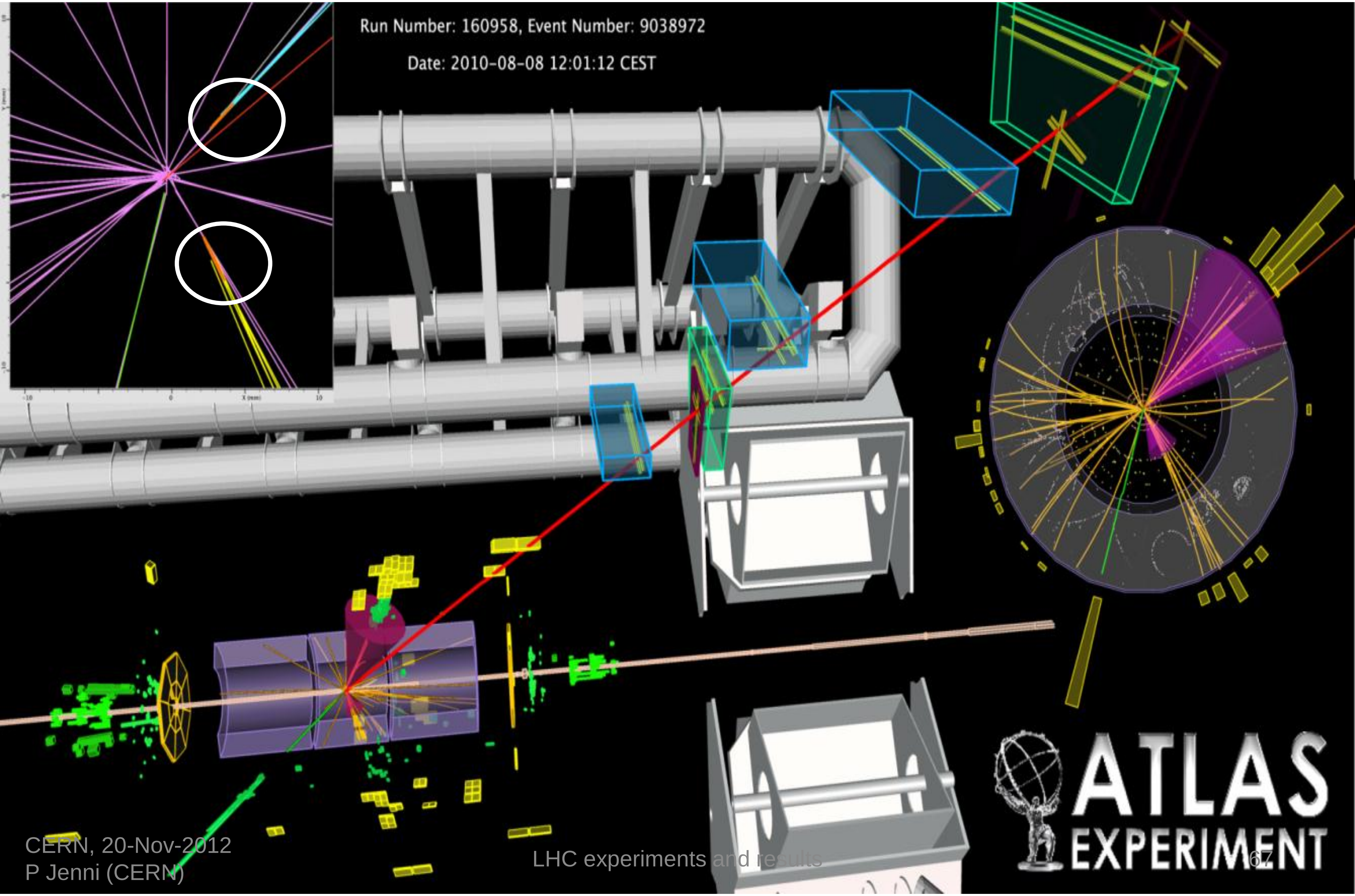
- **Complete set of ingredients to investigate production of ttbar, which is the next step in verifying the SM at the LHC:**
  - **e, μ, E_T^{miss}, jets, b-tag**
- **Assume all tops decay to Wb: event topology then depends on the W decays:**
  - **one lepton (e or μ), E_T^{miss}, jjbb (37.9%)**
  - **di-lepton (ee, μμ or eμ), E_T^{miss}, bb (6.5%)**



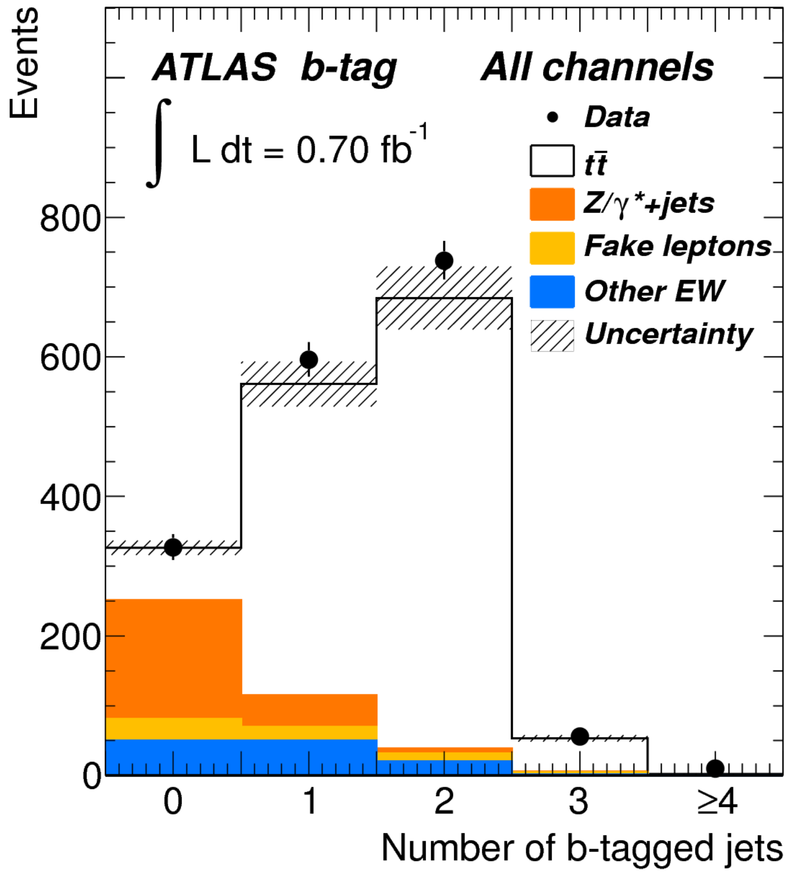
- **Data-driven methods to control QCD and W+jets backgrounds**

$t\bar{t}$ candidate event

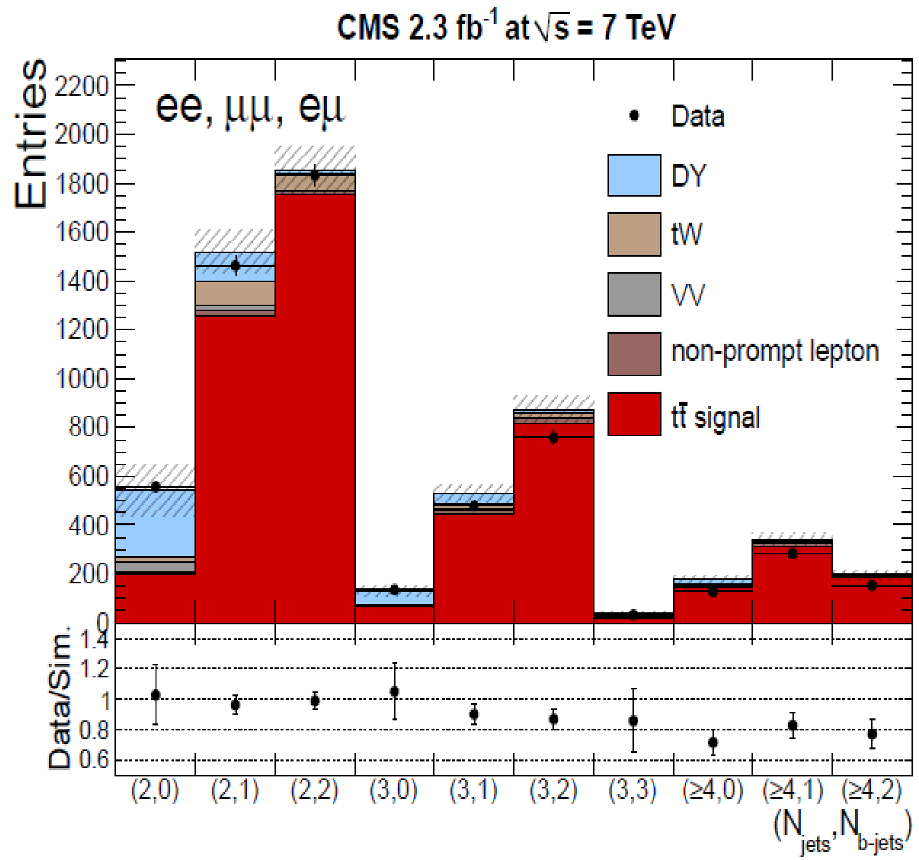
e + μ + 2 jets (b-tagged) +ETmiss

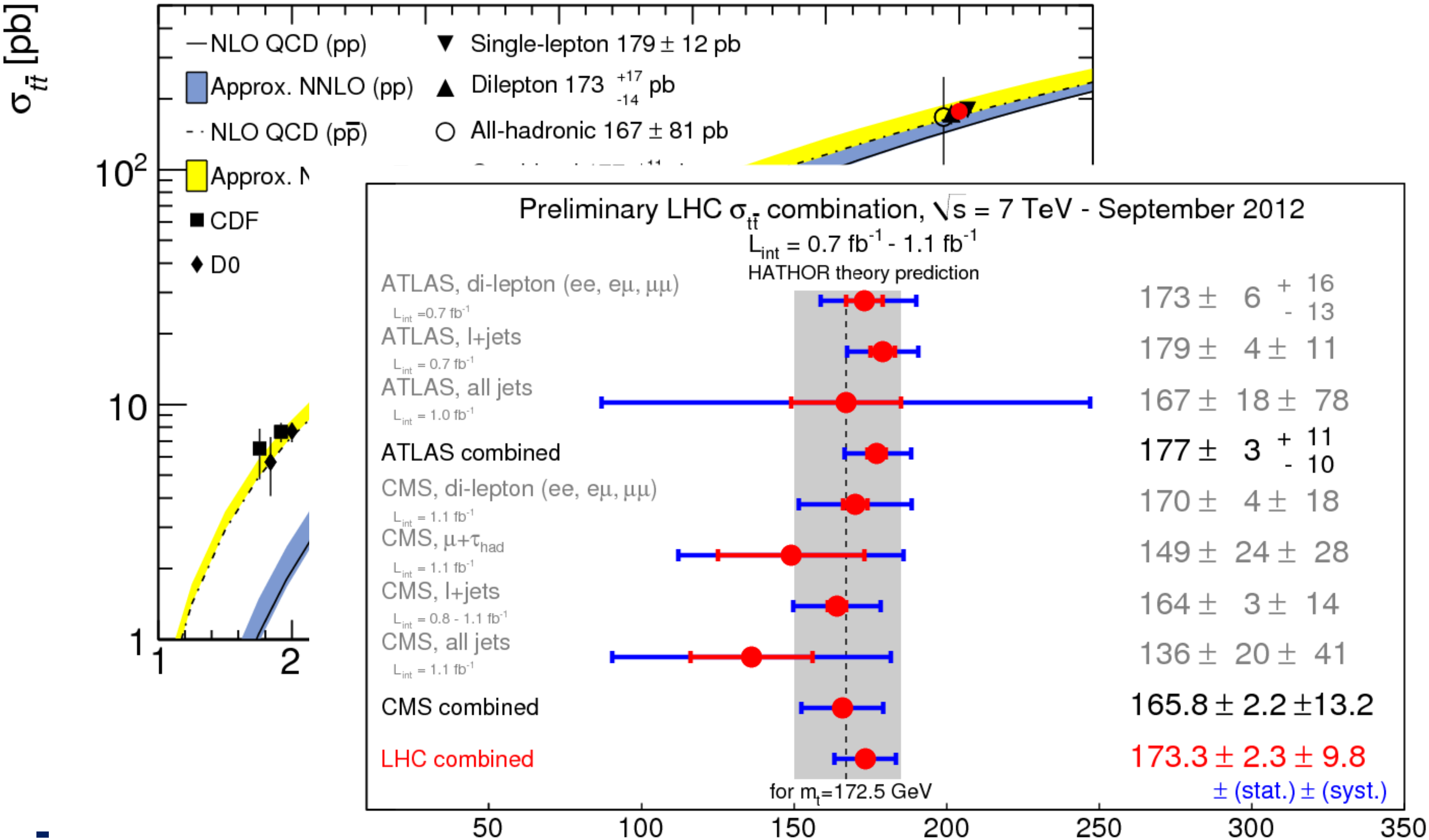


Example of top signals in the case of di-lepton channels



JHEP 1205 (2012) 059





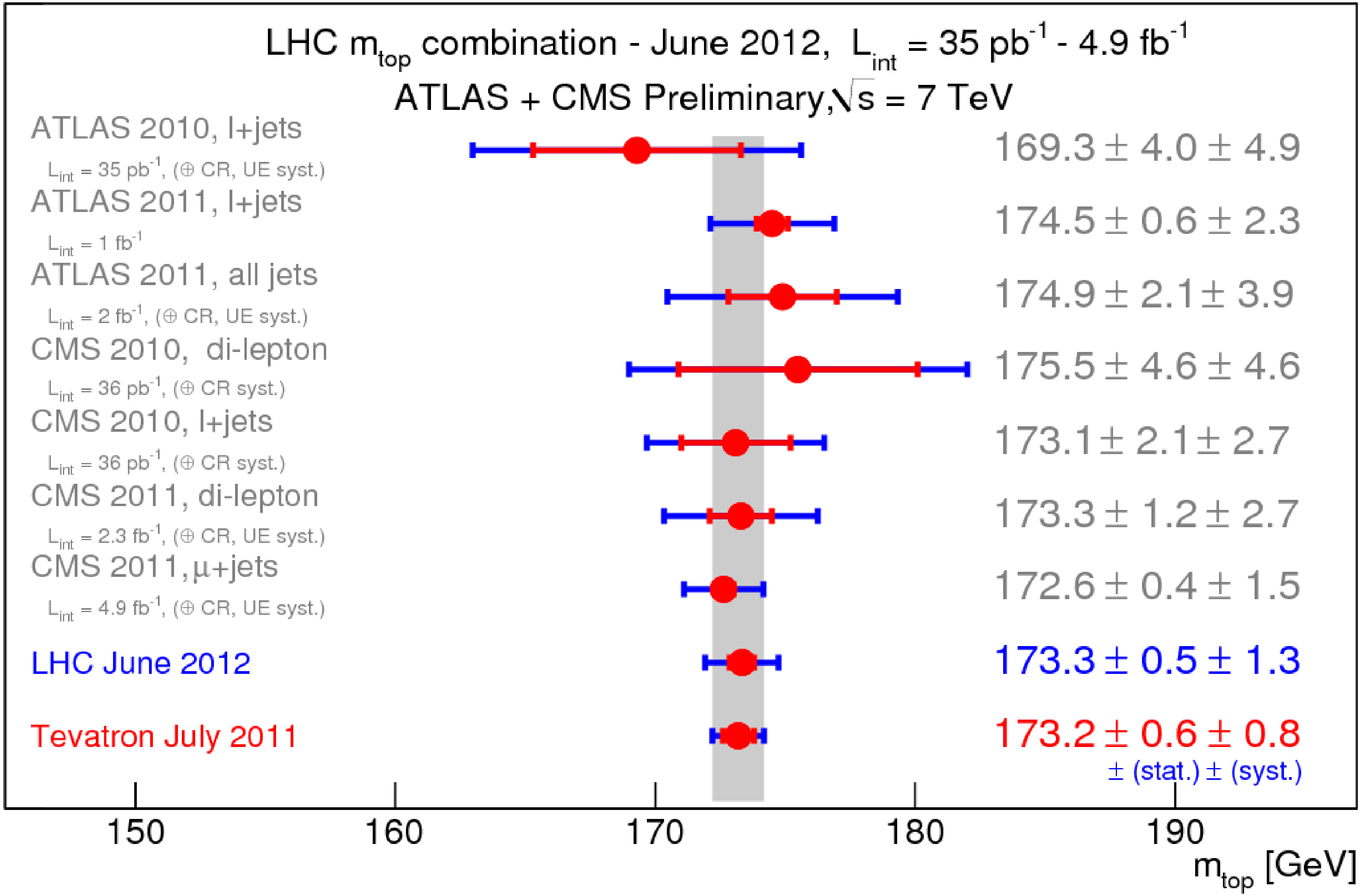
$\sigma_{t\bar{t}}$ [pb]

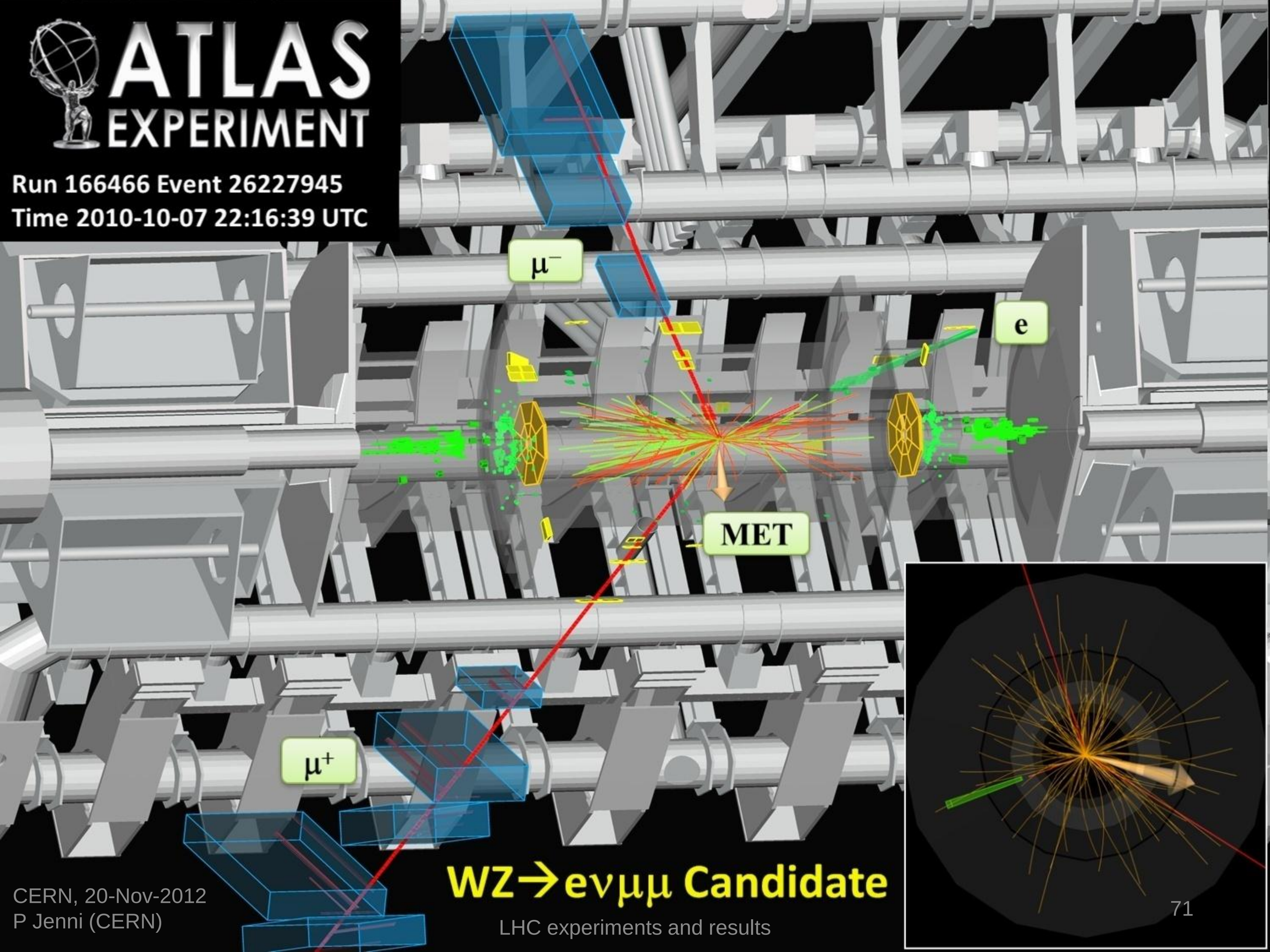
ATLAS-CONF-2012-134
CMS-PAS-TOP-12-003

$t\bar{t}$ pair production cross-sections

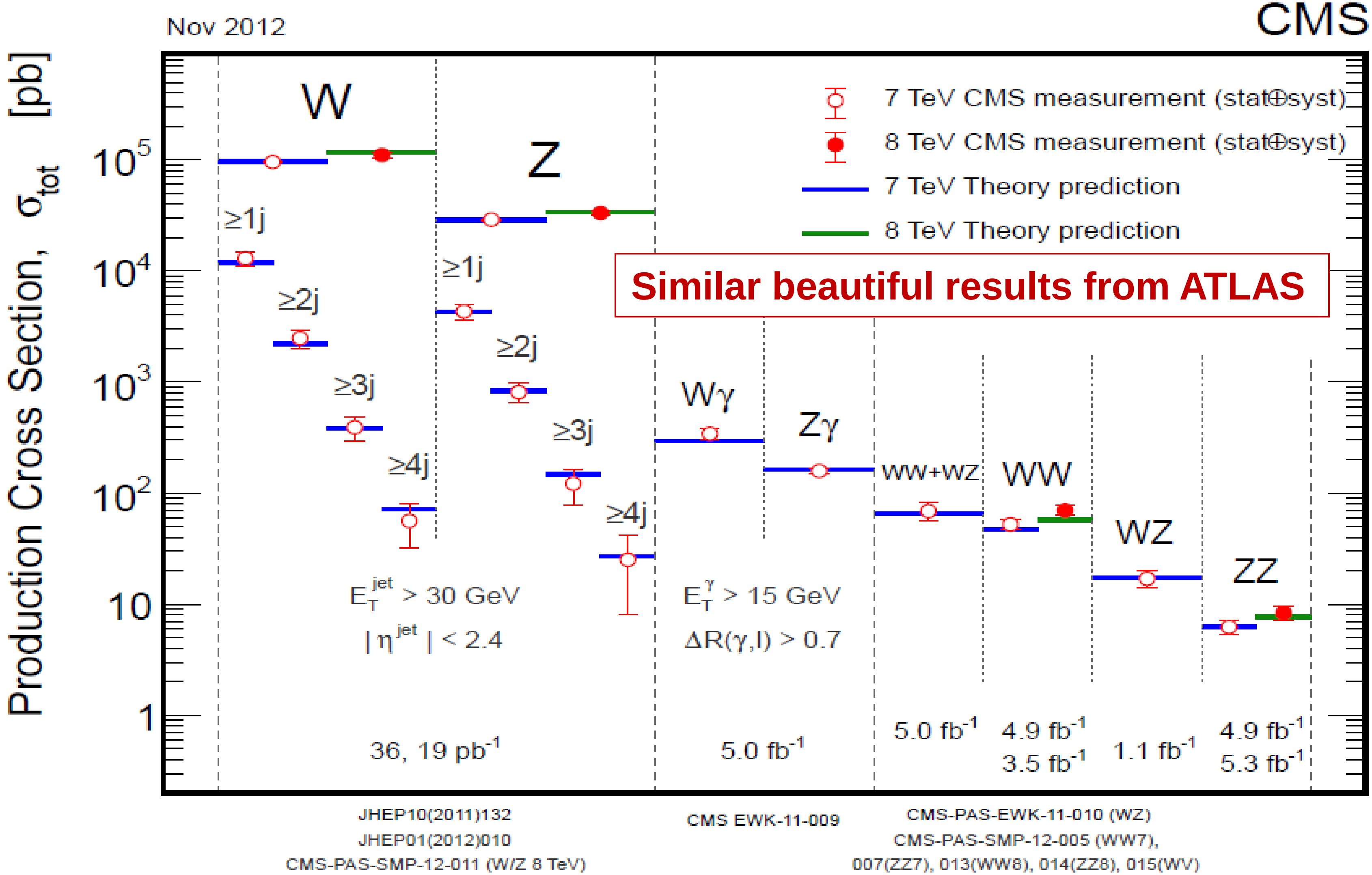
Top mass measurements

ATLAS-CONF-2012-095
CMS-PAS-TOP-12-001




ATLAS
EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate

A summary of Standard Model measurements

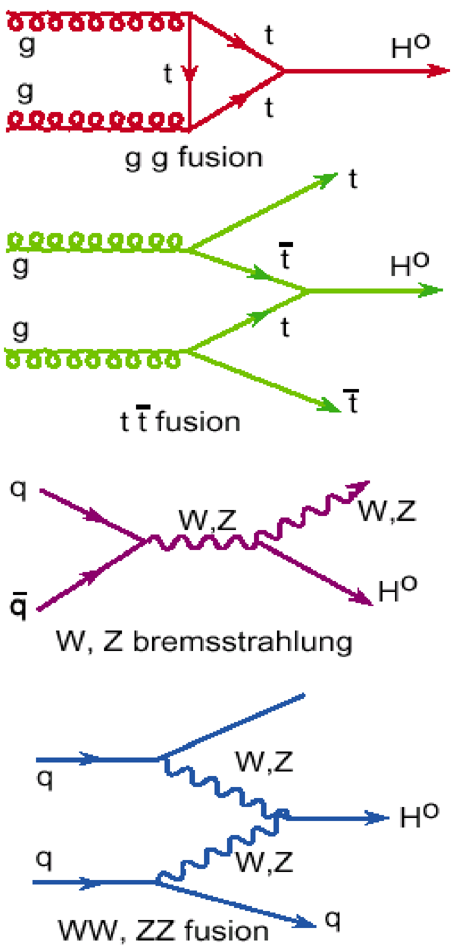


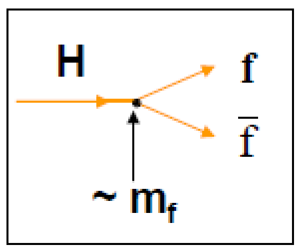
Similar beautiful results from ATLAS

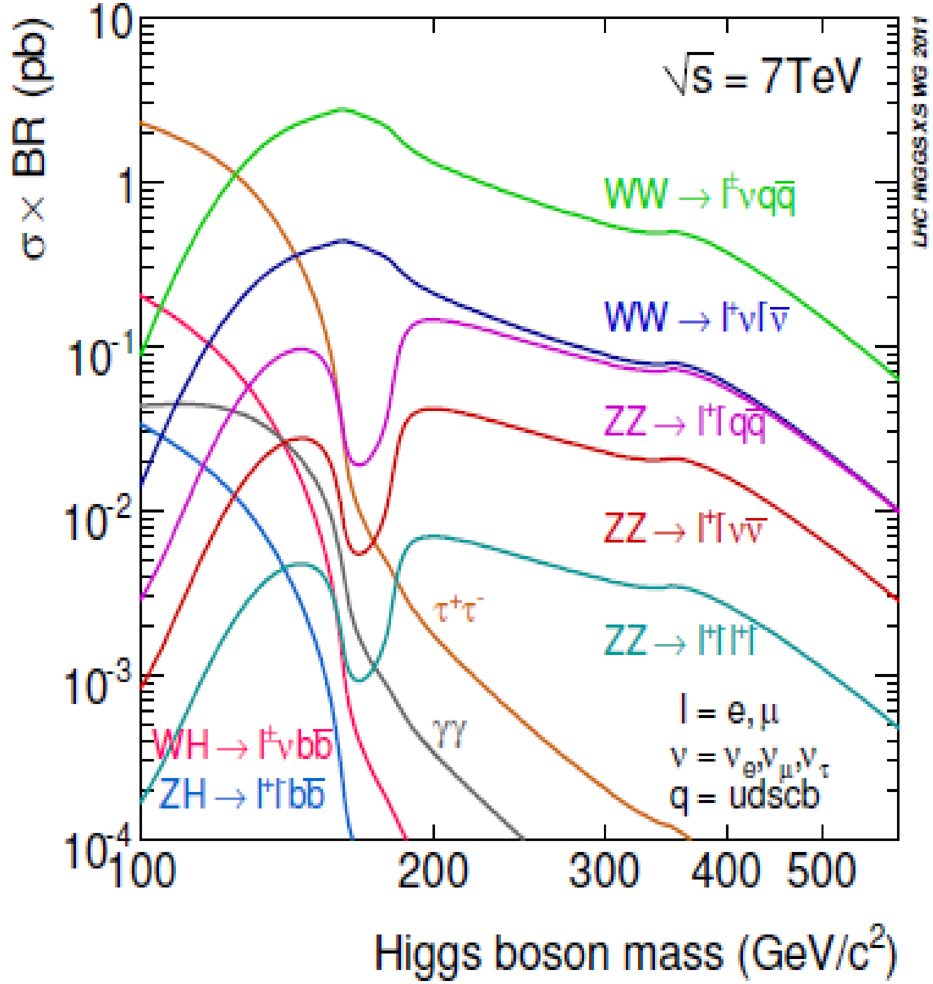
The excellent performance in measuring Standard Model physics gives confidence for the readiness of the two experiments to search for New Physics

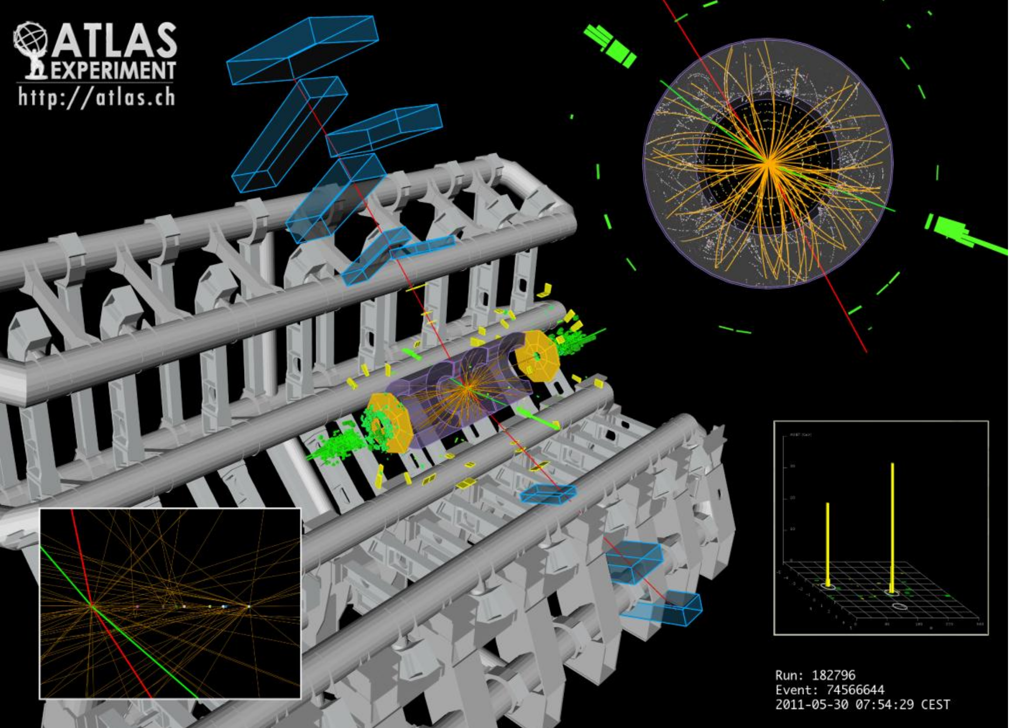
Search for the boson (H) of the EW symmetry breaking

SM H boson production cross sections times observable decay branching ratios at 7 TeV







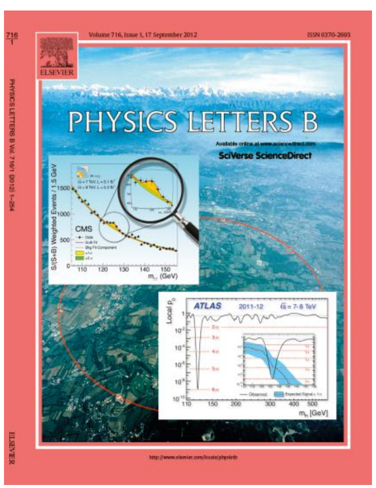


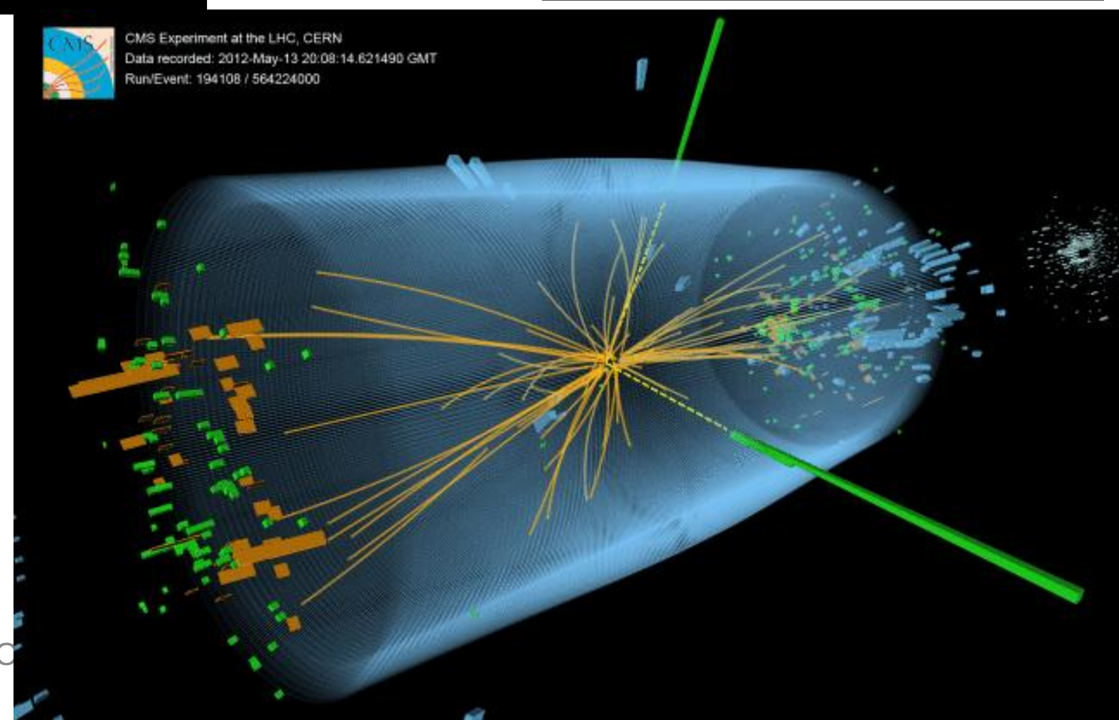
The Higgs(-like) boson

Results shown are based on the two simultaneous publications from ATLAS and CMS plus their partial updates as they were presented last week at the HCP 2012 conference in Kyoto

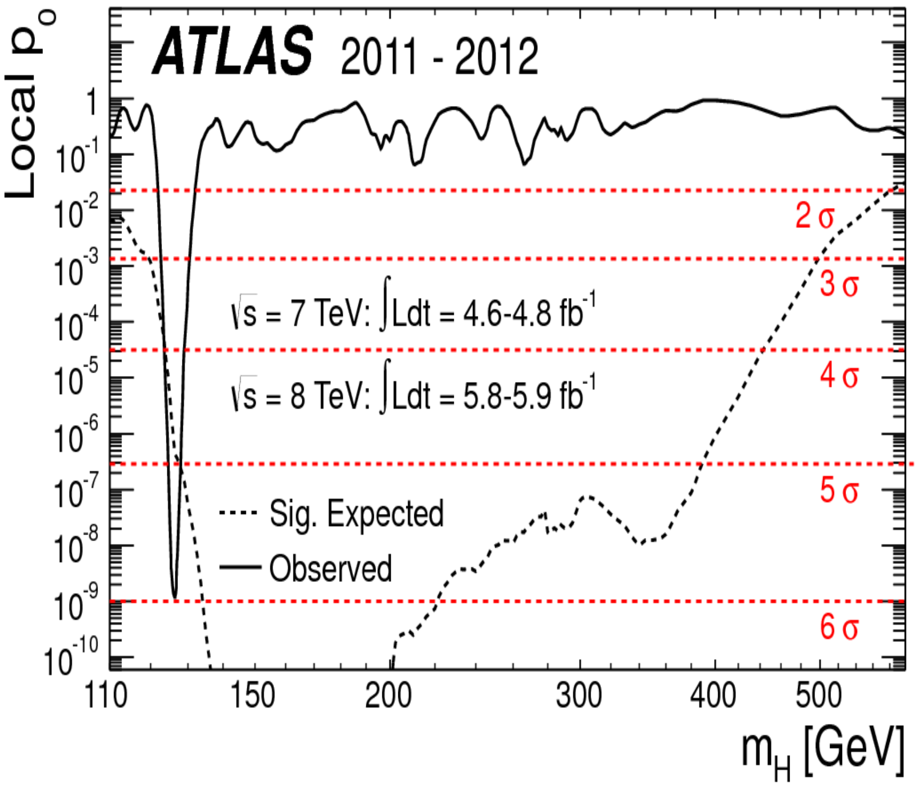
Candidate event for H → $\gamma\gamma$

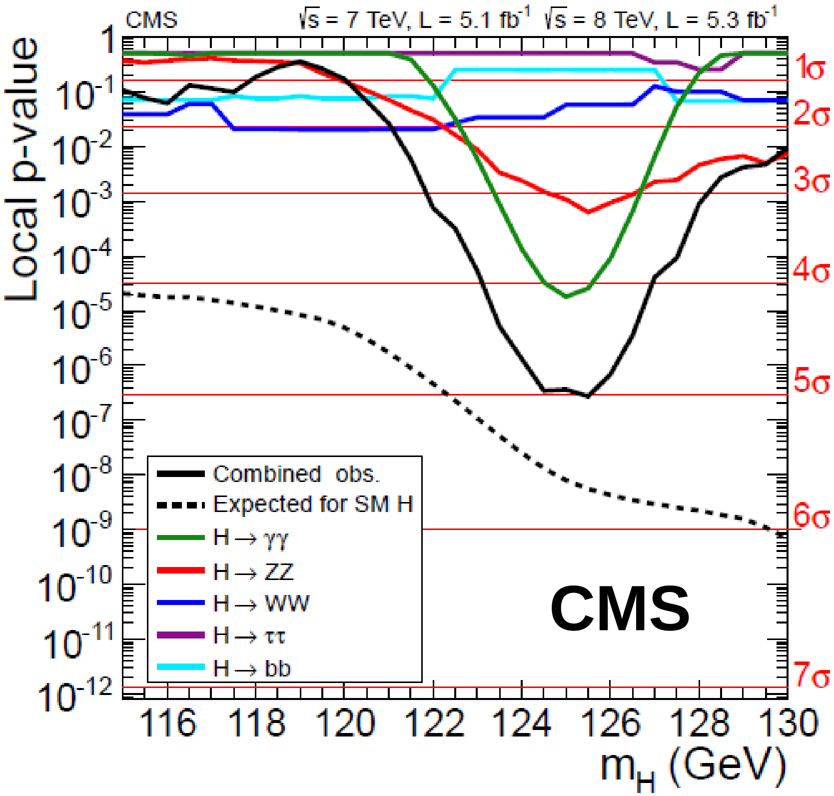
Candidate event for H → ZZ^* → ee $\mu\mu$





Two of the by now historical plots from the July 2012 discovery announcement

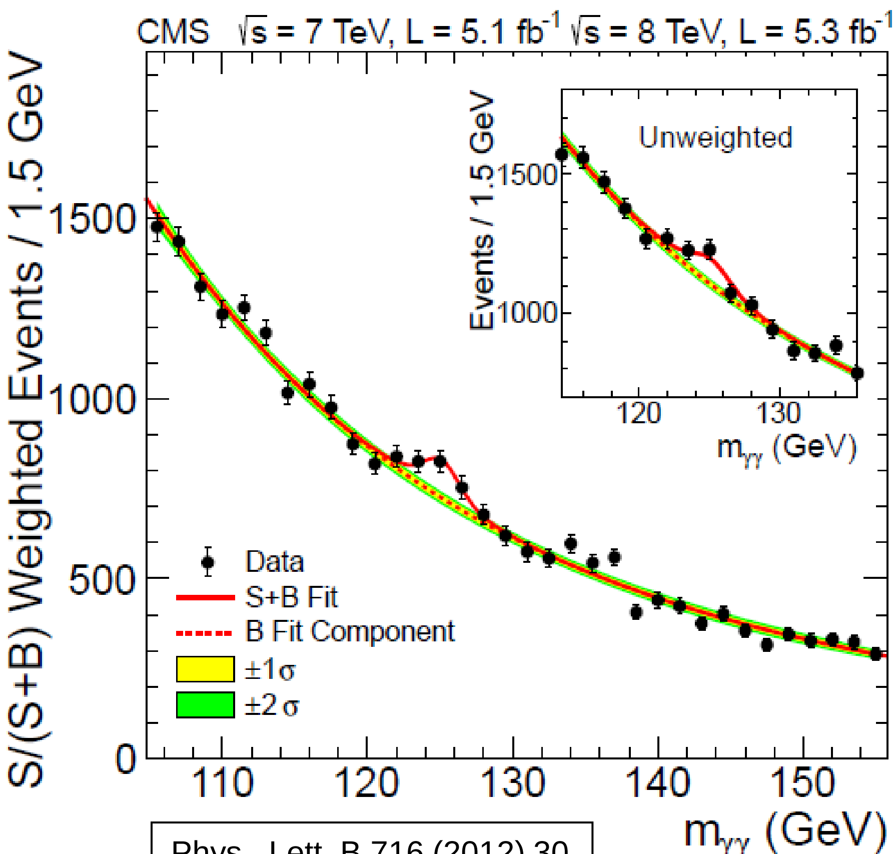




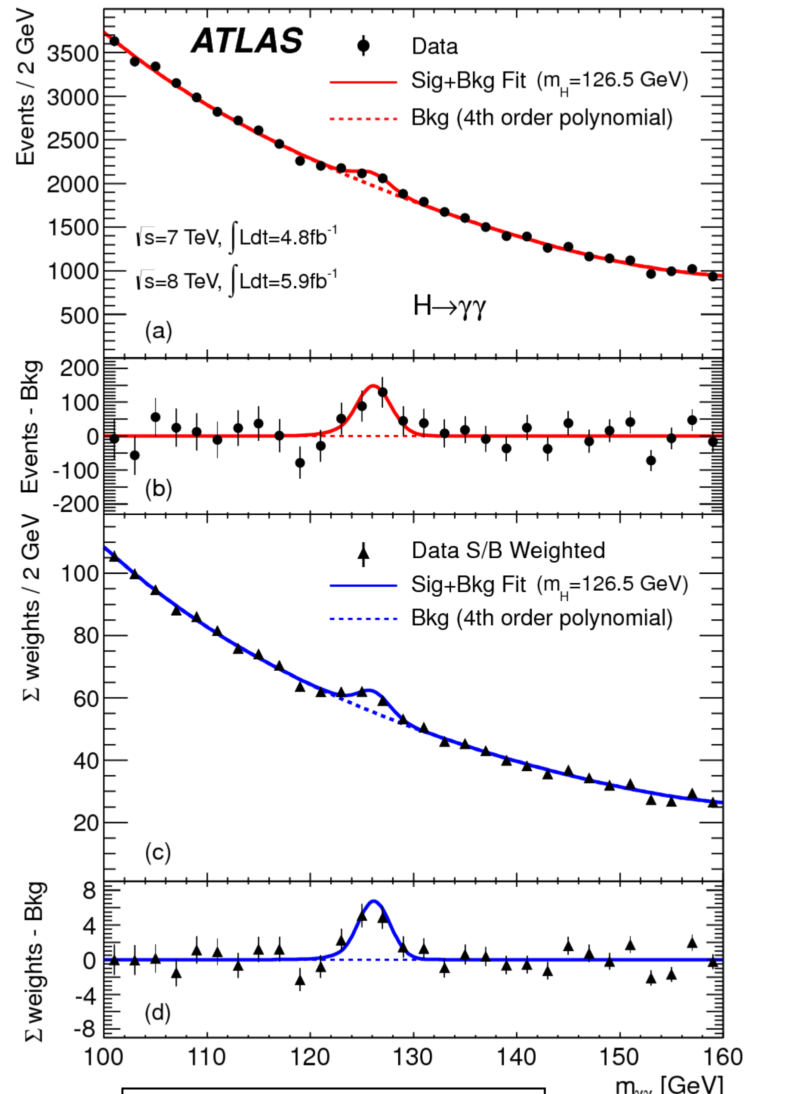
Observed data compared to the probability that the background fluctuates to fake the observed excess of events, and what is expected from a SM Higgs

H → γγ

- Small cross-section: σ ~ 40 fb
- Expected S/B ~ 0.02
- Simple final state: two high-p_T isolated photons
- Main background: γγ continuum (irreducible) and fake γ from γj and jj events (reducible)



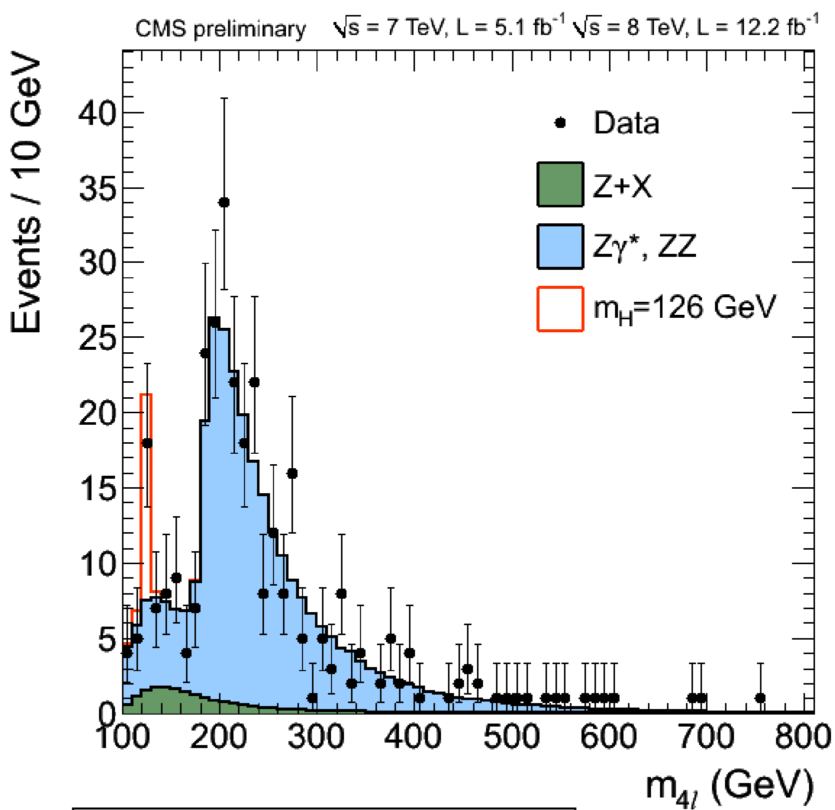
Phys. Lett. B 716 (2012) 30



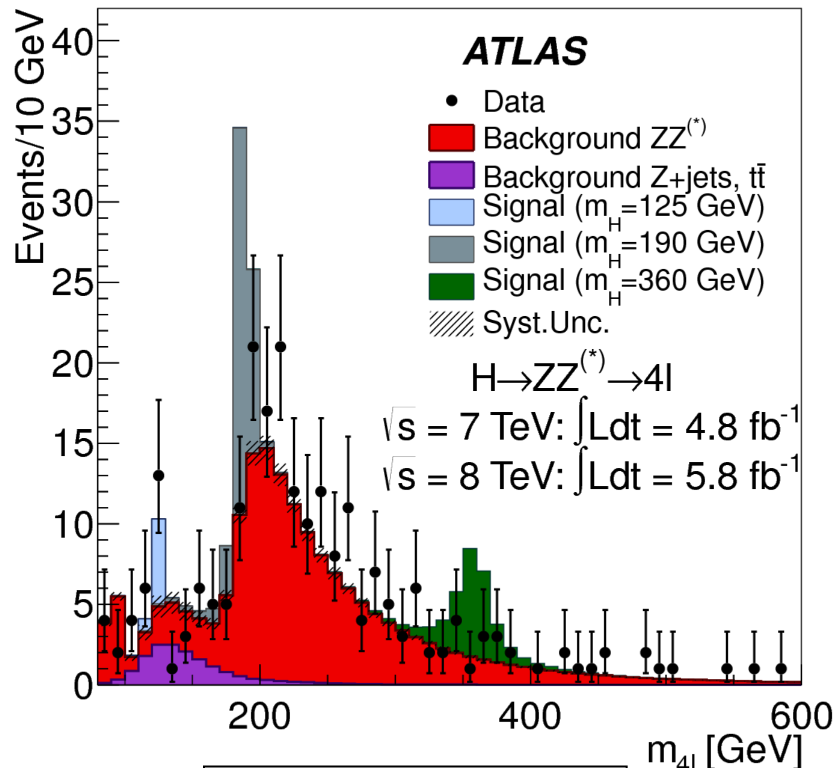
Phys. Lett. B 716 (2012) 1

H → ZZ$^{(*)}$ → 4l (4e, 4μ, 2e2μ)

- Rare process, small cross section: σ ~ 2-5 fb
- However: pure: S/B ~ 1
- 4 leptons:
- Main background: ZZ$^{(*)}$ (irreducible)
  In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets



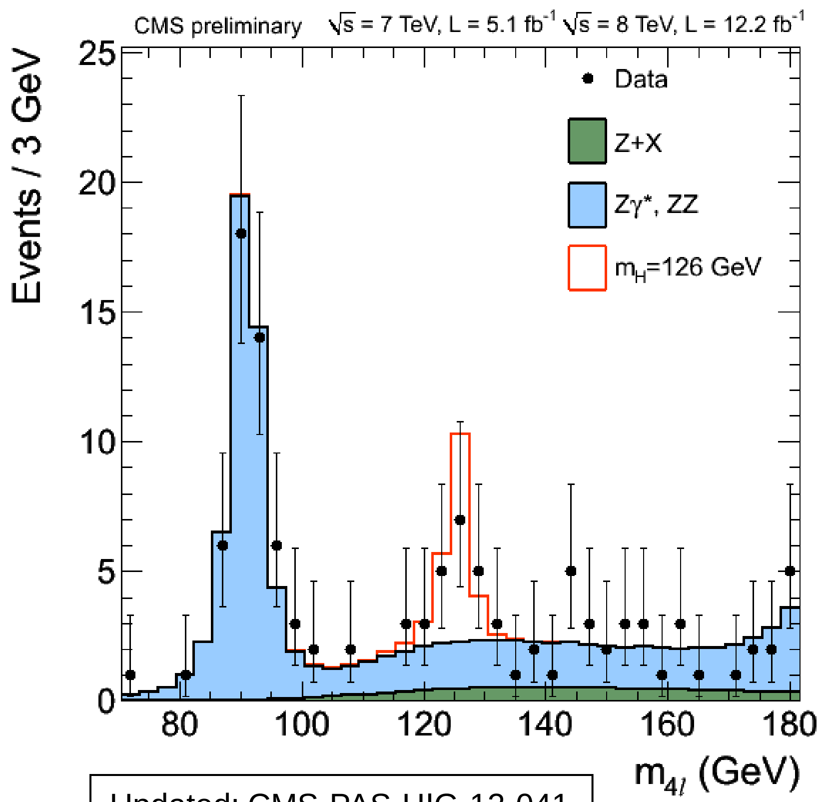
Updated: CMS-PAS-HIG-12-041



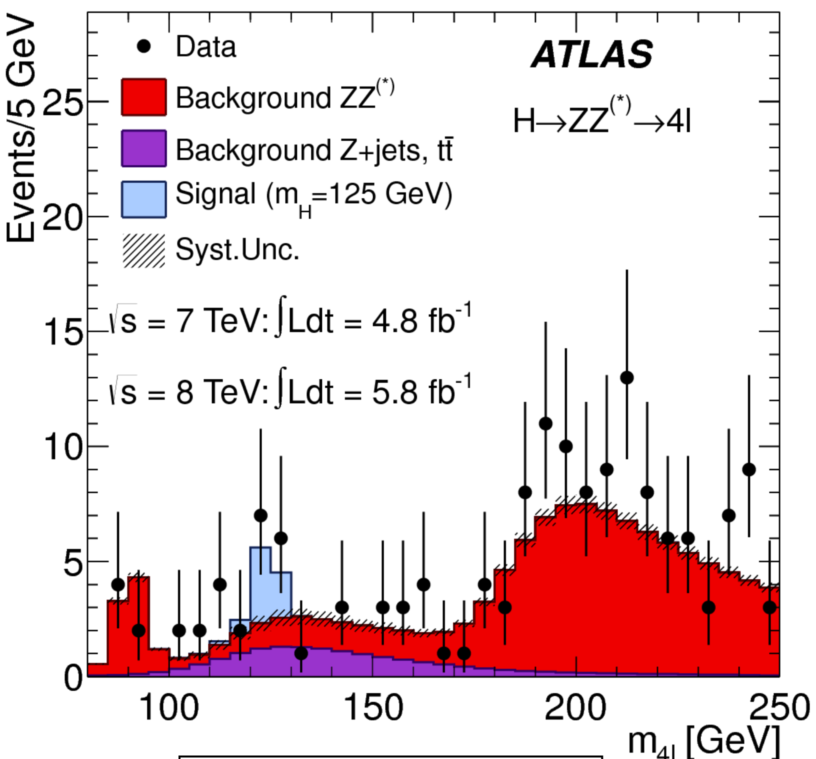
Phys. Lett. B 716 (2012) 1

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ (4e, 4μ, 2e2μ)

- Rare process, small cross section: σ ~ 2-5 fb
- However: pure: S/B ~ 1
- 4 leptons:
- Main background: $ZZ^{(*)}$ (irreducible)
  In addition: Zbb, Z+jets, tt with two leptons from b-quarks or jets



Updated: CMS-PAS-HIG-12-041

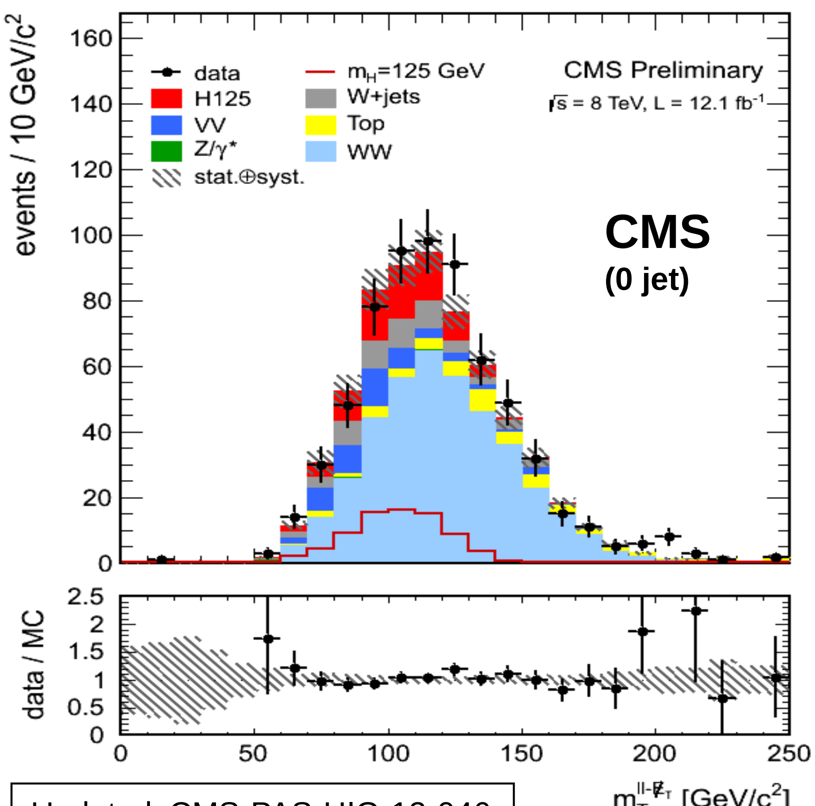


Phys. Lett. B 716 (2012) 1

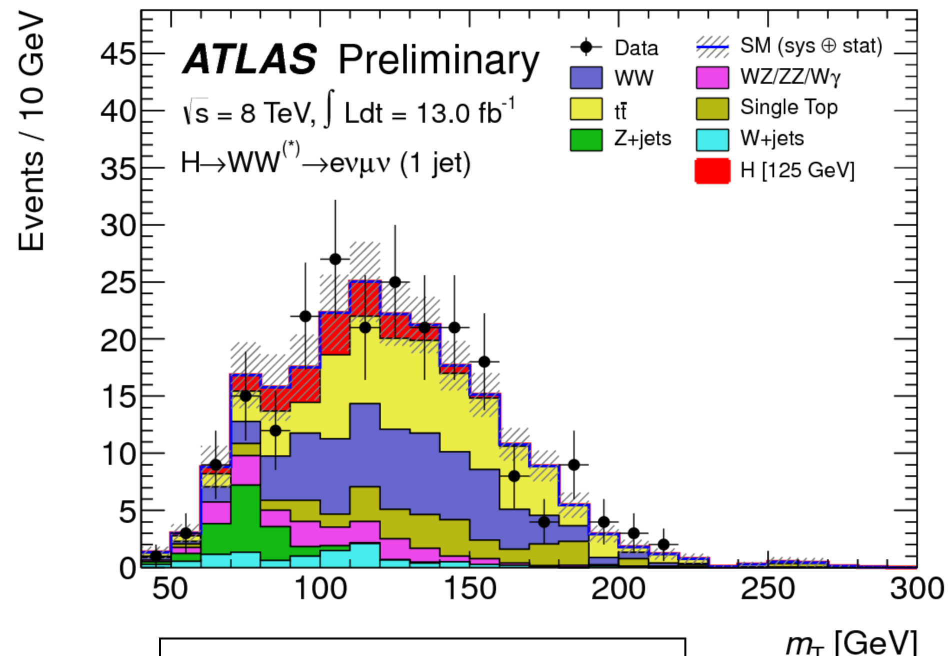
H → WW(*) → lνlν (eνeν, μνμν, eνμν)

- Very sensitive channel over ~ 125-180 GeV (σ ~ 200 fb)
- Challenging: 2ν → no mass reconstruction/peak → “counting channel”
- 2 isolated opposite-sign leptons, use eνμν only for 2012 data, large E_T^{miss}
- Main backgrounds: WW, top, Z+jets, W+jets
- Topological cuts against “irreducible” WW background

(Just two example distributions from several categories used in both experiments)



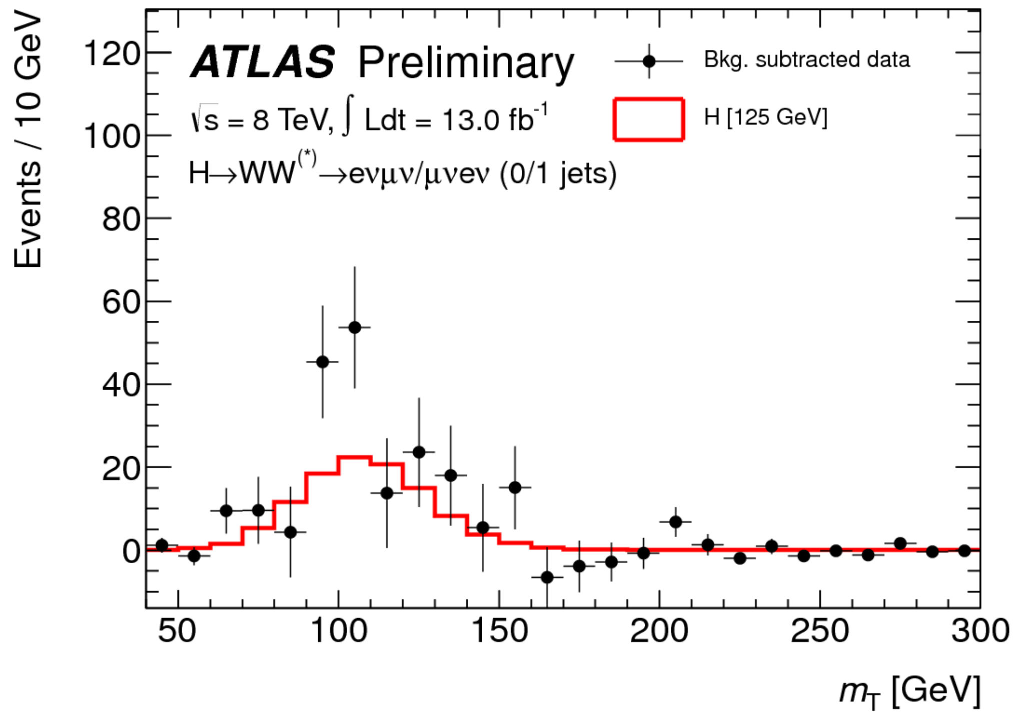
Updated: CMS-PAS-HIG-12-046



Updated: ATLAS-CONF-2012-158

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

To get a feeling for the number of events, and of the background-subtracted distributions (example ATLAS)

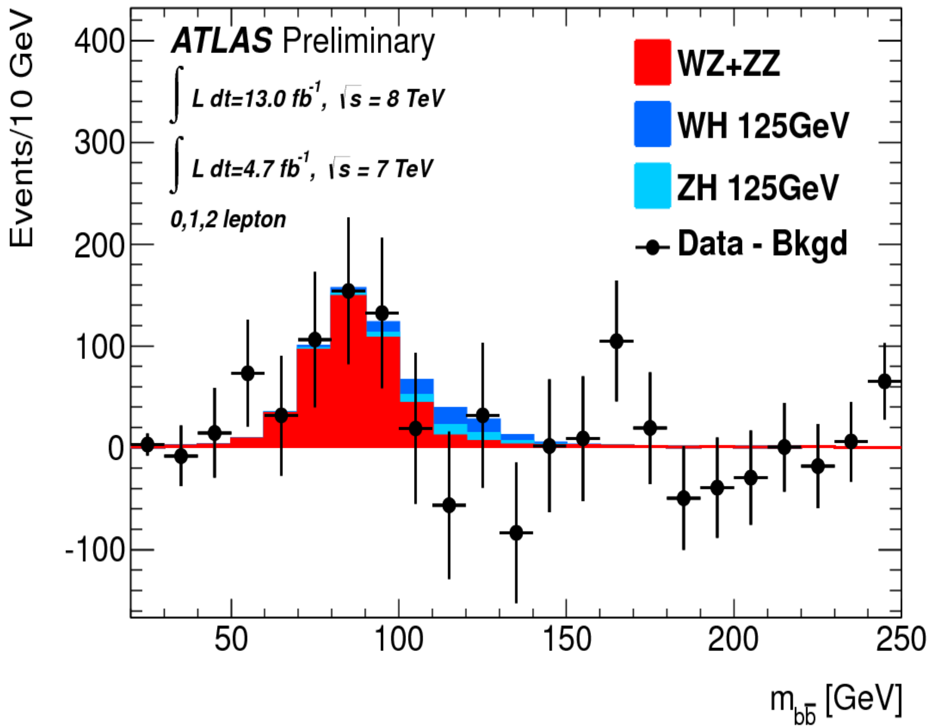


	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + jets	W + jets	Total Bkg.	Obs.
H+ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
H+ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

Updated: ATLAS-CONF-2012-158

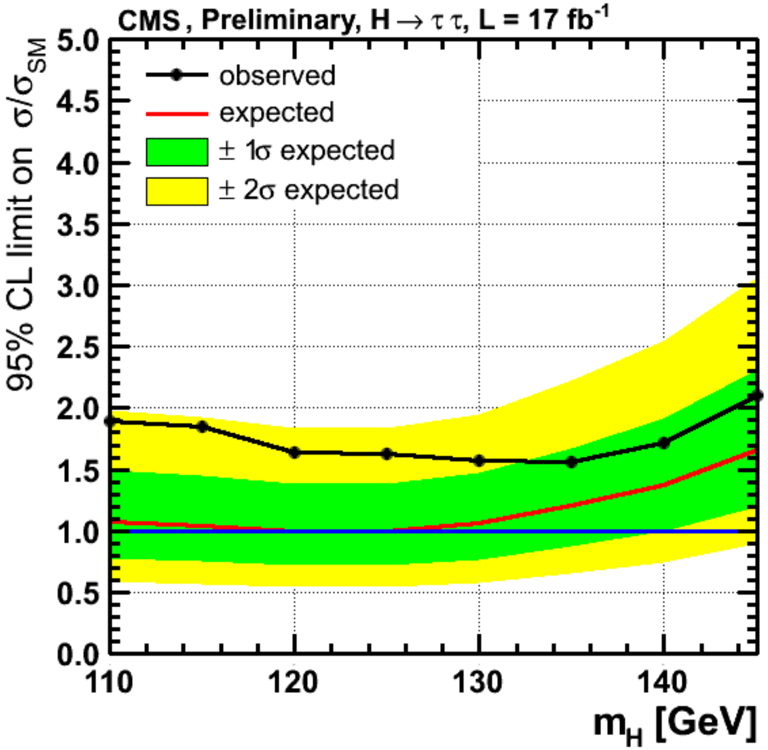
Many more analyses are progressing, and a wealth of results can be expected from the full 7+8 TeV data sets…

Just two examples:



VH production with H → bb

Updated: ATLAS-CONF-2012-161

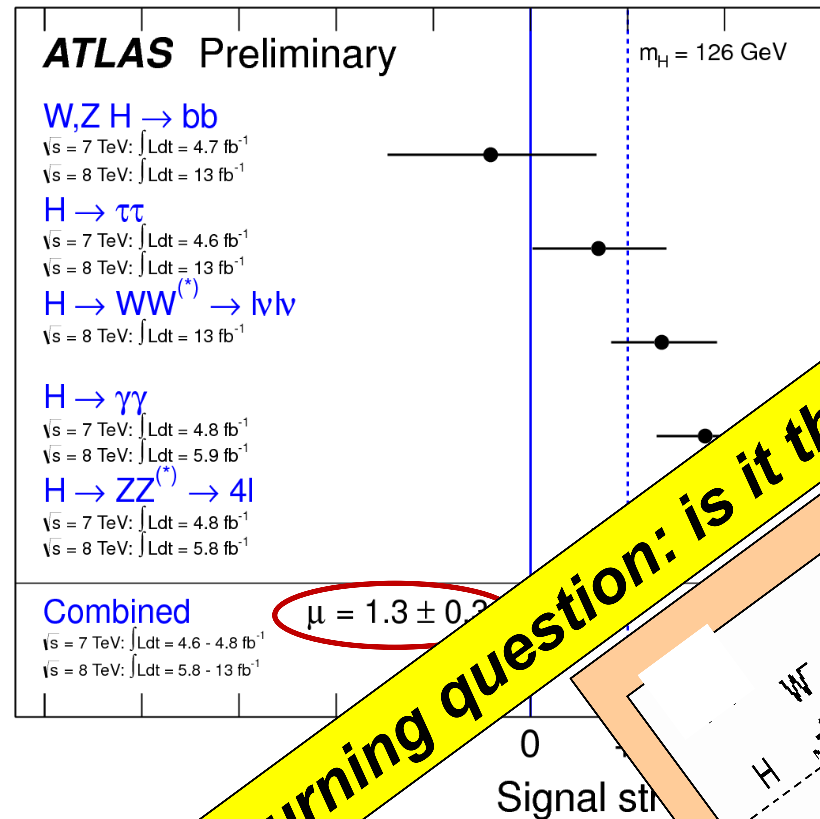


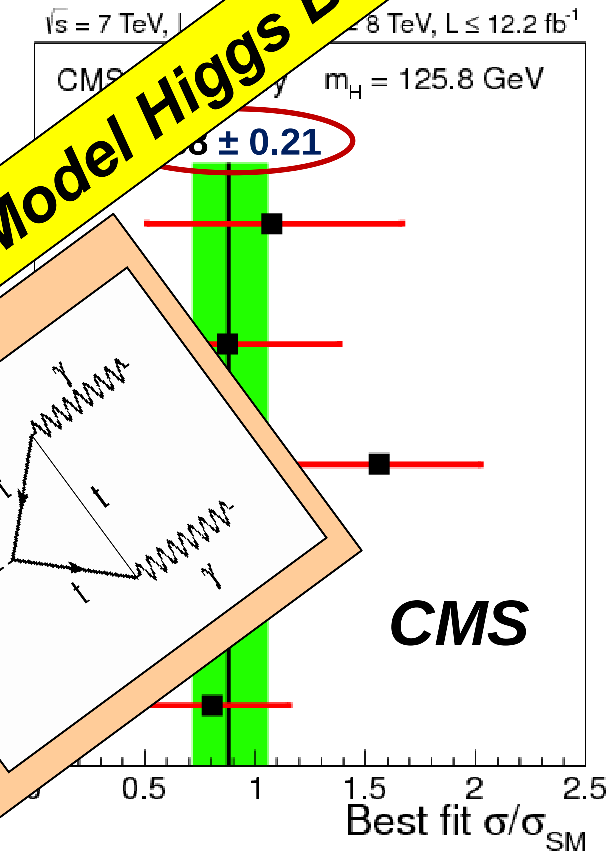
Summary of all ττ channels (including VH)

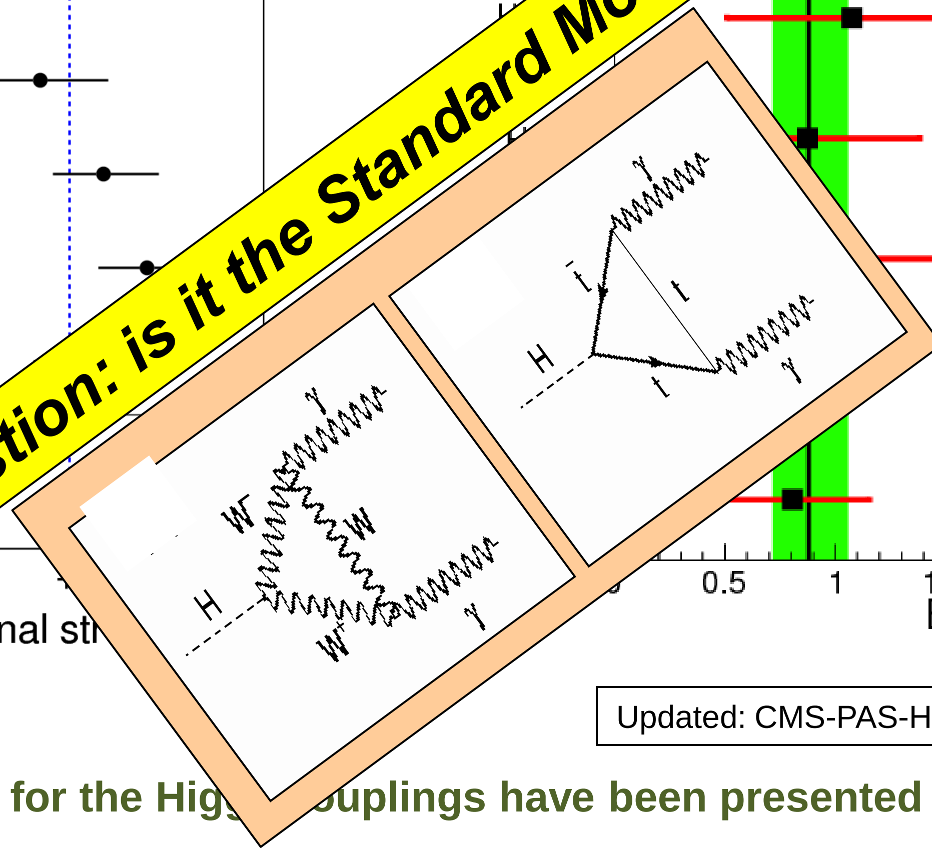
Updated: CMS-PAS-HIG-12-051

Properties, as far as known with the limited statistics…

$\mu = 0$ background only hypothesis
$\mu = 1$ SM Higgs hypothesis





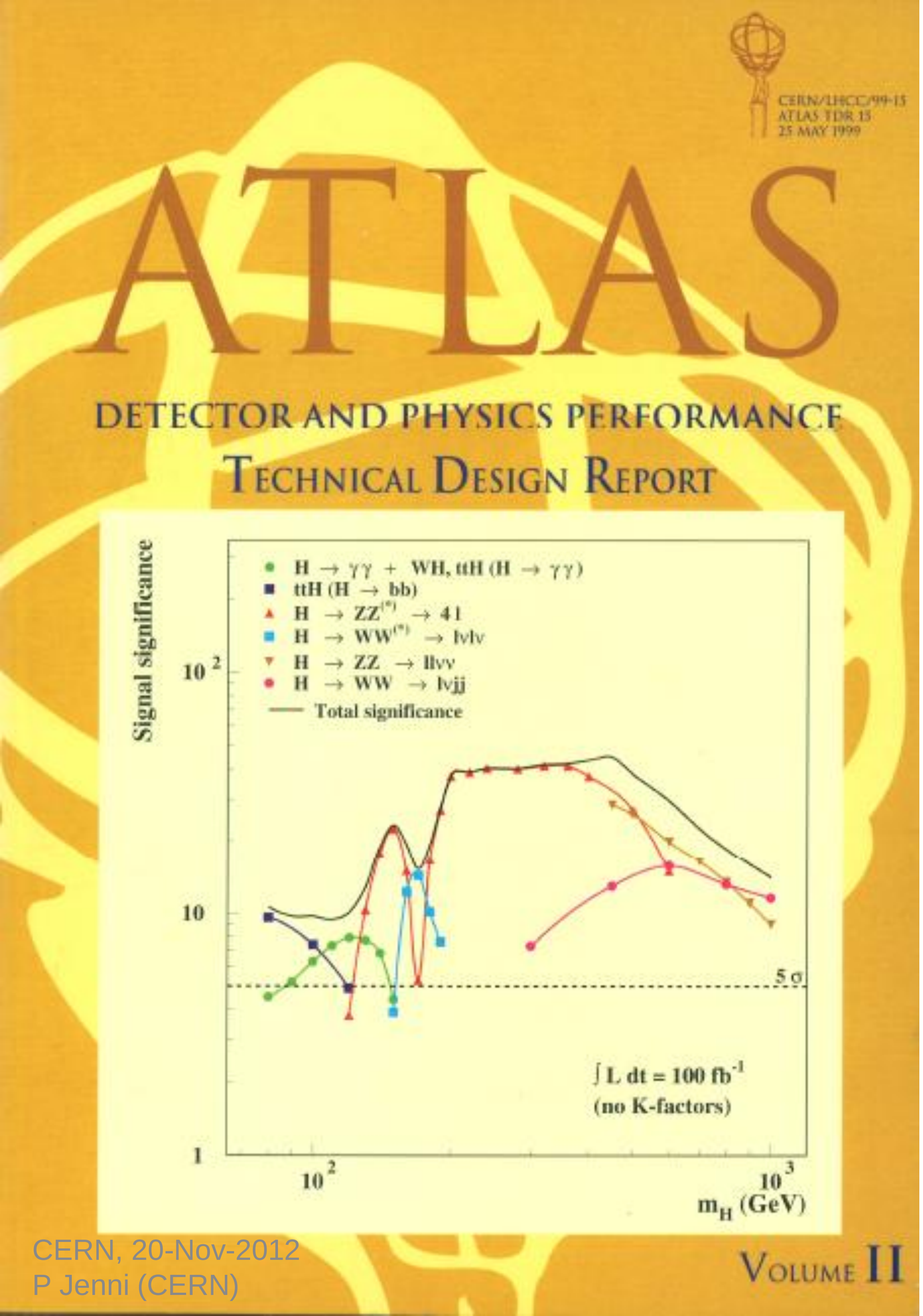


The burning question: is it the Standard Model Higgs Boson?

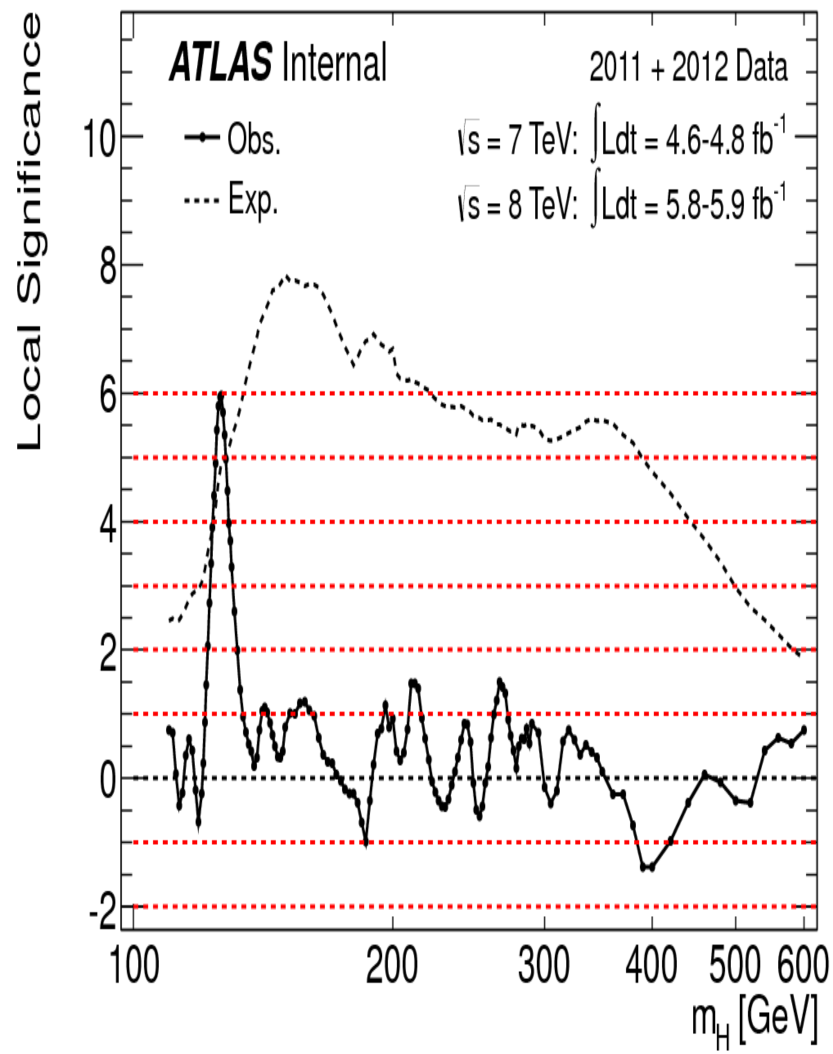
Upd…S-CONF-2012-162

Updated: CMS-PAS-HIG-12-045

(F…st analyses and fits for the Hig… …ouplings have been presented as well)

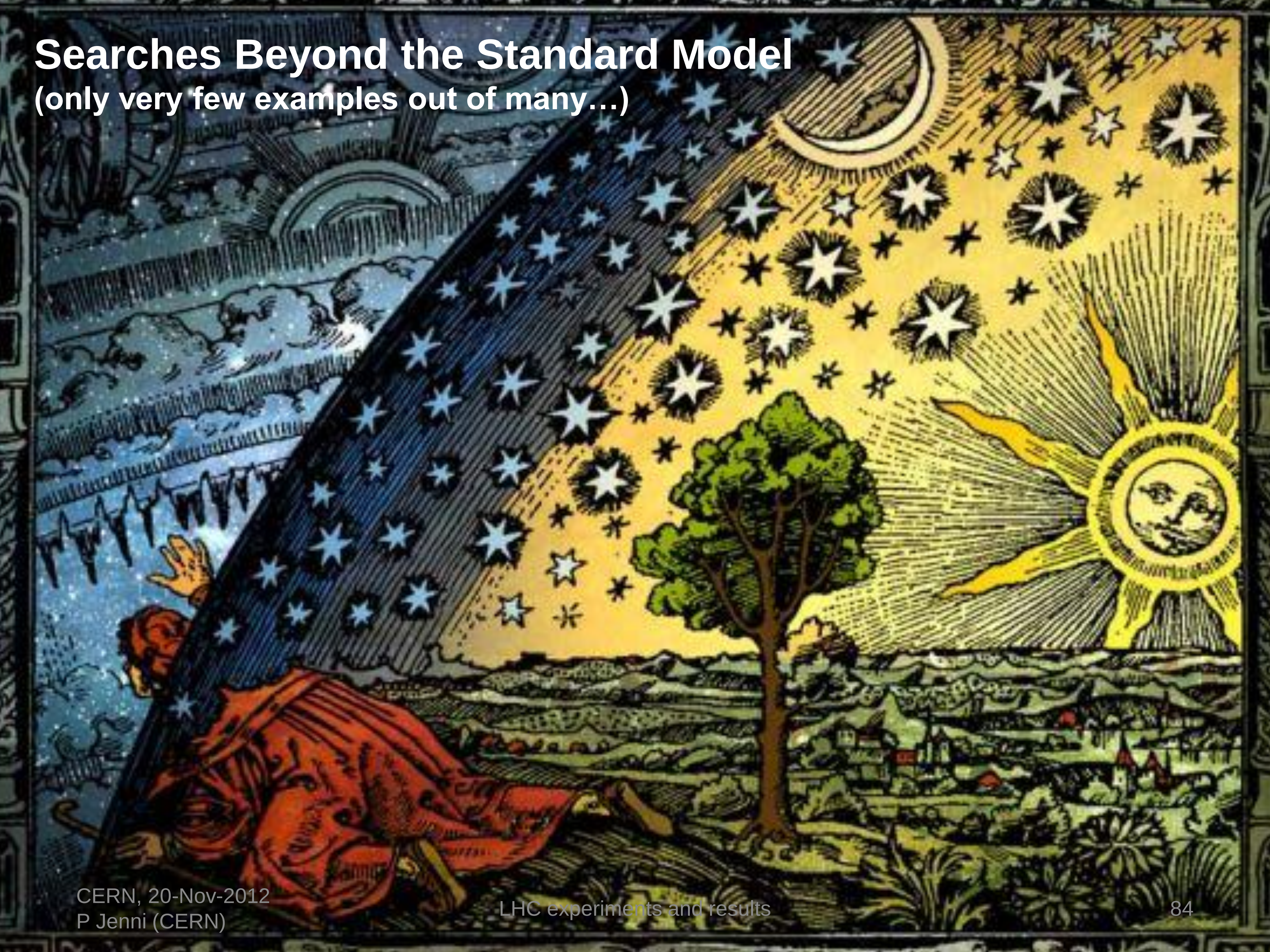


A dream becoming true much faster than anticipated long ago



Searches Beyond the Standard Model

(only very few examples out of many…)



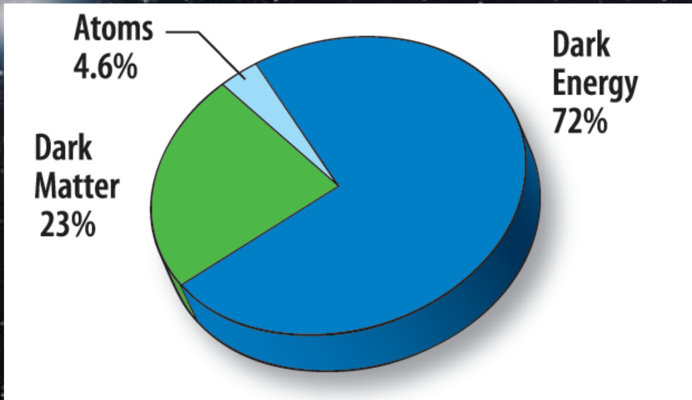
Dark Matter in the Universe

Astronomers found that most of the matter in the Universe must be invisible Dark Matter

Vera Rubin ~ 1970

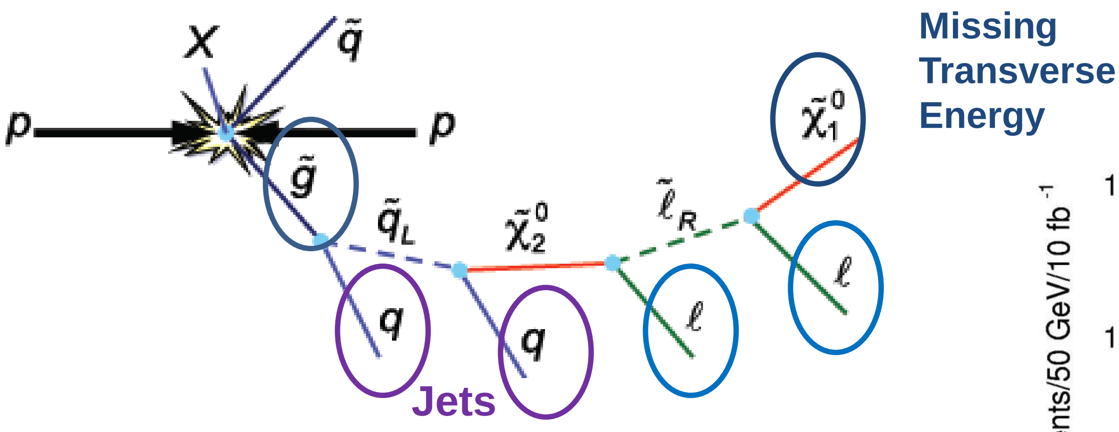
'Supersymmetric' particles ?

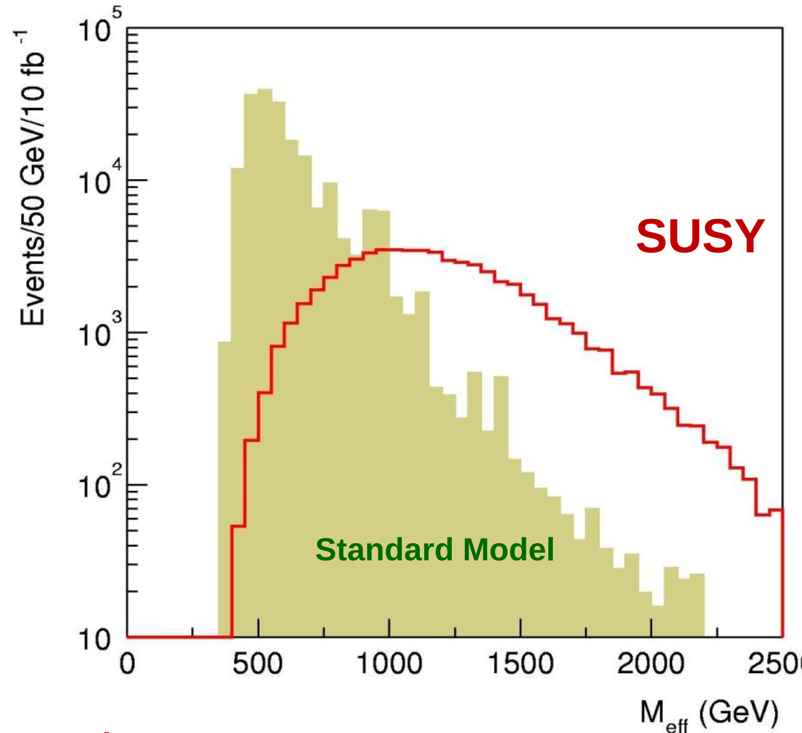
F. Zwicky 1898-1974



In practice SUSY searches at LHC are rather complicated

- **Complex (and model-dependent) squark/gluino cascades**





- **Focus on signatures covering large classes of models while strongly rejecting SM background**
  - **large missing E_T**
  - **High transverse momentum jets**
  - **Leptons**
    - **Perform separate analyses with and without lepton veto (0-lepton / 1-lepton / 2-leptons)**
  - **B-jets: to enhance sensitivity to third-generation squarks**
  - **Photons: typically for models with the gravitino as LSP**

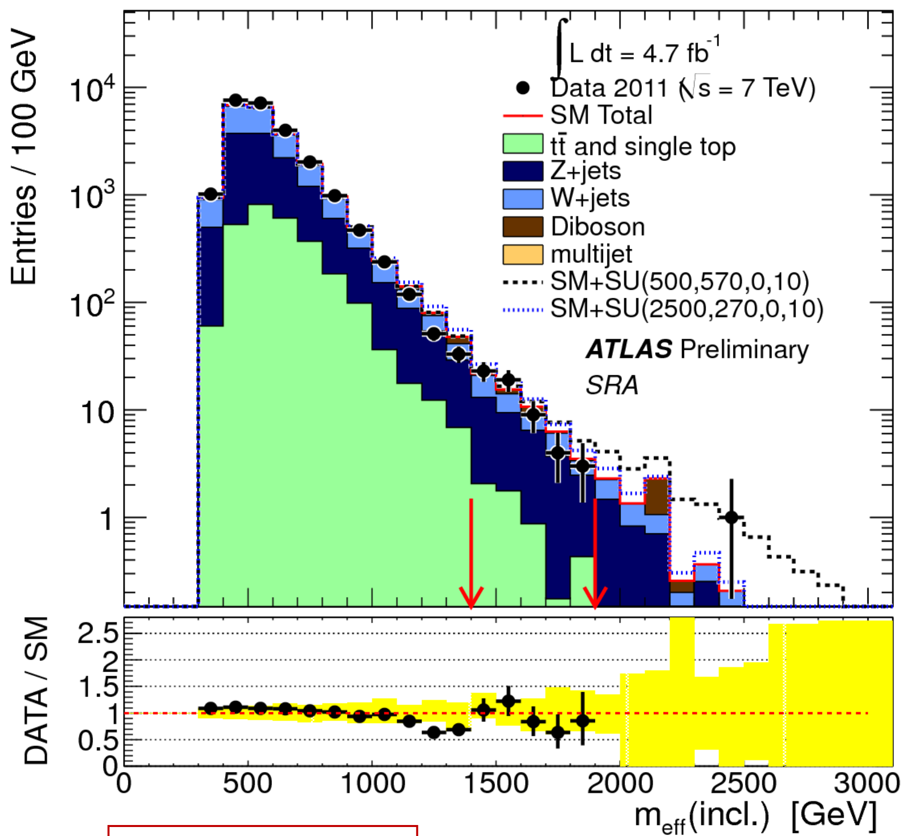
Meff = Etmiss + Σ pT(jets)

Analyses re-optimized and updated with full 2011 Luminosity

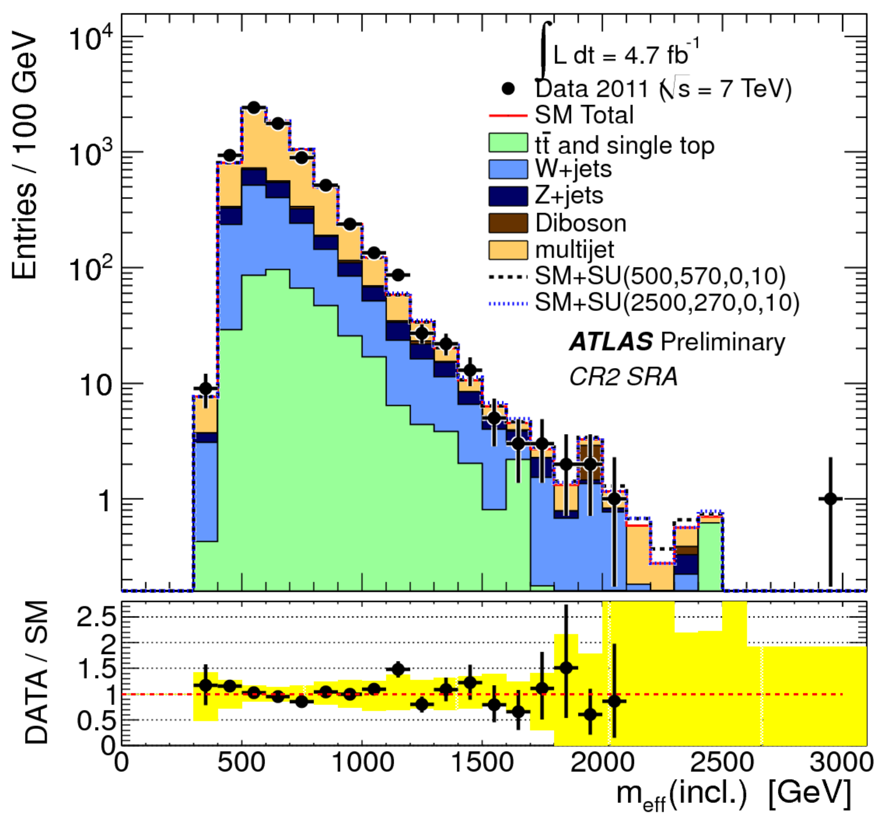
- **0-lepton + 2−6 jets + high MET (based on Et-miss+jet triggers)**
- **0-lepton + 6−9 (multi-)jets + MET (based on multi-jet triggers)**
- **1-lepton + 3,4 jets + high MET (based on lepton triggers)**

Example: O-leptons + 2-6 Jets analysis

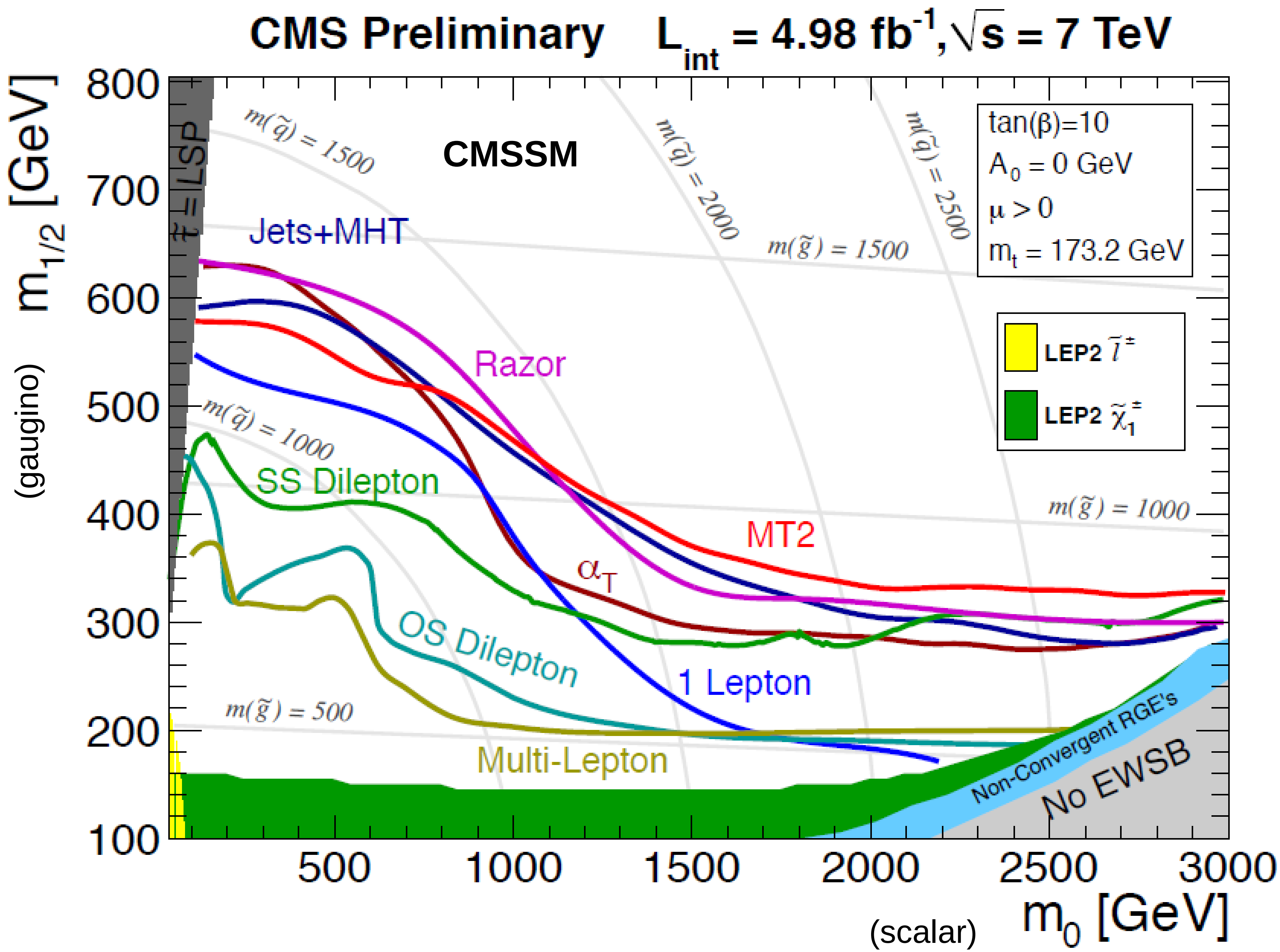
ATLAS-CONF-2012-033, 037, and 041



A signal region

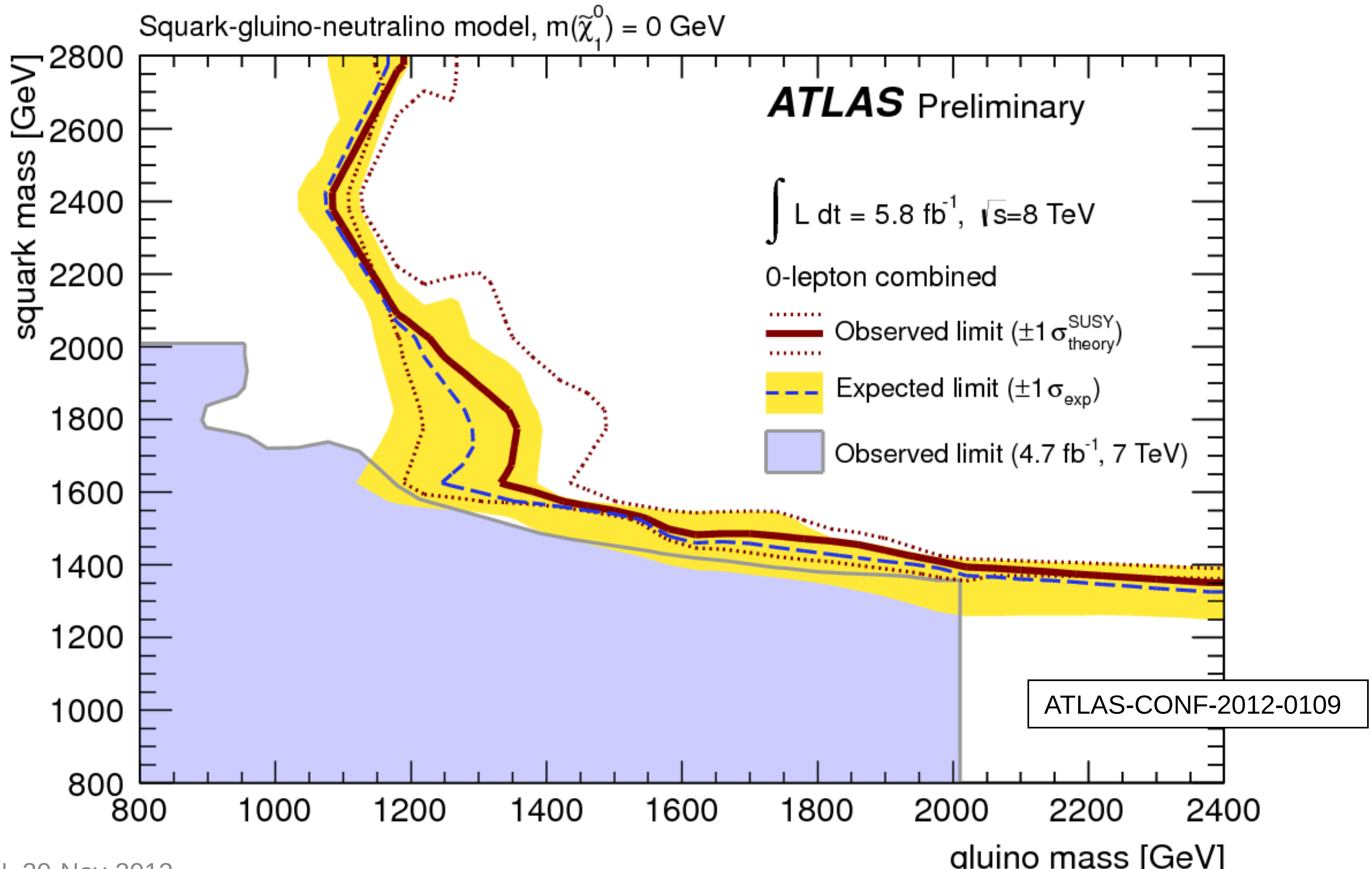


A control region where no signal is expected

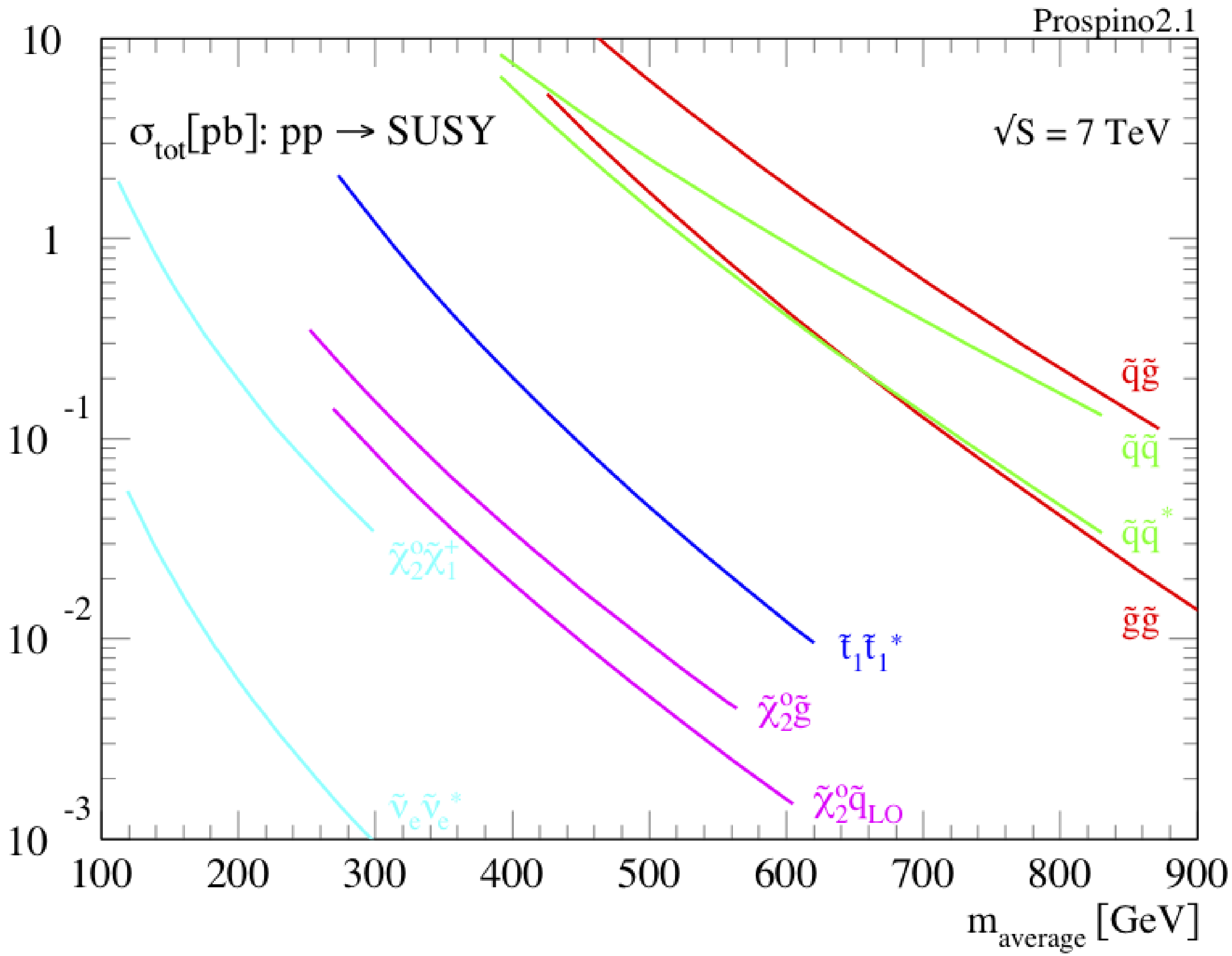

CMS Preliminary L_{int} = 4.98 fb^{-1}, $\sqrt{s}$ = 7 TeV
CMSSM
tan(β)=10
A_0 = 0 GeV
μ > 0
m_t = 173.2 GeV
LEP2 $\tilde{l}^{\pm}$
LEP2 $\tilde{\chi}_1^{\pm}$
$\tilde{\tau}$ = LSP
Jets+MHT
Razor
MT2
α_T
SS Dilepton
OS Dilepton
1 Lepton
Multi-Lepton
Non-Convergent RGE's
No EWSB
$m(\tilde{q})$ = 1500
$m(\tilde{q})$ = 2000
$m(\tilde{q})$ = 2500
$m(\tilde{q})$ = 1000
$m(\tilde{g})$ = 1500
$m(\tilde{g})$ = 1000
$m(\tilde{g})$ = 500
$m_{1/2}$ [GeV]
(gaugino)
m_0 [GeV]
(scalar)
800
700
600
500
400
300
200
100
500
1000
1500
2000
2500
3000

Interpretation of the results

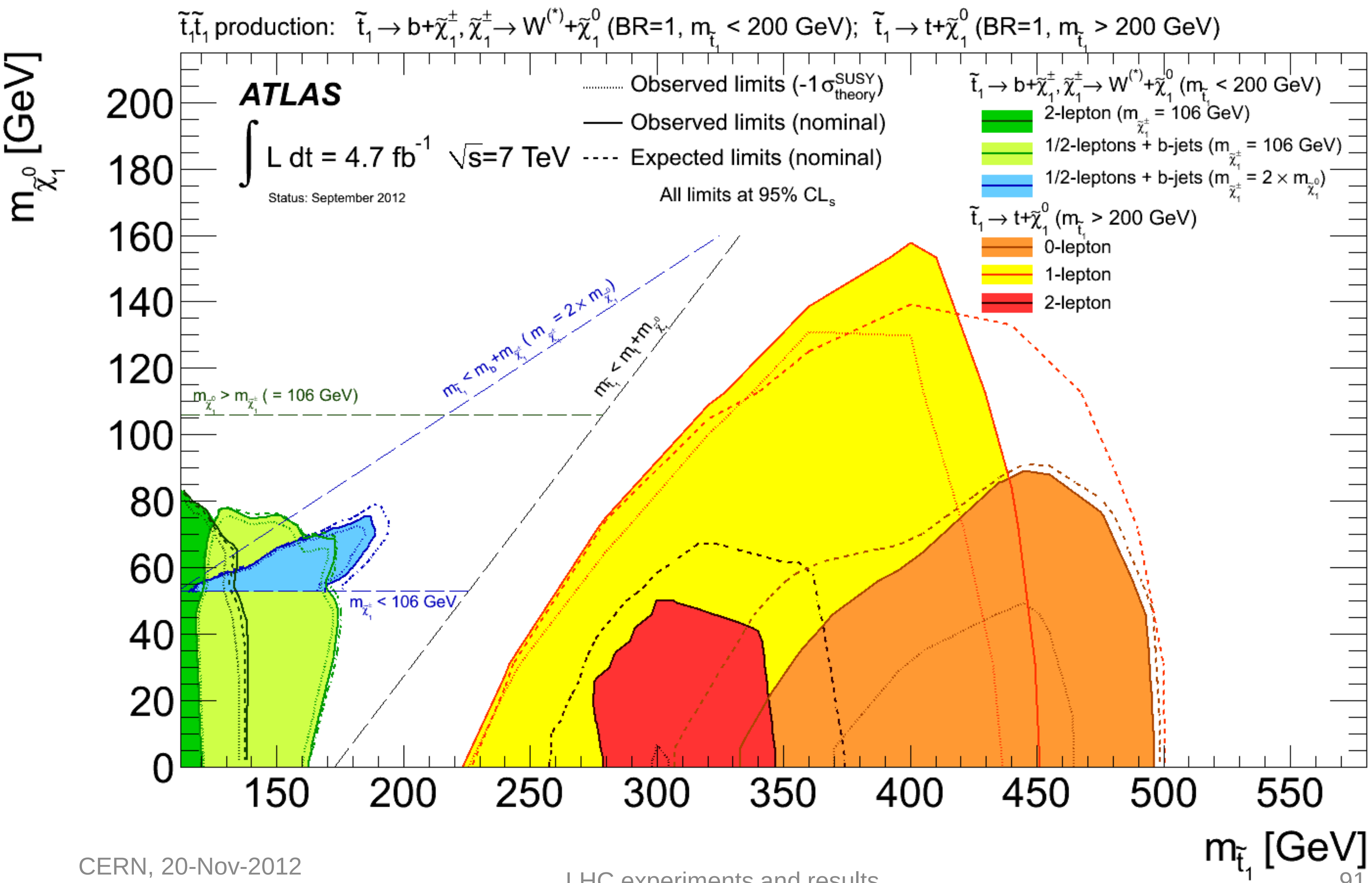
Consider phenomenological MSSM models containing only squarks of 1st and 2nd generation, gluino and light neutralinos



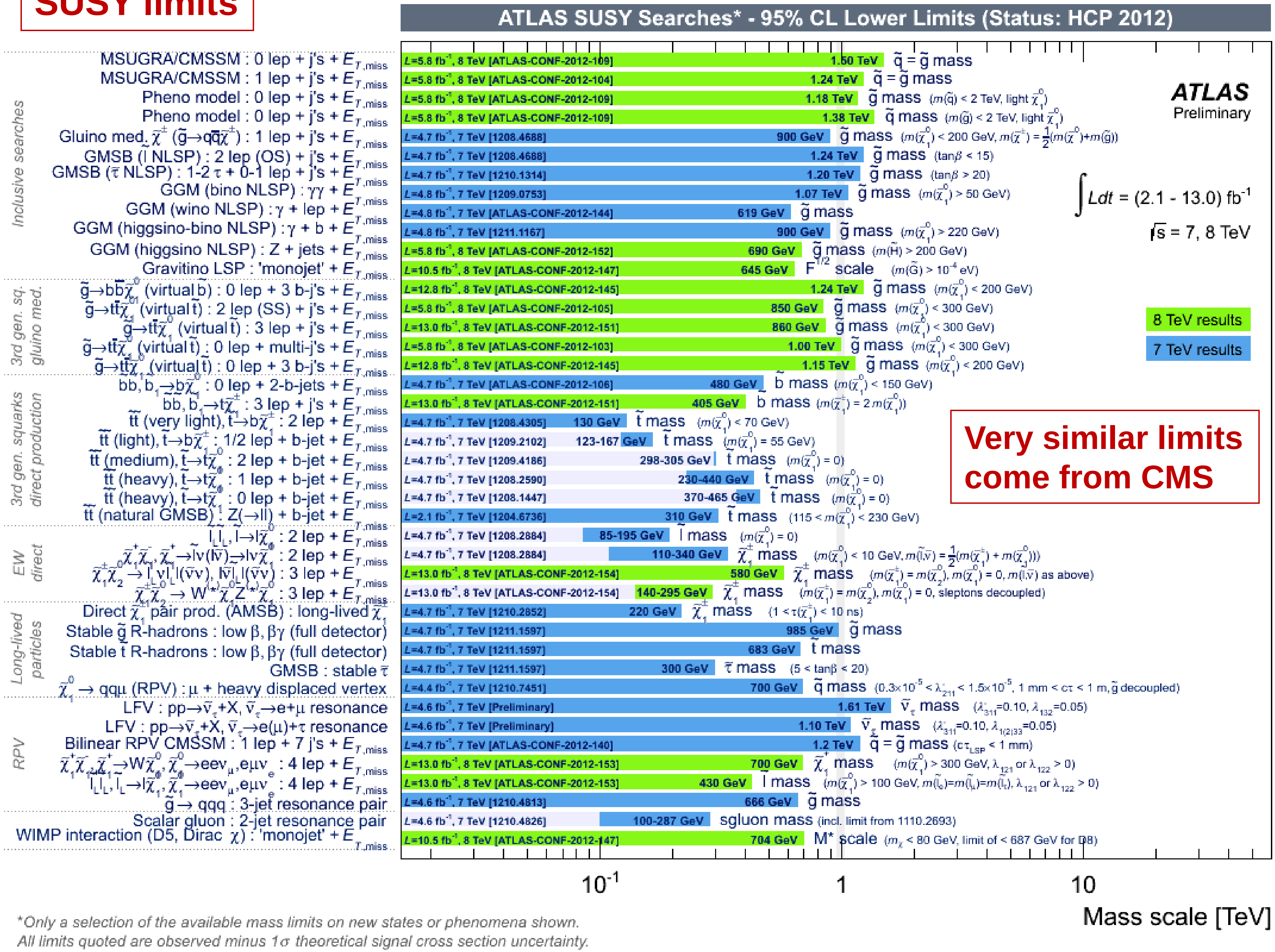
Expected production cross-sections at LHC



Summary of five dedicated searches for top squark pair production for theoretically preferred models with relatively light 3rd generation squarks

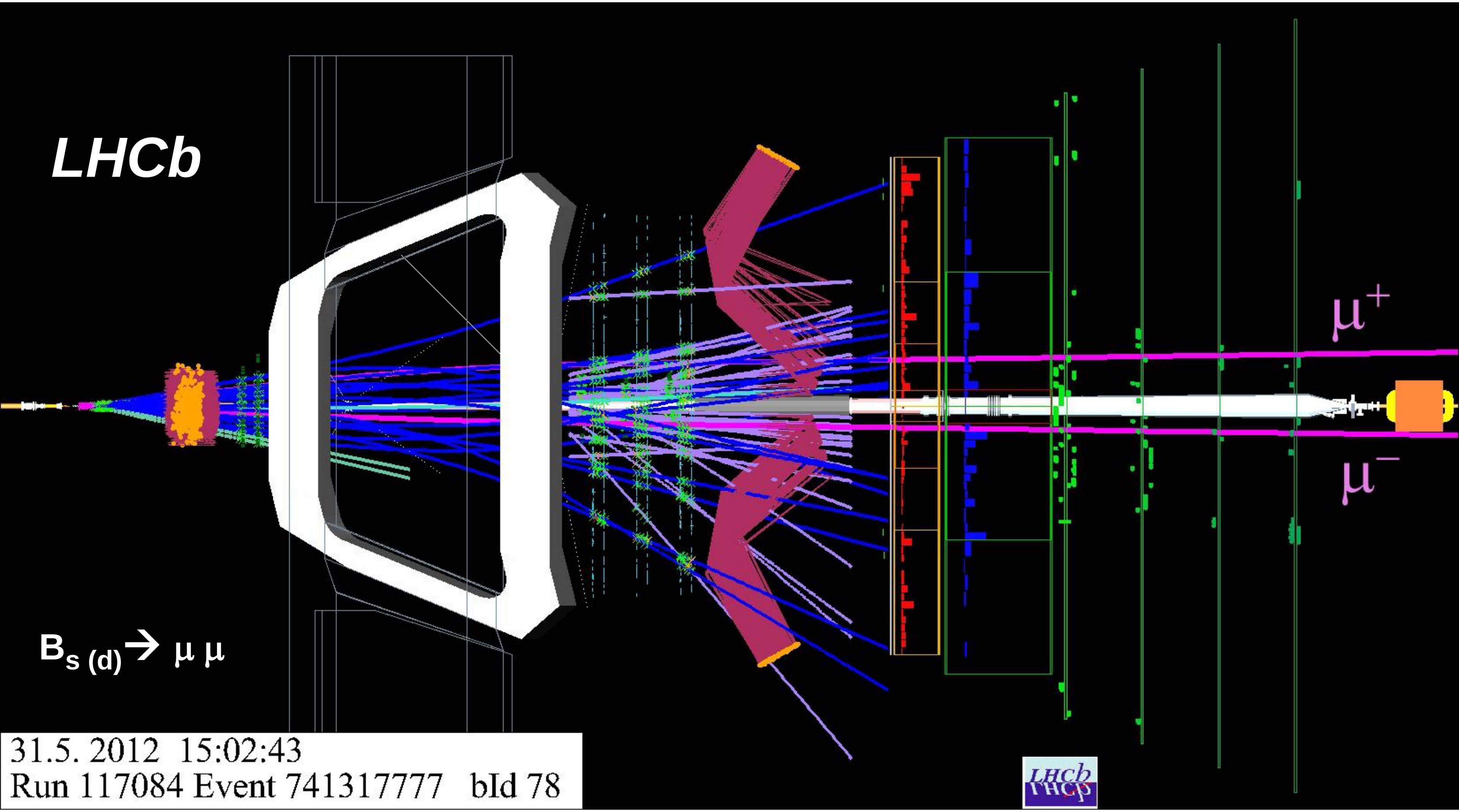


SUSY limits



Very similar limits come from CMS

Indirect indications for physics BSM, like SUSY, could come from rare decays showing rates deviating from the SM expectations



The search for $B_{s\,(d)} \rightarrow \mu\,\mu$

Submitted to Phys. Rev. Lett.
arXiv:1211.2674v1[hep-ex]

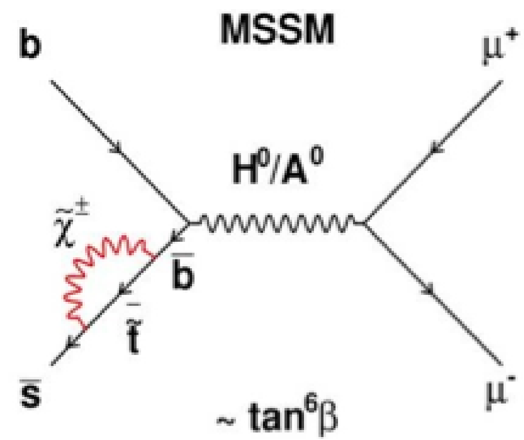
Very rare decay sensitive to New Physics (in particular to models with high *tan β*)

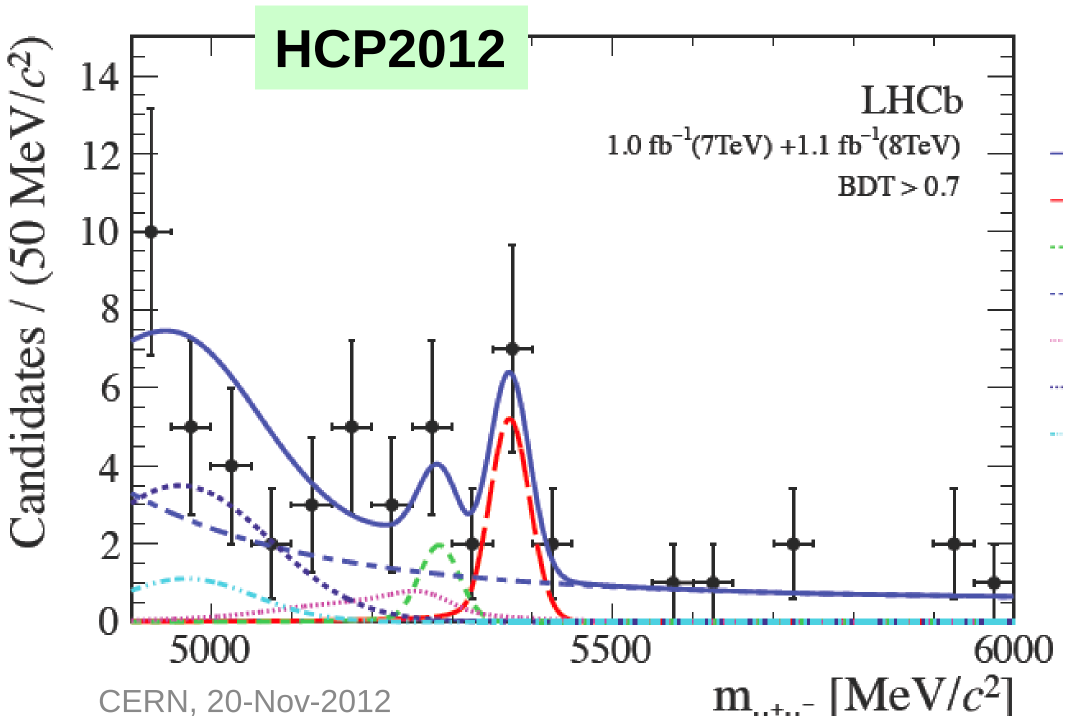
Precise predictions in SM:

$BR(B_s \rightarrow \mu\,\mu) = 3.5 \pm 0.2\ 10^{-9}$

$BR(B_d \rightarrow \mu\,\mu) = 1.1 \pm 0.2\ 10^{-10}$

Very clean experimental signature





With 2011+2012 data (2.1/fb) first evidence of $B_s \rightarrow \mu\,\mu$ decay at ~ 3.5 σ

$$\mathcal{B}(B^0_s \rightarrow \mu^+\mu^-) = (3.2^{+1.5}_{-1.2}) \times 10^{-9}$$

in agreement with SM.
Potential impact on models

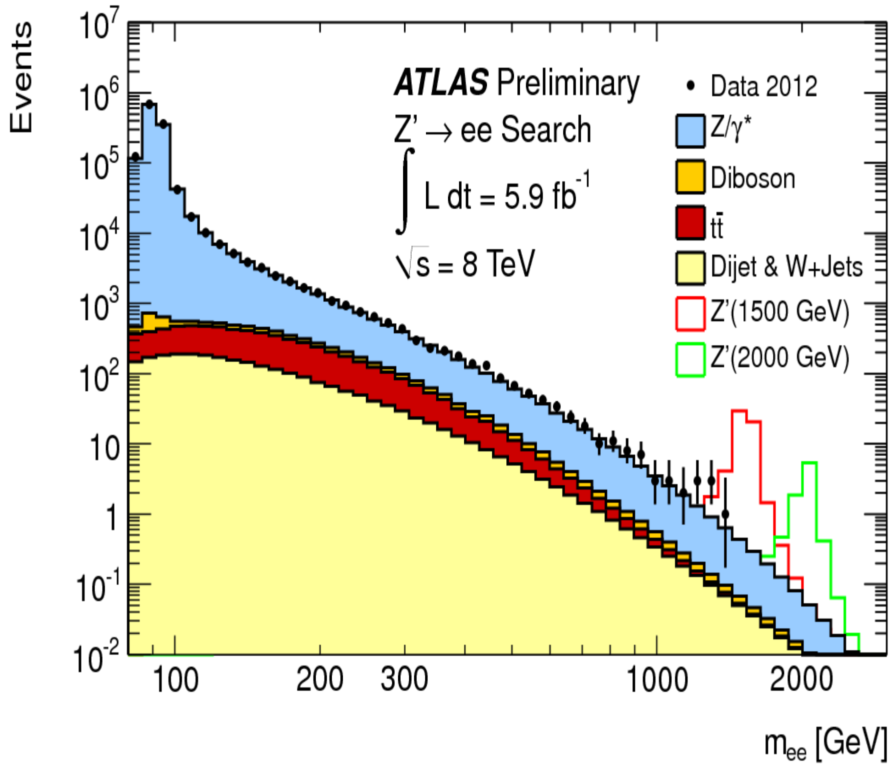
Also best limit on $B_d \rightarrow \mu\,\mu$

$$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10} \text{ at 95\% CL}$$

Searches for heavy W and Z like particles

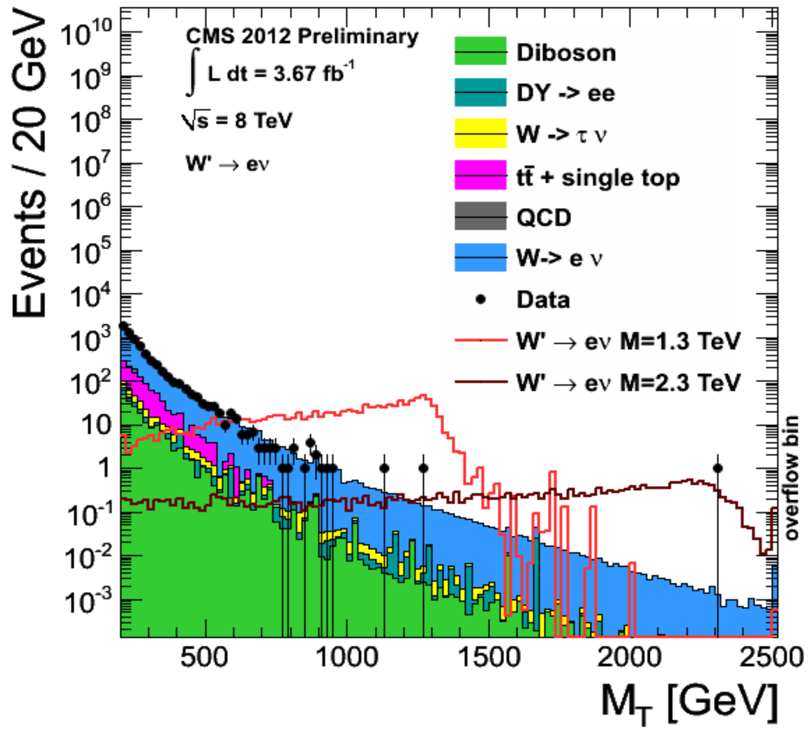
These searches are quite straight-forward, following basically the same analyses as for the familiar W and Z bosons

Z’: Di-lepton pairs



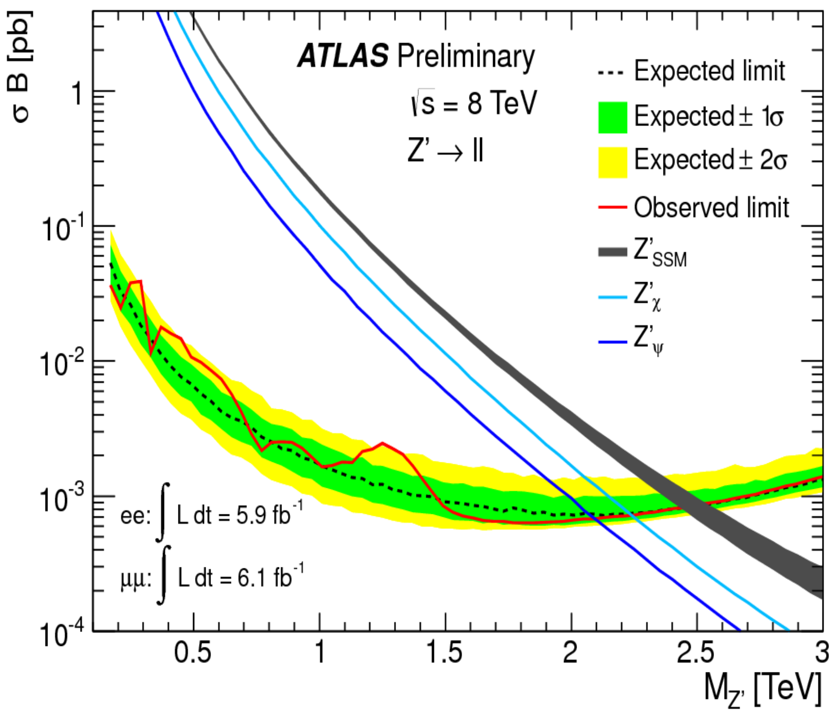
ATLAS-CONF-2012-129

W’: Lepton + ETmiss

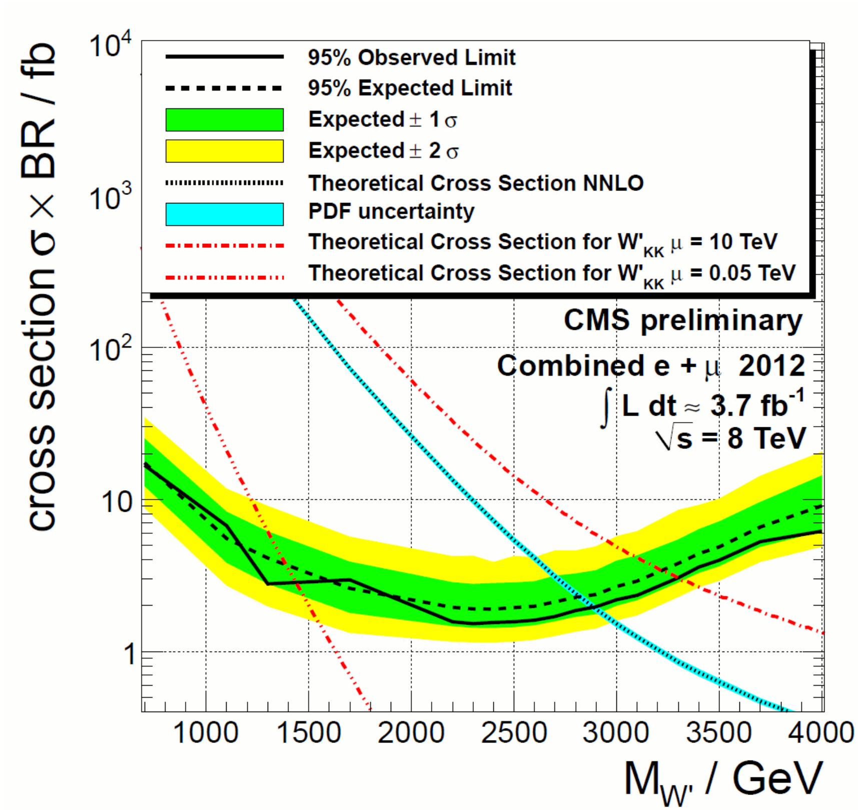


CMS-EXO-12-010

Lower mass limits, at 95% CL, for various Z' and W' like objects

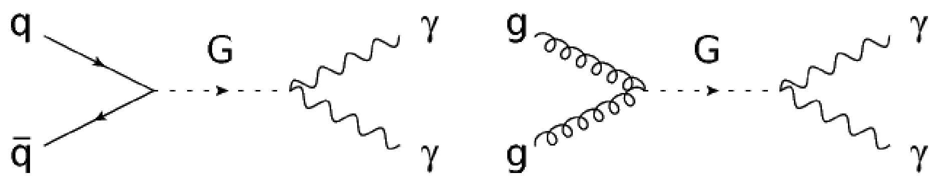


ATLAS-CONF-2012-129

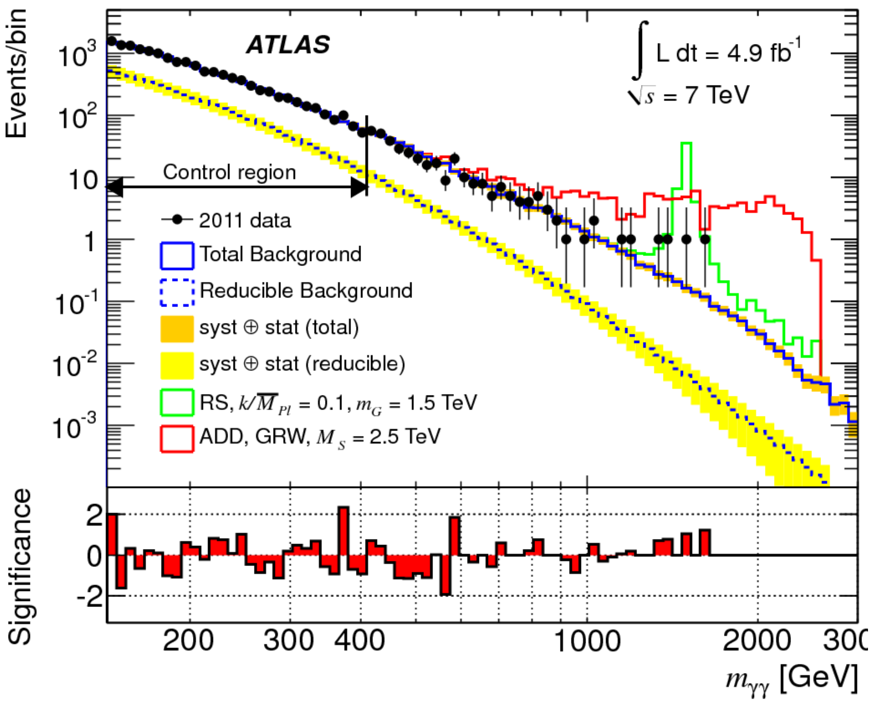


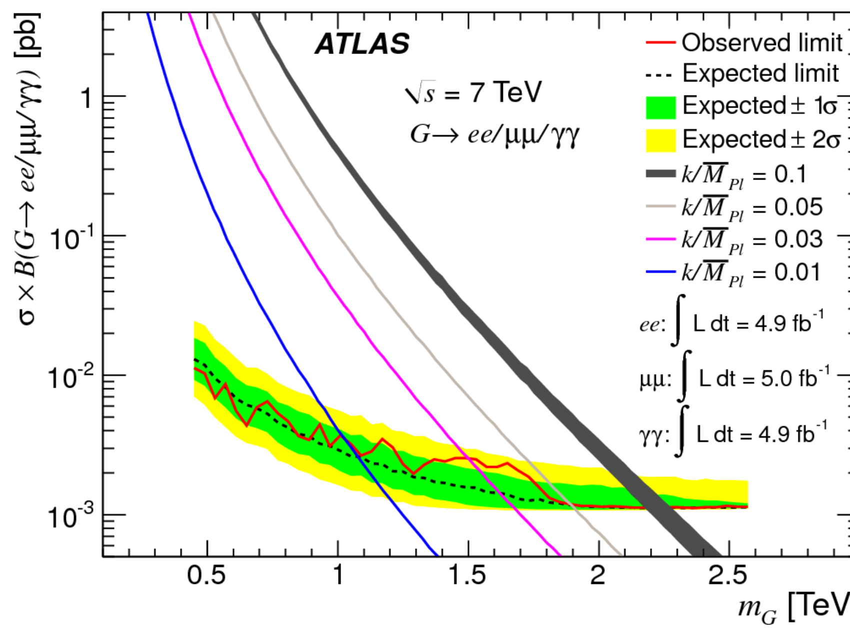
CMS-EXO-12-010

New particles decaying into two photons



Example for a search of extra dimension signals (Kaluza-Klein Graviton in the Randall-Sundrum and Arkani-Hamed, Dimopoulos and Dvali models)

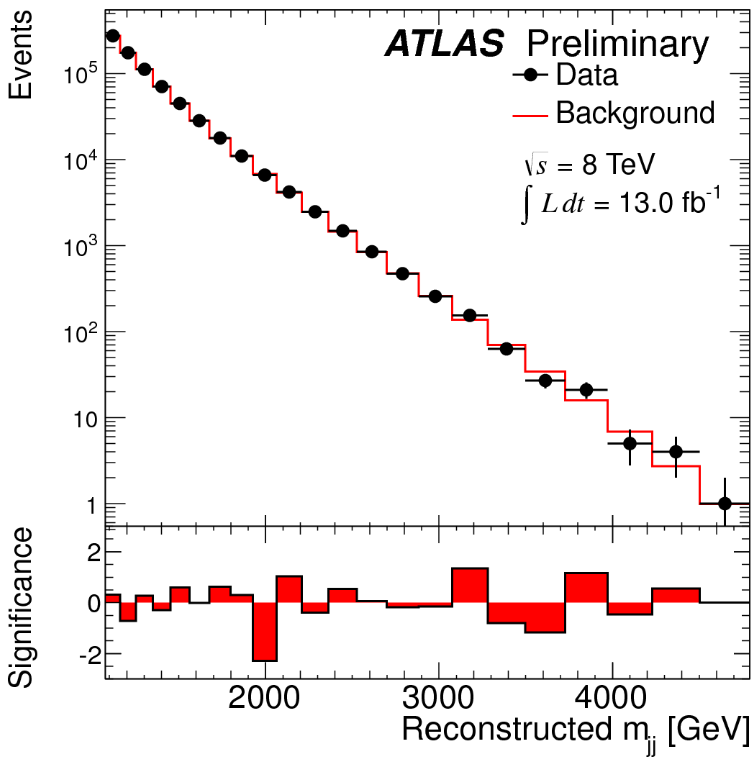




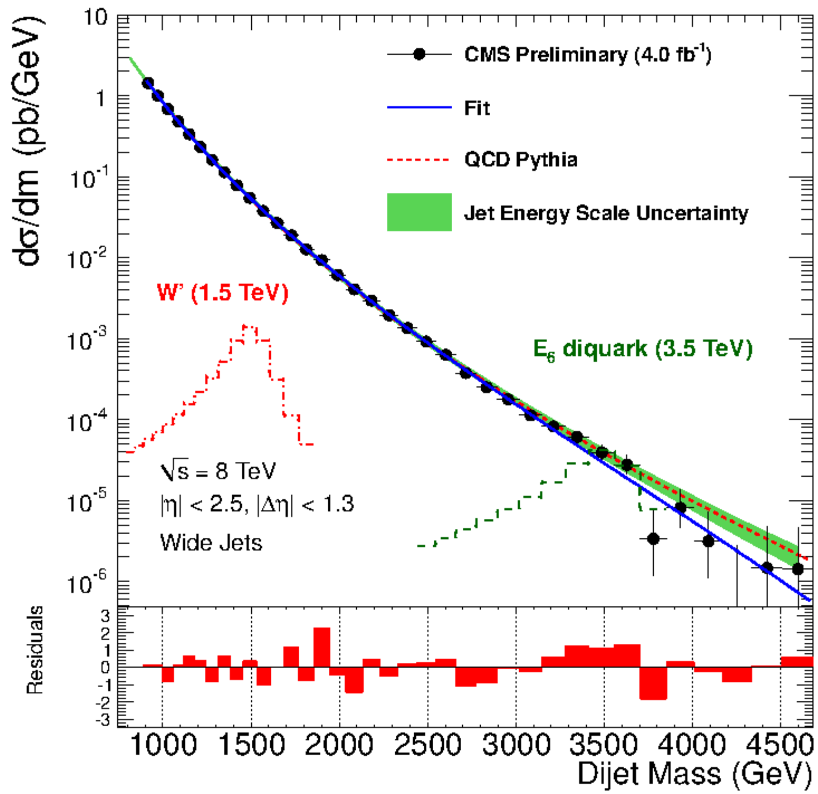
Submitted to Phys. Lett. B
arXiv:1210.8389v1[hep-ex]

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum



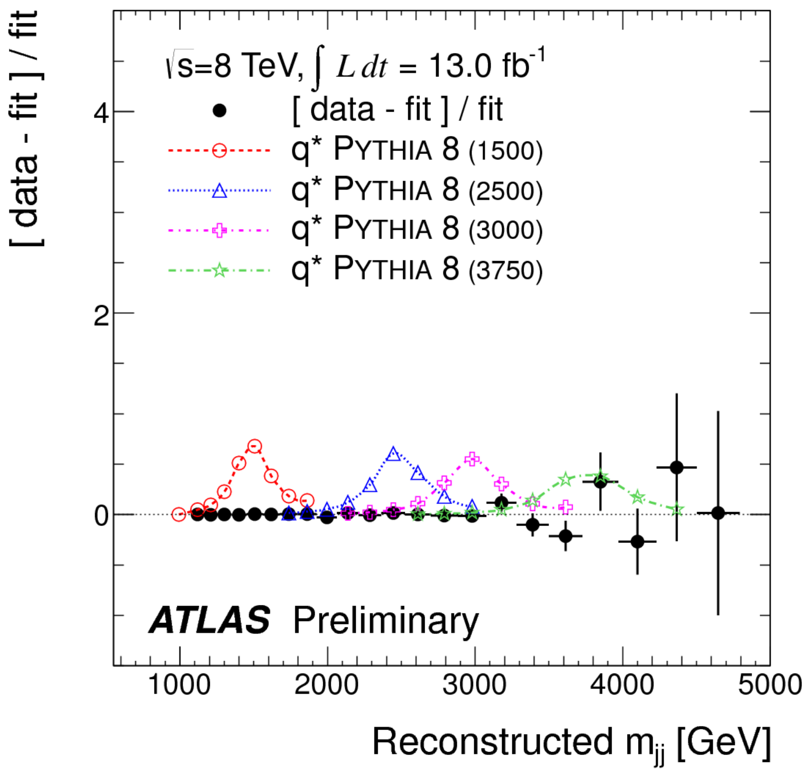
ATLAS-CONF-2012-148



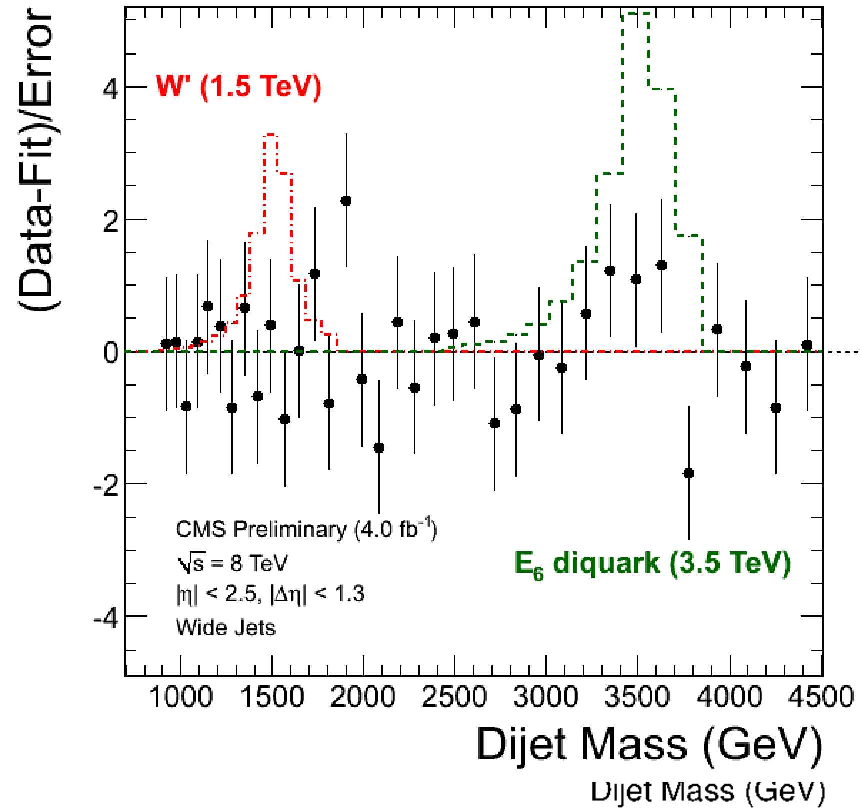
CMS-EXO-12-016

Example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum

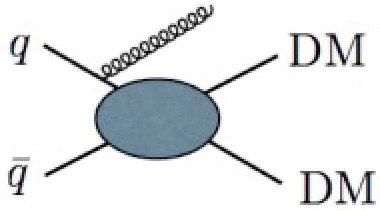


ATLAS-CONF-2012-148

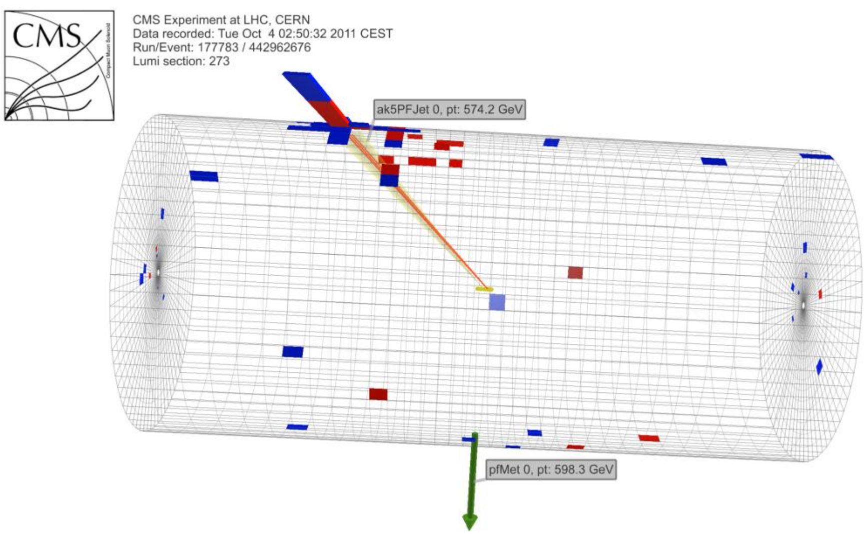


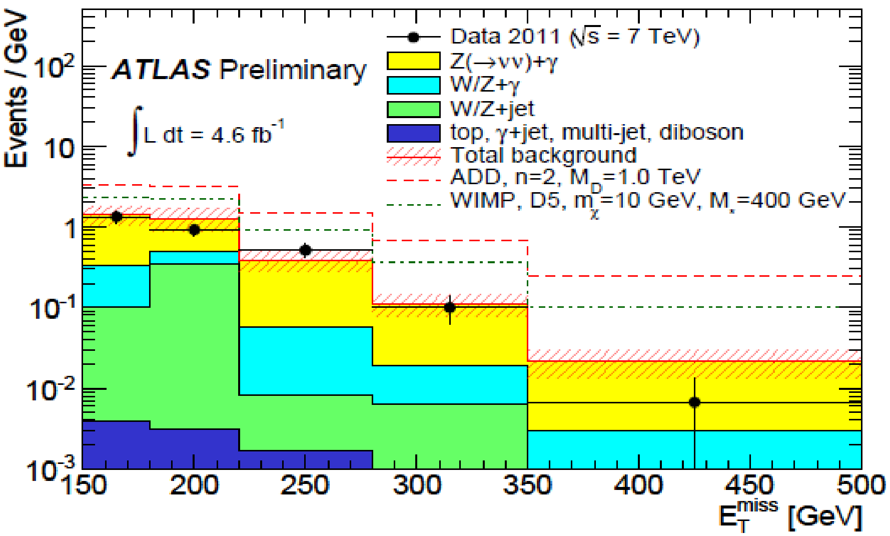
CMS-EXO-12-016

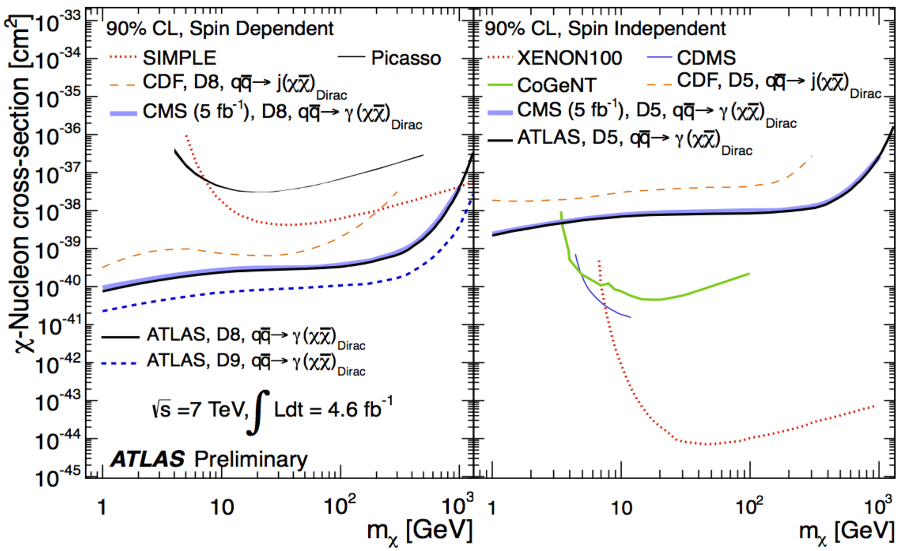
Search for direct Dark Matter (DM) particles in pair-production



A single photon (150 GeV) or jet plus ETmiss



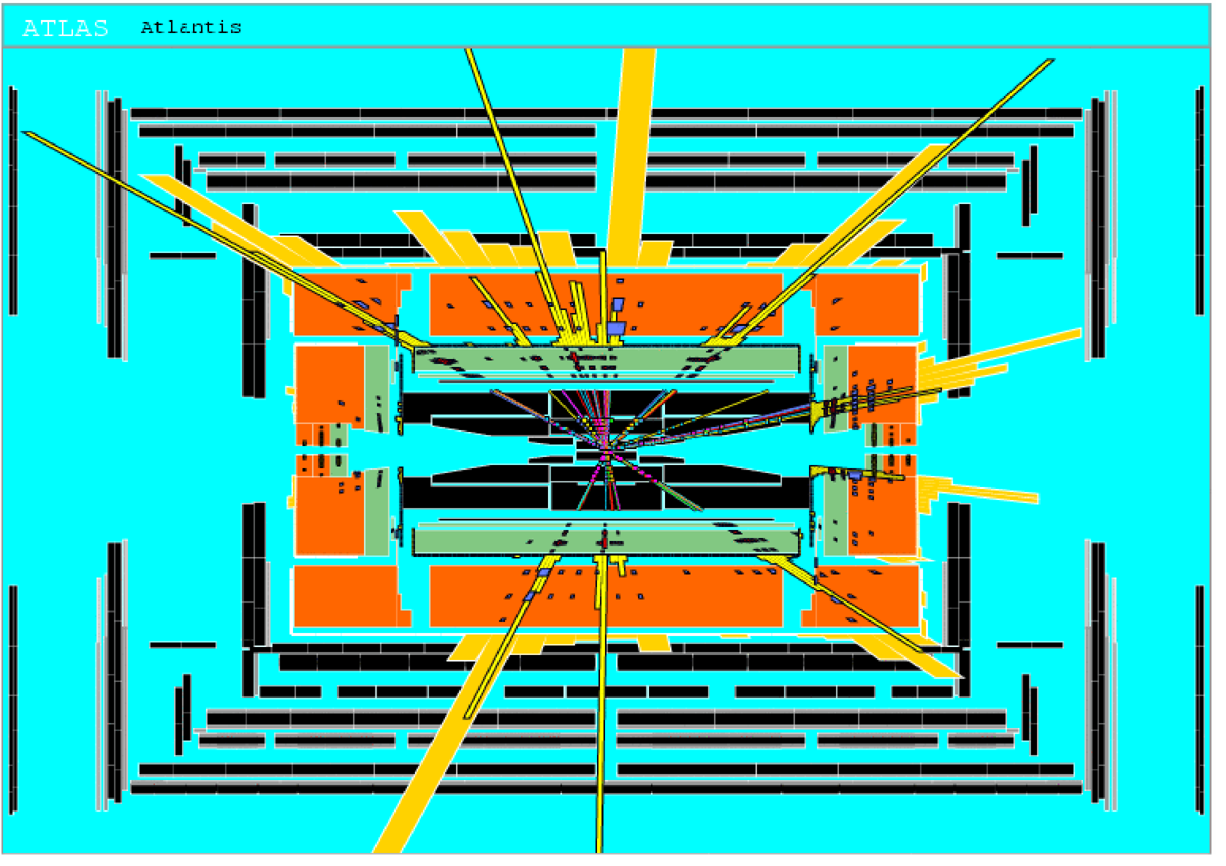




ATLAS-CONF-2012-085
arXiv:1210.4491v1[hep-ex]

CMS: Sub. to Phys. Rev. Lett.
arXiv:1204.0821v1[hep-ex]
arXiv:1206.5663[hep-ex]

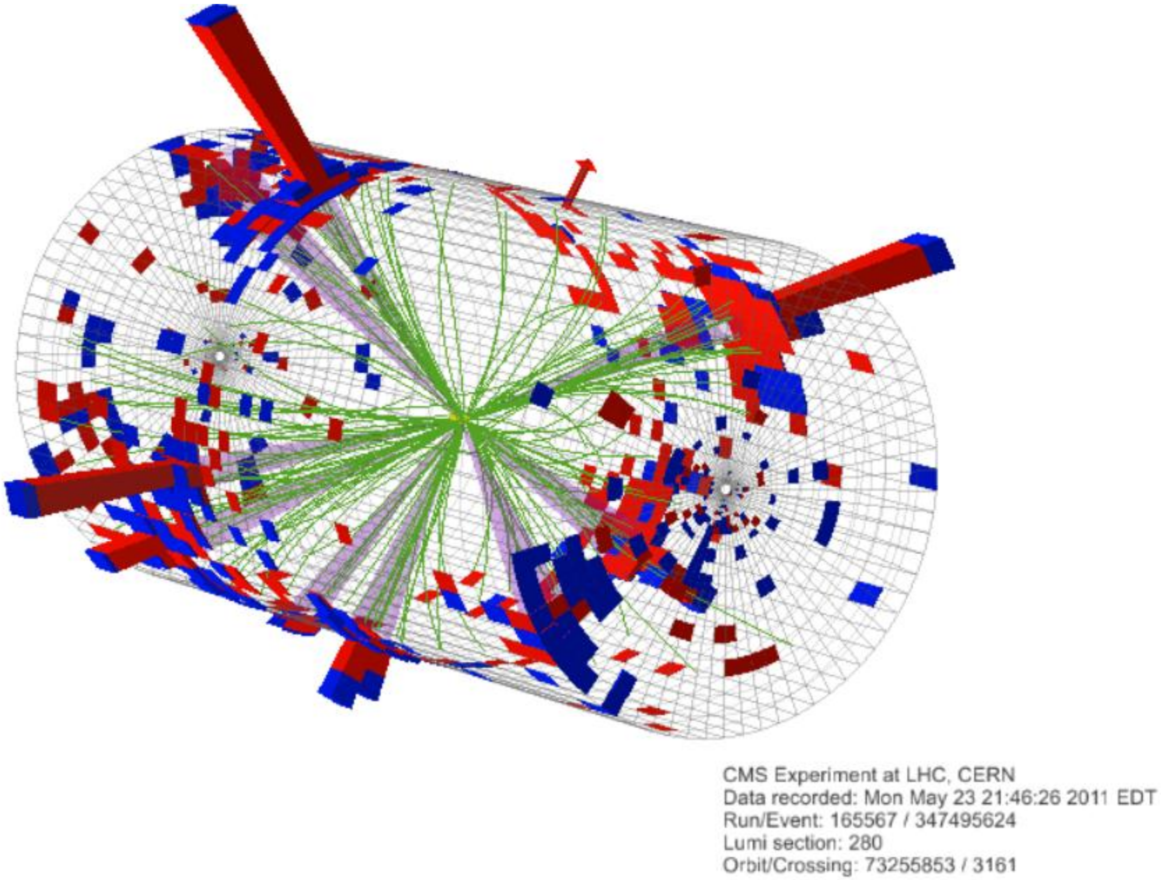
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



Simulation of a black hole event with M_{BH} ~ 8 TeV in ATLAS

They decay immediately through Stephen Hawking radiation

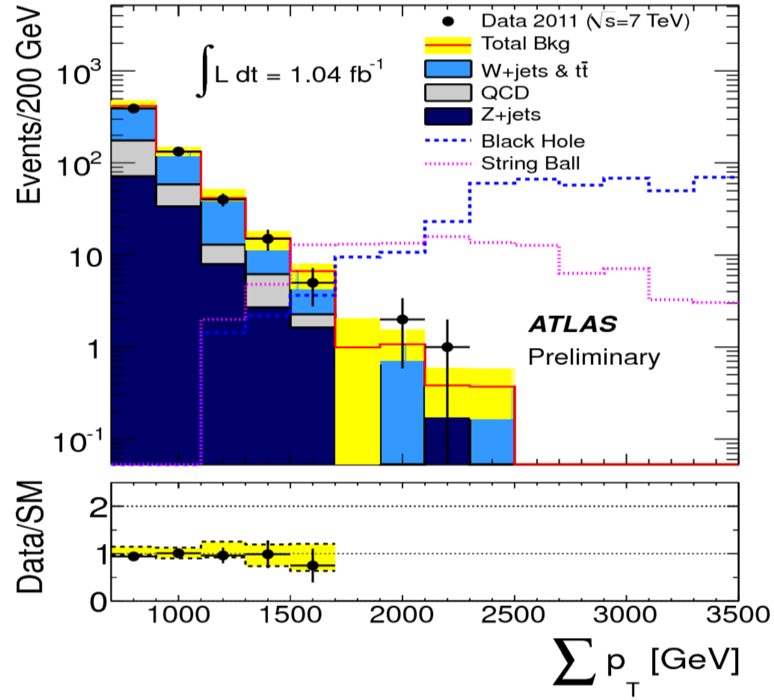
If theories with Extra-dimensions are true, microscopic black holes could be abundantly produced and observed at the LHC



A real 'candidate' event of a 'black hole' in CMS with 9 jets and ST = 2.6 TeV

They decay immediately through Stephen Hawking radiation

Search for Microscopic Black Hole production in models wth large extra dimensions
(Arkani-Hamed, Dimopoulos, Dvali)



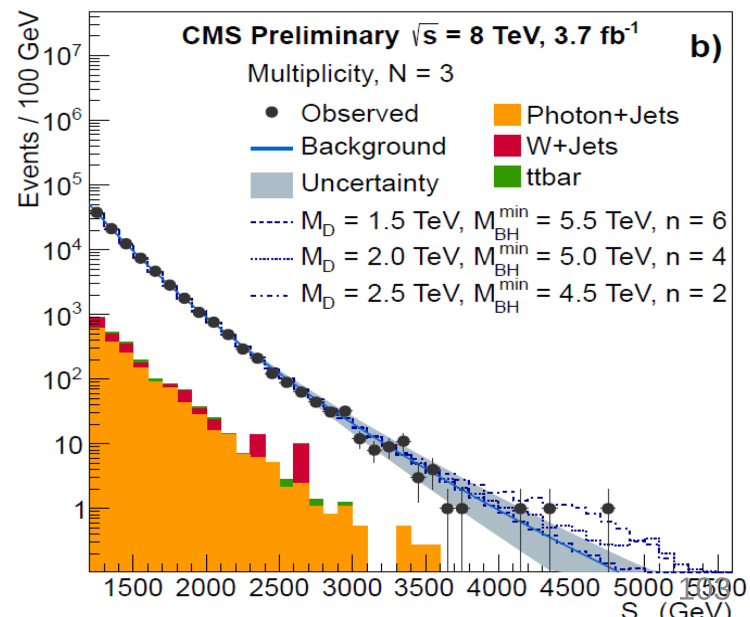
Decay into many objects (jets, leptons, photons)

ATLAS-CONF-2011-147
arXiv:1204.4646v1[hep-ex]

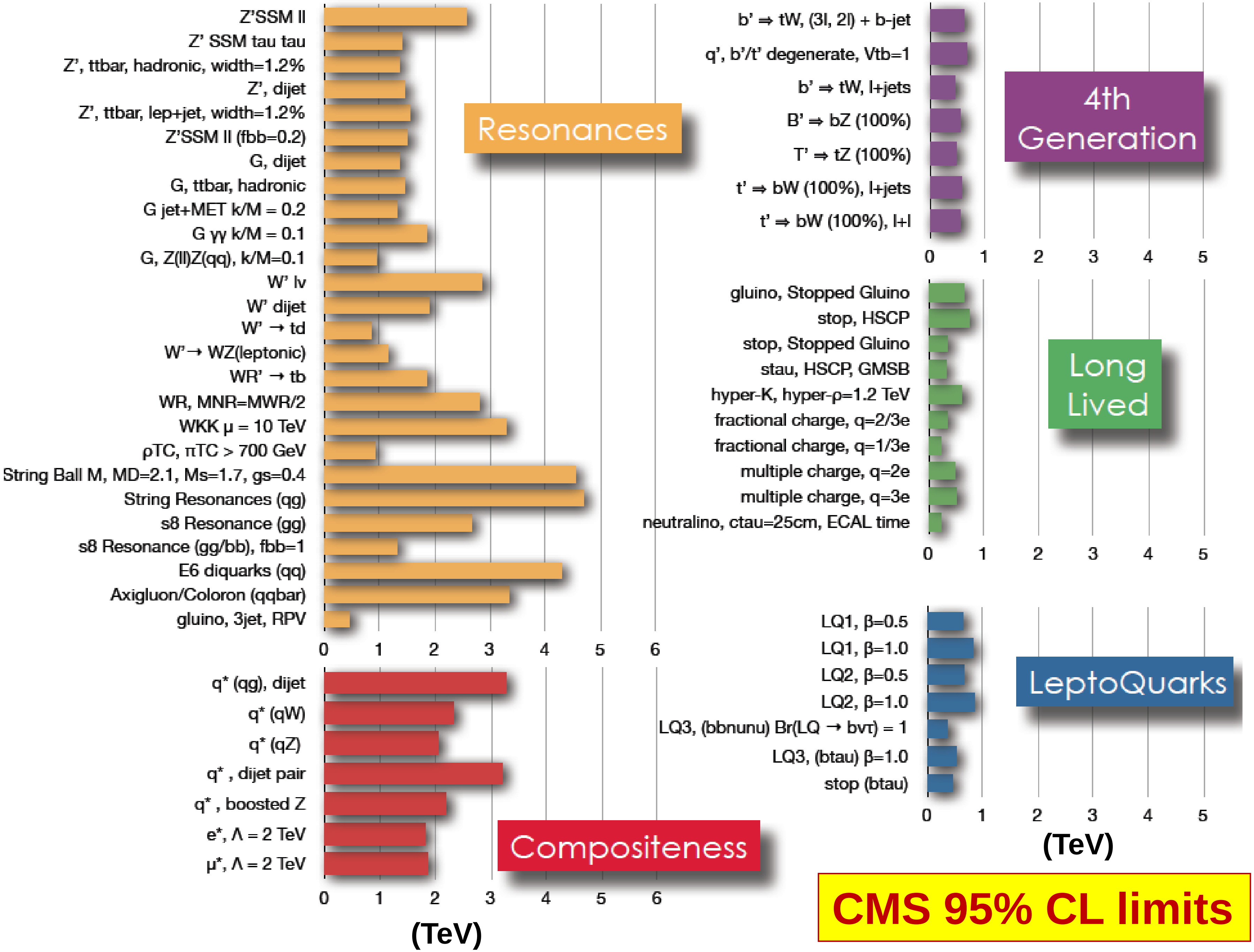
ΣP_T : scalar sum of the E_T of the N objects in the event

<u>Examples:</u> (ATLAS) at least one electron or muon and two or more jets, (CMS) any three objects

No deviation is seen for events with at least 3 objects with > 50 GeV pT

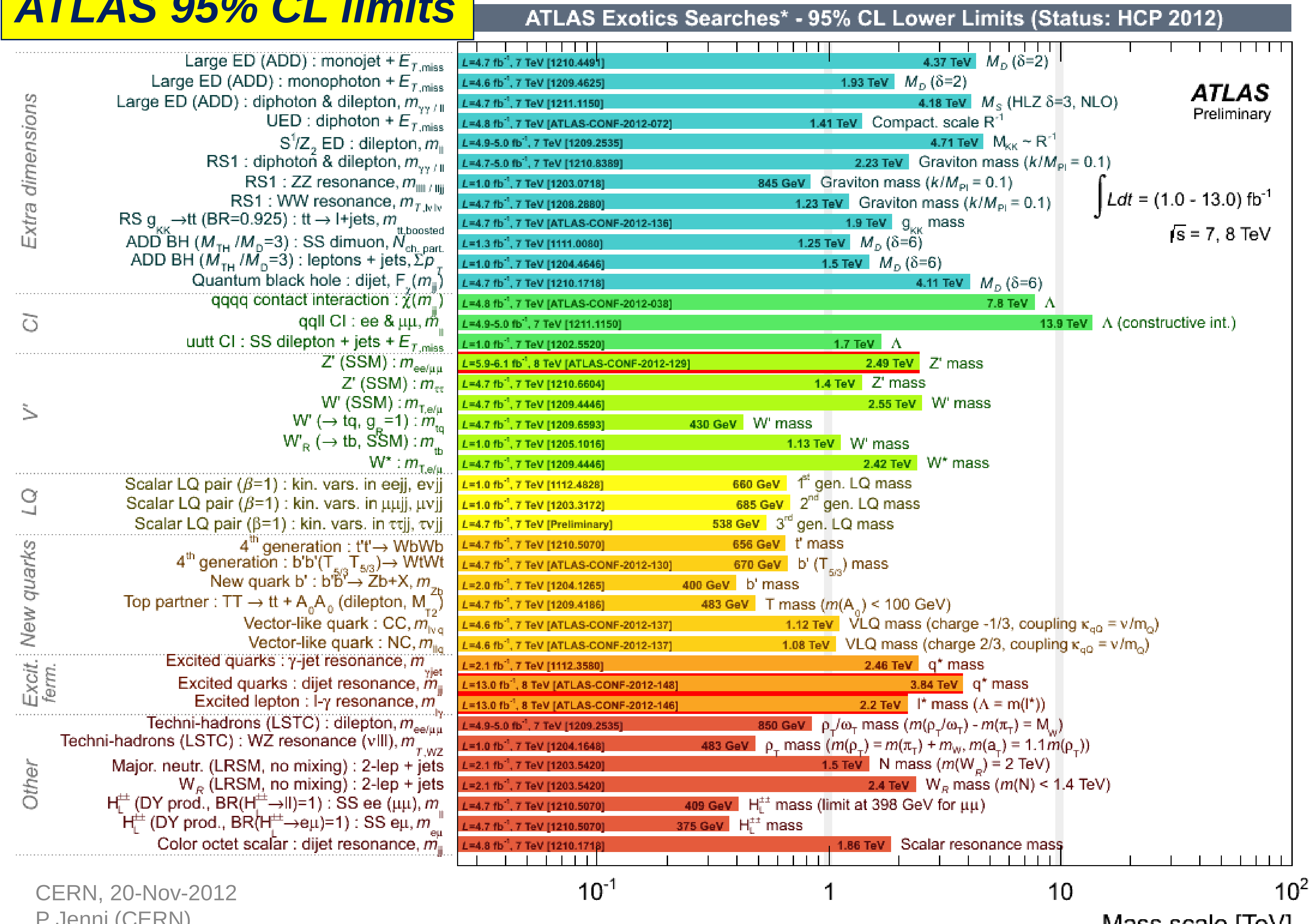


CMS-EXO-12-009



Resonances
Z'SSM ll
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lν
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Ball M, MD=2.1, Ms=1.7, gs=0.4
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
0 1 2 3 4 5 6
Compositeness
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
0 1 2 3 4 5 6
(TeV)
4th Generation
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
0 1 2 3 4 5
Long Lived
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
0 1 2 3 4 5
LeptoQuarks
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bντ) = 1
LQ3, (btau) β=1.0
stop (btau)
0 1 2 3 4 5
(TeV)
CMS 95% CL limits

ATLAS 95% CL limits

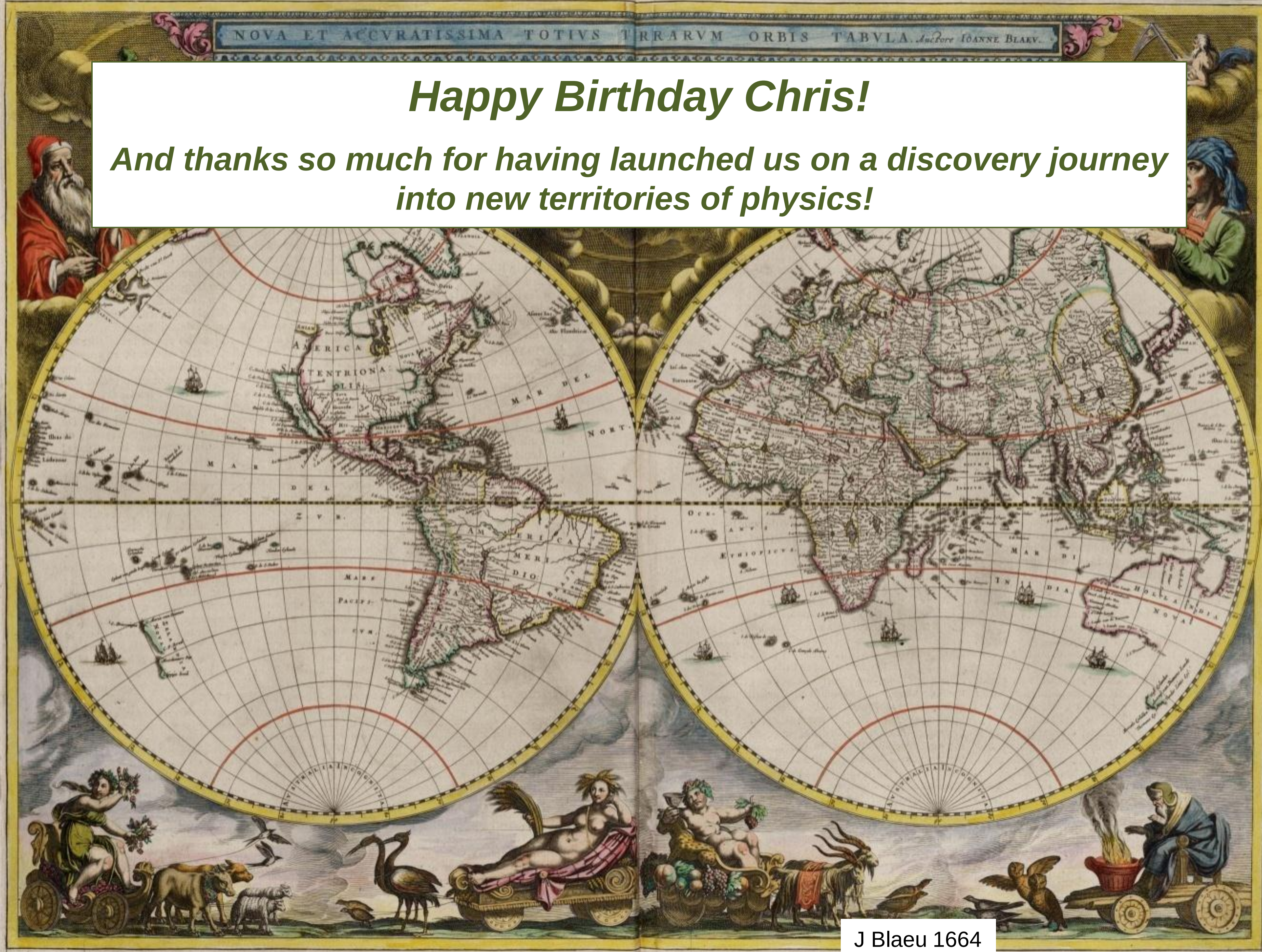


CERN, 20-Nov-2012
P Jenni (CERN)

*Only a selection of the available mass limits on new states or phenomena shown

Happy Birthday Chris!

And thanks so much for having launched us on a discovery journey into new territories of physics!



J Blaeu 1664

Spares

LHC Schedule Assumptions

2009
2010
2011
2012
2013 LS1
2014
2015
2016
2017
2018 LS2
2019
2020
2021
2022 LS3
2023

2030?

LHC start-up $\sqrt{s}$ = 900GeV

$\sqrt{s}$ = 7TeV rising to 8TeV, $\mathcal{L}$= $6\times10^{33}cm^{-2}s^{-1}$, bunch spacing 50ns

~20fb^{-1}

Go to design energy and nominal luminosity

$\sqrt{s}$ = 13-14TeV, $\mathcal{L}$= $1\times10^{34}cm^{-2}s^{-1}$, bunch spacing 25ns

≥50fb^{-1}

Injector and LHC Phase-I upgrade to full design luminosity

$\sqrt{s}$ = 14TeV, $\mathcal{L}$= $2\text{-}3\times10^{34}cm^{-2}s^{-1}$, bunch spacing 25ns

≥300fb^{-1}

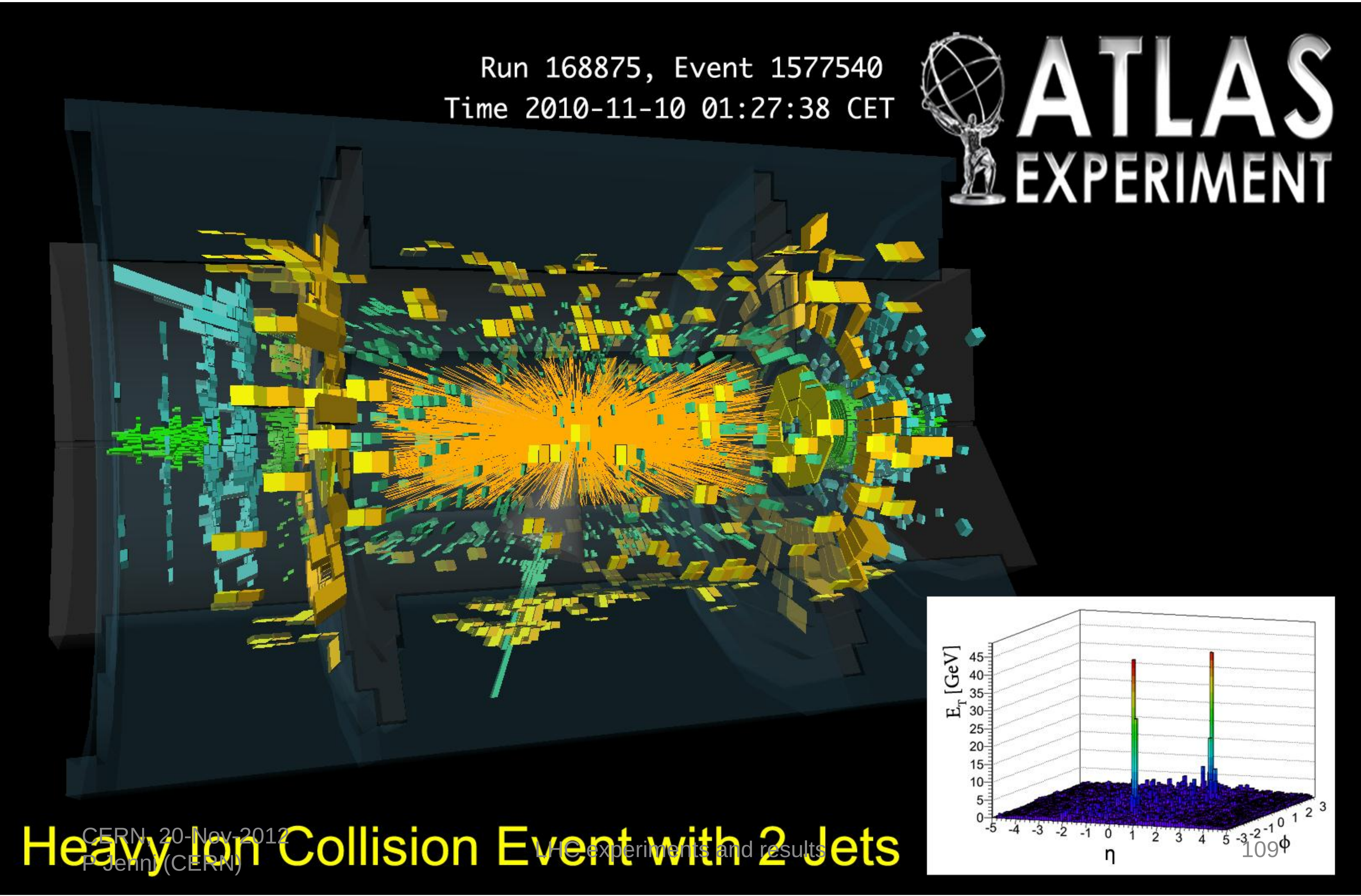
HL-LHC Phase-II upgrade, crab cavities, new IR, ...

$\sqrt{s}$ = 14TeV, $\mathcal{L}$= $5\times10^{34}cm^{-2}s^{-1}$ (luminosity levelling) 25ns

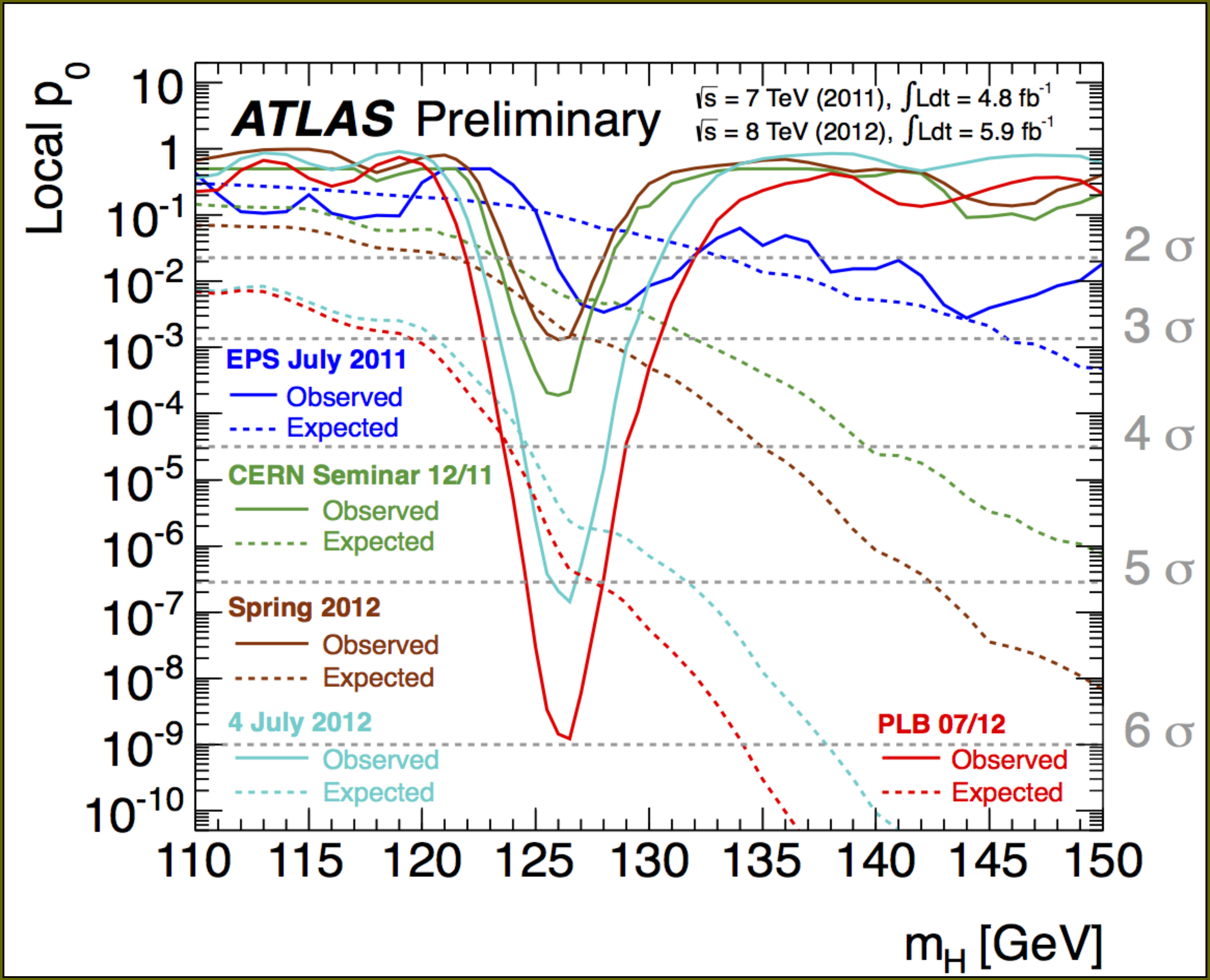
~3000 fb^{-1}

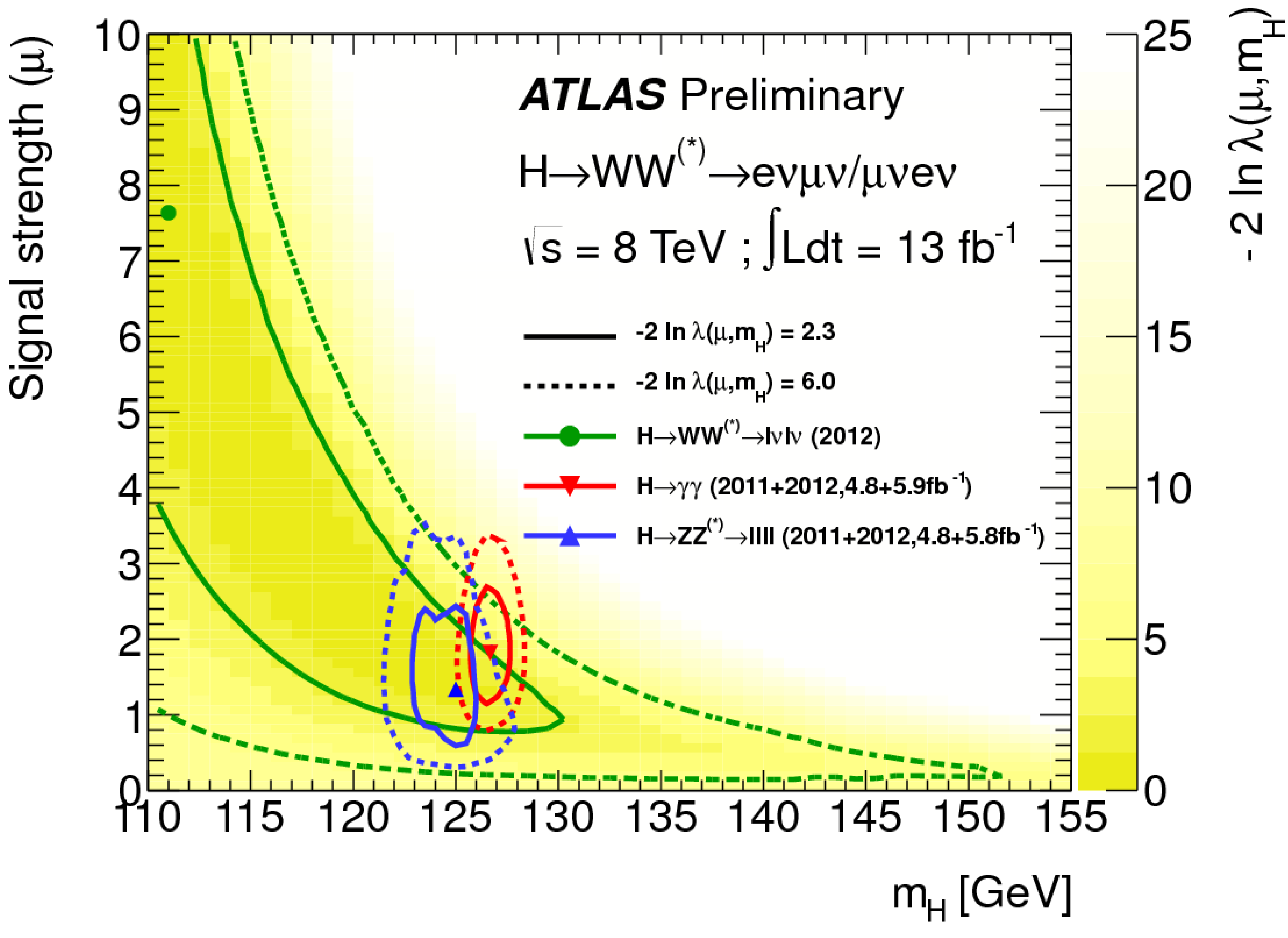
Pb-Pb event with jets

Uncorrected p_T of each jet ~160 GeV



Evolution of the excess with time





ATLAS Preliminary
H→WW(*)→eνμν/μνeν
√s = 8 TeV ; ∫Ldt = 13 fb-1
-2 ln λ(μ,mH) = 2.3
-2 ln λ(μ,mH) = 6.0
H→WW(*)→lνlν (2012)
H→γγ (2011+2012,4.8+5.9fb-1)
H→ZZ(*)→llll (2011+2012,4.8+5.8fb-1)
Signal strength (μ)
mH [GeV]
-2 ln λ(μ,mH)
0
1
2
3
4
5
6
7
8
9
10
110
115
120
125
130
135
140
145
150
155
0
5
10
15
20
25

CDF and D0 Collaborations

Evidence for a particle produced in association with weak bosons and decaying to a bottom-antibottom quark pair in Higgs boson search at the Tevatron, submitted to Phys. Rev. Lett. (2012), arXiv:1207.6436.