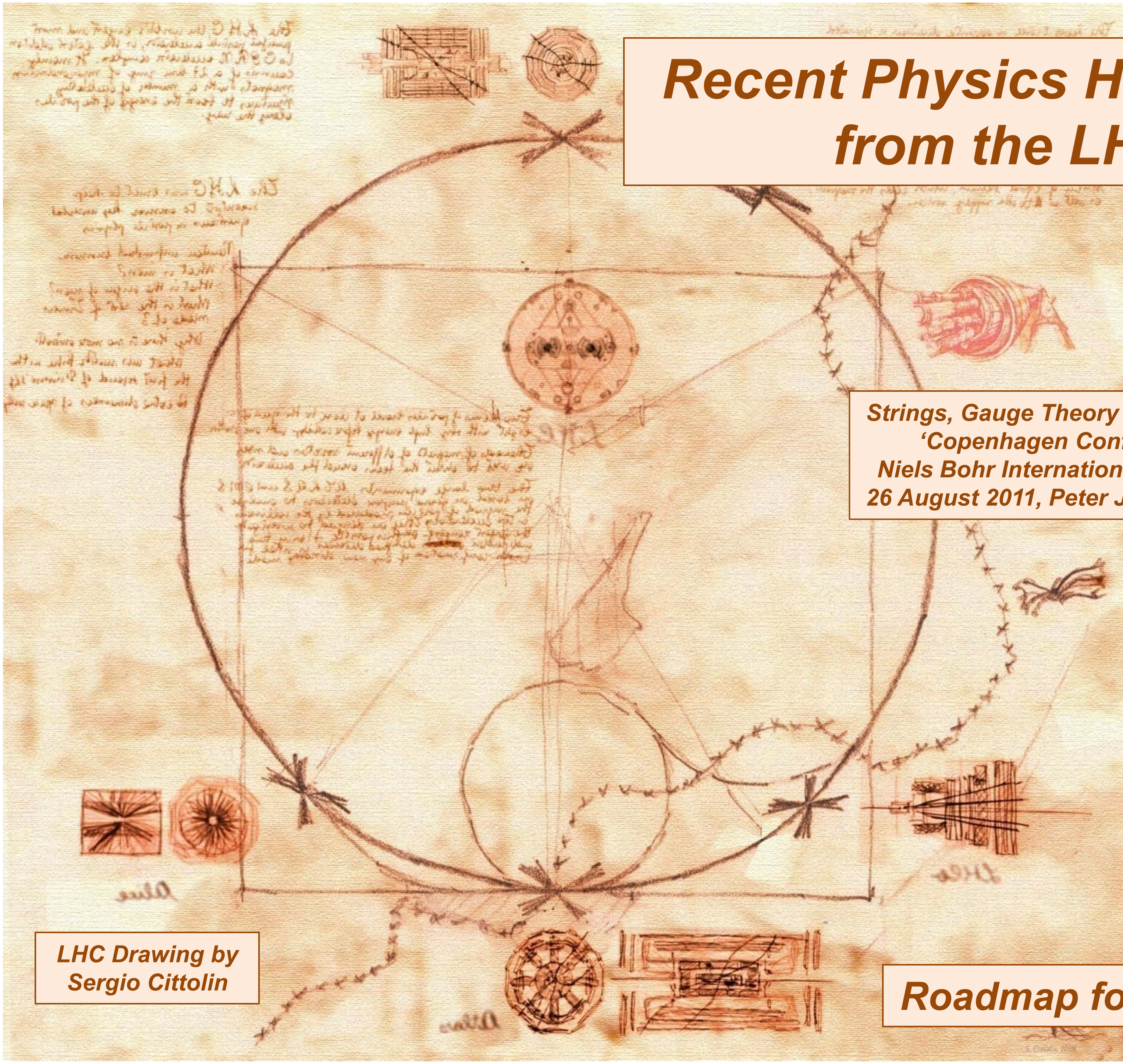
Recent Physics Highlights from the LHC

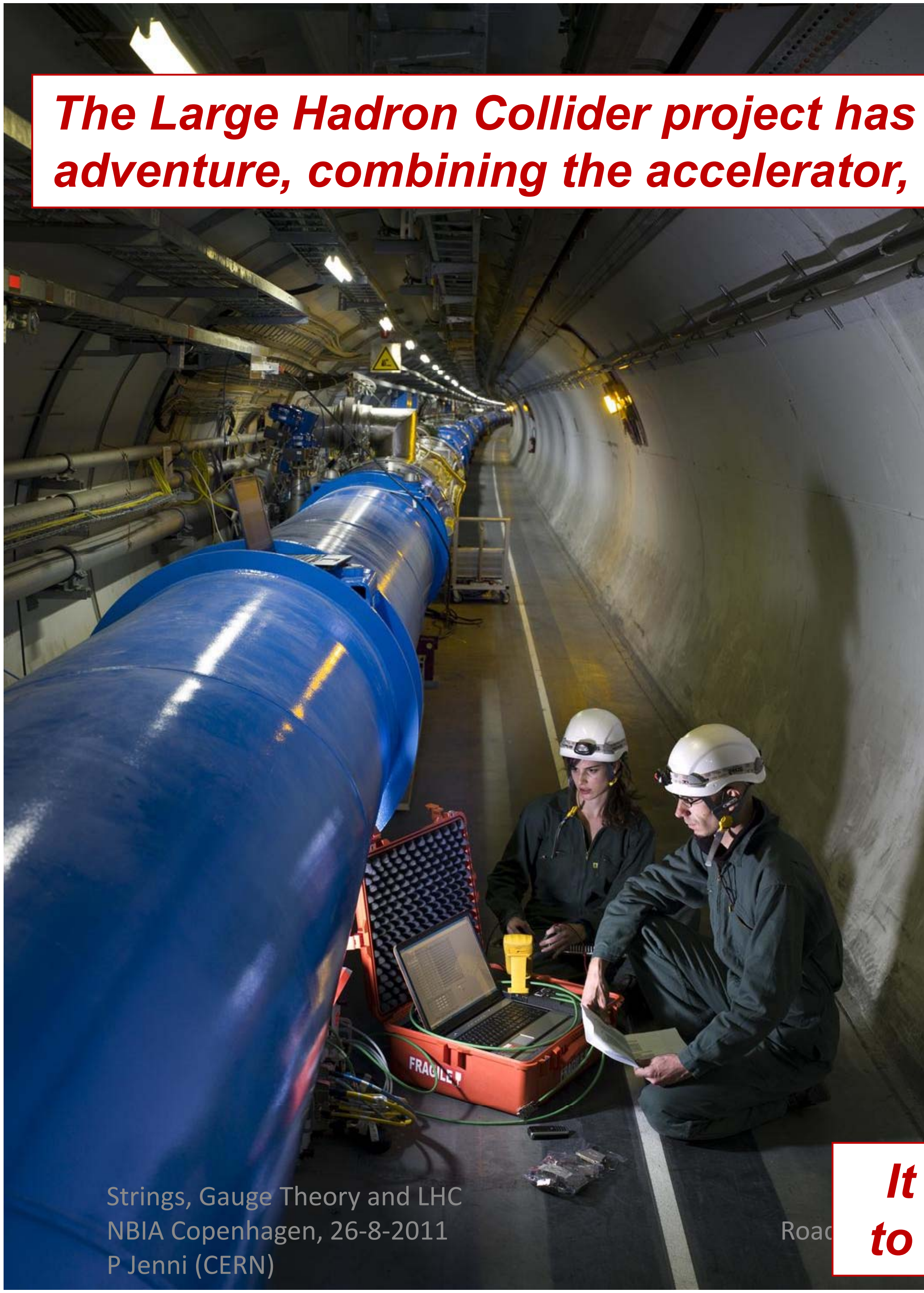


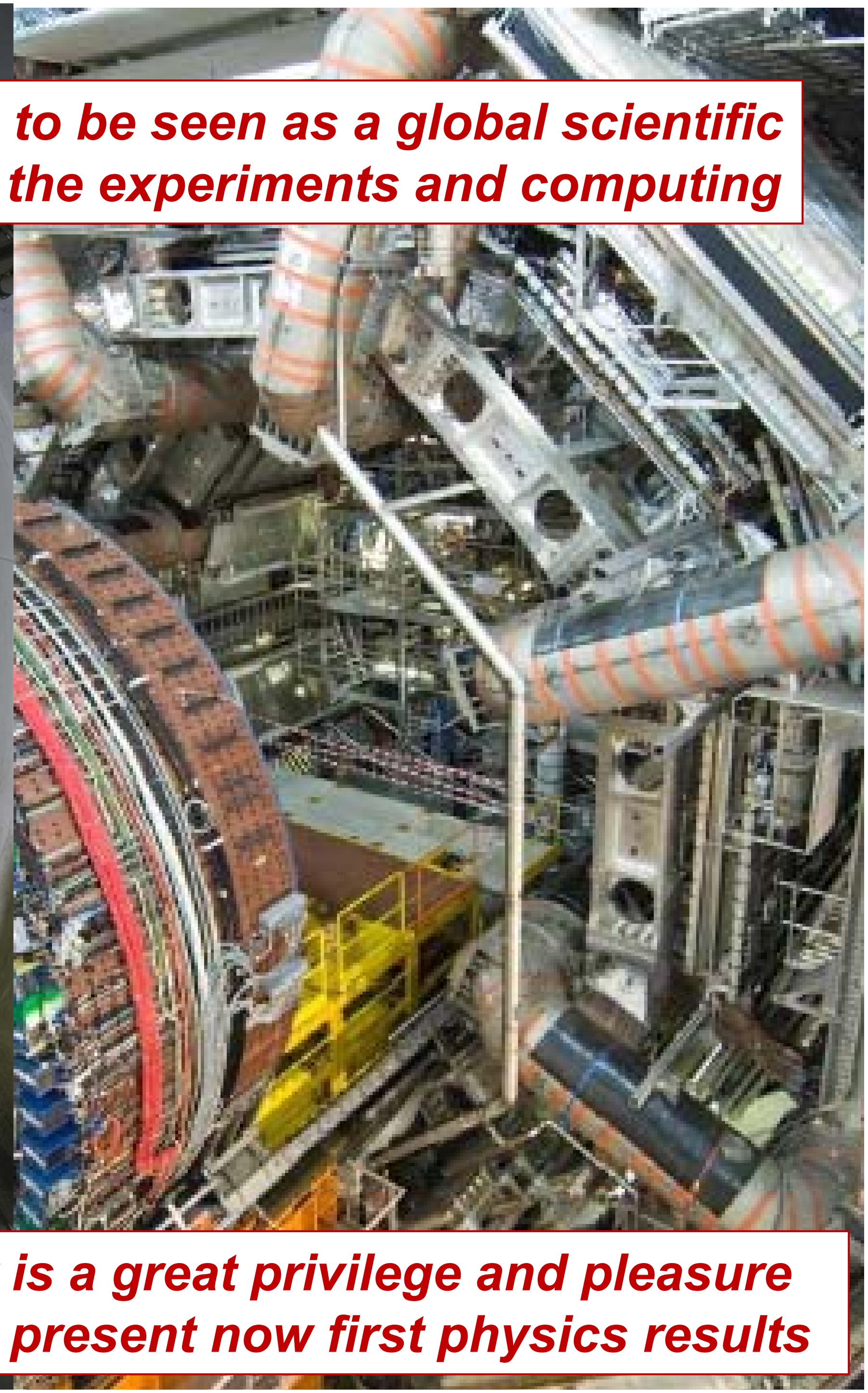
Strings, Gauge Theory and the LHC
'Copenhagen Conference'
Niels Bohr International Academy
26 August 2011, Peter Jenni (CERN)

LHC Drawing by Sergio Cittolin

Roadmap for Discoveries

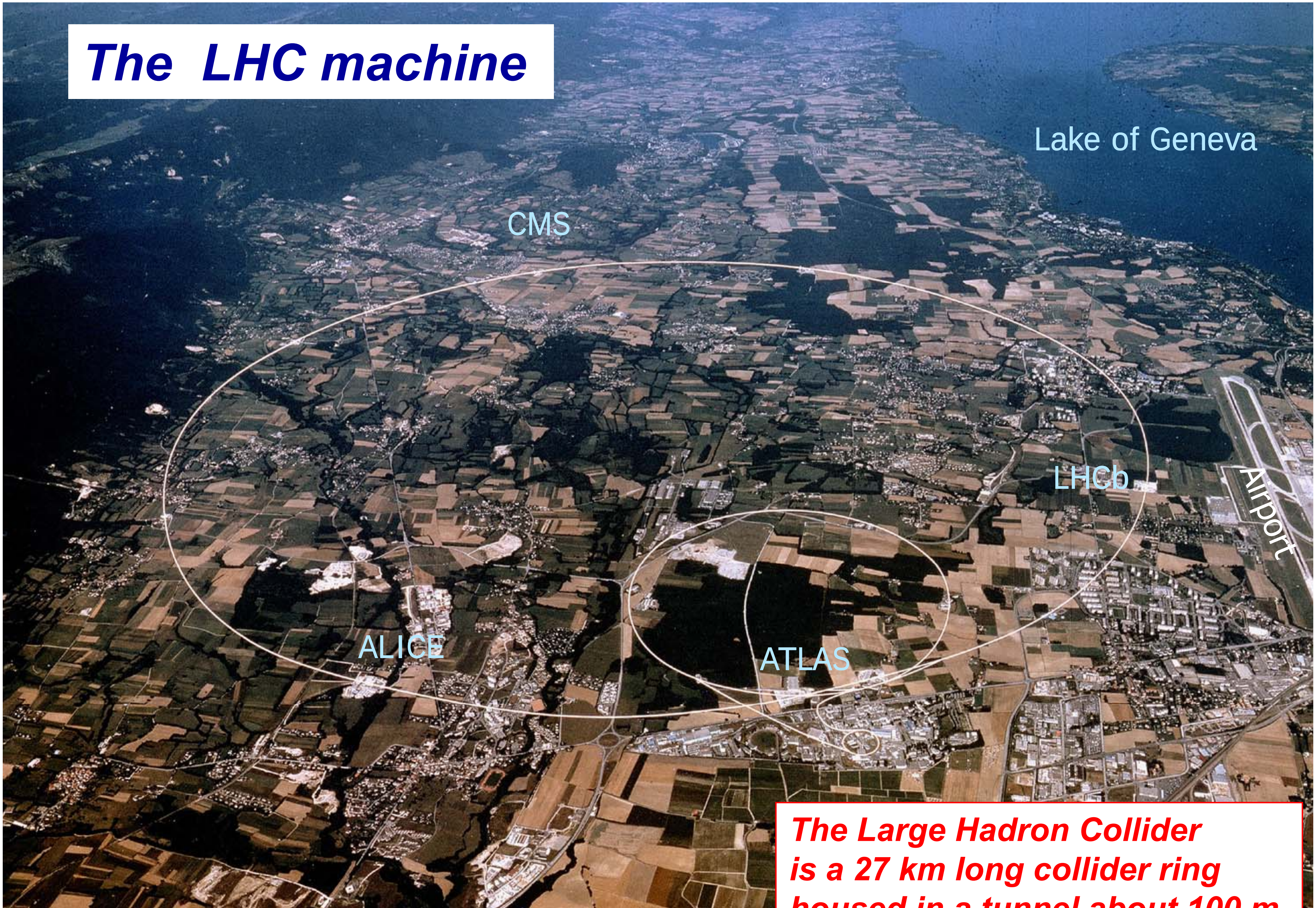
The Large Hadron Collider project has to be seen as a global scientific adventure, combining the accelerator, the experiments and computing





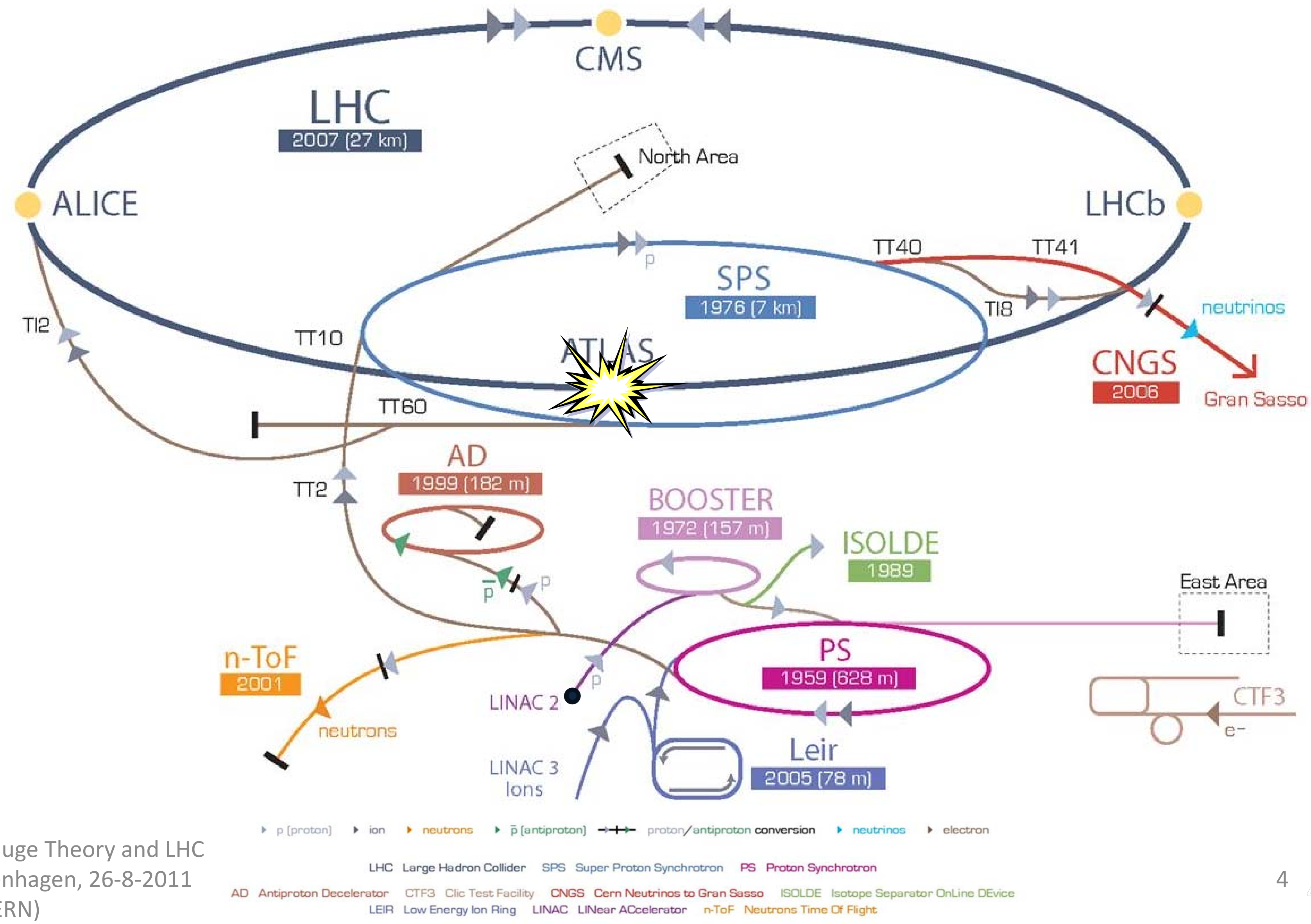
It is a great privilege and pleasure to present now first physics results

The LHC machine



The Large Hadron Collider is a 27 km long collider ring housed in a tunnel about 100 m underground near Geneva

CERN's particle accelerator chain



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**

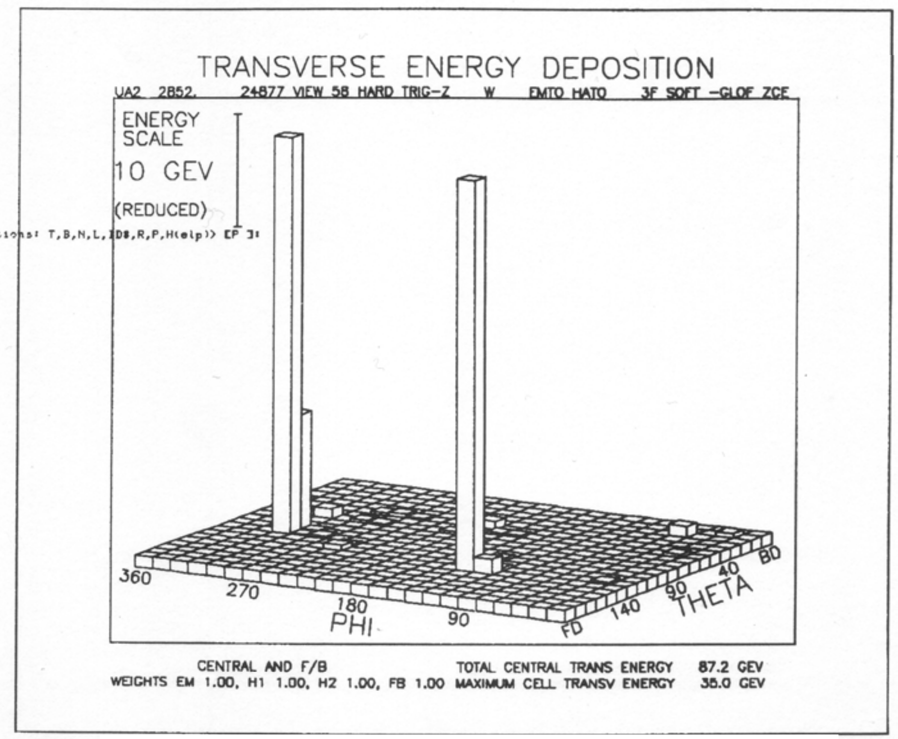
1981 **LEP was approved with a large and long (27 km) tunnel**

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)

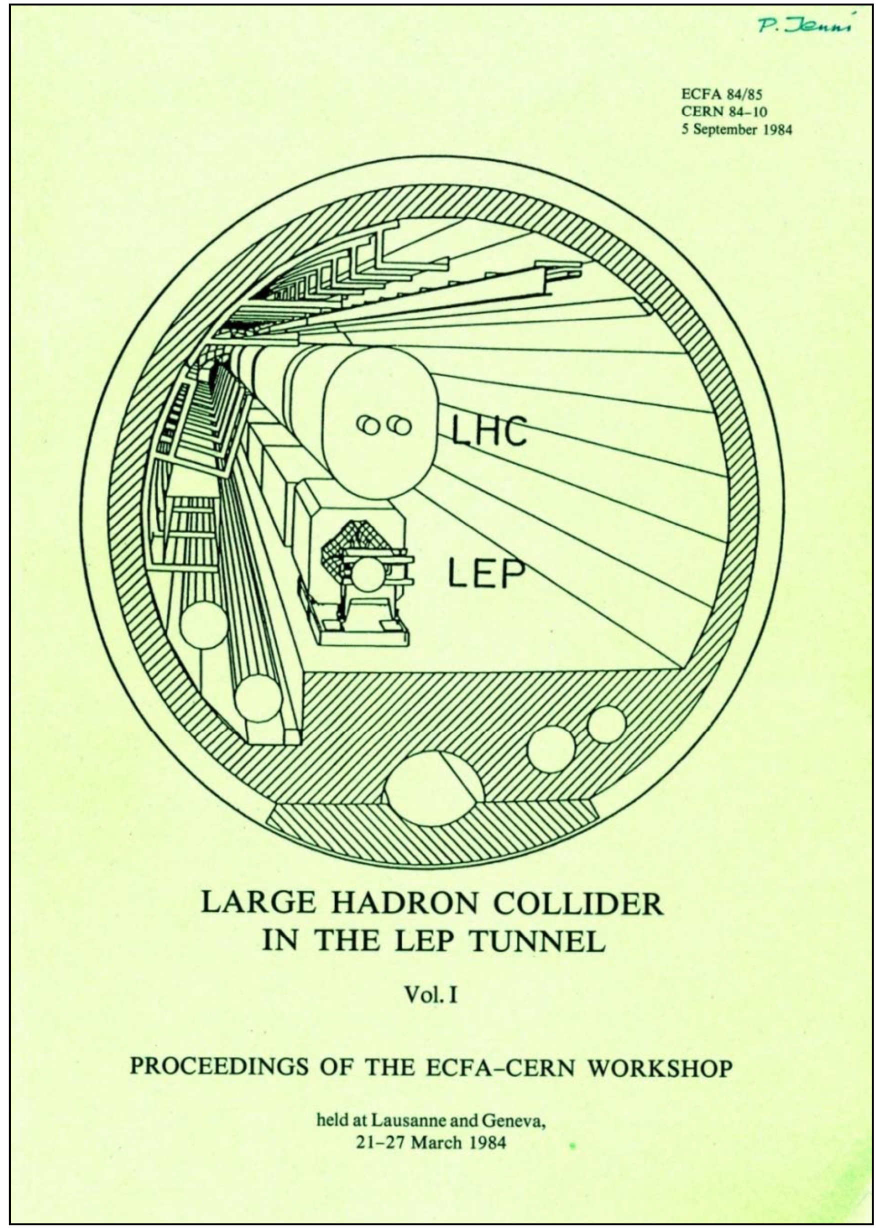
1984 For the community it all started in a way with the 1st CERN – ECFA Workshop Lausanne on the feasibility of a hadron collider in the future LEP tunnel

1987 La Thuile LHC Workshop

Many LHC colleagues were already involved in this, a clear evolution started for detectors away from a 4μ iron-ball experiment (C Rubbia) towards multi-purpose detectors…)

1989 ECFA Study Week in Barcelona for LHC instrumentation

At this conference a few decided to start setting up a structure for an LHC proto-Collaboration….



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)

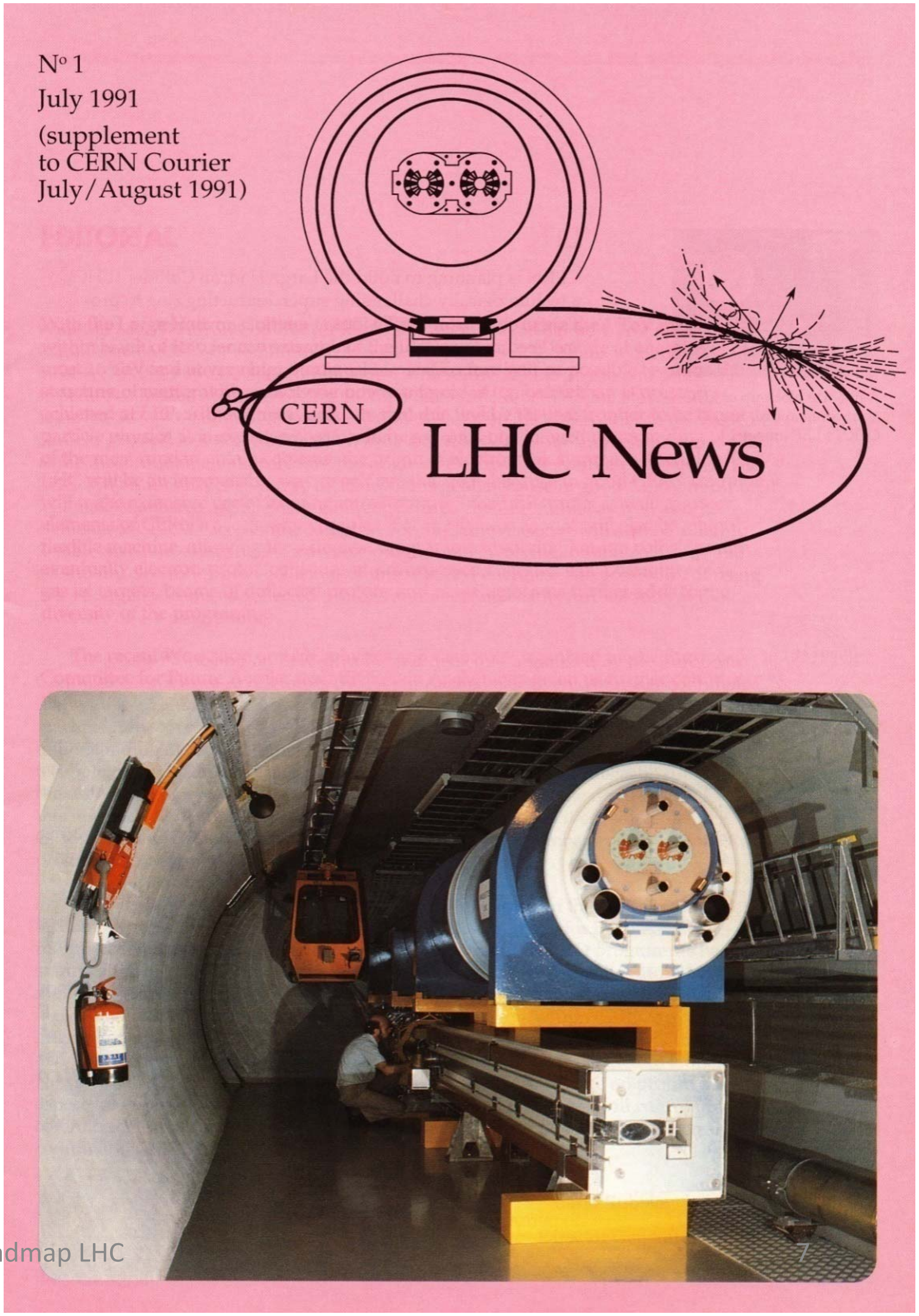
1993 December proposal of LHC with commissioning in 2002

1994 June Council:

Staged construction was proposed, 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



The two-stage approval 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 coming years, 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)

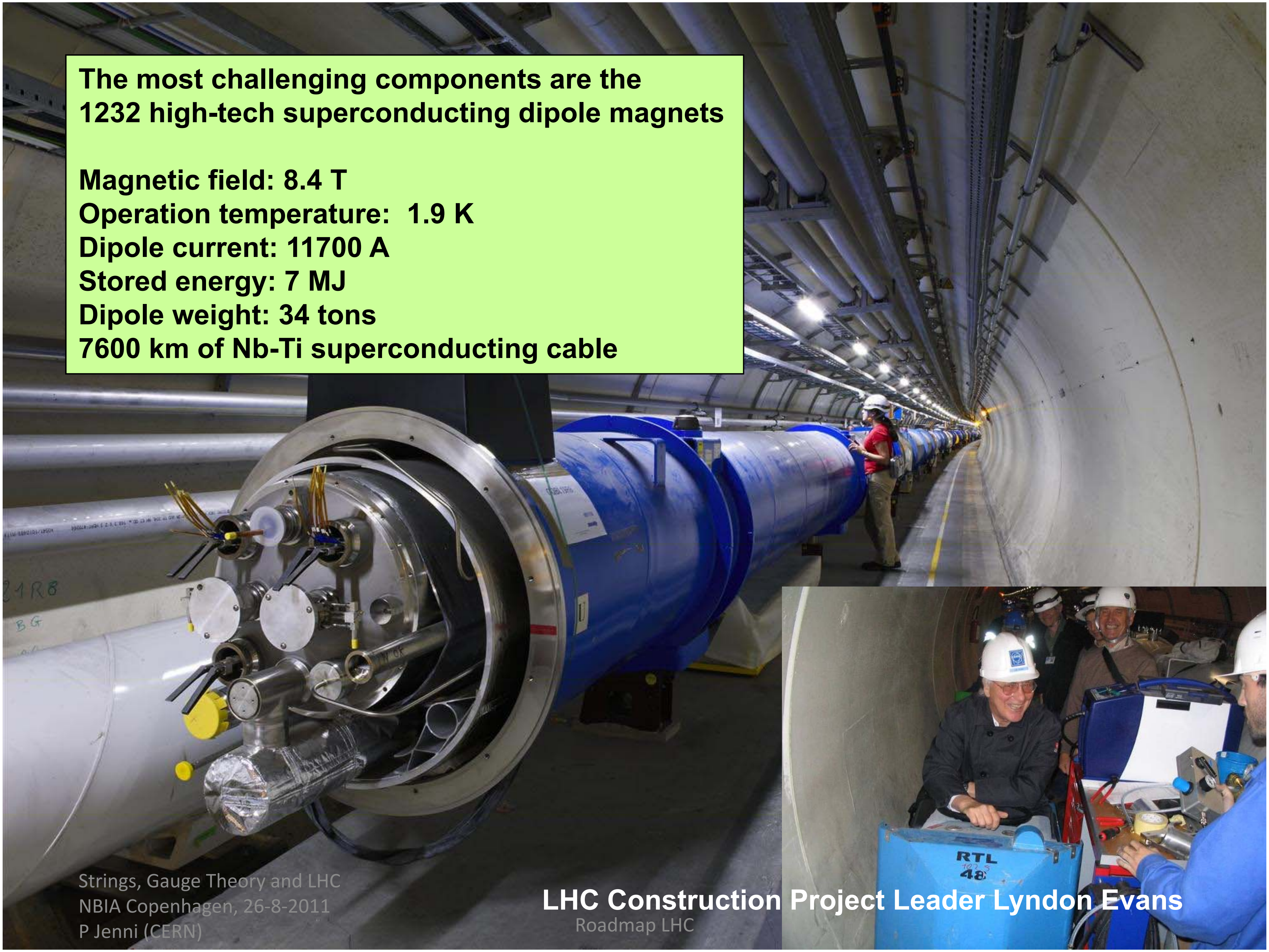
1997

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)

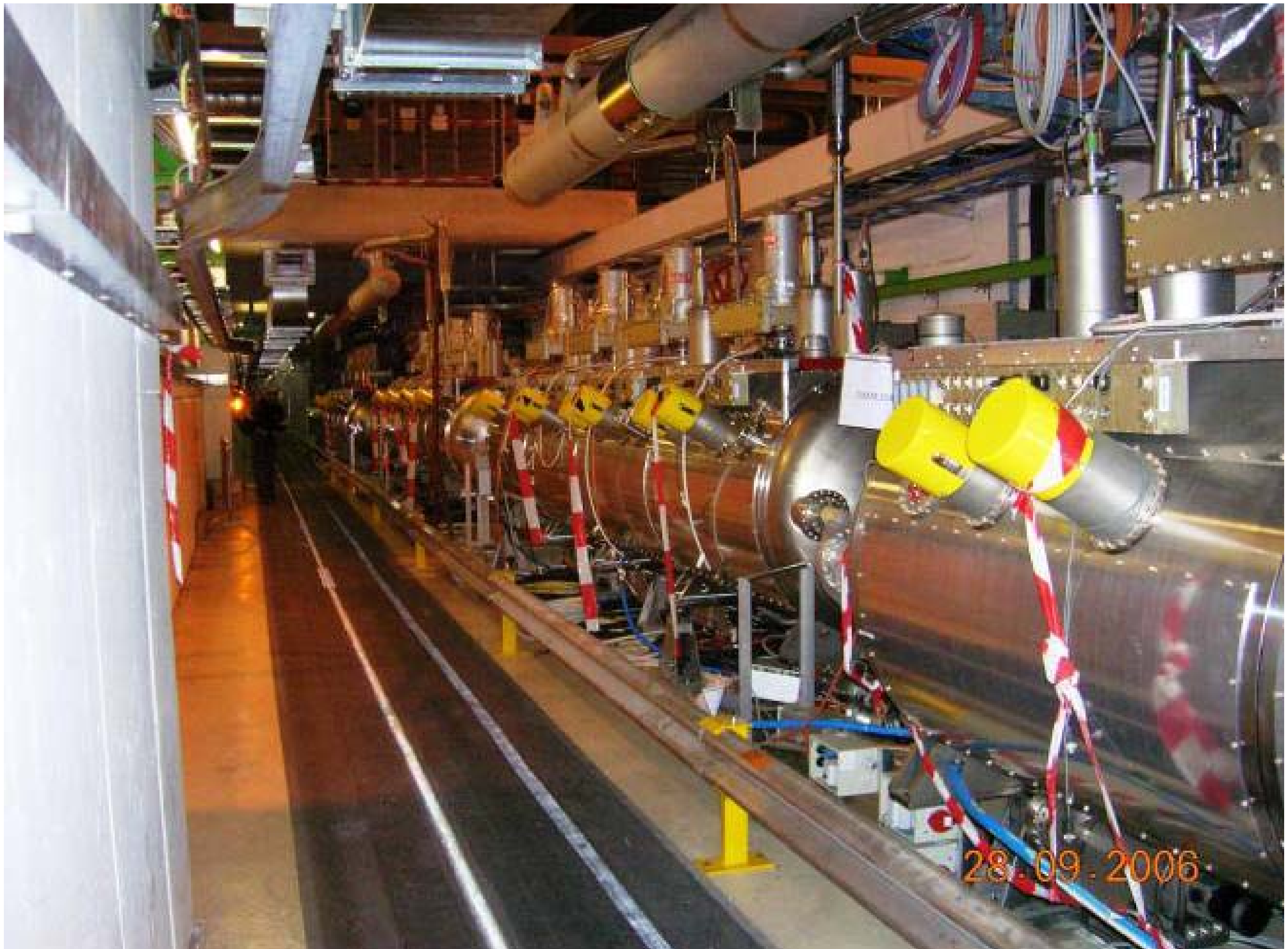
The most challenging components are the 1232 high-tech superconducting dipole magnets

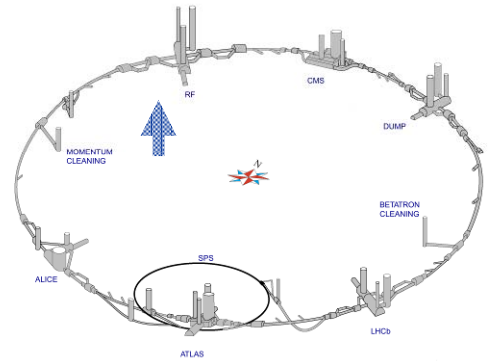
Magnetic field: 8.4 T
Operation temperature: 1.9 K
Dipole current: 11700 A
Stored energy: 7 MJ
Dipole weight: 34 tons
7600 km of Nb-Ti superconducting cable



LHC Construction Project Leader Lyndon Evans

The particle beams are accelerated by superconducting Radio-Frequency (RF) cavities

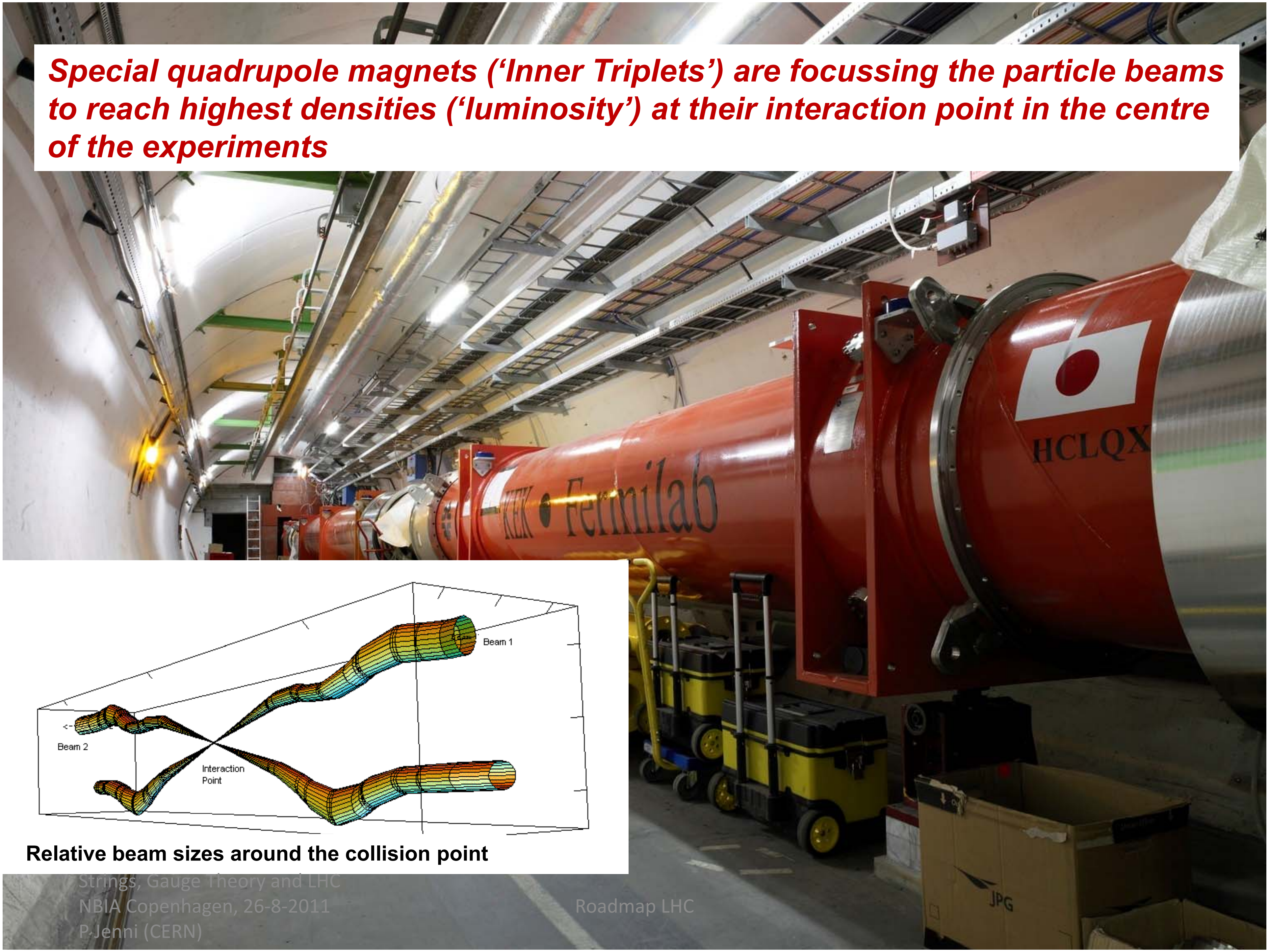




Note: The acceleration is not such a big issue in pp colliders (unlike in e^+e^- colliders), because of the ~ $1/m^4$ behaviour of the synchrotron radiation energy losses [~ E^4_{beam}/Rm^4]

	LHC at 7 TeV	LEP at 100 GeV
Synchrotron radiation loss	6.7 keV/turn	3 GeV/turn
Peak accelerating voltage	16 MV/beam	3600 MV/beam

Special quadrupole magnets ('Inner Triplets') are focussing the particle beams to reach highest densities ('luminosity') at their interaction point in the centre of the experiments

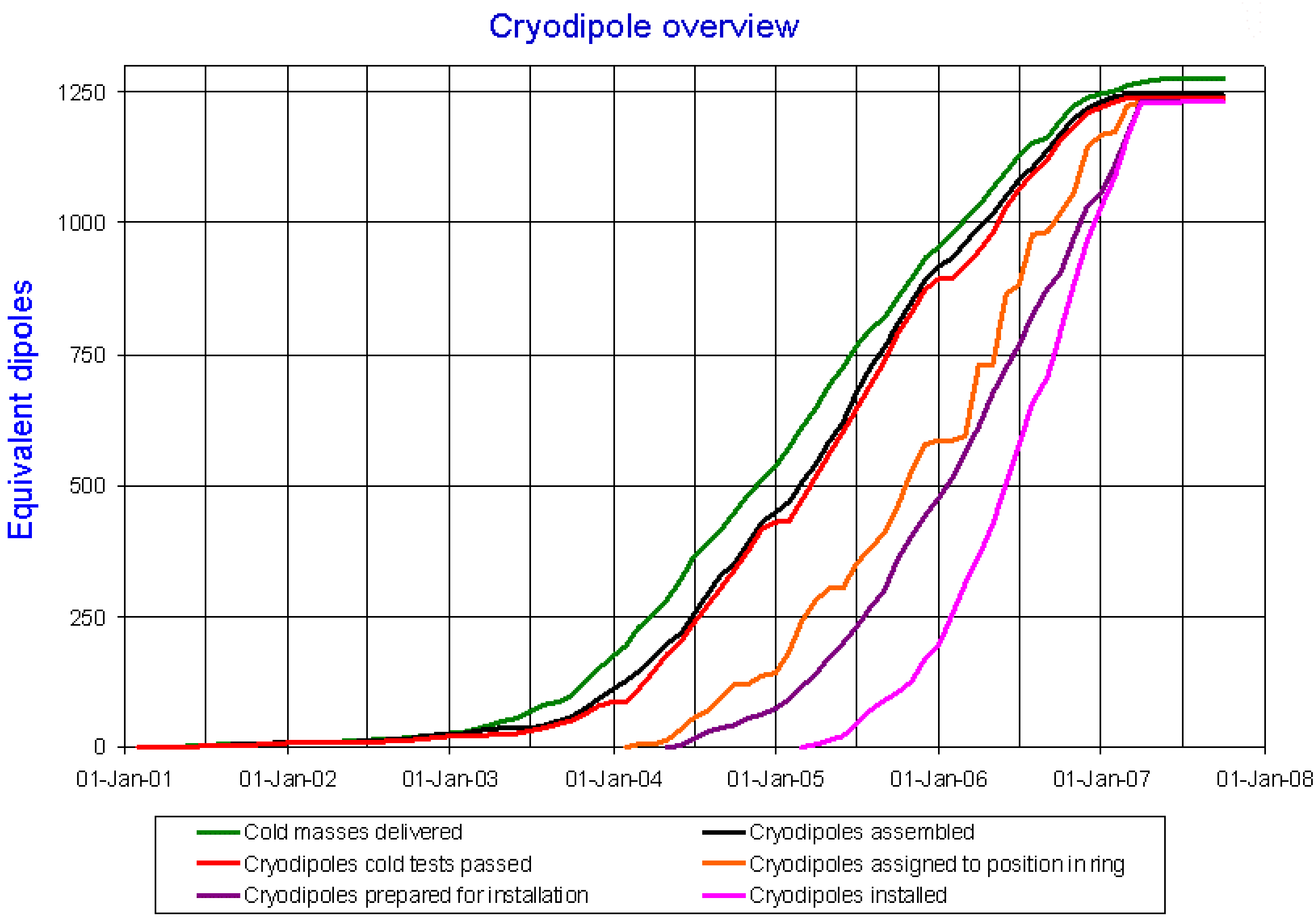


Relative beam sizes around the collision point

LHC Progress Dashboard

History of the dipole magnet construction and installation

Accelerator Technology Department



Roadmap LHC

Updated 30 September 2007

Data provided by D. Tommasini AT-MCS, L. Bottura AT-MTM

10 September 2008: LHC inauguration day

First (single) beams circulating in the machine

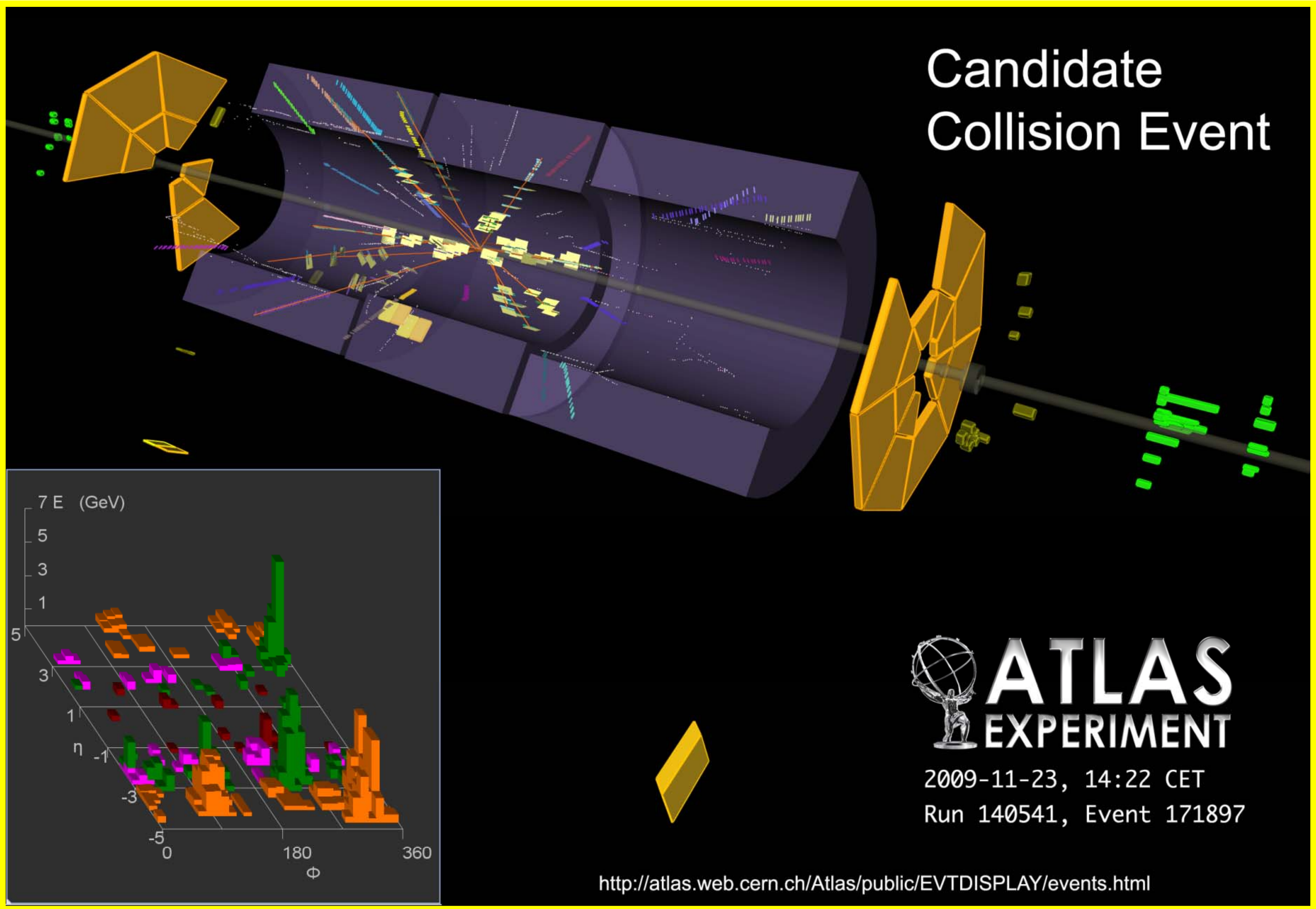
Five CERN DGs, from conception to realization: Schopper, Rubbia, Llewellyn Smith, Maiani, Aymar (from right to left)

Interconnections of two magnets

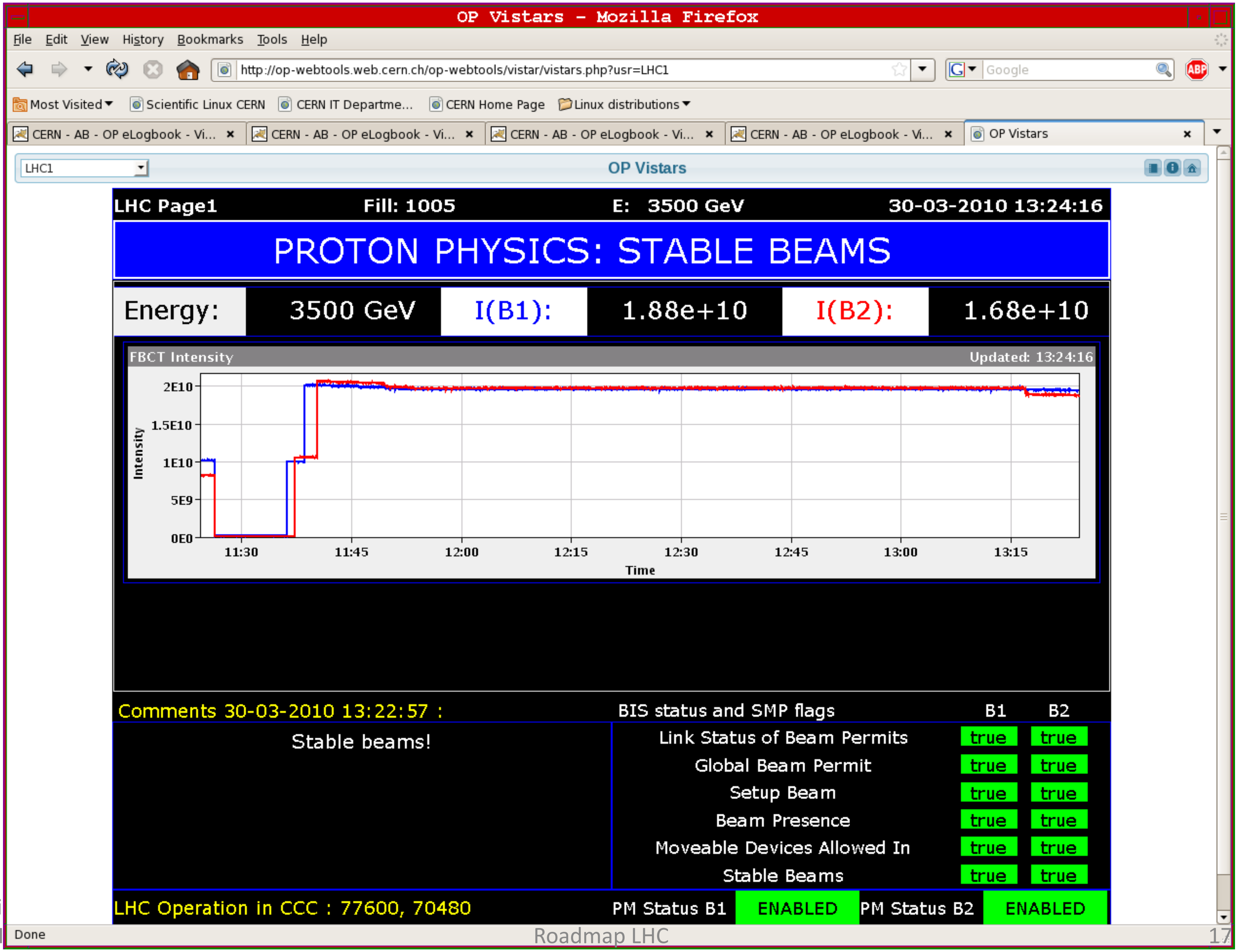
One (superconductor) joint failed on 19^{th} September 2008, and it caused a catastrophic He-release that made serious collateral damage to sector 3-4 of the LHC machine

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



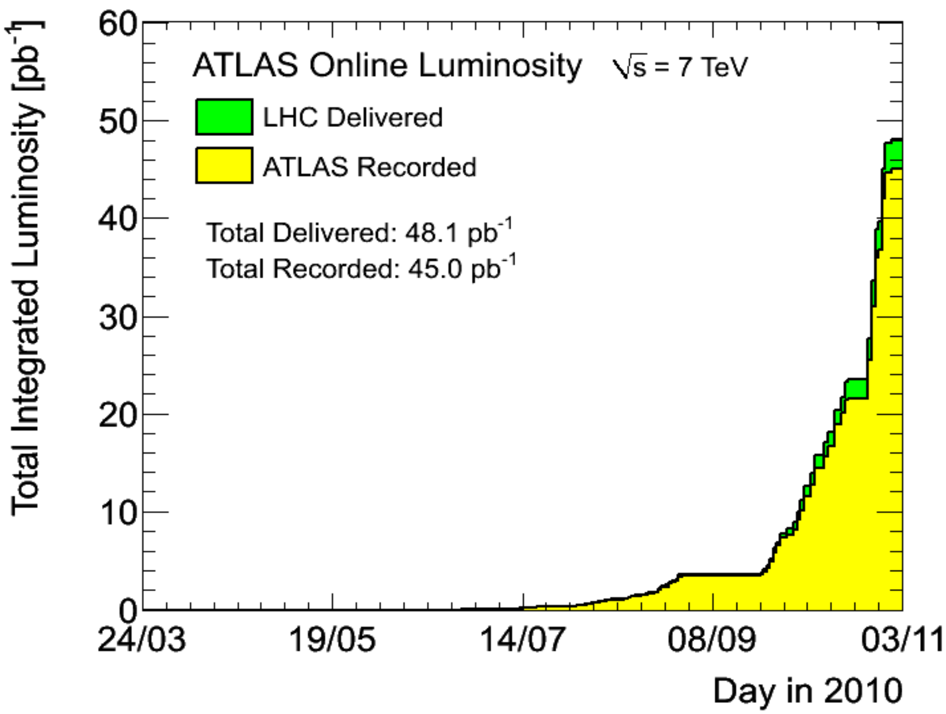
High-energy operation with 3.5 TeV beams started on 30th March 2010

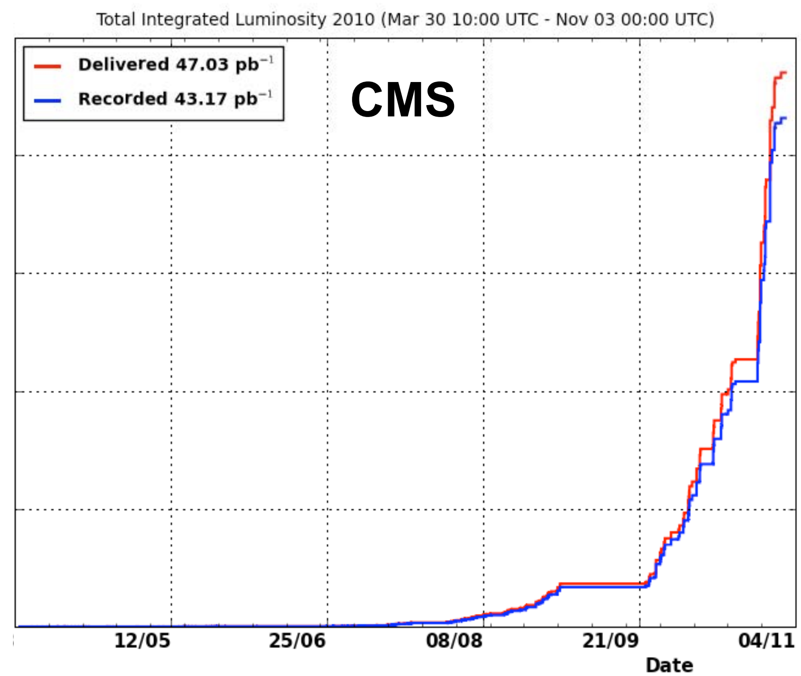


The LHC has performed over 2010 in a superb way at 7 TeV collision energy, and delivered a good sample of data in stable pp beam operation (~ 48 pb^{-1} integrated luminosity)

The high-luminosity general-purpose experiments ATLAS and CMS both have operated efficiently (recorded typically 92 – 94 % of the luminosity delivered in stable conditions)

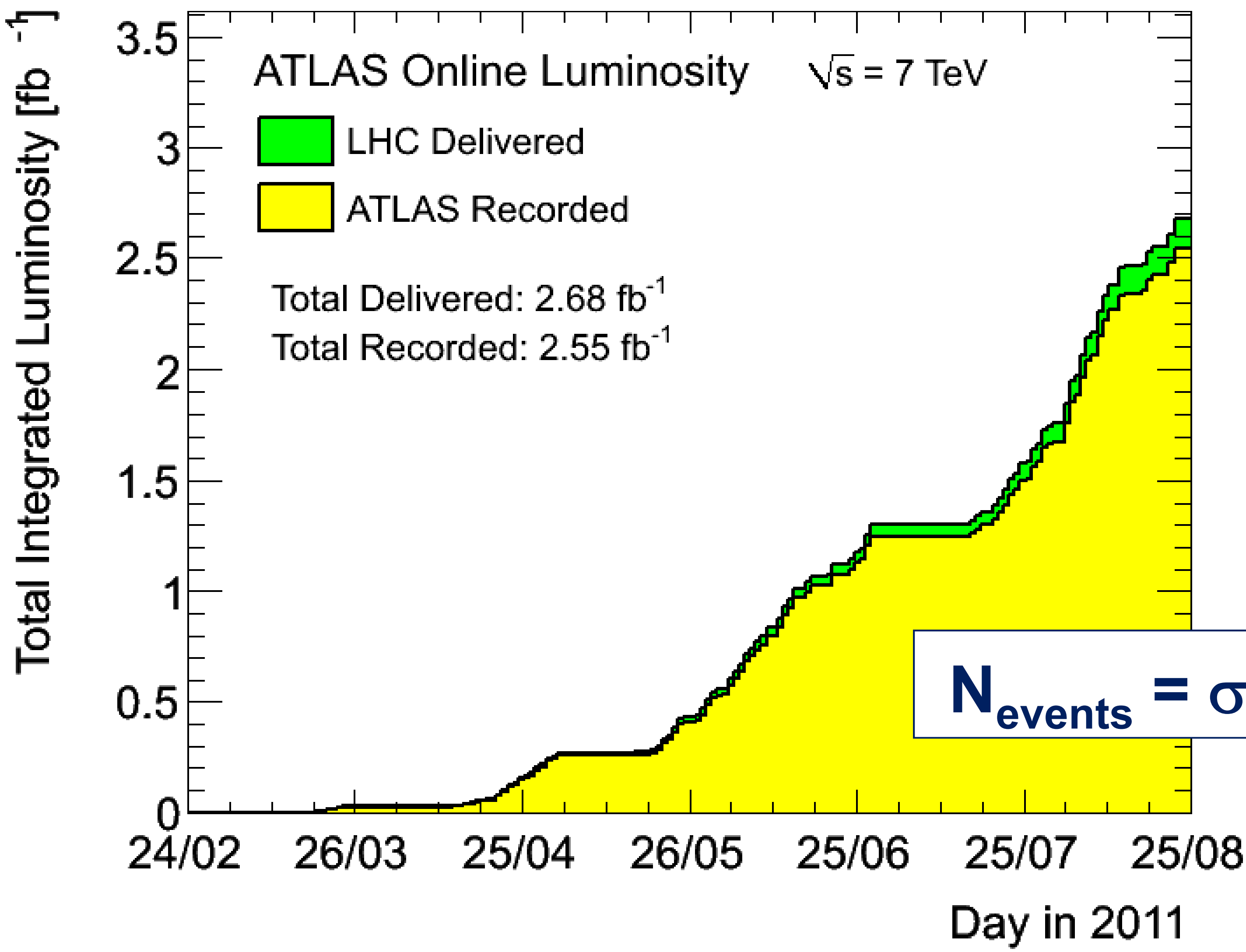
After all data quality criteria, published physics results for the full 2010 data sets are typically based on an integrated luminosity of 35 – 40 pb^{-1} (syst. luminosity errors 3-5%)





(In addition the LHC delivered in 2010 about 10 μb^{-1} of PbPb collisions at 2.76 TeV/nucleon, not covered in this talk)

Integrated Luminosity in ATLAS 2011



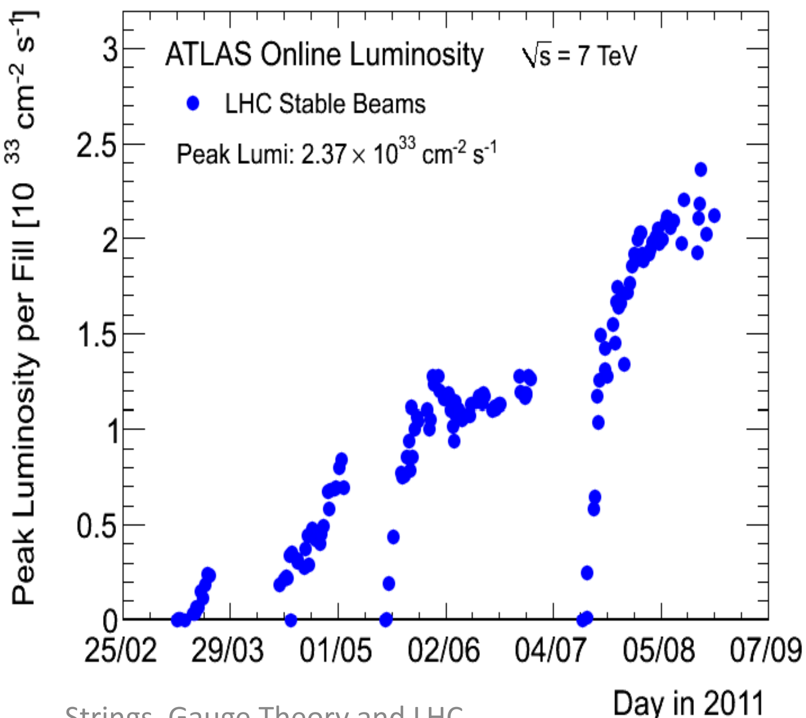
$$N_{events} = \sigma \int L \, dt$$

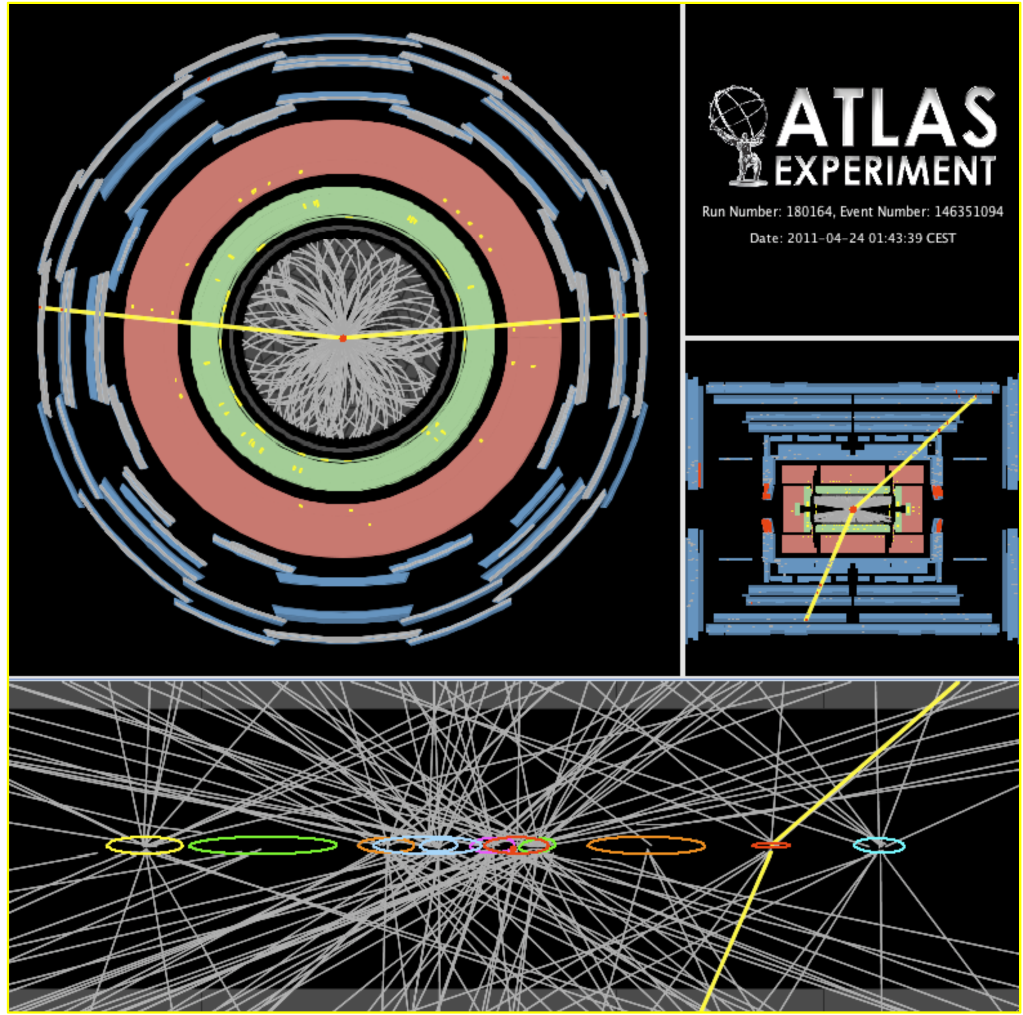
Current LHC Operation:

1380 bunches per beam

50 ns bunch spacing

up to 1.7 x 10^{11} protons per bunch





Z→μμ event with 11 primary vertices

(Typical peak pile-up per bunch crossing: 10)

Road Map of Expected Hadron Collider Performances

End 2010	Tevatron	2 TeV	7 fb^{-1} (analysed)
	LHC	7 TeV	45 pb^{-1}
End 2011	Tevatron	2 TeV	10 fb^{-1} (analysed)
	LHC	7 TeV	4 fb^{-1}
End 2012	LHC	7 TeV	10 fb^{-1}
End 2015	LHC	14 TeV	30 fb^{-1}
End 2017	LHC	14 TeV	100 fb^{-1}
Early 2020s	LHC	14 TeV	500 fb^{-1}
2030	(s)LHC	14 TeV	3000 fb^{-1} (ultimately…)

(These are round numbers and estimates, just to give a rough idea…)

(1 fb^{-1} = 1000 pb^{-1})

New rough draft 10 year plan

2022

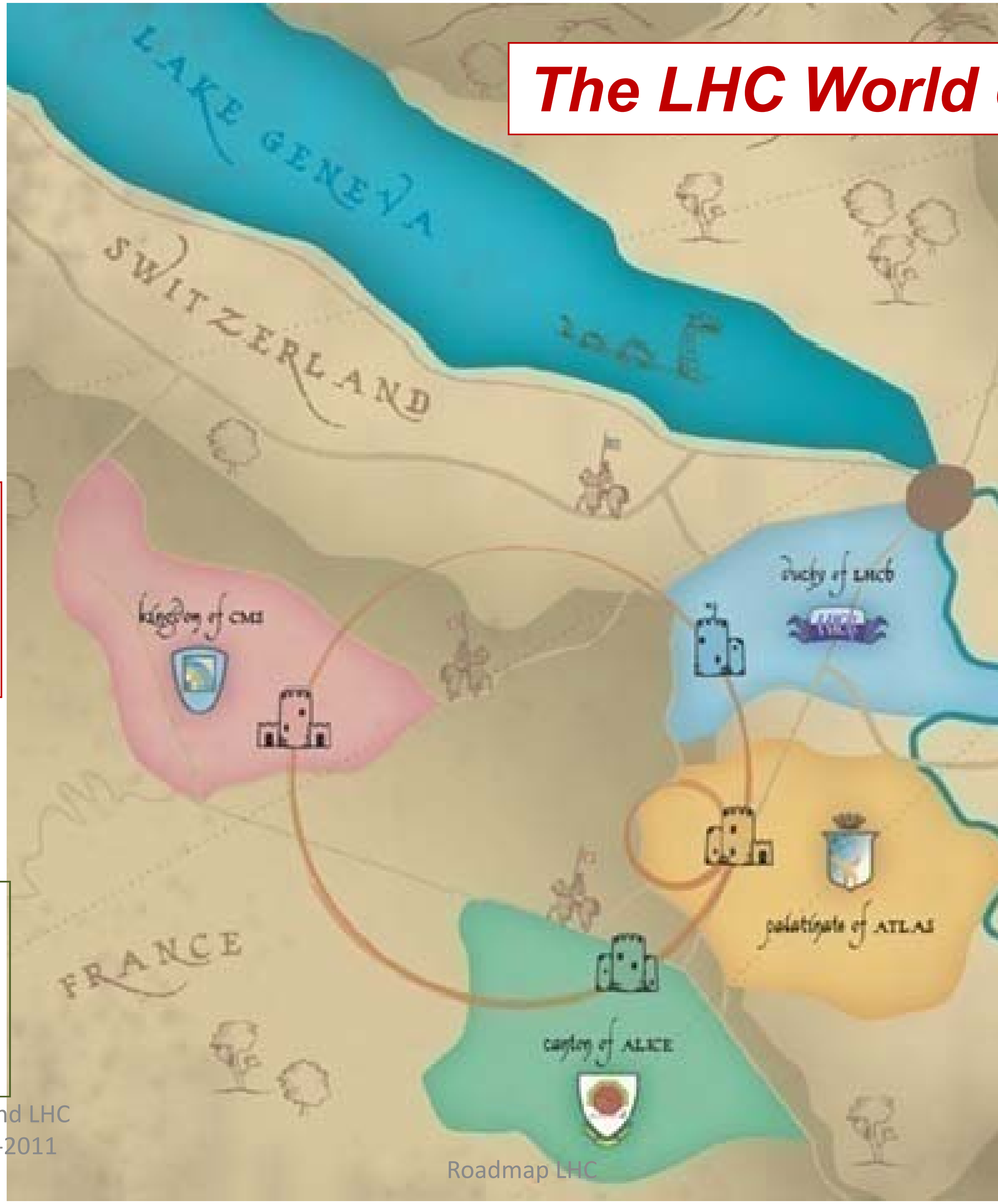
Options

Installation of the HL-LHC hardware.
Installation of LHeC
Preparation for HE-LHC

Detector upgrades

The LHC World of CERN

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



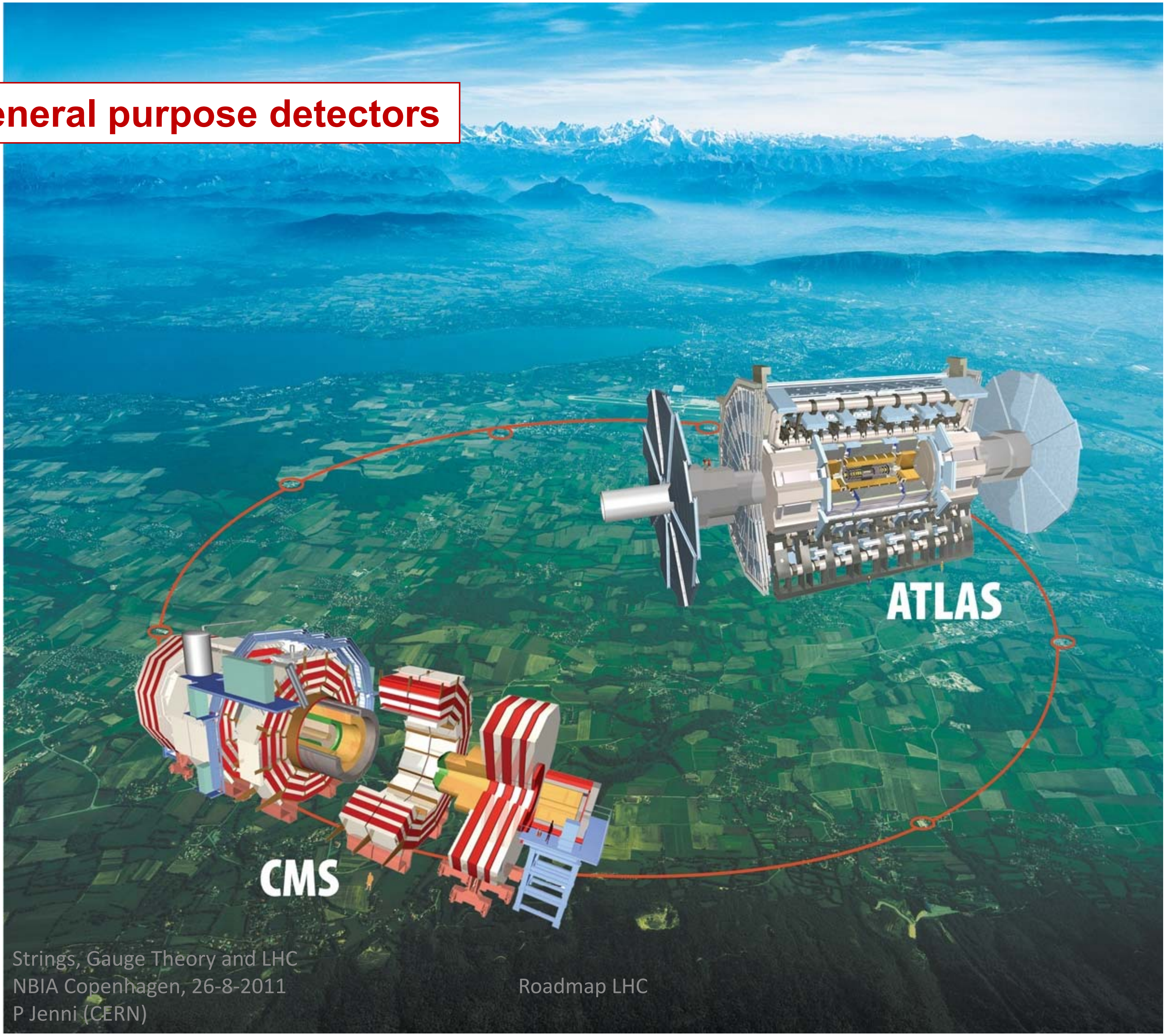
CMS
2900 Physicists
184 Institutions
38 countries
550 MCHF

LHCb
730 Physicists
54 Institutions
15 countries
75 MCHF

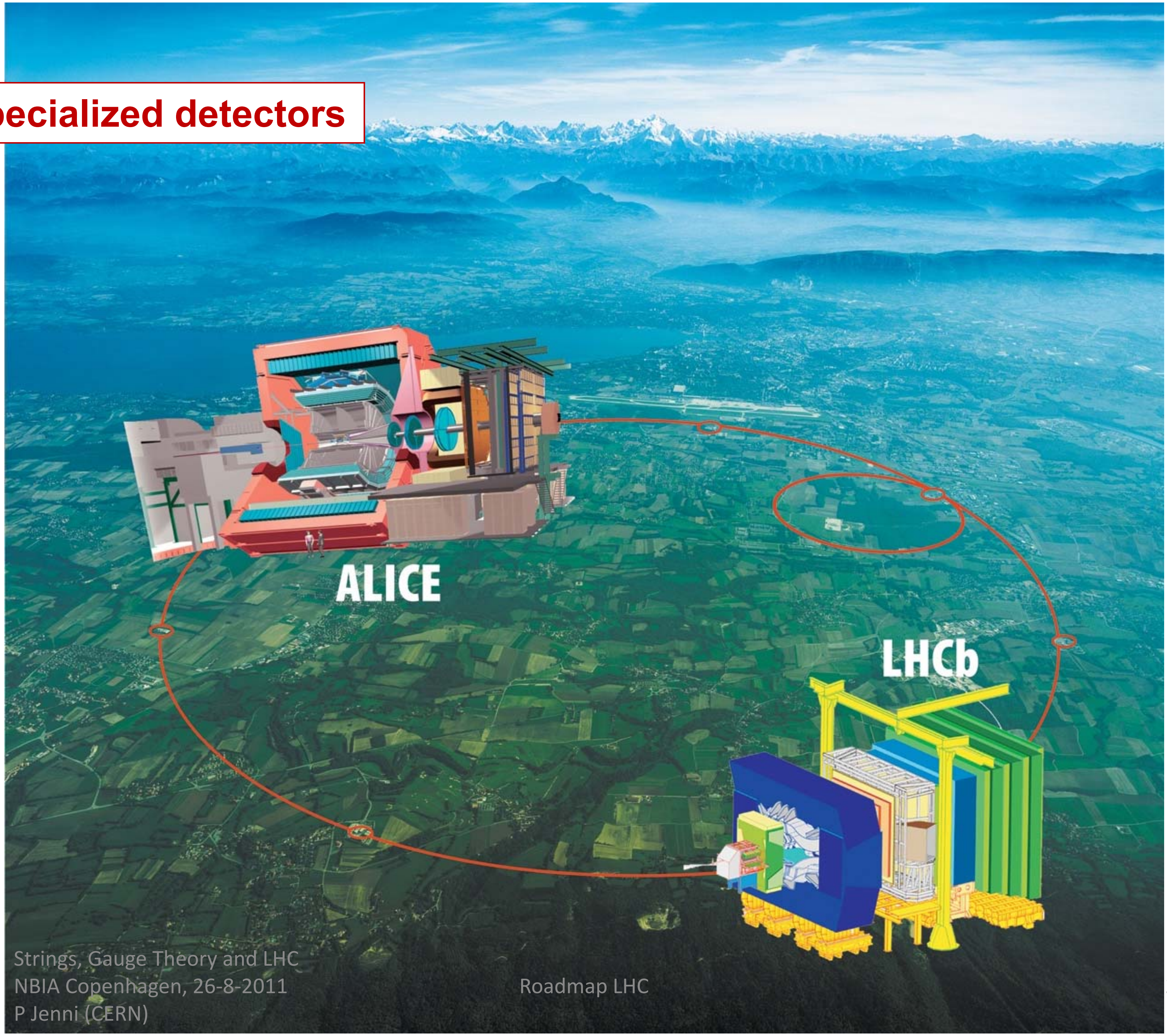
ATLAS
3000 Physicists
174 Institutions
38 countries
550 MCHF

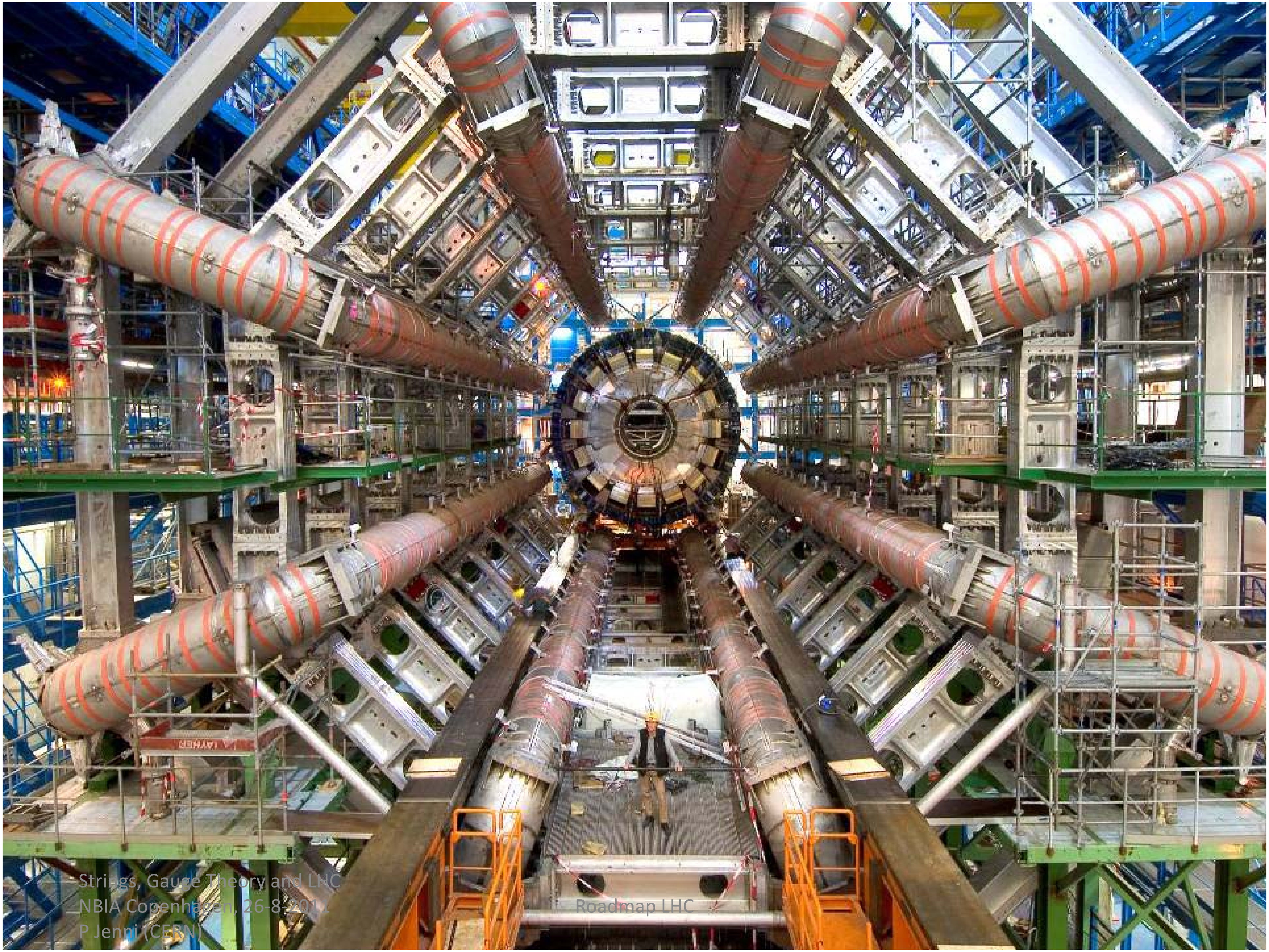
ALICE
1000 Physicists
105 Institutions
30 countries
150 MCHF

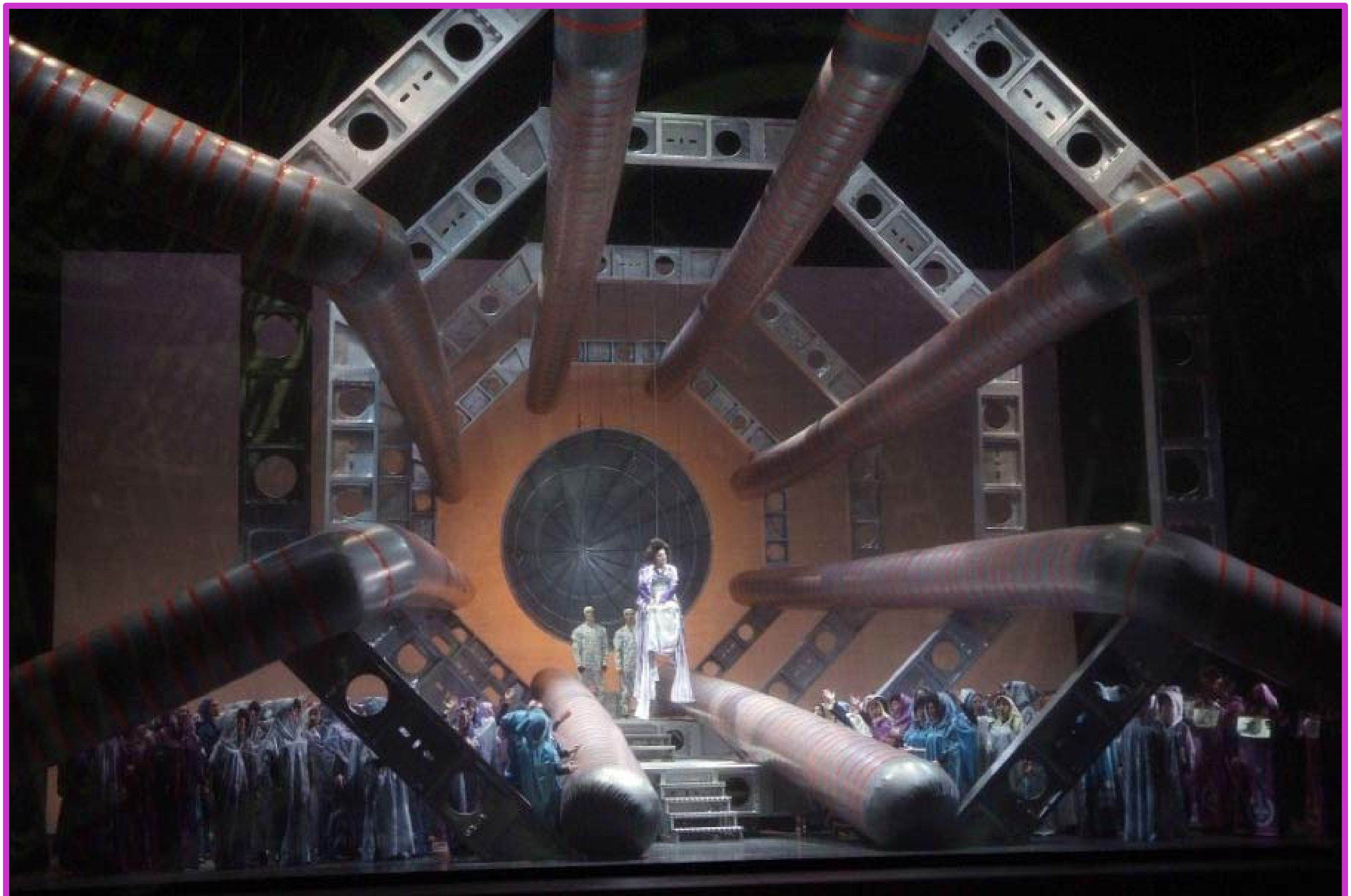
General purpose detectors



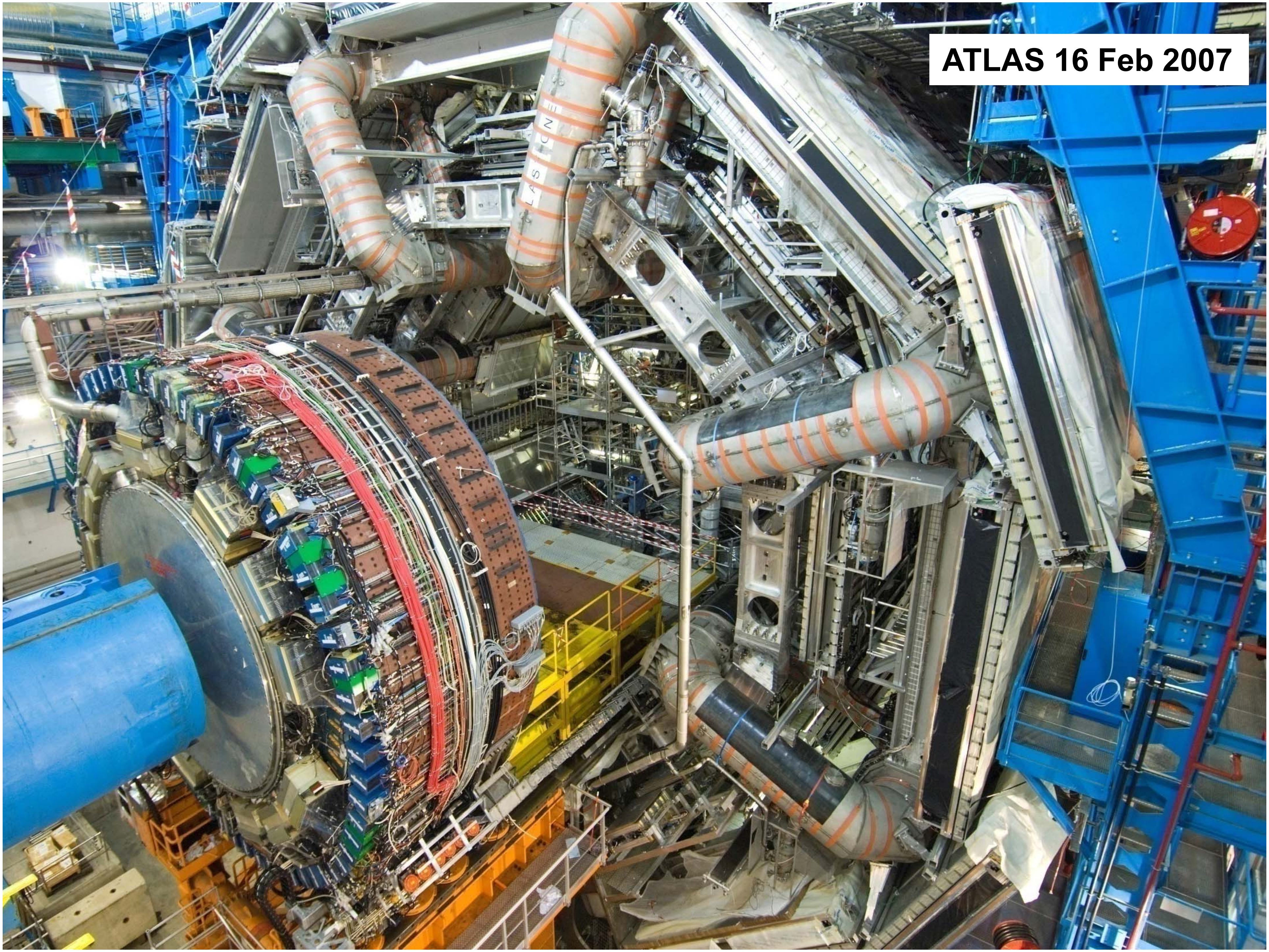
Specialized detectors





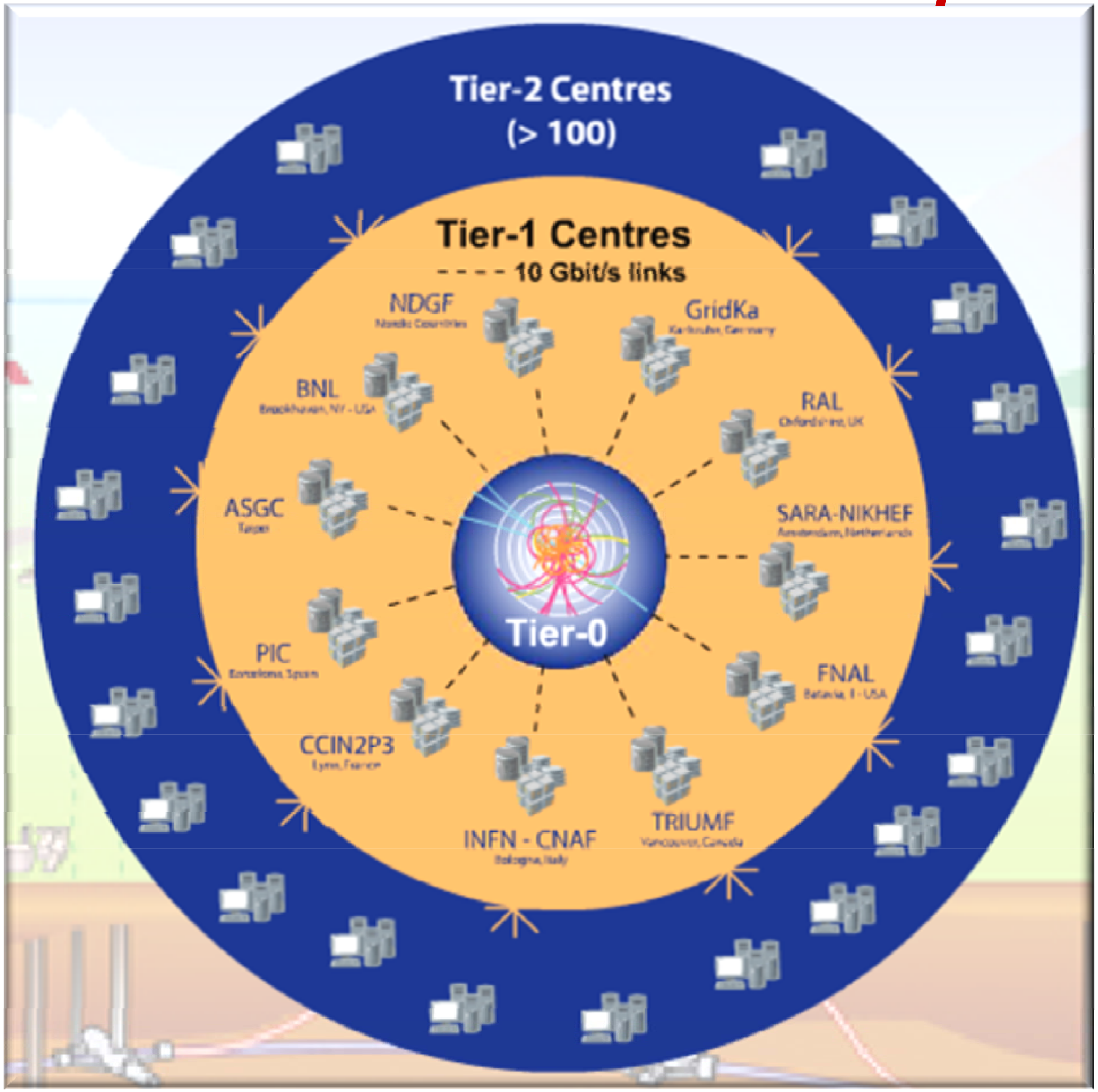


Hector Berlioz, “Les Troyens”, opera in five acts
Valencia, Palau de les Arts Reina Sofia, 31 October -12 November 2009


ATLAS 16 Feb 2007

CMS before closure

The Worldwide LHC Computing Grid (wLCG)



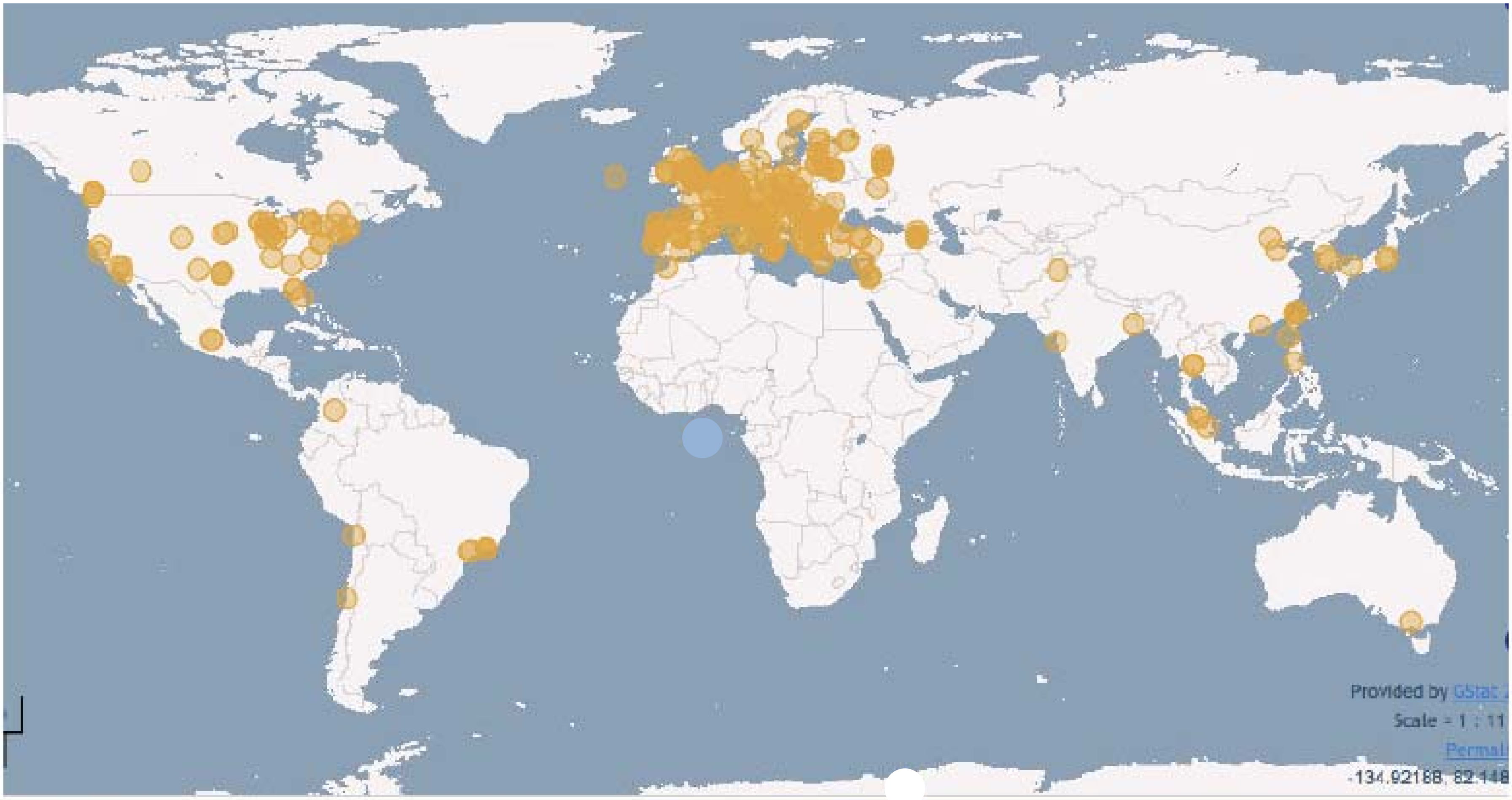
Tier-0 (CERN):
- Data recording
- Initial data reconstruction
- Data distribution

Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis
- Simulation

Tier-2 (federations of ~130 centres):
- Simulation
- End-user analysis

Today's WLCG

- More than 170 computing facilities in 34 countries
  - More than 100k Processing Cores
  - More than 50PB of disk



Computing Grid Delivers Physics

(Example from ATLAS)

Data preparation:

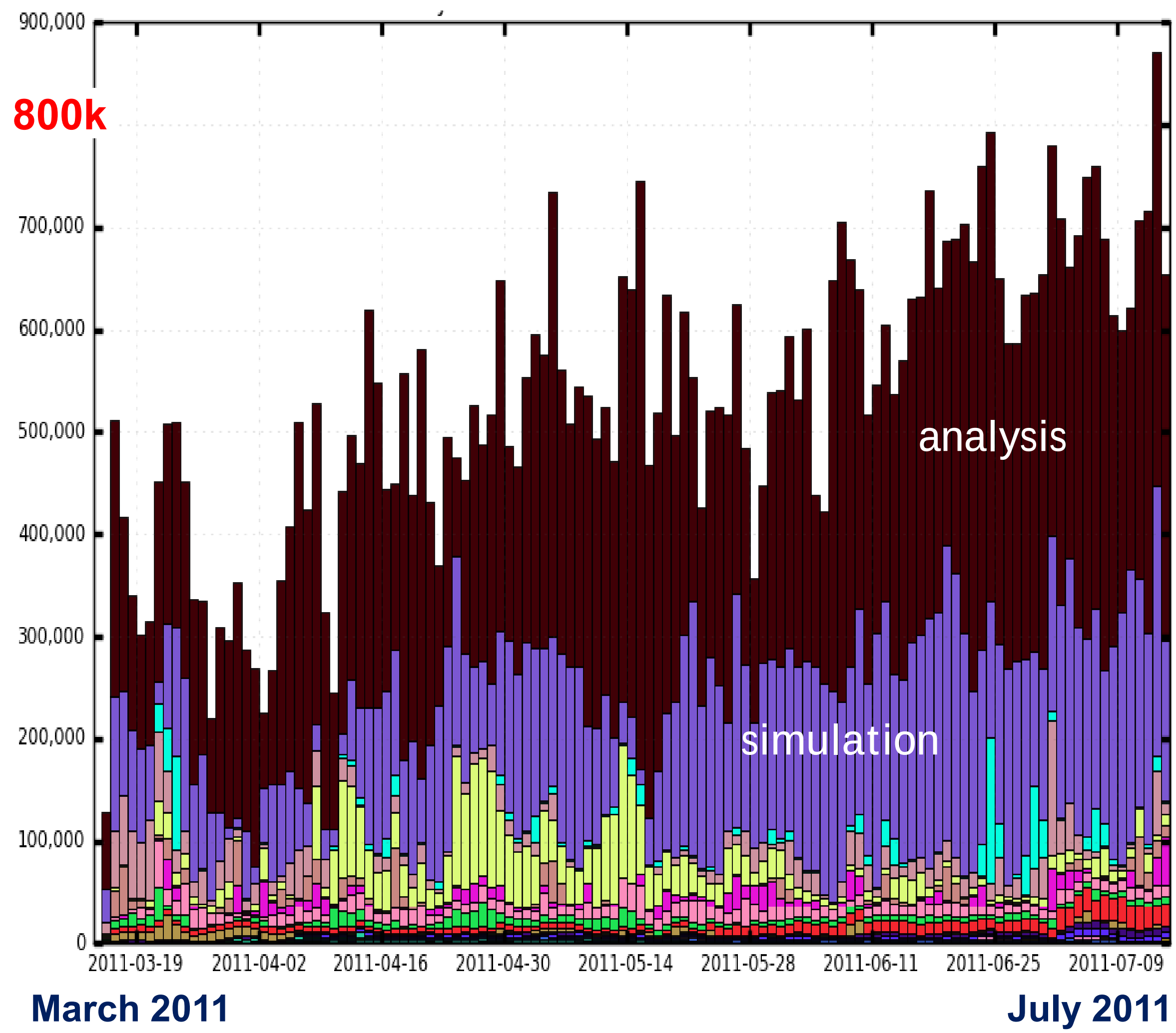
- First-pass reco. at Tier-0 within ~2 days
- Calibration/DQ good for physics analysis
- Data analysable on Grid within ~1 week

Tier-1 and Tier-2's process close to one M jobs per day alone for ATLAS (as example):

- simulation
- re-reconstruction (campaigns)
- group production (ntuples...)
- physics analysis

The high quality of the wLCG computing system allows LHC experiments to show results on data taken just after few weeks already

ATLAS jobs per day across all Tier-1 & Tier-2s



Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation)
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.)
  $\rightarrow$ test and validate calibration/alignment strategies
- Experiment commissioning with cosmics in the underground cavern

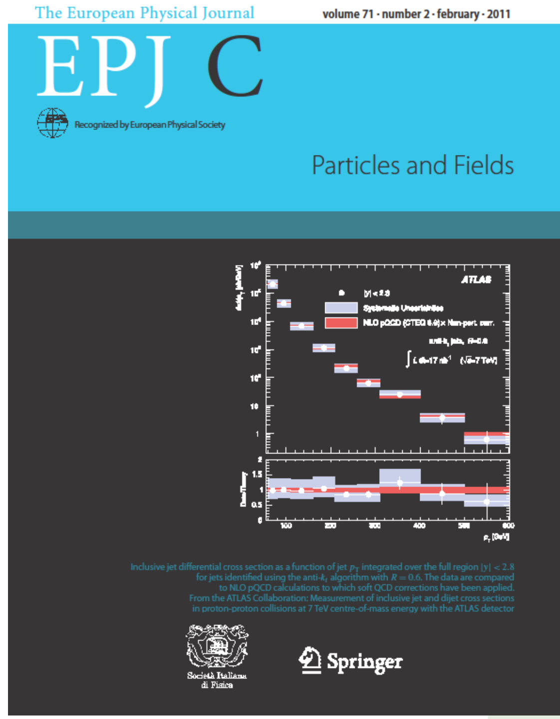
With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, Z$\rightarrow$ll, …)
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators)
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

$\Downarrow$

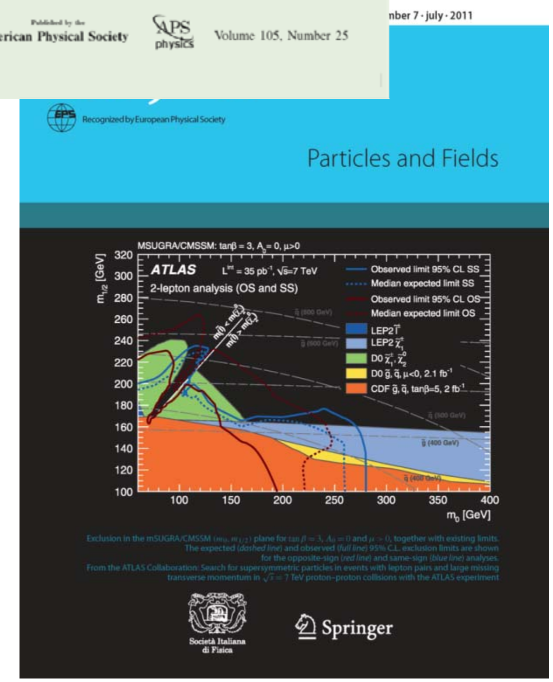
Prepare the road to discoveries …

The scope of this report will be limited to results from the two general purpose experiments CMS and ATLAS (two exceptions include LHCb)



ATLAS and CMS have already published together more than 130 papers in scientific journals (and at least as many public conference notes…)

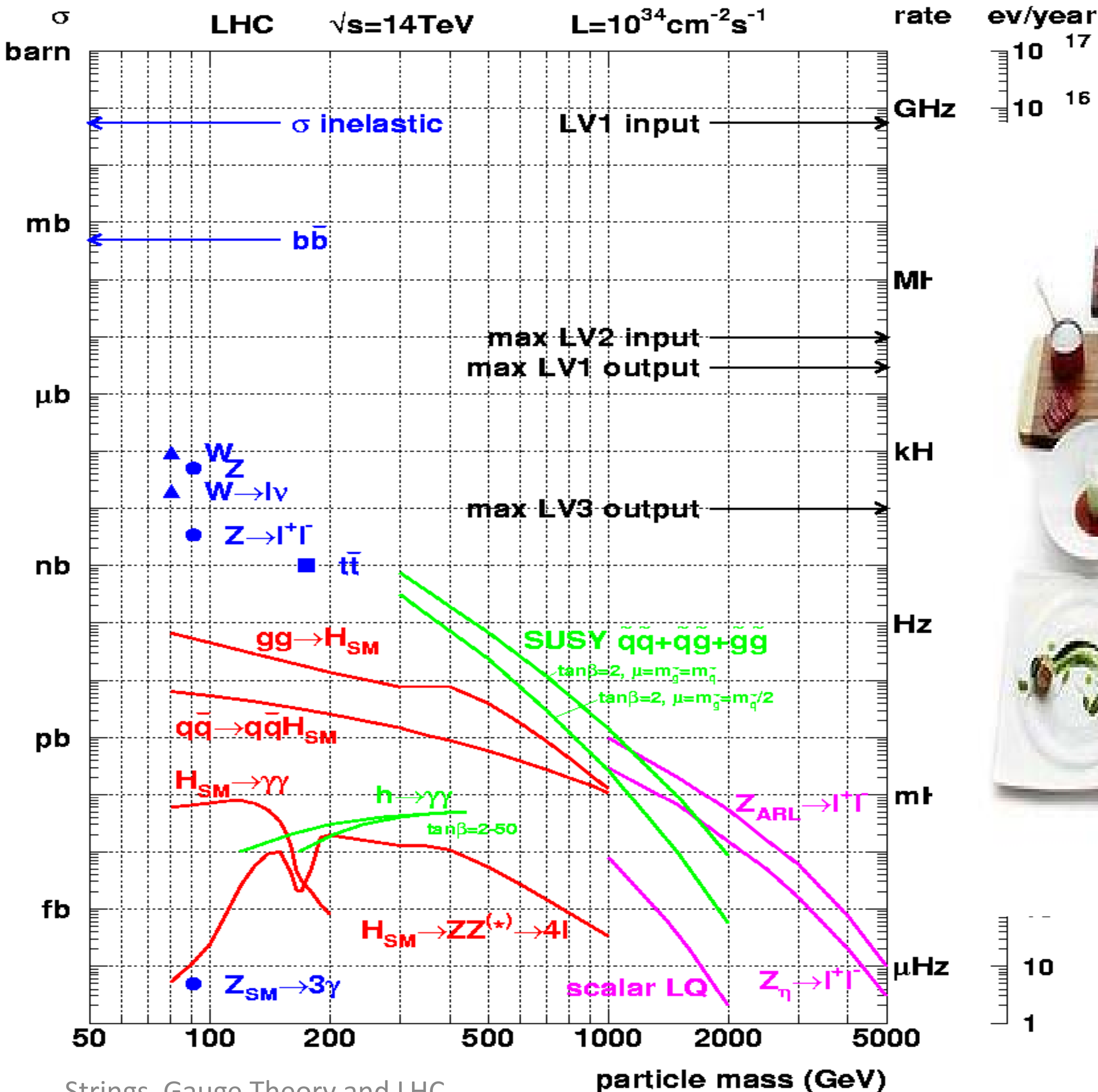
It is obviously not possible to cover all these results…



No attempt is made to show in a democratic way always both CMS and ATLAS results, but rather examples are given that represent typically results from both!

Note that all public results from CMS and ATLAS are available at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Menu Degustation



Menu Degustation

Gastronomical Tour through the
Award-Winning Cuisine of "La Mer"

Carpaccio of Tuna
with Lemon Curd and Marcona Almonds
Marinated Salmon, Aquitaine Caviar,
and Beetroot Mostarda
Carpaccio de Thon, Crème au Citron et Amandes de Marcona
Saumon Mariné, Caviar d'Aquitaine, et Betterave Mostarda

Duo of Foie Gras
with Rice Flake, Candied Rhubarb,
Maraschino Cherries, and Pistachio
Duo de Foie Gras
Flocon de Riz, Rhubarbe Confit,
Cerises de Maraschino, et Pistache

Poached Lobster Tail
Served with Watercress Velouté and Fine Herbs
Queue de Langoustine Pochée
Cresson Velouté et Fines Herbes

Fillet of Opakapaka
Heirloom Tomato and Basil Tartare,
Black Olives and Artichoke à la Barigoule
Filet d'Opakapaka
Tartare de Tomate "Heirloom" et de Basilic,
Olives Noires et Artichaut à la Barigoule

Veal Cheek Braised in Red Wine
with Sweetbreads, Mushroom Duxelles
and Ravioli Niçoise
Joue de Veau Braisée au Vin Rouge,
Ris de Veau, Champignon Duxelles, et Ravioli Niçoise

Lime Gelée with Roquette
Grape Must and Olive Oil
Gelée de Citron Vert, Salade de Roquette
Moût de Raisin et Huile d'Olive

Selection of French Cheese
Sélection de Fromages Français

Chocolate and Wild Hibiscus
with Hot Cocoa Butter and Champagne Sauce
Chocolat et Hibiscus Sauvage
au Beurre de Cacao Chaud et Sauce Champagne

Mignardises
Frivolitées Gourmandes

Content

General event properties

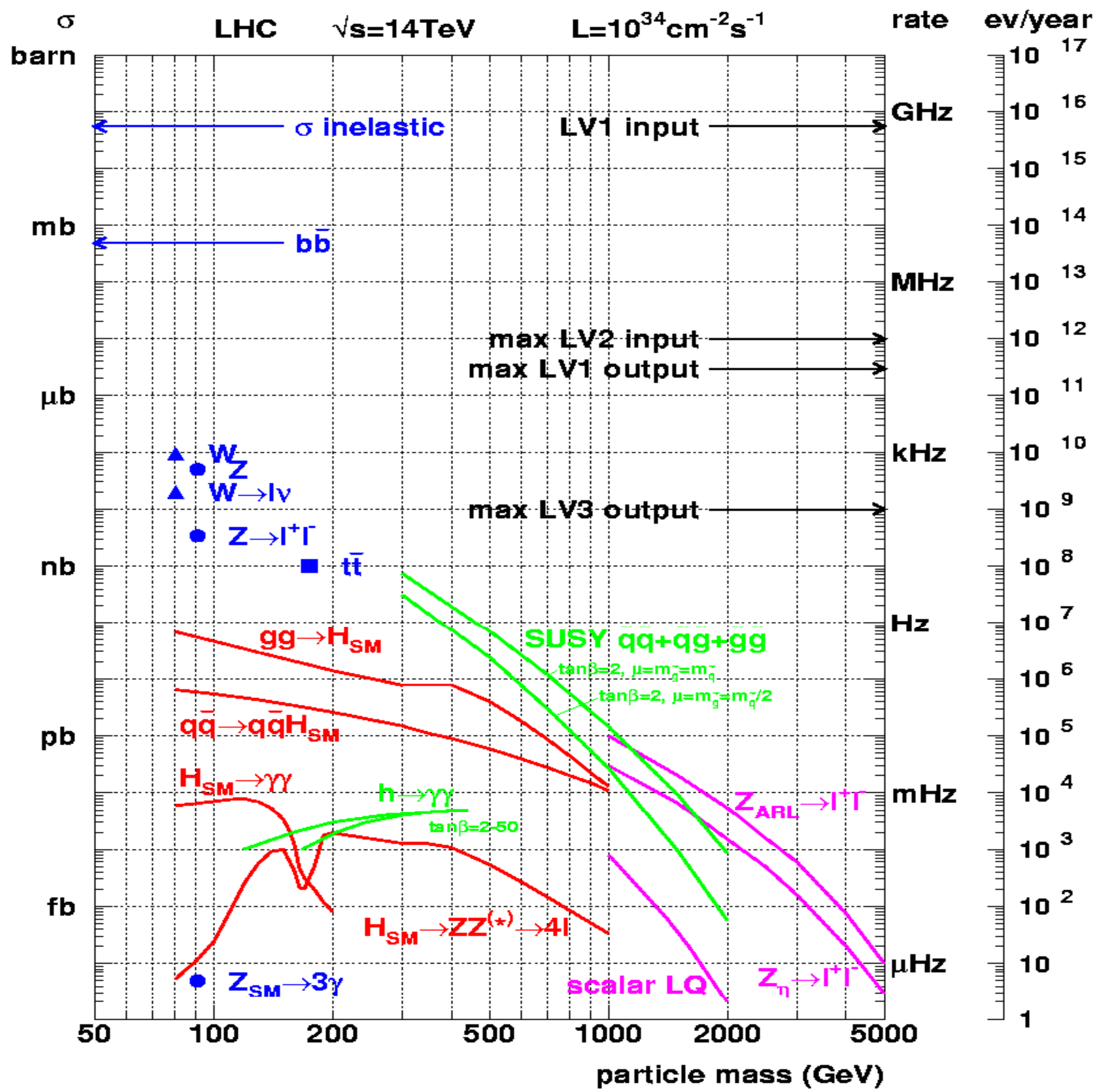
Heavy flavour physics

Standard Model physics including QCD jets

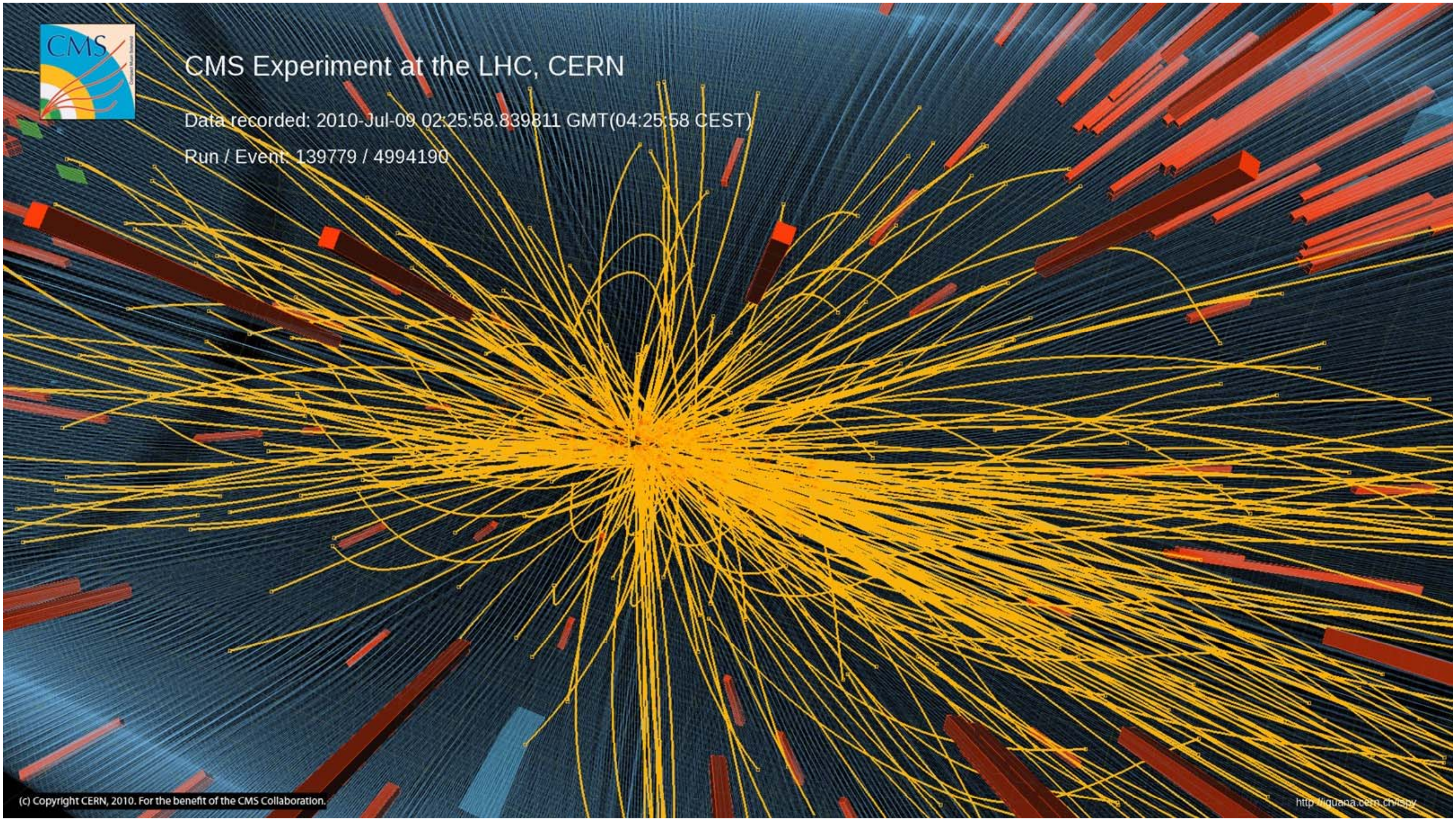
Higgs searches

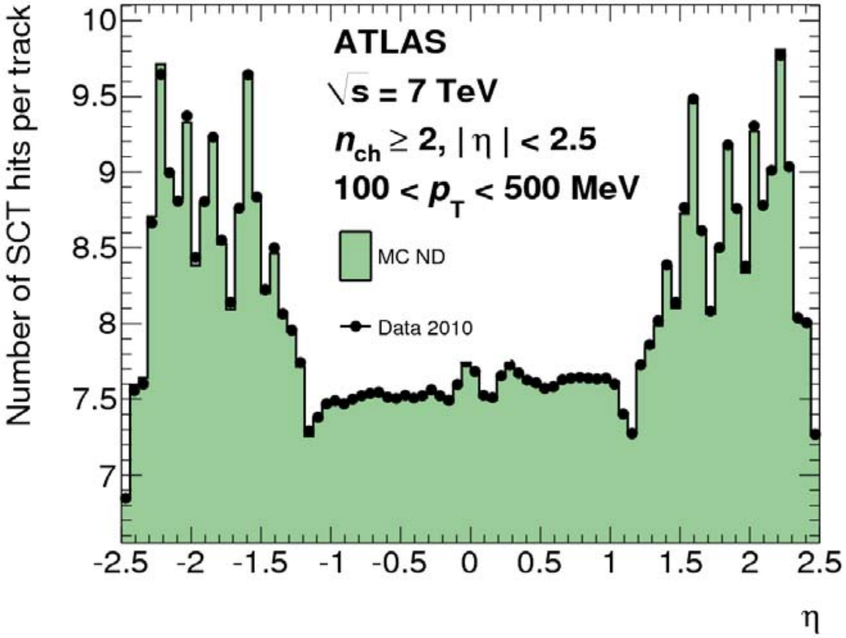
Searches for SUSY

Examples of searches for 'exotic' new physics



General Event Properties

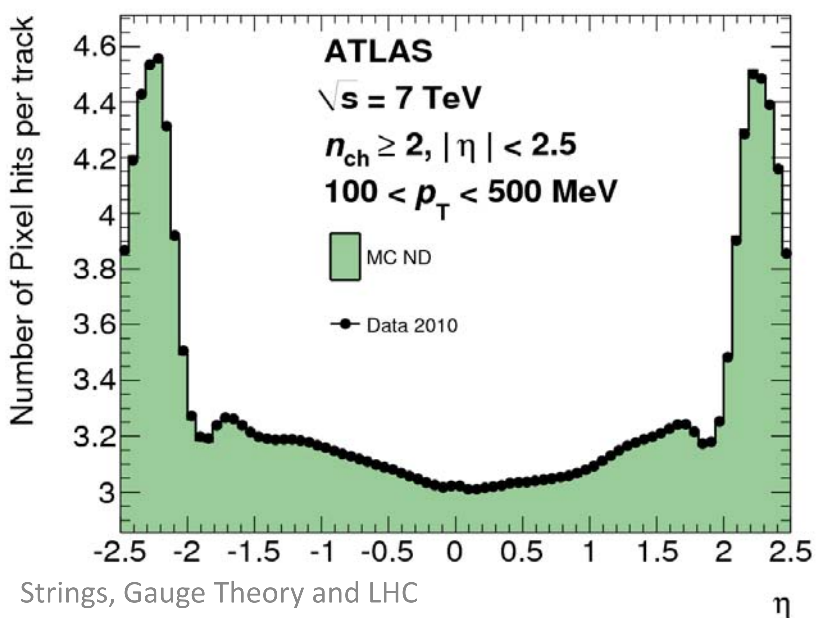


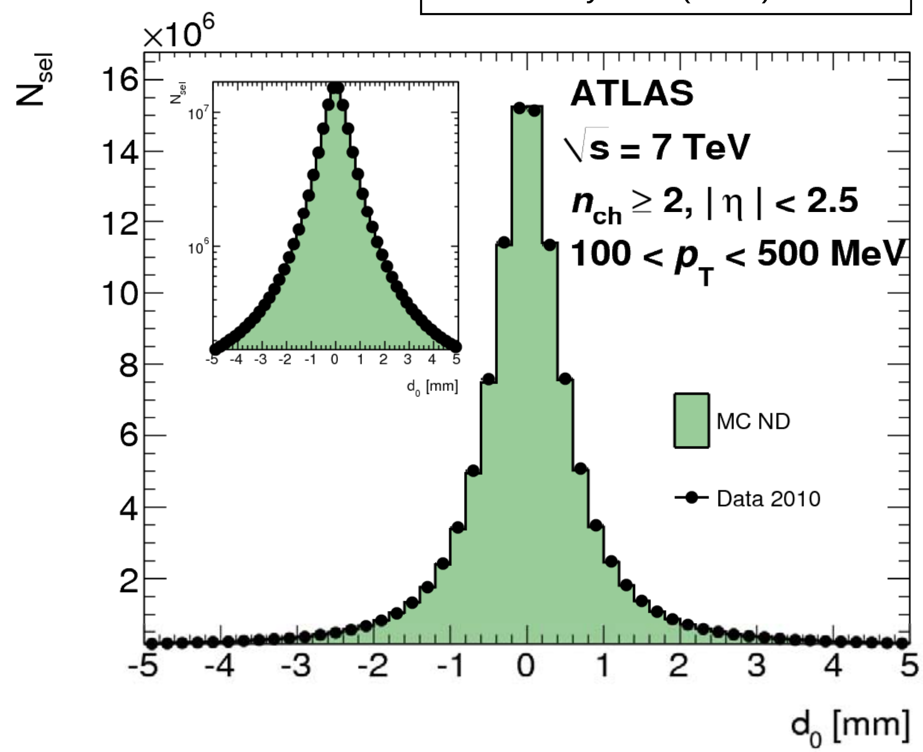


The tracking detector simulations are in a mature state, charged track measurements are well understood

Example shows the ATLAS description of minimum bias tracks (silicon and pixel hits, transverse impact parameter)

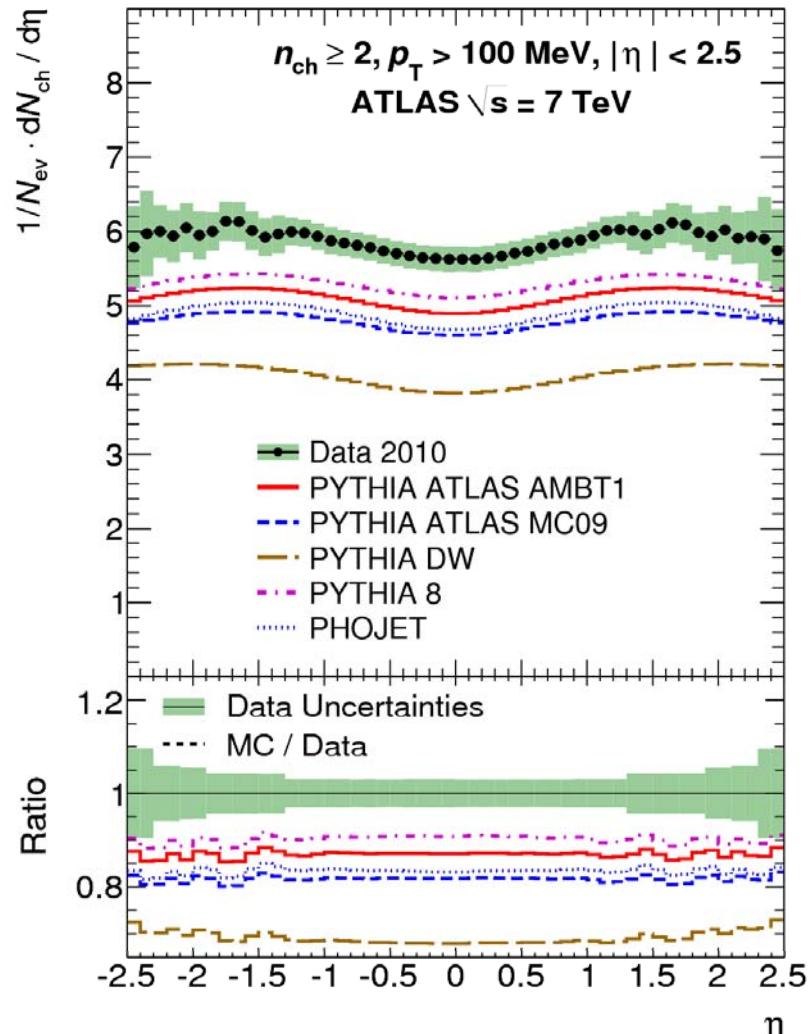
New J. Phys. 13 (2010) 053033

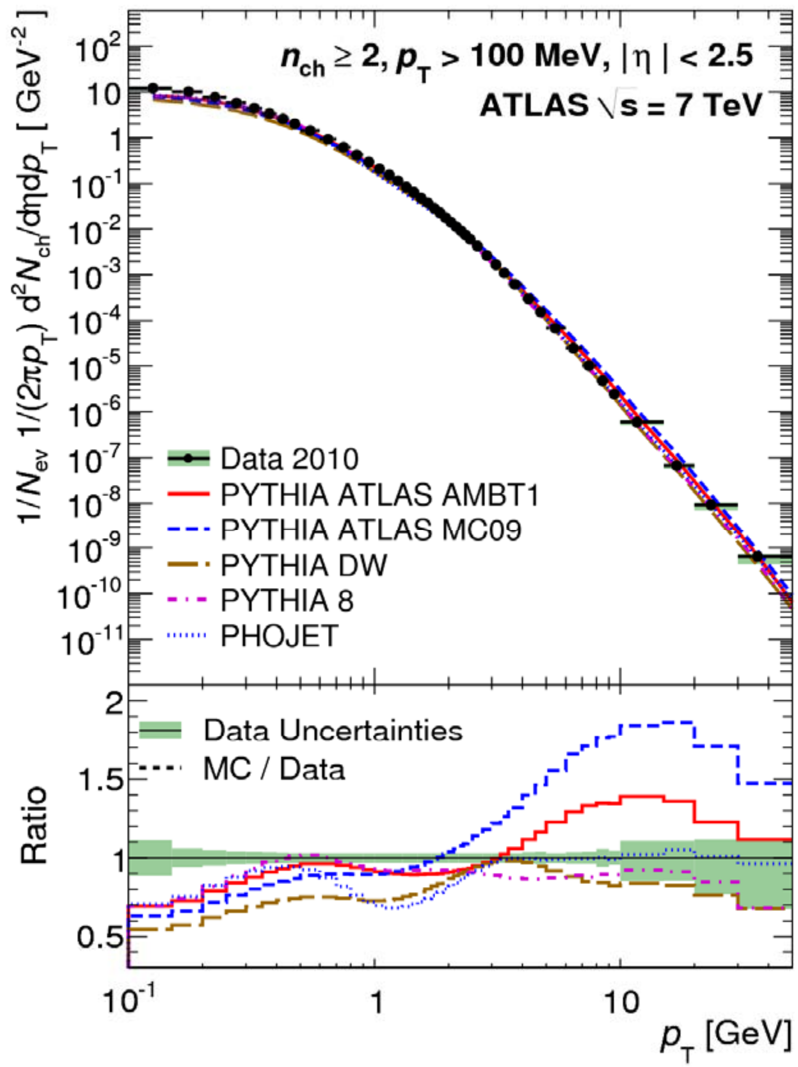




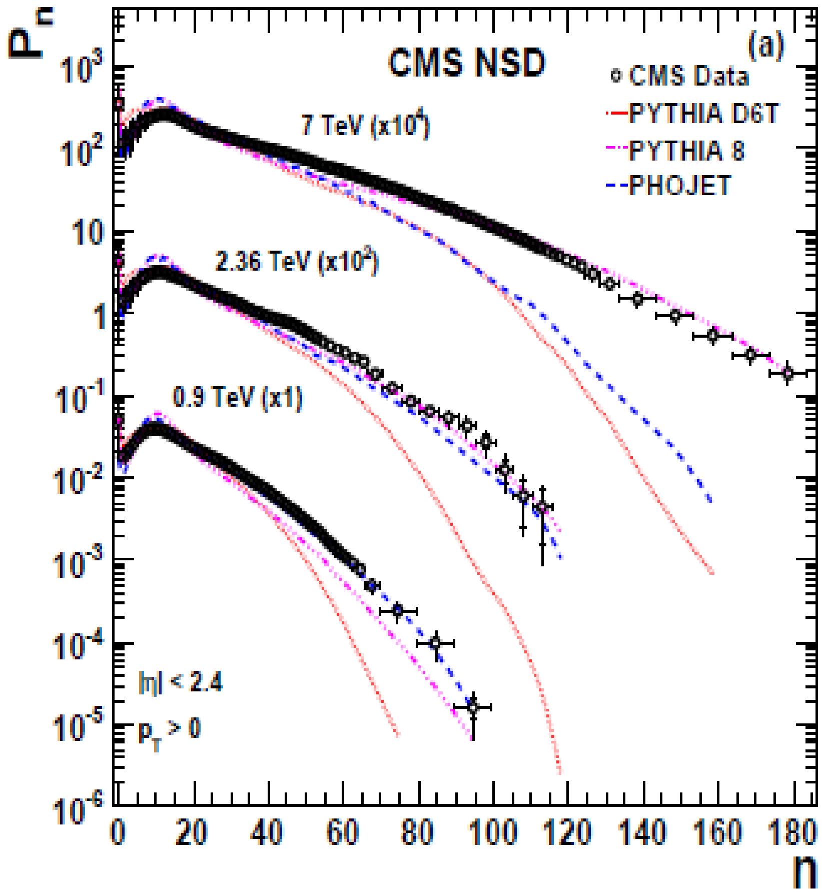
Charged-particle multiplicities as a function of pseudorapidity η and transverse momentum p_T for minimum bias events selected as specified, and compared to various Monte Carlo models

New J. Phys. 13 (2010) 053033



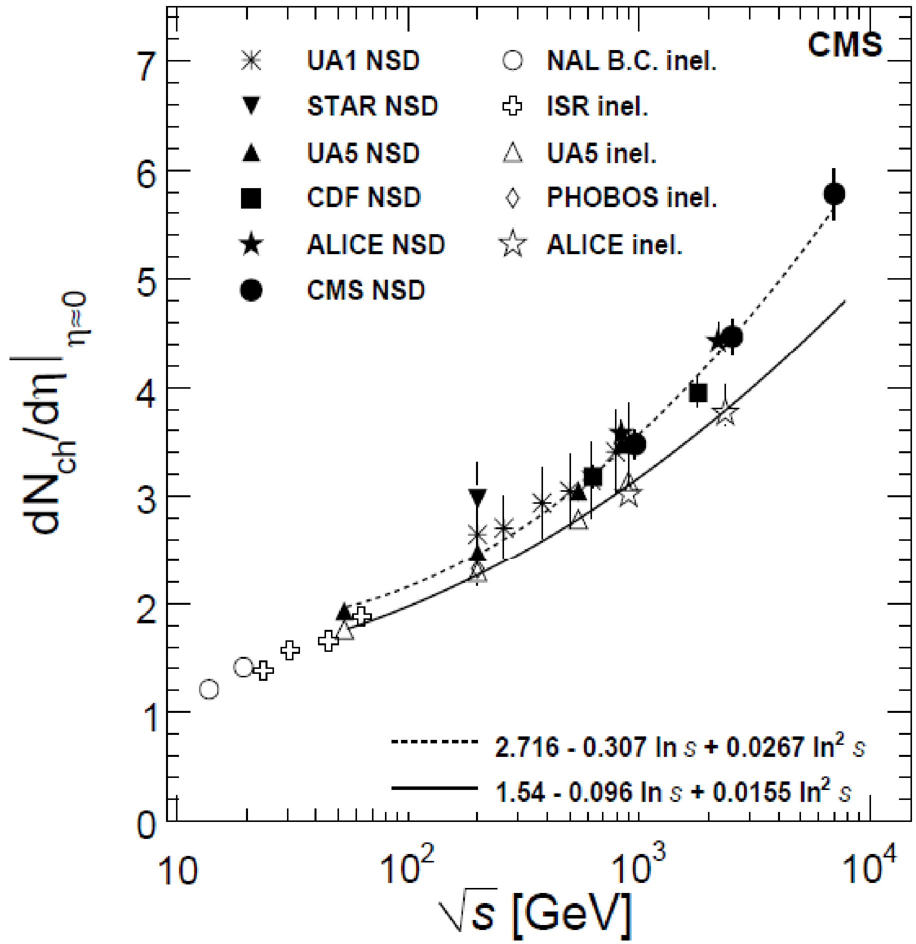


Charged hadron multiplicities at the three different √s

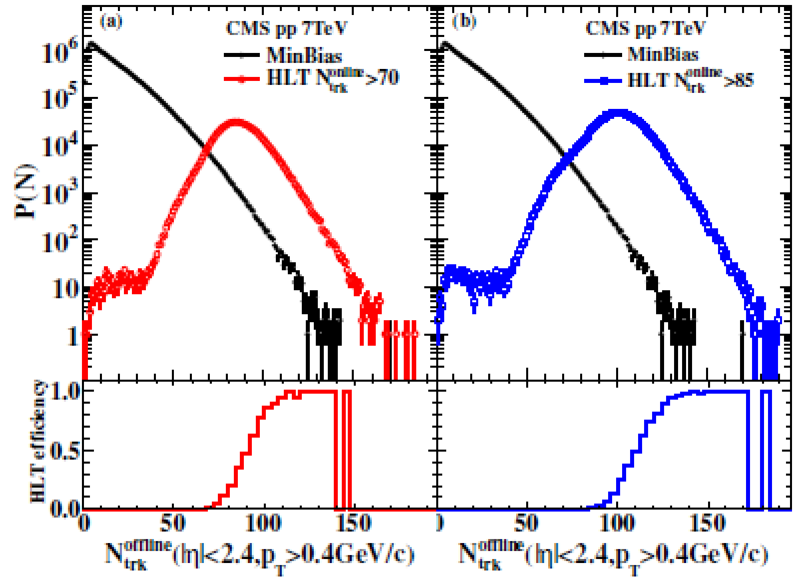


JHEP 01 (2011)079

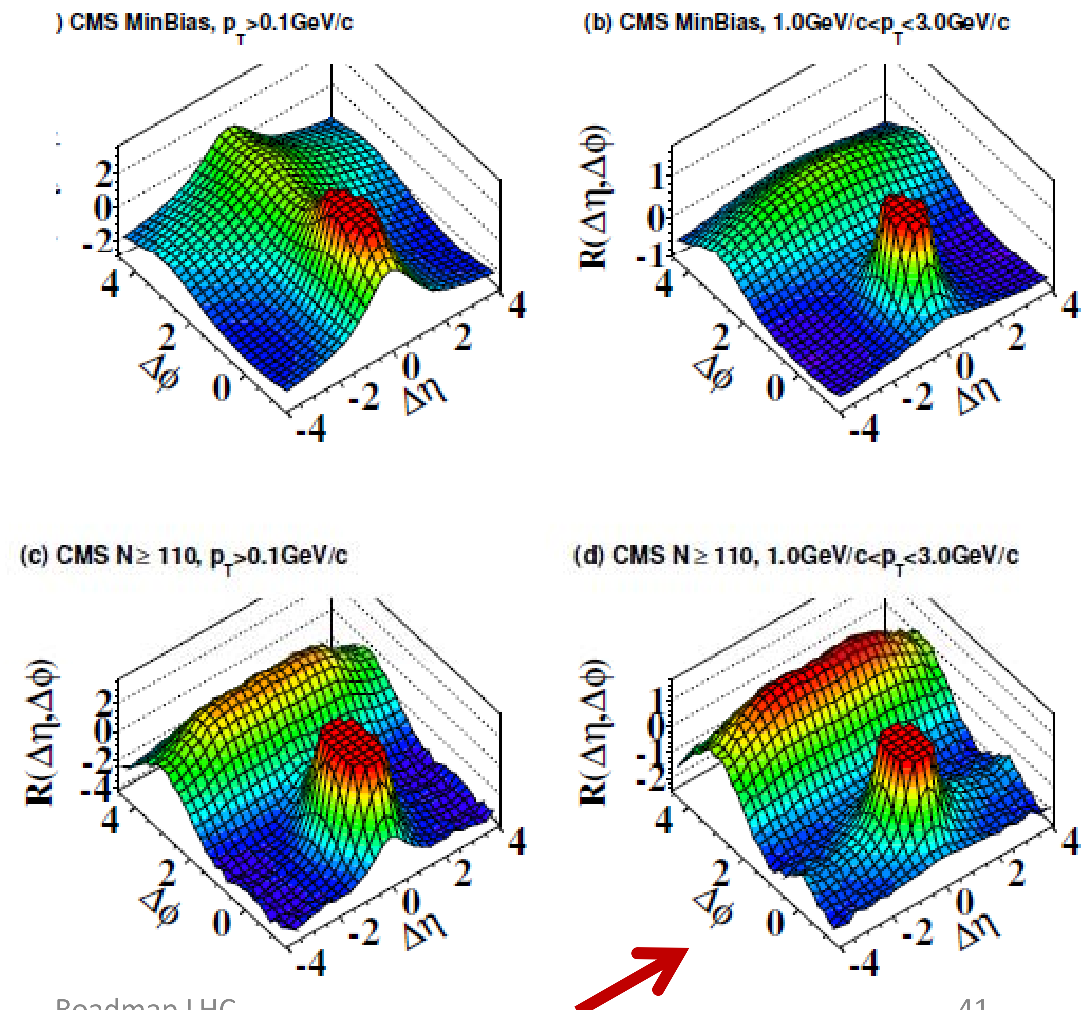
Average charged particle density for the central η region (pp and p̄p)



Phys. Rev. Lett. 105 (2010) 022002



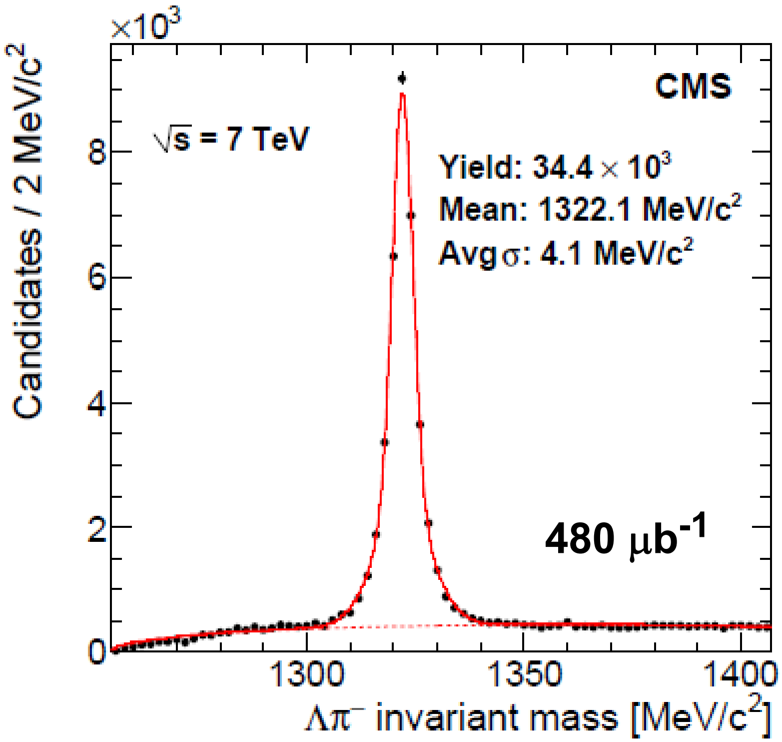
CMS reported an unexpected effect in very high-multiplicity events collected with a dedicated trigger (980 nb^{-1})



Observation of long-range, near-side angular correlations in the two-particle angular correlation of charged particle pairs (→ 'ridge effect')

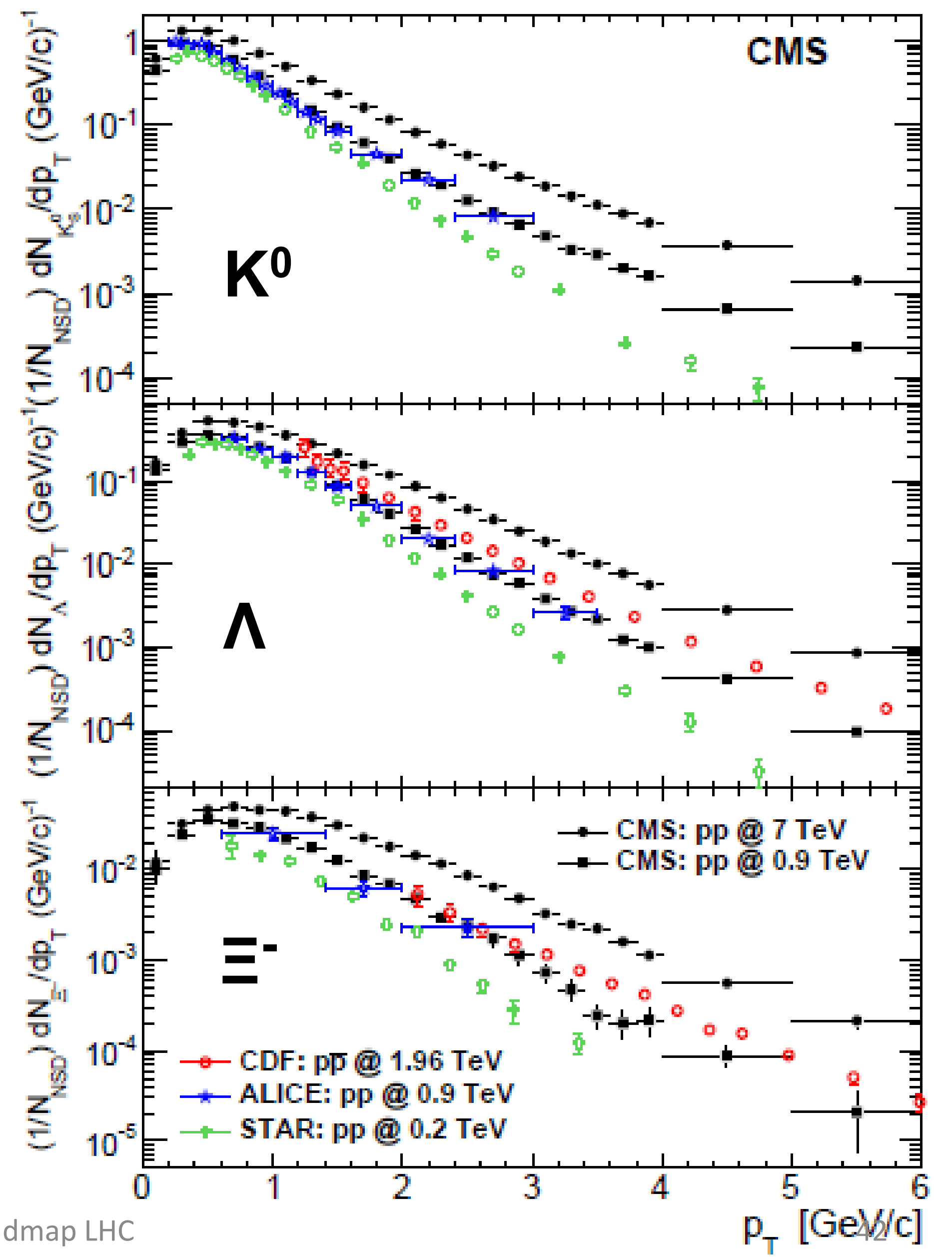
JHEP 09(2010)091

Strange particle production spectra

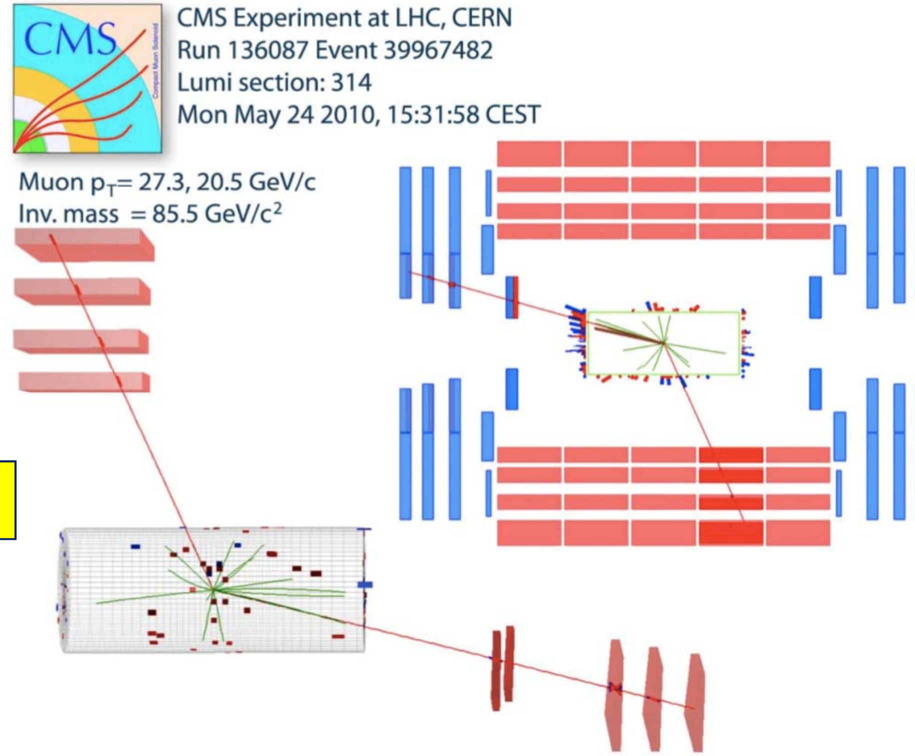


Example $\Xi^- \rightarrow \Lambda\pi^-$

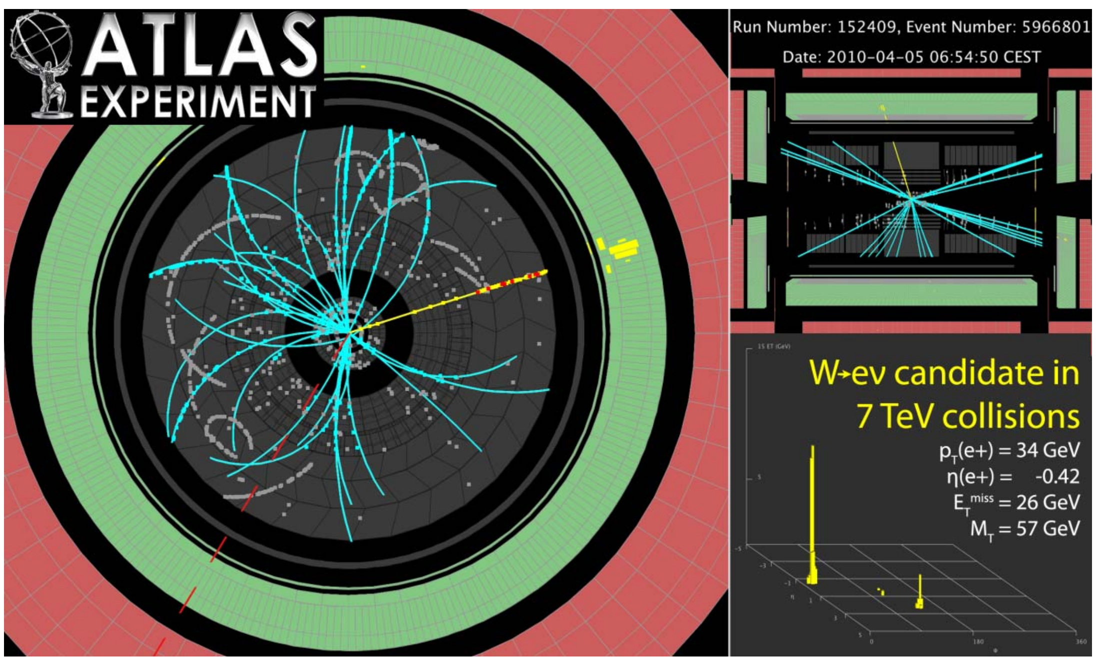
JHEP 05 (2011) 064

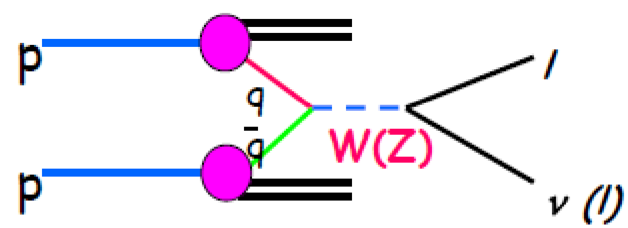


Standard Model Physics



CMS candidate Z → $\mu^+\mu^-$

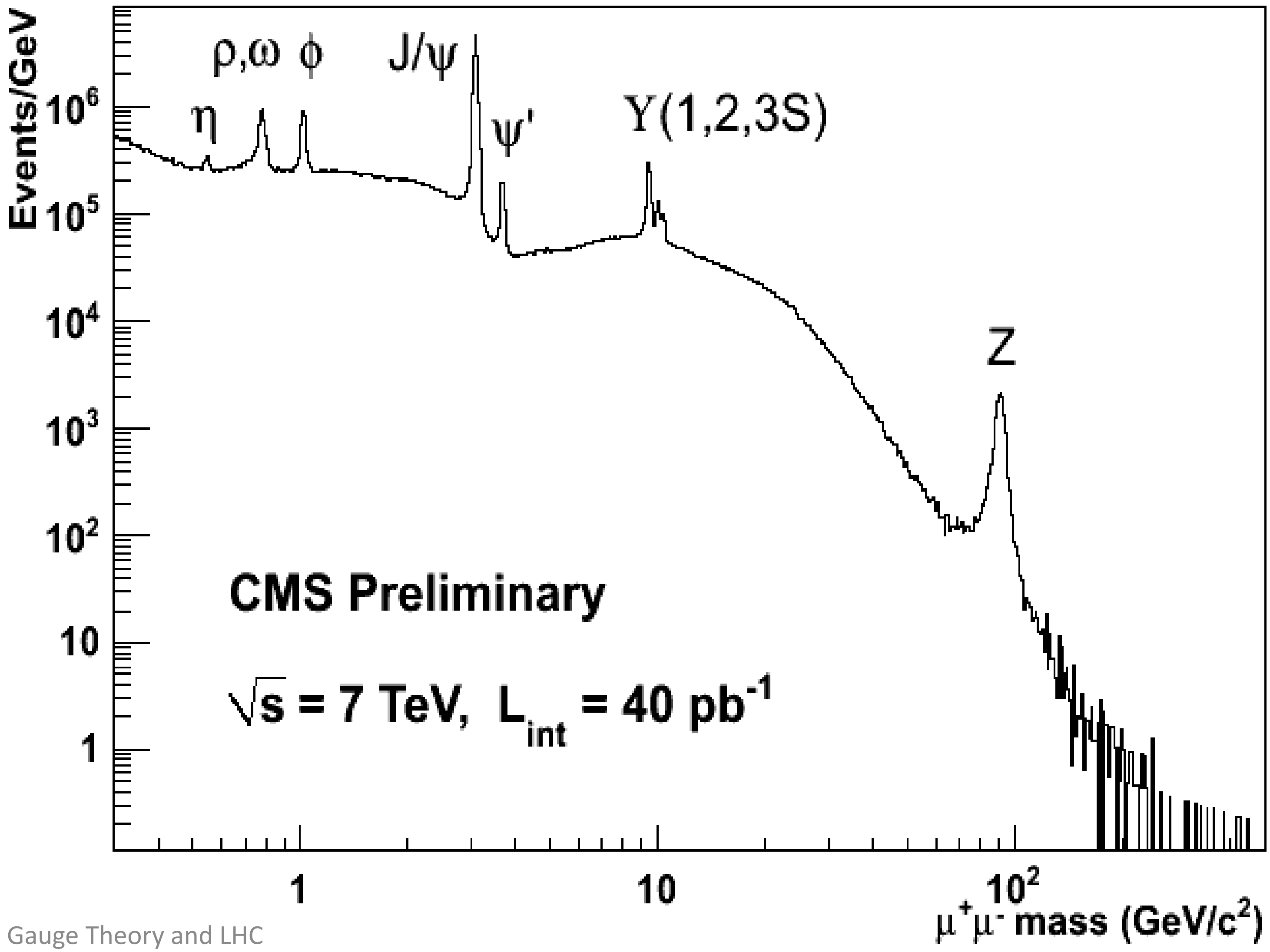




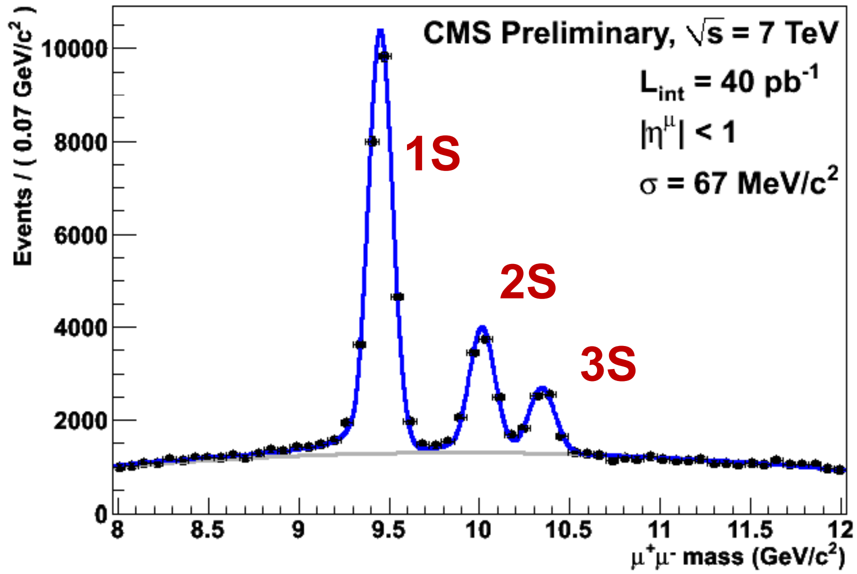
ATLAS W → eν candidate

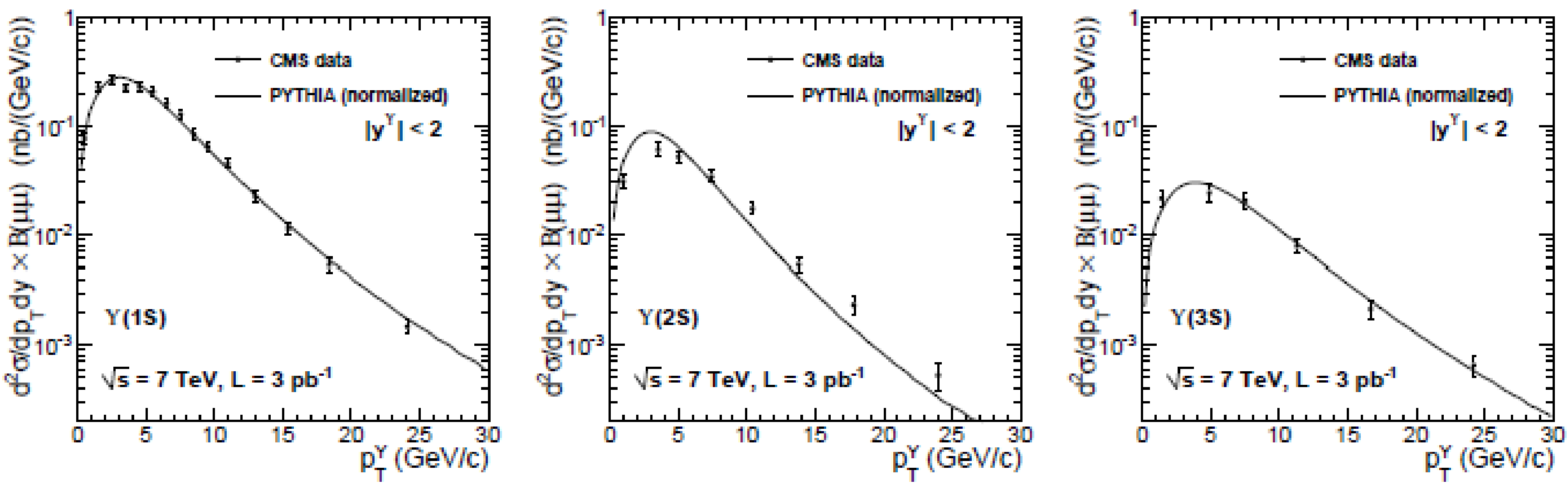
Di-lepton invariant mass spectra

The di-muon spectrum recalls a long period of particle physics:



Observation, and differential cross-section measurements of the Υ – family

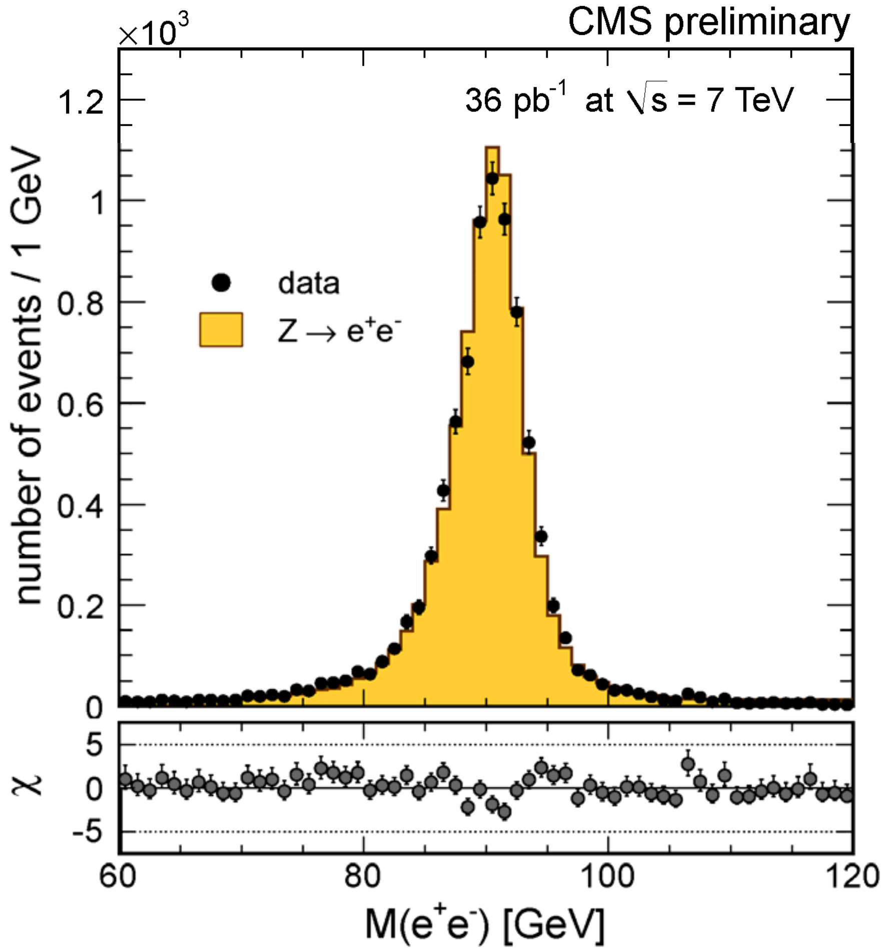


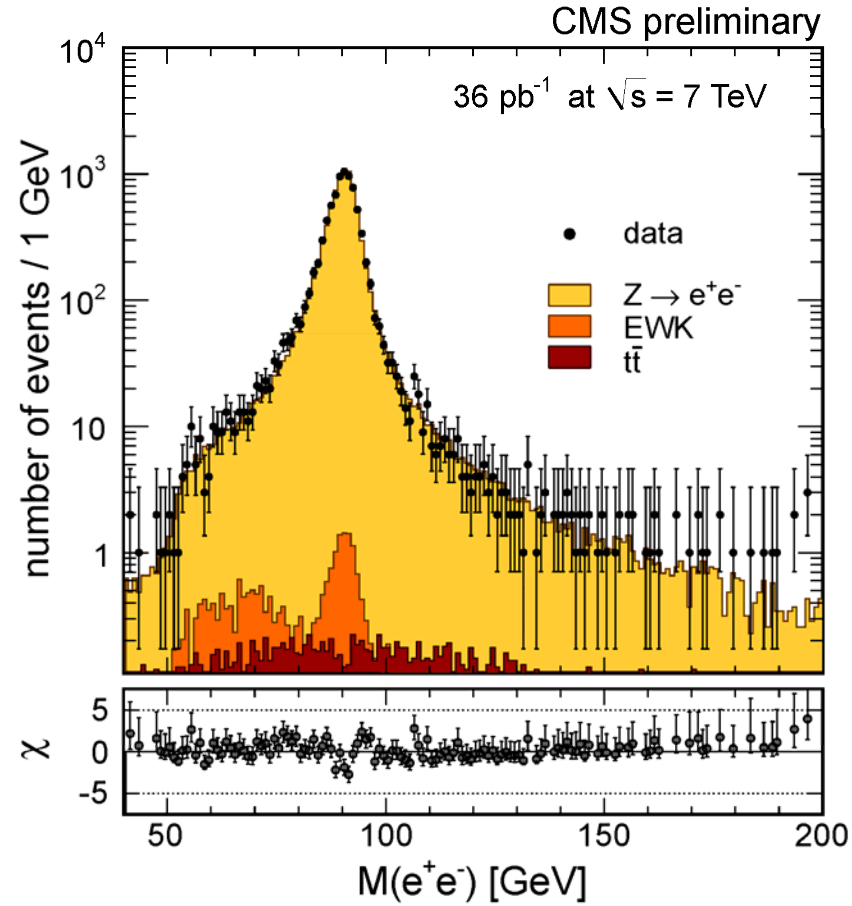


Sub. to Phys. Rev. D
arXiv:1012.5545[hep-ex]

Z and W production

Sub. to JHEP
arXiv:1107.4789[hep-ex]



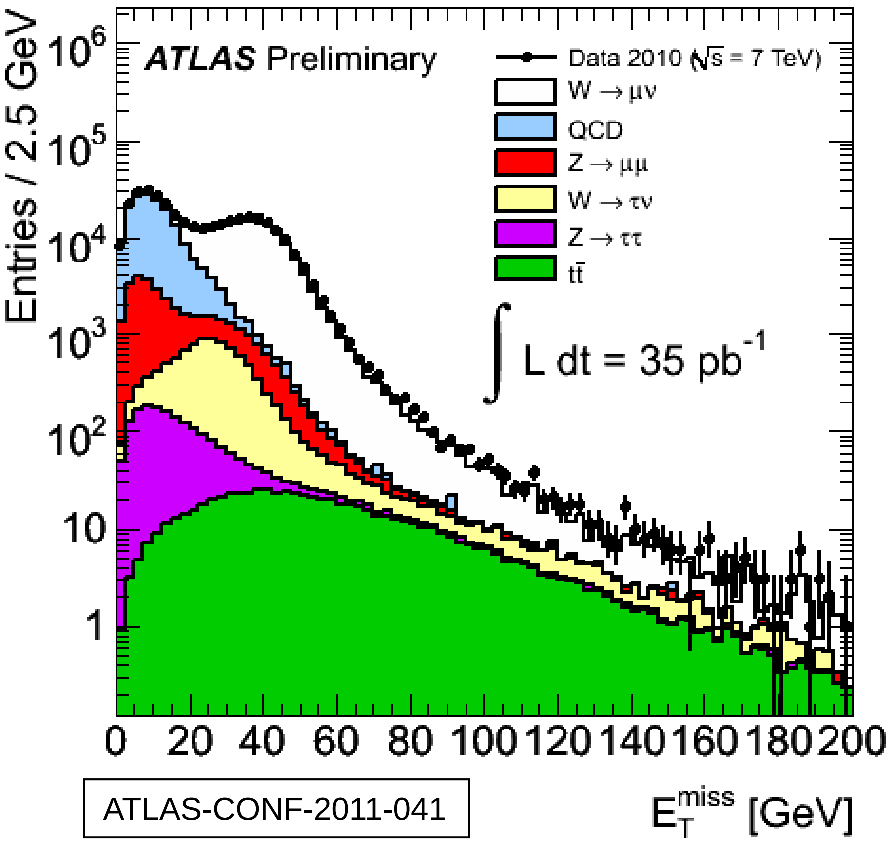


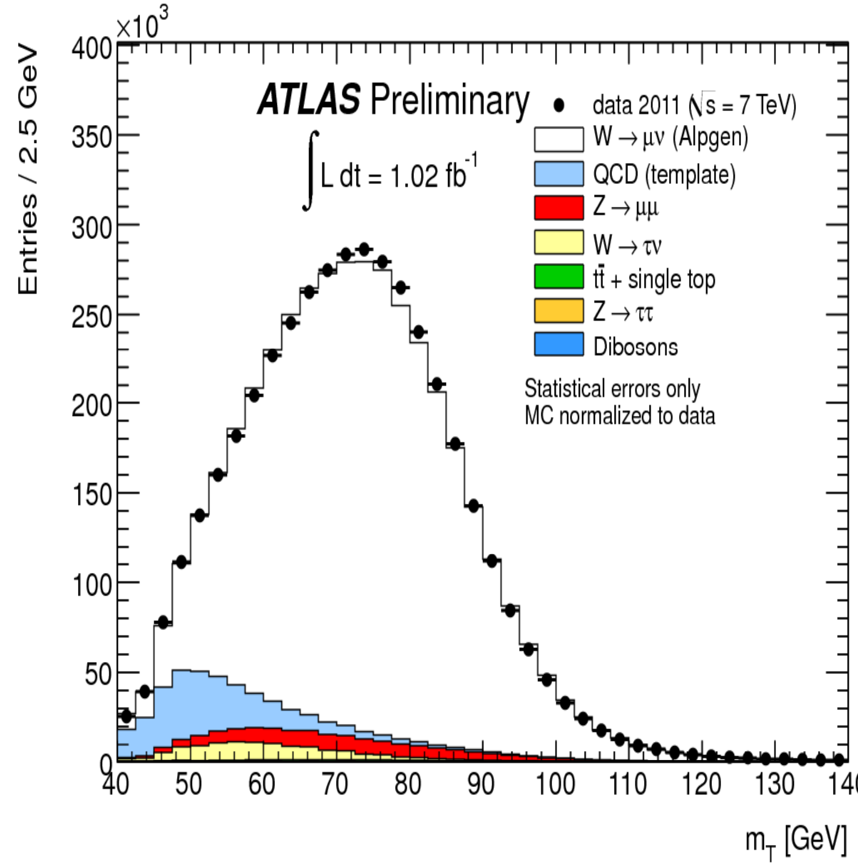
Z peak (di-lepton pair mass distributions)

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

W transverse mass

μ with p_T>20 GeV, E_T^{miss}>25 GeV

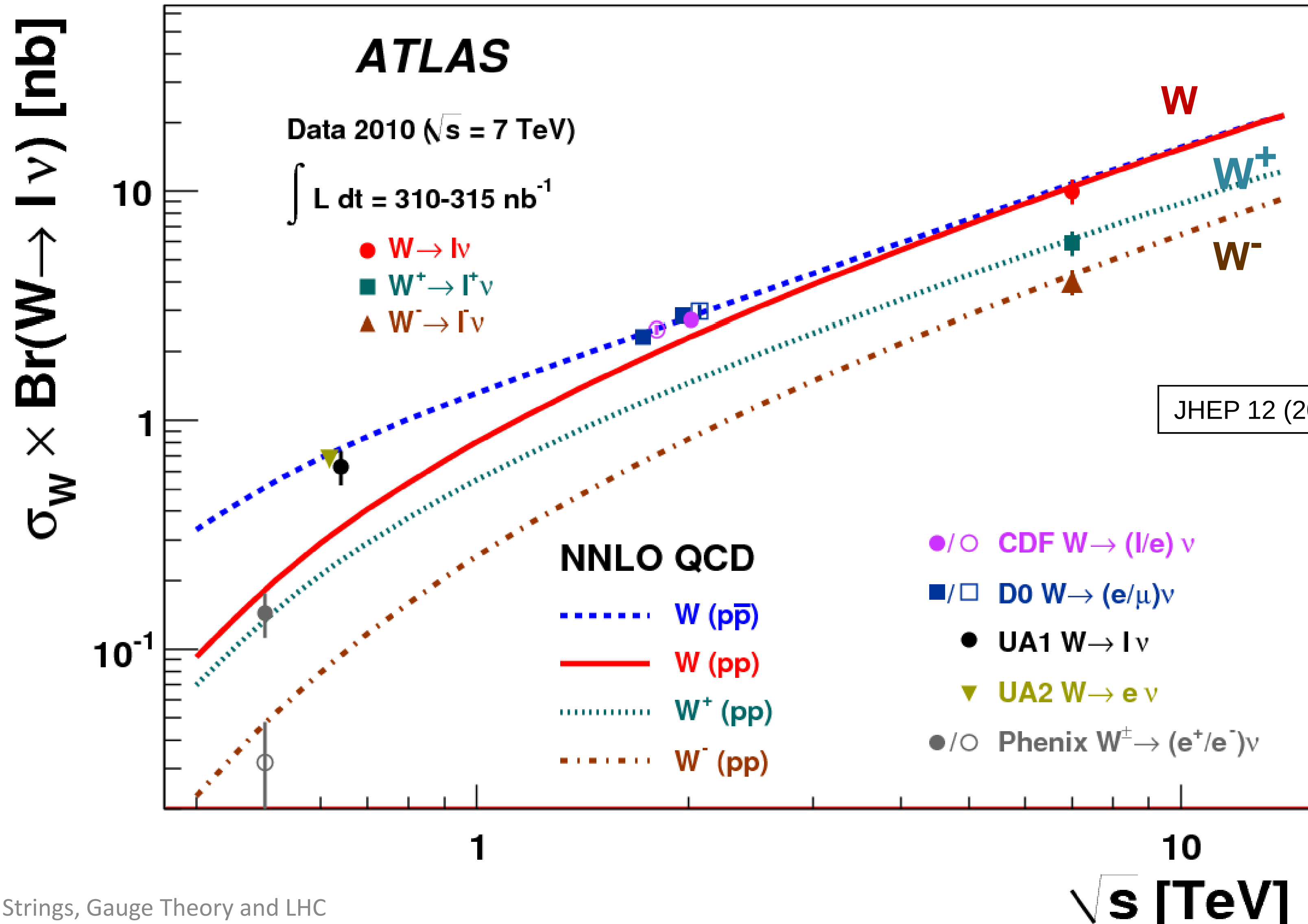




Missing transverse energy from the W → μ + ν decays

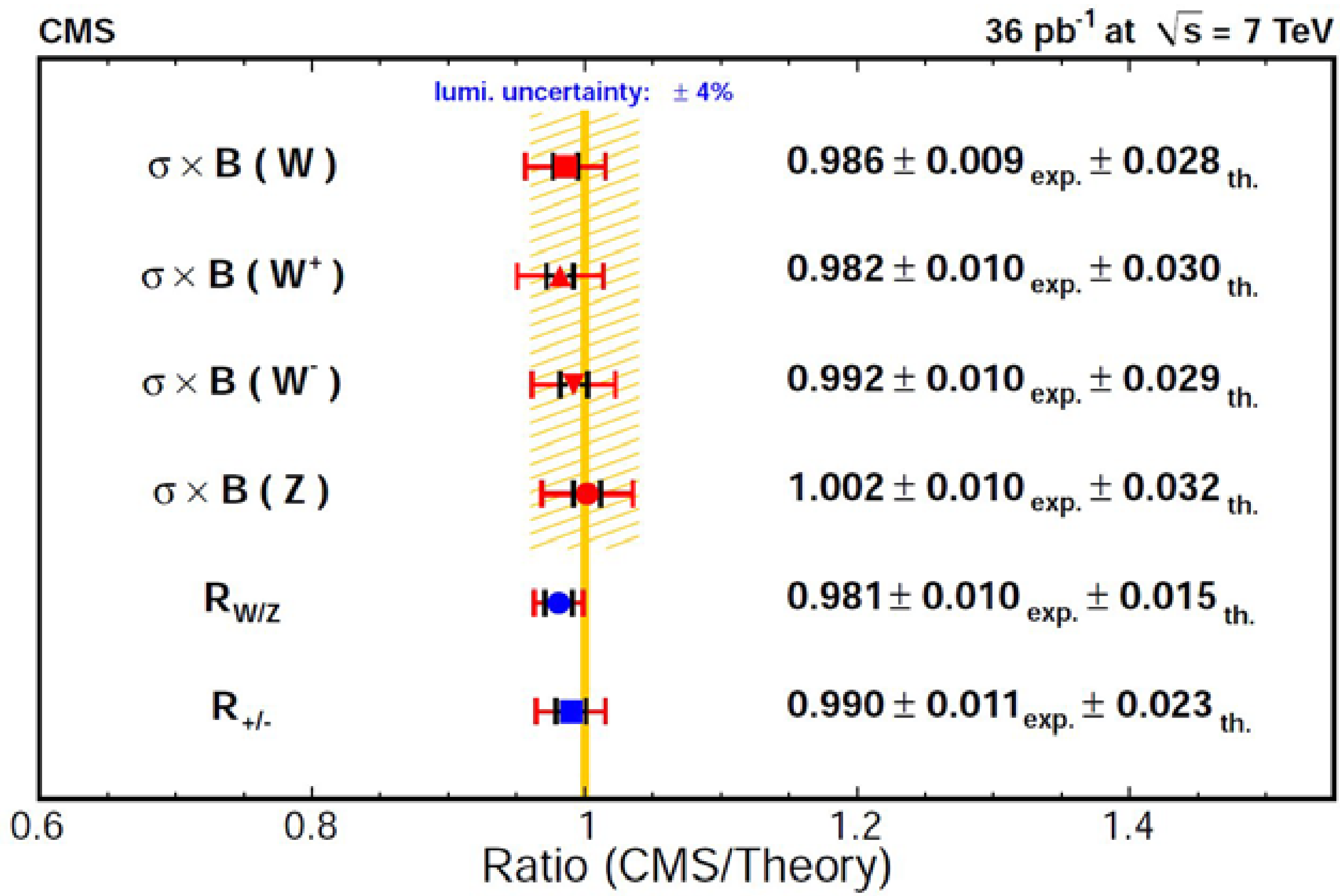
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} p_{\mathrm{T}}^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

Very early W cross section measurement with e and μ

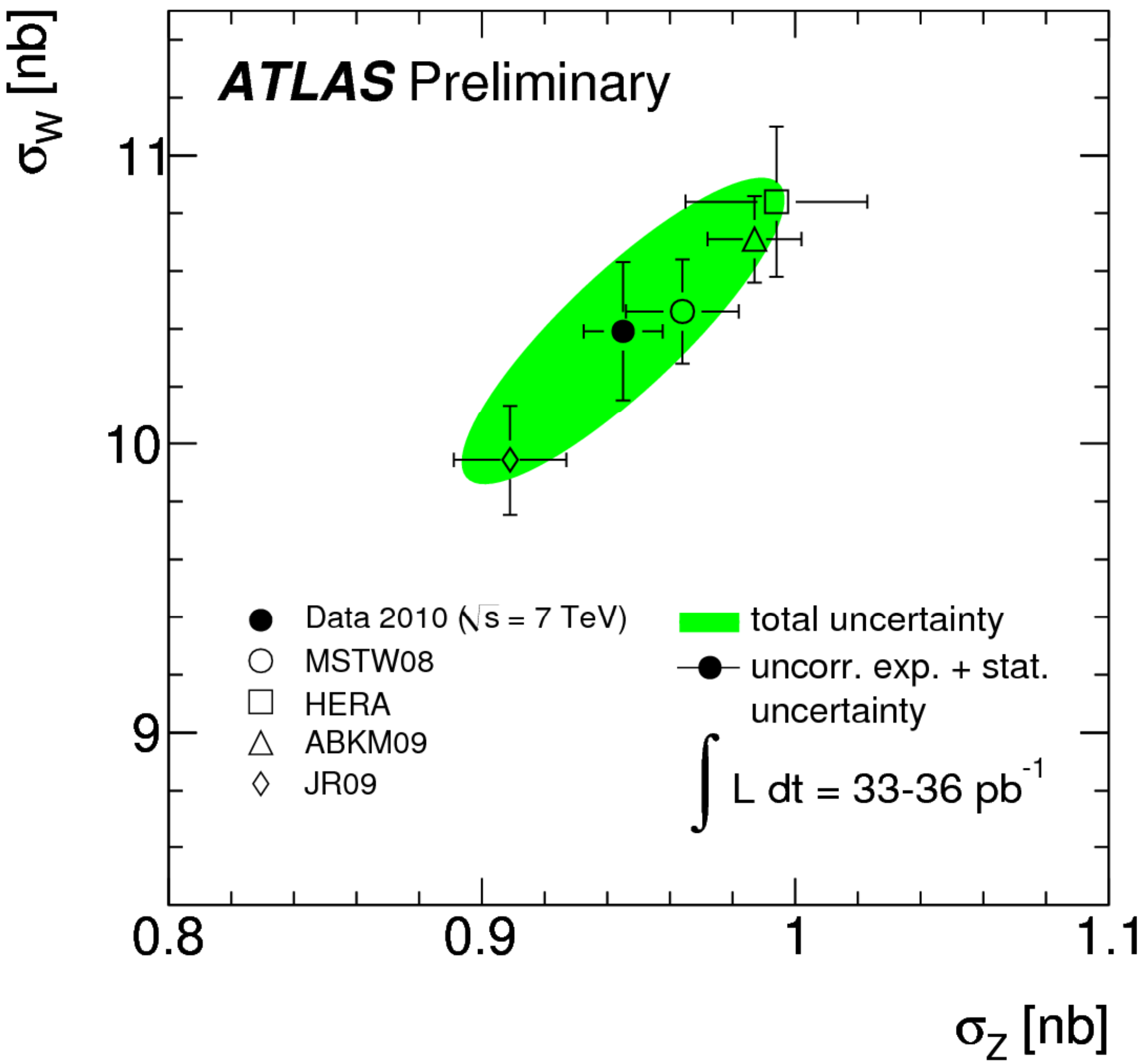


JHEP 12 (2010) 060

Full 2010 data set measurements from CMS



Sub. to JHEP
arXiv:1107.4789[hep-ex]

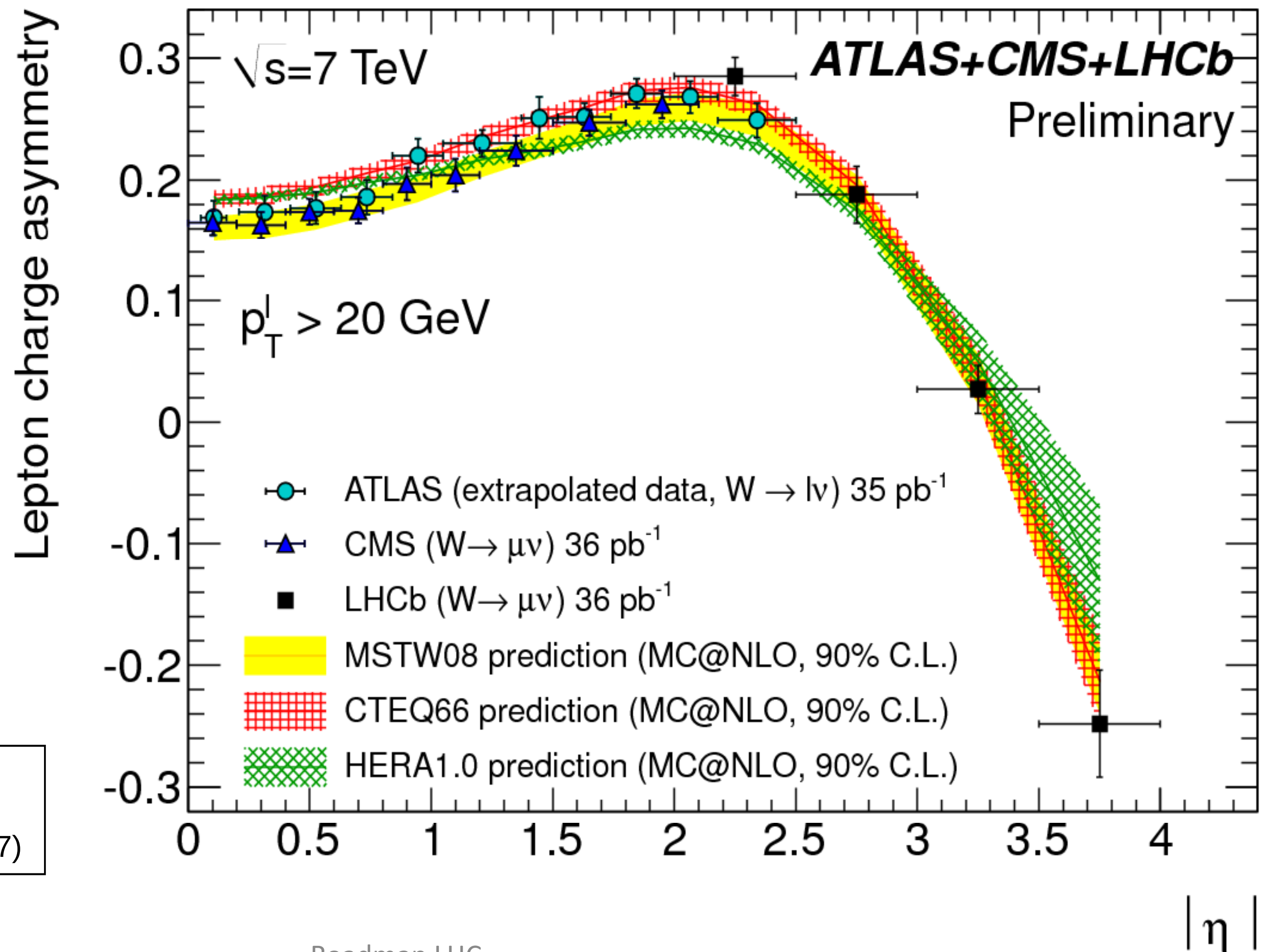


Full 2010 data set from ATLAS

ATLAS-CONF-2011-041

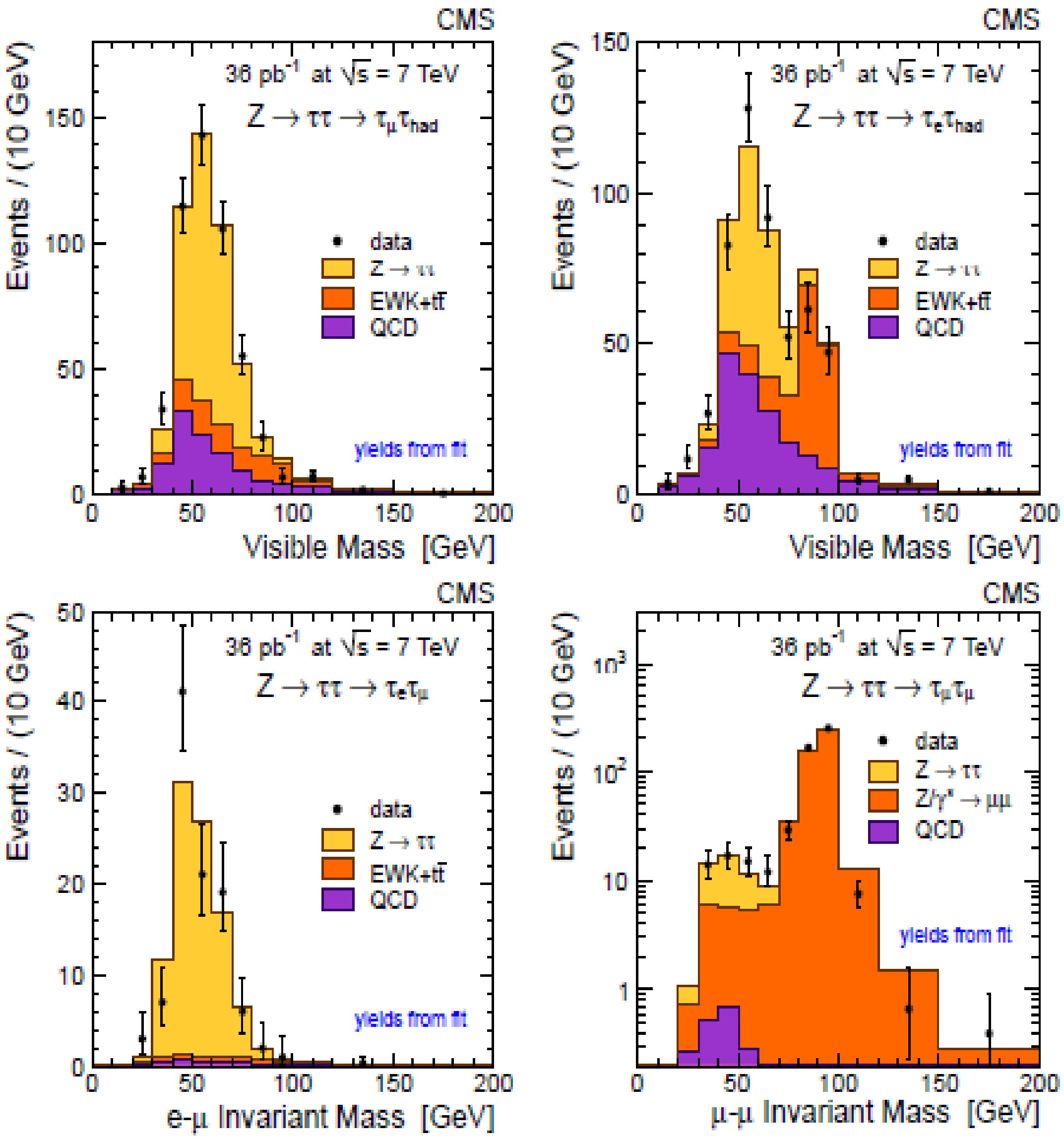
Lepton charge asymmetry from W decays in pp collisions at 7 TeV

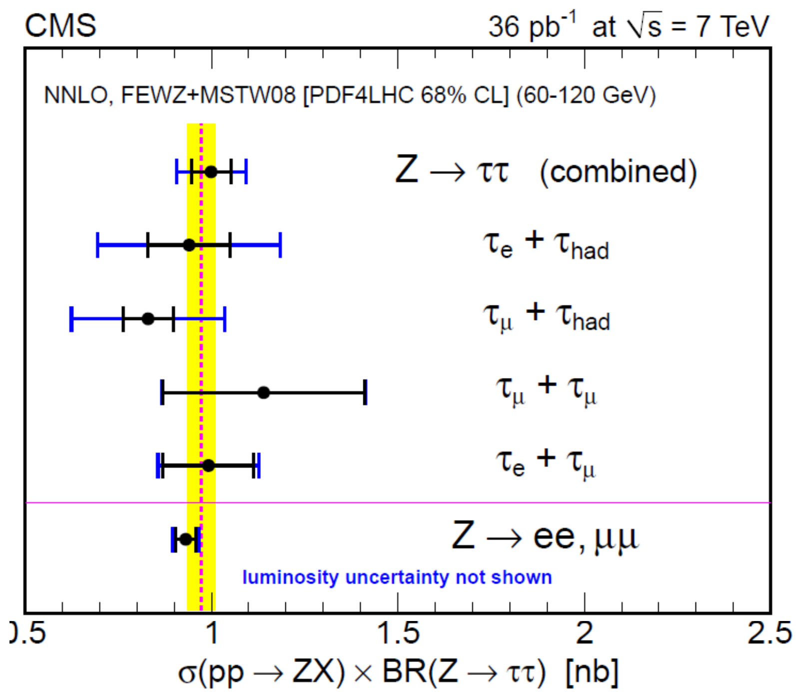
$$A(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})},$$



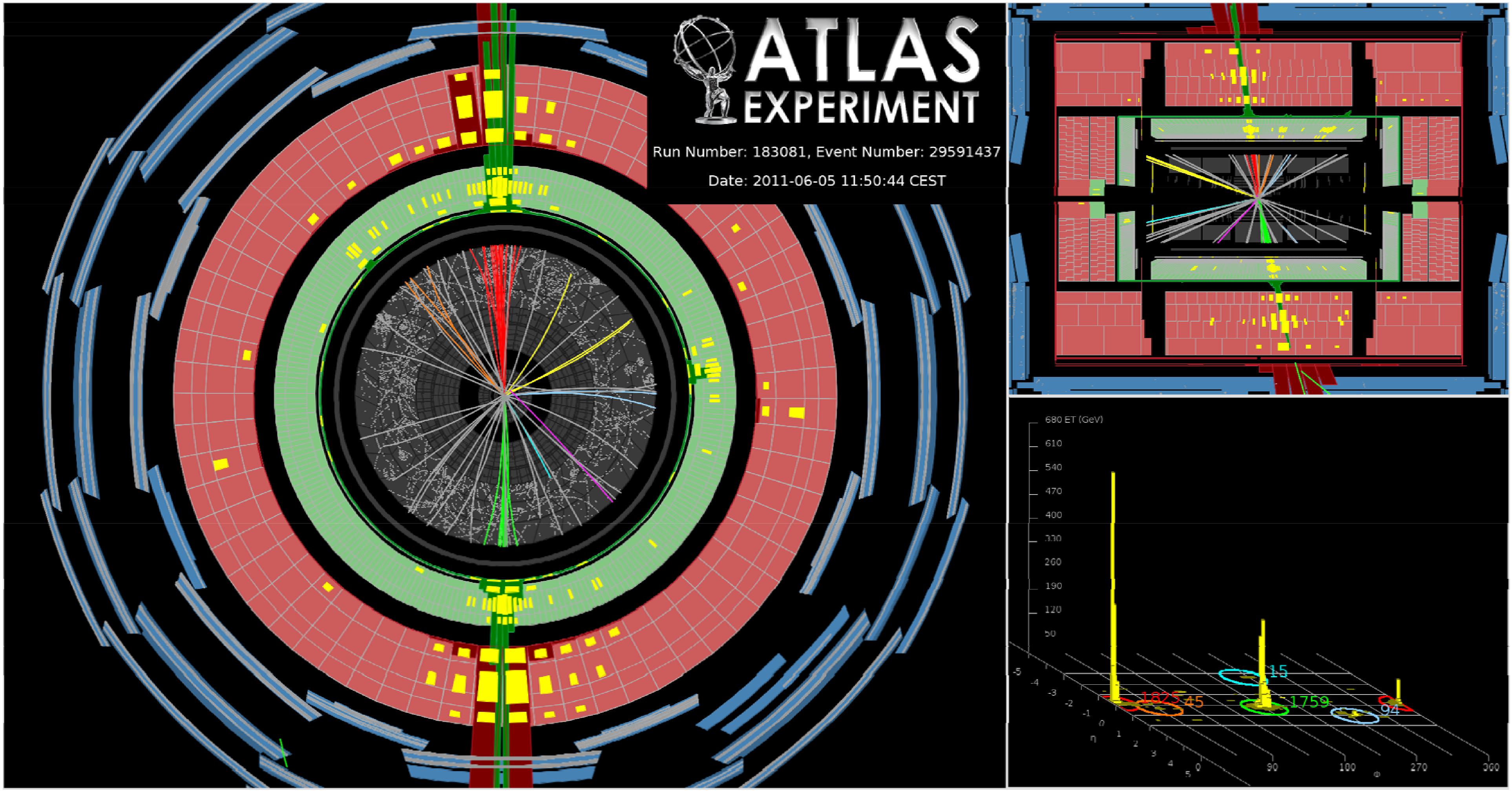
ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

Example of using τ's





Sub. to JHEP
arXiv:1104.1617[hep-ex]

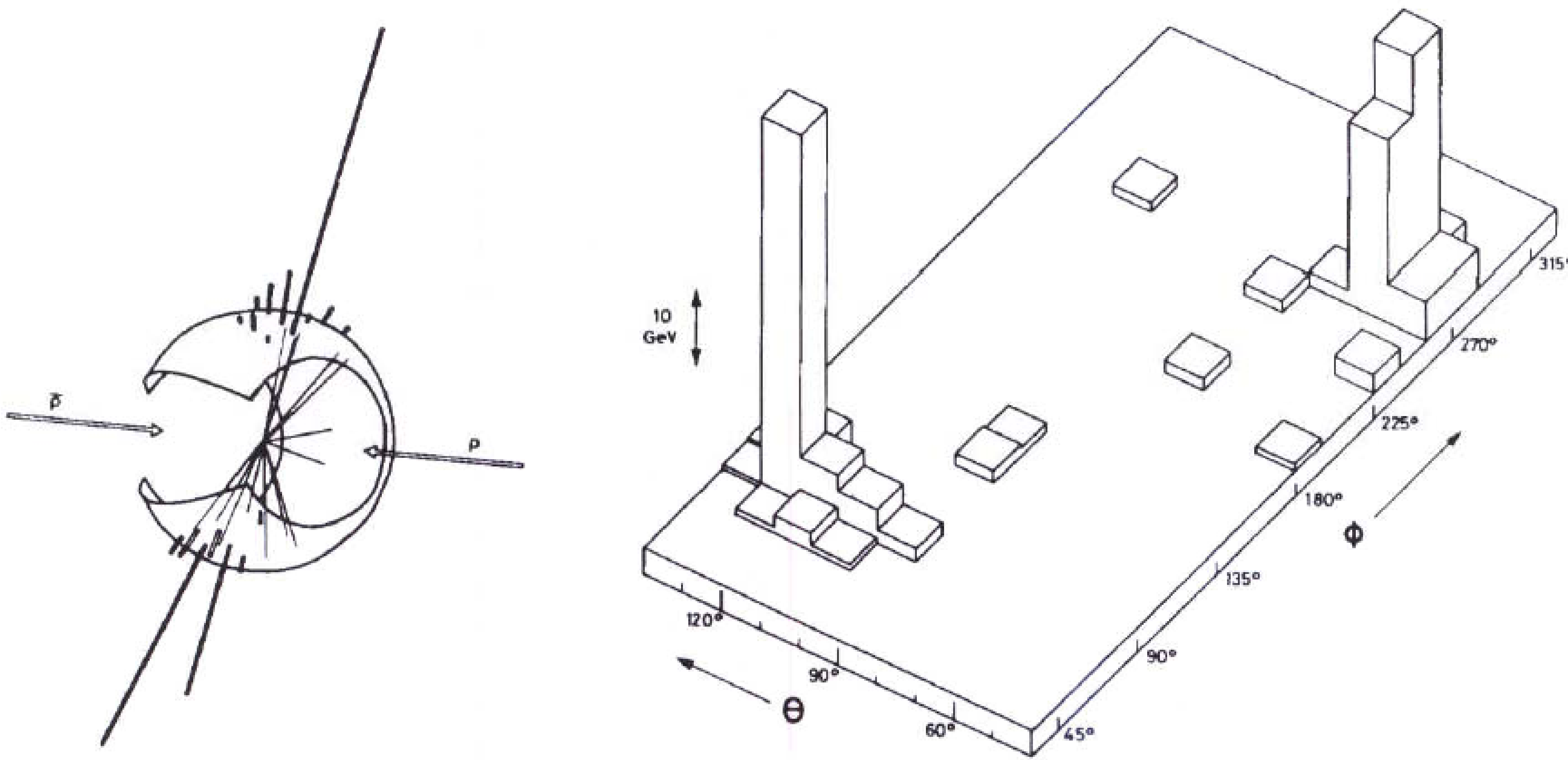


Jets

Jets with 1.9 and 1.7 TeV transverse momenta (p_T)

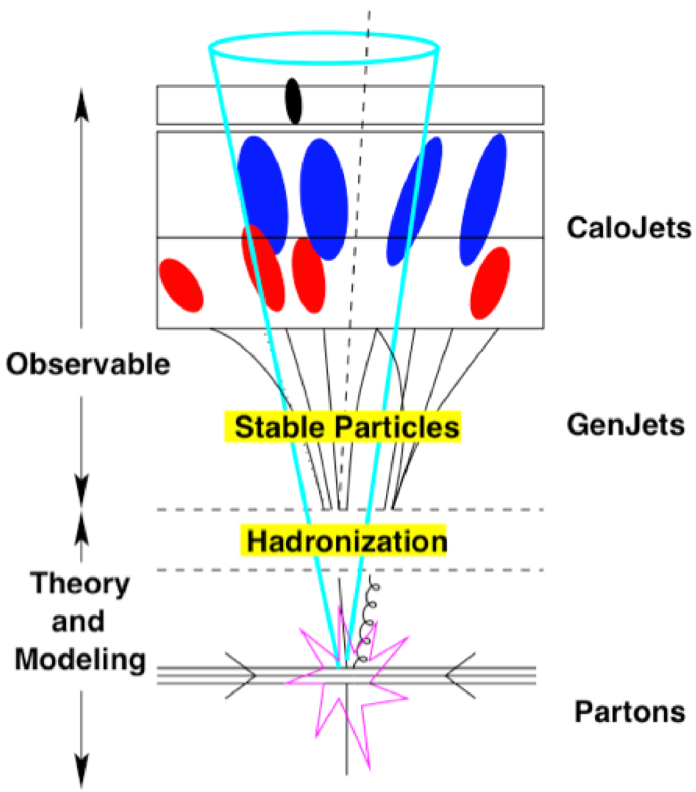
Note also that the event displays have become more sophisticated since the first spectacular events, hand-drawn, at a hadron collider …

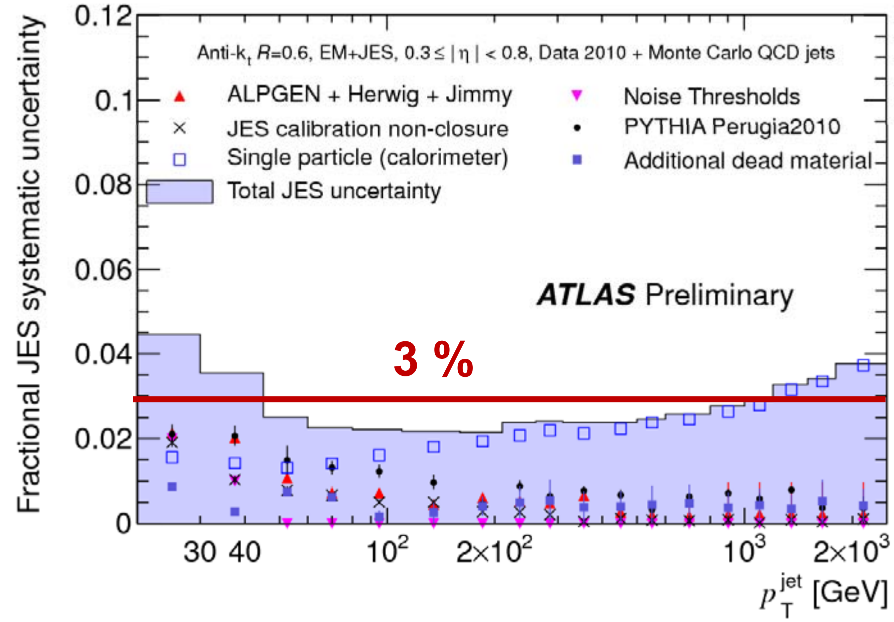
Volume 118B, number 1, 2, 3 PHYSICS LETTERS 2 December 1982

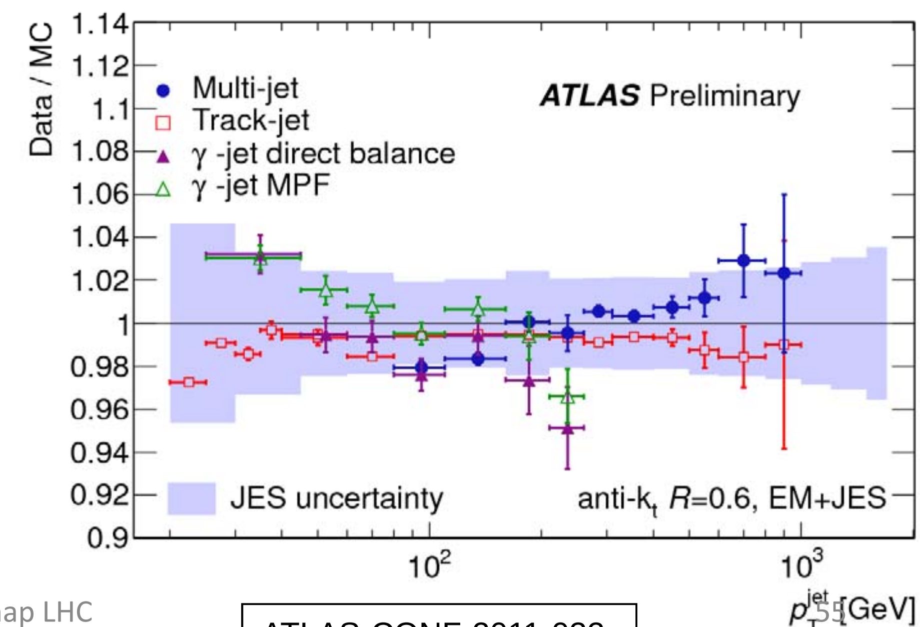


(a) (b)

A considerable effort went into understanding the Jet Energy Scale (JES), the dominant source of uncertainties for most jet measurements







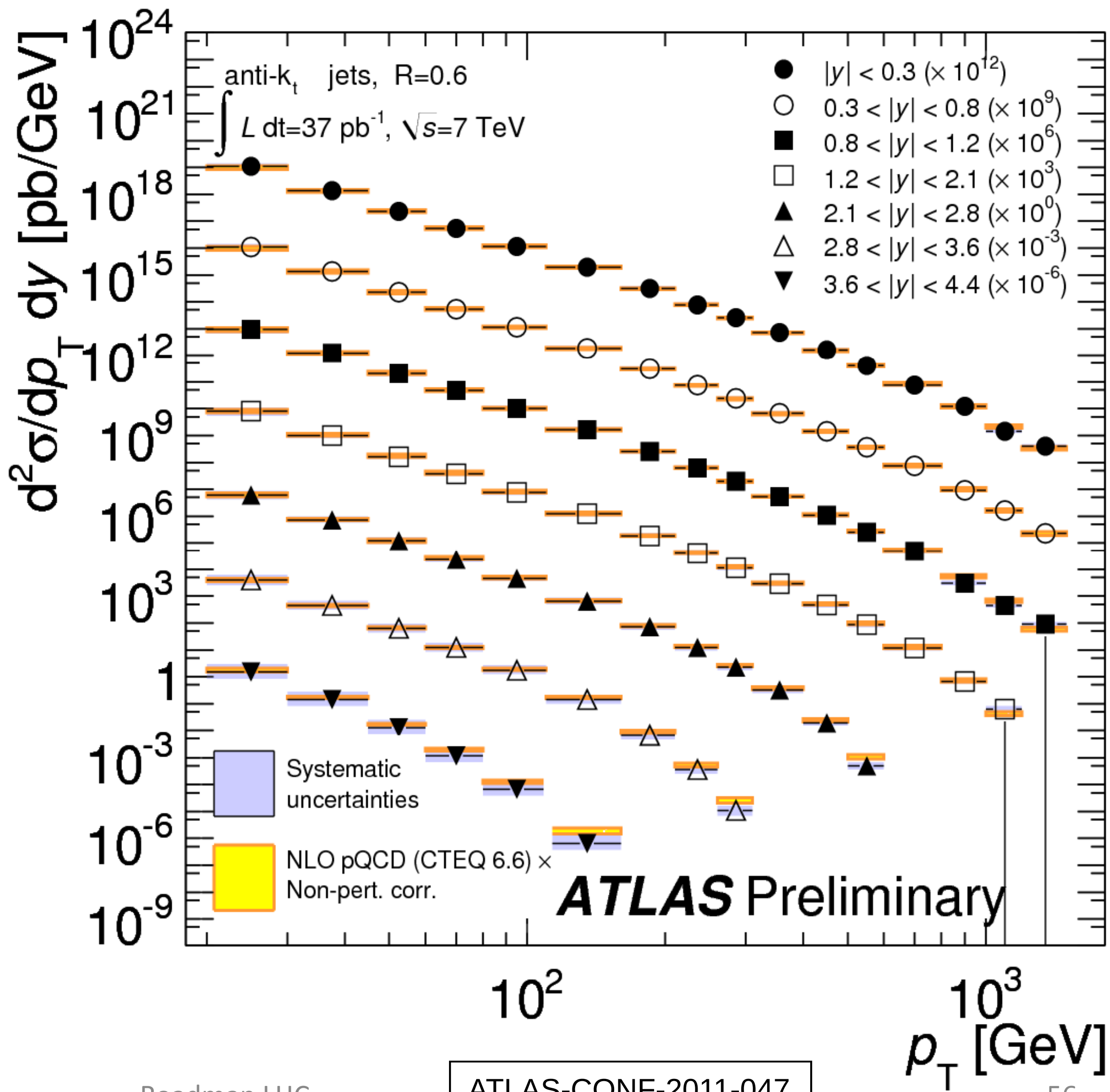
ATLAS-CONF-2011-032

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

Inclusive jet cross sections in various rapidity intervals

The data are spanning:

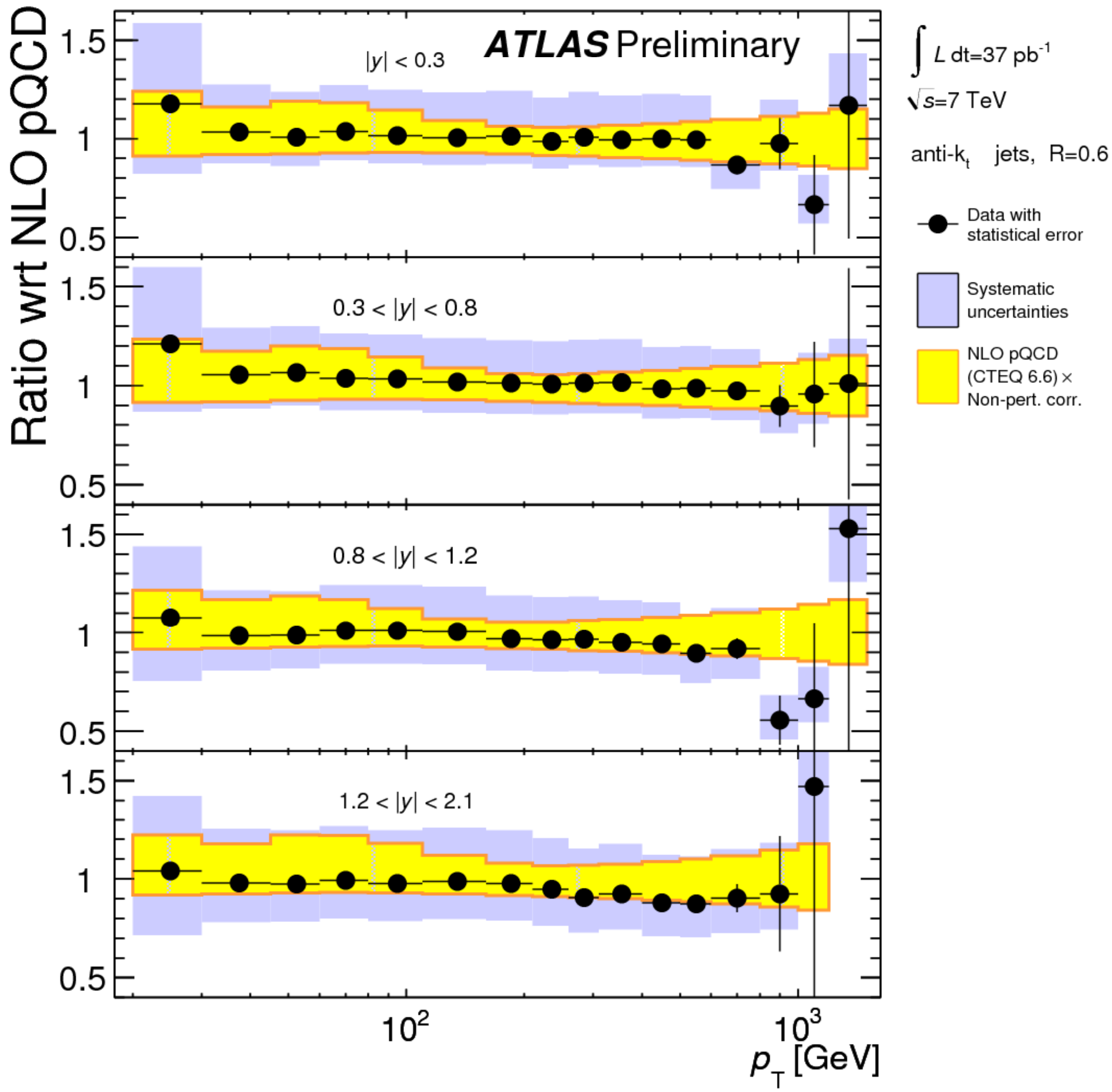
- **$20\ GeV < p_T < 1500\ GeV$**
- **$|\eta| < 4.4$**
- **Up to 12 orders of magnitudes in cross-sections**



ATLAS-CONF-2011-047

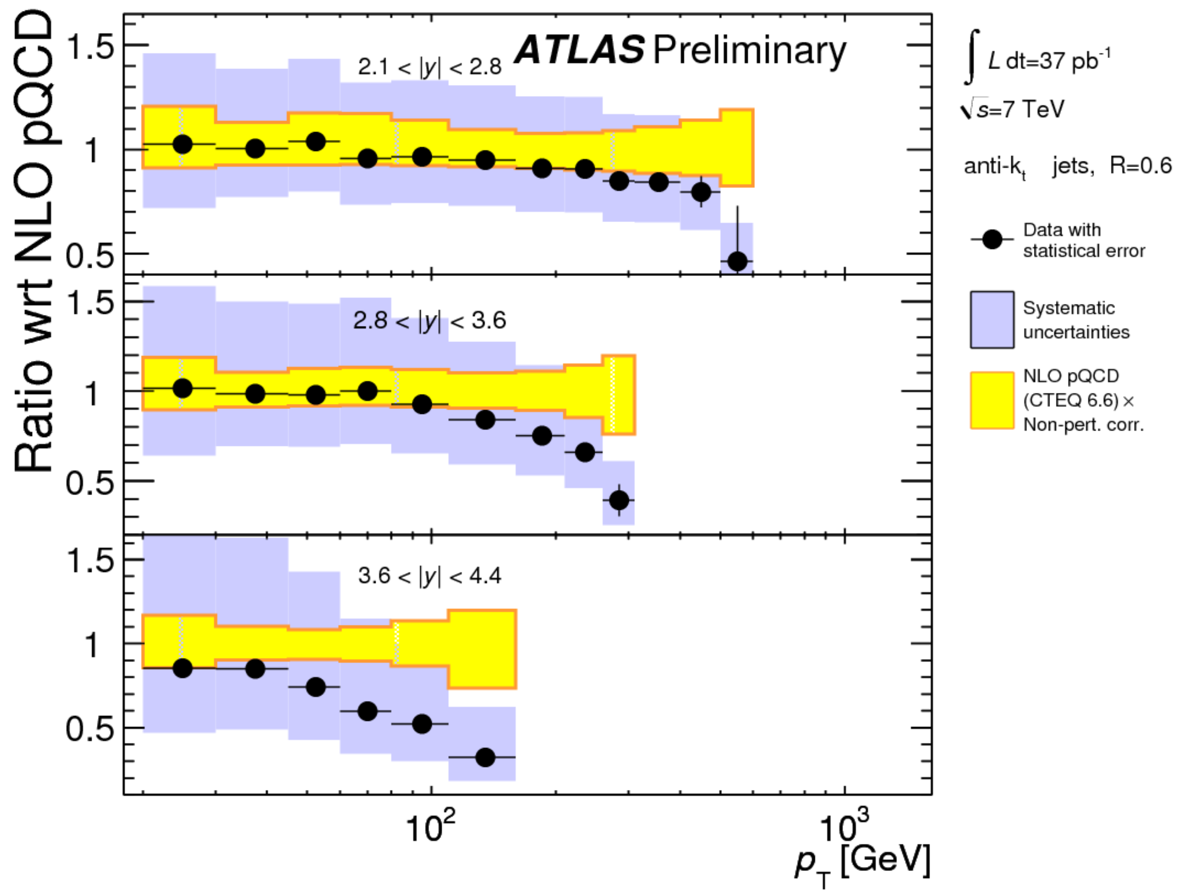
Systematic uncertainty dominated by JES

Good agreement between data and NLO pQCD with various PDFs globally…



ATLAS-CONF-2011-047

Systematic uncertainty dominated by JES

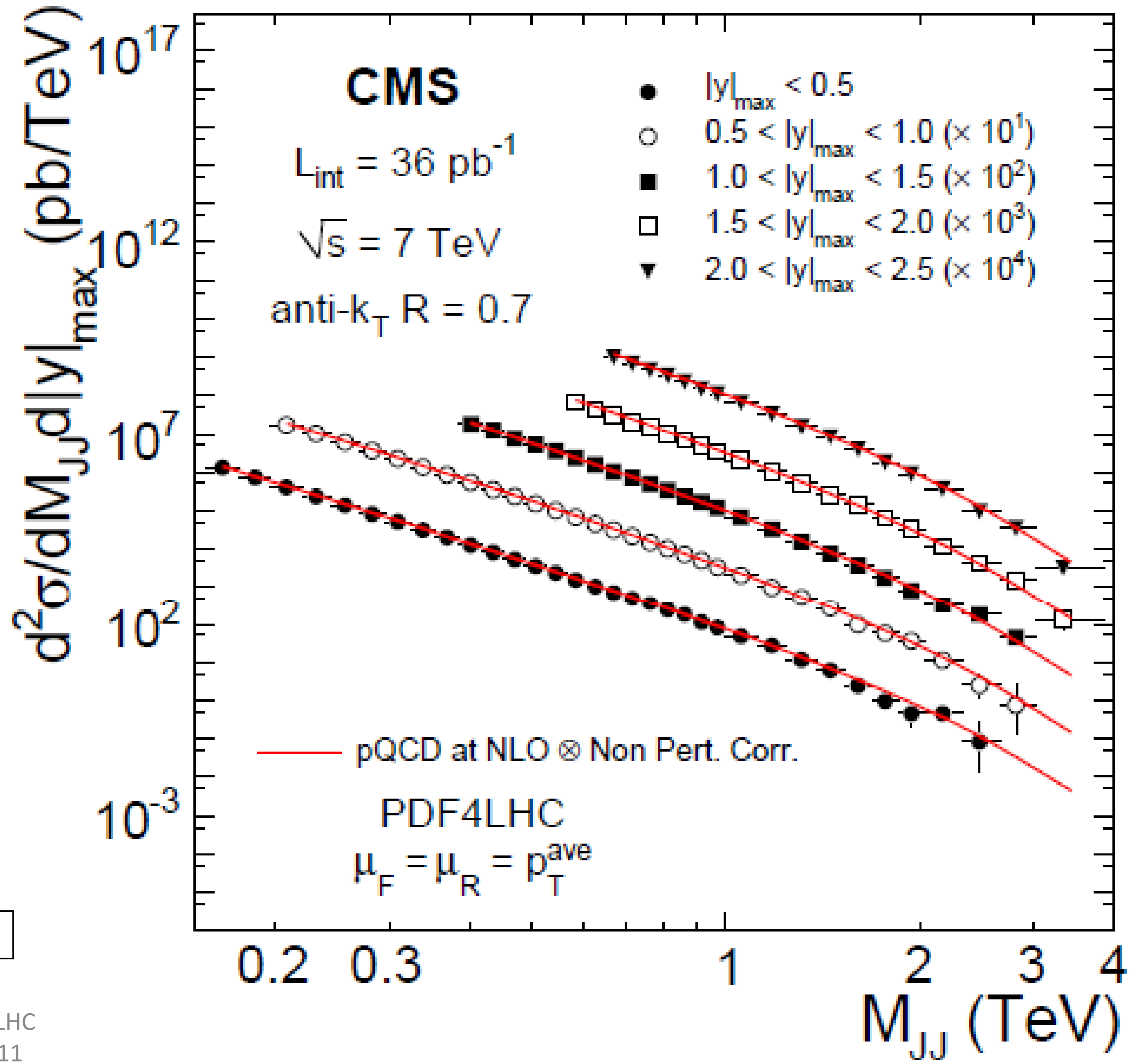


… except in some specific regions, for example in the forward directions

→Should be able soon to constrain PDFs

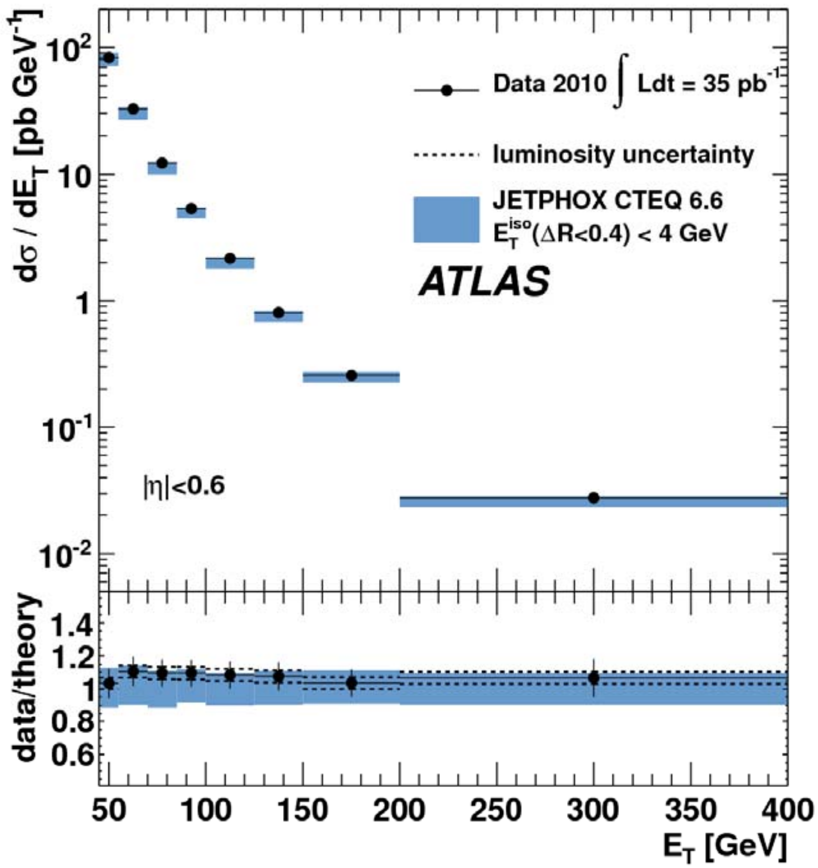
ATLAS-CONF-2011-047

Di-jet cross-sections in various rapidity intervals



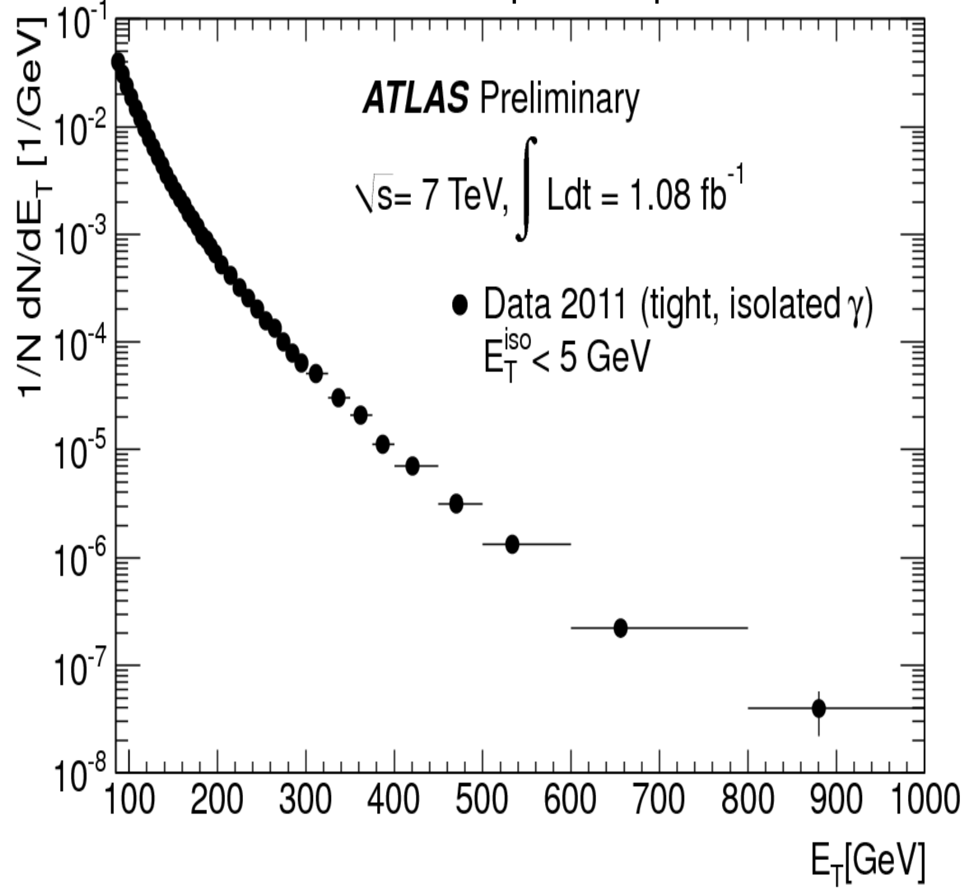
Phys. Lett. B700 (2011) 187

Example of inclusive isolated prompt photon cross-sections



Sub. To Phys. Lett. B
arXiv:1108.0251v1[hep-ex]

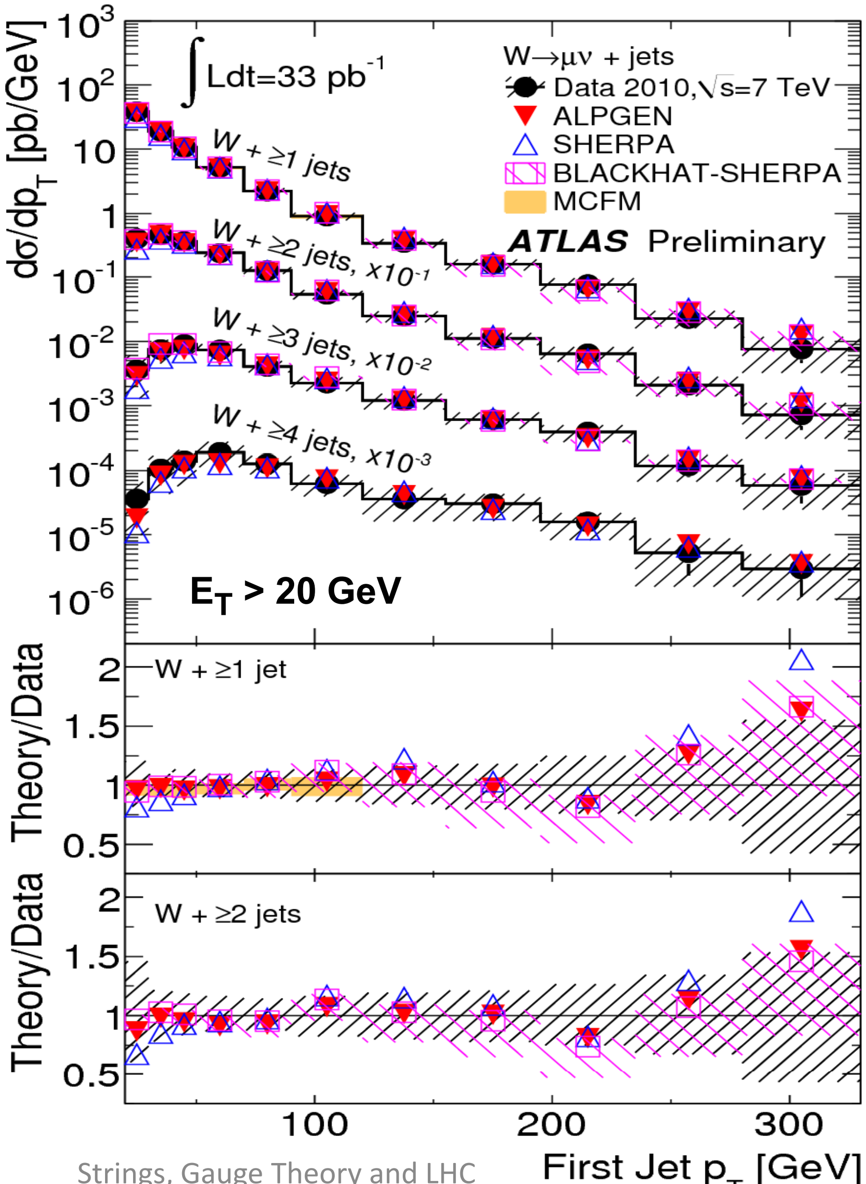
Updated spectrum 2011

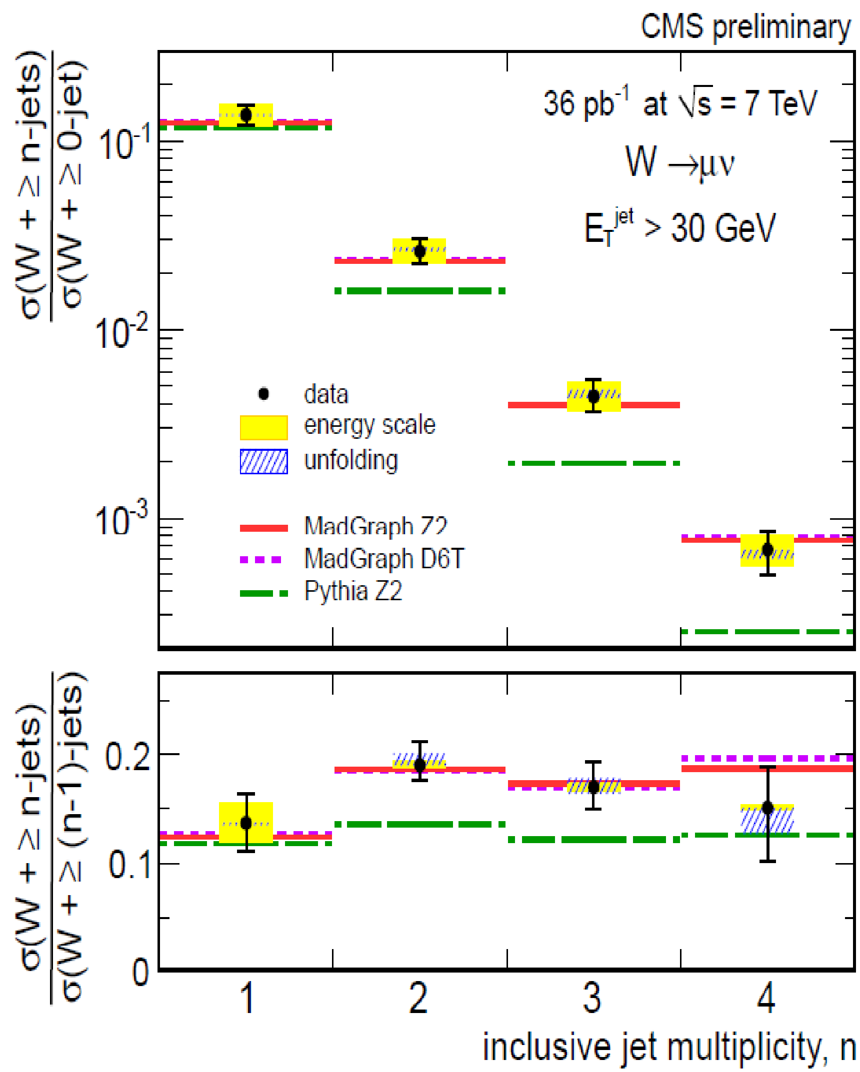


ATLAS-CONF-2011-060

W + jet(s) production

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

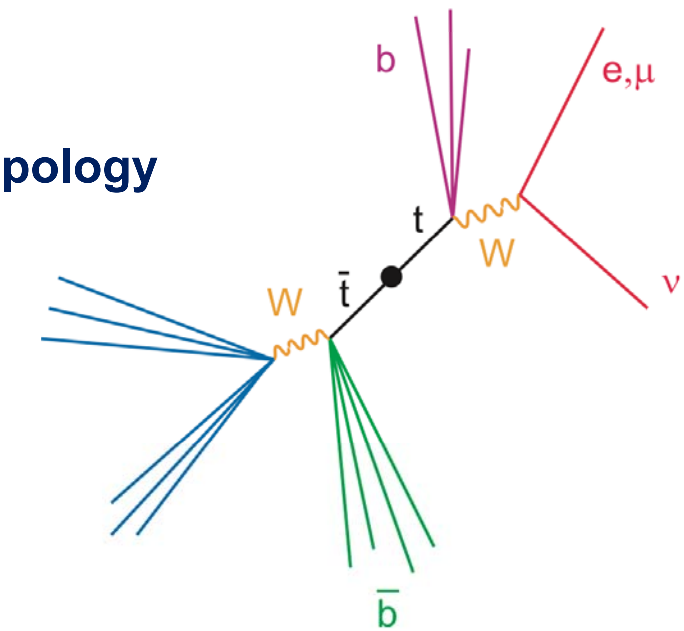




CMS PAS EWK 10-012

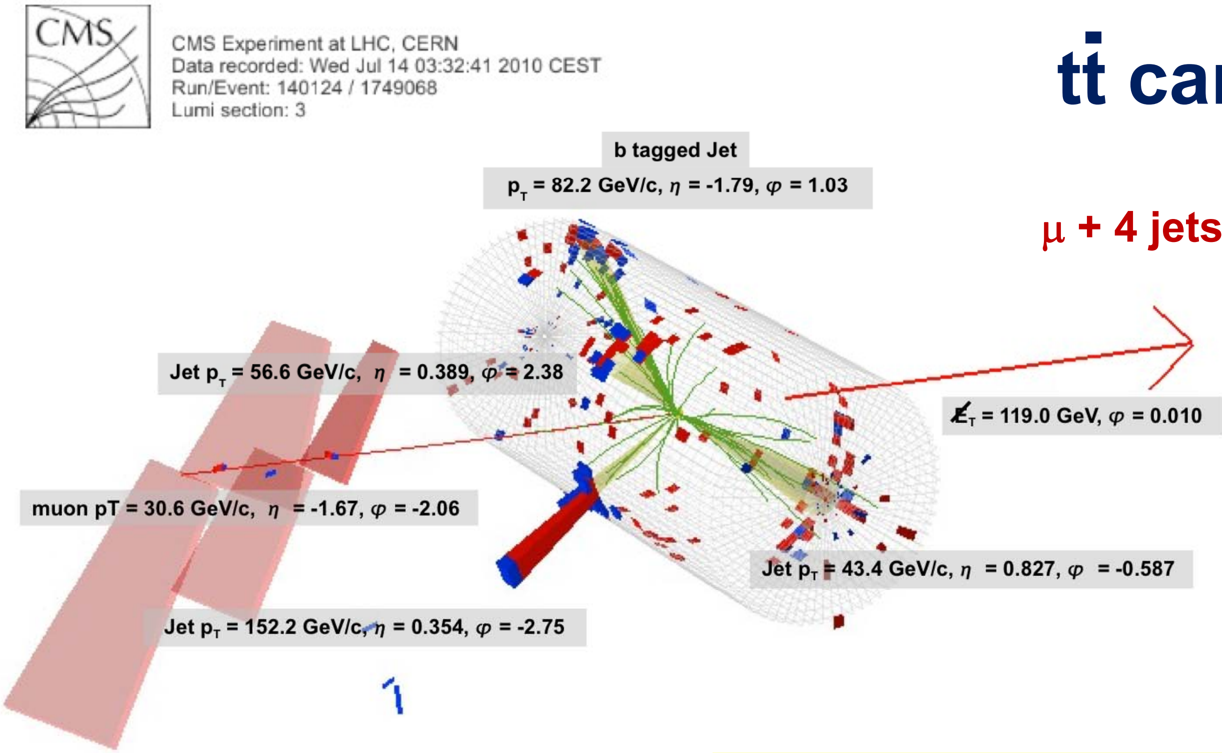
Early LHC measurements of the top cross section

- **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 (6.46%)**

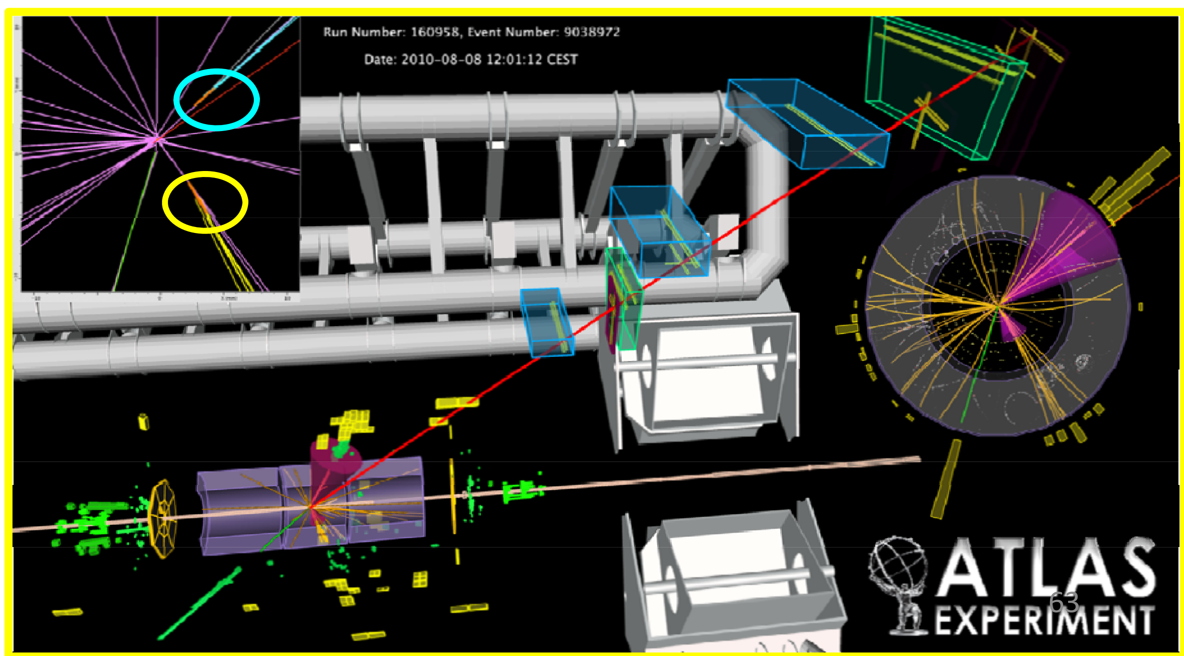


- **Data-driven methods to control QCD and W+jets backgrounds**

$t\bar{t}$ candidate events

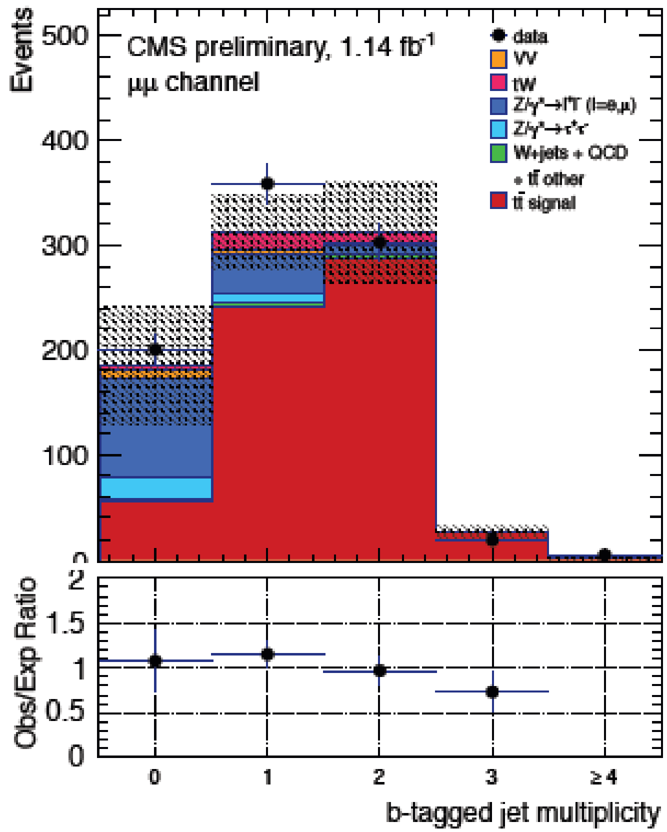


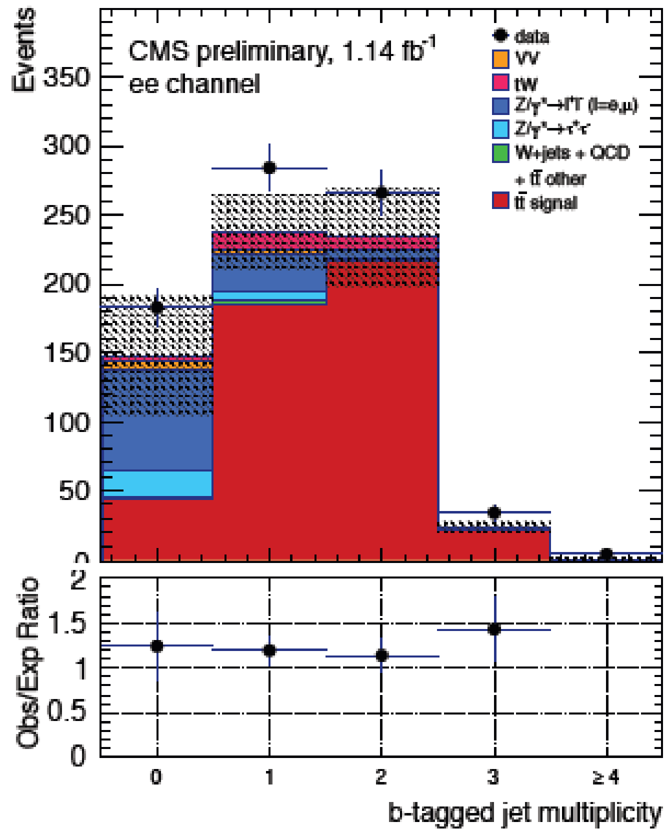
μ + 4 jets (one b-tagged) +ETmiss



e + μ + 2 jets (b-tagged) +ETmiss

2 leptons + jets + ETmiss

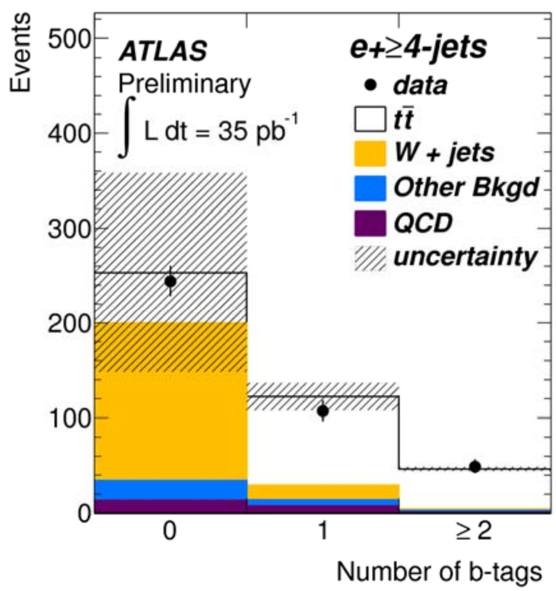




CMS-PAS-TOP-11-005

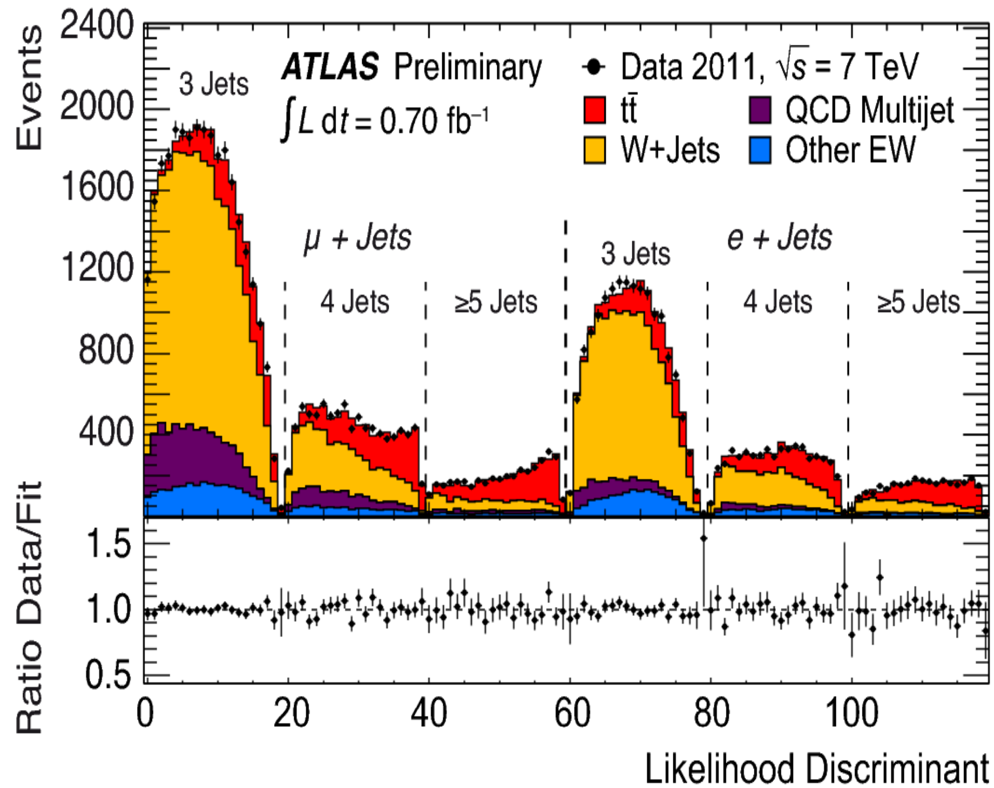
1 lepton + 4 jets + ETmiss

'Classical analysis'

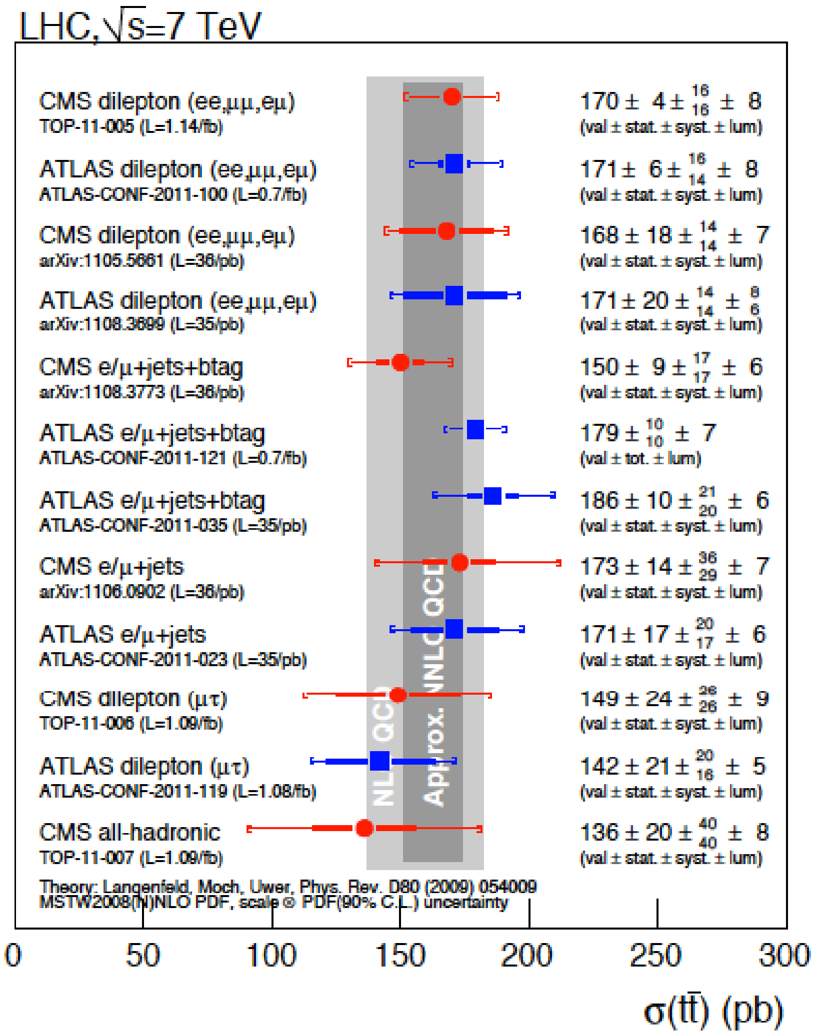


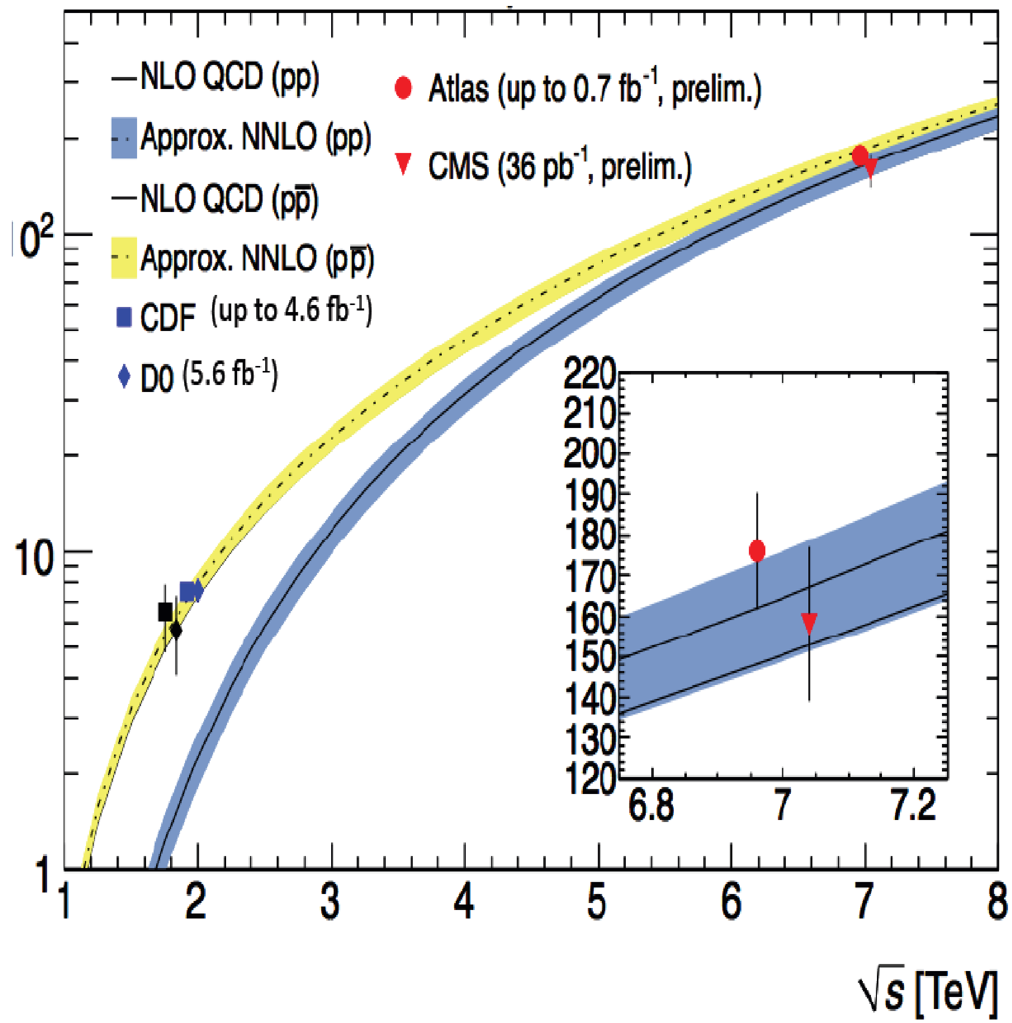
ATLAS-CONF-2011-035

Updated results with global kinematical fit



ATLAS-CONF-2011-121

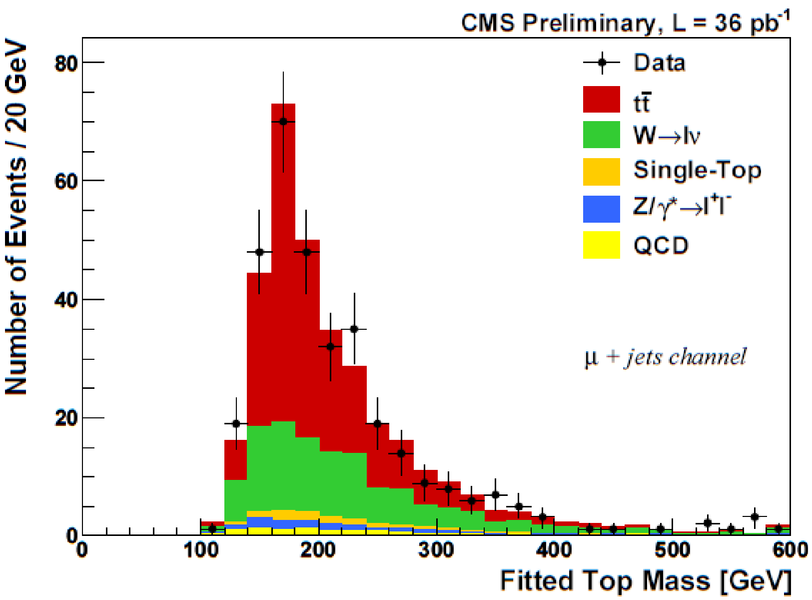




(ATLAS and CMS have also made first single top cross-section measurements in agreement with NLO QCD expectations)

Examples of first measurements of Top quark properties

CMS mass measurement with l + jets (kinematic fit, 4 or more jets)

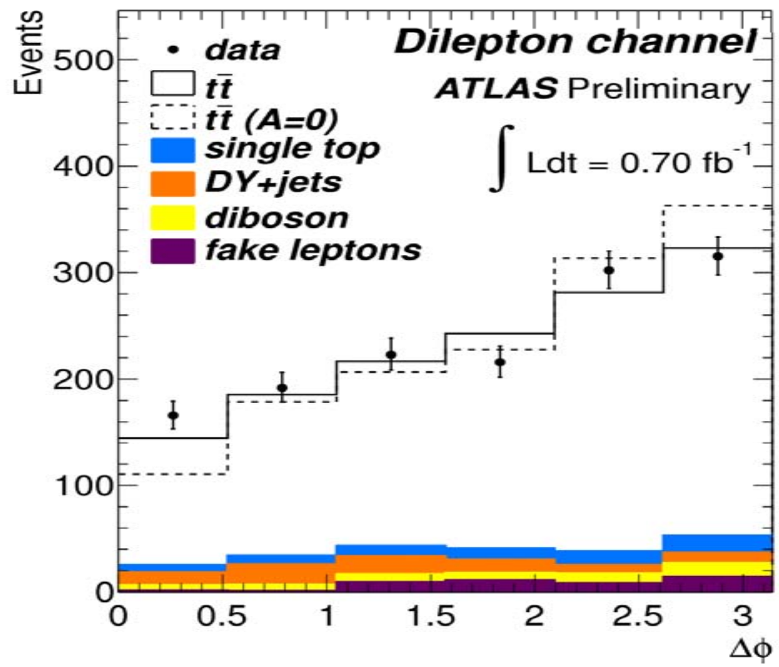


Result when combined with di-lepton analysis

$$m_t = 173.4 \pm 1.9(\mathrm{stat}) \pm 2.7(\mathrm{syst})\ \ \mathrm{GeV}.$$

CMS-PAS-TOP-10-009

ATLAS t-tbar spin correlation as measured in di-lepton events (Δϕ between leptons in azimuthal plane in the t-tbar lab frame)

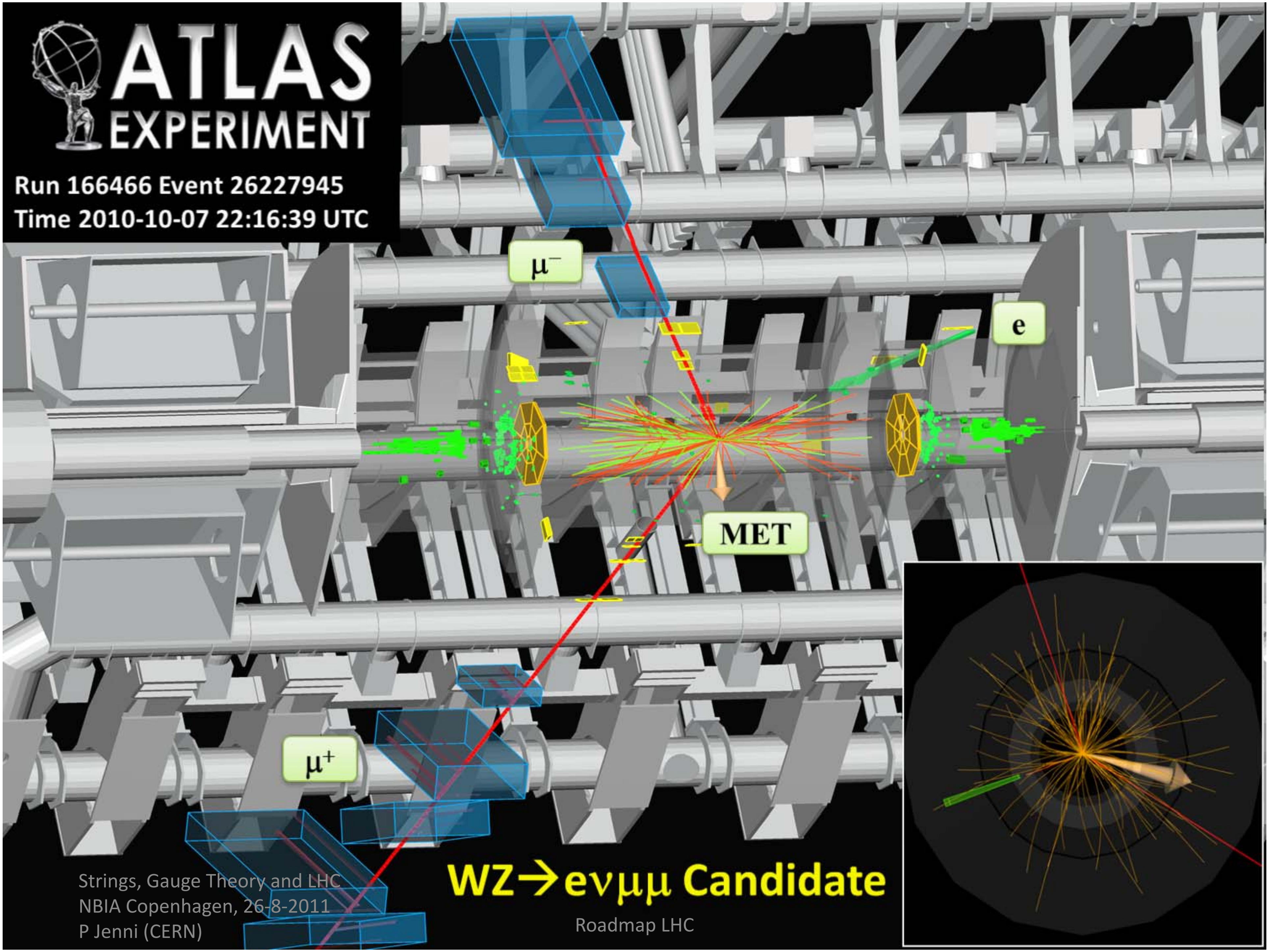


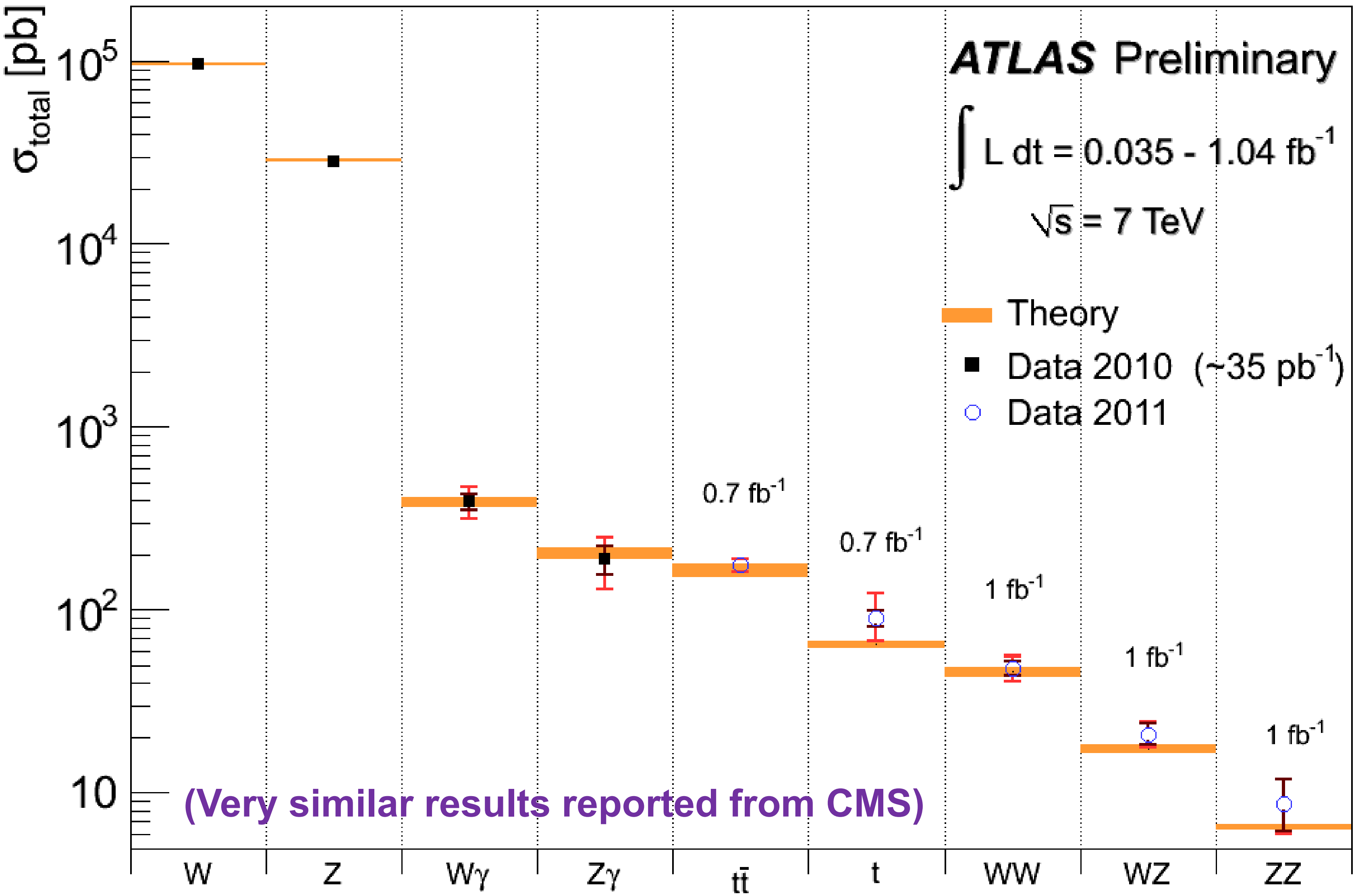
$$C_{\mathrm{helicity}} = 0.34^{+0.15}_{-0.11}$$

(SM predicts ~ 0.32)

ATLAS-CONF-2011-117

(Soon) competitive with TeVatron…


ATLAS EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate
Strings, Gauge Theory and LHC
NBIA Copenhagen, 26-8-2011
P Jenni (CERN)
Roadmap LHC



ATLAS Preliminary
$\int L\,dt = 0.035 - 1.04\ fb^{-1}$
$\sqrt{s} = 7$ TeV
Theory
Data 2010 (~35 pb^{-1})
Data 2011
σ_{total} [pb]
10^5
10^4
10^3
10^2
10
0.7 fb^{-1}
0.7 fb^{-1}
1 fb^{-1}
1 fb^{-1}
1 fb^{-1}
W
Z
Wγ
Zγ
$t\bar{t}$
t
WW
WZ
ZZ
(Very similar results reported from CMS)

Strategy toward physics

Before data taking starts:

- Strict quality controls of detector construction to meet physics requirements ✓
- Test beams (a 15-year activity culminating with a combined test beam in 2004) to understand and calibrate (part of) detector and validate/tune software tools (e.g. Geant4 simulation) ✓
- Detailed simulations of realistic detector "as built and as installed" (including misalignments, material non-uniformities, dead channels, etc.) → test and validate calibration/alignment strategies ✓
- Experiment commissioning with cosmics in the underground cavern ✓

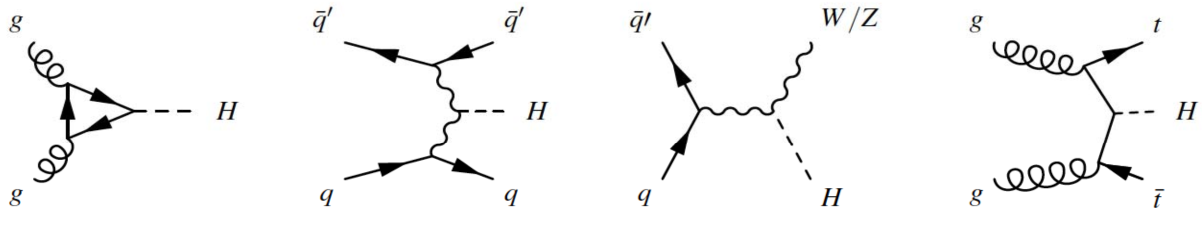
With the first data:

- Commission/calibrate detector/trigger in situ with physics (min.bias, Z→ll, …) ✓
- "Rediscover" Standard Model, measure it at $\sqrt{s}$ = 7 TeV (minimum bias, W, Z, tt, QCD jets, …)
- Validate and tune tools (e.g. MC generators) ✓
- Measure main backgrounds to New Physics (W/Z+jets, tt+jets, QCD-jets,…)

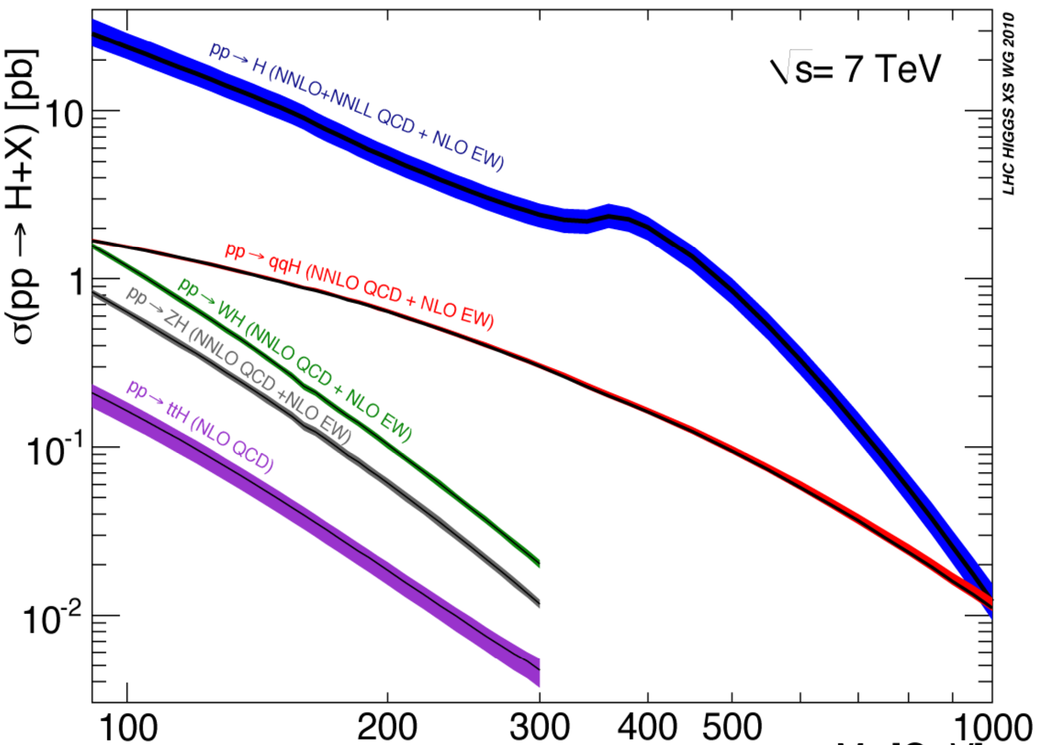
↓

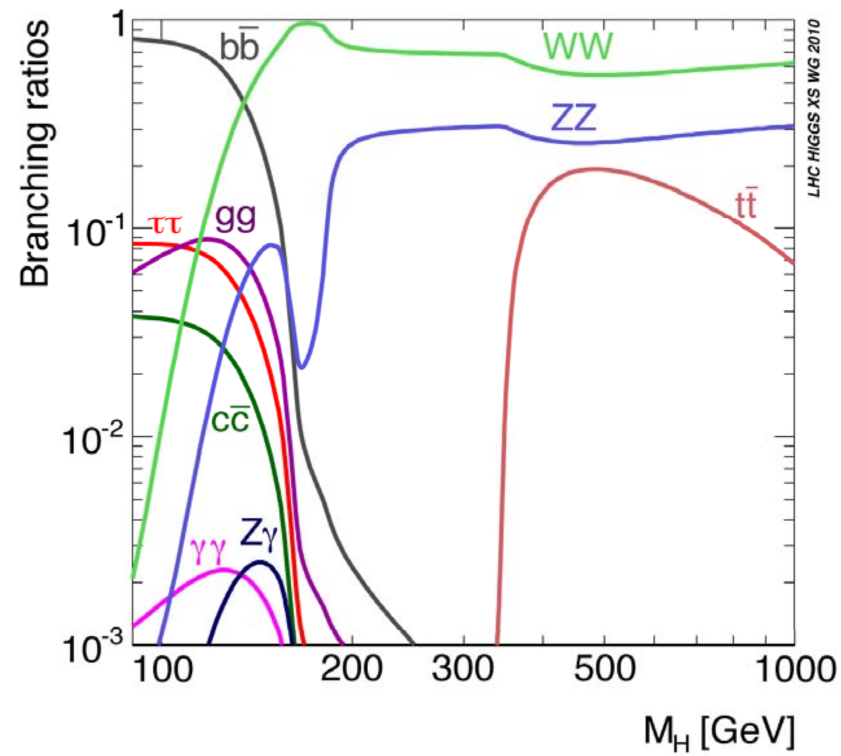
Prepare the road to discoveries …

The Higgs Hunt at LHC



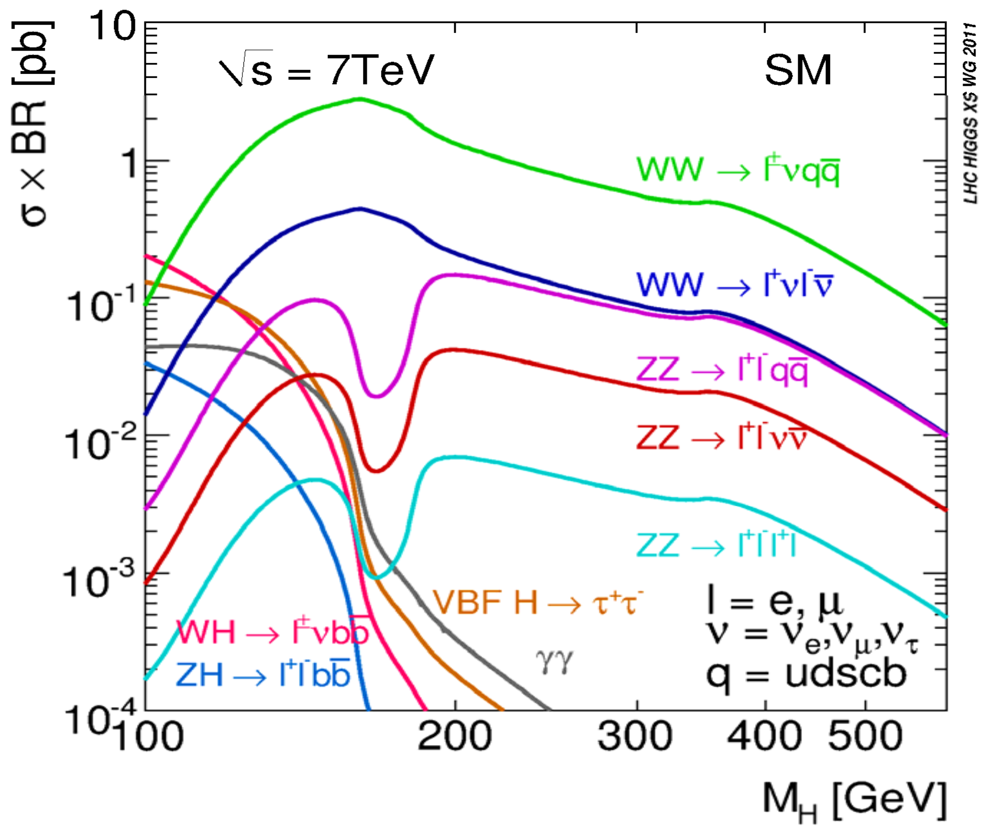
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$





Higgs cross-sections (ATLAS example)

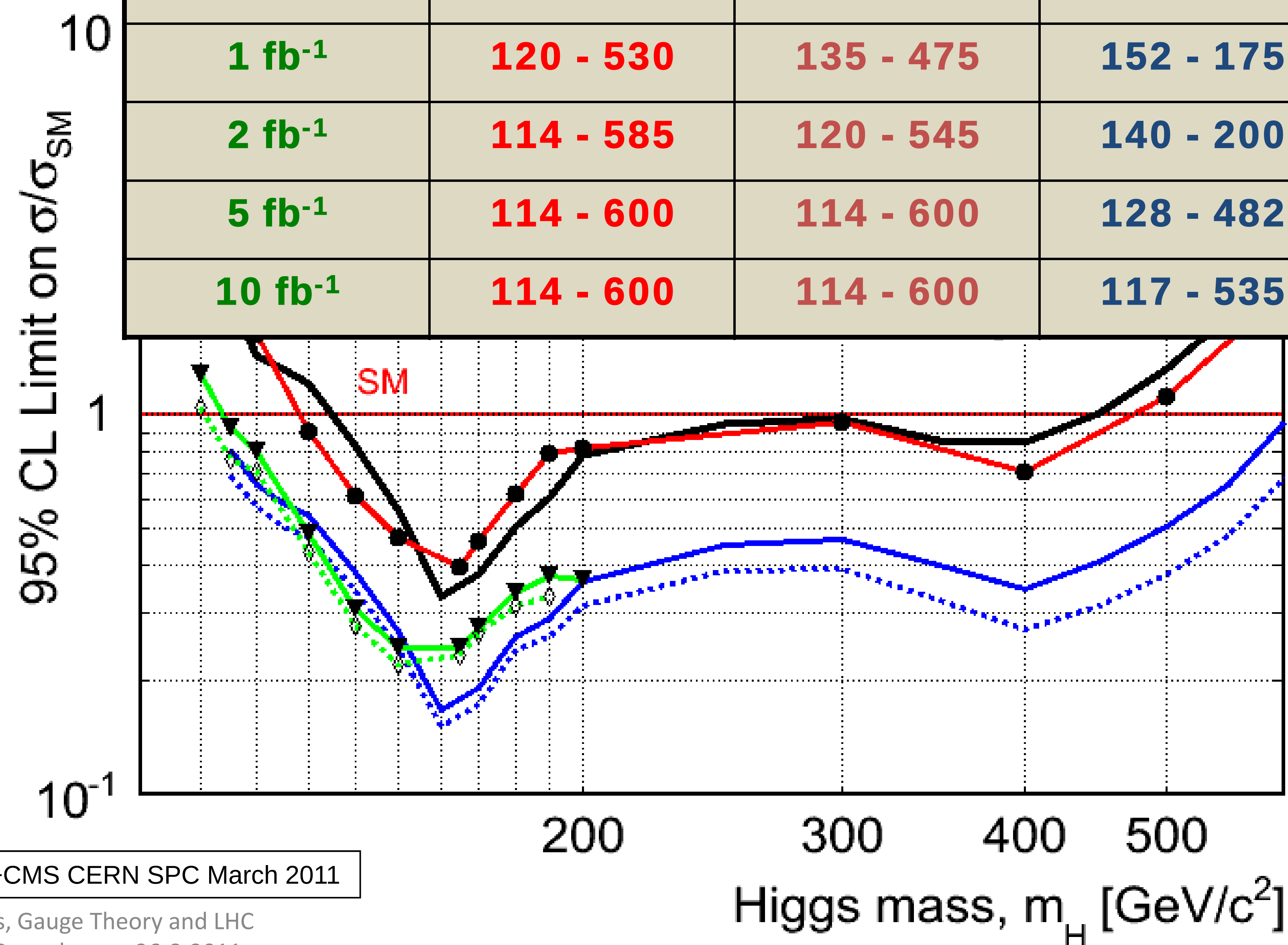
- H→γγ: rare channel, but the best for low mass
- H→WW(*):
  - →lvlv: very important in the intermediate mass range
  - → lvqq: highest rate, important at high mass
- H→ZZ(*):
  - → 4l: golden channel
  - → llvv: good for high mass
  - → llbb: also high mass
- H→ττ: good signal/background, important at low mass, rare, and experimentally challenging
- Associated prod. H→ bb-bar
  - ttH, WH, ZH
  - It is useful for the discovery
  - It is very important for Higgs property studies if SM Higgs is discovered



Events expected to be produced per 1 fb^{-1}

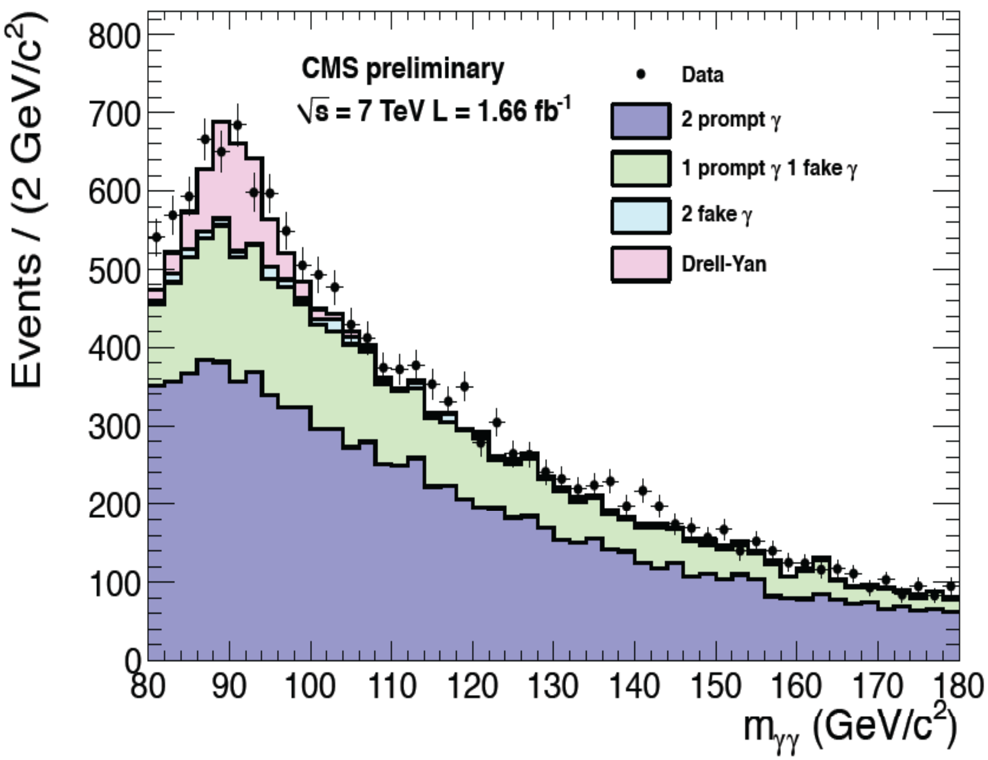
m_H, GeV	WW→lvlv	ZZ→4l	γγ
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

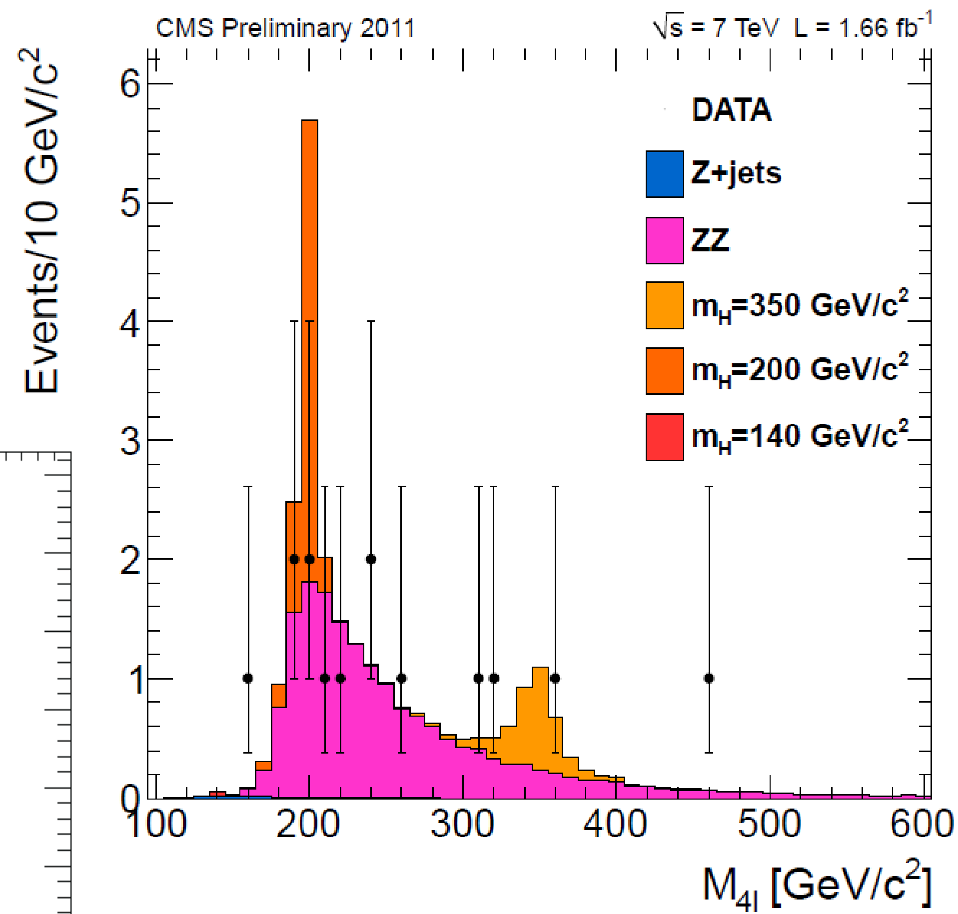
ATLAS+CMS 7 TeV	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535



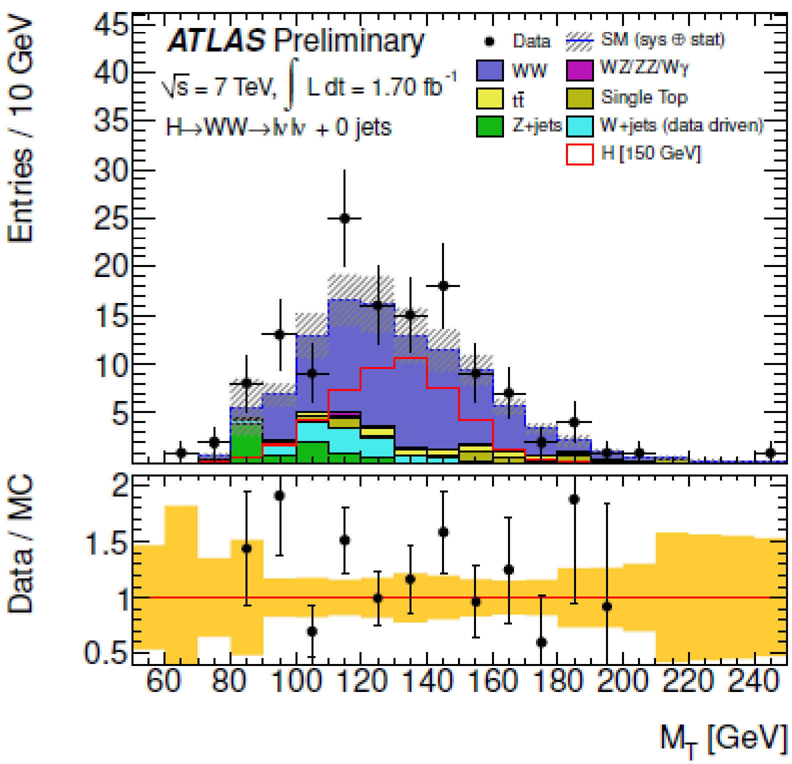
ATLAS+CMS CERN SPC March 2011

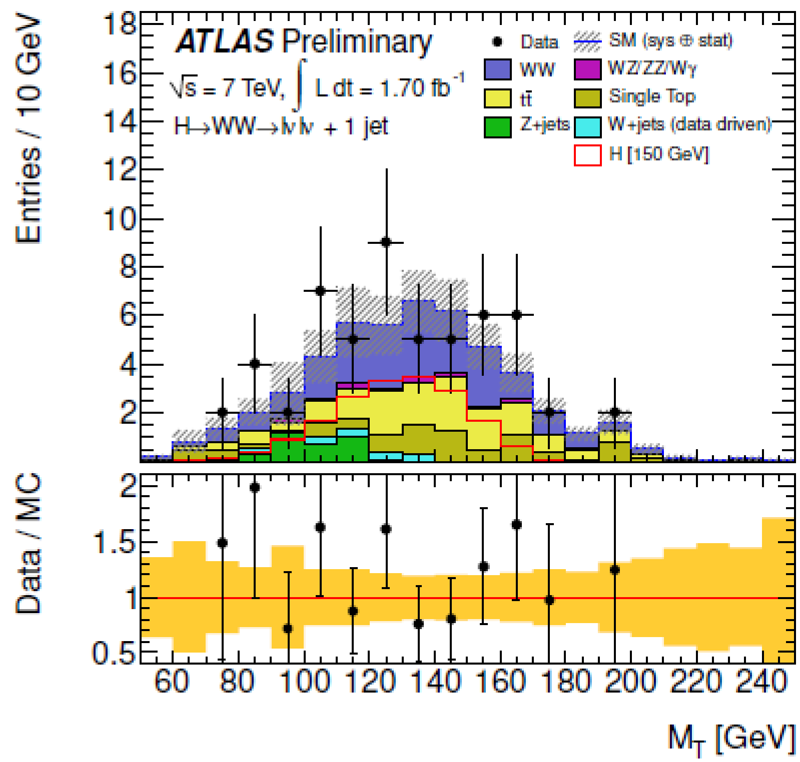
Two examples of 'easy' searches (where one would expect a mass peak)



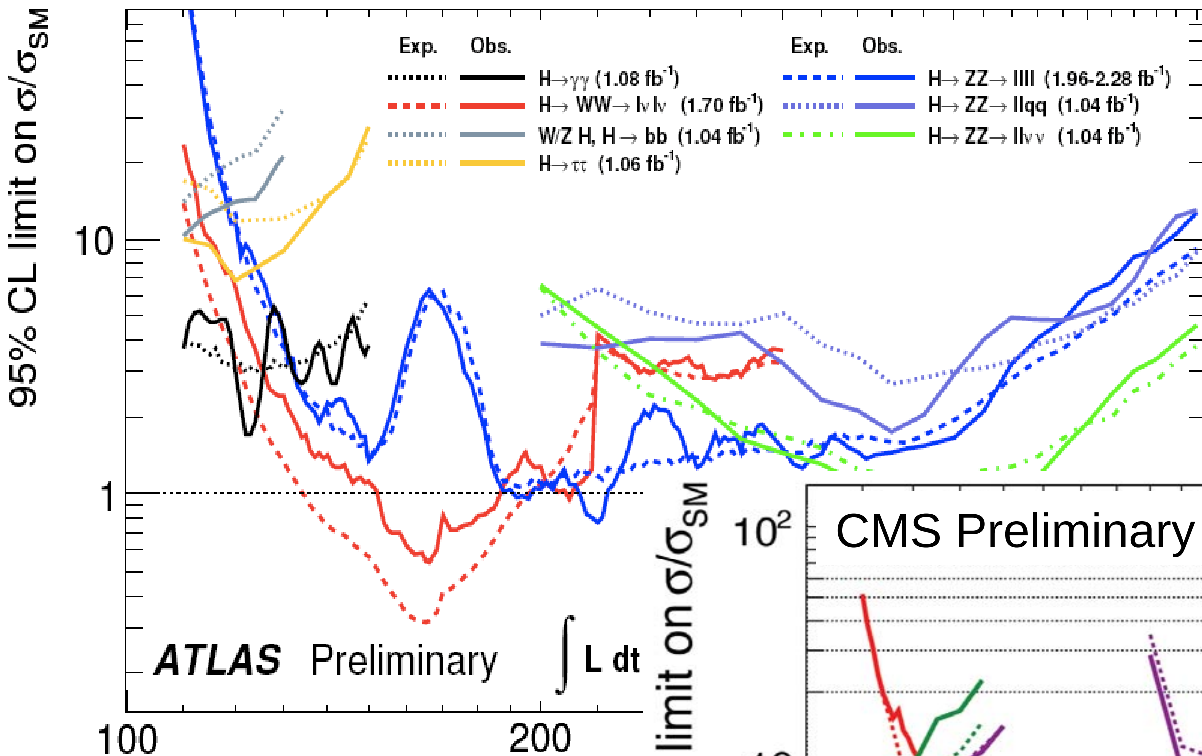


An example of 'difficult' search channel (no peak, counting experiment)



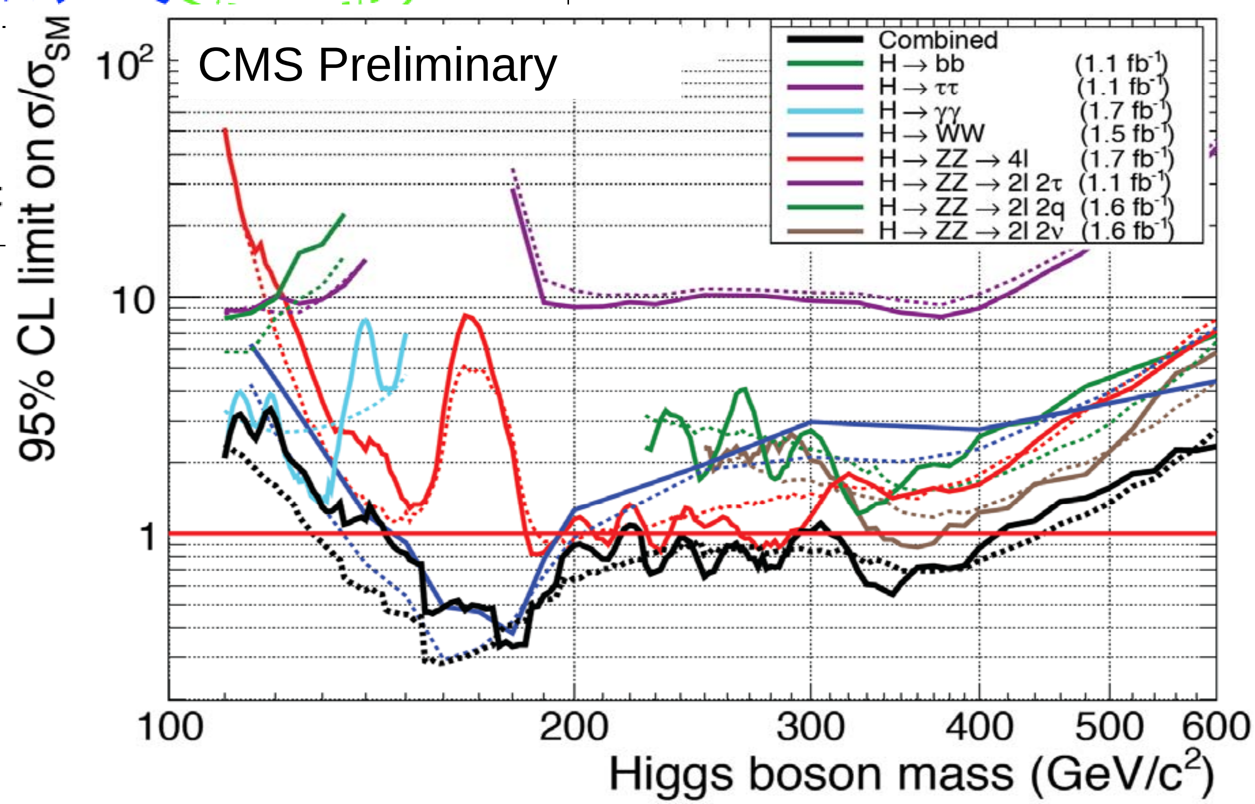


	WW	ttbar	Total SM back.	Data	Higgs m_H=150
0-jet	43±6	2.2±1.4	53±9	70	34±7
1-jet	10±2	6.9±1.9	23±4	23	12±3



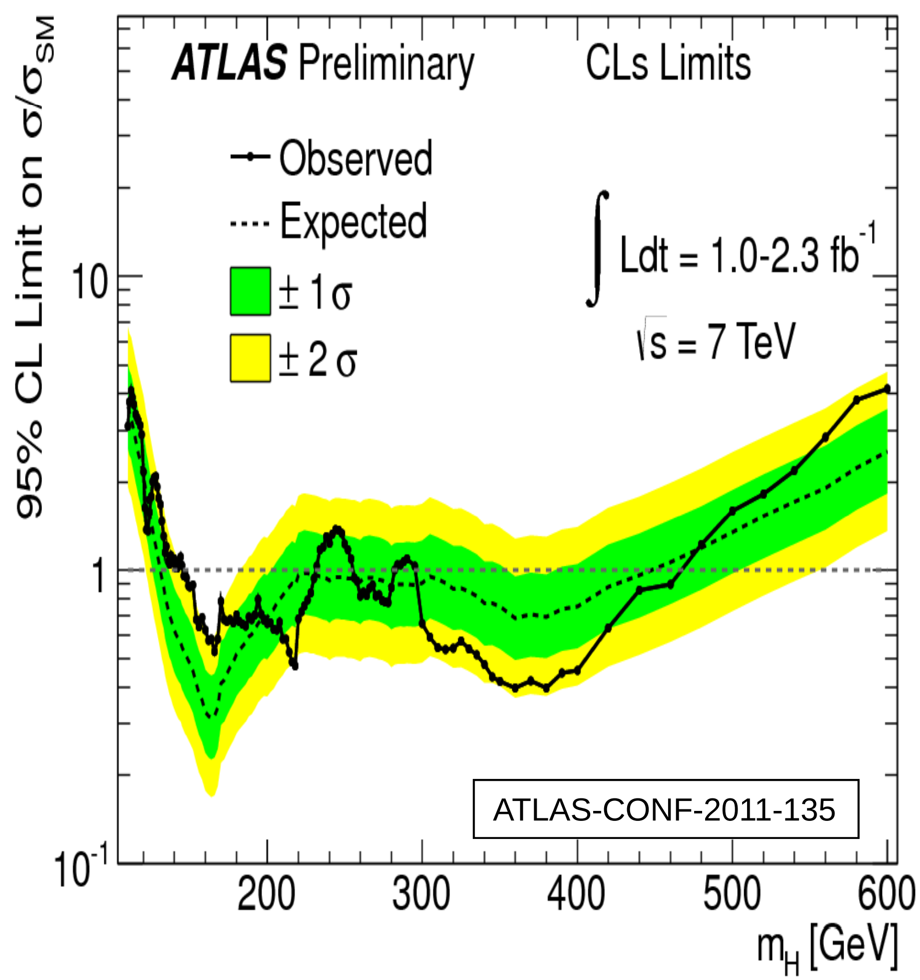
Higgs searches are the focal point at this year's conferences

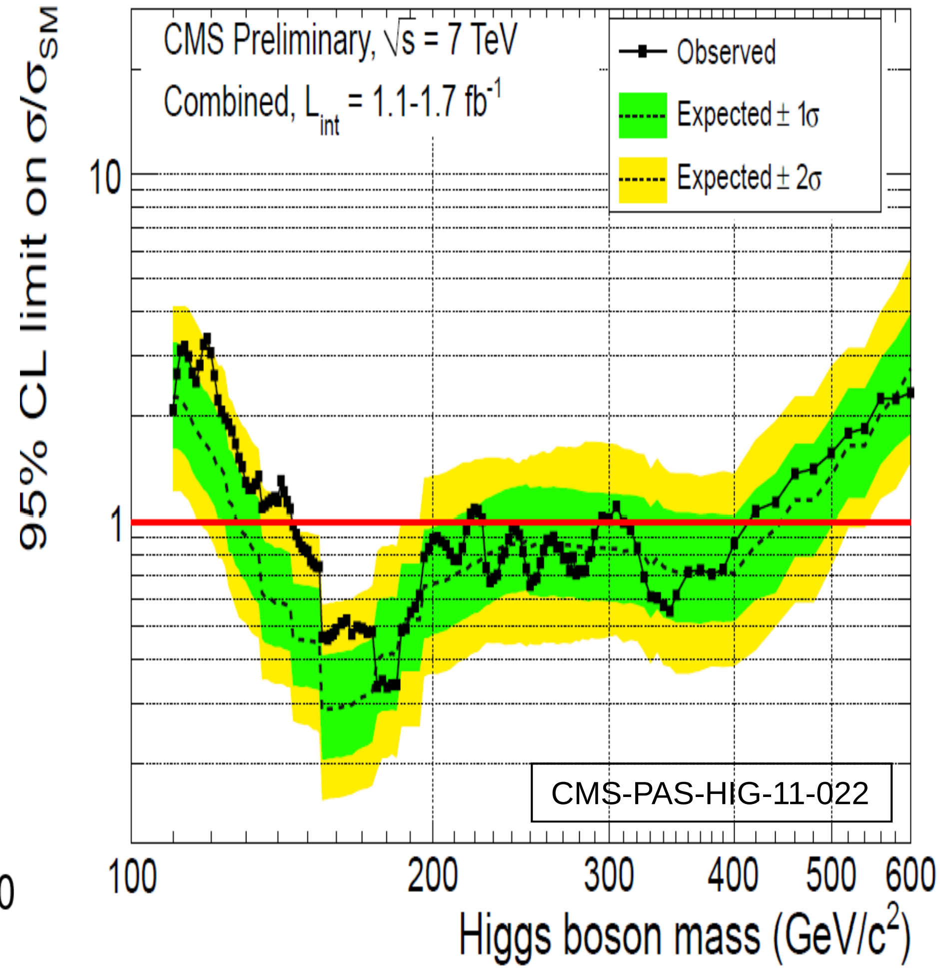
Here this week's status (LP 2011 Mumbai)



The situation is evolving fast with the excellent LHC performance, new results can be expected in the near future well along the shown expectations...

Status of Lepton Photon Conference Mumbai, 22nd Aug 2011



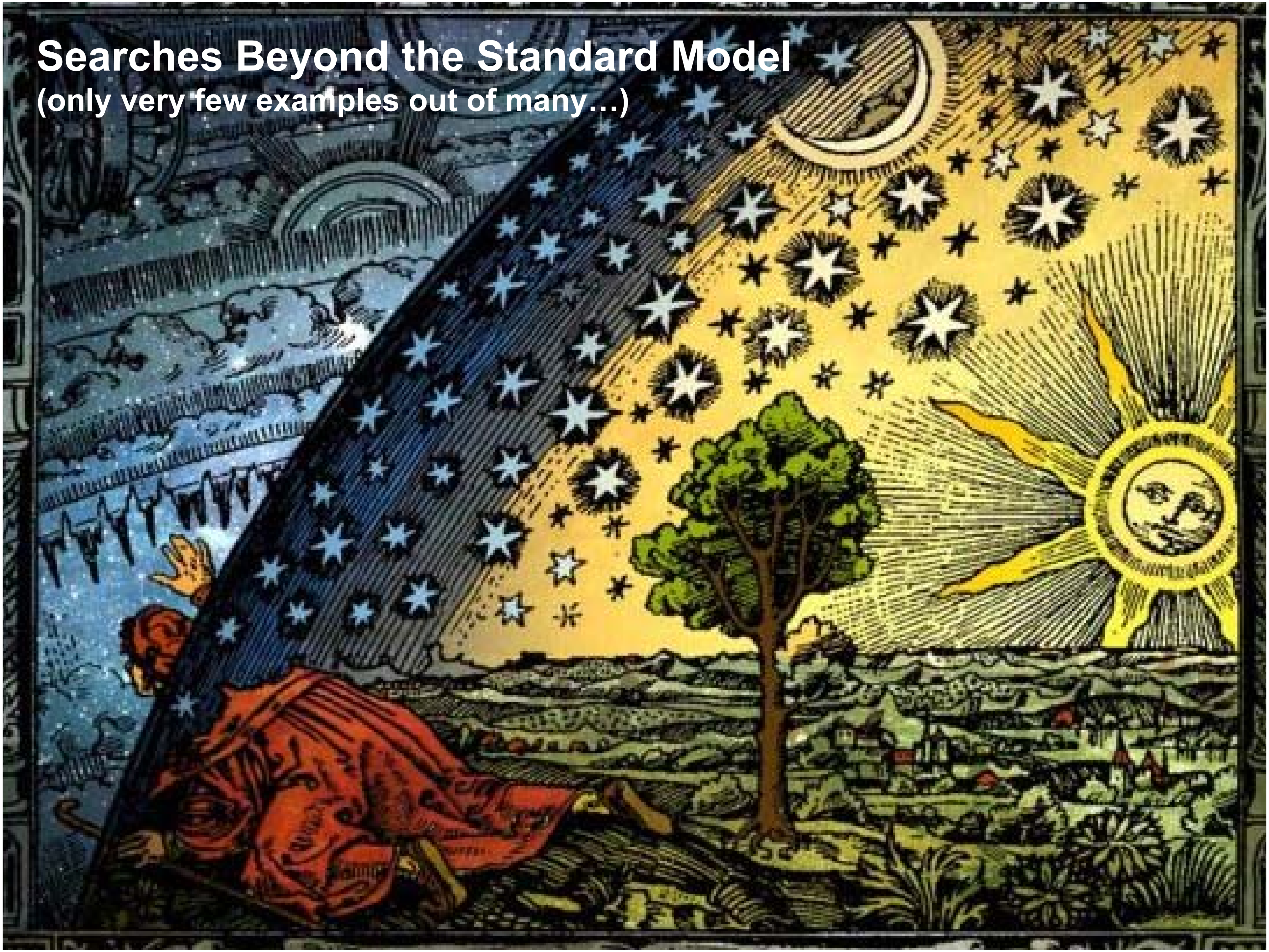


95% CL exclusions SM Higgs mass ranges (GeV)

	ATLAS	CMS
Expected	**131 – 447**	**130 – 447**
Data	**146 – 232, 256 – 282, 296 – 466**	**145 – 216, 226 – 288, 310 - 400**

Searches Beyond the Standard Model

(only very few examples out of many…)



SUSY

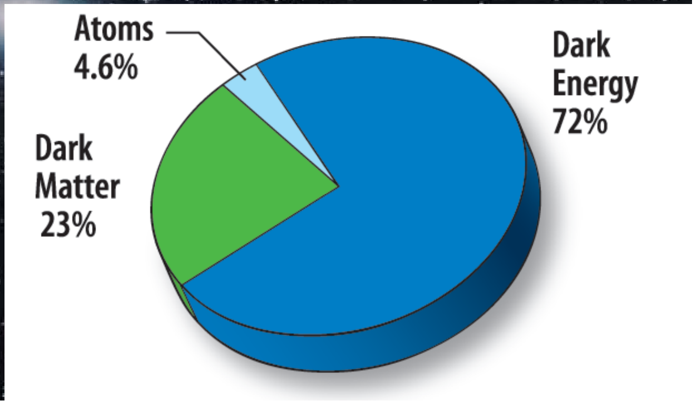
Dark Matter in the Universe

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

Vera Rubin ~ 1970

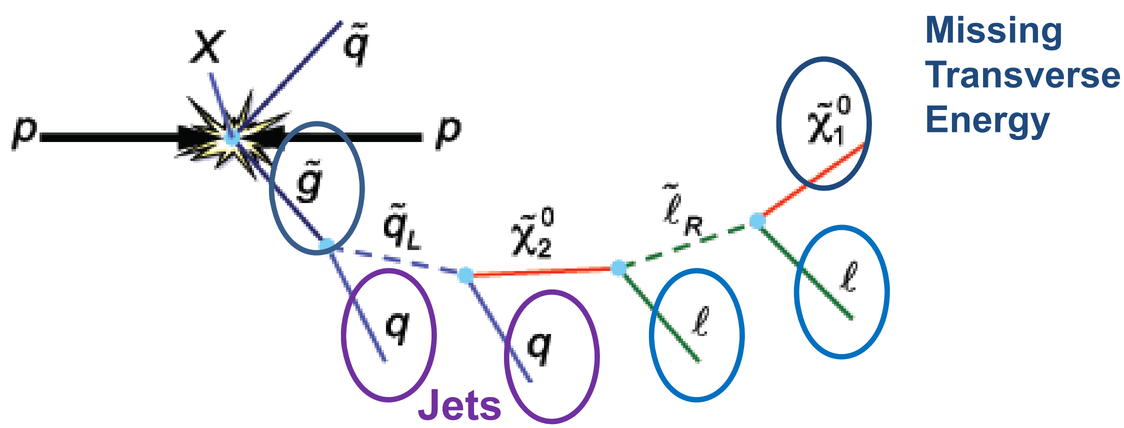
'Supersymmetric' particles ?

F. Zwicky 1898-1974



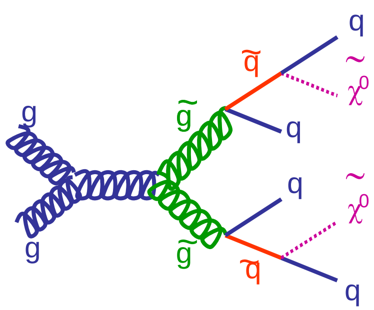
In practice the SUSY searches at LHC are rather complicated

- **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**

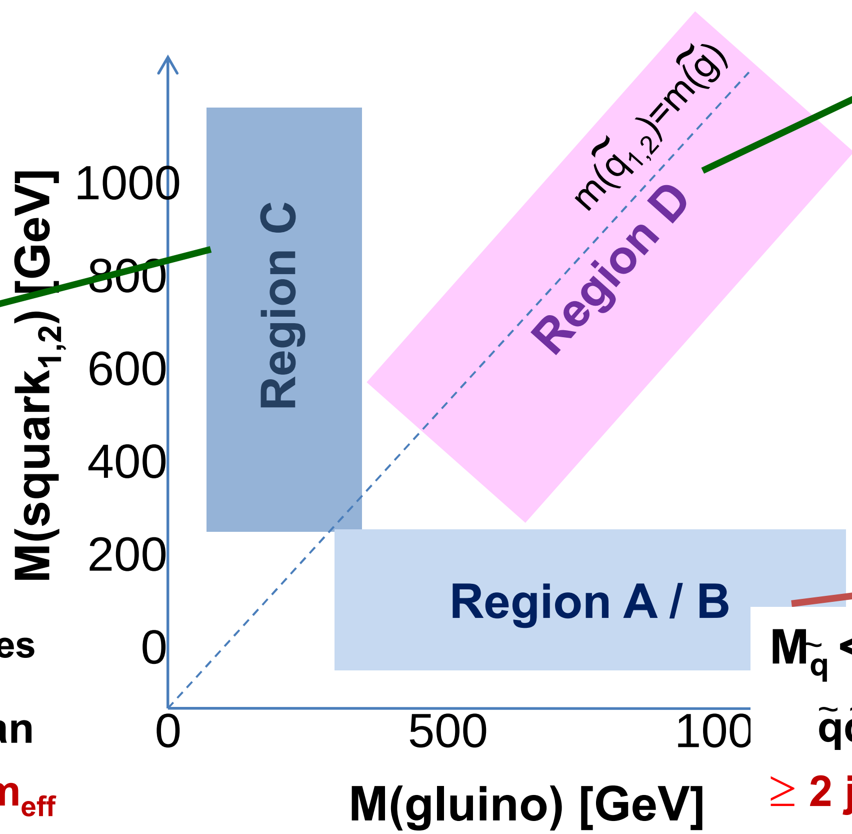
Signal regions sensitivity

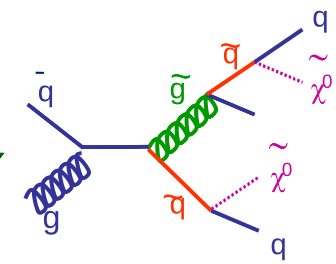


$M_{\tilde{q}} > M_{\tilde{g}}$

$\tilde{g}\tilde{g}$ production dominates

≥4 jets expected, 1 can be soft, selection in m_{eff}

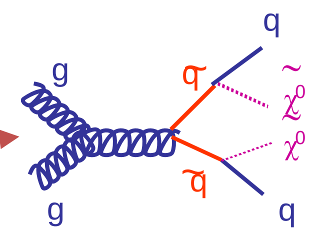




$M_{\tilde{q}} \sim M_{\tilde{g}}$

$\tilde{q}\tilde{g}$ production dominates

≥ 3 jets expected, high m_{eff}



$M_{\tilde{q}} < M_{\tilde{g}}$

$\tilde{q}\tilde{q}$ production dominates

≥ 2 jets expected

m_{eff} or m_{T2} selection

→ for high(B) / low(A) masses

→ exploit dependence in $\Delta M(\tilde{q}_{1,2}-\tilde{\chi}_0^1)$

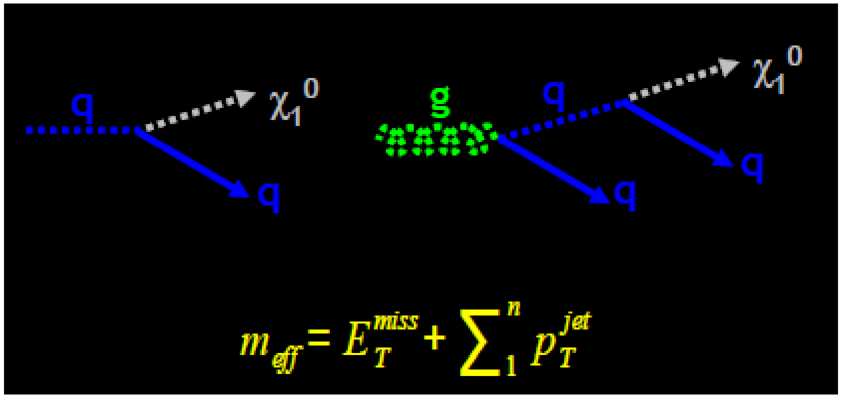
m_{eff} scalar sum pT
m_{T2} transverse mass variable

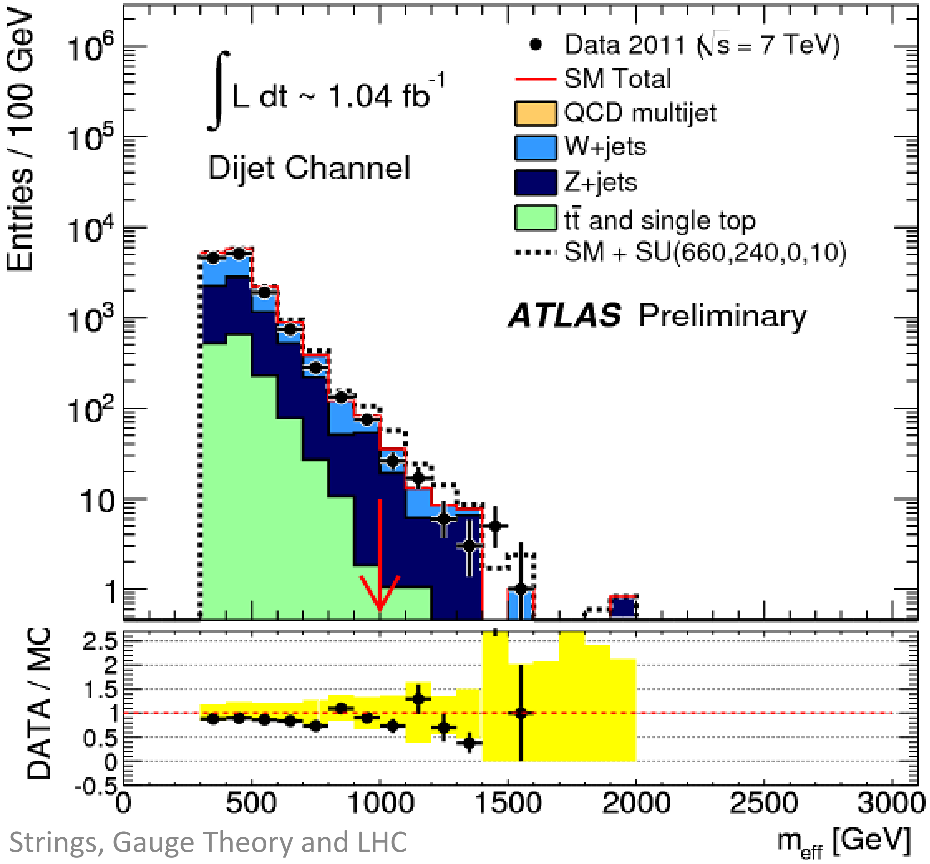
Just as an example:

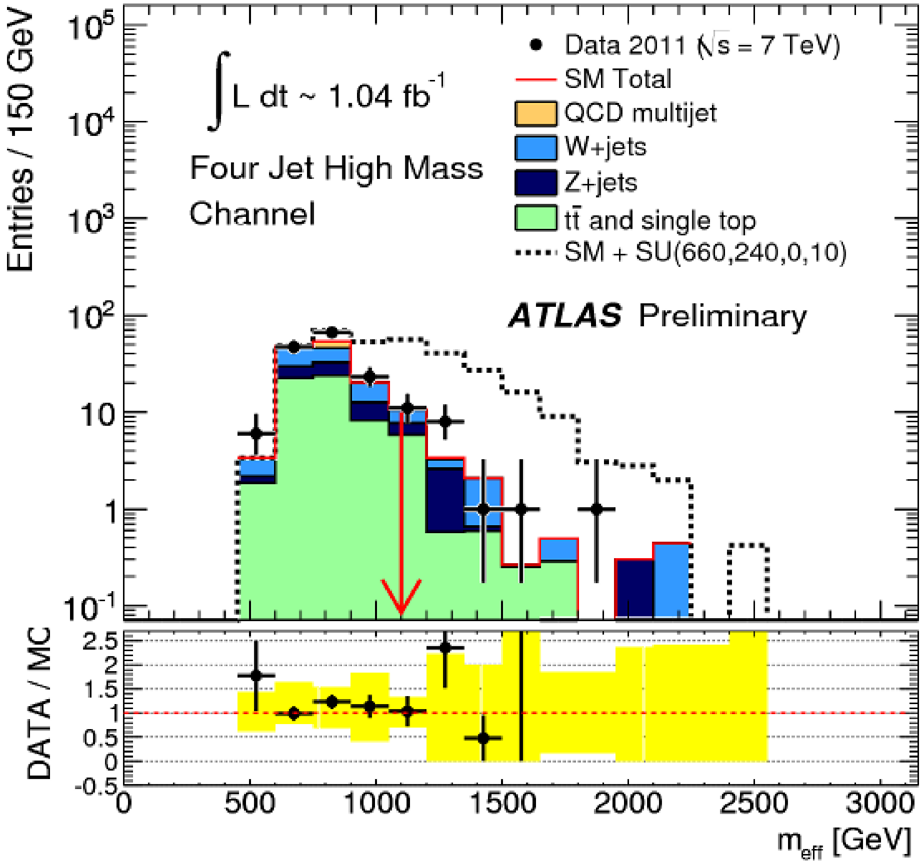
SUSY in 0-lepton channel

Strong production: gg, gq, qq

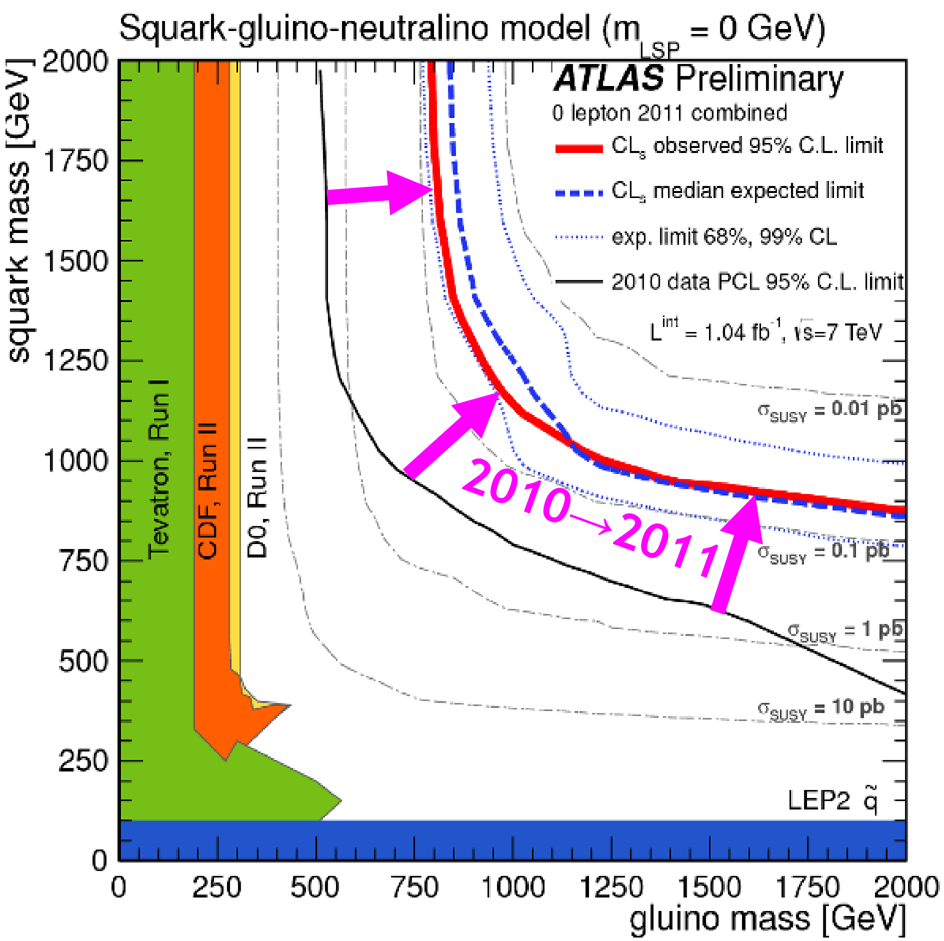
Multi-jet plus E_T^{miss}, e/μ veto
Analysis includes ≥4 jet event category

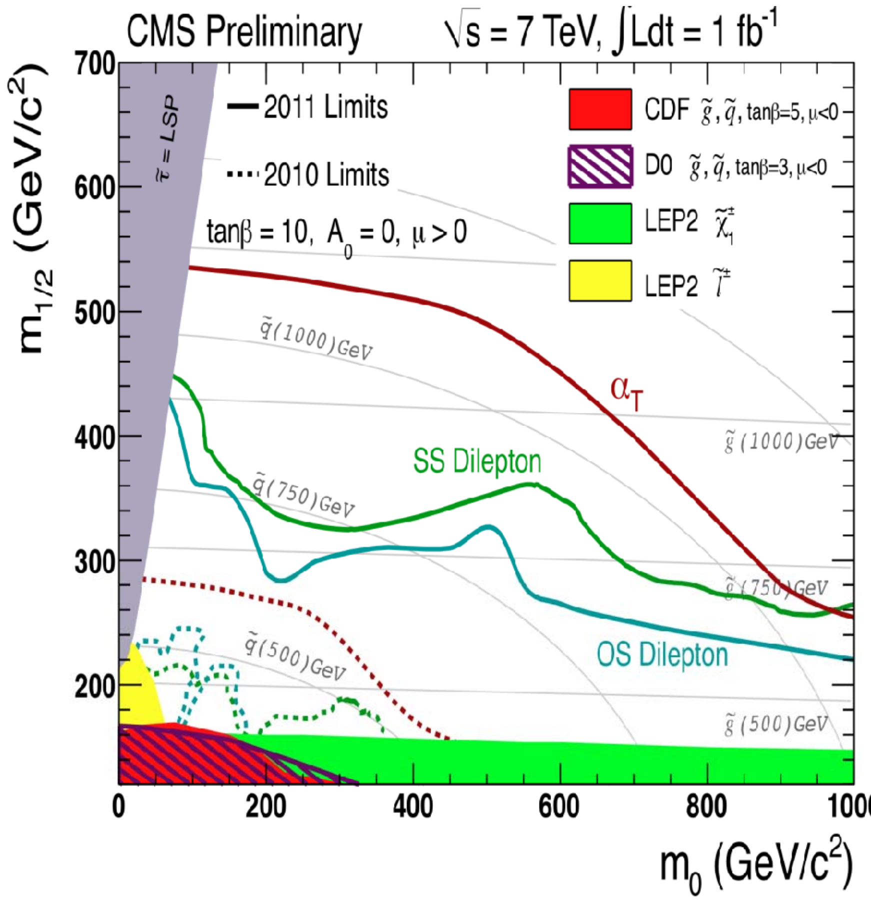






Sample SUSY exclusion limits as presented by ATLAS and CMS

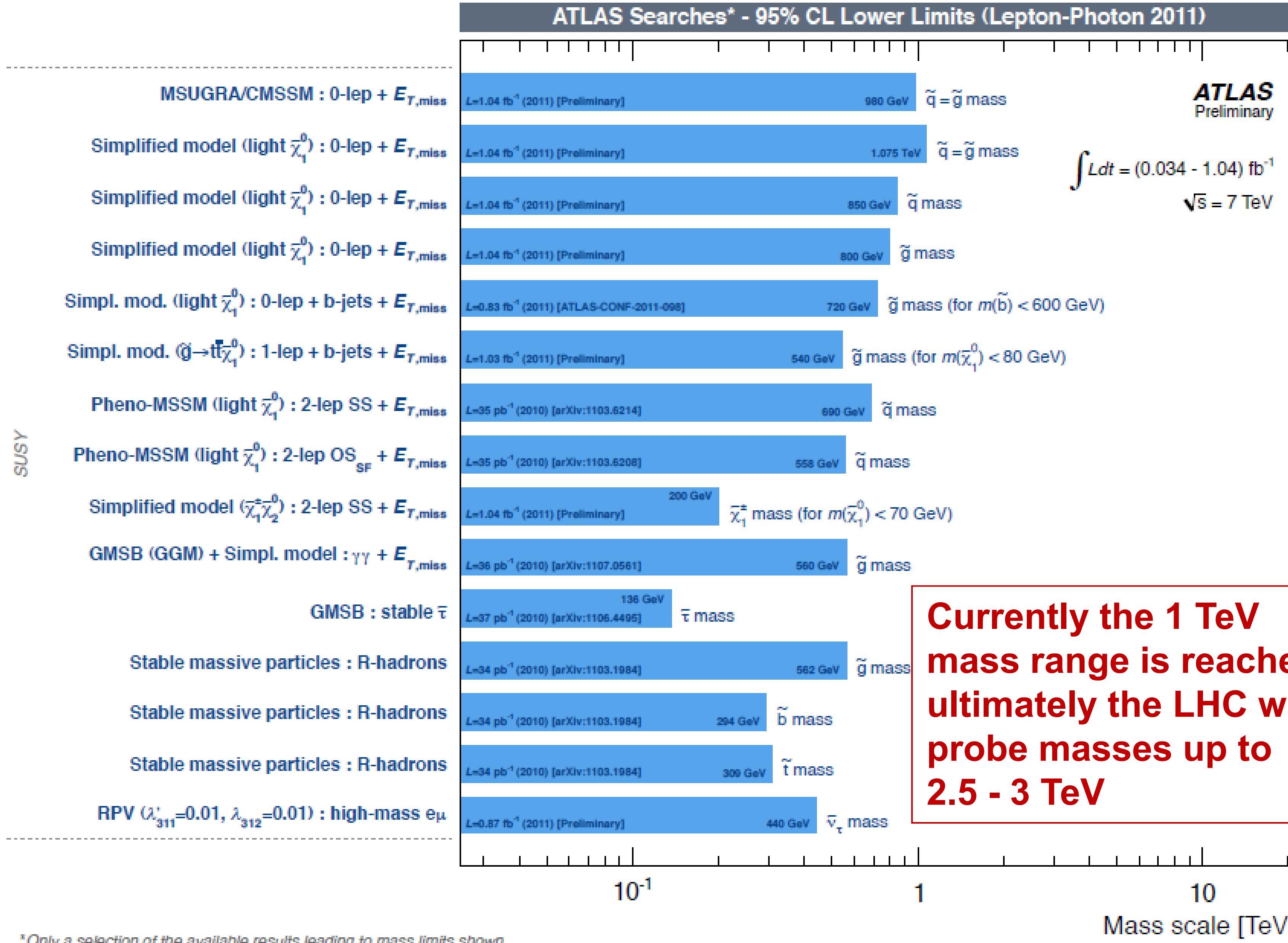




Simplified model with two q generations, $m(\chi_1^0)$~0
m_g>800 GeV, m_q>850 GeV (valid for m_{LSP} < 200 GeV)
Equal mass case: m_g=m_q>1.075 TeV

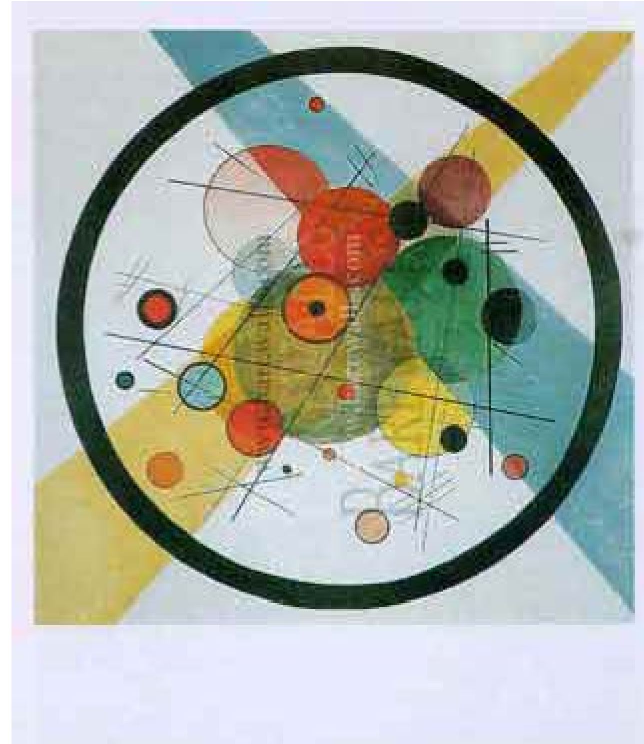
α_T = 2nd jet E_T / Trans. Mass

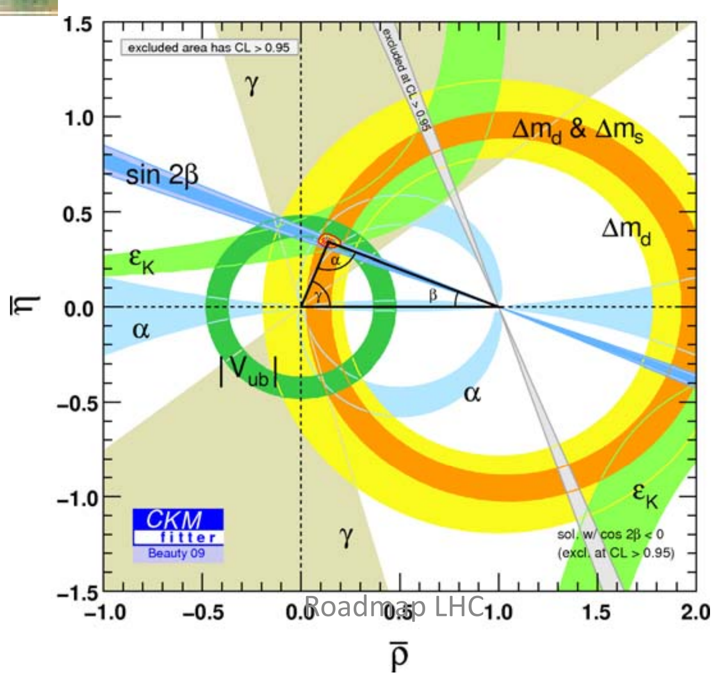
A non-exhaustive summary of current SUSY limits (CMS has similar limits)



Currently the 1 TeV mass range is reached, ultimately the LHC will probe masses up to 2.5 - 3 TeV

Early hints of news from 'Beyond the Standard Model' may come from 'beautiful' flavour physics...



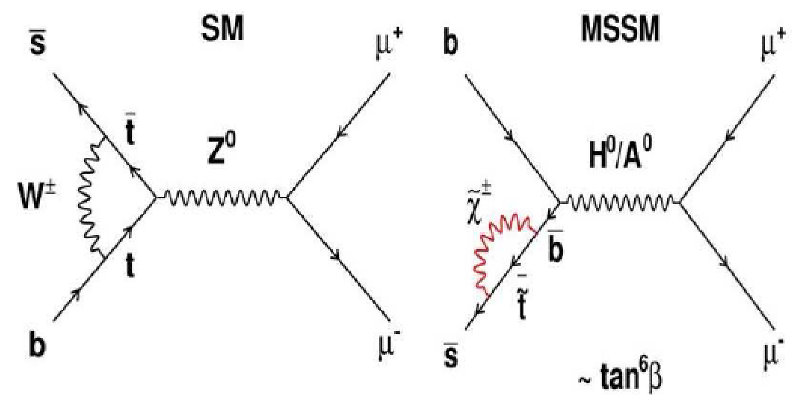


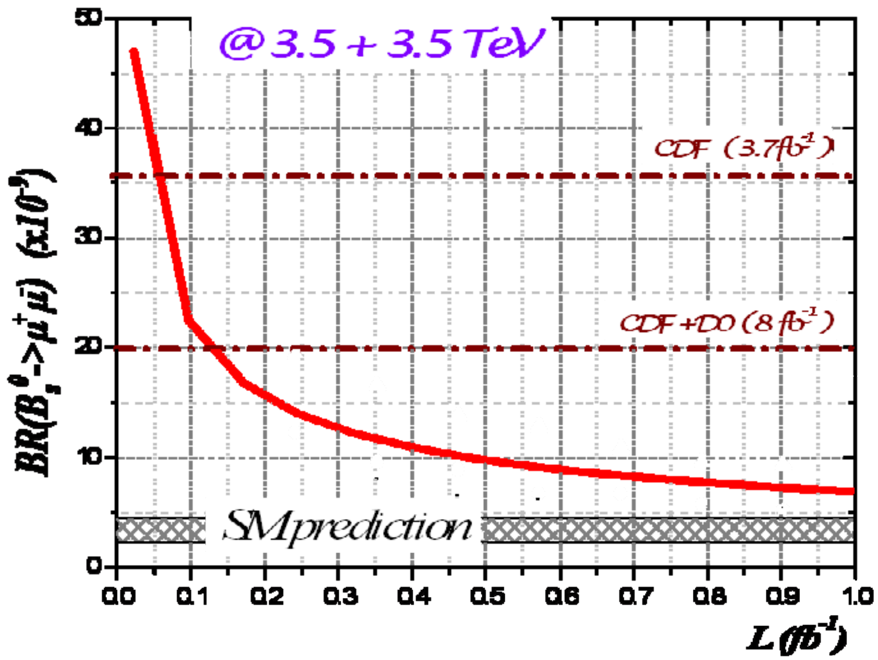
Search for B→$\mu^+\mu^-$

Very rare and golden FCNC b→d,s transition

Mode	SM
$B_s \to \mu^+\mu^-$	$3.2 \pm 0.2\ 10^{-9}$
$B^0 \to \mu^+\mu^-$	$0.10 \pm 0.01\ 10^{-9}$

A.J.Buras: arXiv:1012.1447
E. Gamiz et al: Phys.Rev.D 80 (2009) 014503





Strongly enhanced in MSSM

$$B\left(B_s \to \mu^+\mu^-\right) \propto \frac{\tan^6\beta}{M_A^4}$$

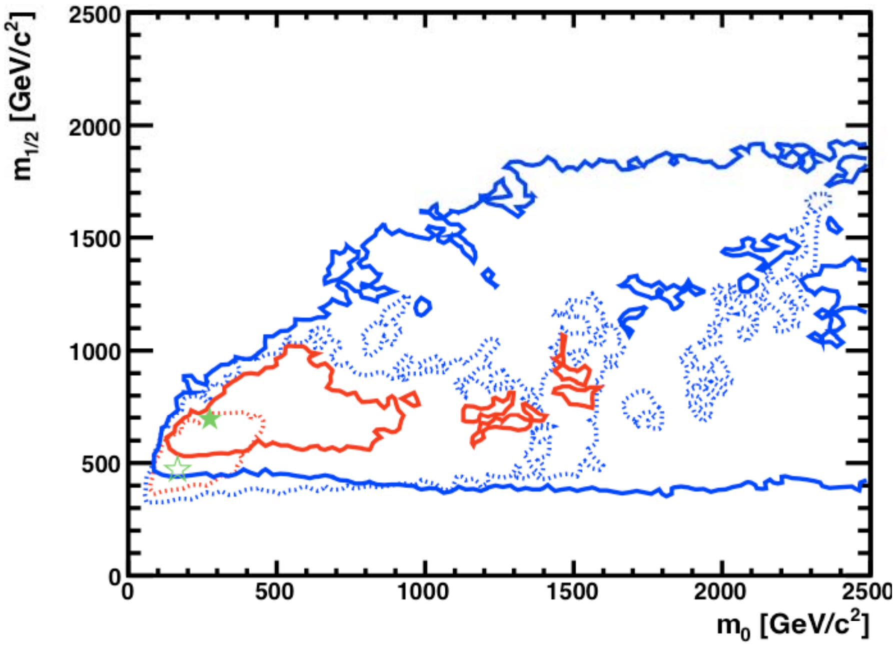
Best 9% CL B_s limits reported at EPS-2011

LHCb	**BR < 1.5 10^{-8} (300 pb^{-1})**
CMS	**BR < 1.9 10^{-8} (1.14 fb^{-1})**
Combined	**BR < 1.08 10^{-8}**

LHCb-CONF-2011-047
CMS-PAS-BPH-11-019

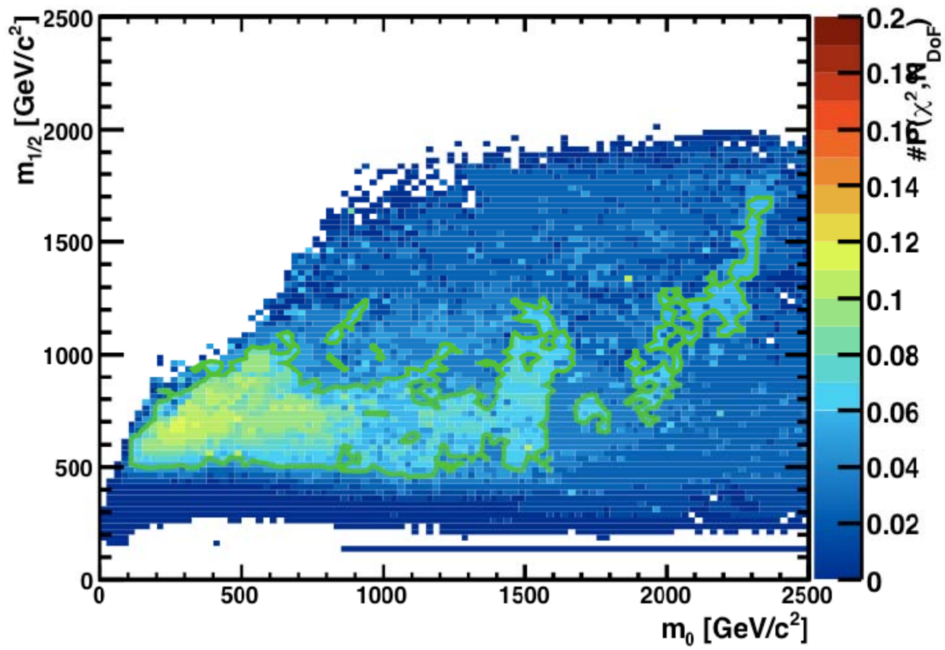
Global constrained MSSM (CMSSM) analysis updated information from LHC (ATLAS, CMS, LHCb), Tevatron and the XENON100 search for DM scattering

Buchmueller et al, MasterCode Project, xaXiv:1106.2529v1[hep-ph], updated with EPS-HEP2011 results



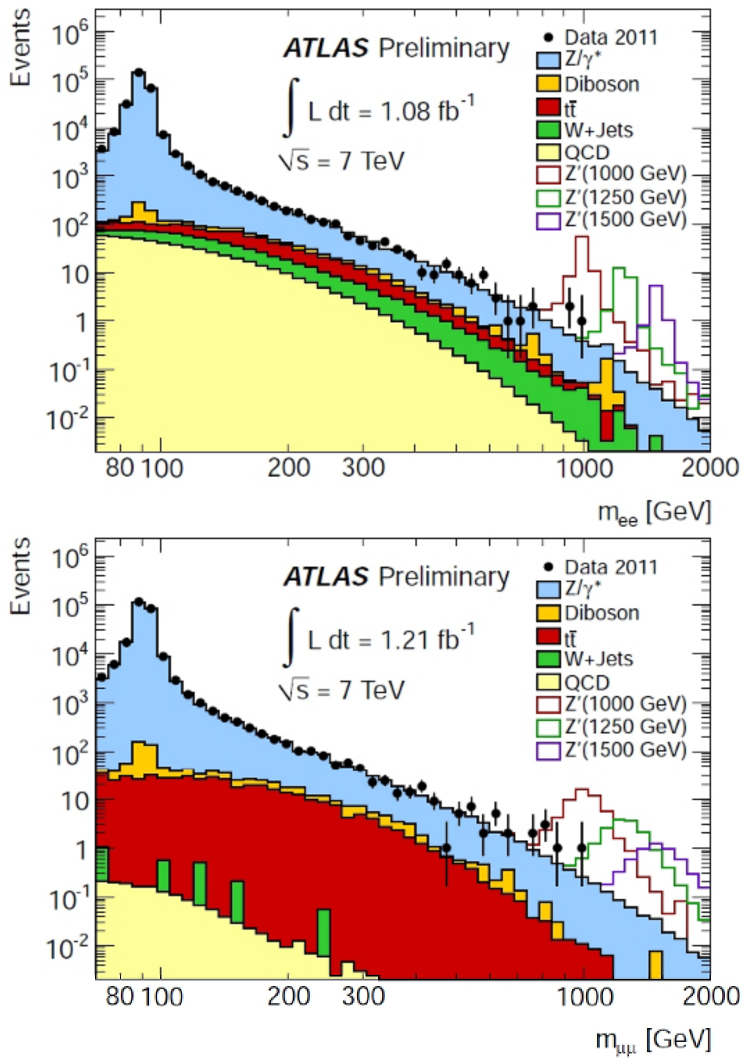
The green star is the best fit, the red and blue lines are the 68 and 95% CL boundaries

Fit probabilities, note that the best-fit has only a 11% probability

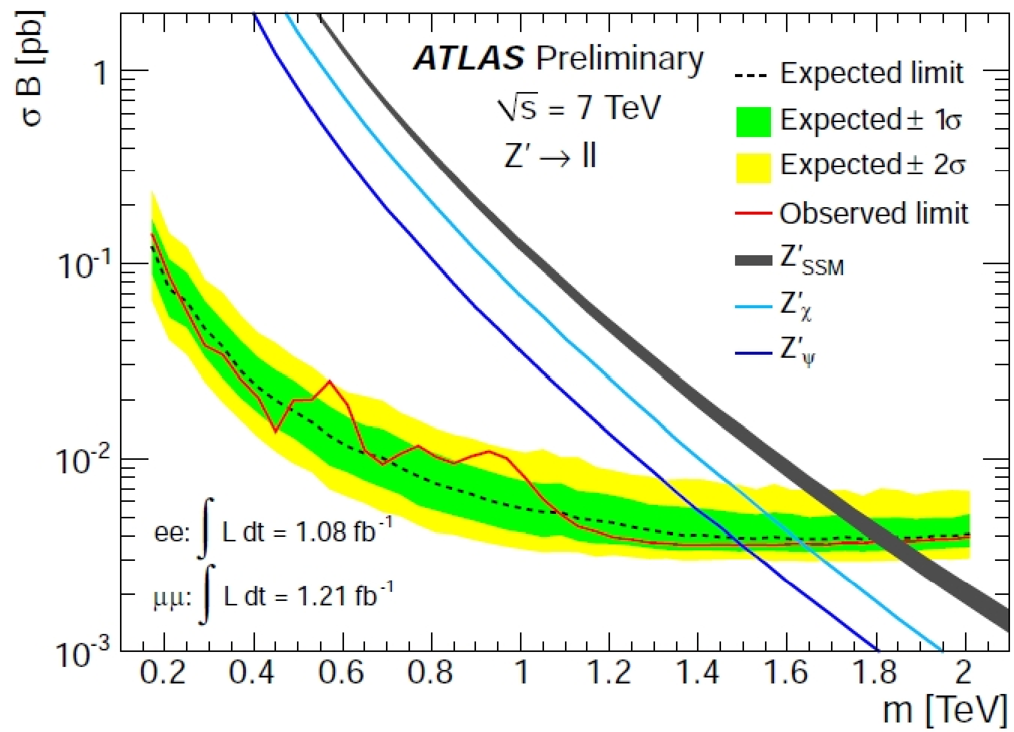


Searches for heavy W and Z like particles

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

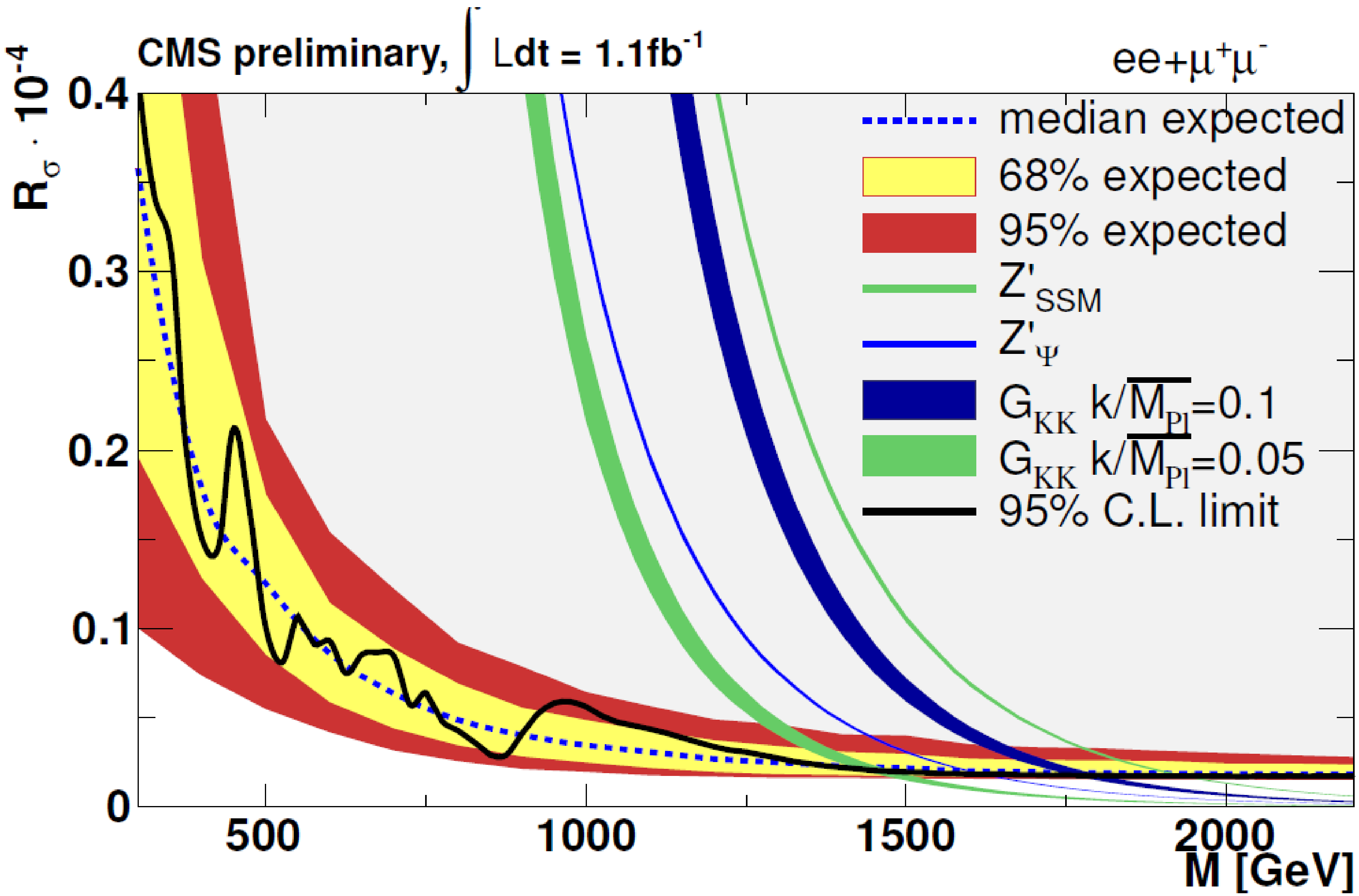


Sub. to Phys Rev Lett
arXiv:1108.1582v1[hep-ex]



Ultimately the reach of such searches will probe masses beyond 5 TeV

$$R_\sigma = \frac{\sigma(\mathrm{pp} \to Z' + X \to \ell\ell + X)}{\sigma(\mathrm{pp} \to Z + X \to \ell\ell + X)}.$$

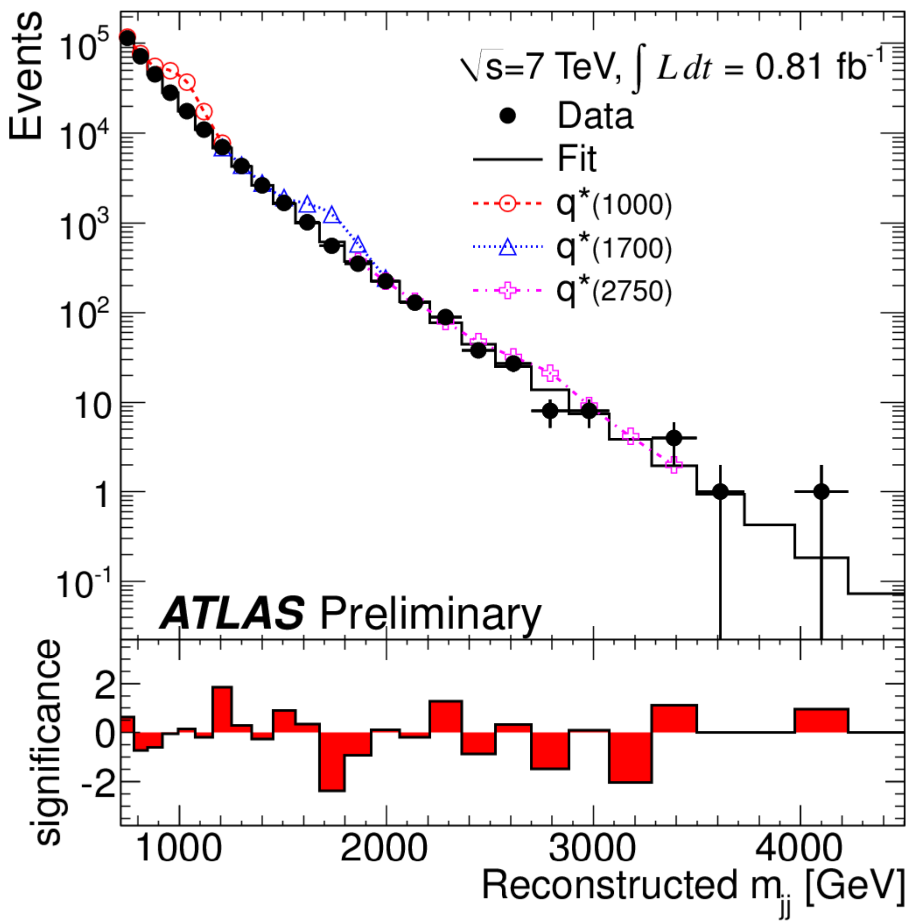


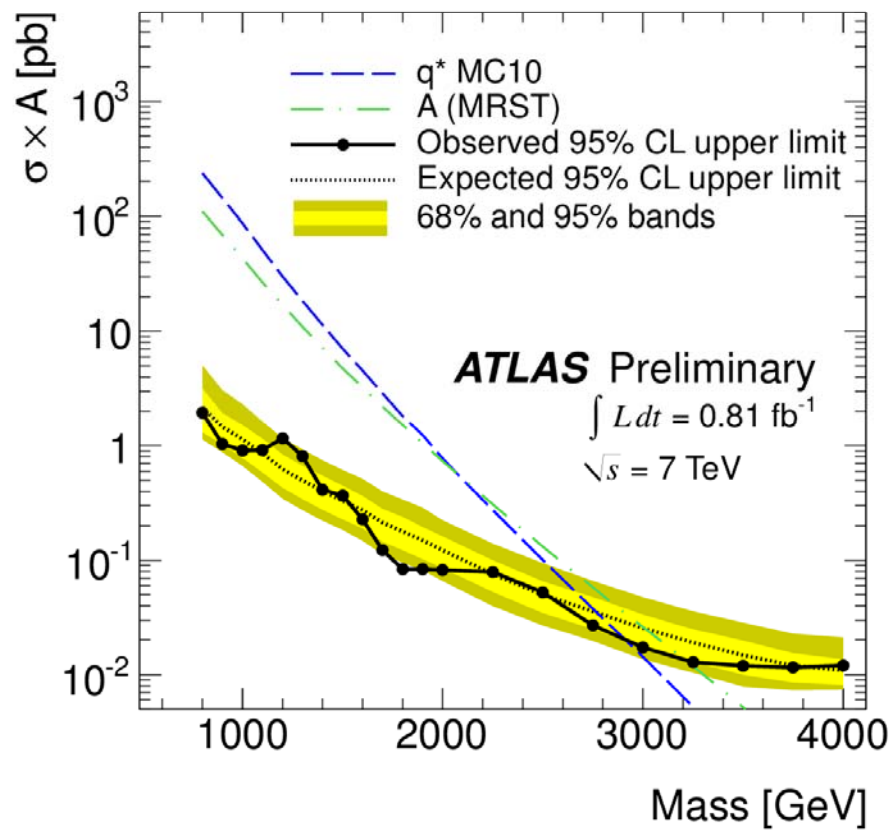
CMS-PAS-EXO-11-019

ATLAS 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-2011-095

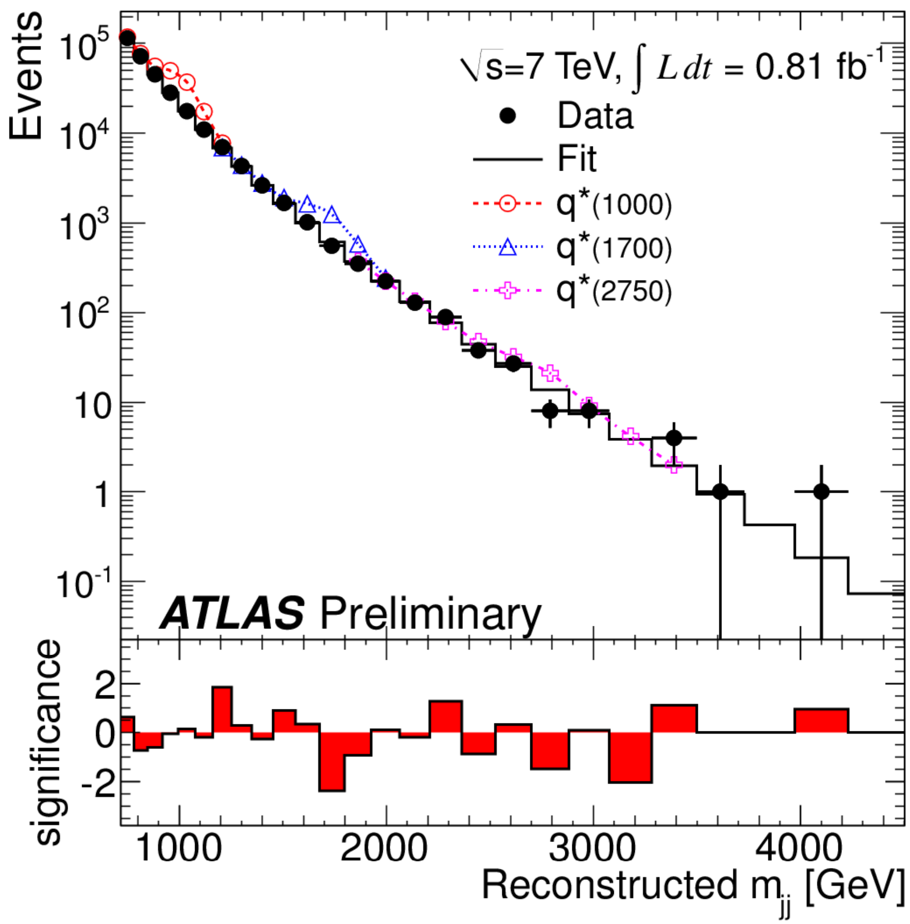


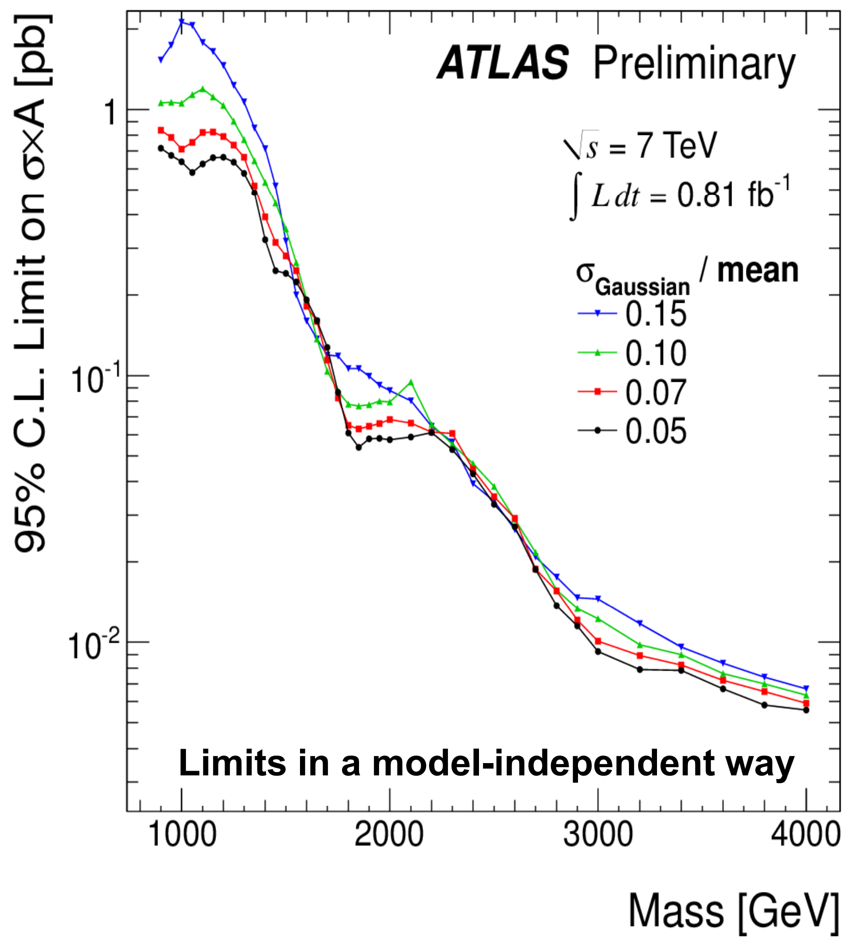


ATLAS example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

Search for resonances in the di-jet mass spectrum

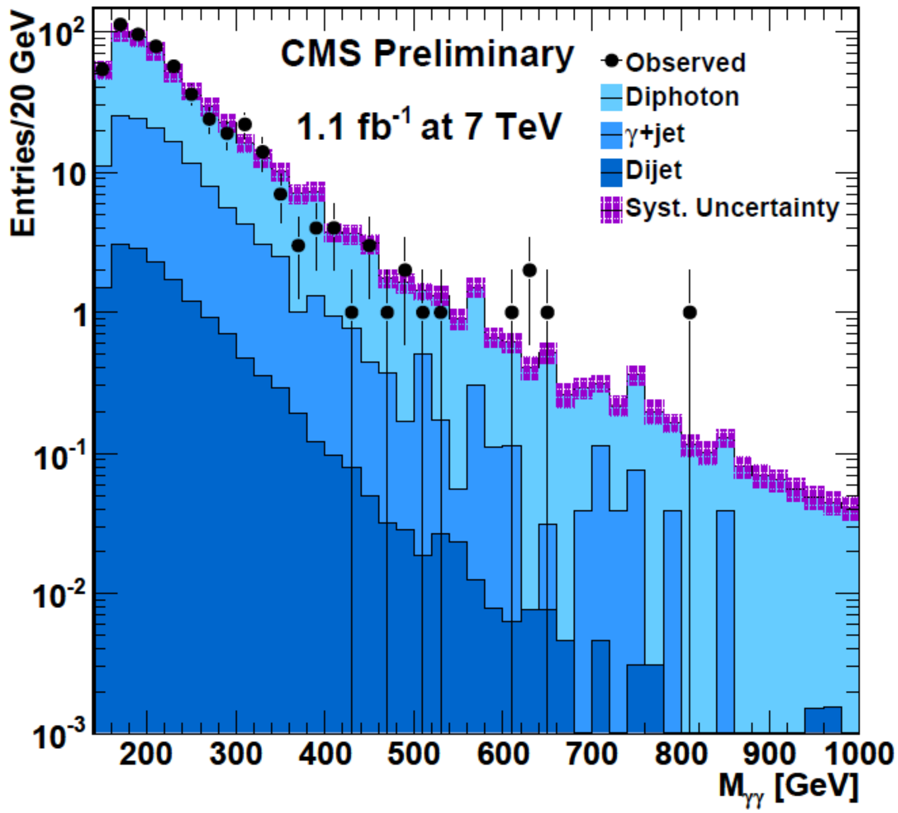
ATLAS-CONF-2011-095

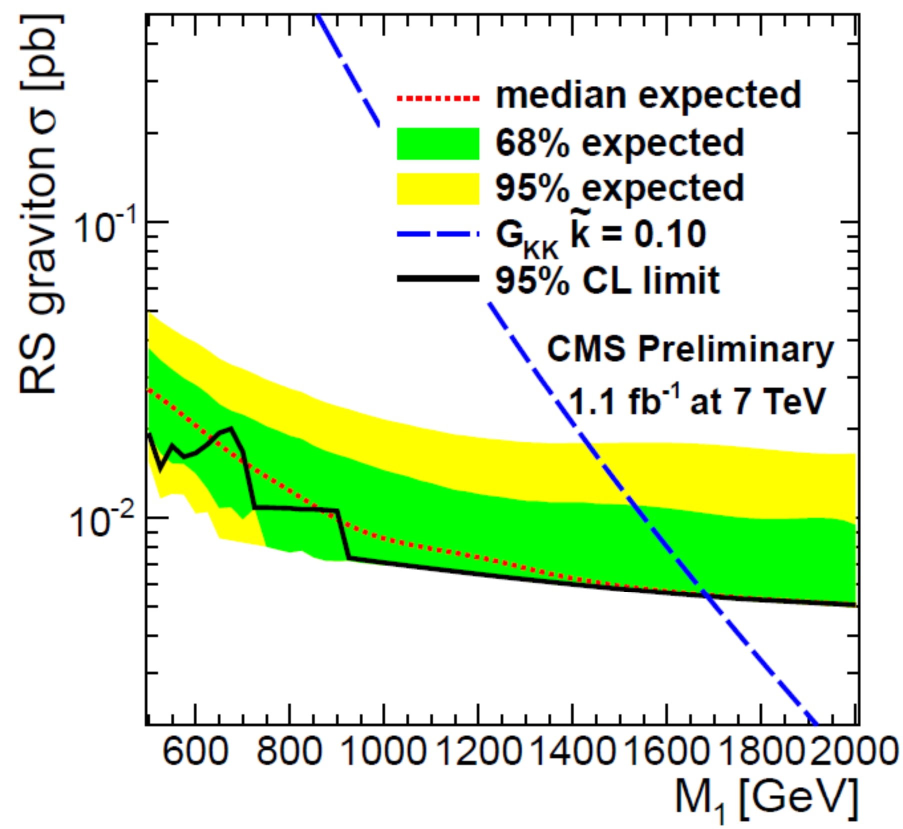




A CMS example of searches for New Physics as deviations from QCD behaviour in the di-photon distribution

Randall-Sundrum KK graviton excitation

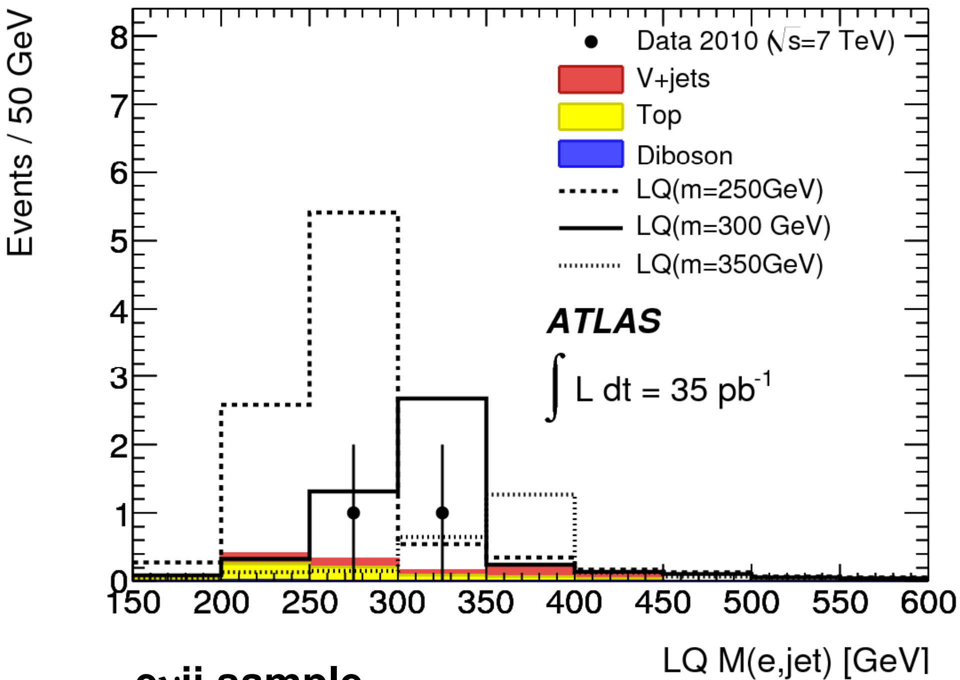




CMS-PAS-EXO-11-038

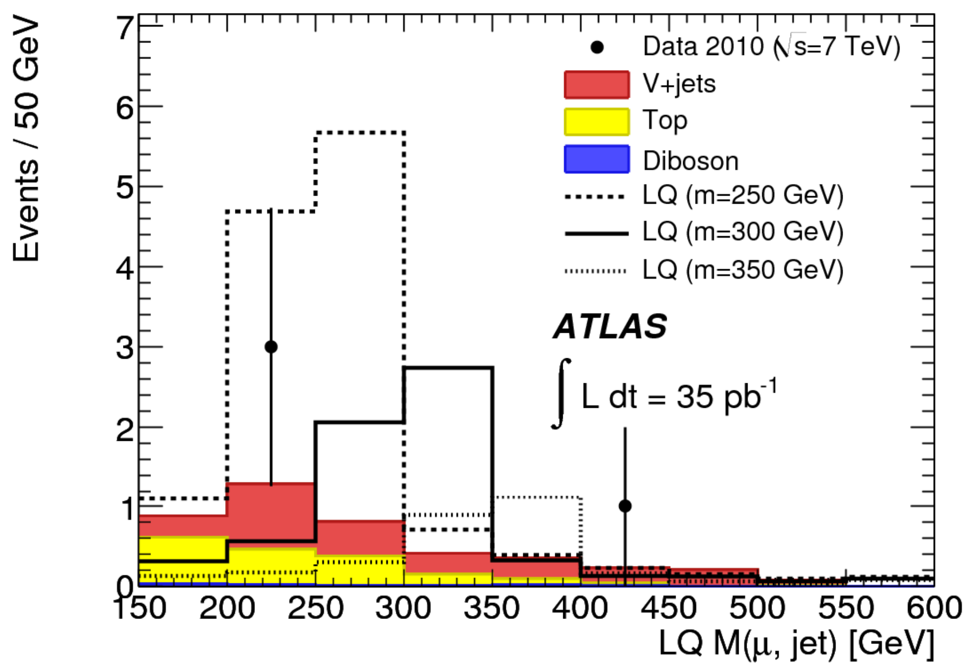
Search for Lepto-Quarks (LQ)

pp → LQ $\overline{\text{LQ}}$ → lljj or lνjj (l = e or μ)



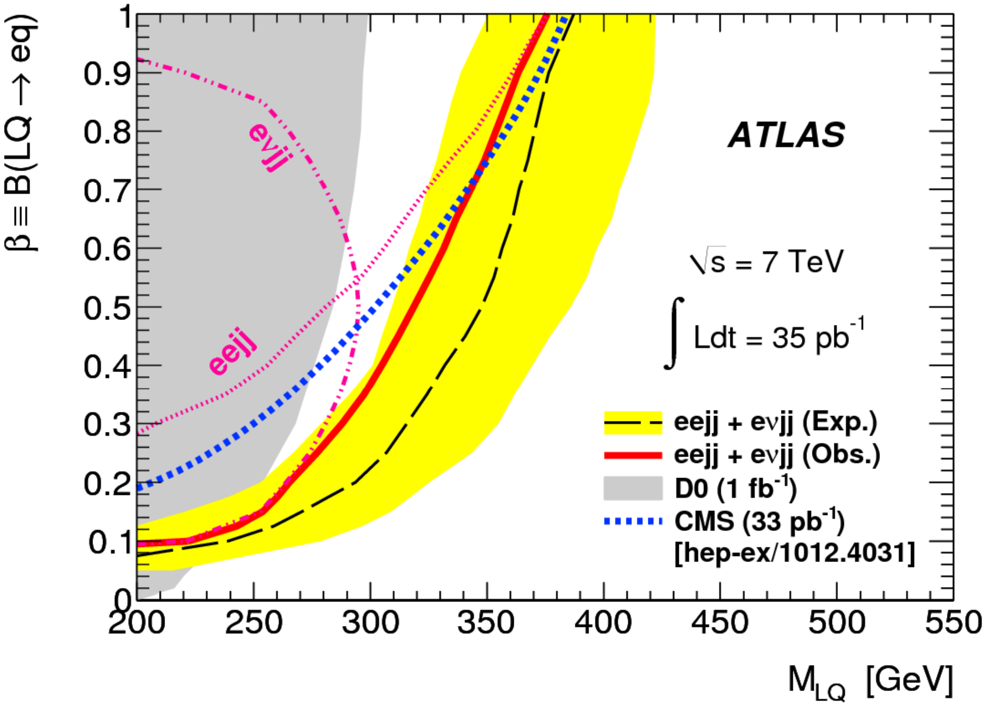
eνjj sample

μνjj sample

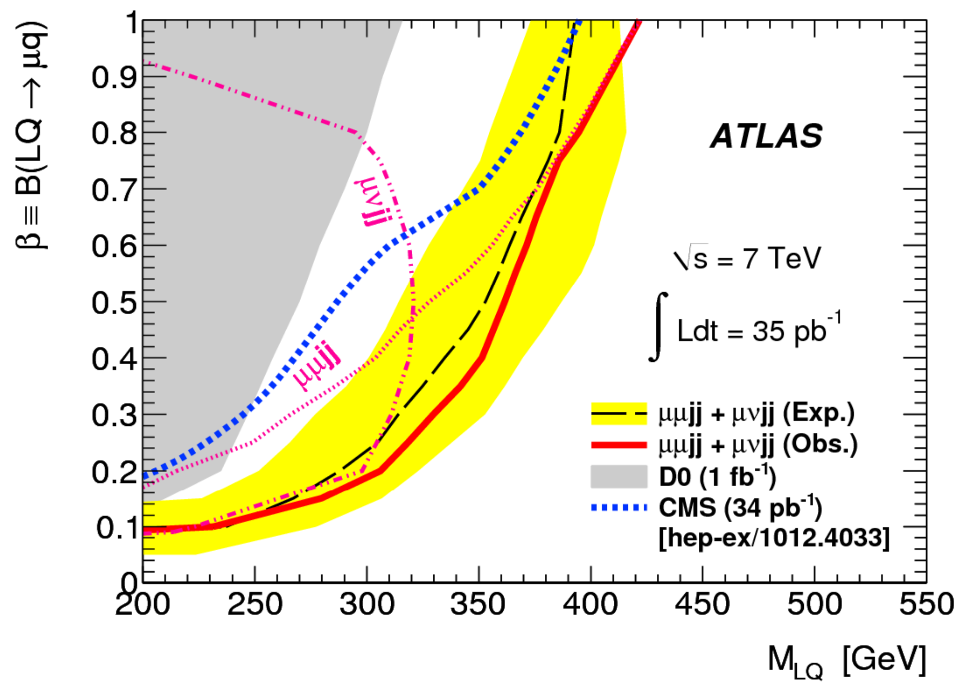


Signal regions, all p_T > 30 GeV

Phys Rev D 83 (2011) 112006



95% CL exclusion limits for Lepto-Quarks

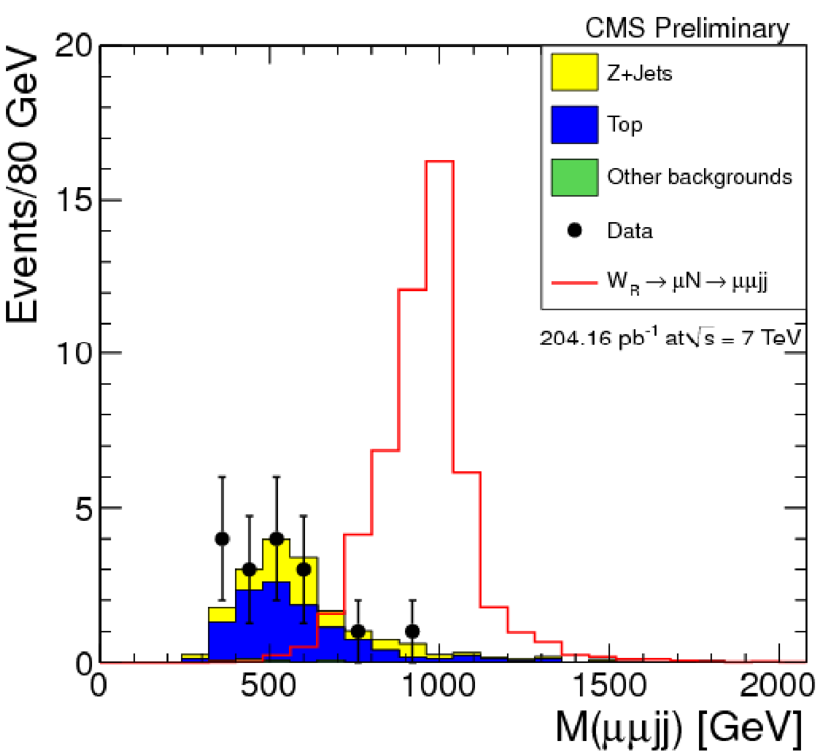


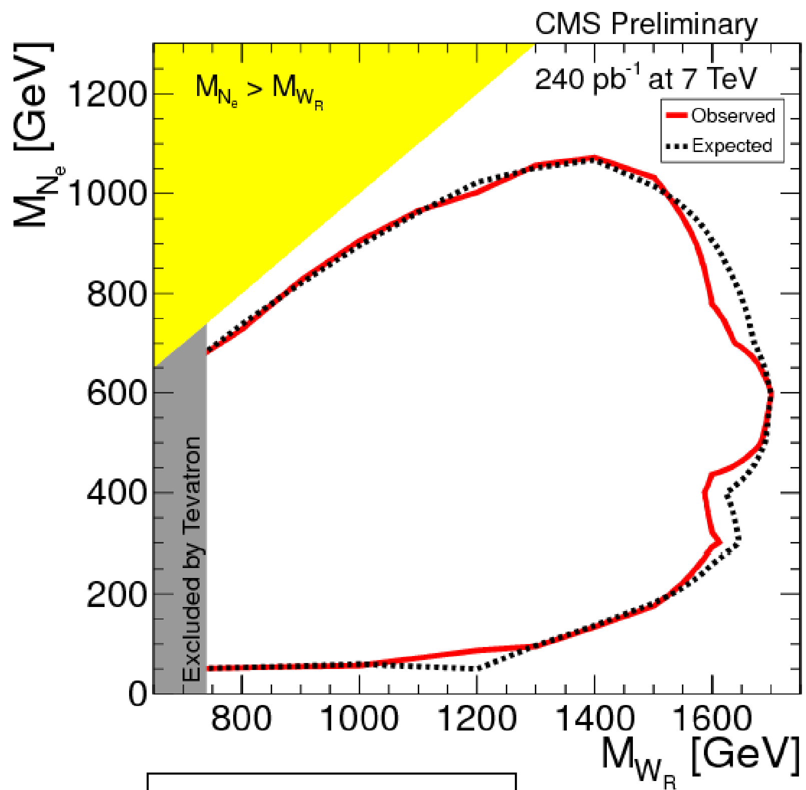
Phys Rev D 83 (2011) 112006

Search for Heavy (Majorana) Neutrino (N) and W_R

Possible decay in LRSM models, resulting in a resonance in the 2*l*+jj system:

$qq \rightarrow W_R \rightarrow l + N \rightarrow l + l + W_R^* \rightarrow l + l + j + j$





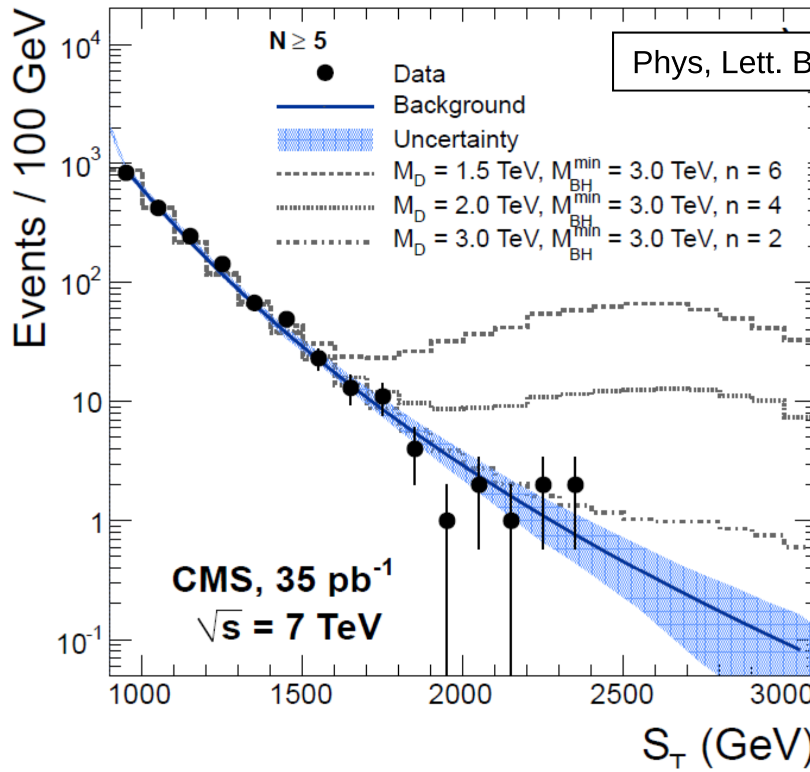
CMS-PAS-EXO-11-002

Example for a search for Microscopic Black Hole production in models with large extra dimensions

(Arkani-Hamed, Dimopoulos, Dvali)

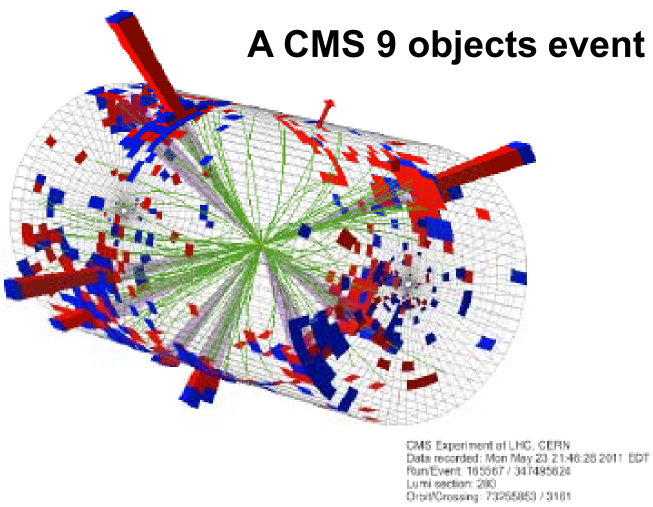
Decay into many objects (jets, leptons, photons)

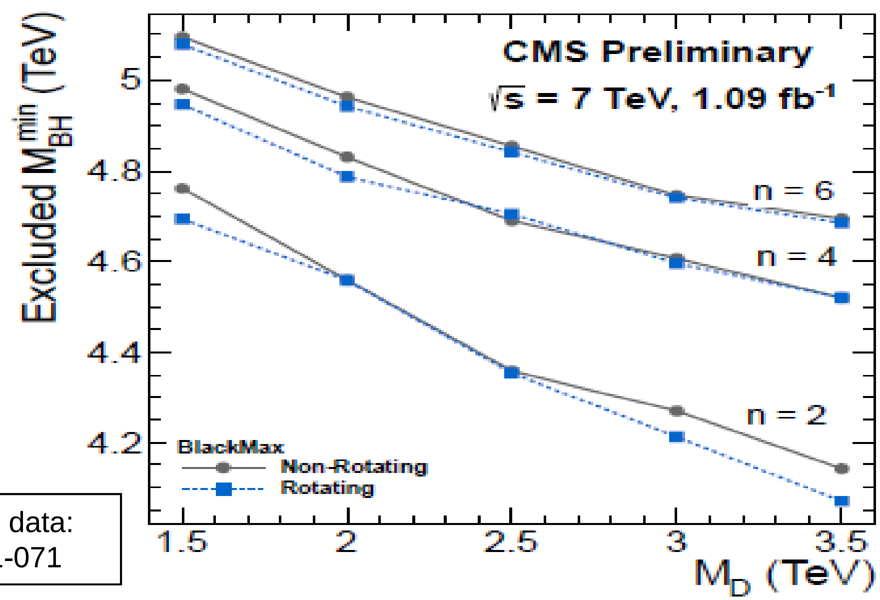
S_T : scalar sum of the E_T of the N objects in the event



Phys, Lett. B 697 (2011) 434

A CMS 9 objects event

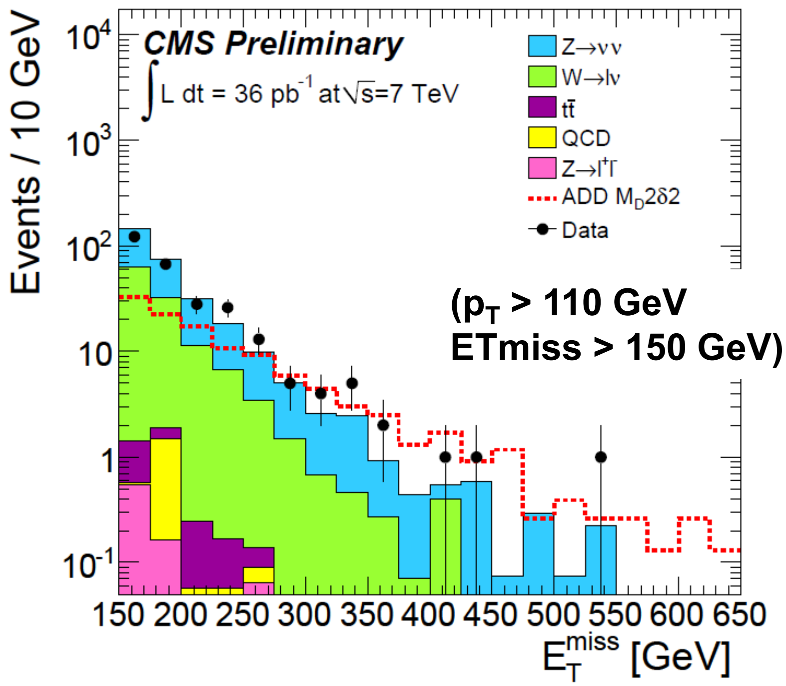




Updated with 2011 data:
CMS-PAS-EXO-11-071

Two more examples of exotic signatures

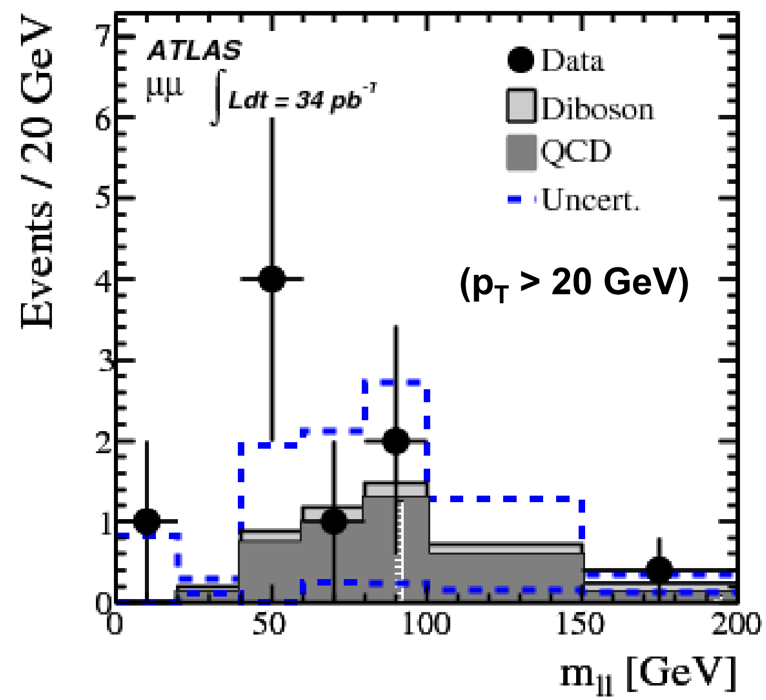
Mono-jet plus missing E_T



Such signature could occur in models:
- **Large Extra Dimensions (ADD)**
- **Unparticle**
- **Split SUSY**
- **Dark Matter**
- **…**

Sub. to Phys Rev Lett
arXiv:1106.4775[hep-ex]

Same-sign di-leptons

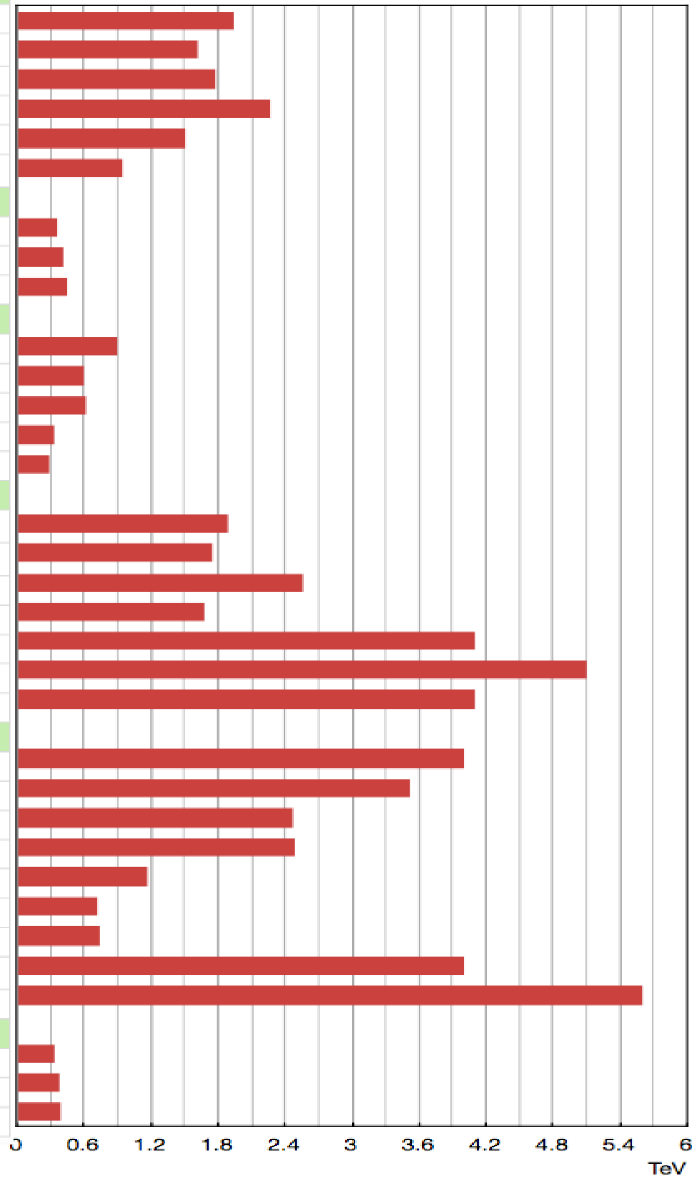


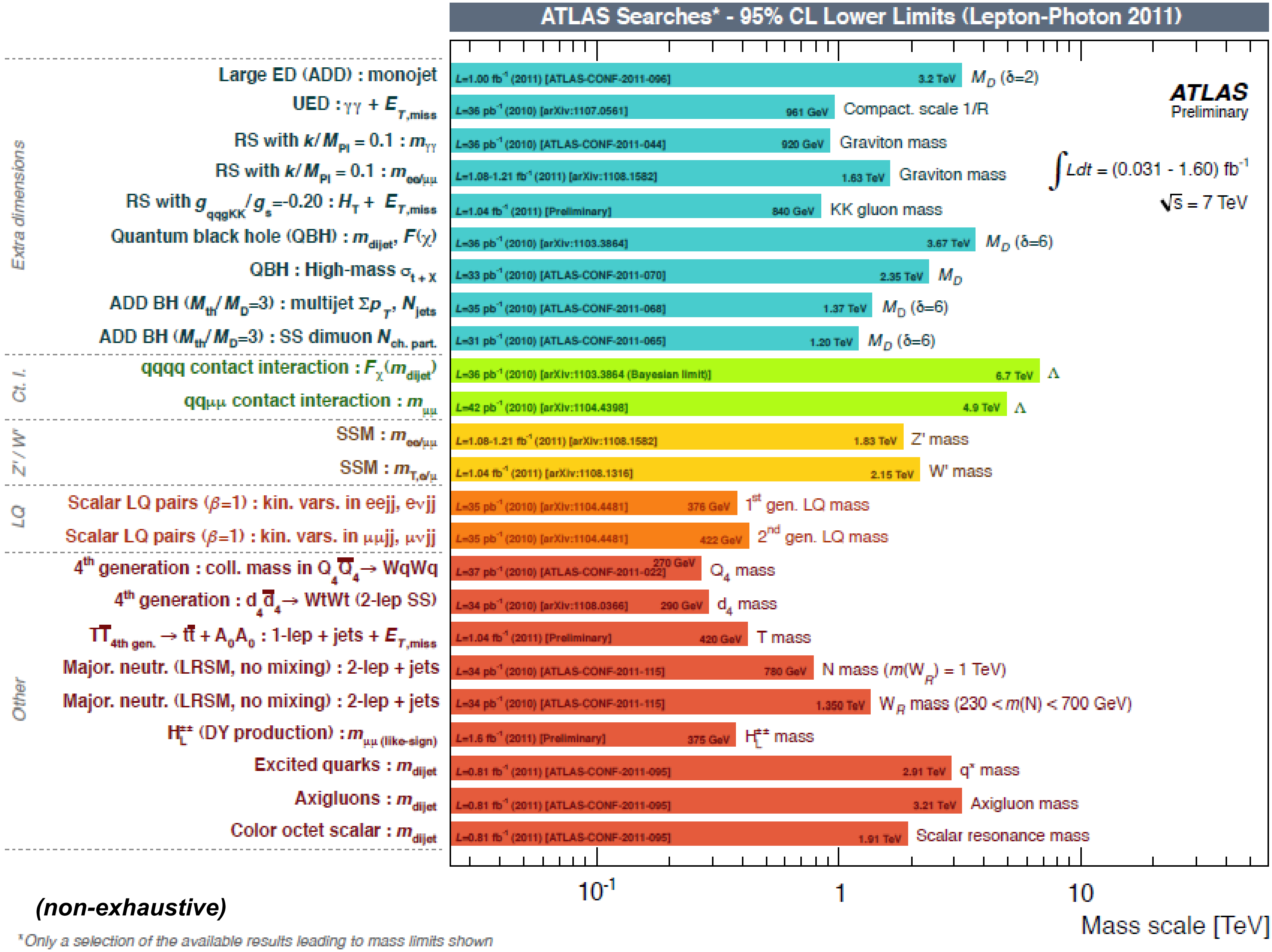
Such signature could occur in models:
- **Majorana neutrinos**
- **Universal Extra Dimensions**
- **4th generation quarks**
- **…**

Sub. to JHEP
arXiv:1108.0366v1[hep-ex]

A non-exhaustive summary of searches for New Physics from 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




ATLAS Searches* - 95% CL Lower Limits (Lepton-Photon 2011)
Extra dimensions
Large ED (ADD) : monojet
L=1.00 fb-1 (2011) [ATLAS-CONF-2011-096]
3.2 TeV
MD (δ=2)
UED : γγ + ET,miss
L=36 pb-1 (2010) [arXiv:1107.0561]
961 GeV
Compact. scale 1/R
RS with k/MPl = 0.1 : mγγ
L=36 pb-1 (2010) [ATLAS-CONF-2011-044]
920 GeV
Graviton mass
RS with k/MPl = 0.1 : mee/μμ
L=1.08-1.21 fb-1 (2011) [arXiv:1108.1582]
1.63 TeV
Graviton mass
RS with gqqgKK/gs=-0.20 : HT + ET,miss
L=1.04 fb-1 (2011) [Preliminary]
840 GeV
KK gluon mass
Quantum black hole (QBH) : mdijet, F(χ)
L=36 pb-1 (2010) [arXiv:1103.3864]
3.67 TeV
MD (δ=6)
QBH : High-mass σt + X
L=33 pb-1 (2010) [ATLAS-CONF-2011-070]
2.35 TeV
MD
ADD BH (Mth/MD=3) : multijet ΣpT, Njets
L=35 pb-1 (2010) [ATLAS-CONF-2011-068]
1.37 TeV
MD (δ=6)
ADD BH (Mth/MD=3) : SS dimuon Nch. part.
L=31 pb-1 (2010) [ATLAS-CONF-2011-065]
1.20 TeV
MD (δ=6)
CI
qqqq contact interaction : Fχ(mdijet)
L=36 pb-1 (2010) [arXiv:1103.3864 (Bayesian limit)]
6.7 TeV
Λ
qqμμ contact interaction : mμμ
L=42 pb-1 (2010) [arXiv:1104.4398]
4.9 TeV
Λ
Z'/W'
SSM : mee/μμ
L=1.08-1.21 fb-1 (2011) [arXiv:1108.1582]
1.83 TeV
Z' mass
SSM : mT,e/μ
L=1.04 fb-1 (2011) [arXiv:1108.1316]
2.15 TeV
W' mass
LQ
Scalar LQ pairs (β=1) : kin. vars. in eejj, eνjj
L=35 pb-1 (2010) [arXiv:1104.4481]
376 GeV
1st gen. LQ mass
Scalar LQ pairs (β=1) : kin. vars. in μμjj, μνjj
L=35 pb-1 (2010) [arXiv:1104.4481]
422 GeV
2nd gen. LQ mass
Other
4th generation : coll. mass in Q4Q̄4 → WqWq
L=37 pb-1 (2010) [ATLAS-CONF-2011-022]
270 GeV
Q4 mass
4th generation : d4d̄4 → WtWt (2-lep SS)
L=34 pb-1 (2010) [arXiv:1108.0366]
290 GeV
d4 mass
TT̄4th gen. → tt̄ + A0A0 : 1-lep + jets + ET,miss
L=1.04 fb-1 (2011) [Preliminary]
420 GeV
T mass
Major. neutr. (LRSM, no mixing) : 2-lep + jets
L=34 pb-1 (2010) [ATLAS-CONF-2011-115]
780 GeV
N mass (m(WR) = 1 TeV)
Major. neutr. (LRSM, no mixing) : 2-lep + jets
L=34 pb-1 (2010) [ATLAS-CONF-2011-115]
1.350 TeV
WR mass (230 < m(N) < 700 GeV)
HL±± (DY production) : mμμ (like-sign)
L=1.6 fb-1 (2011) [Preliminary]
375 GeV
HL±± mass
Excited quarks : mdijet
L=0.81 fb-1 (2011) [ATLAS-CONF-2011-095]
2.91 TeV
q* mass
Axigluons : mdijet
L=0.81 fb-1 (2011) [ATLAS-CONF-2011-095]
3.21 TeV
Axigluon mass
Color octet scalar : mdijet
L=0.81 fb-1 (2011) [ATLAS-CONF-2011-095]
1.91 TeV
Scalar resonance mass
ATLAS
Preliminary
∫Ldt = (0.031 - 1.60) fb-1
√s = 7 TeV
10-1
1
10
Mass scale [TeV]
(non-exhaustive)
*Only a selection of the available results leading to mass limits shown


Note that all public results from CMS and ATLAS are available at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
Exciting times are ahead of us!
Thank You!

Spares

CERN was founded 1954: 12 European States

"Science for Peace"

Today: 20 Member States

~ 2300 staff
~ 930 other paid personnel
> 10500 users
Budget (2011) ~1000 MCHF

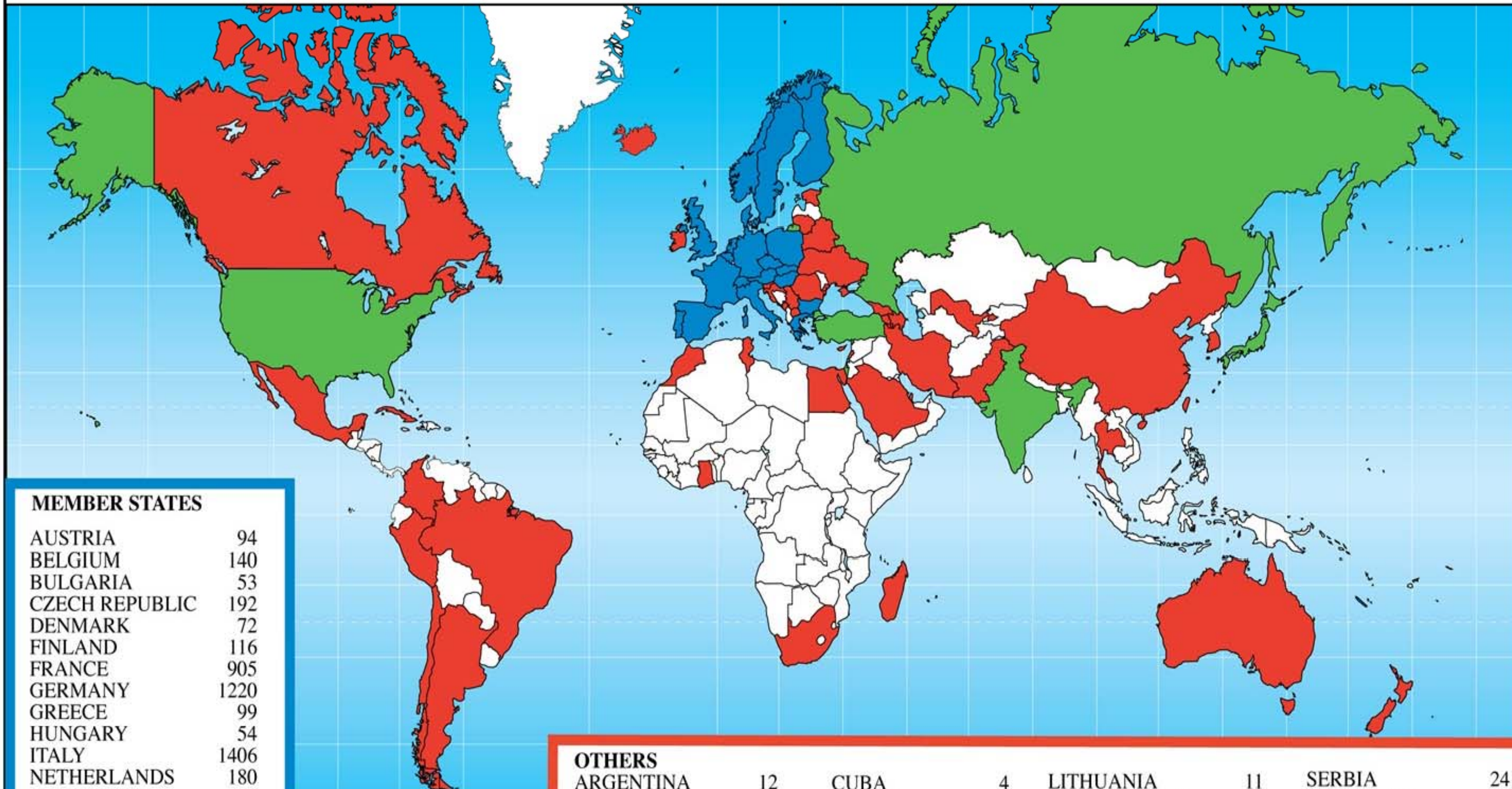
20 Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

1 Candidate for Accession: Romania

8 Observers to Council: India, Israel, Japan, the Russian Federation, the United States of America, Turkey, the European Commission and UNESCO

5 applicants for MS:
Cyprus, Israel, Serbia, Slovenia, Turkey
and **Associate Membership** discussions: Brazil, Ukraine, India, ...

Distribution of All CERN Users by Nation of Institute on 27 June 2011



MEMBER STATES

AUSTRIA	94
BELGIUM	140
BULGARIA	53
CZECH REPUBLIC	192
DENMARK	72
FINLAND	116
FRANCE	905
GERMANY	1220
GREECE	99
HUNGARY	54
ITALY	1406
NETHERLANDS	180
NORWAY	93
POLAND	205
PORTUGAL	141
SLOVAKIA	63
SPAIN	339
SWEDEN	79
SWITZERLAND	359
UNITED KINGDOM	732

6542

OBSERVER STATES

INDIA	109
ISRAEL	60
JAPAN	190
RUSSIA	822
TURKEY	79
USA	1786

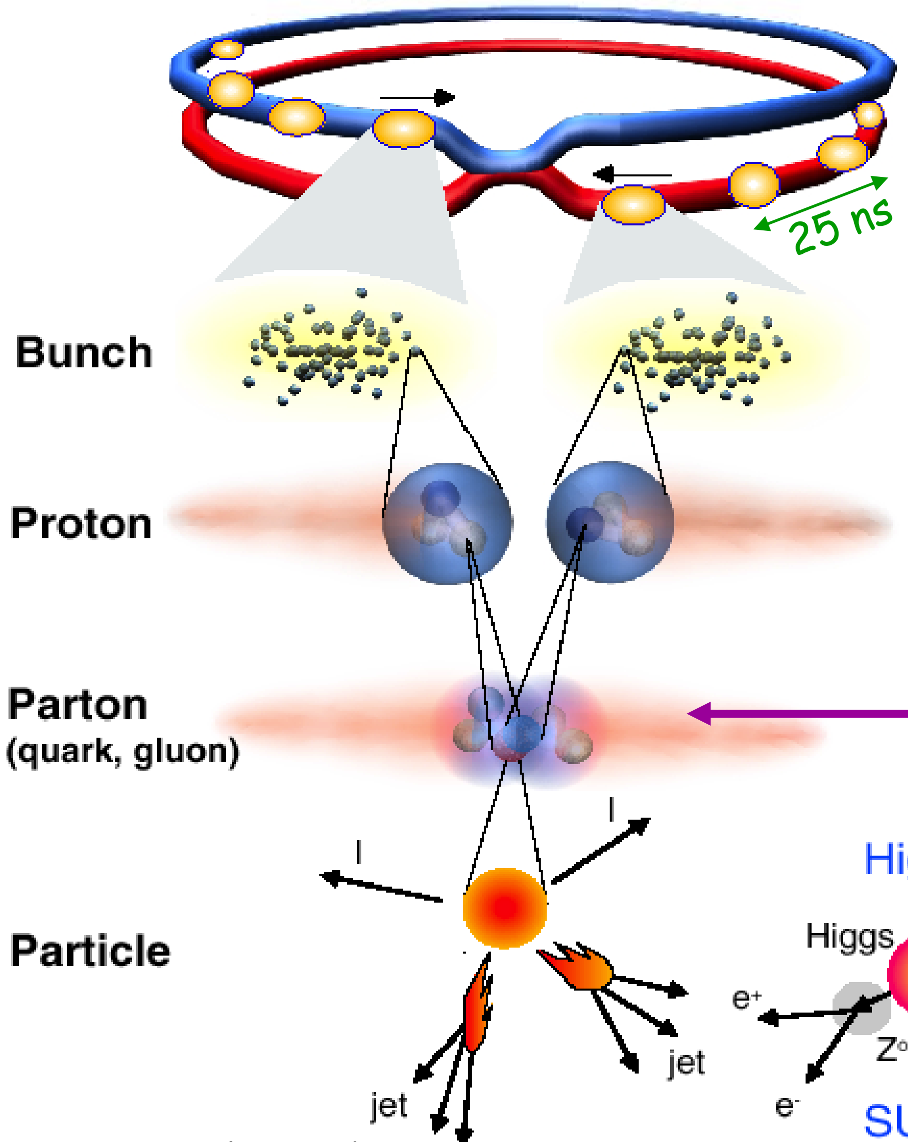
3046

OTHERS

ARGENTINA	12	CUBA	4	LITHUANIA	11	SERBIA	24
ARMENIA	12	CYPRUS	6	MADAGASCAR	1	SINGAPORE	1
AUSTRALIA	22	EGYPT	6	MALTA	1	SLOVENIA	31
AZERBAIJAN	1	ESTONIA	18	MEXICO	39	SOUTH AFRICA	15
BELARUS	19	GEORGIA	10	MONTENEGRO	1	THAILAND	1
BRAZIL	79	GHANA	1	MOROCCO	7	F.Y.R.O.M.	3
CANADA	160	HONG KONG	1	NEW ZEALAND	9	TUNISIA	1
CHILE	3	ICELAND	3	PAKISTAN	19	UKRAINE	19
CHINA	87	IRAN	15	PERU	2	UZBEKISTAN	1
CHINA (TAIPEI)	53	IRELAND	13	QATAR	1		
COLOMBIA	13	KOREA	85	ROMANIA	66		
CROATIA	15	LEBANON	1	SAUDI ARABIA	2		

894

Collisions at LHC



Proton-Proton

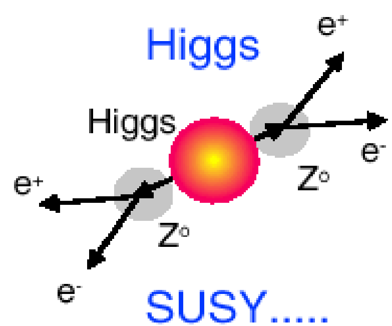
Protons/bunch	**10^{11}**
Beam energy	**7 TeV (7×10^{12} eV)**
Luminosity	**10^{34} cm^{-2} s^{-1}**

Event rate:

N = L x σ (pp) $\approx$ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare

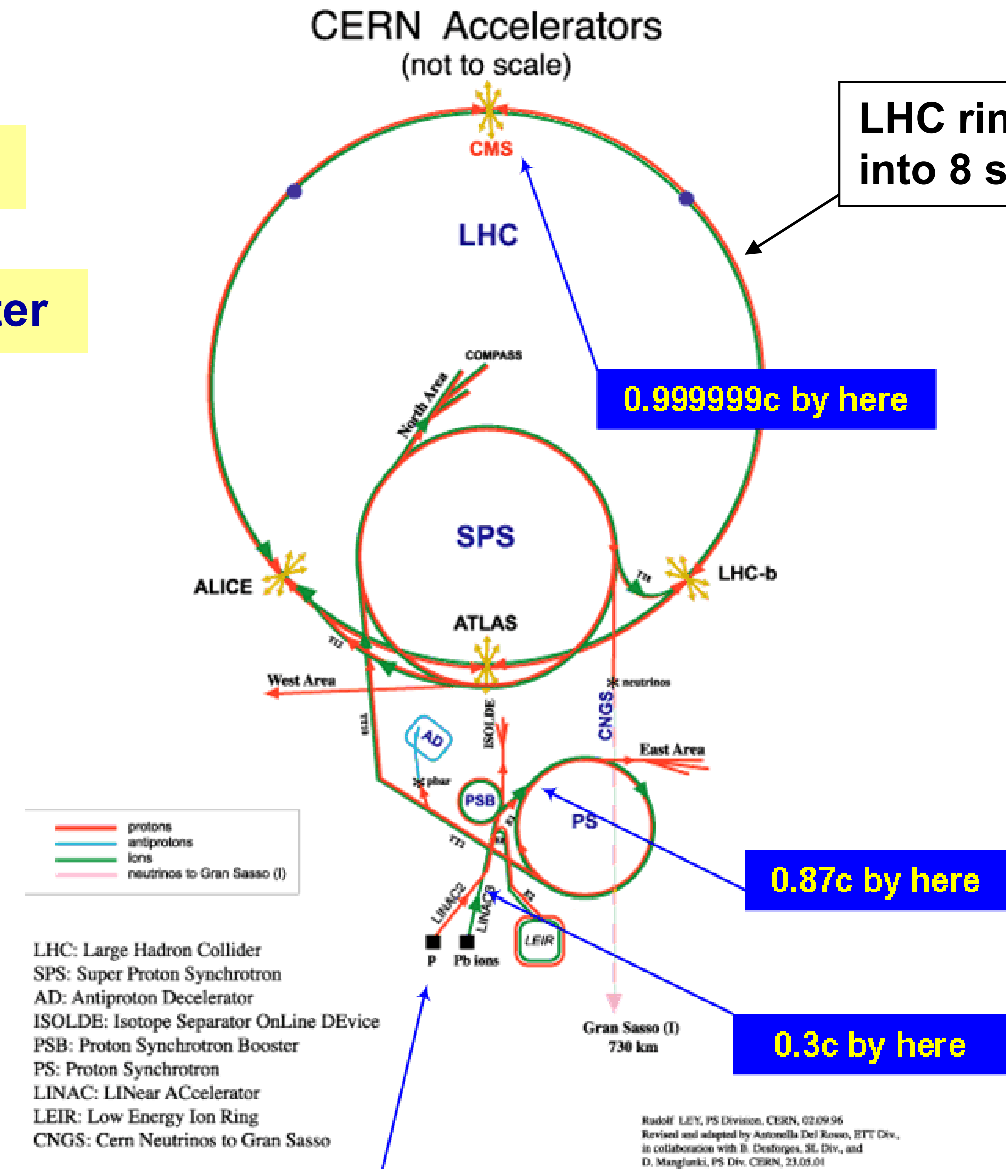


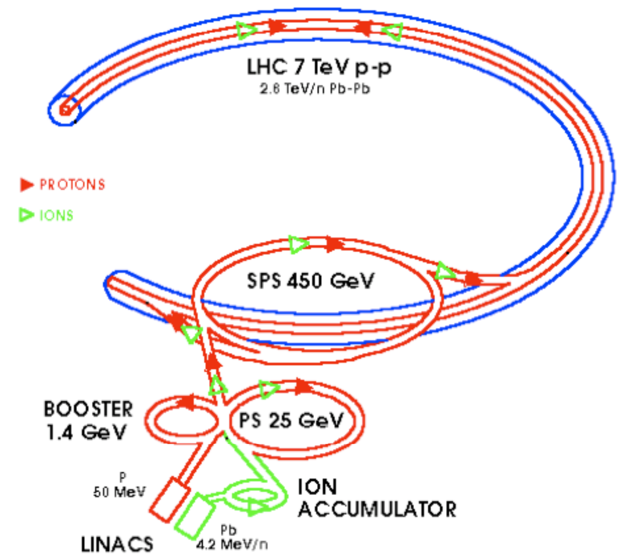
Selection of 1 in
10,000,000,000,000

→ very powerful detectors needed

The full LHC accelerator complex

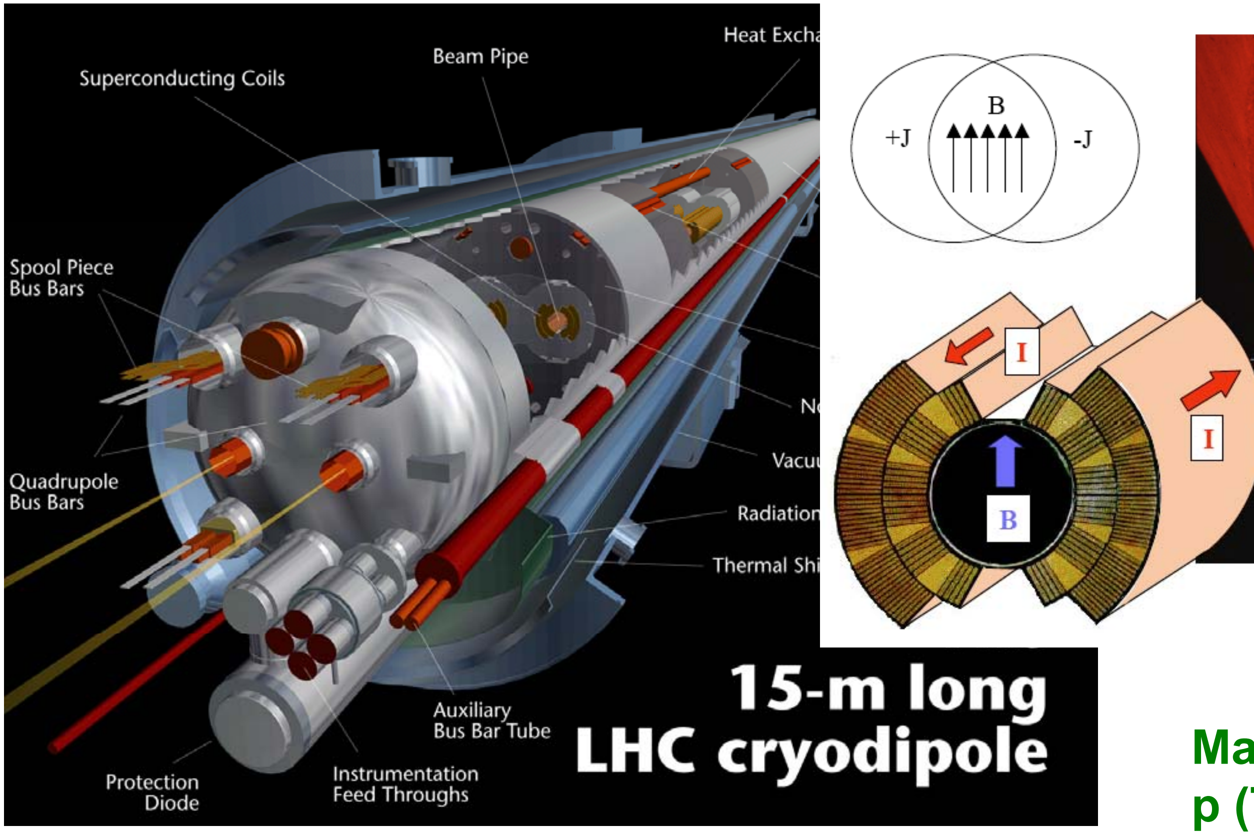
Linac → Booster → PS → SPS → LHC

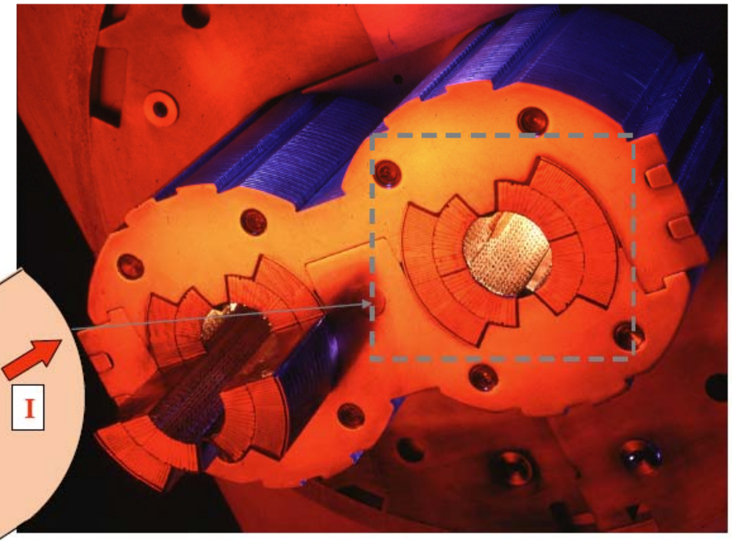




> 50 years of CERN history still alive and operational

LHC Accelerator Challenge: Dipole Magnets





Magnetic Field for Dipoles
p (TeV) = 0.3 B(T) R(km)

Coldest Ring in the Universe ?
1.9 K (CMBR is about 2.7 K)

LHC magnets are cooled with pressurized superfluid helium

For p = 7 TeV and R = 4.3 km
⇨ B = 8.4 T
⇨ Current 12 kA

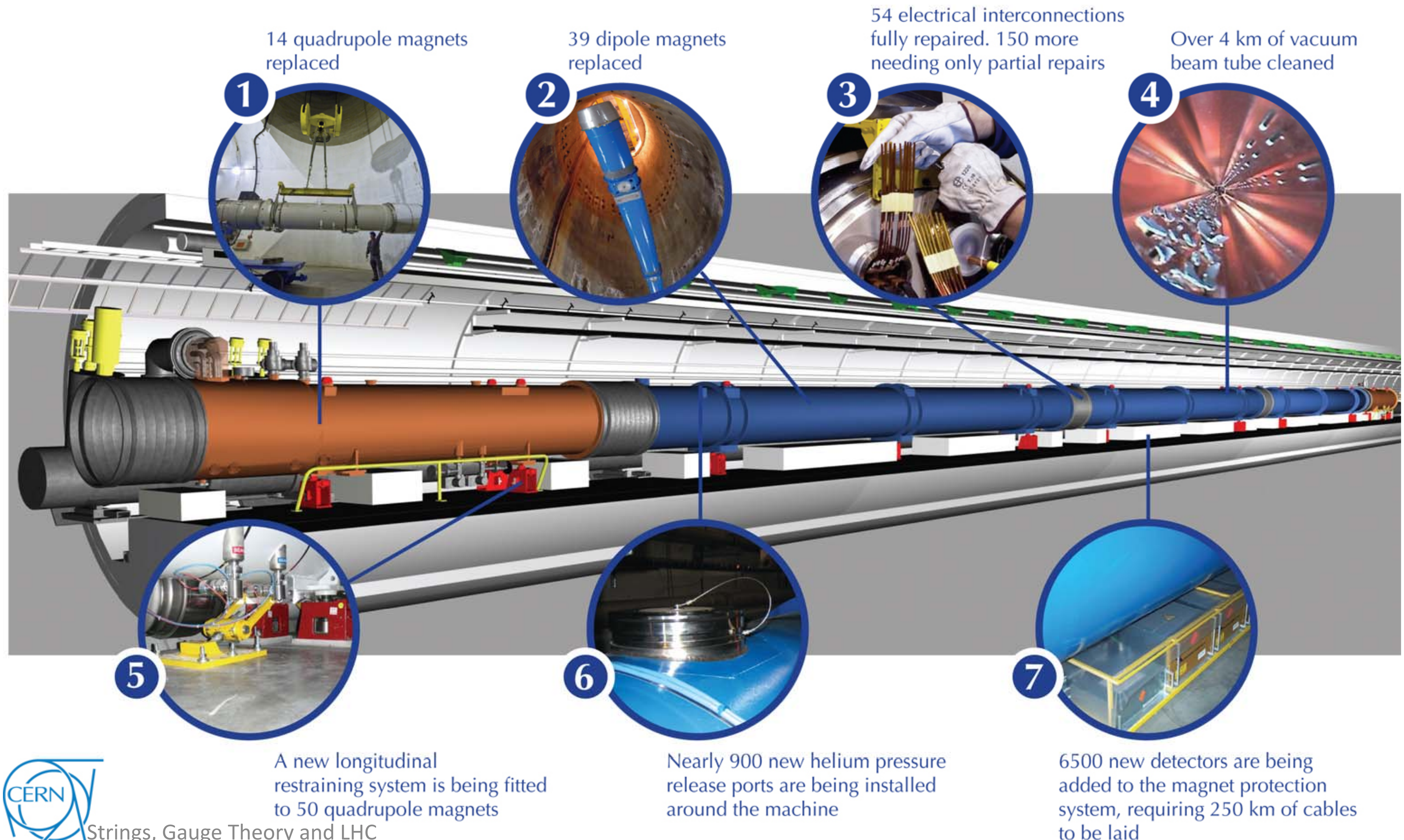
Examples of collateral damage after the 19th September 2008 incident

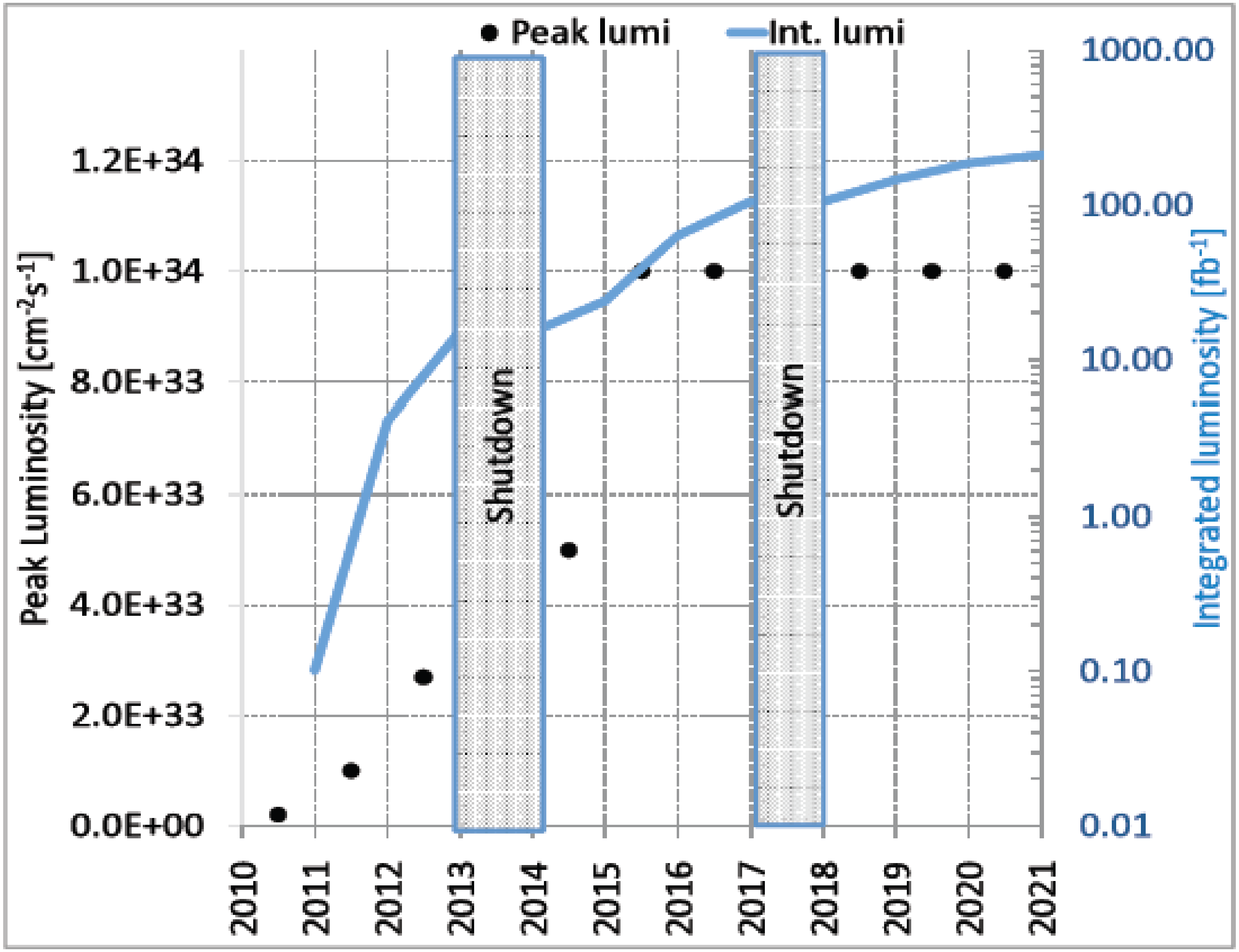
Most likely, an electrical arc developed, which punctured the Helium enclosure

High pressure build-up damaged the magnet interconnects and the super-insulation

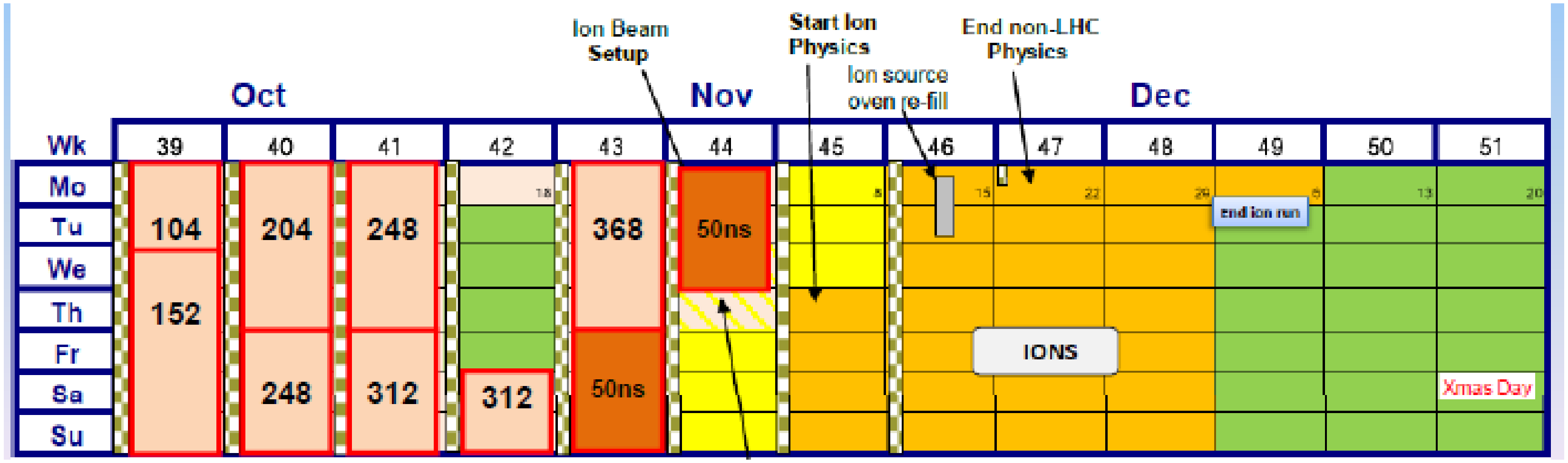
Perforation of the beam tubes resulted in pollution of the vacuum system with soot from the vaporization and with debris from the super insulation.

The LHC repairs in detail

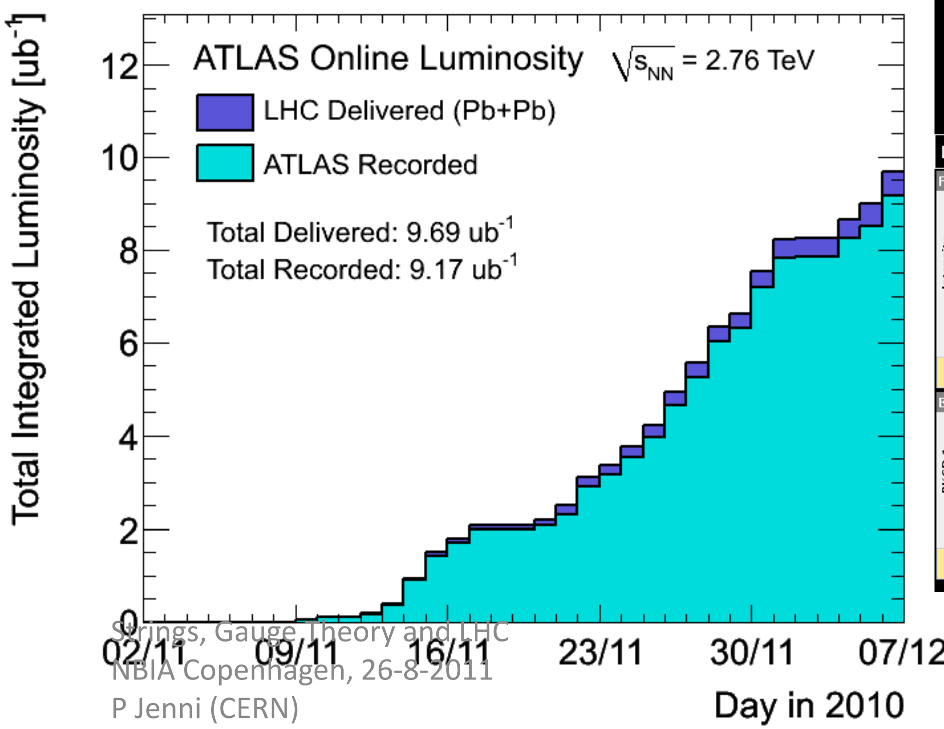


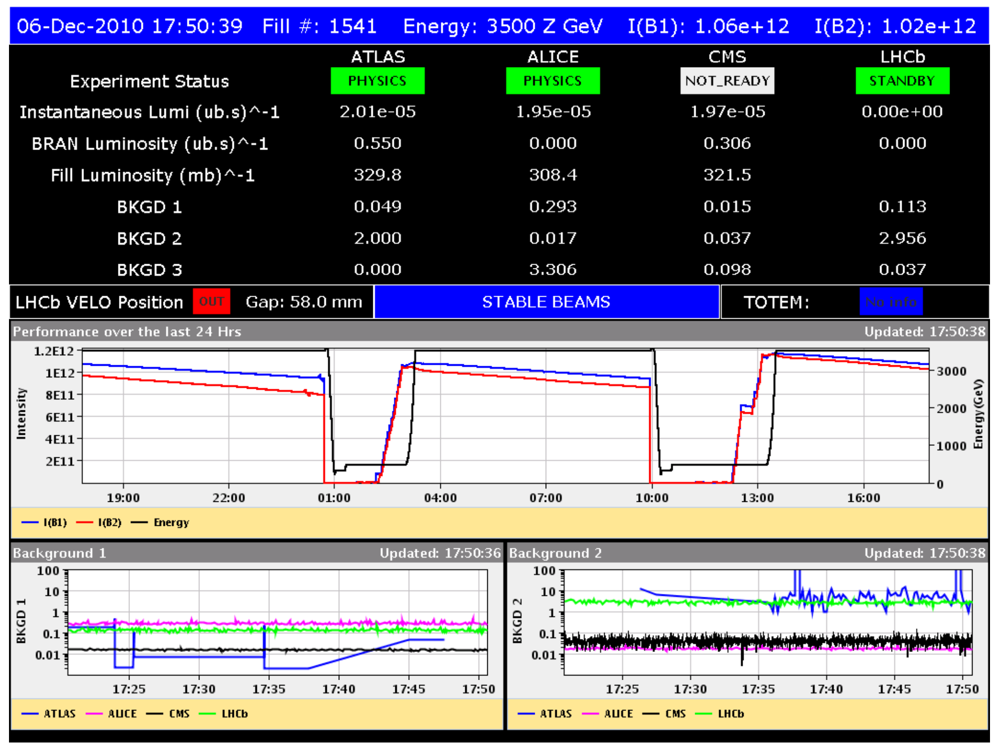


Peak lumi
Int. lumi
Peak Luminosity [cm-2s-1]
1.2E+34
1.0E+34
8.0E+33
6.0E+33
4.0E+33
2.0E+33
0.0E+00
Shutdown
Shutdown
1000.00
100.00
10.00
1.00
0.10
0.01
Integrated luminosity [fb-1]
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021



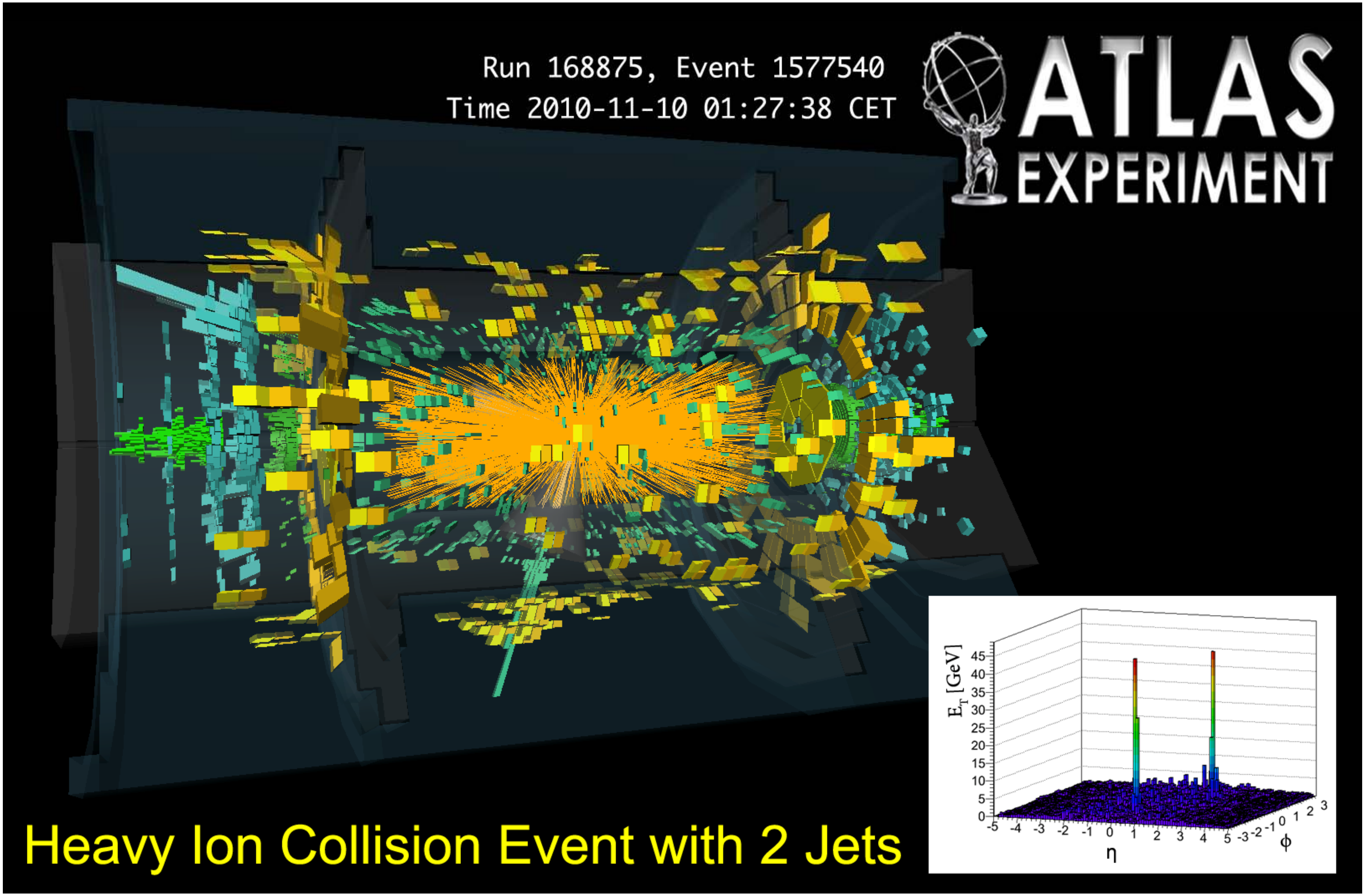
Heavy Ion running





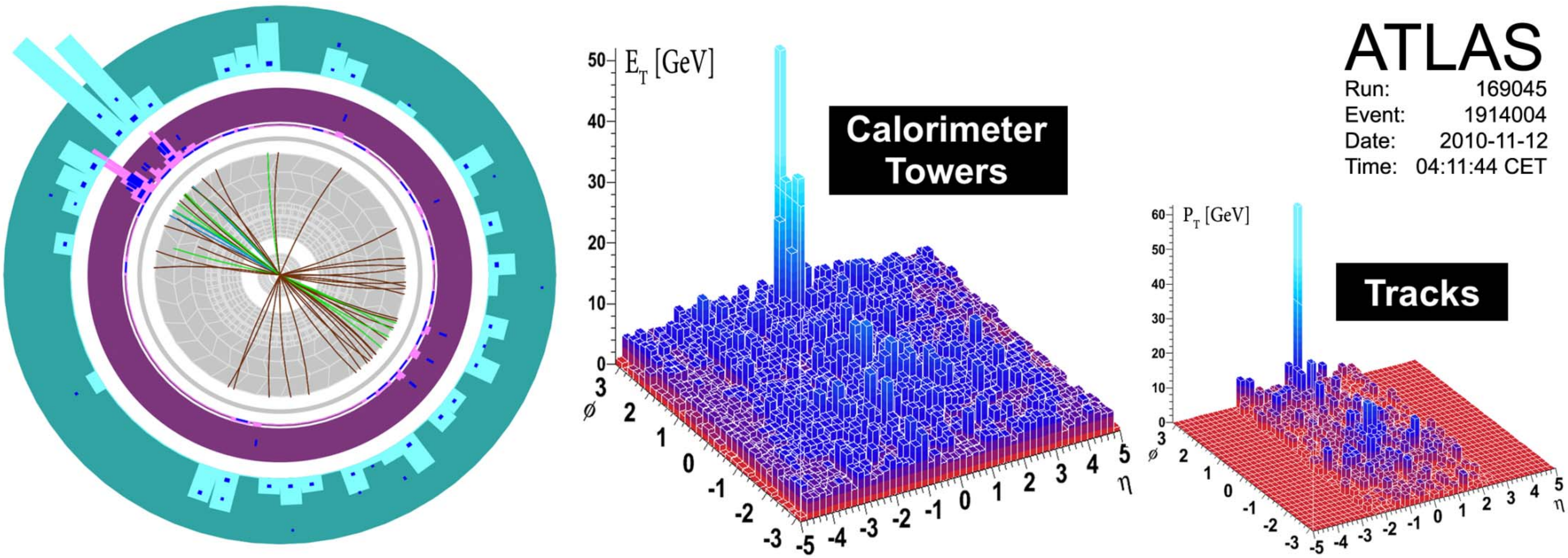
Pb-Pb event with jets

Uncorrected p_T of each jet ~160 GeV



Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad *et al.* (The ATLAS Collaboration)*



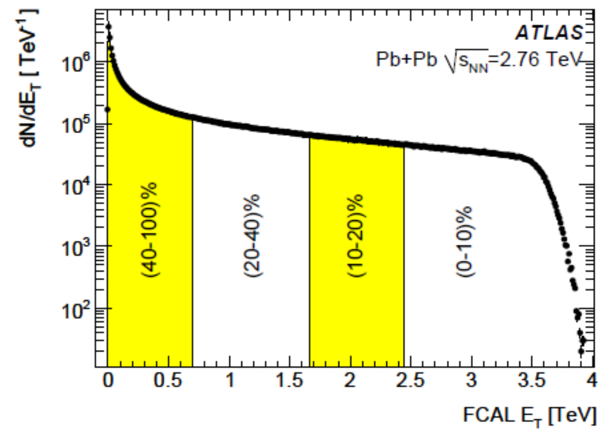
Phys. Rev. Lett. 105 (2010) 252303

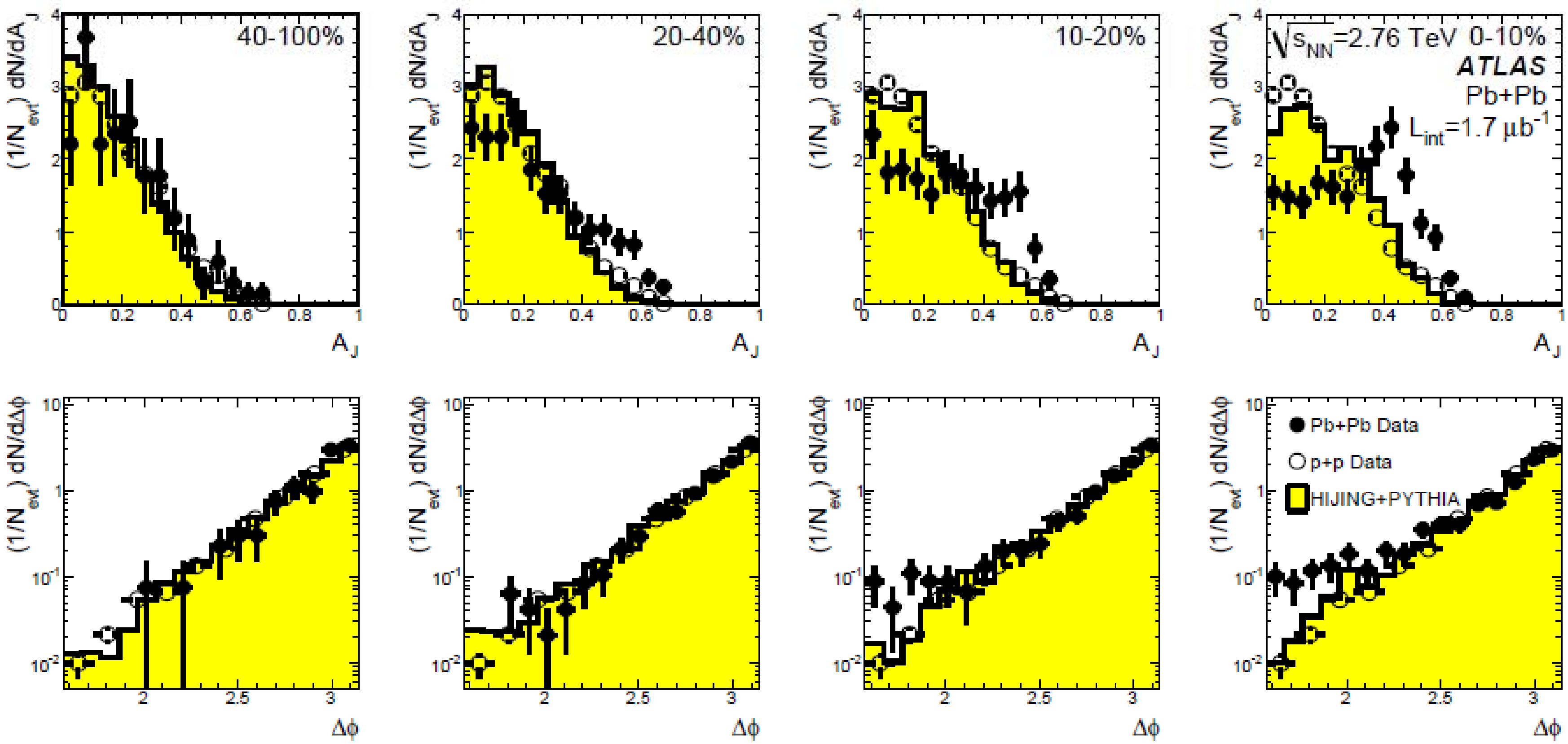
Measured di-jet asymmetry A_J as a function of the centrality

(1.7 μb^{-1})

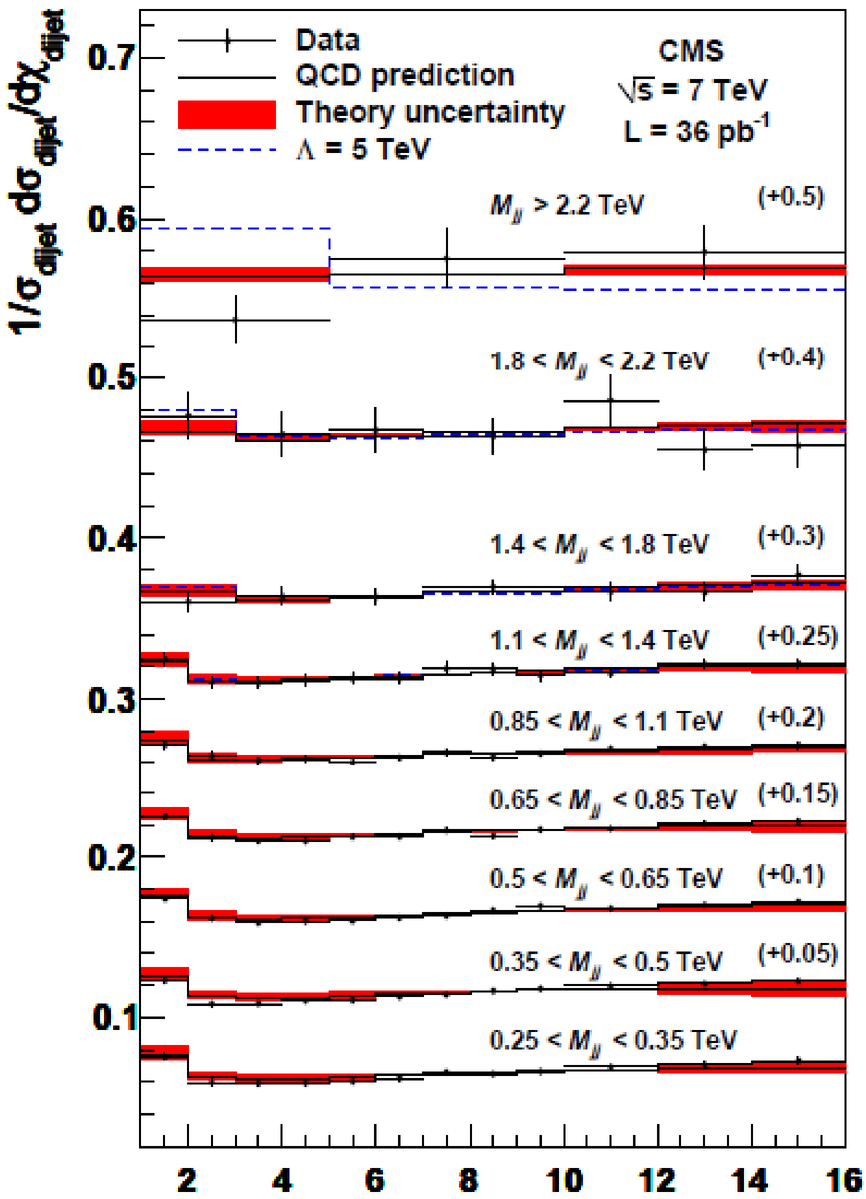
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

Centrality bins defined with the ET in FCAL





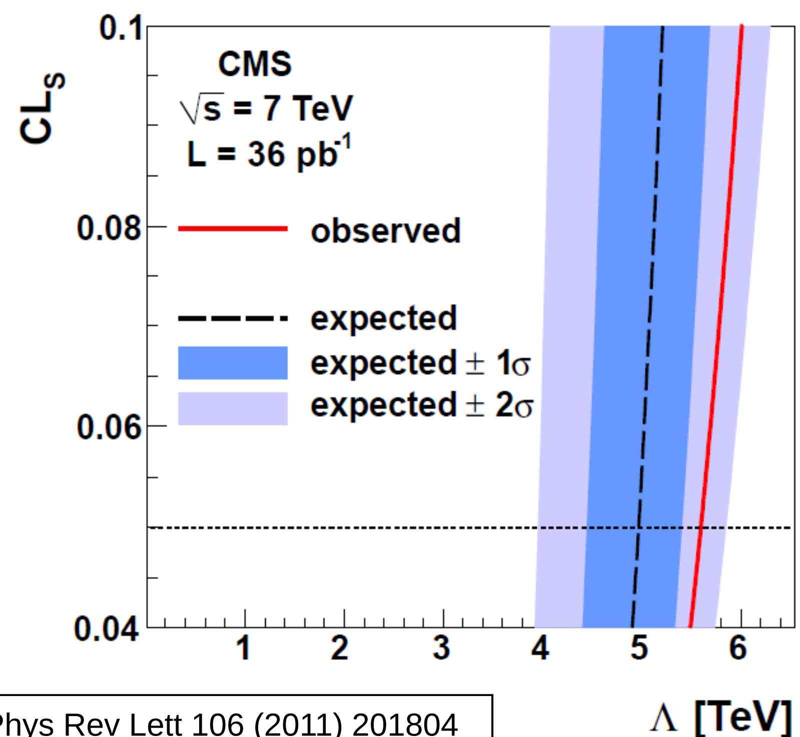
Such an effect could be the first direct indication of 'jet-quenching'



$$\chi = \exp(|y_1 - y_2|) = \frac{1 + \cos\vartheta *}{1 - \cos\vartheta *}$$

Search for deviations from QCD in the di-jet angular distributions

Deviations from the QCD expectation could reveal a substructure of the quarks ('compositeness' at scale Λ) in analogy to the famous Rutherford scattering 100 years ago

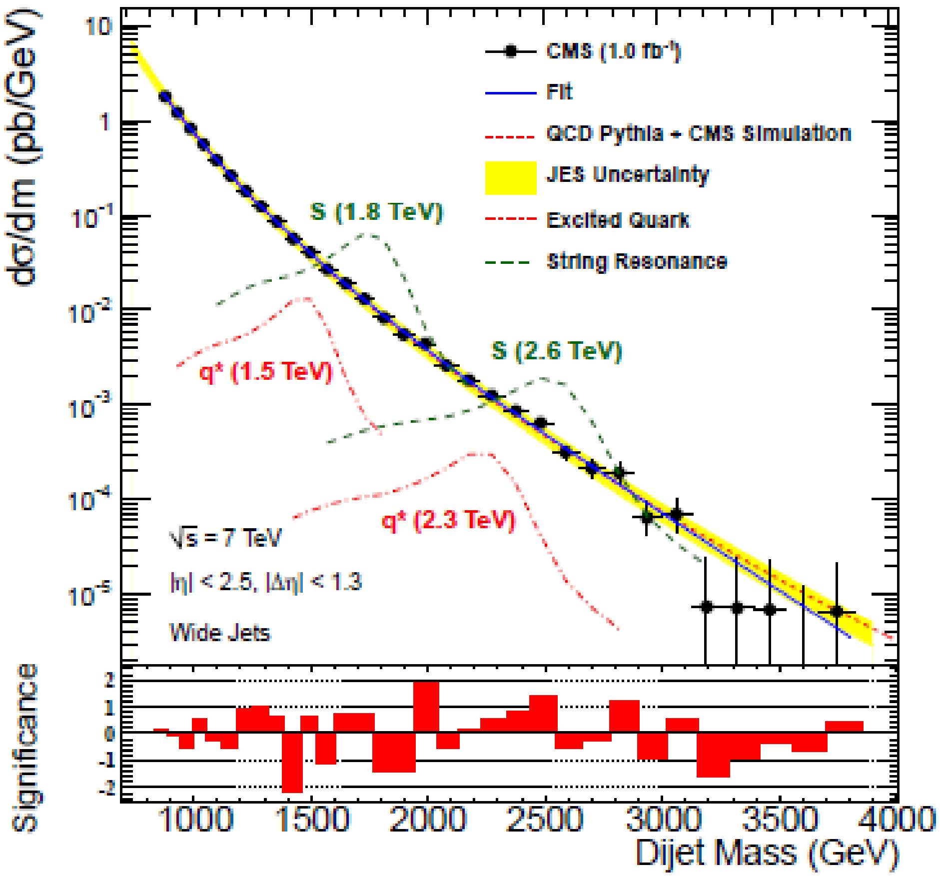


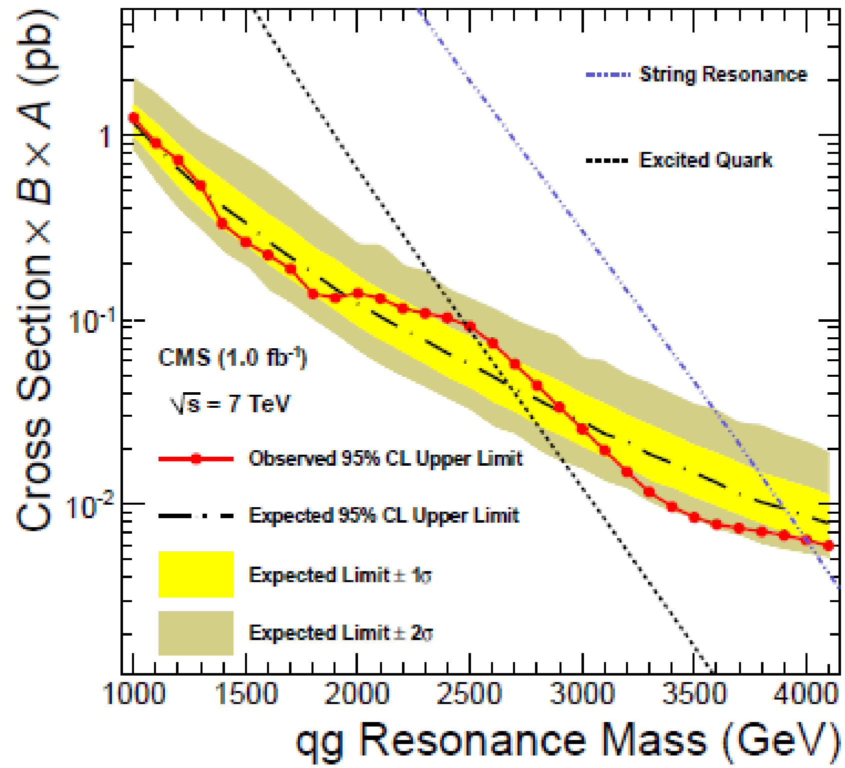
Phys Rev Lett 106 (2011) 201804

A CMS example of searches for New Physics as deviations from QCD behaviour of hadronic jet distributions

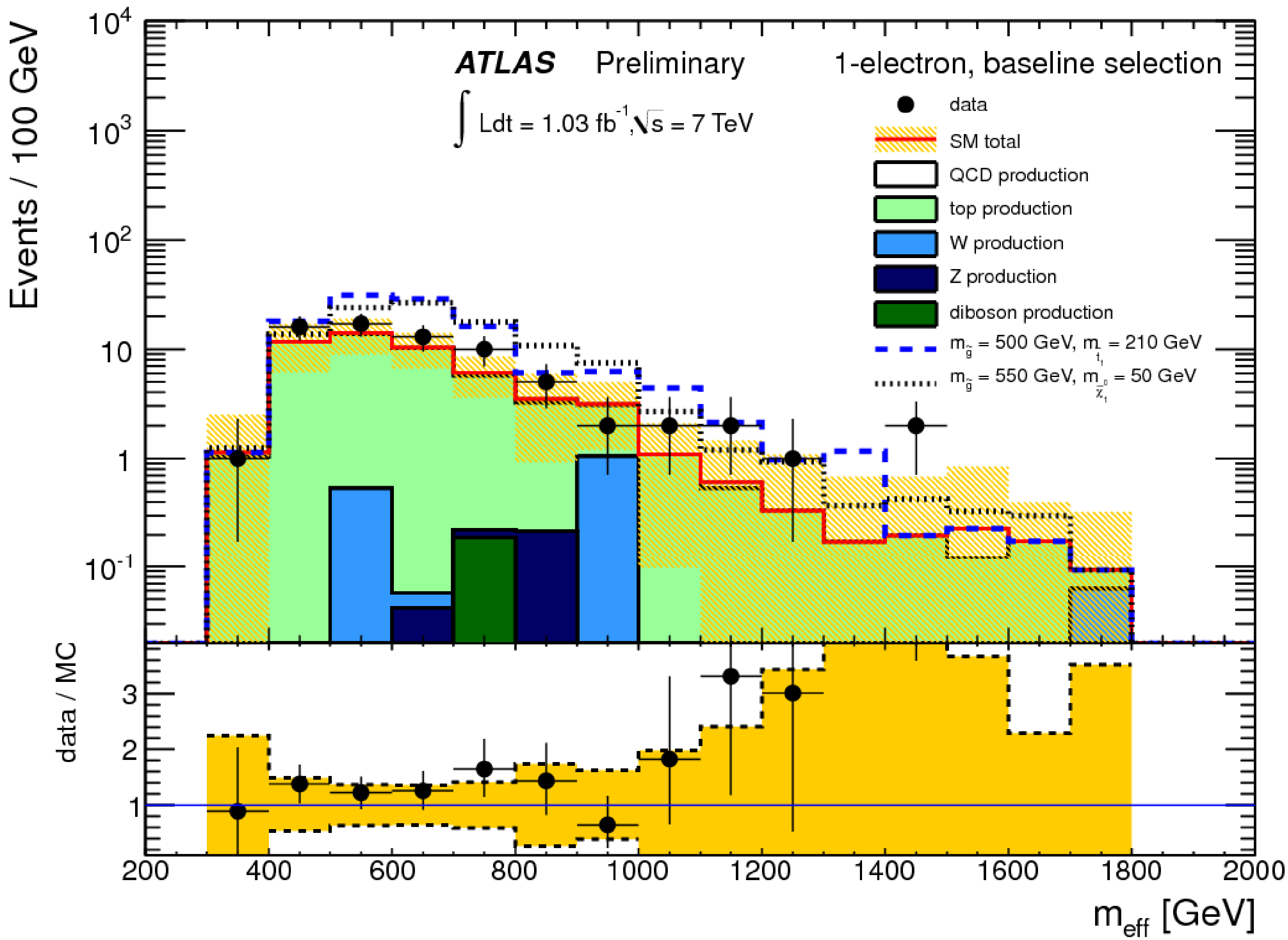
Search for resonances in the di-jet mass spectrum

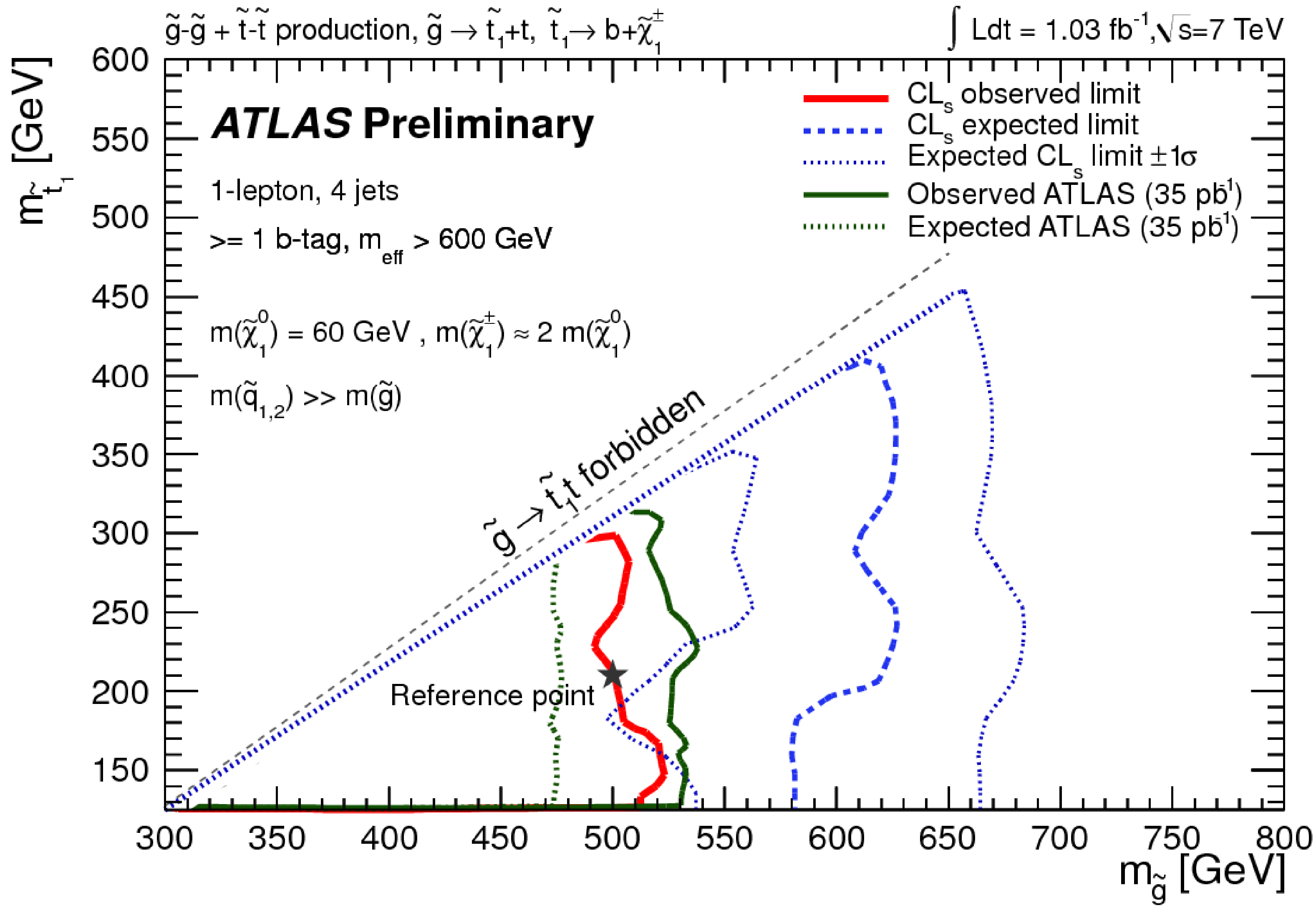
Sub. to Phys Lett B
arXiv:1107.4771[hep-ex]

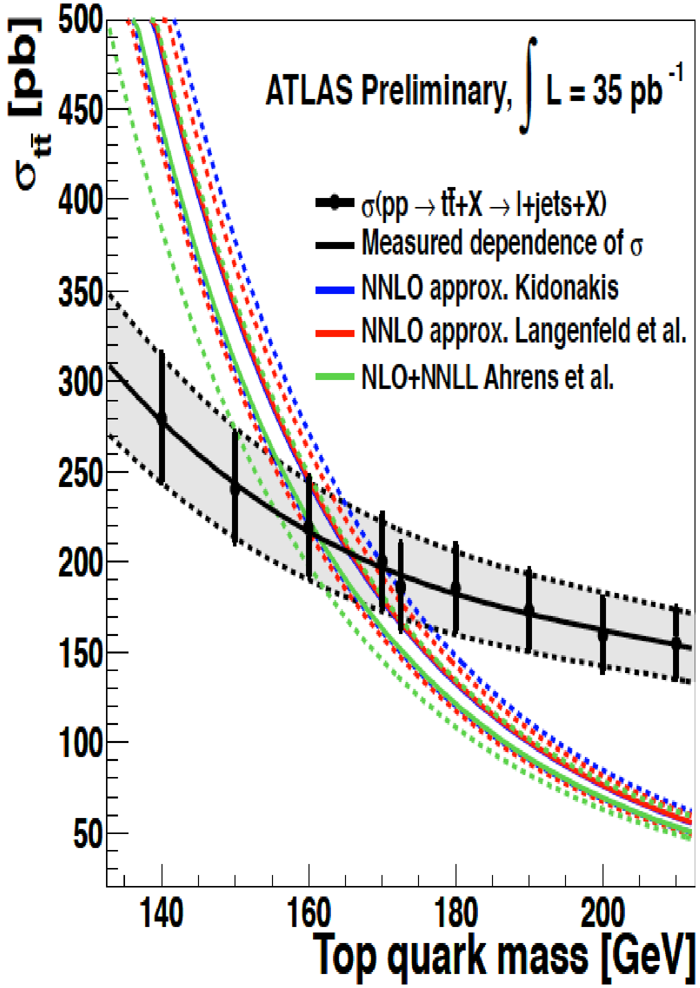




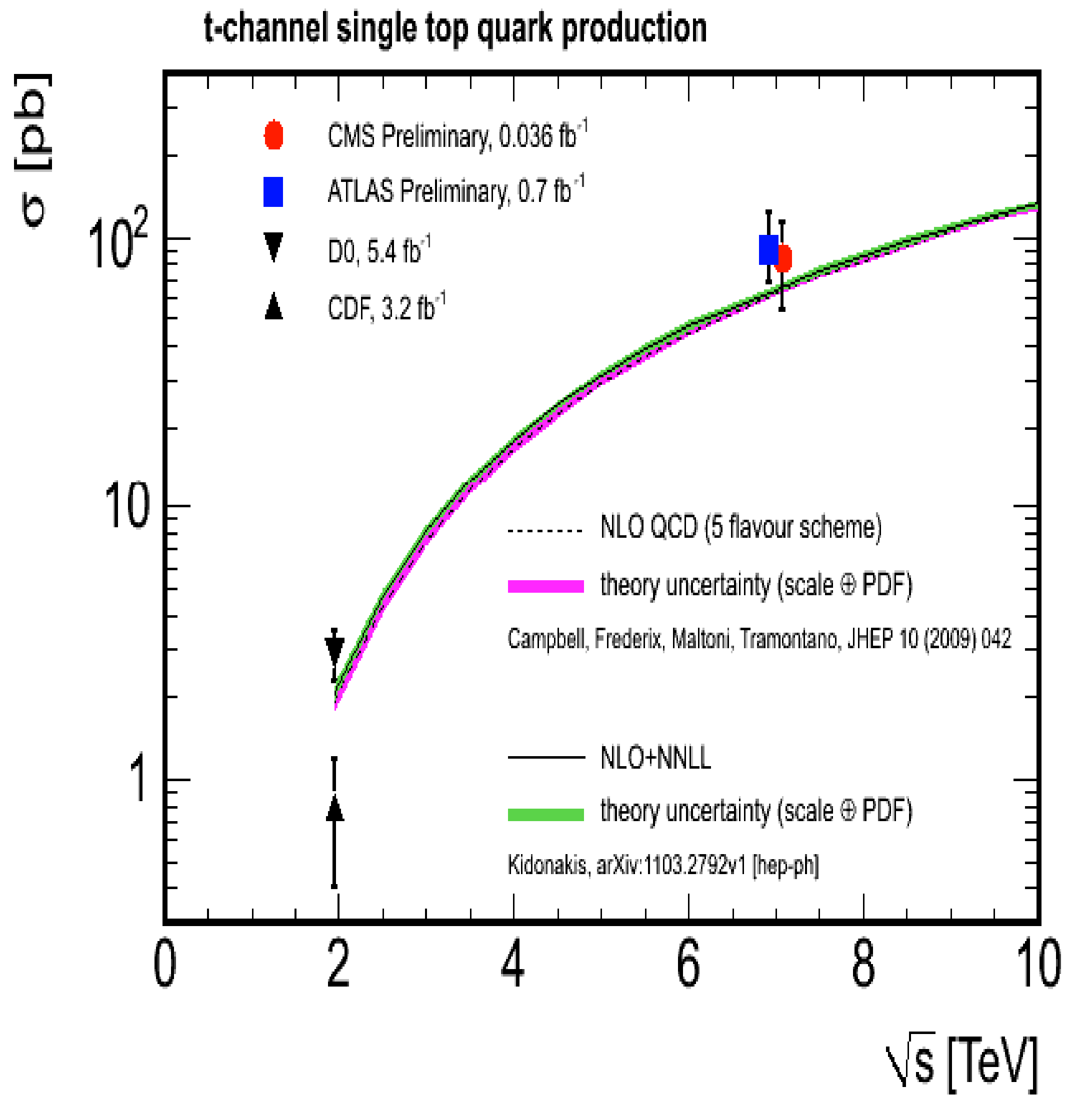
SUSY search with Etmiss, b-jets and one lepton (light s-top)



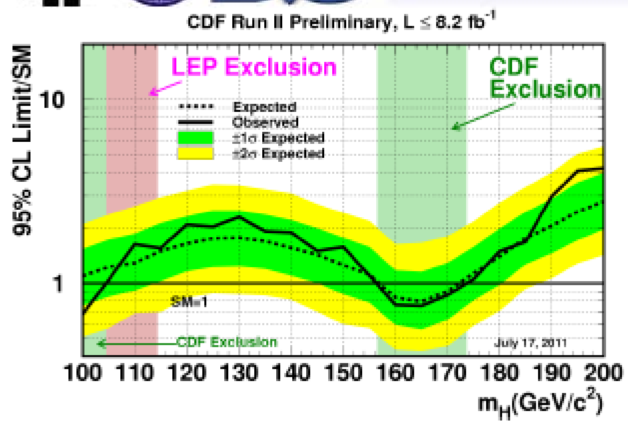

g̃-g̃ + t̃-t̃ production, g̃ → t̃1+t, t̃1→ b+χ̃±1
∫ Ldt = 1.03 fb-1,√s=7 TeV
ATLAS Preliminary
1-lepton, 4 jets
>= 1 b-tag, meff > 600 GeV
m(χ̃01) = 60 GeV , m(χ̃±1) ≈ 2 m(χ̃01)
m(q̃1,2) >> m(g̃)
CLs observed limit
CLs expected limit
Expected CLs limit ±1σ
Observed ATLAS (35 pb-1)
Expected ATLAS (35 pb-1)
g̃ → t̃1t forbidden
Reference point
mt̃1 [GeV]
mg̃ [GeV]
600
550
500
450
400
350
300
250
200
150
300
350
400
450
500
550
600
650
700
750
800

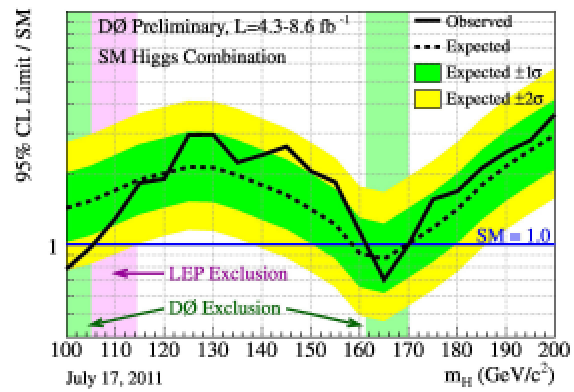


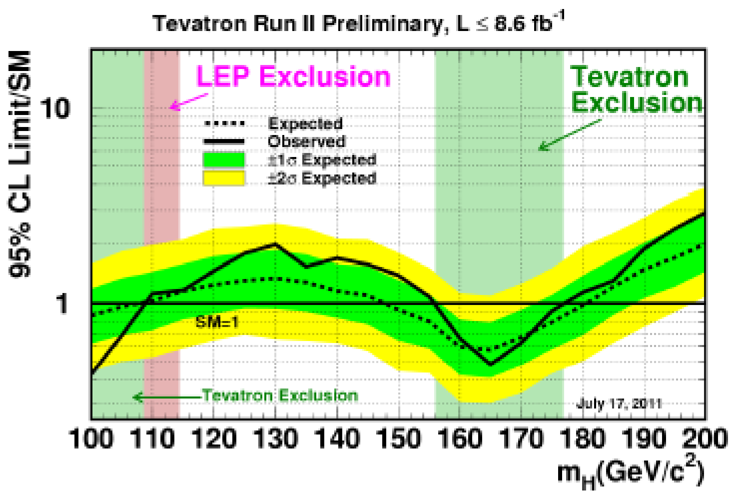
$$m_{\mathrm{top}}^{\mathrm{pole}} = (166.4\,^{+7.8}_{-7.3})\ \mathrm{GeV}.$$



CDF / DØ / Tevatron Limits







Observed exclusion:
100-109 and 156-177 GeV

Expected exclusion:
100-108 and 148-181 GeV

XXV Lepton Photon Symposium - Mumbai *22 Aug 2011* *23*

(Marco Verzocchi)