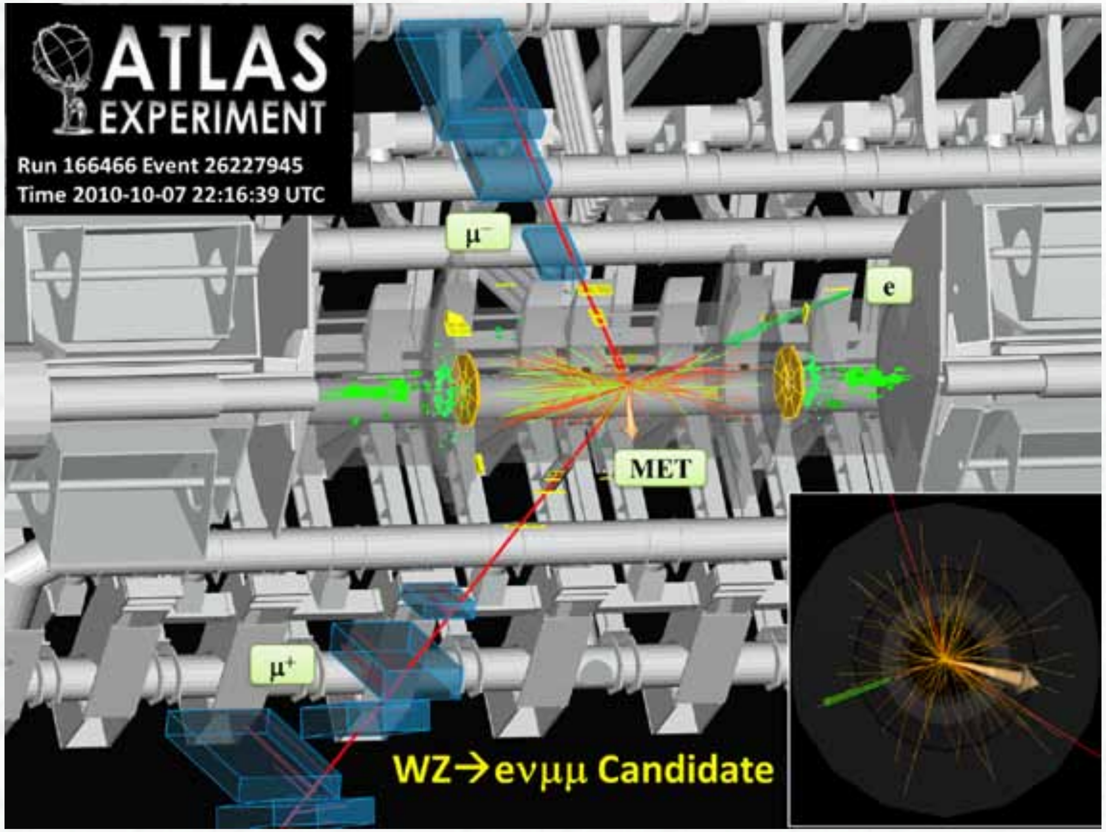
Part III: Physics results at the LHC
-a few selected examples-



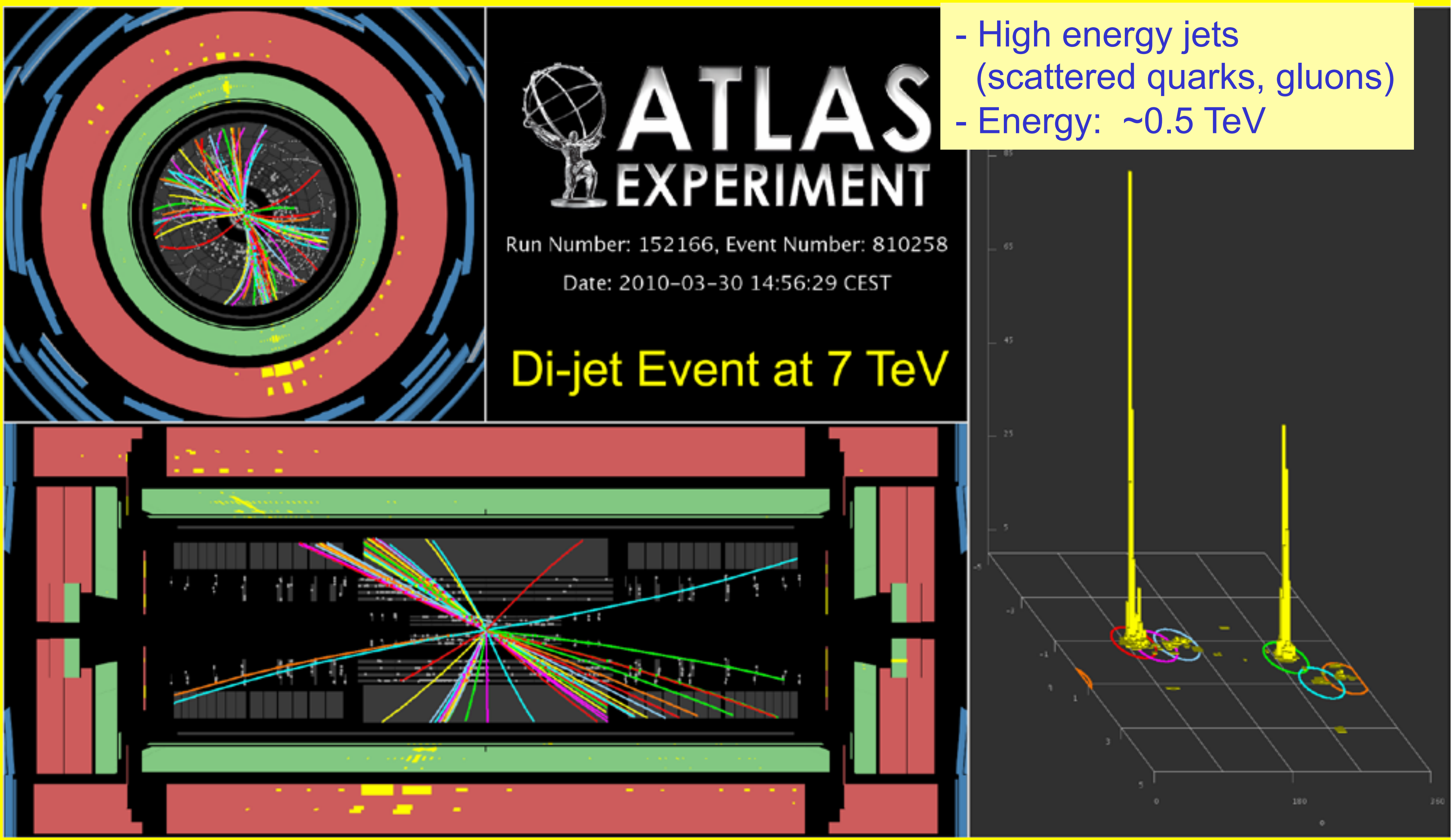
Karl Jakobs
Physikalisches Institut
Universität Freiburg / Germany

Outline of the lectures:

1. Introduction
2. Test of the Standard Model
3. Search for the Higgs Boson (covered by Jan Stark and P.Q.)
4. Search for New Phenomena

Since 30. March 2010: collisions at 7 TeV

(.... first interesting results appeared soon)

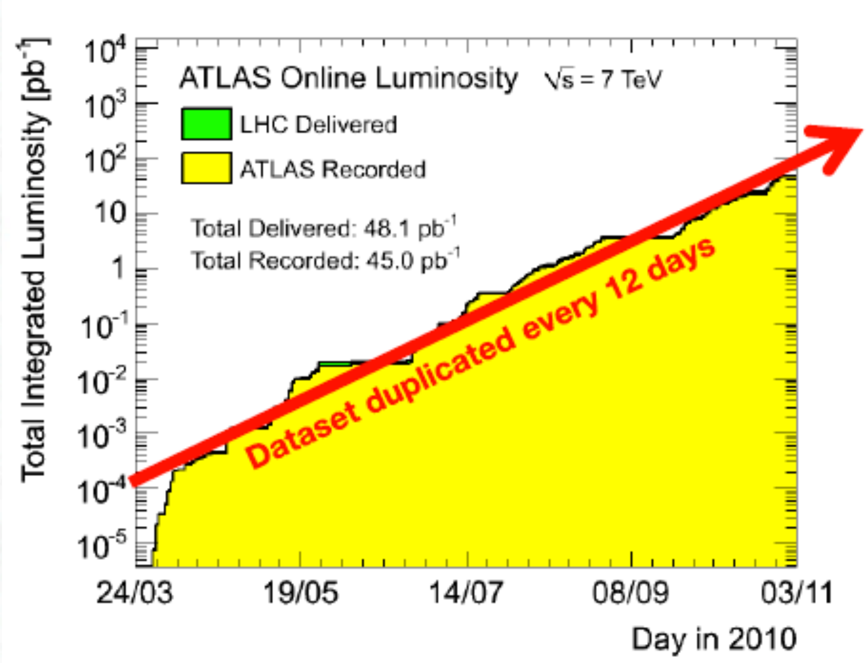


- High energy jets
  (scattered quarks, gluons)
- Energy: ~0.5 TeV

Collected data in 2010:

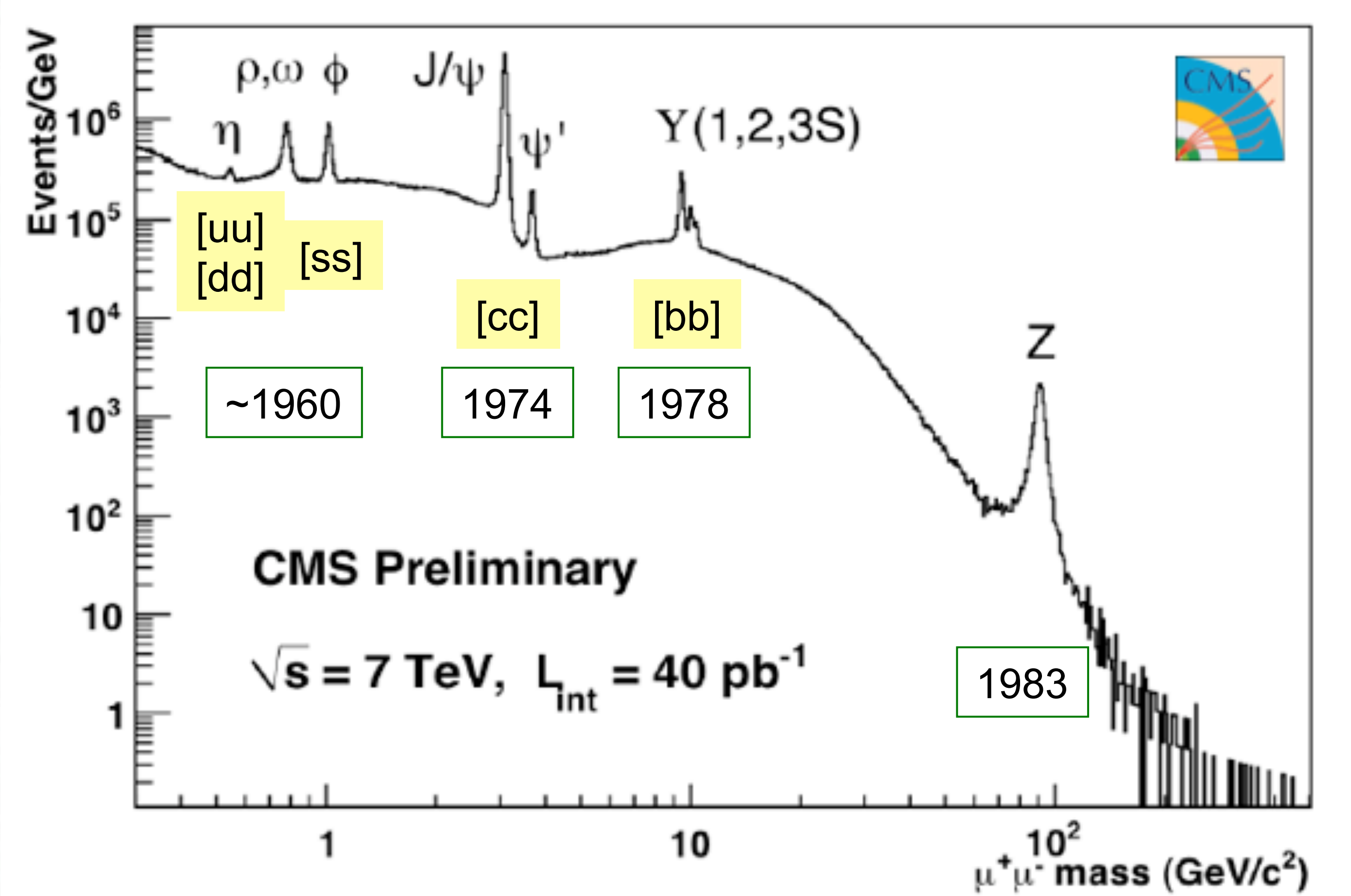
~40 pb^{-1} recorded
~36 pb^{-1} used in analysis
(good quality)

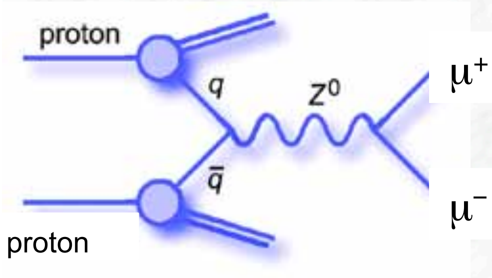
Both experiments have a very high data taking efficiency !



2010

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

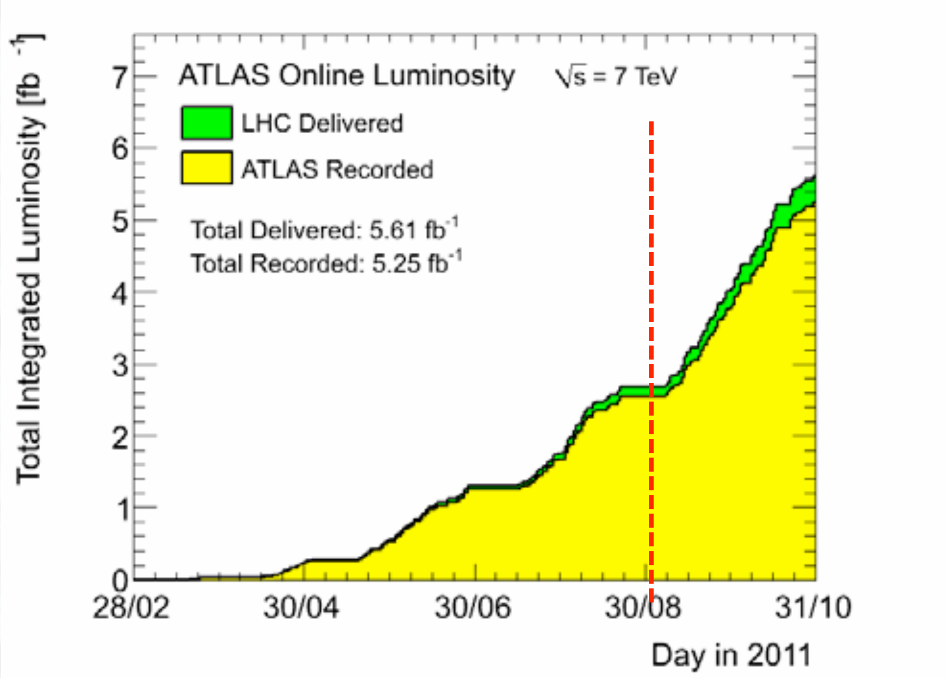




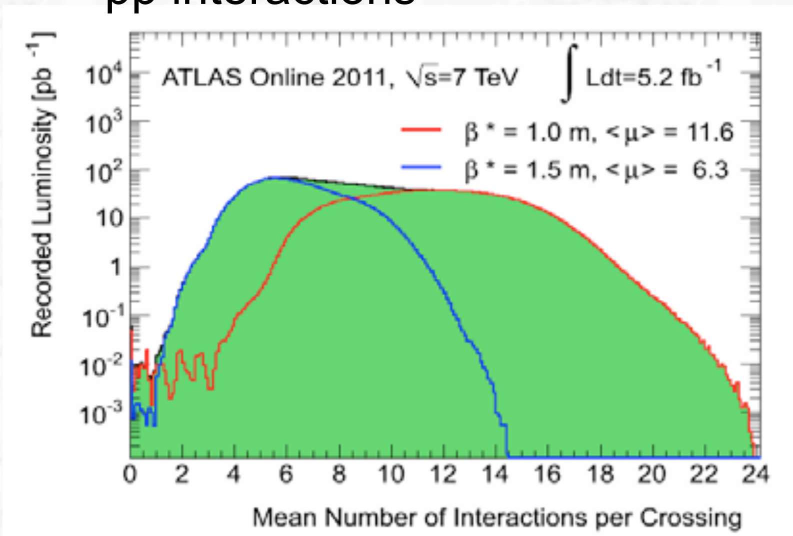
Well known quark-antiquark resonances (bound states) appeared “online”

Data taking in 2011

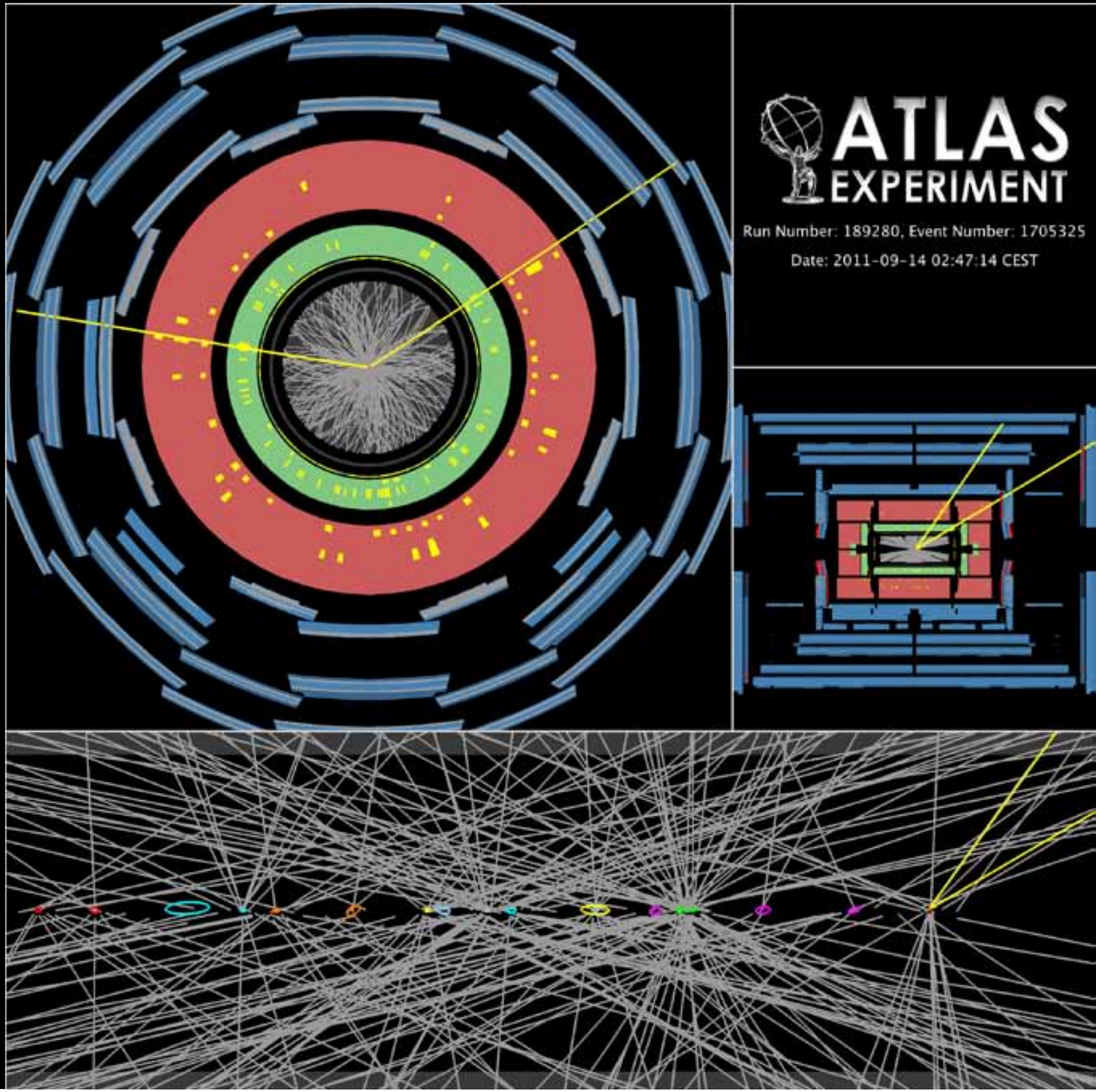
Original goal to collect 1 fb^{-1} already surpassed in June 2011



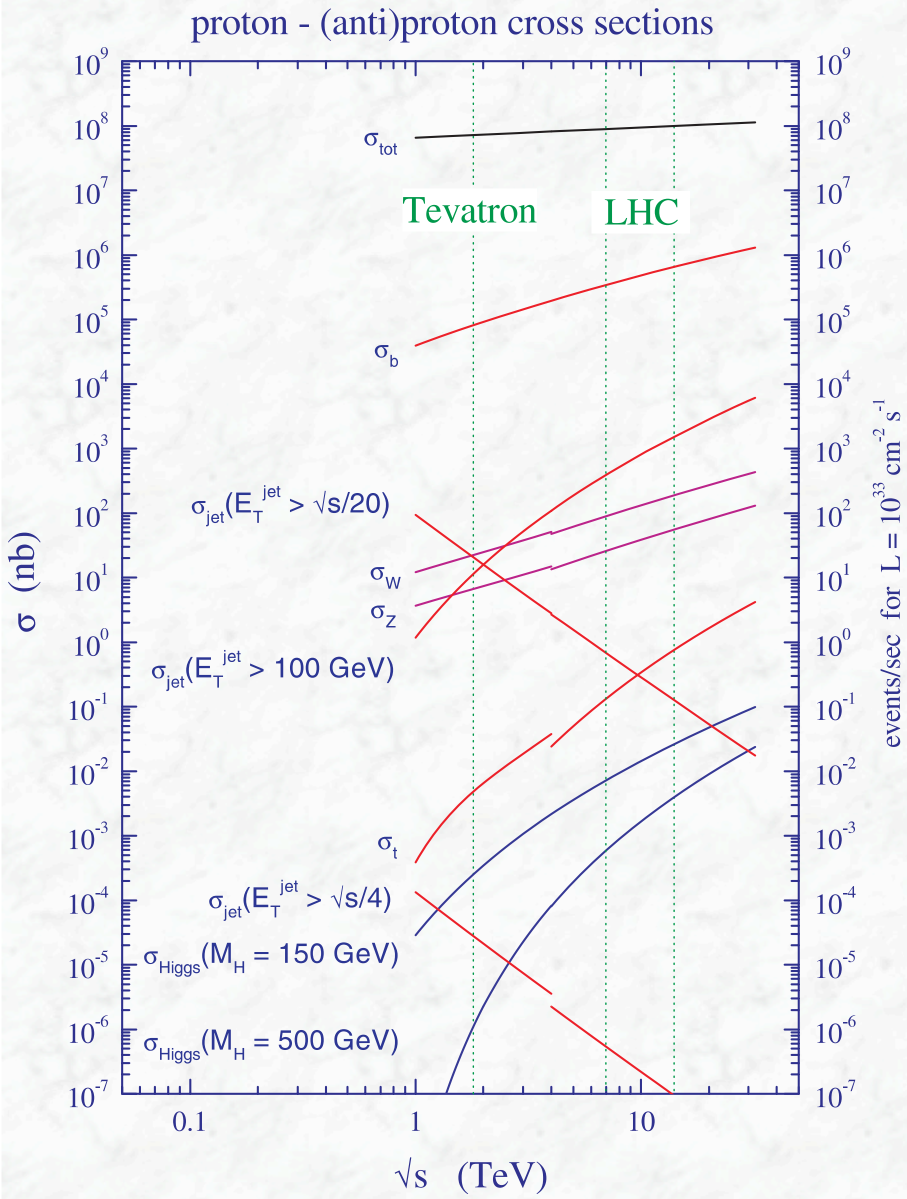
- World record on instantaneous luminosity on 22. April 2011:
  $4.67\ 10^{32}\ cm^{-2}\ s^{-1}$
  (Tevatron record: $4.02\ 10^{32}\ cm^{-2}\ s^{-1}$)
  meanwhile: ~$3 \bullet 10^{33}\ cm^{-2}\ s^{-1}$
- Collect per day as much luminosity as in 2010
- High intensity bunches
  → superposition of several pp interactions



$Z \rightarrow \mu^+ \mu^-$ with 17 superimposed events



Cross Sections and Production Rates

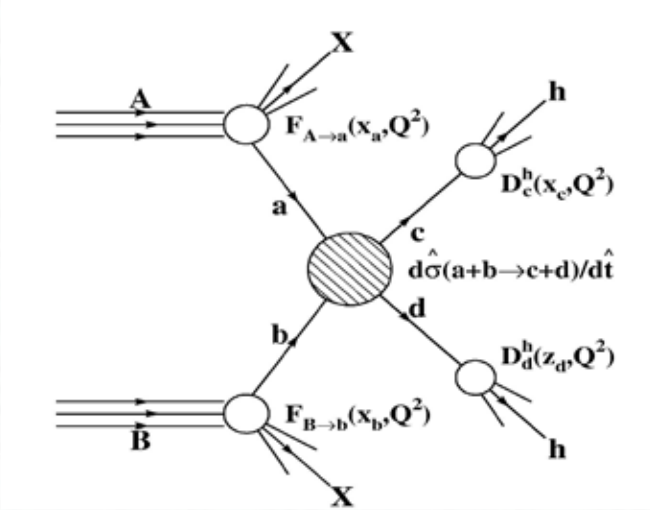


Rates for $L = 10^{34}$ cm^{-2} s^{-1}: (LHC)

• Inelastic proton-proton reactions:	10^9 / s
• bb pairs	$5\ 10^6$ / s
• tt pairs	8 / s
• $W \rightarrow e\,\nu$	150 / s
• $Z \rightarrow e\,e$	15 / s
• **Higgs (150 GeV)**	**0.2 / s**
• **Gluino, Squarks (1 TeV)**	**0.03 / s**

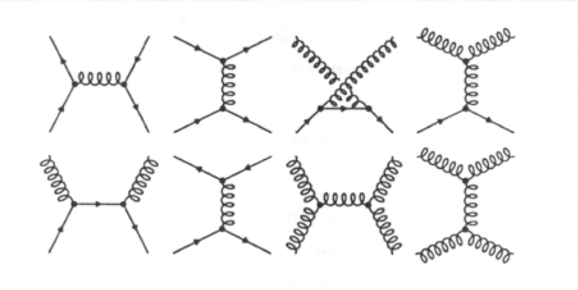
LHC is a factory for:
top-quarks, b-quarks, W, Z, ……. Higgs, ……

QCD processes at hadron colliders

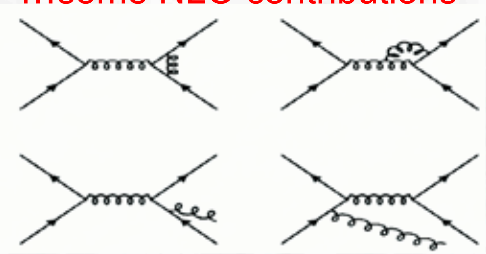


- Hard scattering processes are dominated by QCD jet production
- Originating from qq, qg and gg scattering
- Cross sections can be calculated in QCD (perturbation theory)

Leading order



…some NLO contributions



Comparison between experimental data and theoretical predictions constitutes an important test of the theory.

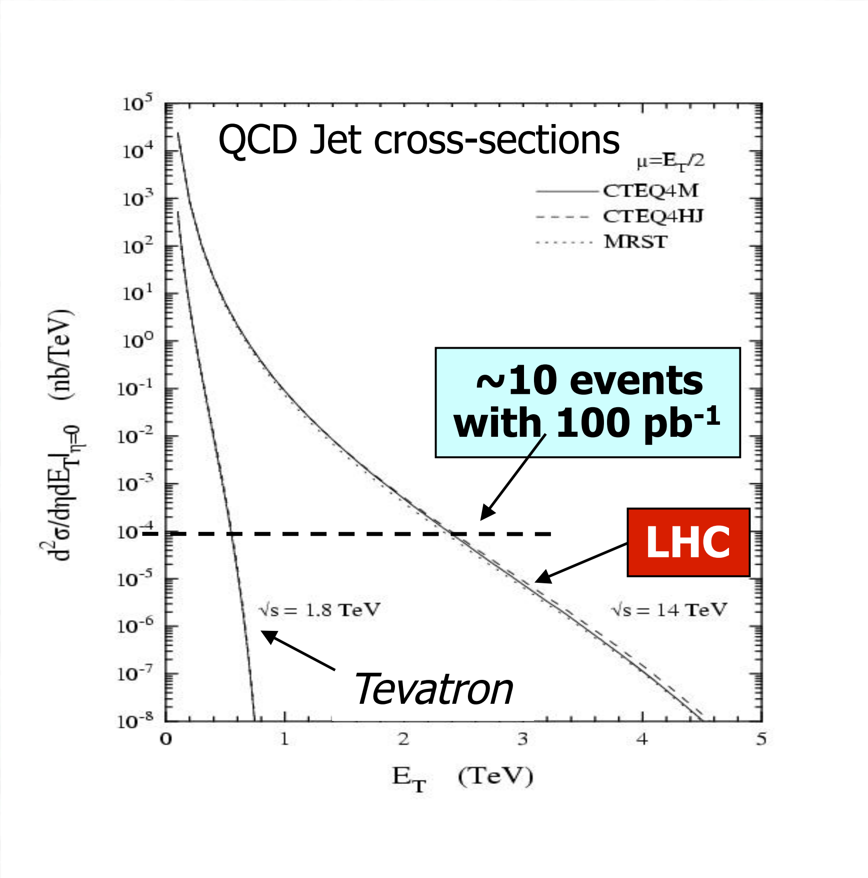
Deviations?
→ Problem in the experiment ?
Problem in the theory (QCD) ?
New Physics, e.g. quark substructure ?

Jets from QCD production: Tevatron vs LHC

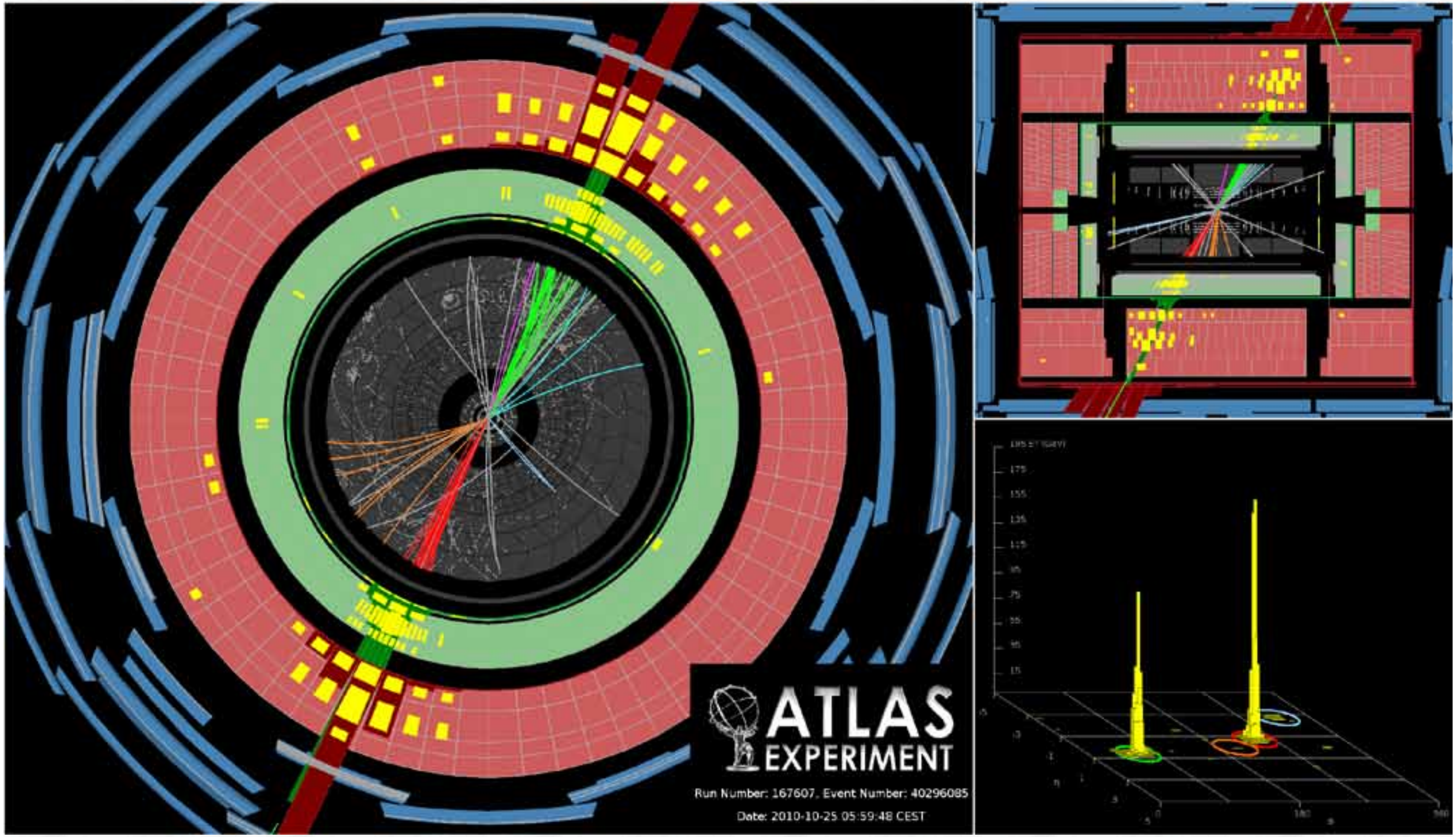
- Rapidly probe perturbative QCD in a new energy regime (at a scale above the Tevatron, large cross sections)

- Experimental challenge: understanding of the detector
  - main focus on jet energy scale
  - resolution

- Theory challenge:
  - improved calculations…
    (renormalization and factorization scale uncertainties)
  - pdf uncertainties

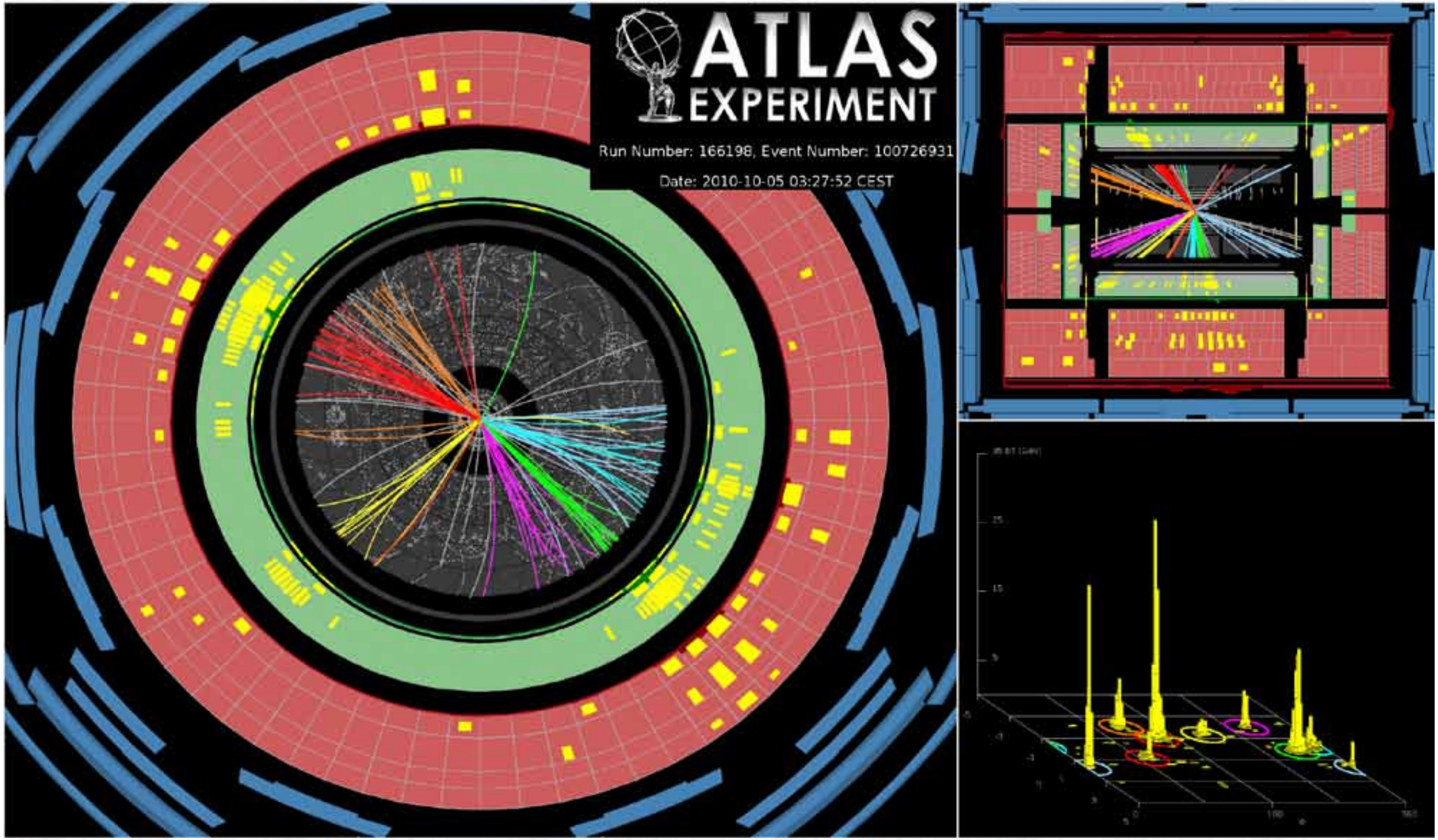


High p_T jet events at the LHC



Event display that shows the highest-mass central dijet event collected during 2010, where the two leading jets have an invariant mass of 3.1 TeV. The two leading jets have (p_T, y) of (1.3 TeV, -0.68) and (1.2 TeV, 0.64), respectively. The missing E_T in the event is 46 GeV. From ATLAS-CONF-2011-047.

An event with a high jet multiplicity at the LHC



The highest jet multiplicity event collected, counting jets with p_T greater than 60 GeV: this event has eight. 1st jet (ordered by p_T): p_T = 290 GeV, η = -0.9, φ = 2.7; 2nd jet: p_T = 220 GeV, η = 0.3, φ = -0.7 Missing E_T = 21 GeV, φ = -1.9, Sum E_T = 890 GeV.

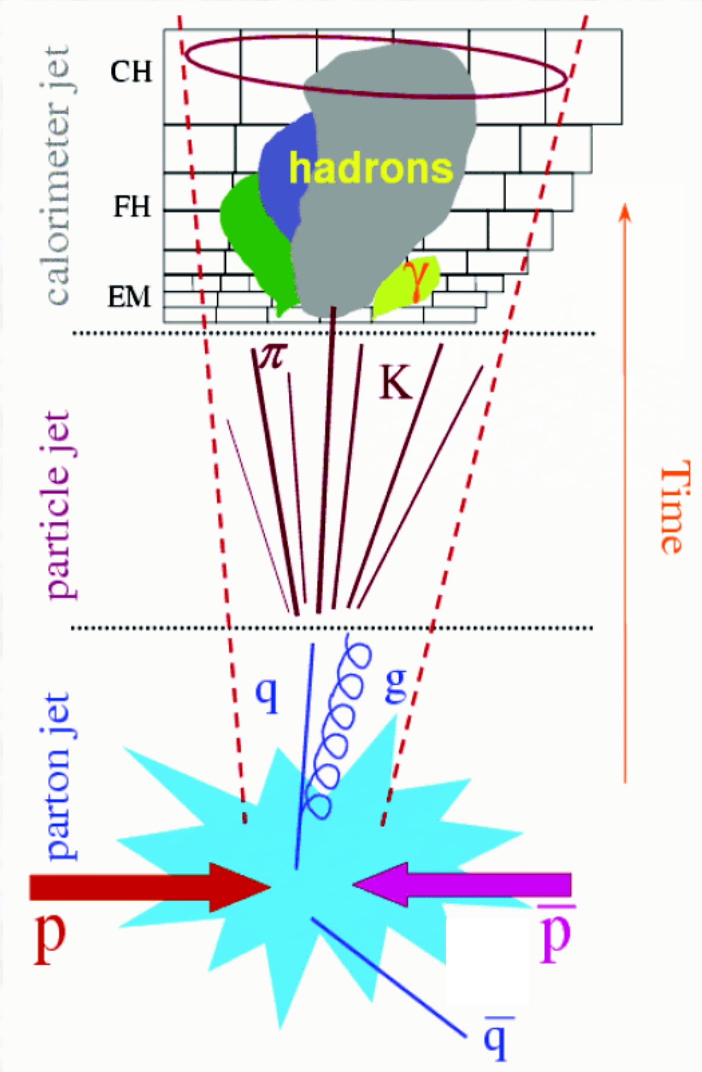
Jet reconstruction and energy measurement

- A jet is NOT a well defined object
  (fragmentation, gluon radiation, detector response)

- The detector response is different for particles interacting electromagnetically (e,γ) and for hadrons
  → for comparisons with theory, one needs to correct back the calorimeter energies to the „particle level“ (particle jet)
  Common ground between theory and experiment

- One needs an algorithm to define a jet and to measure its energy
  conflicting requirements between experiment and theory (exp. simple, e.g. cone algorithm, vs. theoretically sound (no infrared divergencies))

- Energy corrections for losses of fragmentation products outside jet definition and underlying event or pileup energy inside



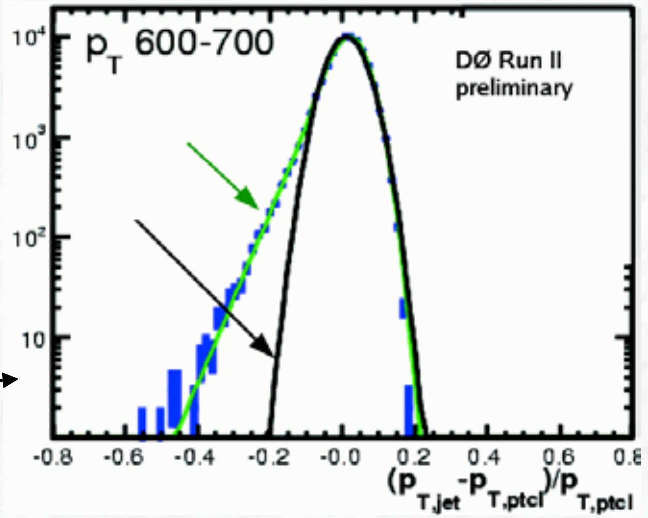
Jet measurements

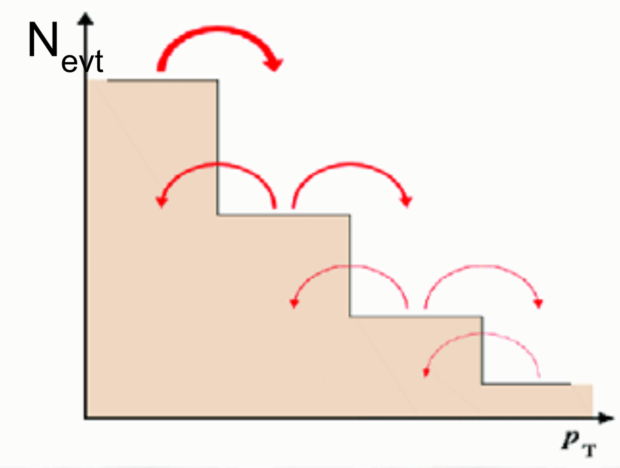
$$d^2\sigma / dp_T\, d\eta \;=\; N \;/\; (\varepsilon \cdot L \cdot \Delta p_T \cdot \Delta\eta)$$

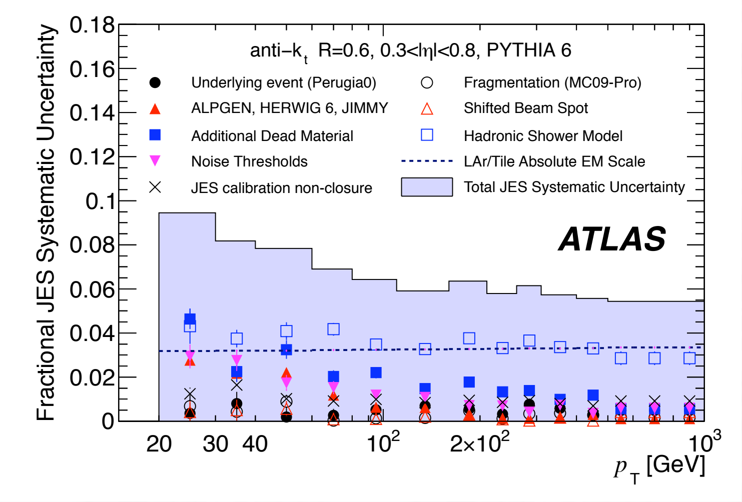
- In principle a simple counting experiment

- However, steeply falling p_T spectra are sensitive to jet energy scale uncertainties and resolution effects (migration between bins) → corrections (unfolding) to be applied

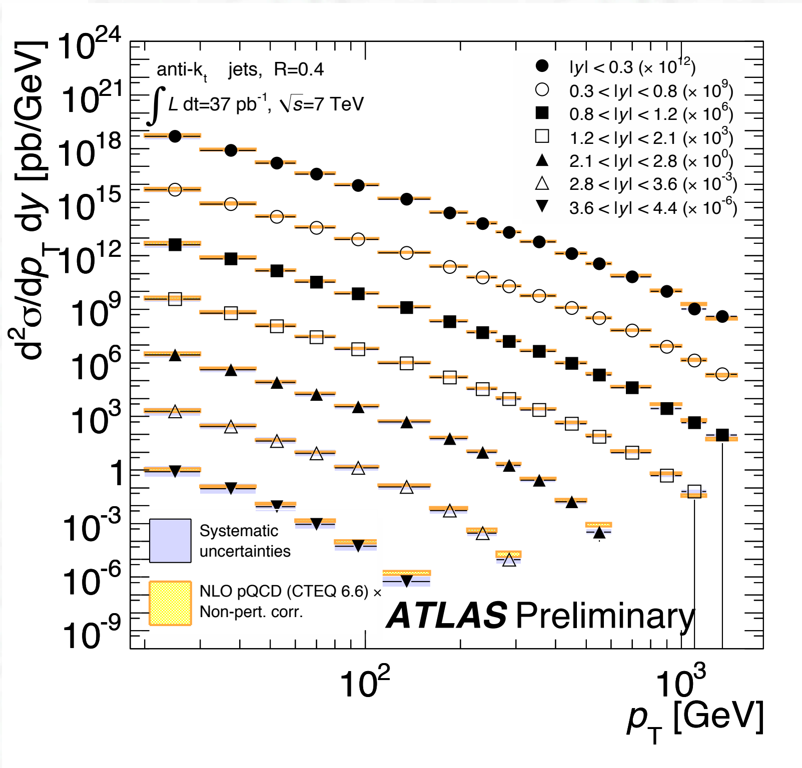
- Jet energy scale uncertainty:
  ATLAS: ~6% (after one year)
  (similar for CMS, impressive achievements)

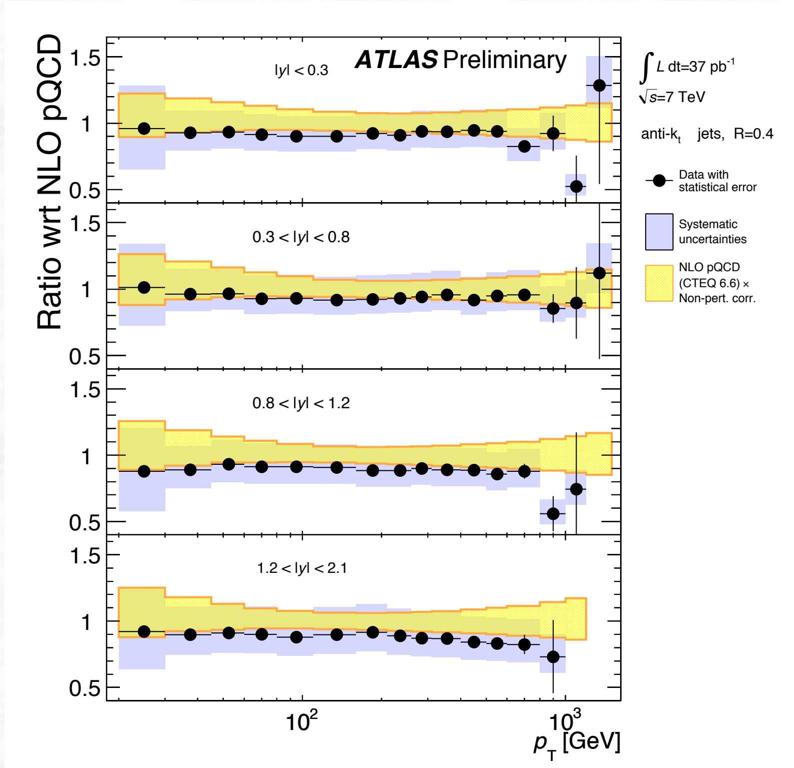






Test of QCD jet production

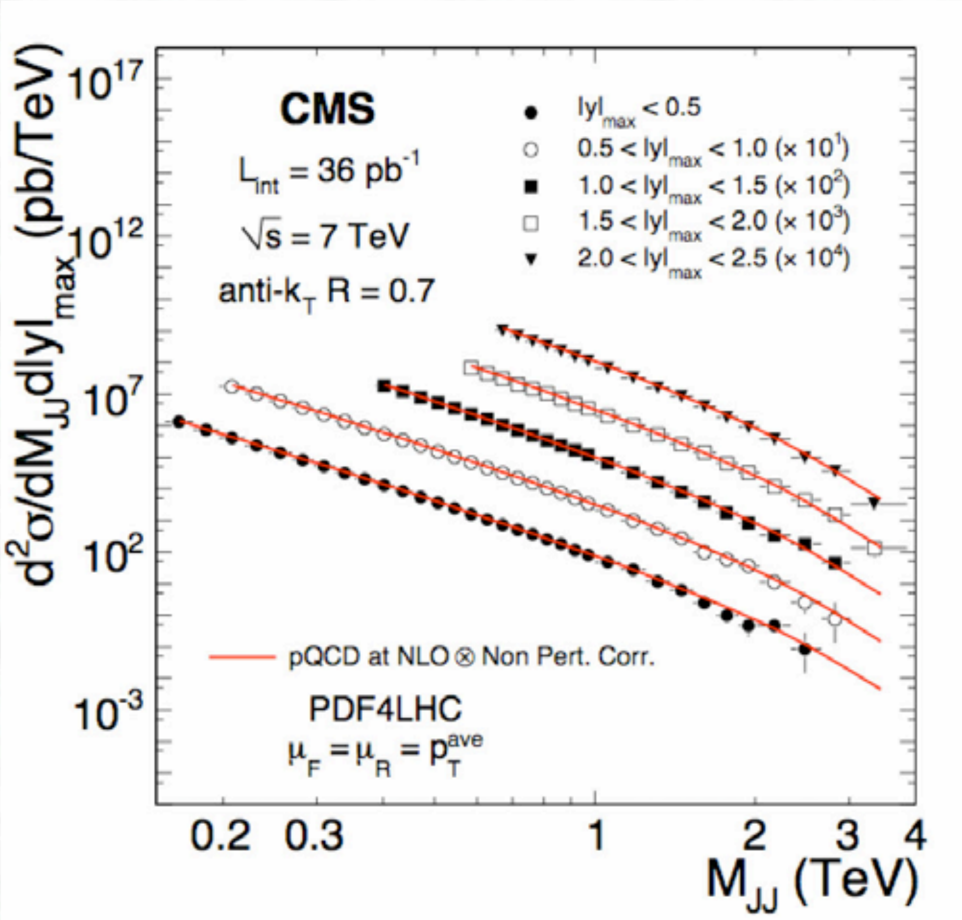




- Double differential cross section in transverse momentum (p_T) and rapidity (y)
- Very good agreement between data and NLO perturbative QCD calculations within the experimental (jet energy measurement) and theoretical uncertainties

rapidity y: $$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) = \tanh^{-1}\left(\frac{p_z}{E}\right)$$

Invariant di-jet mass spectra:



Dijet double-differential cross section as a function of dijet mass, binned in the maximum rapidity of the two leading jets, $|y|_{max}$. The data are compared to NLO pQCD calculations to which soft QCD corrections have been applied.

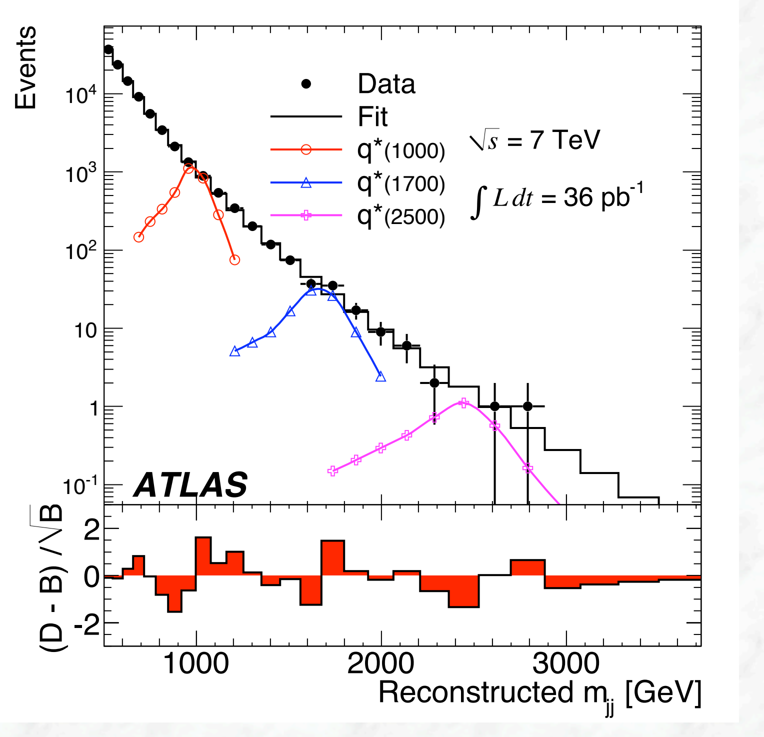
Important for:
- Test of QCD
- Search for new resonances decaying into two jets (see later)

In addition to QCD test: Sensitivity to New Physics

- Di-jet mass spectrum provides large sensitivity to new physics

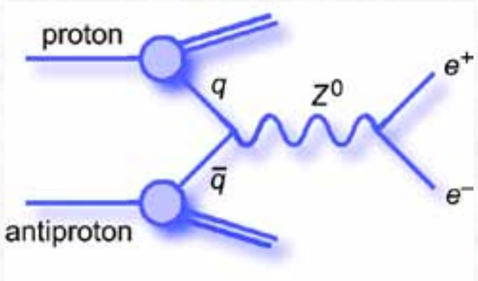
  e.g. Resonances decaying into qq, excited quarks q*, ….

- Search for resonant structures in the di-jet invariant mass spectrum

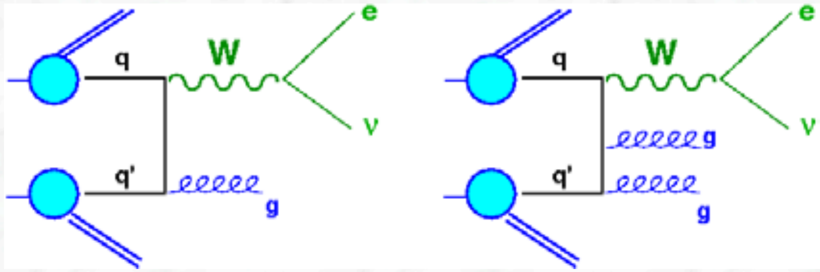


CDF (Tevatron),	L =1.13 fb^{-1}:	$0.26 < m_{q^*} < 0.87$ TeV
ATLAS (LHC),	L = 0.000315 fb^{-1}	exclude (95% C.L) q* mass interval $0.30 < m_{q^*} < 1.26$ TeV
	L = 0.036 fb^{-1}:	$0.60 < m_{q^*} < 2.64$ TeV

QCD aspects in W/Z (+ jet) production



QCD at work



- Important test of NNLO Drell-Yan QCD prediction for the total cross section

- Test of perturbative QCD in high p_T region
  (jet multiplicities, p_T spectra,….)

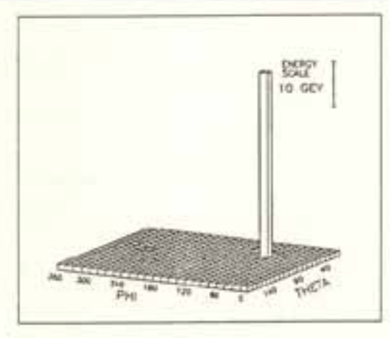
- Tuning and „calibration“ of Monte Carlos for background predictions in searches at the LHC

How do W and Z events look like ?

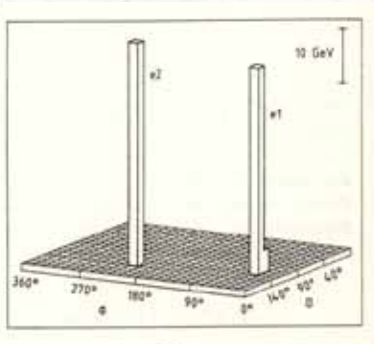
As explained, leptons, photons and missing transverse energy are key signatures at hadron colliders

→ Search for leptonic decays: **W → ℓ ν** (large $P_T(\ell)$, large P_T^{miss})
Z → ℓ ℓ

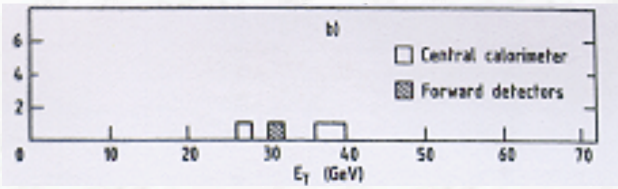
A bit of history: one of the first W events seen; UA2 experiment



W/Z discovery by the UA1 and UA2 experiments at CERN (1983/84)

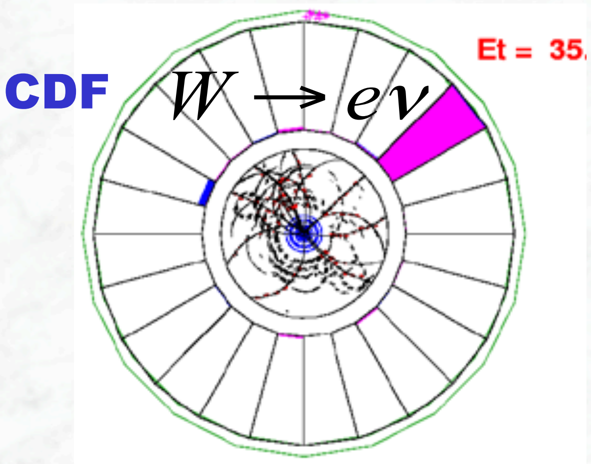


Transverse momentum of the electrons



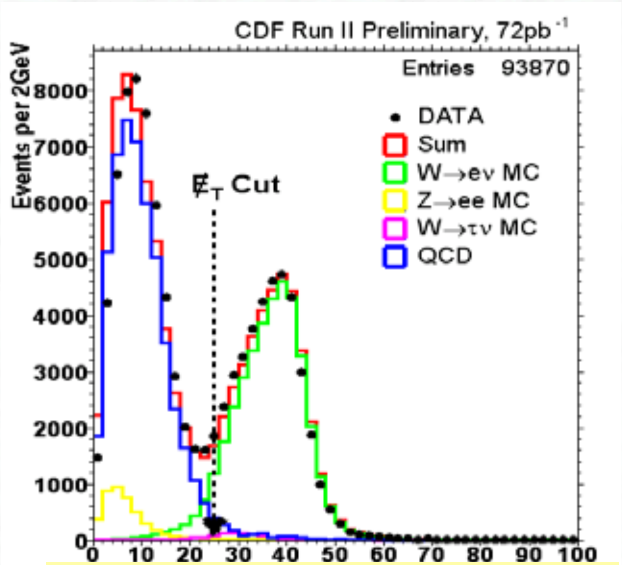
Today's W / Z $\rightarrow$ eν / ee signals

CDF Experiment, Fermilab



Trigger:

- Electron candidate > 20 GeV/c



missing transverse momentum P_T^{miss} (GeV/c)

Electrons:

- Isolated el.magn. cluster in the calorimeter
- P_T> 25 GeV/c
- Shower shape consistent with expectation for electrons
- Matched with tracks

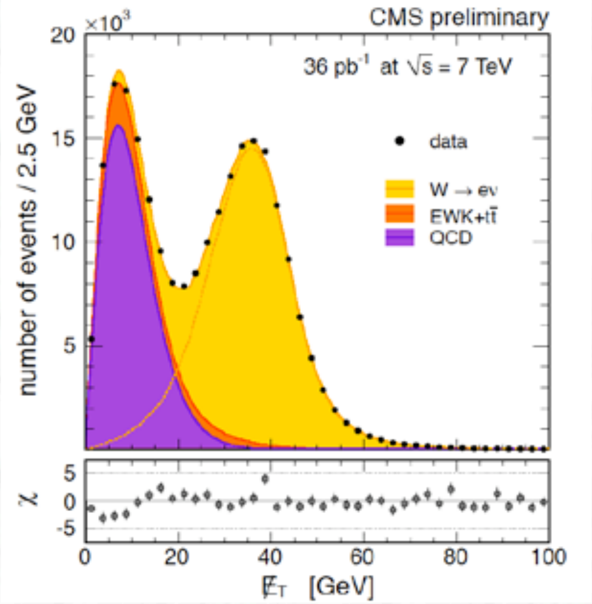
Z $\rightarrow$ ee

- 70 GeV/c^2 < m_{ee} < 110 GeV/c^2

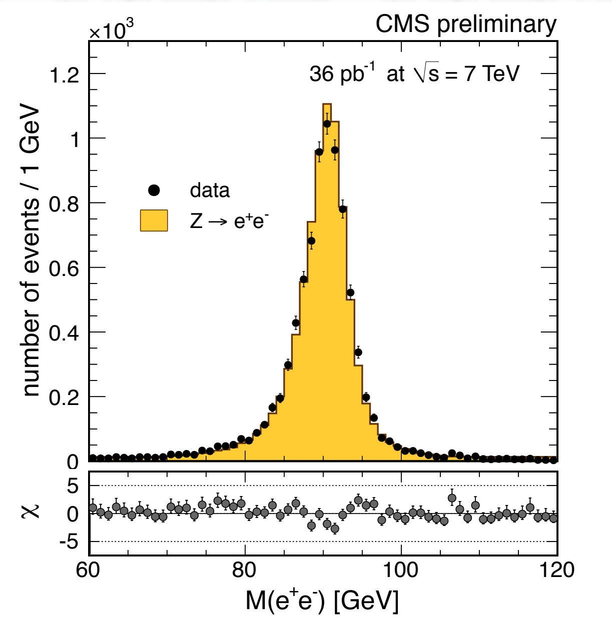
W $\rightarrow$ eν

- Missing transverse momentum > 25 GeV/c

First measurements of W/Z production at the LHC
-CMS data from 2010: 36 pb^{-1} -



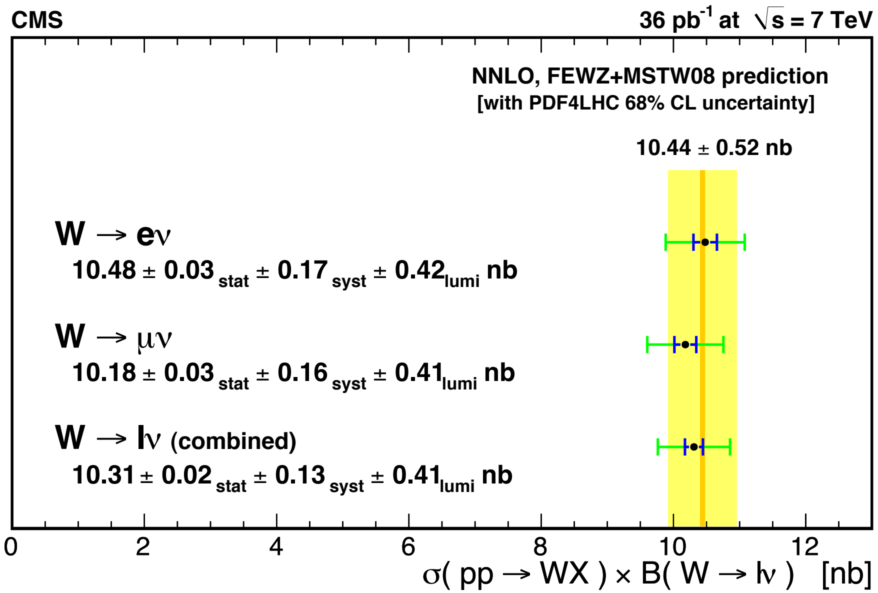
Distributions of the missing transverse energy, E_T^{miss}, of electron candidates for data and Monte-Carlo simulation, broken down into the signal and various background components.

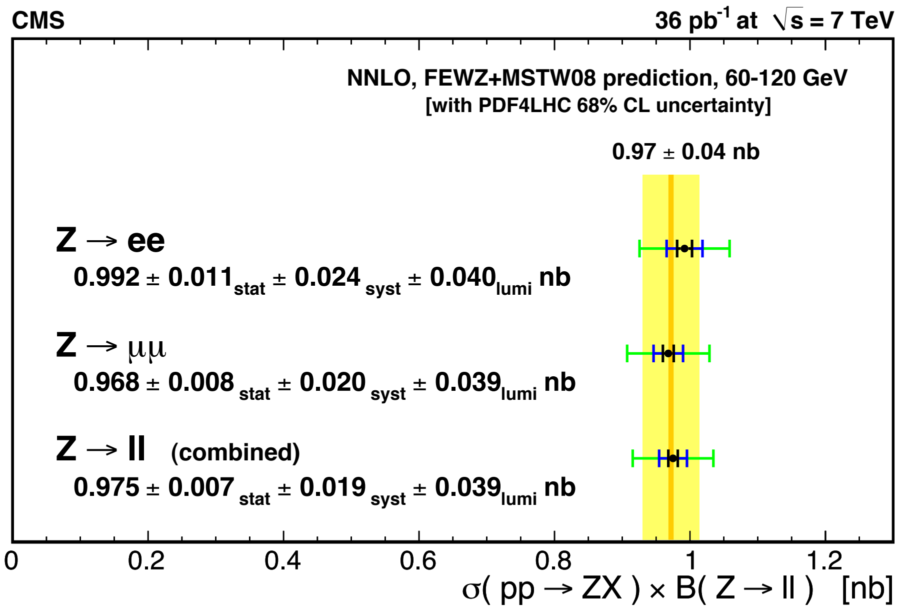


Distributions of the invariant di-electron mass, m_{ee}, for events passing the Z selection. The data are compared to Monte-Carlo simulation, the background is very small.

W and Z production cross sections at LHC

Measured cross section values in comparison to NNLO QCD predictions:

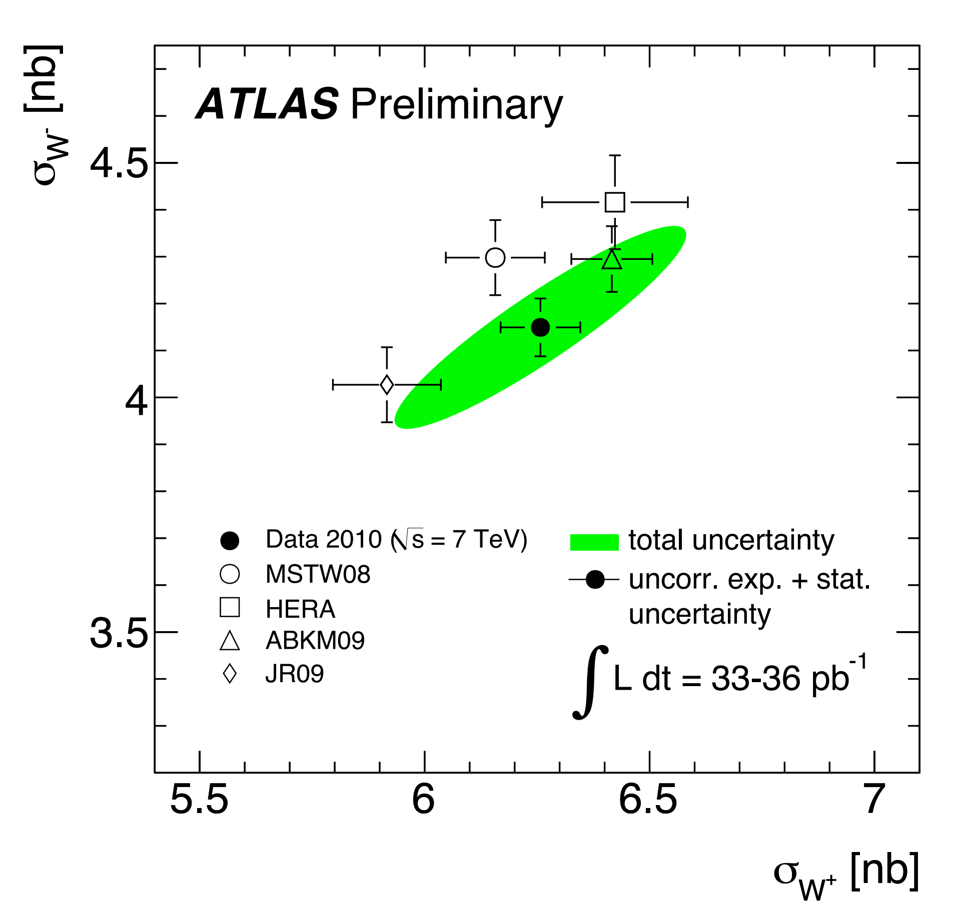




Good agreement with NNLO QCD calculations
C.R.Hamberg et al, Nucl. Phys. B359 (1991) 343.

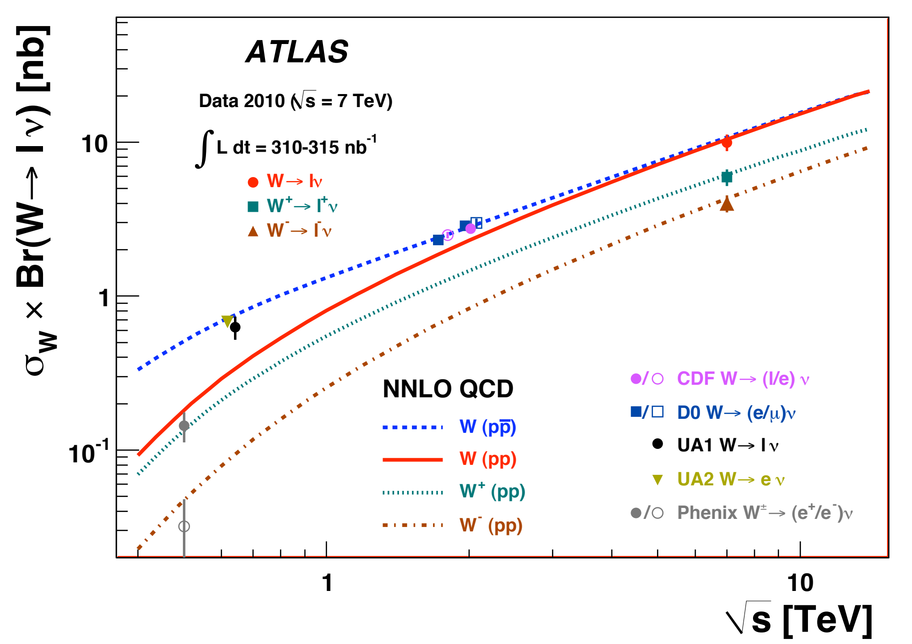
Precision is already dominated by systematic uncertainties
[The error bars represent successively the statistical, the statistical plus systematic and the total uncertainties (statistical, systematic and luminosity). All uncertainties are added in quadrature.]

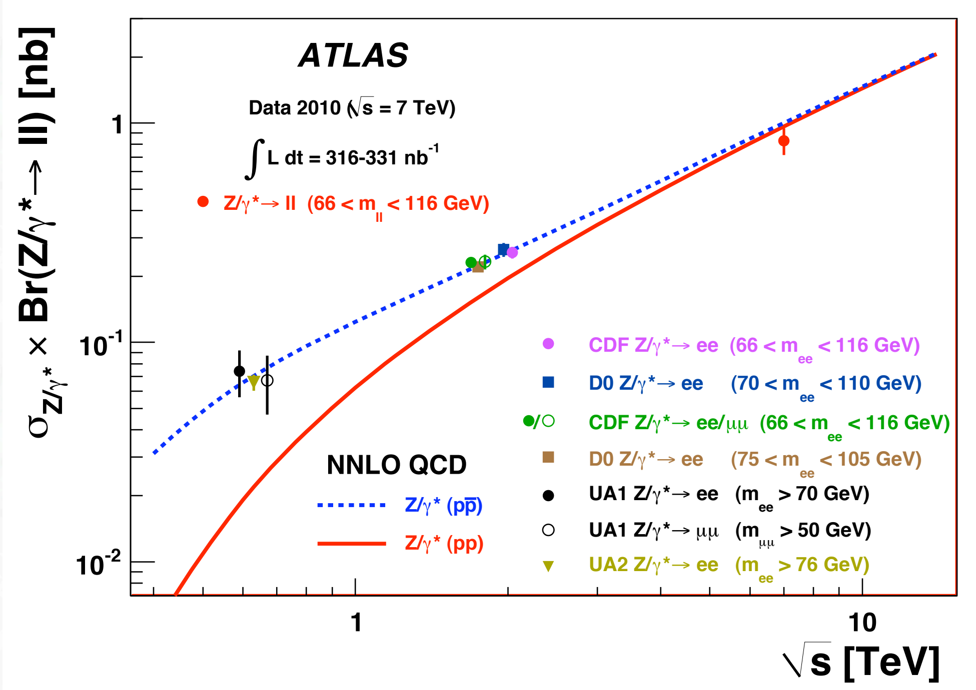
W cross sections at the LHC, charge separated



Provides important constraints on parton distributions (u, d-quark)

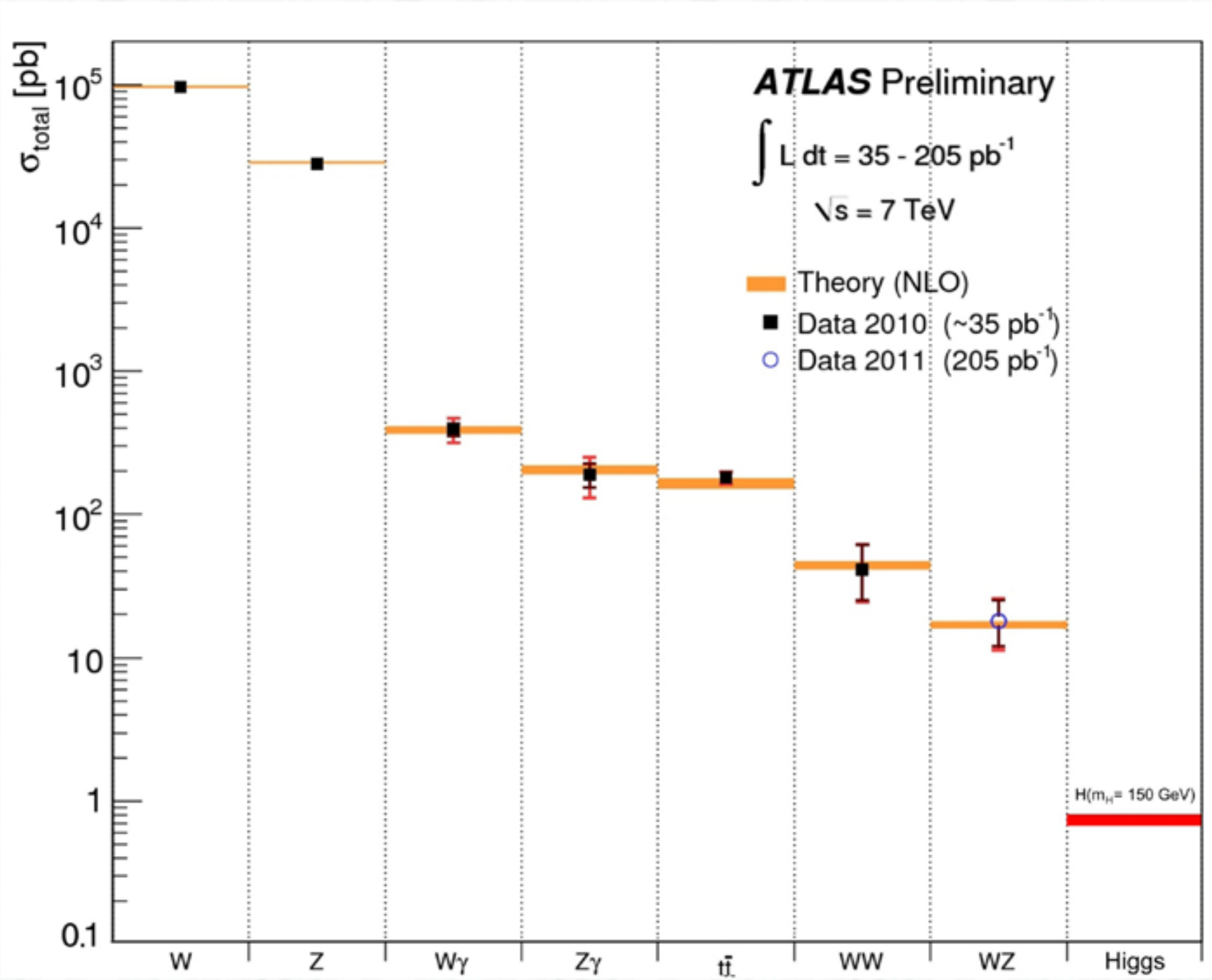
W and Z production cross sections at hadron colliders



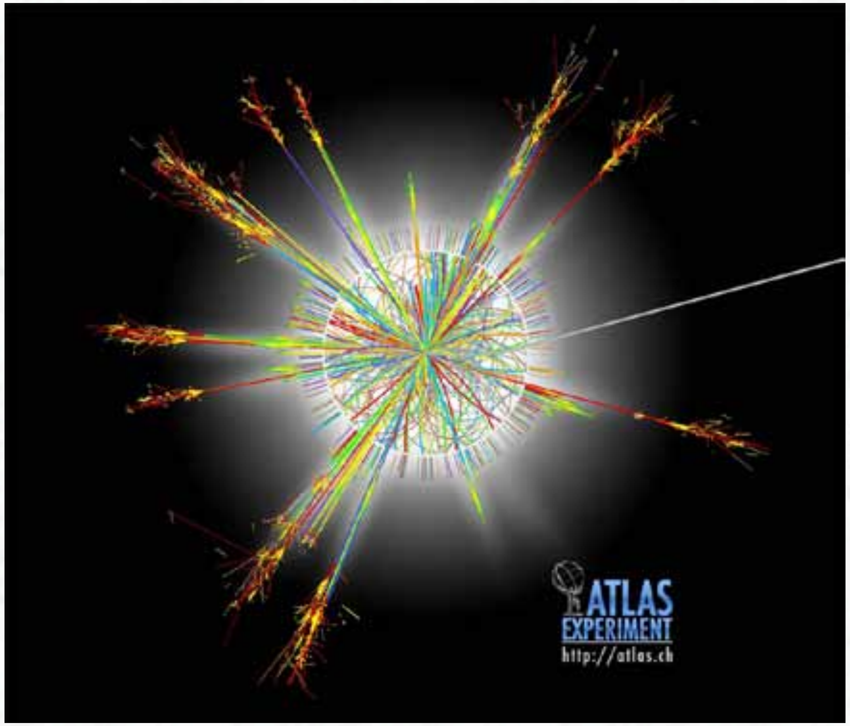


Theoretical NNLO predictions in very good agreement with the experimental measurements (for pp, ppbar and as a function of energy)

Final cross section summary



Search for
Physics Beyond the Standard Model



Why ?

1. Gravity is not yet incorporated in the Standard Model

2. Dark Matter not accomodated

3. Many open questions in the Standard Model
   - Hierarchy problem: m_W (100 GeV) $\rightarrow$ m_{Planck} (10^{19} GeV)
   - Unification of couplings
   - Flavour / family problem
   - .....

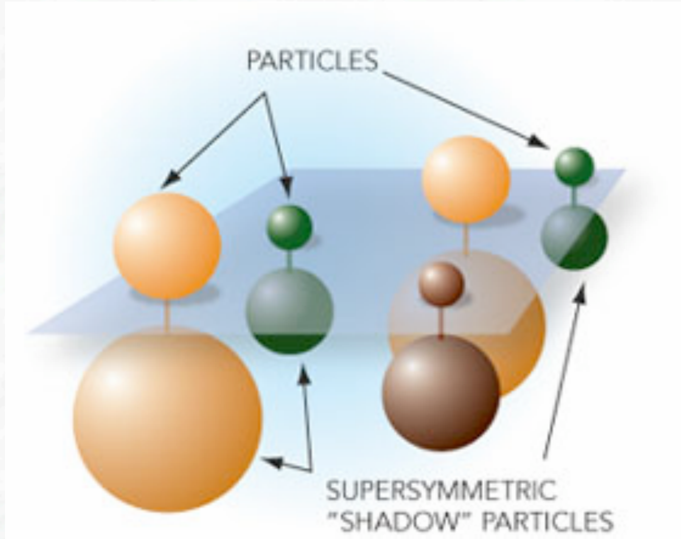
All this calls for a ***more fundamental theory*** of which the Standard Model is a low energy approximation $\rightarrow$ **New Physics**

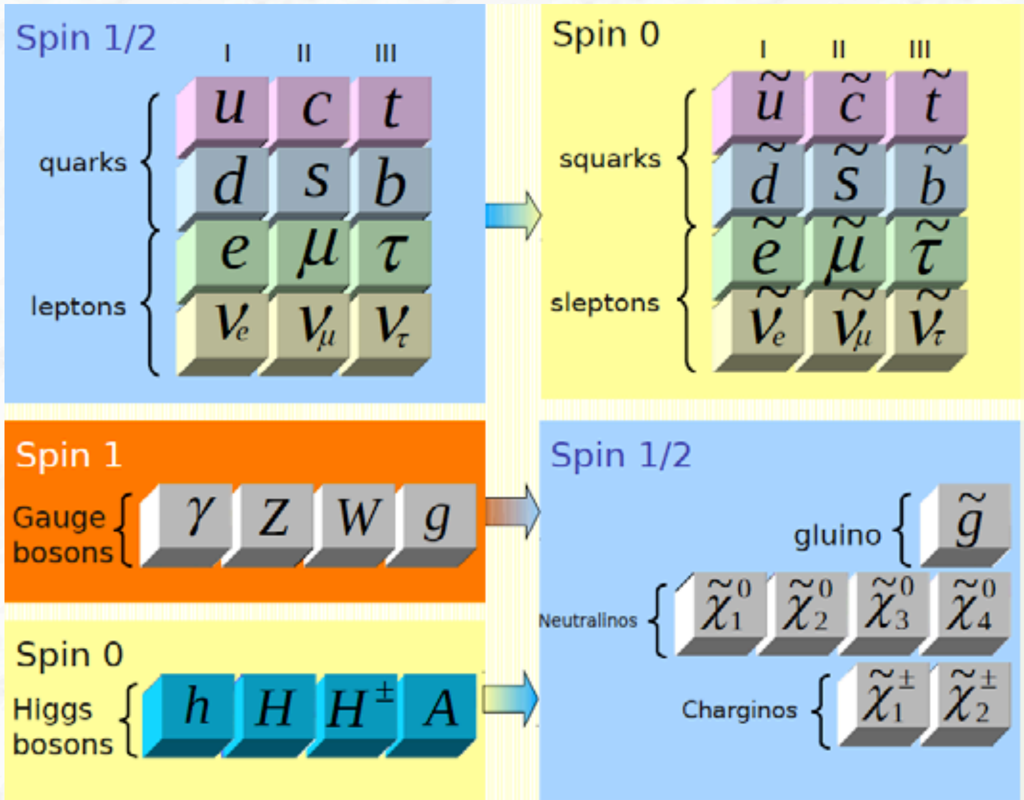
Candidate theories: Supersymmetry
Extra Dimensions
Technicolor
....

Many extensions predict new physics at the TeV scale !!

Strong motivation for LHC, mass reach ~ 3 TeV

Search for Supersymmetry





Experimental consequences of R-parity conservation:

- SUSY particles are produced in pairs
- Lightest Supersymmetric Particle (LSP) is stable.

LSP is only weakly interacting:
LSP $\equiv \chi^0{}_1$ (lightest neutralino, in many models)

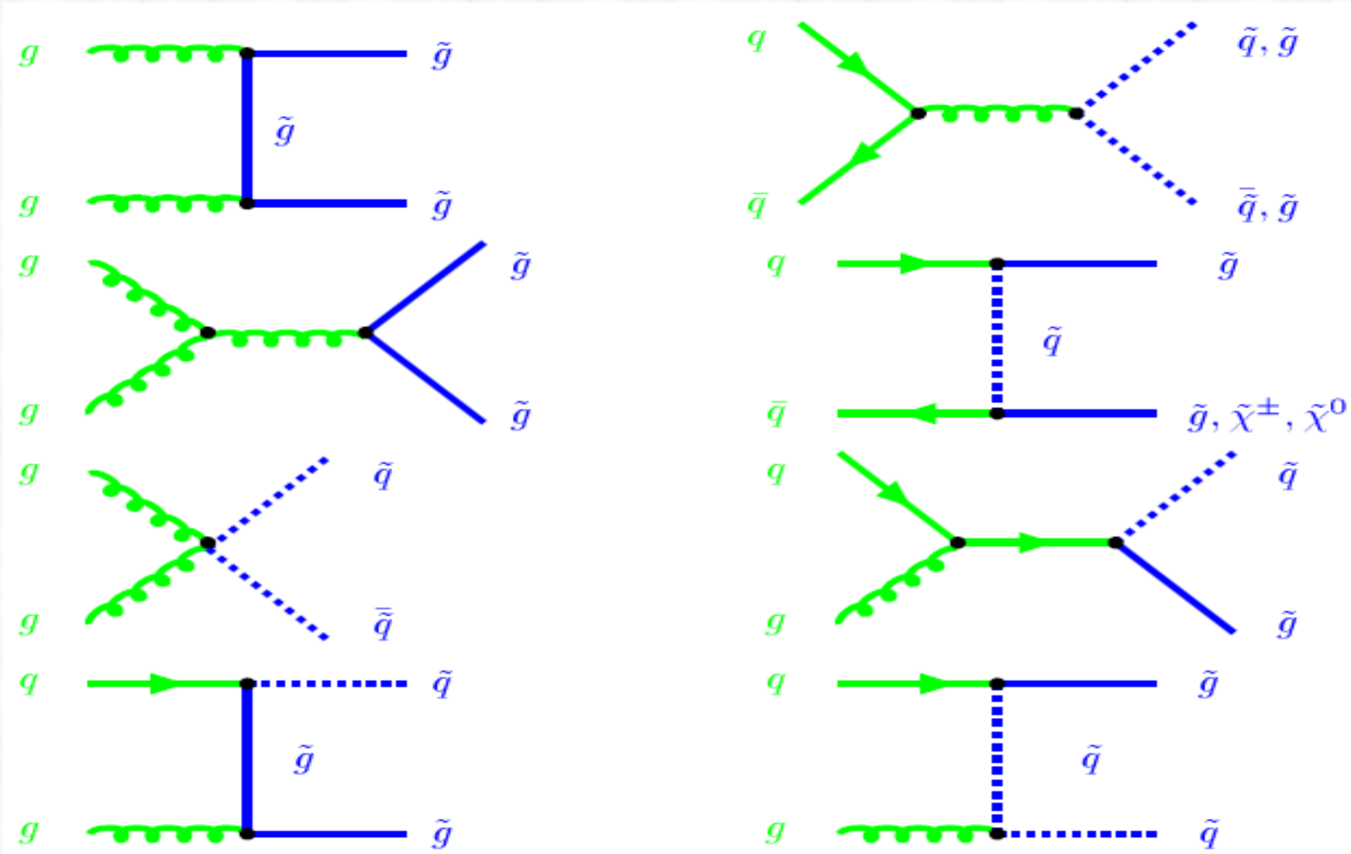
$\rightarrow$ LSP behaves like a ν $\rightarrow$ it escapes detection

$\rightarrow$ E_T^{miss} (typical SUSY signature)

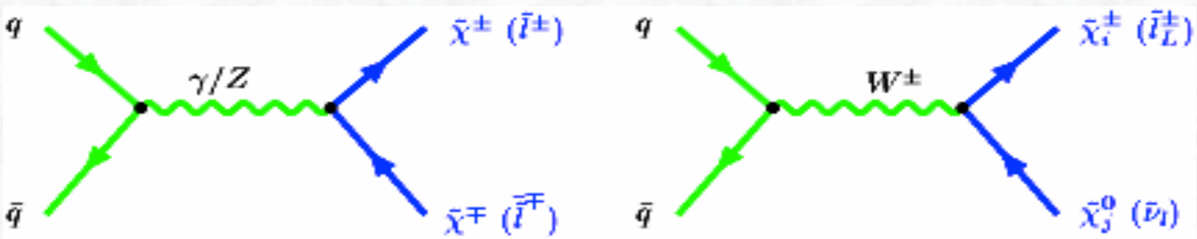
Sparticle production at the LHC

qq, qg and gg
in the initial state

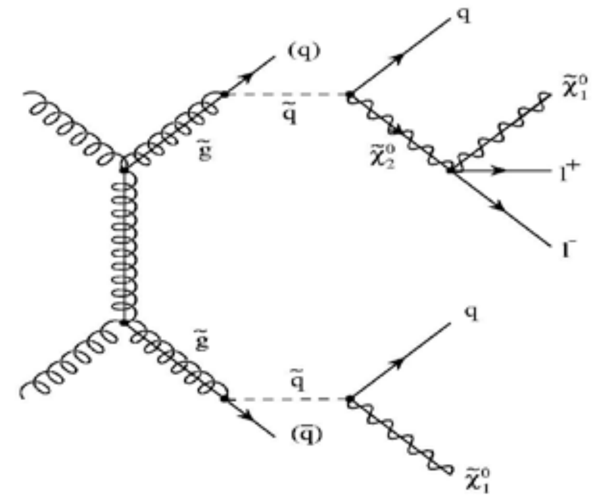
→ production
of coloured SUSY
particles dominant,
via strong interaction



Drell-Yan production
of sleptons, charginos
and neutralinos
(lower cross sections)



Search for Supersymmetry at the LHC

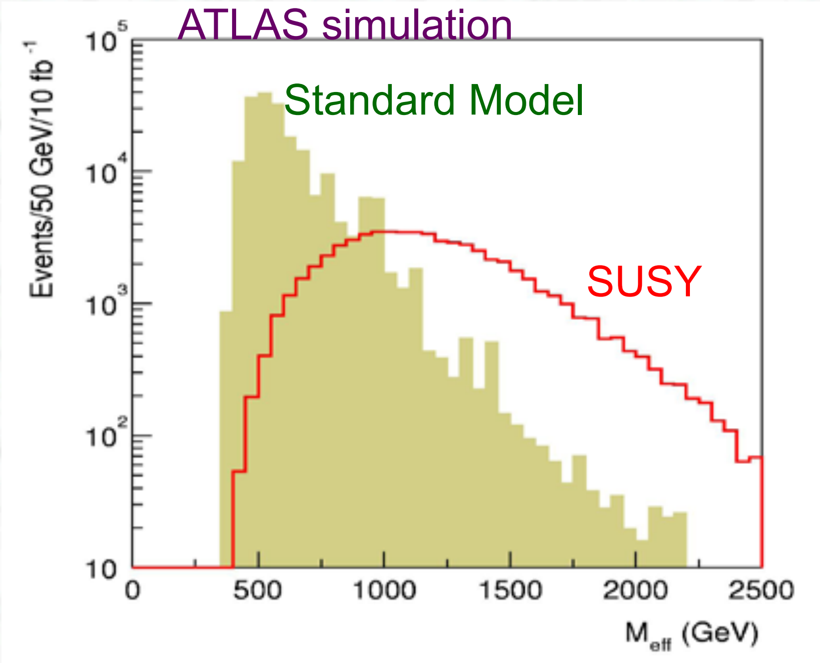


⇒ combination of
Jets, leptons, E_T^{miss}

Weakly interacting LSP
→ missing transverse energy

Search for deviations from the Standard Model, e.g. excess of events with large “missing transverse energy”

The SUSY partners of quarks and gluons can be copiously produced via the strong interaction



What do the LHC data say ?

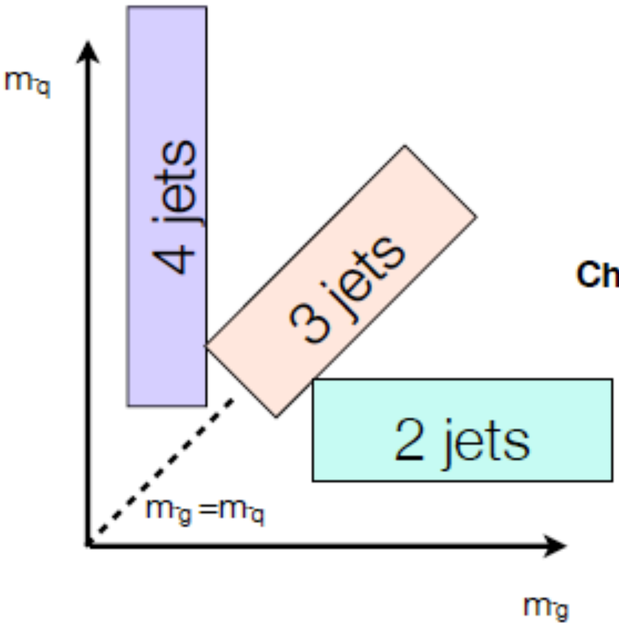
First results on the search for E_T^{miss} + jets (1.04 fb^{-1})

(large part of 2011 data already included)

Selection of events with E_T^{miss} + jets

Split the analysis according to jet multiplicities: 2, 3 and 4 jets
(different sensitivity for different squark/gluino mass combinations,
i.e. in different regions of SUSY parameter space)

Definition of signal regions:



	Signal Region	≥ 2 jets	≥ 3 jets	≥ 4 jets	High mass
Trigger requirements	E_T^{miss}	> 130	> 130	> 130	> 130
	Leading jet p_T	> 130	> 130	> 130	> 130
Channel definition	Second jet p_T	> 40	> 40	> 40	> 80
	Third jet p_T	–	> 40	> 40	> 80
	Fourth jet p_T	–	–	> 40	> 80
Reduce QCD	$\Delta\phi(\mathrm{jet}, E_T^{miss})_{min}$	> 0.4	> 0.4	> 0.4	> 0.4
	E_T^{miss}/m_{eff}	> 0.3	> 0.25	> 0.25	> 0.2
Enhance signal	m_{eff} [GeV]	> 1000	> 1000	> 500/1000	> 1100

$$m_{eff} = \sum_{i=1}^{n} |\vec{p}_T^{\,jet\ i}| + E_T^{miss}$$

First results on the search for E_T^{miss} + jets (1.04 fb^{-1})

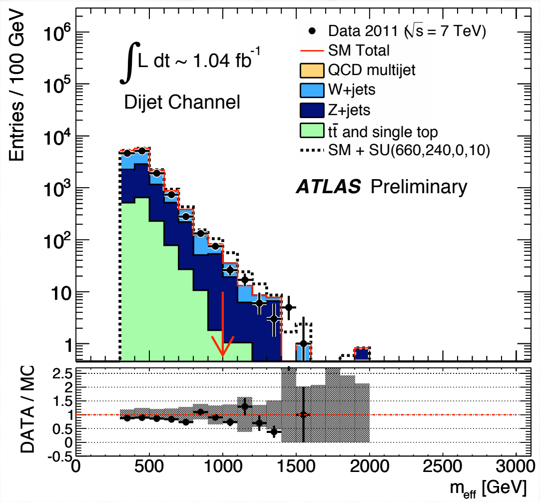
(large part of 2011 data already included)

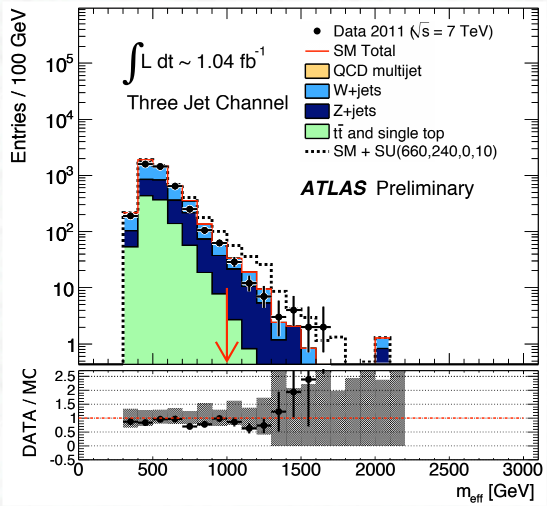
Process	Signal Region				
	$\geq$ 2-jet	$\geq$ 3-jet	$\geq$ 4-jet, m_{eff} > 500 GeV	$\geq$ 4-jet, m_{eff} > 1000 GeV	High mass
Z/γ+jets	$32.5 \pm 2.6 \pm 6.8$	$25.8 \pm 2.6 \pm 4.9$	$208 \pm 9 \pm 37$	$16.2 \pm 2.1 \pm 3.6$	$3.3 \pm 1.0 \pm 1.3$
W+jets	$26.2 \pm 3.9 \pm 6.7$	$22.7 \pm 3.5 \pm 5.8$	$367 \pm 30 \pm 126$	$12.7 \pm 2.1 \pm 4.7$	$2.2 \pm 0.9 \pm 1.2$
$t\bar{t}$+ Single Top	$3.4 \pm 1.5 \pm 1.6$	$5.6 \pm 2.0 \pm 2.2$	$375 \pm 37 \pm 74$	$3.7 \pm 1.2 \pm 2.0$	$5.6 \pm 1.7 \pm 2.1$
QCD jets	$0.22 \pm 0.06 \pm 0.24$	$0.92 \pm 0.12 \pm 0.46$	$34 \pm 2 \pm 29$	$0.74 \pm 0.14 \pm 0.51$	$2.10 \pm 0.37 \pm 0.83$
Total	$62.3 \pm 4.3 \pm 9.2$	$55 \pm 3.8 \pm 7.3$	$984 \pm 39 \pm 145$	$33.4 \pm 2.9 \pm 6.3$	$13.2 \pm 1.9 \pm 2.6$
Data	58	59	1118	40	18

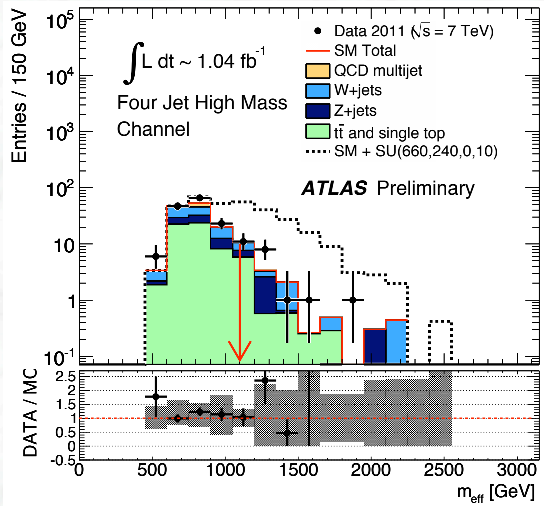
Observed and expected event numbers (from Standard Model processes)

dominant backgrounds:
- W/Z + jets
- tt production

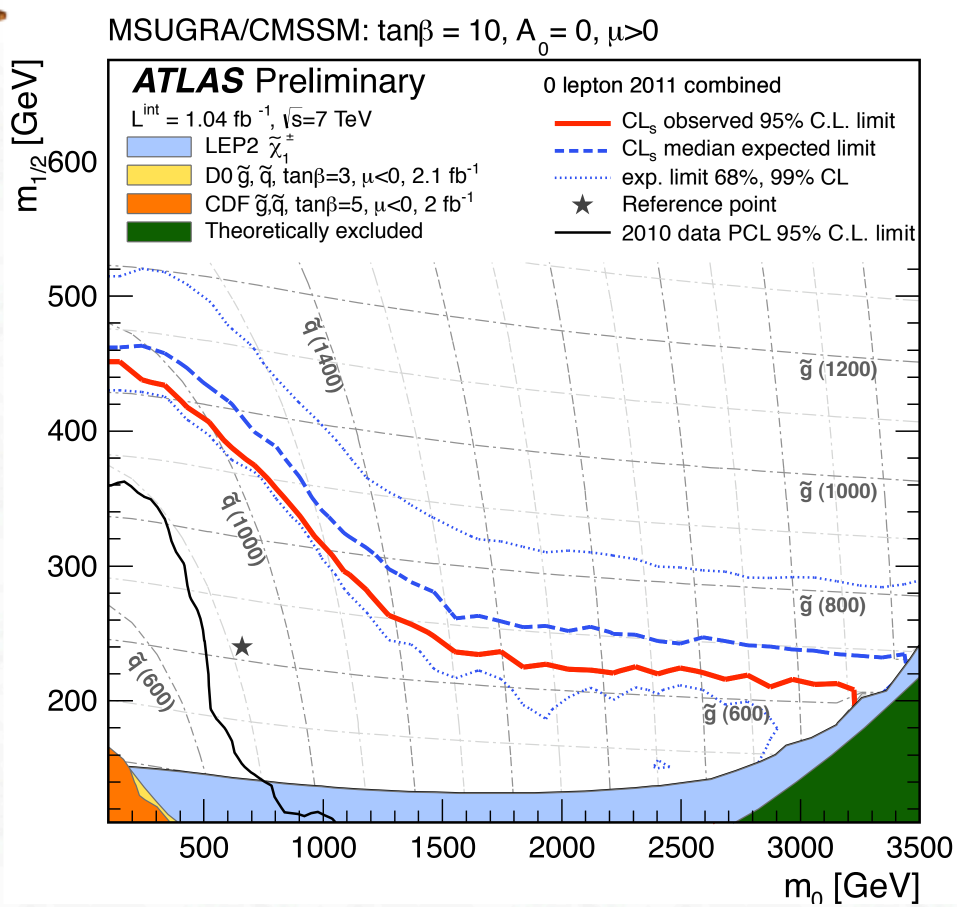
Normalized in control regions !
(as explained on the previous slide)







mSUGRA interpretation



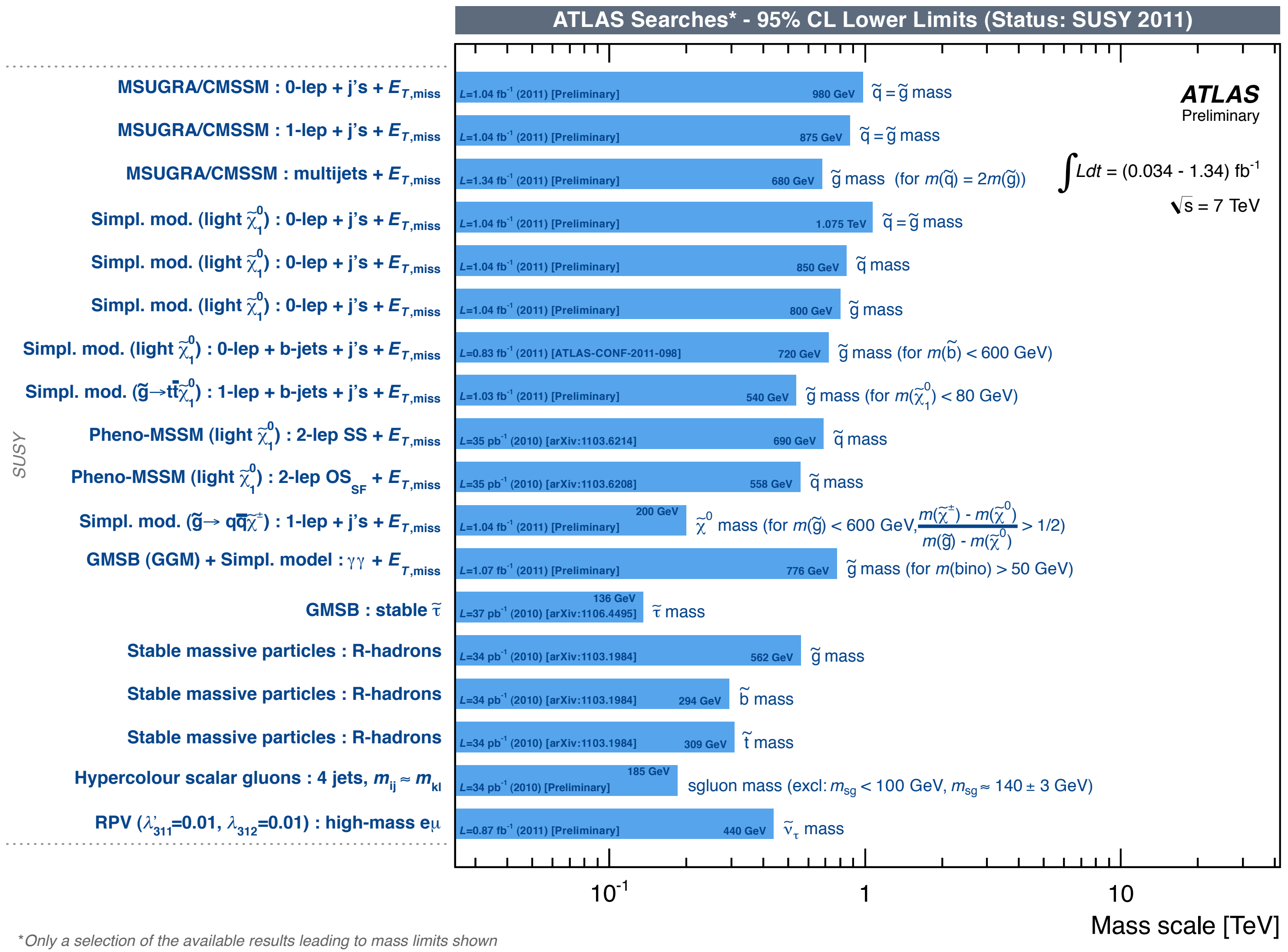
$\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

The channel (2, 3, 4, jets) with the best expected limit is taken at each point in parameter space

MSSM/cMSSM interpretation (for equal squark and gluino masses):

L = 1.04 fb^{-1}: m(squark), m(gluino) > 980 GeV

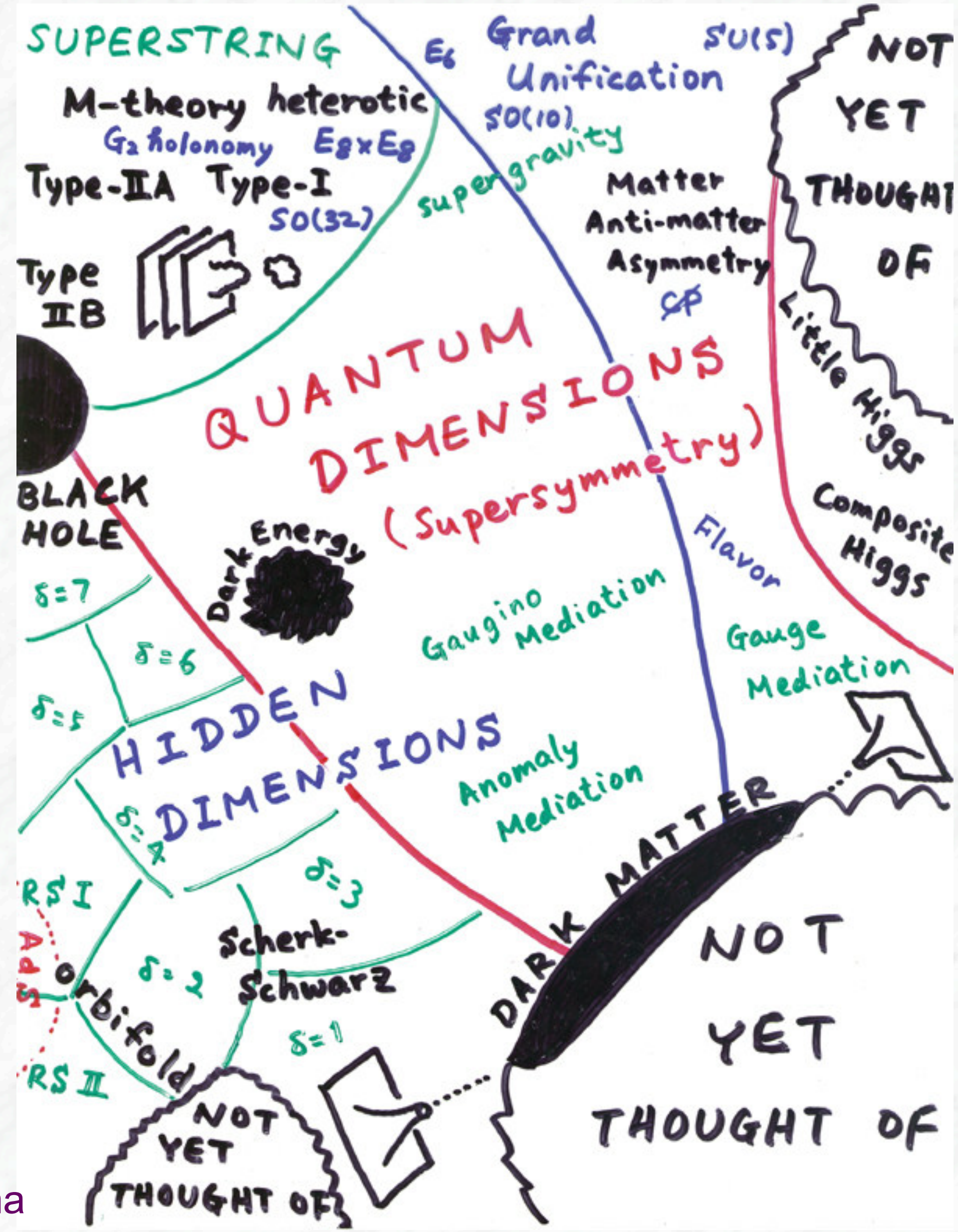
Summary of R-parity conserving SUSY searches in ATLAS



*Only a selection of the available results leading to mass limits shown

Other Extensions of the Standard Model

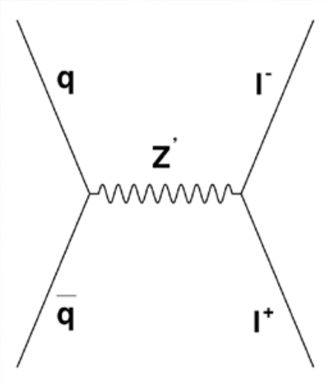
- Additional Gauge bosons, Z' and W' searches
- Search for signals from Extra Dimensions



Hitoshi Murayama

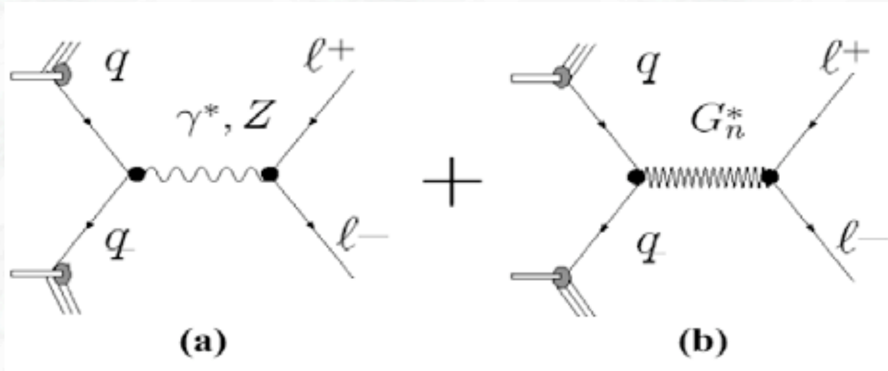
Search for new, high-mass di-lepton resonances

- Additional neutral Gauge Boson Z´



- Randall-Sundrum narrow Graviton resonances decaying to di-lepton

  appear in Extra Dim. Scenarios



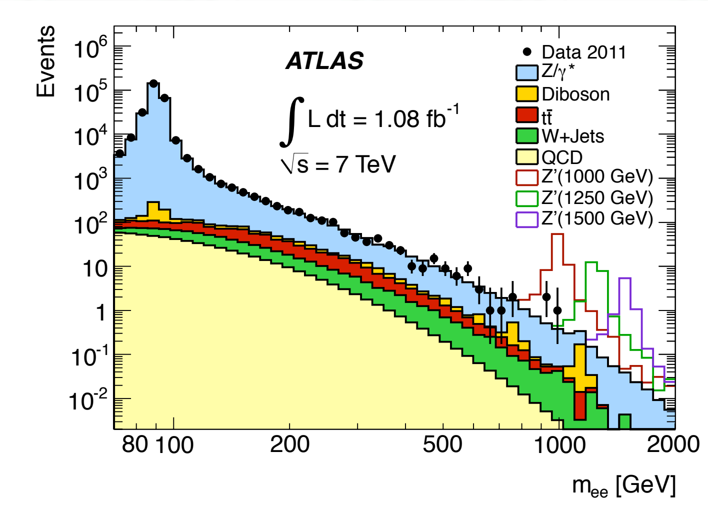
Standard Model background process

Signal

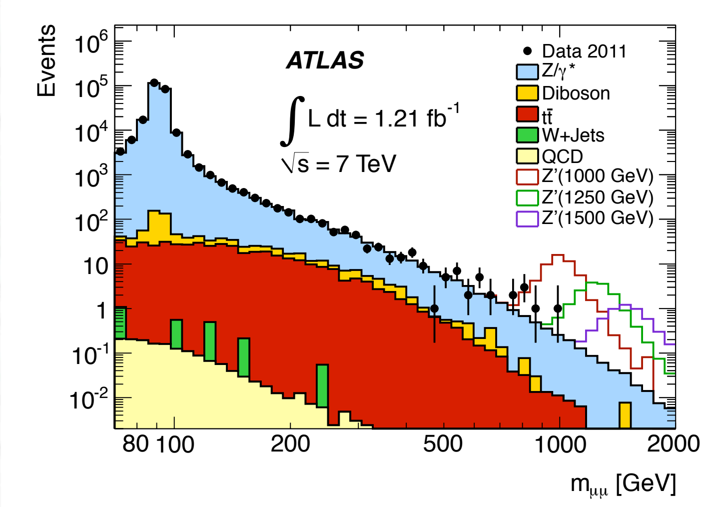
- Identical final state (two leptons), same analysis, interpretation for different theoretical models
- Main background process: Drell-Yan production of lepton pairs

Search for New Resonances in High Mass Di-leptons

Di-electron invariant mass



Di-muon invariant mass



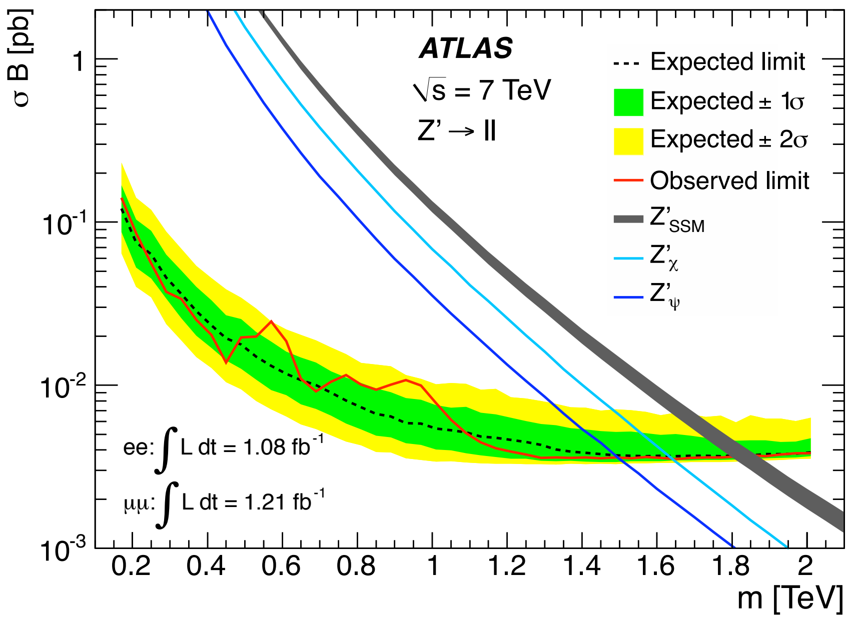
Data are consistent with background from SM processes. No excess observed.

Detailed numbers on signal and background for the ee channel:

$m_{e^+e^-}$ [GeV]	70-110	110-200	200-400	400-800	800-3000
DY	258482 ± 410	5449 ± 180	613 ± 26	53.8 ± 3.1	2.8 ± 0.1
$t\bar{t}$	218 ± 36	253 ± 10	82 ± 3	5.4 ± 0.3	0.1 ± 0.0
Diboson	368 ± 19	85 ± 5	29 ± 2	3.1 ± 0.5	0.3 ± 0.1
W+jets	150 ± 100	150 ± 26	43 ± 10	4.6 ± 1.8	0.2 ± 0.4
QCD	332 ± 59	191 ± 75	36 ± 29	1.8 ± 1.4	< 0.05
Total	259550 ± 510	6128 ± 200	803 ± 40	68.8 ± 3.9	3.4 ± 0.4
Data	259550	6117	808	65	3

Drell-Yan background can be normalized in the Z peak region, 70-110 GeV

Interpretation in the SSM and E6 models:



Resulting mass limits: ee + μμ
95% C.L.

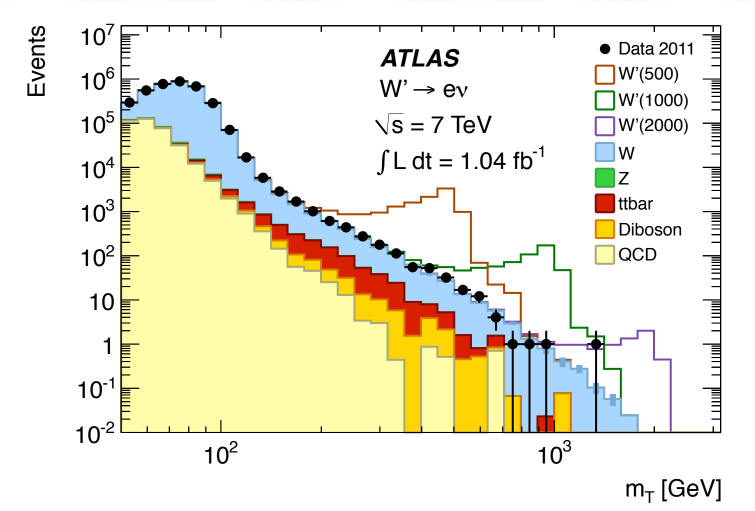
Sequential SM: $m_{Z'} > 1.83$ TeV
E_6 models: $m_{Z'} > 1.49 – 1.63$ TeV

Summary of 95% C.L. SSM exclusion limits from various experiments:

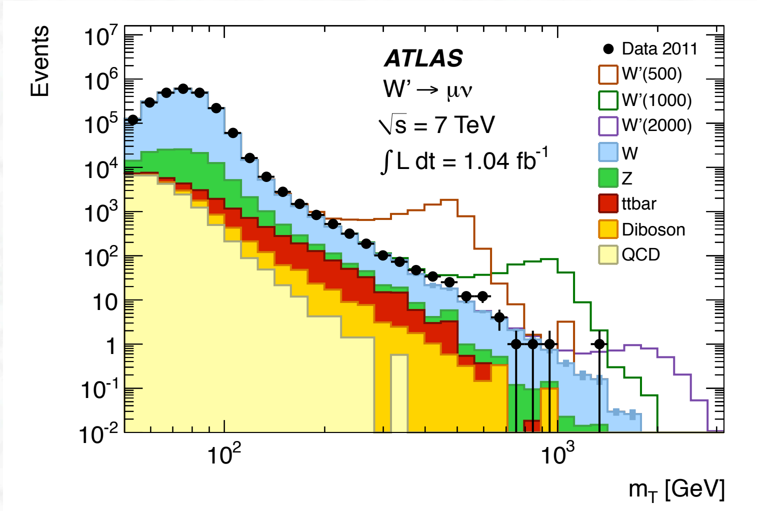
95% C.L. limits (SM couplings)		ee	μμ	ll combined
CDF / D0	5.3 fb^{-1}			1.07 TeV
ATLAS	0.036 fb^{-1}	0.96 TeV	0.83 TeV	1.05 TeV
ATLAS	1.1 / 1.2 fb^{-1}	1.70 TeV	1.61 TeV	1.83 TeV
CMS	1.1 fb^{-1}			1.94 TeV

Search for New Resonances in High Mass lν events (W')

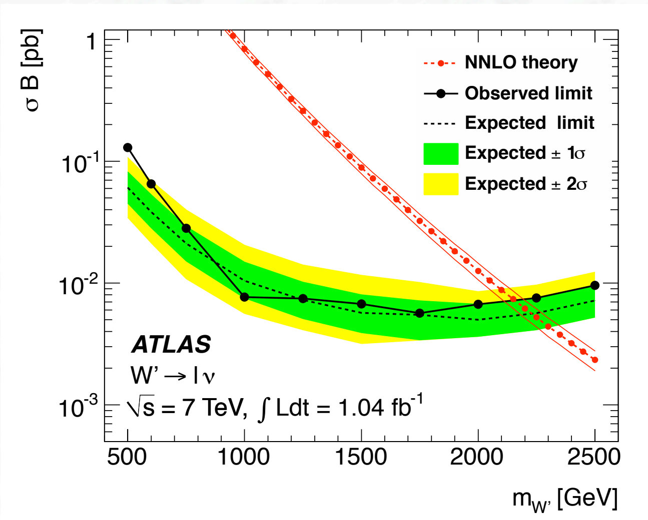
Transverse mass (e, E_T^{miss})



Transverse mass (μ, E_T^{miss})

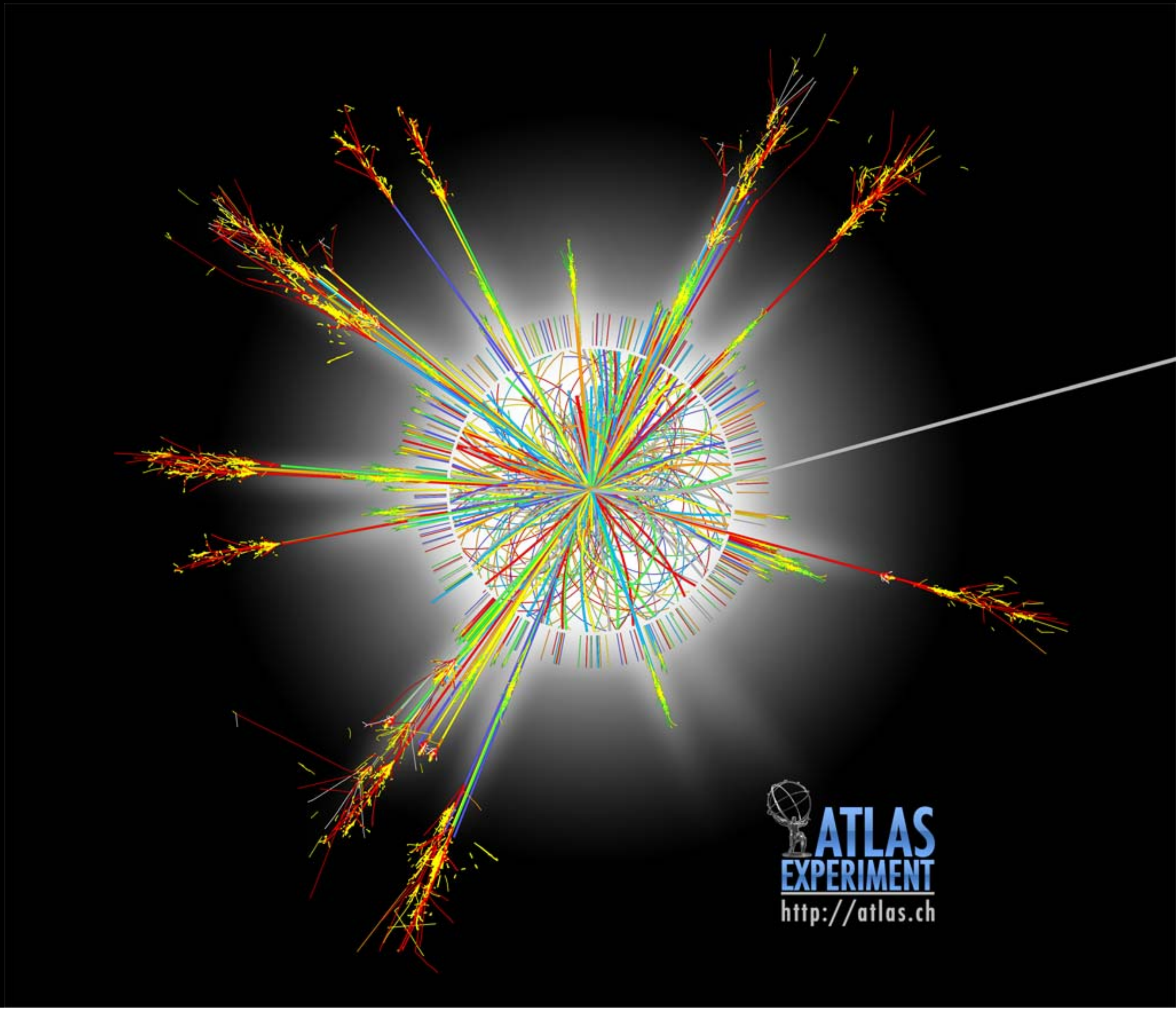


Data are consistent with background from SM processes. No excess observed.



95% C.L. limits (SM couplings)		ll combined
ATLAS	1.1 fb^{-1}	2.23 TeV
CMS	1.1 fb^{-1}	2.27 TeV

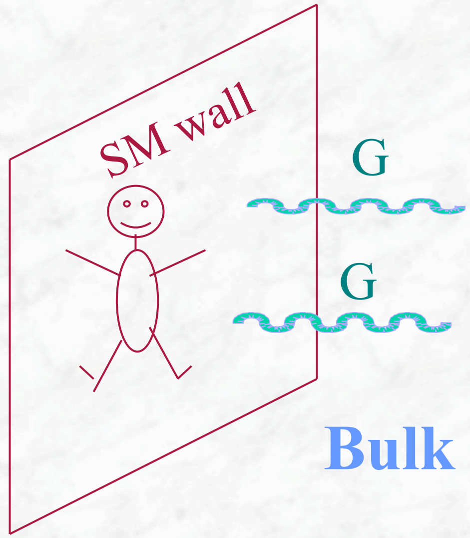
Microscopic-Black Hole Events at the LHC ?



Can LHC probe extra dimensions ?

- Much recent theoretical interest in models with extra dimensions
  (Explain the weakness of gravity, or the hierarchy problem, by extra dimensions)

- New physics, scale of gravity M_D, can appear at the TeV-mass scale, i.e. accessible at the LHC

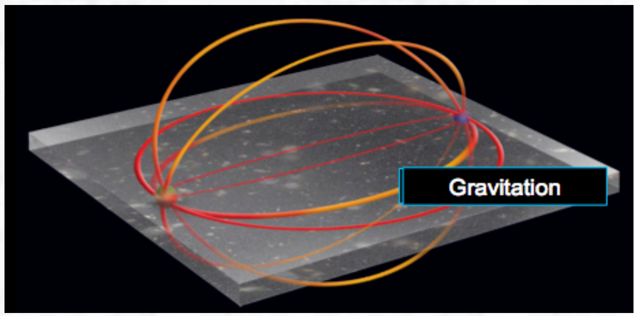


- Extra dimensions are compactified on a torus or sphere with radius r

  relation between Planck mass in 4 and (4+n) dimensions: $$M_{\mathrm{Pl}}^2 = 8\pi M_D^{n+2} r^n$$

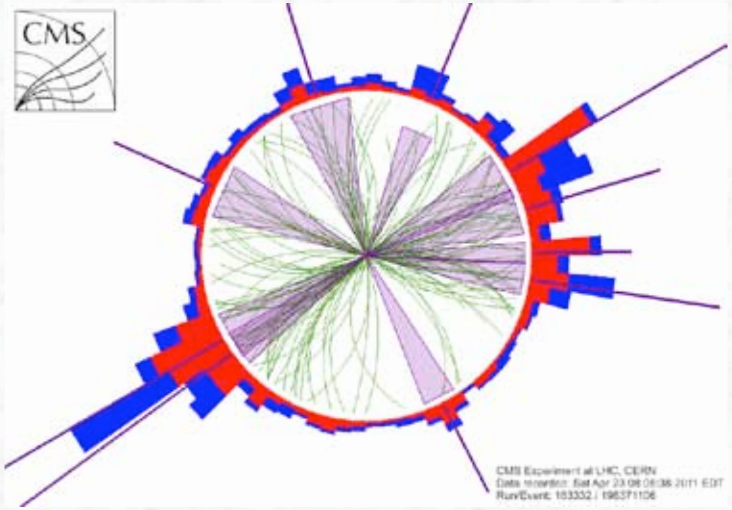
- Black hole formation at energies greater than M_D

  Production cross section can be in the order of 100 pb for M_D ~1 TeV (large model dependence)



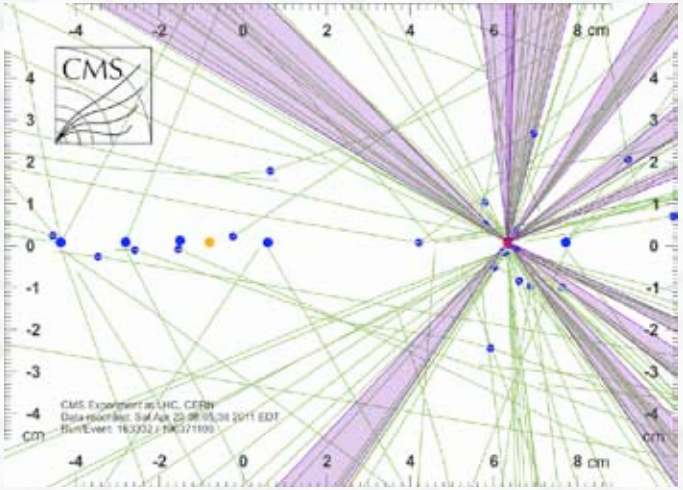
- Once produced, the black hole is expected to decay via Hawking radiation, democratically to all Standard Model particles (quarks and gluons dominant,75%)
  → multijet events with large mass and total transverse energy

CMS search for events with high jet multiplicity and large transverse energy



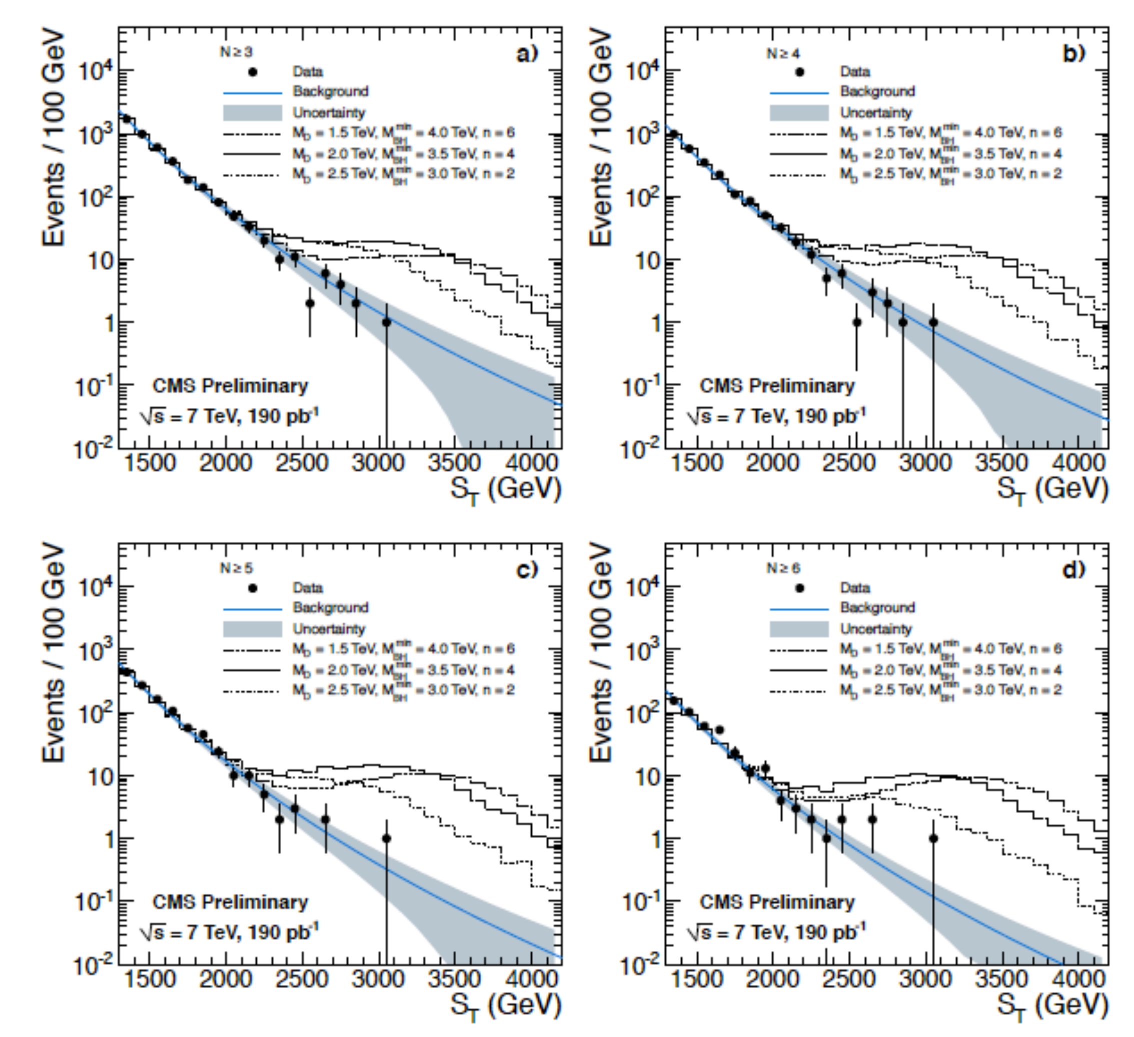
Candidate events exist….

event with high multiplicity of jets, high mass….



all particles coming from one interaction vertex

Is there an excess above the expectation from QCD production?



Total transverse energy S_T for events with N>3, 4, 5, 6 objects

No evidence for excess above the QCD expectations
→ No evidence for the formation of micro Black Holes

Conclusions

- With the operation of the LHC at high energies, particle physics has entered a new era

- Detectors and accelerator work extremely well;
  Already 5 fb^{-1} of data collected (more than expected at the running time we are)

- Many Standard Model measurements have already been performed in 2010/11, (important for searches for new physics, precision will increase with more data)

  The Standard Model is still alive

- LHC has reached the threshold for new discoveries; higher sensitivity than the Tevatron in searches. Sensitivity for the Standard Model Higgs boson reached.

- 2012 will be an exciting year,
  LHC will come to a conclusion on the Standard Model Higgs boson
  and will largely extend the range for new particle searches.

There are very exciting times ahead of us !!

We hope that many of you will join us in the discovery enterprise

• In case you have any questions:
please do not hesitate to contact me: karl.jakobs@uni-freiburg.de

End of lectures