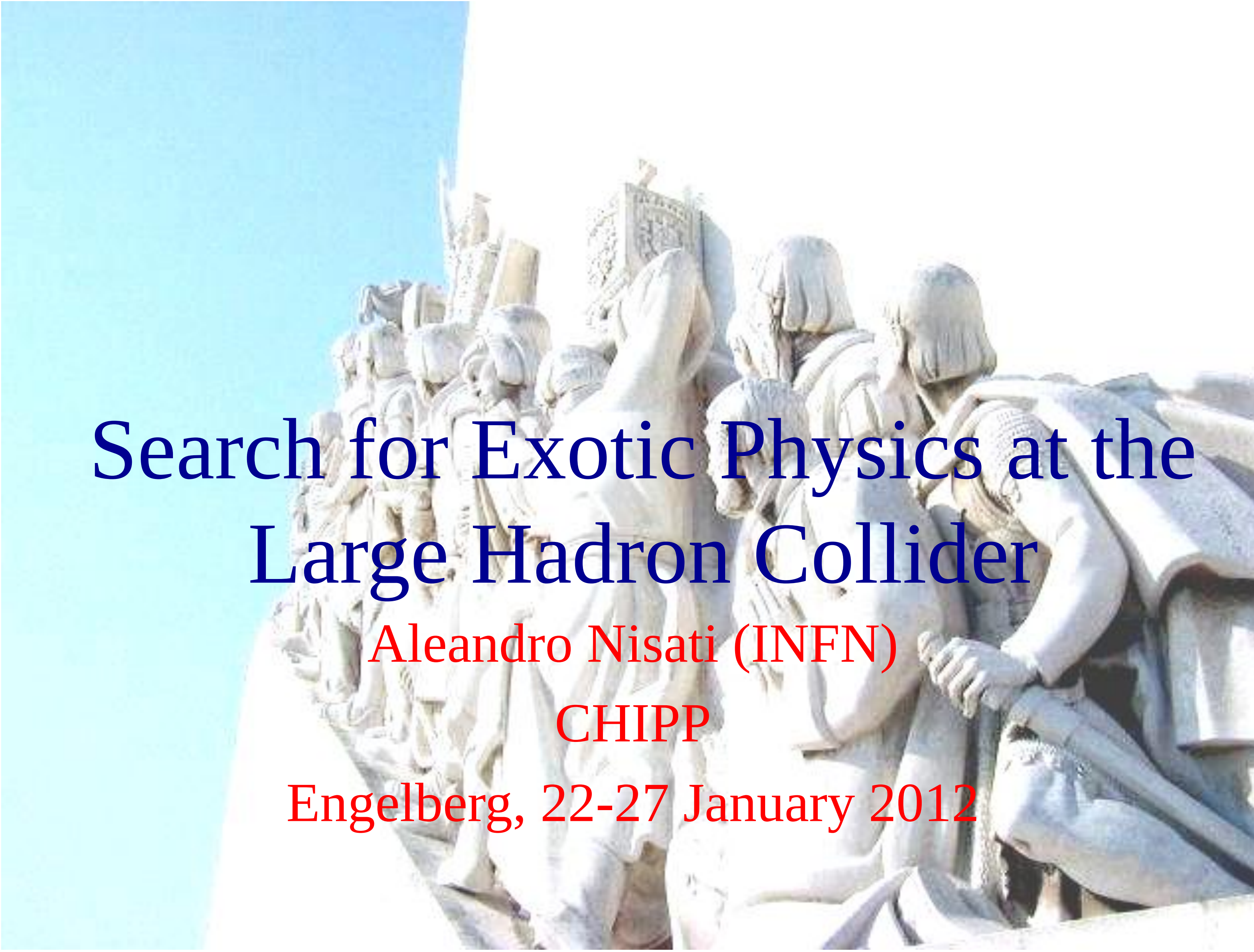


Search for Exotic Physics at the Large Hadron Collider

Aleandro Nisati (INFN)

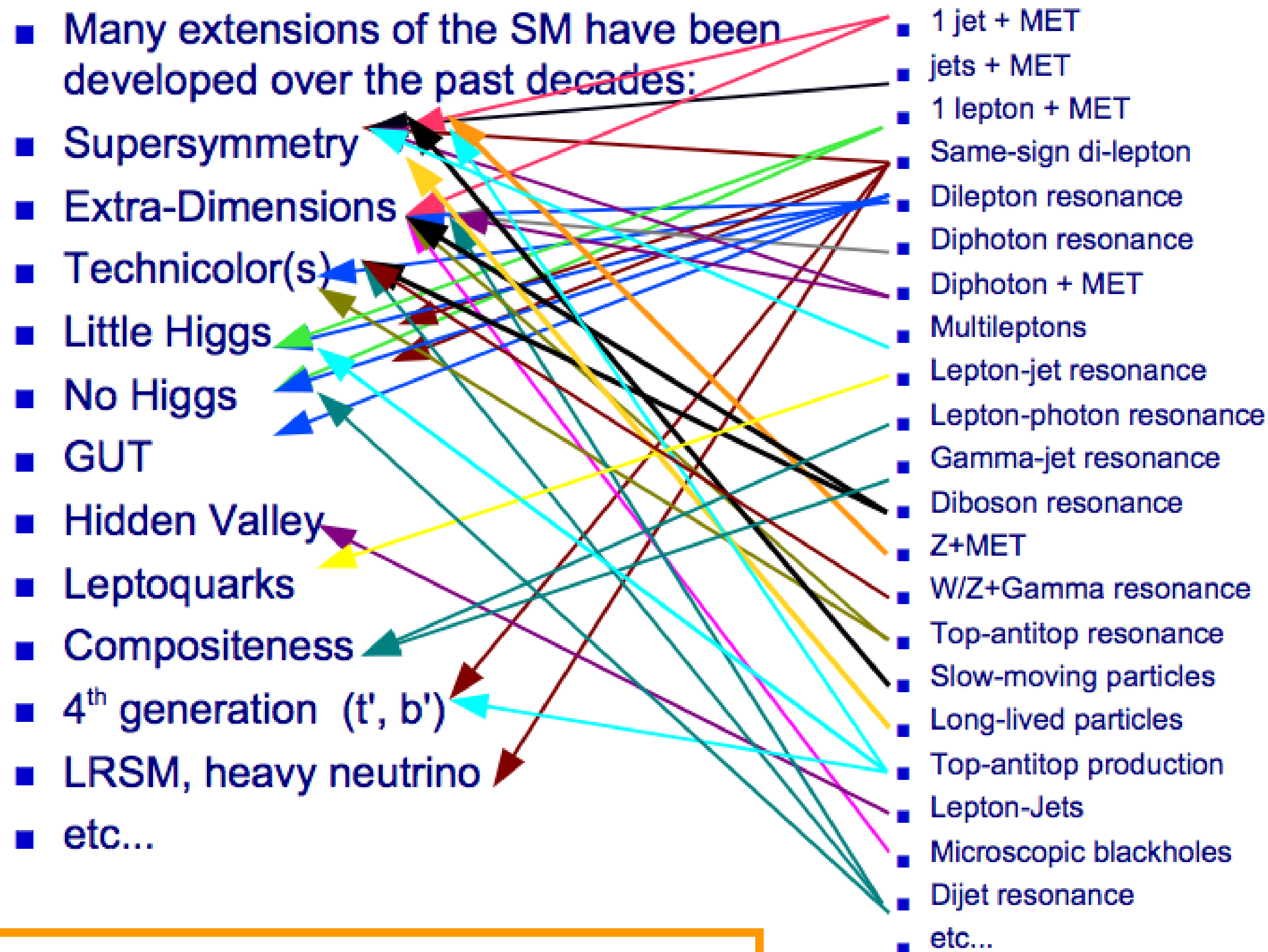
CHIPP

Engelberg, 22-27 January 2012

Outline

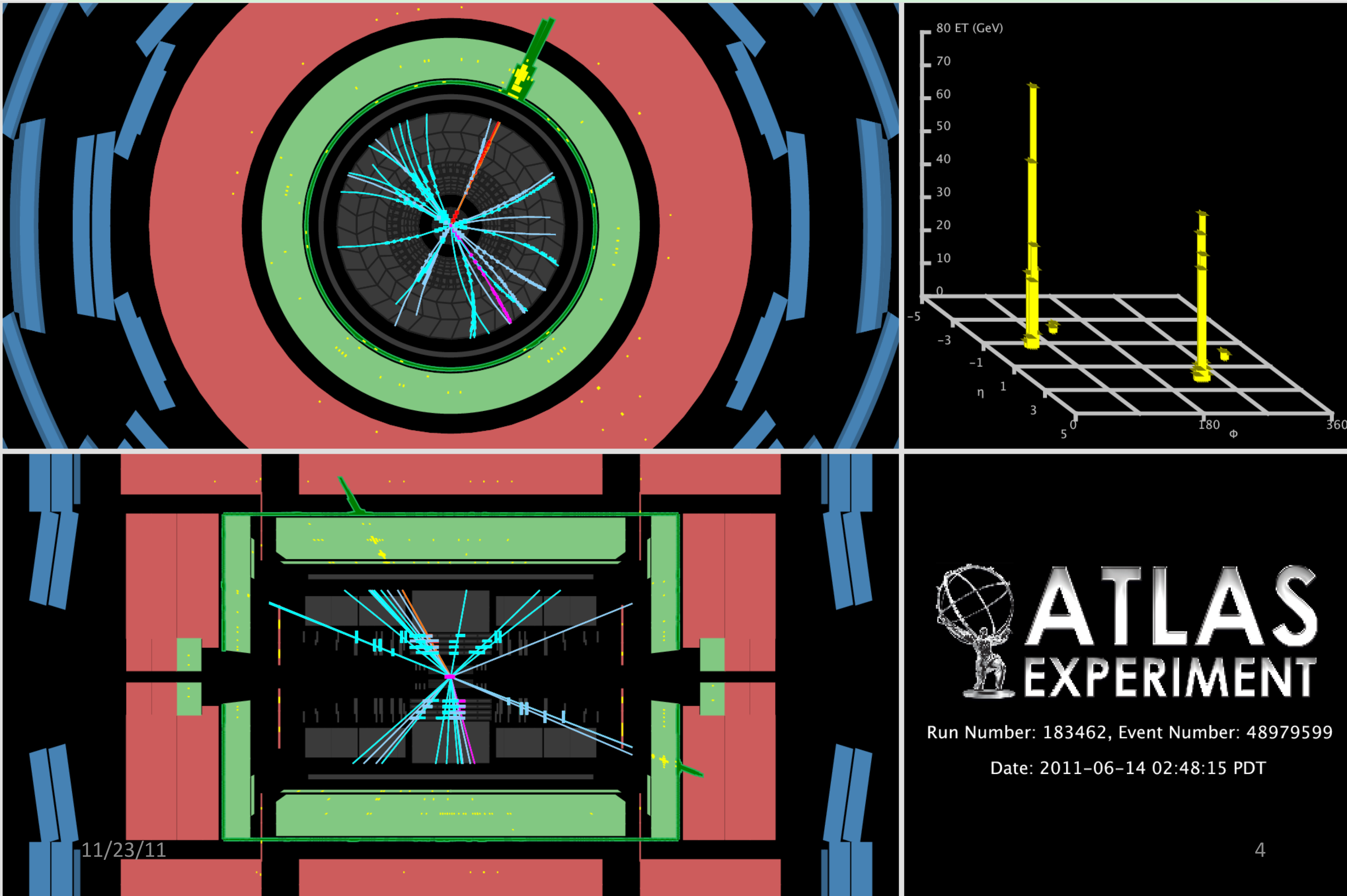
- Searches for new heavy resonances
  - Dilepton
  - Lepton + E_T^{miss}
  - Same-sign dimuon
  - Dilepton + jets
  - Dijet
- Search for strong gravity / extra-dimensions
  - Monojet
  - Dilepton
  - Diphoton
  - Diphoton + E_t^{miss}
- Search for contact interactions
  - Dijets
  - Dielectrons, dimuons
- Search for black holes
- Search for long-lived particles
  - Many results, not covered in this talk

Models vs Signatures



(From Henri Bachacou, Lepton-Photon talk)

Search for resonances with dileptons



Search for heavy dilepton resonances

- Predicted by many extensions of the Standard Model (SM)
  - GUT-inspired theories, little Higgs
  - → new heavy gauge boson W' and Z'
- Technicolor
  - → technihadron particles
- Randall-Sundrum (RS) extra dimension theory
  - →Kaluza-Klein (KK) graviton
- ➔ see next slides

- Experimental challenge:
- Understand the detector in a unexplored kinematic region (p_T > 1 TeV) with little or no data
- Understand the data in lower energy regions, and extrapolate them to the signal regions. Crucial are:
  - Accuracy of signal efficiency
  - Accuracy of background predictions
  - Accuracy on detector calibration and alignment
  - Understanding of physics objects reconstruction

Z' production

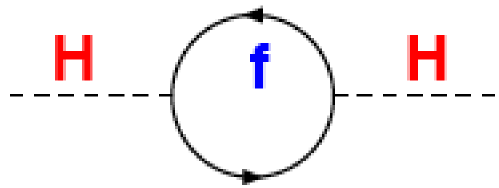
- Additional U(1) gauge symmetries and associated *Z* gauge bosons are one of the best motivated extensions of the Standard Model (SM).
- Benchmark: Sequential Standard Model (SSM)
  - Heavy boson with spin 1 and Z-like couplings

- Also E6 Grand Unified Theory (GUT), broken in U(5) and two U(1) groups, giving raise to two new U(1) fields. Their mixing can give rise to Z' candidates

The hierarchy problem -1

- **The question: why the weak force is ~ 10^{32} times stronger than the gravitational force?**
  - **F ~ $1/[M^2_{Pl} \bullet r^2]$; $M_{Pl} = 1.22\times10^{19}$ GeV ⇔ $M_H \sim 10^2$ GeV**
- Both forces involve constants of nature:
  - The Fermi's constant
  - The Newton's constant
- In the Standard Model the quantum corrections to the Fermi constant appear unnaturally large, unless a delicate cancellation between the bare value of this constant and its quantum corrections take place (**fine tuning**).

$$\Delta M_H^2 \equiv$$

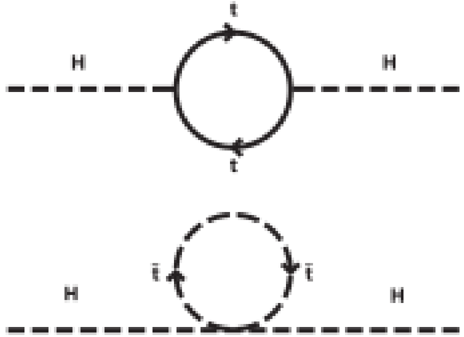


$$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$$

  - More technically the question is why the Higgs boson mass is so much lighter than the Planck mass (or the Grand Unification energy)

The hierarchy problem -2

- **Three main avenues** for solving the hierarchy problem:
- ***Supersimmetry***
  - *A set of new (light) SUSY particles cancel the divergence*



- ***Extra dimensions***
  - *There is a cut-off at the ~TeV scale where gravity sets in; in other words the "actual" gravity constant is larger then the one observed (or the Planck mass is much smaller)*
- ***Strong interactions/compositness***
  - *The Higgs is not an elementary scalar particle*
  - *The Higgs emerges as a Nambu-Goldostone of a strongly interacting sector*

The hierarchy problem -3

- **Extra Dimensions theories**:
  - **Kaluza-Klein** model (1921)
  - **Large Extra Dimensions**, or ADD model (Nima Arkani-Hamed, Savas Dimopoulos and Gia Dvali, 1998)
  - **Universal Extra Dimensions** (UED, 2001)
  - **Randall-Sundrum** model (1999)
  - **DGP Model** (Gia Dvali, Gregory Gabadadze and Massimo Porrati; 2000)

Extra Dimensions

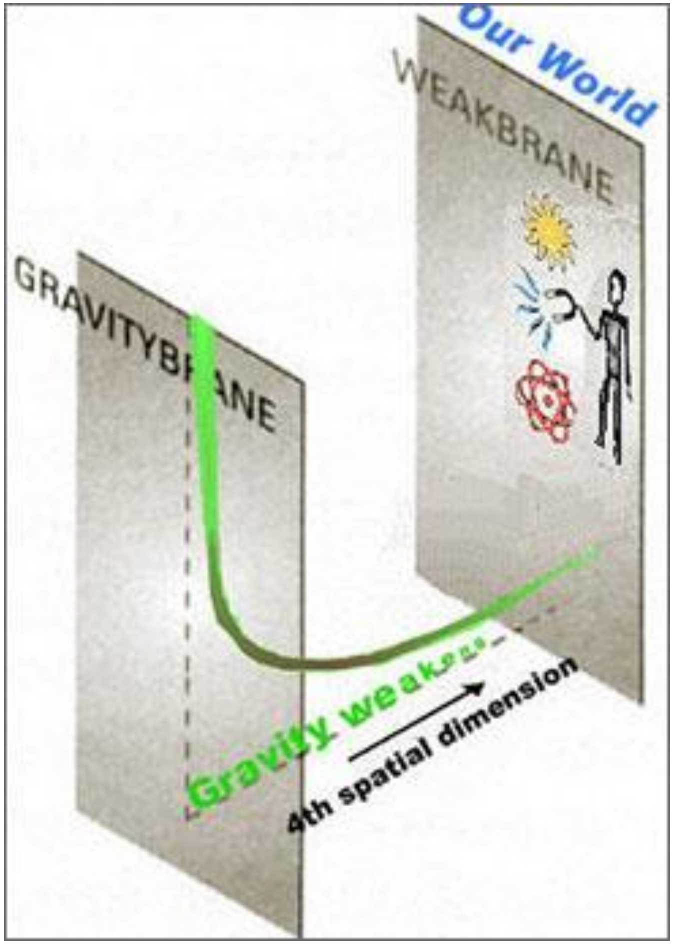
- **Extra Dimensions** models propose that there are one or more additional dimensions beyond the three spatial dimensions and one temporal dimension that are observed.
- The universal extra dimensions are assumed to be ***compactified*** with radii much larger than the traditional Planck length ($\sim 10^{-35}$ m)
- The basic idea is in the fact that in an Universe of (3+1)+**δ**_extra-dimensions the gravitational field is
  $g \sim 1/[M^2_D(3+1+\delta) \bullet r^{2+\delta}]$
- If the extra-dimensions have a finite "**size ρ**" (also called "compactification scale"), then for r>>ρ the field in the extra-dimension becomes a constant:
  $g \sim 1/[M^2_D(3+1+\delta) \bullet \rho^\delta r^2]$
- At this point $M^2_{Pl} = M^2_D(3+1+\delta) \bullet \rho^\delta$: the "real" **Planck mass** could be actually **small**, but it "observed" value M_{Pl} in our Universe is actually amplified by the presence of compact extra dimensions

Extra dimensions

- **Universal Extra Dimensions**:
  - there are one or more additional dimensions beyond the three spatial dimensions and one temporal dimension that are observed. All fields propagate universally in the extra dimensions
  - Compactification scale: $\sim 10^{-18}$ m.
- The **ADD Model** (N. Arkani-Hamed, S. Dimopoulos and G. Dvali; 1998) postulates the existence on *n* flat additional dimensions, compactified with radius ρ. It also requires that the fields are confined to a four-dimensional *membrane* while gravity propagates in several additional spatial dimensions that are large compared to the Planck scale
  - $M_{Pl}^2 = M_{Pl}^2/8\pi = M_D^2\,(3+1+\delta)\bullet\rho^{\delta}$ **M_D is the Planck mass in the (3+1+δ) space**
- The **Randall-Sundrum model**: there is only 1 strongly warped extra dimension ➔ see next slide

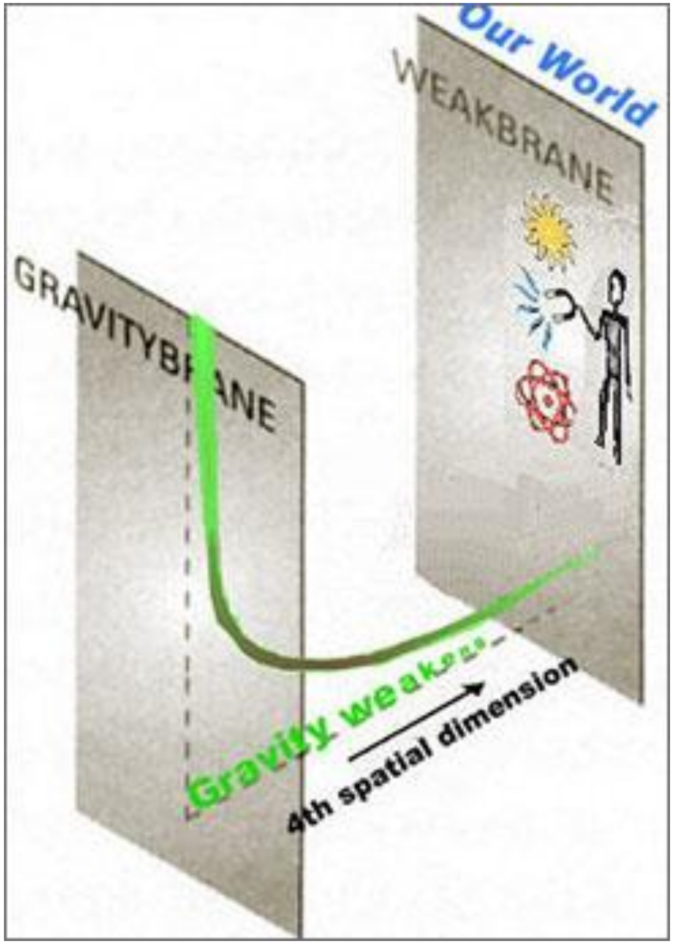
Randall-Sundrum graviton

- Our 3+1-dimensional Universe is embedded in a 5-dimensional space spacetime ; this extra dimension is the *bulk*, and it is extremely warped. This dimension is the only one warped.
- It contains two braines:
  - The **Weakbrane** (or **TeV brane**; it contains the SM)
  - The **Gravitybrane** (or **Planck brane**)
- Our ordinary Standard Model world seats on the Weakbrane; the gravity force spans over the two branes: the graviton's density function is very high at the Planckbrane, and drops exponentially when moving to the Weakbrane
- The gravity intensity seen in the Weakbrane is much weaker than the one expected in the TeVbrane:
  - **$M_{Pl}= M_D \bullet \exp(k\rho)$, where k=curvature scale**



Randall-Sundrum graviton

- In minimal RS model, it give rise to Kaluza Klein massive graviton G* states separated by ~TeV energy
  - **G* have k/$\underline{M}_{Pl}$ coupling to SM particles**
    - $\underline{M}_{Pl}$ is the Planck Mass $/\sqrt{(8\pi)}$
    - K is the spacetime curvature in the extradimension
  - G* have spin 2 → more central decays
- G* width proportional to $(k/M_{Pl})^2$



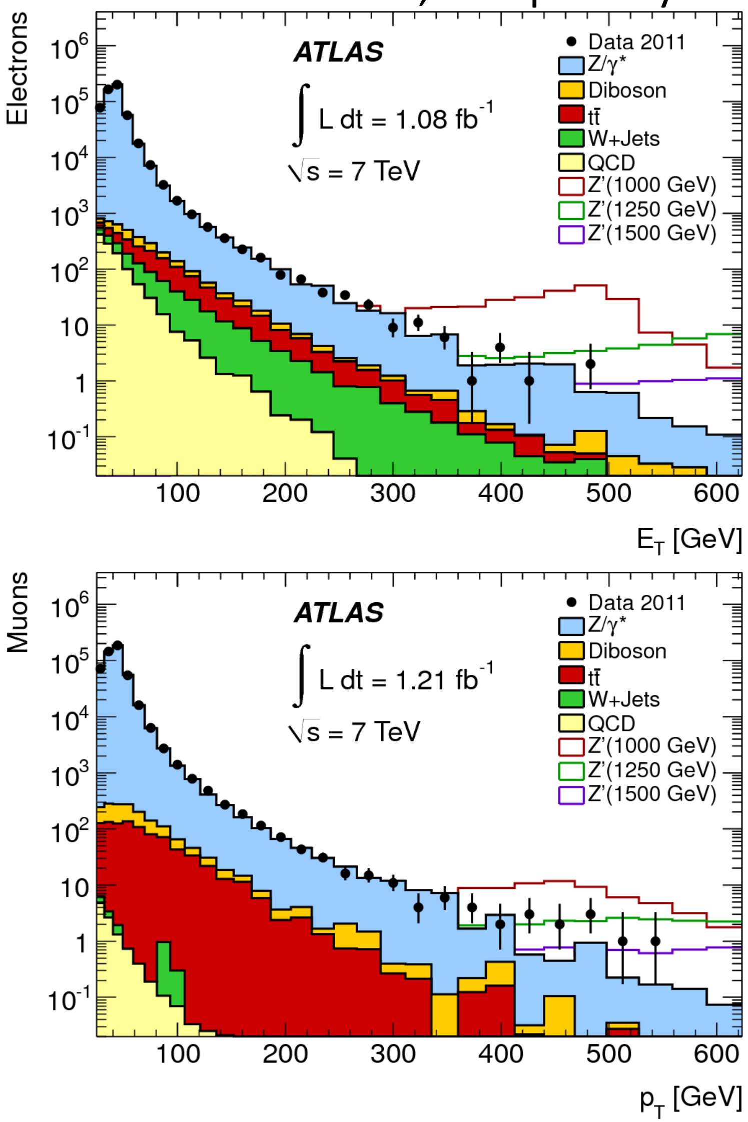
Search for resonances with dileptons

- Benchmark Z'→e^+e^-,$\mu^+\mu^-$
- Very clean signature: bump in the l^+l^- invariant mass distribution: ➔ good experimental mass resolution required
- Backgrounds:
  - dominated by Drell-Yan (+ jets) processes
  - Dibosons
  - ttbar
  - QCD (semileptonic b-c decays; fake electrons from jets; in flight meson decays, etc)
- Data sample: 1.08(1.21) fb^{-1} for e^+e^- ($\mu^+\mu^-$)

Search for resonances with dileptons -1

arXiv:1108.1582, accepted by PRL

- Event selection:
  - *Lepton trigger*
  - *Electron: "medium quality"; $E_T > 25$ GeV;*
  - *Muon: reconstructed in MS (three stations required) and ID; $p_T > 25$ GeV; impact parameter cut to suppress cosmic ray contamination;*
  - *Lepton isolation in the calorimeter (Inner Detector) for electrons (muons), to reduce QCD background*
- Z'(G*) 1.5 TeV mass signal acceptance: e+e- 65(69)%; 40(44)%
- Muon p_T resolution @ 1 TeV ranges from 14% to 44%
- Backgrounds are evaluated with simulation samples rescaled using the most precise available cross section predictions
- Due to the poor modeling and low Monte Carlo statistics, QCD dijet backgrounds are evaluated from data for both channels



Search for resonances with dileptons -2

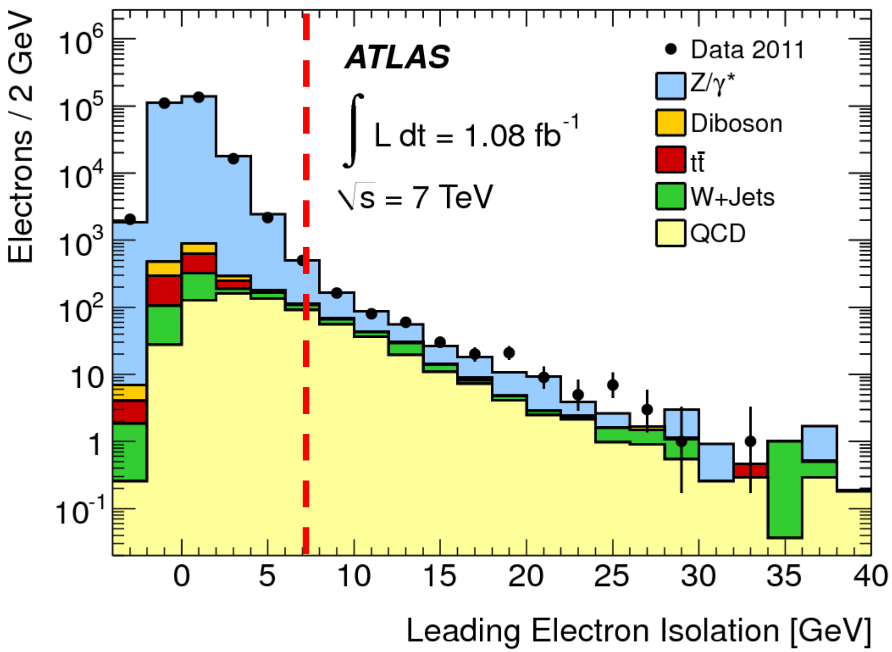
- All background sources are evaluated with Monte Carlo samples, except QCD jets.
- Due to the poor modeling and low Monte Carlo statistics, dijet background is measured from data
- In the e^+e^- channel, three independent methods are used. The baseline method is the “inverted identification”

Inverted identification

- In a QCD dijet data sample, select $e^\pm$ candidates which passes ***loose quality*** and **fail *medium quality*** identification. Then run the analysis as for the ***signal region*** ➔ determine the **shape** of $m(e^+e^-)$
- Normalize to luminosity fitting the **signal region** invariant mass $m(e^+e^-)$ with all MC processes (cross-section weighted) and the **measured** dijet shape in the region $70<m(e^+e^-)<110$ GeV

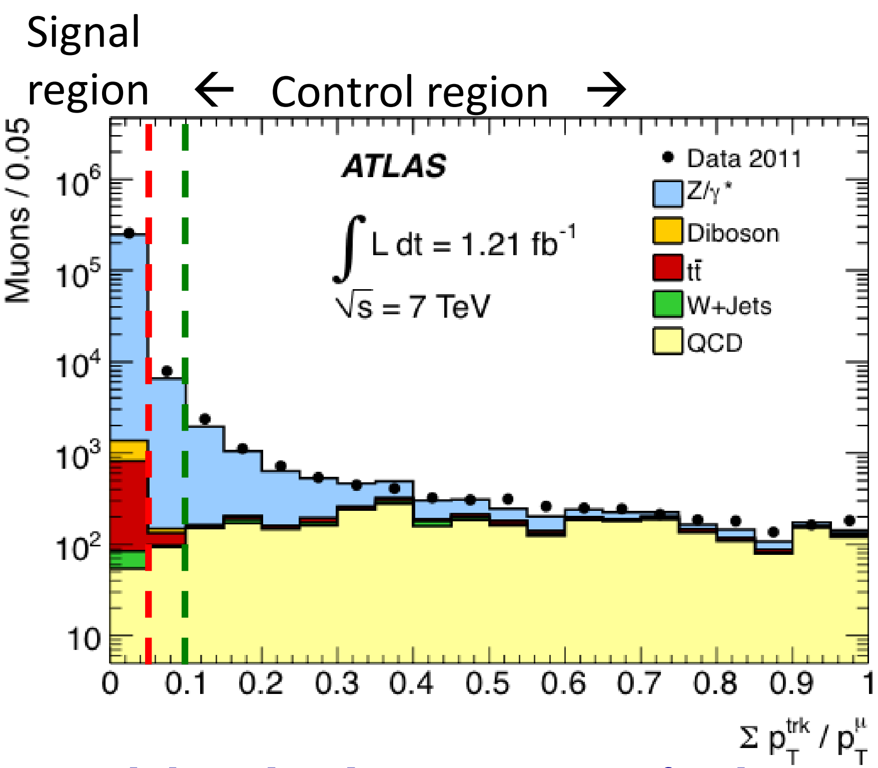
Search for resonances with dileptons -3

- "Isolation fits" method: study the electron isolation in data using *templates* for (isolated) electrons and for fake electrons;
  - For isolated electrons use electrons from W→eν decays, while the QCD electron template is taken from data reverting the electron identification cuts
  - Fit the leading and subleading electron isolation separately.
- Good agreement with the baseline method within uncertainties



Search for resonances with dileptons -4

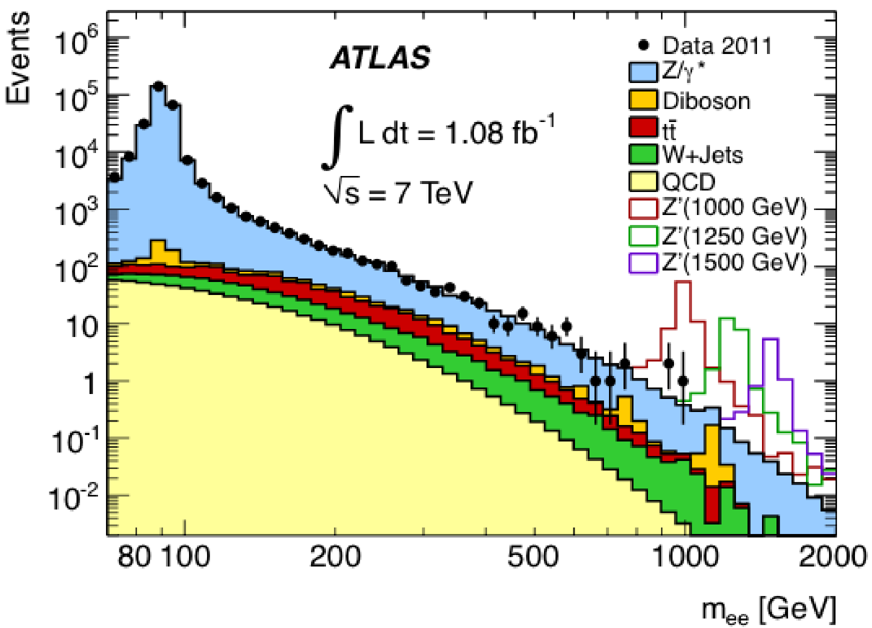
- **QCD background measurement in the muon channel**: study the muon isolation.
- Muon isolation: $I=\Sigma p_T^{trk}/p_T^{\mu}$ around the muon in a cone $\Delta R=0.3$
- Look to non-isolated muon events: 0.1<I<1.0; and select those with both muon non-isolated: dominated by heavy-flavours; the number of events in the signal region is obtained scaling the number of events in the control region with the signal/background ratio from MC.



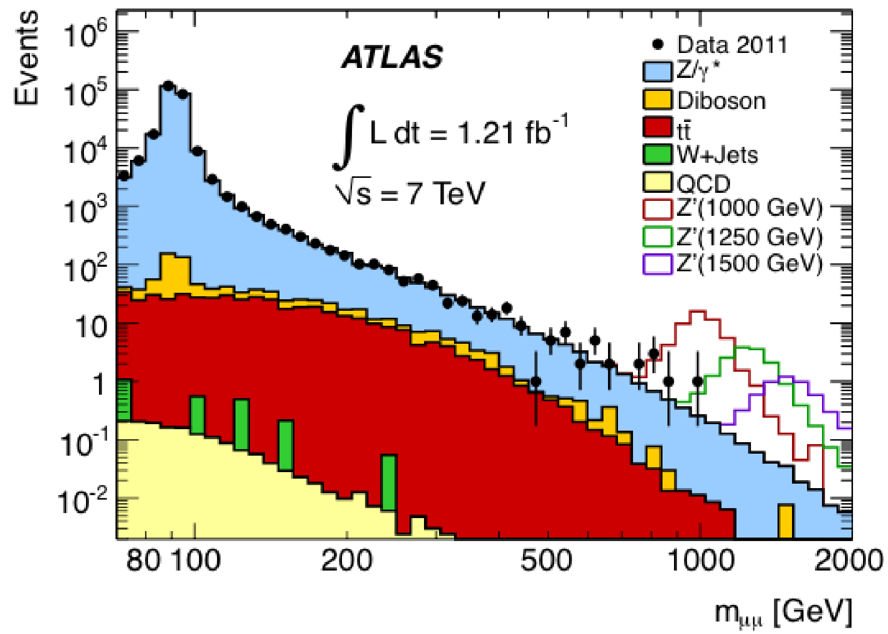
Track-based isolation spectrum for the muon channel after event preselection, that is immediately before the isolation. The range shows the non-isolated region dominated by QCD.

Search for resonances with dileptons -5

e+e-



μ+μ-



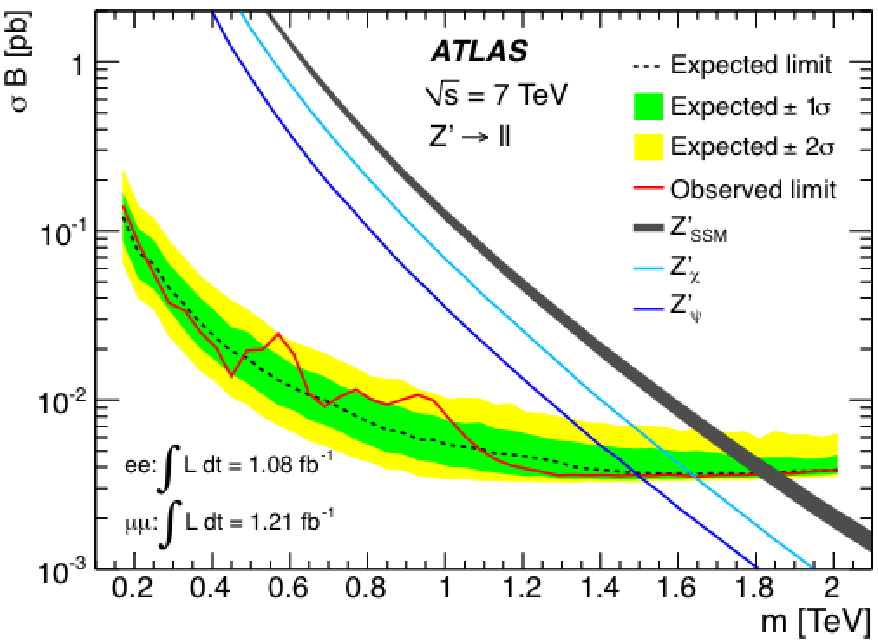
Dielectron and dimuon invariant mass distributions after final selection, compared to the stacked sum of all expected backgrounds, with three example SSM Z' signals overlaid. The bin width is constant in log m_{ll}.

Main systematic uncertainties:

- Background: 11% Theory, 5% exp. - Signal 5%

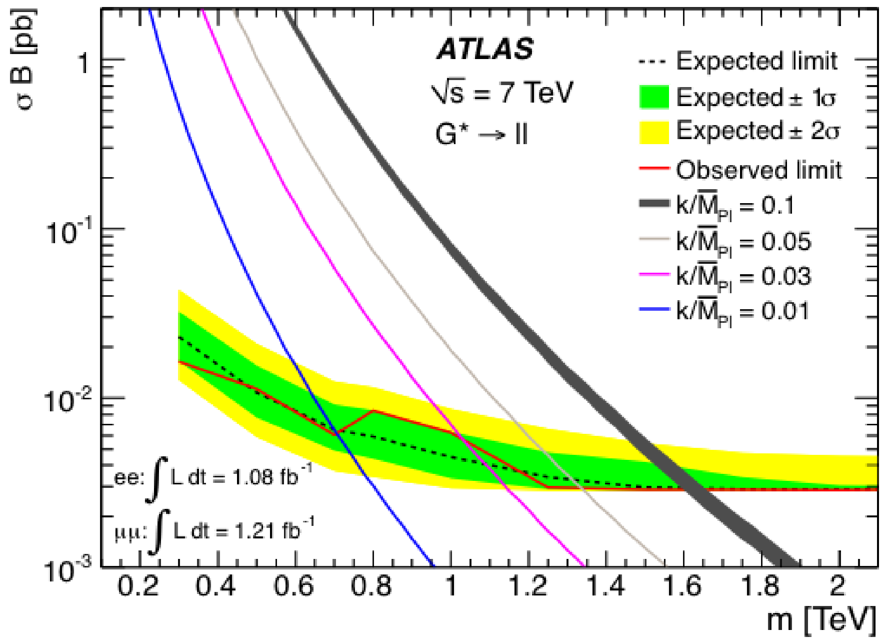
Search for resonances with dileptons -5

Z’-E6



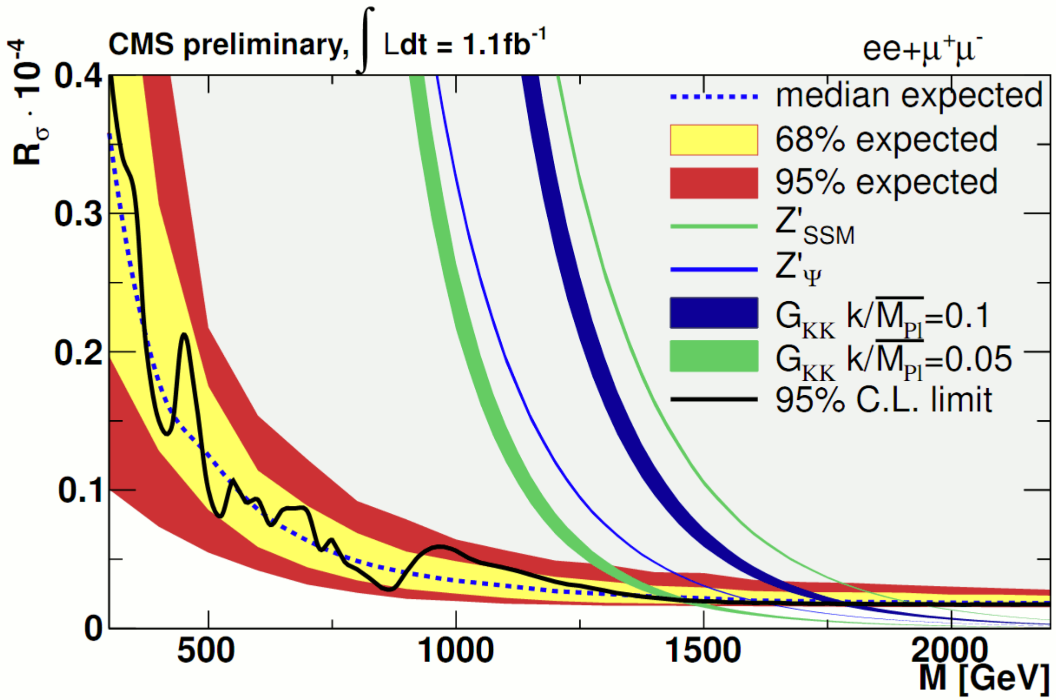
Expected and observed 95% C.L. limits on cross section times branching ratio and expected cross sections for SSM production and the two E6-motivated Z' models with lowest and highest cross section for the combination of dielectron and dimuon channel. The thickness of the SSM theory curve illustrates the theoretical uncertainties.

G* Randall-Sundrum



Expected and observed 95% C.L. limits on cross section times branching ratio and expected cross sections for Randall-Sundrum gravitons with various couplings k/M_Pl for the combination of dielectron and dimuon channel. The thickness for the k/M_Pl=0.1 curve illustrates the theoretical uncertainties.

Search for resonances with dileptons -6



CMS results

CMS PAS EXO-11-019

analysis similar to the one from ATLAS

Model	ATLAS Mass (Tev) 95% C.L. limit	CMS Mass (Tev) 95% C.L. limit [Prel.]	publication
Z'SSM	**1.83 (1.83)**	**1.94**	http://arxiv.org/abs/1108.1582, subm. PRL
G* (k/MPl = 0.1)	**1.63 (1.63)**	**1.78**	http://cdsweb.cern.ch/record/1369192/files/EXO-11-019-pas.pdf

Search for Technicolor particles

- Technicolor avoids this problem by hypothesizing a new gauge interaction coupled to new massless fermions
- New gauge interactions with new fermions are introduced. This new force, asymptotically free at high energy, becomes strong at low energies, around the value $\Lambda_{TC} \sim 250$ GeV
- Briefly, the electroweak symmetry is broken "dynamically" producing W and Z masses
  - The new strong interaction leads to new composite, short-lived particles at energies accessible at the LHC (techni-hadrons)

Search for Technicolor particles

- Example of the lightest techno-particles: the scalar π_T, and vector ρ_T, ω_T.
- Techni-vector objects can decay into a SM gauge boson + a π_T, pairs of SM gauge bosons, and fermion-antifermion pairs
- Techni-particle searches can be made looking to lepton-antilepton final states

- ATLAS performed recently a new interpretation of the same-flavour opposite-sign dilepton analysis to set limits to the ρ_T, ω_T mass in the context of the "Low Scale TC" (LSTC) (assuming $m(\rho_T)=m(\omega_T)$).

Search for Technicolor particles

New

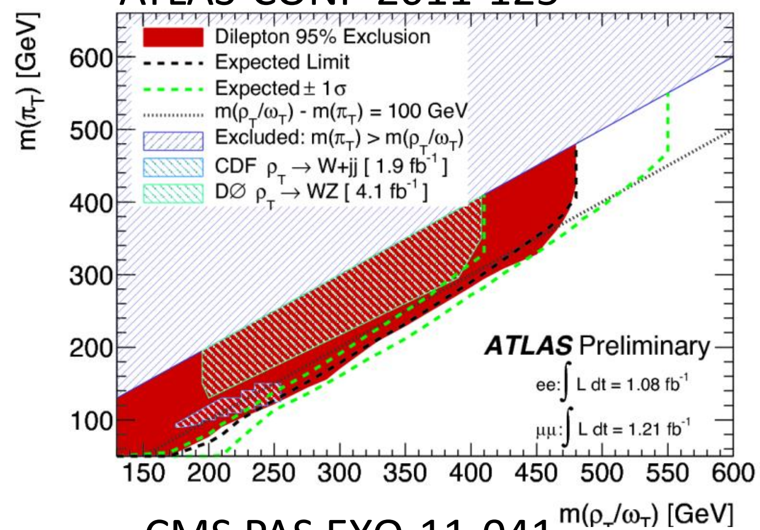
ATLAS

- Scan for $m(\rho_T)$ and $m(\pi_T)$ simultaneously;
- Masses of the ρ_T and ω_T in the range 130 – 480 GeV are excluded at 95% C.L..
  - For $m(\rho_T) - m(\pi_T) = 100$ GeV: $m(\rho_T) > 470$ GeV

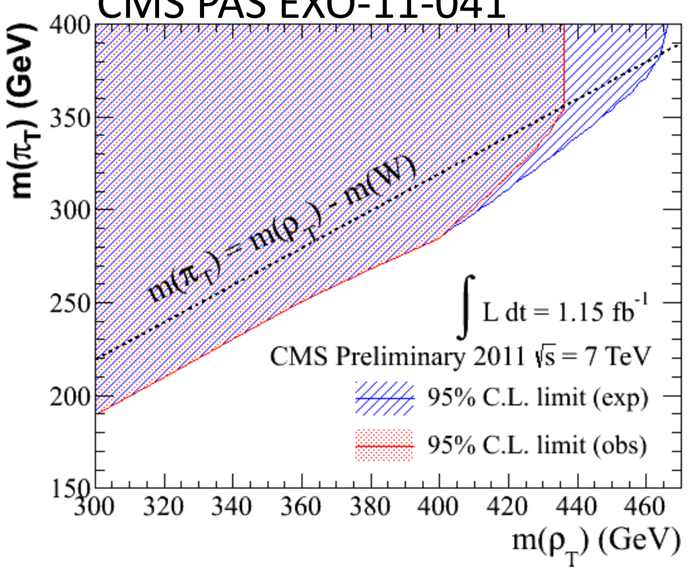
CMS

- Two-dimensional exclusion limit for Technicolor as a function of the ρ_{TC} and π_{TC} masses.
- For $m(\rho_T) < m(\pi_T) + m_W$, $m(\rho_T) > 436$ GeV 95% C.L. [Prel.]

ATLAS-CONF-2011-125



CMS PAS EXO-11-041



Searches with same-sign same flavour dimuons

- Predicted by many BSM models
  - Left-Right symmetric models
  - Higgs triplet models
  - Little Higgs
- Very clear signature, small background
  - Dibosons
  - Charge misreconstruction
  - Non prompt muons (HF and π/K decays)
- Event selection:
  - Require isolated muons reconstructed in the ID and MS with the same charge, and well associated to the primary vertex position
- Measure backgound from data

Searches with same-sign same flavour dimuons

- Prompt muon efficiency "r" evaluated from Z
- Fake rate "f": large impact parameter sample
- Identify two types of muons
  - Tight (T): pass isolation requirements
  - Loose (L): fail isolation requirements
- Four possible dimuon combinations:

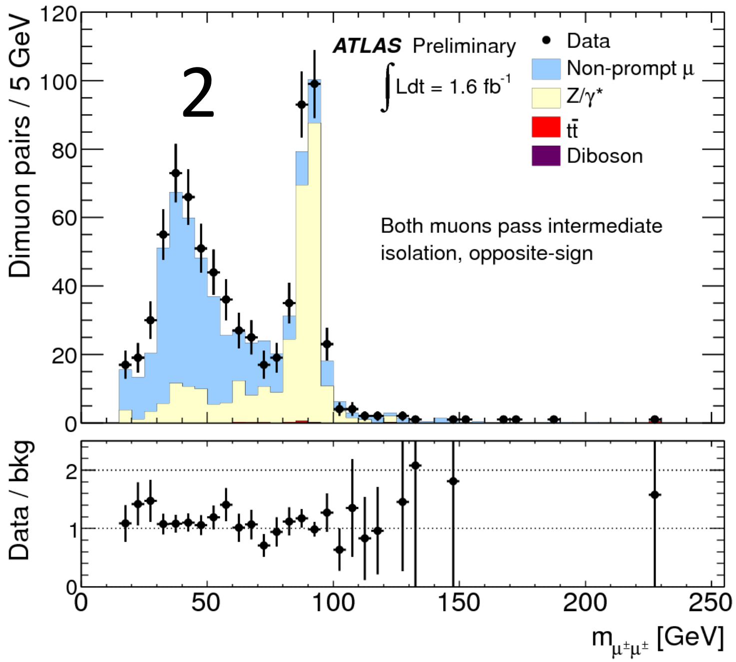
$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \begin{bmatrix} N^{ll}_{RR} \\ N^{ll}_{RF} \\ N^{ll}_{FR} \\ N^{ll}_{FF} \end{bmatrix}$$

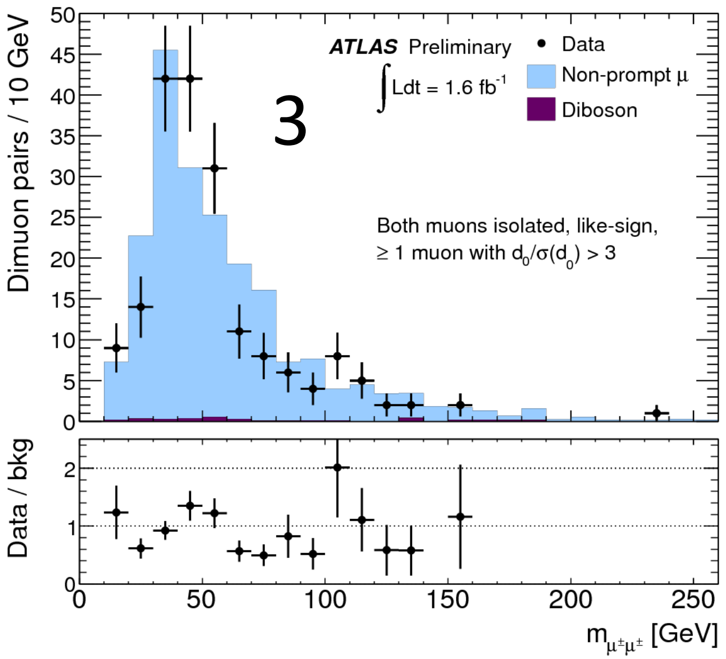
  - r: prompt muon efficiency
  - f: fake muon acceptance
- Total background from non-prompt is the sum of

$$N_{RF} = r_1 f_2 N^{ll}_{RF},\ N_{FR} = f_1 r_2 N^{ll}_{FR} \text{ and } N_{FF} = f_1 f_2 N^{ll}_{FF}$$

Searches with same-sign same flavour dimuons

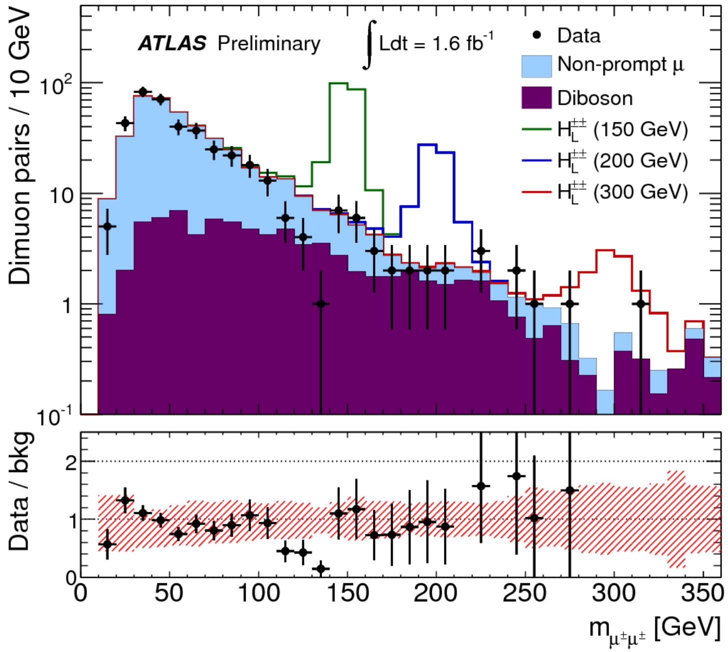
- Test matrix method over different control samples
  1. Opposite charge + both muons pass tight isolation
  2. Opposite charge + both muons fail tight isolation
  3. Same charge + at least one muon fails impact parameter
  4. Same charge + both muons fail tight isolation
- Prediction agree within uncertainties

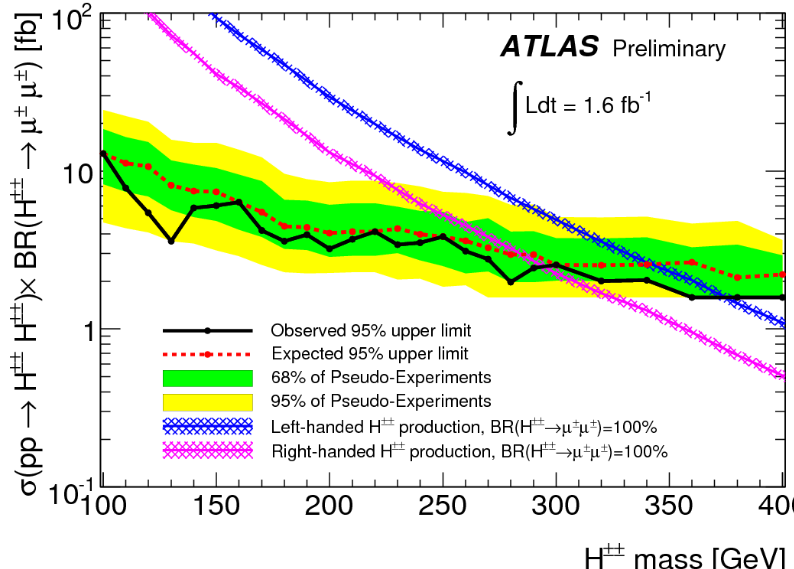




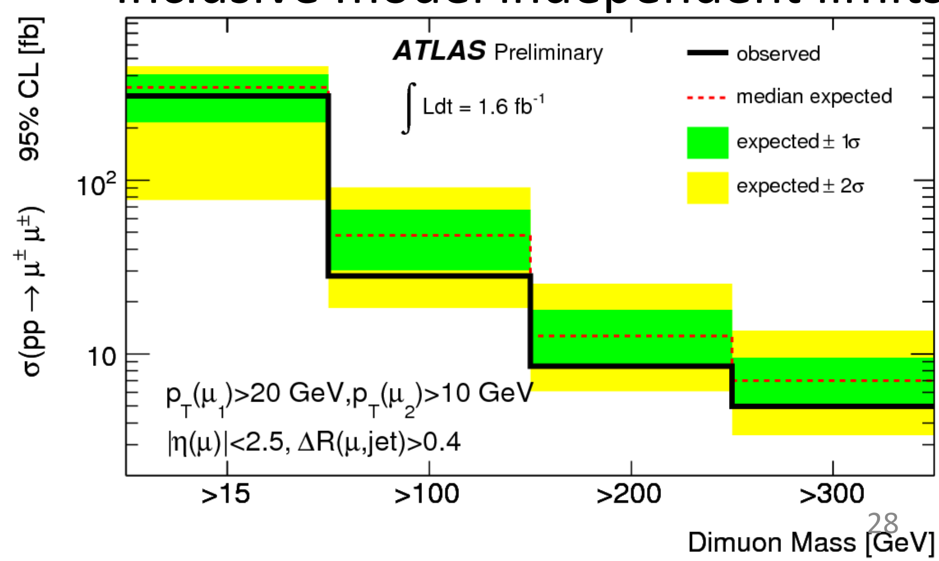
Searches with same-sign same flavour dimuons

ATLAS-CONF-2011-126



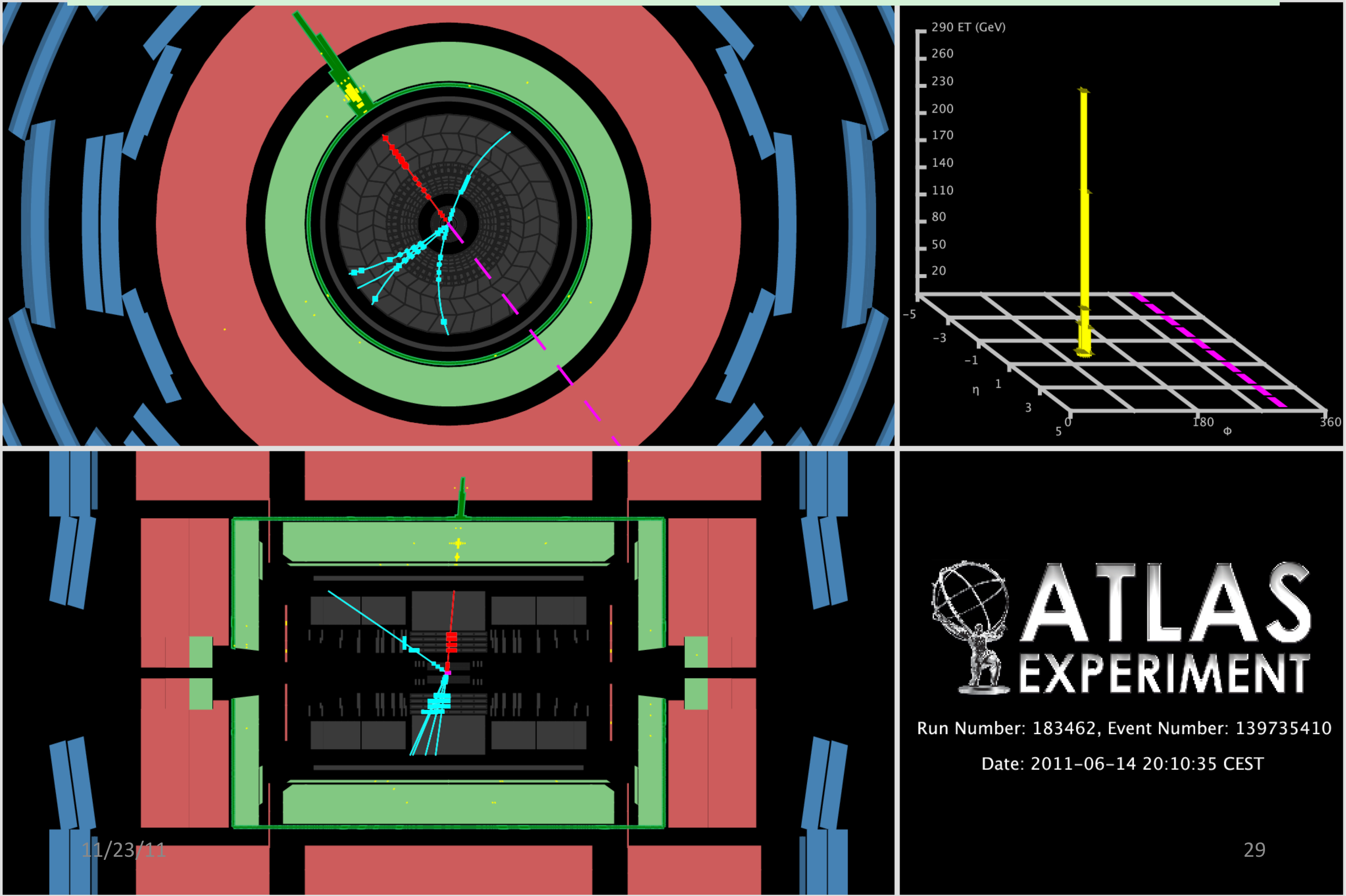


Inclusive model independent limits



- **Obtain following mass limits**
  - **mass(H_L) > 375 GeV (exp. 342 GeV)**
  - **mass(H_R) > 295 GeV (exp. 286 GeV)**

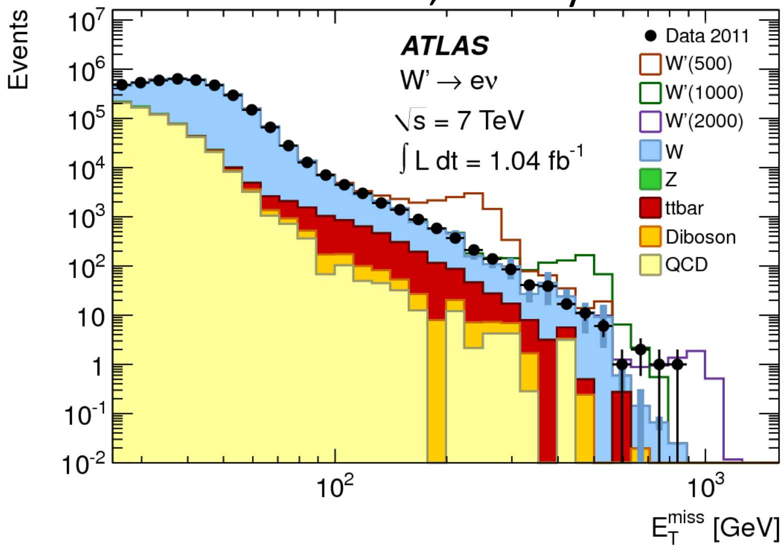
Search for resonances with lepton + MET

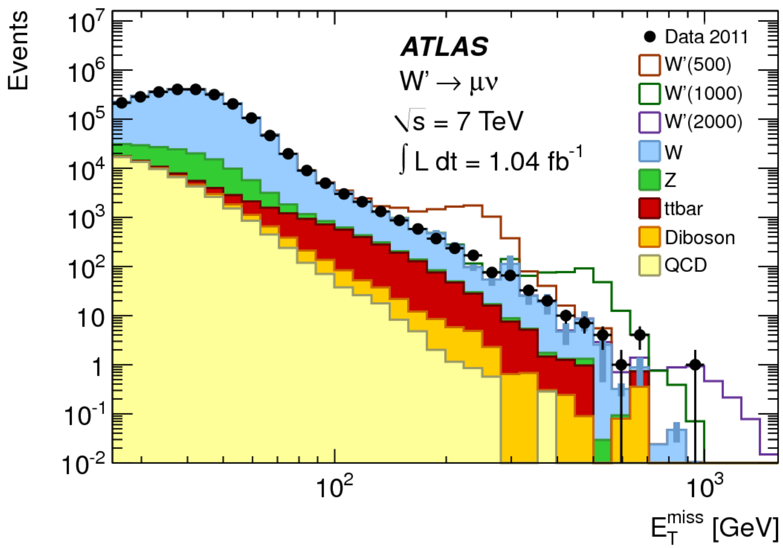


Search for resonances with lepton + MET -1

arXiv:1108.1316, acc. by PLB

- Search for new heavy charged bosons, SM W-like;
  - SSM: W'
  - TC: Techni-rho
  - Little Higgs
- Signature: isolated high-p_T lepton (e or μ) and large MET



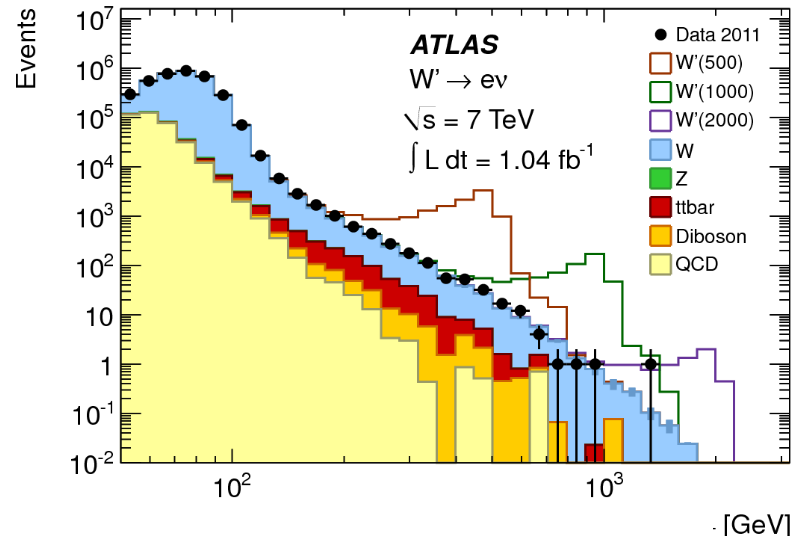


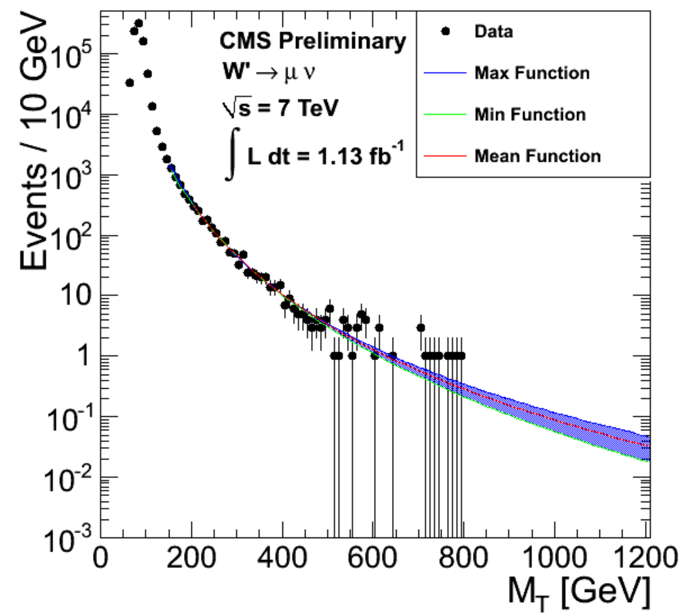
Search for resonances with lepton + MET -2

- Study the transverse mass:

$$m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$$

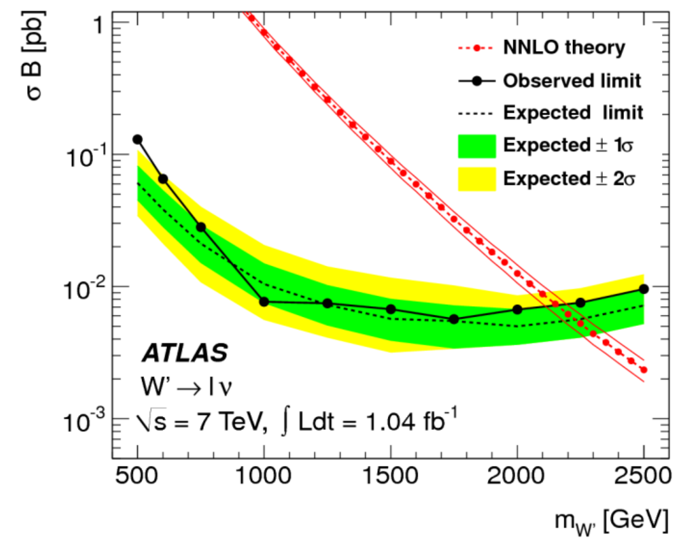
- SM background processes: W→lν, Z→ll, ttbar, Dibosons, QCD jets;
- Background estimation: two complementary approaches are used by **ATLAS** and **CMS**
  - **ATLAS**: estimates all sources with MC, except QCD measured in data
  - **CMS**: fit with a few emprical functions the m_T distribution in the mass interval $180<m_T<600$ GeV and extrapolate it to larger m_T values. The spread in the extrapolation is used as background uncertainty.

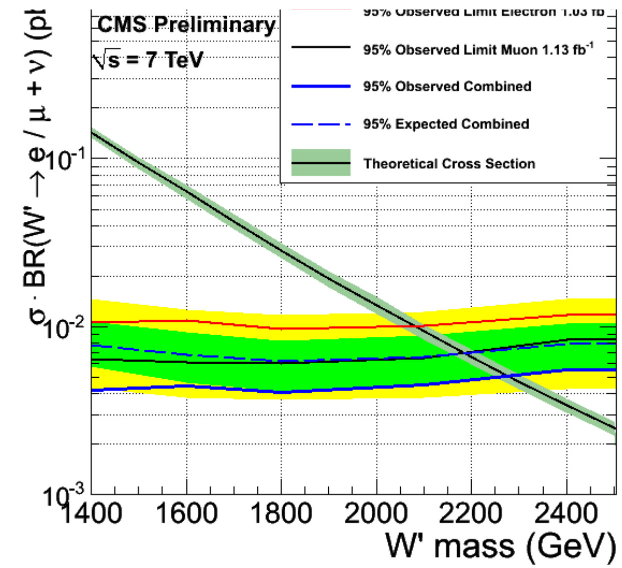




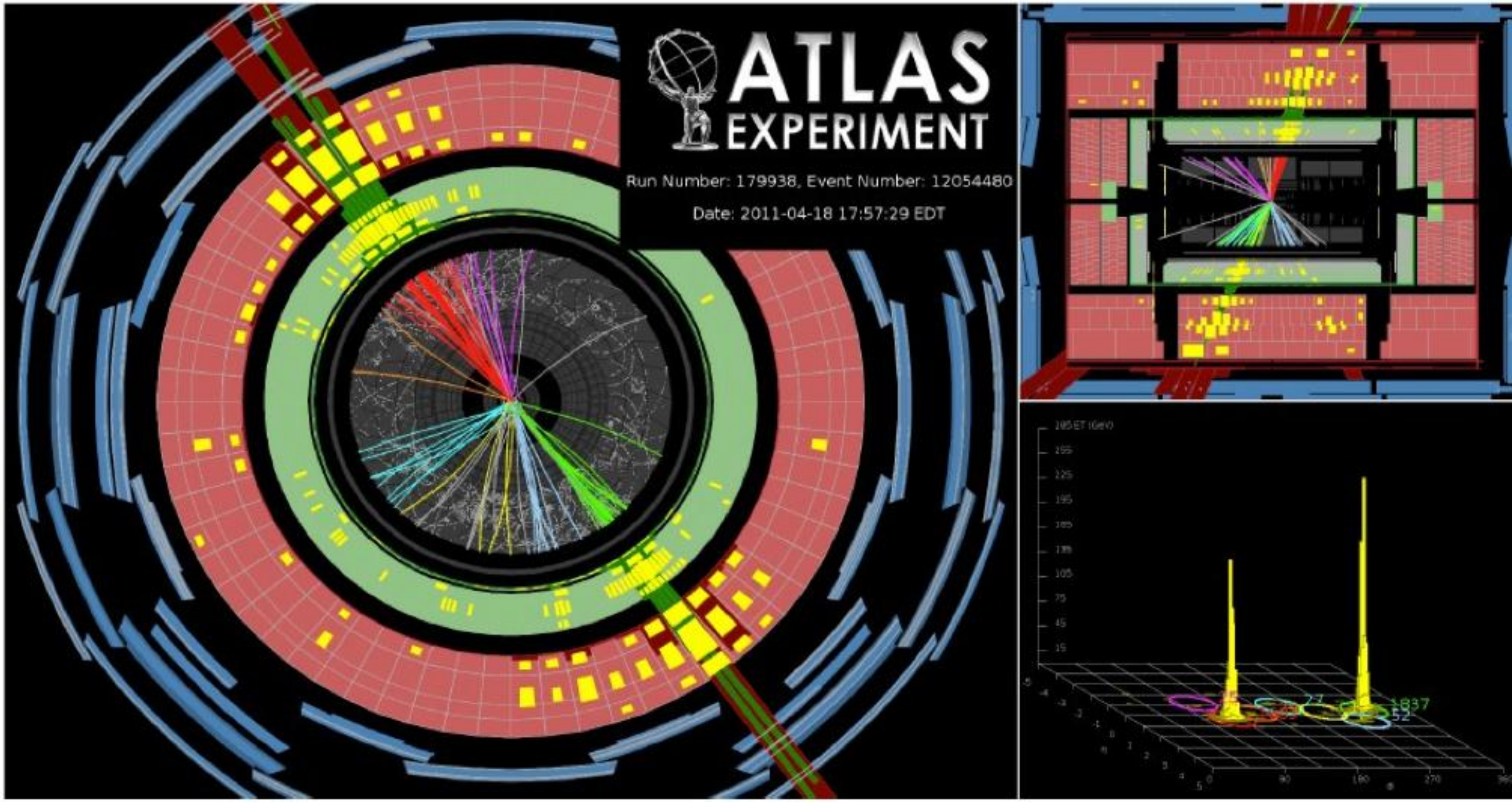
Search for resonances with lepton + MET -3

- A Bayesian approach is adopted by both ATLAS and CMS with a flat prior probability distribution for the signal cross section.
- Results: set a 95% C.L. exclusion of $\sigma_{W'} \times BR(W' \rightarrow l\nu)$. A W' with SSM couplings is excluded with mass up to $\mathbf{m_{W'}=2.15}$ GeV [ATLAS] or $\mathbf{m_{W'}=2.27}$ GeV [CMS – prel.]





Dijet resonances



mass of jet-jet system 4.0 TeV MET = 0.1 TeV

Dijet resonances -1

- Composite models generally predict the existence of excited quark and lepton states.
  - Are quarks and leptons elementary particles, or do they exhibit a structure at some energy scale?
- The most convincing evidence for a substructure of quarks and leptons would be the discovery of excited states towering over the leptonic and quark ground states

decay mode	br. ratio [%]	decay mode	br. ratio [%]
$U^* \to ug$	83.4	$D^* \to dg$	83.4
$U^* \to dW$	10.9	$D^* \to uW$	10.9
$U^* \to u\gamma$	2.2	$D^* \to d\gamma$	0.5
$U^* \to uZ$	3.5	$D^* \to dZ$	5.1

Branching ratios of excited up- and down-quarks for f_s=f=f' and α_s=0.1

- **See for example U.Baur I.Hinchliffe and D.Zeppenfeld, Int. Journal of Mod. Phys. A2 (1987)**
- According to $(g-2)_{e-\mu}$ measurements, the substructure scale Λ is < 1 TeV, and excited states not much lighter than Λ.
- **➔ LHC is the right machine to search for excited fermions at the energy scale of few TeV**

Dijet resonances -1

- ATLAS: study based on 1 fb^{-1} of data
- Analysis very simple:
  - reconstruct jets with the anti-kt algorithm with distance parameter R=0.6
  - Jet 4-momentum: vectorial sum of calorimeter cluster cells treating each cluster as an (E,p) 4-vector with E=|p| (i.e. m=0), and assuming that the jets originates from the reconstructed pp interaction vertex
  - Calibration procedure is applied to evaluate the jet energy at the hadronic scale
- jet-jet mass resolution: ~ 5% at m_{jj} = 1 TeV, ~ 4% at m_{jj} = 5 TeV
- Select dijets with p_T > 180 GeV (online) (each), m_{jj} > 717 GeV (trigger acceptance > 99%); require also and |η<2.8 and |y*|<0.6

Dijet resonances -2

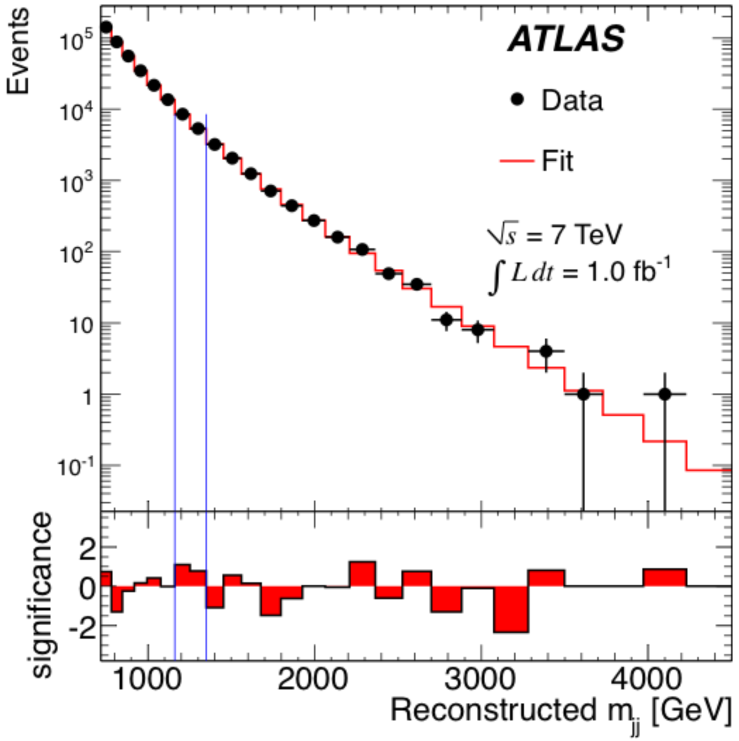
- Study the m_{jj} distribution assuming only QCD contributions and fitting it with the function

$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

where $x \equiv m_{jj}/\sqrt{s}$

- Use the *BumpHunter* algorithm to establish the presence or absence of a resonance

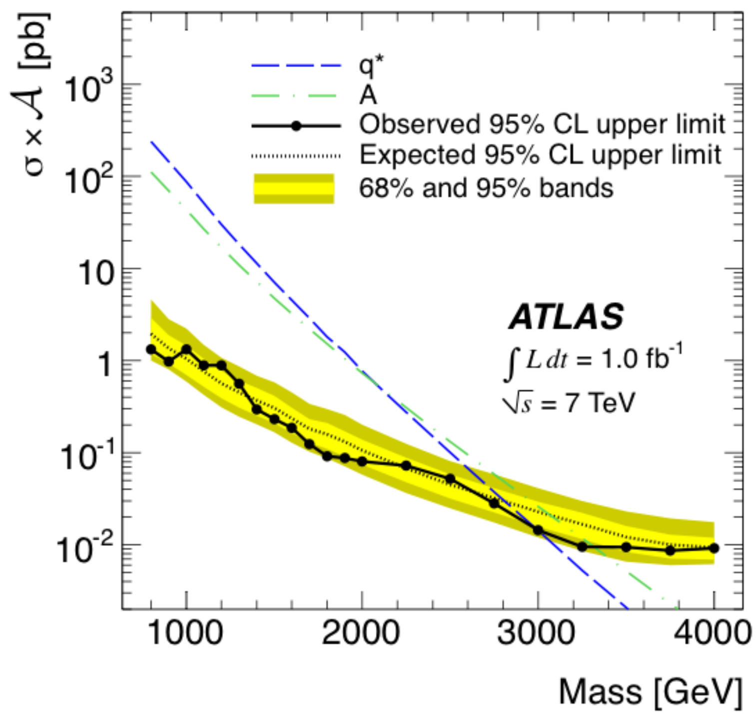
arXiv:1108.6311, subm. Phys. Lett.B



The measured dijet mass distribution (points) compared to the fitted function used to describe the QCD background. The binning is chosen accounting for the jet-jet mass resolution. The bin-by-bin significance (statistics only) is shown in the lower insert. The two vertical lines indicate the region where the most significant excess is found.

Dijet resonances -3

- No significant excess is found in data:
- ➔ set exclusion limits on production cross-section of new particles predicted by models beyond SM
- ➔ set exclusion limits on production cross-sections as much as possible model independent

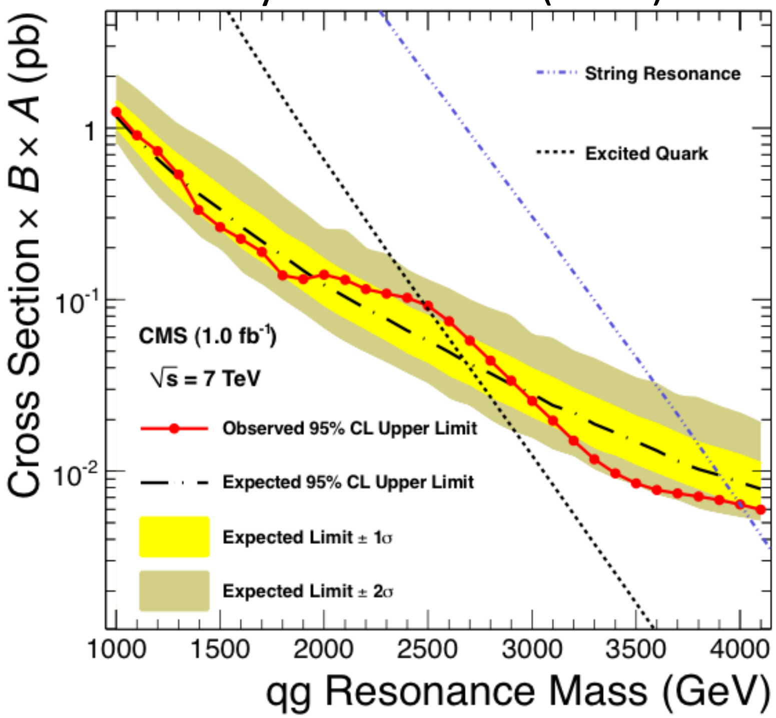


The 95% CL upper limits on σ×Acceptance as a function of particle mass (black filled circles). Theoretical predictions for σ×A are shown in for excited quarks (blue dashed) and axigluons (green dot-dashed. Theoretical uncertainties are not considered in this plot).

Model	95% CL Exp.	95% CL Obs.
Excited Quark, q*	2.81 TeV	2.99 TeV
Axigluon	3.07 TeV	3.32 TeV
Colour Octet Scalar	1.77 TeV	2.92 TeV

Dijet resonances -3

CMS Phys. Lett. B 704 (2011) 123

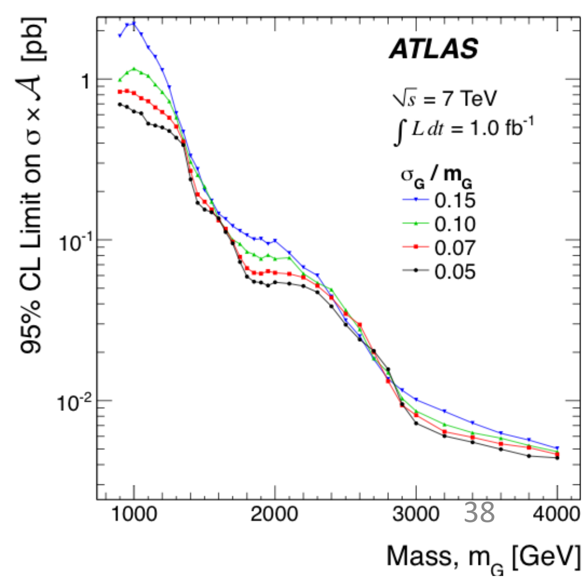


The observed 95% CL upper limits on $\sigma \times B \times A$ for quark-gluon dijet resonances (points) are compared to the expected.

CMS

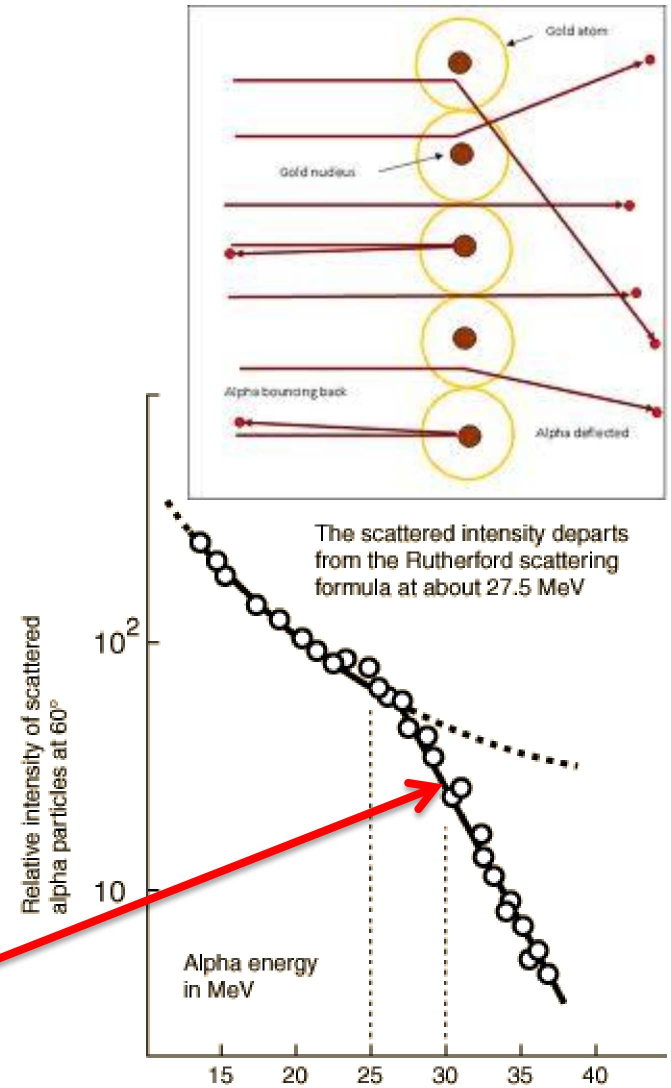
Model	Excluded Mass (TeV) Observed	Excluded Mass (TeV) Expected
String Resonances	4.00	3.90
E_6 Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
W′ Bosons	1.51	1.40

The 95% CL upper limits on σ×BxA for a simple Gaussian resonance decaying to dijets as a function of the mean mass, m_G, for four values of σ_G/m_G, taking into account both statistical and systematic uncertainties.



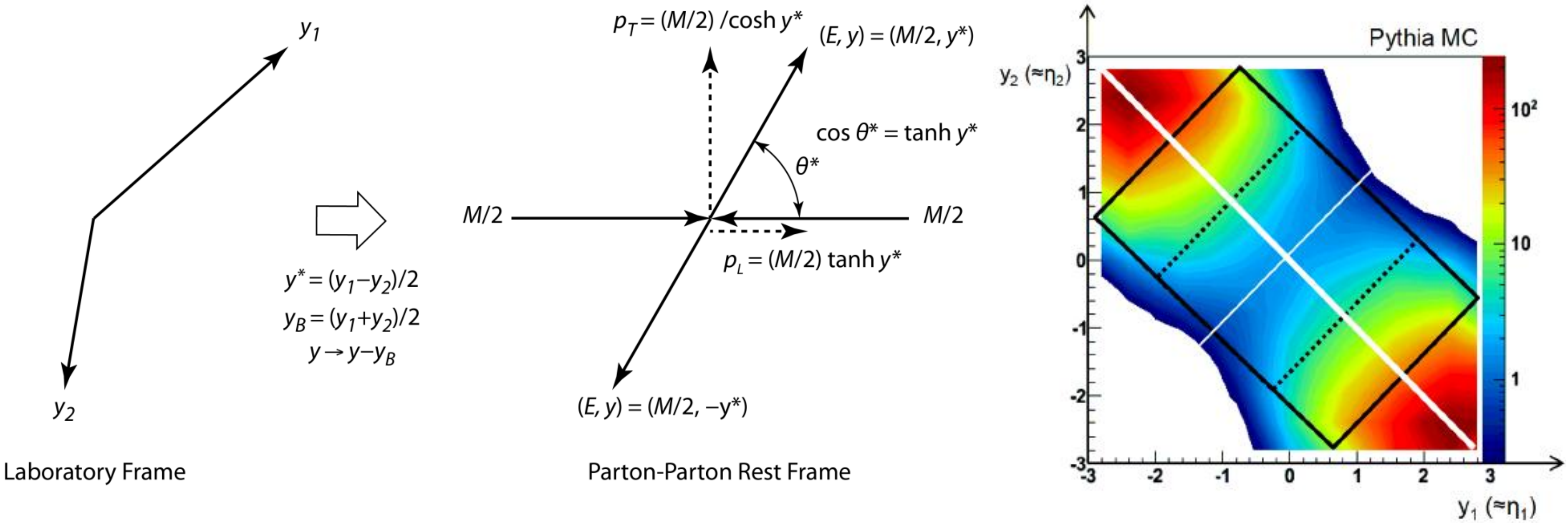
Dijet angular distribution -1

- The study of quark-quark scattering is a powerful method to probe the presence of "New Effects" in the structure of matter
- Classical example is the Rutherford scattering:
  - It not only demonstrated the structure of the atom, but it gave indications on the structure of the nucleus



The deviation from the Rutherford cross section with the increasing projectile energy are an evidence for nuclear reactions

Dijet angular distribution -2



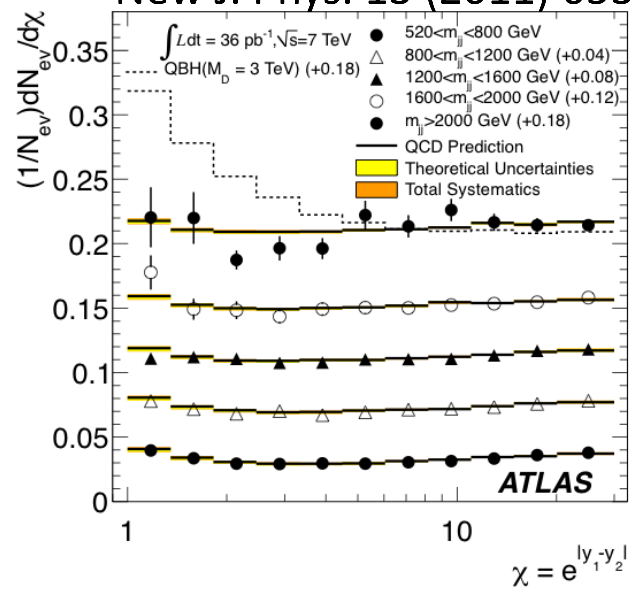
- Select high-p_T jets in dijet events;
- Study the distribution of the "opening angle" **y*** of the new physics at high mass appears first as central production (s-wave)

Dijet angular distribution -3

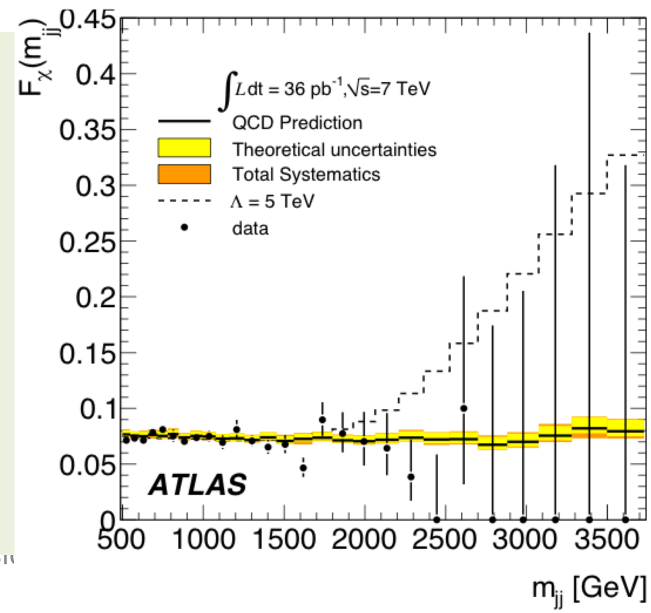
New J. Phys. 13 (2011) 053044

- Study two variables:
  - The χ distribution: $\chi=\exp 2|y^*|$ as a function of m_{jj}, the jet-jet system invariant mass
    - QCD is almost flat in this variable

  $F_\chi(m_{jj}) = n(|y^*|<0.6)/n(|y^*|<1.7)$ as a function of m_{jj}



- **Limits are set by ATLAS on:**
  - **Quark Contact Interactions with a scale Λ_C < 6.7 TeV (bayesian) 95% CL**
  - **Axigluon mass $0.60<m_A<210$ GeV**
  - **Randall-Meade quantum black holes with $0.75<M_D<3.67$ TeV, assuming N=6 Extra Dimensions**



Dilepton invariant mass

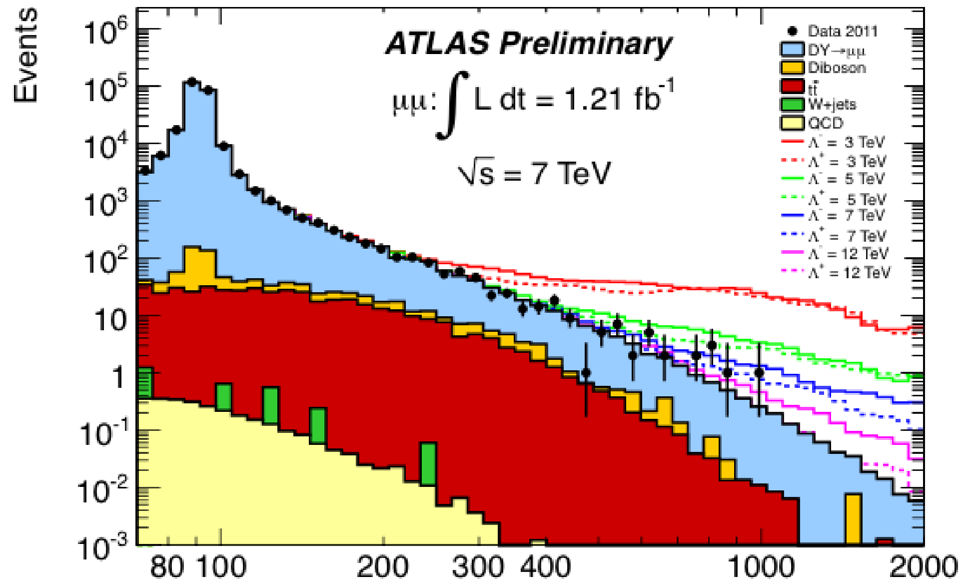
New

- quark/lepton compositeness may be described as a four-fermion ***Contact Interaction*** (CI) in the low energy limit.
  - Contact Interactions (CI) : approach similar to that used by Fermi to describe nuclear β decay long before the discovery of the W boson.
- With the introduction of a contact interaction, the differential cross section for the **process qq→μμ** becomes:

$$\frac{d\sigma}{dm_{\mu\mu}} = \frac{d\sigma_{\rm DY}}{dm_{\mu\mu}} - \eta_{LL}\frac{F_I(m_{\mu\mu})}{\Lambda^2} + \frac{F_C(m_{\mu\mu})}{\Lambda^4},$$

- FI: interfernce term between CI and Drell-Yan (DY)
- FC: pure CI term

- F_I: interfernce term between CI and Drell-Yan (DY)
- F_C: pure CI term



Results:

qq→ee: Λ⁻ > 10.1 TeV (Λ⁺ > 9.4 TeV)

qq→μμ: Λ⁻ > 8.0 TeV (Λ⁺ > 7.0 TeV)

for constructive (destructive) interference in the left-left isoscalar compositeness model.

Photons + MET

- **UED models** postulate the existence of additional spatial dimensions **in which all SM particles can propagate**, leading to the existence of a series of excitations for each SM particle known as a Kaluza-Klein (KK) tower.
- An ATLAS analysis considered the case of a single TeV^{-1}-sized UED, with *compactification* radius **R**.
  - The masses of the states of successive levels in the tower are separated by ~ 1/R. For a given KK level, the approximate mass degeneracy of the KK excitations is broken by radiative corrections
- The lightest KK particle (LKP) is the KK photon of the first level, denoted γ^*.
- At the LHC, the main UED process would be the production via the strong interaction of a pair of first-level KK quarks and/or gluons which would decay via cascades involving other KK particles until reaching the LKP γ^* at the end of the decay chain, followed by:

$$\gamma^* \rightarrow \gamma + G \text{ (graviton)}$$

- With two decay chains per event, the final state would again be

$$pp \rightarrow \gamma\gamma + E_T^{miss} + X$$

where E_T^{miss} results from the escaping gravitons and X represents SM particles emitted in the cascade decays.

Photons + MET

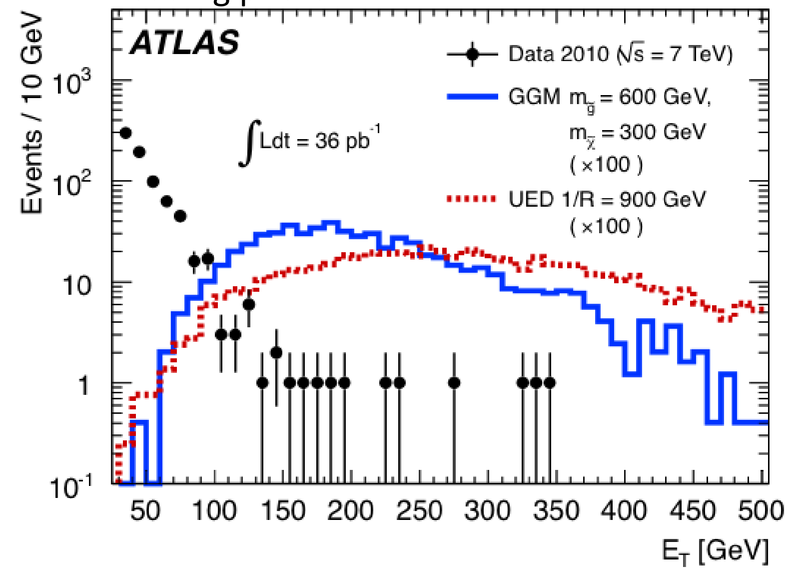
- Model considered here:
  - 1/R = 700 GeV
  - KK photon, quark and gluon are 700, 815 and 865 GeV mass
  - The decay width are set by the number N of extra dimensions and the Planck mass M_D in the = (4+N) space
  - For N=6, M_D = 5 TeV, 1/R< TeV, the LKP is the only KK particle to have an appreciable rate of gravitational decay

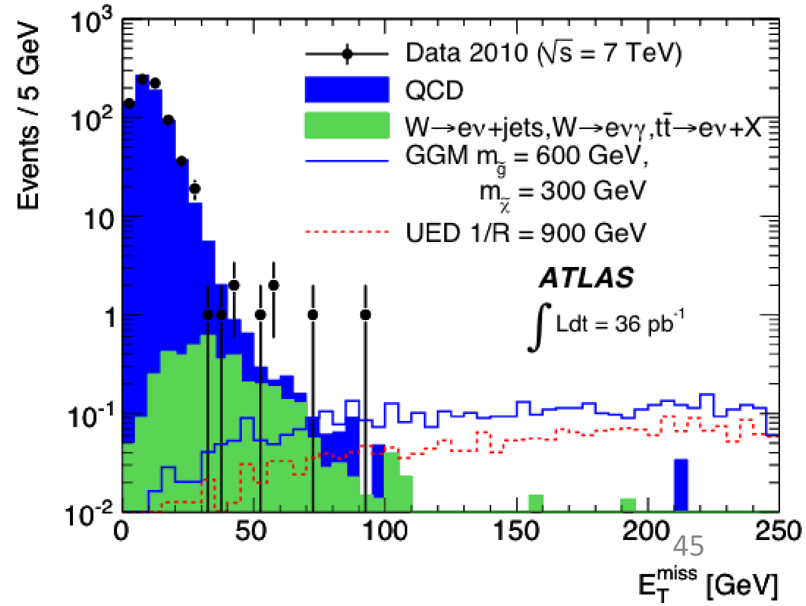
ATLAS: EPJ C 71 , 10 (2011)

Photons + MET

- Event selection:
  - Two – high-quality – photons with E_T>30,20 GeV respectively
  - E_T^{miss} > 125 GeV
- Data: 762 candidate passing all cuts except E_T^{miss} cut
- **Data: 0 events** pass also the E_T^{miss} > cut
- Background:
  1. **γγ, γ+jets, jet→misidentifed γ**
  2. **W+jets,Wγ+jets, jet→misidentifed γ**
- Background estimated from data using control samples
- **Expected background** after E_T^{miss} cut: **0.10±0.04±0.05 events**

Leading photon

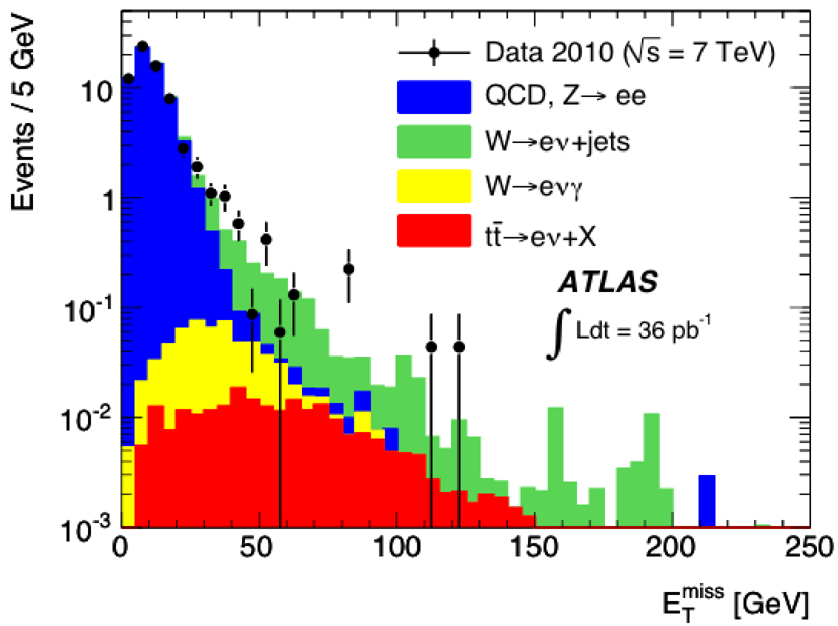




Photons + MET

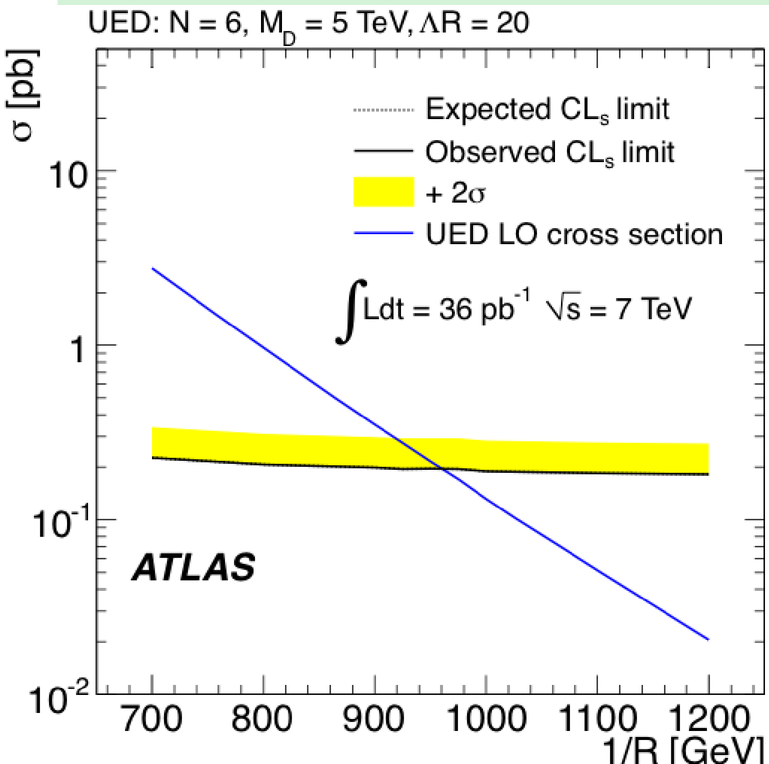
W+jets background estimation

- Select an e-γ sample with E_T>20 GeV, and one of the two with E_T>30 GeV
- Rescale the yield with the probability e→misidentified γ, estimated with a real data sample Z→ee for which one electron fakes a photon
- Need to subtract the estimate the contribution from Z→ee and QCD, dominating the low-E_T^{miss} region: normalize this control sample to data for E_T^{miss} < 20 GeV, see right plot

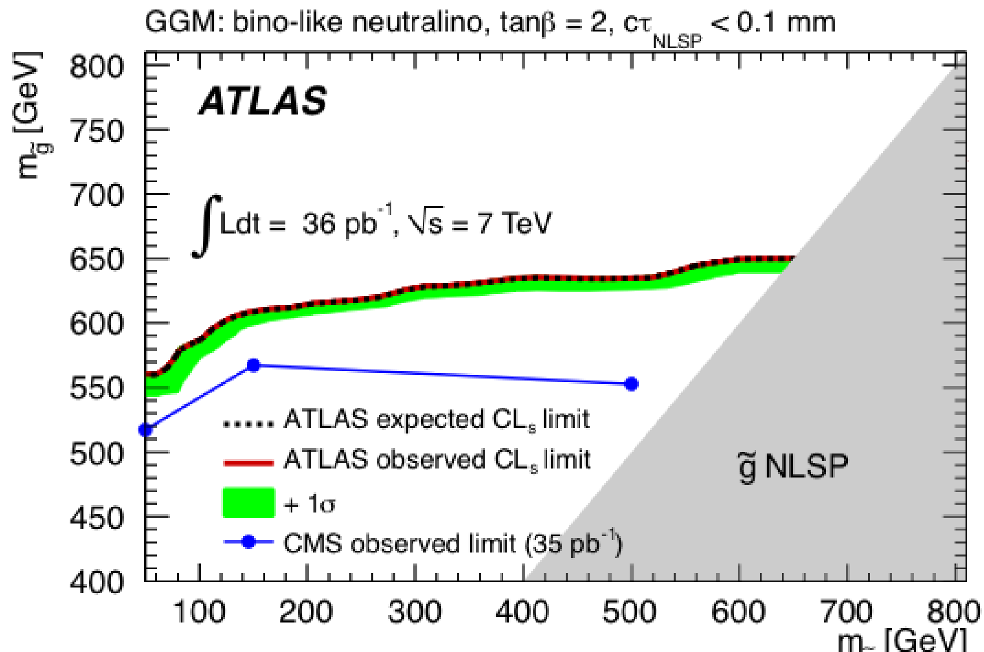


E_T^{miss} spectrum of the electron-photon control sample (points, statistical uncertainty only), normalised according to the probability for an electron to be misidentified as a tight photon, compared to the sum of the expected background, broken down by component (stacked histograms).

Photons + MET



Expected and observed 95 % CL upper limits on the UED production cross section, and the LO theory cross section prediction, as a function of 1/R.

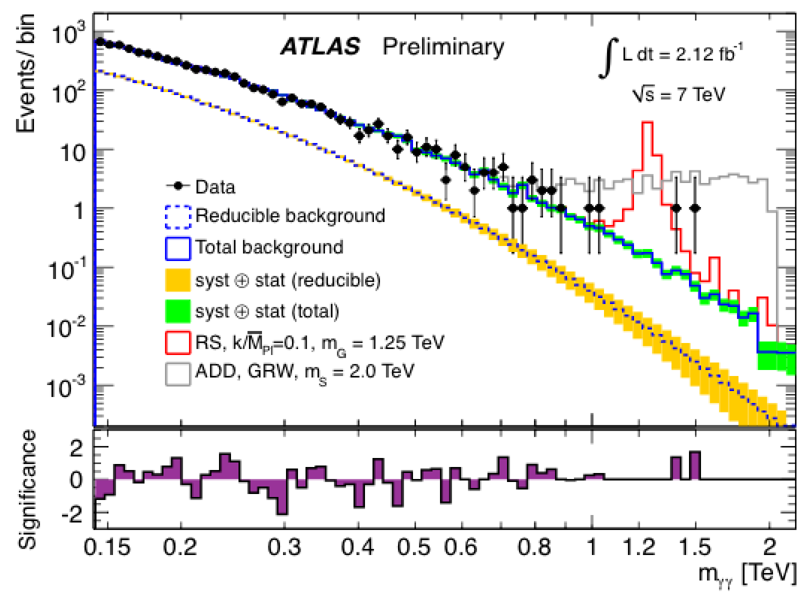


Expected and observed 95 % CL lower limits on the gluino mass as a function of the neutralino mass in the General Gauge Mediated model with a bino-like lightest neutralino as NLSP (the grey area indicates the region where the NLSP is the gluino, which was not considered here). The other sparticle masses are fixed to ~ 1.5 TeV. CMS limits are from Phys. Rev. Lett. 106, 211802 (2011). More recent CMS study in: http://cdsweb.cern.ch/record/1377324?ln=en

Searches in γγ final states

- In ADD and RS models the graviton G* can produce γγ final states:
  - G*→γγ
- ATLAS has performed an analysis based on 2.12 fb^{-1} studying the invariant mass of isolated “high-quality” high-p_T diphoton events
- Background composition:
  - Irreducible: QCD γγ
  - Reducible: γ-jet and jet-jet
- Background shape measured with data:
  - Study the events where one or both photons pass “low quality” cuts and fail “high-quality” cuts

  and normalized to data in the control region 140<$m_{\gamma\gamma}$ <400 GeV.

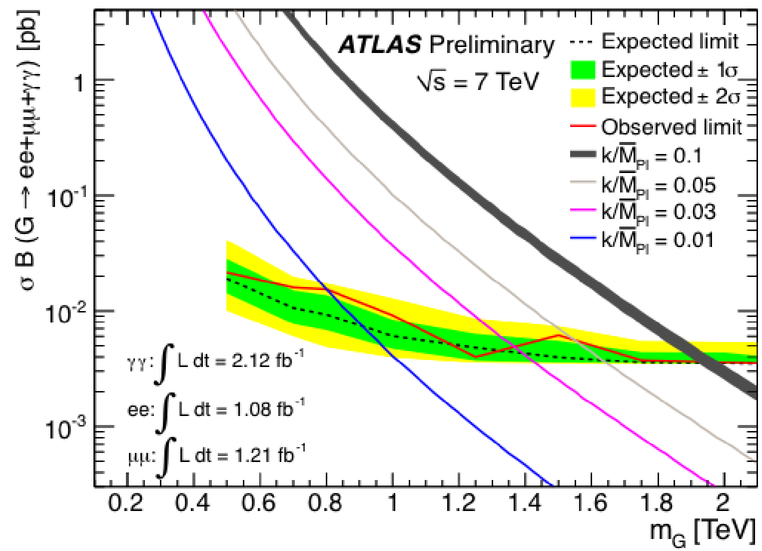


The observed invariant mass distribution of diphoton events, superimposed with the predicted SM background and expected signals for ADD and RS models with certain choices of parameters.

Searches in γγ final states

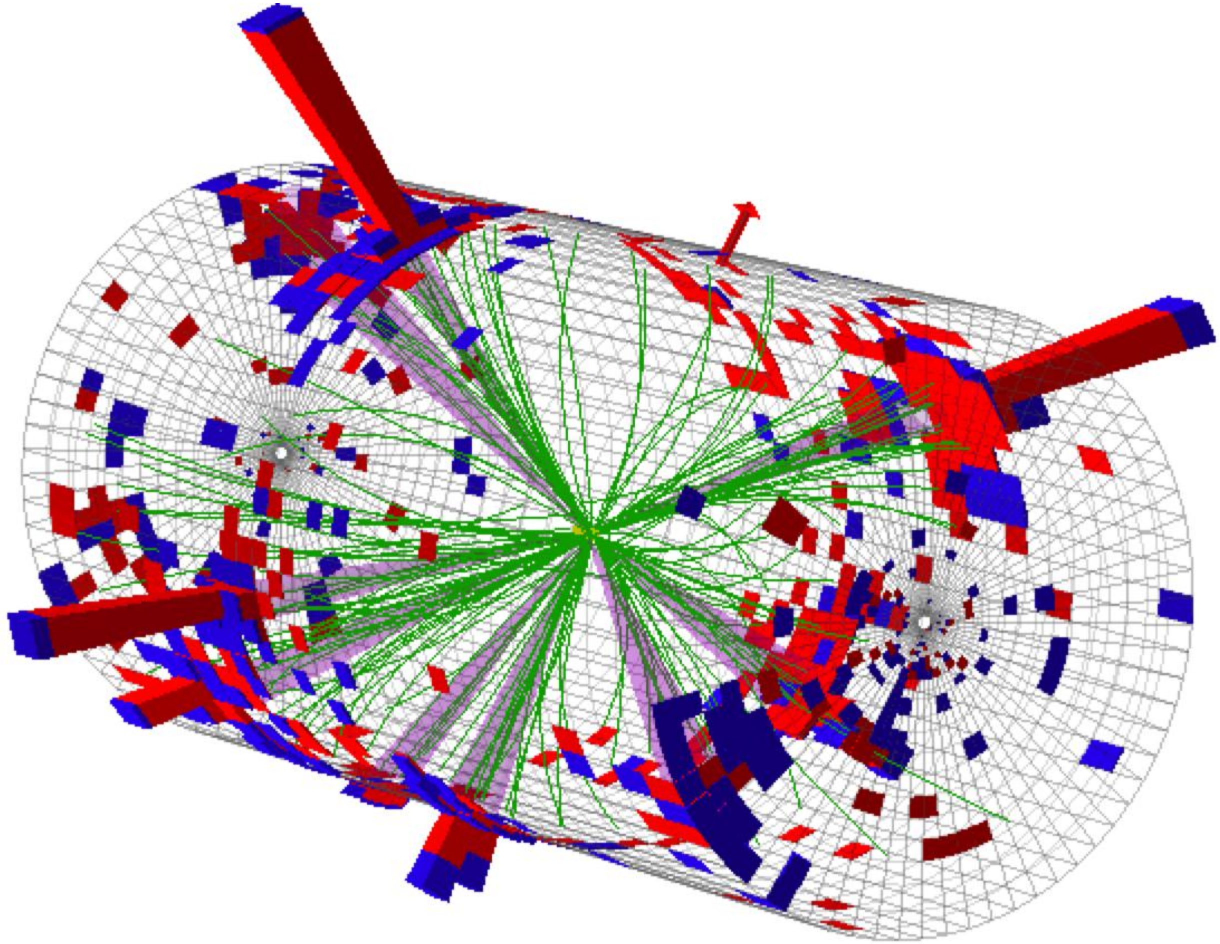
New

- No significant number of events are found exceeding the SM prediction
- 95% C.L. graviton production cross section exclusion limits are set.



Expected and observed 95% CL limits from the combination of $G^* \rightarrow \gamma\gamma, ee, \mu\mu$ on σB, the product of the Randall Sundrum graviton production cross section and the branching ratio for graviton decay via $G^* \rightarrow \gamma\gamma, ee, \mu\mu$, as a function of the graviton mass. The thickness of the theory curve for k/M_{Pl} illustrates the theoretical uncertainties.

Search for black holes



3-D view of 9-jet candidate event; S_T = 2.6 TeV

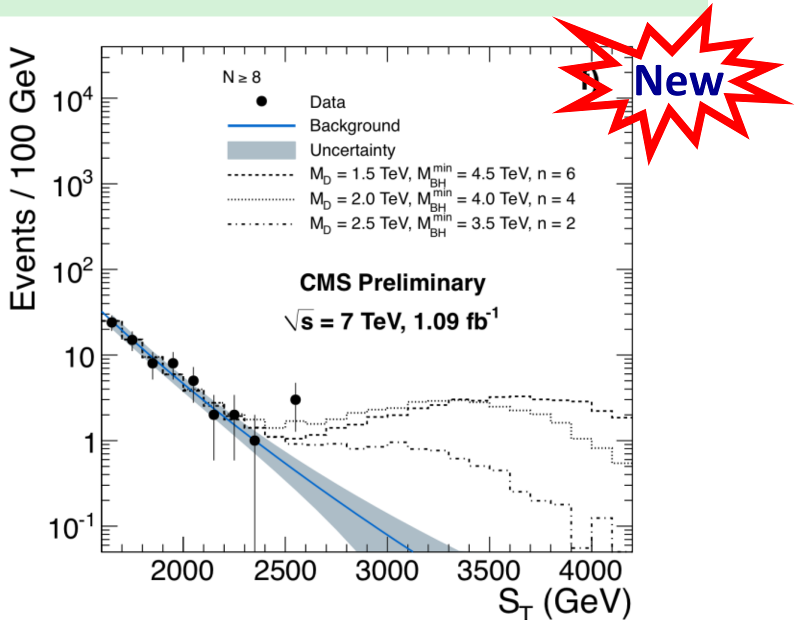
CMS Experiment at LHC, CERN
Data recorded: Mon May 23 21:46:26 2011 EDT
Run/Event: 165567 / 347495624
Lumi section: 280
Orbit/Crossing: 73255853 / 3161

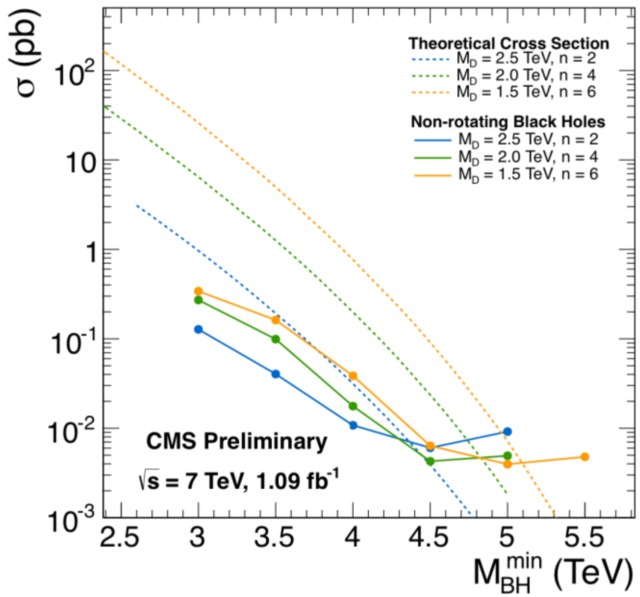
CMS: PAS EXO-11-071

Search for black holes

- Here a CMS study is presented, based on 1.09 fb^{-1}.
- Select events with leptons, photons, and jets all produced with large transverse energies; each object is asked to have E_T>20 GeV
- Define $\mathbf{S_T}$ as

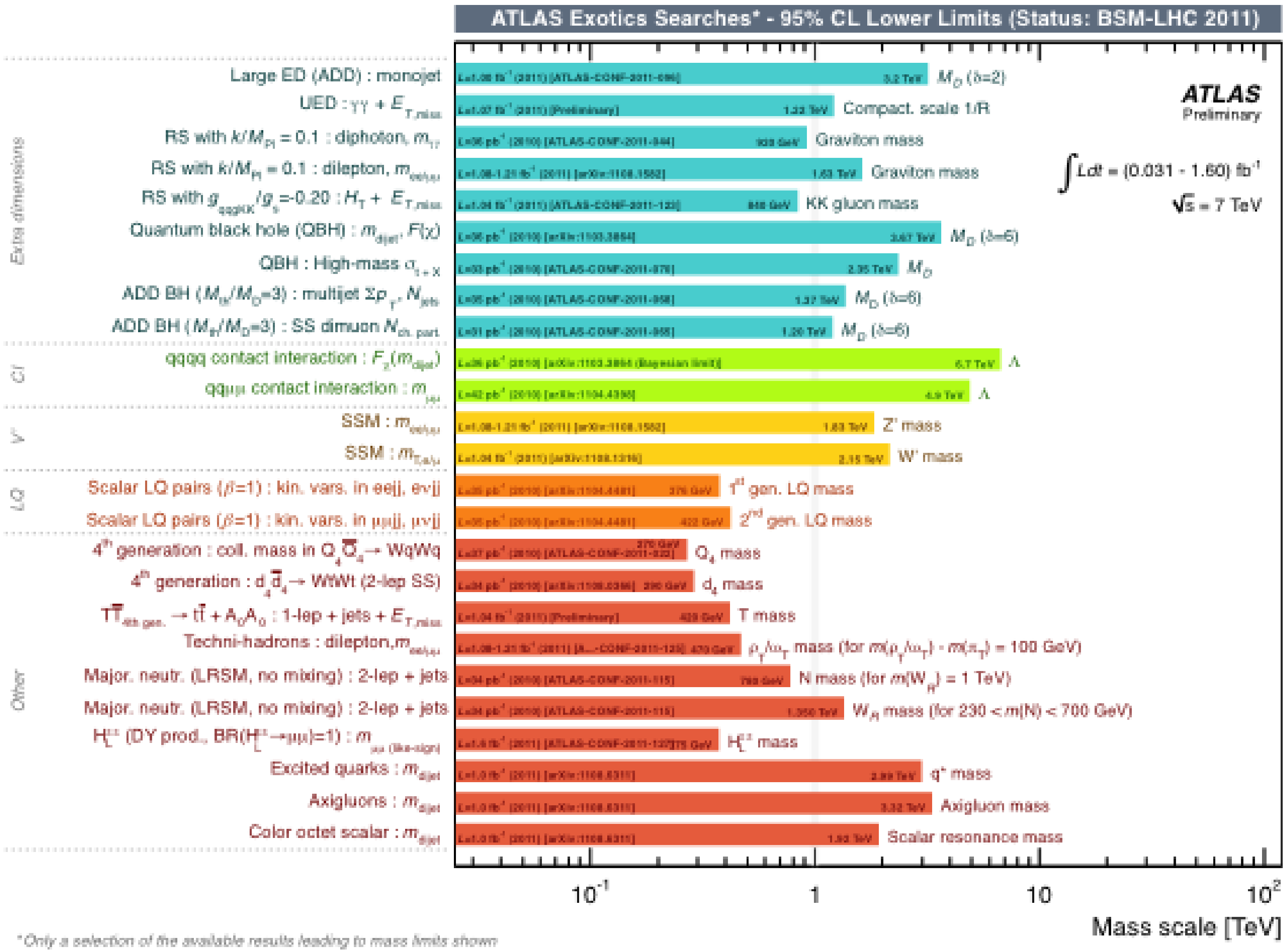
  $\mathbf{S_T = \Sigma_{(e,\mu,\gamma,jets)} |E_T|}$
- study S_T as a function of N, the number of high-E_T objects
- Model-independent production cross-section limits have been provided
- Translating these cross-section limits into expectations to the ADD model, we can exclude the production of black-holes with a minimum mass from 4.0 to 5.1 TeV for values of M_D up to 3.5 TeV





Exotics Summary (ATLAS)

24 Aug 2011



Conclusions

- Past sixteen month of data taking at the LHC have been very intense and productive
- Many searches of New Physics in several complementary final states have been performed, and many analyses are ready to process new data to come in 2012
- With 5 fb^{-1} LHC can explore larger mass intervals, and set limits to ~2.2 TeV if no new particles exist in nature in this mass domain
- With 30 fb^{-1} the exclusion could extend to ~ 2.7 TeV
- Another exciting year ahead!

BACKUP

LHC – end of August

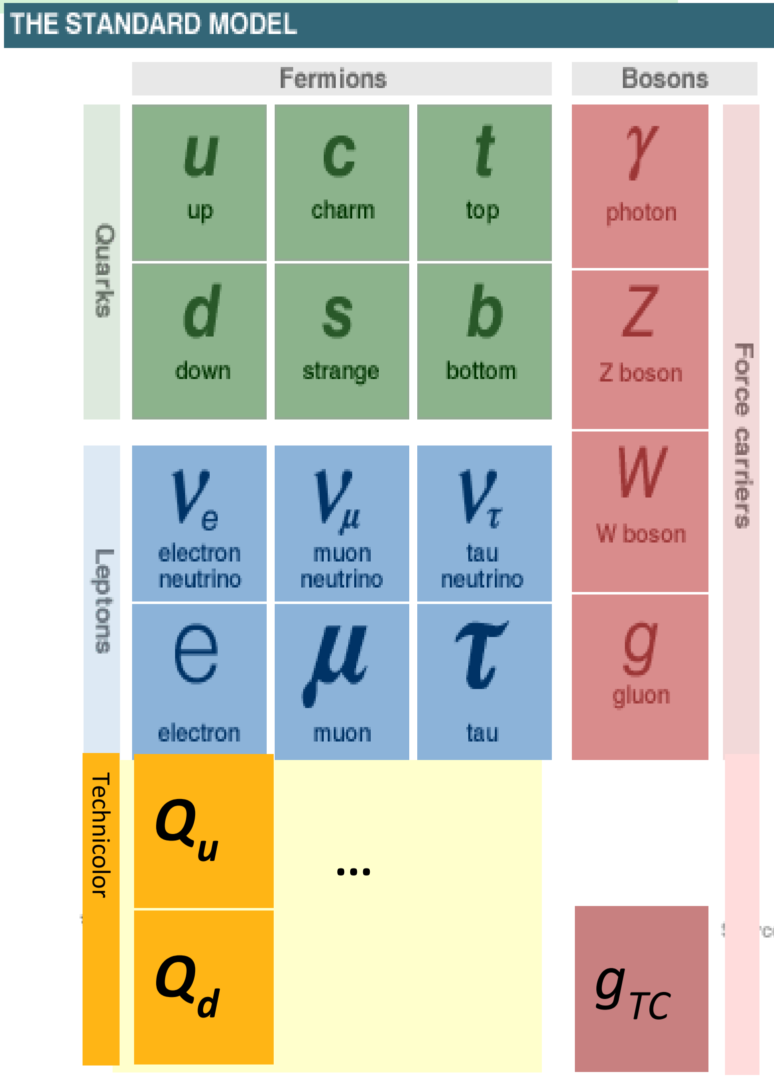
	2010	2011	Nominal
Energy [TeV]	3.5	3.5	7
β* [m] (IP1,IP2,IP5,IP8)	3.5, 3.5, 3.5, 3.5	1.5, 10, 1.5, 3.0	0.55, 10, 0.55, 10
Emittance [μm] (start of fill)	2.0 – 3.5	**1.5 – 2.2**	3.75
Transverse beam size at IP1&5 [μm]	60	28	16.7
Bunch population	1.2×10^{11} p	**1.35×10^{11} p**	1.15×10^{11} p
Number of bunches	368	1380	2808
Number of collisions (IP1 & IP5)	348	1318	-
Stored energy [MJ]	28	110	360
Peak luminosity [$cm^{-2}s^{-1}$]	2×10^{32}	**2.41×10^{33}**	1×10^{34}
Max delivered luminosity (1 fill) [pb^{-1}]	6.23	100.7	-
Longest Stable Beams fill [hrs]	12:09	25:59	-

Search for Technicolor particles

- The Standard Model of fields and particles has a number of "problematic" areas. One of these is associated to the "naturalness" of the Higgs mechanism used to introduce the electroweak symmetry breaking
- In brief: the corrections to the (unpredicted by SM) bare Higgs mass are divergent:
  - To get a physical Higgs mass around say 100 GeV, the bare Higgs mass must be "tuned" against its radiative corrections to the fantastic precision of $M^2_{Pl}/M^2_H \sim 10^{34}$!!
- Several alternative models have been proposed to avoid tis problem
  - SUSY theories
  - Technicolor-based theories

More on Technicolor

- Technicolor: alternate mechanism of EWSB
- Introduce new strong gauge interaction
  - Typically some $SU(N_{TC})$
- New fermions sensitive to TC → techniquarks
  - N_D isospin doublets of techniquarks
- TC becomes large for $\Lambda_{TC} \sim O(100\ \text{GeV})$
  - Chiral symmetry breaking
- EW precision constraints on FCNC:
  - Scaled-up QCD models excluded, but TC with a walking coupling is ok
    - Can chose N_{TC} and N_D accordingly…



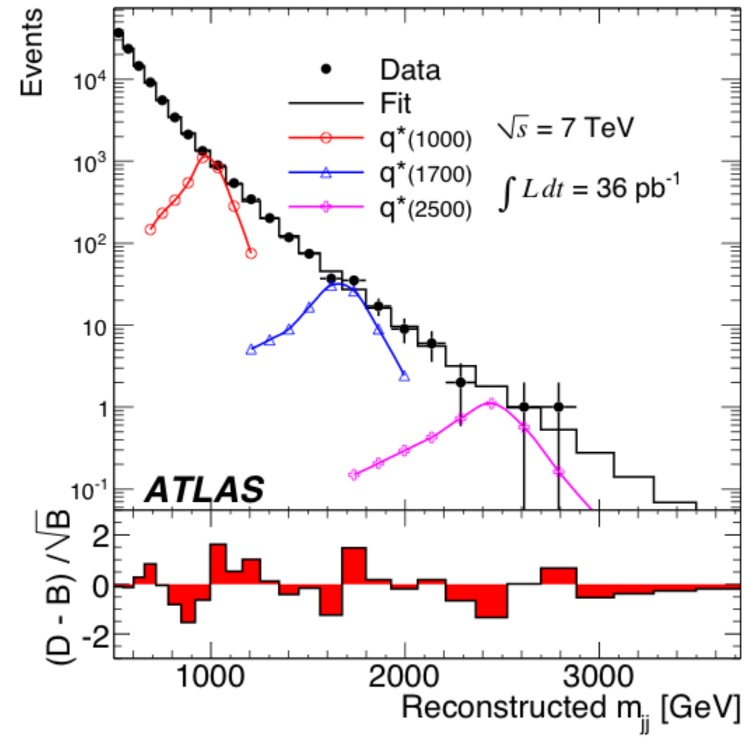
Dijet resonances -2

- Study the m_{jj} distribution assuming only QCD contributions and fitting it with the function

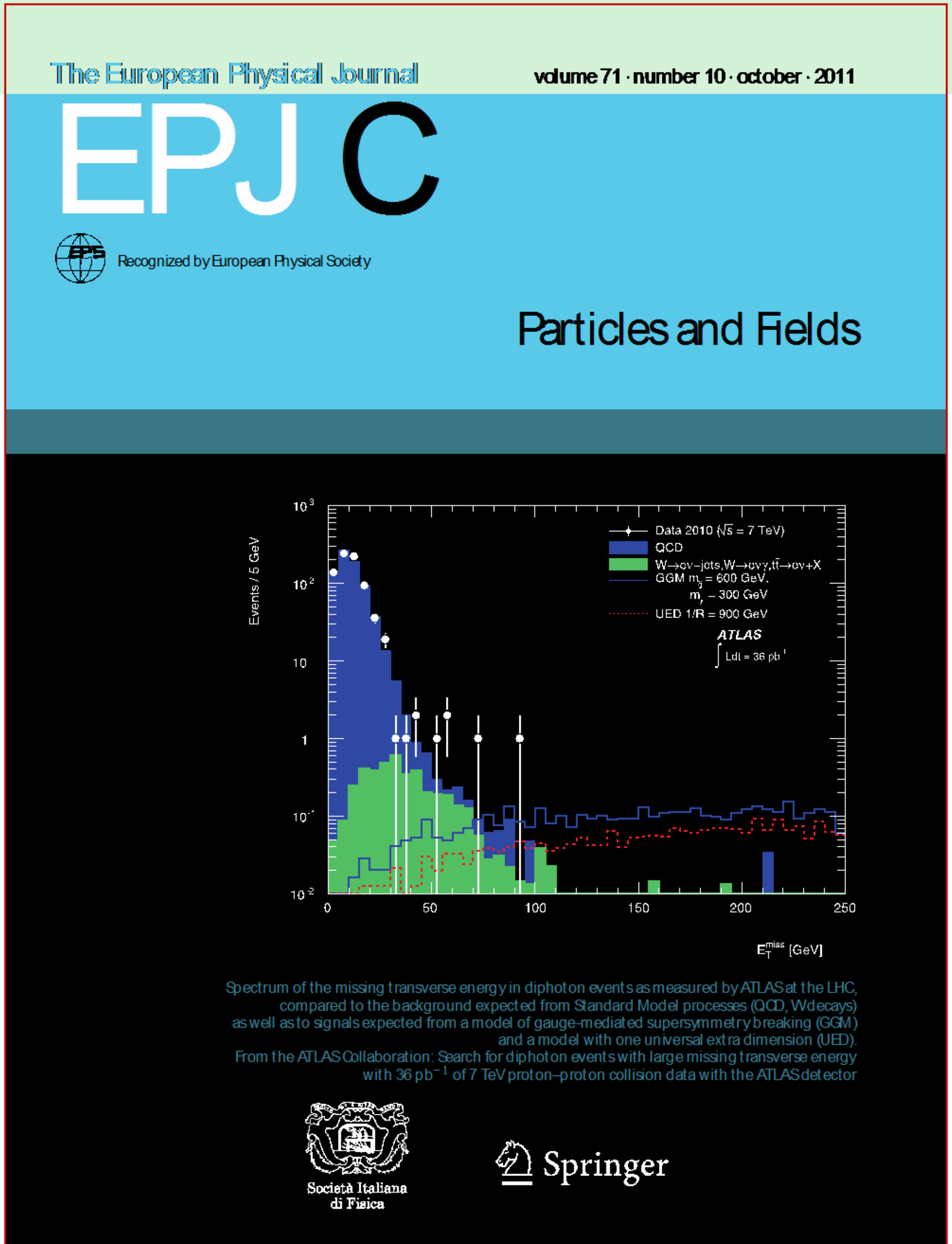
$$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \ln x}$$

where $x \equiv m_{jj}/\sqrt{s}$

- Use the BumpHunter algorithm to establish the presence or absence of a resonance



The measured dijet mass distribution (points) compared to the fitted function used to describe the QCD background. The binning is chosen accounting for the jet-jet mass resolution. The bin-by-bin significance (statistics only) is shown in the lower insert.


The European Physical Journal
volume 71 · number 10 · october · 2011
EPJ C
Recognized by European Physical Society
Particles and Fields
Events / 5 GeV
Data 2010 (√s = 7 TeV)
QCD
W→eν–jets,W→eνγ,tt̄→eν+X
GGM m_g̃ = 600 GeV, m_χ̃ = 300 GeV
UED 1/R = 900 GeV
ATLAS
∫ Ldt = 36 pb⁻¹
E_T^miss [GeV]
Spectrum of the missing transverse energy in diphoton events as measured by ATLAS at the LHC,
compared to the background expected from Standard Model processes (QCD, W decays)
as well as to signals expected from a model of gauge-mediated supersymmetry breaking (GGM)
and a model with one universal extra dimension (UED).
From the ATLAS Collaboration: Search for diphoton events with large missing transverse energy
with 36 pb⁻¹ of 7 TeV proton–proton collision data with the ATLAS detector
Società Italiana di Fisica
Springer

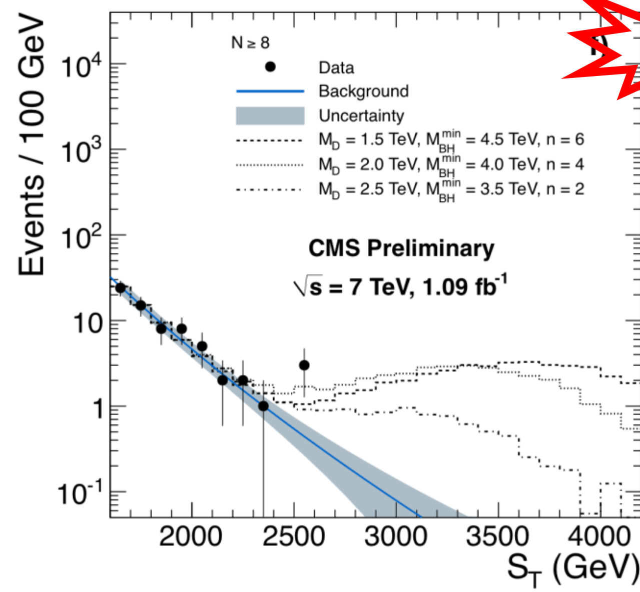
Search for black holes

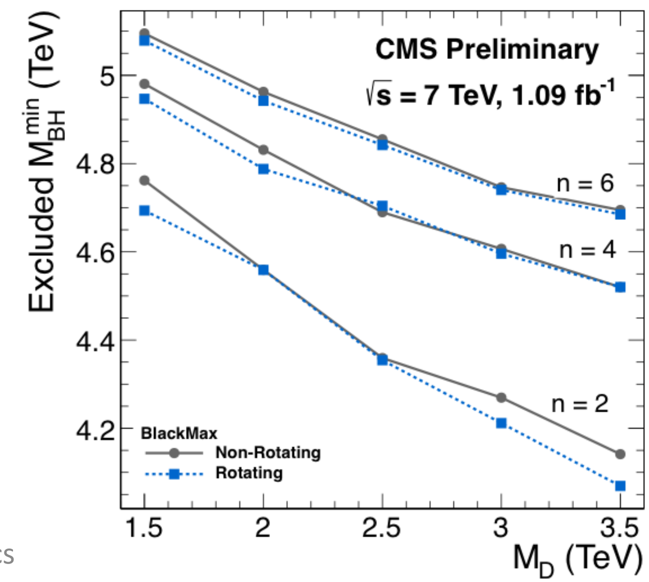
- Here a CMS study is presented, based on 1.09 fb^{-1}.
- Select events with leptons, photons, and jets all produced with large transverse energies; each object is asked to have E_T>20 GeV
- Define $\mathbf{S_T}$ as

  $$S_T = \Sigma_{(e,\mu,\gamma,jets)} |E_T|$$

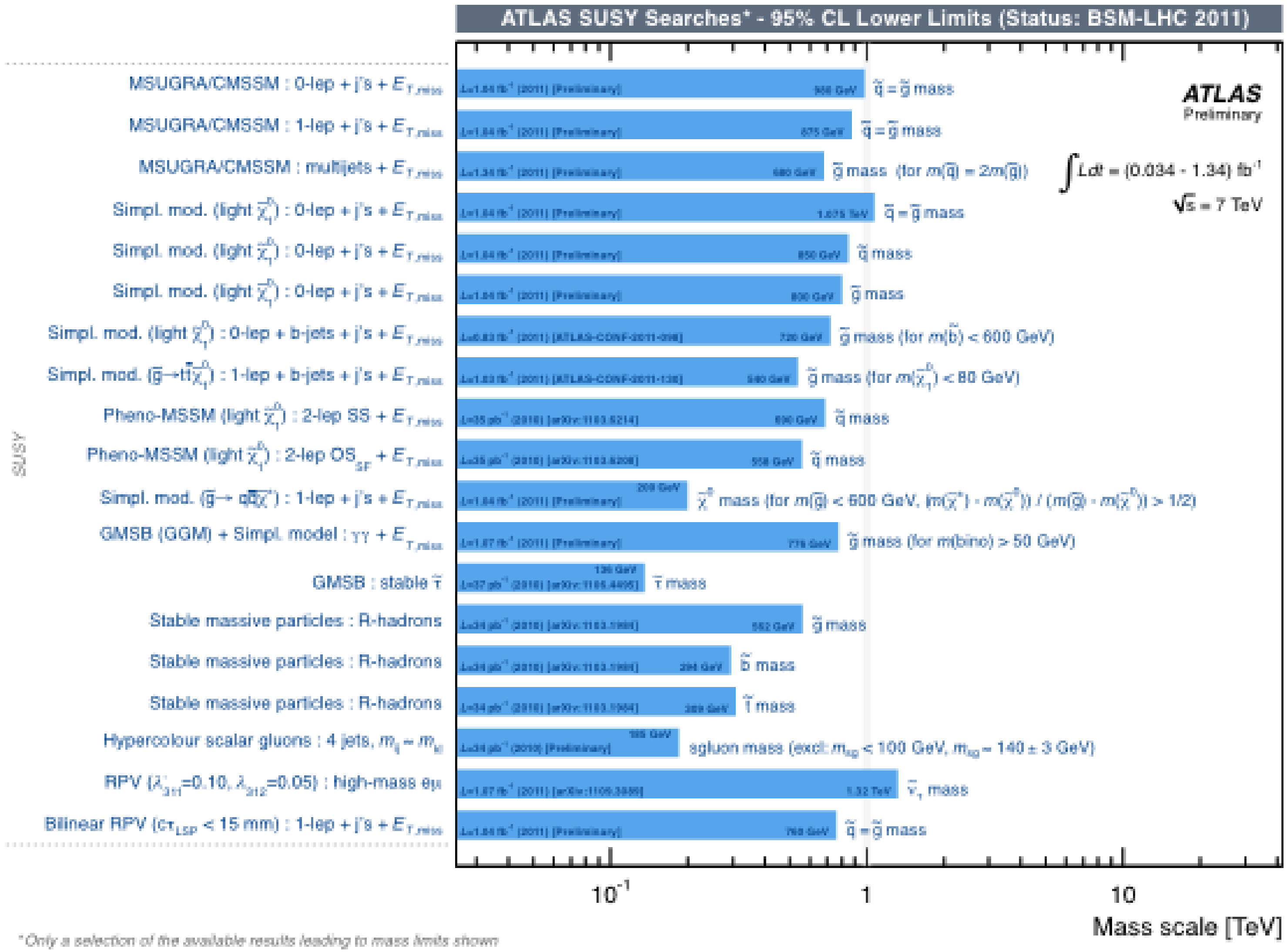
- study S_T as a function of N, the number of high-E_T objects
- Traslating the cross-section limits into expectations to the ADD model, we can exclude the production of black-holes with a minimum mass from 4.0 to 5.1 TeV for values of MD up to 3.5 TeV

New





SUSY limits


ATLAS SUSY Searches* - 95% CL Lower Limits (Status: BSM-LHC 2011)
MSUGRA/CMSSM : 0-lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : 1-lep + j's + $E_{T,miss}$
MSUGRA/CMSSM : multijets + $E_{T,miss}$
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + j's + $E_{T,miss}$
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + j's + $E_{T,miss}$
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + j's + $E_{T,miss}$
Simpl. mod. (light $\tilde{\chi}_1^0$) : 0-lep + b-jets + j's + $E_{T,miss}$
Simpl. mod. ($\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$) : 1-lep + b-jets + j's + $E_{T,miss}$
Pheno-MSSM (light $\tilde{\chi}_1^0$) : 2-lep SS + $E_{T,miss}$
Pheno-MSSM (light $\tilde{\chi}_1^0$) : 2-lep OS_{SF} + $E_{T,miss}$
Simpl. mod. ($\tilde{g} \to q\bar{q}\tilde{\chi}^{\pm}$) : 1-lep + j's + $E_{T,miss}$
GMSB (GGM) + Simpl. model : $\gamma\gamma$ + $E_{T,miss}$
GMSB : stable $\tilde{\tau}$
Stable massive particles : R-hadrons
Stable massive particles : R-hadrons
Stable massive particles : R-hadrons
Hypercolour scalar gluons : 4 jets, $m_{ij} \sim m_{kl}$
RPV (λ'_{311}=0.10, λ_{312}=0.05) : high-mass eμ
Bilinear RPV ($c\tau_{LSP}$ < 15 mm) : 1-lep + j's + $E_{T,miss}$
SUSY
$\tilde{q} = \tilde{g}$ mass
$\tilde{q} = \tilde{g}$ mass
$\tilde{g}$ mass (for $m(\tilde{q}) = 2m(\tilde{g})$)
$\tilde{q} = \tilde{g}$ mass
$\tilde{q}$ mass
$\tilde{g}$ mass
$\tilde{g}$ mass (for $m(\tilde{b})$ < 600 GeV)
$\tilde{g}$ mass (for $m(\tilde{\chi}_1^0)$ < 80 GeV)
$\tilde{q}$ mass
$\tilde{q}$ mass
$\tilde{\chi}^{\pm}$ mass (for $m(\tilde{g})$ < 600 GeV, $(m(\tilde{\chi}^{\pm}) - m(\tilde{\chi}^0)) / (m(\tilde{g}) - m(\tilde{\chi}^0))$ > 1/2)
$\tilde{g}$ mass (for m(bino) > 50 GeV)
$\tilde{\tau}$ mass
$\tilde{g}$ mass
$\tilde{b}$ mass
$\tilde{t}$ mass
sgluon mass (excl: m_{sg} < 100 GeV, m_{sg} = 140 ± 3 GeV)
$\tilde{\nu}_\tau$ mass
$\tilde{q} = \tilde{g}$ mass
ATLAS
Preliminary
$\int L dt = (0.034 - 1.34)\ fb^{-1}$
$\sqrt{s}$ = 7 TeV
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available results leading to mass limits shown