ATLAS Exotic Searches

Hadron Collider Physics Symposium
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Centre de Physique des Particules de Marseille
CPPM

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ATLAS

Introduction

➢LHC has been performing extremely well this year!
→Will focus on ATLAS results with ~1-2 fb^{-1}

➢SUSY, BSM Higgs and heavy-resonances were already covered (cf talks from O. Igonkina, P. De Jong, W. Fedorko)

➢All but one of the results in this talk are NEW
→ https://twiki.cern.ch/twiki/bin/view/AtlasPublic
for complete information about all results.

Why searching for exotics ?

→ To answer very fundamental problems:

Hierarchy problem

EW symmetry breaking

Fermion mass hierarchy

Dark Matter

Baryon Asymmetry of the Universe

Grand Unification

……

→Solutions might come from rich and diverse models:

Composite Higgs models ?

Technicolor ?

Extra dimensions ?

Heavy-quarks ?

Leptoquarks ?

Surprises?!

→ Many exciting searches!

Outline

Searches for new particles

- Leptoquarks
- New heavy quarks
- Vector-like quarks

Searches for strong gravity

- Black Holes

Generic searches for new physics

- Hidden-valley scenario
- Contact interactions

Outline

Searches for new particles

- Leptoquarks NEW
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Search for first generation of scalar leptoquarks

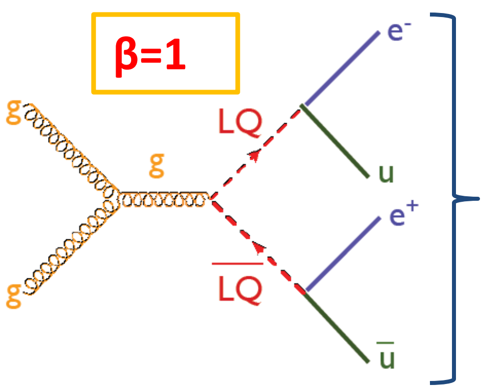
L_{int}: 1.03 fb^{-1}

Motivations: Leptoquarks (LQ) are color-triplet bosons that carry both lepton and baryon numbers, and fractional electric charge

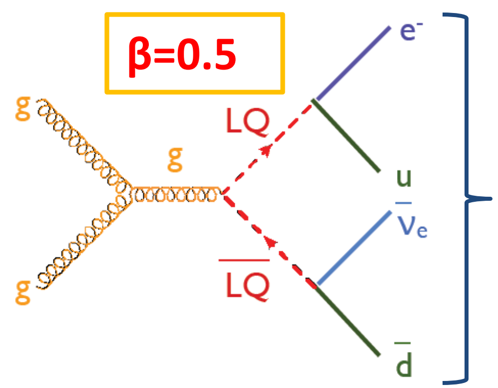
- Introduced by various extension of the SM (technicolor, GUTs, etc)
- Could explain **similarities between the 3 generations of leptons and quarks in the SM**, and lead to some **symmetry at high energy scale**

Analysis strategy: Search for pair-produced LQs assumed to couple only to quarks and leptons of the same SM generation

→ Focus here on 1st generation for 2 scenarii: β=BR(LQ→eq)

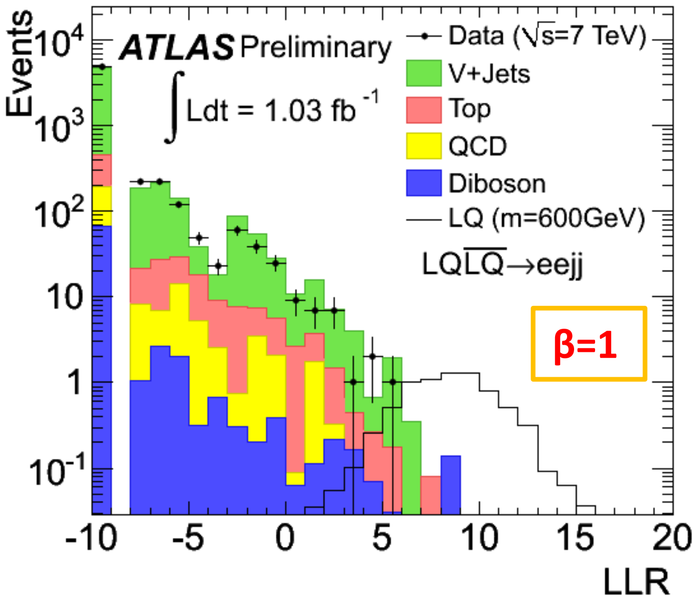


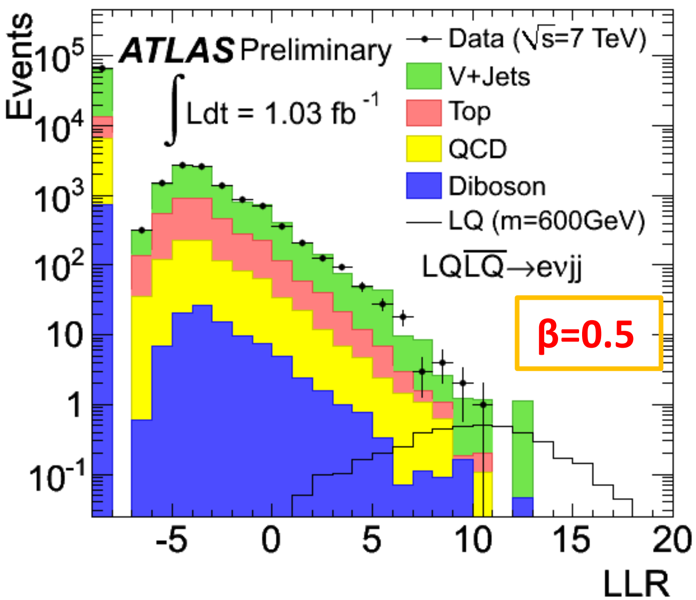
Select:
- **2 electrons**
- **2 jets**



Select:
- **1 electron**
- **2 jets**
- **Missing energy**

Search for first generation of scalar leptoquarks

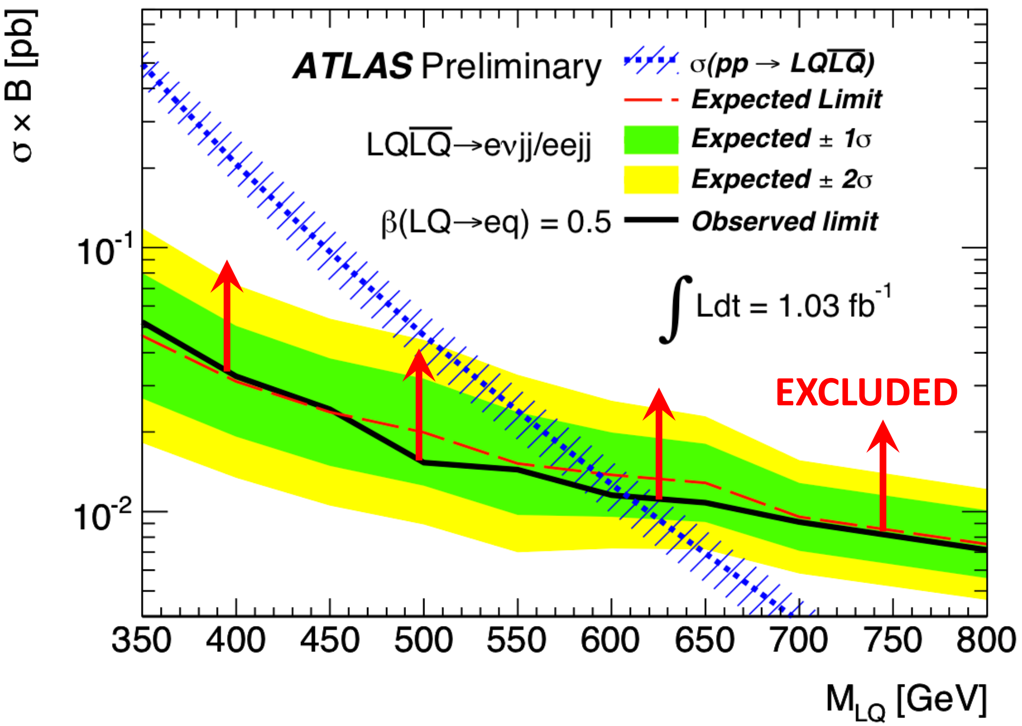


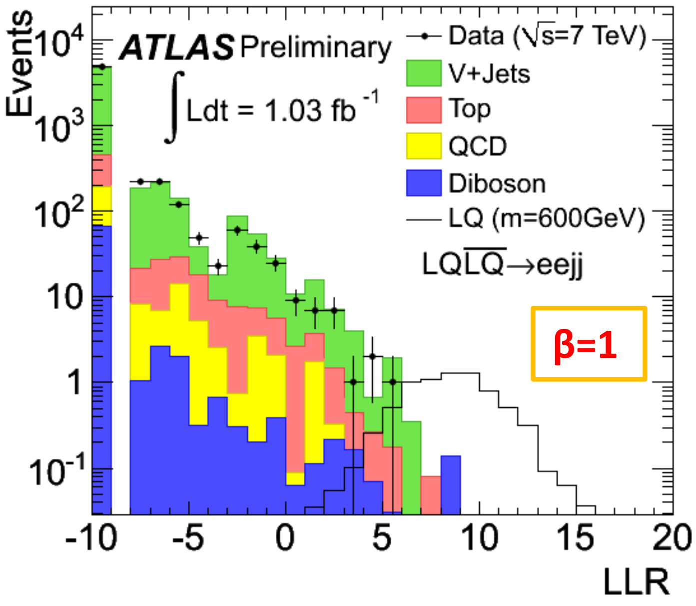


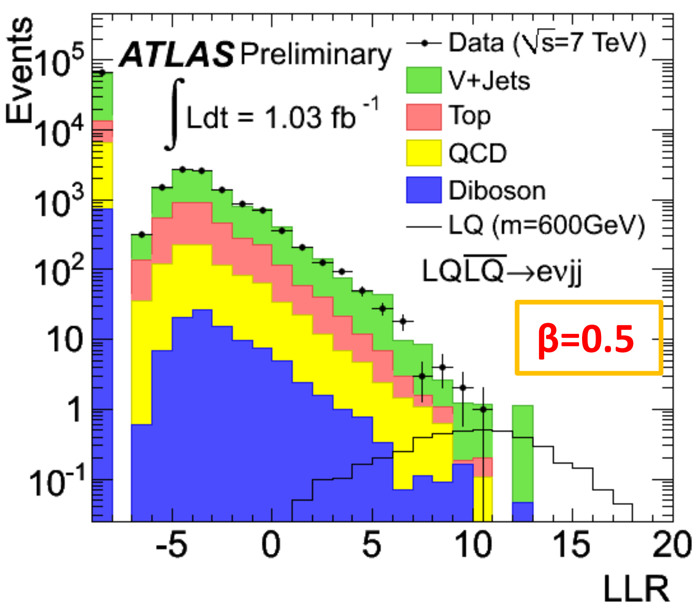
Analysis strategy cont'd:

Use of Likelihood ratio method to discriminate signal from SM backgrounds

… then put 95% CLs upper limits on σxBR:







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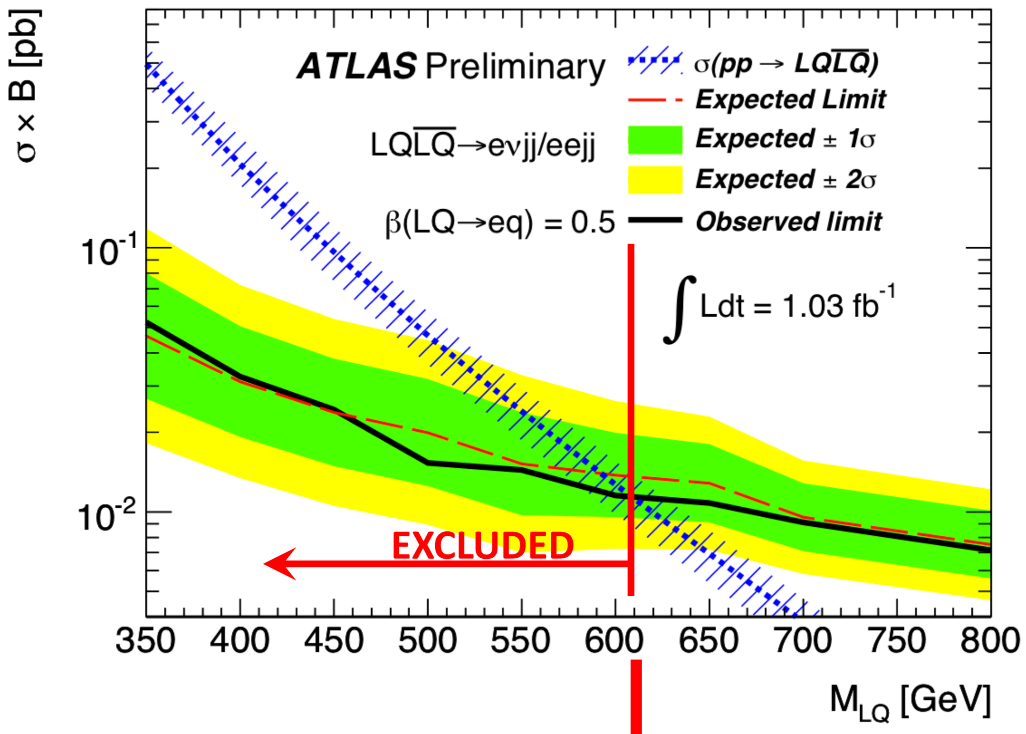
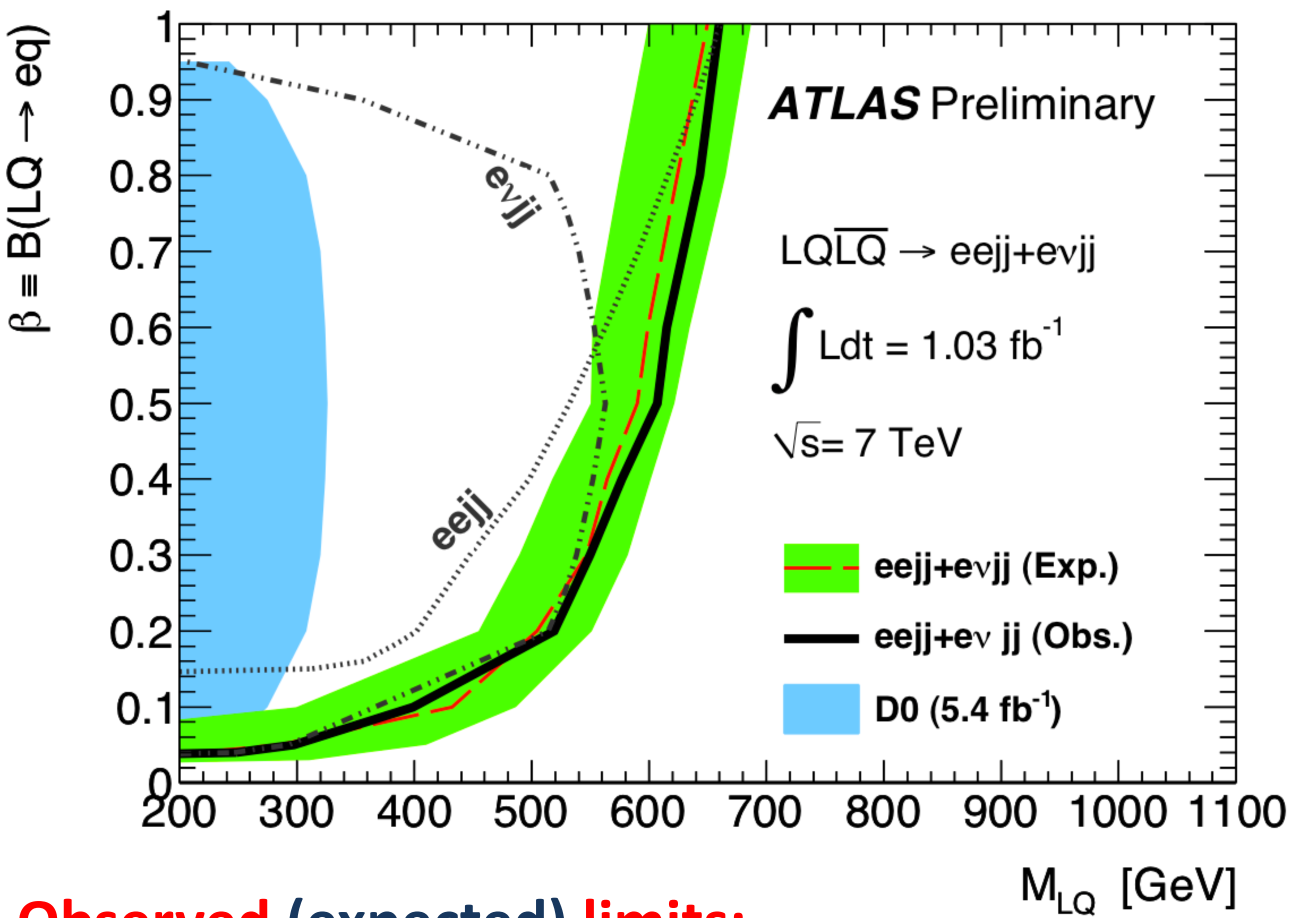


m_{LQ} > 607 GeV

Results: 95% CL exclusion regions



Observed (expected) limits:

- $\beta=1$: $m_{LQ} > 660(650)$ GeV
- $\beta=0.5$: $m_{LQ} > 607(587)$ GeV

→See poster by John Stupak

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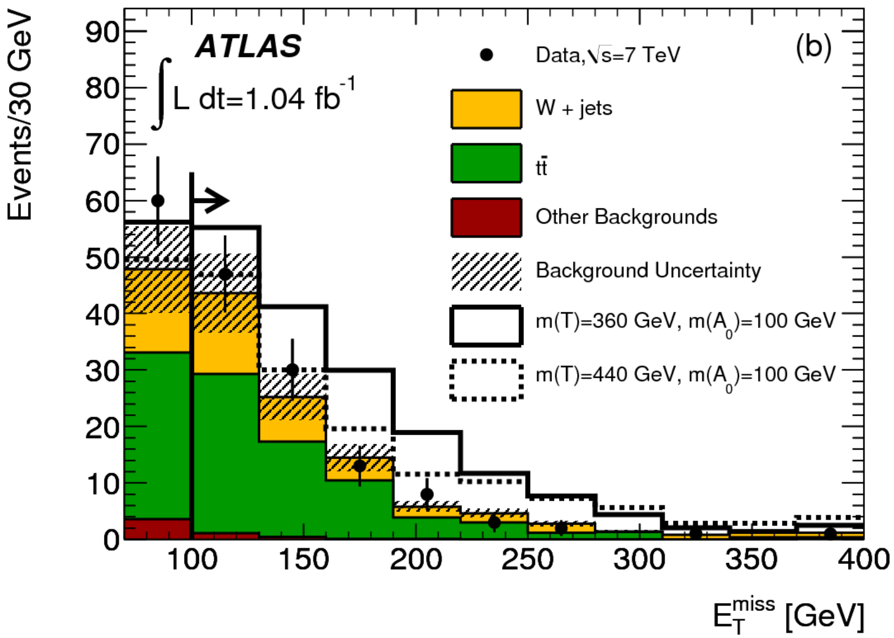
Search for exotic top partners $T\bar{T}$ with large missing transverse momentum

arXiv:1109.4725 L_{int}: 1.04 fb^{-1}

Motivations: **Top quark is the main contributor to quadratic divergence in the Higgs mass → *light* top partners T (m_T<1TeV) could allow to cancel part of this divergence, and provide solutions to the hierarchy problem**

Analysis strategy: Search for $T\bar{T} \rightarrow t\bar{t}\, A_0 A_0$ with A_0 **a stable, neutral weakly-interacting particle**

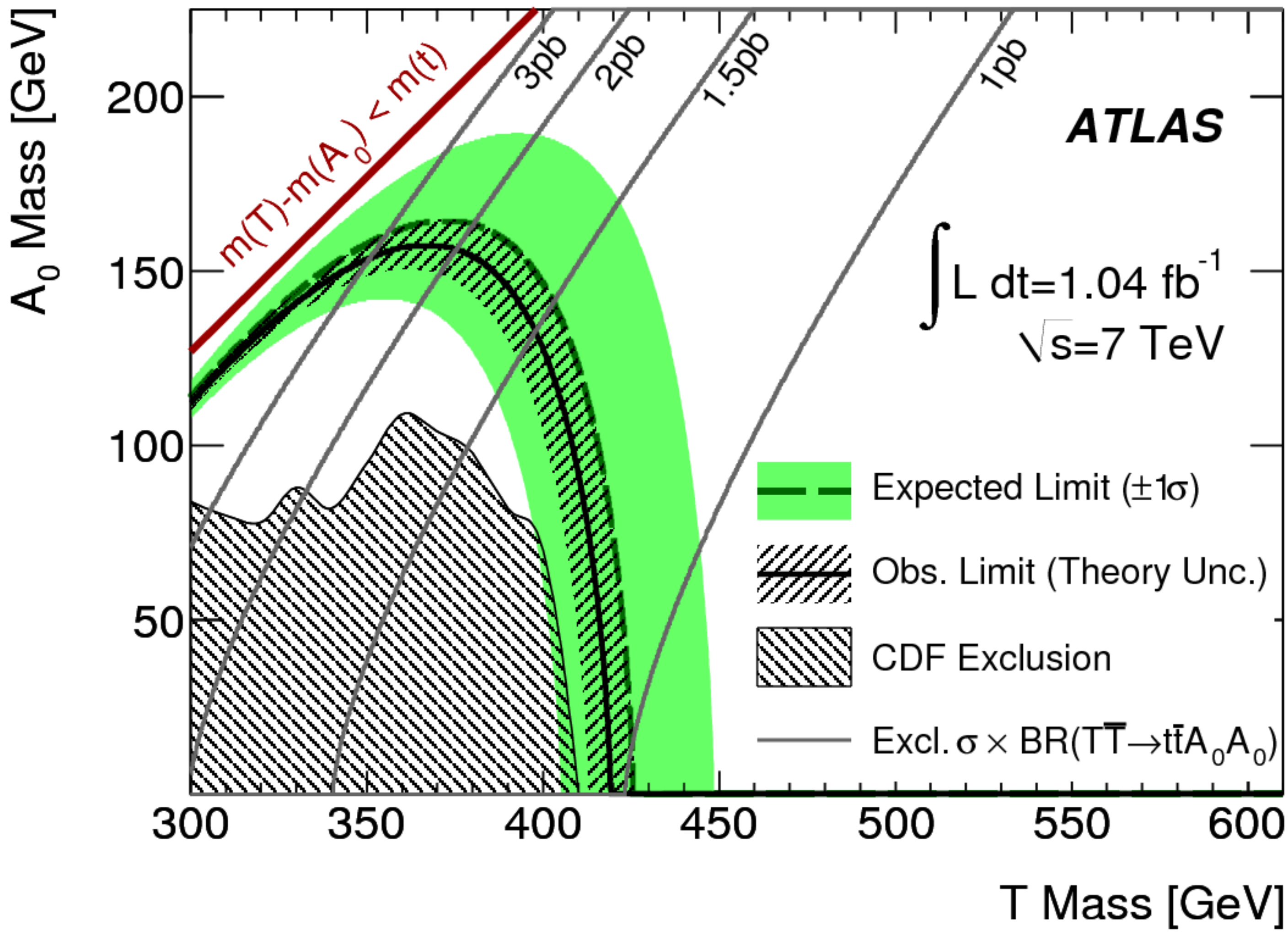


→**Introduced by many models, *e.g.:***
SuSy, little Higgs, 3rd generation of leptoquarks, extra dimension, etc

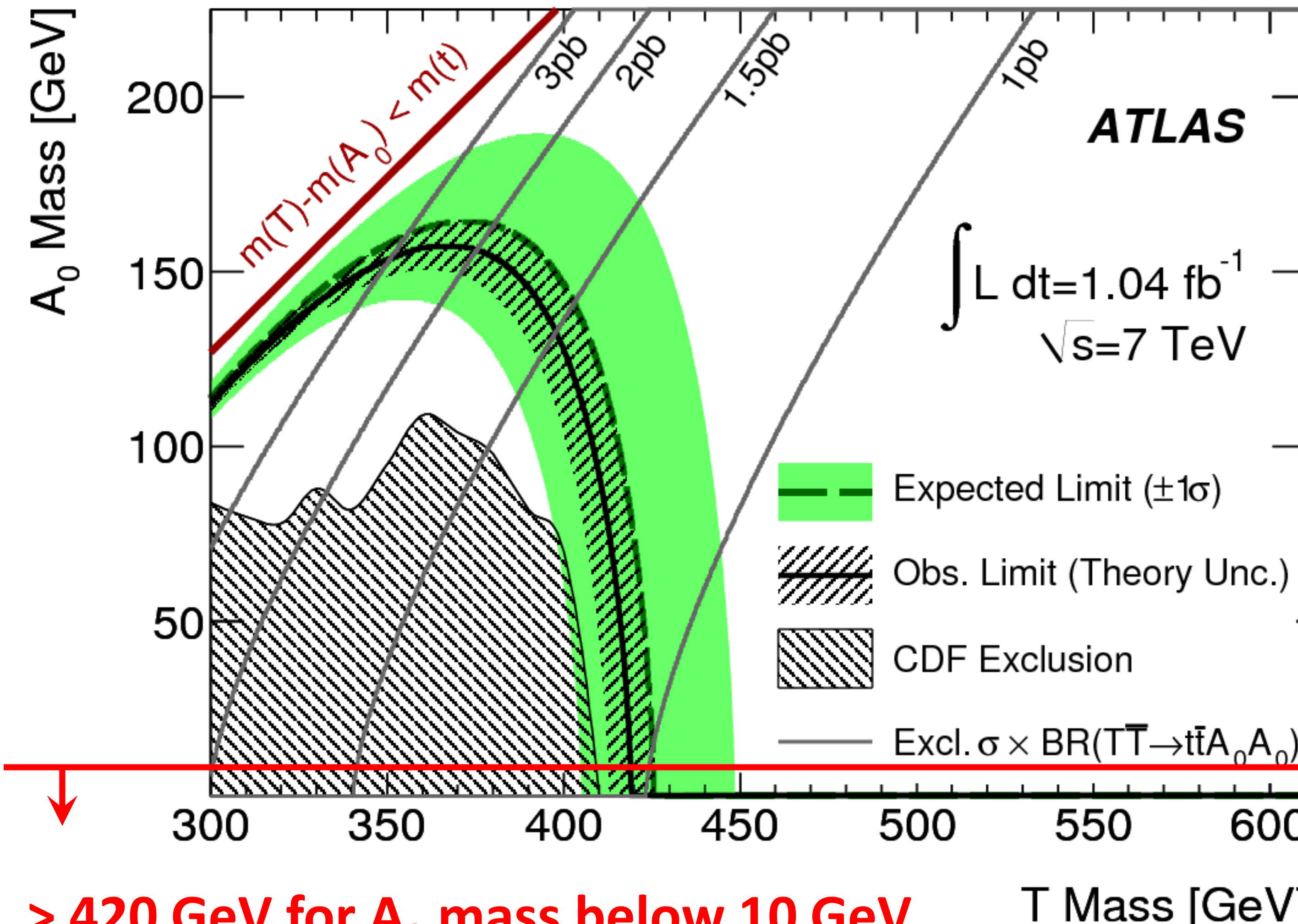
➢**Many provide mechanism for EWSB, and dark matter candidates**

→Signature identical to $t\bar{t}$, with larger amount of E_T^{miss} (focus here on single-lepton channel)

Results: 95% CL exclusion regions assuming B.R.($T\bar{T} \rightarrow t\bar{t}\, A_0 A_0$)=100%



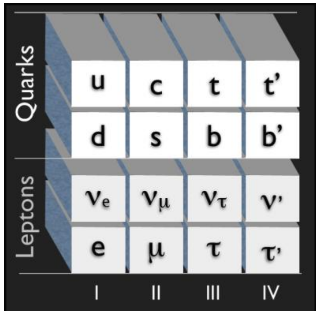
Results: 95% CL exclusion regions assuming B.R.($T\bar{T} \rightarrow t\bar{t} A_0 A_0$)=100%

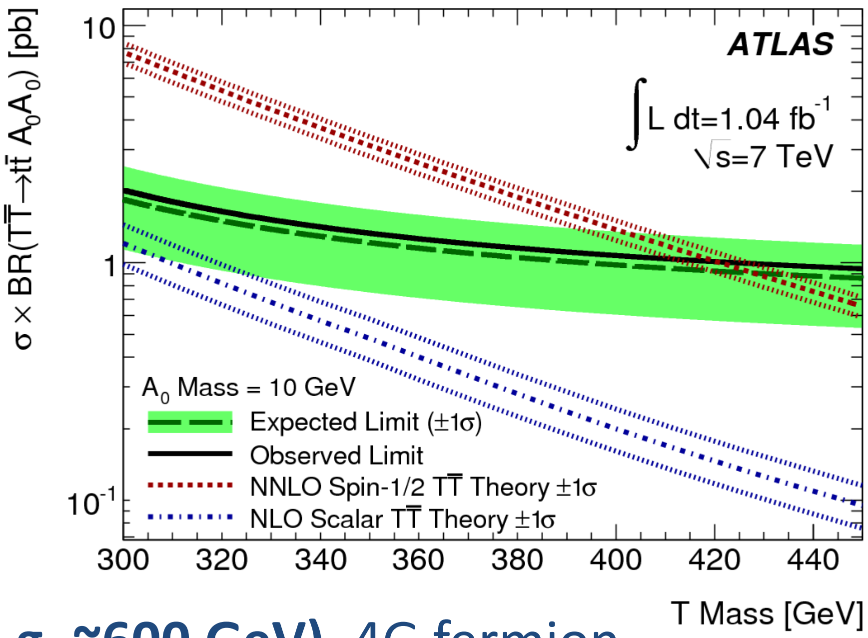


→ m_T > 420 GeV for A_0 mass below 10 GeV

Interesting interpretation:

4th generation (l4,v4,u4,d4) is a natural and simple extension of the SM





Would have major implications:

- Can **allow a heavy Higgs**
- **If there is no Higgs and u4 is heavy (e.g. ~600 GeV)**, 4G fermion condensates could play the **role of the Higgs via some strong interactions !**
- **In 5D** AdS space, K-K excitations of gauge bosons interacting with 4G fermions **give rise to Yukawa couplings** and to the **mass hierarchy**
- Could provide 10^{13} to 10^{15} more CP Violation to **solve the Baryon Asymmetry of the Universe problem**

→ m_{u4} > 420 GeV @ 95% CL ; σxBR < 1.1 pb (with m_{A_0}=10 GeV)

N.B.: limits in blue also ~valid for scalar models, e.g. stop quark pair production

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Search for heavy vector-like quarks coupling to light generations

L_{int}: 1.04 fb^{-1}

Motivations: 4^{th} Gen. of chiral fermions may exist, but there are strong constraints on it from EW measurements

→**Vector-like** (i.e. non-chiral) **fermions** are not constrained, and are predicted by many SM extensions: **would be novel form of matter!**

Analysis strategy: **In certain scenario, e.g. extra-dimensions, VL-Quarks could couple sizably to the light generation quarks, leading to a strong signal @LHC**

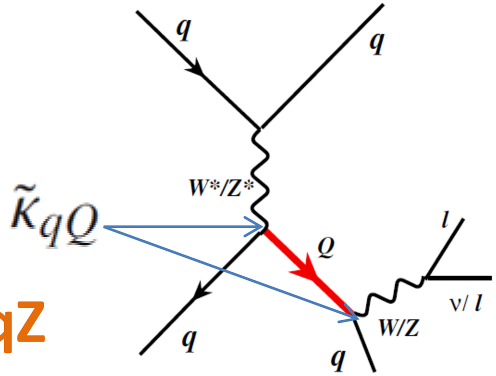
→**Most promising:**

Look at single-production:
(t-channel dominant)

$$qq \xrightarrow{W^*/Z^*} qQ$$

with Q→qW or qZ

Assuming $\tilde{\kappa}_{qQ} = 1$

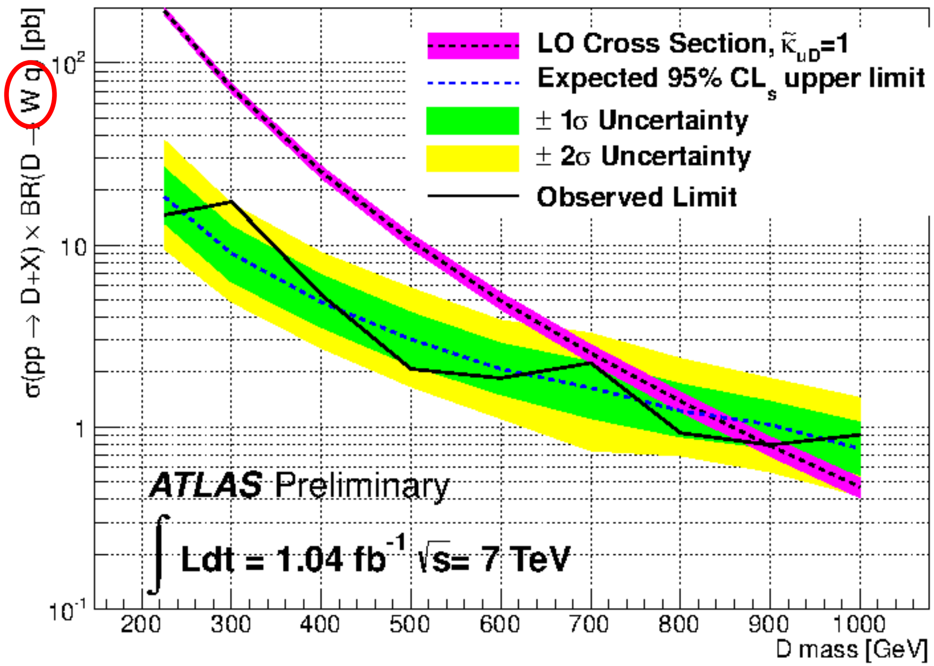


Selection:
- >=2jets
- (1 lepton+ Missing energy) or 2 leptons

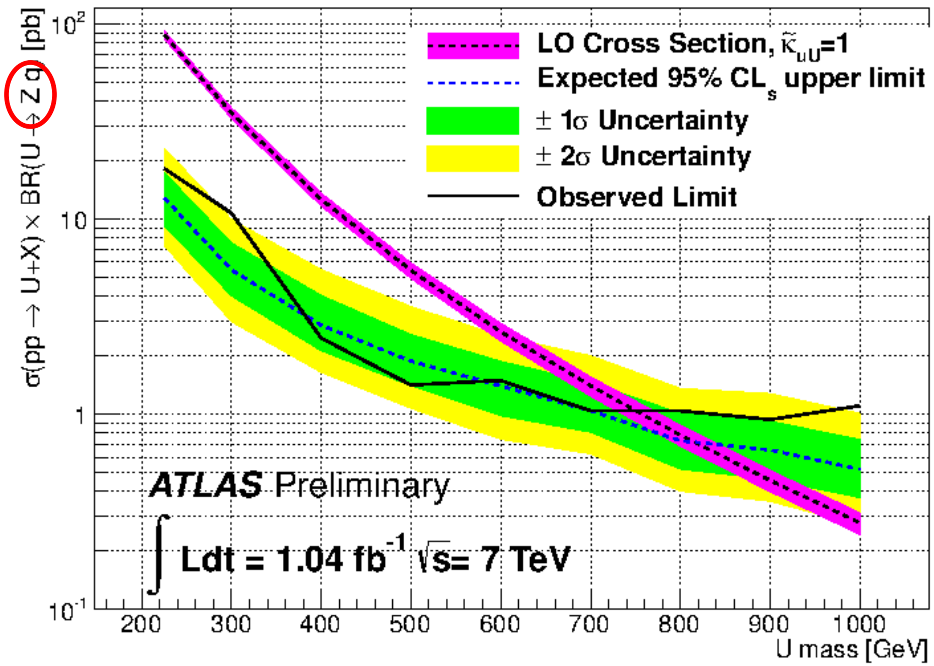
Results: 95% CL upper limits on $\sigma(pp \rightarrow Q) \times BR(Q \rightarrow W/Zq)$

Assuming B.R.(Q→jet+W/Z)=100%

CC channel



NC channel



Observed(expected) limits:

→ m_{VLQ} > 900(840) GeV

→ m_{VLQ} > 760(820) GeV

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- **Black Holes**

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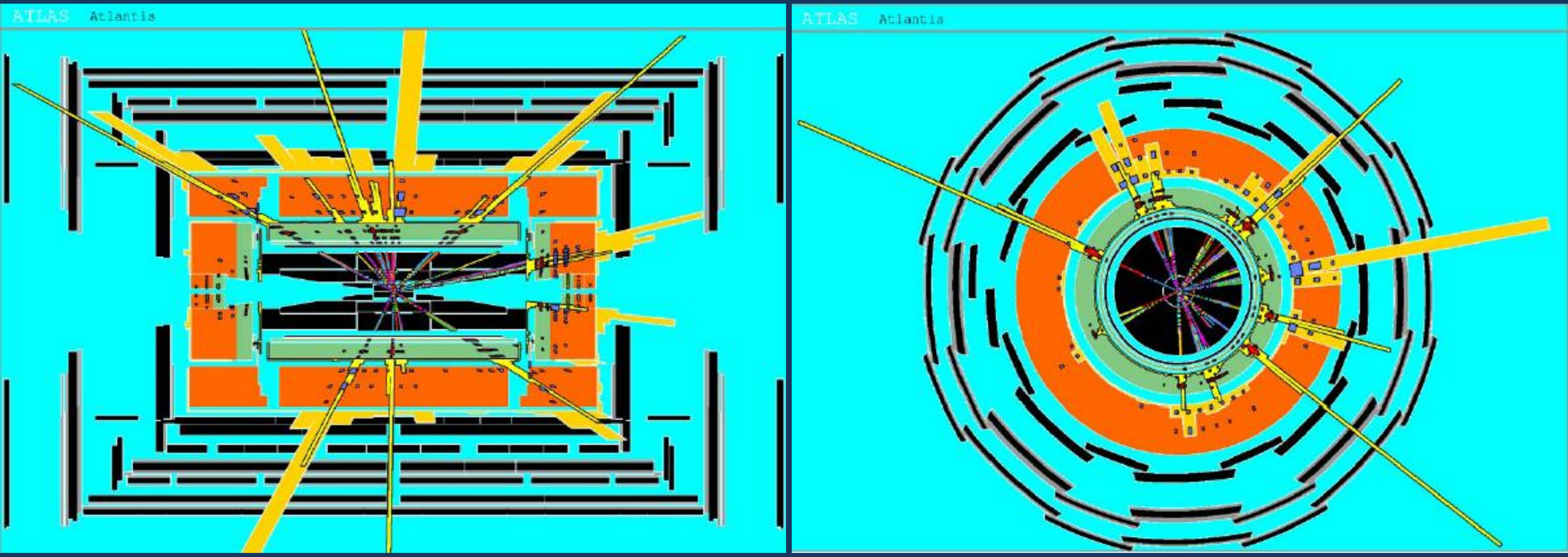
2 searches with different final states:

- Same-sign dimuon
- Lepton+jets

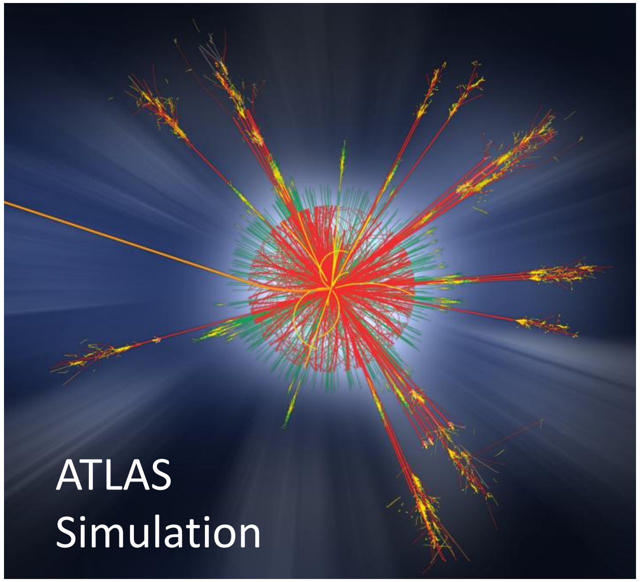


Simulated black hole event in the ATLAS detector

Searches for Black Holes

Motivations: **Models introducing extra dimensions can provide a solution to the hierarchy problem (M_{Pl} ~10^{16}GeV >> M_{EW})**

→The Planck scale in (n+4)-dimensions, M_D, would be much smaller than in 4D, because gravity propagates in all dimensions



If M_D is in the TeV range, **microscopic black-holes** could appear @LHC!...

… **and evaporate by Hawking radiation**

Large uncertainties on models due to our ignorance of quantum gravity, but semi-classical approximation assumed valid for: m(B.H.) > $M_{Threshold}$ >> M_D

Search for strong-gravity signatures in same-sign dimuon final states

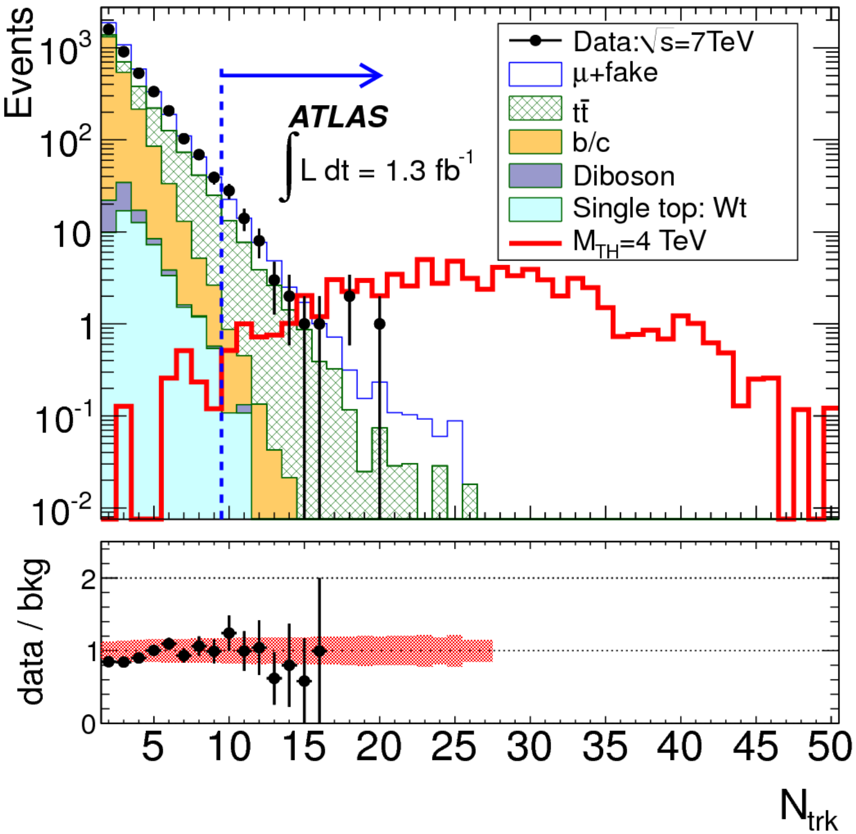
arXiv:1111.0080 L_{int}: 1.3 fb^{-1}

Analysis strategy: **Multiplicities of emitted particles are determined by the n_{dof} of each particle types and their decay modes**

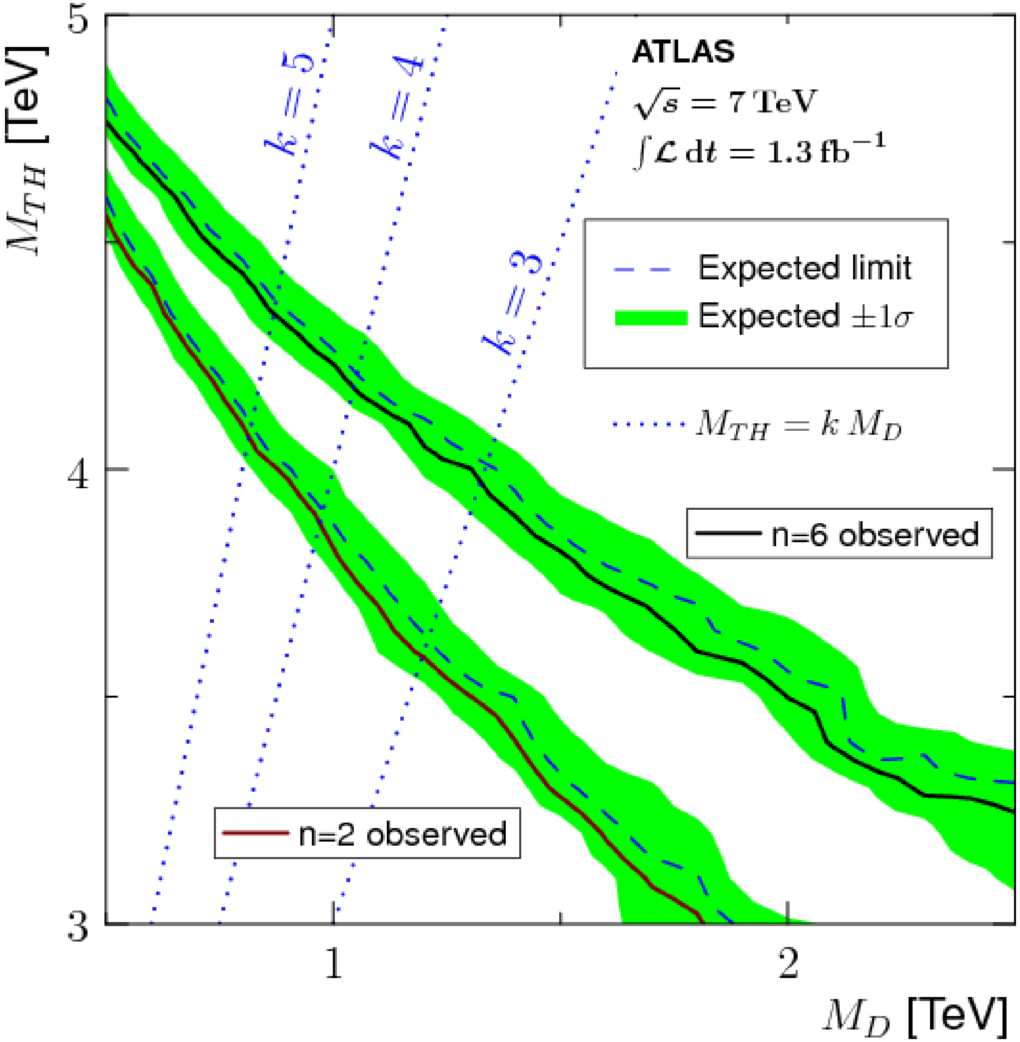
→ Black Hole events should have high multiplicity of high-p_T tracks

Selection:

- **2 same-sign muons** (reducing SM background):
  - **Leading one isolated**
  - Sub-leading: no-isolation required (to maintain signal acceptance despite semi-leptonic decays in jets from emitted b- and c- quarks)
- **At least 10 tracks** (with p_T> 10 GeV)



Results: 95% CL exclusion contours for different scenarii (here for non-rotating B.H.)



NB:

- Semi-classical approximation for production and decay only valid for $k = M_{TH} / M_D >> 1$
- **As PDF's rapidly fall in this physically favored region: no significant improvements expected on these limits until increase of LHC energy**

→ **k=5 and n=6: M_{TH} up to ~4.3 TeV ruled out**

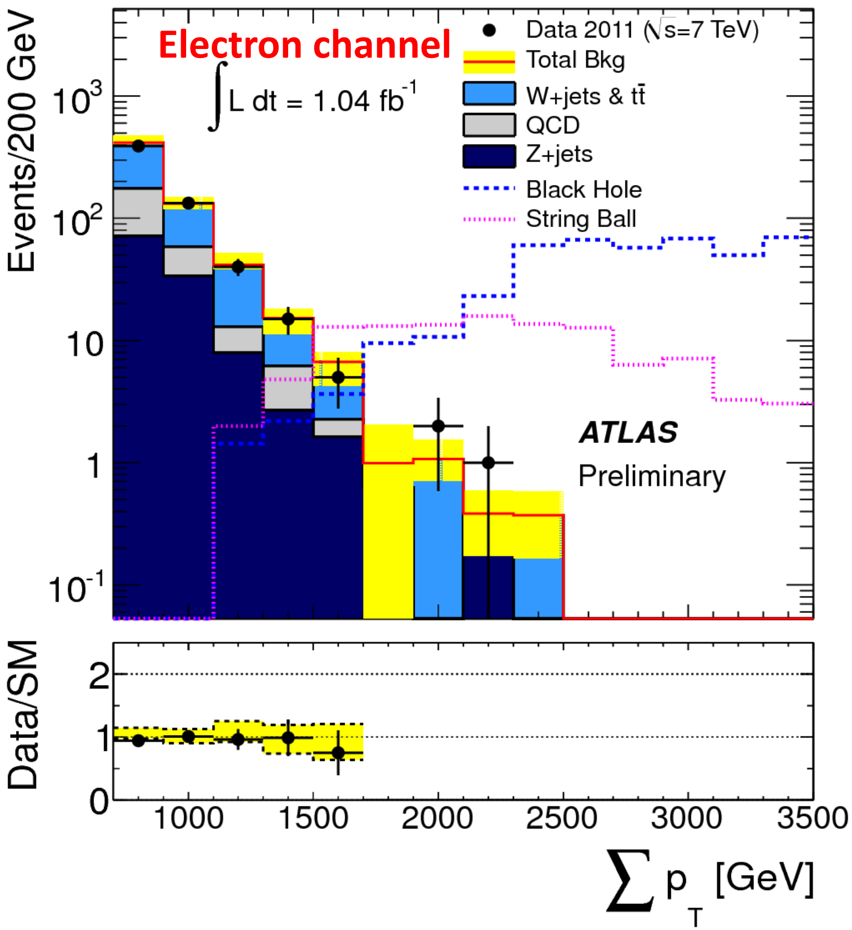
Search for strong-gravity signatures in leptons + jets final states

ATLAS-CONF-2011-147 L_{int}: 1.04 fb^{-1}

Analysis strategy: Another way to exploit the high-multiplicity of emitted particles is to search for excess of multi-object events produced at high Σp_T (leptons+jets)

Selection:

- 1 high-pt (>40 GeV) isolated lepton (reducing QCD background)
- At least 3 objects (leptons or jets) with p_T > 100 GeV (at least one being a lepton)
- Σp_T above 1500 GeV

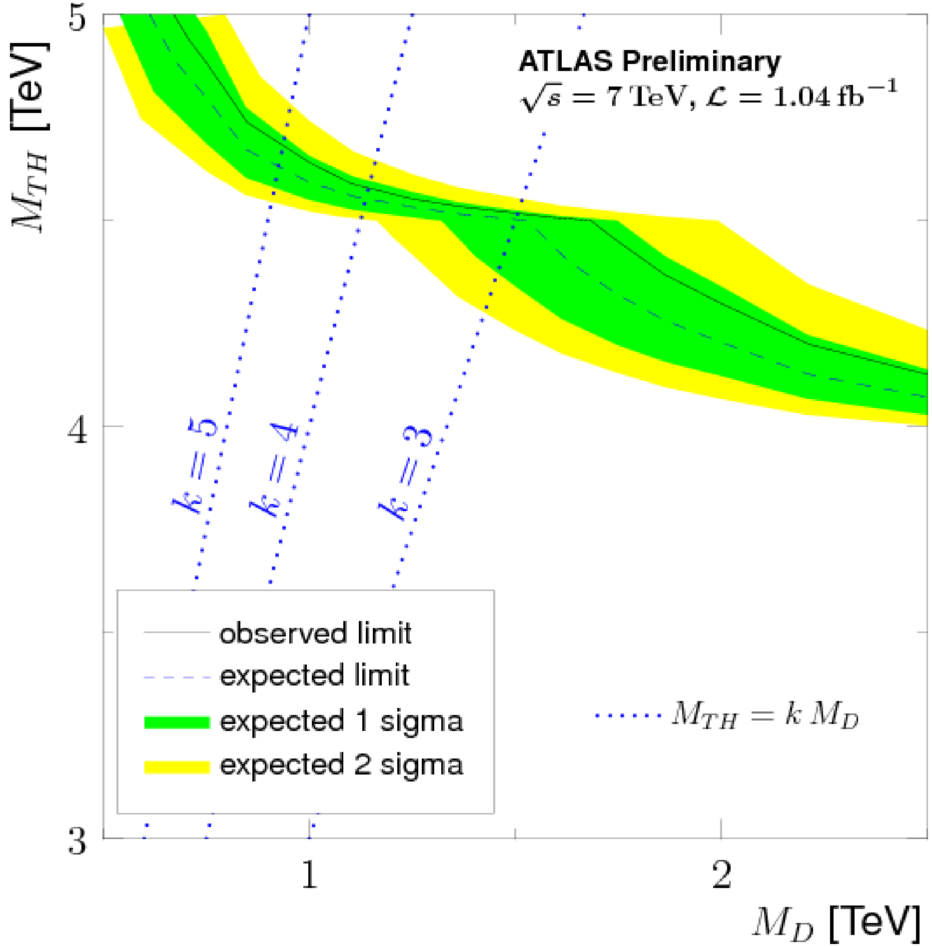


"Black Hole" here is a non-rotating B.H. sample with n=6, M_D=0.8 TeV and M_{TH} = 4TeV

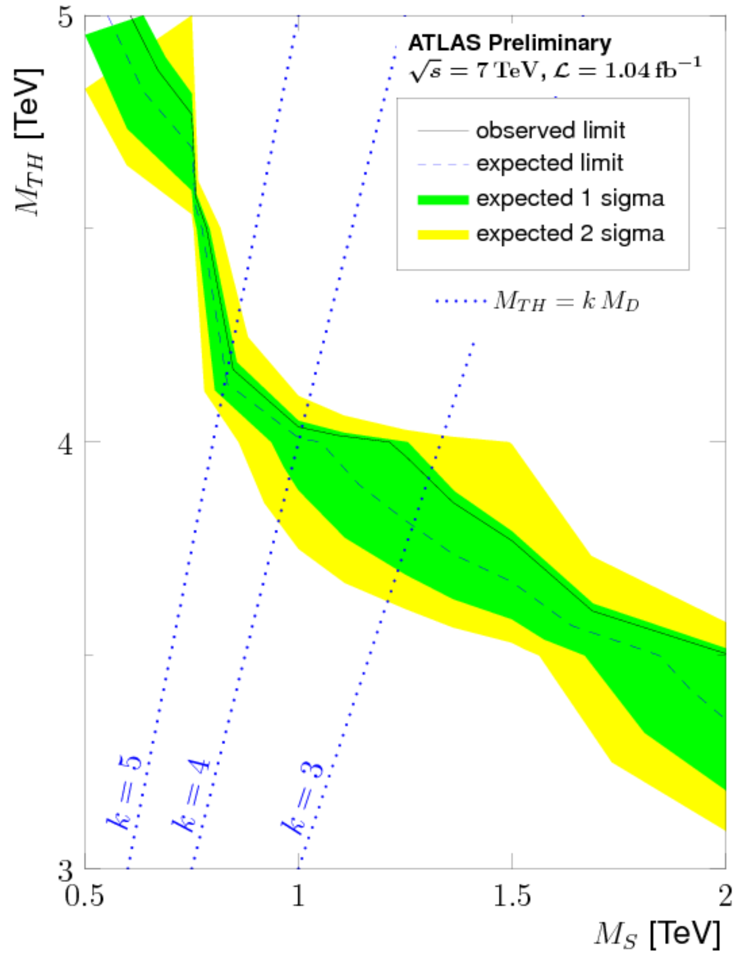
"String Ball" is a rotating string ball sample with n=6, M_D=1.26 TeV and M_{TH} = 3TeV

Results: 95% CL exclusion contours for different scenarii with n=6

Rotating B.H.



Non-rotating string ball



→ **k=5:** M_{TH} up to ~4.7 TeV ruled out →**k=3:** M_{TH} up to ~3.9 TeV ruled out

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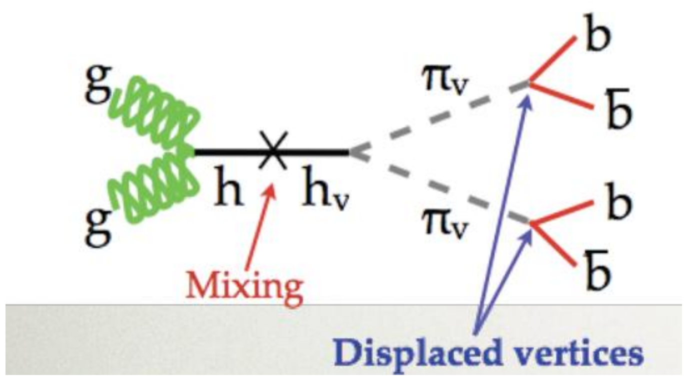
Search for a light Higgs decaying to long-lived neutral particles

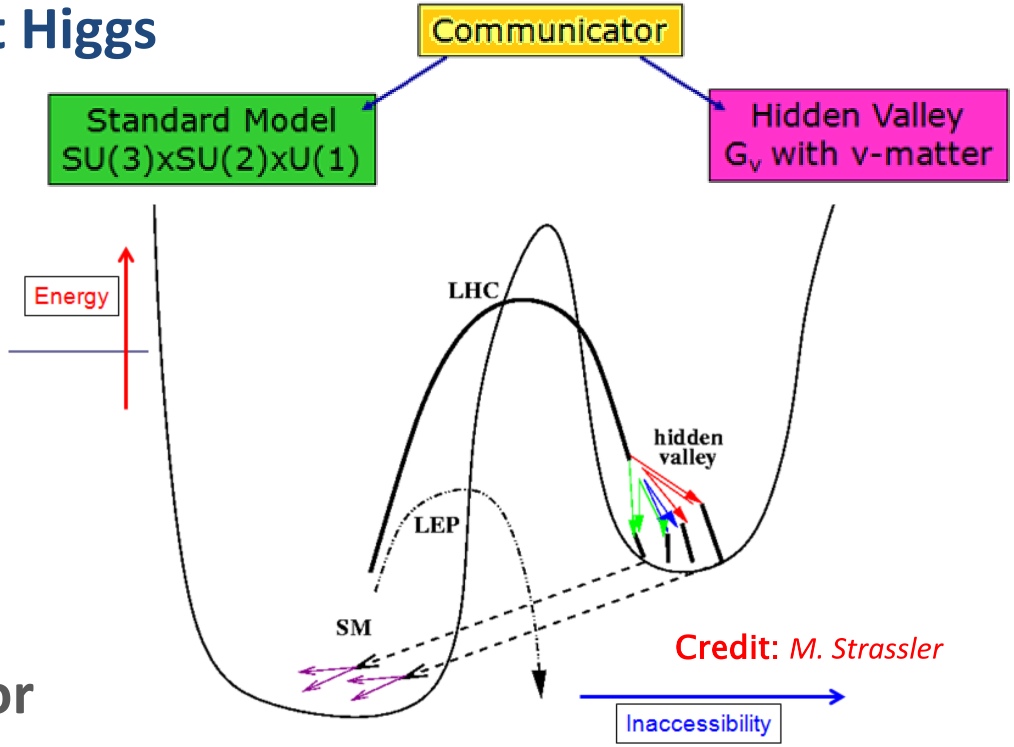
L_{int}: 1.94 fb^{-1}

Motivations: *Hidden Valley* models imagine a hidden sector weakly coupled to the SM, through a communicator (Z', Higgs, LSP, sterile ν...)

→ Can accommodate for a light Higgs

Focus here on: $\boxed{h^0 \to \pi_v \pi_v}$





Credit: *M. Strassler*

where π_v is a neutral pseudo-scalar living in the hidden sector

- ➢ π_v is long-lived with lifetime that can be comparable to the ATLAS detector dimensions, and decays to $b\bar{b}$, $c\bar{c}$ and τ+τ− in the ratio 85:5:8%

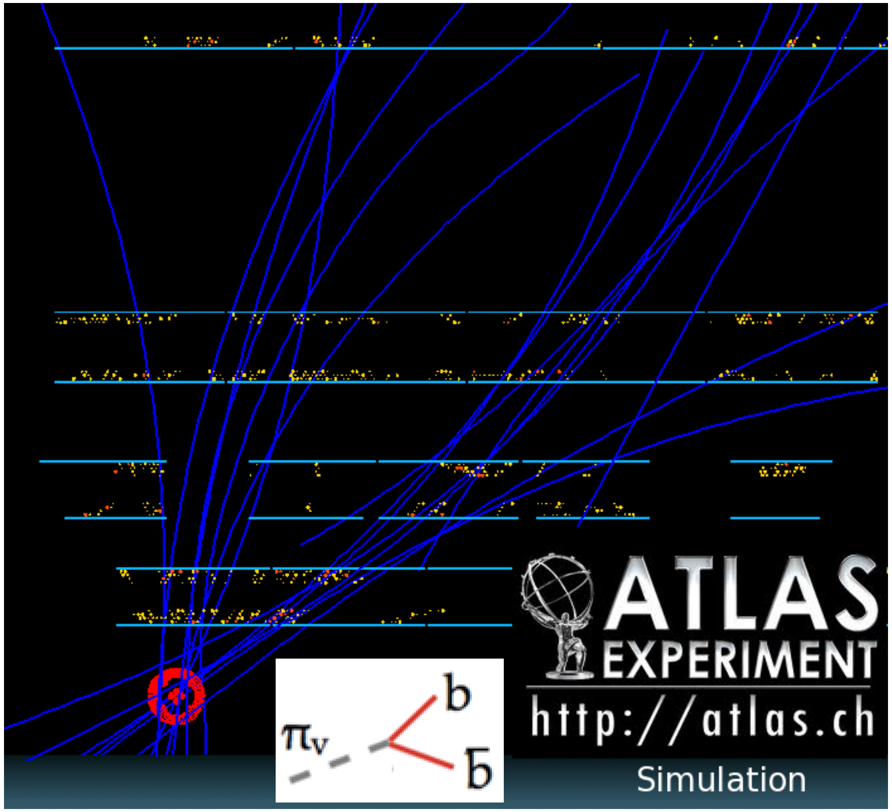
Search strategy: **Look for π_v's decays in the Muon Spectrometers (MS)**

Challenge: **Develop specialized tracking and vertex reconstruction algorithms to identify vertices from the π_v's decays in the MS!**

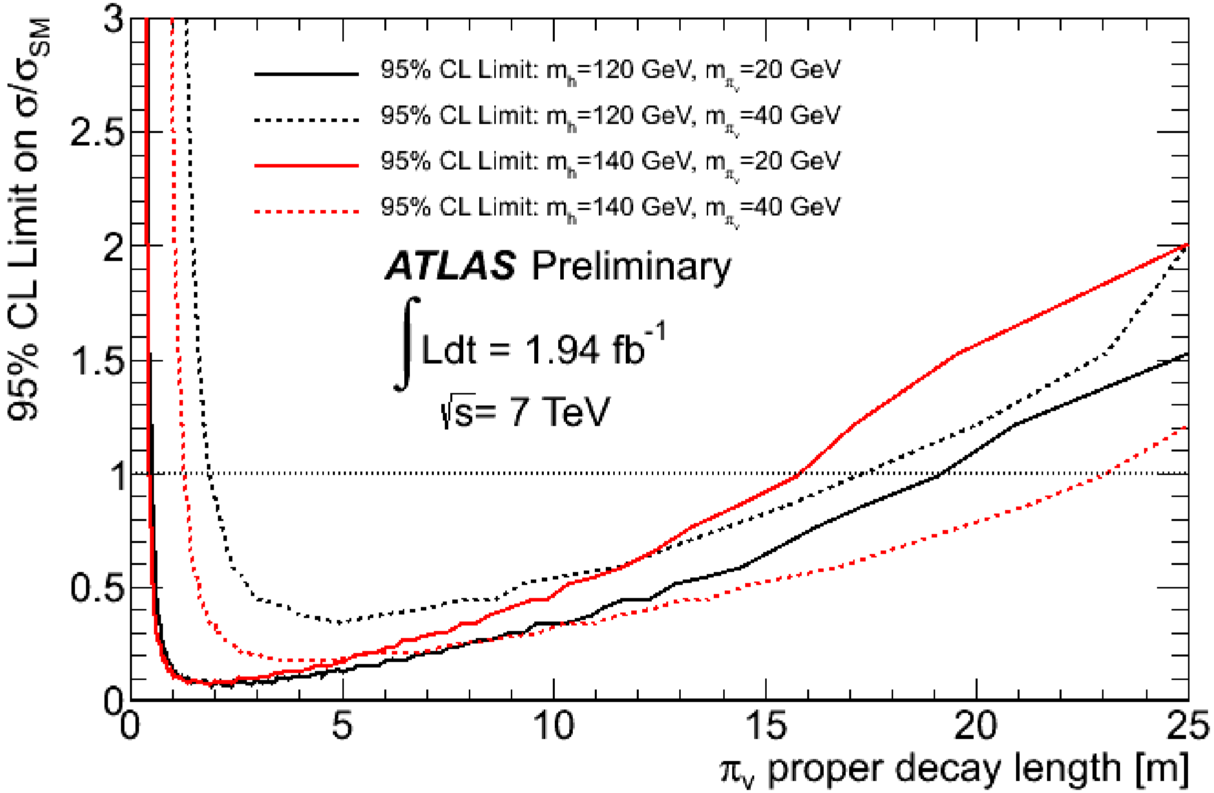
→ Exploits the average:
- ~10 low p_T charged tracks
- ~5 π^0's in $b\bar{b}$ decays

Selection:
- ➢**Signal from dedicated trigger that selects decays inside the MS**
- ➢**2 good vertices in the MS separated by ΔR≥2**
 ($\Delta\Phi=180^o$ between 2 π_v's)

Analysis	Expected Background	Measured Number
MS vertex	0.03±0.02	0



Results: 95% CLs exclusion limits on σ/σ_{SM}



Excluded regions:

First limits on long-lived particles decaying to jet pairs

m_{h^0} (GeV)	m_{π_v} (GeV)	Excluded Region
120	20	0.5 m $\leq c\tau \leq$ 19.15 m
120	40	1.9 m $\leq c\tau \leq$ 17.25 m
140	20	0.5 m $\leq c\tau \leq$ 15.5 m
140	40	1.25 m $\leq c\tau \leq$ 23 m

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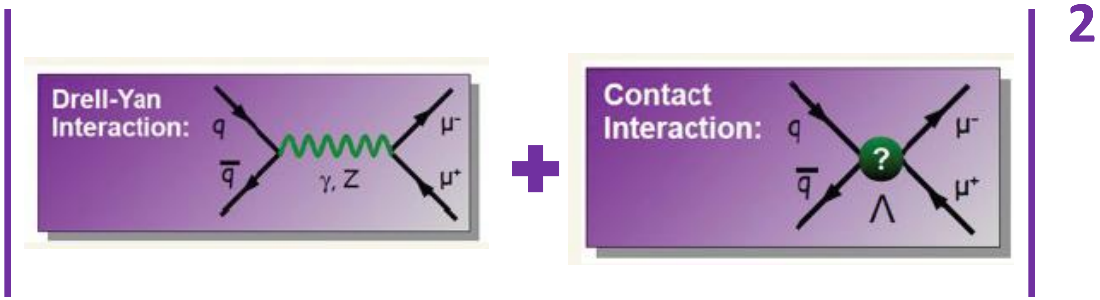
Search for contact interactions L_{int}: 1.21 fb^{-1}

Motivations: **4-fermion contact interaction (CI) can be a low-energy description of:**

- **Large Extra Dimension ADD model**
- **Quark-lepton compositeness**

Analysis strategy:

Look for excess over Drell-Yan production selecting high-quality leptons



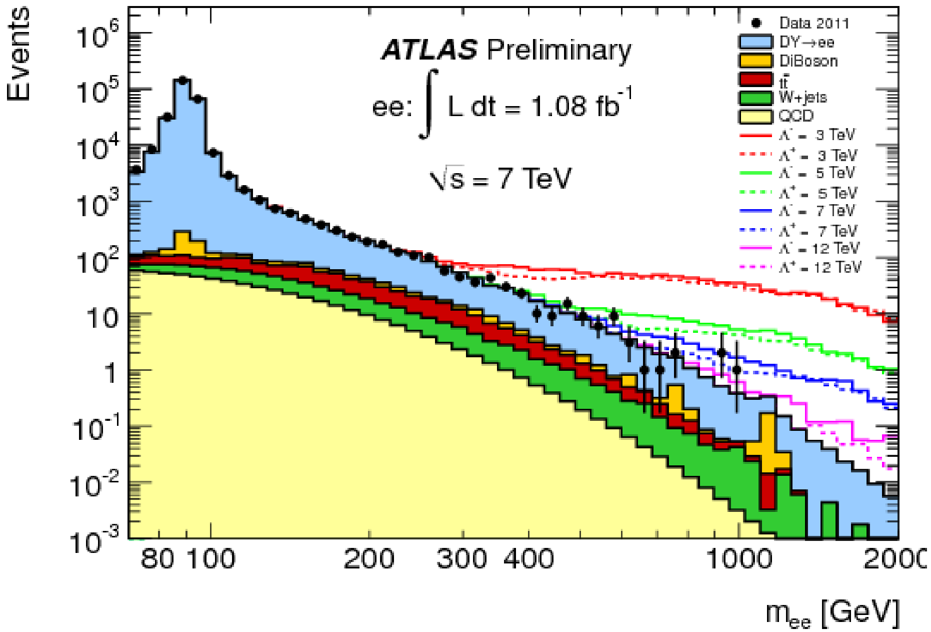
Context of left-left isoscalar model:

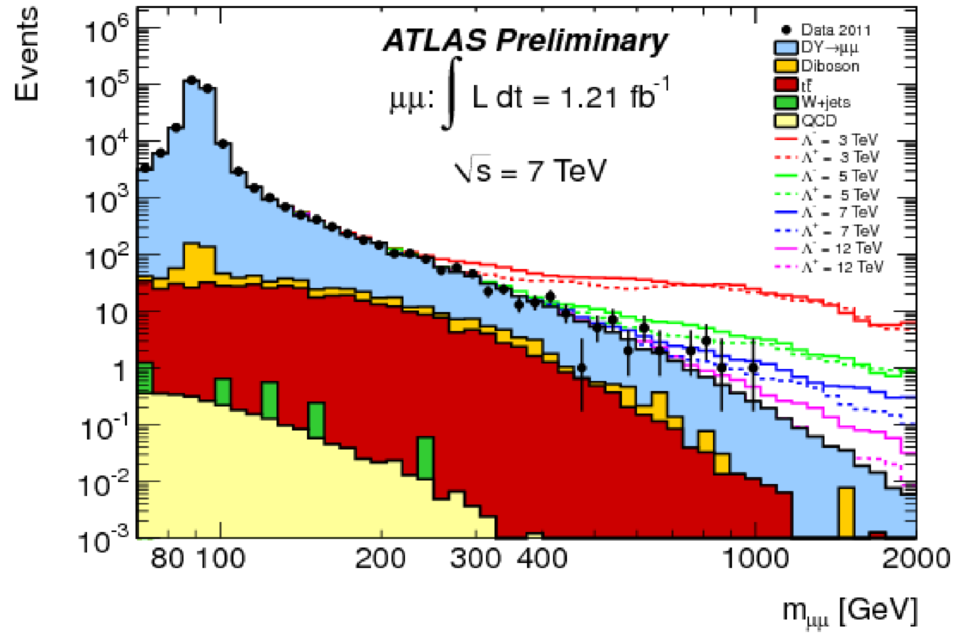
$$\frac{d\sigma}{dm_{\ell\ell}} = \frac{d\sigma_{DY}}{dm_{\ell\ell}} - \eta_{LL}\frac{F_I(m_{\ell\ell})}{\Lambda^2} + \frac{F_C(m_{\ell\ell})}{\Lambda^4}$$

- F_I: interference interaction
- η_{LL} ±1
- F_C: pure contact interaction

•Λ: Energy scale below which fermion constituents are bound

Results: Electron channel / Muon channel





Lower limits on scale Λ at 95% of Credibility Level:

Channel	Prior	Expected limit (TeV) Constr.	Expected limit (TeV) Destr.	Observed limit (TeV) Constr.	Observed limit (TeV) Destr.
e^+e^-	$1/\Lambda^2$	9.6	9.3	10.1	9.4
	$1/\Lambda^4$	8.9	8.6	9.2	8.6
$\mu^+\mu^-$	$1/\Lambda^2$	8.9	8.6	8.0	7.0
	$1/\Lambda^4$	8.3	7.9	7.6	6.7
Combined	$1/\Lambda^2$	10.4	10.1	10.2	8.8
	$1/\Lambda^4$	9.6	9.4	9.4	8.4

Most stringent limits to date

Conclusions and perspectives

No new physics discovered yet… but very stringent limits (@95%CL) have been set on many models :

- Searches of new particles:
  - m_{LQ} >~ 600 GeV
  - m_T > 420 GeV (m_{A_0}=10GeV)
  - m_{VLQ} >~ 900 GeV
- Search for black holes:
  - $m_{D,TH}$ >~ a few TeV
- Search for *hidden valley*:
  - $c\tau_{\pi_v}$ ~< 1m or $c\tau_{\pi_v}$ ~>20m
- Search for contact interactions: Λ>~10TeV

Improvements to come using the 5.2 fb^{-1} and when the LHC will increase its energy!

→Stay tuned! ☺

Thank you for your attention!
Questions?

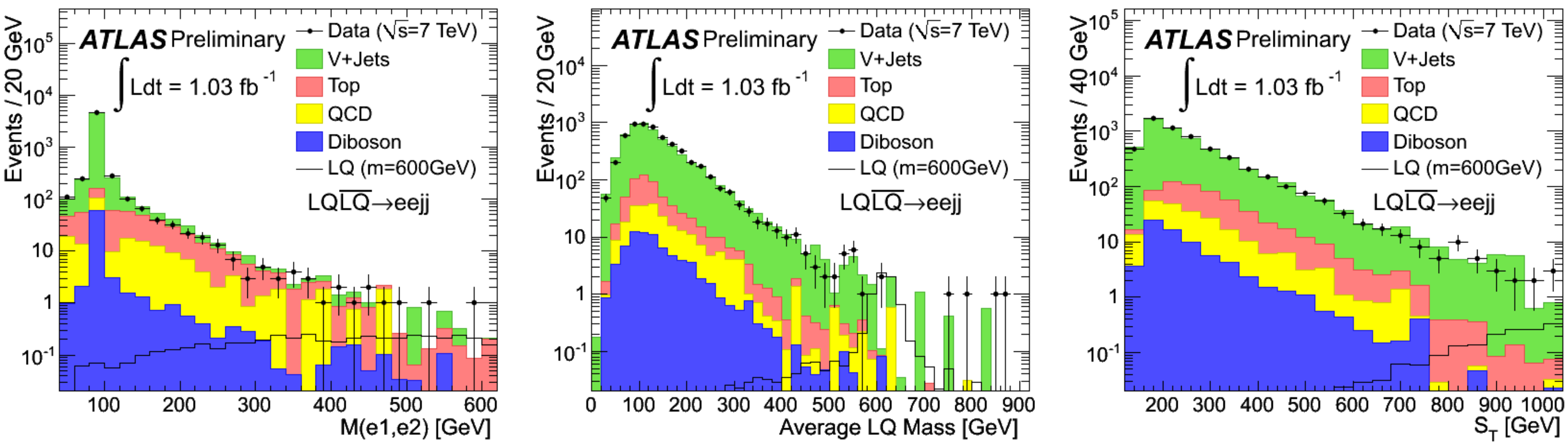
Back-up slides

Search for first generation of scalar leptoquarks

We use a likelihood ratio method to separate signal and SM backgrounds. The likelihoods are constructed separately for background (L_B) and signal (L_S) hypotheses from a set of discriminating variables as follows: $L_B \equiv \prod b_i(x_j)$, $L_S \equiv \prod s_i(x_j)$, where b_i, s_i are the probabilities of the i–th input variable from the normalized summed background and signal distributions respectively, and x_j is the value of that variable for the j–th event in a given sample.

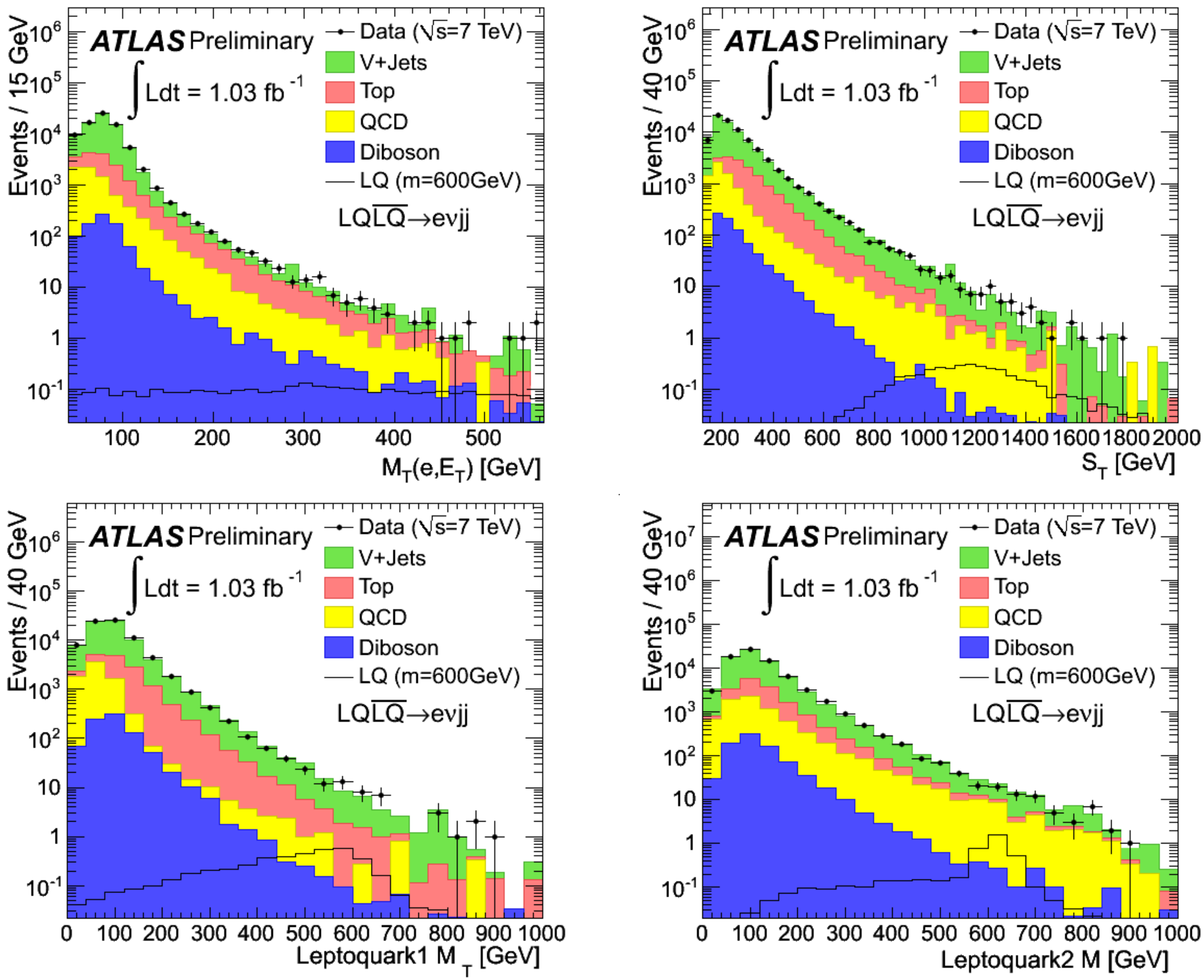
$$LLR = \log(L_S/L_B)$$

We chose the following discriminating variables shown to give the best separation between signal and background: m_{ee}, S_{T} and average invariant LQ mass $\bar{m}_{LQ}$ for the di-electron leptoquark topology; and $m_{\mathrm{T}}(e, E_{\mathrm{T}}^{\mathrm{miss}})$, S_{T}, transverse LQ mass $m_{\mathrm{T}}^{LQ1}(j, E_{\mathrm{T}}^{\mathrm{miss}})$ and invariant LQ mass m_{LQ2}. We calculate the invariant mass of the electron-jet system and the transverse mass of the $E_{\mathrm{T}}^{\mathrm{miss}}$-jet system. Since the LQ are produced in pairs there are two possible mass combinations for the electron-jet and $E_{\mathrm{T}}^{\mathrm{miss}}$-jet pairs. We choose the combination which gives the smallest mass difference. In the $eejj$ channel, we take the average mass $\bar{m}_{LQ}$ from this combination for the analysis.



S_{T}, defined as the scalar sum of the E_{T} of the electron, the p_{T} of the two most energetic jets and the $E_{\mathrm{T}}^{\mathrm{miss}}$

Search for first generation of scalar leptoquarks



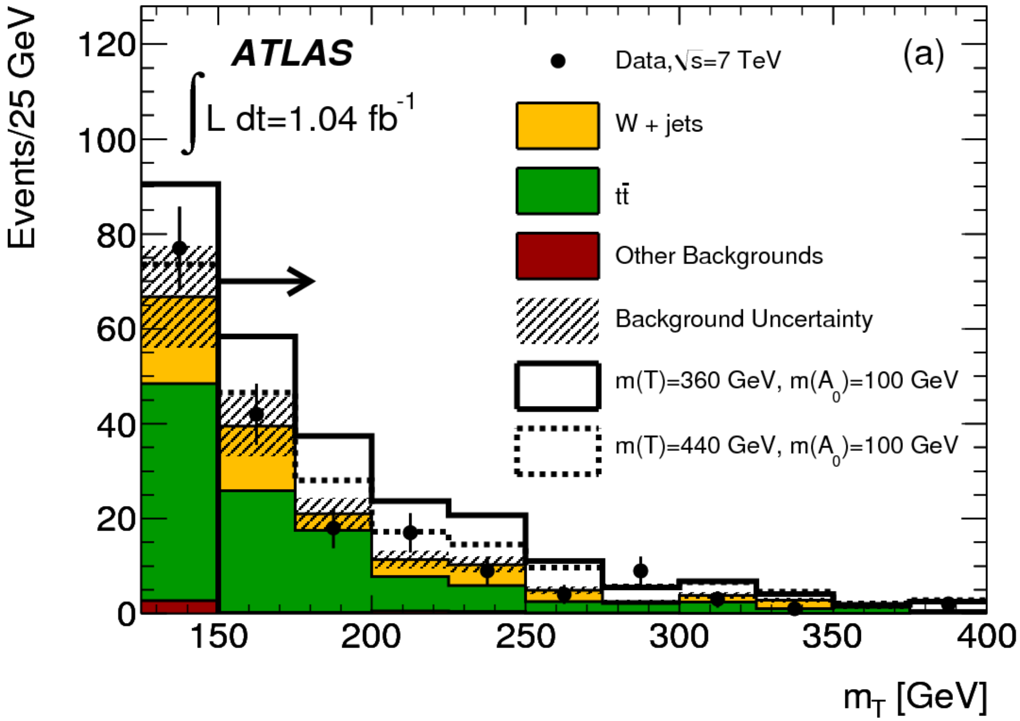
Search for exotic top partners with large missing transverse momentum

Analysis strategy: Selections on top of the standard ttbar selection:

- In order to reduce the W+jets background:

$E_T^{miss} > 100$ GeV and $mT > 150$ GeV, where mT is the transverse mass of the lepton and E_T^{miss}

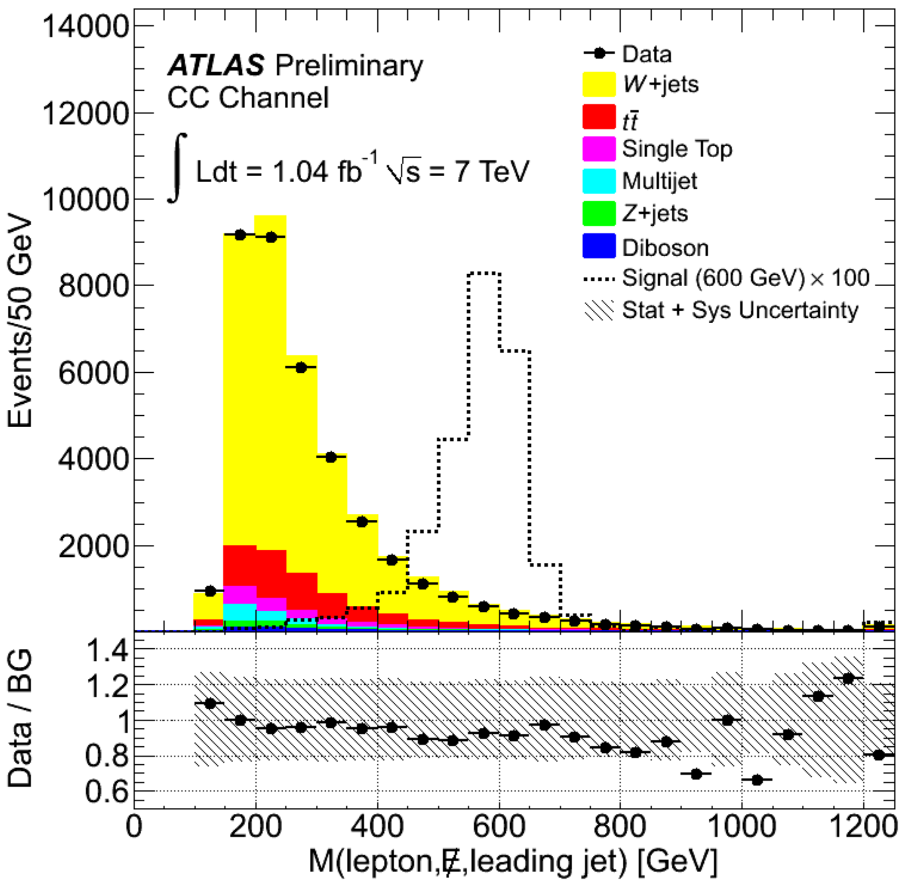
- Tight veto on additional lepton, since the largest background is not ttbar l+jets but ttbar dilepton



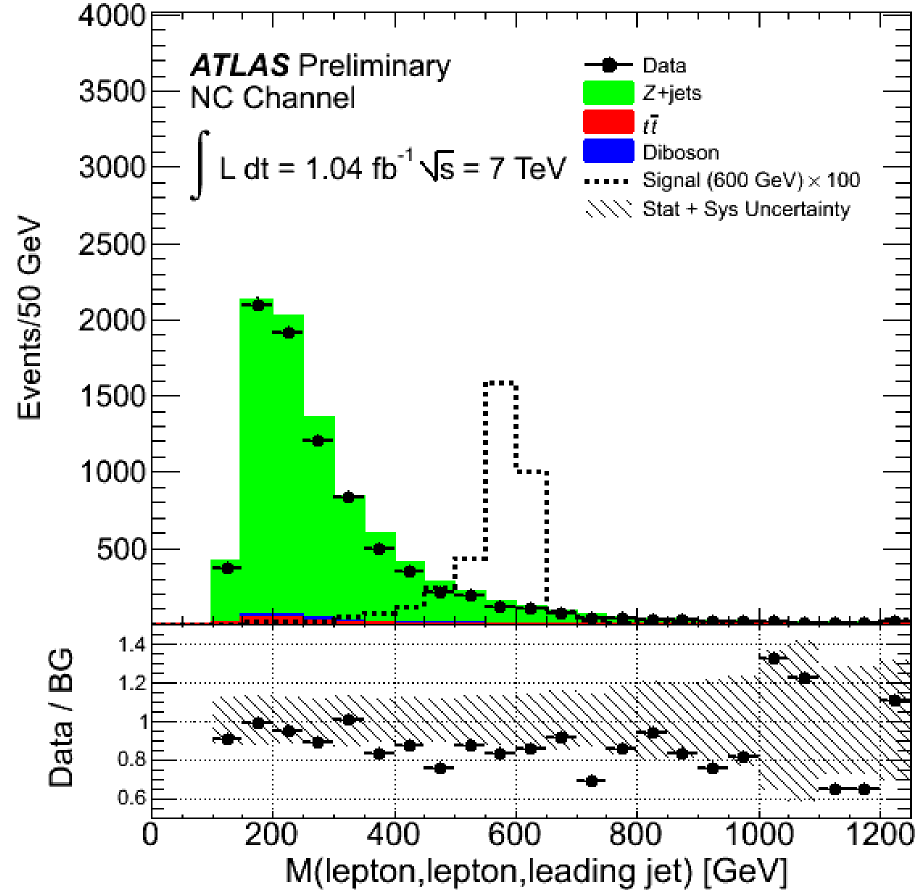
Source	Number of events
Dilepton $t\bar{t}$	62 ± 15
Single-lepton $t\bar{t}/W$+jets	33.1 ± 3.8
Multi-jet	1.2 ± 1.2
Single top	3.5 ± 0.8
Z+jets	0.9 ± 0.3
Dibosons	0.9 ± 0.2
Total	101 ± 16
Data	105

Invariant mass distribution of VLQ candidates summed over both electron and muon final states:

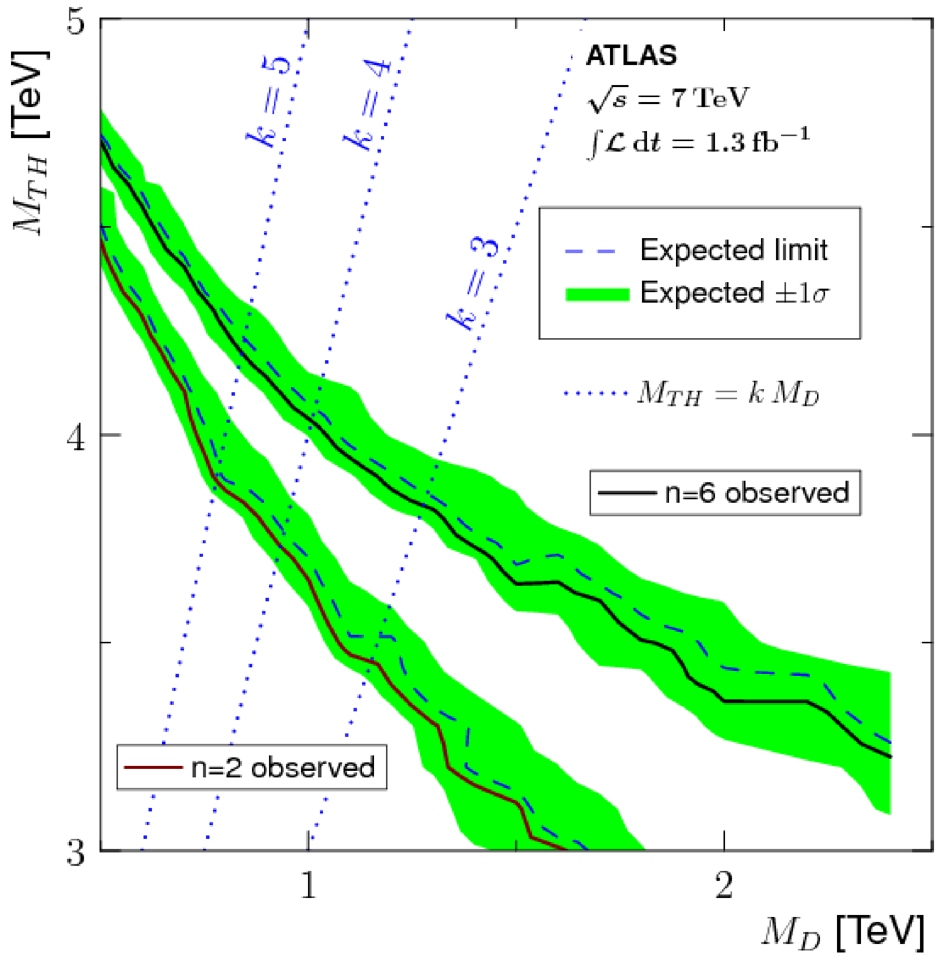
CC channel



NC channel



Results: 95% CL exclusion contours for different scenarii (here for rotating B.H.)



Signal generation:

- using Blackmax
- strongly dependent on which PDF is used. We use CTEQ66. The prediction from MRST2007lomod is higher by 50%, the prediction from Hera PDF is lower by 50%.

Limit settings:

Modified frequentist CLs method

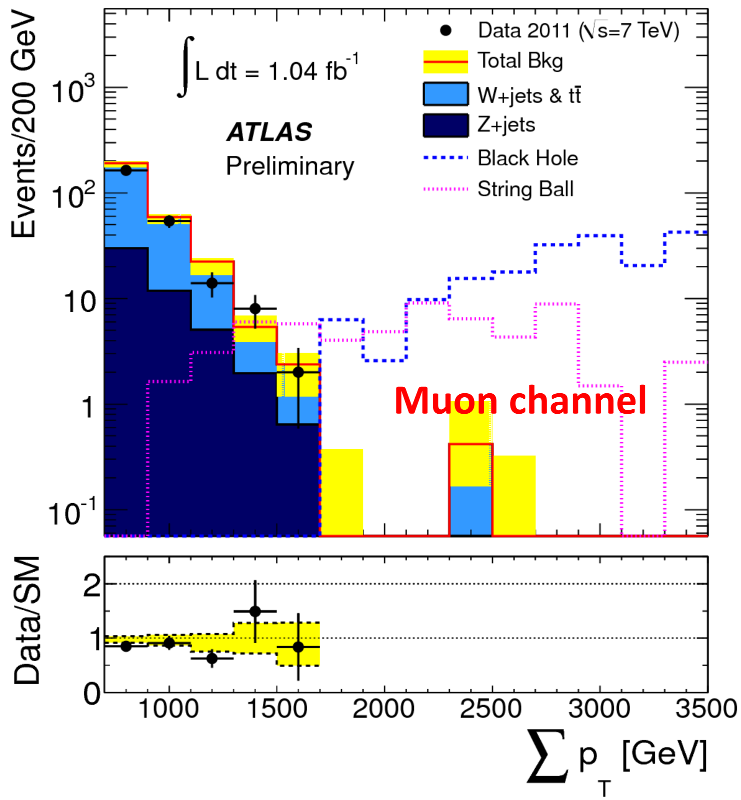
References:

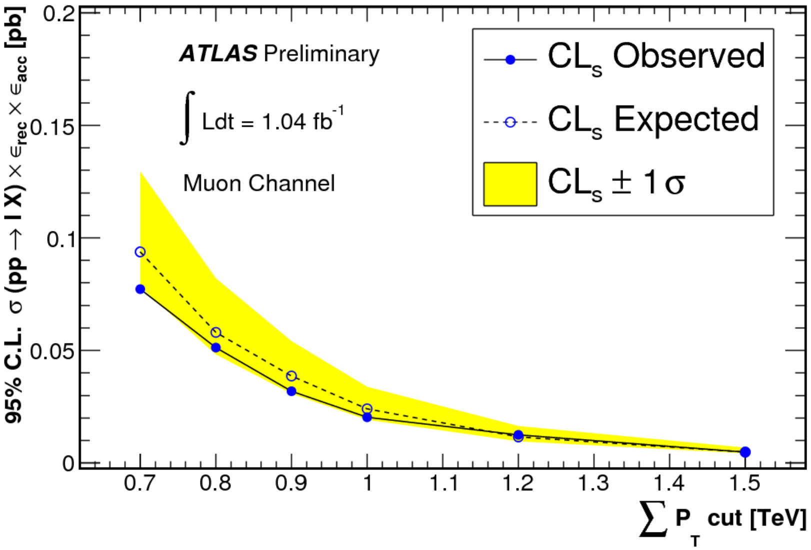
http://arxiv.org/abs/1111.0080

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2011-15/

Search for strong-gravity signatures in leptons + jets final states

Although inspired by string theory, the large extra dimensional paradigm is not based on it. However, embedding large extra dimensions into weakly-coupled string theory could provide an understanding of the strong-gravity regime and the picture of the evolution of a black hole at the last stages of evaporation [9, 10]. In this picture, black holes end their Hawking evaporation when their mass reaches a critical mass M_S. At this point they transform into high-entropy string states – string balls – without ever reaching the singular zero-mass limit.





$\sum p_T$ (GeV)	$\sigma_{\rm eff}$ 95% C.L. Upper Limit (fb) Observed (Expected)	
	Muon Channel	Electron Channel
> 700	77 (94)	169 (188)
> 800	51 (58)	102 (112)
> 900	32 (39)	65 (73)
> 1000	20 (24)	43 (45)
> 1200	13 (12)	20 (22)
> 1500	4.8 (4.8)	8.7 (9.7)

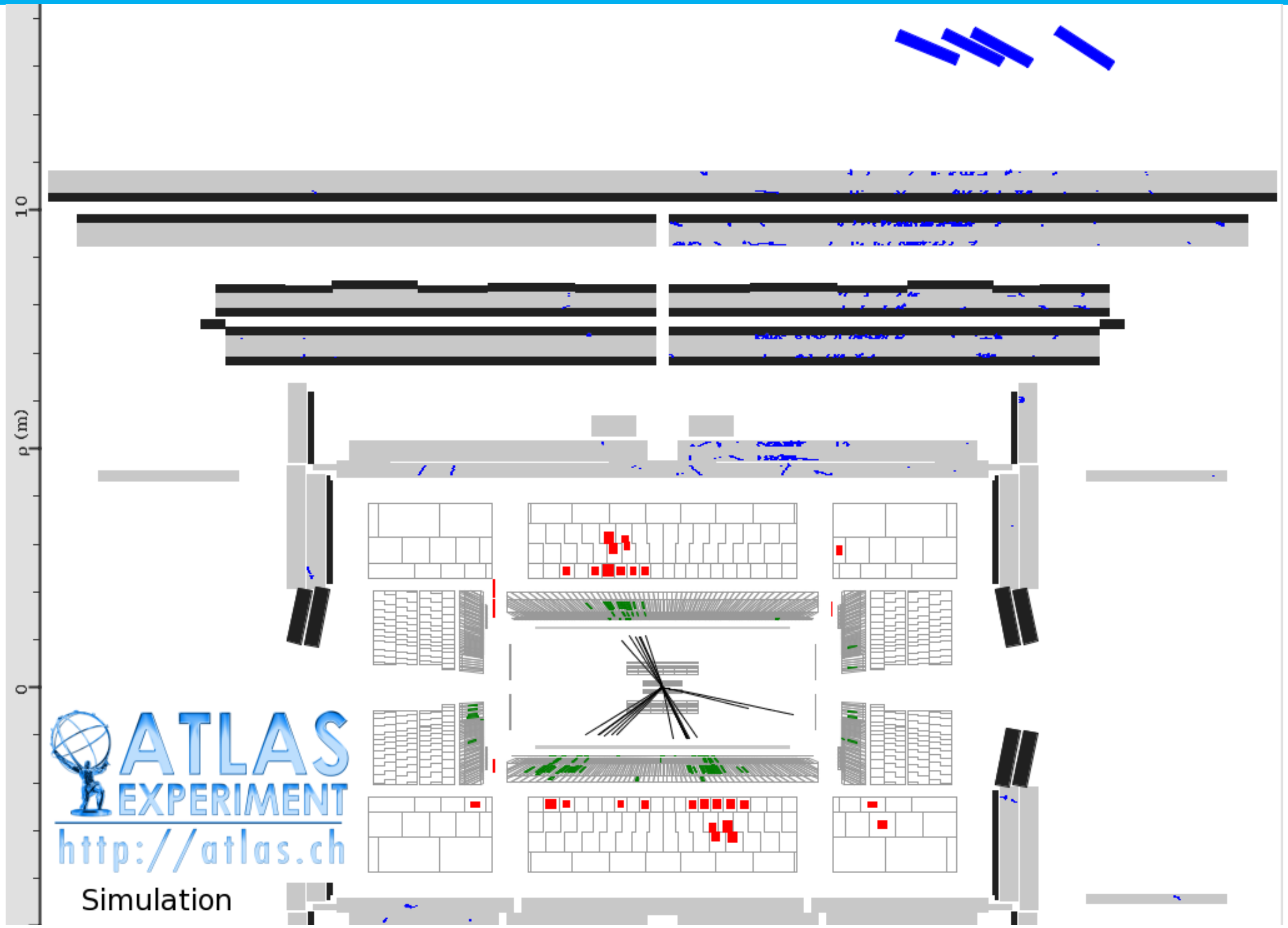
Signal generation:

Signal samples are generated with the `Charybdis` [16] and `Blackmax` [40, 41] generators. The shower evolution and hadronisation uses `Pythia`, with the `CTEQ6.6` PDF sets using the black hole mass as the QCD scale. No radiation losses in the formation phase are modelled. The `Charybdis` samples are generated with both low and high multiplicity remnants, whilst the `Blackmax` samples use the final burst remnant model, which gives high multiplicity remnant states [40]. Samples are generated for both rotating and non-rotating black holes for six extra dimensions. Focus is placed on models with six extra dimensions due to the less stringent limits on M_{D}. String ball samples are produced with `Charybdis` for both rotating and non-rotating cases, for six extra dimensions, and a string coupling, g_{S}, of 0.4. Two

Analysis strategy:

The analysis starts from events that pass the ATLAS Muon RoI Cluster Trigger, a dedicated, signature-driven trigger developed for long-lived neutral particles that decay anywhere in the detector volume. There is a public note that describes the ATLAS dedicated triggers: ATL-PHYS-PUB-2009-082

Search for a light Higgs decaying to long-lived neutral particles

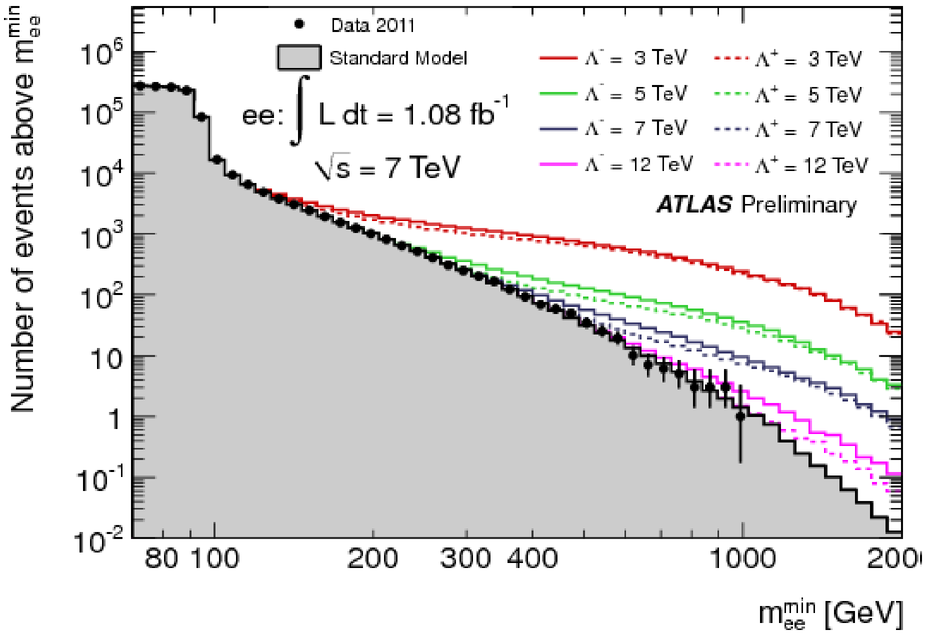


Event display from Monte Carlo showing one π_{v} decay in the barrel muon spectrometer and the second decay in the inner detector. Reconstructed inner detector tracks are shown in black, energy deposits in the hadronic calorimeter are shown in red and energy in the electromagnetic calorimeter are shown in green. MDT hits are shown as blue points, and the location of the Level 1 muon RoI's are shown by the blue bars located outside the spectrometer.

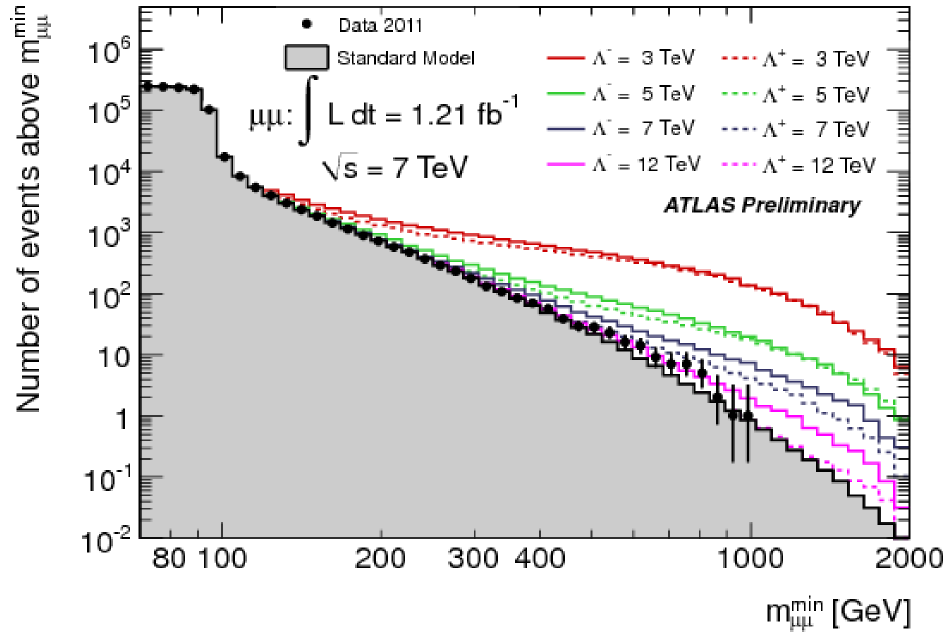
Search for contact interactions

Results: Integral of m_{ll} -> infinity as a function of m_{ll}

Electron channel



Muon channel



Limit settings:

Bayesian statistical analysis

Posterior PDF integrated using Markov Chain Monte Carlo technique