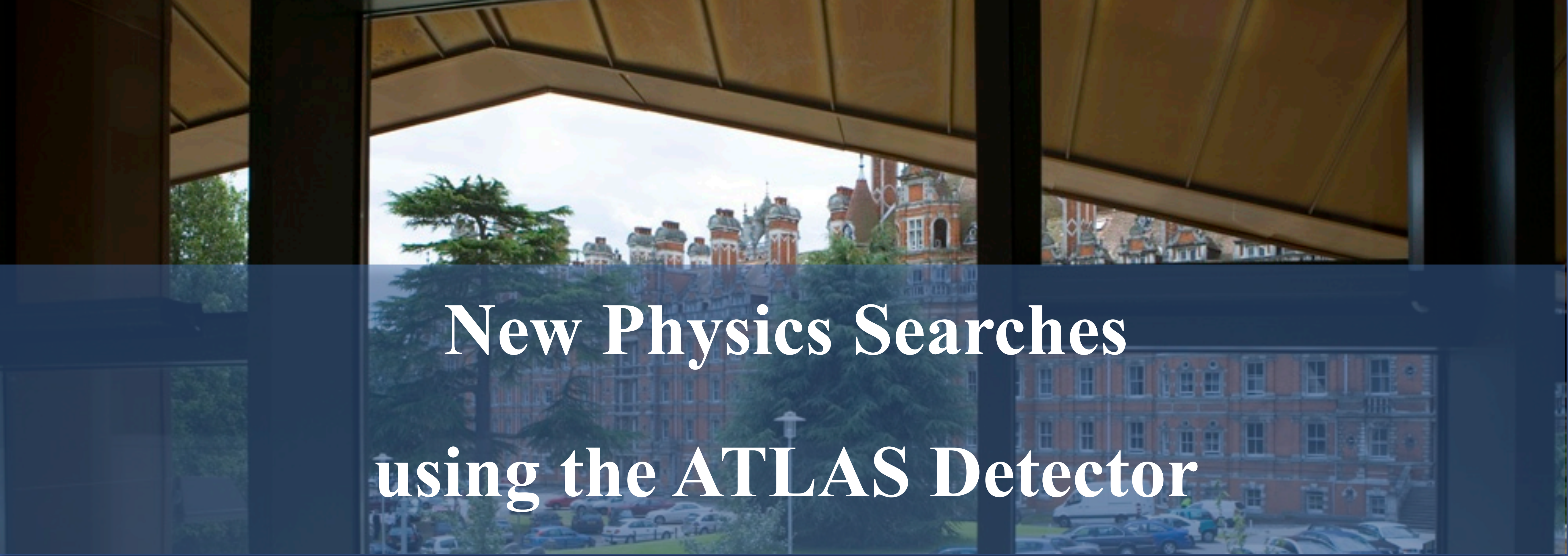

New Physics Searches using the ATLAS Detector

NExT Meeting
14th of November 2012

Dr. Daniel Hayden

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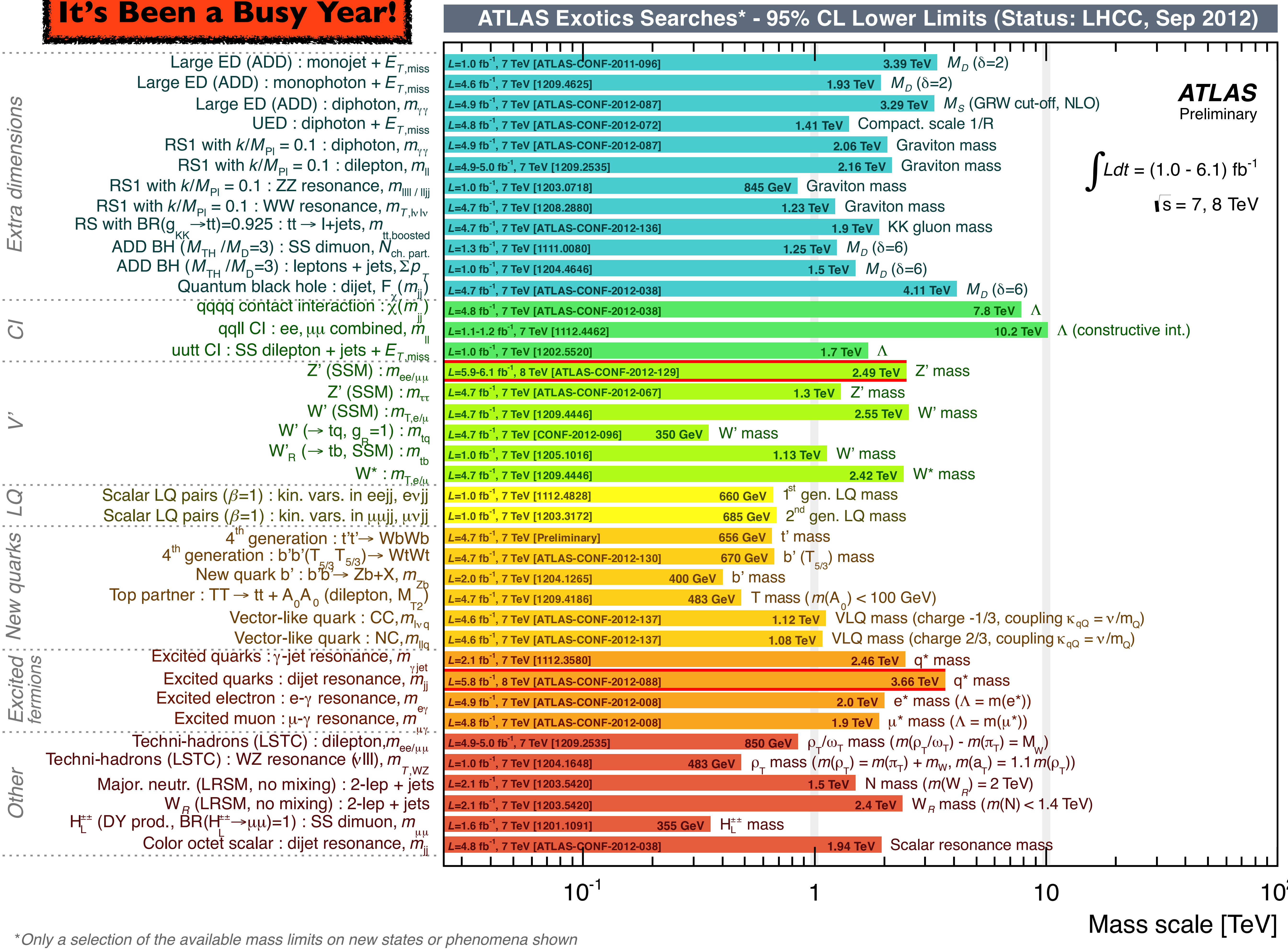
Royal Holloway University of London

Science & Technology Facilities Council

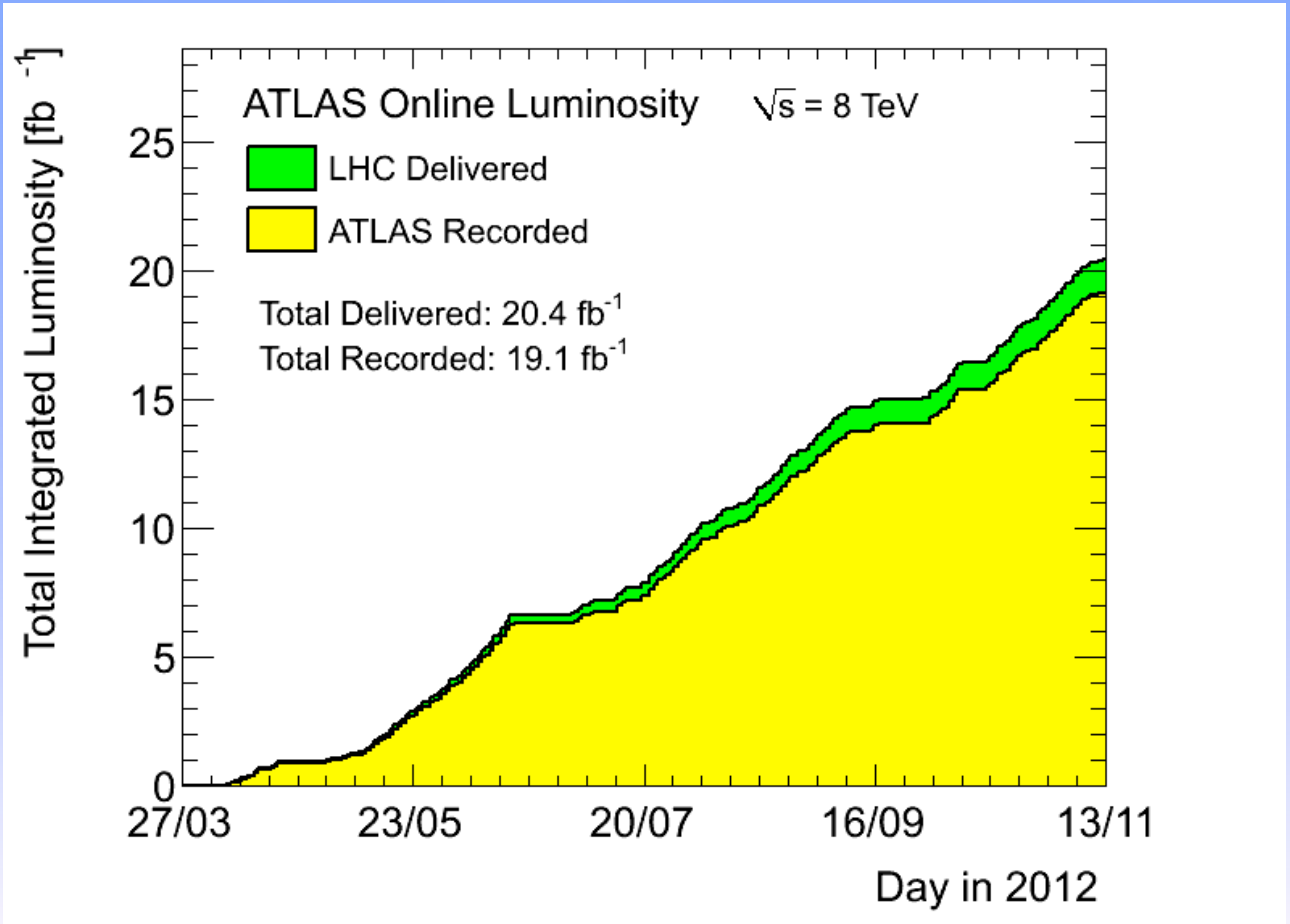
SEPnet South East Physics Network

ATLAS

It's Been a Busy Year!



... and the Data is still coming like a tidal wave!



Focus of Talk Today

Type	Physics / Model(s)	ee	μμ	γγ
Resonant New Physics	Z′ (E_6, SSM)	✓	✓	
	G* (RS)	✓	✓	✓
Non-Resonant New Physics	CI (η_{LL})	✓	✓	
	G* (ADD)	✓	✓	✓

Dijet mass and angular distributions	Excited quarks, colour octets, heavy W bosons, string resonances, quantum black holes, contact interactions.

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Resonant New Physics Signatures

Resonant New Physics: Z′ Theory

Many natural extensions to the SM involve the addition of **new symmetries**, such as the addition of a U(1) symmetry. The simplest of these is called the Sequential Standard Model (SSM), where U(1)′ is added to the existing SM gauge symmetries:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)^{'}$$

- $SU(3)_c$: Strong Force (8 Gluons)
- $SU(2)_L \times U(1)_Y$: Electro-Weak Force ($W^{\pm}$, Z^0, γ)
- $U(1)^{'}$: New Physics (Z′)

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Resonant New Physics: Z′ Theory

However the SSM model is mainly used as a benchmark between experiments and is fairly unphysical. The E_6 GUT provides a more realistic model, where the decomposition of E_6 gives:

$$E_6 \rightarrow SO(10) \times U(1)_\psi \rightarrow SU(5) \times U(1)_\chi \times U(1)_\psi$$

GUT Decomposition — SM Forces — New Physics

The linear combination of these U(1)′ states gives different possible Z′ states depending on the mixing angle θ which sets the coupling the fermions:

$$Z'(\theta) = Z'_\chi cos\theta + Z'_\psi sin\theta$$

The theoretically motivated most likely values for θ leads to six different models with specific Z′ states named:

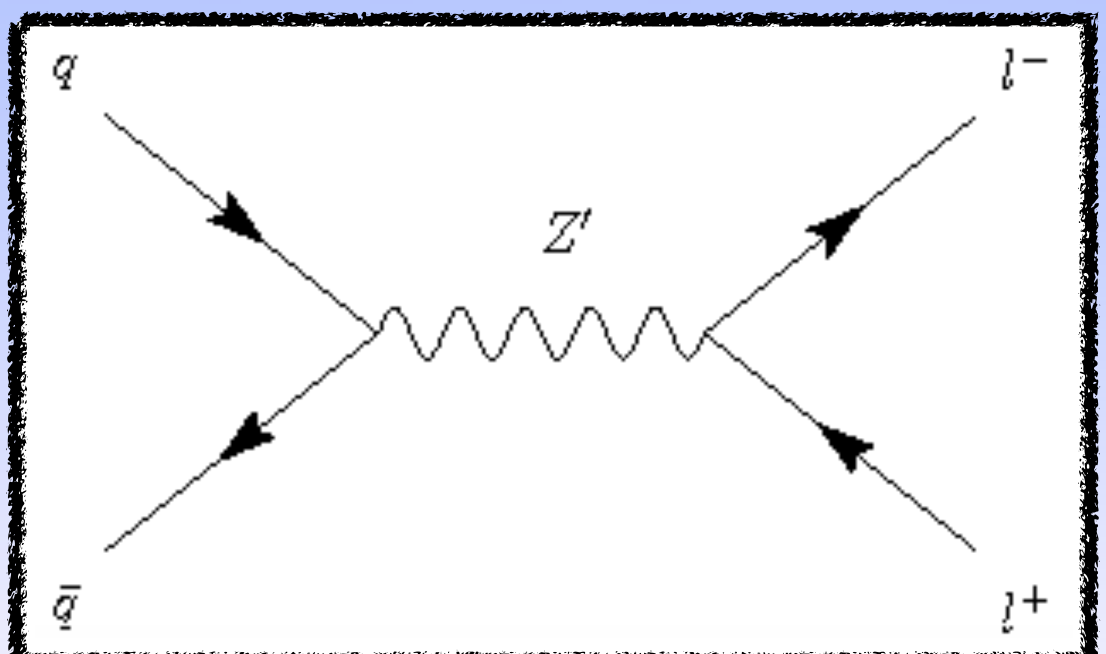
$$Z'_\psi \;,\; Z'_N \;,\; Z'_\eta \;,\; Z'_I \;,\; Z'_S \;,\; Z'_\chi$$

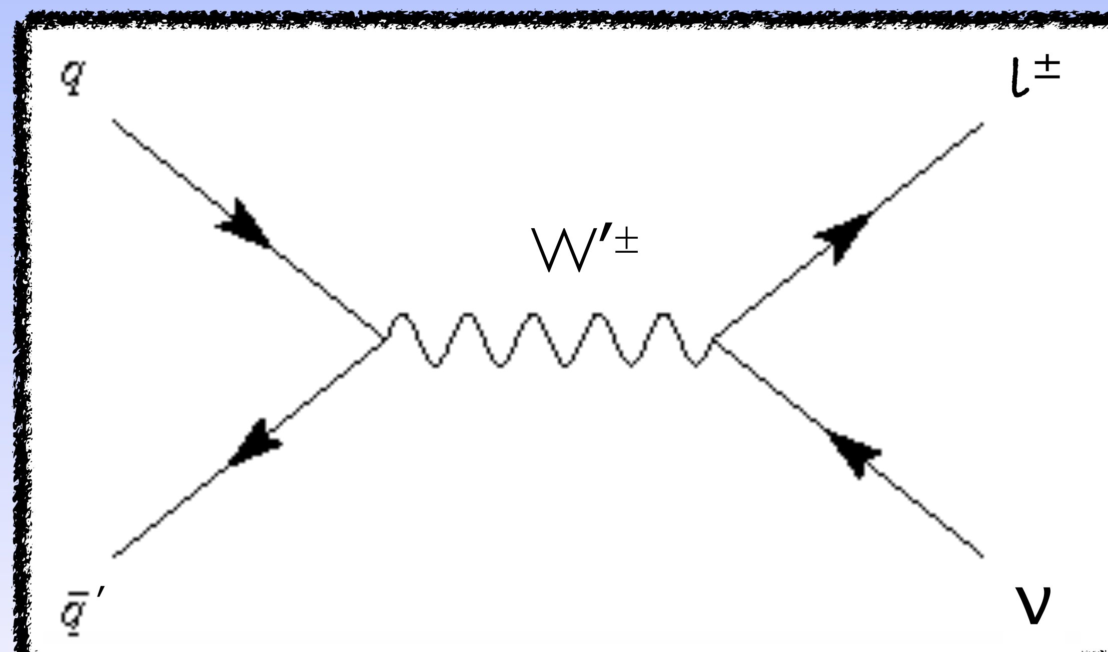
Resonant New Physics: Z′ Theory

Other GUT decompositions such as that leading to the Left-Right Symmetric Model (LRM), even predict an extended Weak like structure:

$$SO(10) \rightarrow SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- $SU(3)_c$: Strong Force (8 Gluons)
- $SU(2)_L$: EW Force ($W^{\pm}$, Z^0)
- $SU(2)_R$: New Physics ($W'^{\pm}$, Z')
- $U(1)_{B-L}$: EM (γ)





Resonant New Physics: RS G* Theory

As well as new Gauge Bosons arising from beyond the standard model symmetries, a resonance could be observed in the form of a Tensor Boson, if Gravity effects become visible at the TeV scale.

If we roughly compare the everyday strength of the known fundamental forces, a hierarchy problem is apparent. Why is Gravity so weak?

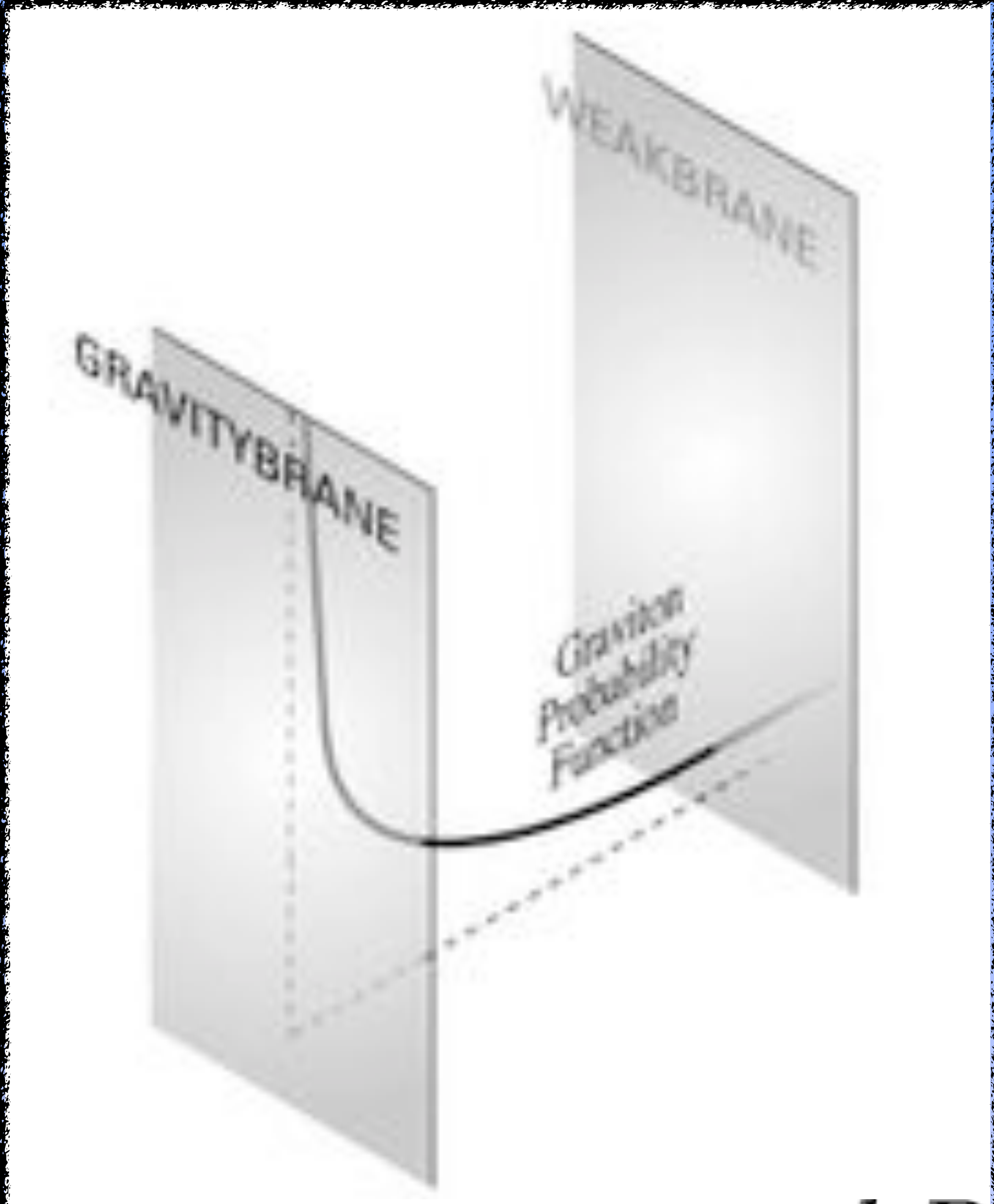
Interaction	Strong	E/M	Weak	Gravity
Coupling	1	1×10^{-2}	1×10^{-6}	1×10^{-39}

Attempting to resolve this hierarchy led to the rise in popularity towards the end of the millennium with models involving **extra spatial dimensions**.

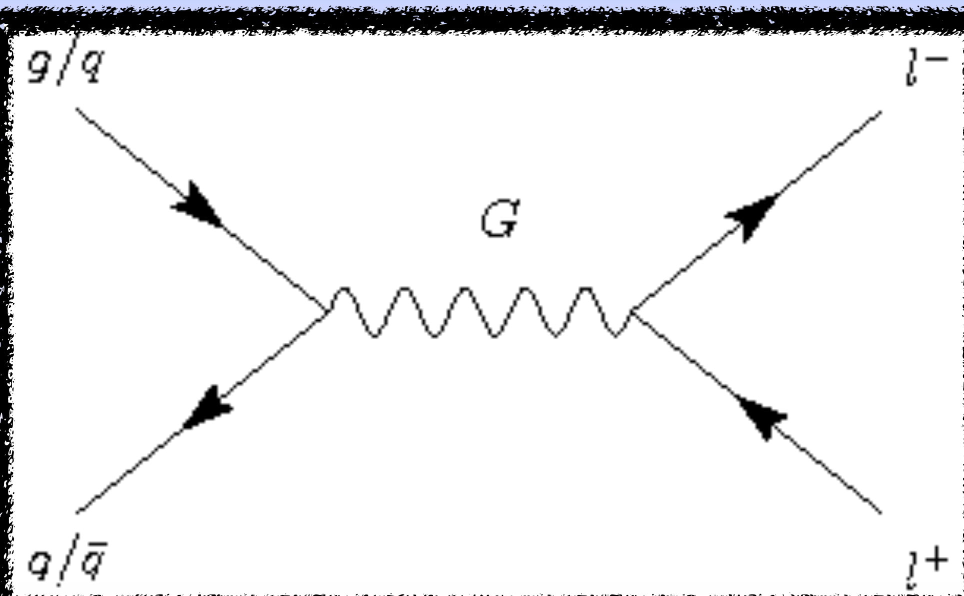
While the ADD model[1] was among the first, involving large flat extra dimensions (see later), the RS model[2] is relevant in the context of searching for new resonances with the ATLAS Detector, and involves warped extra dimensions.

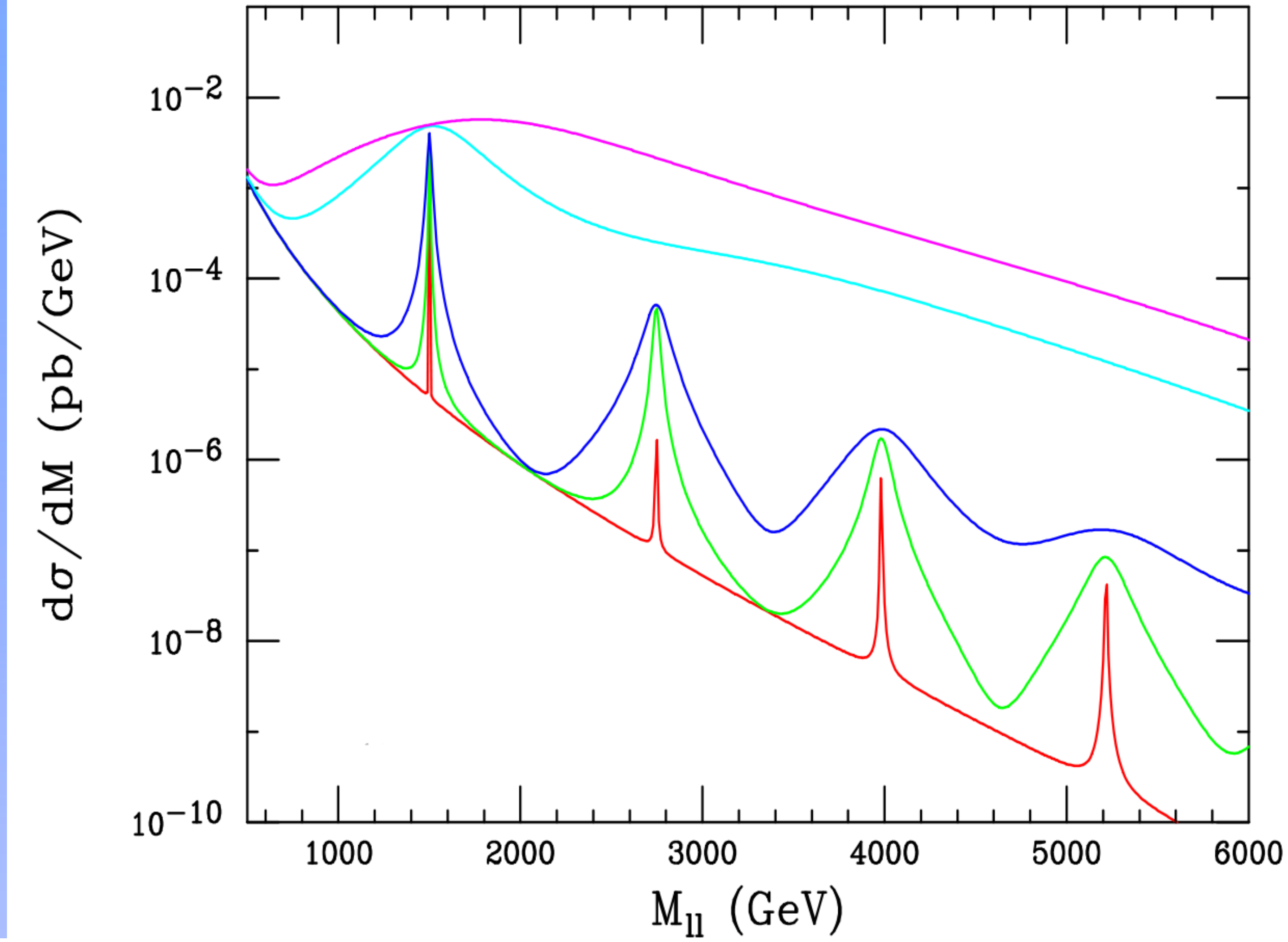
[1] Proposed in 1998 by Nima Arkani-Hamed, Savas Dimopoulos, and Gia Dvali

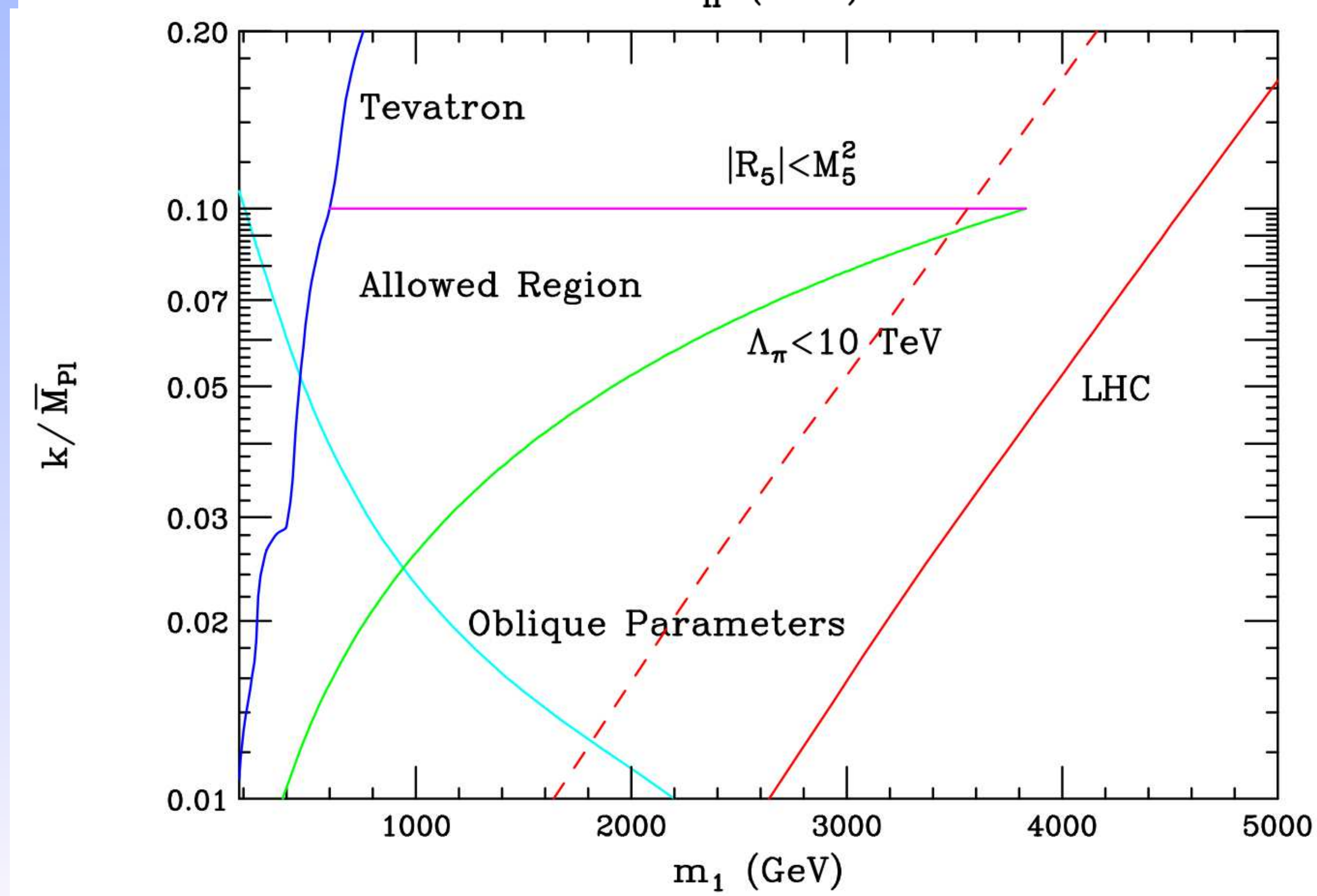
[2] Proposed in 1999 by Lisa Randall and Raman Sundrum



$$\Lambda_\pi = \bar{M}_{Pl}.e^{-\pi kR}$$

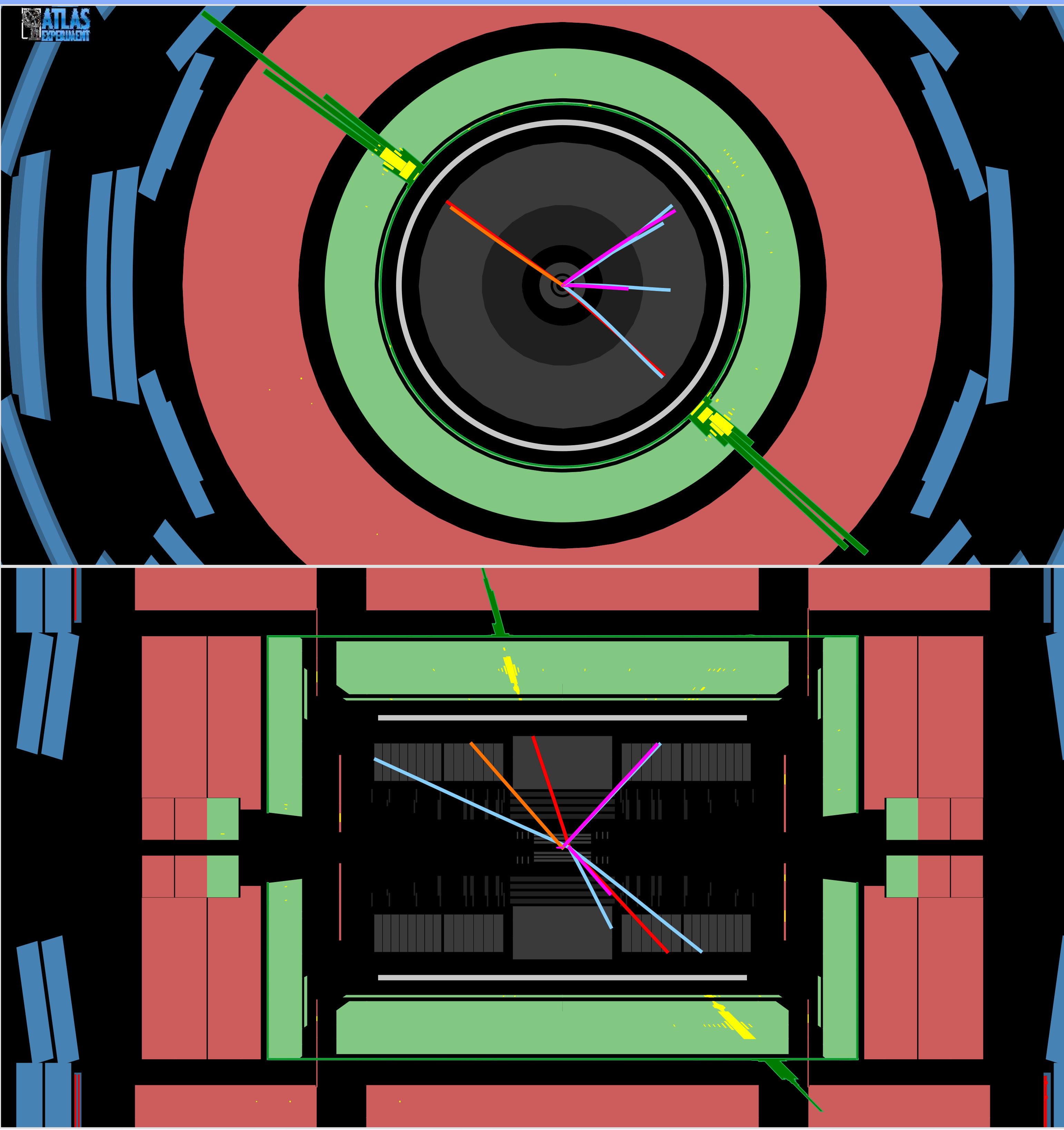


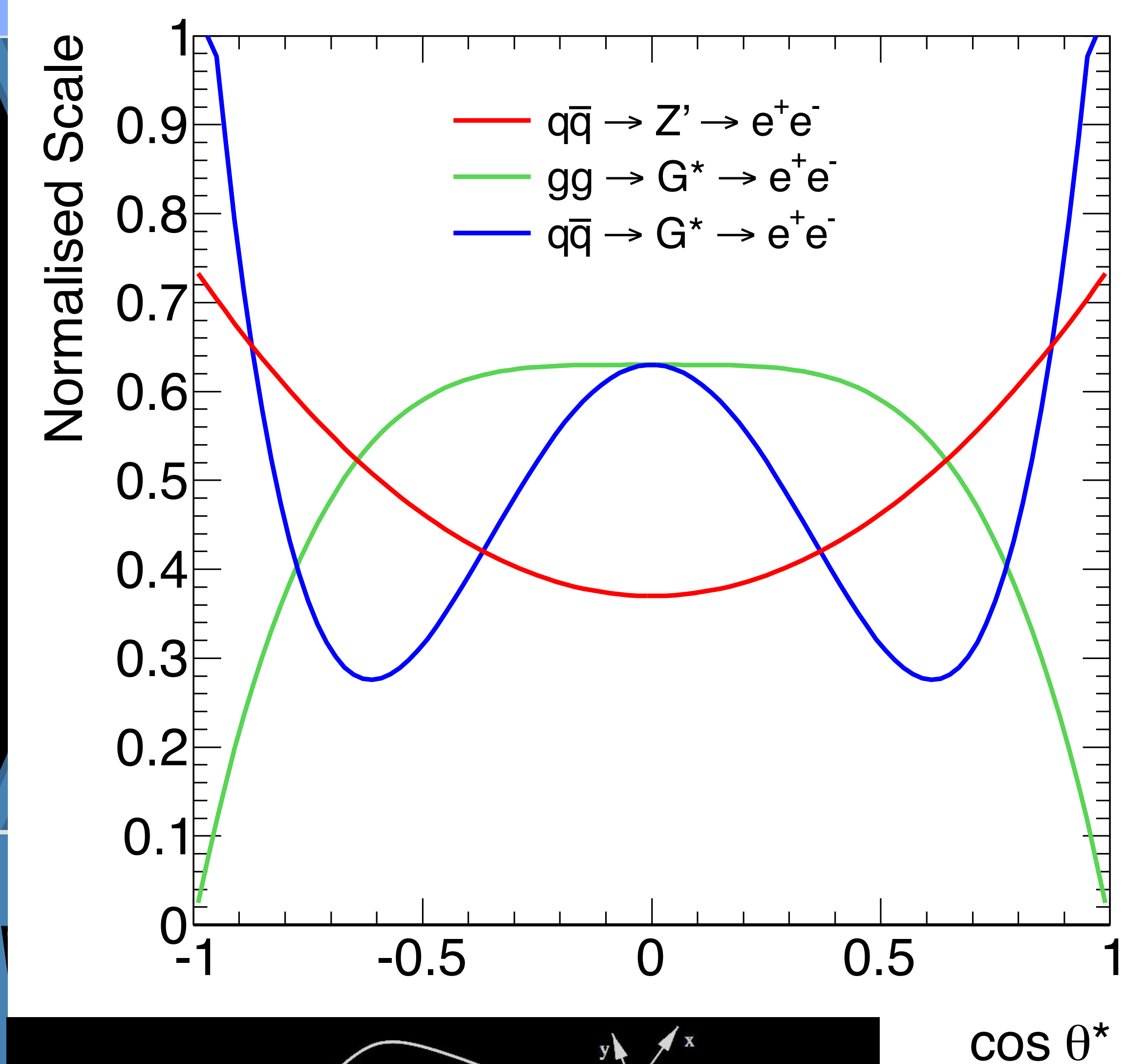


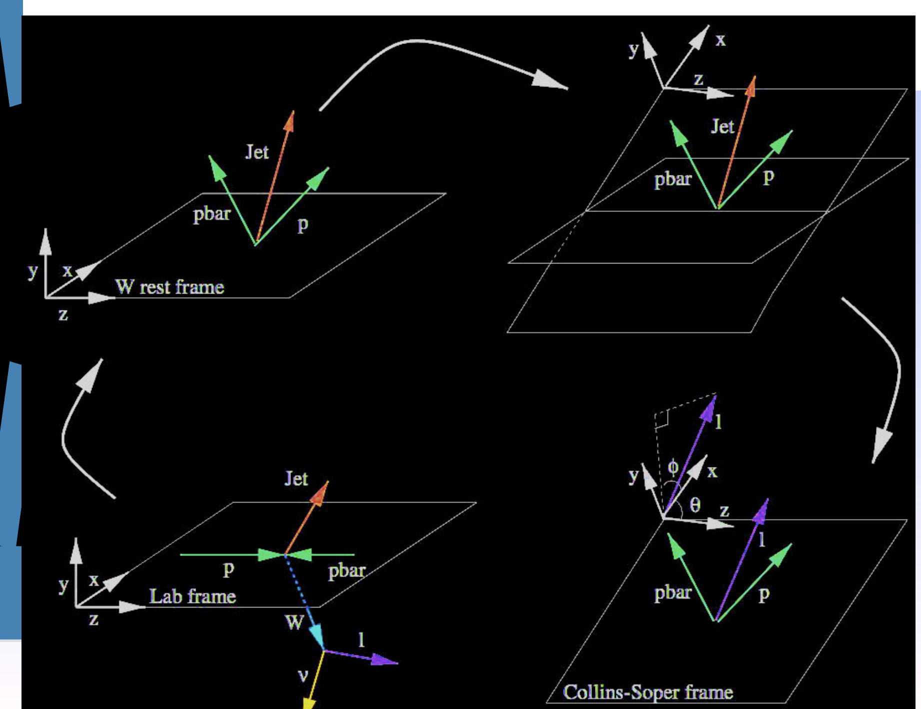


Above Figures from: H. Davoudiasl, J. L. Hewett, and T. G. Rizzo, Experimental probes of localized gravity: On and off the wall, Phys. Rev D 63 (2001) .

Resonant New Physics: Experimental Signature



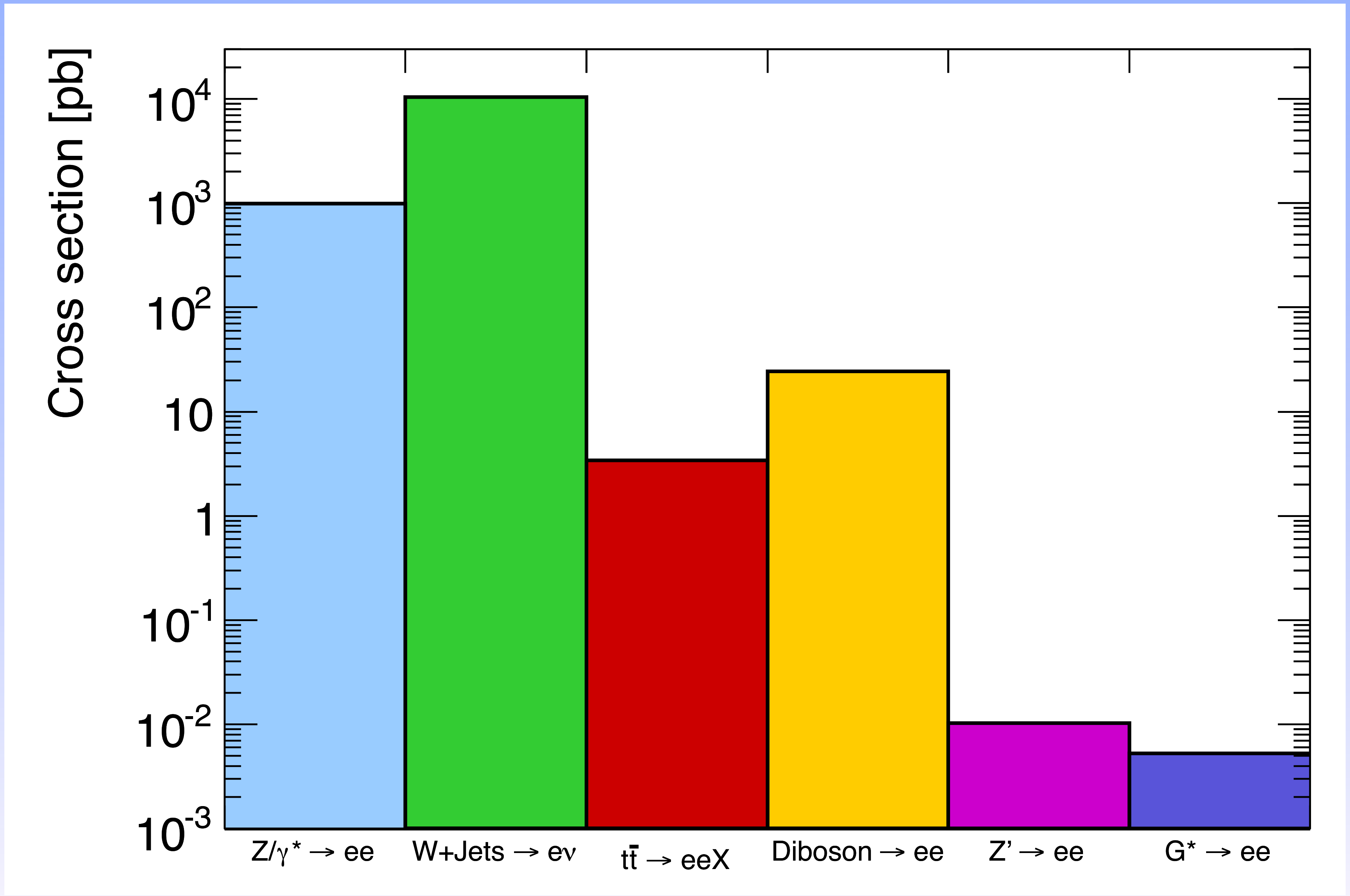




Distributions for above plot from: B. C. Allanach, K. Odagiri, M. A. Parker, and B. R. Webber, Searching for Narrow Graviton Resonances with the ATLAS Detector at the Large Hadron Collider, JHEP 9 (2000) .

Dilepton Analysis: SM Backgrounds

Below is a graph showing the respective cross sections of the main backgrounds to a dielectron resonance search (except QCD dijets which is estimated in Data).



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Dilepton Analysis: Event Selection

Event-Level Cuts	Value
e/γ Good Runs List (GRL)	DQ::PassRunLB(RunNumber,lbn) == true
Event Trigger	EF_g35_loose_g25_loose == true
Incomplete Event Veto	coreFlats&0x40000 != 0
# Electron Check	el_n > 1
Primary Vertex	Loop over vxp_n, Check vxp_trk_n > 2 for each
LAr Error	larError < 2
Tile Error	tileError < 2

Object-Level Cuts	Value
p_T	> 30 GeV
Author	1 OR 3
η	abs(η) < 2.47 and 1.37 > abs(η) > 1.52
Object Quality	egammaPID:BADCLUSELECTRON
Electron ID	Medium++
Leading p_T	> 40 GeV
Leading Isolation	< 7 GeV
Electron Pair Invariant Mass	>= 80 GeV

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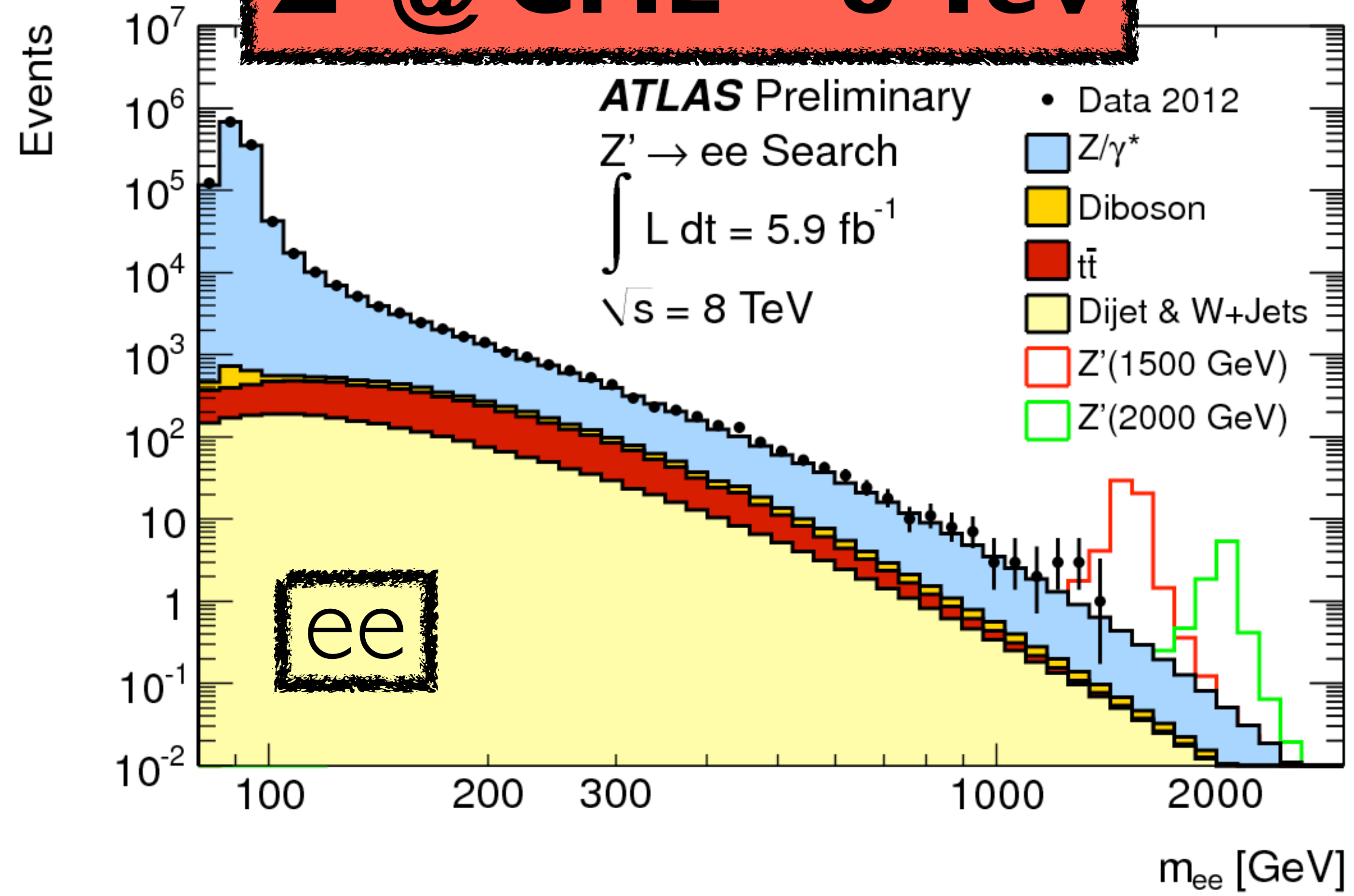
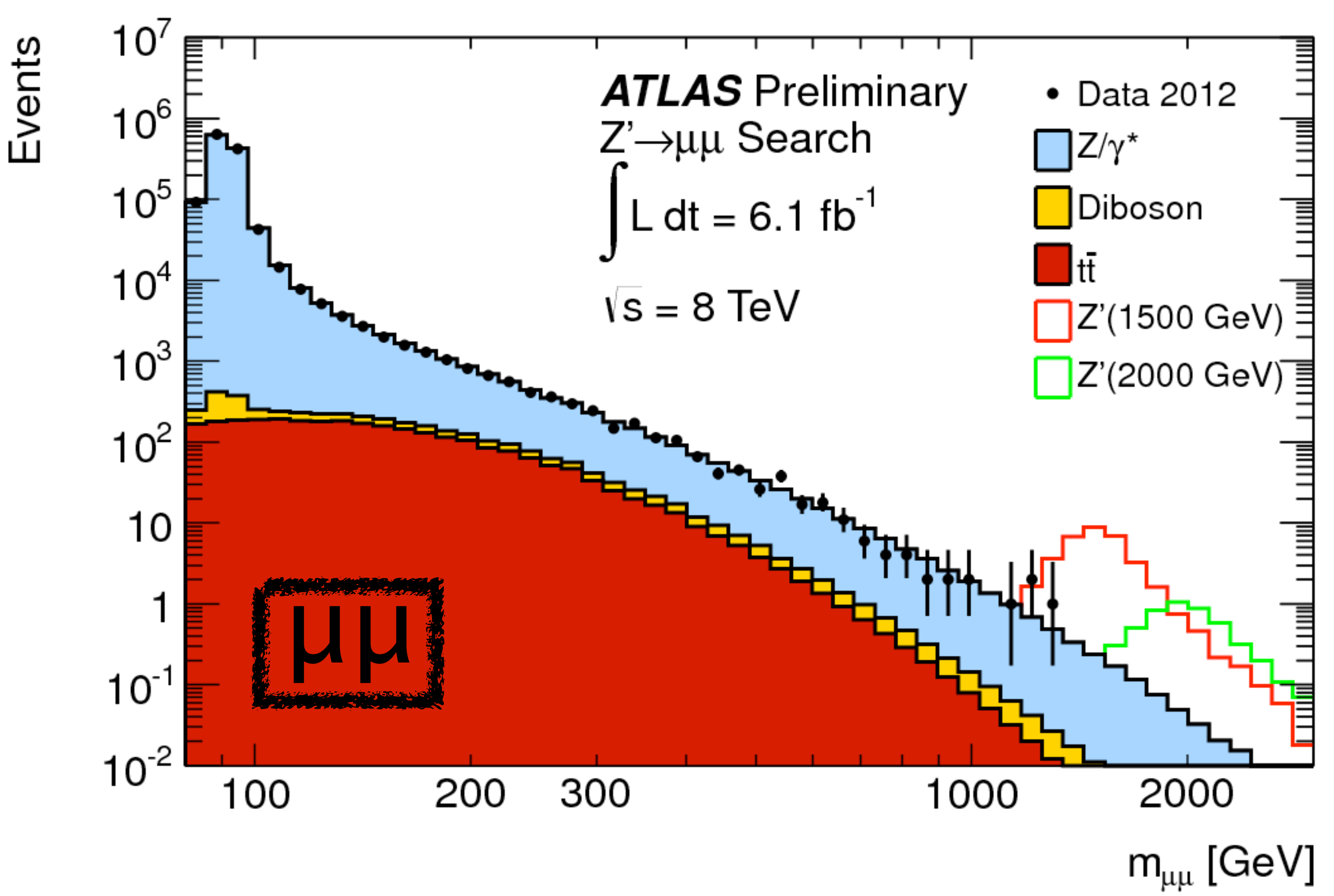
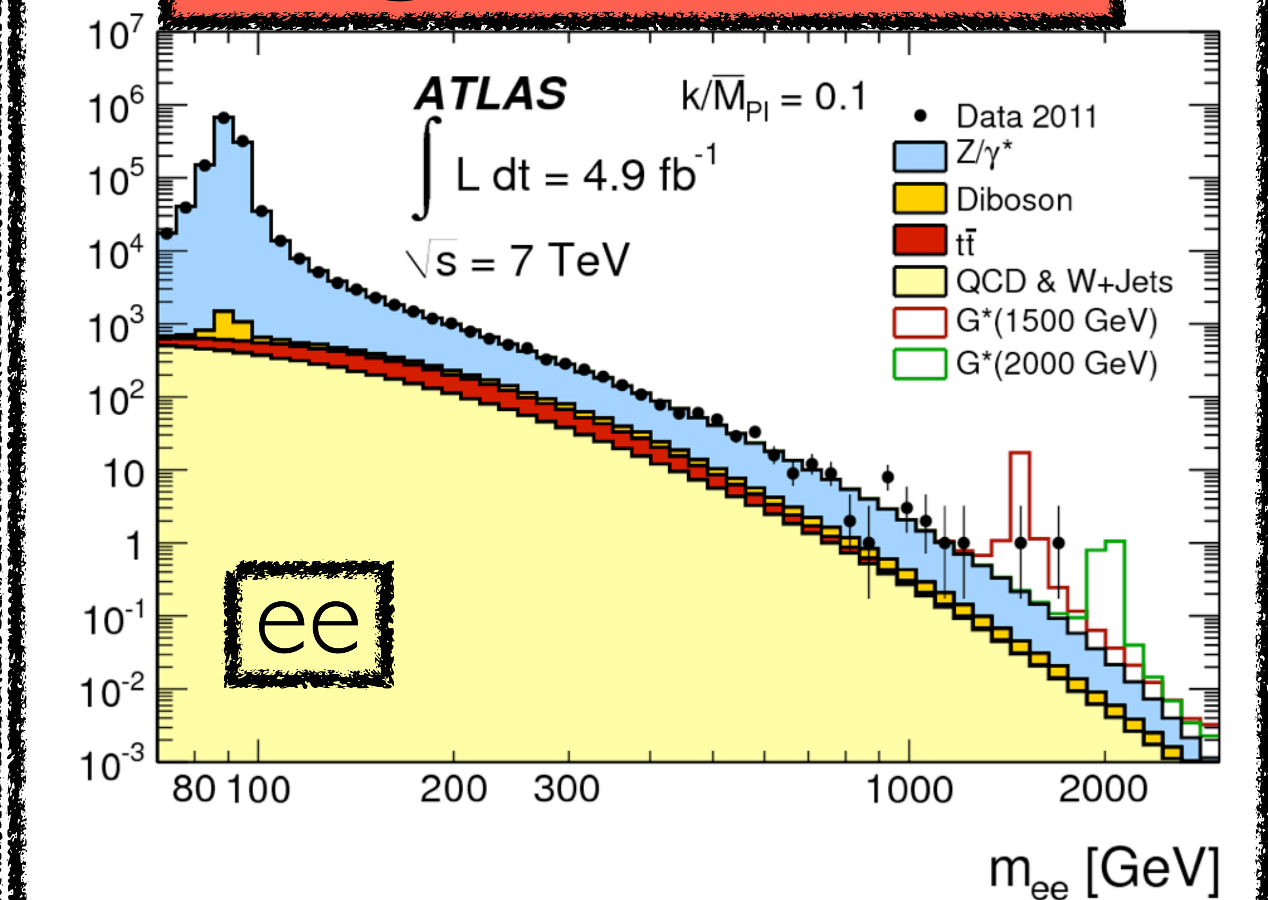
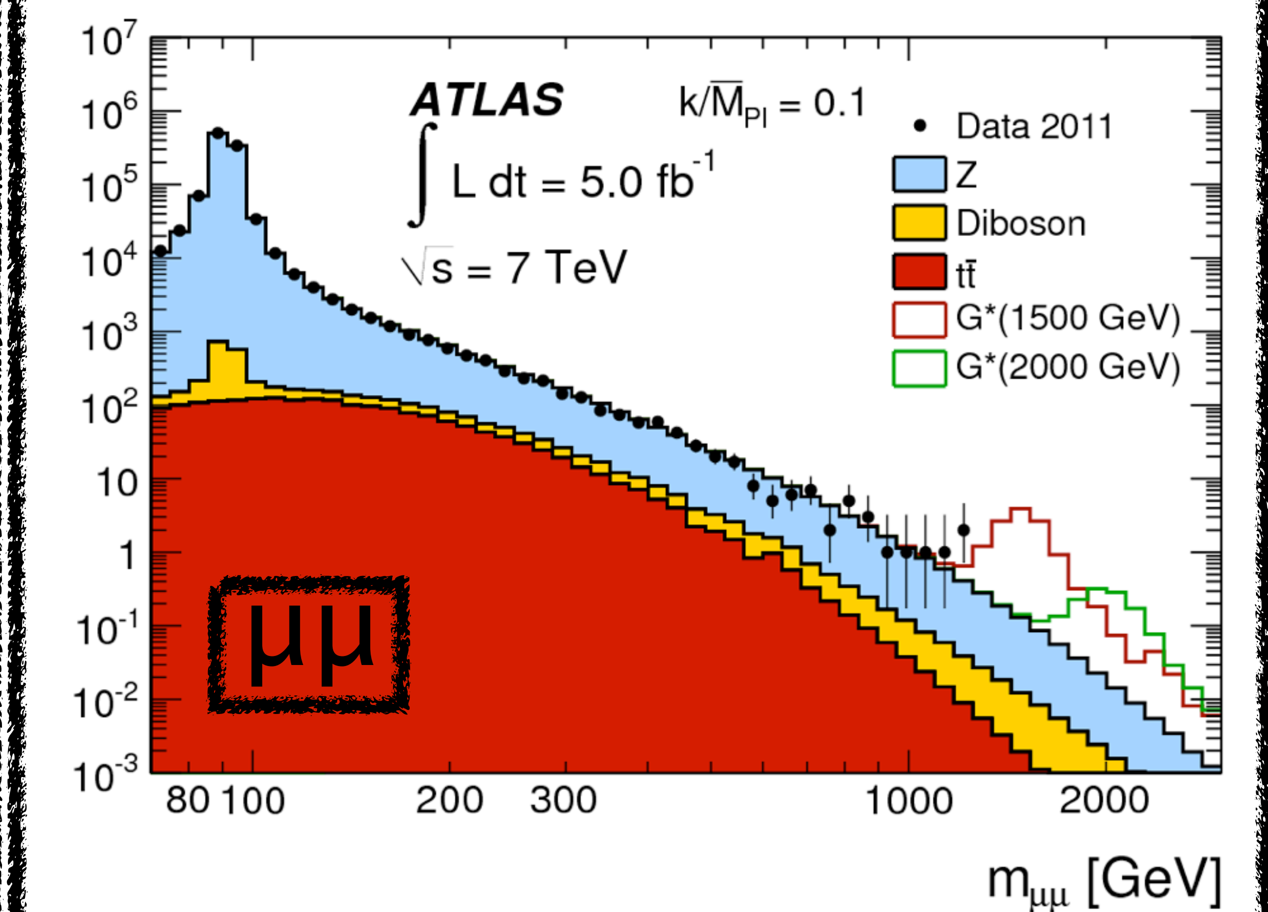
Z′ @ CME = 8 TeV





G* @ CME = 7 TeV

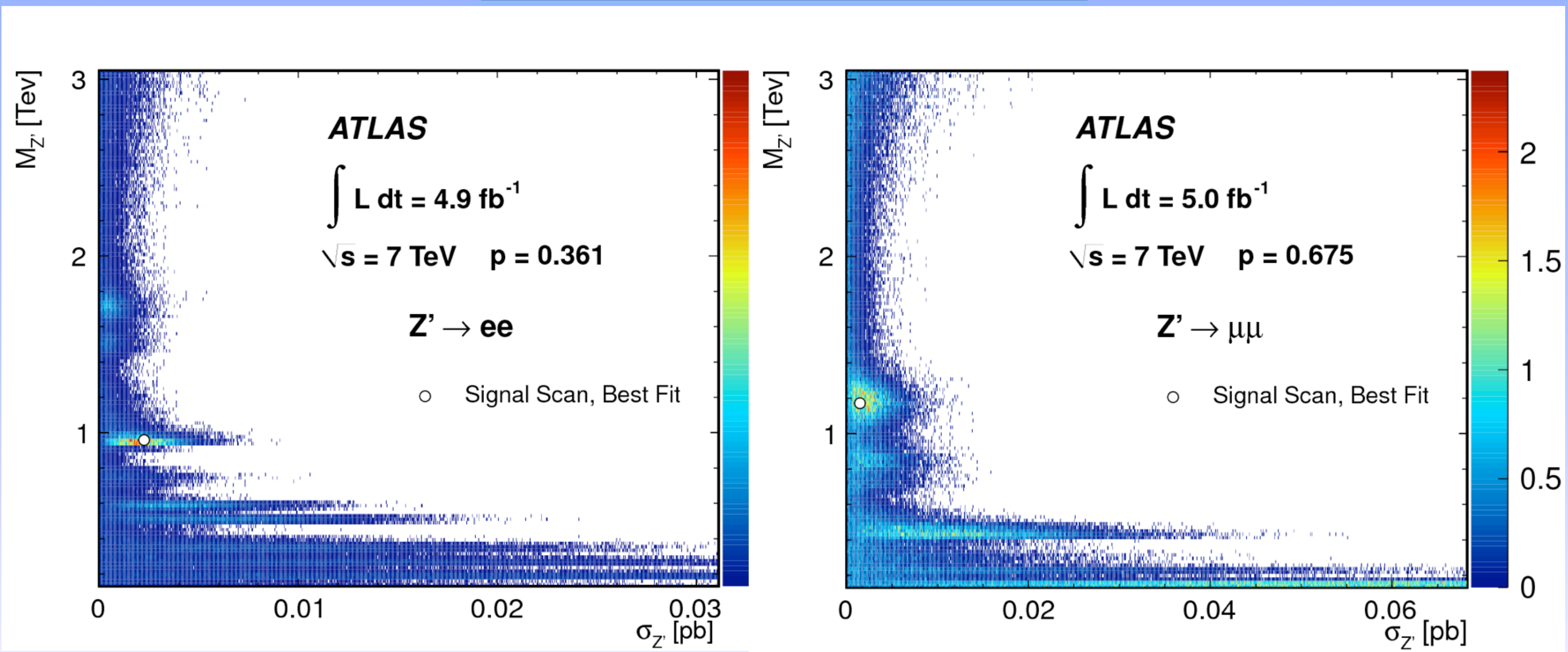




Statistical Interpretation: Discovery Search

$$LLR = -2\ln\frac{\mathcal{L}(data|\hat{N}_{Z'},\hat{M}_{Z'},\hat{\theta}_i)}{\mathcal{L}(data|(N_{Z'}=0),\hat{\hat{\theta}}_i)}$$

$$p = p(LLR < LLR_{obs}|S\,M\ only)$$

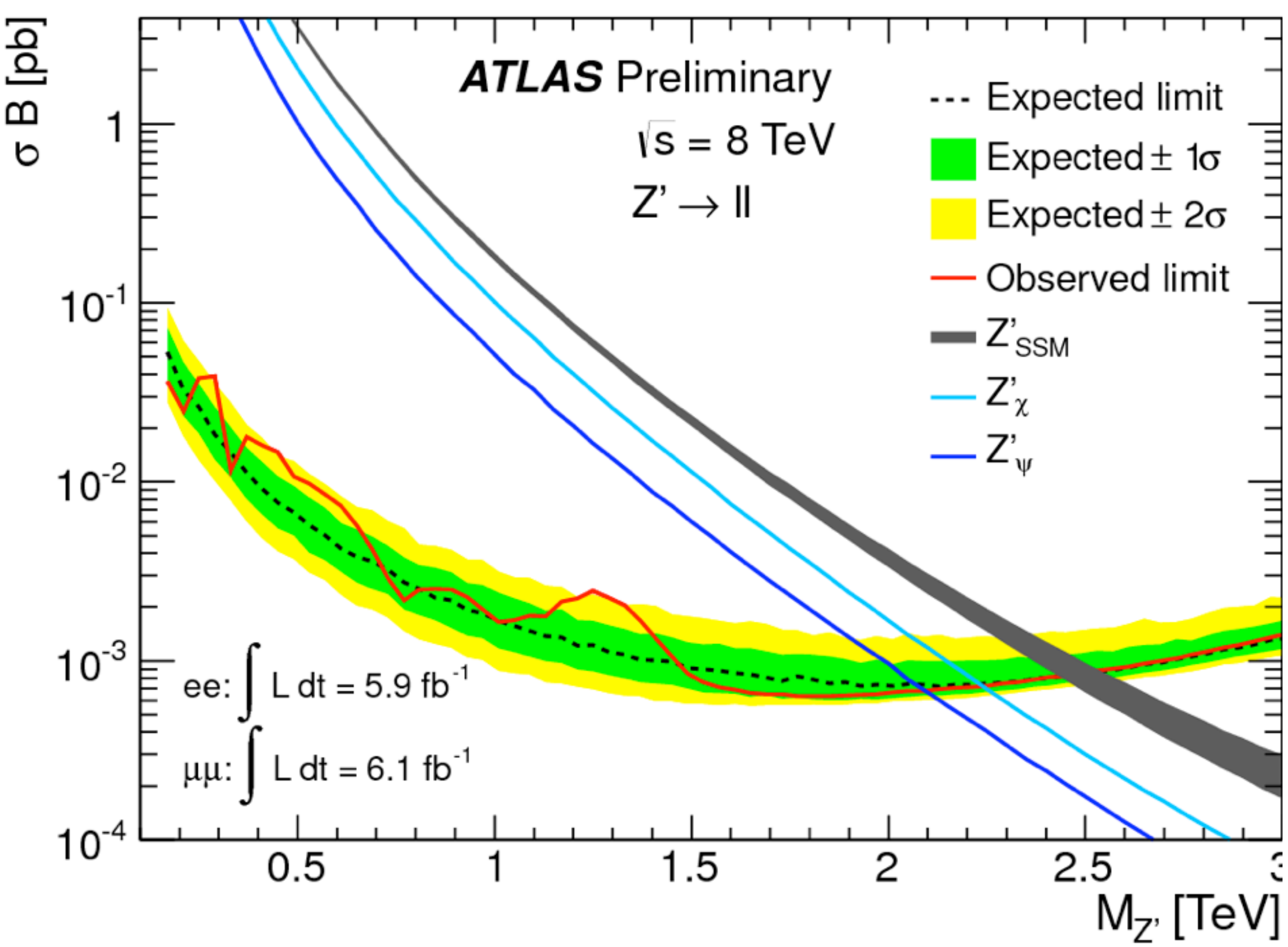


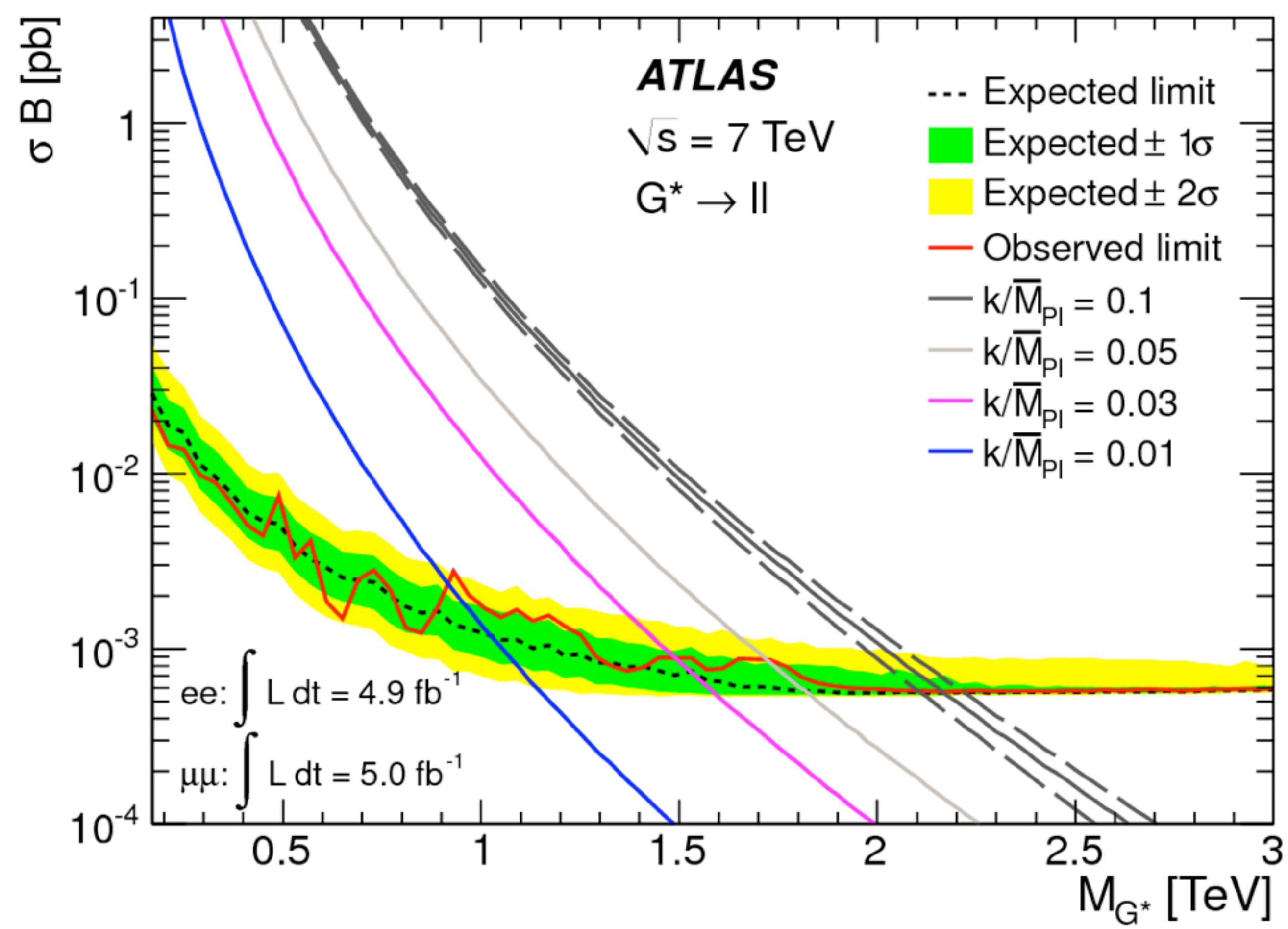
Statistical Interpretation: Exclusion Limits

$$\mathcal{L}(data|\sigma B, \theta_i) = \prod_{l=1}^{N_{channel}} \prod_{k=1}^{N_{bin}} \frac{\mu_{lk}^{n_{lk}} e^{-\mu_{lk}}}{n_{lk}!} \prod_{i=1}^{N_{sys}} G(\theta_i, 0, 1)$$

$$\mathcal{L}'(\sigma B|data) = \int \mathcal{L}(\sigma B, \theta_1, ..., \theta_N) d\theta_1, ..., d\theta_N$$

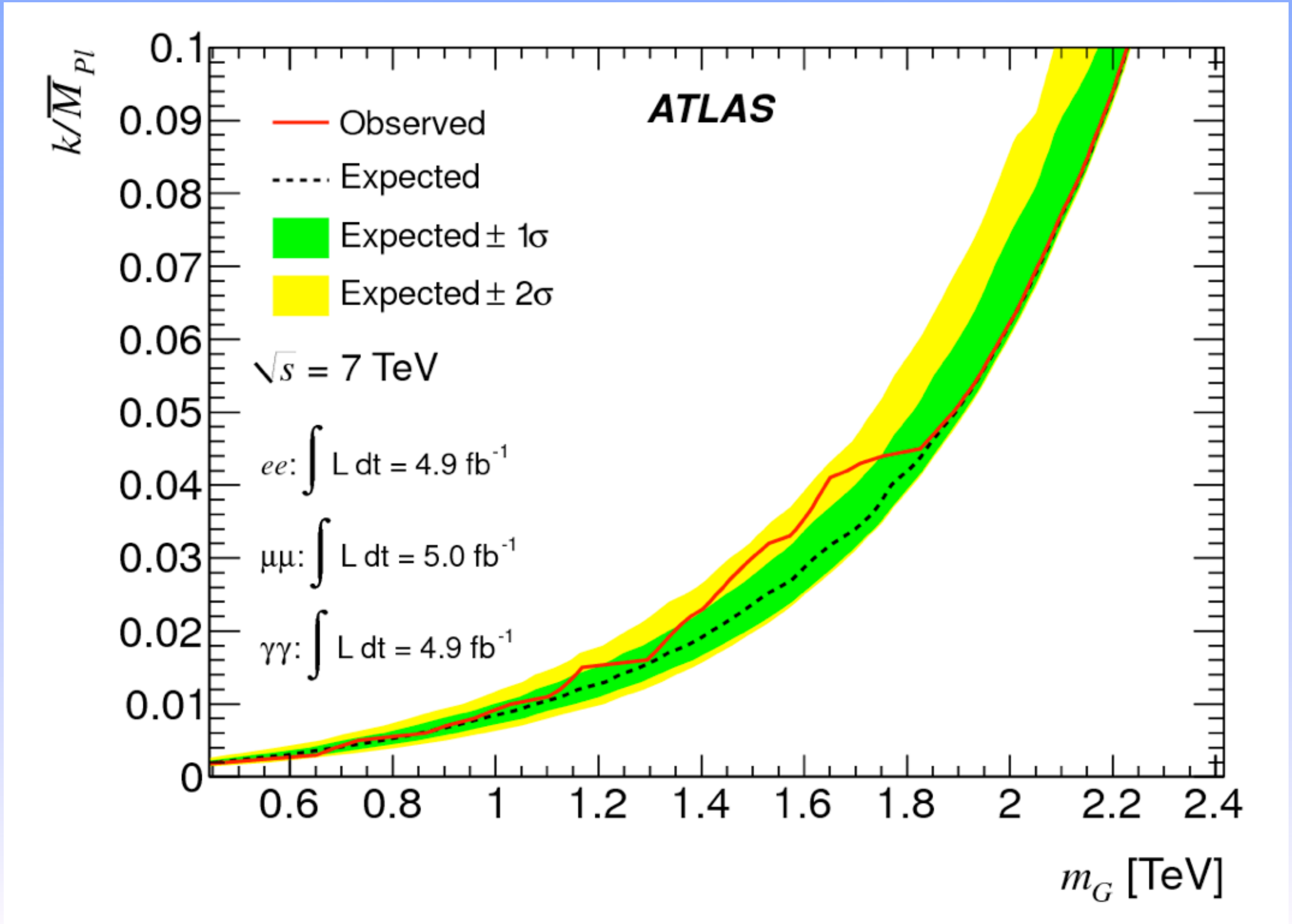
$$0.95 = \frac{\int_0^{(\sigma B)_{95}} \mathcal{L}'(\sigma B)\pi(\sigma B)d(\sigma B)}{\int_0^{\infty} \mathcal{L}'(\sigma B)\pi(\sigma B)d(\sigma B)}.$$



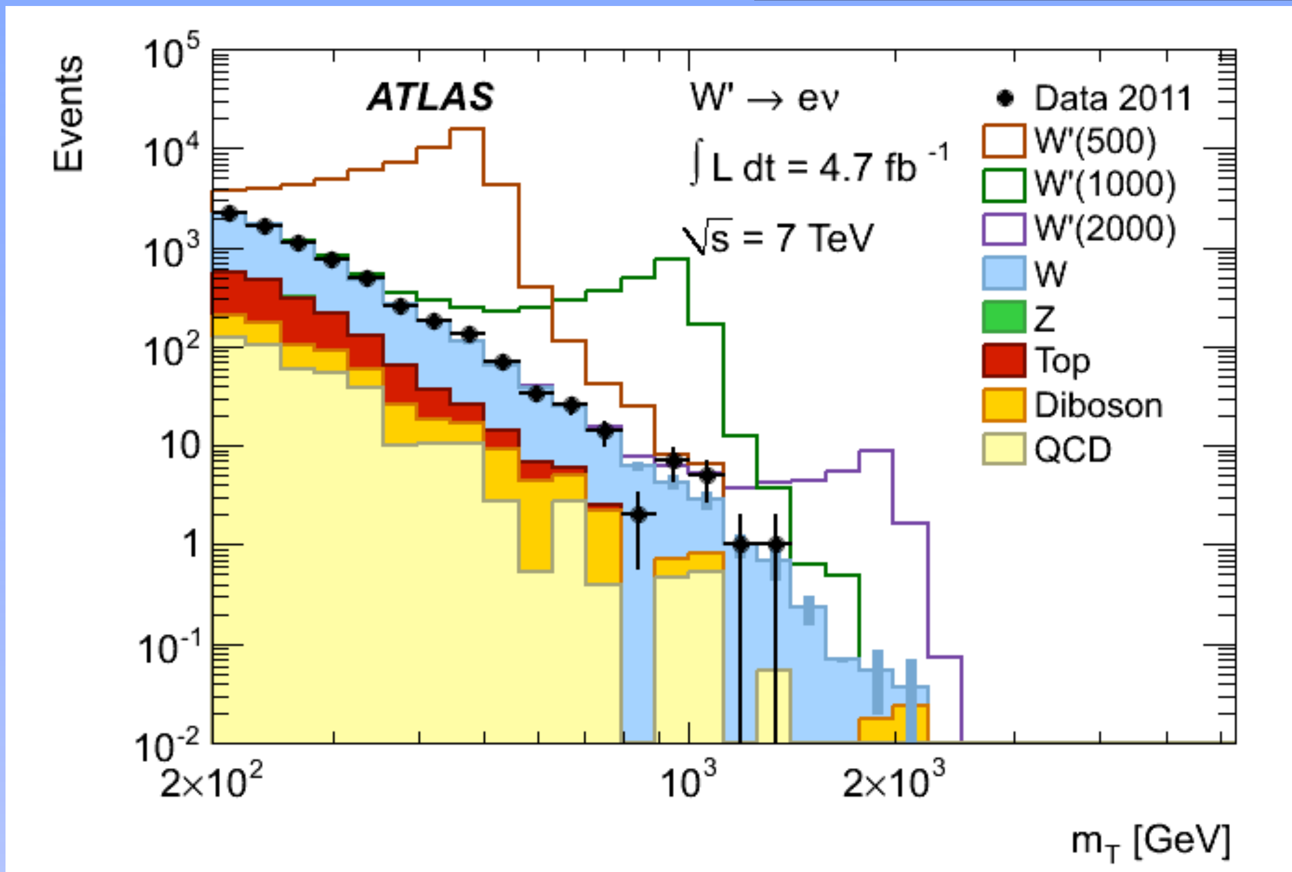


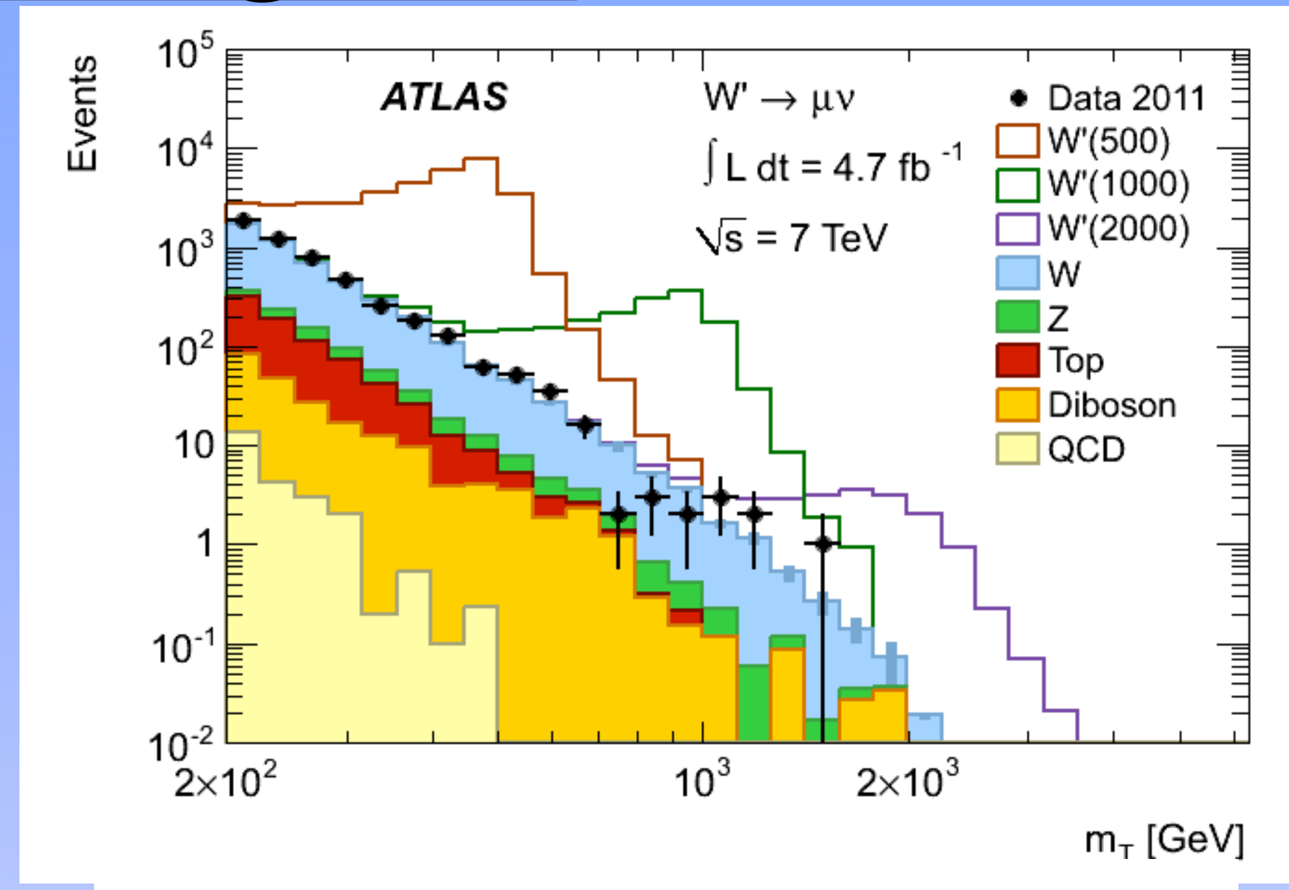
Statistical Interpretation

Combination with γγ channel for RS G* search.



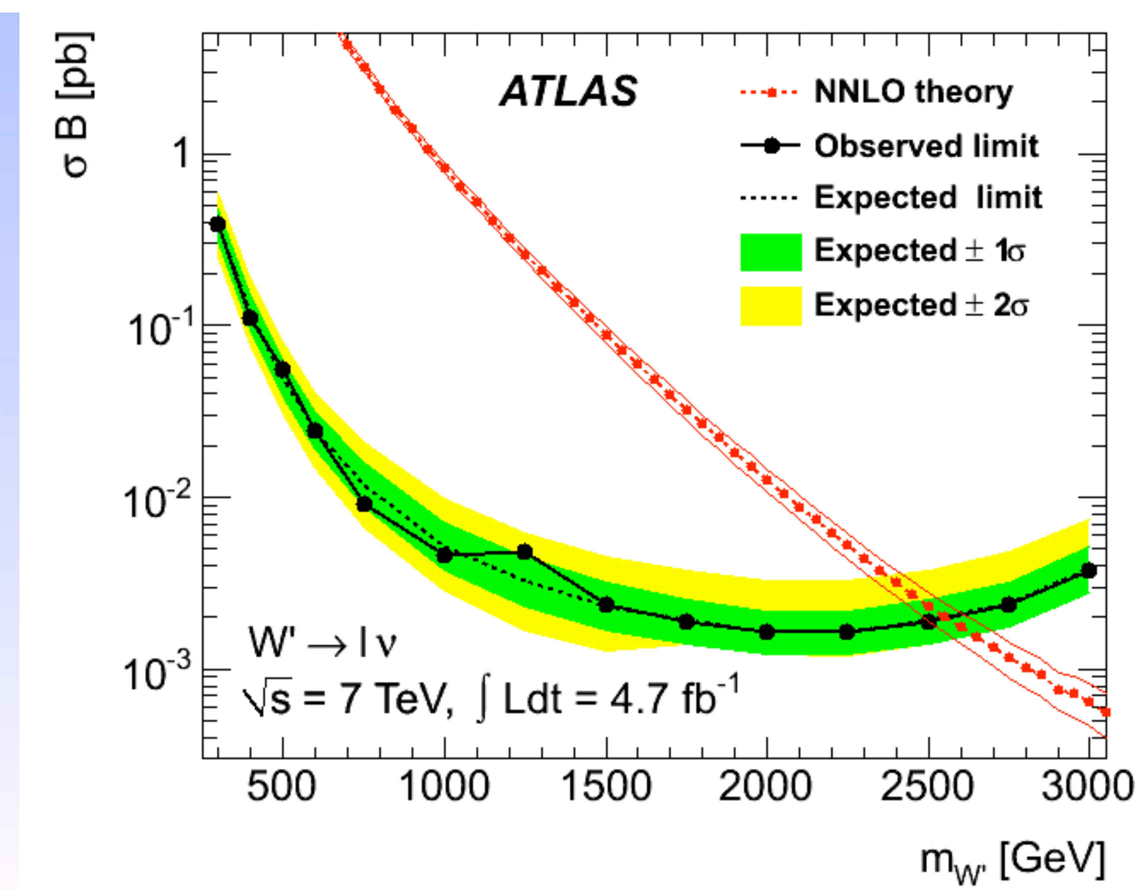
Aside: W′ Results @ 7 TeV





Note: This is a different analysis to the dilepton analysis described on the previous slides.

All papers are linked in the Backup.

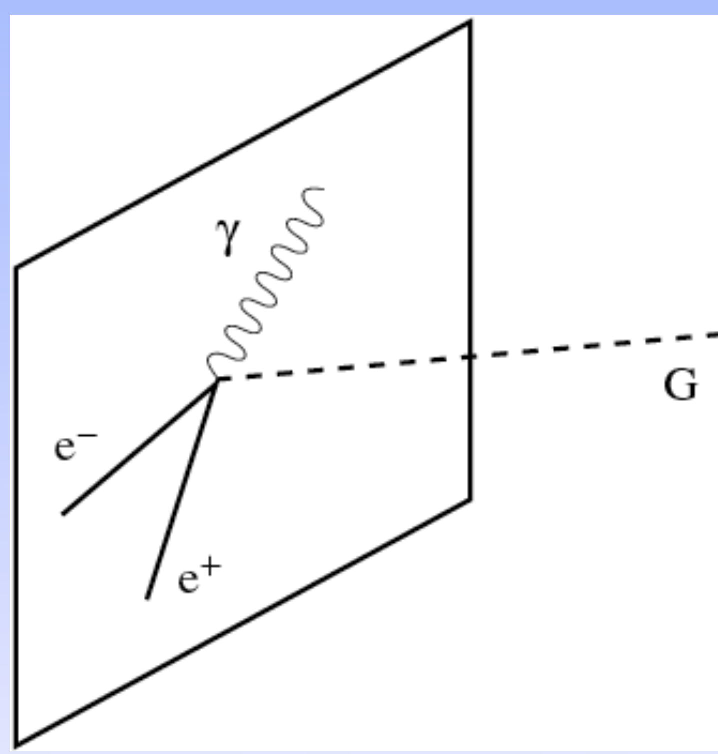


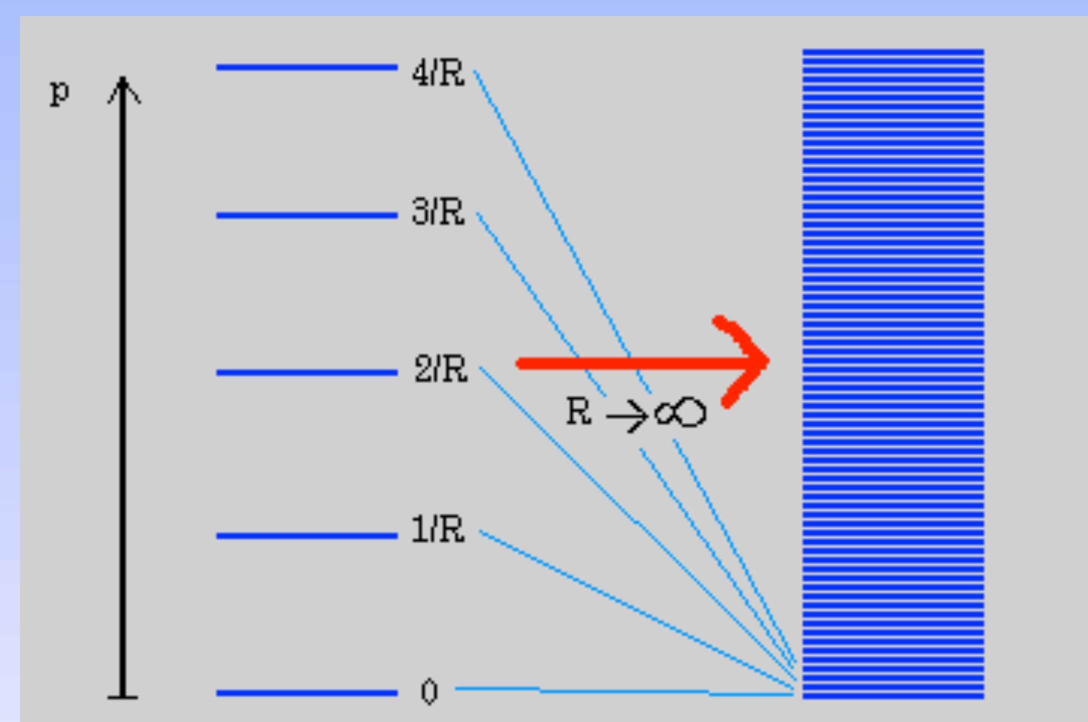
Non-Resonant New Physics Signatures

Non-Resonant New Physics: ADD Theory

In the ADD Paradigm, large flat extra spatial dimensions are introduced to dilute gravity, so that it appears weak in the 3+1 space-time dimensions to which the other known forces are constrained.

Model parameters include: Size of ED, (R), number of ED, ($n \geq 2$), and the fundamental Planck scale in 4+n dimensional space-time, (M_D), which can be related to the string scale, (M_S).





G* is the only particle that propagates in the bulk, giving Kaluza-Klein (KK) mode excitations on the SM brane.

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Non-Resonant New Physics: ADD Theory

Therefore broad excesses are expected over the SM prediction, with a cut off imposed at M_S in the dilepton invariant mass spectrum to avoid UV divergences when summing over KK modes.

The total expected cross section can be expressed as:

$$\sigma_{total} = \sigma_{SM} + \eta_G . F_I + \eta_G^2 . F_G$$

Where F_I is the SM+ADD interference term, F_G is the pure ADD term, and η_G is the formalism dependent parameter of interest:

$$\eta_G = \frac{\mathcal{F}}{M_s^4} \qquad \mathcal{F} = 1 \quad \text{(GRW)} \qquad \mathcal{F} = \pm\frac{2}{\pi} \quad \text{(Hewett)}$$

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Non-Resonant New Physics: Contact Interaction Theory

If Quarks and Leptons are composite, with at least one common constituent, the interaction would likely be manifested through an effective four-fermion contact interaction at energies well below the compositeness scale (Λ).

Such a Contact Interaction (CI) could also describe a new interaction with a messenger too heavy for direct observation at the LHC.

Here we consider the Left-Left Isoscalar Model, which is often used as a benchmark, and gives the Lagrangian:

$$\mathcal{L} = \frac{g^2}{2\Lambda^2}[\eta_{LL}(\bar{\psi}_L\gamma_\mu\psi_L)(\bar{\psi}_L\gamma^\mu\psi_L)]$$

Where $\eta_{LL} = \pm 1$, defines whether the interaction interferes constructively (-1) or destructively (+1) with SM DY.

Non-Resonant New Physics: Contact Interaction Theory

The differential cross-section for the process $q\bar{q} \rightarrow l^+l^-$ at the LHC, with the introduction of CI, can then be written as:

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

Where F_I is the DY-CI interference term, and F_C is the pure CI term.

At the largest Λ values to which the analysis to be shown is sensitive to, both interference and pure CI terms are significant, i.e. at m_{ll} = 300 GeV, Λ = 9 TeV: F_I = 1.5 x F_C.

The present analysis focuses on identifying a broad deviation from the SM dilepton mass distribution at masses well above the Z peak, and investigates both $1/\Lambda^2$ and $1/\Lambda^4$ dependence.

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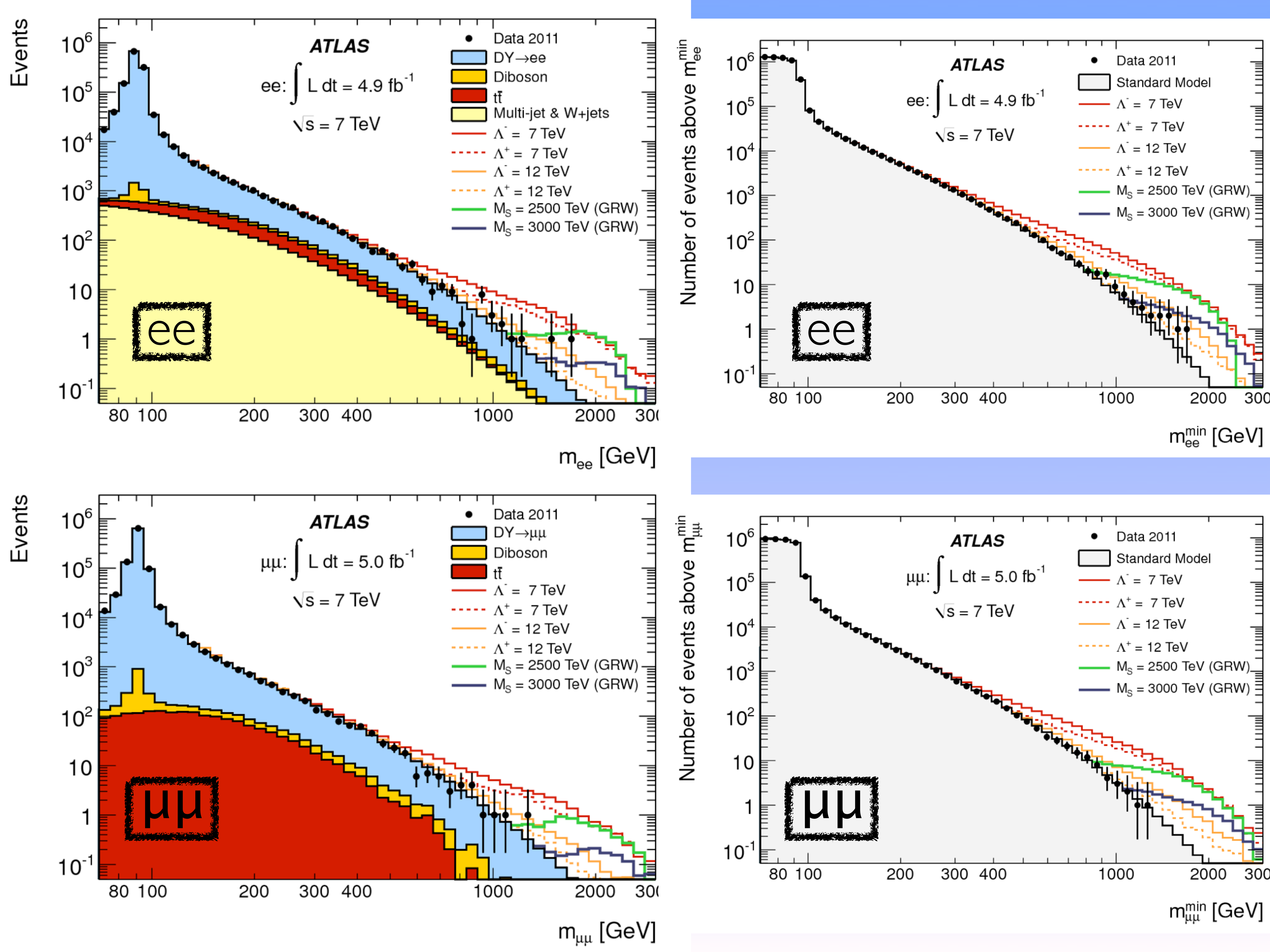

ATLAS
ee: ∫ L dt = 4.9 fb-1
√s = 7 TeV
Data 2011
DY→ee
Diboson
tt̄
Multi-jet & W+jets
Λ- = 7 TeV
Λ+ = 7 TeV
Λ- = 12 TeV
Λ+ = 12 TeV
MS = 2500 TeV (GRW)
MS = 3000 TeV (GRW)
ee
Events
mee [GeV]
ATLAS
ee: ∫ L dt = 4.9 fb-1
√s = 7 TeV
Data 2011
Standard Model
Λ- = 7 TeV
Λ+ = 7 TeV
Λ- = 12 TeV
Λ+ = 12 TeV
MS = 2500 TeV (GRW)
MS = 3000 TeV (GRW)
ee
Number of events above mee min
mee min [GeV]
ATLAS
μμ: ∫ L dt = 5.0 fb-1
√s = 7 TeV
Data 2011
DY→μμ
Diboson
tt̄
Λ- = 7 TeV
Λ+ = 7 TeV
Λ- = 12 TeV
Λ+ = 12 TeV
MS = 2500 TeV (GRW)
MS = 3000 TeV (GRW)
μμ
Events
mμμ [GeV]
ATLAS
μμ: ∫ L dt = 5.0 fb-1
√s = 7 TeV
Data 2011
Standard Model
Λ- = 7 TeV
Λ+ = 7 TeV
Λ- = 12 TeV
Λ+ = 12 TeV
MS = 2500 TeV (GRW)
MS = 3000 TeV (GRW)
μμ
Number of events above mμμ min
mμμ min [GeV]

Statistical Interpretation: Exclusion Limits

To quantify any excess seen in data, a Bayesian approach is used once again.

For the ADD model, counting is done in a single bin above a mass threshold, which is optimised to give the highest expected limit on M_S.

For the CI model, ~10 bins are used to include the kinematic information from the expected signal shape.

$$\mathcal{L}(n|\mu,\bar{\theta}) = \frac{\mu^n e^{-\mu}}{n!}\prod_{i=1}^{N_{sys}} G(\theta_i,0,1) \quad , \text{ where } \quad \mu = \sum_j \mu_j \Big(1+\sum_i \theta_i \varepsilon_{ji}\Big)$$

In both the ADD and CI model statistical analyses, the parameter of interest is not directly the number of expected signal events, but the expected signal as a function of the parameters M_S and Λ, respectively.

Therefore, signal parameterisations are made as inputs, using the available MC, so that lower limits are set on these parameters of interest.

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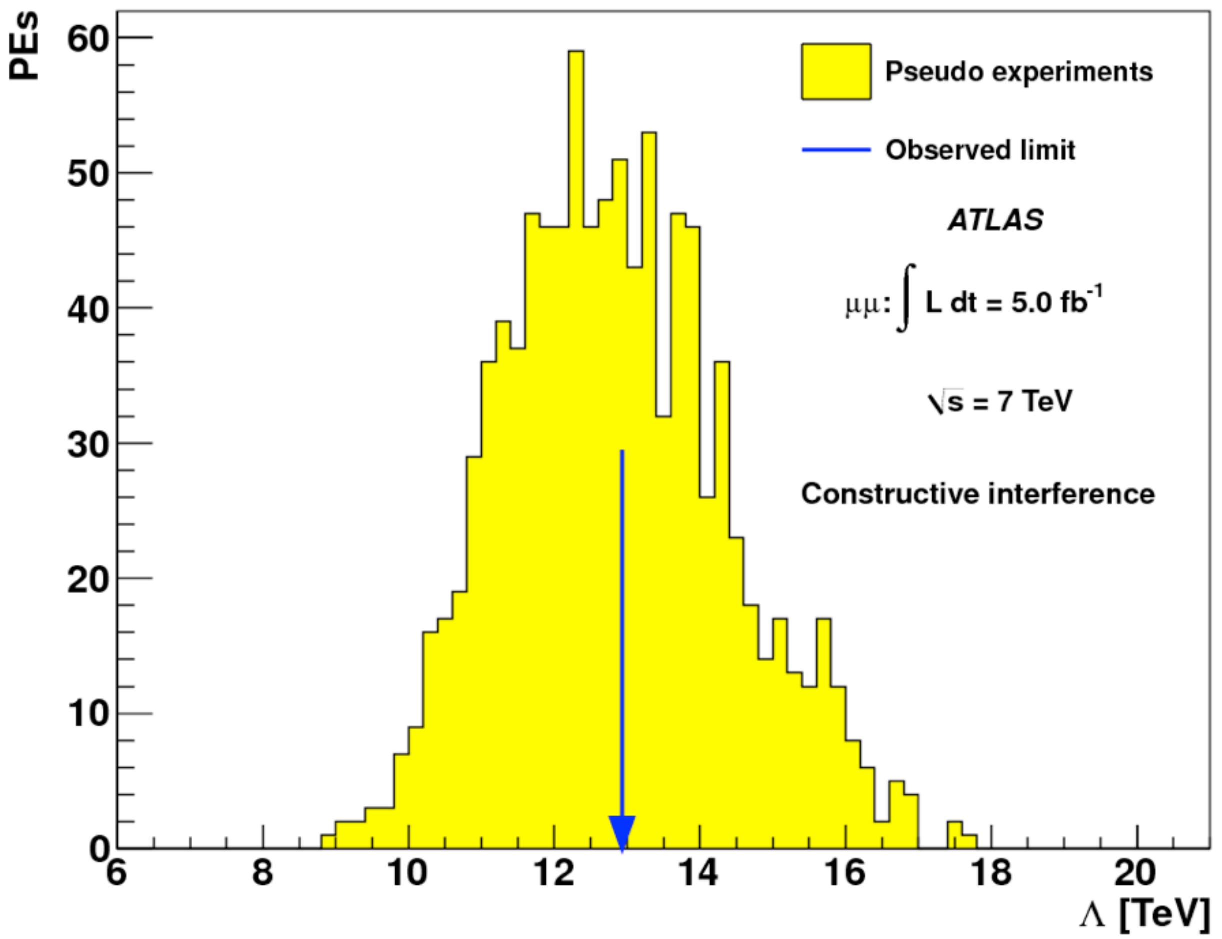
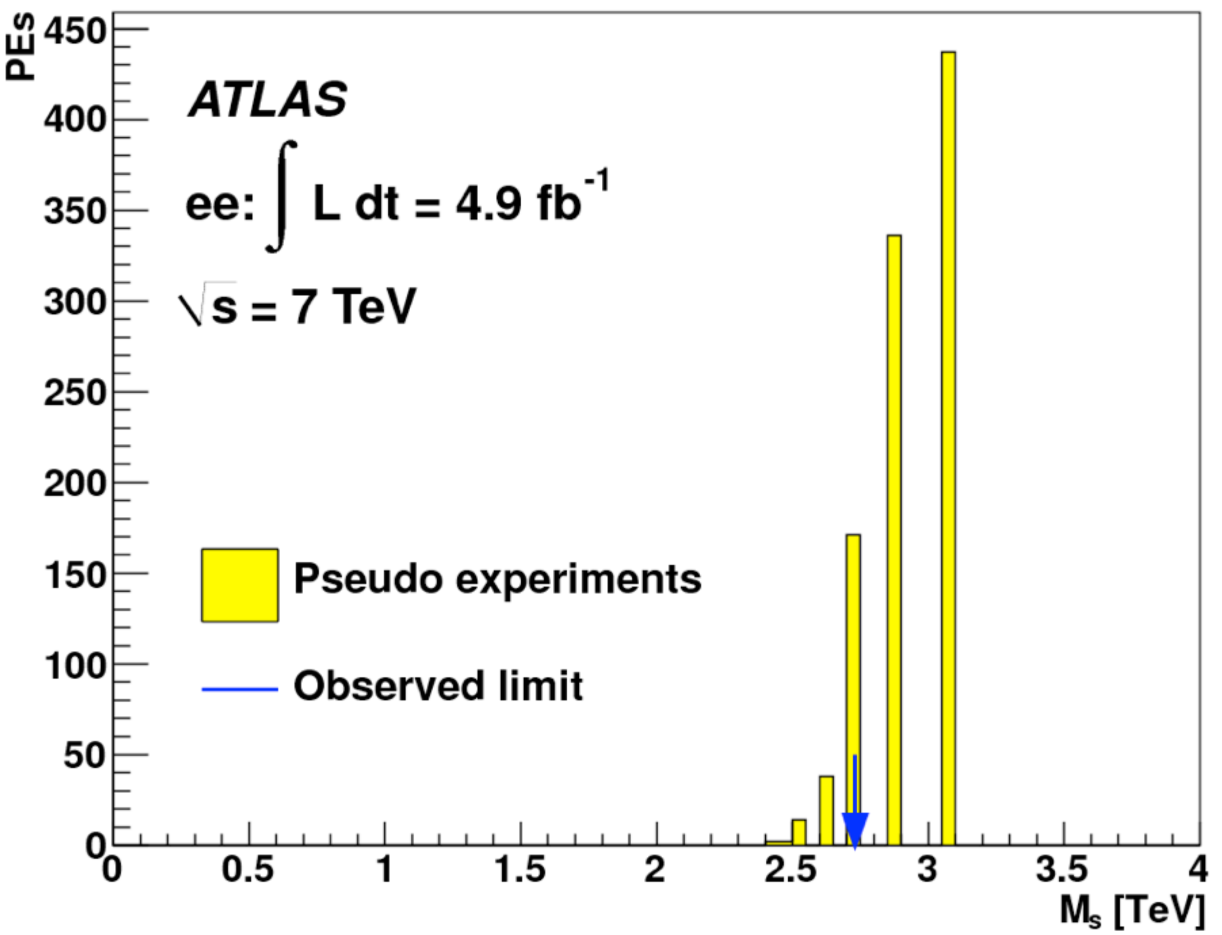
CI Limits

Channel	Prior	Expected limit [TeV] Constr.	Expected limit [TeV] Destr.	Observed limit [TeV] Constr.	Observed limit [TeV] Destr.
ee	$1/\Lambda^2$	13.8	10.4	12.1	9.5
	$1/\Lambda^4$	12.5	9.8	11.4	9.1
$\mu\mu$	$1/\Lambda^2$	12.7	9.9	12.9	9.6
	$1/\Lambda^4$	11.6	9.1	11.7	9.0
$ee+\mu\mu$	$1/\Lambda^2$	15.0	11.3	13.9	10.2
	$1/\Lambda^4$	13.8	10.5	12.9	9.8



ADD Limits

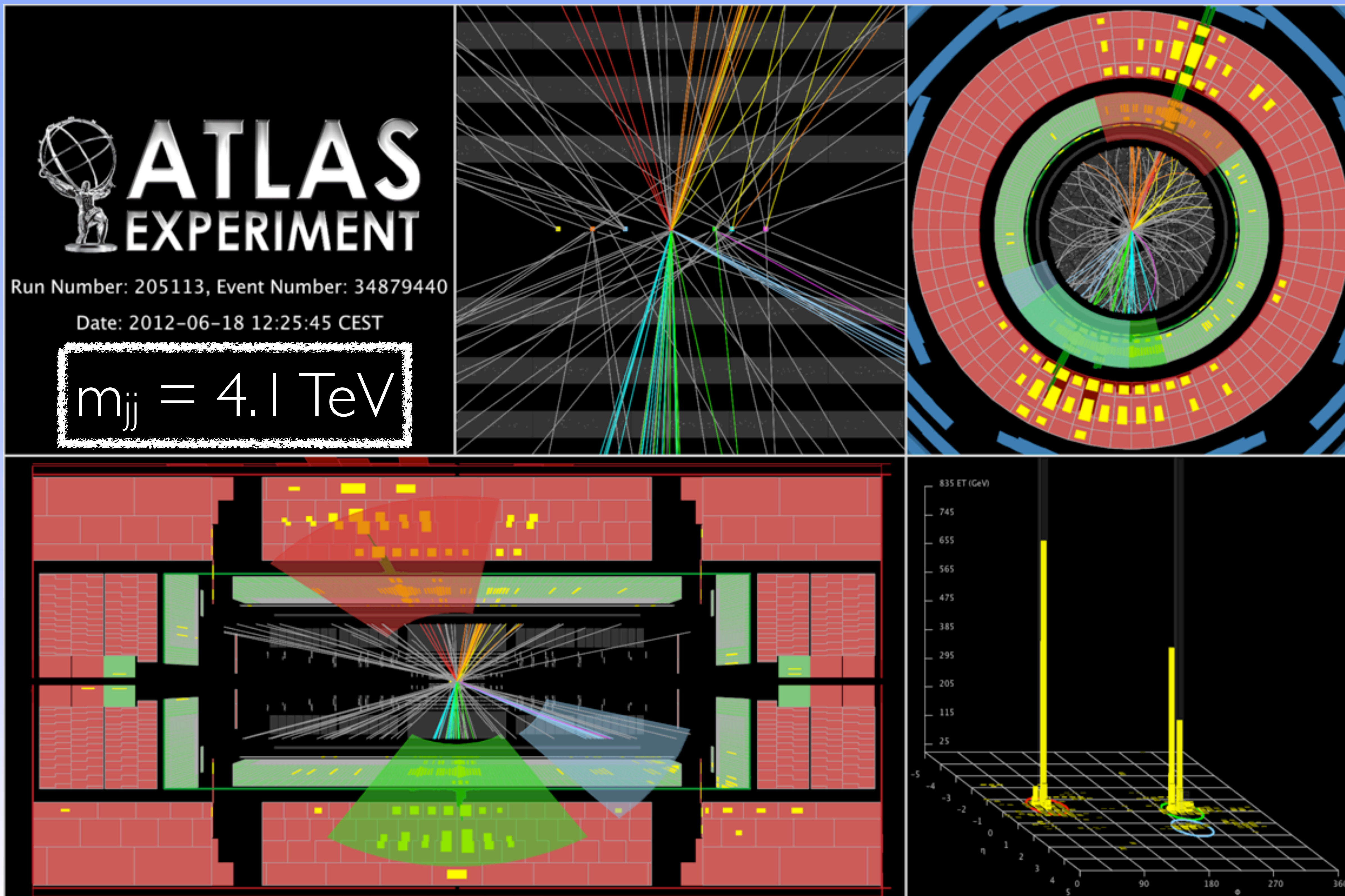
Channel	Prior	Exp. limit [TeV]	Obs. limit [TeV]
ee	$1/M_S^4$	2.88	2.73
	$1/M_S^8$	2.72	2.62
$\mu\mu$	$1/M_S^4$	2.83	2.83
	$1/M_S^8$	2.61	2.61
$ee+\mu\mu$	$1/M_S^4$	3.16	3.00
	$1/M_S^8$	2.96	2.85
$ee+\mu\mu+\gamma\gamma$	$1/M_S^4$	3.43	3.22
	$1/M_S^8$	3.27	3.12



Dijet
Mass and
Angular Distributions

Dijet Analysis

"At the LHC, collisions with the largest momentum transfer typically result in final states with two jets of particles with high transverse momentum (pT). The study of these events tests the Standard Model (SM) at the highest energies accessible at the LHC." - 7 TeV Dijet Paper.



Excited Quarks

If quarks are composite, the observation of excited states is also expected.

Dijet final state appears as a resonance, but has a large background from the SM. However the isotropic production and decay of the excited state can enhance a given search.

Quantum Black Holes

Possible only in very limited region of parameter space. However, may be visible at the LHC if higher dimensional quantum gravity scale is low.

Significant change in two particle final states expected at onset of quantum gravity, dominated by QCD jets.

String Resonances

Possible in scenarios with low scale strings, and large extra dimensions.

Given this, amplitudes can almost completely be determined, and leads to dijet resonance at the string scale M_S.

Colour-Octets

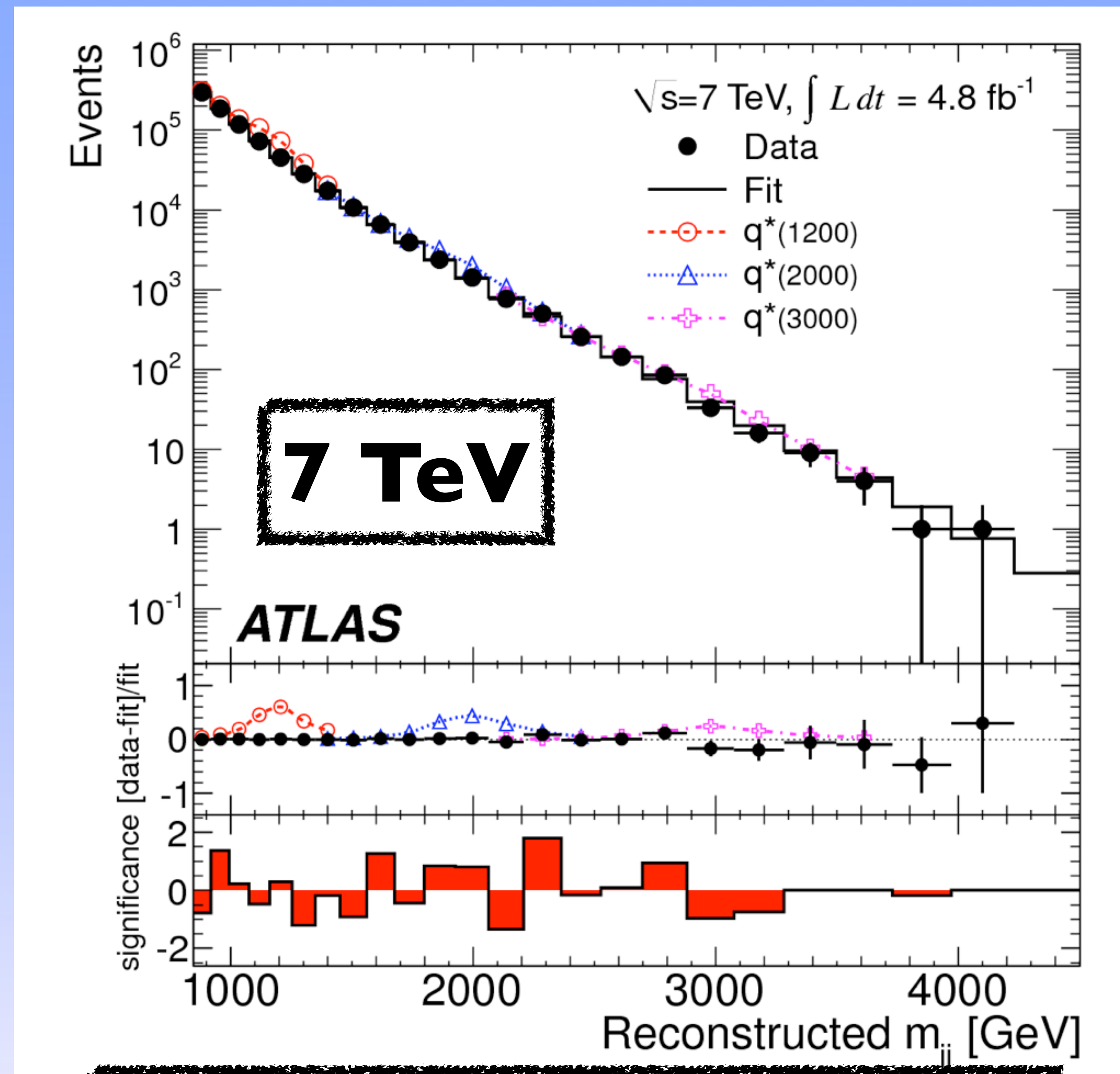
Colour-Octet scalars that are $SU(2)_L$ singlets can arise in techni-colour, and universal extra dimension models.

Dominant branching ratio to dijets, simple signal topology.

As well as other theories already described: W′, CI, etc...

Dijet Analysis: m_{jj} Spectrum

The m_{jj} spectrum is used to search for new resonances. The SM dijet background is expected to have a very smooth and predictable shape, therefore a dijet function is fitted directly to data to estimate the total background, making any deviation from this due to new physics, easily visible.



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

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

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Dijet Analysis: m_{jj} Spectrum

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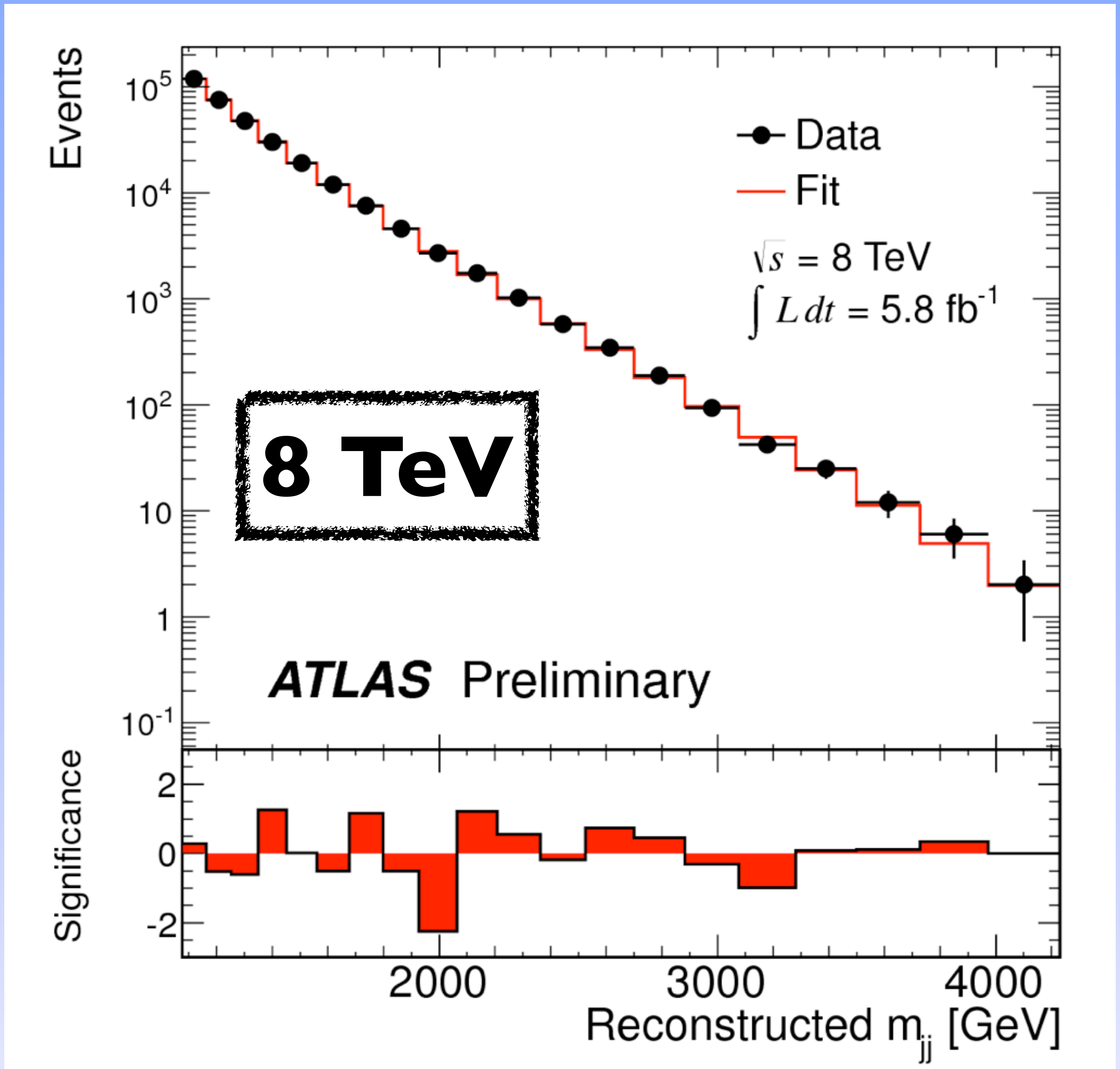
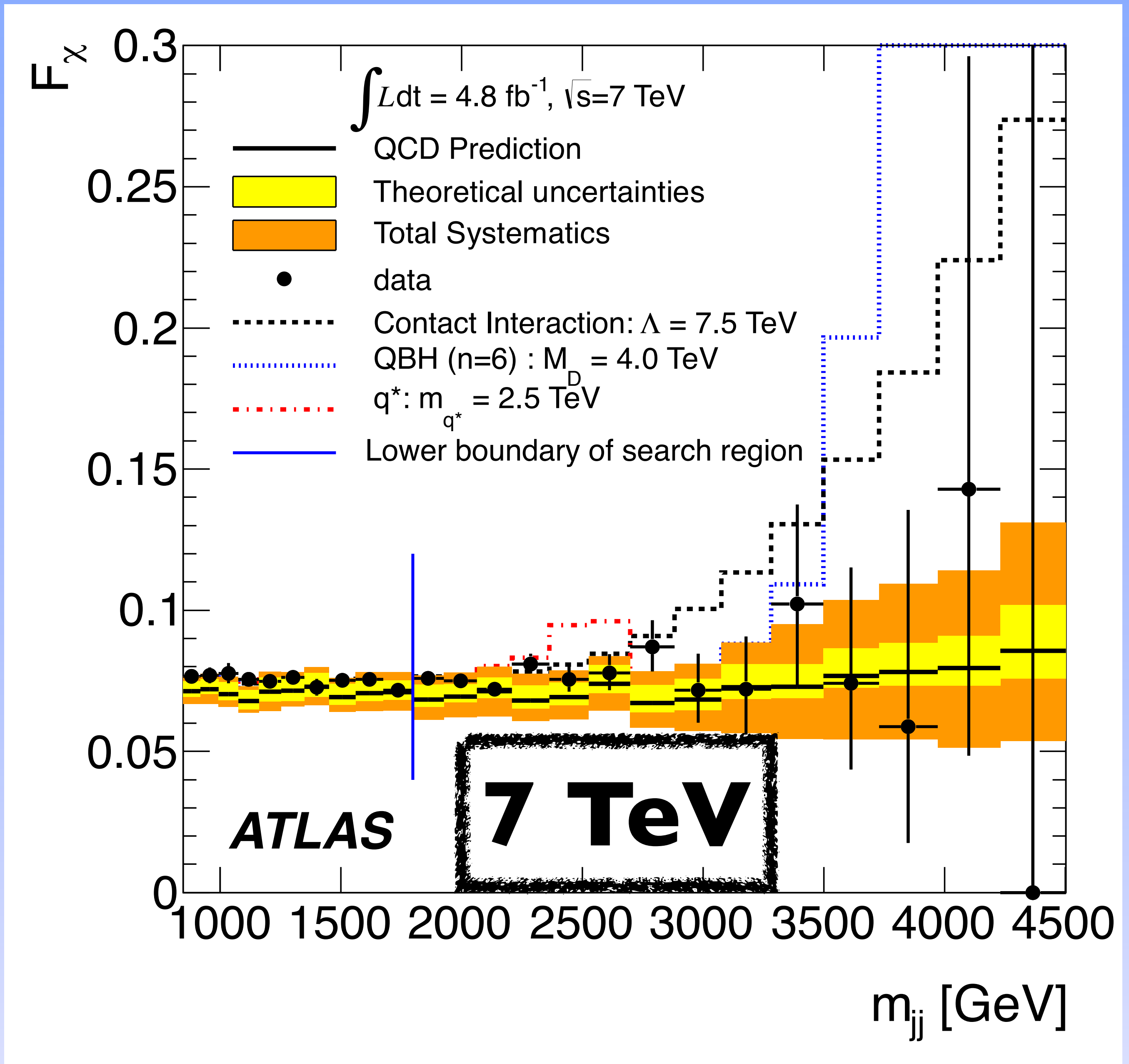


$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x}$$

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

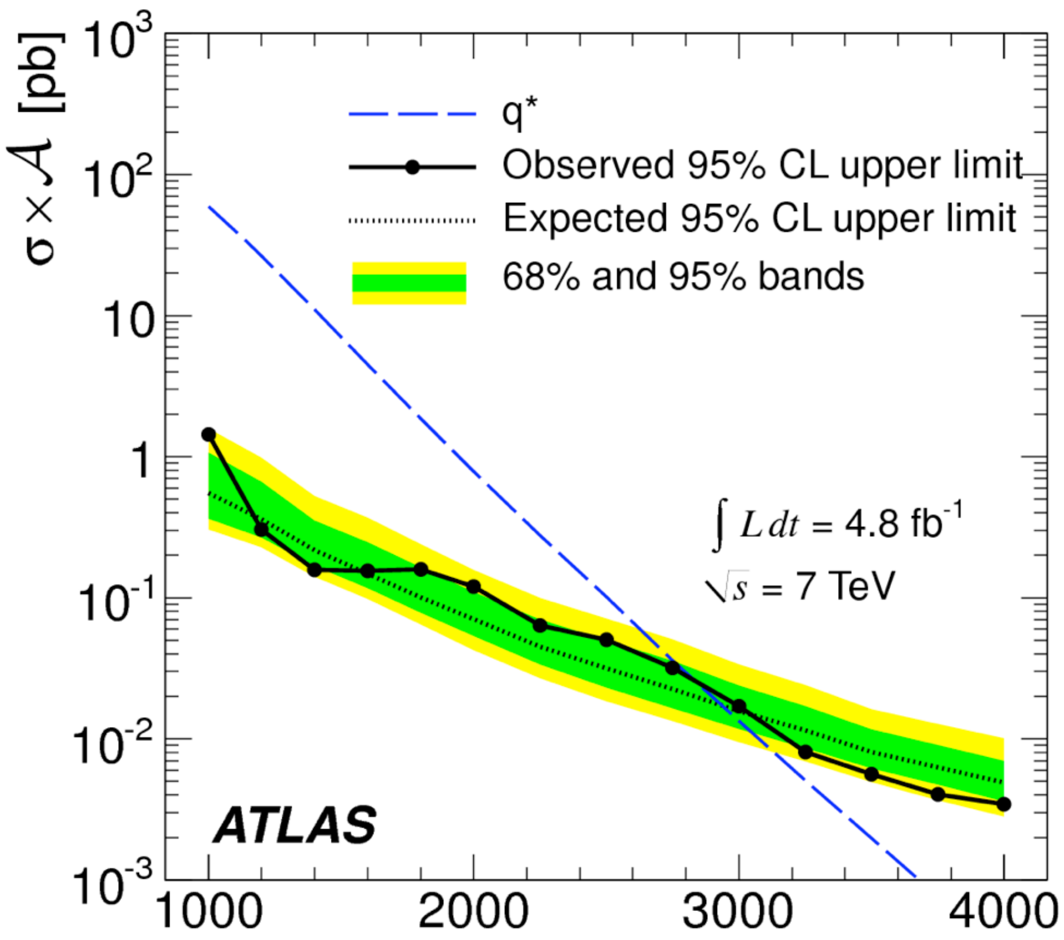
Dijet Analysis: Angular Distribution

The angular distribution of dijets is used to look for non-resonant excesses that would be washed out by the dijet fit. Because the fit is not used, the QCD dijet background is estimated by MC generated with Pythia 6 and corrected with NLOJET++.

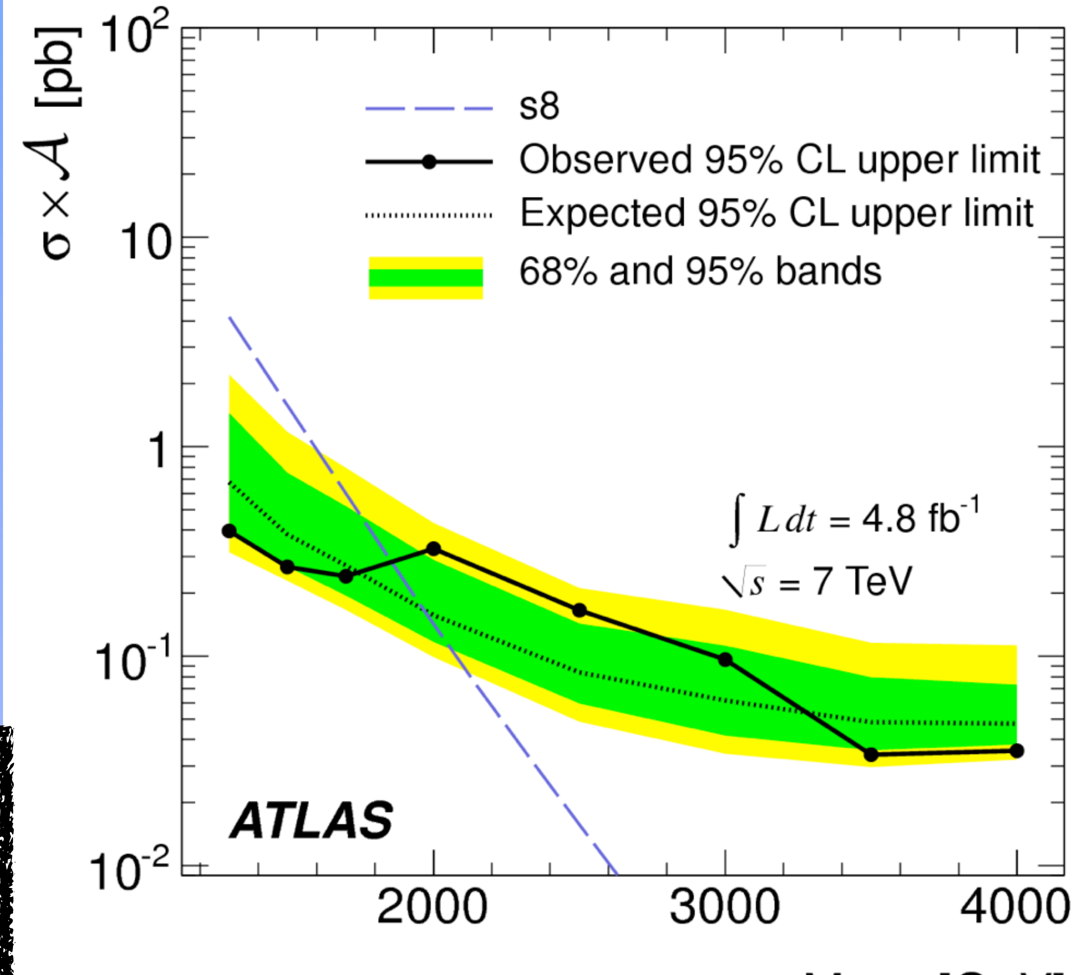


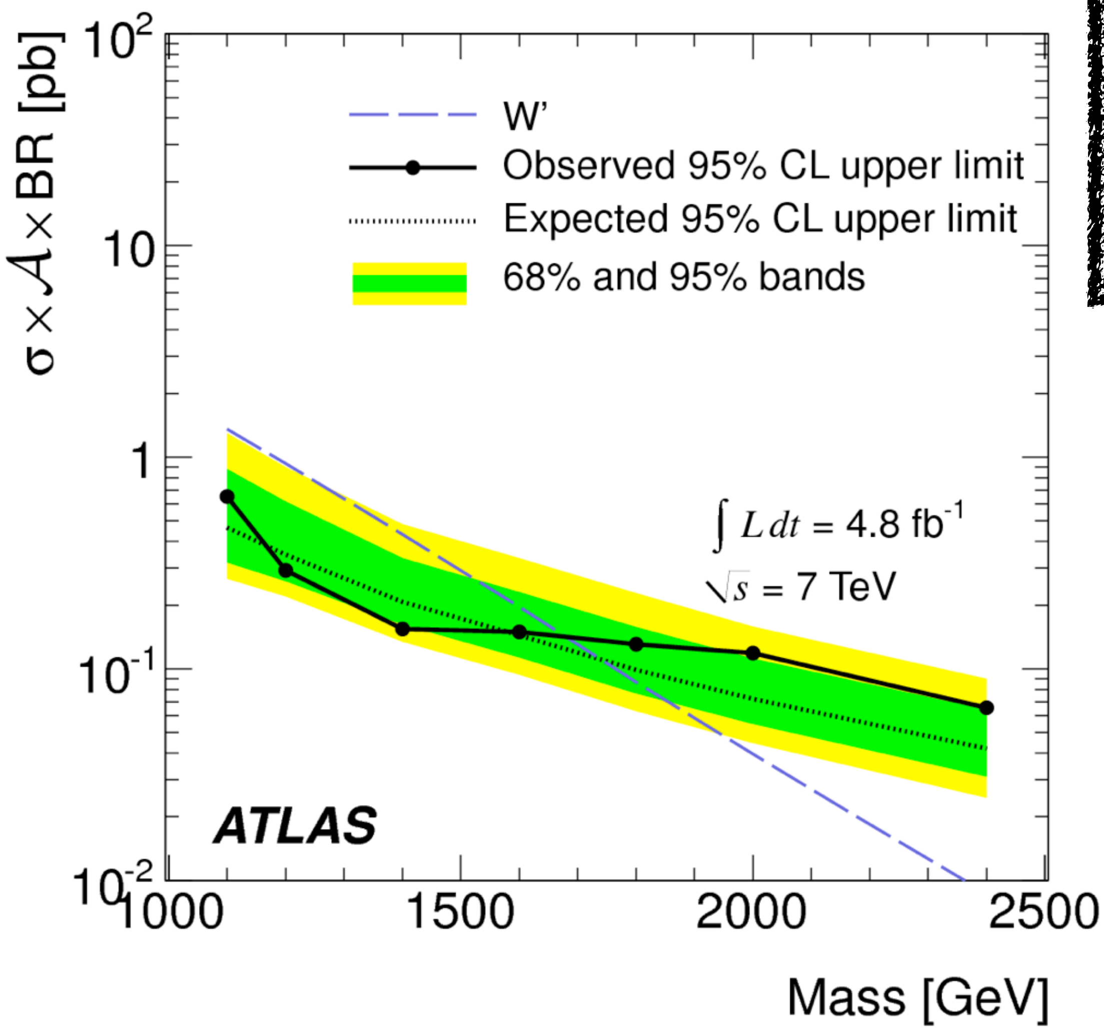
$$\chi \equiv \exp(|y_1 - y_2|) = \exp(2|y^*|).$$

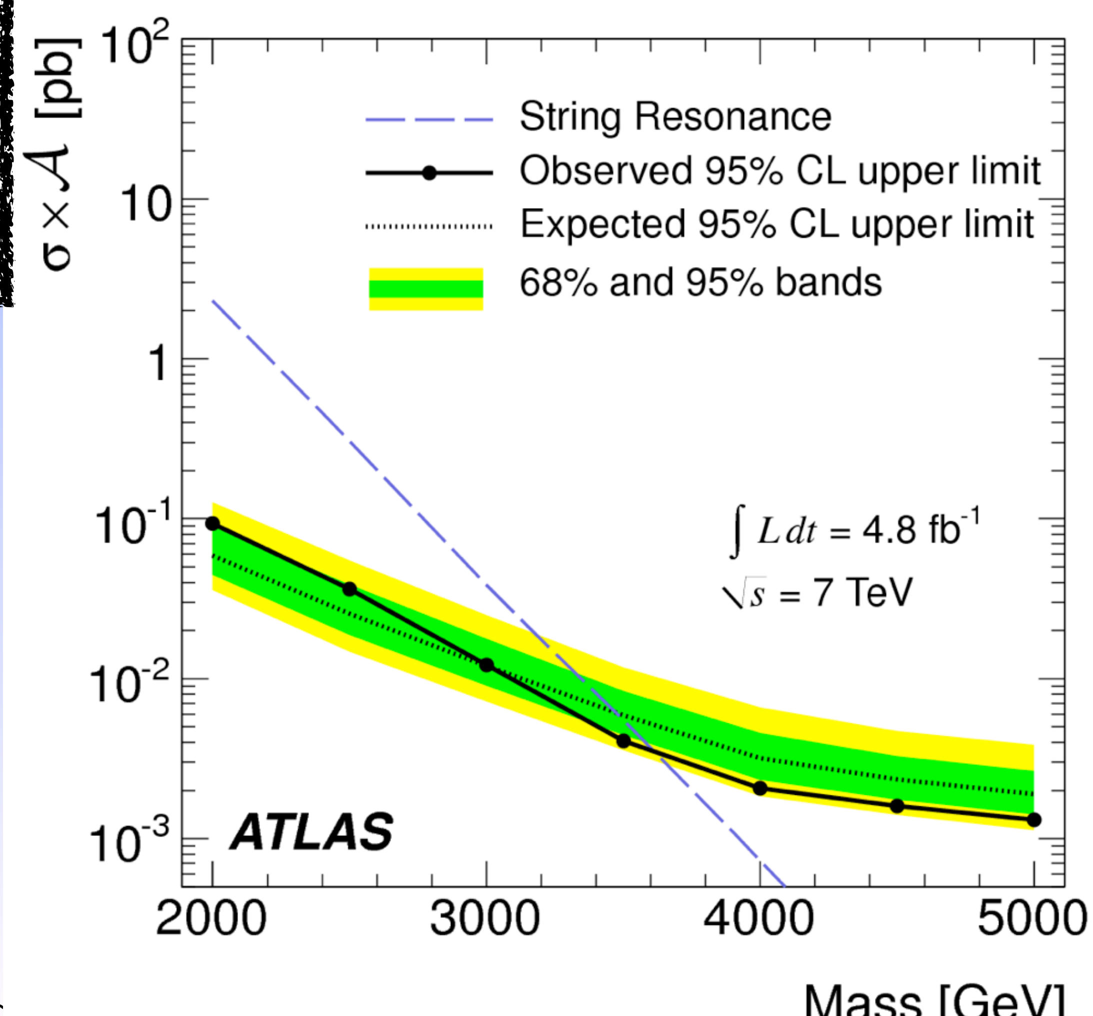
$$F_\chi(m_{jj}) \equiv \frac{\mathrm{d}N_{\mathrm{central}}/\mathrm{d}m_{jj}}{\mathrm{d}N_{\mathrm{total}}/\mathrm{d}m_{jj}},$$



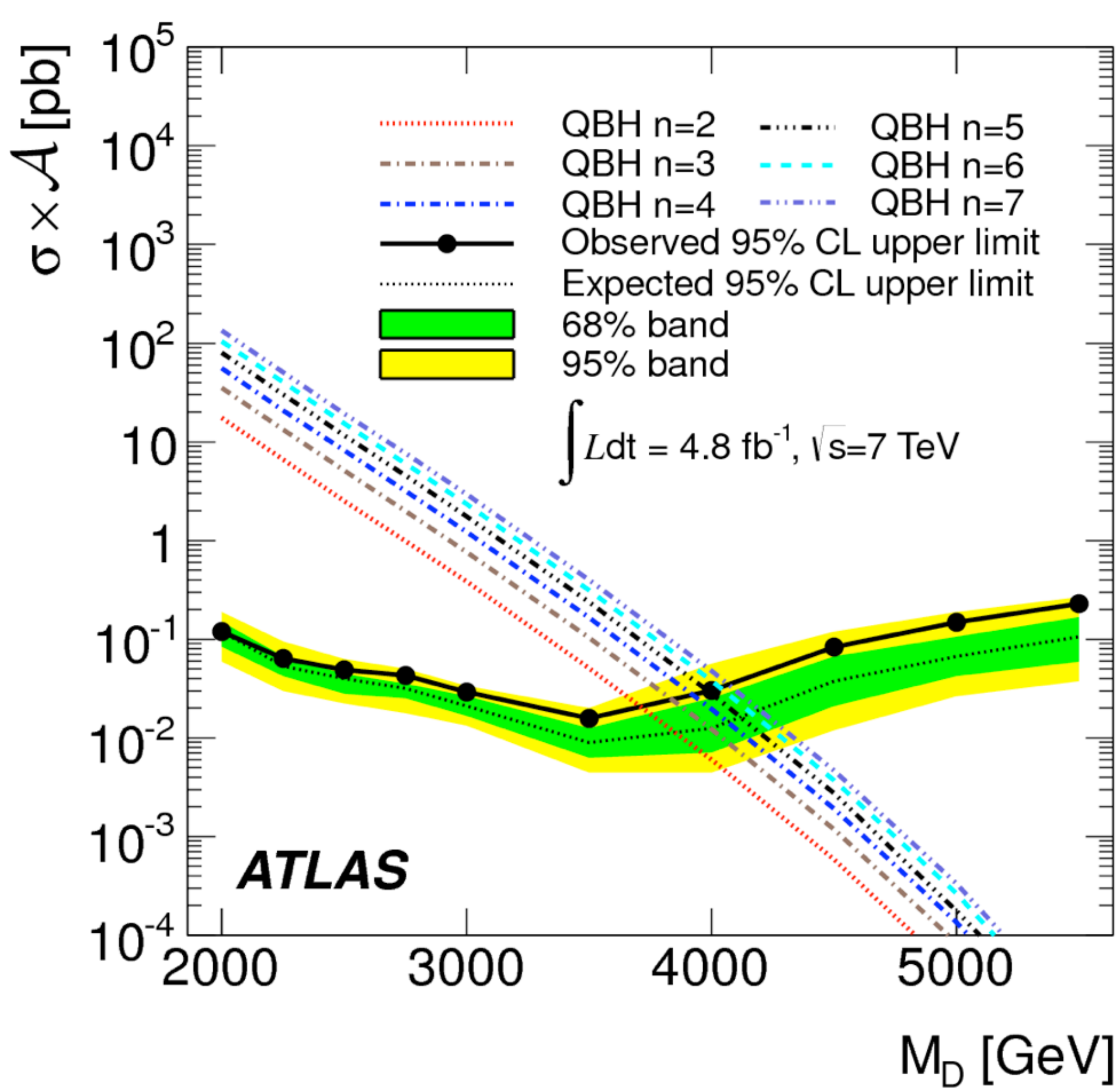
Dijet Limits @ 7 TeV







Dijet Limits @ 7 TeV



Model and Analysis Strategy	95% CL Limits [TeV] Expected	Observed
Excited quark, mass of q^*		
Resonance in m_{jj}	2.94	2.83
Resonance in $F_\chi(m_{jj})$	2.85	2.75
Colour octet scalar, mass of s8		
Resonance in m_{jj}	1.97	1.86
Heavy W boson, mass of W'		
Resonance in m_{jj}	1.74	1.68
String resonances, scale of SR		
Resonance in m_{jj}	3.47	3.61
Quantum Black Hole for $n = 6$, M_D		
$F_\chi(m_{jj})$	4.16	4.03
χ , $m_{jj} > 2.6$ TeV	4.20	4.11
Contact interaction, Λ, destructive interference		
$F_\chi(m_{jj})$	7.7	7.6
χ , $m_{jj} > 2.6$ TeV	7.7	7.6

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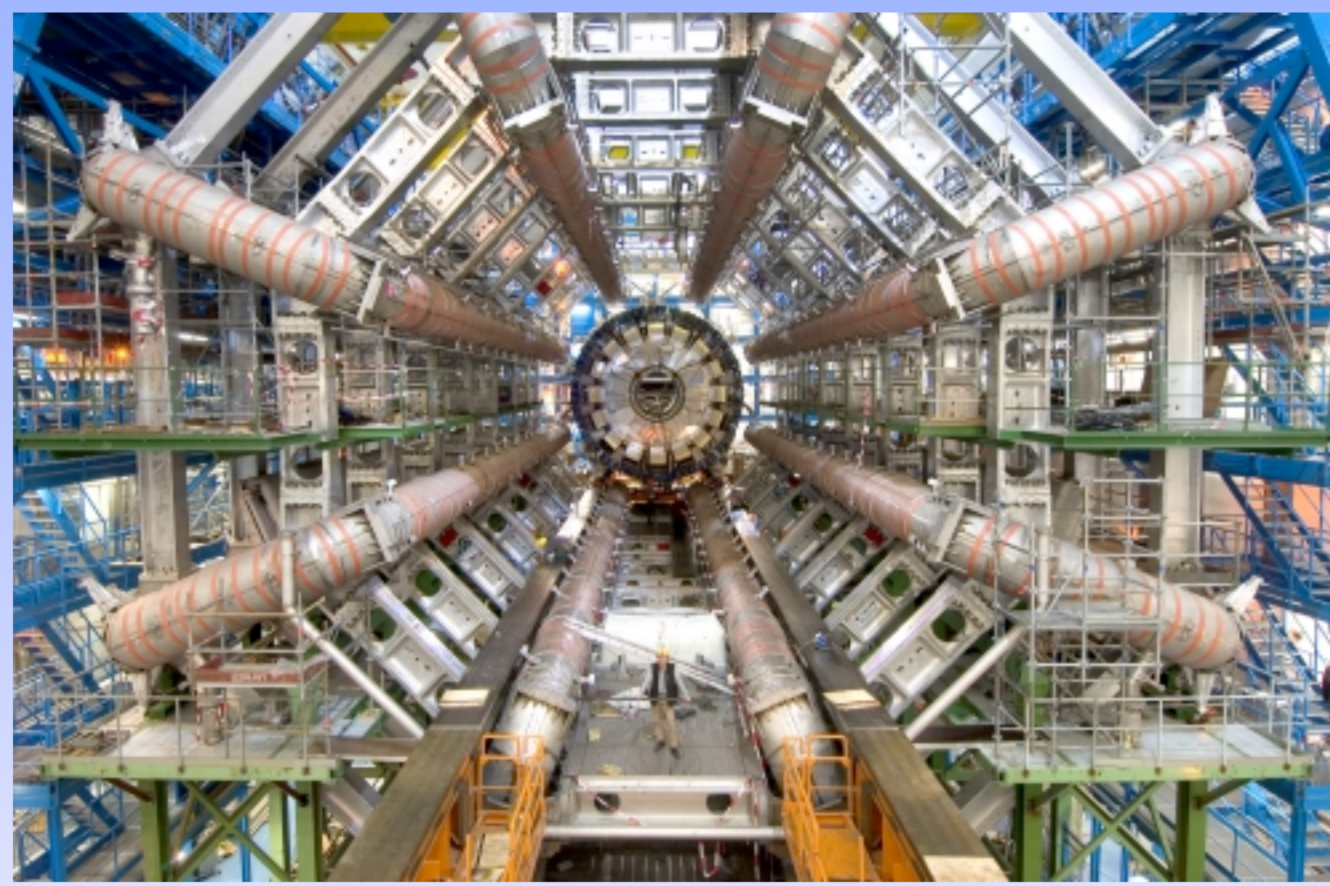
Summary

Lots of exciting new results from ATLAS!

I have only shown a small fraction of ATLAS Exotics results here, see other talks today for more.



Data is still coming in, +20 fb^{-1} @ 8 TeV before the end of the year, meaning large discovery potential!

Thanks for Listening!

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Questions

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Backup

Experimental Papers used in this Talk

Z′/G* → dilepton @ 8 TeV: Link

Dijet Resonances @ 8 TeV: Link

W′ → lepton+ν @ 7 TeV: Link

Z′/G* → dilepton @ 7 TeV: Link

G* → diphoton @ 7 TeV: Link

G*/CI → dilepton @ 7 TeV: Link

Dijet Resonances @ 7 TeV: Link

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