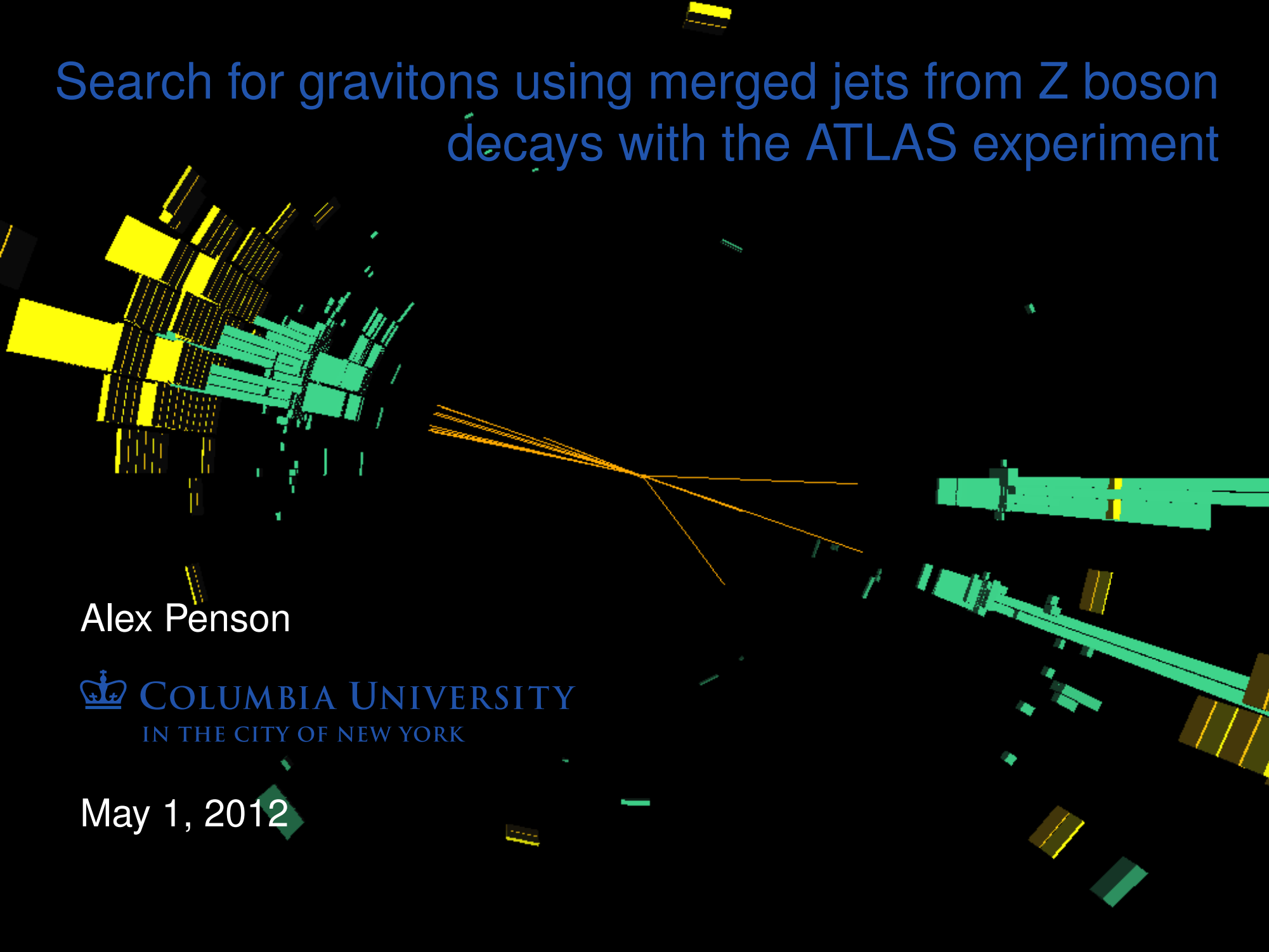
Search for gravitons using merged jets from Z boson decays with the ATLAS experiment



Alex Penson

Columbia University
IN THE CITY OF NEW YORK

May 1, 2012

Outline

Gravitons and Warped Extra Dimensions

Experimental Apparatus

Background Monte Carlo Samples

Object and Event Selection

Background Estimation

Signal Region Data

Statistical Analysis

Results

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Warped Extra Dimensions

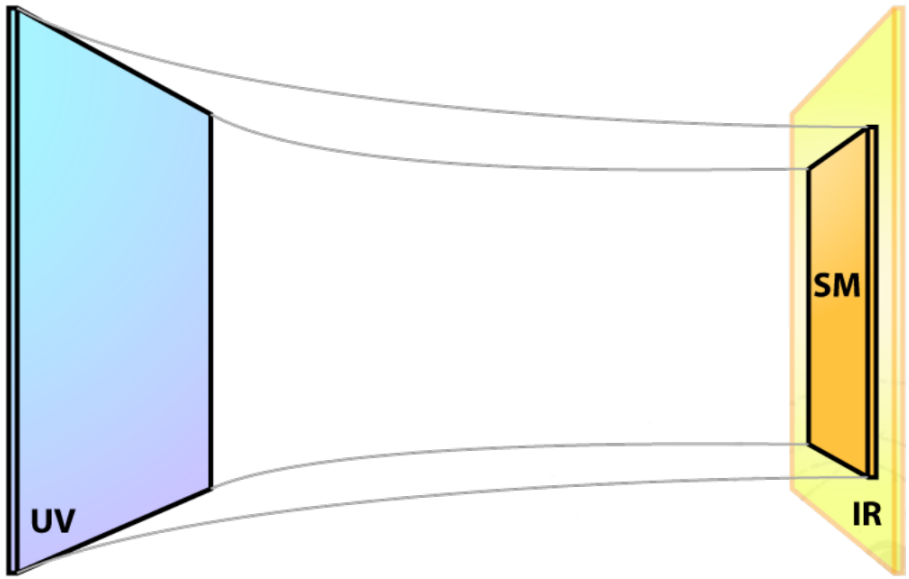
A prominent way of addressing the hierarchy problem of the Standard Model involves **five-dimensional** spacetime, warped by the metric:

$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

where $0 \leq y \leq R\pi$ is the extra dimension, and k^{-1} is its curvature

In the **RS1 model** (the original Randall-Sundrum model):

the graviton is concentrated here



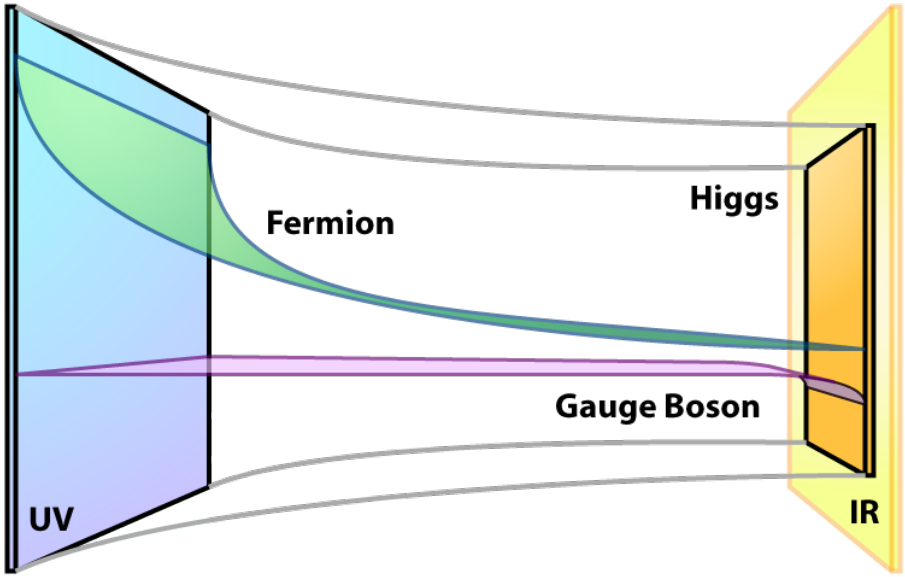
the entire SM is localized here

where gravity is weak

Massive excited graviton modes (G^*) are a defining feature

In the **bulk RS model**:

SM particles propagate in the 5D bulk...



...which can explain the wide spectrum of fermion masses

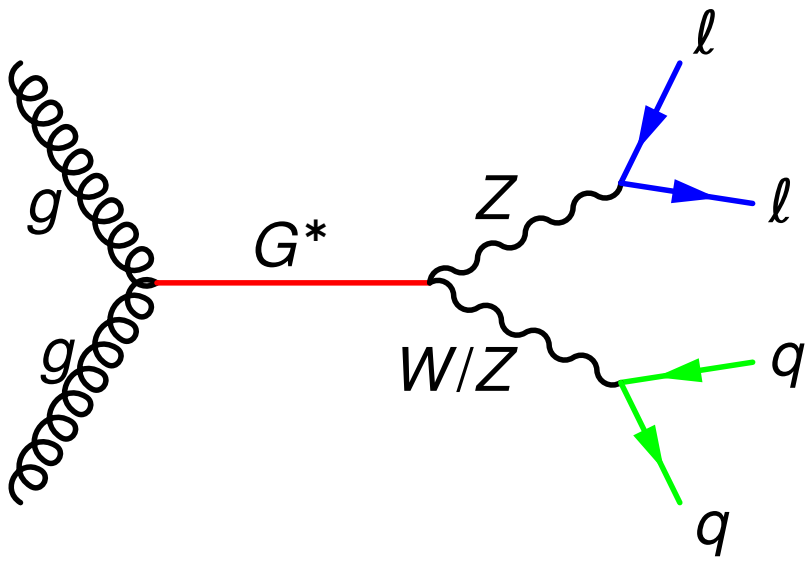
This results in heavy suppression of:

- $qq \rightarrow G^*$ production and
- easily detectable $G^* \rightarrow \ell\ell$ or $\gamma\gamma$ decays

Decays to pairs of heavy particles, $t\bar{t}$, WW, ZZ and perhaps Higgs bosons are preferred

This analysis searches for $G^* \rightarrow ZZ$

$G^* \to ZZ \to \ell\ell qq$ Final State



In this search, one Z decays leptonically and a W or a Z decays hadronically this features:

- larger branching ratio (BR) than fully leptonic decays
- fully reconstructed graviton
- much lower background than all-hadronic decays

Previous diboson resonance searches at the Tevatron

experiment	$\mathscr{L}_{\text{int}}$ [fb^{-1}]	process	mass exclusion [GeV]
D0	5.4	$G^* \to WW$	300 – 754
D0	5.4	$W' \to WZ$	180 – 690
CDF	2.9	$G^* \to ZZ$	300 – 491

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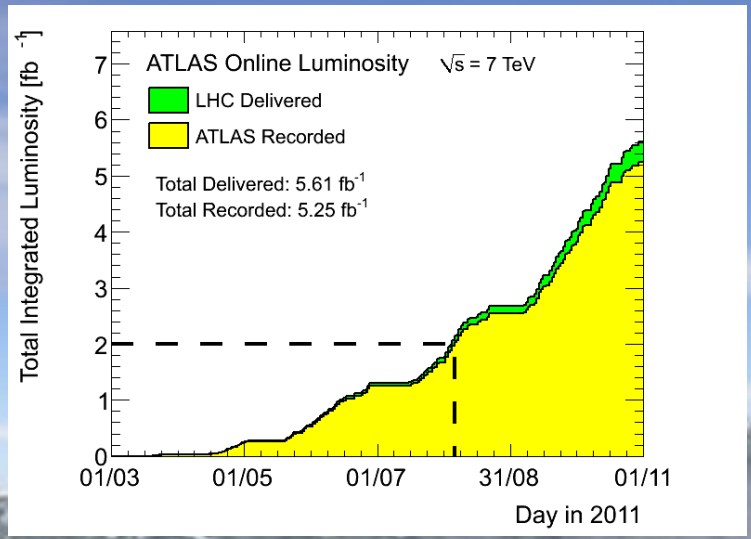
The Large Hadron Collider

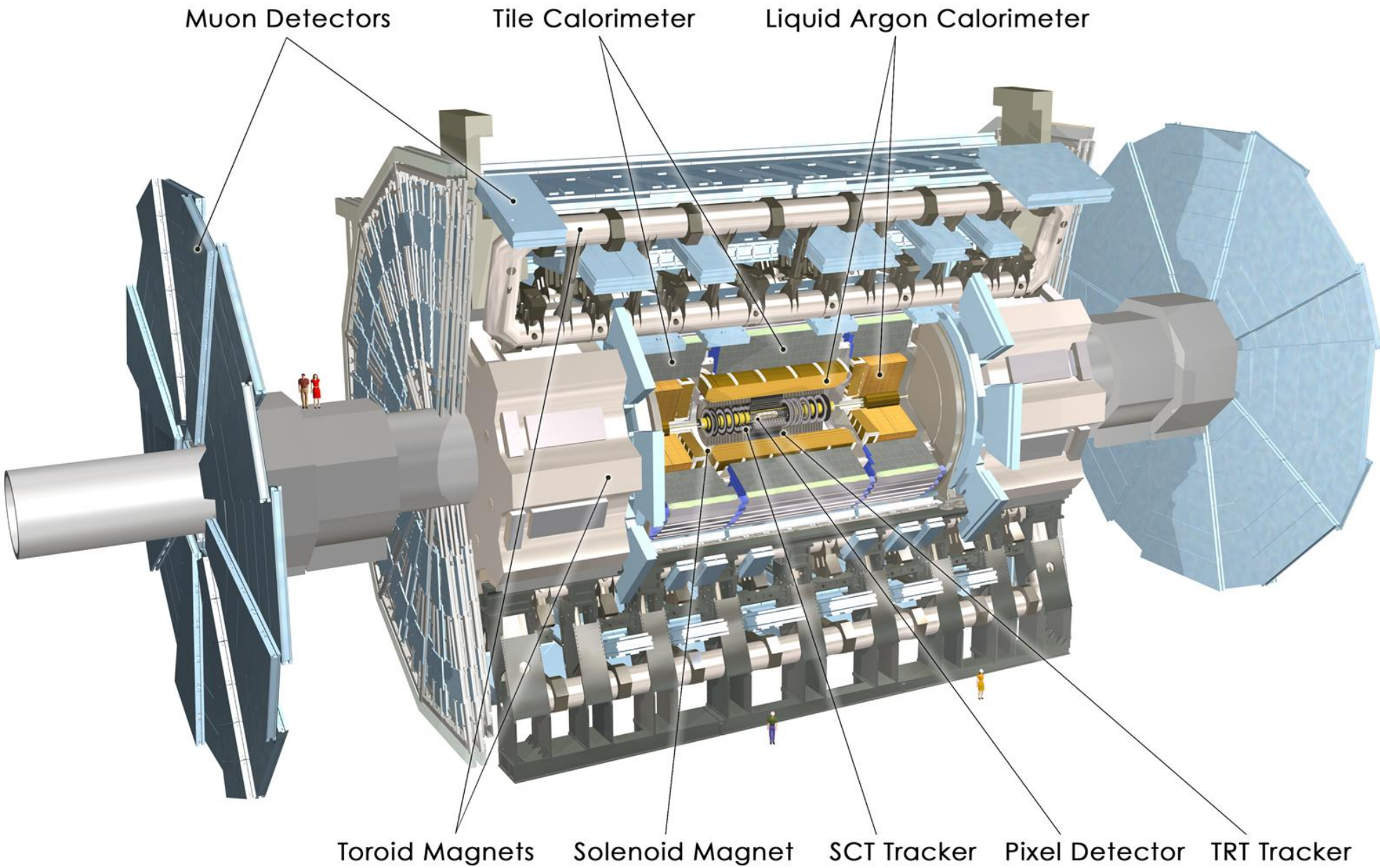
LHC delivered more than 5 fb^{-1} of 7 TeV data to ATLAS in 2011

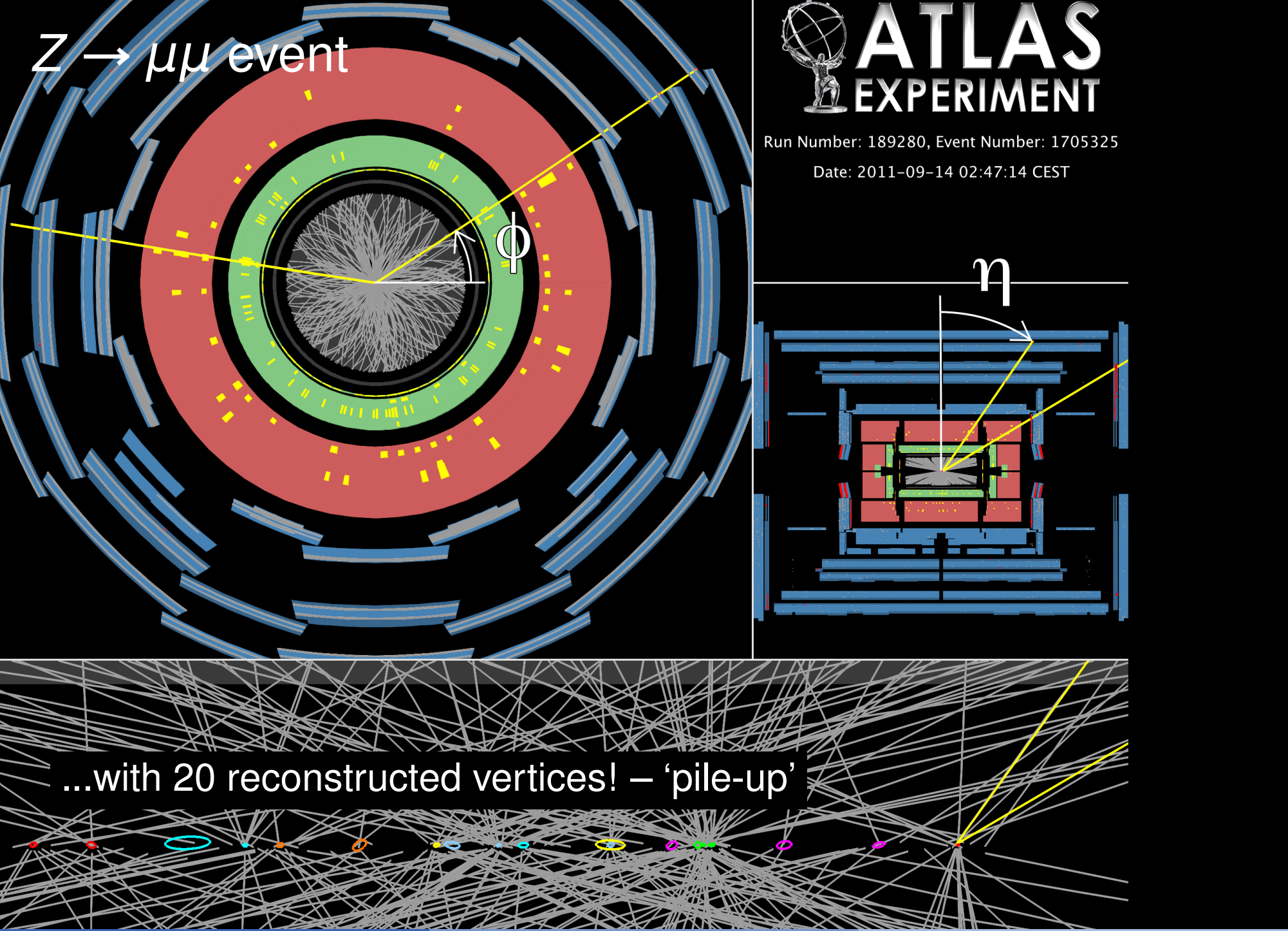
This analysis uses 2 fb^{-1} of data (Apr – Aug 2011)



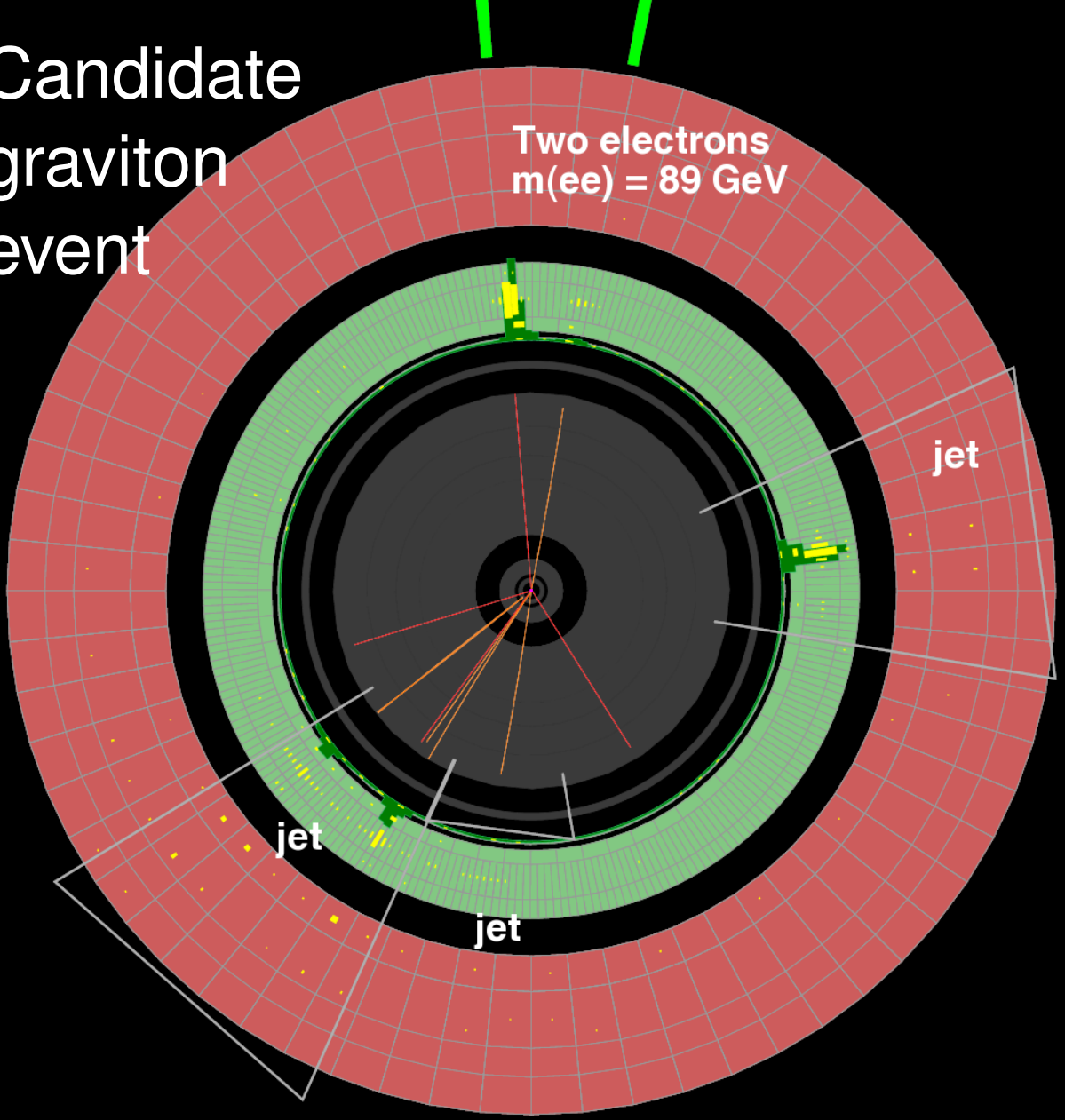
The LHC has already delivered almost 1 fb^{-1} at 8 TeV in 2012!

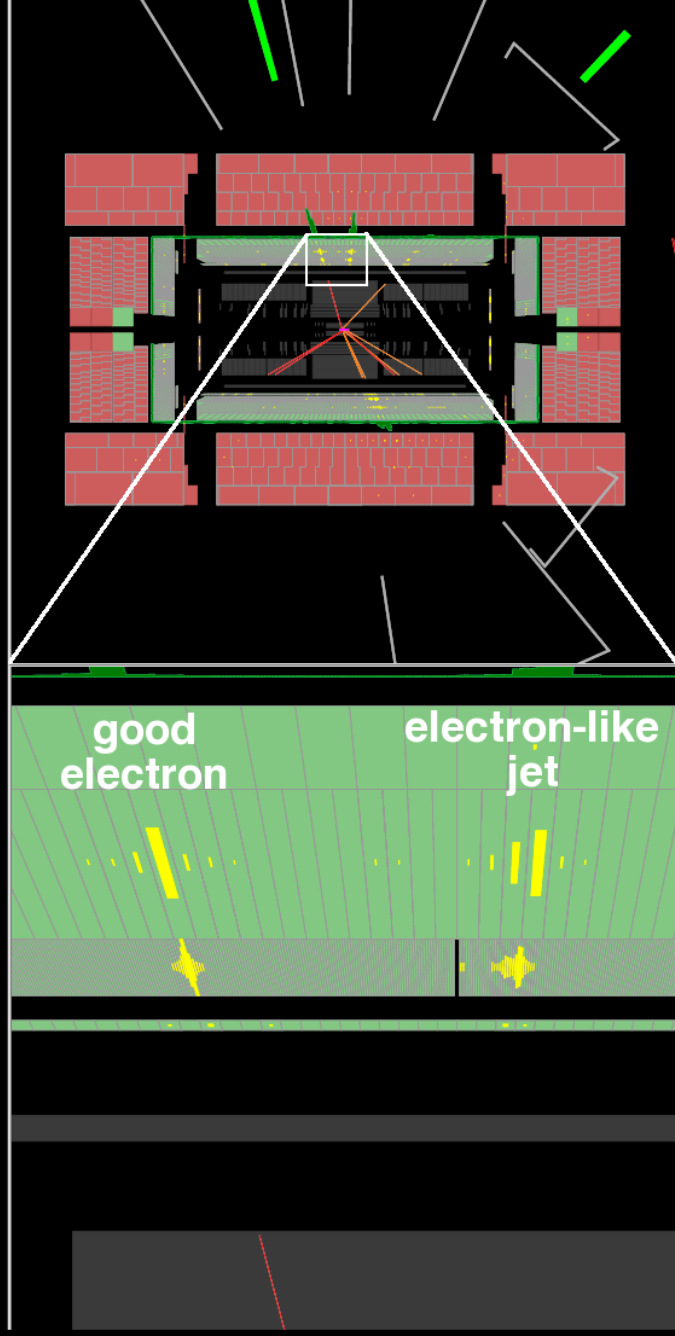
The ATLAS Detector




$Z \rightarrow \mu\mu$ event
ATLAS
EXPERIMENT
Run Number: 189280, Event Number: 1705325
Date: 2011-09-14 02:47:14 CEST
ϕ
η
...with 20 reconstructed vertices! – 'pile-up'

Candidate graviton event



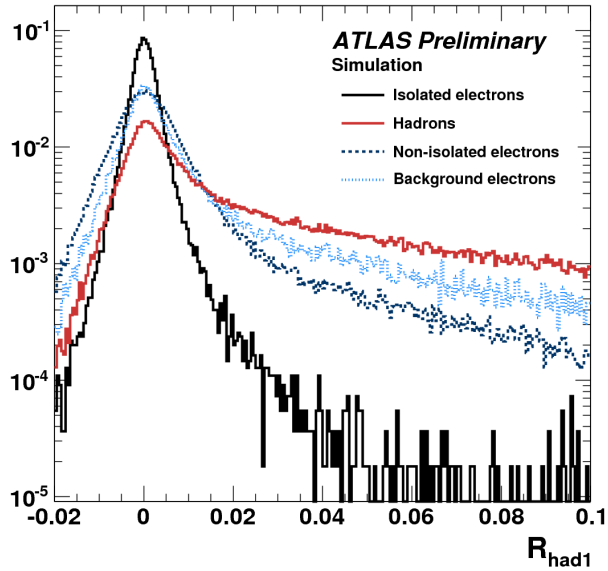


Electron identification

cut values depend on η and p_T

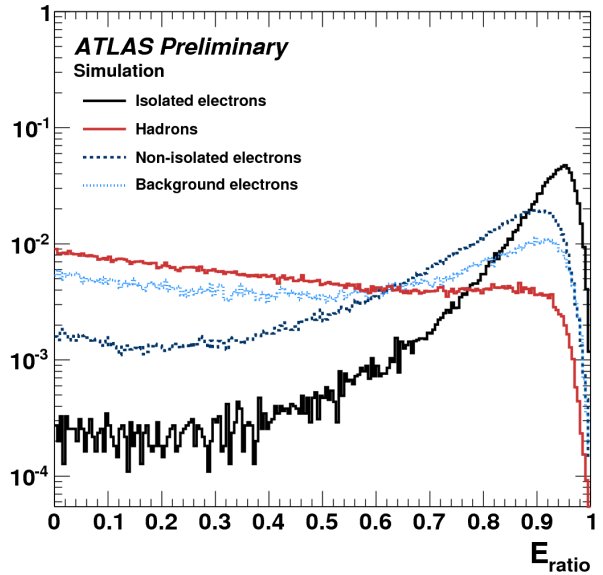
Loose cuts:

- **Hadronic leakage →**
- Ratio in η of cell energies in 3×7 versus 7×7 cells
- Lateral width of the shower



Medium cuts:

- Loose cuts
- shower width in the first layer
- **difference between the largest two energy deposits / their sum →**
- Track quality
- Track matching



'background electrons' from photon

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Background Monte Carlo Samples

Z+jets production represents around 90% of the background

Production of top quarks, dibosons, W+jets and multijets is also estimated

Monte Carlo

Several MC generators are used to simulate physics processes

Z+jets:	ALPGEN	RS1 model:	PYTHIA
	SHERPA	bulk RS model:	CALCHEP

MC events are passed through a full detector simulation and reconstructed with the same software as data

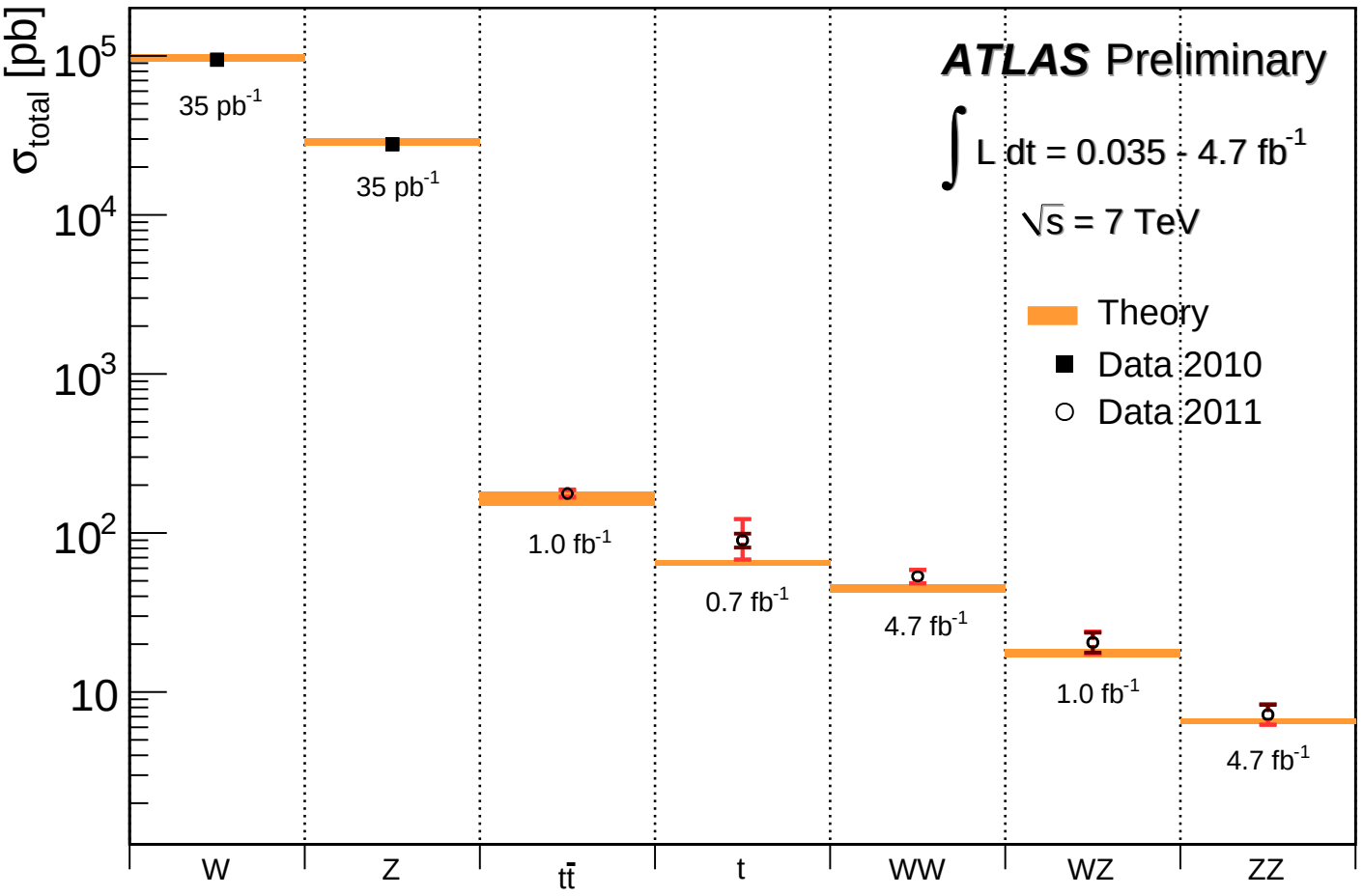
Correction factors are applied to MC events, accounting for pile-up, trigger and reconstruction efficiencies

MC events are scaled by:

- the luminosity and
- the cross section of the process...

Cross section measurements at ATLAS

Cross sections of Standard Model electroweak processes have been measured at ATLAS, in excellent agreement with predictions



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Electrons and Muons $Z \rightarrow \ell\ell$ Preselection

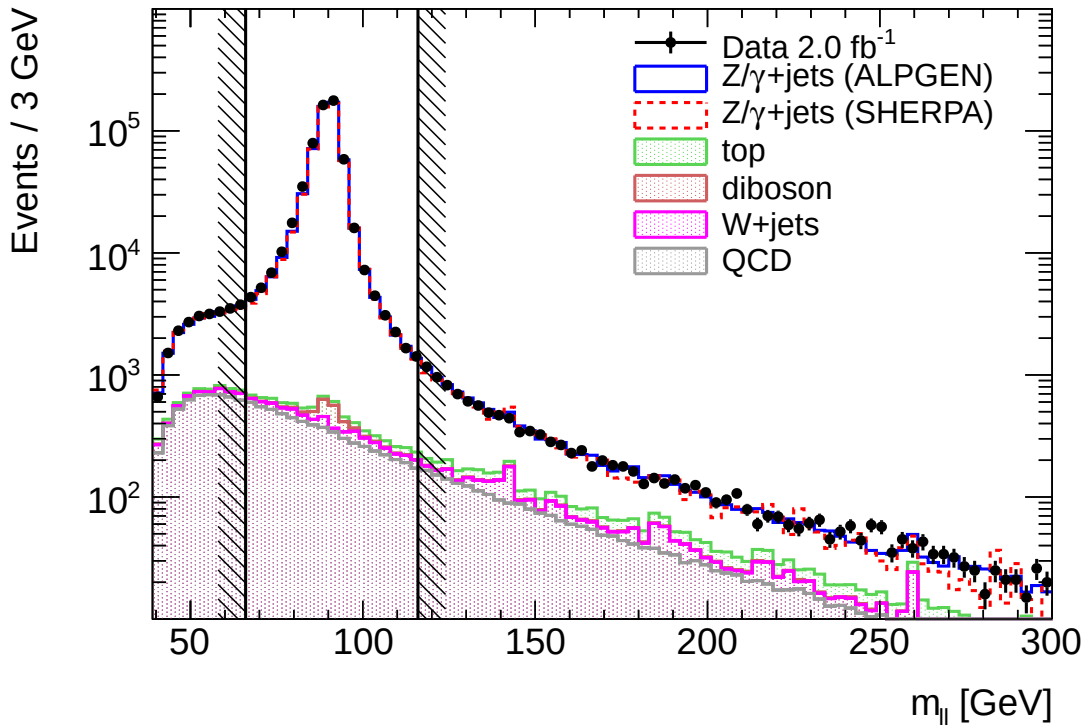
Electrons are selected based on shower shape and cluster/track matching and rejected in poorly understood regions of the calorimeter

Muons are selected based on track quality

$p_T > 20$ GeV (both electrons and muons)

An isolation requirement is used to reject leptons within jets

- two electrons **or** two oppositely-charged muons
- dilepton mass consistent with Z boson
  ($|m_{\ell\ell} - 91\ GeV| < 25$ GeV)
- no other electrons or muons



Jets

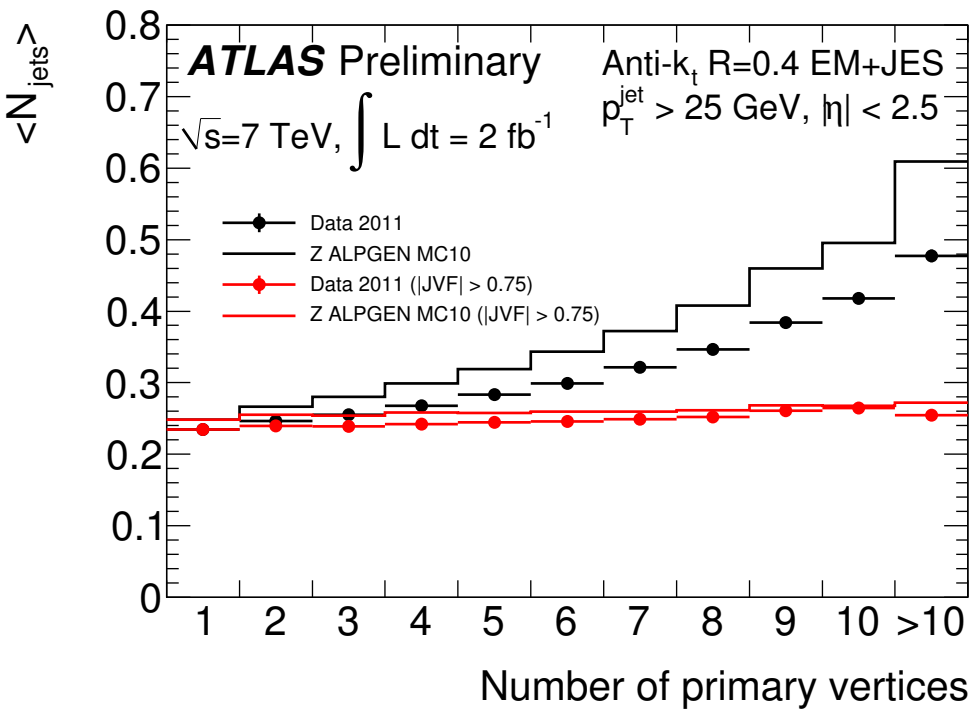
Jets are reconstructed using the anti-k_t algorithm with cone size 0.4

Jet energies are calibrated to the hadronic scale

Standard quality criteria based on the time and pulse shape of energy deposits are applied

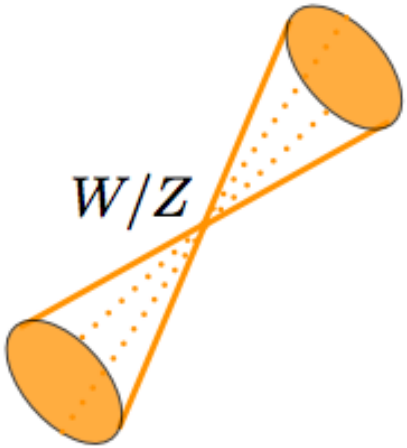
$p_T > 25$ GeV, $|\eta| < 2.8$

Jet vertex fraction JVF
- the energy fraction associated with the leading primary vertex - is used to reject pile-up jets: |JVF| > 0.75

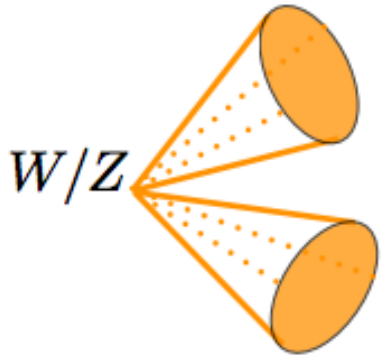


Jet Merging

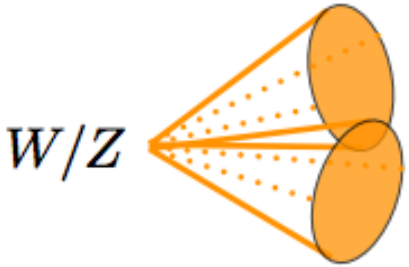
As the transverse momentum of hadronic W and Z bosons increases, the decay products will become increasingly collimated



$p_T(W/Z) \sim 0$



$p_T(W/Z) \sim m(W/Z)$



$p_T(W/Z) \gg m(W/Z)$

The quark separation $\Delta R \sim \dfrac{2m}{p_T}$

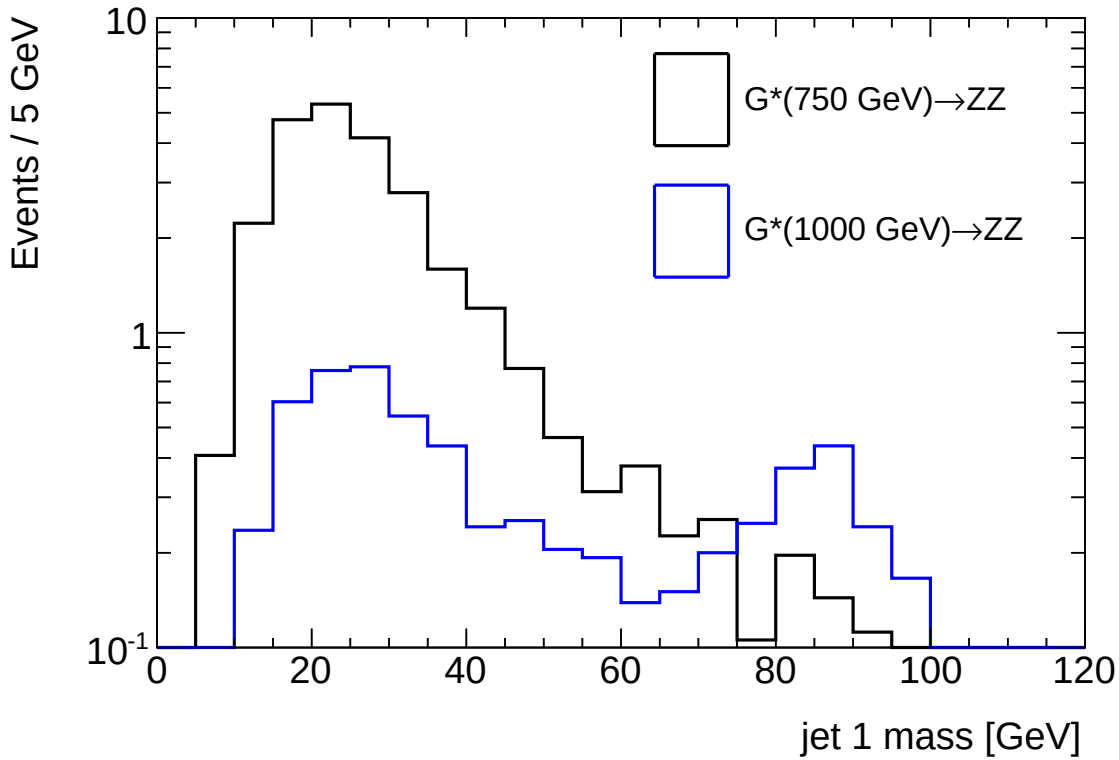
$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$

With a jet cone size of 0.4, 'jet merging' becomes significant when W/Z $p_T \gtrsim 400$ GeV

Jet Mass

The mass of merged jets peaks at the boson mass!

Quark/gluon initiated jets have low mass, peaked at 20 – 25 GeV



The jet mass resolution is around 8 GeV for signal mass
$\sim$ 1 – 1.5 TeV $\Rightarrow$ *W* and *Z* are difficult to distinguish

Jet Mass Scale Uncertainty

It is important to validate the jet mass measurement

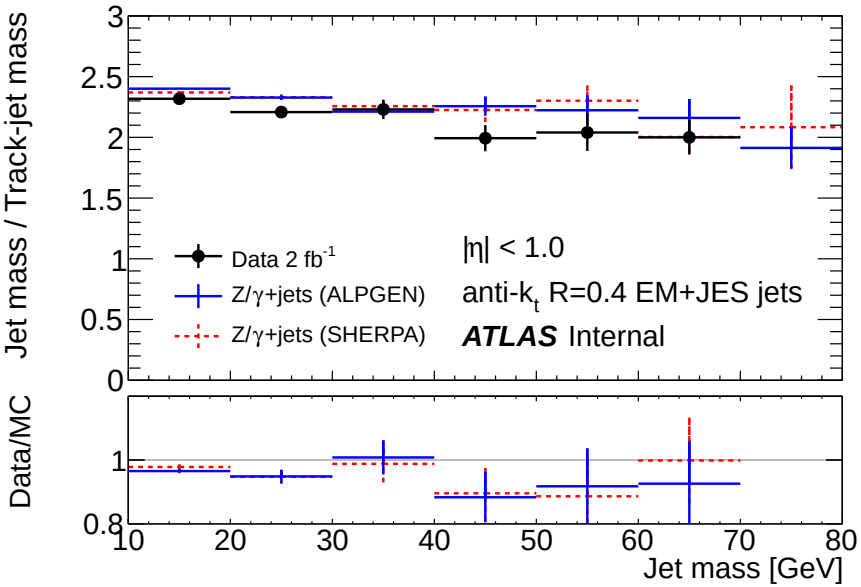
Track-jets are used since they are independent...

but around half of jet energy comes from neutral particles which leave no track!

So the 'double ratio' is used:

$$\frac{\left\langle \frac{m_{\text{jet}}}{m_{\text{track-jet}}} \right\rangle_{\text{data}}}{\left\langle \frac{m_{\text{jet}}}{m_{\text{track-jet}}} \right\rangle_{\text{MC}}} \approx 1$$

The largest deviation from one is taken as JMS uncertainty: $\sim 10\%$



method follows studies with larger jets

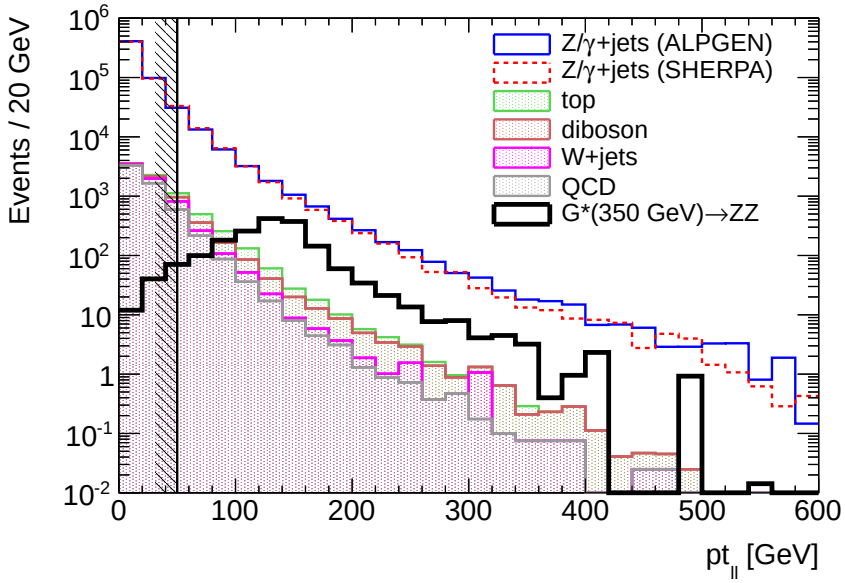
Event Selection

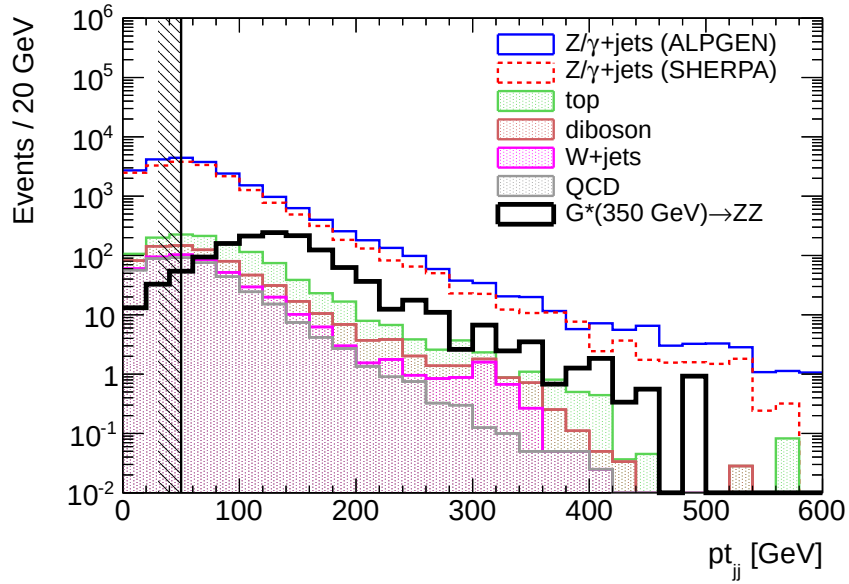
	Signal region
Resolved jets	$65 < m_{jj} < 115$ GeV,
(Low Mass signal)	$p_T^{jj} > 50$ GeV,
$m_{G^*} < 500$ GeV	$p_T^{\ell\ell} > 50$ GeV.
Resolved jets	$65 < m_{jj} < 115$ GeV,
(High Mass signal)	$p_T^{jj} > 200$ GeV,
$m_{G^*} \geq 500$ GeV	$p_T^{\ell\ell} > 200$ GeV,
	veto events in **Merged jet** region.
Merged jet	$m_j > 65$ GeV,
$m_{G^*} \geq 750$ GeV	$p_T^j > 200$ GeV,
	$p_T^{\ell\ell} > 200$ GeV.

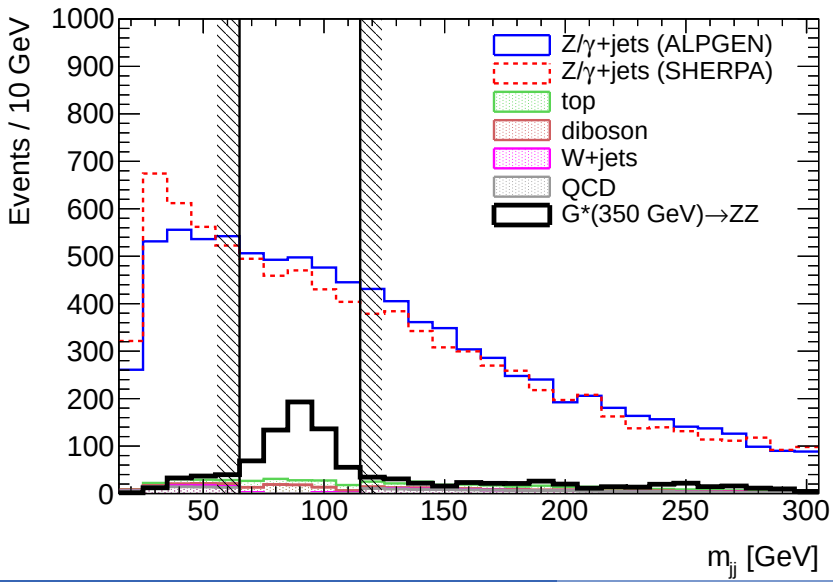
Resolved Jets (Low Mass signal) Region

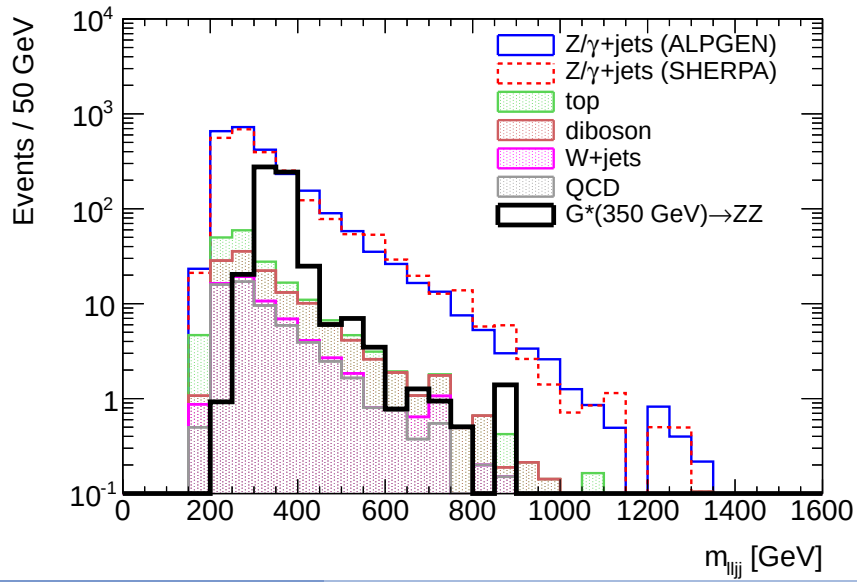
$m_{G^*} < 500$ GeV

no data on plots



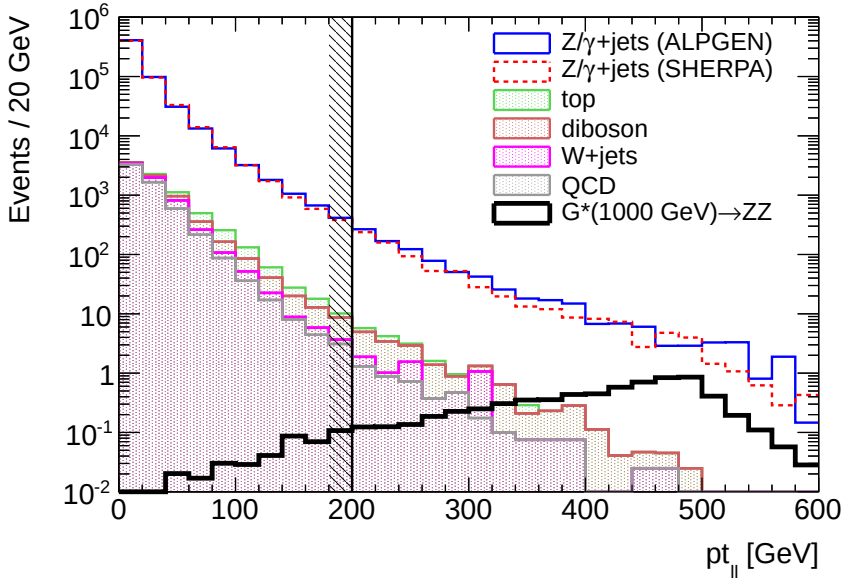


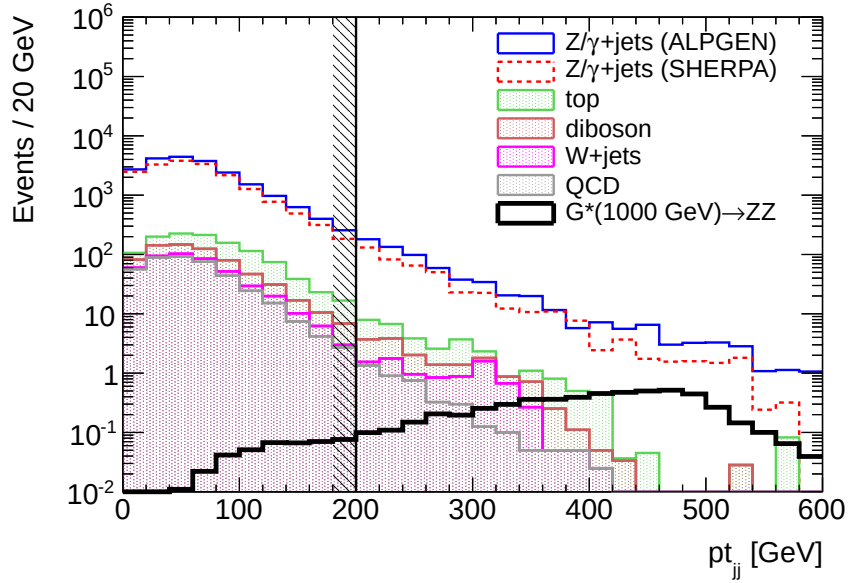


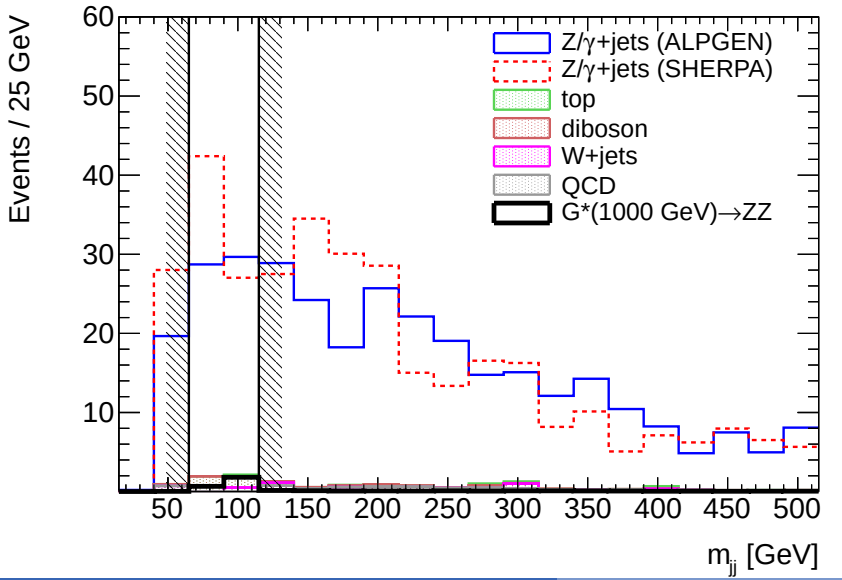


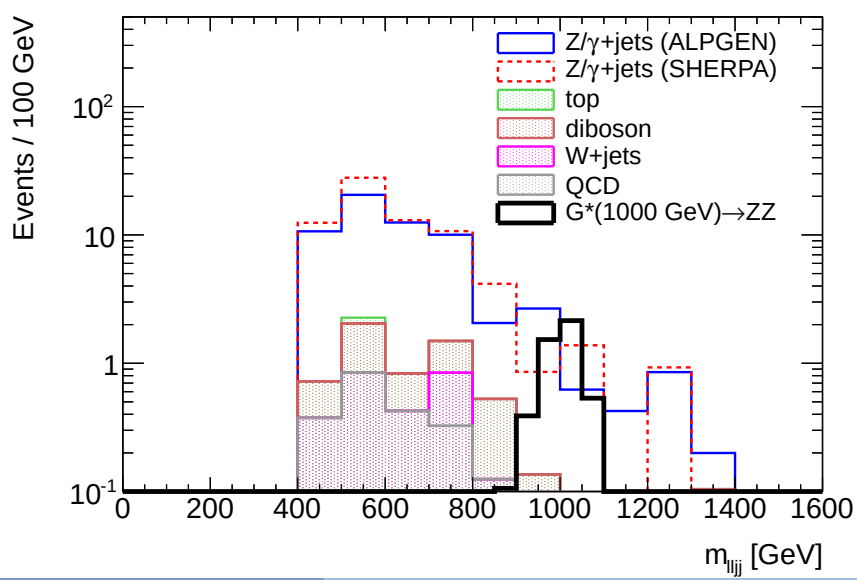
Resolved Jets (High Mass signal) Region

$m_{G^*} \geq 500$ GeV

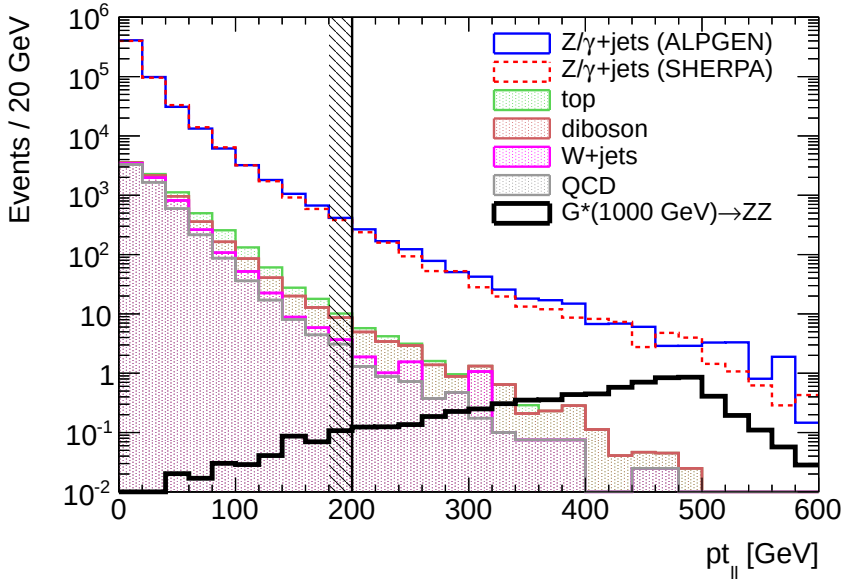


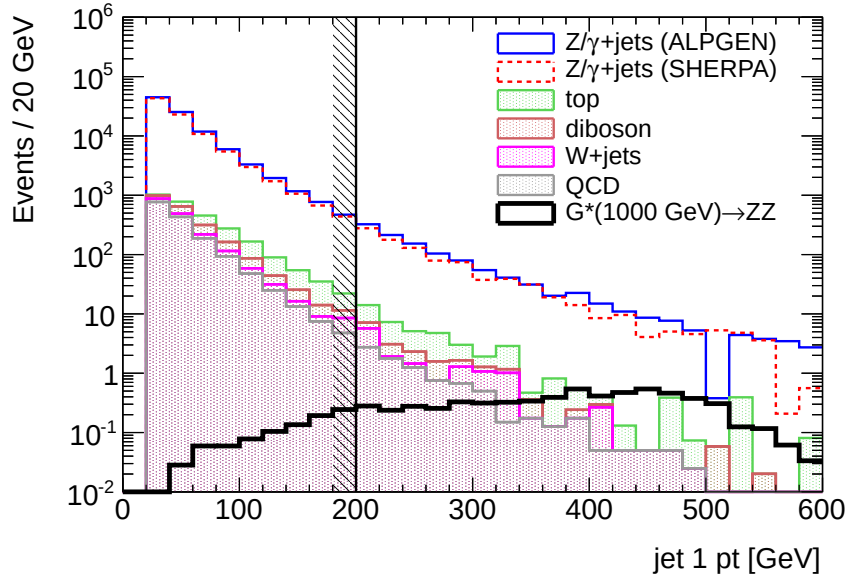


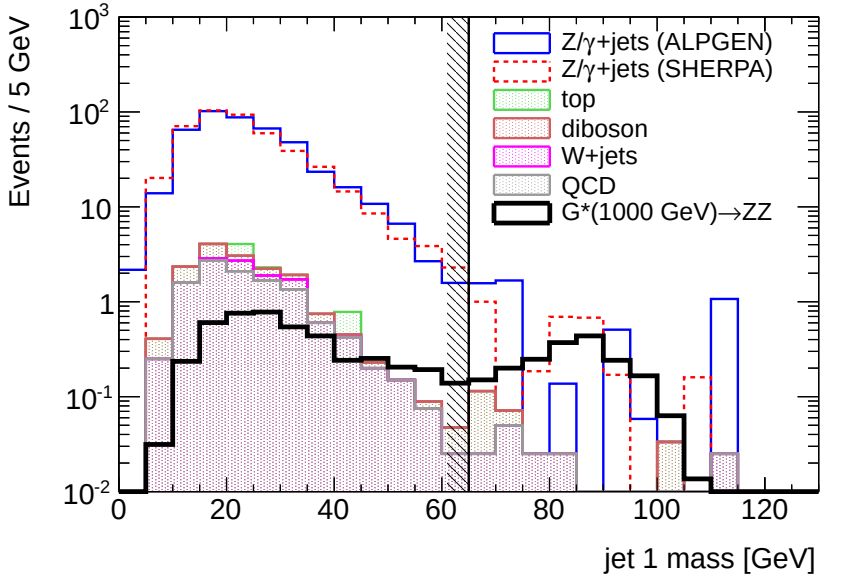


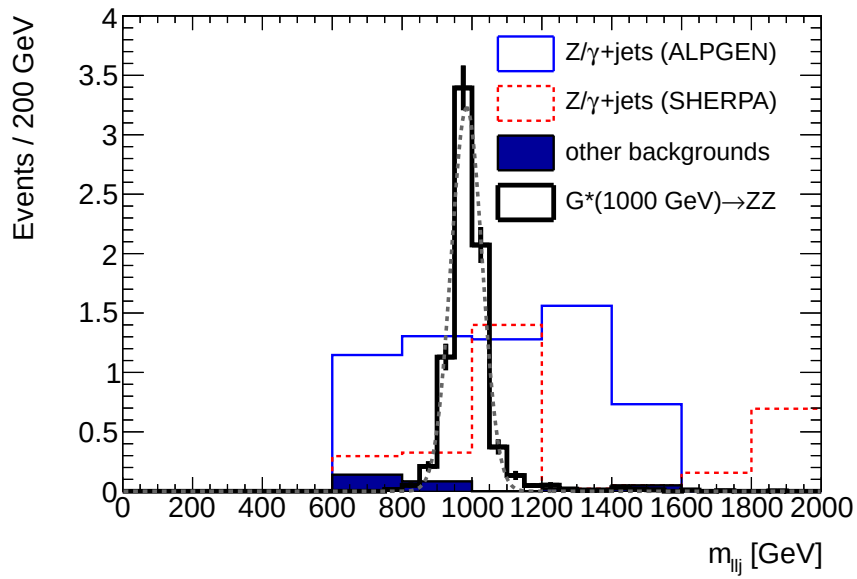


Merged Jet Region $m_{G^*} \geq 750$ GeV









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Z+jets background normalization

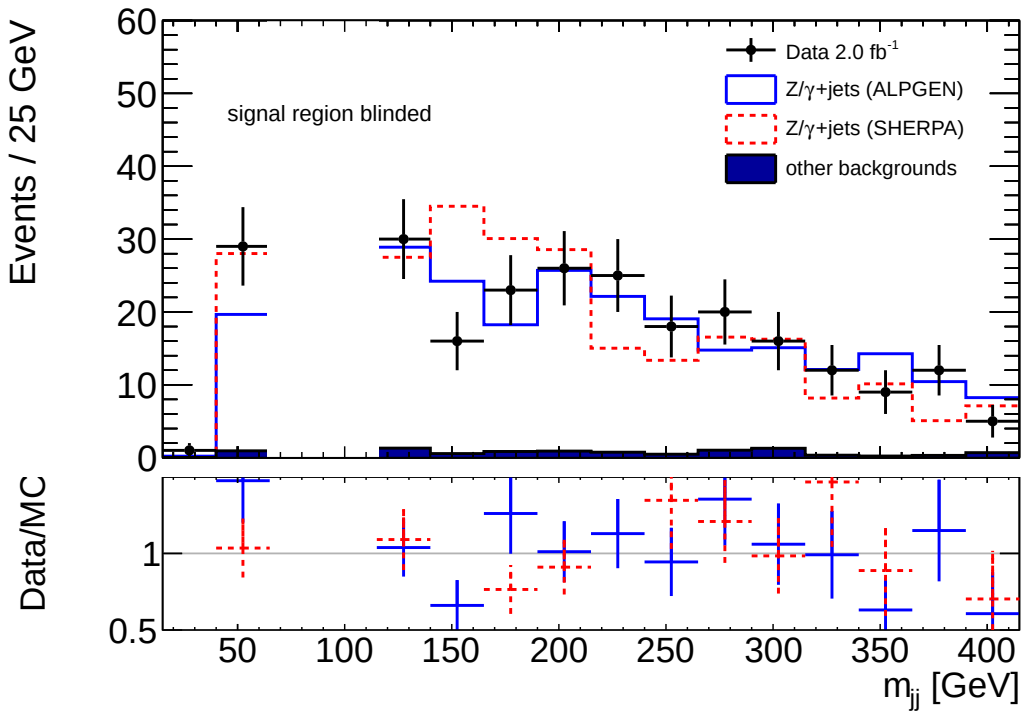
For the dominant Z+jets background, both SHERPA and ALPGEN generators are used

The difference between the two is used to estimate systematic uncertainty

In the signal regions, data/MC disagreement can be as much as 30%

Z+jets MC (both ALPGEN and SHERPA) is scaled to data in control regions - 'sidebands' in the dijet mass - scale factors:

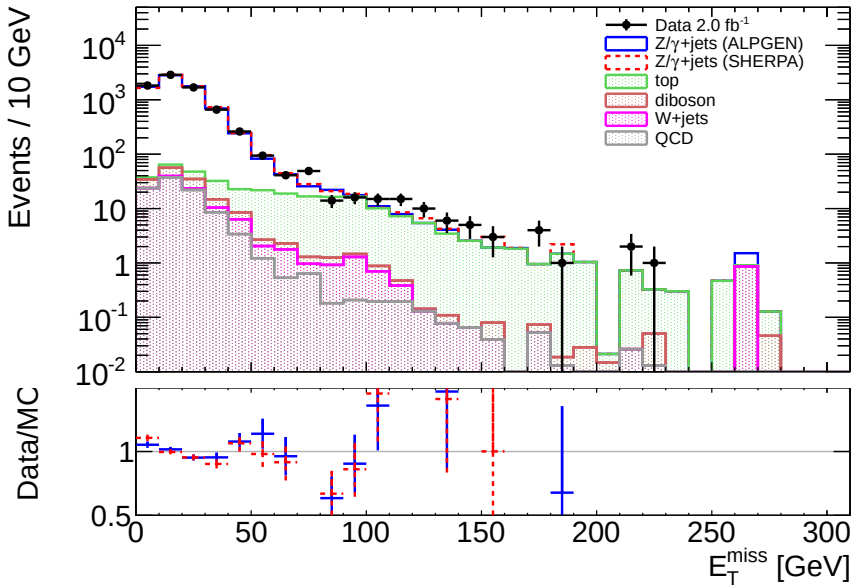
	eejj
ALPGEN	0.84 ± 0.08
SHERPA	1.34 ± 0.12



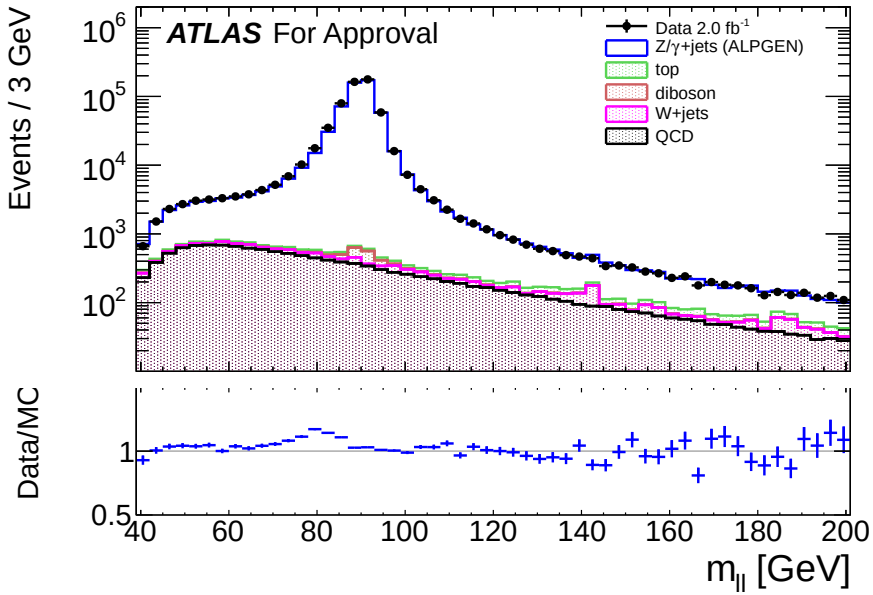
m_{jj} distribution (Electron channel)

Other Backgrounds

Top background
is checked using the E_T^{miss}
distribution in Low Mass Region



Multijet background
is estimated using a
fake-dominated sample of data



Diboson and W+jets backgrounds are estimated using MC scaled by the cross section (σ)

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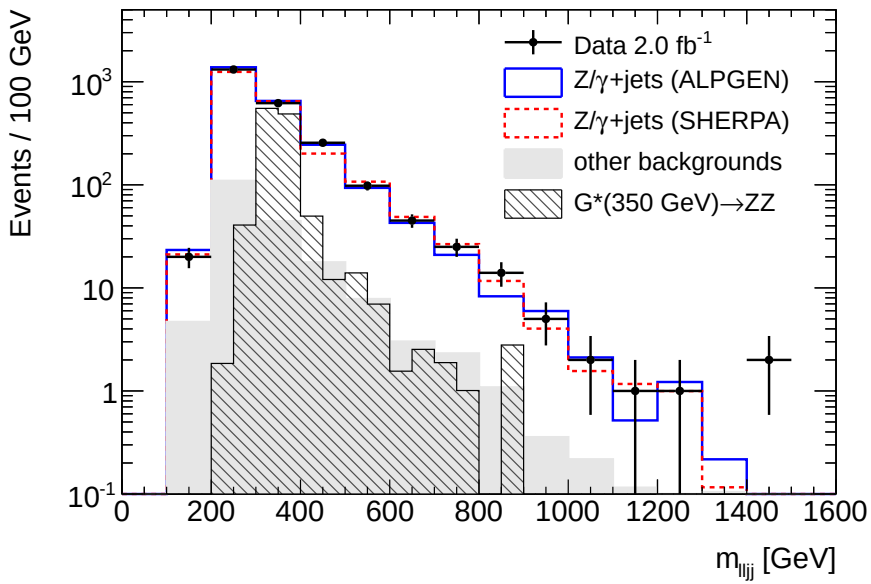
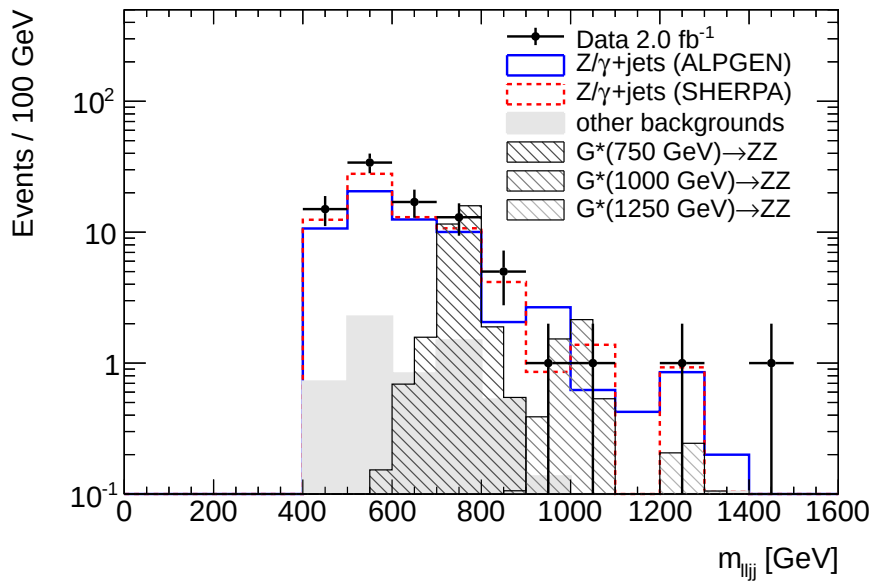
Resolved Jets Signal Regions

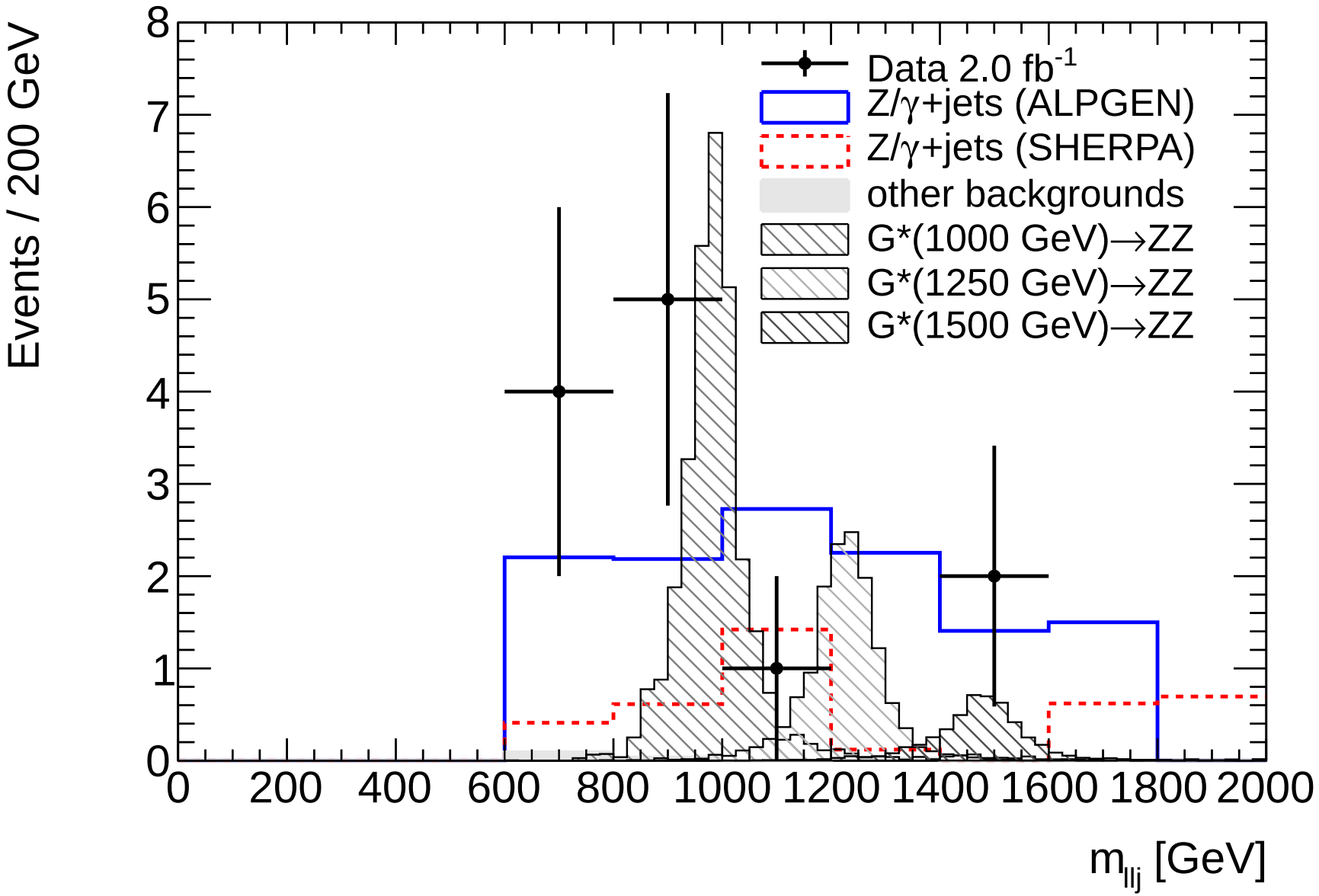
Low Mass signal region



High Mass signal region



Merged jet Signal Region



Systematic Uncertainties

Systematic uncertainties on the Z+jets background derived from:

- 100% systematic uncertainty on the scaling of ALPGEN
- ALPGEN − SHERPA shape difference
- MC statistics
- Heavy flavor

Largest systematics in the **Resolved jets High mass region** are:

- difference between ALPGEN and SHERPA: ±34%
- ALPGEN scale factor: 15 – 30%
- Jet energy scale uncertainty: $^{+\,12\%}_{-\,11\%}$
- MC statistics: ±5%

Largest systematics in the **Merged jet region** are:

- difference between ALPGEN and SHERPA: ±80%
- Jet mass scale uncertainty: $^{+\,80\%}_{-\,28\%}$
- Jet energy scale uncertainty: $^{+\,14\%}_{-\,15\%}$
- MC statistics: ±12%

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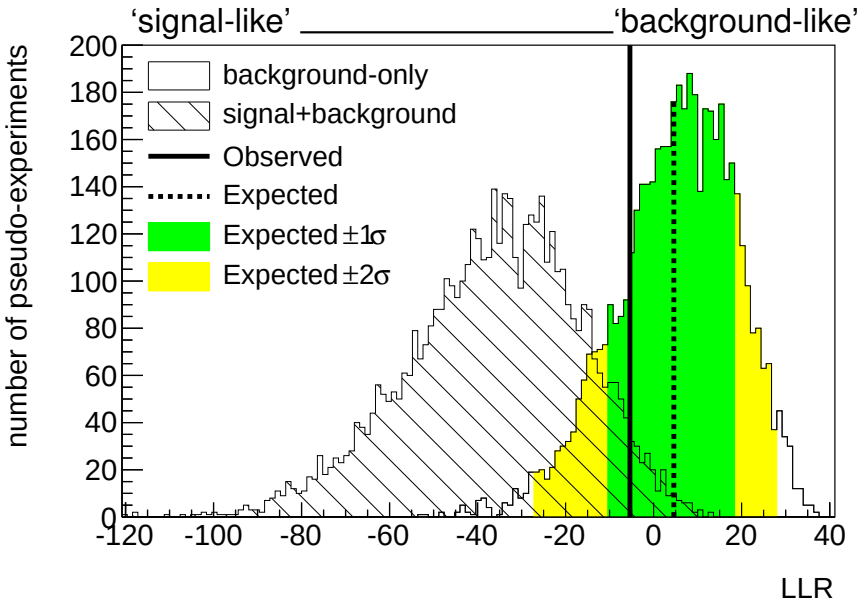
The CL_s Method

Events are counted in windows around each signal peak

Data is compared to background-only and signal+background pseudo-experiments (PEs) including statistical and systematic uncertainties.



Confidence levels (CL) are fractions of PEs to the right of the solid line

$$CL_s = \frac{CL_{s+b}}{CL_b} = \frac{0.04}{0.79} < 1 - 0.95 \quad \Rightarrow \text{excluded at 95\% CL}$$

For each mass point a value of $\sigma \times BR$ is excluded

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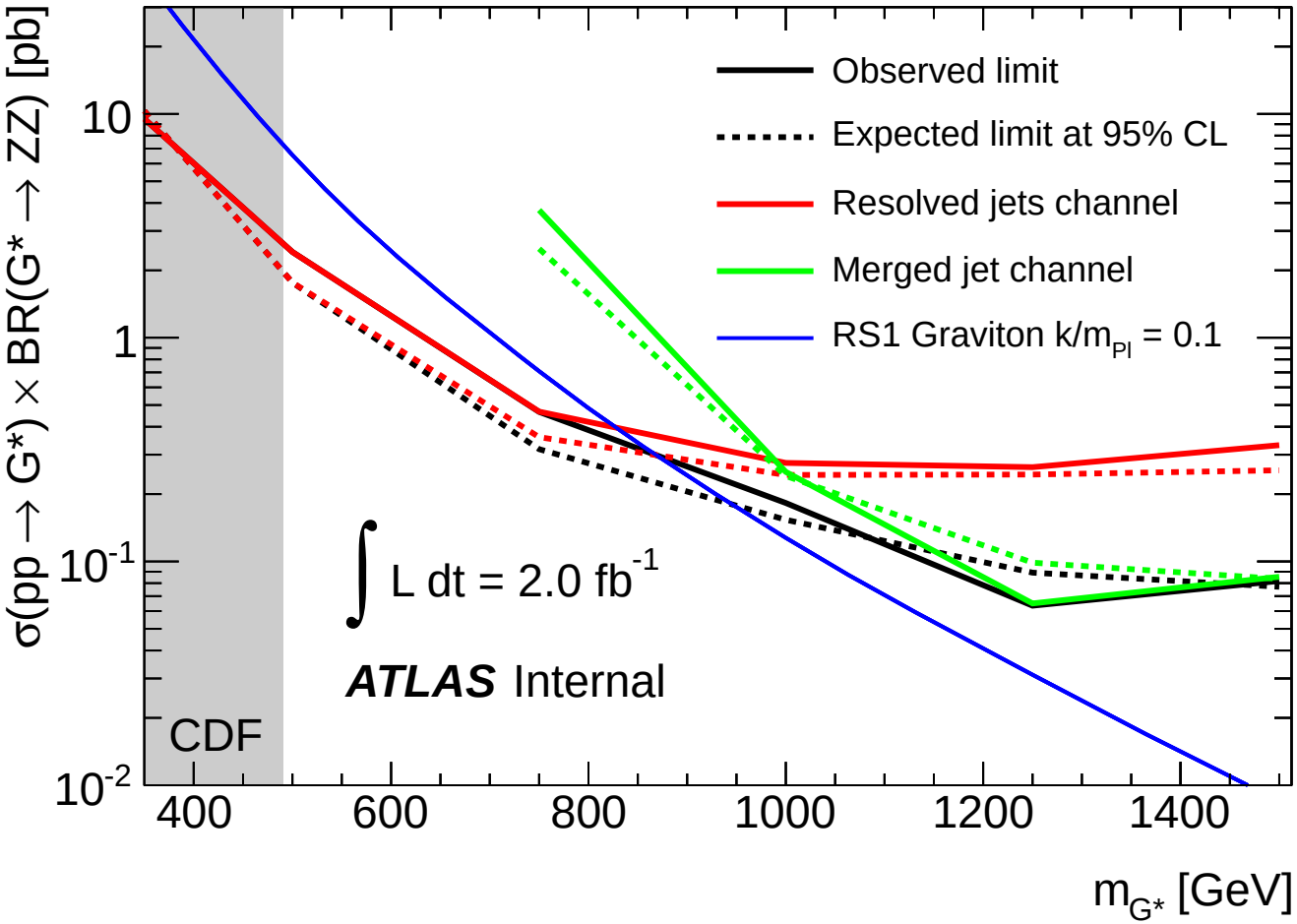
Limits on $\sigma \times$ BR in the **RS1 model**



Merged jets channel reduces limits on $\sigma \times$ BR by up to a factor of five!

Observed (expected) limits on the mass of the KK graviton are extended to 870 (950) GeV

Results and Conclusions

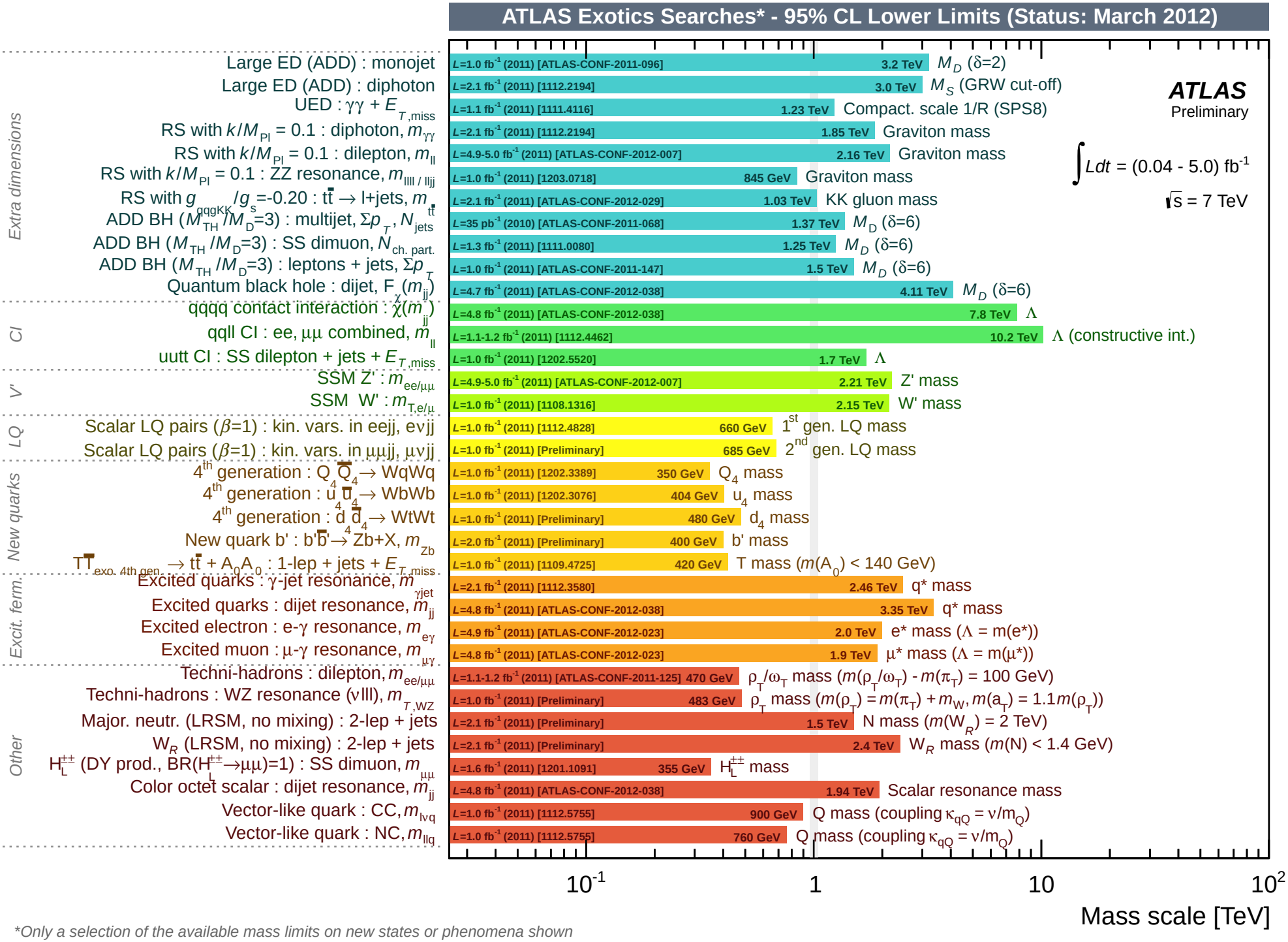
Also...
First ever limits are set on the KK graviton in the **bulk RS model**:
Observed (expected) limits on the mass are 630 (590) GeV

Merged jets can provide a large gain in sensitivity to high mass signals

They will become an essential part of many new physics searches, with the full 2011 data set (~ 5 fb^{-1}) and 8 TeV collisions in 2012

Part of this analysis has been submitted to Physics Letters B
arXiv:1203.0718

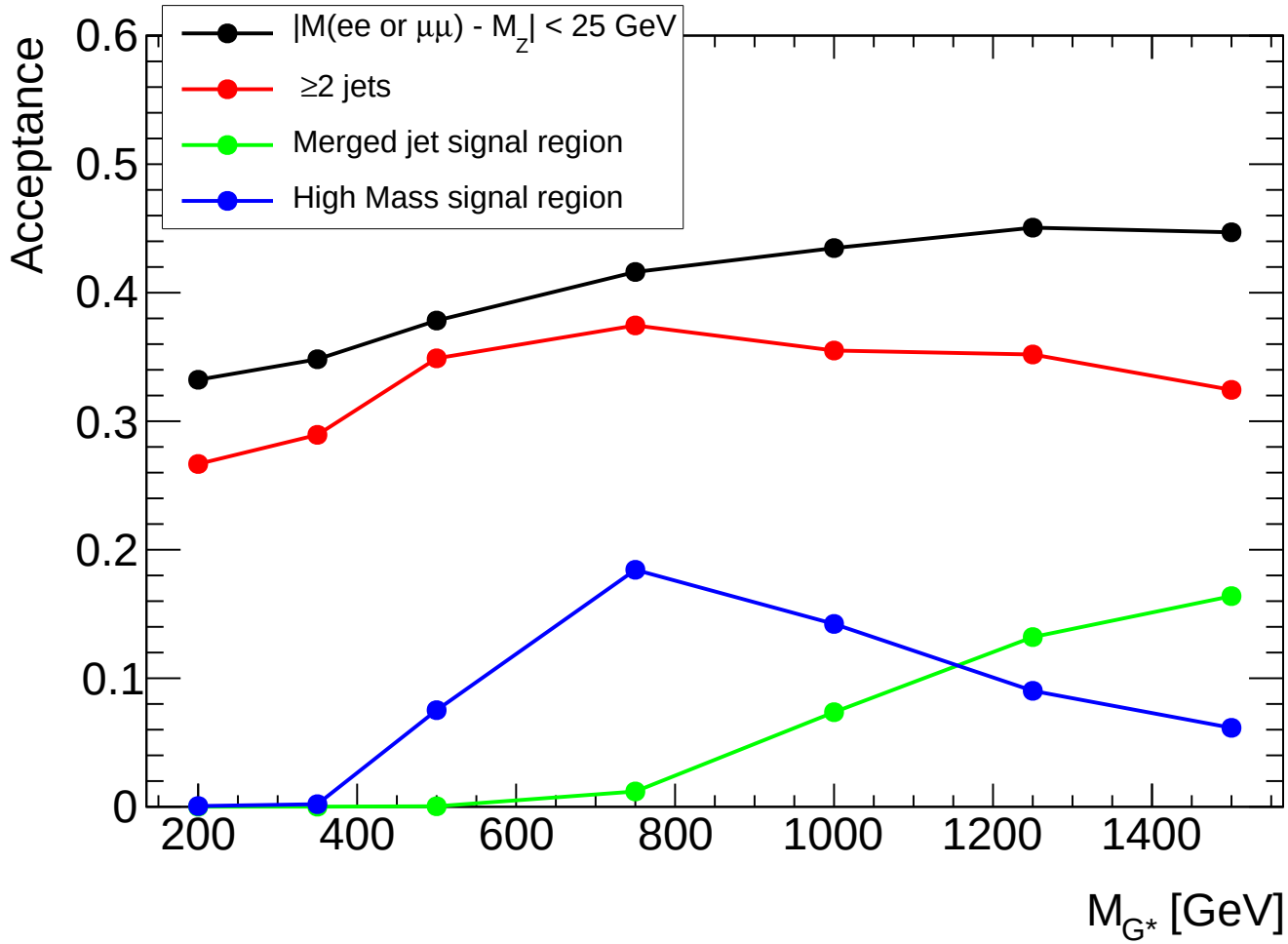
Just one of many limits set on extra dimensions and other new physics models at ATLAS...



*Only a selection of the available mass limits on new states or phenomena shown

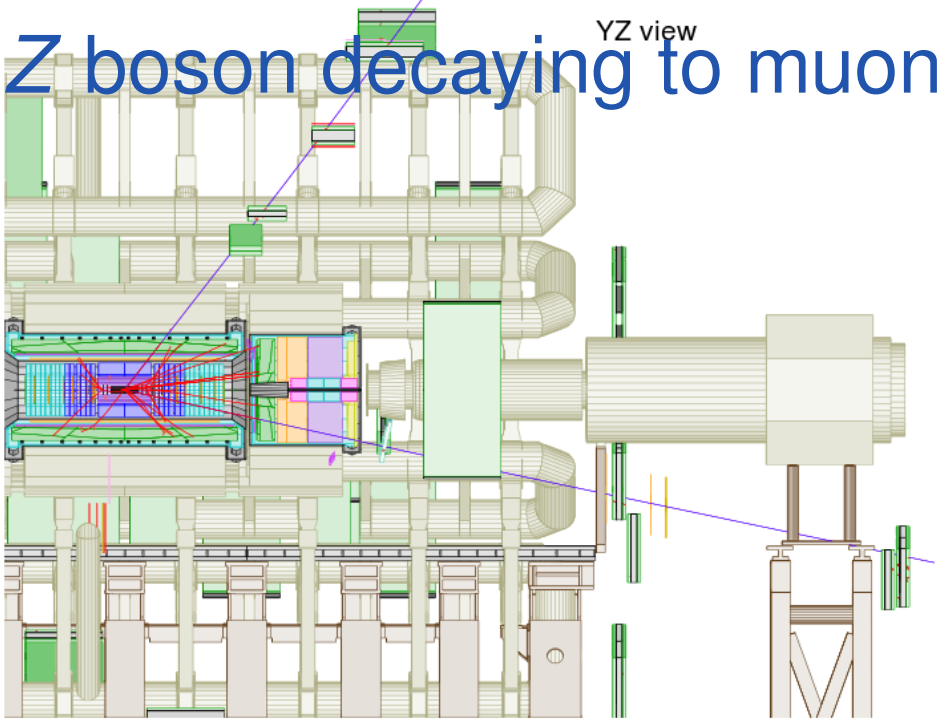
Backup Slides

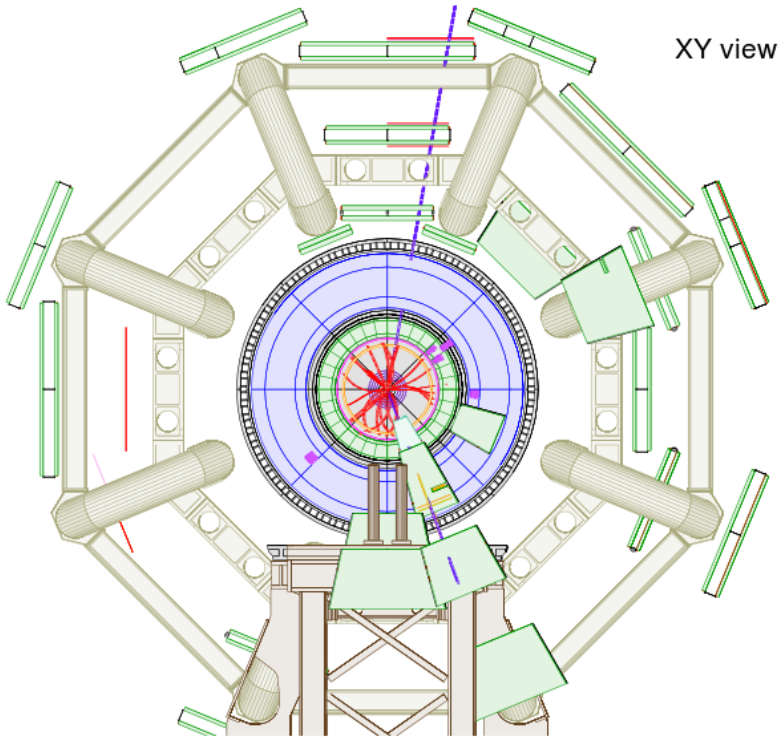
Acceptance for RS1 graviton

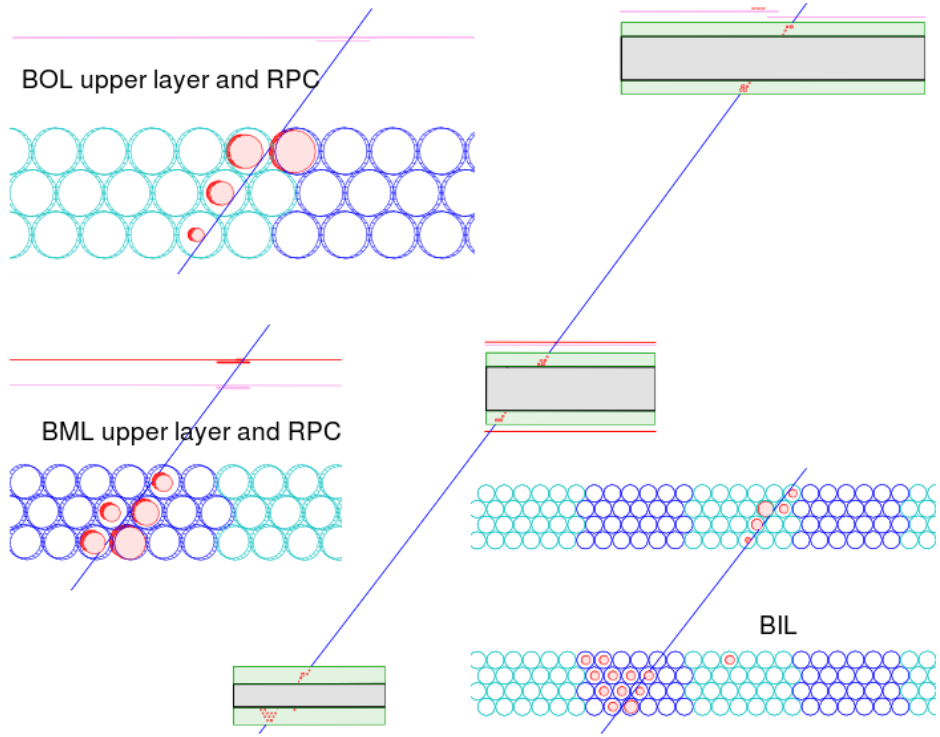


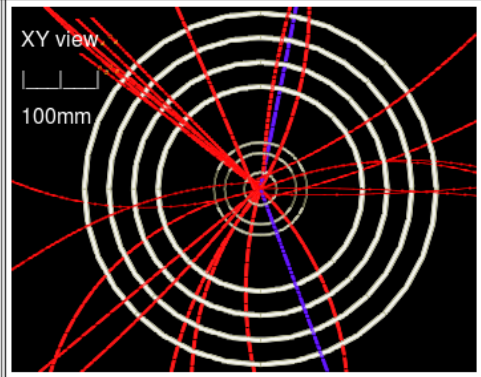
Jet merging becomes significant for $m_{G^*} \gtrsim 1$ TeV

Z boson decaying to muons





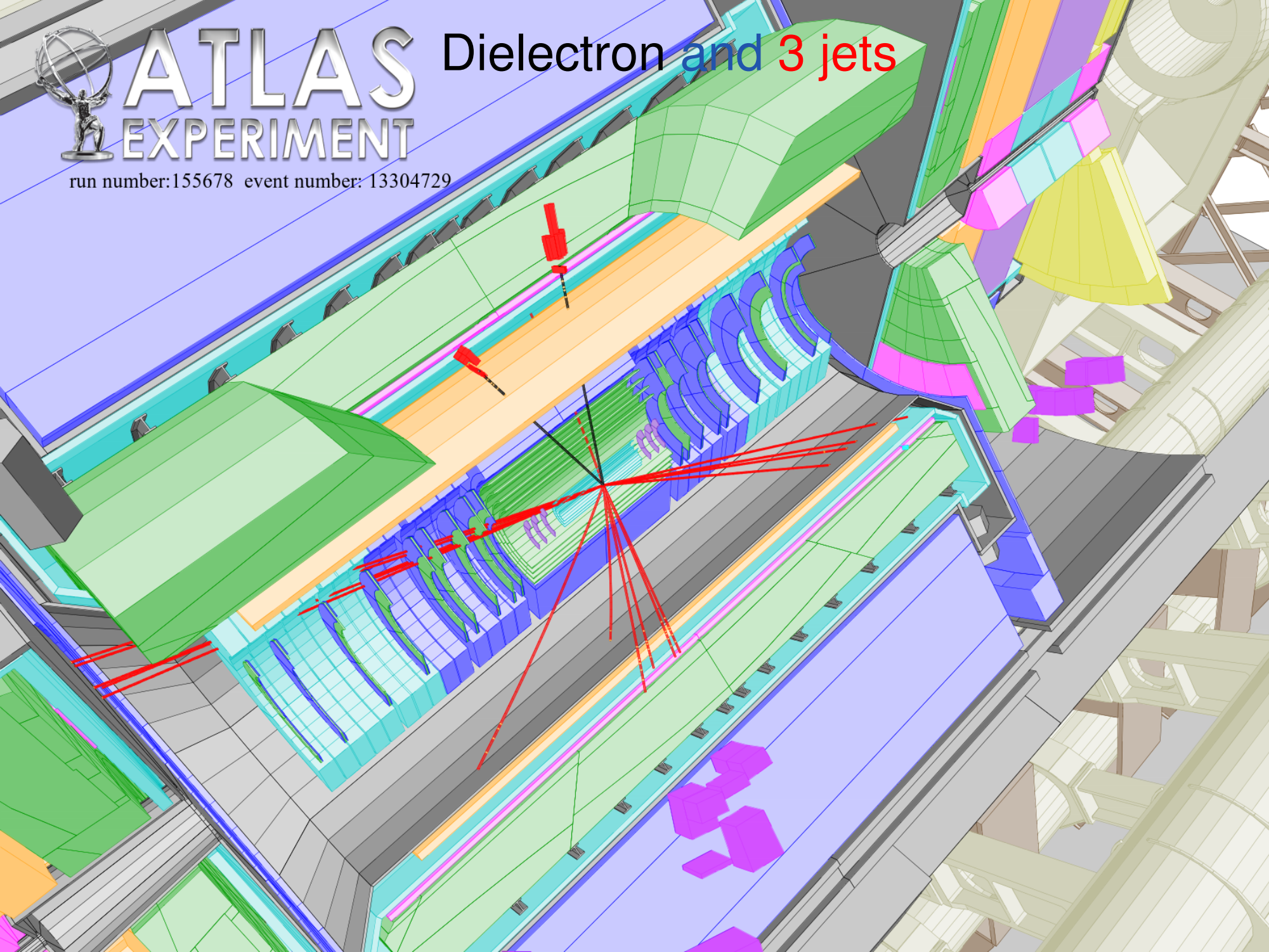




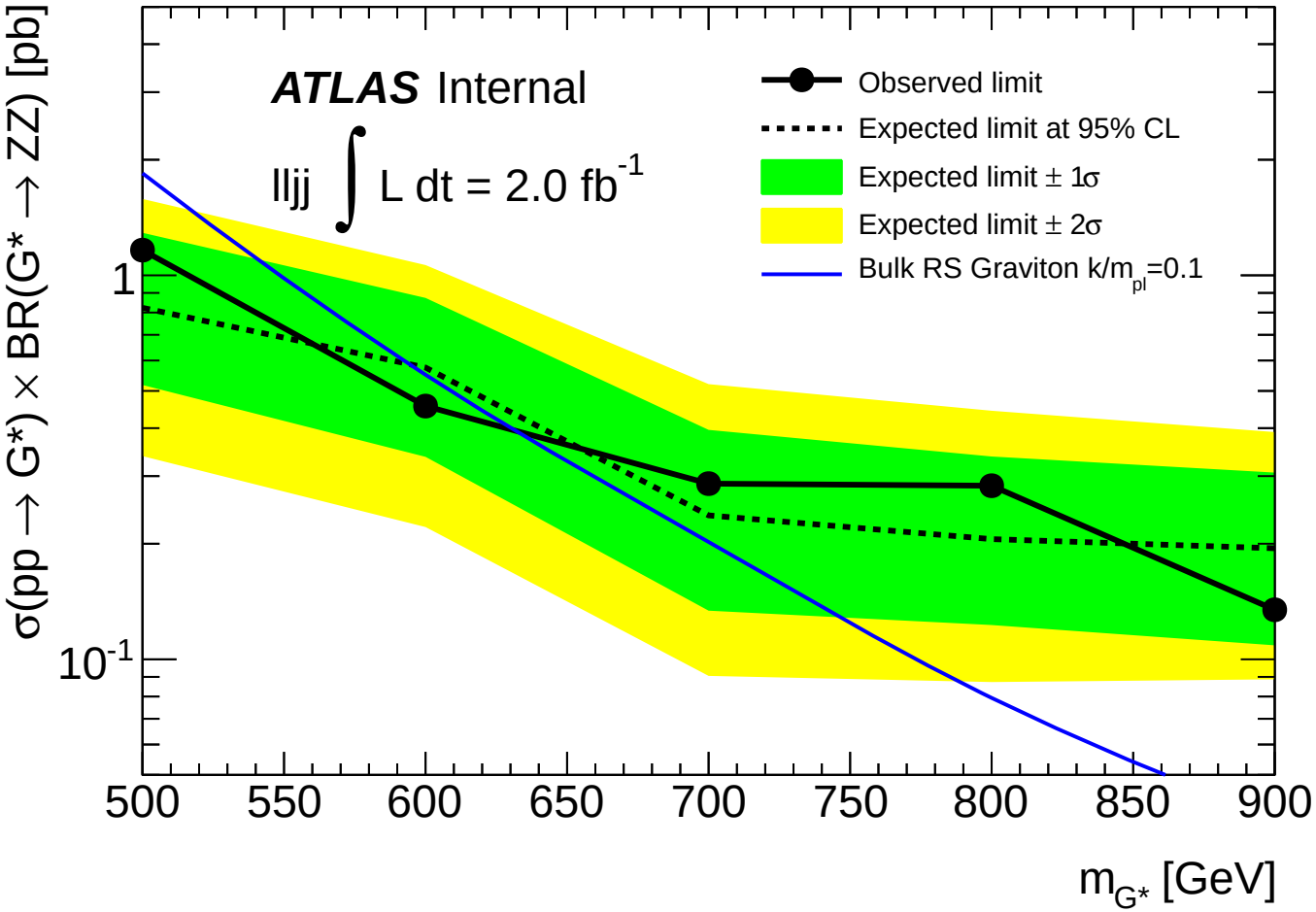
Z->μμ candidate in 7 TeV collisions

Run Number:154822, Event Number: 14321500
Z: Minv=87 GeV, Pt=26 GeV
Pt(μ+) =45 GeV, η=2.2
Pt(μ-) =27 GeV, η=0.7

ATLAS EXPERIMENT
http://atlas.ch


ATLAS
EXPERIMENT
Dielectron and 3 jets
run number:155678 event number: 13304729

Limits on the graviton in the Bulk RS model



Observed (expected) limits on the mass of the KK graviton in the bulk RS model are 630 (590) GeV