Searches for Gravitons at colliders

Results from the LHC general purpose experiments

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1. Theory Handwaving
   - ADD Large Extra-Dimensions
   - Kaluza-Klein Gravitons
   - Randall-Sundrum Models
2. Tools of the trade
   - The LHC, ATLAS, & CMS
3. The searches
   - RS1 KK-graviton resonance searches
   - Bulk-RS KK-graviton resonance searches
   - ADD KK-graviton ‘non-resonant’ searches
4. Current state and future searches

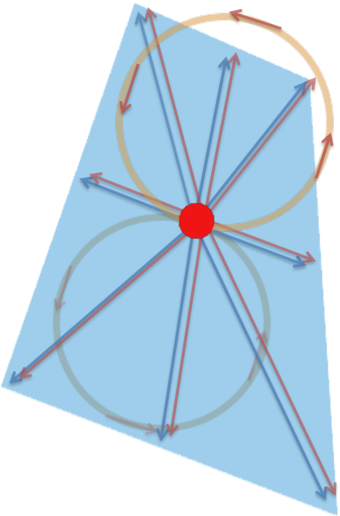
Please feel free to interrupt me at any point with questions!

Theory handwaving - Gravitons

- The **graviton** is theorised to be the **mediator** of gravitation in a quantum field theory
- Range of gravity is **infinite**, therefore the graviton should be **massless** and **stable**
- **Infinitesimal** interactions c.f. to the other gauge bosons
  - Weak force $\mathcal{O}(10^{24})$ times **stronger!**
  - **Hierarchy problem!!!**
- Production cross section at colliders **essentially 0**
  - The LHC (or any future collider) would **never be able** to produce them
  - **Collider signatures** talk done...

Theory handwaving - ADD model

- We need ways to be able to **produce** gravitons at colliders
- **Arkani-Hamed, Dimopoulos, and Dvali** (or Large extra-dimensions) model, ADD (LED), offers one **solution** to the hierarchy problem
- Our 3+1 **brane** is joined by n compactified extra–dimensions of radius R
- Only gravity can **propagate** through the **extra–dimensions**
- **Planck–scale**, $M_{pl} \approx 10^{16}$ TeV, reduced $M_D \approx 1$ TeV in our **brane**
- Requires **large** extra–dimensions, $M_{pl}^2 = M_D^{2+n} R^n$, to pull the **mass scale** of gravity down
  - $R < 1$ mm for $n = 2$ and $M_D \approx 1$ TeV
  - Size decreases with additional extra dimensions
- Kaluza-Klein modes of graviton are **closely spaced** and appear as a '**non-resonant**' excess
- LHC **can search** for these modes!



Theory handwaving - General K–K modes

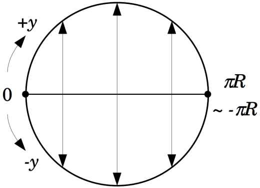
- What are **Kaluza–Klein modes**?
- Graviton's wave function can **propagate** in extra-dimension, only allowed to have certain **quanta** of momentum, in original KK model;

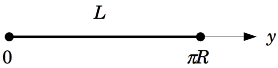
$$p_5 = \frac{\hbar}{R} = \frac{2\hbar}{R} = \frac{3\hbar}{R} \cdots = \frac{n\hbar}{R}$$

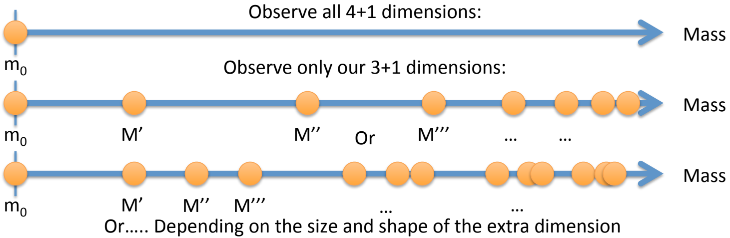
- In our 3+1 dimensions we see **momentum** in the 5th dimension as additional **'rest' mass**

$$M^2 = m_0^2 + (p_5/c)^2 > m_0^2$$

- We therefore see a **tower** of Kaluza-Klein particles, masses dependent upon the **size/shape** of the 5th dimension



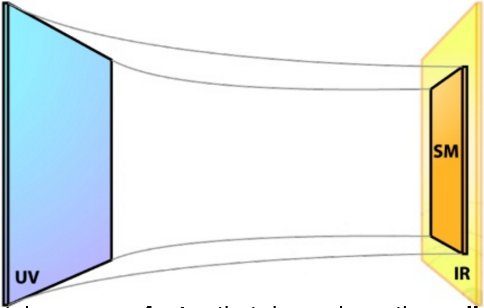




Theory handwaving - RS1 Model

- Original **Randall–Sundrum** model, RS1, offers a further **solution** to the hierarchy problem
- 5^{th} anti-de-Sitter **spacial** dimension bounded by two 3+1 **branes**

- Graviton is **localised** at $y = 0$ on the UV or **Planck–brane**
- M_{pl} mass scales
- Only gravity can **propagate** through the '**bulk**'



- Standard Model particles **localised** at $y = \pi R$ on the IR or **TeV–brane**
- TeV mass scales

- The metric contains a **warp factor** that depends on the **radius** R and **curvature** k of the extra-dimension

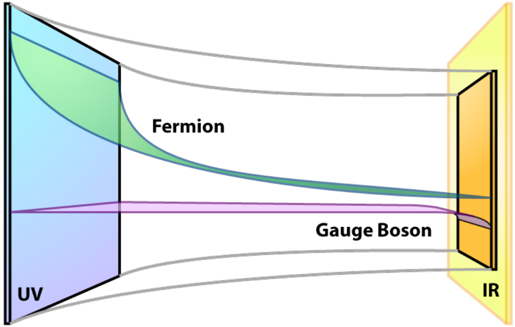
$$\partial s^2 = e^{-2kR|\phi|}\eta_{\mu\nu}\partial x^\mu \partial x^\nu + R^2 \partial\phi^2$$

- Planck–brane mass scales **rescaled** by warped metric: gravity becomes **weak**
- Hierarchy problem **solved!**
- Gain **Kaluza–Klein** modes of gravitons as they can **travel** in the bulk
- The LHC can **produce** and therefore search for these particles!

Theory handwaving - Bulk RS Model

- Graviton still localised on the **Planck–brane**
- Higgs localised on the **TeV–brane**
- KK-modes can be found **near** the TeV brane (others exist in bulk)
- **All** Standard Model particles (except the Higgs) can **propagate** into the bulk

- **Light** fermions localised closer to the **Plank–brane**
  - **Small** overlap with Higgs field
  - Masses are naturally **low**
- t_R, vector–bosons localised closer to the **TeV–brane**
  - **Large** overlap with Higgs field
  - Masses naturally **higher**
- Explaination for hierarchy in fermion **Yukawa couplings!**
- CKM **mixing angles** can appear naturally



Theory handwaving - KK-Gravitons

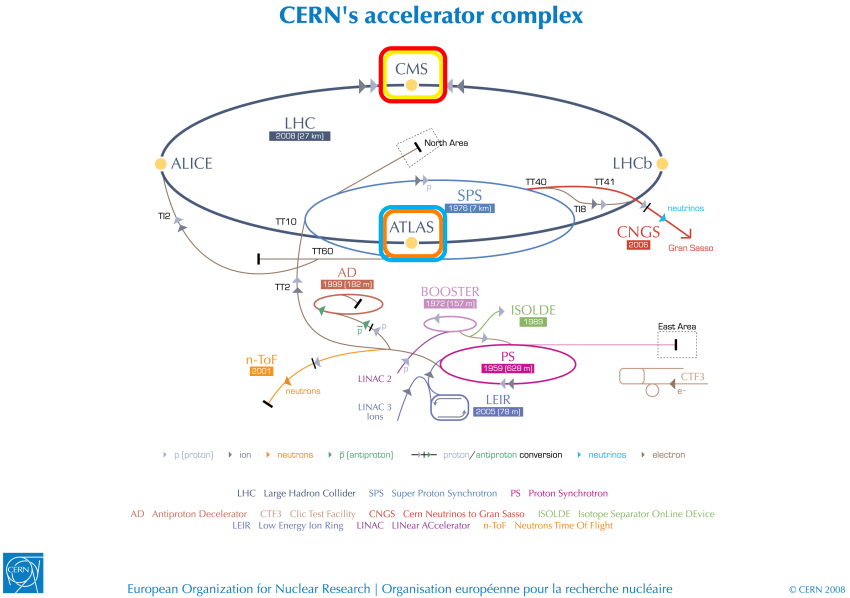
1. In the **RS1** model:
   - All SM particles located on the **TeV-brane**
   - KK-Gravitons can be **produced** at the LHC via *g*–*g* fusion, or $q\bar{q}$ annihilation
   - KK-graviton modes decay **relatively uniformly** to SM particles as they are located on the TeV–brane near the KK-mode
   - Therefore can use **'clean'** channels $\gamma^+\gamma^-$, e^+e^-, $\mu^+\mu^-$ etc. to search for the **KK resonances**

Theory handwaving - KK-Gravitons

2. In the **bulk–RS** model:
   - KK-Gravitons **predominantly** produced at the LHC via g–g fusion
   - $q\bar{q}$ annihilation is **suppressed** as light fermions located on the **Planck–brane**
   - KK-graviton decays to $t\bar{t}$, VV and HH states are **enhanced** (w.r.t. RS1) as they are localised near the **TeV–brane** along side the KK-graviton
   - Decays to light fermions **suppressed** for the converse reason
   - Logical to search for this model using **enhanced** $t\bar{t}$, and VV final states

Theory handwaving - KK-Gravitons

3. In the **ADD** model:
   - Only the **graviton** propagates in the extra–dimensions
   - KK-Gravitons can be **produced** at the LHC via g–g fusion, or $q\bar{q}$ annihilation
   - KK-graviton modes **close together**, appear as **non-resonant** deviations in mass spectra, beyond a **turn on** threshold, M_{TH}
   - Search for non-resonant behaviours in **tails** of mass distributions


CERN's accelerator complex
CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
n-ToF
2001
PS
1959 (628 m)
CTF3
e–
neutrons
LINAC 2
LINAC 3
Ions
LEIR
2005 (78 m)
p (proton)
ion
neutrons
p̄ (antiproton)
proton/antiproton conversion
neutrinos
electron
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight
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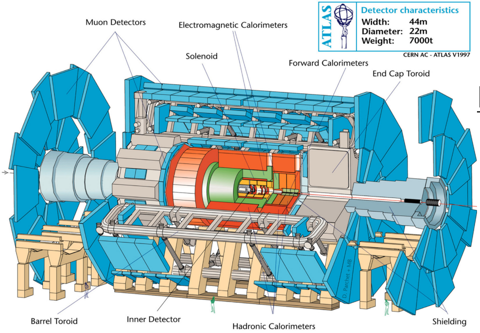
The General Purpose Detectors

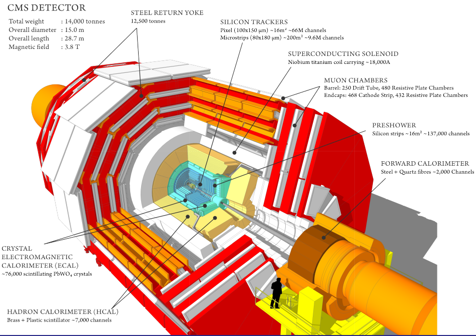


Differences

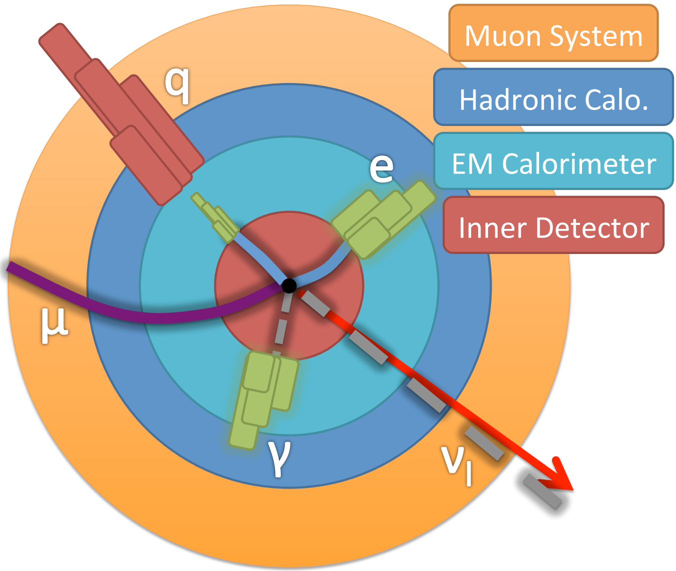
- Detector **technology** choices
- *B*-field **configuration**: Solenoid vs Solenoid+Toroid
- **Size/weight** (though both are colossal!)

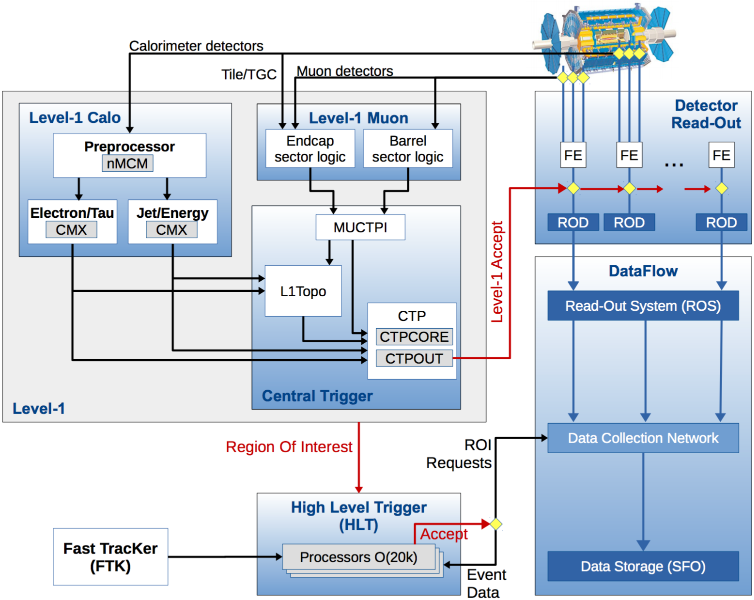
Similarities

- **Cylindrical** detectors: barrel & end-caps
- **Concentric** detectors: Tracking, EM$\rightarrow$had-calorimetry, muon chambers
- Close to 4π solid angle coverage
- Hardware/software **combined** trigger systems



The General Purpose Diagram

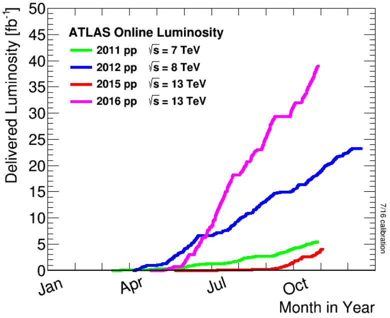


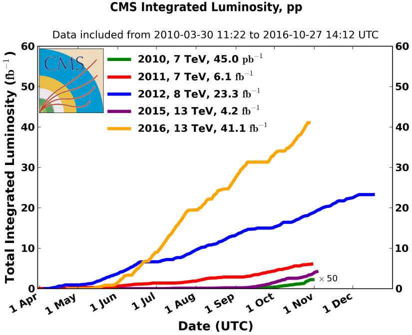


Calorimeter detectors
Tile/TGC
Muon detectors
Level-1 Calo
Preprocessor
nMCM
Electron/Tau
CMX
Jet/Energy
CMX
Level-1 Muon
Endcap sector logic
Barrel sector logic
MUCTPI
L1Topo
CTP
CTPCORE
CTPOUT
Central Trigger
Level-1
Level-1 Accept
Detector Read-Out
FE
FE
...
FE
ROD
ROD
ROD
DataFlow
Read-Out System (ROS)
Data Collection Network
Data Storage (SFO)
Region Of Interest
ROI Requests
High Level Trigger (HLT)
Accept
Processors O(20k)
Event Data
Fast TracKer (FTK)

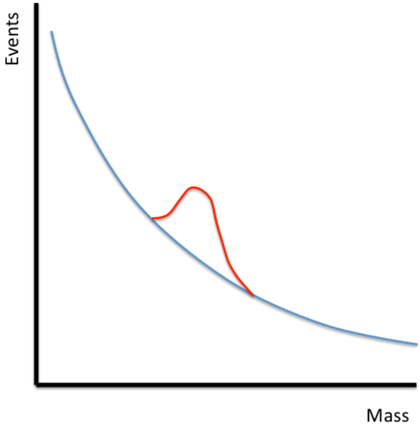
Data recorded

- The LHC has the **pedal to the metal**
- Collisions now **flooding** into the detectors, at a rate that we actually **had issues** dealing with!!!
- Some problems are **nice** to have... (for a while...)



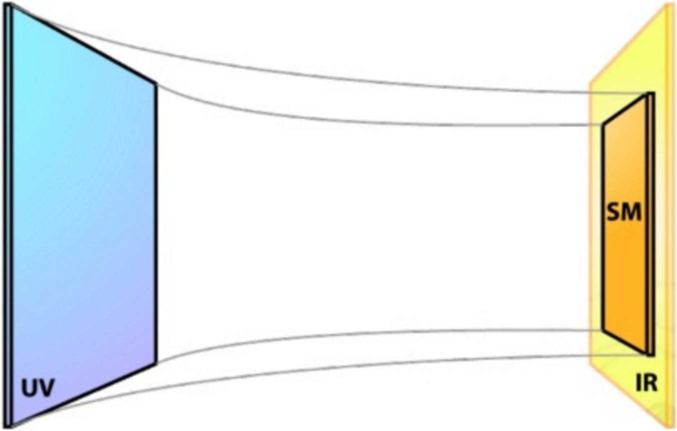


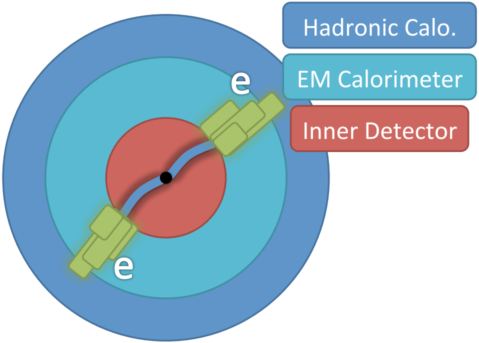
- Resonance searches are the **classic collider methodology** in searches for **new particles** and their excitations
- Try to **infer** the presence of a **new particle** by combining its decay products
  - Reconstruct 4-vectors of decay products
  - Combine and plot the invariant mass
- In essence they boil down to, ‘Look for an unexpected **peak** on a **smooth background**’
- **Spin** analysis would be needed to **distinguish** a graviton from new scalar/vector particles



- In the following analyses **ATLAS and CMS** are searching various **invariant mass spectra** for resonant bumps
- The first set of analyses are looking for **RS1** models, the second **bulk-RS**

- SM particles on **TeV–brane** close to KK-modes
- Use **clean** channels
- $G^* \to e^+e^-$
- $G^* \to \mu^+\mu^-$
- $G^* \to \gamma\gamma$





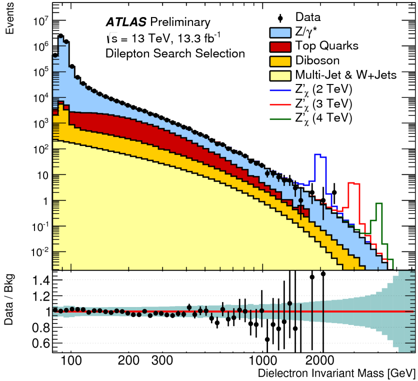
Event Selection – $G^* \to e^+e^-$

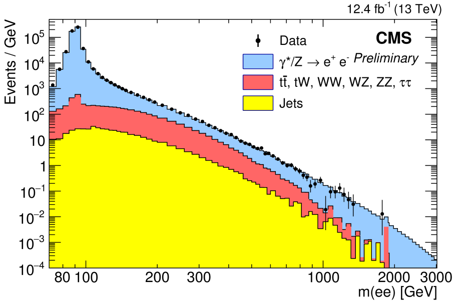
- Select events with **high**-p_T, **central**, electron pairs
- Require that the electrons's **shower shapes**, and **track properties** are consistent with the **expectation** for a single electron
- Remove electrons that are surrounded by **large additional** calorimeter deposits or a **high scalar sum** of p_T from adjacent tracks
- Due to **misidentification** at high-p_T, **no** opposite charge requirement is made

ATLAS: ATLAS-CONF-2016-045 | CMS: EXO-16-031

Di–electron results – $G^* \to e^+e^-$

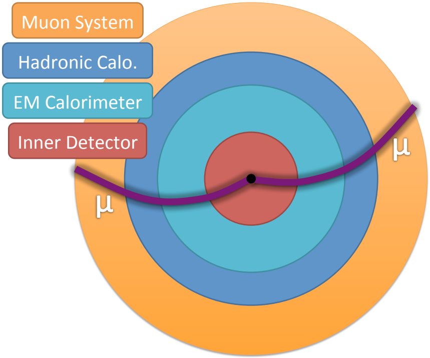
- Drell-Yan, $t\bar{t}$, and diboson backgrounds all modelled by **simulation**
- Non-prompt and mis-identified jet backgrounds modelled by **data-driven** methods





- **No significant** deviation seen from the SM backgrounds in either search
- Limits **not set** on G^* production in this round, but limits on spin–1 Z' models $\mathcal{O}3-4$ TeV range (similar expectation for $k/\bar{M}_{pl} = 0.10$)

Di–muon Reco – $G^* \rightarrow \mu^+\mu^-$

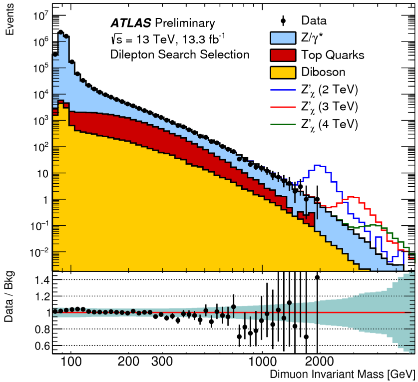


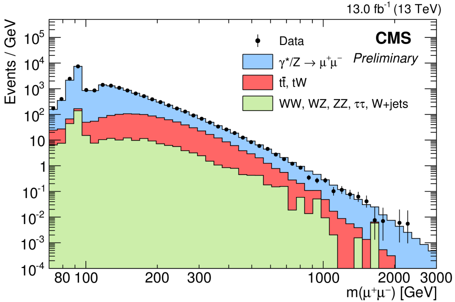
Event Selection – $G^* \rightarrow \mu^+\mu^-$

- Select events with **high** p_T, **central**, muon pairs
- Require that the muon's **track** has hits through all layers and does not have significant holes
- Remove muons that are surrounded by **large additional** calorimeter deposits or a **high scalar sum** of p_T from adjacent tracks
- Require that the muons have **opposite** charge

ATLAS: ATLAS-CONF-2016-045 | CMS: EXO-16-031

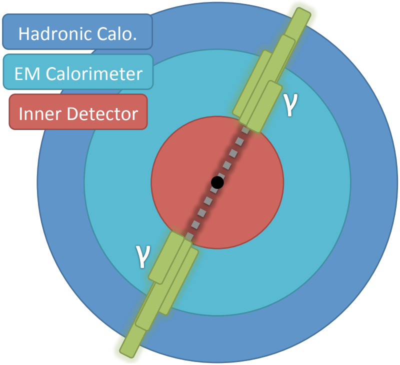
- Drell-Yan, $t\bar{t}$, and diboson backgrounds all modelled by **simulation**
- **No significant** non-prompt and mis-identified jet backgrounds for muons





- No significant deviation seen from the SM backgrounds in either search
- Limits not set on G^* production in this round, but limits on spin-1 models $\mathcal{O}3 - 3.5$ TeV range (similar expectation for $k/\bar{M}_{pl} = 0.10$)
- Combined $ee + \mu\mu$ limits push towards the 4 TeV range

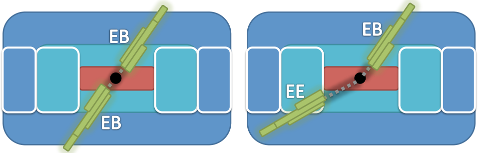
Di–photon Reco – $G^* \to \gamma\gamma$



ATLAS: ATLAS-CONF-2016-059
CMS: EXO-16-027

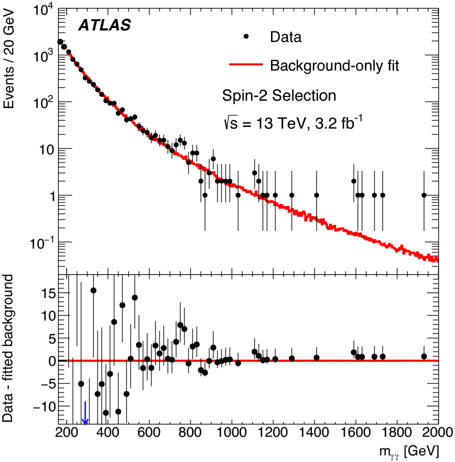
Event Selection – $X \to \gamma\gamma$

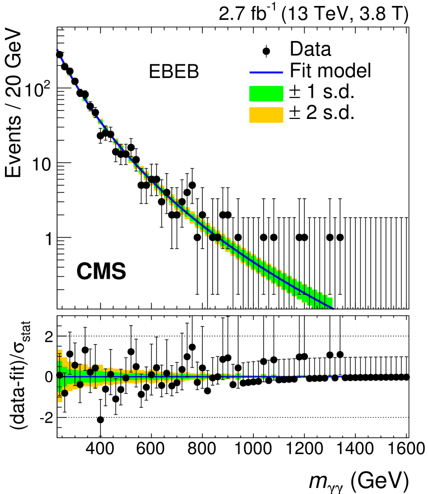
- Select events with **high** p_T, photon pairs
- Require that the photon's **shower shapes** are consistent with the expectation for a **prompt** photon
- Remove photons that are surrounded by **large additional** calorimeter deposits or a **high scalar sum** of p_T from adjacent tracks
  - Allowances for **converted** photons
- Require a **high** $m_{\gamma\gamma}$
- CMS splits into **EBEB** and **EBEE** regions



Di–photon 2015 results – $G^* \to \gamma\gamma$

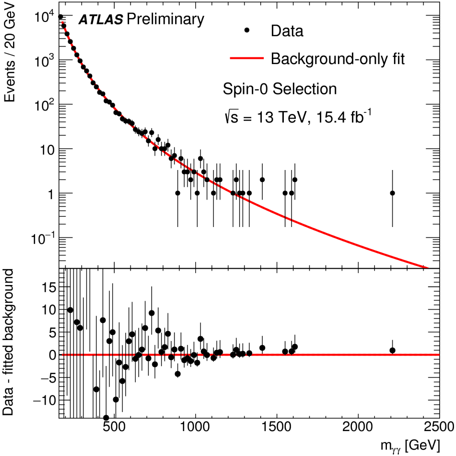
- Some **excitement** in this channel in the early Run-2 data ($\approx 3.5\sigma$ local, $\approx 1.7\sigma$ global)
- **'Bump'** seen by **both** ATLAS and CMS at 750 GeV (HIGG-2016-08, EXO-16-018)

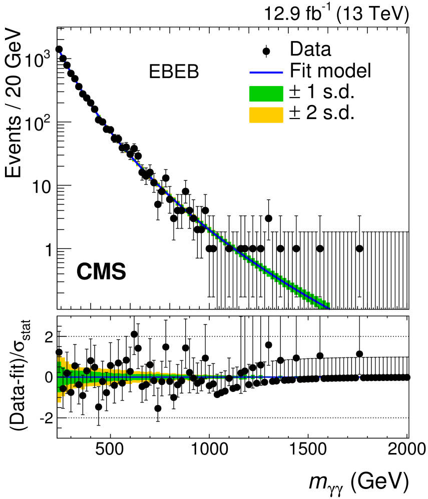




- Absolute **deluge** of theory papers, even papers modelling the flood (1603.01204,) and awards for papers/citations in theory blogs, Resonaances

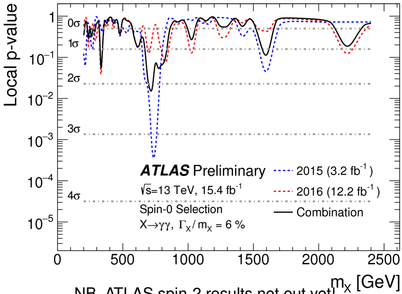
- Excitement **faded** with the full 2015+2016 results (Spin-2 ATLAS not in time)
- Bump did **not survive** the addition of new data
- **Cautionary** tale for both experiment and theory communities!



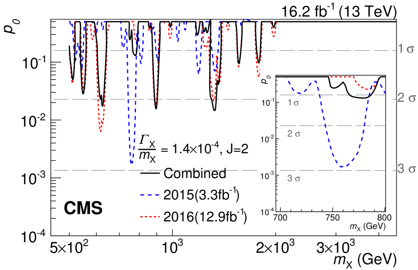


Di–photon Run-2 results – $G^* \to \gamma\gamma$

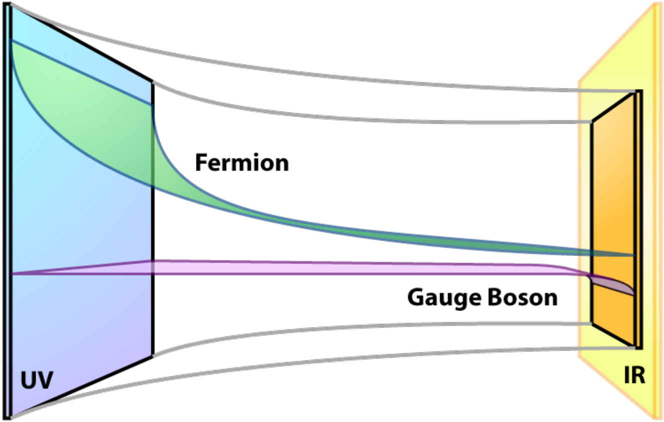
- Nearly 4 times the data, and **no sign** of the bump!
    - If real, **both** experiments would naively expect to **approach** 5σ local
- Local *p*-values do not always tell you the **full story!**
- Global *p*-values cover the **'look elsewhere effect'**
    - How likely is this deviation given the size of the other bumps in the spectrum?
    - Applies a penalty factor to the local significance for each other bump
- **Personal opinion:** $\gamma\gamma$ bumps gain additional **'priors'** as they are experimentally **'clean'** and theoretically **'easy'** to explain
- Always remain **cautious!** Avoid our **human biases** as much as possible!



NB. ATLAS spin-2 results not out yet!

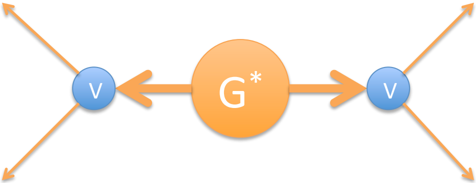


- Light fermions near **Planck–brane**
- Heavy particles near **TeV–brane**, close to KK-modes
- $G^* \to VV$
- $G^* \to HH$
- $G^* \to t\bar{t}$



Bulk-RS – $G^* \rightarrow VV$

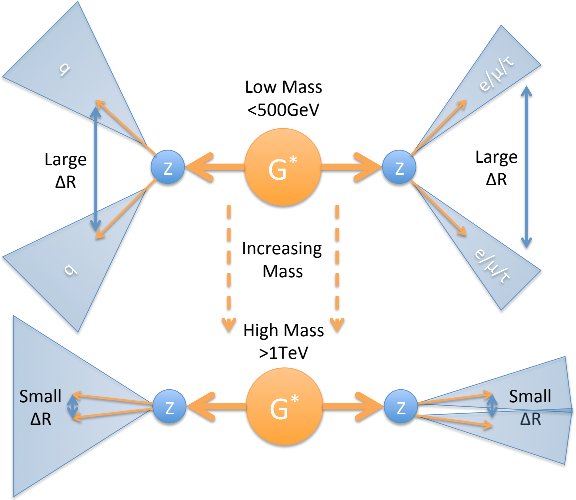
- **Diboson resonances**, of the form $G^* \rightarrow VV$, appear with **large branching** ratios in the bulk–RS model
- **Leptonic** decay channels have **lower** branching ratios, but are **cleaner** signals in hadronic environments
  - Channels containing neutrinos have **additional complications** to fully reconstruct the initial particle
- The **fully hadronic** channel has a **larger** branching ratio, but suffers from **huge** QCD initiated multi-jet backgrounds



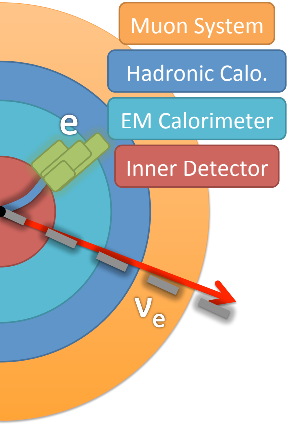
$W \Downarrow$	Diboson* branching ratios	
qq (67%)	45%	22%
$l\nu$ (33%)	22%	11%
$W \Rightarrow$	qq (67%)	$l\nu$ (33%)

$Z \Downarrow$	Diboson* branching ratios		
qq (70%)	49%	14%	7%
$\nu\nu$ (20%)	14%	~~4%~~	2%
ll (10%)	7%	2%	1%
$Z \Rightarrow$	qq (70%)	$\nu\nu$ (20%)	ll (10%)

Boosting bosons – Collimation

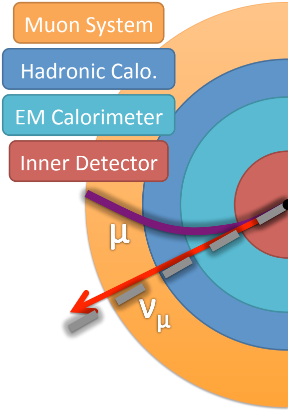


- Vector bosons have mass $\mathcal{O}$**(0.1 TeV)**
- We are interested in particles of mass $\geq \mathcal{O}$**(1 TeV)**
- Therefore the decays of the form, $X \rightarrow VV$ with **large** m_X, lead to vector bosons with **very high** p_T
- Boosted decay products become more **collimated**
- Have **sufficient granularity** to resolve most leptonic decays
- Sub-jets begin to **merge** in hadronic decays at high m_X
- **Rule of thumb** for angular separation of decay products:
- $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} \approx \frac{2m}{p_\mathrm{T}}$

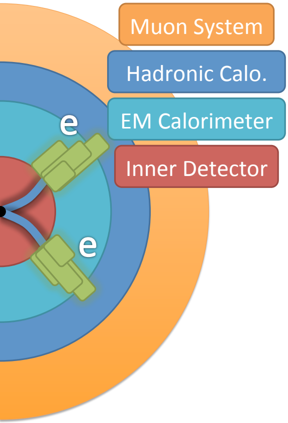


Event Selection – $W \rightarrow l\nu_l$

- Select singlular, **high** p_{T}, **central** leptons
- Remove leptons that are surrounded by **large additional** calorimeter deposits or a **high scalar sum** of p_T from adjacent tracks
- Select events with a **large** $E_{\mathrm{T}}^{\mathrm{miss}}$
- **Assume** that $E_{\mathrm{T}}^{\mathrm{miss}} \equiv p_{\mathrm{T}}^{\nu_l}$
- $p_z^{\nu_l}$ calculated by solving a **quadratic** holding $m_{l\nu_l} = m_W$
- **Reconstruct** the W's kinematics by **combining** the 4–momenta of the lepton and ν_l

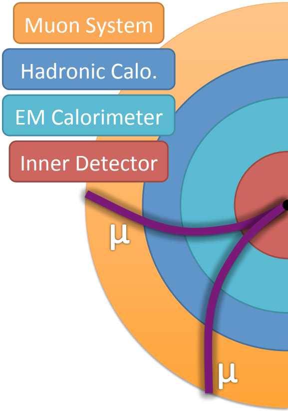


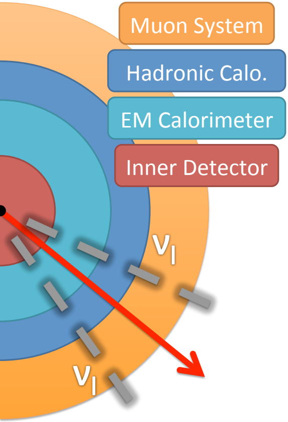
Leptonic Z Reco. – $Z \to ee$ / $Z \to \mu\mu$



Event Selection – $Z \to ll$

- Select pairs of **oppositely** charged, **same** flavour, **high** p_T, **central** leptons
- Remove leptons that are surrounded by **large additional** calorimeter deposits or a **high scalar sum** of p_T from adjacent tracks
- **Reconstruct** the Z's kinematics by **combining** the 4–momenta of the leptons
- Require that the invariant mass of the dilepton pair is **consistent** with the Z mass





Event Selection – $Z \to \nu\nu$

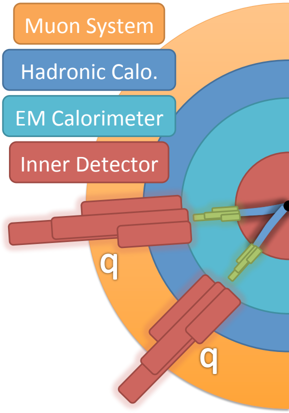
- Select events with a **large** $E_{\mathrm{T}}^{\mathrm{miss}}$
- Use the $E_{\mathrm{T}}^{\mathrm{miss}}$ as a **proxy** to the **invisibly** decaying Z
- For the final discriminating variable use a **transverse mass** parameter formed with the other V **candidate** in the event, defined by,

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{V} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{\mathrm{T}}^{\,V} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}}\right)^2}$$

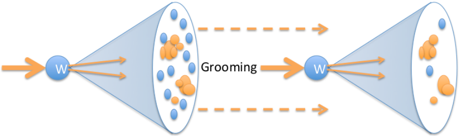
- For signal should form a **Jacobian peak** at the new particles **mass**

Hadronic W/Z Reco. – $W/Z \to qq$

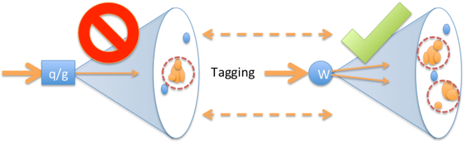
Event Selection – $W/Z \to qq$



1. Select events with **high** p_T, **central** jets
   - Use **large-R** parameter jet to collect **'all' radiation** from the original V decay
2. **Groom** the jets
   - Signal: Remove **unwanted** jet constituents not from the signal, e.g. **pile-up**
   - Background: **Preserve** the background characteristics

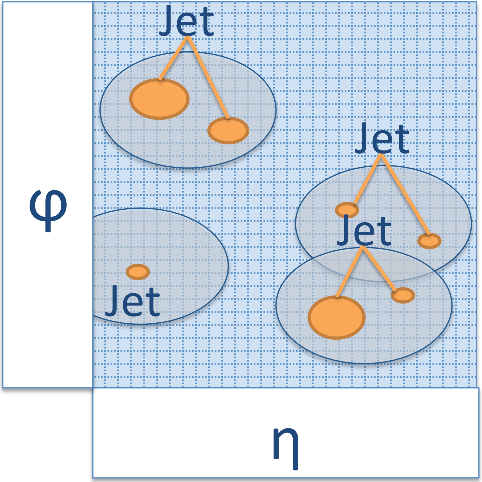


3. **Tag** as bosonic jet (or indeed a Higgs or top jet)
   - Use **differences** between signal and background jet characteristics to **reject** background jets



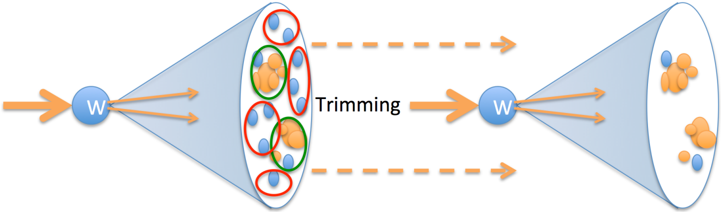
(1) Jet: Algorithm

- **anti-k_t** 1.0 jets used in Run-2 (ATLAS)
  - [arXiv:9707323] or [arXiv:0802.2470]
- Part of the **sequential recombination** family of jet reconstruction algorithms
  - Starts from local cluster weighted (LCW) topological clusters
  - Calculate the $d_{ij} = \min(k_{ti}^{-2}, k_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}$ between all jet constituents
  - Combine **closest constituents** first, i.e. high p_{T} and close-by
  - Merge while $R_{ij} \leq 1.0$ (in this analysis)
  - If there are no components within 1.0, **redefine as a jet** and remove from the collection of constituents
  - Merge until there are **no components** left
- Anti-kt jets have **have** p_{T} dependence
- Form more "conical" jets



(2) Groom: Anti-k_t Trimming

- The **trimming** algorithm, [arXiv:0912.1342], does what it says on the tin
- Aims to identify **soft** contamination from **pile-up/underlying event** and remove them from the jet



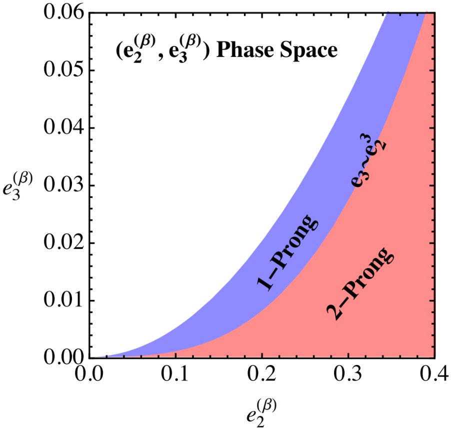
- The method is a few simple steps
  - For jet j, **re-cluster** the constituents into smaller-R **sub-jets** ($R = 0.2$)
  - If a sub-jet's $p_T^{\text{sub}} < 0.05 \times p_T^{\text{jet}}$ **discard** this sub-jet as a soft contribution
  - Otherwise keep the sub-jets constituents in the **final jet**

- Can make a simple **mass window** cut on the jet mass around the **boson** mass you want to tag
- $D_2^{\beta=1}$ is a tagging variable based on **2/3 point energy correlation functions**, [arXiv:1409.6298]
- Analogous to **n-subjettiness**, i.e. it tries to quantify how much a jet looks like a collection of n-sub-jets (CMS uses this)

$$e_2^\beta = \frac{1}{p_{TJ}^2} \sum_{1 \le i \le j \le n_J} p_{T_i} p_{T_j} \Delta R_{ij}^\beta$$

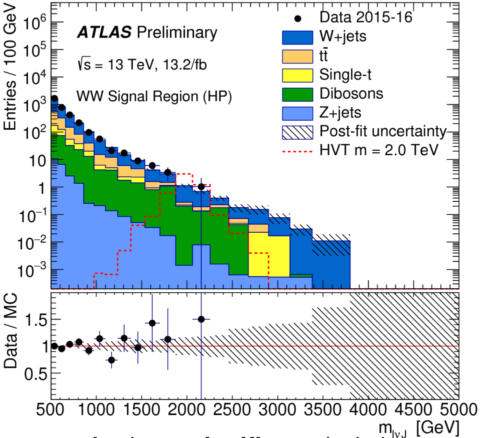
$$e_3^\beta = \frac{1}{p_{TJ}^3} \sum_{1 \le i \le j \le k \le n_J} p_{T_i} p_{T_j} p_{T_k} \Delta R_{ij}^\beta \Delta R_{ik}^\beta \Delta R_{jk}^\beta$$

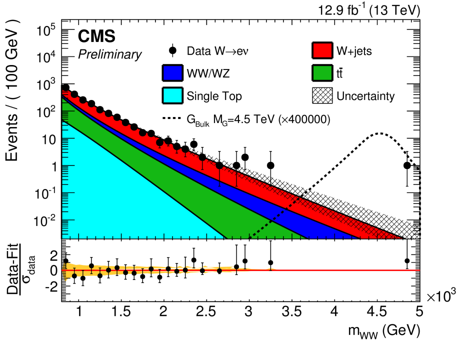
$$D_2^\beta = \frac{e_3^\beta}{(e_2^\beta)^3}$$



Bulk-RS – $G^* \rightarrow WW \rightarrow l\nu qq$

- Backgrounds are normalised/modelled with **data sidebands** and simulation



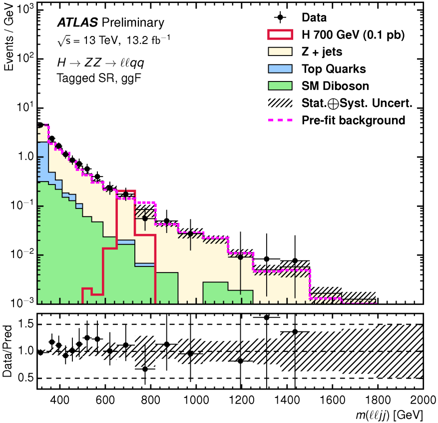


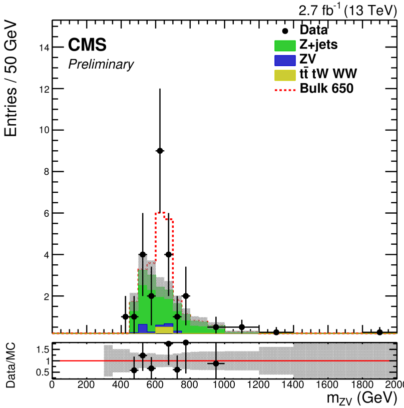
- Again **no significant** deviations seen from the SM backgrounds in **either** search
- ATLAS sets **limits** of $\mathcal{O}(1.24)$ TeV for **bulk-RS** models with $k/\bar{M}_{pl} = 1.0$
- CMS is **close** to excluding in the same region

ATLAS: EXOT-2016-62 | CMS: B2G-16-020

Bulk-RS $-G^* \rightarrow ZZ \rightarrow llqq$

- Backgrounds normalised/modelled with **data sidebands**/simulation





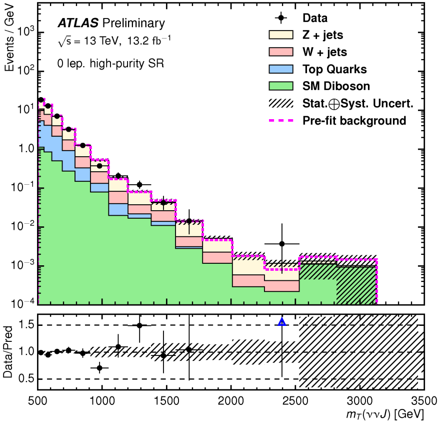
- CMS **observes** a 3.5σ **global** deviation at 650 GeV in the low mass search
- ATLAS sets **limits** of $\mathcal{O}(1)$ TeV for bulk-RS models with $k/\bar{M}_{pl} = 1.0$

ATLAS: EXOT-2016-82 | CMS: B2G-16-010

Bulk-RS – $G^* \to ZZ \to \nu\nu qq$

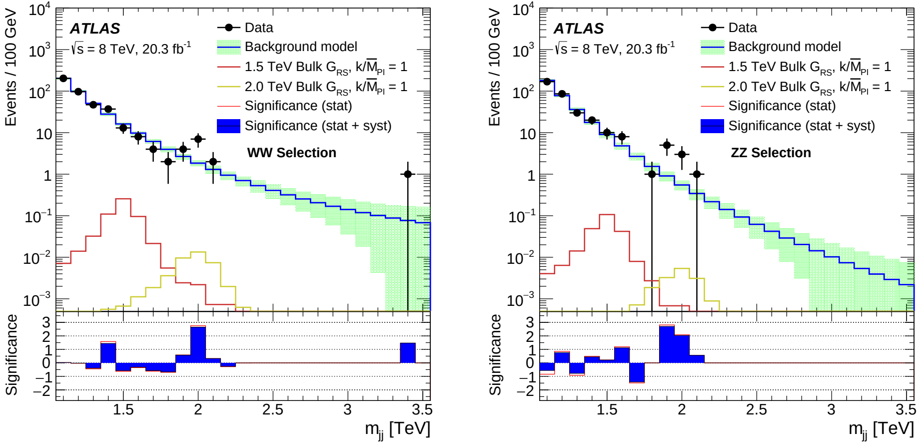
- **New** channel explored by ATLAS
- Uses M_T to **partially** reconstruct system
  - Signal would form a **Jacobian** peak on top of this distribution
- Backgrounds **modelled** by simulation, normalisation **constrained** by control regions in fit
- **No significant** excess seen, sets 95% CL limits of 1.1 TeV on G^* masses

ATLAS: EXOT-2016-82



Bulk-RS $-G^* \to ZZ/WW \to qqqq$

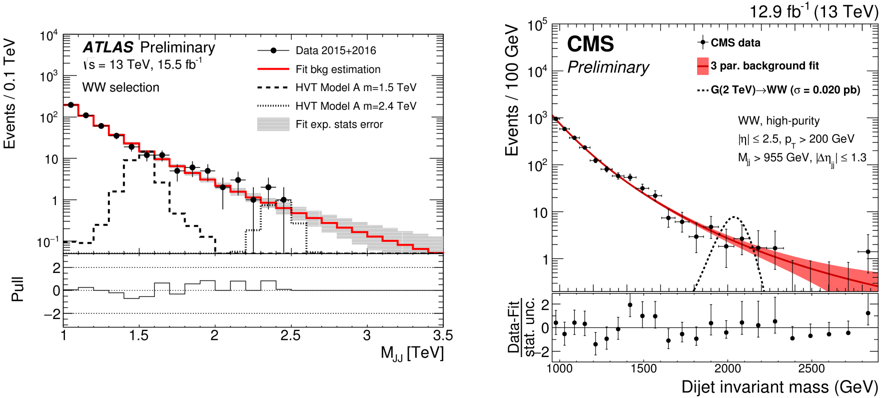
- Also some **excitement** in this channel in the Run-1 data ($\approx 3.5\sigma$ local, $\approx 2.4\sigma$ global)
- **Only** really seen by ATLAS ($\approx 1.9\sigma$ local in CMS) but none the less **exciting**
- Unable to fully **distinguish** W/Z peaks in fully hadronic channel, so events are **shared** between the *WW* and *ZZ* channels



Full disclosure I work on this channel

Bulk-RS – $G^* \to ZZ/WW \to qqqq$

- Both experiments follow separate **grooming/tagging** of large-R jets
- QCD background modelled by a **smoothly falling** parameterised fit



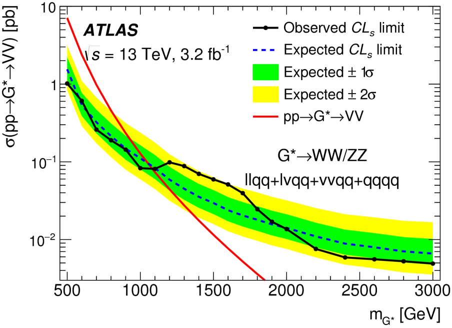
- Excess **not seen** in Run-2 data, another disappointment
- **Neither analysis** has the power to exclude a bulk-RS graviton with this data

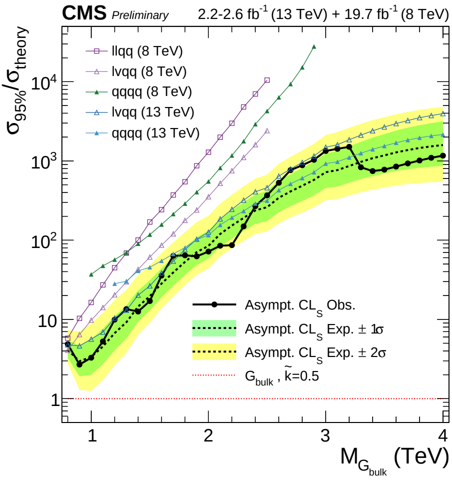
ATLAS: ATLAS-CONF-2016-055 | CMS: B2G-16-021

Bulk-RS – $G^* \to ZZ/WW$

- The **combination** of the diboson channels can push the limits **further** than the individual measurements can reach alone

- CMS limits do not exclude as their benchmark point has a **lower expected** cross-section

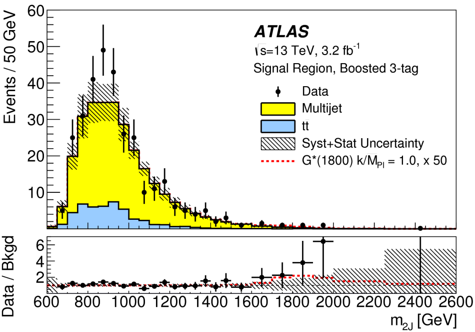


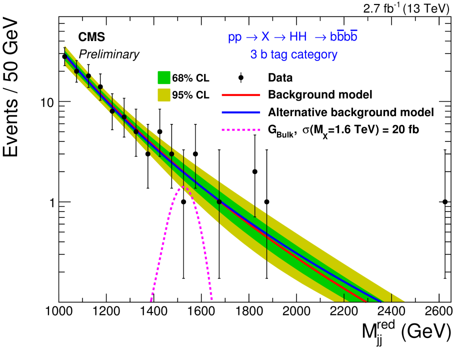


ATLAS: EXOT-2016-01 | CMS: B2G-16-007

Bulk-RS – $G^* \to HH \to bbbb$

- Jets tagged as **'Higgs' candidates** using mass window and *b*-tags (1 || 2)
- Backgrounds modelled using **un-tagged data** sideband regions



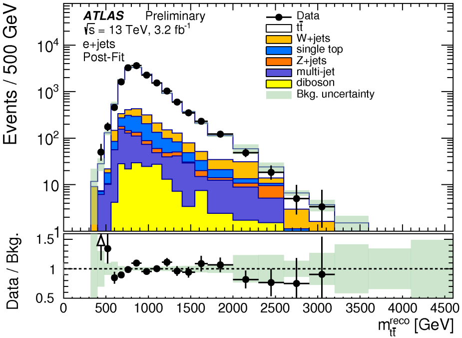


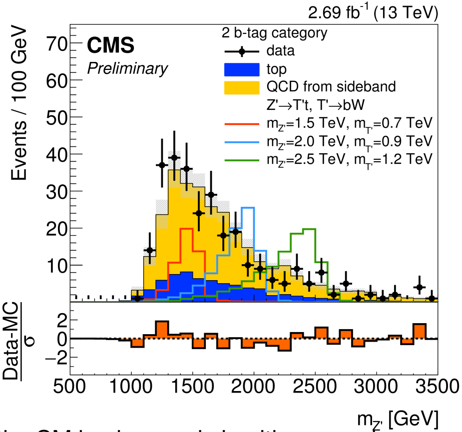
- **No significant** deviations seen from the SM backgrounds in either search
- ATLAS sets limits of $\mathcal{O}(0.75(1.0))$ TeV for bulk-RS models with $k/\bar{M}_{pl} = 1.0(2.0)$, driven mainly by the resolved channel (not shown)
- CMS does **not quite** have the reach to exclude
- Already using **Higgs tagging** in searches!

ATLAS: EXOT-2015-11 | CMS: B2G-16-008

Bulk-RS – $G^* \to t\bar{t}$

- Jets tagged as **top candidates** using mass window, jet sub-structure (N-subjettiness) and *b*-tagging requirements
- Backgrounds modelled by simulation and **data-driven** methods

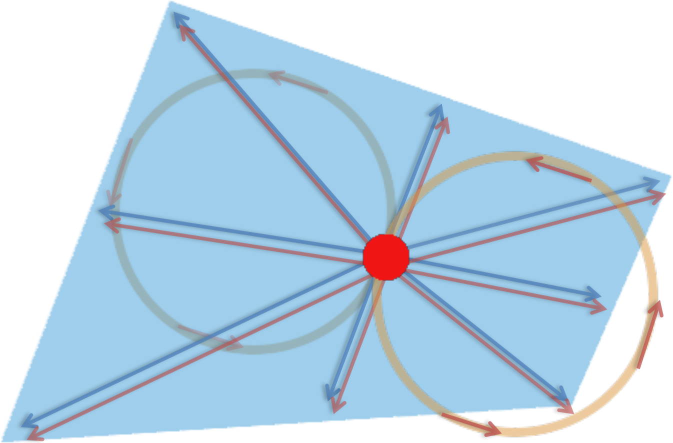




- **No significant** deviations seen from the SM backgrounds in either search
- No limits on G^* set by **either analysis** this time

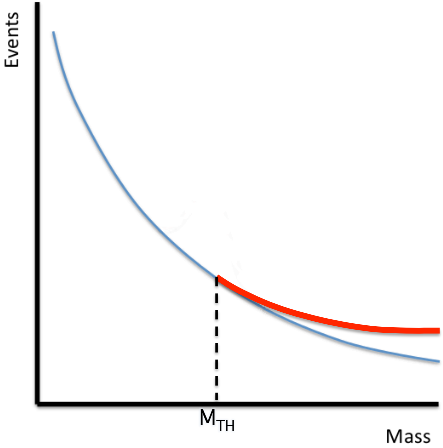
ATLAS: ATLAS-CONF-2016-014 | CMS: B2G-16-013

- Only graviton **propagates** in extra–dimension
- Clean channels!
- $G^* \to e^+e^-$
- $G^* \to \mu^+\mu^-$



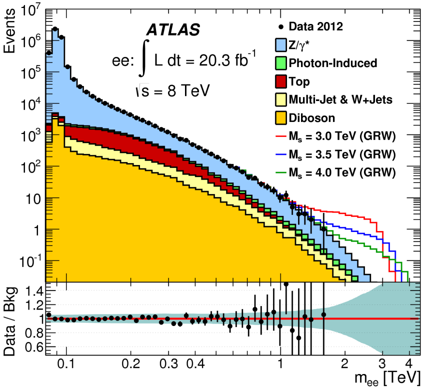
‘Non-resonant’ – $G^* \to XX$

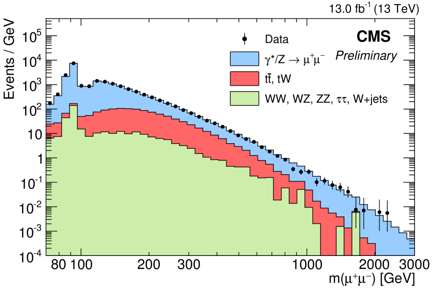
- In the **large extra-dimension** ADD model the KK–modes are **so close** together that they become **unresolvable**
- They therefore appear as a **deviation** to the expected slope of the SM background process, more **subtle** than a bump!
- Deviation would begin at a **threshold mass**, M_{TH}, at the mass of the **first** KK–mode/turn on of quantum gravity
- If found would need to be **disentangled** from processes such as **contact–interactions**



'Non-resonant' – $G^* \to ll$

- Using the same clean di-lepton decay modes as for RS1, can search for deviations in the tails
- Backgrounds modelled using simulation, normalised in Z control





- No deviation seen in the tails by either experiments, limits set on the threshold around 4 – 5 TeV in Run-1, no limits set in Run-2 yet
- Similar message from $\gamma\gamma$

ATLAS: ATLAS-CONF-2016-045 | CMS: EXO-16-031

Current Limits – ATLAS Exotics

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

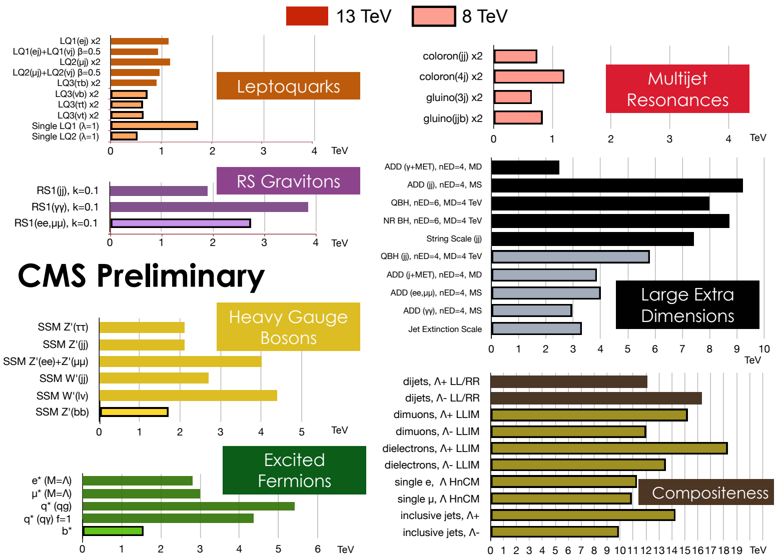
$\int \mathcal{L}\,dt = (3.2 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s}$ = 8, 13 TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	13.2	G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	13.3	Z' mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	13.3	W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	W' mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \to WZ \to qqqq$ model B	–	2 J	–	15.5	W' mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \to WH/ZH$ model B	multi-channel			3.2	V' mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	Λ 19.9 TeV $\eta_{LL} = -1$		ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	Λ 25.2 TeV $\eta_{LL} = -1$		1607.03669
	CI $uutt$	2(SS)/≥ 3 e,μ	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/≥ 3 e, μ	≥ 2/≥ 1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \to WtWt$	2(SS)/≥ 3 e,μ	≥ 1 b, ≥ 1 j	Yes	3.2	$T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	15.7	q^* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	8.8	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to ee$	2 e (SS)	–	–	13.9	$H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \to ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\sqrt{s}$ = 13 TeV

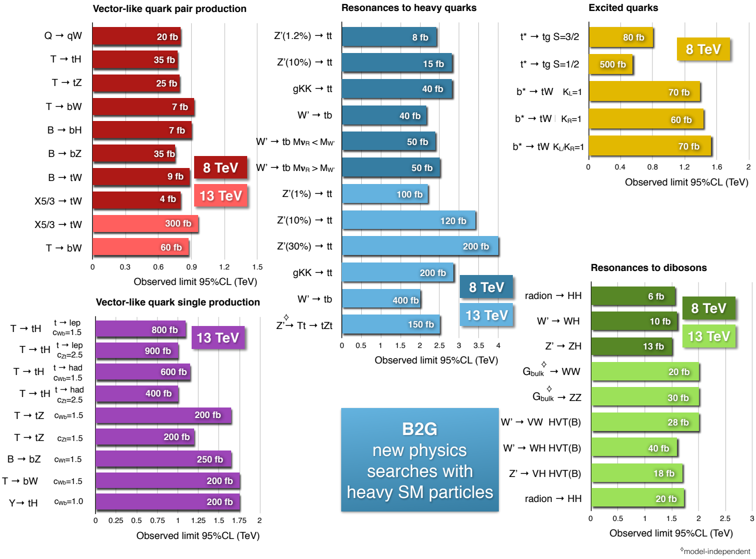
10^{-1} 1 10

Current Limits – CMS Exotica



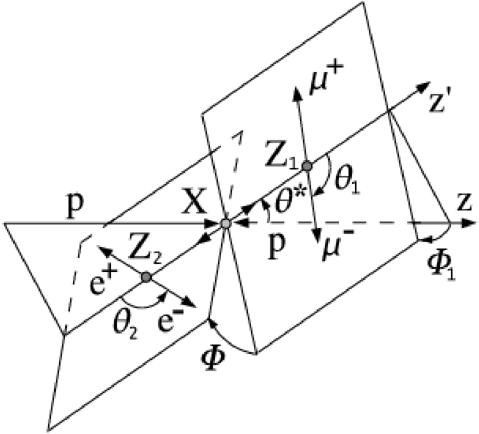
CMS Exotica Physics Group Summary – ICHEP, 2016

Current Limits – CMS B2G



If a resonance is found?

1. **Confirm** spin of the particle (arXiv[1001.3396])
   - Measure decay angles
   - Use cos θ^* and ϕ^1 distributions to determine if it is spin-2? (next slide)
2. Can try to **disentangle** the production mode
   - Mix of $q\bar{q}$, gg and VBF would alter between models
   - Can then try to **separate** possible ADD vs bulk-RS vs RS1 models
3. Search for additional G^*s
   - Would be able to determine **curvature**/**size** of the extra-dimension
4. If in bulk-RS, then look for other **expected KK-modes** for other SM particles travelling in the bulk
5. A non-resonant ADD G^* would need to be distinguished from **contact interactions**



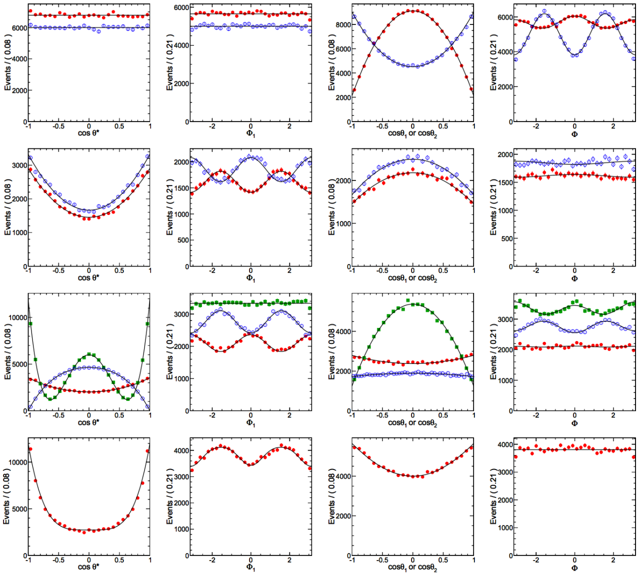
If a resonance is found?

Spin-0
0+
0-

Spin-1
1+
1-

Spin-2
2+ (min)
2+ (long)
2-

Background



Conclusions

- **KK-modes** of a graviton would be observable at **colliders** such as the LHC
- Many **extra-dimension** models contain them,
  - **ADD** large extra–dimension models
  - **Randall-Sundrum** models: RS1, bulk-RS
- LHC **general purpose** experiments driving current search limits in a **wide range** of channels
  - Resonant **RS1**, e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$
  - Resonant **bulk-RS**, VV, HH, $t\bar{t}$
  - Non-resonant **ADD**, e^+e^-, $\mu^+\mu^-$, $\gamma\gamma$
- Limits pushing out to **multi-TeV** level in many cases with the **latest data**
- Some **hints** seen along the way but none **confirmed** yet
- **Watch this space...**