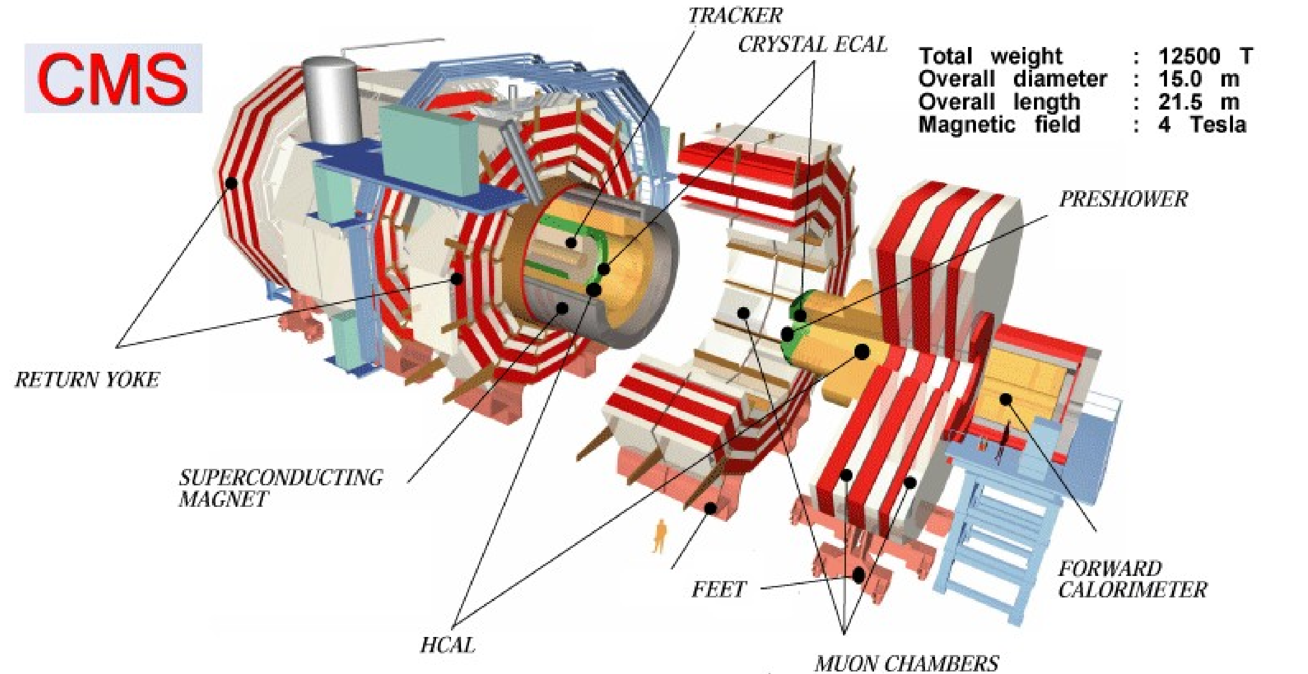
LISHEP 2009

Search for Extra Dimensions With Massive Hadronic Jets (at CMS)

Thiago Tomei
IFT-UNESP and SPRACE

The Compact Muon Solenoid



- The Compact Muon Solenoid (CMS) is a general-purpose, state-of-the-art particle detector designed to record data from 14 TeV proton-proton collisions at the Large Hadron Collider.
  - A main goal: ascertain the existence of the Standard Model Higgs Boson.
  - Also: unravel the structure of matter at the TeV scale.

The Hyerarchy Problem

- How come $M_H << M_P$?
  - The Planck scale M_P is the scale where gravity is thought to become strong, which defines M_P as a natural cutoff Λ for the Standard Model. In this case, however, M_H gets quantum corrections ~ Λ^2, bringing M_H ~ M_P.
    - Unless, at M_P , a 1 in 10^{34} fine tuning brings M_H down to ~ 100 GeV.
  - But the SM is not stable with M_H > 1 TeV, due to loss of unitarity in 2 → 2 gauge boson scattering.
  - Therefore, new Physics must appear in a scale ~ M_H in order to stabilize the Higgs mass.
- Some possibilities for the new Physics:
  - Modifications to the Standard Model (like Supersymmetry).
  - Modifications to Gravitation (like Extra Dimensions – ADD, RS, UED).

The Randall-Sundrum 1 Model

- Basic proposal: Universe is an AdS_5 space, endowed with two 3+1 branes, called "Planck brane" and "Weak brane".
- The 5th dimension is assumed to have orbifold (S_1 / $\mathbf{Z}_2$) topology, with compactification radius r_c. The branes sit at the fixed points of the extra dimension ($\phi = 0, \pi$).
- Normal (3+1) dimensional field theories in each brane – the SM is localized in the Weak brane. Gravity extends through the bulk, and will be subject to canonical quantization.
- Classical action + Einstein equations for this setup leads to a warped geometry. (Poincare invariance is required in the usual dimensions.)

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

Warp factor

5^{th} dimension

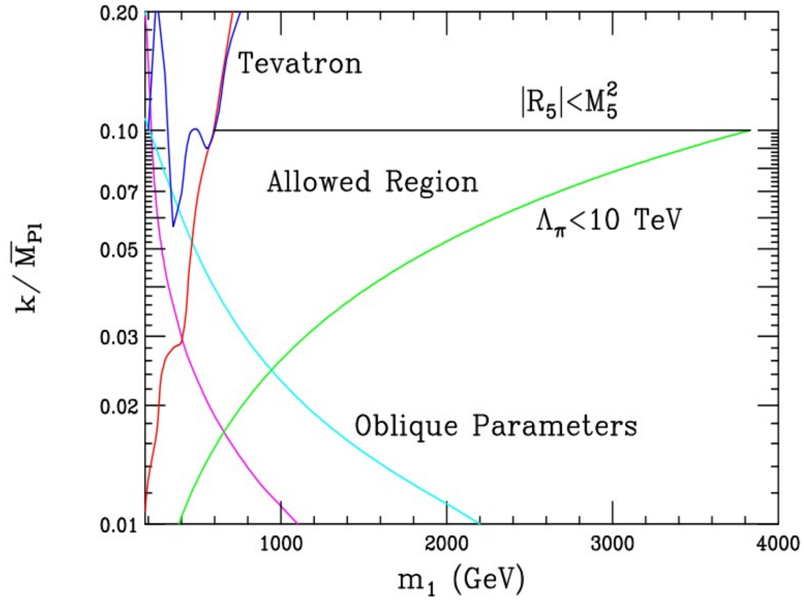
The Randall-Sundrum 1 Model

- Phenomenology:
  - Mass spectrum and couplings of the graviton. Propagation in the compact 5th dimension → Kaluza-Klein expansion:

$$\mathcal{L} = -\frac{1}{\overline{M}_{Pl}} T^{\alpha\beta}(x) h^{(0)}_{\alpha\beta}(x) - \frac{1}{\Lambda_\pi} T^{\alpha\beta}(x) \sum_{n=1}^{\infty} h^{(n)}_{\alpha\beta}(x)$$

    $\Lambda_\pi = e^{-kr_c\pi} \bar{M}_{Pl} = m_1 \bar{M}_{Pl} / k x_1$ is the inverse of the coupling constant of the graviton to matter. Therefore, there are two free parameters in the model: the graviton mass and the ratio k / M_P.

  - The graviton will show up in collider as a heavy (~ 1 TeV) resonance, and be detected through its decay products.



An "allowed region" plot, showing the region in the parameter space where the standard Randall-Sundrum 1 isn't excluded – a combination of direct searches from the Tevatron, indirect LEP limits, and theoretical constraints.

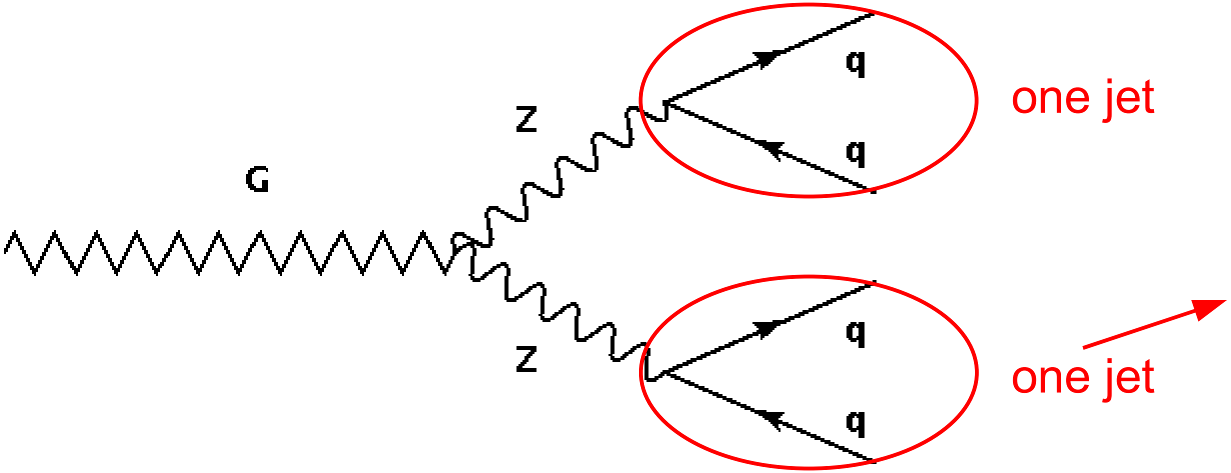
Plot by H. Davoudiasl, J.L. Hewett and T.G. Rizzo

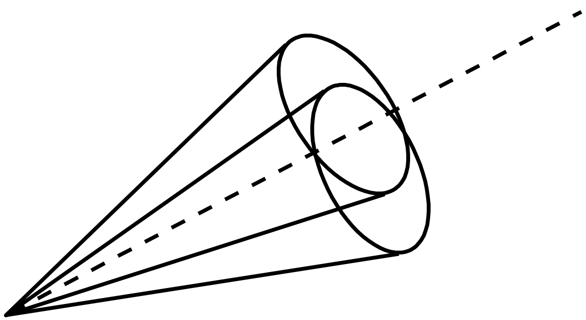
Search Strategy

- Searching for new Physics is a little like searching for someone in the dark – it is easier if you have a candle.
  - Candle in this sense means a well-known, easily recognizable and reconstructable signal. Ex: the leptonic Z decay.
- But selecting a very specific channel (graviton going to Z, Z decaying leptonically) takes its toll on the x-section.
- A possible compromise: the $G \rightarrow VV \rightarrow 4q$ channel.
  - Here, V stands for a W or Z boson.
  - Handle on the signal: a pair of invariant masses (80 or 90 GeV).
  - More favourable branching ratio due to the all-hadronic decay.
- Main disadvantage: searching for an all-hadronic signal at a hadron collider is hard due to the QCD background.

A Novel Phenomenum

- High-mass resonance → V becomes very boosted in the transverse direction.
  - In practical terms, that means that the quarks the V decays unto are so close that, after showering and hadronization, the resulting hadronic jets merge into a single jet.
  - From the macroscopic point of view, everything happens as if the vector boson had decayed to a single hadronic jet. That jet's properties therefore, approximate the vector boson's.



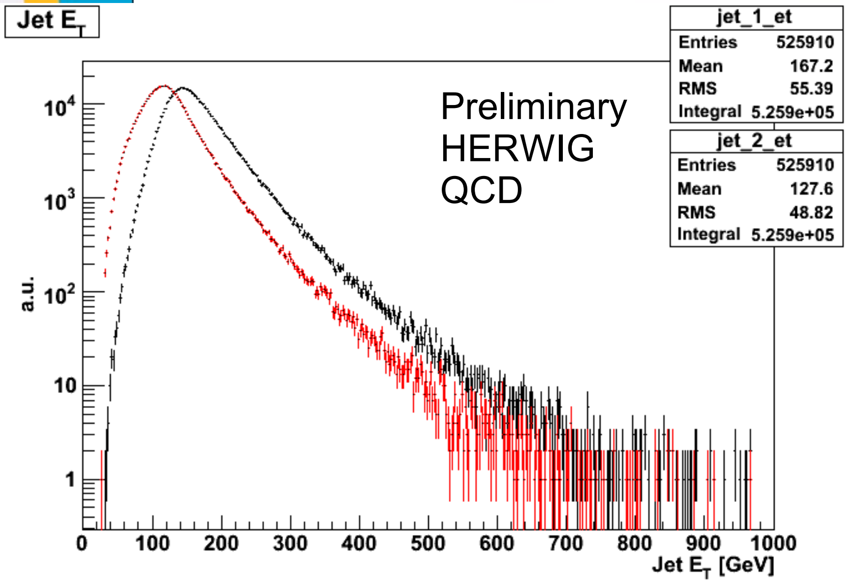


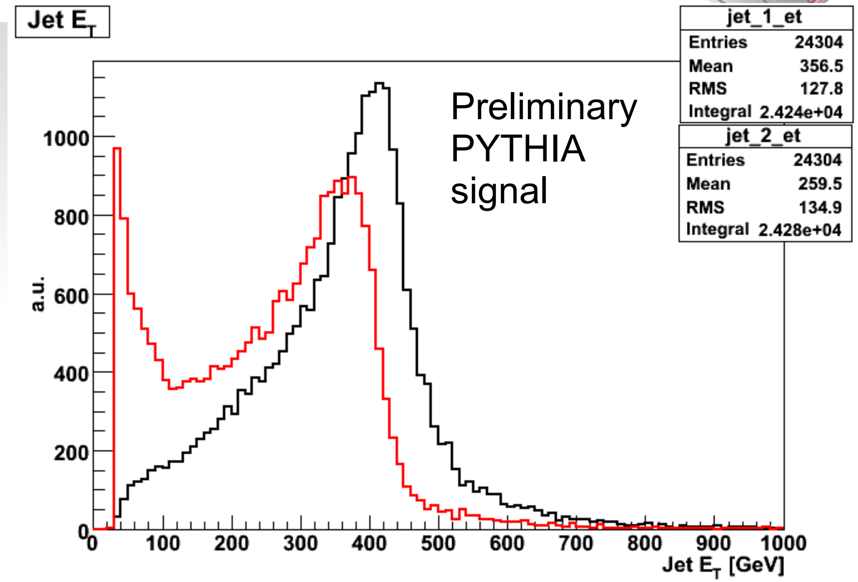
Each cone represents the hadronization and showering of one quark.

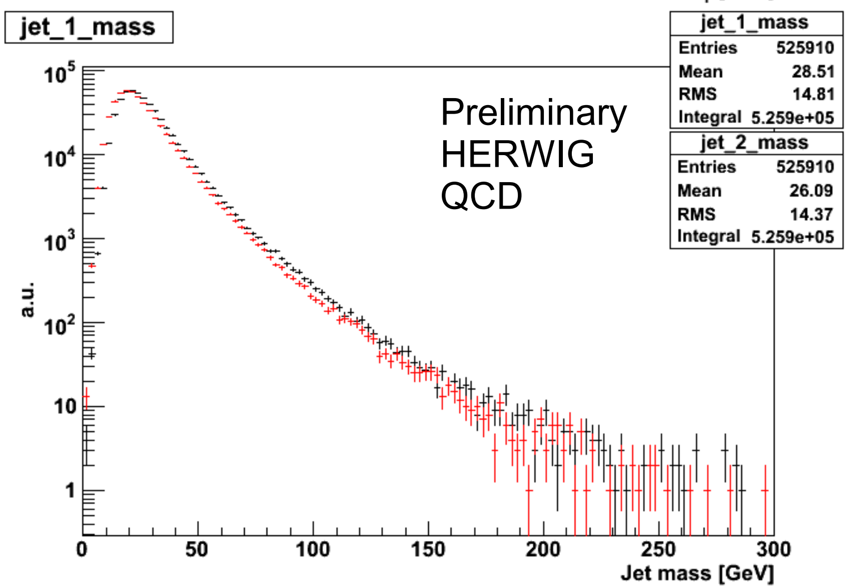
Monte Carlo Studies

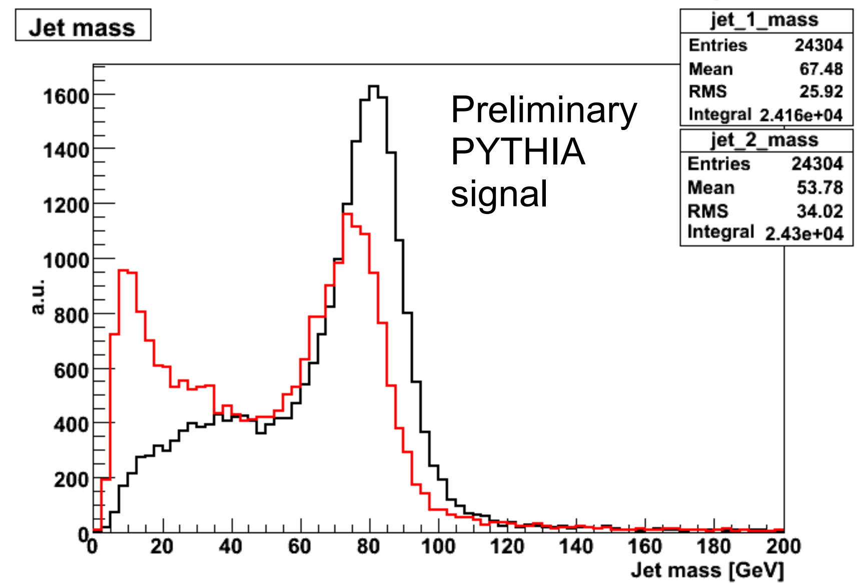
- An initial set of studies is being realized in the EXOTICA group of the CMS collaboration.
- At this initial stage, Monte Carlo simulations are being employed to investigate the basic characteristics of the signal, in search of traits that allow its separation from the QCD background.
  - Simulated signal (1 TeV RS $\rightarrow$ ZZ $\rightarrow$ 4q) events generated with PYTHIA v6.419
  - QCD background events generated with Herwig++. Generation pthat threshold of 170 GeV.
  - Detector effects simulated with the help of the GEANT4 toolkit.
  - Standard track and jet reconstruction algorithms, based on the Kalman filter technique and the Seedless Infrared Safe algorithm, respectively.
- DISCLAIMER: all plots shown through the talk are completely preliminary.

Jet Kinematics





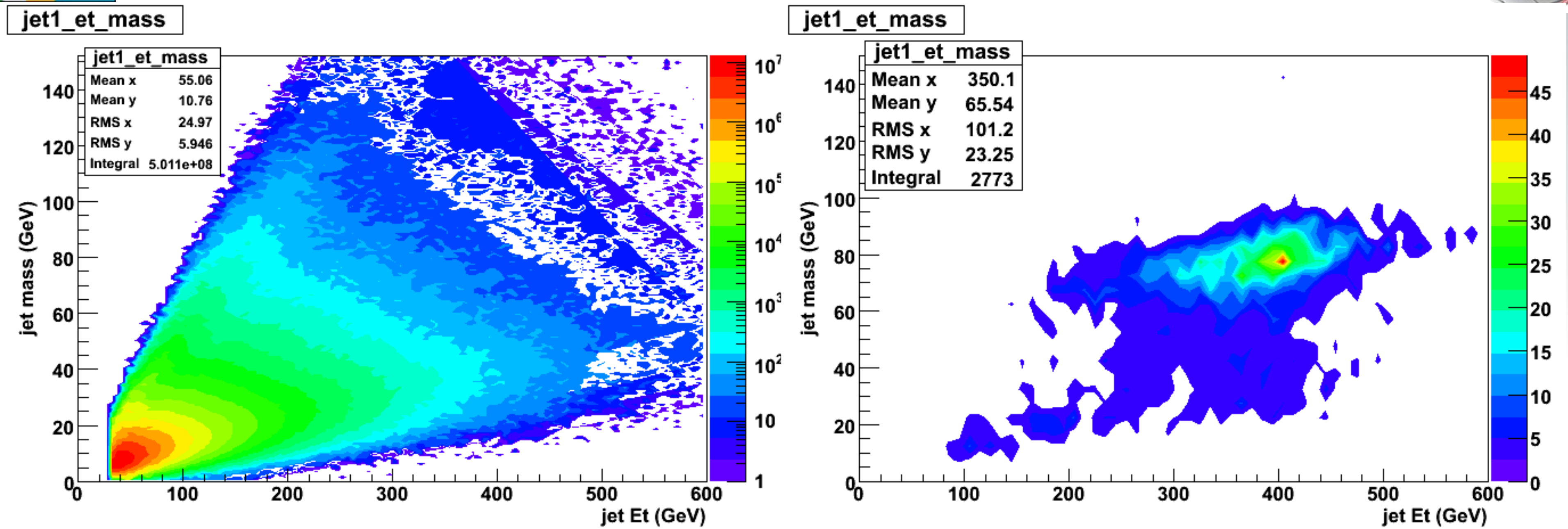




Jet Kinematics

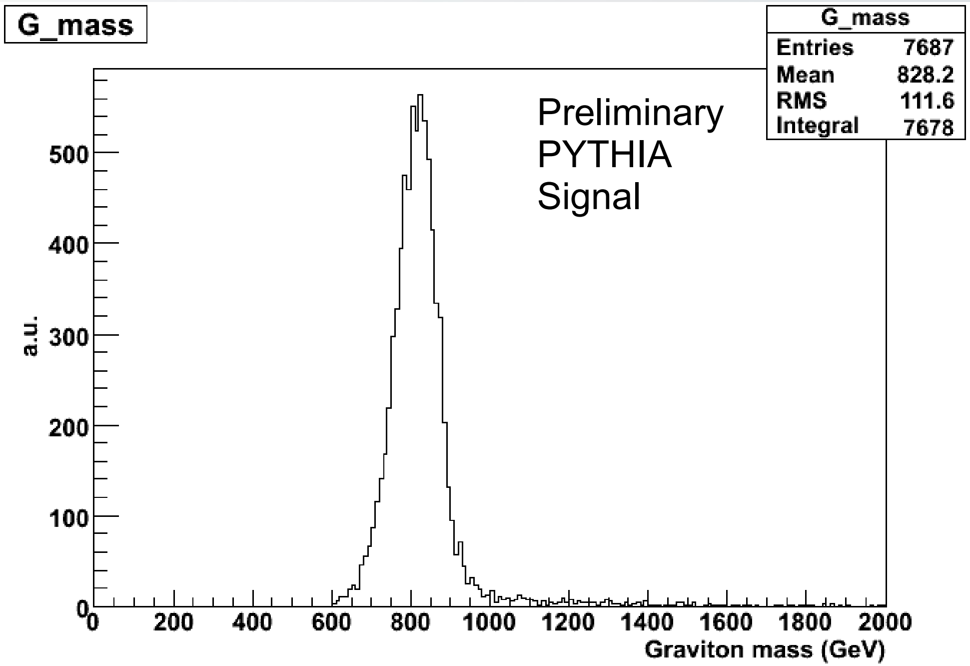
- The 1st and 2nd jet have very different behaviours in the signal and background samples.
  - Signal: the jets have a well-defined structure in the mass spectrum, near the mass of the Z – the difference in the value is due to the misreconstruction of the hadronic jet. Also, they are generally moderate-to-high (> 100 GeV) E_T jets. These are the so called "massive, boosted jets".
  - Background: both the mass and the E_T spectra are smooth (the structure at the lower end of the E_T is an artifact introduced due to the generation threshold).
- It seems that a first step in the analysis would be to define a set of thresholds ("cuts") to be applied to the jets.
  - Namely, an E_T threshold and a mass window.
  - Question that poses itself – are those cuts correlated?

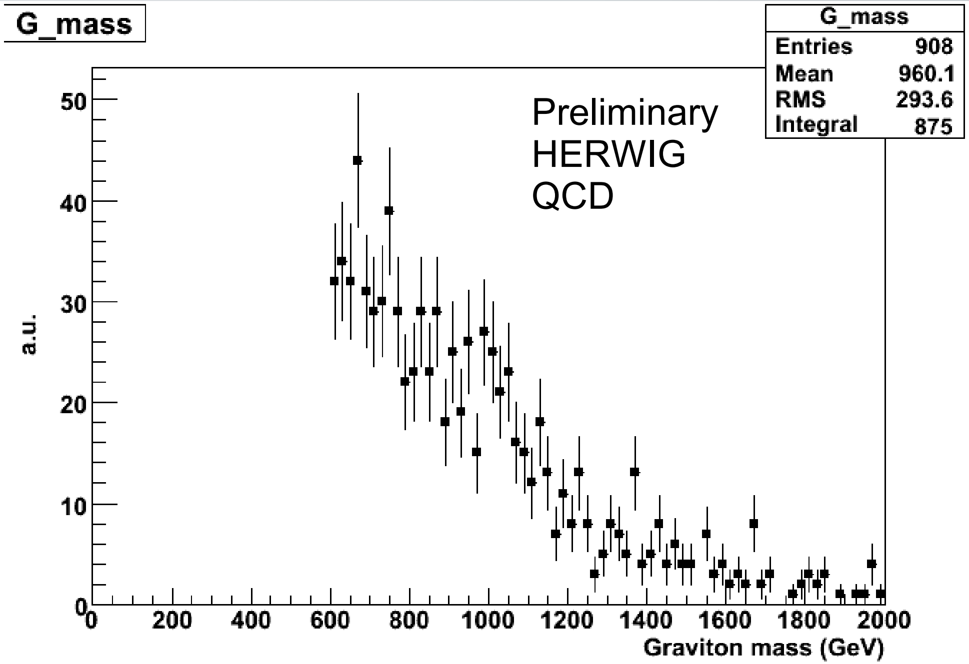
E_T and Mass Correlations



- Generally, in QCD events there is a positive correlation between the mass and the jet E_T. In signal events, there is a well-defined blob just below the vector boson mass.
- That means that, compared to standard QCD jets, the boosted jets from the signal events are much more massive than what would be expected.

Dijet Invariant Mass





- After enforcing two sets of cuts – a minimum E_T for the jets a mass window around the Z mass, one can plot the invariant mass of the two most energetic jets.
- A peak structure is clearly visible in the signal events spectrum, while no such structure is visible in the QCD one.

Broader Horizons

- Some other tecniques to study these boosted jets are in development.
  - Searching for subjets inside the boosted jets.
  - Studying the energy distribution (through calorimetric deposits and / or tracks) inside the jets.
- But why so much interest in boosted jets?
- In general, any heavy resonance can decay hadronically through heavy objects (W, Z or top), giving rise to boosted jets. So, the applicability of these techniques goes beyond RS gravitons.
  - In particular, it is even more interesting in the case of tops – the 3rd generation appears to hold the key to Physics Beyond the Standard Model.

Conclusions

- The LHC and the Compact Muon Solenoid are coming online this year, allowing us to probe the TeV energy scale.
- Studies are underway to test many models for the Physics Beyond the Standard Model. In particular, the Randall-Sundrum 1 Model – a model for Warped Extra Dimensions – posits a heavy resonance (the graviton) that can be detected at CMS.
- The all-hadronic channel through heavy objects for the graviton decay produces a novel signature – the presence of a pair of massive, boosted jets whose invariant mass is the mass of the heavy resonance itself.
- The techniques used for this search are not specific to this – they are applicable to any heavy resonance that decays in the prescripbed way.

Thanks

- To the LISHEP 2009 organizers.
- To the SPRACE team.
- To FAPESP for the financial support.