Warped Geometry

Consequences and LHC Signatures

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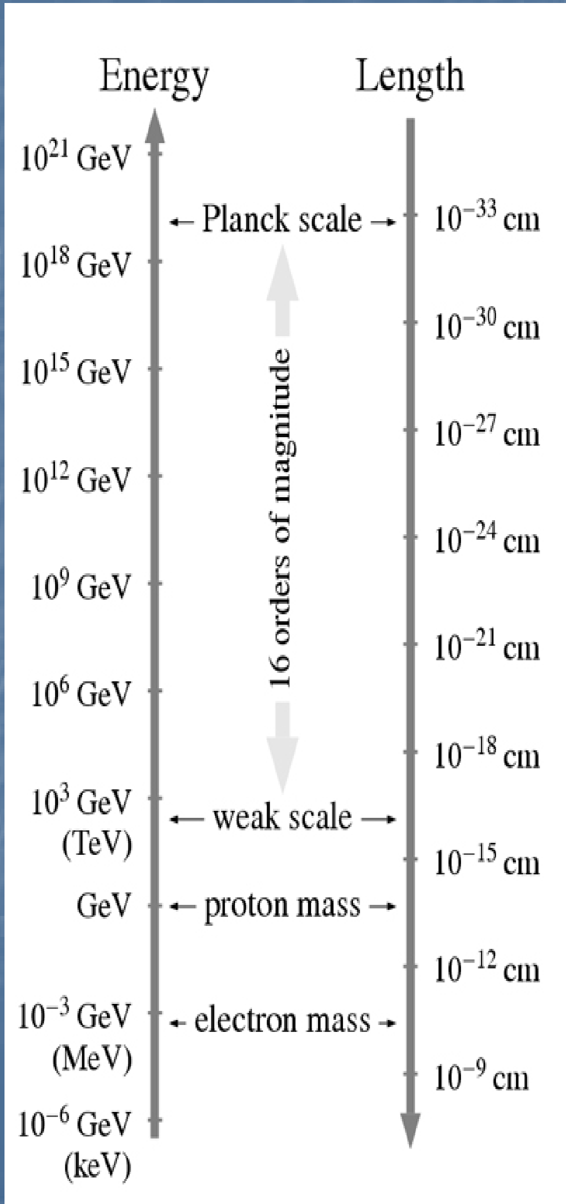
Entering LHC Era

- Many challenges as LHC approaches
- Critical questions:
  - Are we optimizing existing searches?
  - Are we doing all the searches possible?
    - Models
      - Lower-Scale: Supersymmetry, Little Higgs
      - Higher-Scale: Strongly Interacting theories, Extra dimensions
- Focus today on extra dimensions
  - Bonus: Way to learn about quantum gravity and strongly interacting physics

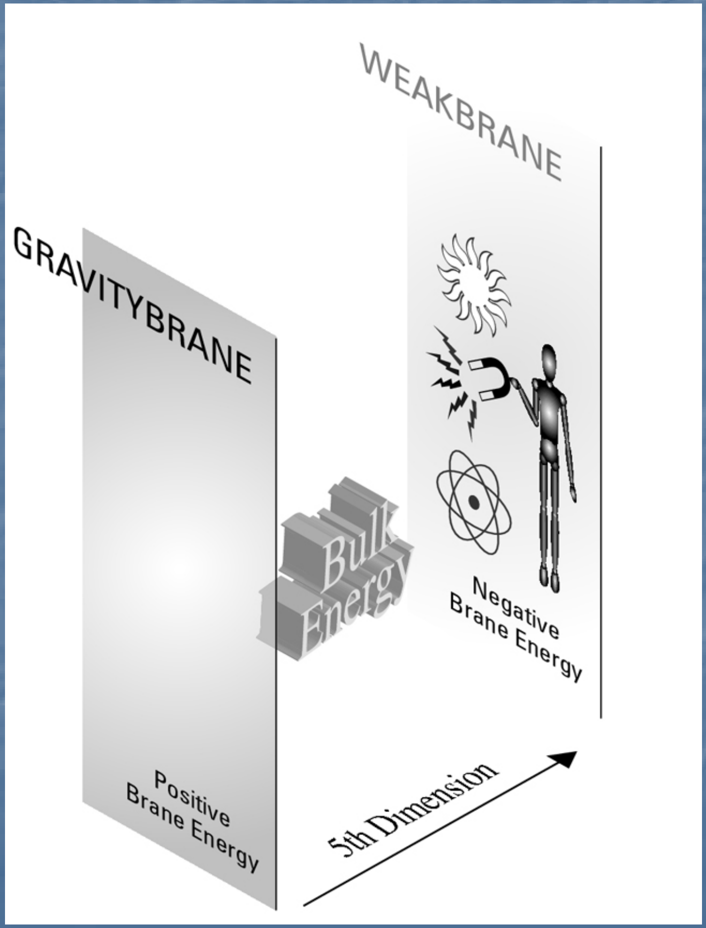
Use Extra D to address Hierarchy Problem

Need "fine-tuning" to get very different masses

Key issue in particle physics today

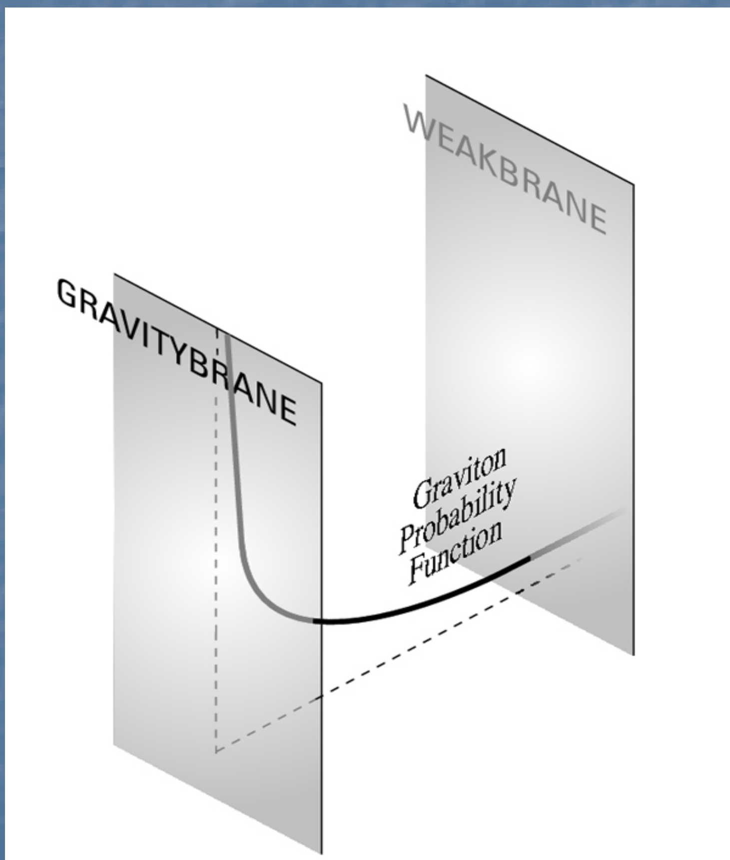


RS1 “Multiverse” Warped Spacetime



- Two branes
- Gravity will be concentrated on Gravitybrane
- But we live on a second brane:
- The Weakbrane/TeV Brane

Natural for gravity to be weak!



- Small probability for graviton to be near the Weakbrane
- If we live anywhere but the Gravitybrane, gravity will seem weak
- Natural consequence

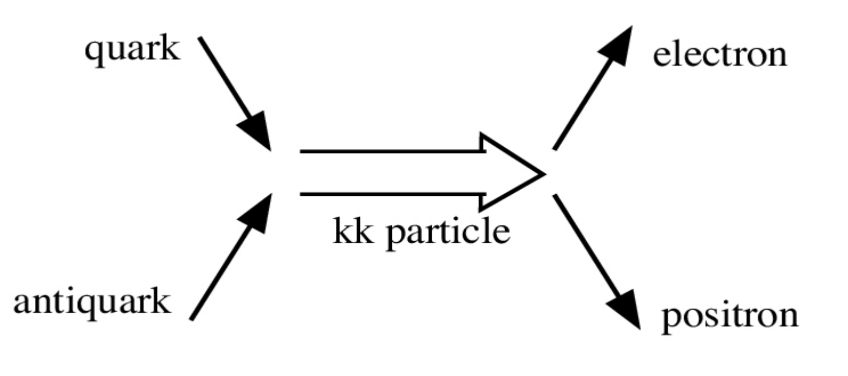
$$ds^2 = g_{MN}\,dx^M dx^N = e^{-2\sigma}\eta_{\mu\nu}\,dx^\mu dx^\nu - dy^2\,,$$

How to test?

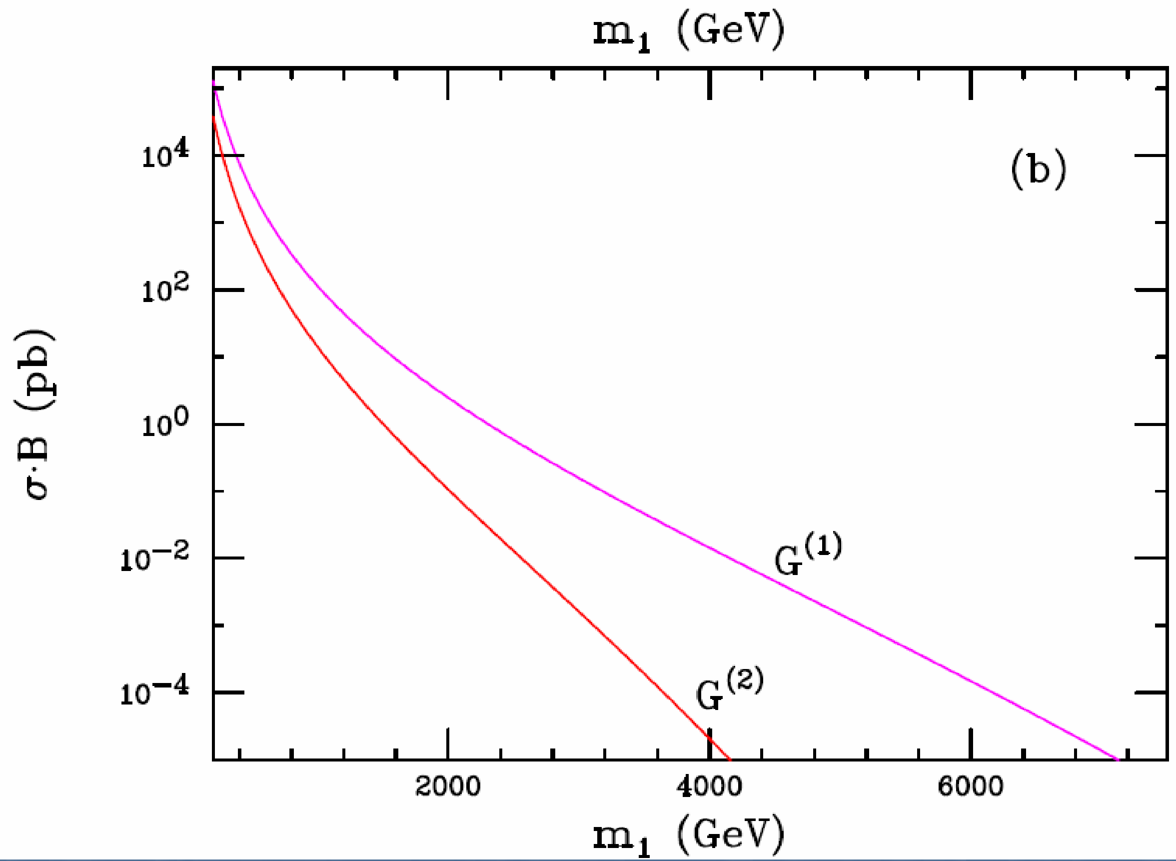
- Search for new particles!
- Kaluza-Klein (KK) particles
- Carry momentum in extra dimensions
- Looks like mass in 4 dimensions
- Connection to mass and weakness of gravity relative to other known forces tells us
- LHC will have the right energy to search for consequences of this theory

Experimental Signal: Can search for extra dimensions!

- Kaluza-Klein particles
- TeV, 2 TeV, 3 TEV (rough) spectrum
- With much stronger than gravitational interaction strength!
- Definite mass spectrum and “spin”-2
  - Truly different than other strongly interacting theories
  - Light spin-2 but gap
  - No other strongly interacting states as light



Reach for Graviton KK Modes

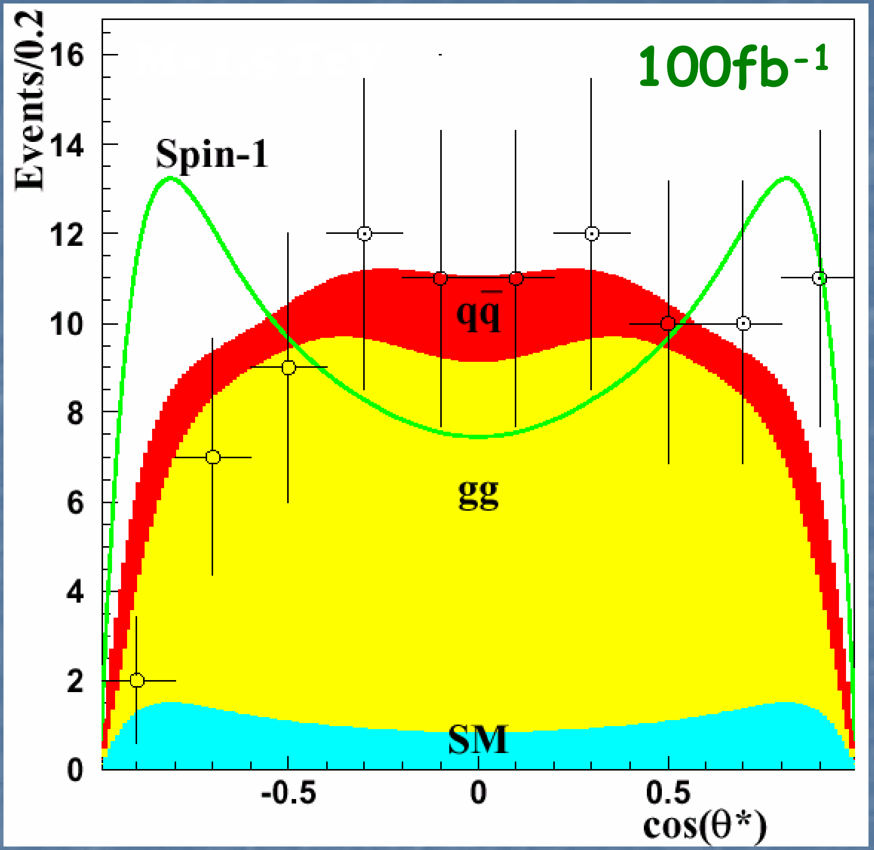


Davoudiasl, Hewett, Rizzo

graviton has spin 2

Angular distributions

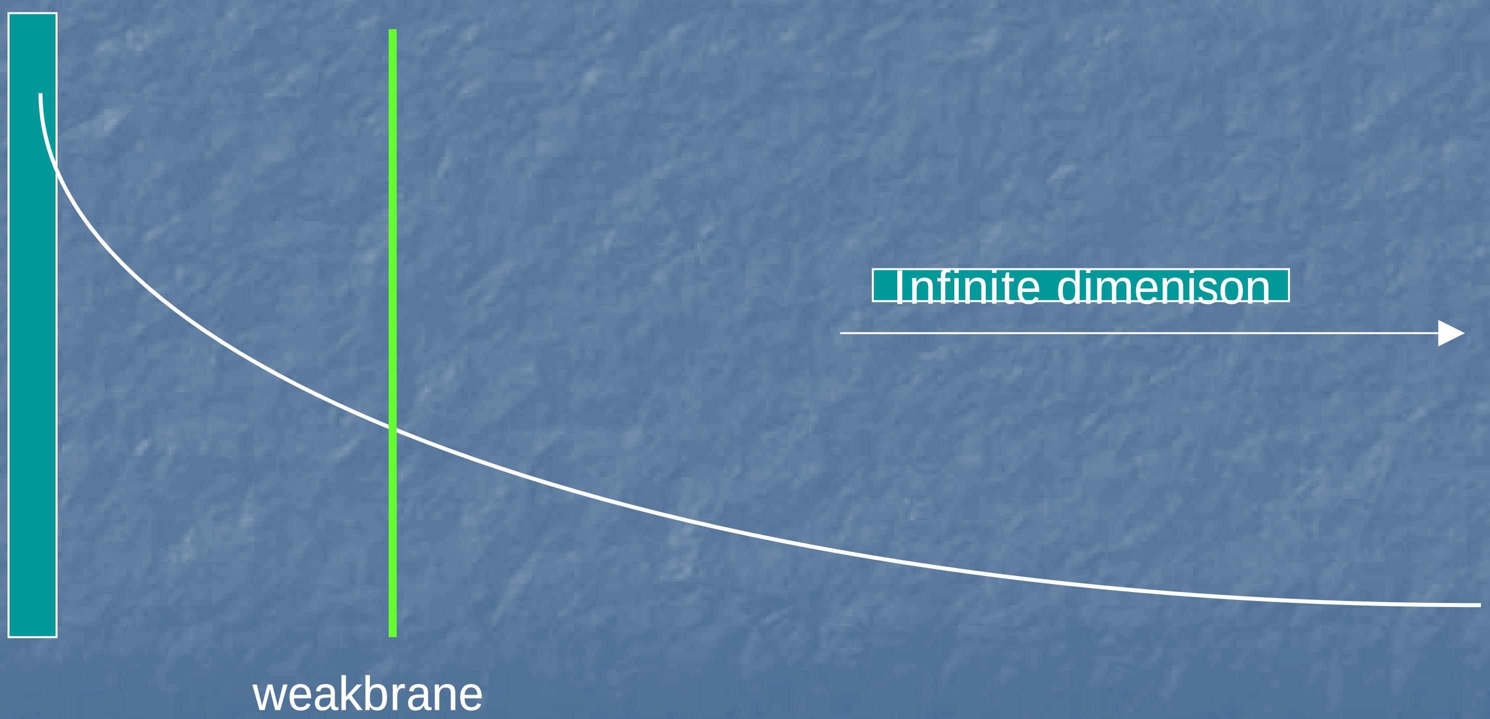
- $qq \to G \to ff$: $1 - 3\cos^2\theta + 4\cos^4\theta$
- $gg \to G \to ff$: $1 - \cos^4\theta$
- $qq \to G \to VV$: $1 - \cos^4\theta$
- $gg \to G \to VV$: $1 + 6\cos^2\theta + \cos^4\theta$
- DY background: $1 + \cos^2\theta$



- RS1 gives clean TeV-KK-graviton signal
- One of first things LHC could find
- Spin-2 and gap in spectrum definite indication of warped extra-dimensional geometry
- Could also exist lots of strongly interacting TeV-scale physics to complement this measurement
- **But not the only implementation of RS1 mechanism**
- **What does this imply about search strategies?**

Other warped models addressing the hierarchy?

Variations on RS1: Infinite extra dimension



Missing Energy Signal

- Looks like 6 large dimensions
- In this case KK mode decays to lighter KK modes
- KK energy goes to missing energy

- Variations of RS1:

matter in bulk or on brane??

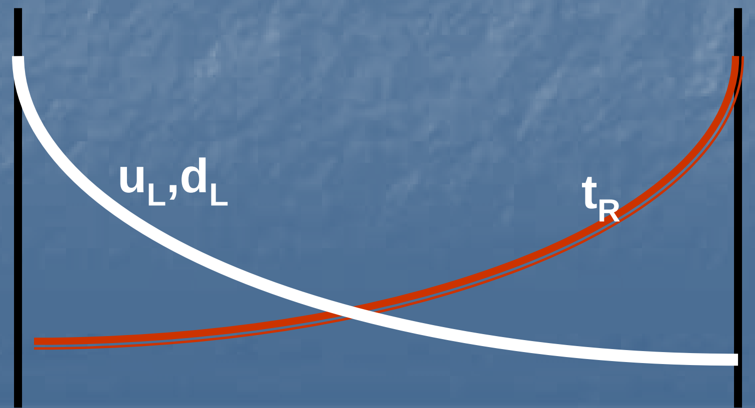
- Two key features that make bulk matter possible
  - Size of fifth dimension extremely small (only about 30 times fundamental scale—exponential hierarchy)
    - Means coupling won't be too diluted/weak
  - You only need Higgs on the Weakbrane to address the hierarchy
    - Problem only for the Higgs scalar: gauge boson and fermion masses are protected

Merits of bulk fermions and gauge fields

- Because **5D** cut-off is Planck scale
  - ✓ Allows for unification!
- Allows for interesting model-building:
  - ✓ Fermion masses from wavefunction overlap with Higgs field (on Weakbrane)
- We’ll see that bulk scenarios have distinctive signatures

Precise signatures depend on fermion wavefunction profiles

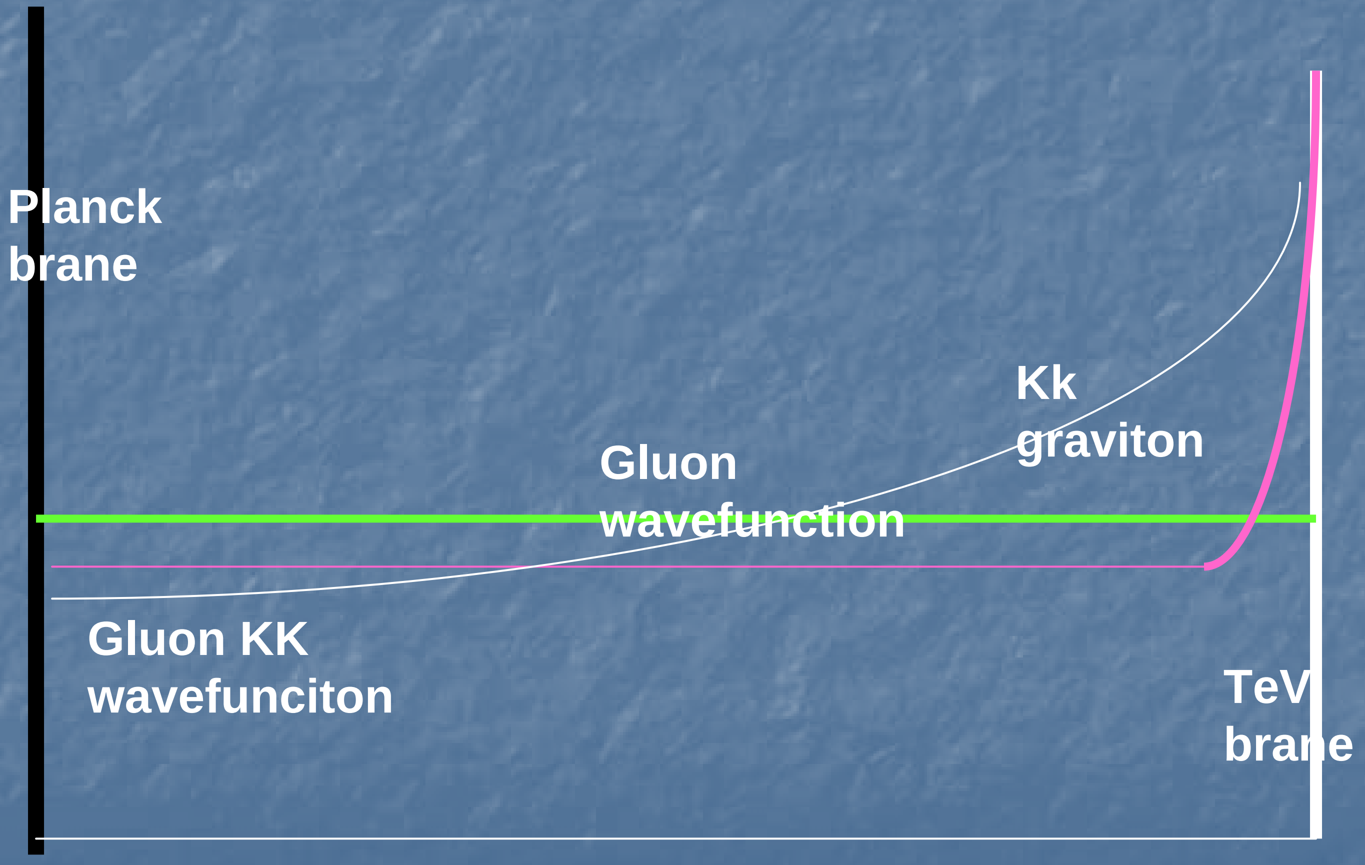
- Might expect nontrivial profiles
- Masses depend on overlap with Higgs
- Expect light fermions localized near Planck/Gravity brane
- Top near Weakbrane since it's heavy



Important Differences from Brane-Localized Matter

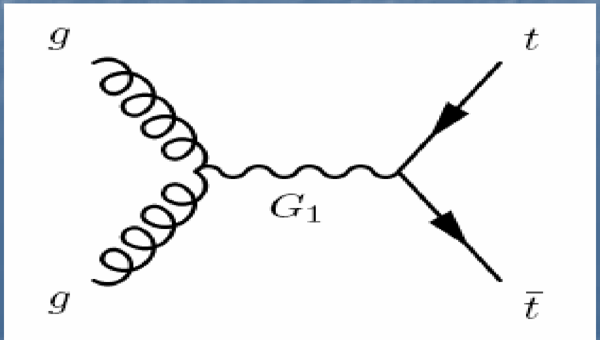
- Richer Spectrum
- KK modes of
  - Weak bosons
  - Gluons
  - Fermions
  - As well as gravitons
- But...lower Production Cross Section for Graviton
- Plus decays primarily into tops
  - Changes search strategies dramatically

Gluon, Gluon KK WFs



Lower Production Cross Section for the Graviton

- Light quarks are localized away from Higgs
  - Hence away from TeV brane
  - No Drell-Yan production from quarks
- Gluons are spread throughout the bulk
  - Coupling to graviton volume-suppressed



w/Liam Fitzpatrick,Jared Kaplan, Liantao Wang

KK Graviton Production

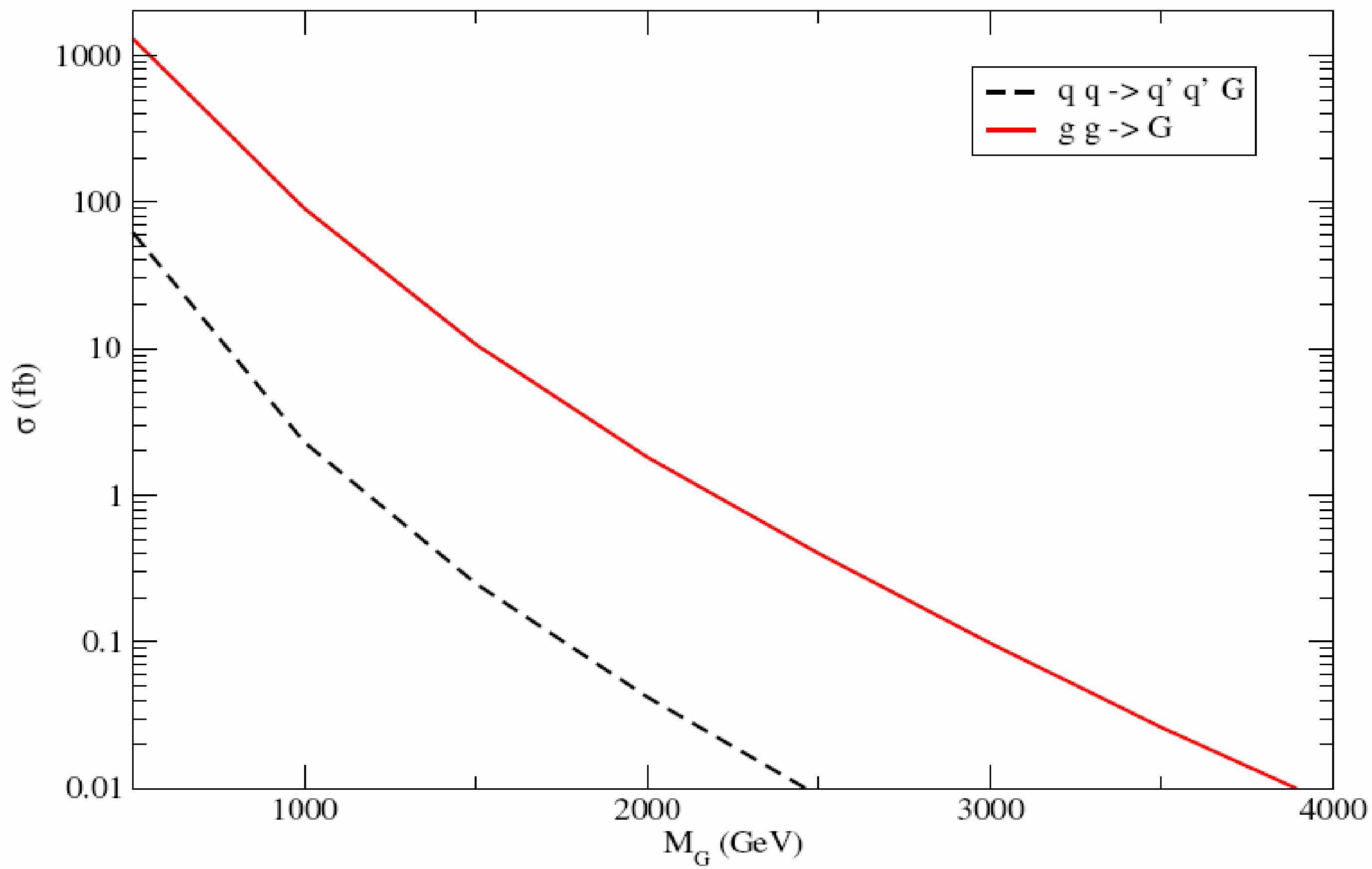


Figure 1: Cross section of KK-graviton production.

Final State? Dominant Decay to right-handed tops

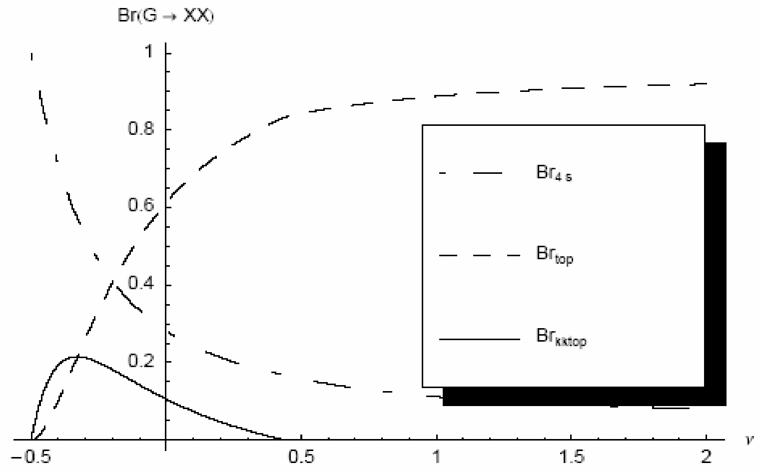
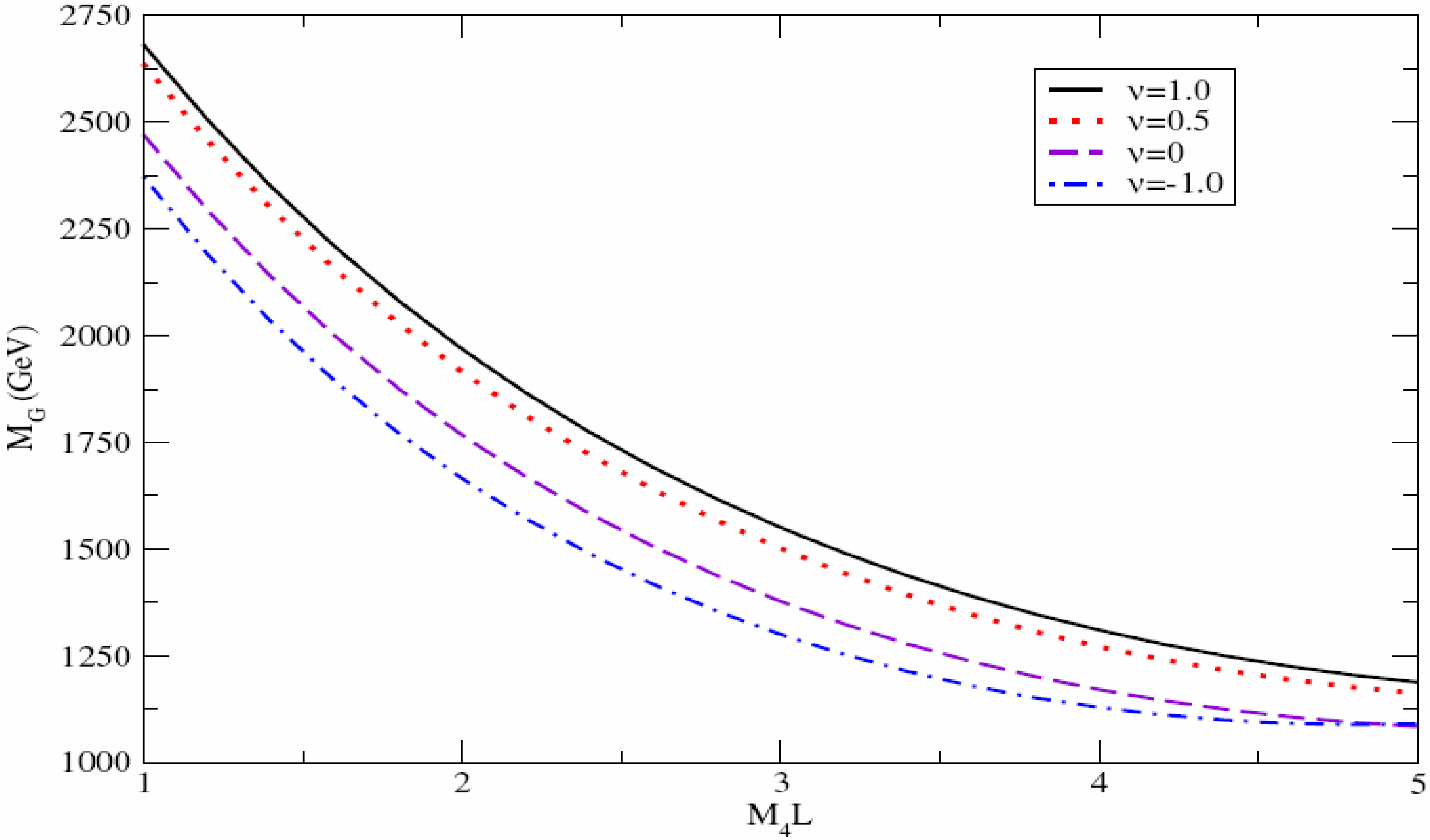


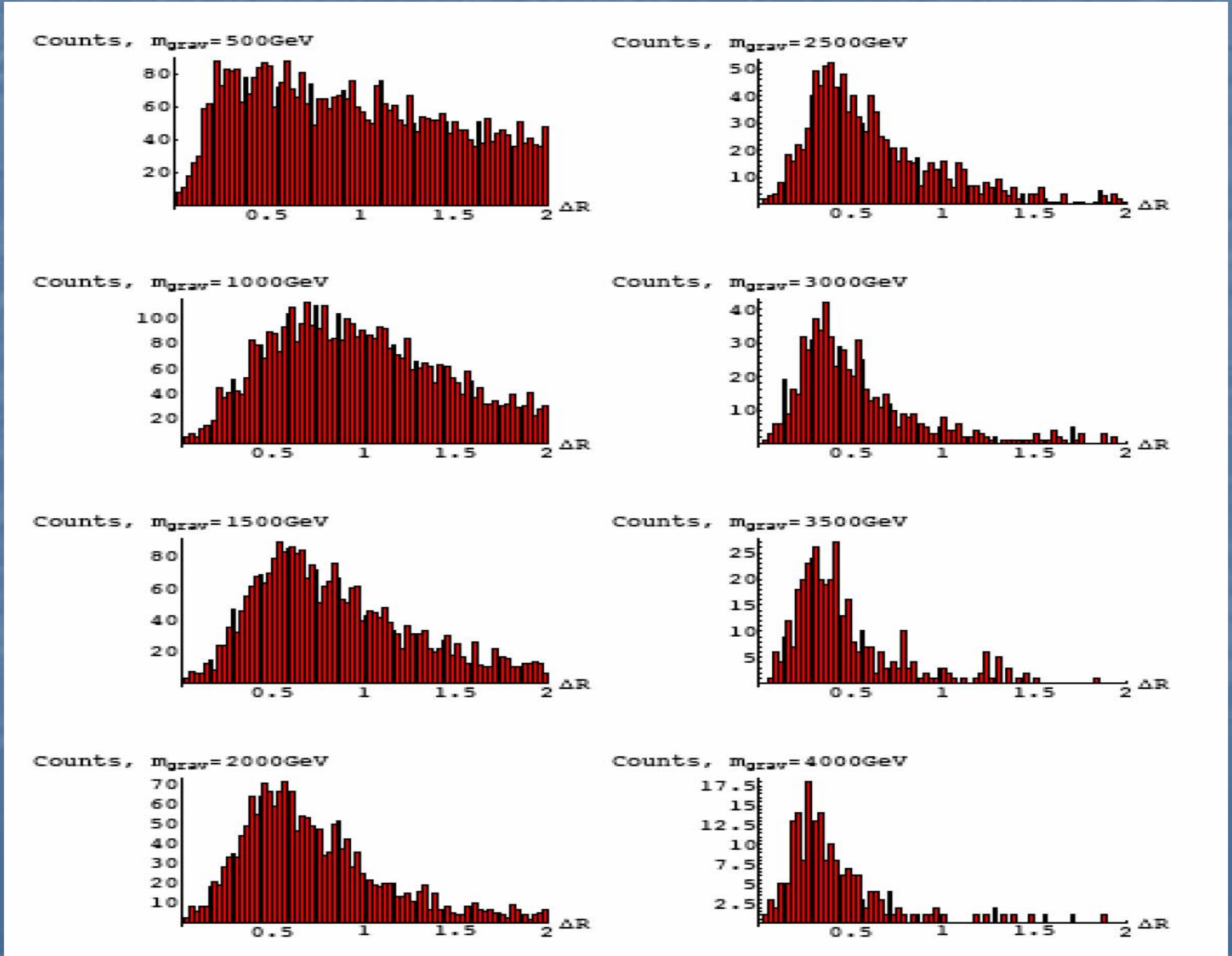
Figure 1: Branching Ratios for graviton decay to scalars and quarks.

$$\Gamma_{top} = \frac{1}{(M_4 L)^2 \mu_{TeV}^2} \left(\frac{1+2\nu}{1-e^{-\pi k r_c (1+2\nu)}} \frac{\int_0^1 dy\, y^{2+2\nu} J_2(3.83y)}{J_2(3.83)} \right)^2 \frac{3 m_{grav}^3}{160\pi}$$



3: The $s/\sqrt{b} = 5$ reach as a function of graviton mass and the parameter (M_4L). From
ach is shown for $\nu = 1.0, 0.5, 0.0, -0.1$.

Determining top jets: delta R: Angle between decay products



More Promising With Other Bulk Modes?

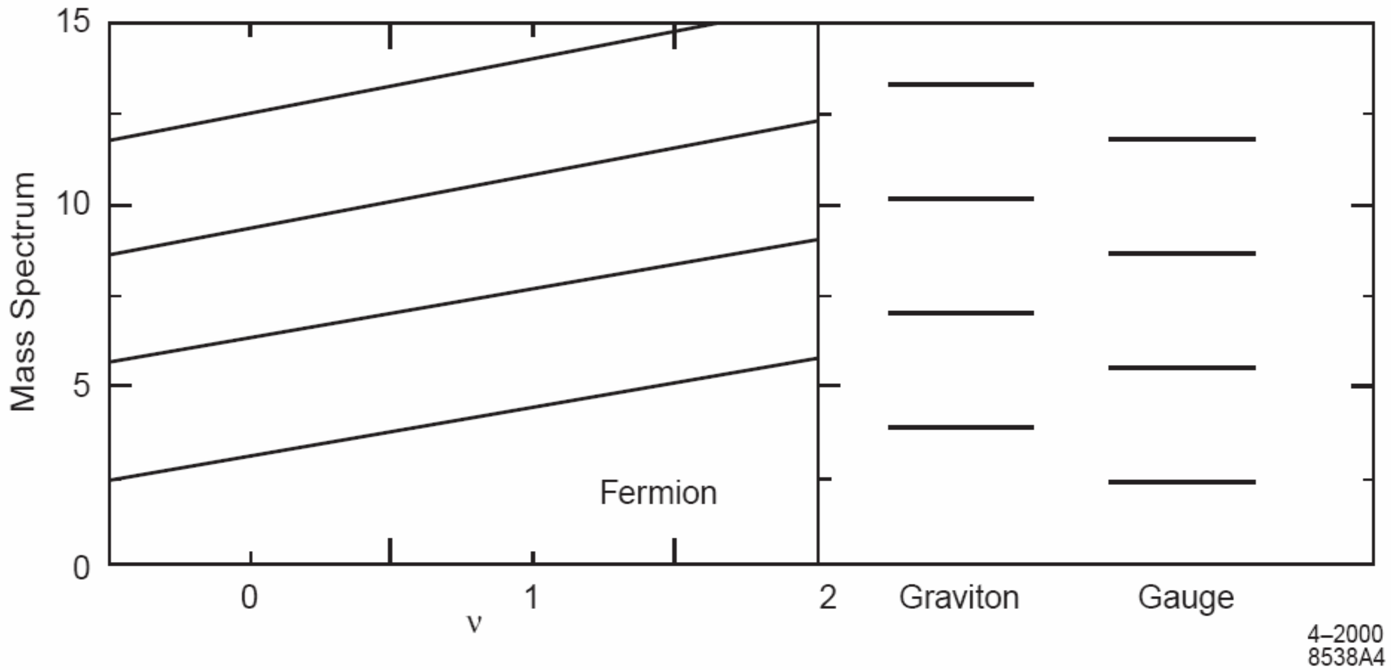
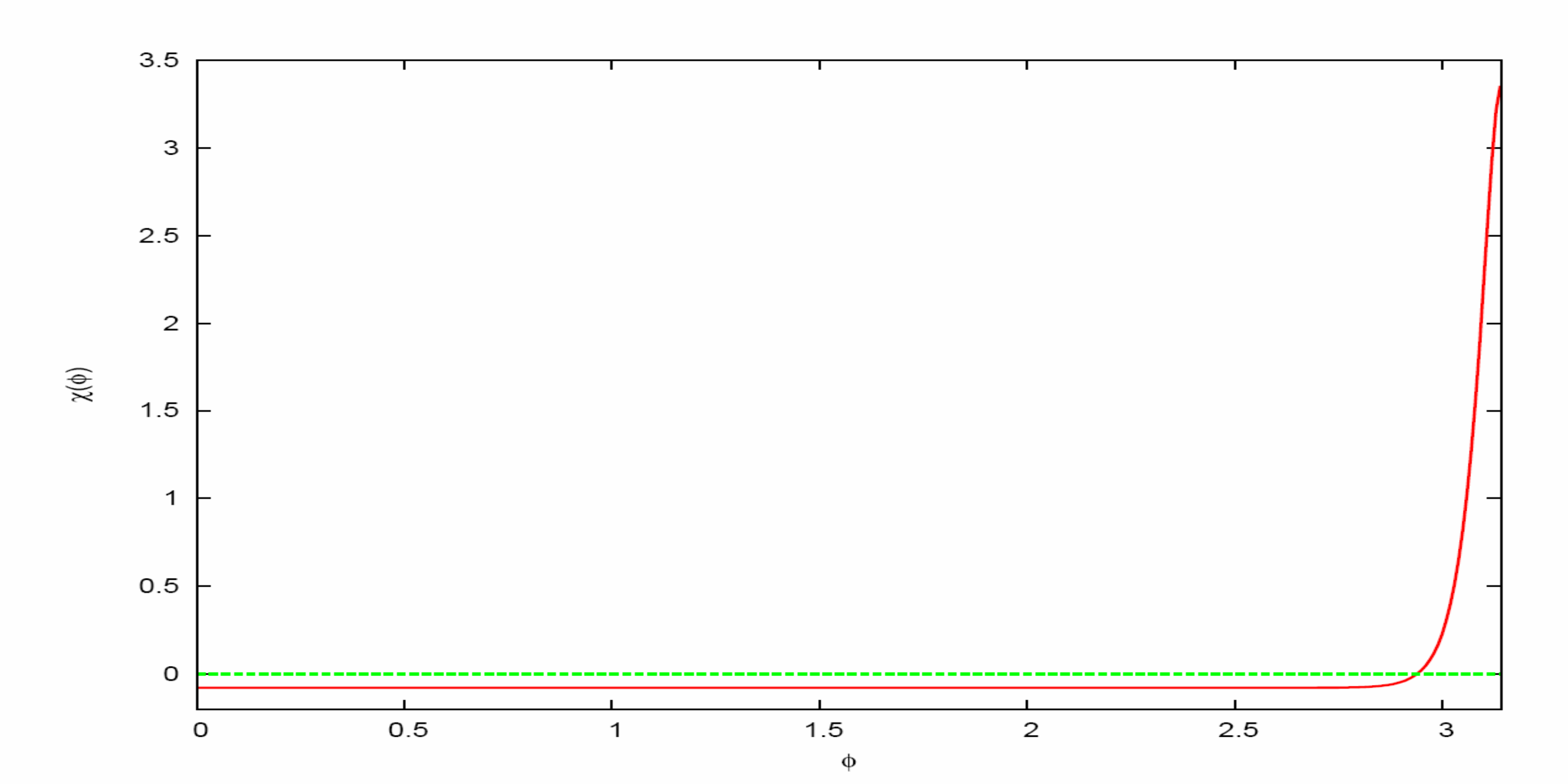


Figure 1: Relative mass spectra in units of $ke^{-kr_c\pi}$ of the KK excitations of the fermion fields as a function of their bulk mass parameter ν, as well as for the graviton and the gauge boson fields as described in the text.

Gluon KK Mode!

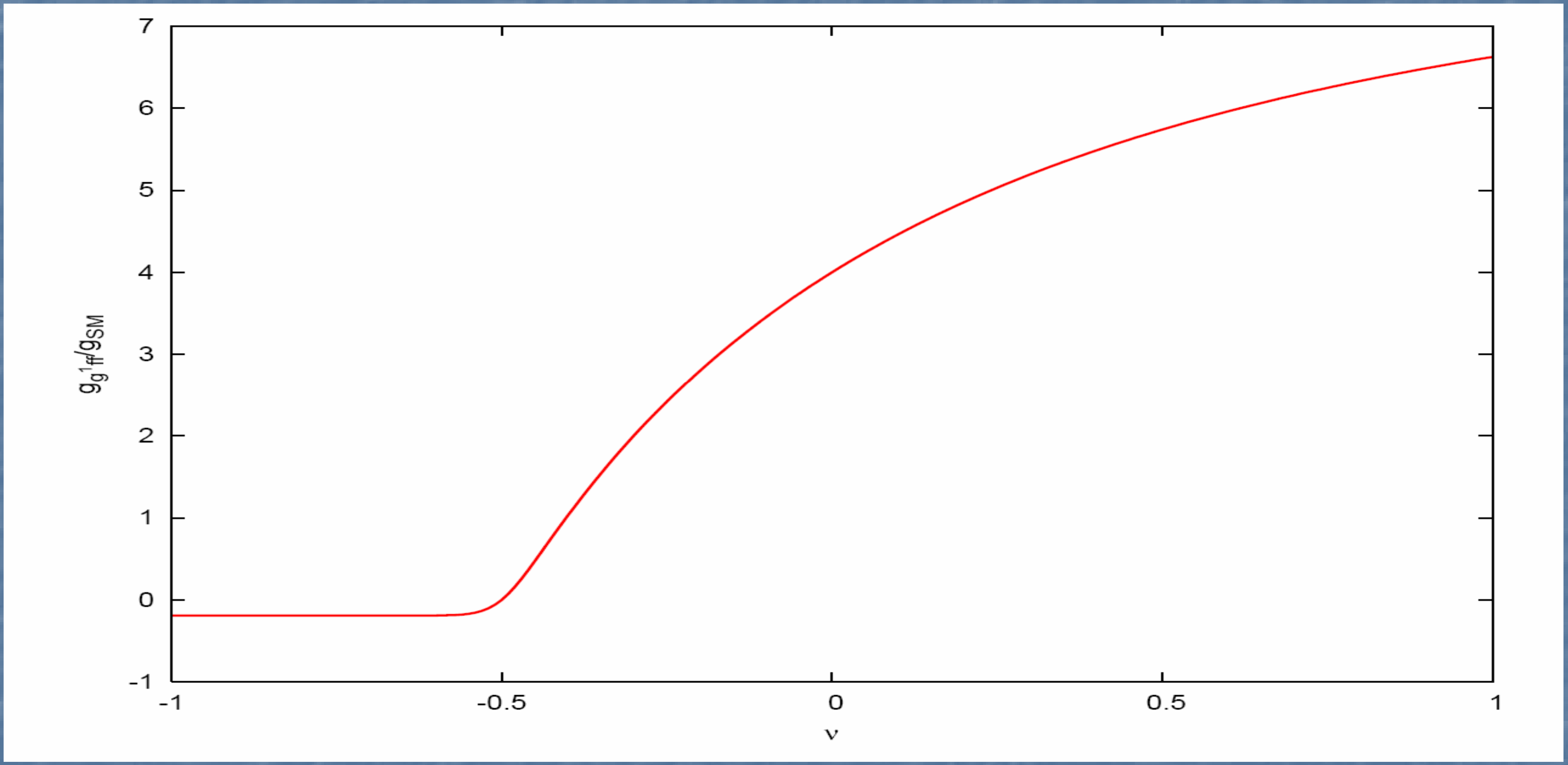
- Gluon KK mode coupling to light quarks is much bigger than graviton
  - Gluon KK mode wave function peaked at TeV brane
  - But relatively flat in bulk
- Also expect gluon KK mode lighter by factor 1.5
- Finally no 1/M
- Much larger reach for gluon KK mode

$$\chi_A^{(n)} = \frac{e^{\sigma}}{N_n^A} \left[J_1(z_n^A) + \alpha_n^A Y_1(z_n^A) \right] ,$$

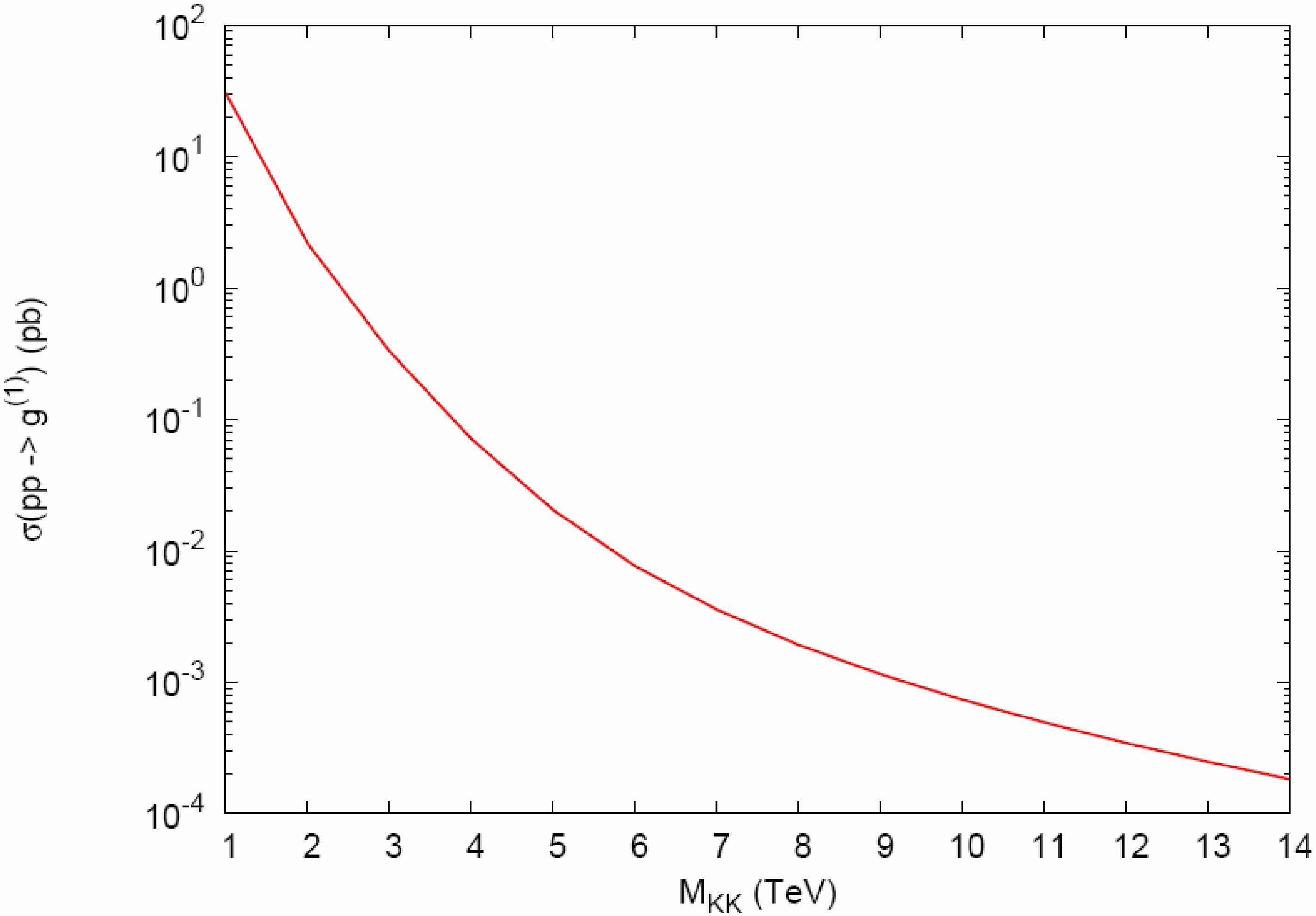


Gluon wave function

Gluon fermion interaction



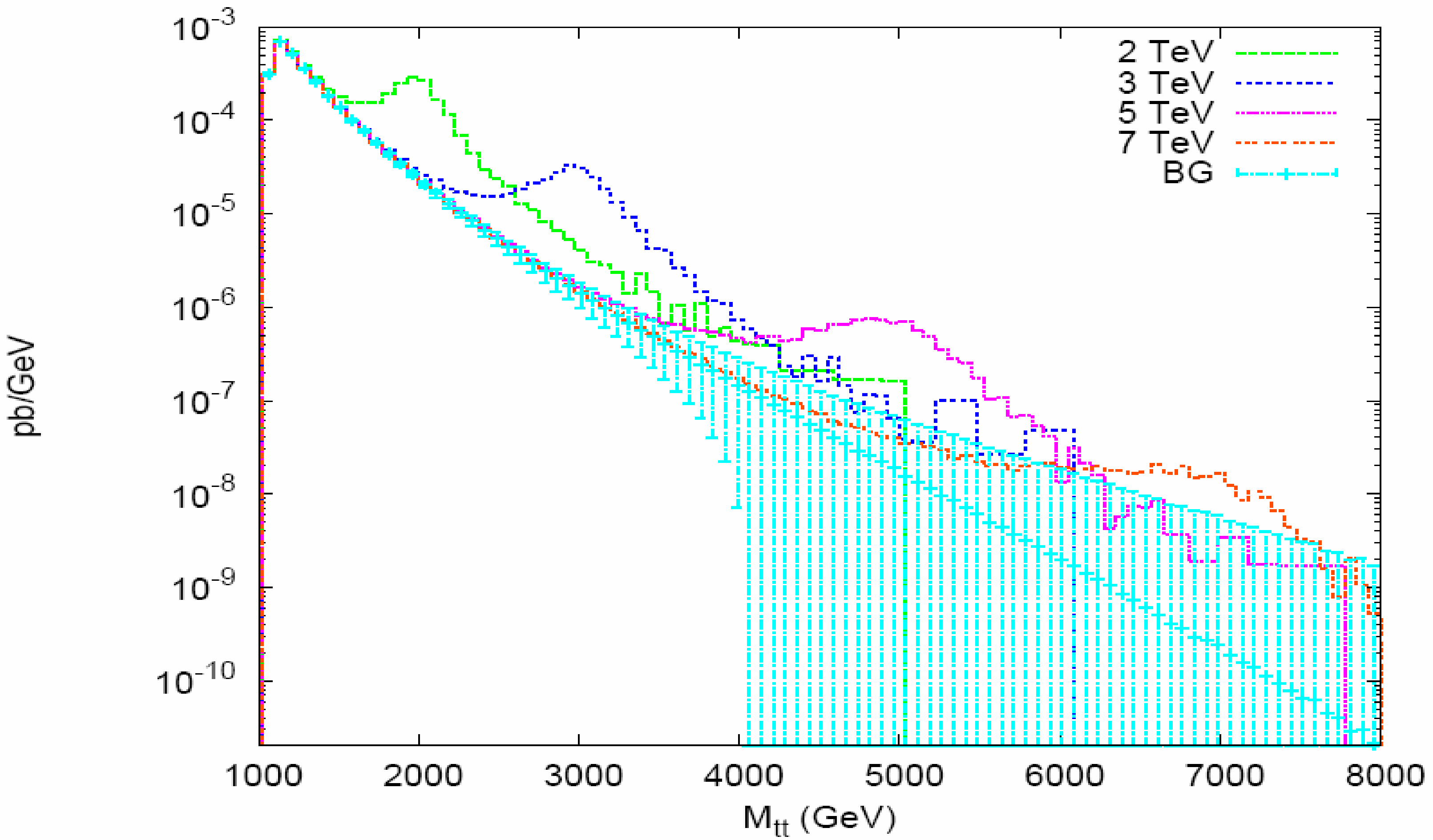
$$C^{f\bar{f}A}_{00n} = \frac{g^{(n)}}{g^{SM}} = \sqrt{2\pi k r_c}\left[\frac{1+2\nu}{1-\epsilon^{2\nu+1}}\right]\int_\epsilon^1 dz\ z^{2\nu+1}\frac{J_1(x_n^A z)+\alpha_n^A Y_1(x_n^A z)}{|J_1(x_n^A)+\alpha_n^A Y_1(x_n^A)|}$$



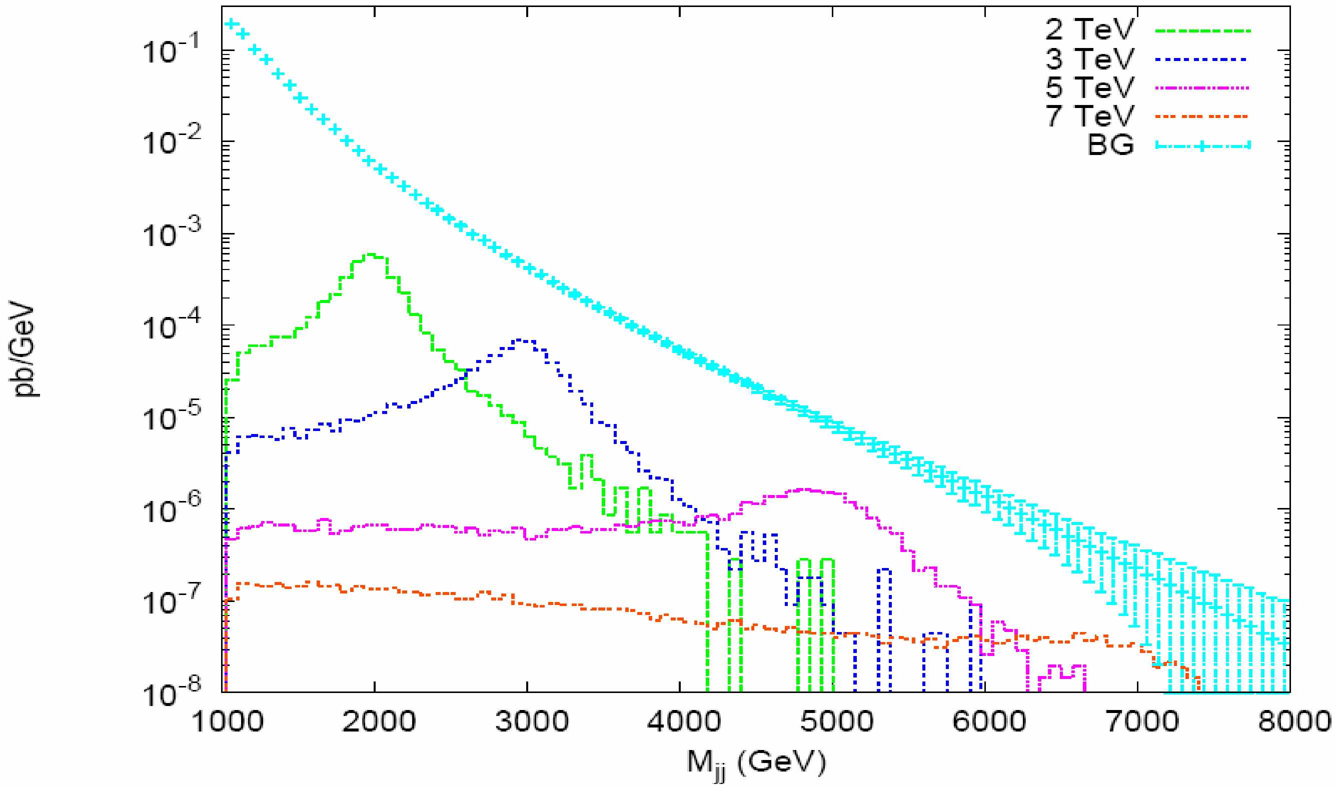
Total cross-section for production of the first KK gluon, as a function of KK mass.

w/Ben Lillie,
Liantao Wang

Dominates over top jet background

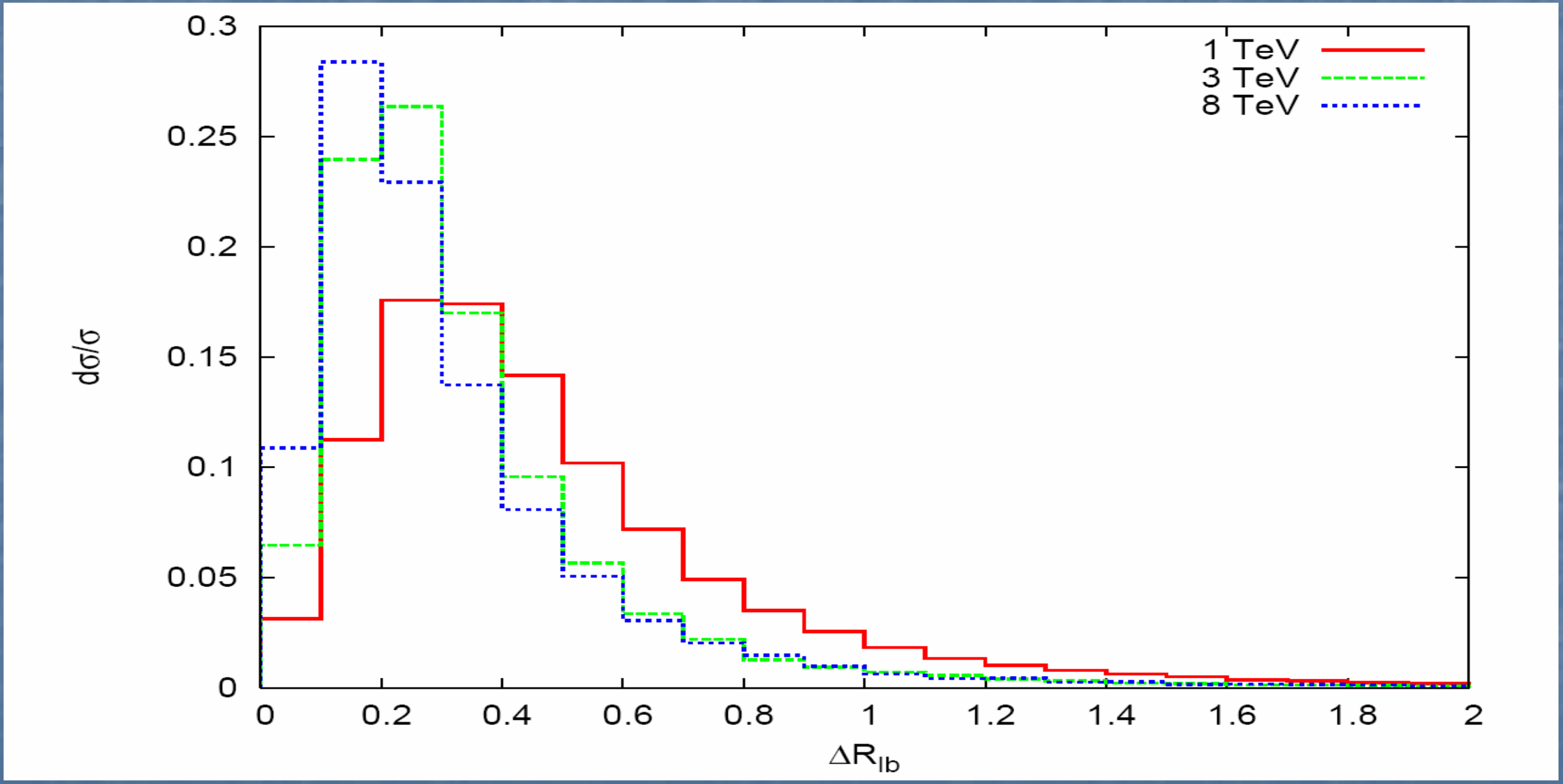


However, signal doesn't dominate over jet background



': Invariant mass distribution of the decay products for several masses of the KK gluon. sumes all $t\bar{t}$ events are fully collimated. "BG" is QCD dijet production. All jets are

Top mass determination: dR?



Clearly...

- Efficient top jet identification required, especially for heavier KK gluons
- Could be:
  - Top jet mass measurement
  - Detailed substructure of jets
- Critical to do energetic top ID!
- Had been neglected but essential to any study of electroweak sector

Summary So Far

- Weak scale physics should be testable at LHC
- Including RS1, whatever the implementation
- Best signature: spin-2 resonance and mass gap
- In bulk, gluon KK mode will be important
- Decays into tops critical
- Challenge is to maximize energy reach
- But hope for pinning this down

Other Signals?

Indications of Low Scale Gravity?

- Small higher-dimensional black holes?
- Since geometric cross section

$$\sigma(E) \sim \pi R_S(E)^2$$

$$\sigma(E) \sim \frac{1}{M^2}\left(\frac{E}{M}\right)^\alpha$$

M~TeV=>~100 pb cross section

Not suppressed by gauge couplings or phase space factors

Original claims:
Prolific Production!

Signature

- Claim was multiparticle final state
- Spherically distributed: particles in all directions
- Characteristic of Hawking radiation

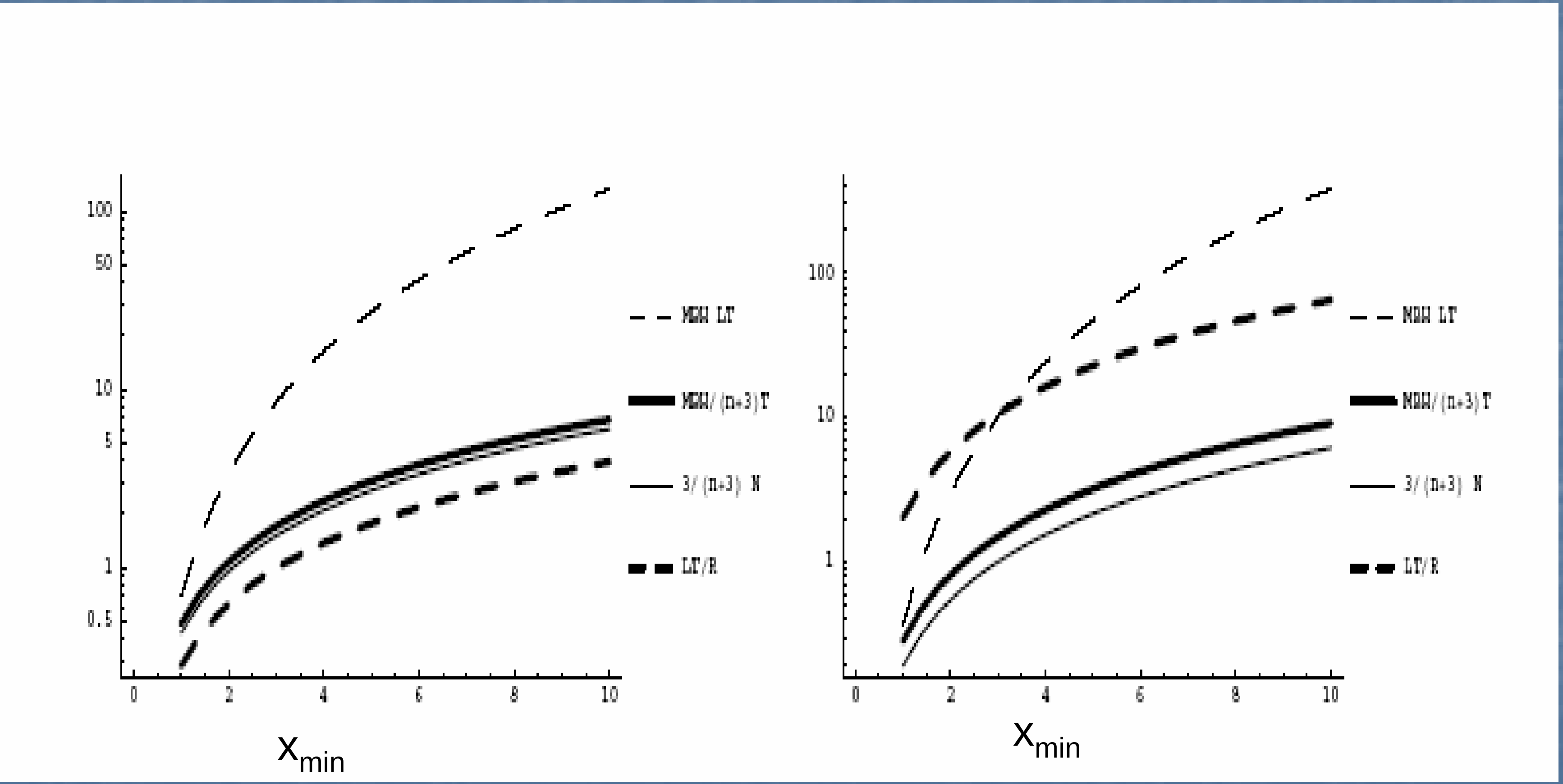
Spectacular fireball final states!

w/Patrick Meade

More realistically:

- LHC unlikely to make classical black holes states that decay with high multiplicity via Hawking radiation
- Theshold above M
- Not all energy trapped behind horizon : inelasticity
- PDFs fall rapidly so cross section rapidly declines

Constraints: Min value of M_{BH}



ADD RS

2->2! will be changed

All is not lost

- Potentially much more prolifically produced 2 body final states
- Uncalculable, but distinctive experimental signatures that will distinguish among modes
- Might teach us about *quantum* gravity

What to study?

- 2 Quantities
  - Differential Cross Section
  - R : tells us about angular distribution
  - Key point is quantum gravity events much harder scattering than Standard Model QCD

Example: Dijet "Black Holes"

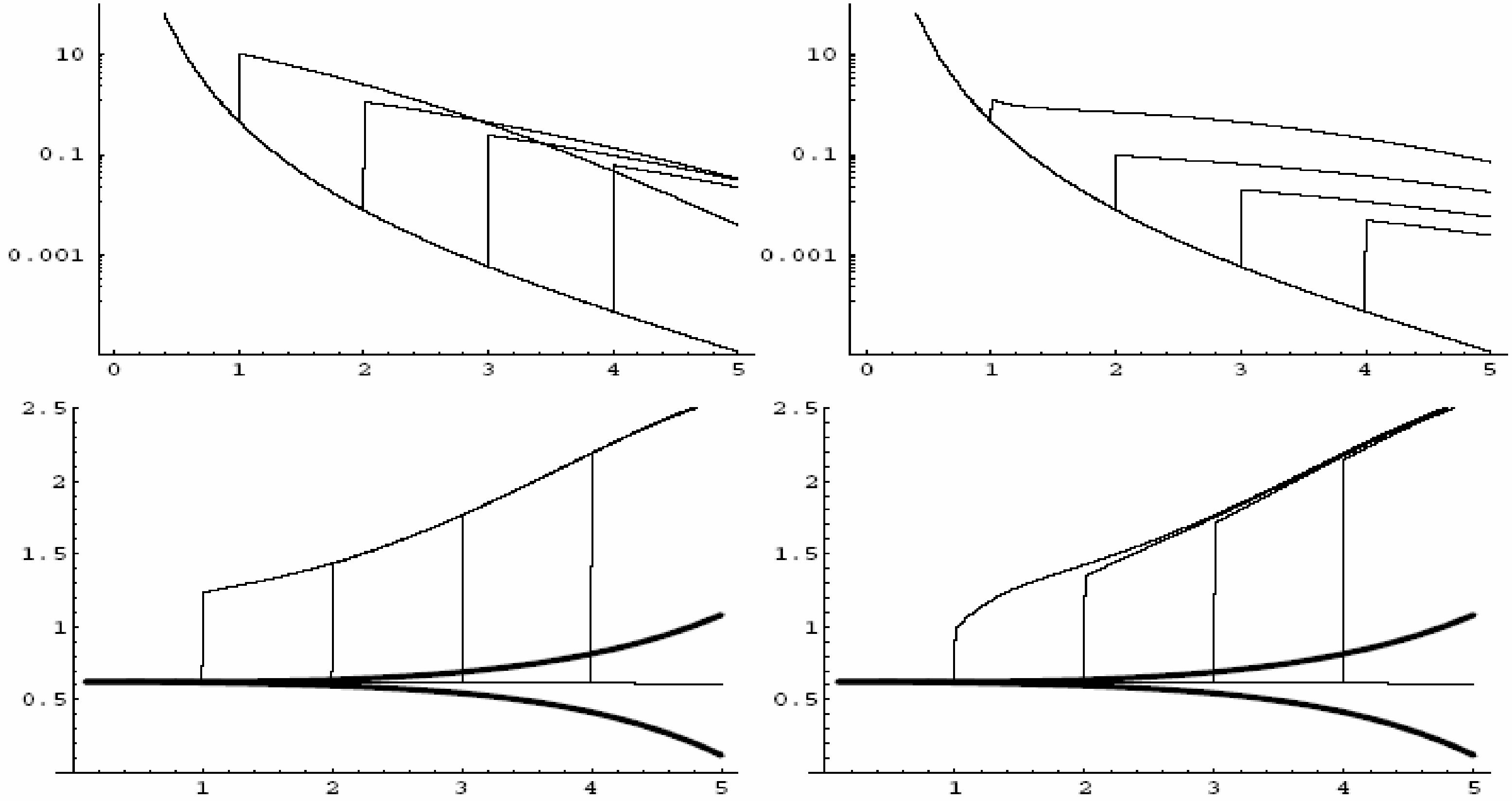


Figure 6: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background, and a n=6 ADD model "black hole" behavior with M_D=1,2,3,4 TeV and $x_{min} = 1$ in the lefthand plot and a RS1 black hole behavior with $M = 1, 2, 3, 4$ TeV and $x_{min} = 1$ in the righthand plot. For other values of x_{min} the curves simply start at the corresponding dijet mass. In the lower two plots the R_η is plotted for the same parameters.

Stringy Results

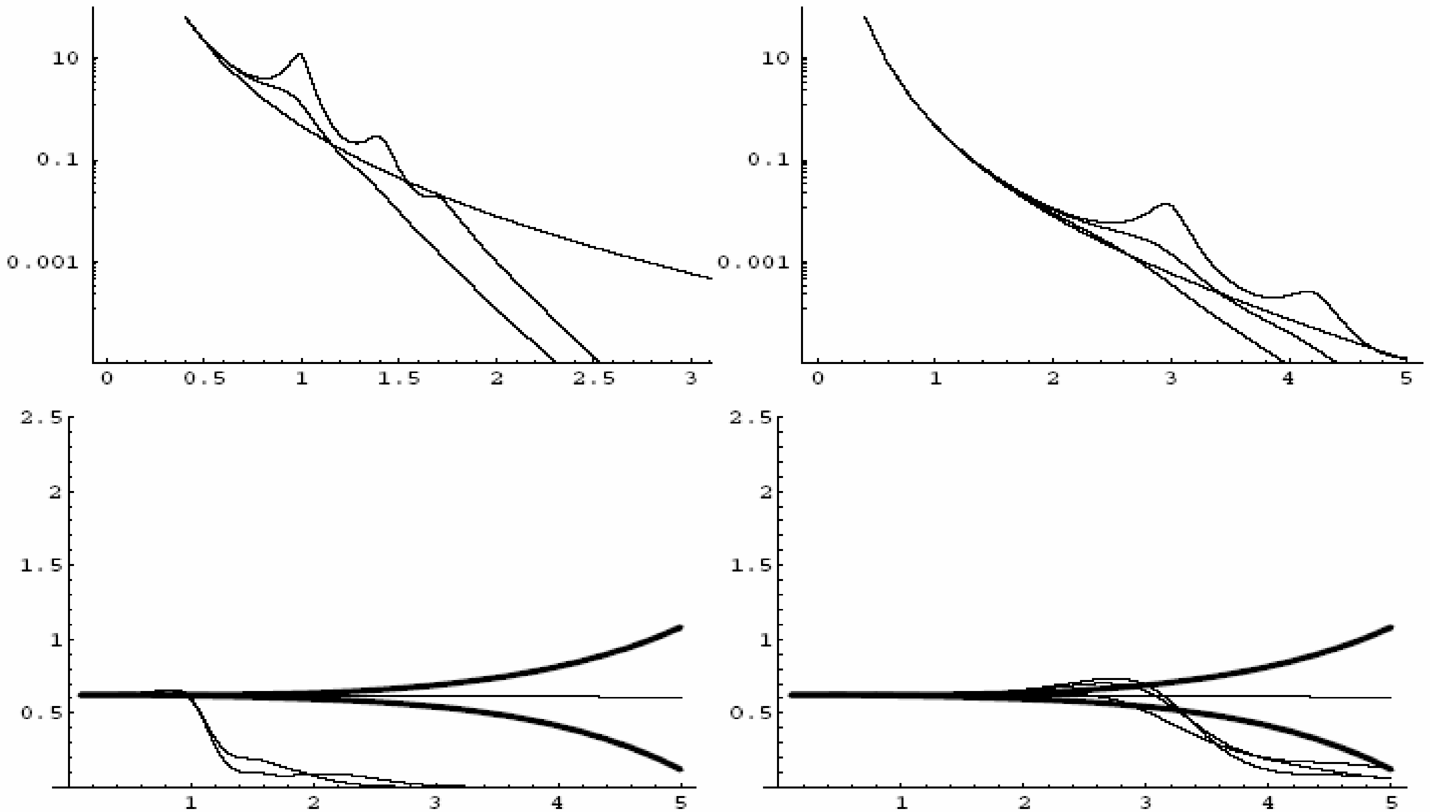


Figure 8: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background(thicker curve), and a toy stringy behavior with M_s=1 TeV in the lefthand plot with $\gamma = .1, .3$ and M_s=3 TeV in the righthand plot with $\gamma = .1, .3, .6$. In the lower two plots the R_η is plotted for the same parameters.

Summary

- Black holes not as "spectacular" as advertised

BUT

- Lots of information about quantum gravity buried in 2->2!
- Hadron AND Lepton cross sections!
- Initial increase in rate for more central processes always occurs
- "Black hole", string resonances, different forms for string, Z' all distinctive

Testing for Warped Geometry

- Resonance and Compositeness Signals of Interest
  - Could be KK modes
  - Could be “compositeness effects”
  - Could be other models…
- Need to be prepared
- Means thinking about high energy signals
- Top quark ID, optimizing compositeness, etc.