Warped Geometry

Consequences and LHC Signatures

Lisa Randall, Harvard University

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

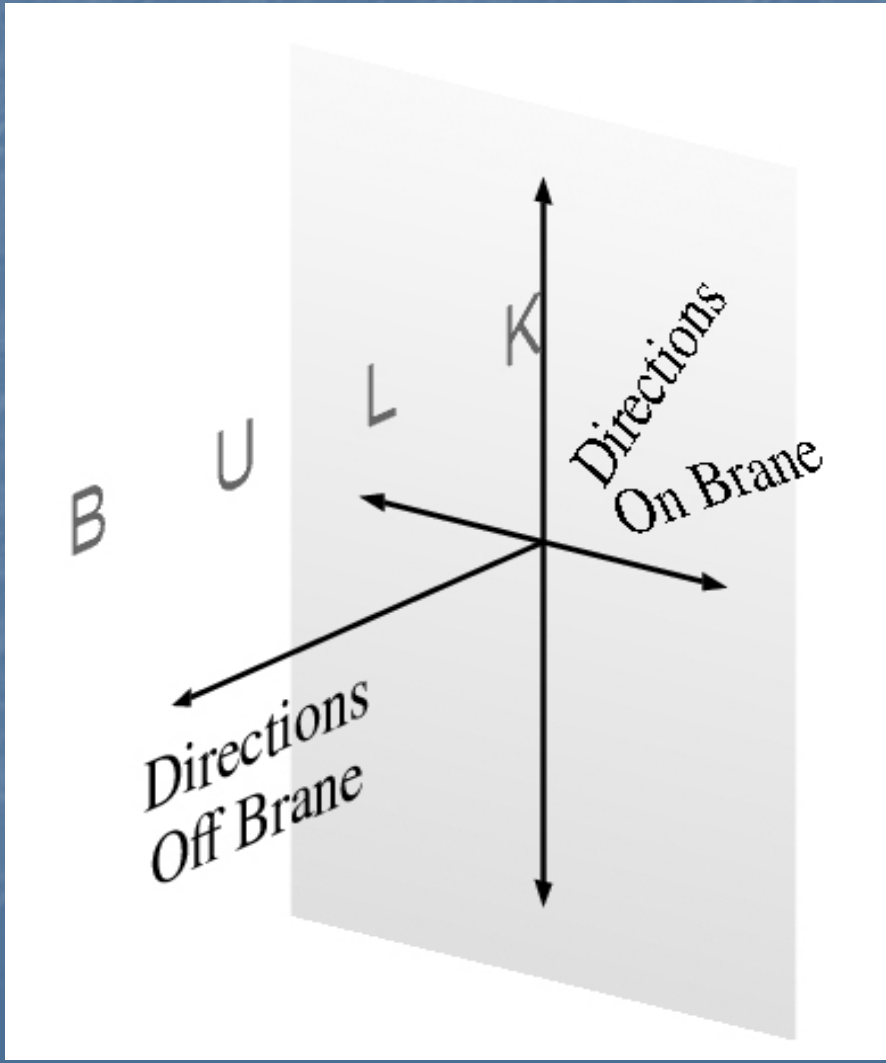
Why Extra Dimensions?

A New View of Weak Scale Physics

- Many new results in physics in last ten years
- Some of the most exciting involve extra dimensions of space
- Intriguing possibilities for our universe: both theoretical and experimental
- Warped geometry plays a central role in string theory today
- Warped geometry has particularly interesting signatures: resonances!
- Critical to explore theoretical possibilities and experimental consequences

Lesson? Higher energies?

What's New? Branes

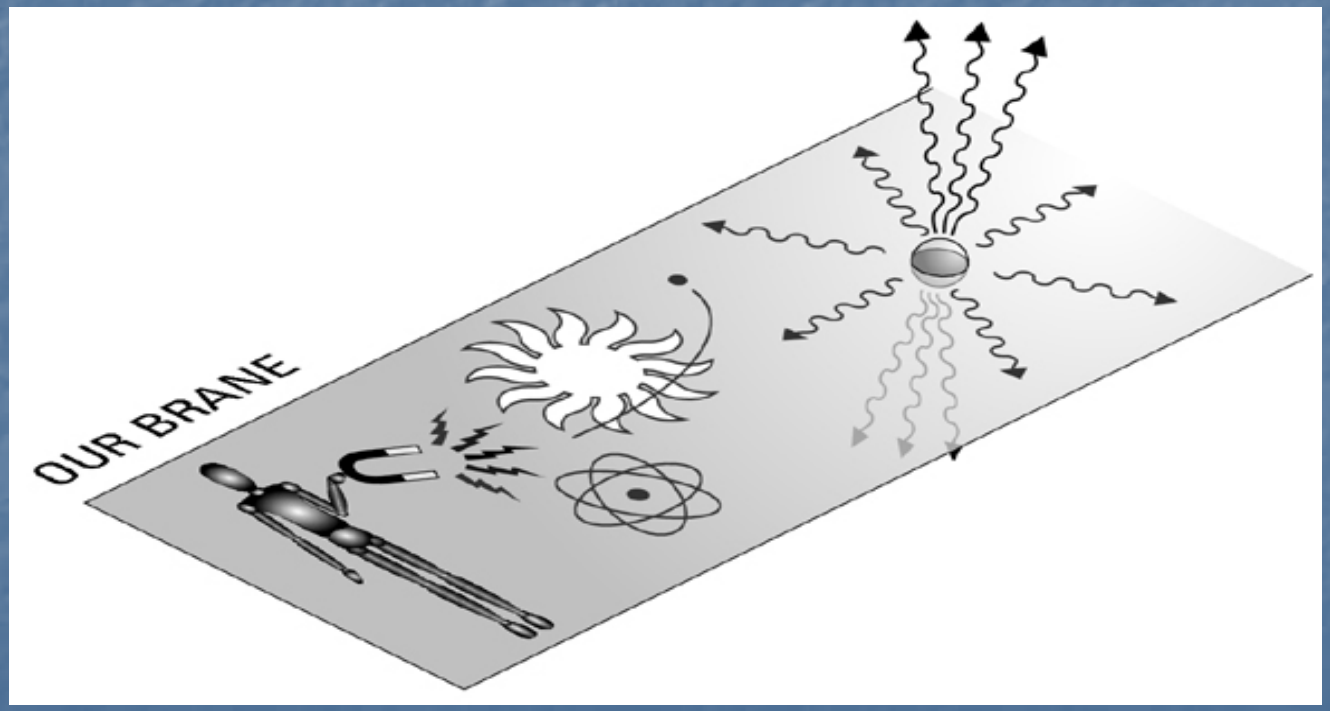


Branes:

Distinguish dimensions along a brane from those perpendicular to it

Braneworld

Higher-dimensional world in which particles and matter are stuck on a brane



Drawn as 2D

Really 3D

And really

infinite

With branes, we’ve found warped geometry solutions that provide:

- New way to hide dimensions
- New concept of our place in the universe
- New way to explain weakness of gravity

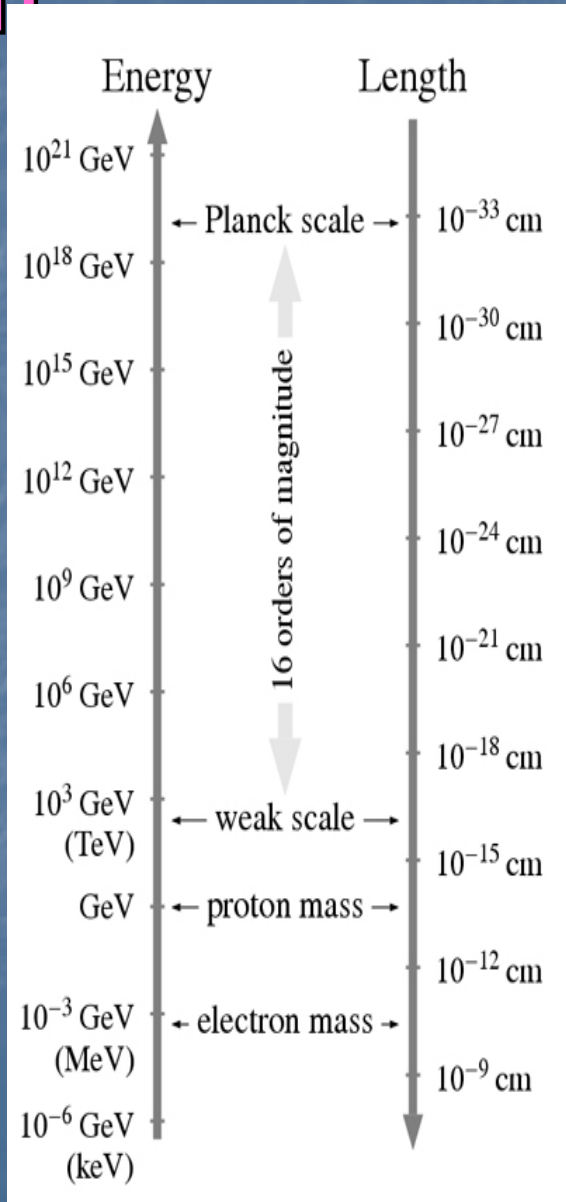
Warping and Hierarchy [RS1]

Hierarchy Problem

Need “fine-tuning” to get very different masses

Key issue in particle physics today

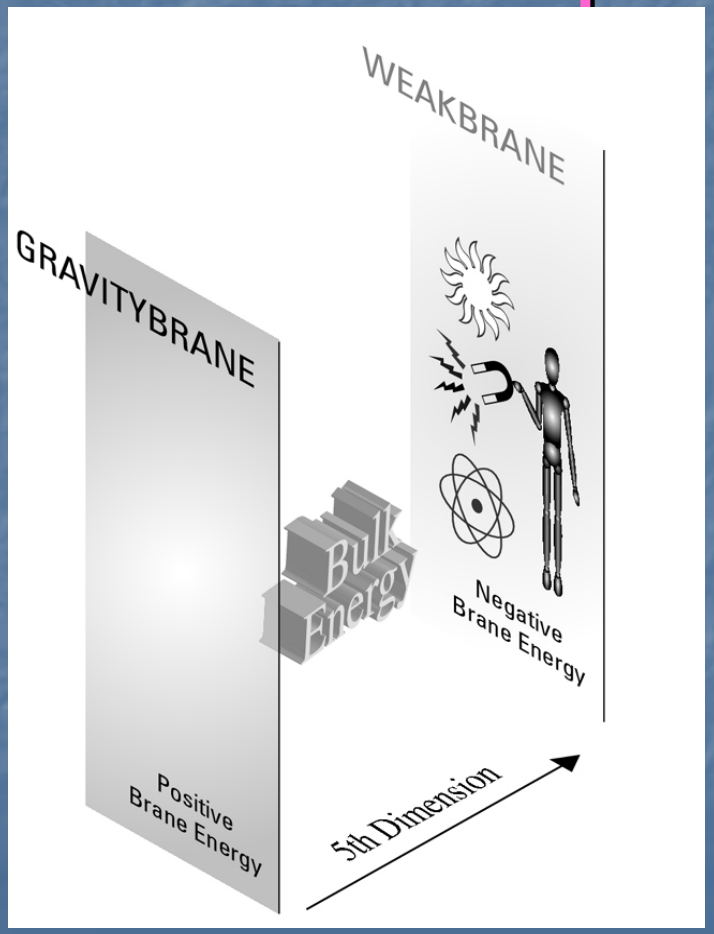
One that will be resolved at LHC



“Fine-tuning” is unlikely:

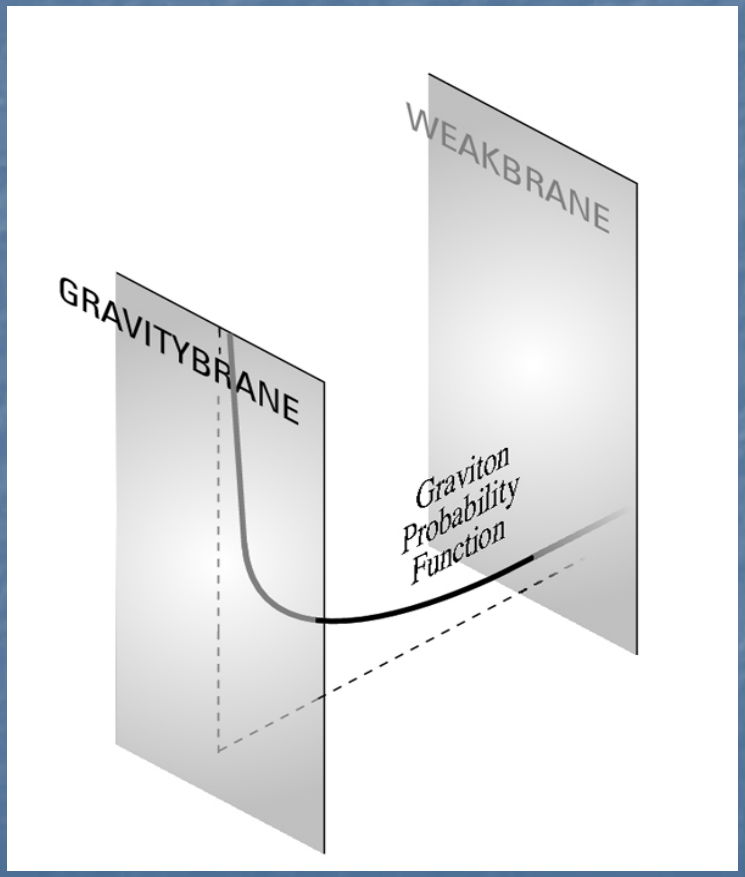
Barnett Newman: *Broken Obelisk*

RS1 “Multiverse to Address Hierarchy:” Warped Spacetime



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

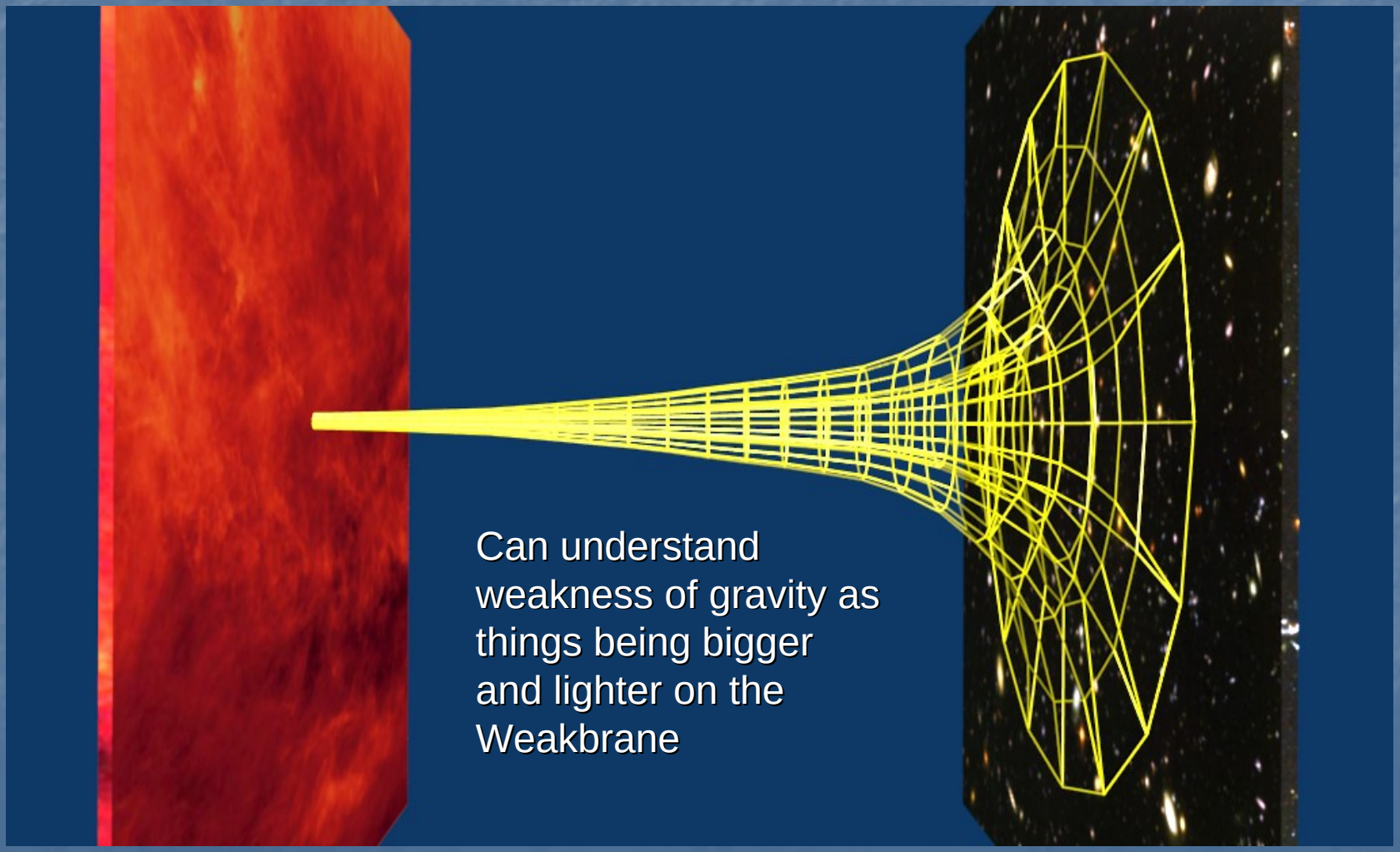
Natural for gravity to be weak!



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

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

Rescaling Across Fifth Dimension



Higgs mass rescaled

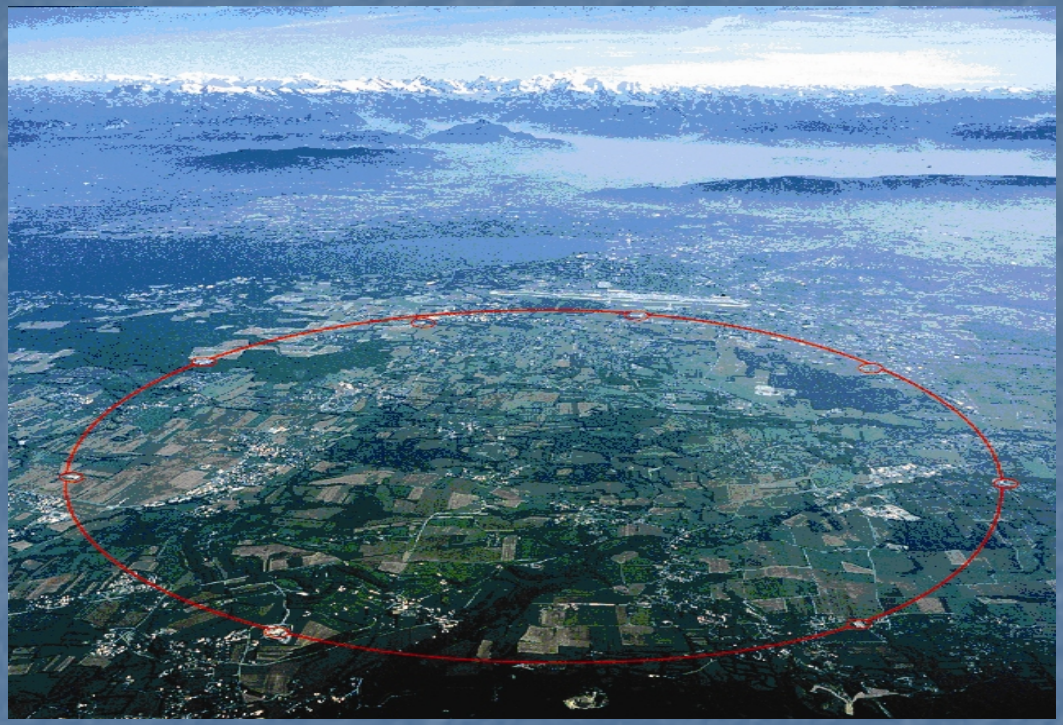
- Kinetic term has 2 powers of warp factor
- Mass term has 4
- Result is mass rescaled
- In fact warp factor is like conformal factor

- So...if modes localized near TeV brane
- Expect TeV mass
- Turns out to be true for all modes near TeV brane

How to test?

- Search for new particles!
- Everything near weak brane should have TeV mass
- 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

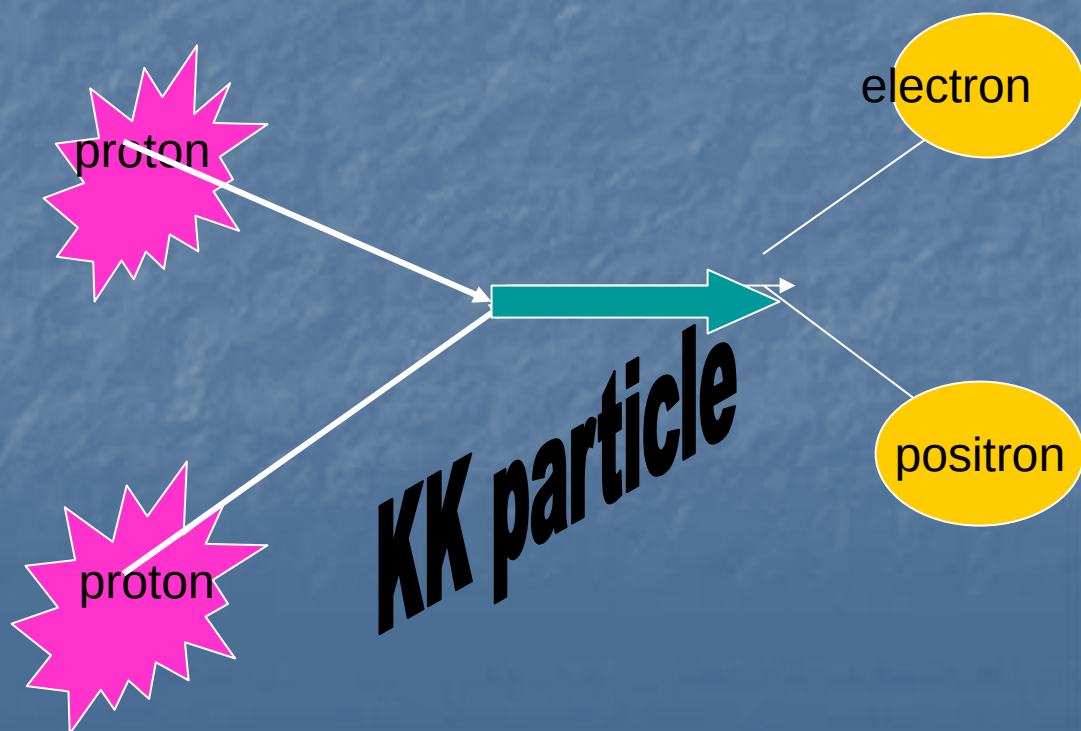
Will search soon:
Large Hadron Collider at CERN



- **Collide together two proton beams: make new particles**

Experimental Signal: TeV-scale Graviton Resonances!

- **Protons collide**
- **Produce a Kaluza-Klein particle**
- **Which Decays**
- **Definite mass spectrum and "spin"-2**



Observable KK modes

- In RS1, KK spectrum very distinctive
- TeV, 2 TeV, 3 TEV (rough) spectrum

- TeV scale modes localized on weak brane
- Have “warped” gravitational interaction
- So 1/TeV scale graviton interaction with Standard Model particles (not $1/M_{Pl}$)
- Much stronger than gravitational!

Search for Resonances

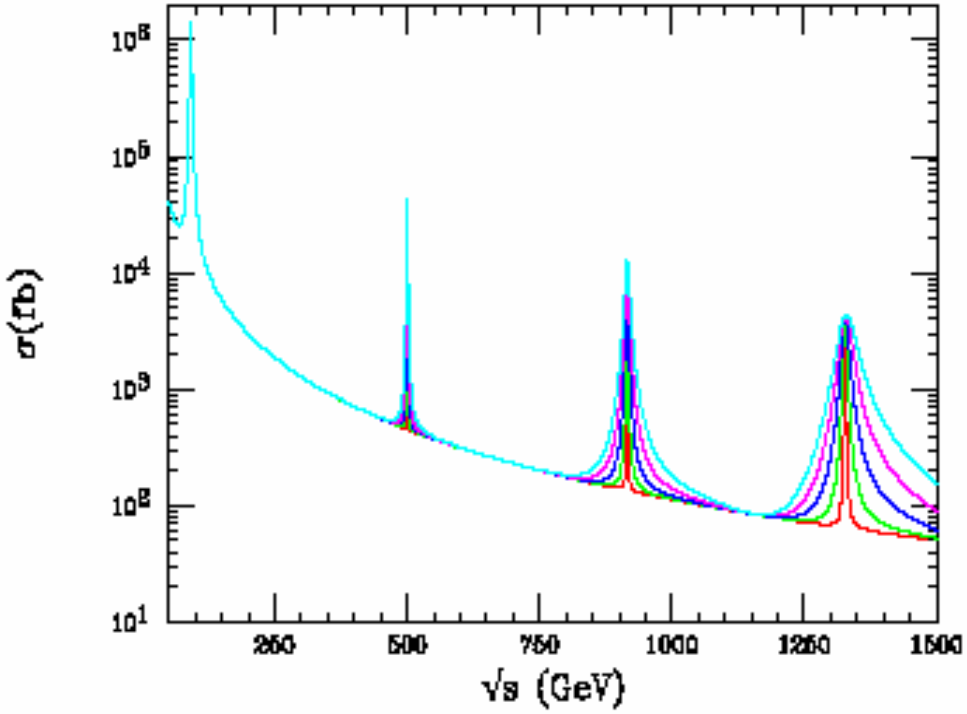
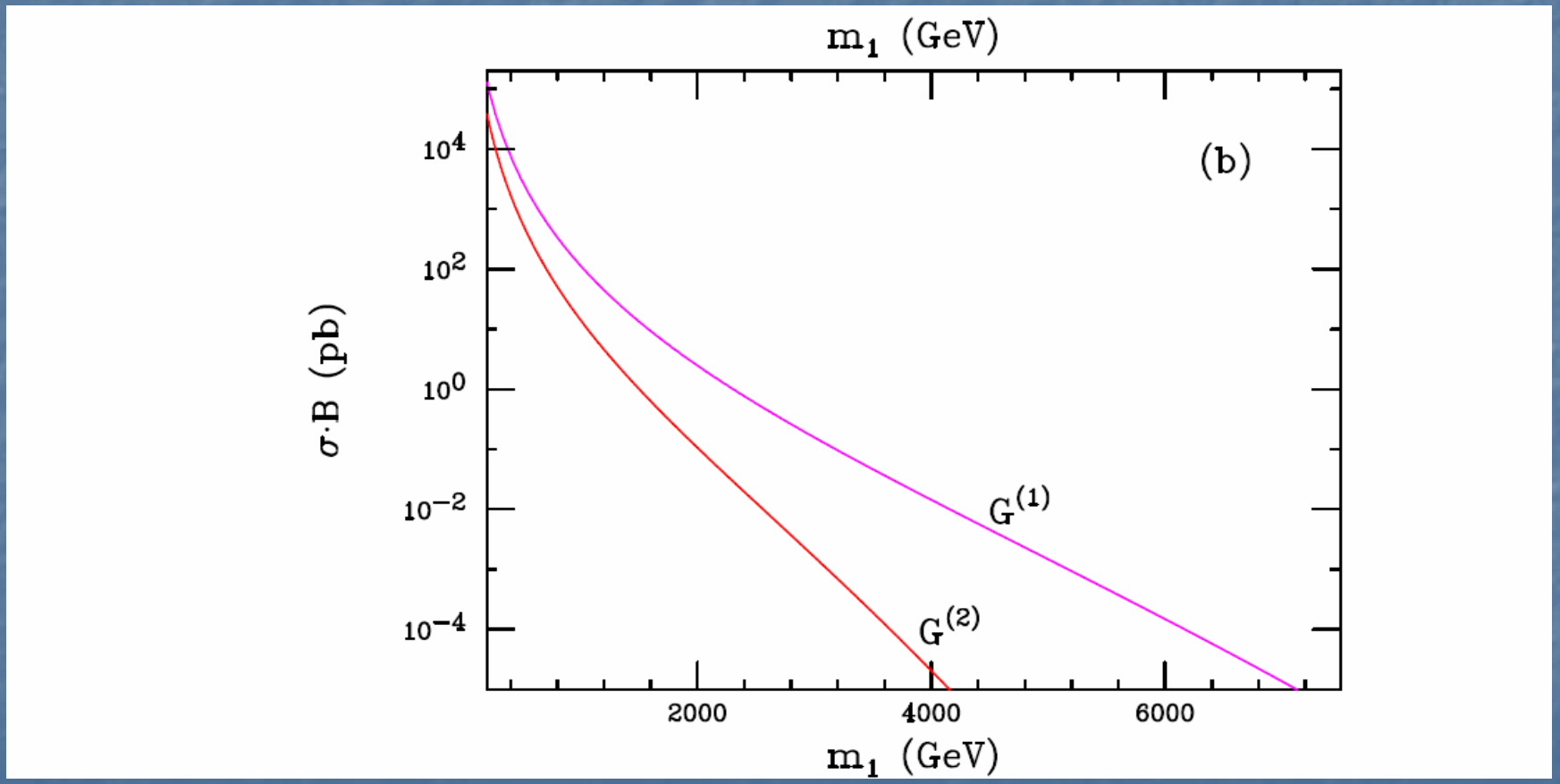


Figure 4: The cross section for $e^+e^- \to \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to $k/\overline{M}_{\rm Pl} =$ in the range $0.01 - 0.05$.

H. Davoudiasl, J. Hewett, T. Rizzo

- If you produce a KK mode of the gravition
- Not just missing energy!
- Mode decays inside detector—just like most other heavy particles we hope to discover
- ✓ Means we can reconstruct mass, spin (we hope!)
- ✓ Would be first genuine signature of quantum gravity
- ✓ Graviton itself too weakly interacting to detect directly
- ✓ Not true for its KK modes!

Reach for Graviton KK Modes

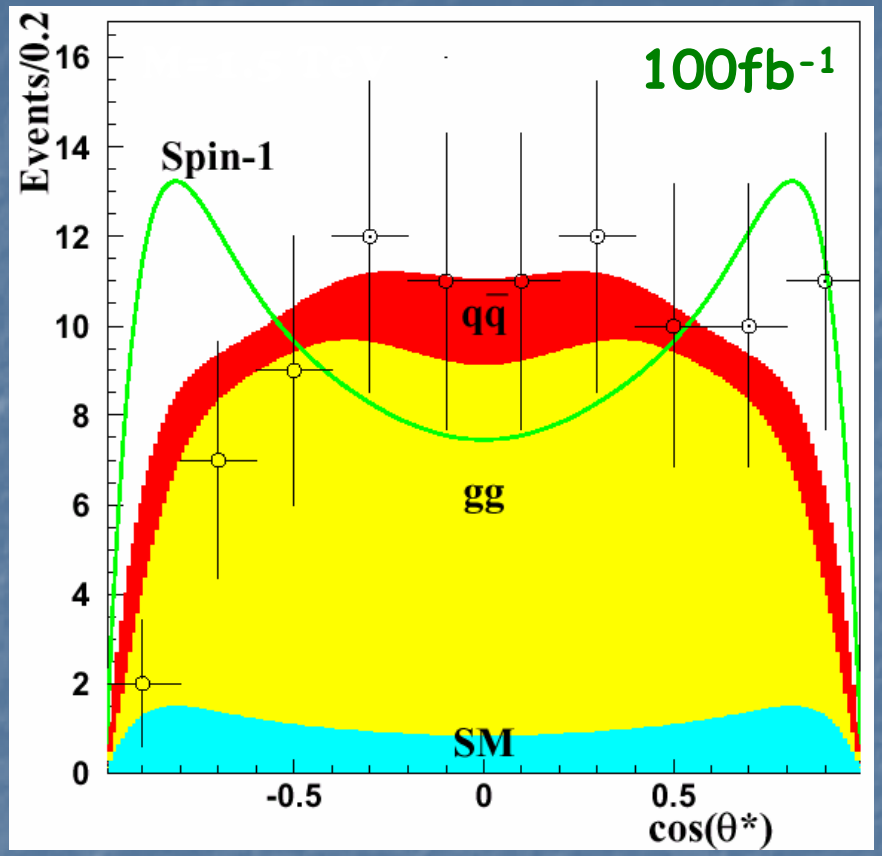


Davoudiasl, Hewett, Rizzo

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 of RS1:

matter in bulk or on brane??

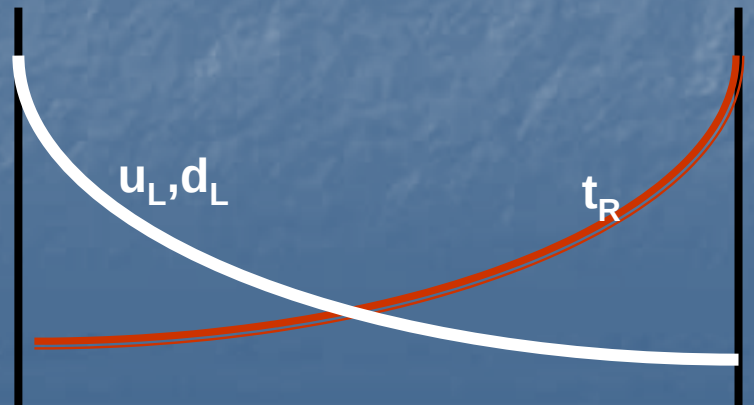
- Two key features that make bulk matter possible
  - Size of fifth dimension extremely small (only about 30 times fundamental scale—exponential hierarchy)
    - Means coupling won't be too diluted/weak
  - You only need Higgs on the Weakbrane to address the hierarchy
    - Problem only for the Higgs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



Bulk RS

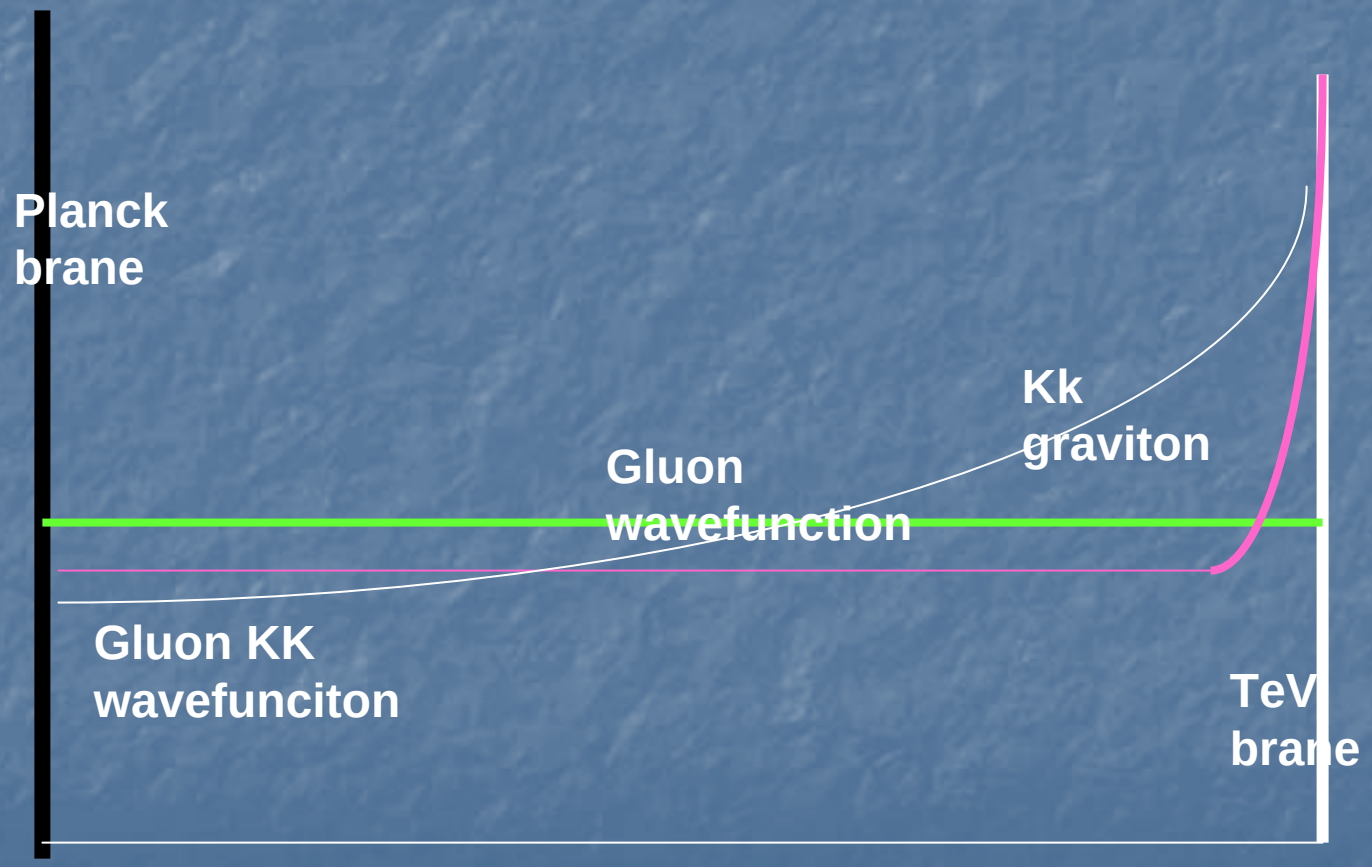
- Variation of RS1: fermions and gauge bosons in bulk
- Hierarchy just like before
- But flavor, unification possibilities

Important Differences from Brane-Localized Matter

- Richer Spectrum
- KK modes of
  - Weak bosons
  - Gluons
  - Fermions
  - As well as gravitons

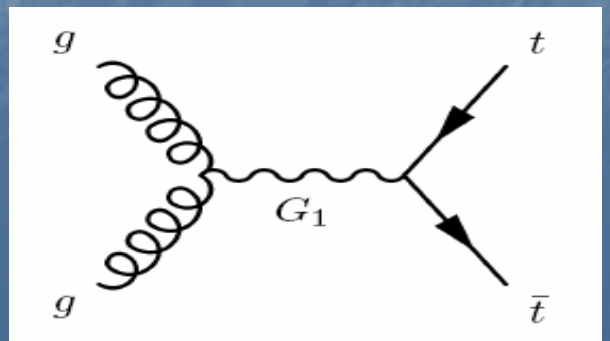
- But...lower Production Cross Section for Graviton
- Plus decays primarily into tops
  - Changes search strategies dramatically

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



Graviton Interactions

$$C_{xxG} \int d^4x h_{\mu\nu} T^{\mu\nu}_{xx}$$

$$C_{ggG} = \frac{1}{(\pi k r_c)(M_4 L)\mu_{TeV}} \frac{\int_0^1 dy\ y J_2(3.83y)}{J_2(3.83)} \approx \frac{0.47}{(\pi k r_c)(M_4 L)\mu_{TeV}}$$

Volume suppressed

O(1), 1/ k¼r c; or 0

$$C_{ffG} = \frac{1}{(M_4 L)\mu_{TeV}} \left(\frac{1+2\nu}{1-e^{-\pi k r_c(1+2\nu)}} \right) \frac{\int_0^1 dy\ y^{2+2\nu} J_2(3.83y)}{J_2(3.83)}$$

$$C_{ssG} = \frac{2}{(M_4 L)\mu_{TeV}}$$

w/Liam Fitzpatrick,Jared Kaplan, Liantao Wang

KK Graviton Production

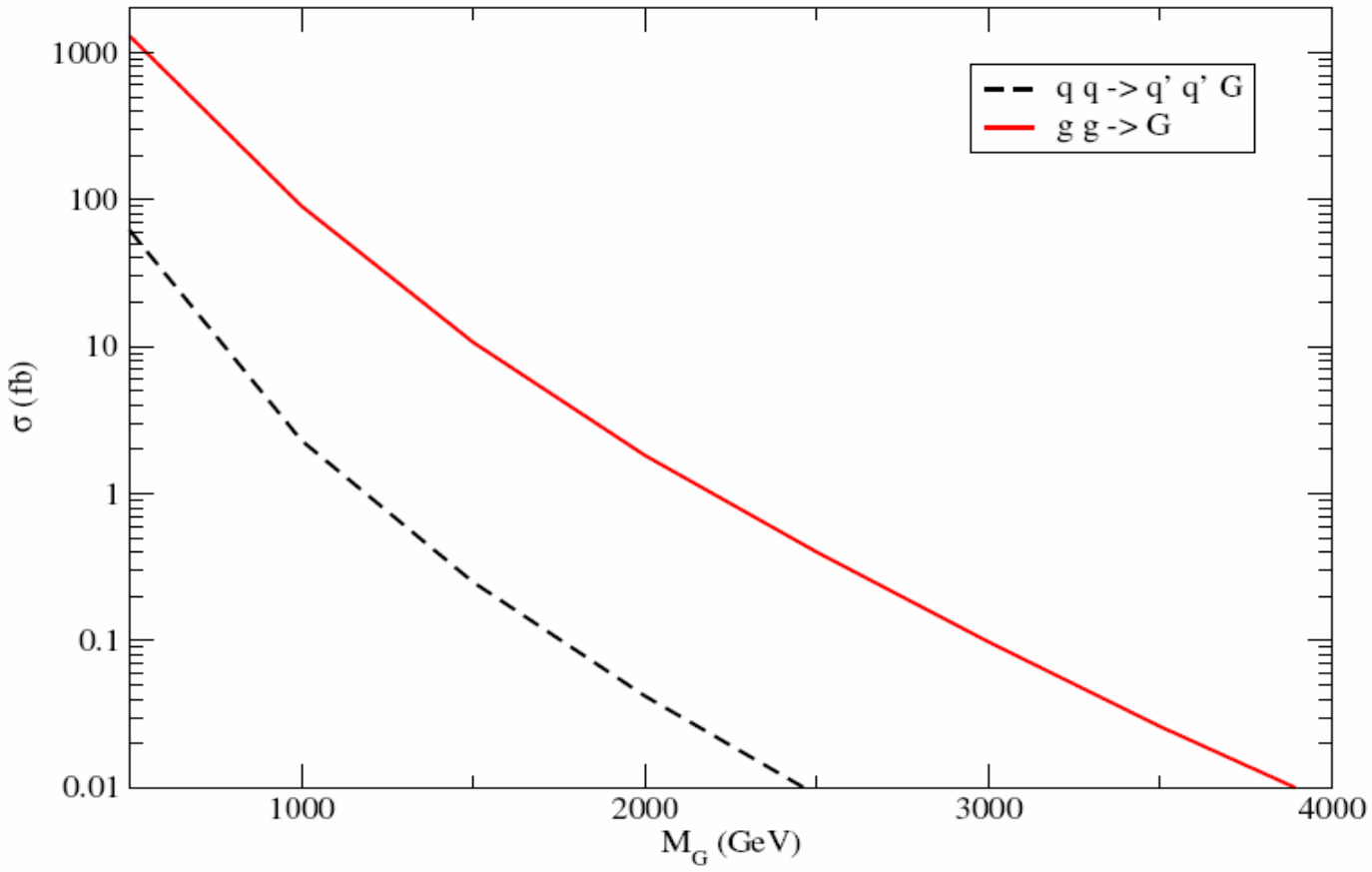


Figure 1: Cross section of KK-graviton production.

See also Agashe, Davoudiasl, Perez, Soni

Final State? Dominant Decay to right-handed tops

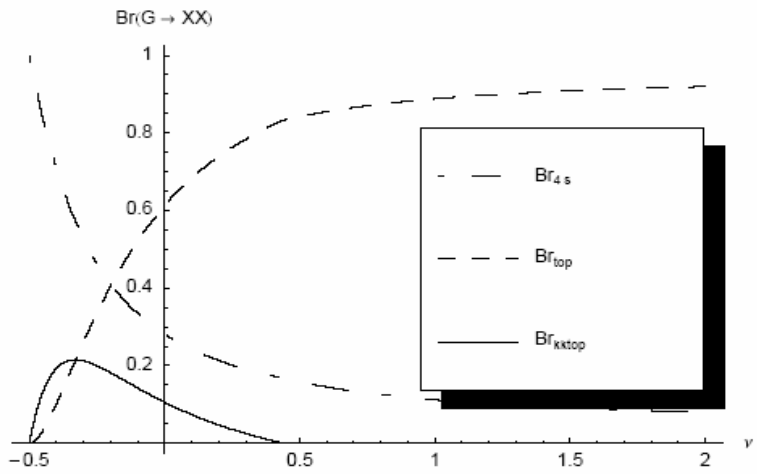
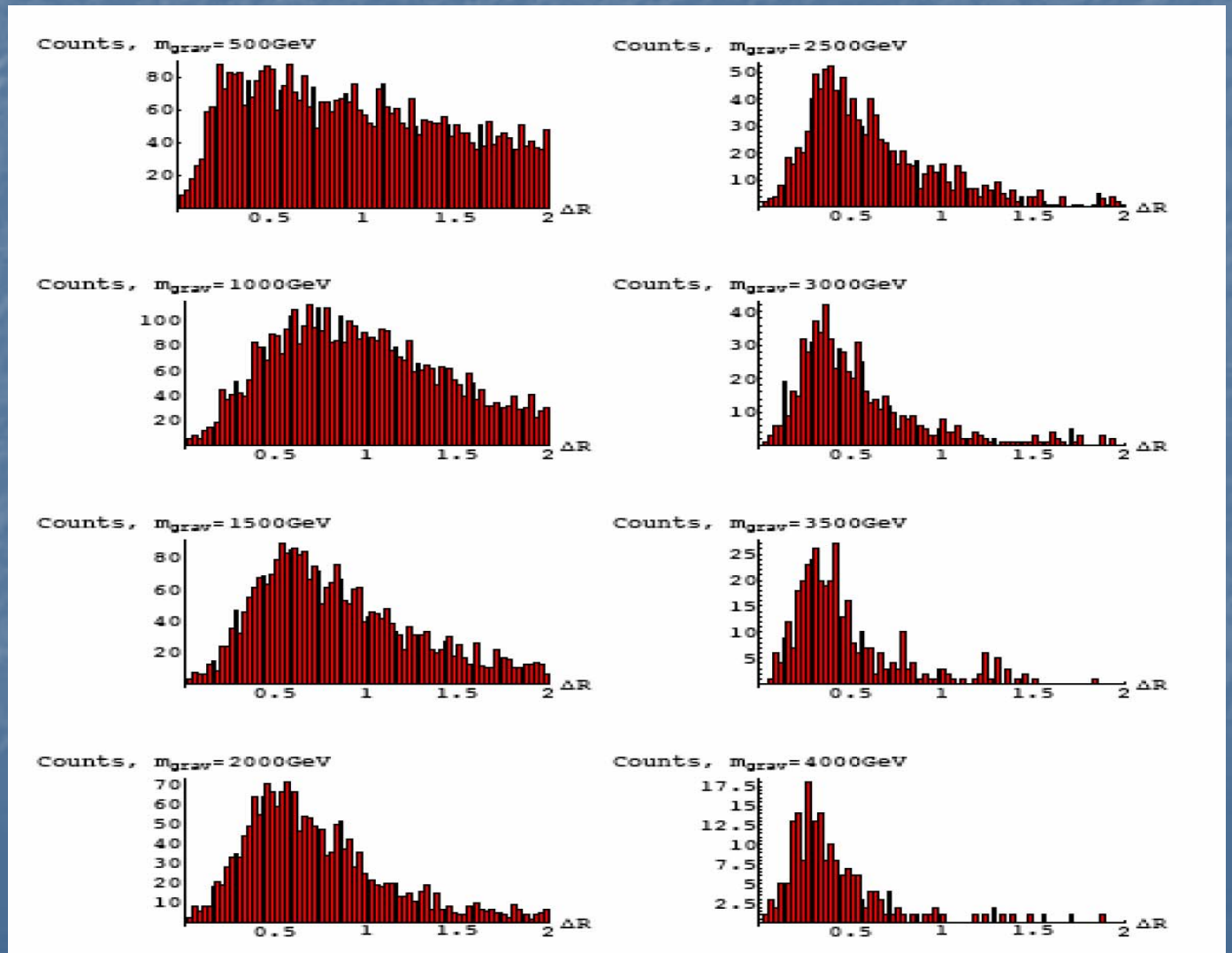


Figure 1: Branching Ratios for graviton decay to scalars and quarks.

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

Determining top jets: delta R: Angle between decay products



More Promising With Other Bulk Modes?

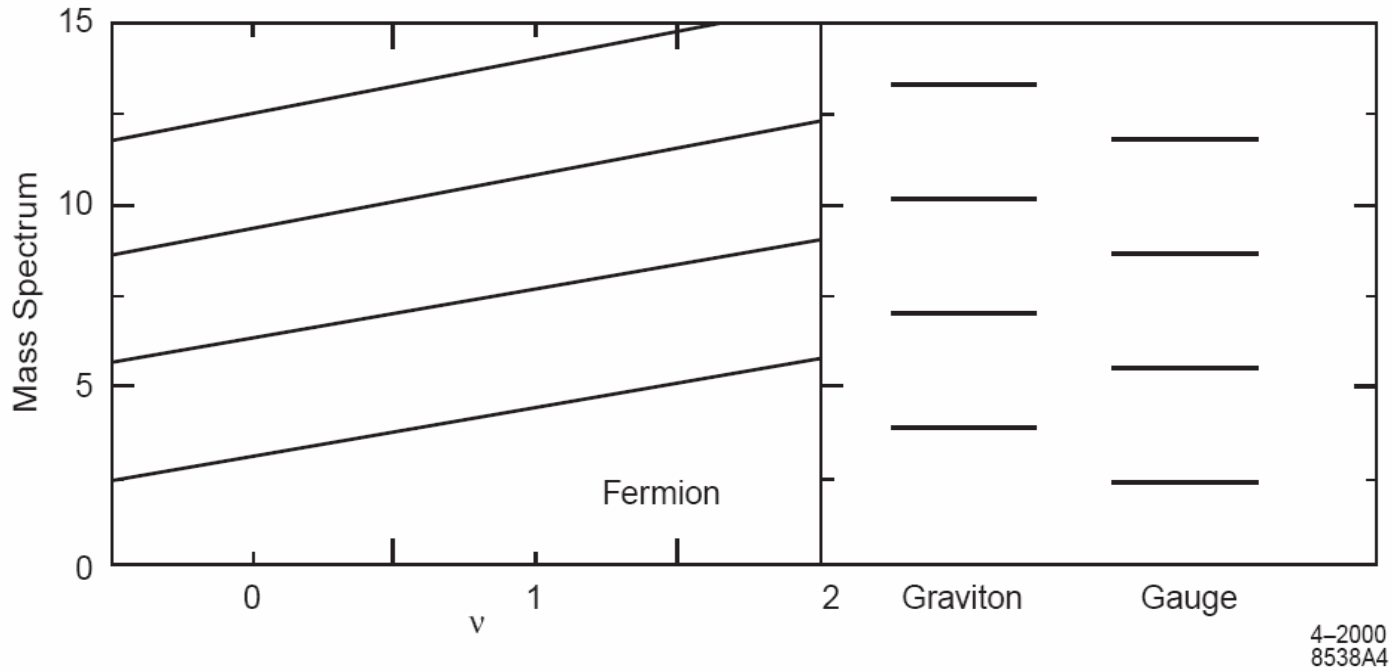
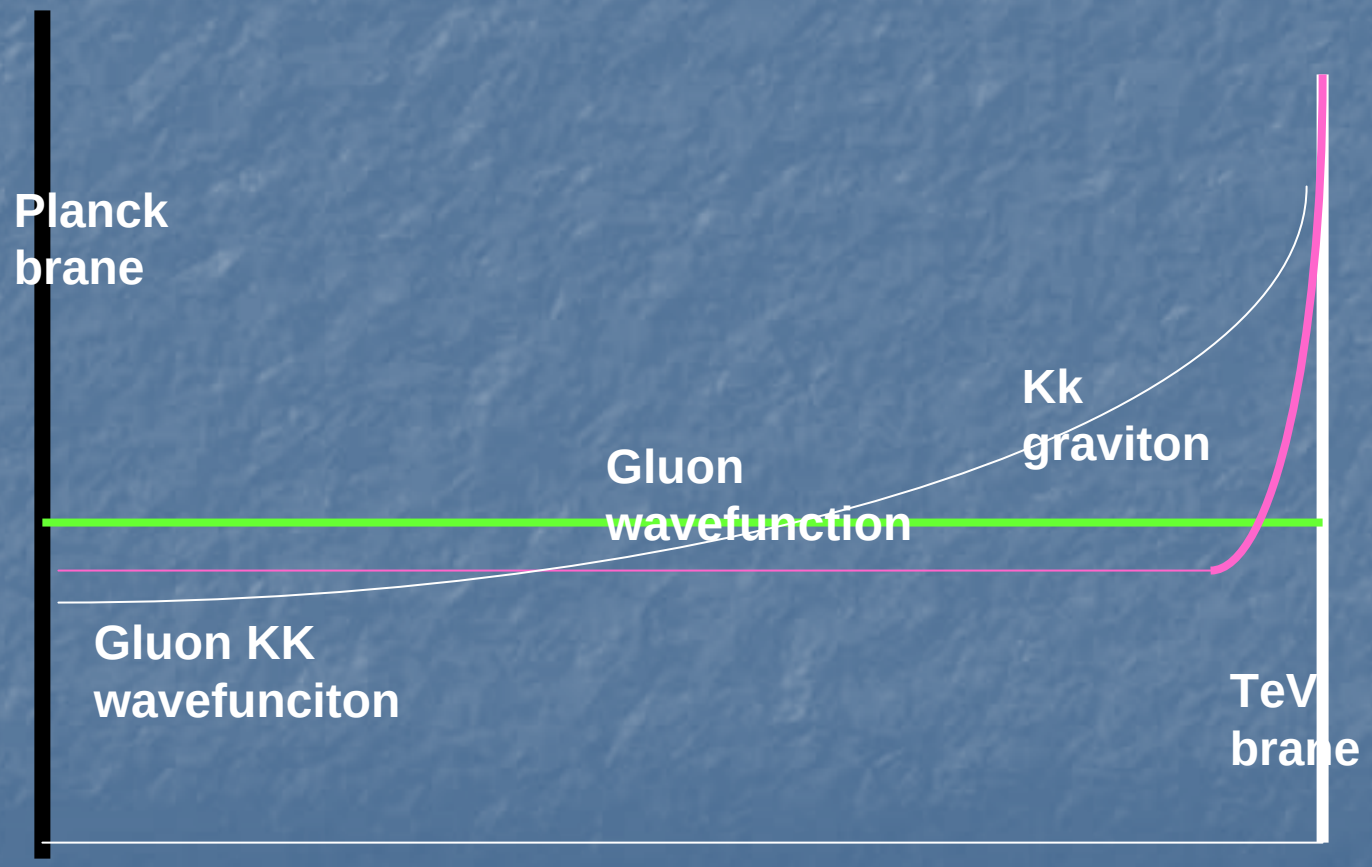


Figure 1: Relative mass spectra in units of $ke^{-kr_c\pi}$ of the KK excitations of the fermion fields as a function of their bulk mass parameter ν, as well as for the graviton and the gauge boson fields as described in the text.

Gluon, Gluon KK WFs



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

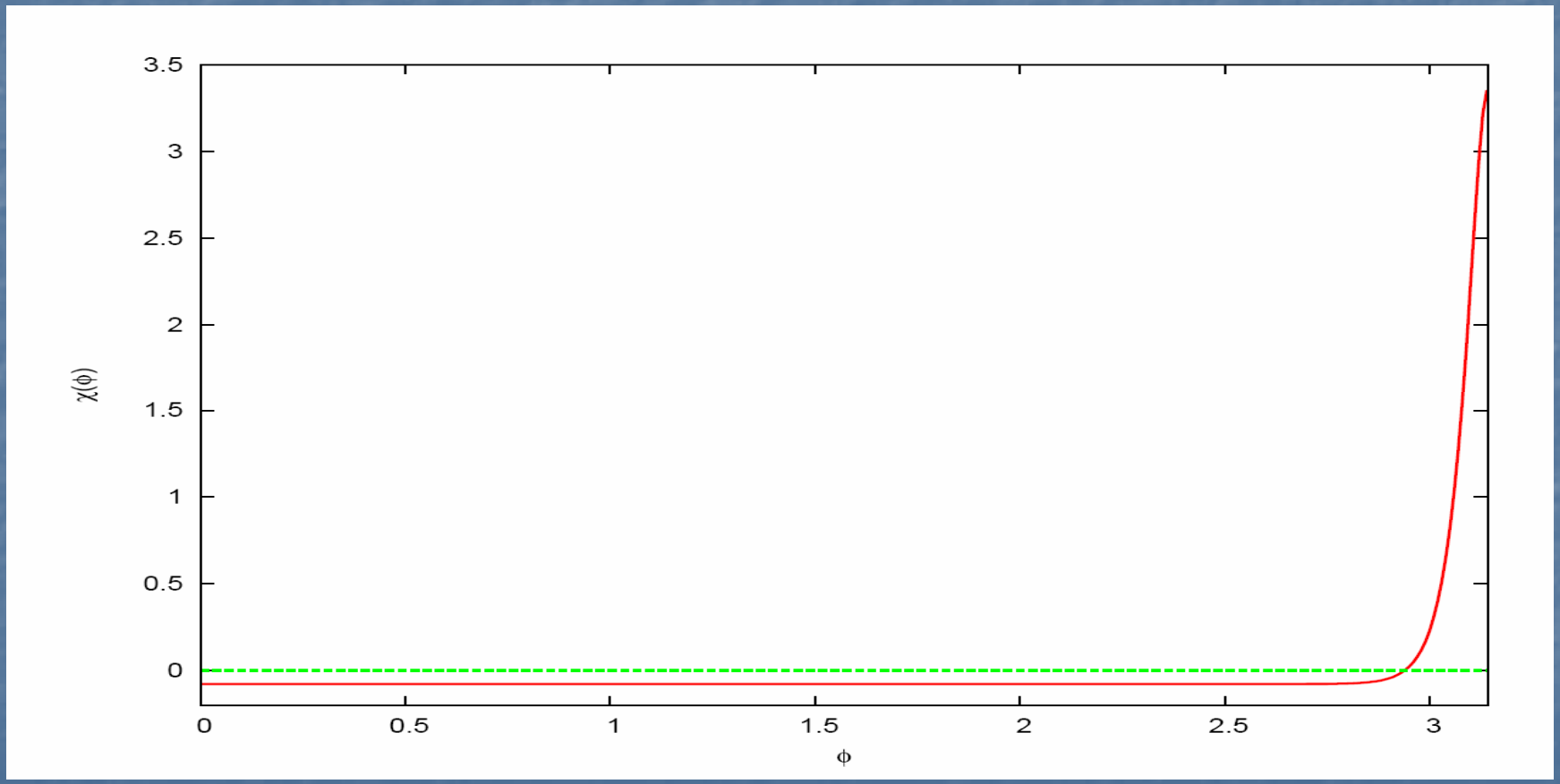
$$\frac{g_{f\bar{f}A^{(n)}}}{g_{SM}} \simeq -\frac{1}{\sqrt{\pi k r_c}}\frac{1}{\sqrt{n-0.2}} + \mathcal{O}\left[(\pi k r_c)^{-3/2}\right].$$

Understand from dual point of view in terms of gluon KK mixing-vector meson dominance

Note only gluon production from quarks.

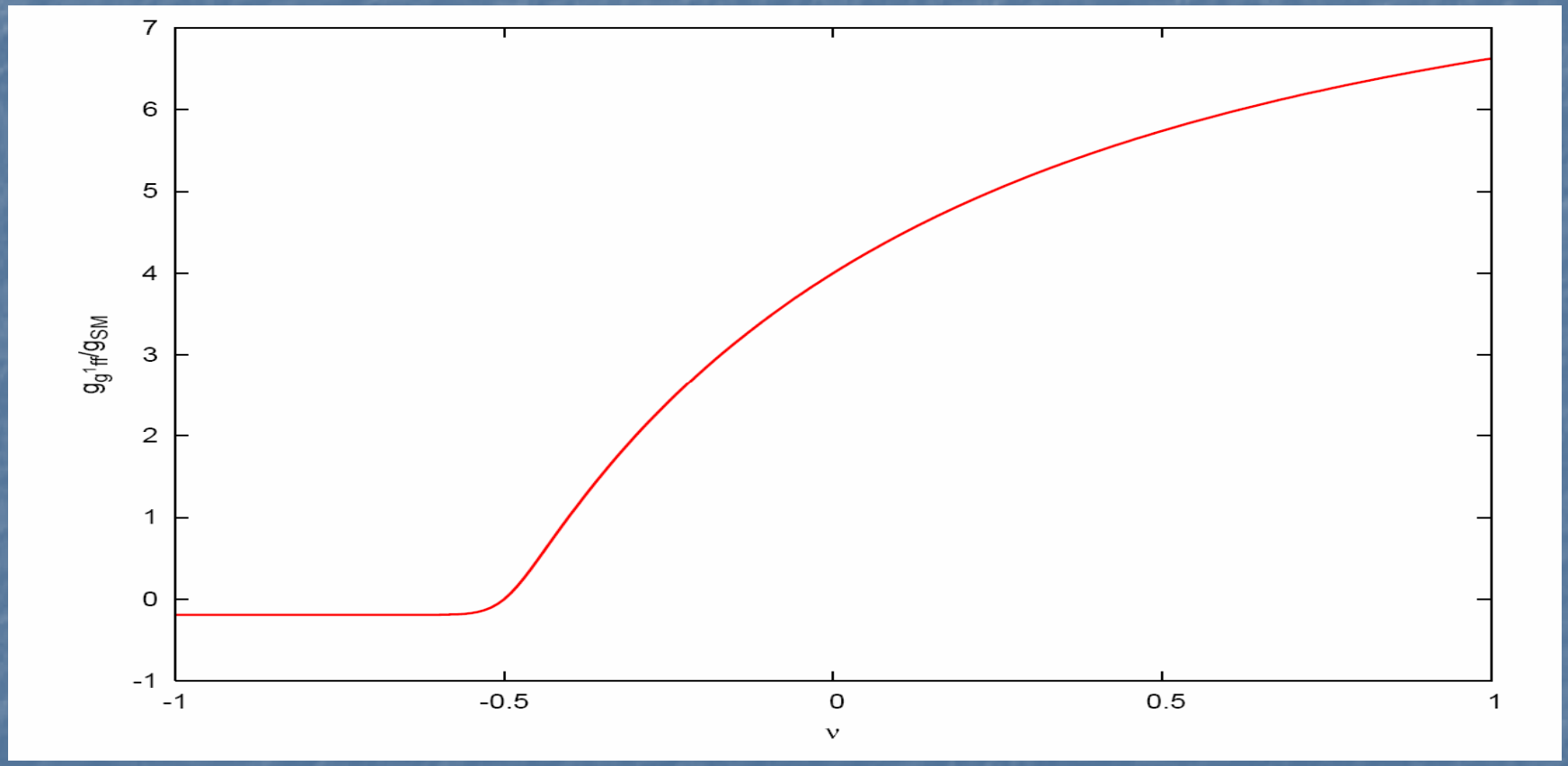
At tree level, gluon coupling vanishes.

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

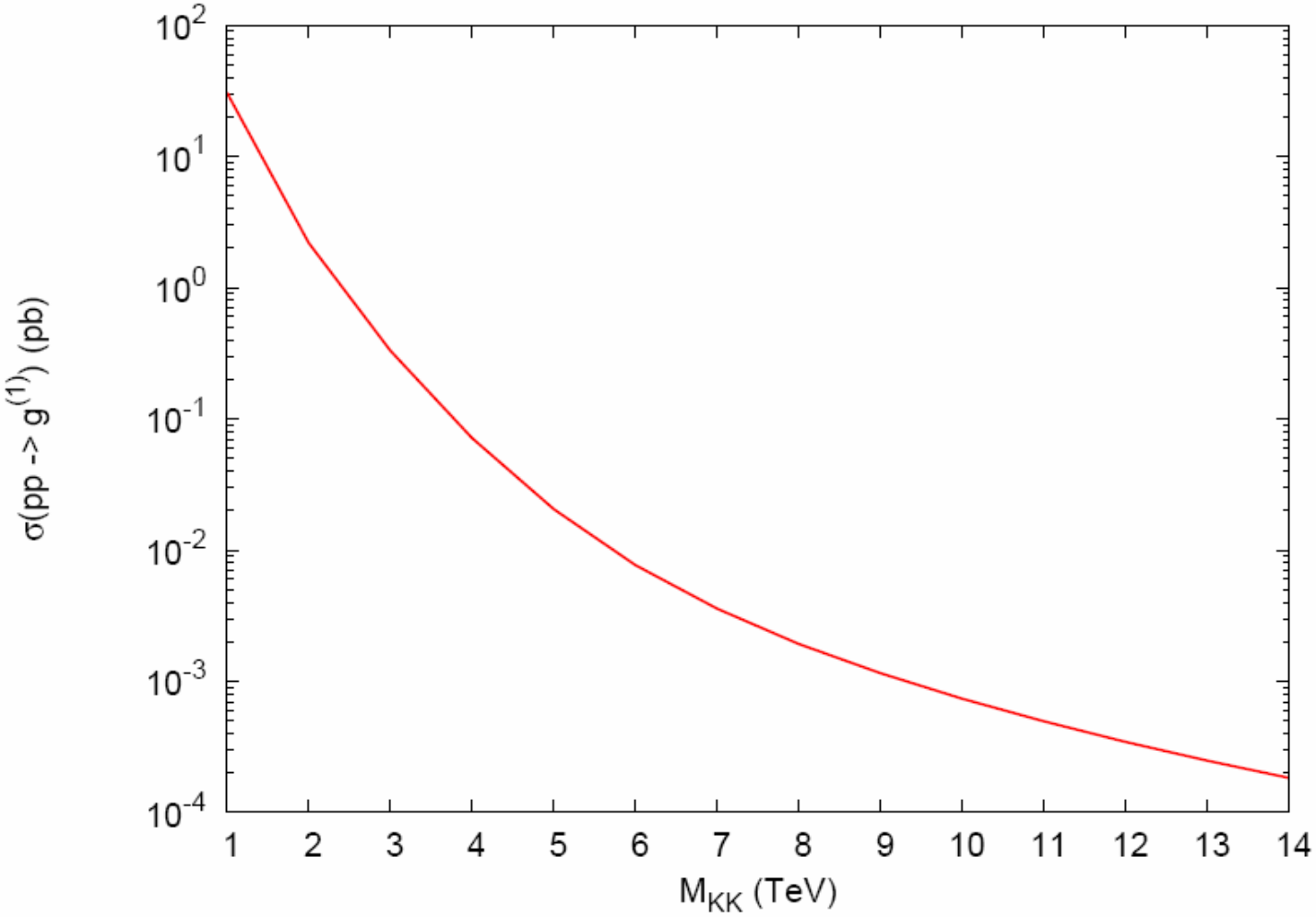


Gluon wave function

Gluon fermion interaction



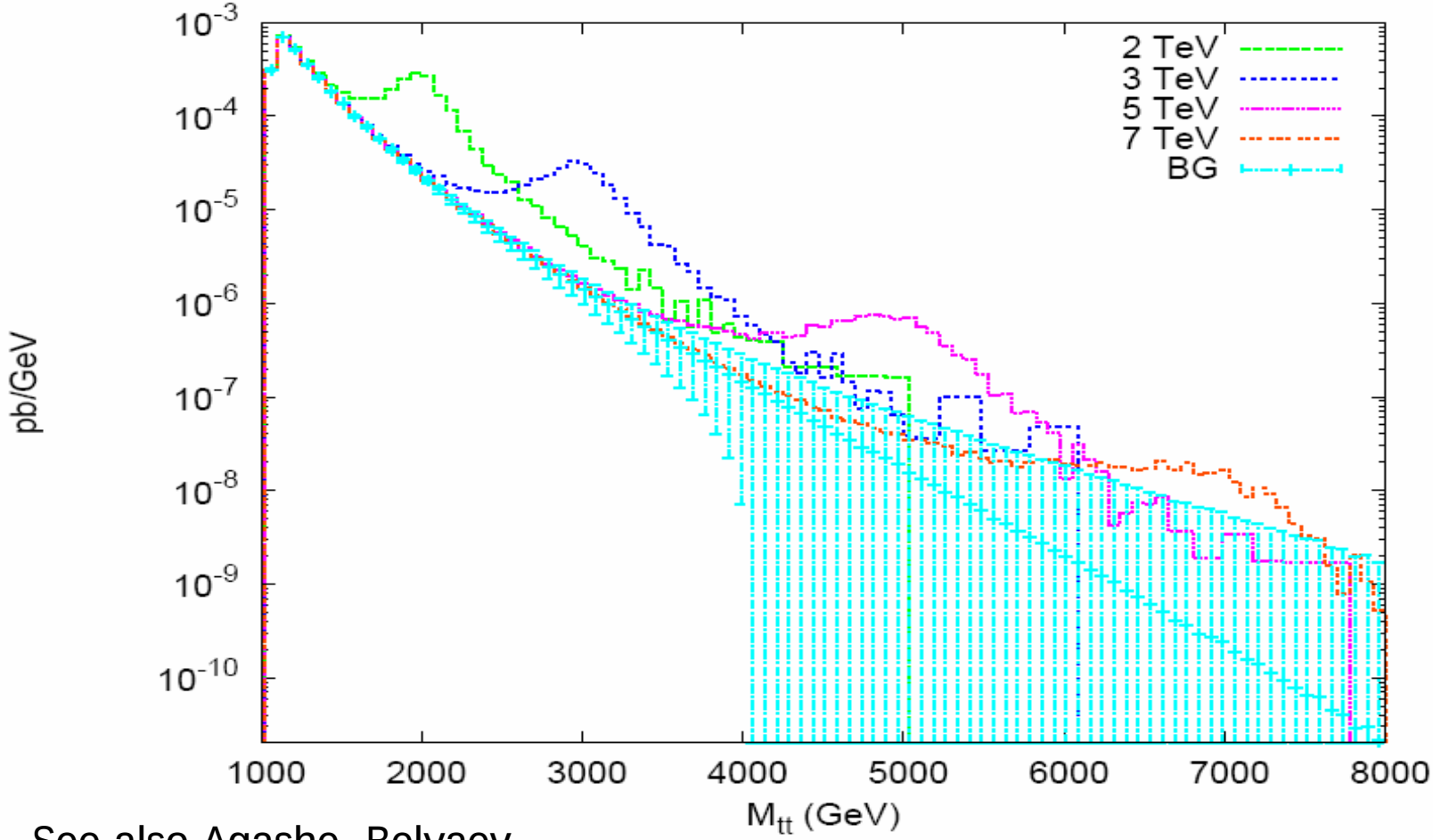
$$C_{00n}^{f\bar{f}A} = \frac{g^{(n)}}{g^{SM}} = \sqrt{2\pi k r_c}\left[\frac{1+2\nu}{1-\epsilon^{2\nu+1}}\right]\int_{\epsilon}^{1} dz\ z^{2\nu+1}\frac{J_1(x_n^A z)+\alpha_n^A Y_1(x_n^A z)}{|J_1(x_n^A)+\alpha_n^A Y_1(x_n^A)|}$$



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

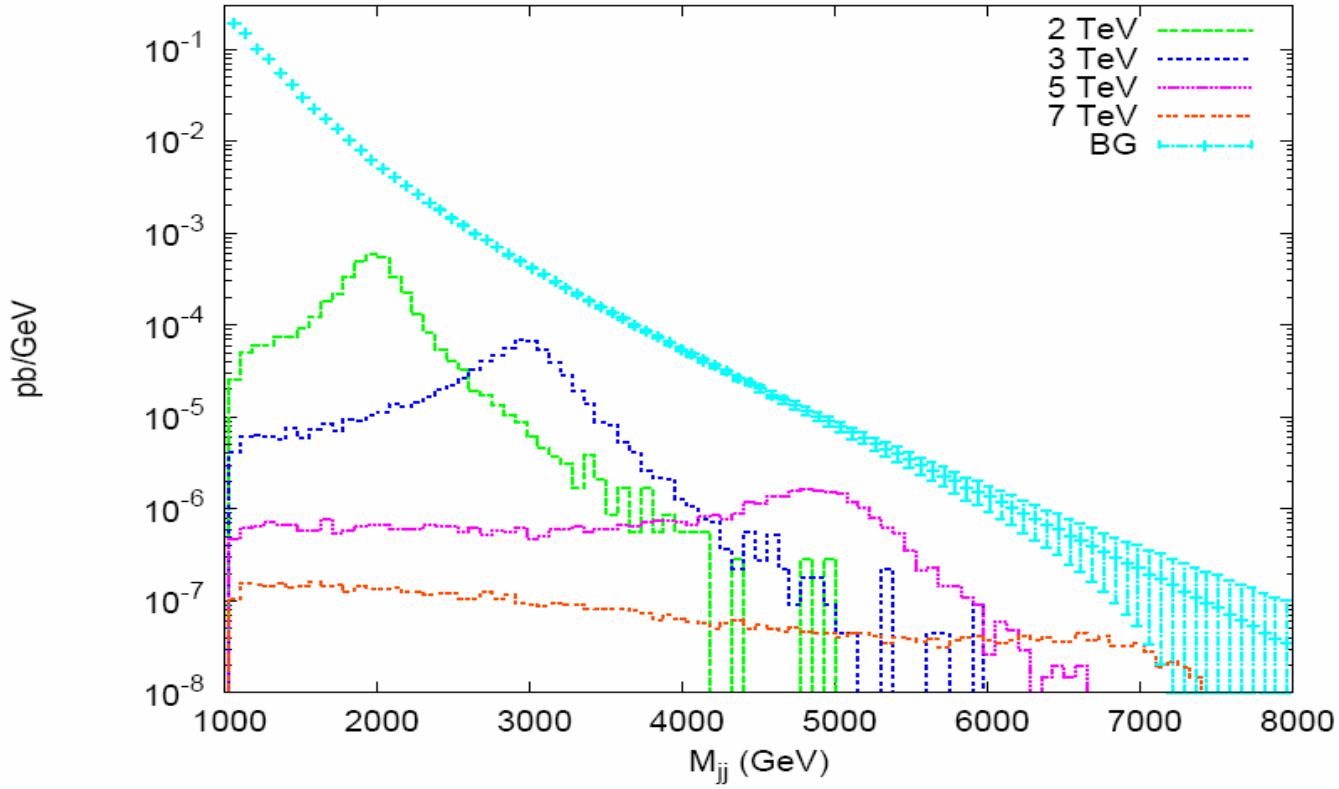
w/Ben Lillie,
Liantao Wang

Dominates over top jet background



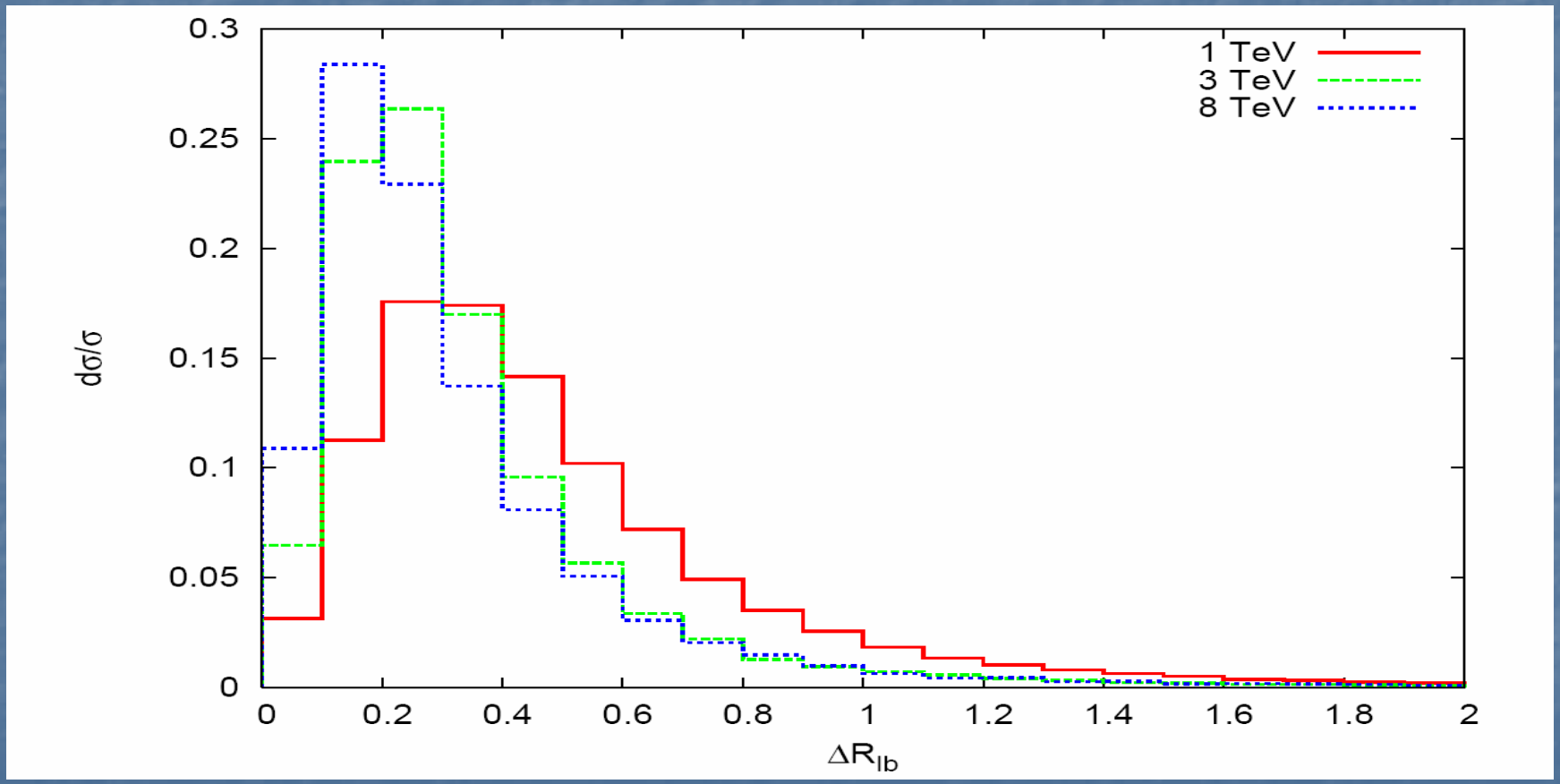
See also Agashe, Belyaev, Krupovnickas, Perez, Virzi

However, signal doesn't dominate over jet background



7: 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

Conclude require at most 10% fake rate

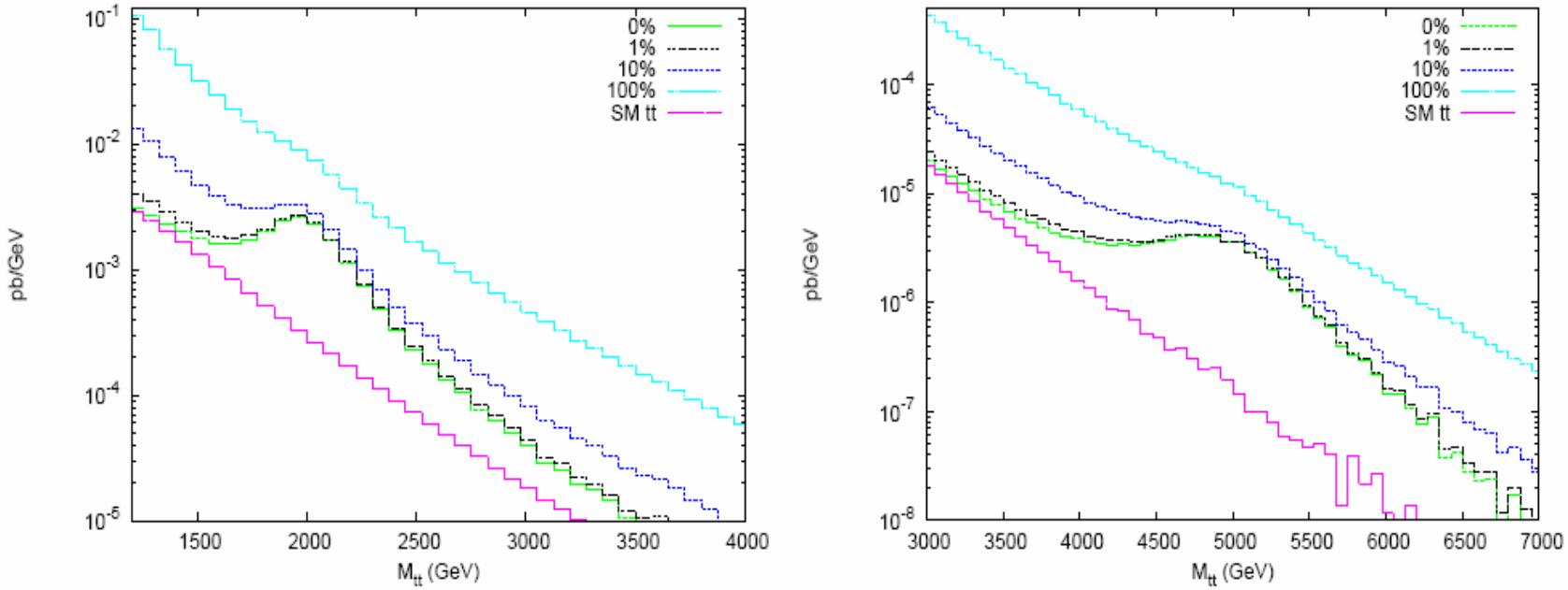


Figure 9: $t\bar{t}$ invariant mass distribution for signal plus some background assuming various values of the t-tagging fake rate for a resonance at 2 (left) and 5 (right) TeV.

Also Electroweak Sector Neutral:

- Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si, Soni

- $SU(2)_L x SU(2)_R x U(1)$ framework
- Decays to tops, bottoms dominate
- But also decays to long W, Z, Higgses
- 2 TeV at 100 fb^{-1}

Charged EW Sector

- Agashe, Kopalakrishna, Han, Huang, Soni
- Observed top/bottom final state avoids irreducible background (gluon KK, QCD)
- Also accessible leptonic modes
  - (Long W, Z)
- 2 TeV 100 fb^{-1}

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

Low Scale Gravity Signal?

- 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

Criteria for a Black Hole?

- $M_{BH}>M$
  - As advertised, not even convention independent
- $2\pi/(M/2)<R_S$
  - More stringent version of above
  - ADD (n=6) $M_{BH}>4M$—almost at experimental limit
  - RS $M_{BH}>16M$—if taken seriously, bhs already out of reach

Constraints on x_{min}

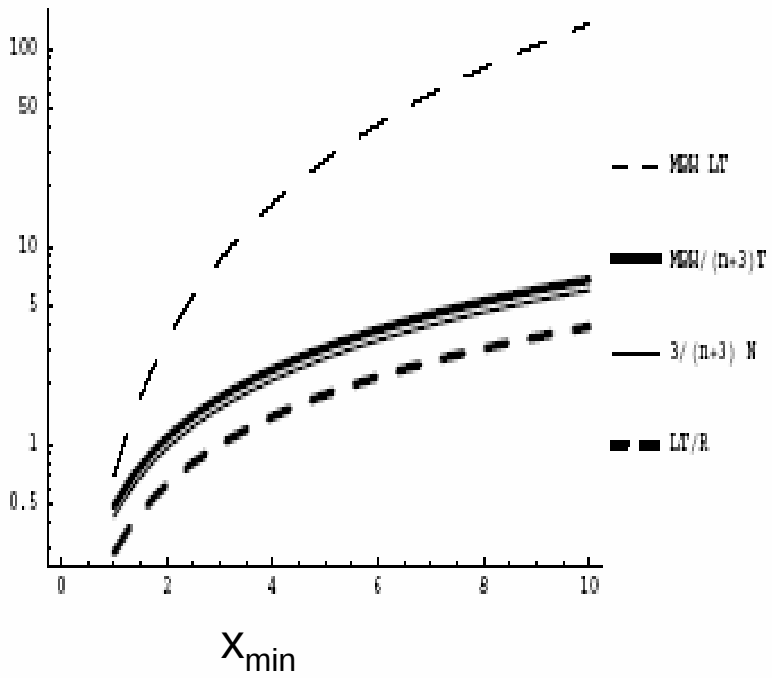
- Small back reaction on temperature
  $\partial T/\partial M \sim 1/((n+2)S)$ <<1; weak constraint that is readily satisfied
- Model-dependent constraint on black hole mass vs. brane tension.
- Individual degree of freedom should carry small fraction of mass: (n+3) T<M
- Black hole lifetime bigger than 1/M

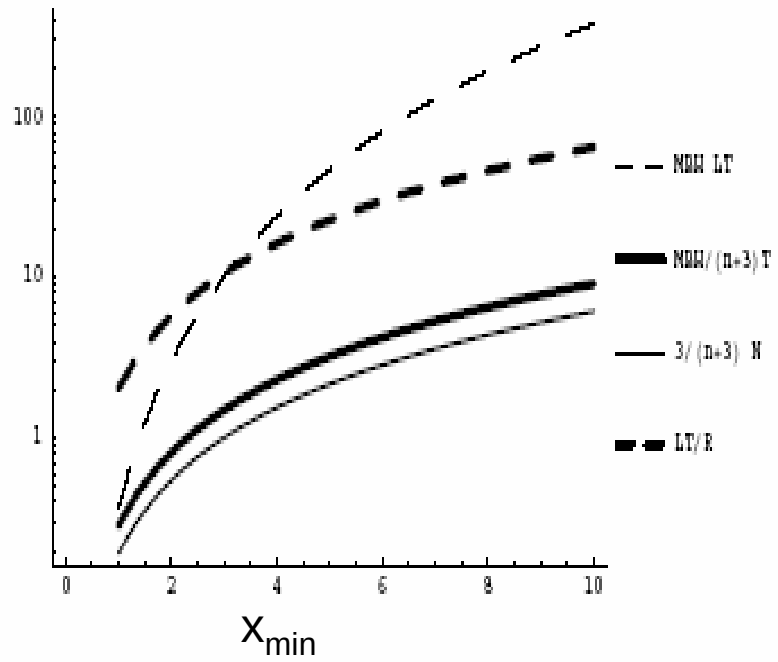
ADD: $\tau = .38\frac{x_{min}^2}{M}.$ RS: $\tau = .7\frac{x_{min}^{9/7}}{M_D}.$

- Really black hole lifetime greater than R_S

  ADD: $x_{min}>3$

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"

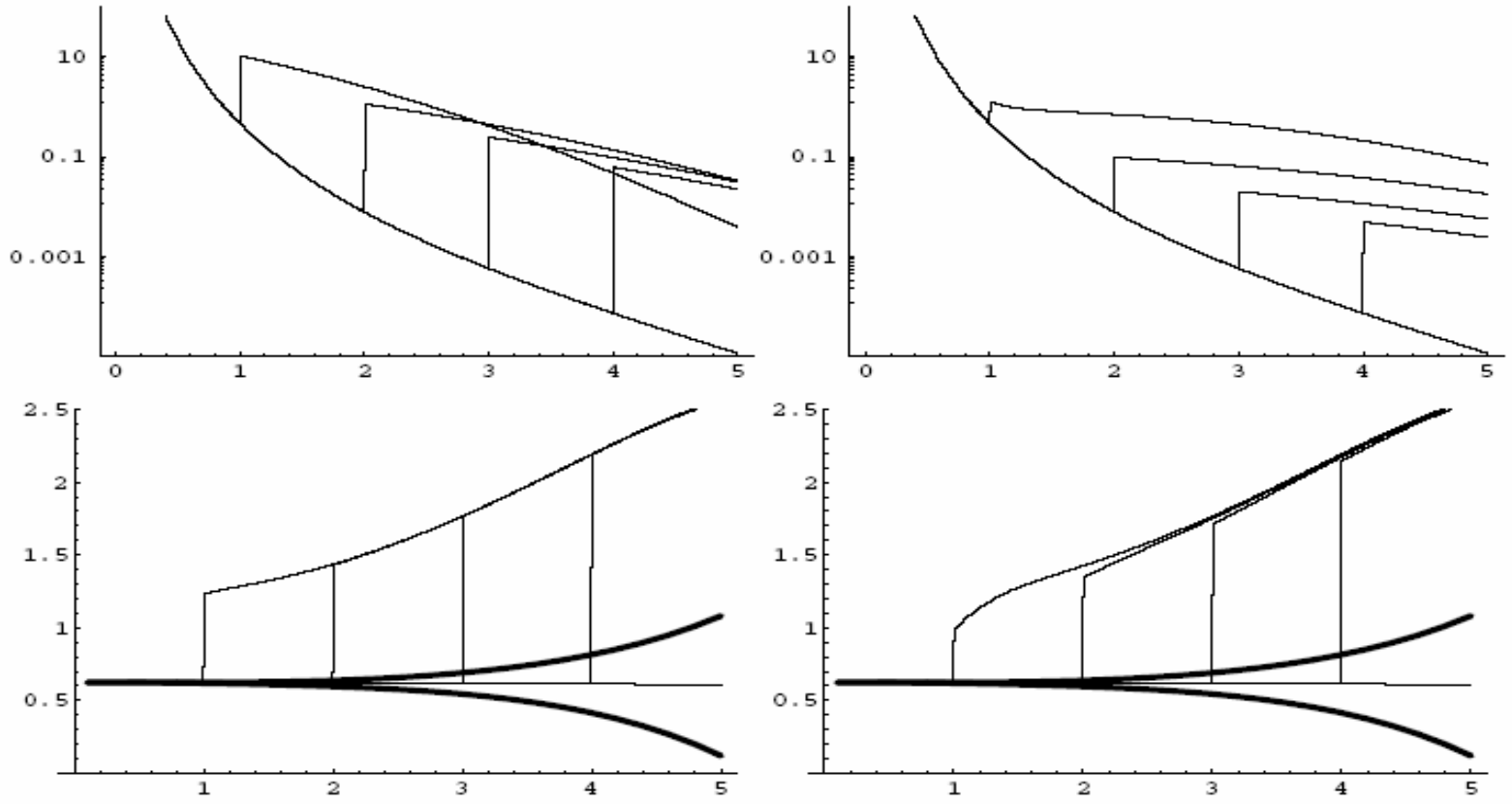


Figure 6: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background, and a n=6 ADD model "black hole" behavior with M_D=1,2,3,4 TeV and $x_{min} = 1$ in the lefthand plot and a RS1 black hole behavior with $M = 1, 2, 3, 4$ TeV and $x_{min} = 1$ 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

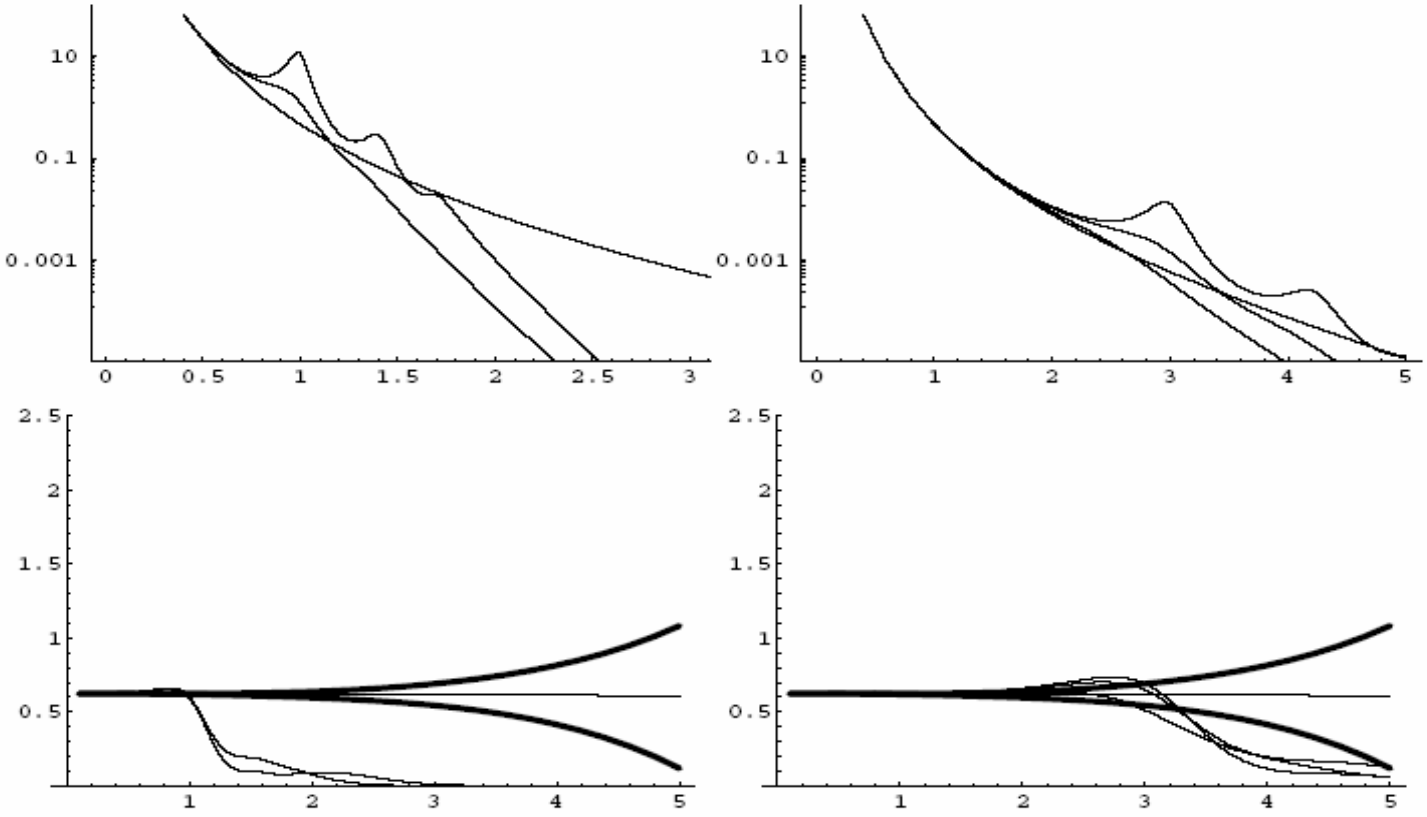


Figure 8: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background(thicker curve), and a toy stringy behavior with M_s=1 TeV in the lefthand plot with $\gamma = .1, .3$ and M_s=3 TeV in the righthand plot with $\gamma = .1, .3, .6$. In the lower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

Entering a new era in physics

- Every time we've explored smaller or larger length scales, we've found new phenomena, new connections
  - Could be KK modes
  - Could be "compositeness effects"
  - Could be other models…
- More connections are there—we just have to find them
- Secrets of the universe are about to unravel

Hidden riches in the universe