# Black Holes and Quantum Gravity at the LHC

LR with
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# Introduction

- LHC era approaching
- Many challenges
- Are we doing the best searches we can?
- Are we doing all the searches possible?
  - First principles calculations
  - Models
    - Low-Scale: Supersymmetry, Little Higgs
    - Higher-Scale: Strongly Interacting theories or Extra dimensions
- Focus today on extra dimensions and low scale gravity
- Way to study quantum gravity
    - KK Gravitons
  - And also higher-dimensional black holes

# Why Black Holes Appear Promising

- Estimate black hole production 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!

Spectacular fireball final states!

# This Talk

- How much could we really hope to learn from black holes?
  - Do we even produce them?
- We will see:
  - LHC unlikely to make classical black holes states that decay with high multiplicity via Hawking radiation
- However…all is not lost
  - Potentially much more prolifically produced 2 body final states
  - Uncalculable, but we will see distinctive experimental signatures that will distinguish among modes
  - Might teach us about *quantum* gravity

# Why Change in Expectations?

- Estimate was always a bit optimstic
- Understanding uncertainties and making refinements essential
- Because PDFs drop rapidly and
- We are necessarily near black hole production threshold
- Every term in original estimate must be considered carefully
  - M: quantum gravity scale
  - $M_{BH}$: black hole mass relative to center of mass energy

# Preliminaries

- We'll consider ADD and RS type black holes
- ADD
  - Experimental bound strong for low n
  - We'll calculate for least constrained case of n=6
  - $M_D$>900 GeV
- RS
  - Not usually considered for phenomenological black holes
  - People consider either
    - Pancake (UV)
    - Strong bound states characteristic of AdS
  - However, for k<M, regime $M<M_{BH}<M^2/k$
  - Traditional 5d (almost) flat space black holes
  - M>500 GeV

# I: "M"-- Convention Dependent

Myers-Perry Convention:

$$\frac{1}{16\pi G_D}\int d^{D+1}x\sqrt{g}R$$

$$r_S = \left(\frac{M_{BH}}{\mathcal{L}_N 6\pi^2}\right)^{1/2}$$

Different Normalizations for $G_D$: eg for 5d:

$M_P^3/16\pi$ with the convention used in [1], $M^3/2$ with the RS convention, and $M_D^3/4\pi$

Convention-dependent Schwarschild Radius:

$$r_S = \left(\frac{M_{BH}}{M^3 3\pi^2}\right)^{1/2}$$

$$r_S^{dimopoulous} = \left(\frac{8M_{BH}}{M_P^3 3\pi}\right)^{1/2} \qquad r_S^{feng} = \left(\frac{2M_{BH}}{M_D^3 3\pi}\right)^{1/2}$$

$M_P$, 1.6 $M_D$, 2.9 M

# II: "$M_{BH}$" Thermal Black Hole Threshold?

- Quantum gravity scale convention dependent
- Really physical question is black hole threshold relative to experimental bound
- Begs question: at what energy can we safely say we are making black holes?
- Clearly $E>M$, but insufficient
- Need sufficiently high entropy

# 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

# Additional Criteria for Thermality

- Express in terms of threshold parameter
- $M_{threshold}=x_{min}\ M$
- Useful formulae:

$$r = \frac{1+n}{4\pi T} = \frac{k(n)}{M_D}\left(\frac{M}{M_D}\right)^{\frac{1}{1+n}},$$

$$k(n) = \left(2^n \pi^{\frac{n-3}{2}} \frac{\Gamma\left(\frac{n+3}{2}\right)}{2+n}\right)^{\frac{1}{1+n}}$$

$$S = \frac{1+n}{2+n}\frac{M_{BH}}{T_{BH}}$$

# More:
# Decays and particle number

- Can compute time-dependent decay including grey-body factors
- Also critical to computing particle number is assumption of decays on the brane
- dE/dt~ f(E/T) E $d^4k \sim \Gamma(4)$
- dN/dt~ f(E/T)  $d^4k \sim \Gamma(3)$
- (General n would have given $\Gamma(n)$, $\Gamma(n-1)$)

$$\langle N \rangle \sim \frac{4\pi\rho k(6)}{8}\left(\frac{M_{BH}}{M_D}\right)^{\frac{8}{7}}$$

$$\rho = \frac{\sum c_i g_i \Gamma_i \zeta(3)\Gamma(4)}{\sum c_i f_i \Phi_i \zeta(4)\Gamma(4)}$$

$$\langle N \rangle \sim \frac{4\rho}{3\sqrt{3}}\left(\frac{M_{BH}}{M}\right)^{\frac{3}{2}}$$

# 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

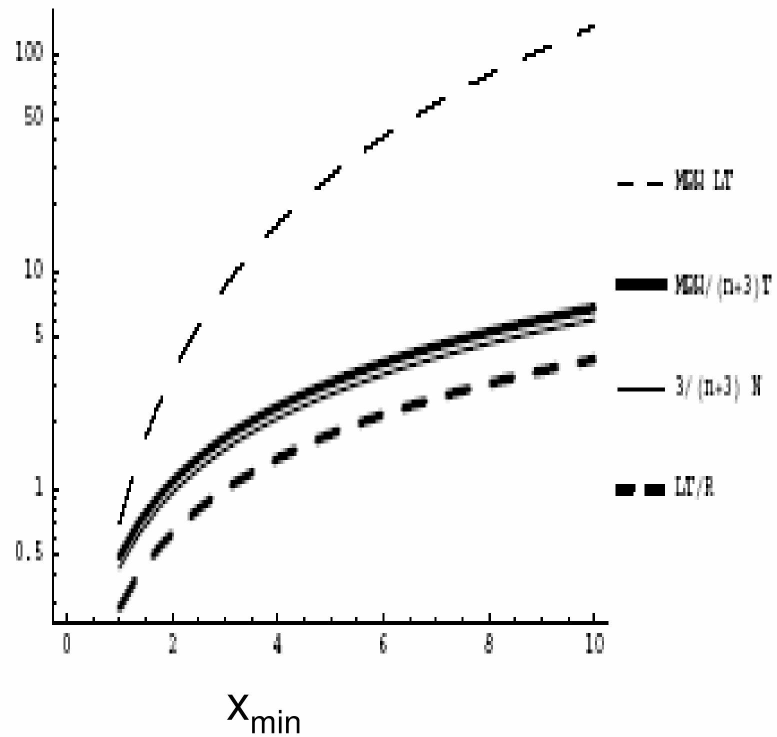
- Individual degree of freedom should carry small fraction of mass: (n+3) T<M
  - Decay dof carry 3 T; but for bulk N require 3/(n+3) <N>>>1
  - Bound is $x_{min}$~3 for RS, xmin~ 2 for ADD (n=6);
    - But this is one dof!
  - Max $x_{min}$ within reach for ADD: $x_{min}$~6 yielding 3 bulk particles!
  - Max $x_{min}$ for RS: $x_{min}$~10 yielding about 6 particles…
- Black hole lifetime bigger than 1/M

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

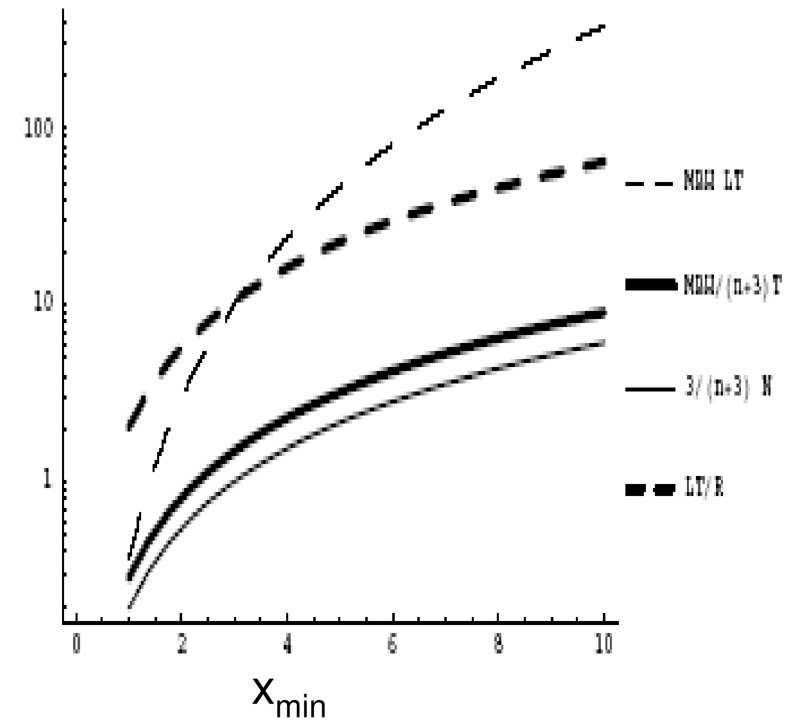
- Really black hole lifetime greater than $R_S$

  ADD: $x_{min}$>3
- Model-dependent constraint on black hole mass vs. brane tension.

# Constraints: Min value of $M_{BH}$




ADD




RS

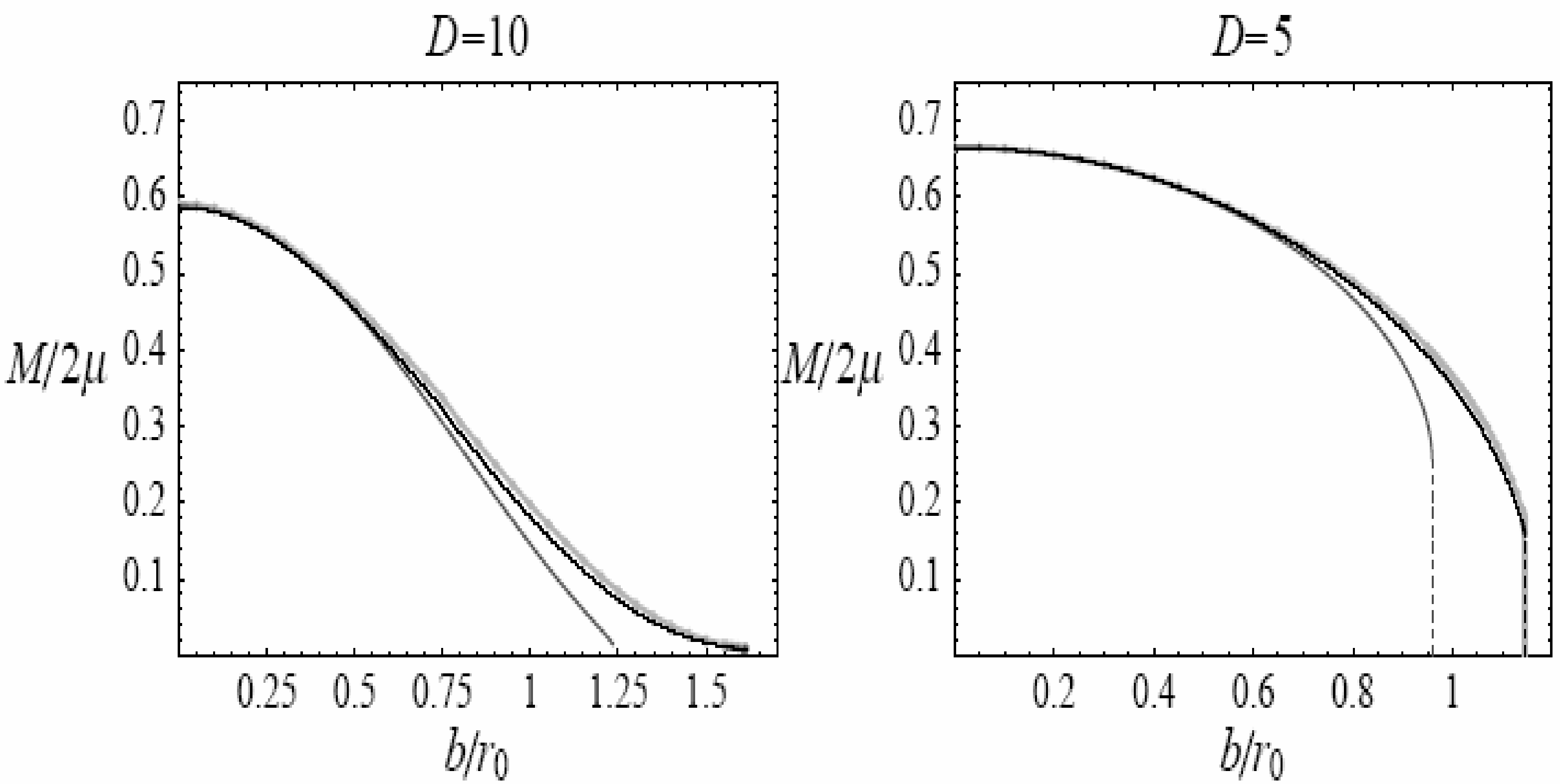
# Conclude from this

- $x_{min}$ should be reasonably high
  - Notice that even if a black hole, nontrivial $x_{min}$ obscures ability to extract M from total cross section
    - In principle, energy dependence gives number of dimensions—but tough
    - Differential cross section (threshold behavior) could be used in principle to extract M
    - But confused by inelasticity we now discuss

# What is true threshold energy?: Inelasticity as function of impact parameter

- What fraction of com energy goes into black hole
- Define $y=M_{BH}/\sqrt{(s)}$
- Important since PDFs fall rapidly—effectively increases threshold
- Penrose, D'eath and Payne, Eardley and Giddings, Yoshino and Rychkov
- Parameterize two Aichelberg-Sexl shock waves (two highly boosted particles) intersecting
- What fraction of energy gets trapped behind horizon?
- Of course applies in classical regime but we use to estimate

# Inelasticity is significant




From Yoshino and Rychkov

# σ w/ and w/o inelasticity; Impact parameter weighted

$$\sigma(pp \to BH) \equiv \sum_{i,j} \int_0^1 2z dz \int_{\frac{(x_{min} M_D)^2}{y(z)^2 s}}^1 du \int_u^1 \frac{dv}{v} f_i(v,Q) f_j(u/v,Q) \sigma_{i,j\to BH}(M_{BH} = us),$$

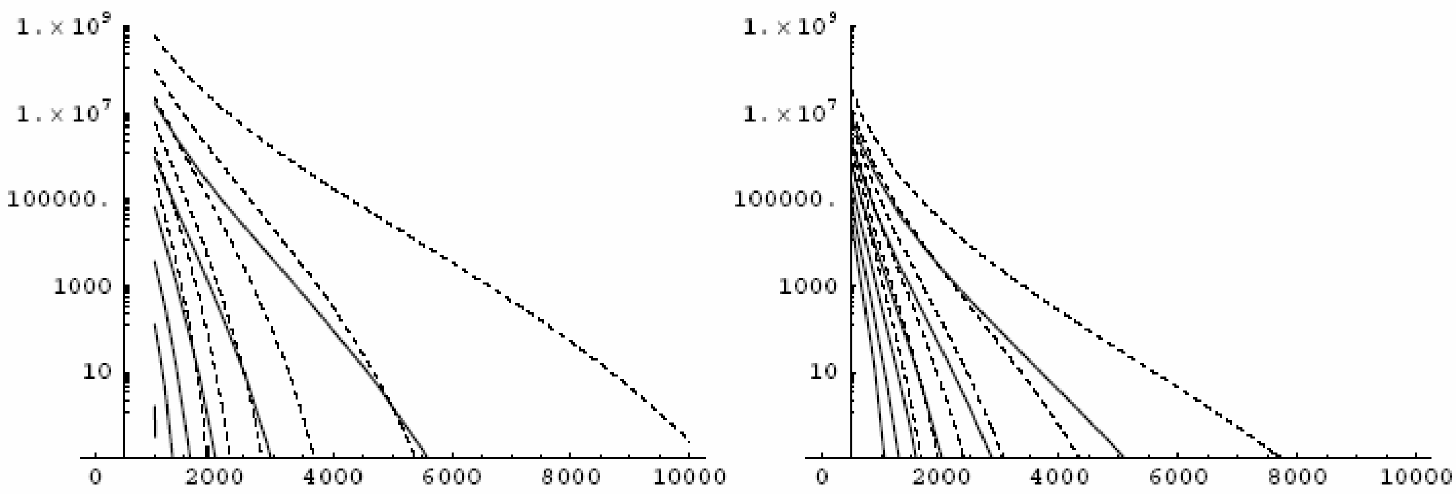



Figure 3: Total black hole cross section in femtobarns, including(solid curves) and not including(dashed) inelasticity as a function of $M_D$ for ADD with $n = 6$ and $M$ for RS1. The different curves from highest to lowest correspond to $x_{min} = 1 - 6$.

# Upshot

- Black hole production threshold ($M_{BH}$) higher than originally thought
- Means
  - Lower production cross section
  - Lower reach in black hole mass
  - Translates into lower entropy reach as well
- Don't produce *classical thermal* black holes
  - What do we produce?
    - What type of multiplicities might we expect?

# Multiplicities

- <N> calculation not necessarily reliable in quantum regime
- Nonetheless, use as guide
- Even if untrustworthy…
- Conclusion obvious
- Low multiplicity final states will dominate and be worthy of study

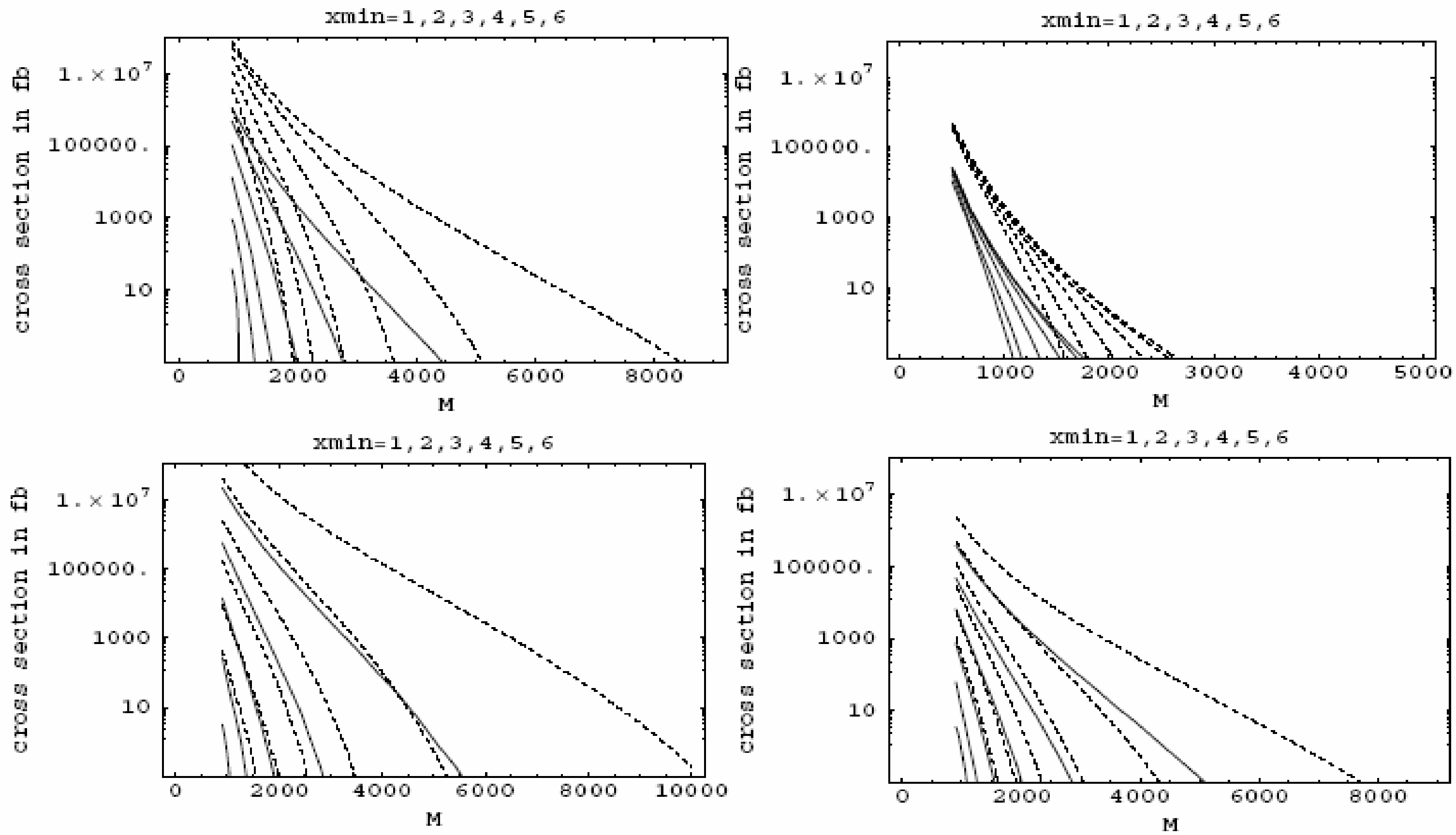



Figure 4: In the upper plots curves of total cross section for having 6 or more particles, including(solid curves) and not including(dashed) inelasticity as a function of $M_D$ for ADD with $n = 6$ and $M$ for RS1. The different curves from highest to lowest correspond to $x_{min} = 1 - 6$. In the lower plots the same curves are plotted for having 2 particles instead of 6 or more.

# 6 vs. 2

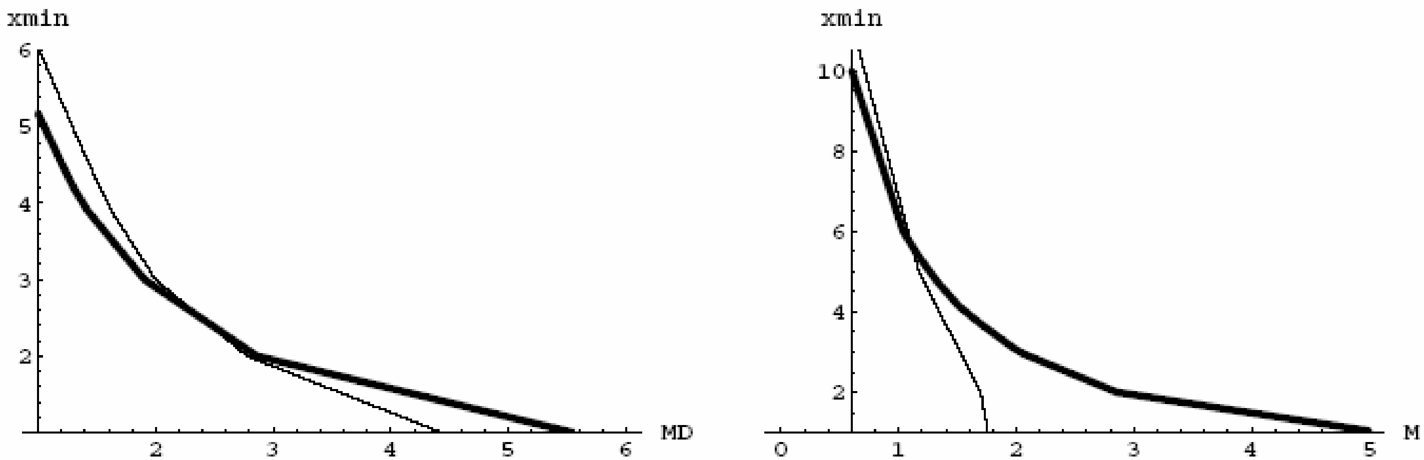



Figure 5: Curves of constant .1 femtobarn cross section including the effects of inelasticity and a probability for getting either 2 particles(thicker curve) or greater than 6 particles(thin curve). In the left hand panel the curves are for ADD with 6 extra dimensions and are plotted as a function of $x \equiv M_{BH}/M_D$ and $M_D$. In the right hand panel the curves are for RS1 as a function of $x \equiv M_{BH}/M$ and $M$.

# Upshot

- Even 6 particle production cross section has markedly lower reach than 2 particle state
- Furthermore we don't trust 6 particle states to be thermal anyway!
- Face facts!
  - Study 2 body final states: jets and leptons
  - Can they be distinguished from background?
  - Yes! For jets, transversality is key.
    - QCD dominated by t-channel exchange: forward
    - Black hole events isotropic—larger transverse xsection

# Compositeness Searches for Quantum Gravity

- Measure differential cross section
- Measure angular dependence through Rη (much less systematic error)
- Look for effect of strong dynamics
- Hopefully have already found KK modes
- Can also try to directly distinguish from compositeness
  - Especially distinctive (flavor violating) must be forbidden
  - But we will  see distinctive features of energy dependence in “compositeness” signal
  - And relative lepton rate

$$R_\eta \equiv N_{events}(0 < |\eta|) < .5)/N_{events}(.5 < |\eta|) < 1)$$

# Clarification

- We don’t really think we can make precise predictions
- We use *models* for quantum gravity
- To see what to look for
- Take advantage of potentially rich data
- Ask: what are distinguishing features that
- *Experimentally* probe quantum gravity

# Result for Dijet "Black Holes"

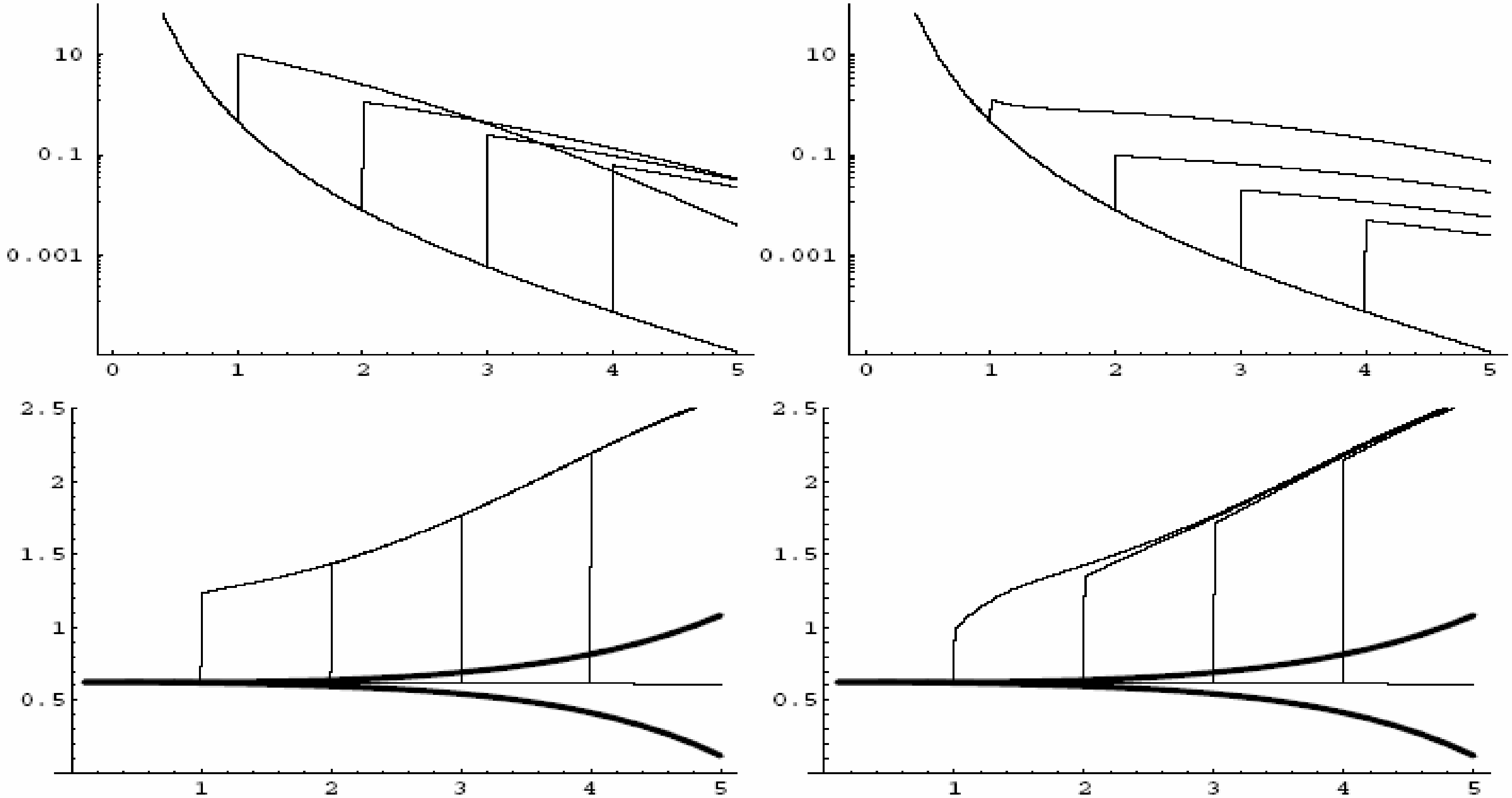
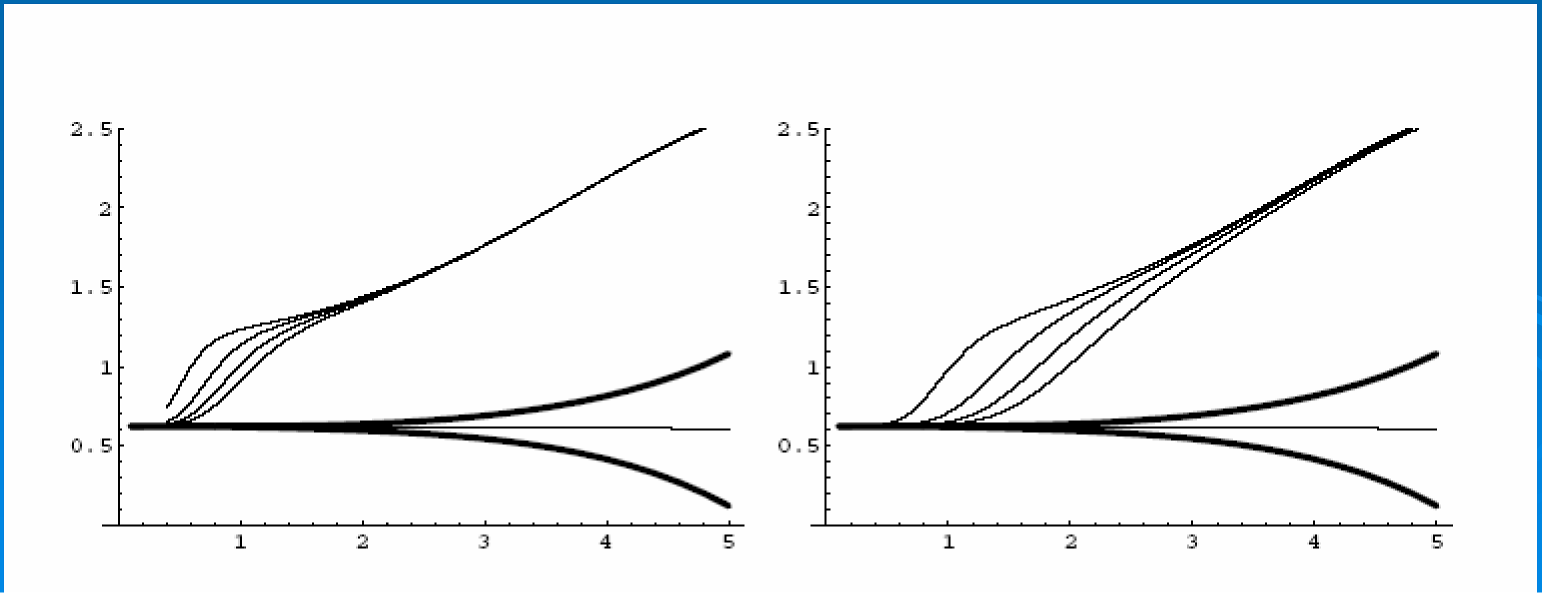



Figure 6: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background, and a n=6 ADD model "black hole" behavior with $M_D$=1,2,3,4 TeV and $x_{min} = 1$ in the lefthand plot and a RS1 black hole behavior with $M = 1, 2, 3, 4$ TeV and $x_{min} =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

# Distinctive Features

- Sudden turn on of cross section
- And transversality
- Even with slower turn on distinguishable
- And interference can distinguish among M



# Alternative Model of QG: Weakly Coupled String Theory

- Use Veneziano amplitude
- Exhibit resonance behavior
- Then dramatic drop in transverse cross section
  - Can readily distinguish from Z'
  - Can distinguish among different forms for Veneziano amplitude

$$A^0_{ST} \equiv \frac{\Gamma\left(1-\frac{s}{M_S^2}(1+i\gamma)\right)\Gamma\left(1-\frac{t}{M_S^2}(1+i\gamma)\right)}{\Gamma\left(2-\frac{s}{M_S^2}(1+i\gamma)-\frac{t}{M_S^2}(1+i\gamma)\right)}$$

$$A_{pp\to jj} \equiv A_{SM}A_{ST}$$

$$A_{ST} \equiv \frac{\Gamma\left(1-\frac{s}{M_S^2}(1+i\gamma)\right)\Gamma\left(1-\frac{t}{M_S^2}(1+i\gamma)\right)}{\Gamma\left(1-\frac{s}{M_S^2}(1+i\gamma)-\frac{t}{M_S^2}(1+i\gamma)\right)}$$

# Stringy Results

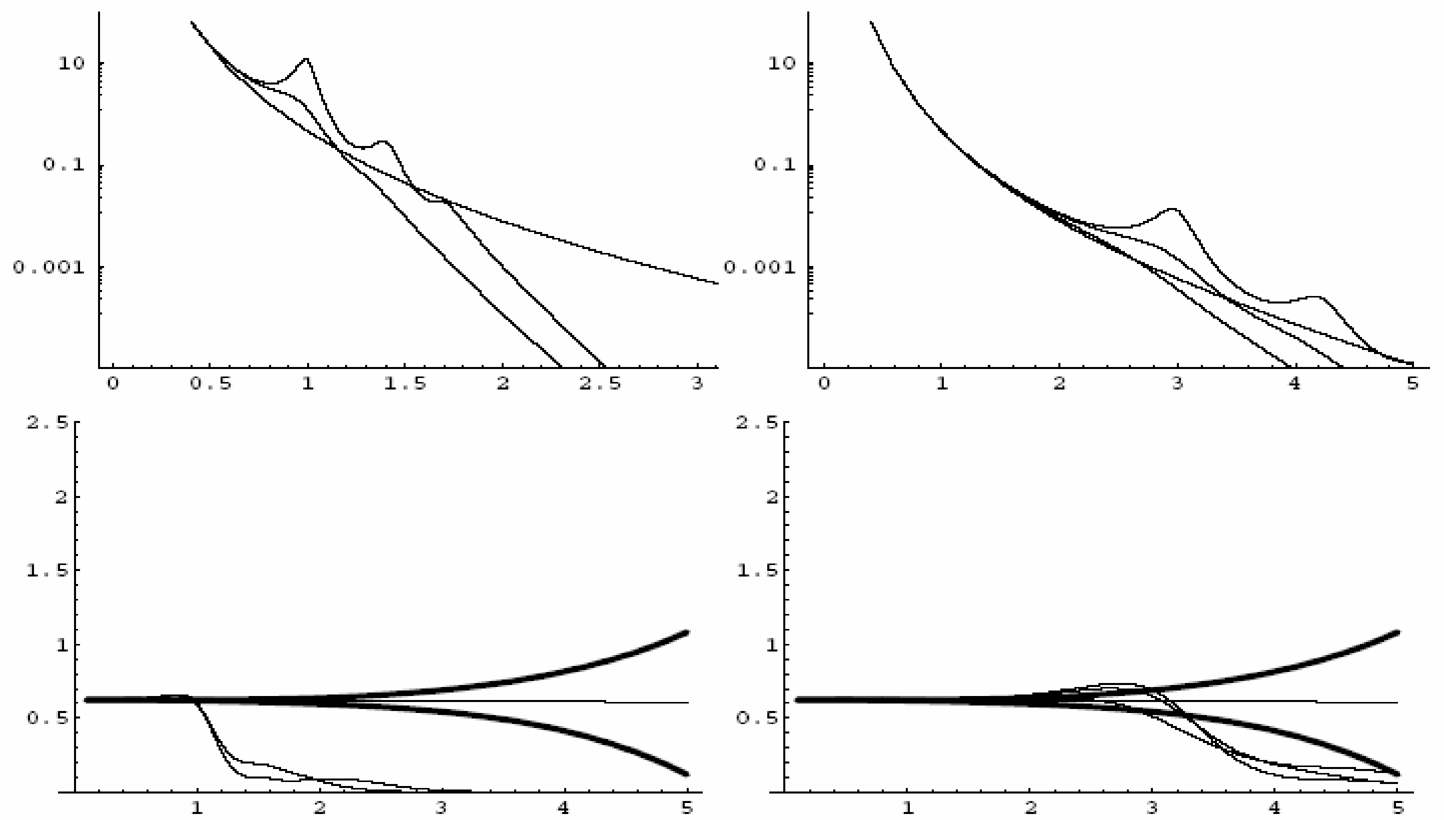



Figure 8: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background(thicker curve), and a toy stringy behavior with $M_s$=1 TeV in the lefthand plot with $\gamma = .1, .3$ and $M_s$=3 TeV in the righthand plot with $\gamma = .1, .3, .6$. In the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

# Can Distinguish Models

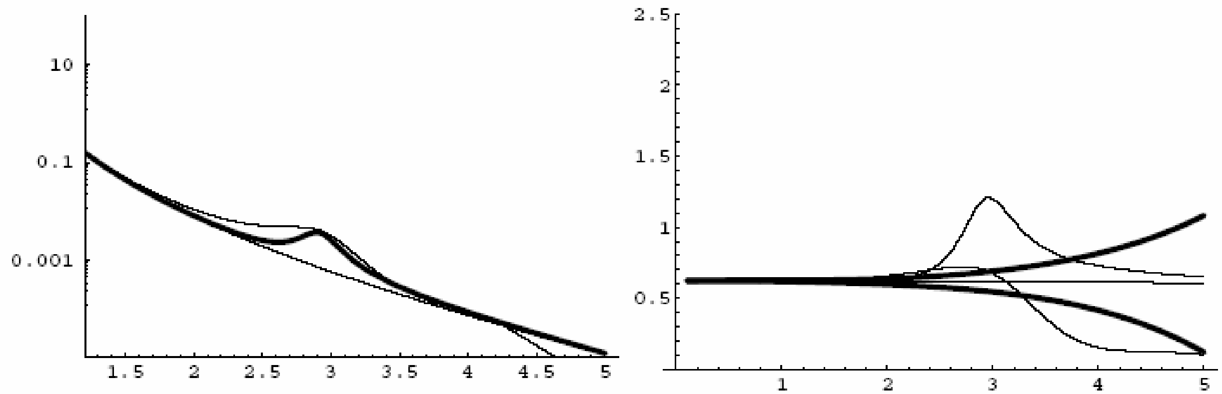
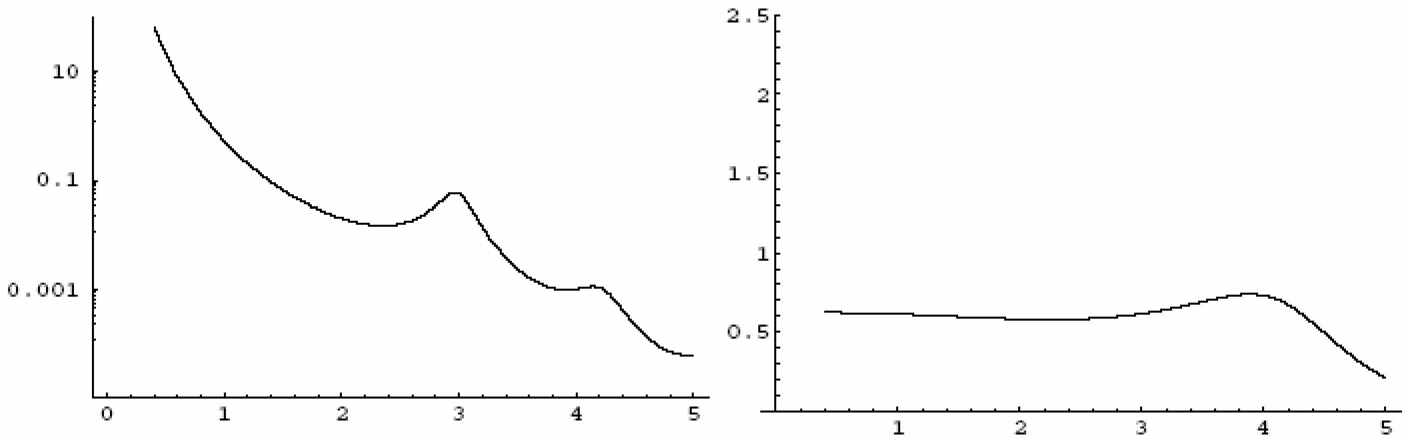



Figure 10: In the left plot $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background, a toy stringy behavior with $M_s$=3 TeV and $\gamma$ = .2 and a massive colored octet resonance(thicker curve) with mass and width chosen to mimic the differential cross section behavior near the resonance. In the right hand plot the same curves are plotted for $R_p$, note the easily discernible difference between field theory resonance and "string"



# Scales

- If you see strings, you won't see black holes
- $M_s/g_s^2$
- Should be able to readily make some gross distinctions about which regime of quantum gravity you are probing

# Alternative QG: Higher Dimension Operators

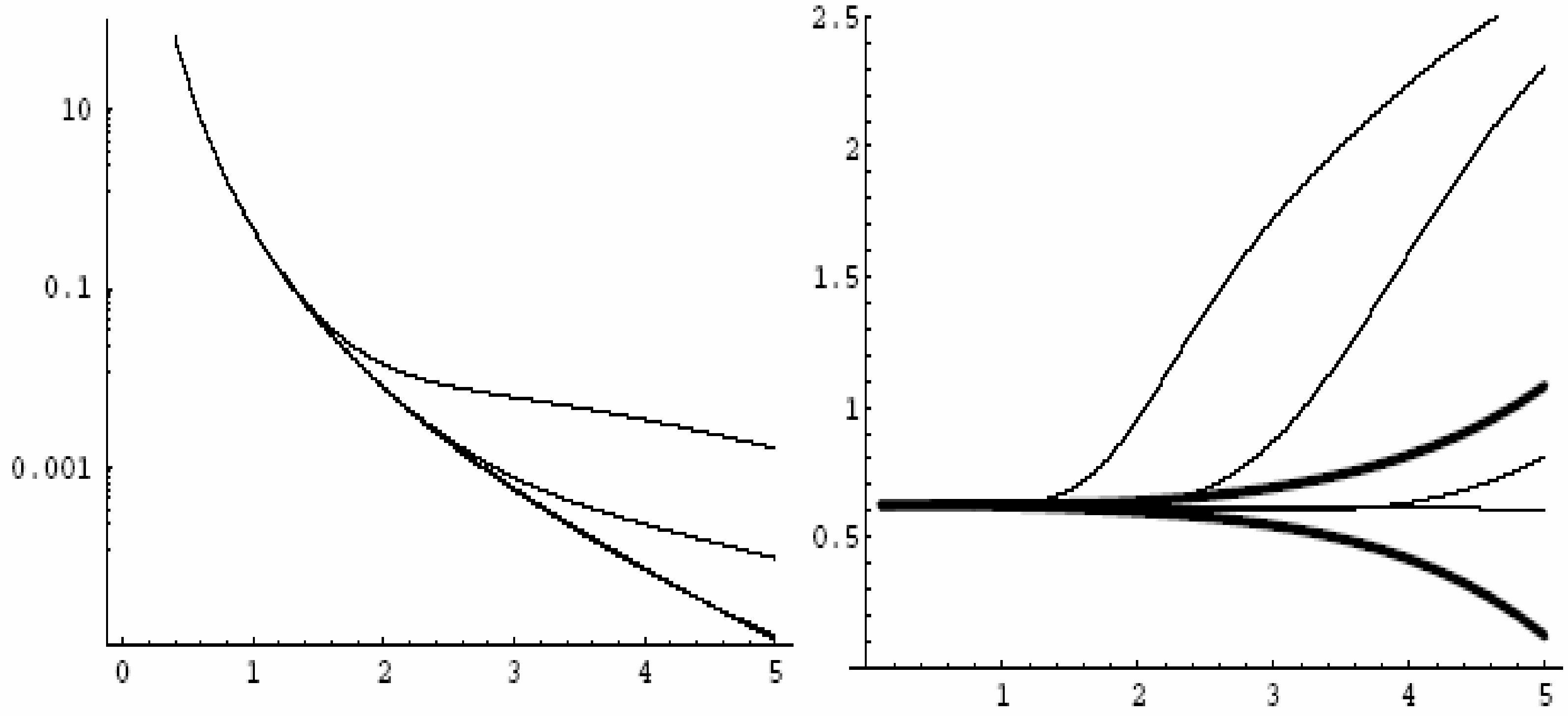
- Sources:
  - Black Holes
  - Multigraviton exchange
  - High scale string theory (4 fermion for original Veneziano amplitude)
  - String theory in warped space

# Distinctive Features

- Energy dependence
- Threshold behavior: extend to low energies
- Spin structure
- Spacetime symmetries
- Charge and gauge structure

$$\frac{c}{\Lambda^2}\Sigma(\bar{f}\gamma^\mu f)^2.$$

# Result




Λ=1,2,4 TeV (c=1)

# Lepton cross section might be key

- Lepton rate significantly higher from black holes (pdf and branching fraction)

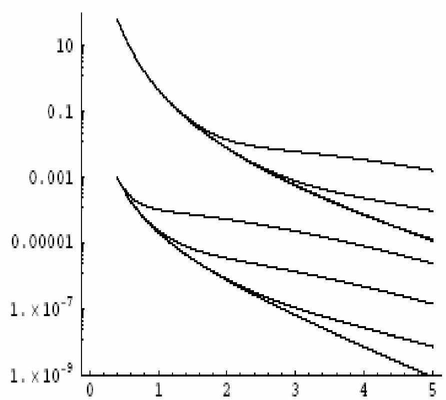
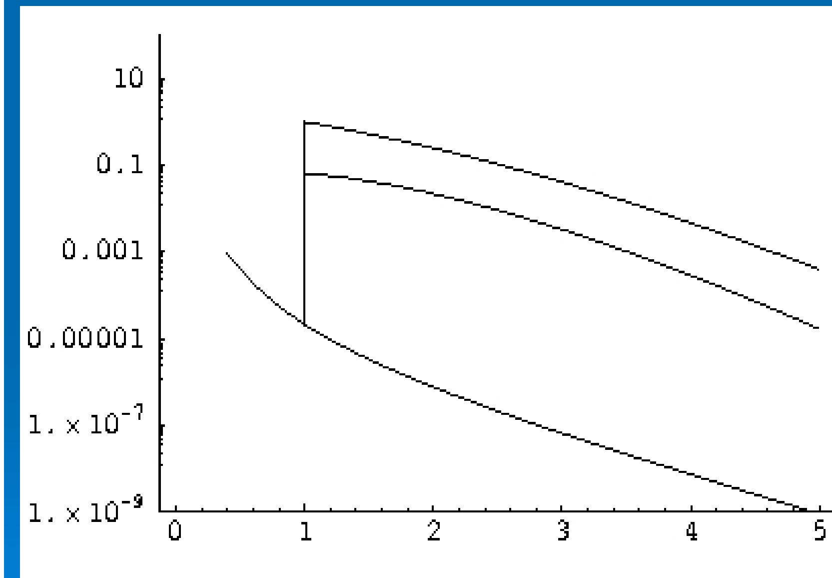



Figure 13: $d\sigma/dM$(units of pb/GeV) vs two body invariant mass(TeV) is plotted for QCD(the lowest curve) and a set of four fermion operators with $\Lambda = 1, 2, 4$ TeV for di-jets in the upper curves. In the lower curves SM Drell-Yan production of leptons is plotted in combination with a four fermion operator that generates a $l^+l^-$ final state with various $\Lambda = 1, 2, 4$ TeV.




ADD:MD=1TeV

# Summary

- Black holes not as "spectacular" as advertised

  BUT

- Lots of information about quantum gravity buried in 2->2!
- Initial increase in rate for more central processes always occurs
- Could be related to fundamental partons in black holes?
- R behavior: bh, string resonances, different forms for string, Z' all distinctive
- Threshold behavior where interference matters
- Hadron vs. Lepton cross section
- Remain:
  - Charge, spin
  - Signatures with missing energy, multibody final states (lepton and jet or more jets),

# Goal

- Get as much info as possible
- At as high energies as we can reach
- Compositeness type studies might be key