Black Holes and Quantum Gravity at the LHC

LR with

Patrick Meade

Introduction

- 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 and low scale gravity
- Way to learn about quantum gravity and strongly interacting physics

Calculable Gravity Effects

- Existing literature focuses on
  - Graviton emission and exchange
  - Transplanckian regime
  - Black holes
- KK modes will hopefully be accessible up to a few TeV
- Other possibilities outside calculable regime

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
  - 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

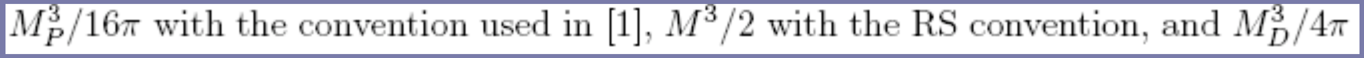
I: "M"-- Convention Dependent

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

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 $M<M_{BH}<(M/k)^2\,k$
  - Traditional 5d (almost) flat space black holes
  - M>500 GeV

RS Flat Space Black Holes

$$r_S << 1/\left(ke^{-kr_c}\right)$$

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

- How to see this?
  - Just use metric with $\tilde{M}$ as fundamental variable
    - We are just interested in TeV physics here…
  - Use conformal coordinates where flat space metric is manifest

$$ds^2 = \frac{1}{(kz)^2}\left(dz^2 + dx_\mu^2\right)$$

And find gravitational action

$$M^3\left(\frac{1}{kz_0}\right)^3 \int d^4x dz \sqrt{g}R = \tilde{M}^3 \int d^4x dz \sqrt{g}R$$

- Use original coordinates and match to classical potential

$$V(r) \sim \frac{1}{M_{Pl}^2}\frac{m_a m_b}{r} + \frac{1}{M_{Pl}^2 k \exp -3kr_c}\frac{m_a m_b e^{-m_1 r}}{r^2}$$

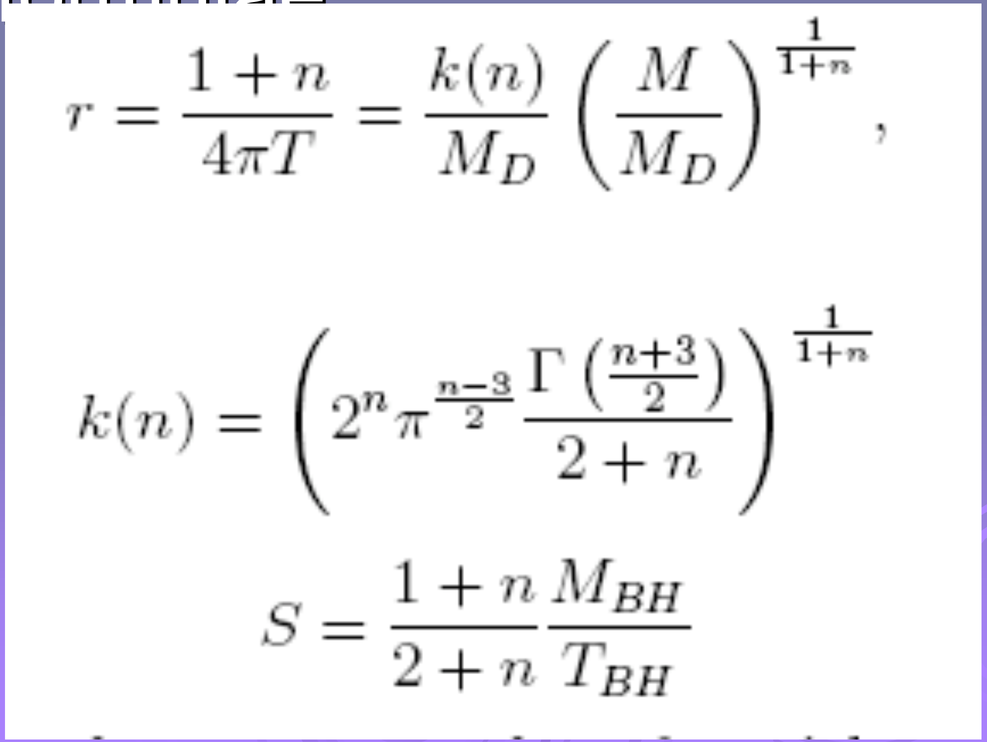
$$r_S \sim \left(\frac{M_{BH}}{\tilde{M}^3}\right)^{1/2}$$

Criteria for a Black Hole?

- $M_{BH} > M$
  - As advertised, not even convention independent
- $2p/(M/2) < R_S$
  - 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:



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

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

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

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: $x_{min}>3$

Fraction of Energy Constraint

- Compute time-dependent decay including grey-body factors
- Critical to computing particle number is assumption of decays on the brane
- dE/dt~ f(E/T) E d^4k~G(4)
- dN/dt~ f(E/T) d^4k~G(3)
- (General n would have given G(n), G(n-1)

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

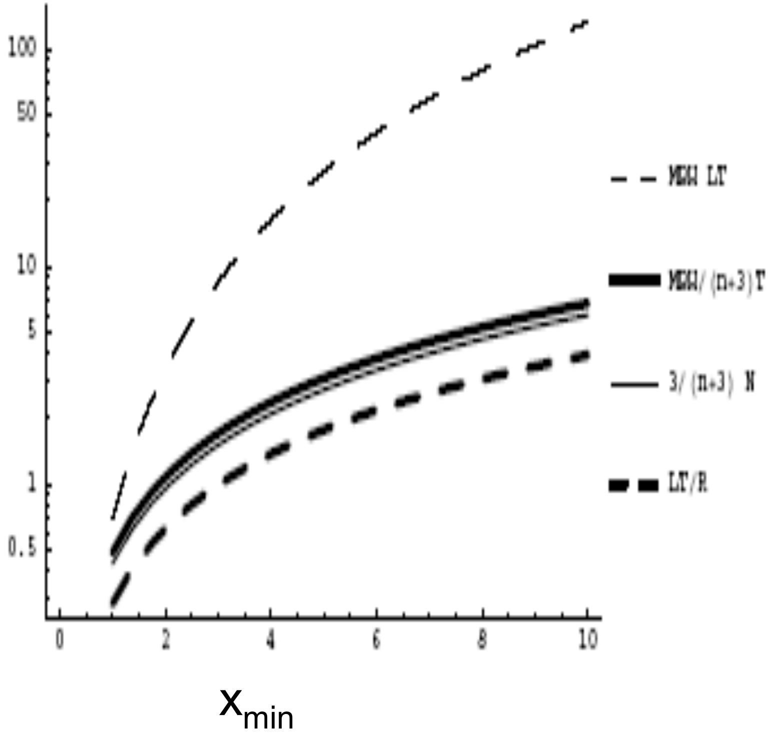
$$\rho = \frac{\sum c_i g_i \Gamma_i \zeta(3)\Gamma(4)}{\sum c_i f_i \Phi_i \zeta(4)\Gamma(4)}$$

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

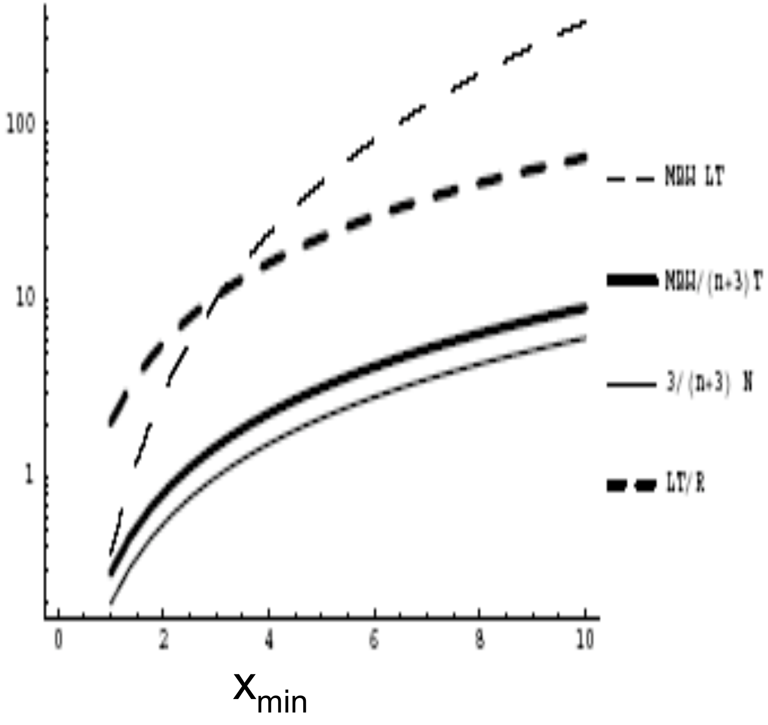
Not many dofs carrying bh energy…

- 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…

Constraints: Min value of M_{BH}



ADD



RS

Conclude from this

- x_{min} should be reasonably high
- Furthermore, even if a black hole produced, 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
- 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 Reduction

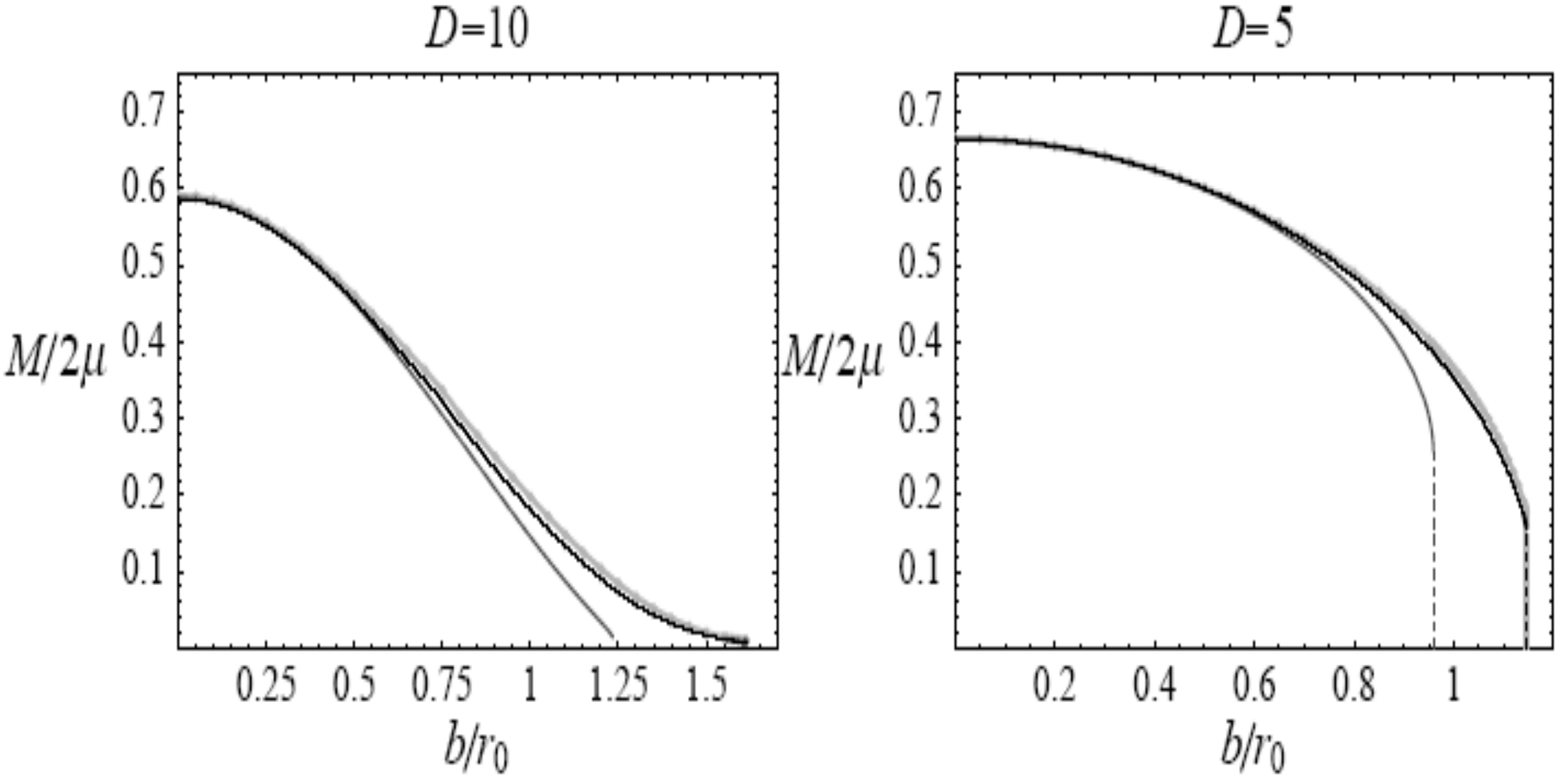
- Without inelasticity

$$\sigma(pp \to X) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \sigma(ij \to X)$$

- With inelasticity
- Define $y = M_{BH}/\sqrt{(s)}$

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

Inelasticity is significant



From Yoshino and Rychkov

s w/ and w/o inelasticity; Impact parameter weighted

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

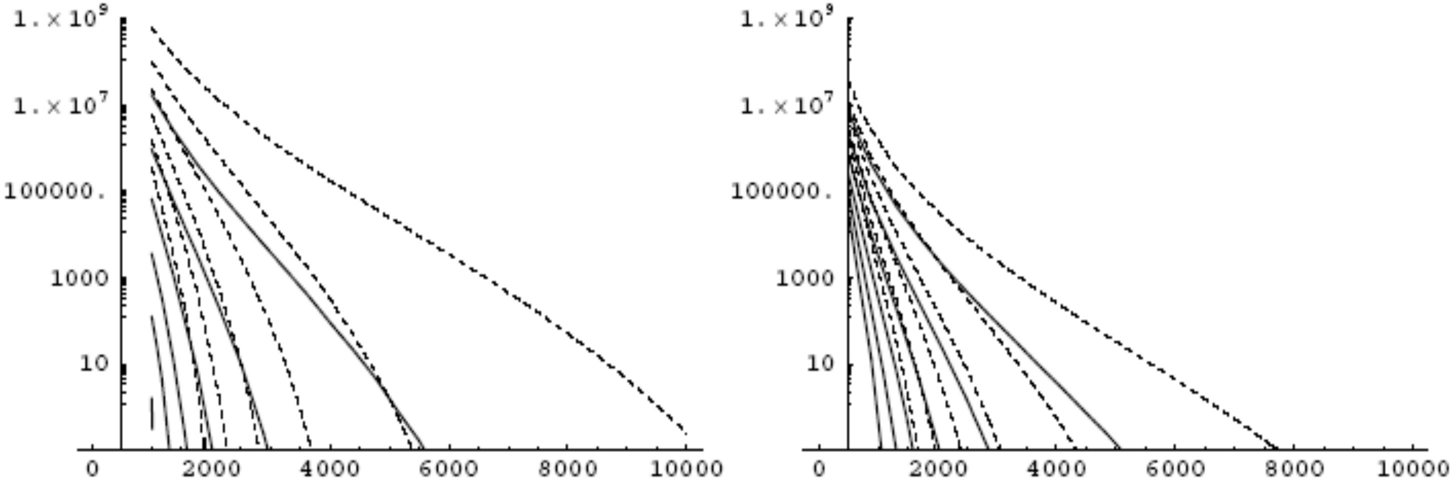


Figure 3: Total black hole cross section in femtobarns, including(solid curves) and not including(dashed) inelasticity as a function of M_D for ADD with $n = 6$ and M for RS1. The different curves from highest to lowest correspond to $x_{min} = 1 - 6$.

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

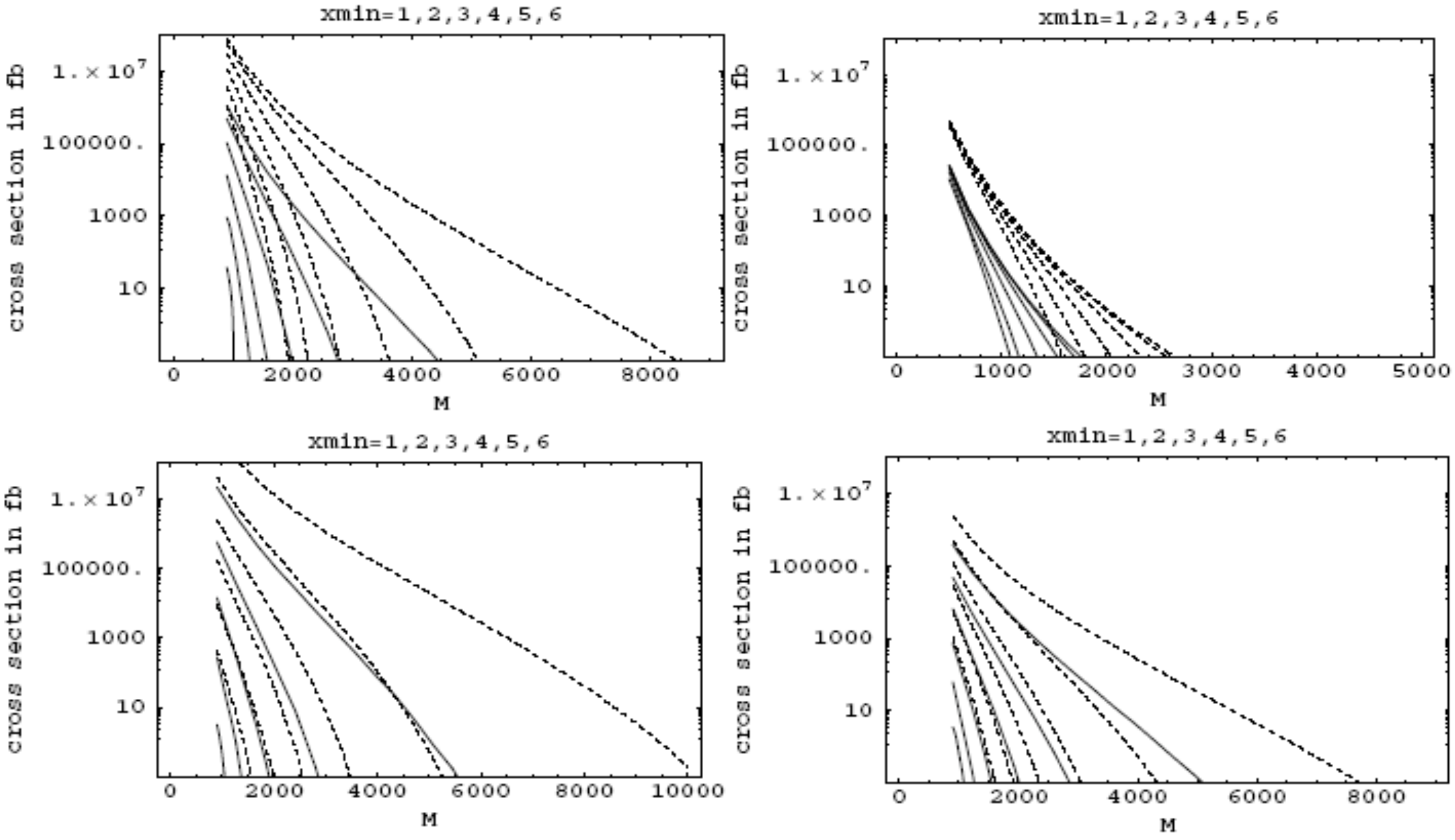


Figure 4: In the upper plots curves of total cross section for having 6 or more particles, including(solid curves) and not including(dashed) inelasticity as a function of M_D for ADD with $n = 6$ and M for RS1. The different curves from highest to lowest correspond to $x_{min} = 1 - 6$. In the lower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

6 vs. 2

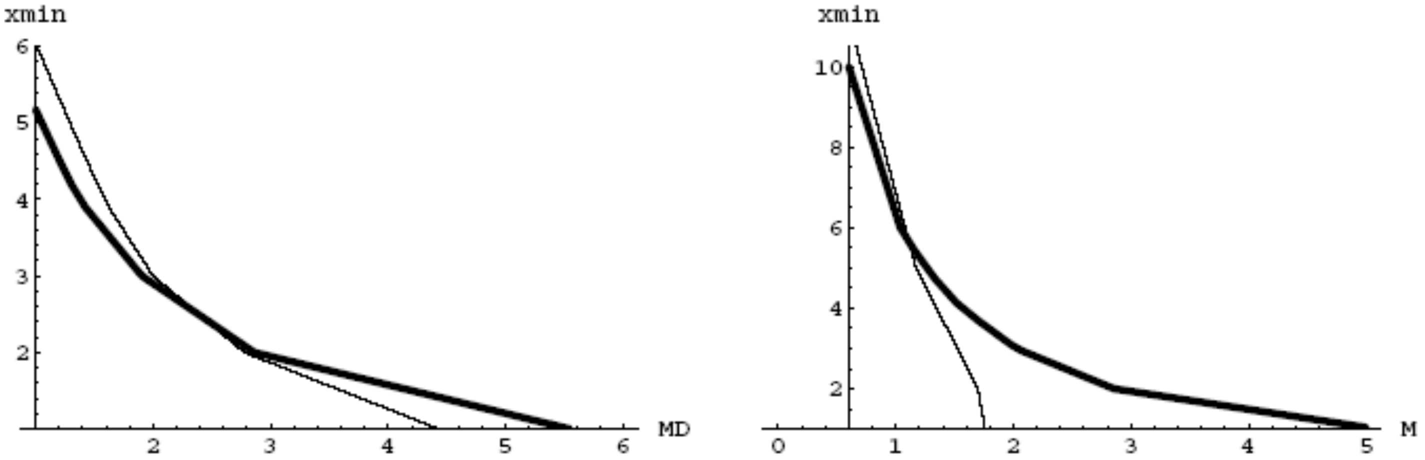


Figure 5: Curves of constant .1 femtobarn cross section including the effects of inelasticity and a probability for getting either 2 particles(thicker curve) or greater than 6 particles(thin curve). In the left hand panel the curves are for ADD with 6 extra dimensions and are plotted as a function of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

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

How do we know quantum gravity?

- We don't (necessarily)!
- But
- Hopefully have already found KK modes
- Can also try to directly distinguish from compositeness
  - Distinctive features of energy dependence in "compositeness" signal
  - Relative lepton rate

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
- Also note we forbid global quantum number violating transitions so we focus on B-conserving jets and lepton-number conserving processes

Suggested Search

- 2 jet channel
- Cross section
- Angular dependence
  - Take advantage of t-channel SM cross section
  - R=0.6 for SM
- Look for distinctive characteristics

Contrast to Transplanckian Studies

Giudice, Rattazzi, Wells

- $E >> M_D$
  - Look at large impact parameter elastic collisions
  - Small angles (linear regime)
  - Classical elastic scattering regime
  - Predictable perturbatively
  - Would be true distinguishable gravity signature
- But
  - Event rate suffers relative to background at small angles
  - $3 < \eta < 4$ for example
  - Mass reach relatively low though could reach a few TeV optimistically
- We instead investigate large angle region where event rate (vs. bg) should be larger
- Interesting range where it's not predictable
- Might learn about quantum gravity!

Result Model I: Dijet “Black Holes”

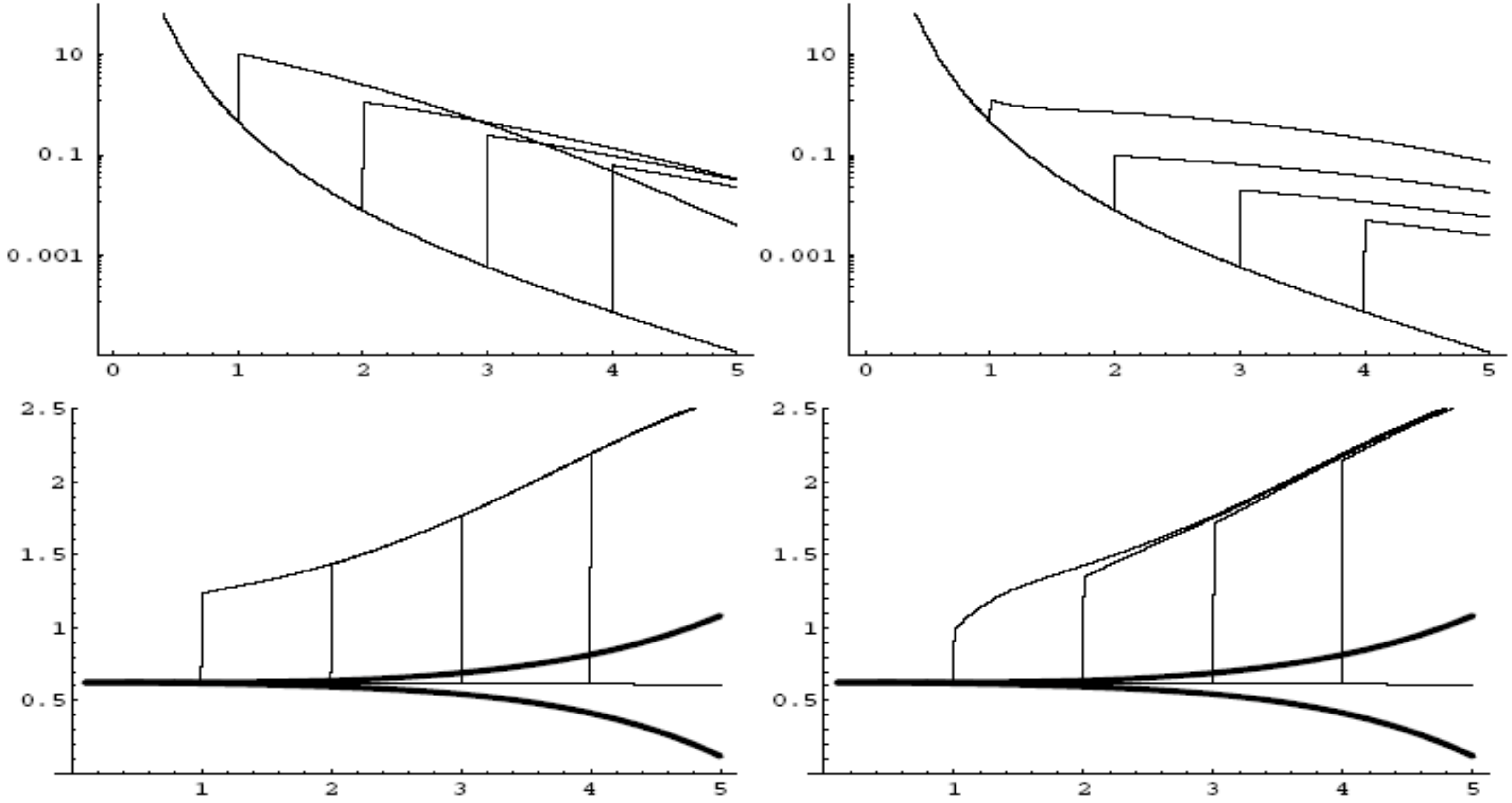
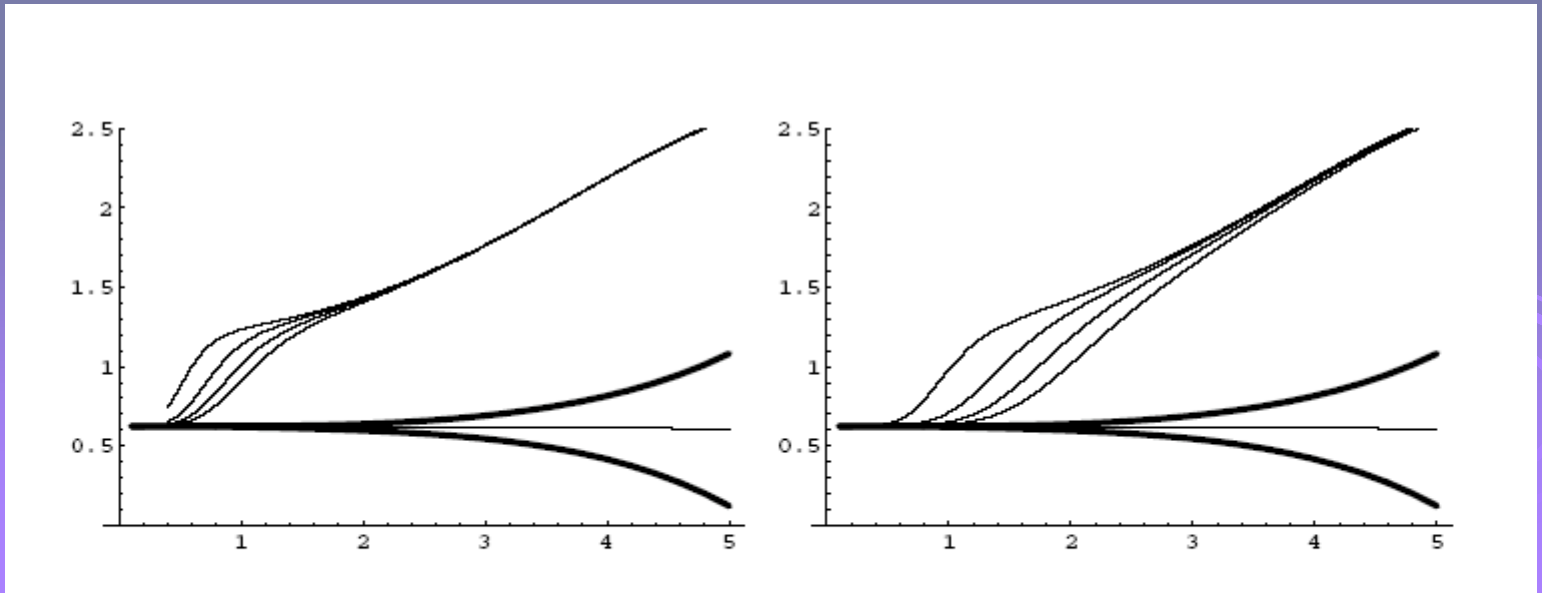


Figure 6: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background, and a n=6 ADD model “black hole” behavior with M_D=1,2,3,4 TeV and $x_{min} = 1$ in the lefthand plot and a RS1 black hole behavior with $M = 1, 2, 3, 4$ TeV and $x_{min} = 1$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

Distinctive Features

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



Alternative Model of QG: Weakly Coupled String Theory

- Model: Veneziano amplitude
- Expect 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

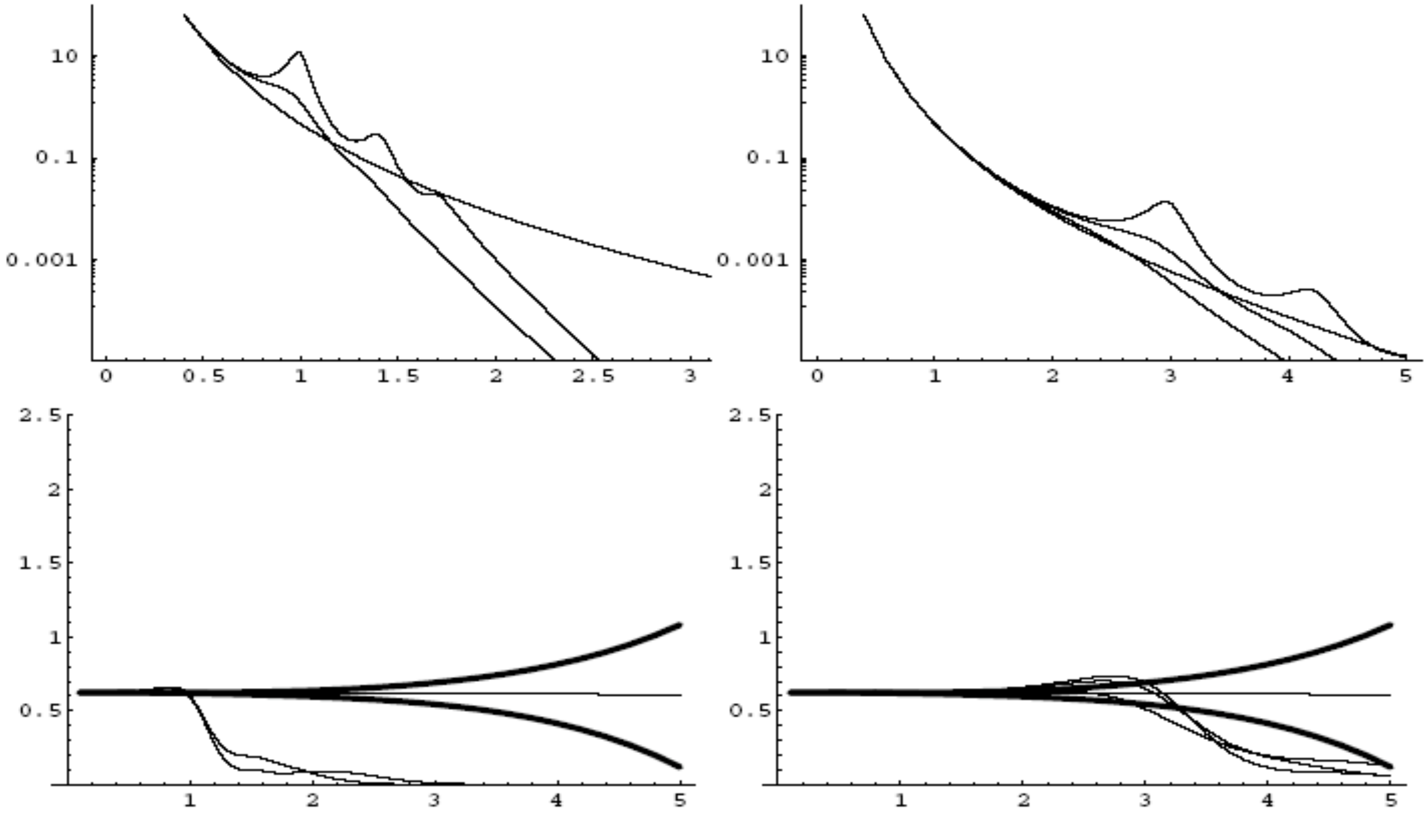


Figure 8: In the upper plots $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background(thicker curve), and a toy stringy behavior with M_s=1 TeV in the lefthand plot with $\gamma = .1, .3$ and M_s=3 TeV in the righthand plot with $\gamma = .1, .3, .6$. In the lower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

Can Distinguish Models

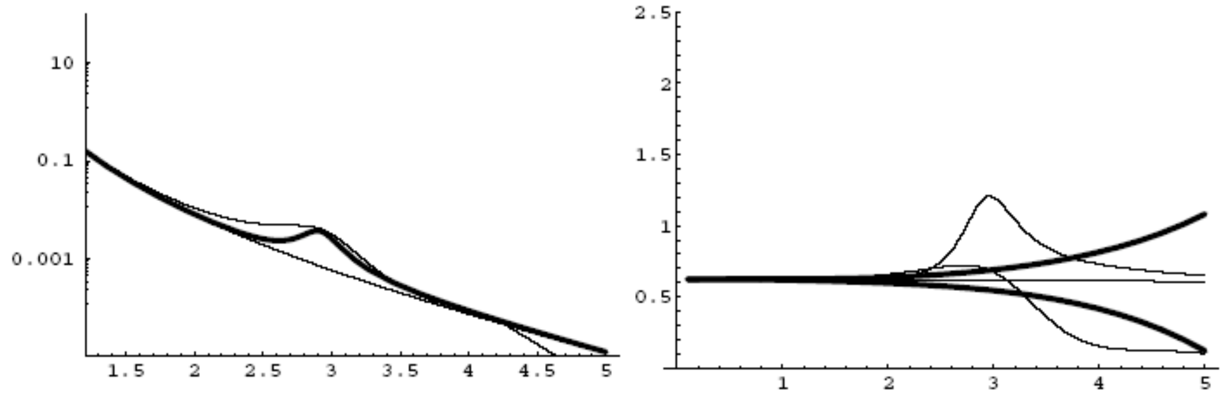
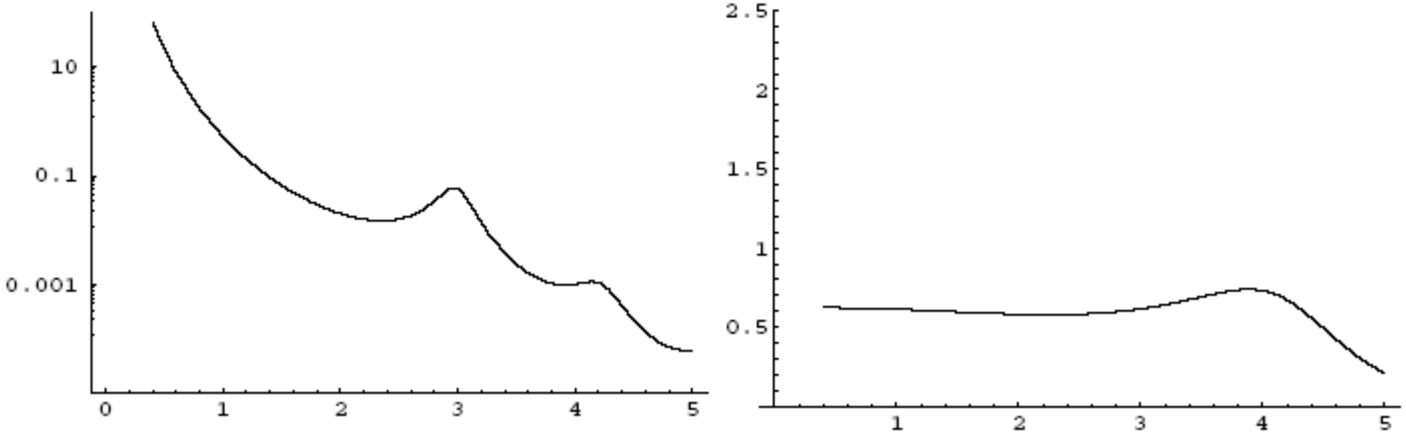


Figure 10: In the left plot $d\sigma/dM_{jj}$(units of pb/GeV) vs $M_{jj}(TeV)$ is plotted for the case of SM QCD background, a toy stringy behavior with M_s=3 TeV and $\gamma = .2$ and a massive colored octet resonance(thicker curve) with mass and width chosen to mimic the differential cross section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

Vs. Z'



Different stringy models

Strings vs. Black Holes

- Black hole threshold is M_s/g_s^2
- String resonances only visible for small g_s
- Furthermore string bound might already be a few TeV (Antoniadis)
  - Model dependent so maybe more accessible range
- If you see strings, you certainly won’t see black holes (at LHC energies!)

Alternative QG: Higher Dimension Operators

- Black holes: we assumed high energy turn on and distinctive energy dependence
- Alternative: higher dimension operators
- Possible Sources:
  - Black Holes
  - Multigraviton exchange
  - High scale string theory (4 fermion for original Veneziano amplitude)
  - String theory in warped space

Existing Bounds?

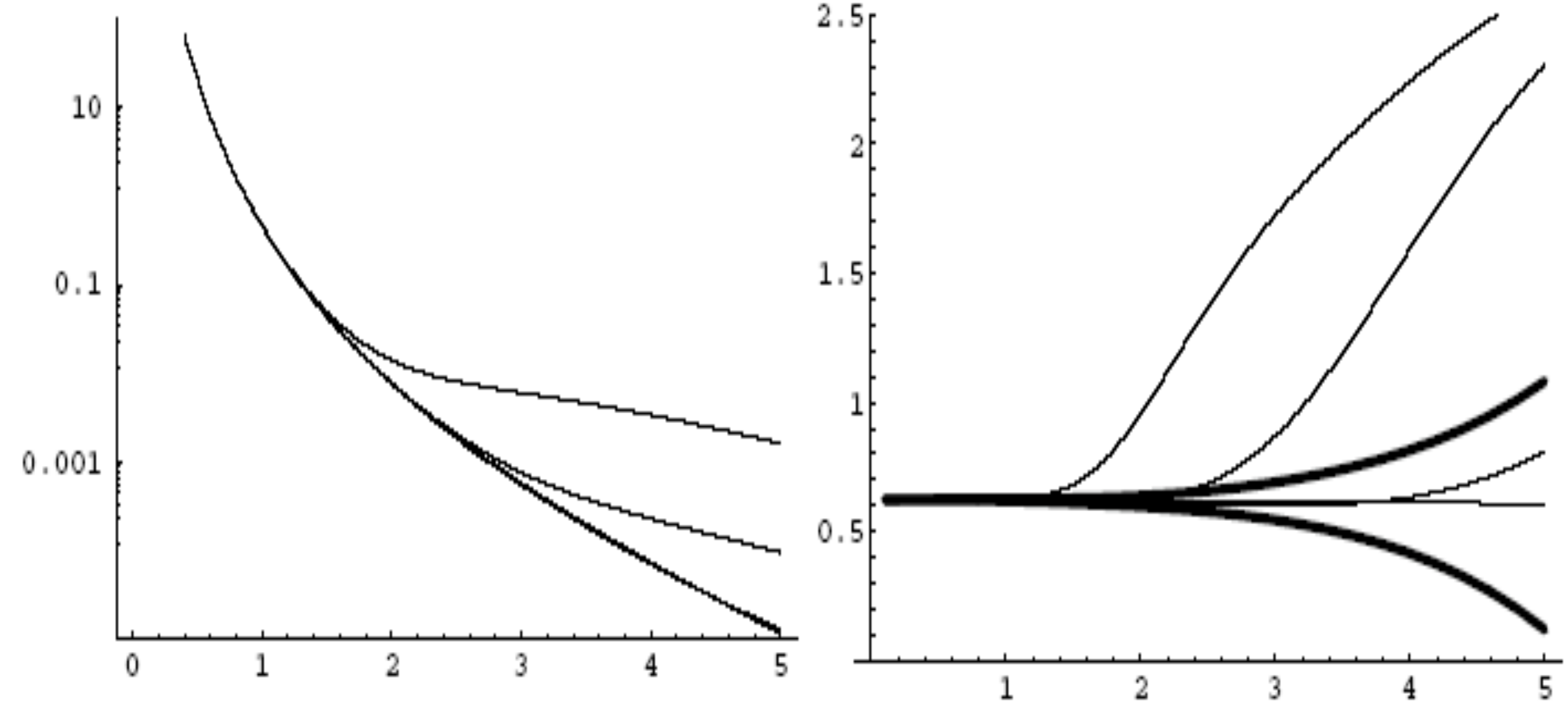
- LEP bounds on quark-lepton operators very strong: ~7 TeV (without 4π)
- Can calculate loop gravity effects that generate such four-fermion operators
- Seems to preclude strong scale without a lower cutoff (such as string theory)-Guidice, Strumia
- However, brane width is also a natural cutoff since fermions necessarily on branes when black hole production conceivable
- L^{2n+2} vs. $L^2 L_{KK}^n$
- Allows lower quantum gravity scales

Distinctive Features for Higher Dimension Operators

- 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: 4-fermion



L=1,2,4 TeV (c=1)

How to Distinguish Quantum Gravity?

- Could be higher-dimension fermion operators arise from quantum gravity
- But also could be that signal is very different:
  - Energy dependence
  - Energy onset
  - Leptons vs. Jets
    - Assuming neutral state 10% for thermal black holes vs. 20% for four-fermion operators
  - More dramatic: do we produce neutral black hole—does it shed charge?
    - If yes, lepton rate much higher
    - If four –fermion (or charged object), jet jet final state from qq pdf vs. Lepton final state from q qbar initial pdf

For the Future

- Follow ups:
  - Experiments:
    - Study energy-dependent angular dependence
    - Don’t assume particular form
  - Phenomenology:
    - Monte Carlos: allow decay to solely to 2 particles
    - Maybe remnant all there is!
    - Shedding of charge in initial state?
    - Different possible distributions of final states
  - Theory
    - What are possible string models?
- Remain:
  - Charge, spin
  - Signatures with missing energy, multibody final states (lepton and jet or more jets),
    - Compositeness type studies might be key
- Get as much info at as high energies as possible
- If low quantum gravity scale, opportunities are rich

Lepton cross section might be key

- Four-fermion operators: large lepton suppression
- Pdf, alpha, u/s

TeVADD:MD=1

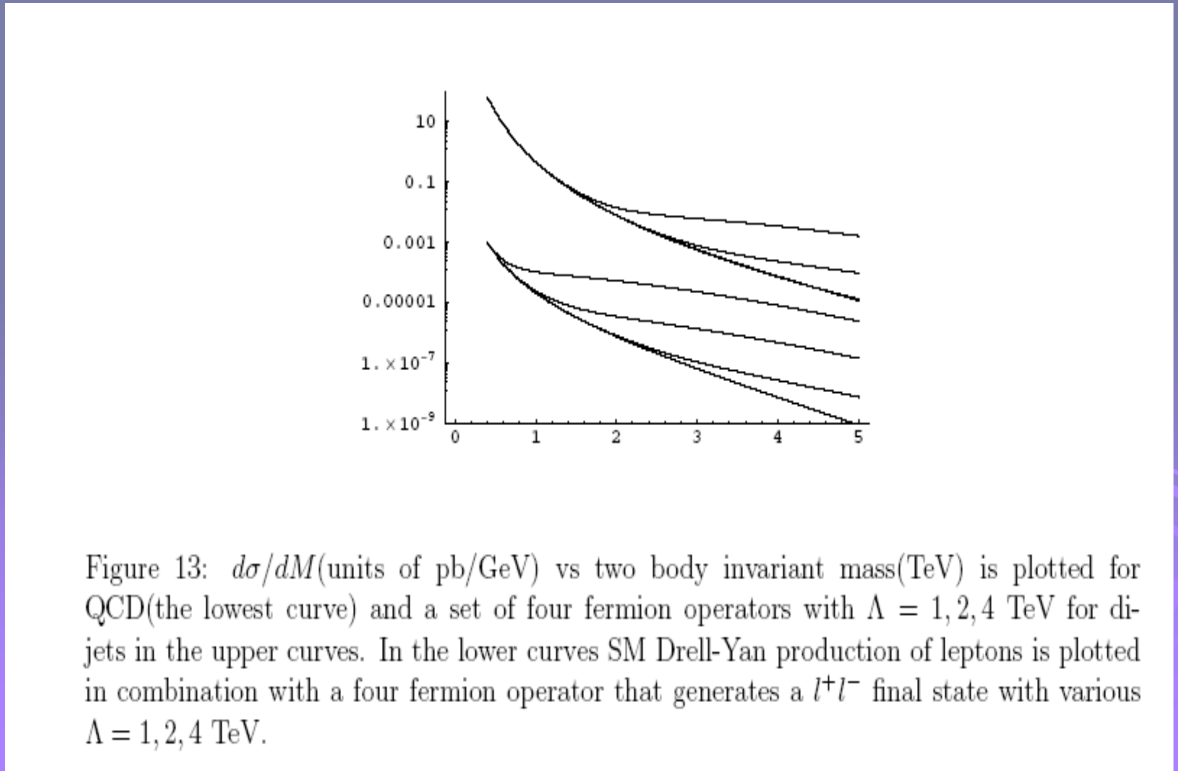


Figure 13: $d\sigma/dM$(units of pb/GeV) vs two body invariant mass(TeV) is plotted for QCD(the lowest curve) and a set of four fermion operators with $\Lambda = 1, 2, 4$ TeV for di-jets in the upper curves. In the lower curves SM Drell-Yan production of leptons is plotted in combination with a four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

From Black Holes

Much higher cross section since large fraction with larger pdfs

Even just losing u/s, alpha

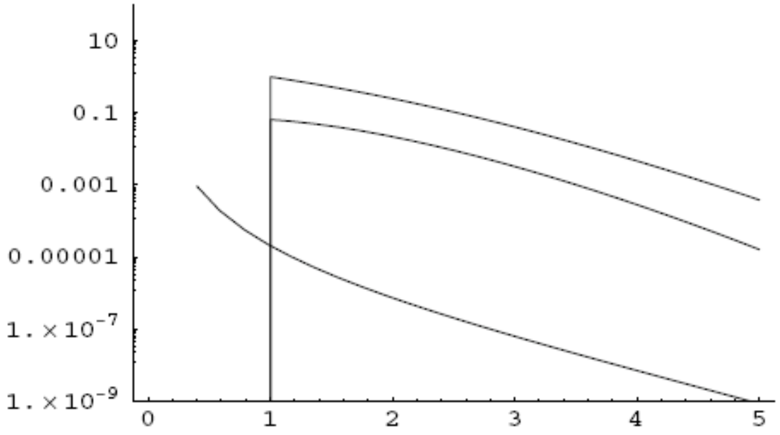


Figure 15: $d\sigma/dM$(units of pb/GeV) vs two body invariant mass(TeV). The curves from top to bottom represent black hole cross section for $M_D = 1$ TeV , $n = 6$, and $x_{min} = 1$ for a black hole decaying into l^+l^- (assuming any initial gauge charge is radiated softly), black hole cross section for $M_D = 1$ TeV and $x_{min} = 1$ for a "charged" black hole decaying into $l\nu$, and the lowest curve is the Drell Yan background.

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

For the Future

- Experiment
  - Energy-dependent angle studies in dijets
  - Don’t assume particular energy dependence
- Phenomenology
  - Allow 2 particle states in Monte Carlo
  - Issues of shedding charge-final state distribution
- Theory
  - String theory models
- Promising if low scale gravity to get insights into behavior
- Compositeness studies rich!