Low-scale gravity phenomenology

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Introduction

- Brane-world scenarios offer paradigms to reinterpret the 4-D Planck scale as an effective gravity scale arising from a more fundamental lower gravity scale in higher dimensions.

- Allows new phenomenological models to be developed and helps guide searches for low-scale gravity in experiments, such as, at the LHC.

- An exciting outcome of these models is the possibility to produce non-perturbative gravitational states at the LHC.

- LHC experiments have recently published a round of searches for non-perturbative gravitational states which seriously confront the models for the first time.

- How can the models now be viewed in light of the experimental constraints?
Paradigms for low-scale gravity

- Extra dimensions:
  - Large flat extra dimensions (LED): Arkani-Hammed, Dimopoulos, Dvali (ADD).
  - A warped extra dimension in AdS space: Randall-Sundrum (RS1).
  - Universal extra dimensions (not discussed here).

- Large number of particle species (messenger particles).

- In general, need something to reduce the Planck scale $M_p$ to a lower gravity scale $M_*$: $M_p \gg M_*$

$$M_p^2 = V_\delta M_*^{2+\delta} \quad \text{in ADD (}M_* = M_D\text{)}$$
$$M_p^2 = (k^2 x_1^3/m_1^3) M_*^3 \quad \text{in RS1 (}M_* = M_5\text{)}$$
$$M_p^2 = N M_*^2 \quad \text{in Dvali (particle species)}$$
Models usable at the LHC

- Classical (semi-classical) black holes.
  - Let’s call them GR black holes.
- String balls.
- Non-thermal black holes:
  - Often called quantum black holes or QBH.
  - Let’s use QBH for short-form.
- Non-commutative gravity embedded into ADD.
- Trapped surface calculations: not used yet.
- Split-fermion models: not used yet.
Which Planck scale?

- What should we take as the limits on the fundamental Planck scale $M_D$?
- Virtual graviton emission depends on ultra-violet cutoff $M_S$, which is not $M_D$.
- Real graviton emission depends on $M_D$: mono-jet and mono-photon searches.
  - But is this the scale for GR and non-thermal black holes?
- Limits from classical black hole searches: $M_D$ function of $M_{\text{th}}$ (mass threshold).
- Limits from non-thermal black hole searches: $M_D = M_{\text{th}}$. 
Best limits on Planck scale

CMS mono-jet ($M_D > 3.26-5.61$ TeV, $\delta = 6-2$)

What about $\delta > 6$?

Most calculations assuming $M_D = 1$ TeV should be revised.

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Searches for non-perturbative states

- ATLAS and CMS have performed searches for non-perturbative states.
- I will divide searches into thermal (GR) and non-thermal (QBH) “black holes”.
- Thermal black holes (GR) and string balls searches:
  - multi-jet (ATLAS and CMS)
  - lepton+jets (ATLAS: electron and muon)
  - same-sign di-muon and large number of tracks (ATLAS)
- Non-thermal black hole (QBH) searches:
  - di-jet (ATLAS and CMS)
  - photon+jets (ATLAS)
  - di-lepton (ATLAS: di-electron and di-muon)
  - lepton+jets (ATLAS: electron and muon)
Thermal (GR) black holes

- Classical (semi-classical) black holes:
  - The key feature is Hawking evaporation (so they are thermal states).
  - Model valid for \( E > M_{\text{th}} \gg M_D \).
  - No predictive power of what we would see first at the LHC.
    - Best to look for ADD perturbative states (KK gravitons, etc.).
- Hawking evaporation to high multiplicity of high-\( p_T \) particles (mostly jets).
- High-\( p_T \) lepton should be emitted in a significant fraction of the events.
  - Requiring a high-\( p_T \) lepton significantly reduces QCD background.
- Artificial mass threshold \( M_{\text{th}} \) introduced to keep black holes classical.
Model-independent limits

\[ H_T = \sum p_T(\text{jets}) \]

\[ N_{\text{jet}} \geq 3 \]

\[ \sigma(H_T > H_T^{\text{min}}) \times A = \text{fb} \]

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

95% CL upper limits

\[ \sigma < 0.16 \text{ fb} \]

\[ H_T > 4.3 \text{ TeV} \]

arXiv:1503.08988

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GR black holes not allowed at LHC

- **Current limits on $M_D$:**
  - $n=2$, $M_D > 5.6$ TeV.
  - $n=4$, $M_D > 3.9$ TeV.
  - $n=6$, $M_D > 3.3$ TeV.

- For GR black holes $M_{th} > 5 \times 3.3 \sim 16.5$ TeV.

- Current limits on $M_D$ exclude GR black hole searches.

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*ATLAS*

$\sqrt{s}=8$ TeV, 20.3 fb$^{-1}$

arXiv:1503.08988
String balls

- Embed weakly-coupled string theory into ADD.
- Changes cross-section, but leaves decays similar to thermal black holes (different temperature).
- Introduces another scale (string scale) that allows $E > M_{\text{th}} \gg M_s$ and $M_D > M_s$.
- Really just pushes the problems of classical black holes to higher energies at the expense of more speculation (low-scale string theory).
String balls not allowed at LHC

- LHC exclusion limits on a variety of exotics physics means string scale $\gtrsim 3$ TeV.
- For string balls in weakly coupled string theory $M_{th} > 3 \times 3 \approx 9$ TeV.
- Current limits on $M_S$ exclude string ball searches at run 1 (8 TeV LHC).

**Figure 7**: Exclusion contours in the $M_{th}$–$M_s$ plane for non-rotating and rotating string ball models simulated with CHARYBDIS2. The solid/dashed lines show the observed/expected 95% CL limits. Masses below the corresponding lines are excluded. Lines of fixed $M_{th}$ are shown. The assumptions of the models are valid for $k \lesssim 1$ here being about 0.1 TeV higher in mass. The results presented here are also compared with those of ref [14]. In the low $M_D$ region the results are comparable while in the high $M_D$ region the results presented here are a significant improvement over those in ref [14]. The latter analysis is affected by a significant loss in sensitivity for the cases of rotating black holes and string balls, while the results presented here and those in ref [17] are rather independent of rotation.

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arXiv:1503.08988
Non-thermal black holes (QBH)

- LHC parton energy needs to be high relative to $M_D$ for black holes to Hawking evaporate thermally.
- Black holes with threshold mass $M_{th}$ near $M_D$ probably do not decay thermally.
- Non-thermal black holes:
  - Extrapolate classical cross section down to Planck scale.
  - Replace Hawking evaporation (thermal decay) by particle decays.
  - Branching fractions determined by conservation principles.
  - Or, extrapolation of Hawking evaporation
    - Not really non-thermal in this case.
Non-thermal black hole searches

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### ATLAS

**ATLAS**

- **$\sqrt{s} = 8$ TeV**
- $\int L dt = 20.3$ fb$^{-1}$

- **QBH, BlackMax gen.**
- **QBH, QBH gen.**
- **Observed 95% CL upper limit**
- **Expected 95% CL upper limit**
- **68% and 95% bands**

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**QBH** $\rightarrow jj$

- **ATLAS**
- $\int L dt = 20.3$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV

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**QBH** $\rightarrow \gamma j$

- **ATLAS**
- $\int L dt = 20.3$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV

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**QBH** $\rightarrow ll$

- **ATLAS**
- $\int L dt = 20.3$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV

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**QBH** $\rightarrow lj$

- **ATLAS**
- $\int L dt = 20.3$ fb$^{-1}$
- $\sqrt{s} = 8$ TeV

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What we think we know

- A search for non-perturbative gravity is enabled by the highest energies, not high luminosity.

- Instant discovery physics at new energy turn-on:
  - If the LHC energy is near the new gravity scale.

- Of course this could be wrong and black holes could be produced at some low rate at our current energies, or in some other signature.
  - Trap-surface models may reduce the cross section.
  - Split-fermion models may reduce the cross section.
  - One of the only models that could predict new signatures, that I know of, is non-commutative geometry black hole models.
Could it be that the black hole production cross section at the LHC is just too low to allow observation?
Split fermion pp cross section

\[ c = \frac{L}{\mu^{-1}} \]

\[ \mu^{-1} = \text{Gaussian width} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

\[ n = 3 \]

\[ c = 30 \]

\[ M_{ms} = 2M_s \]

\[ L = 0 \text{ TeV}^{-1} \]

\[ L = 2 \text{ TeV}^{-1} \]

\[ L = 5 \text{ TeV}^{-1} \]

\[ L = 10 \text{ TeV}^{-1} \]

\[ L = 12.5 \text{ TeV}^{-1} \]
Non-commutative geometry

- Non-commutative gravity embedded into ADD:
  - Has hopefully some aspects of a theory of quantum gravity.
  - Model exits and gives rather different signatures then usual models.

Main experimental differences from GR black holes:
- Larger missing energy.
- Soft $\Sigma p_T$ spectra.
- Possible trigger issues.

black hole

8 TeV
How we do things

- In most cases, searches are performed in the $\Sigma p_T$ variable.
  - $\Sigma p_T$ is not directly related back to theory.
  - Determine fiducial cross-section lower limit above some $\Sigma p_T$ value.
  - No good method for removing model-dependence and making results generic.

- Model-dependent limits.
  - Set limits in 2-D parameter space ($M_D, M_{th}$).
  - Fix the other parameters and called this a model (not unique).
  - Lower mass limits for a given (arbitrary) $M_D$ and model.
  - Allows some general conclusions and comparisons, but still involves a wide range of mass limits to be set.
Summary

● About 9 LHC publications.

● Thermal black holes
  ■ Black holes probably excluded at the LHC.
  ■ But maybe not string balls yet at 14 TeV.

● Non-thermal black holes
  ■ Di-jet most powerful channel.
  ■ LFV (lepton flavour violating) channel also interesting.

● Low-scale gravity studies benefit more from increased LHC energy than luminosity.
  ■ For nominal models.
  ■ Quantum gravity effects, or others, may cause cross sections to be lower.

● Phenomenology should be rewritten with $M_D > 3$ TeV (c.f. 1 TeV).
  ■ It makes difference.
Extras
History

- 1998-99: Low-scale gravity thought to be possible in brane-world scenarios.
- 1999: First low-scale gravity models of perturbative KK states.
- 2001: First low-scale gravity models of thermal black holes.
- 2008: Other low-scale non-perturbative gravity models:
  - string-balls.
  - non-thermal black holes (QBH).
- 2010: Even non-commutative black holes.
- 2010-11: First LHC search results.
- 2015: Complete LHC results at 8 TeV.
Large flat extra dimensions: ADD

- Fields of the standard model confined to a 4-D membrane.
- Gravity propagates in several additional spatial dimensions which are large compared to the Planck scale.
- The power-law of gravity changes at small distances.

\[ M_p^2 = V_\delta M_D^{2+\delta} \]
Warped extra dimension: RS

- A warped extra dimension in AdS space: RS1.
- Standard model particles localized on 4-D brane.

\[ M_p^2 = \left( \frac{k^2 x_1^3}{m_1^3} \right) M_5^3 \]

Can tread RS black hole like ADD black hole in 5-D with modified mass.

\[ M = \frac{m_1}{(x_1 c^{2/3})}; \quad c = \frac{k}{M_p} \]
Non-perturbative gravitational states

- Way of thinking is slightly different than main-stream particle physics.
- Particle physicists are use to searching for new particles.
  - Need quantum mechanics and special relativity to describe them.
  - For calculations, usually have a Lagrangian in field theory, and use perturbative techniques to expand in a series of Feynman diagrams.
- States with energy above the gravity scale (transplanckian scale physics) should behave non-perturbatively.
  - Classical (semi-classical) mechanics should hold.
  - Being non-perturbative, expansions in a coupling constant and Feynman diagrams do not make much sense.
- Like particle searches, we usually think of one force (in this case gravity) dominating the interaction and ignore the others (in this case QCD).
- So a lot of the QCD issues (LO, NLO, NNLO, etc.) make little sense for non-perturbative gravitational states.
Monte Carlo event generators

- **Charybdis2**
  - GR black holes (string balls added).
  - Thermal QBH possible but never tried.
  - Code extended to non-commutative black holes.

- **BlackMax**
  - GR black holes (string balls added).
  - Thermal QBH used in ATLAS di-jet searches.
  - Split-fermion models possible.

- **QBH**
  - Non-thermal black holes.
Non-thermal quantum black limits

\[ \sigma \times B(\text{fb}) \]

95% CL observed limits

- QBH → e⁺e⁻+μ⁺μ⁻
  - Phys.Rev. D90 (2014) 5, 052005
- QBH → e⁺e⁻+μ⁺μ⁻
  - Phys.Rev.Lett. 112 (2014) 9, 091804
- QBH → γj
- QBH → j j
  - Phys.Rev. D91 (2015) 5, 052007

\[ \sigma \text{ BR} < 0.2 \text{ fb} \]

\[ \sigma < 0.2 \text{ fb} \]

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Assume 300 fb⁻¹

QBH → jj
5.7 → 10 TeV

QBH → μj
5.3 → 9.2 TeV

QBH → γj
4.6 → 8 TeV

QBH → eμ
3.6 → 6.8 TeV
Typically a total inelastic $\sigma = \pi r_g^2$ form is used for the parton-parton cross section.

All energy of partons goes into producing the black hole.

Various GR calculations estimate the amount of energy in a parton-parton collision trapped behind the horizon formed.

- Analytical lower-bounds for 4-D black holes.
- Numerical lower-bounds for higher-dimension black holes.

The excess energy “appears” as radiation.

- Initial-state radiation, if before black hole formation.
- Balding radiation, if after black hole formation.

In the former case, less energy is available for black hole formation and the cross section is reduced.
Split-fermion models

- Mechanism for generating Yukawa hierarchies by displacing the standard model fermion fields in a high-dimensional space.
  - Overlap of wave functions gives couplings.
- A set of spacings giving masses consistent with data has been determined in a 2-D split-fermion model.
- Can embed black holes and string balls in split-fermion models.
- Causes reduction in cross section relative to usual ADD case.
- Split-fermion models not yet used to interpret LHC results.
Non-commutative geometry inspired black holes

- Smear matter distributions with resolution of non-commutativity scale (extra parameter $\sqrt{\theta}$).

- Temperature well behaved.
  - Canonical ensemble treatment of entropy valid for entire decay.

- Gravitational radius has non-zero minimum.
  - Stable remnant with mass different from Planck scale.

\[ \sqrt{\theta} \, M_D = 0.6 \]

14 TeV

arXiv:1003.1798
Some “cheap” comments

- Use mass as limit setting (search) variable.
  - This is related directly to theory.
  - MET should also be used to account for neutrinos and gravitons.

- Need better strategy for model-independent limits.

- Improvements to model-dependent limits:
  - By and large, I think the models chosen are the useful ones.
  - Extend $M_D$ range.
Summary of results to 2011