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_*: $M_p \gg M_*$

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

Models usable at the LHC

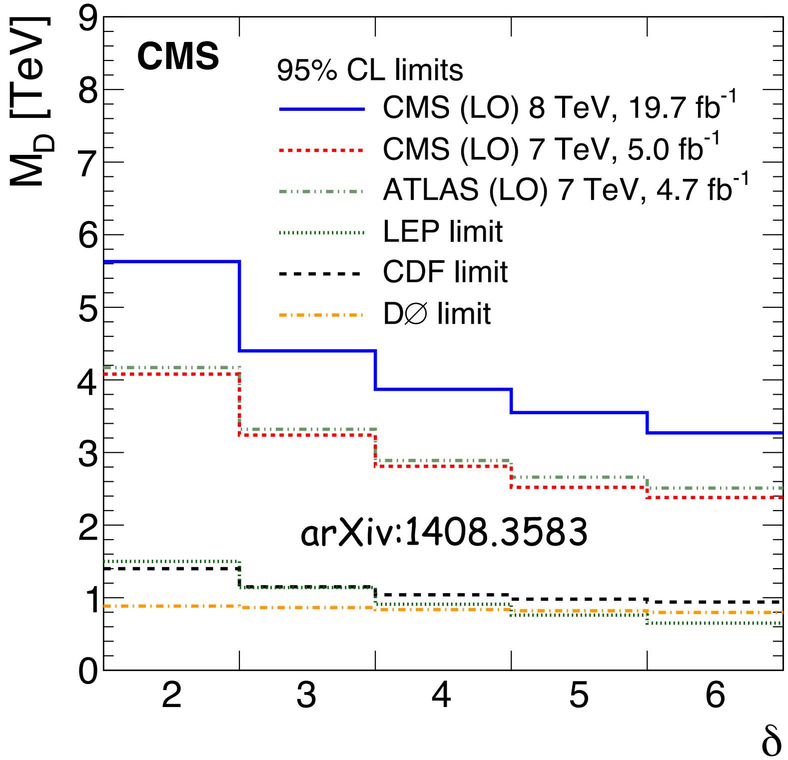
- Classical (semi-classical) black holes.
  - Let's call them GR black holes.
- String balls.
- Non-thermal black holes:
  - Often called quantum black holes or QBH.
  - Let's use QBH for short-form.
- Non-commutative gravity embedded into ADD.
- Trapped surface calculations: not used yet.
- Split-fermion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

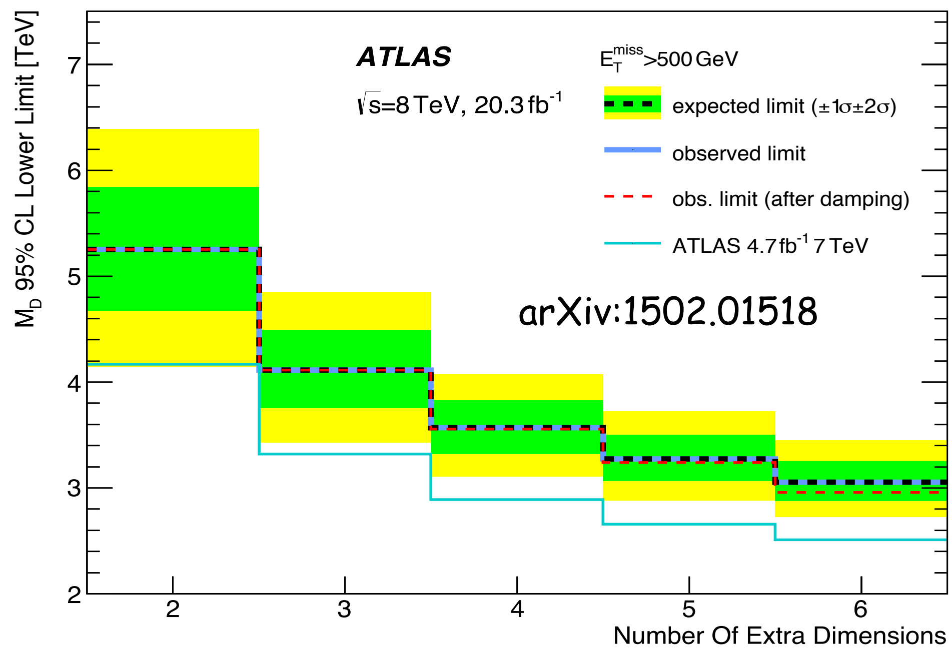
Which Planck scale?

- 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_{th} (mass threshold).
- Limits from non-thermal black hole searches: $M_D = M_{th}$.

Best limits on Planck scale

CMS mono-jet (M_D > 3.26-5.61 TeV, δ = 6-2)





What about δ > 6?

Most calculations assuming M_D = 1 TeV should be revised.

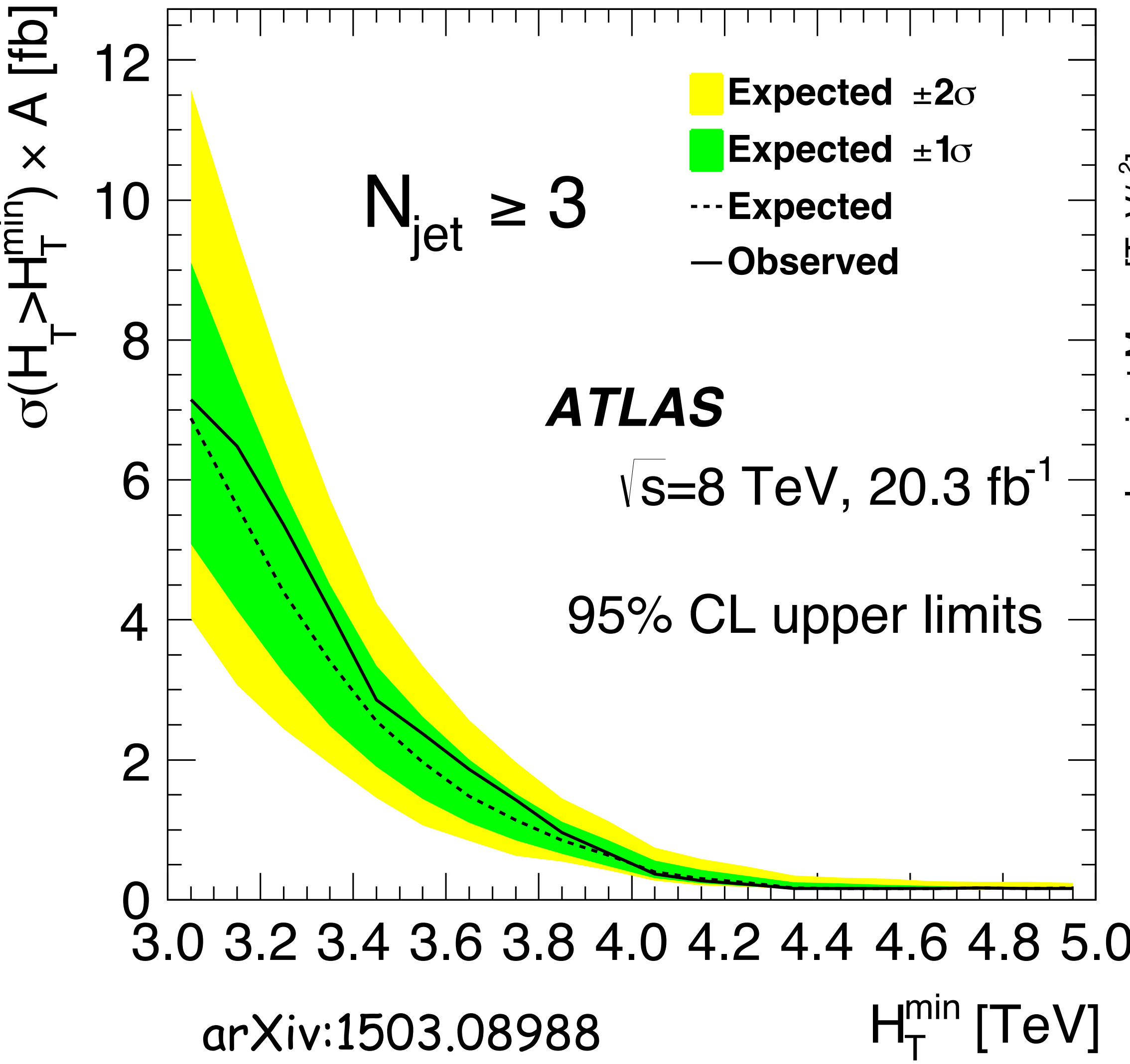
Searches for non-perturbative states

- 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

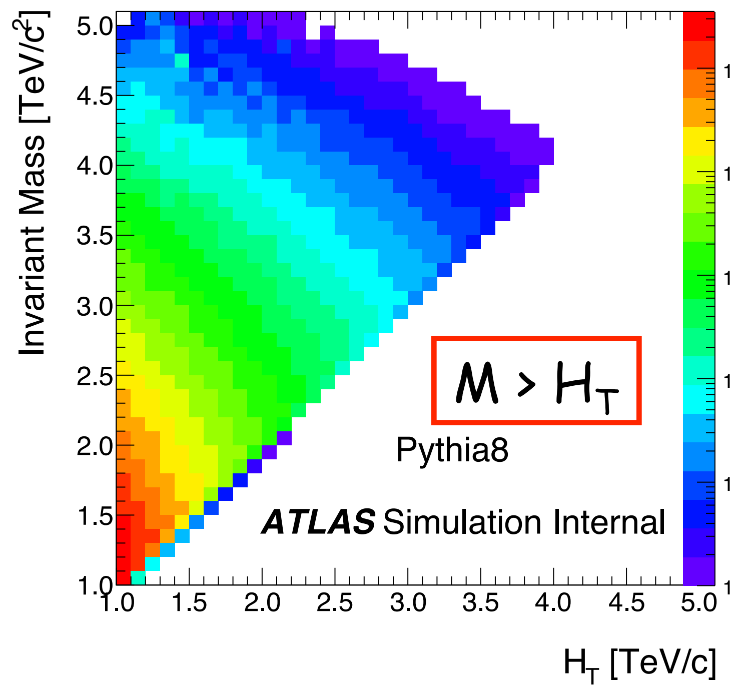
- Classical (semi-classical) black holes:
  - The key feature is Hawking evaporation (so they are thermal states).
  - Model valid for $E > M_{th} \gg M_D$.
  - No predictive power of what we would see first at the LHC.
    - Best to look for ADD perturbative states (KK gravitons, etc.).
- Hawking evaporation 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_{th} introduced to keep black holes classical.

Model-independent limits



arXiv:1503.08988

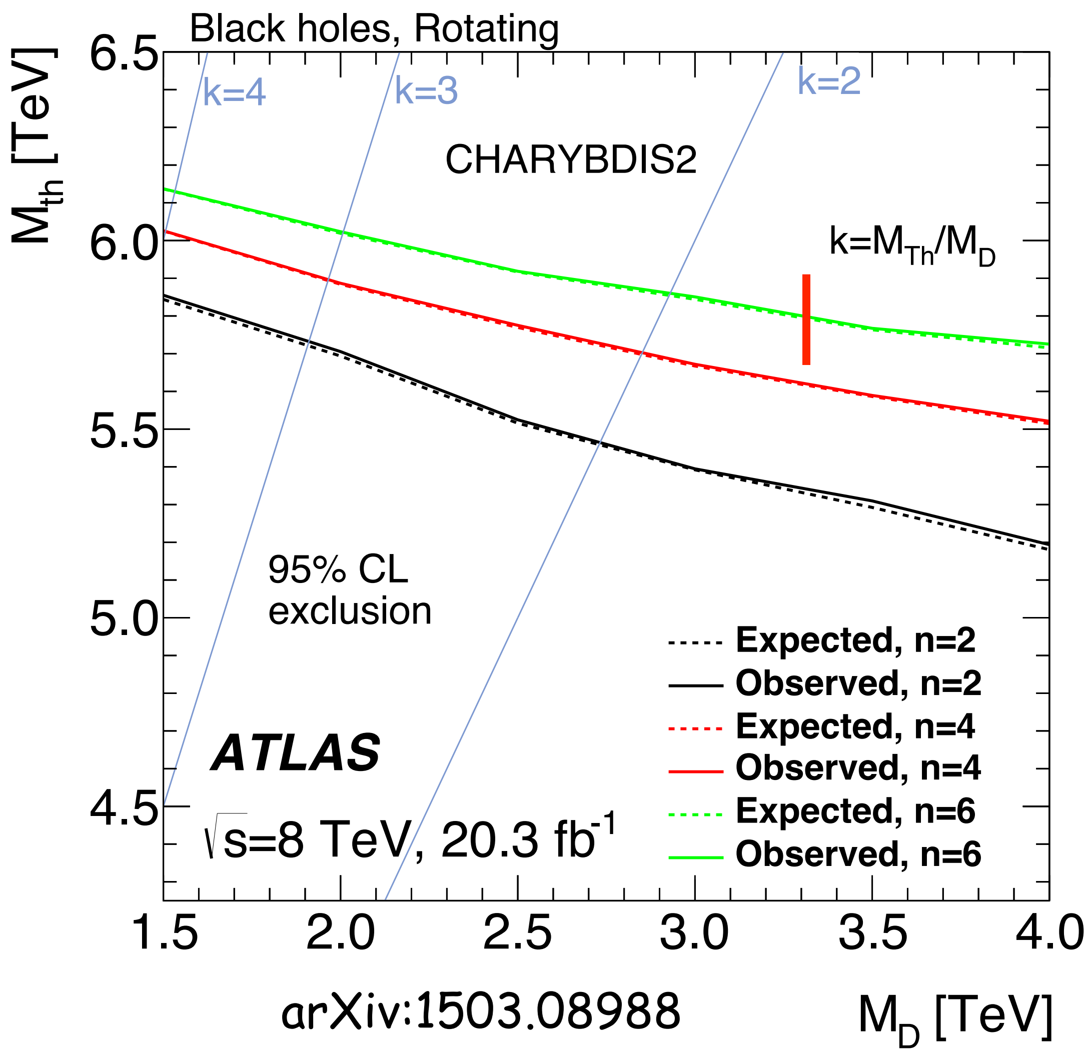
$H_T = \Sigma\, p_T(\text{jets})$



$M > H_T$

$\sigma < 0.16$ fb
$H_T > 4.3$ TeV

GR black holes not allowed at LHC



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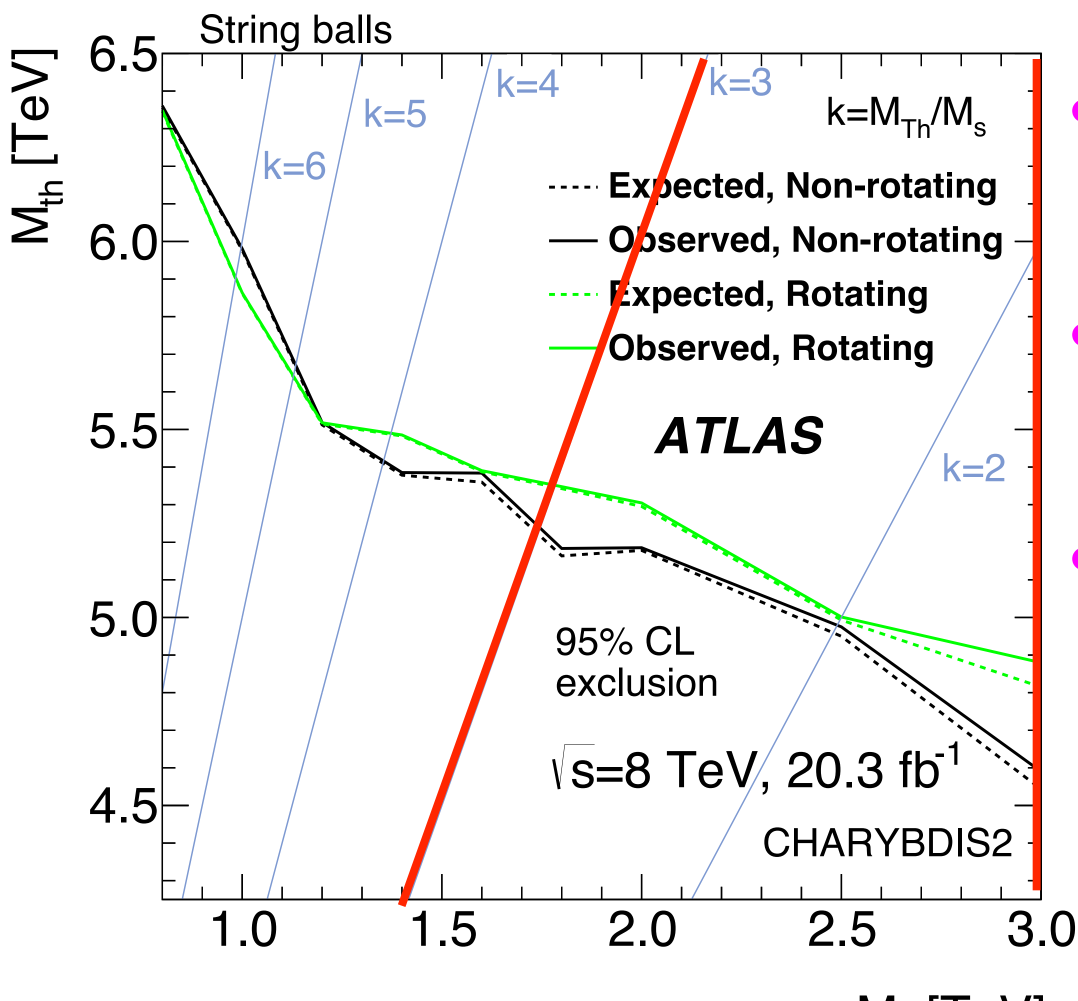
- Current limits on M_D:
  - n = 2, M_D > 5.6 TeV.
  - n = 4, M_D > 3.9 TeV.
  - n = 6, M_D > 3.3 TeV.
- For GR black holes M_{th} > 5 × 3.3 ~ 16.5 TeV.
- Current limits on M_D exclude GR black hole searches.

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 $E > M_{th} \gg M_s$ 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



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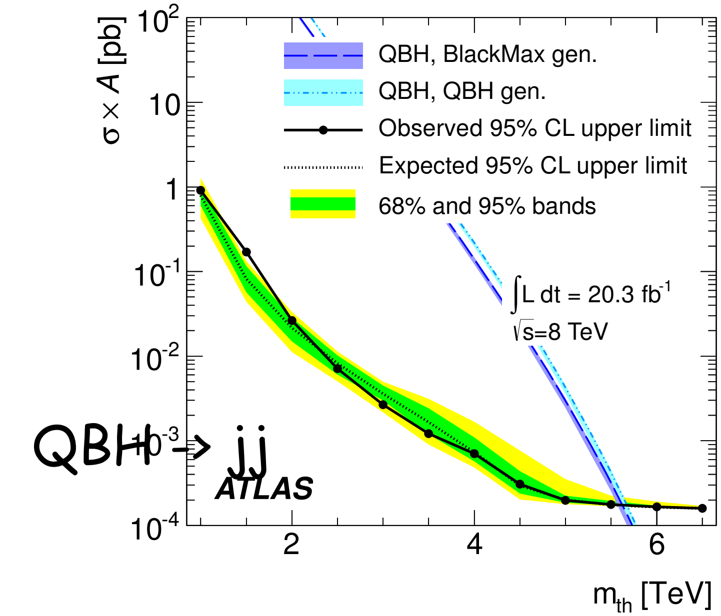
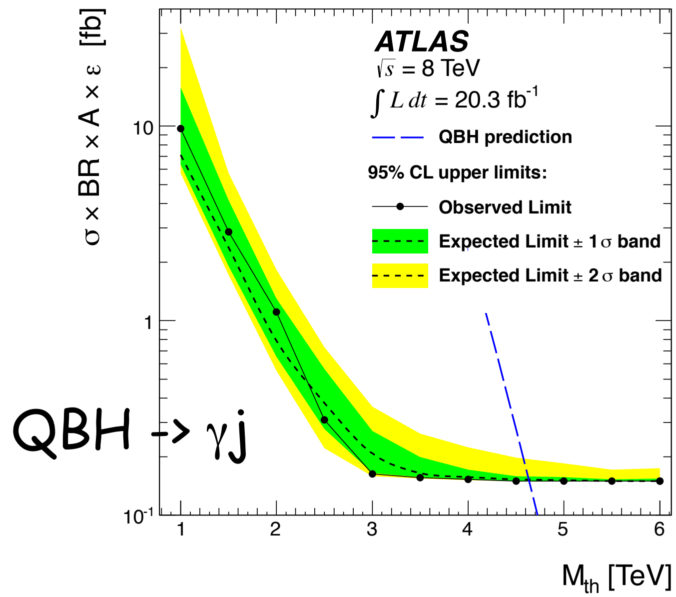
- LHC exclusion limits on a variety of exotics physics means string scale >~3 TeV.
- For string balls in weakly couple string theory M_{th} > 3 × 3 ~ 9 TeV.
- Current limits on M_S exclude string ball searches at run 1 (8 TeV LHC).

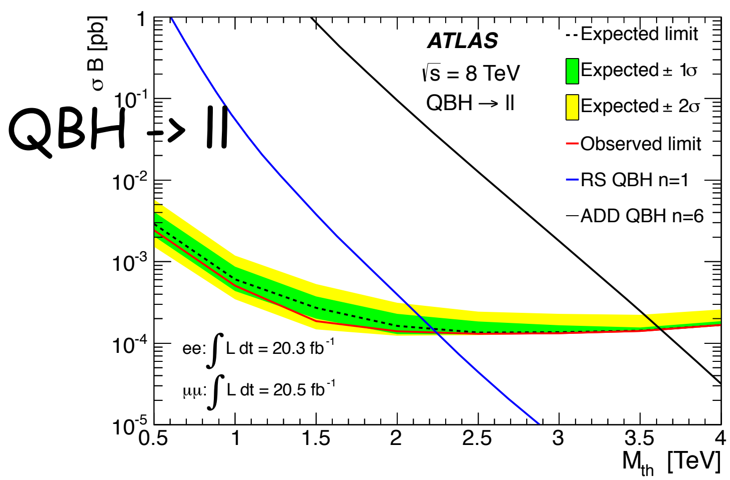
Non-thermal black holes (QBH)

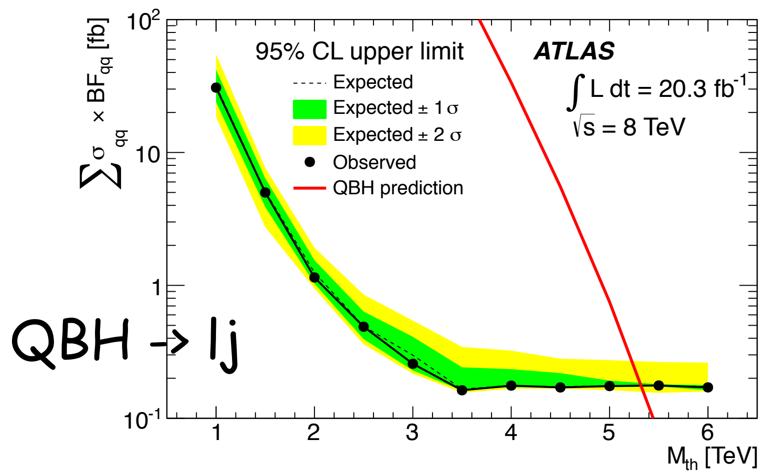
- LHC parton energy needs to be high relative to M_D for black holes to Hawking evaporate thermally.
- Black holes with threshold mass M_{th} near M_D probably do not decay thermally.
- Non-thermal black holes:
  - Extrapolate classical cross section down to Planck scale.
  - Replace Hawking evaporation (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





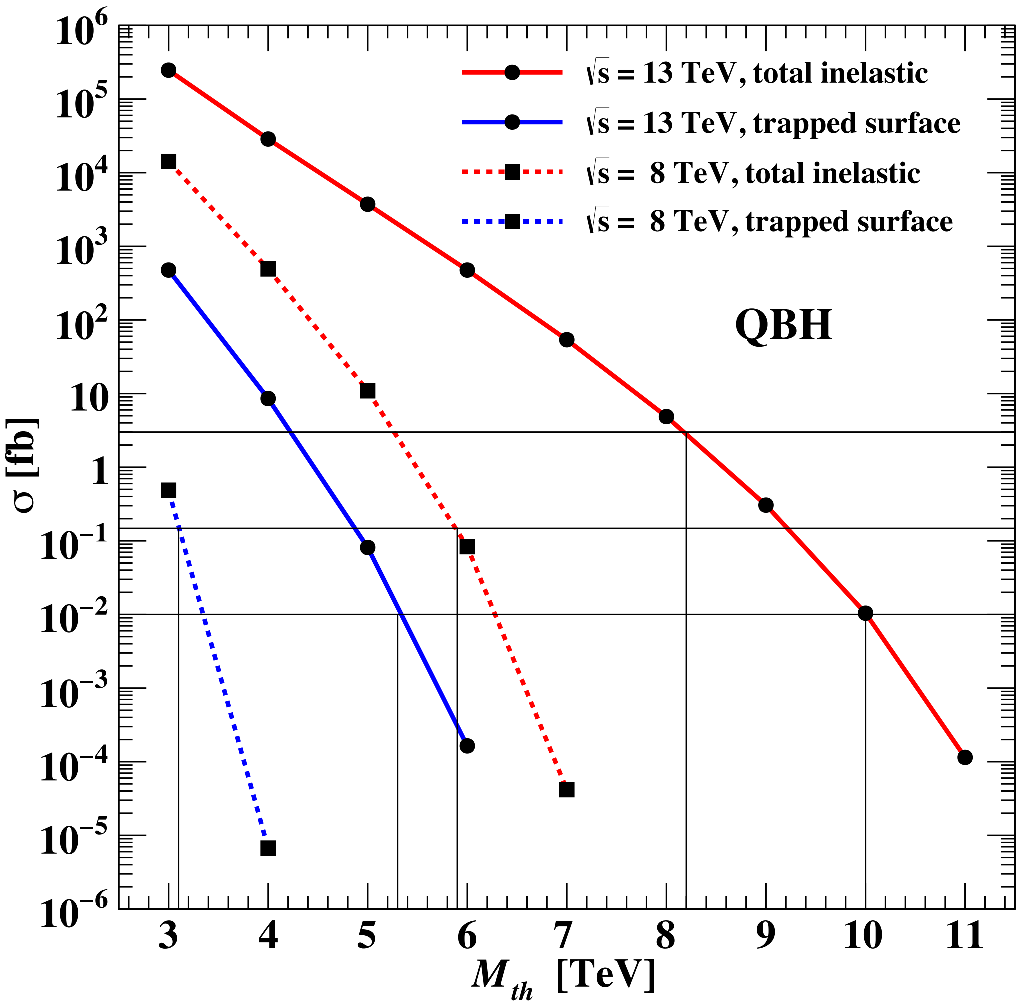




What we think we know

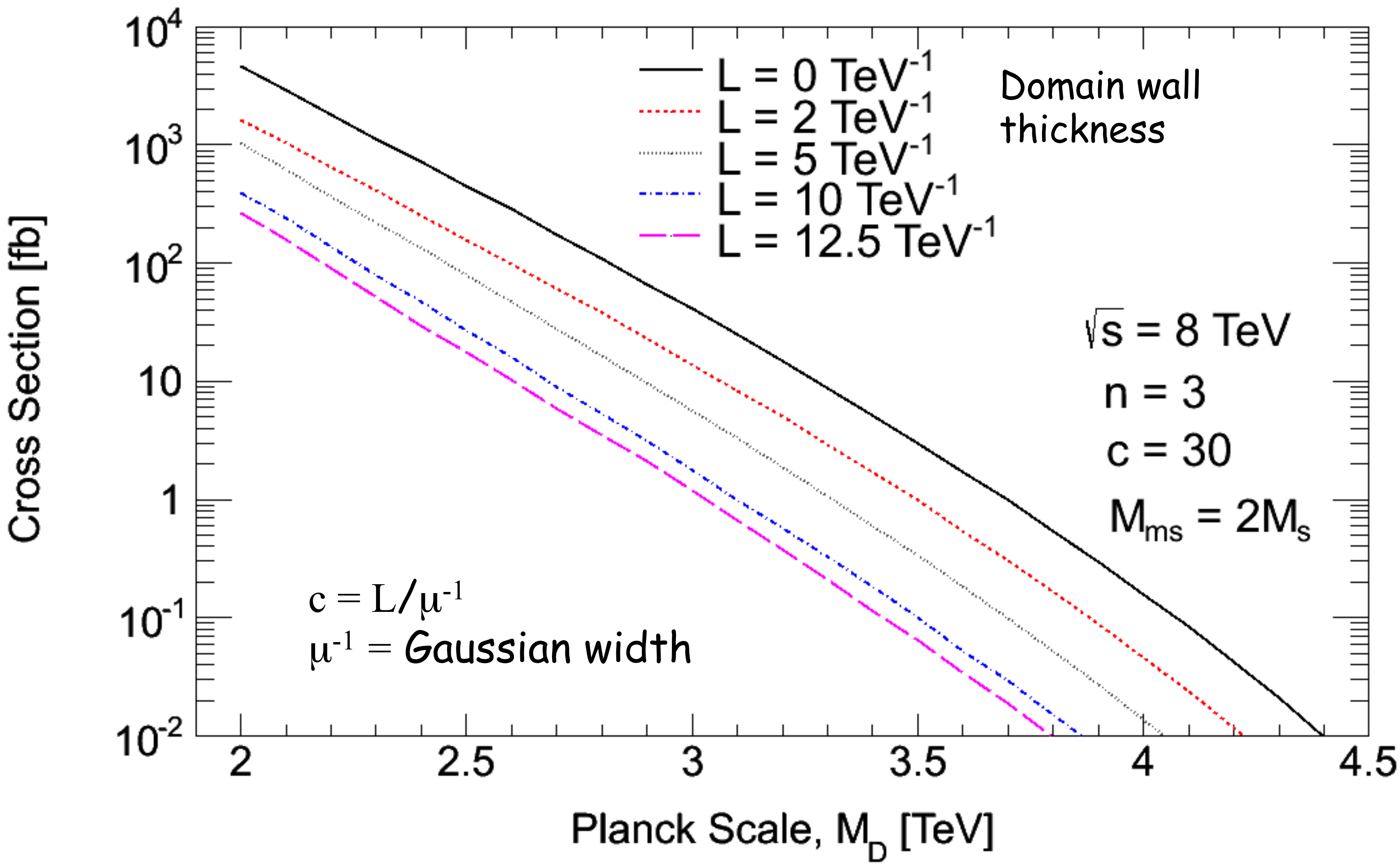
- A search for non-perturbative gravity is enabled by the highest energies, not high luminosity.
- Instant discovery physics at new energy turn-on:
  - If the LHC energy is near the new gravity scale.
- Of course this could be wrong and black holes could be produced at some low rate at our current energies, 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.

Trapped energy estimates



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



Non-commutative geometry

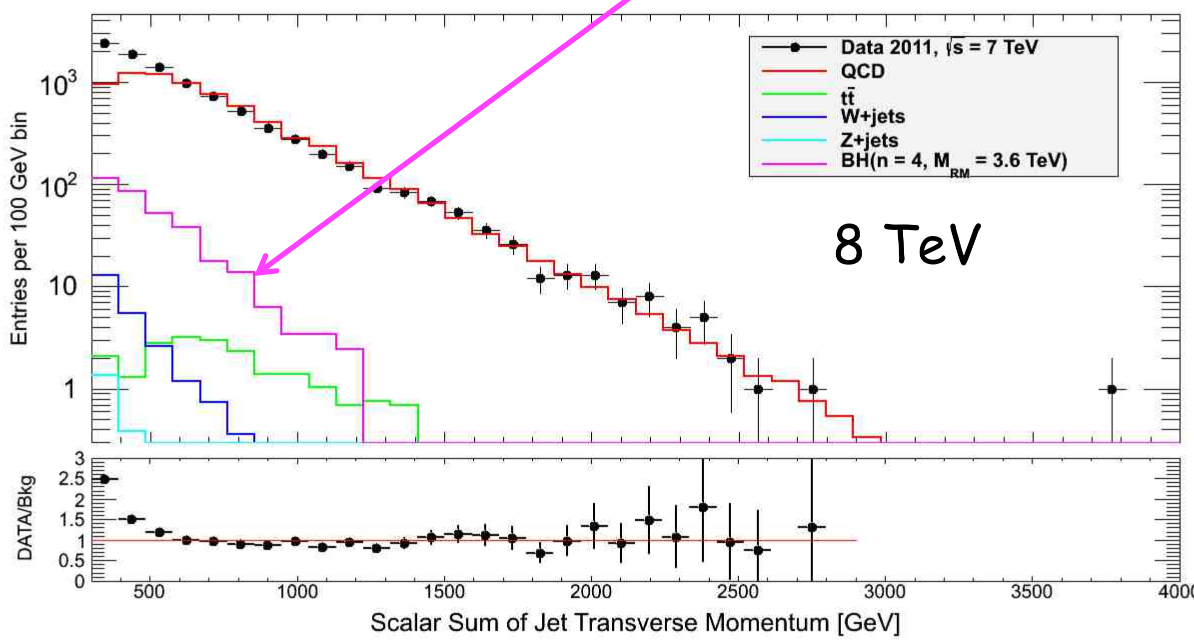
- Non-commutative gravity embedded into ADD:
  - Has hopefully some aspects of a theory of quantum gravity.
  - Model exits and gives rather different signatures then usual models.

black hole

Main experimental differences from GR black holes:

- Larger missing energy.
- Soft Σ p_T spectra.

Possible trigger issues.



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

Outline of talk

- Introduction
- History
- Different way of thinking
- Paradigms for low-scale gravity
- Models usable at the LHC
- Limits on the fundamental Planck scale
- Searches at the LHC
- What we think we know
- Alternatives
- How might we do things differently
- Summary

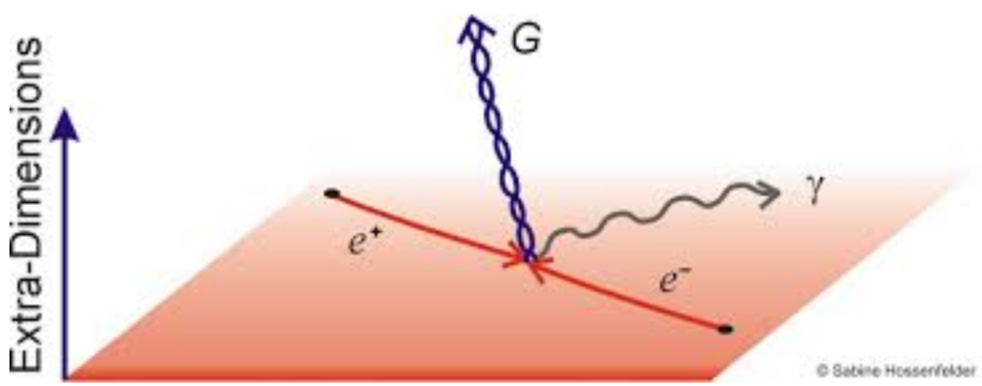
History

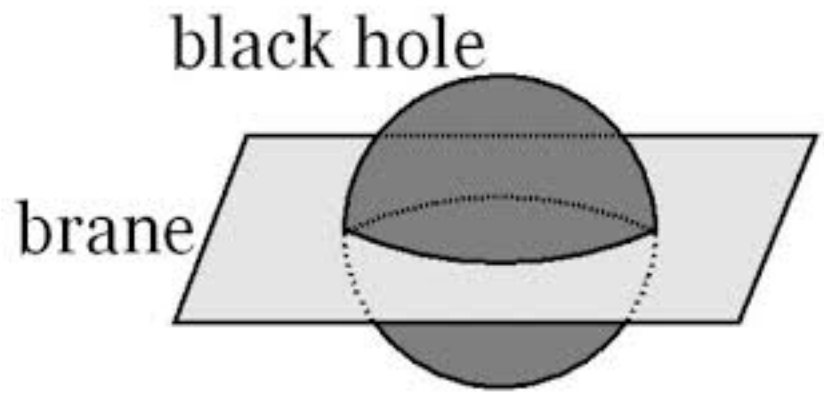
- 1998-99: Low-scale gravity thought to be possible in brane-world scenarios.
- 1999: First low-scale gravity models of perturbative KK states.
- 2001: First low-scale gravity models of thermal black holes.
- 2008: Other low-scale non-perturbative gravity models:
  - string-balls.
  - non-thermal black 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.

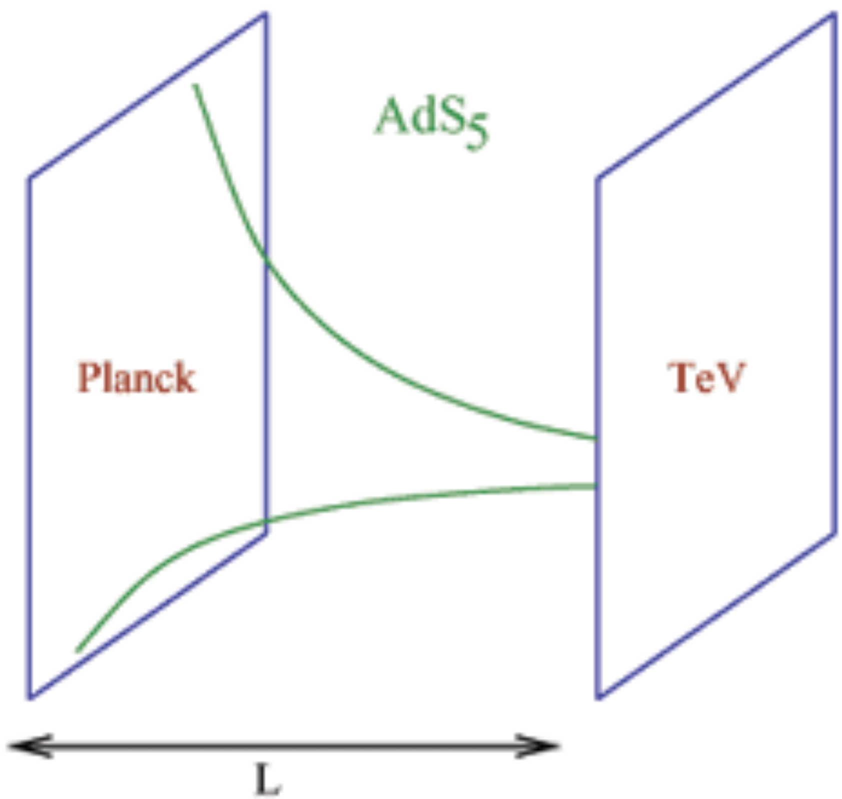
$$\boxed{M_p^{\,2} = V_\delta\, M_D^{\,2+\delta}}$$





Warped extra dimension: RS

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



$$M_p^2 = (k^2 x_1^3 / m_1^3)\, M_5^3$$

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

$$M = m_1/(x_1\, c^{2/3}); \quad c = k/M_P$$

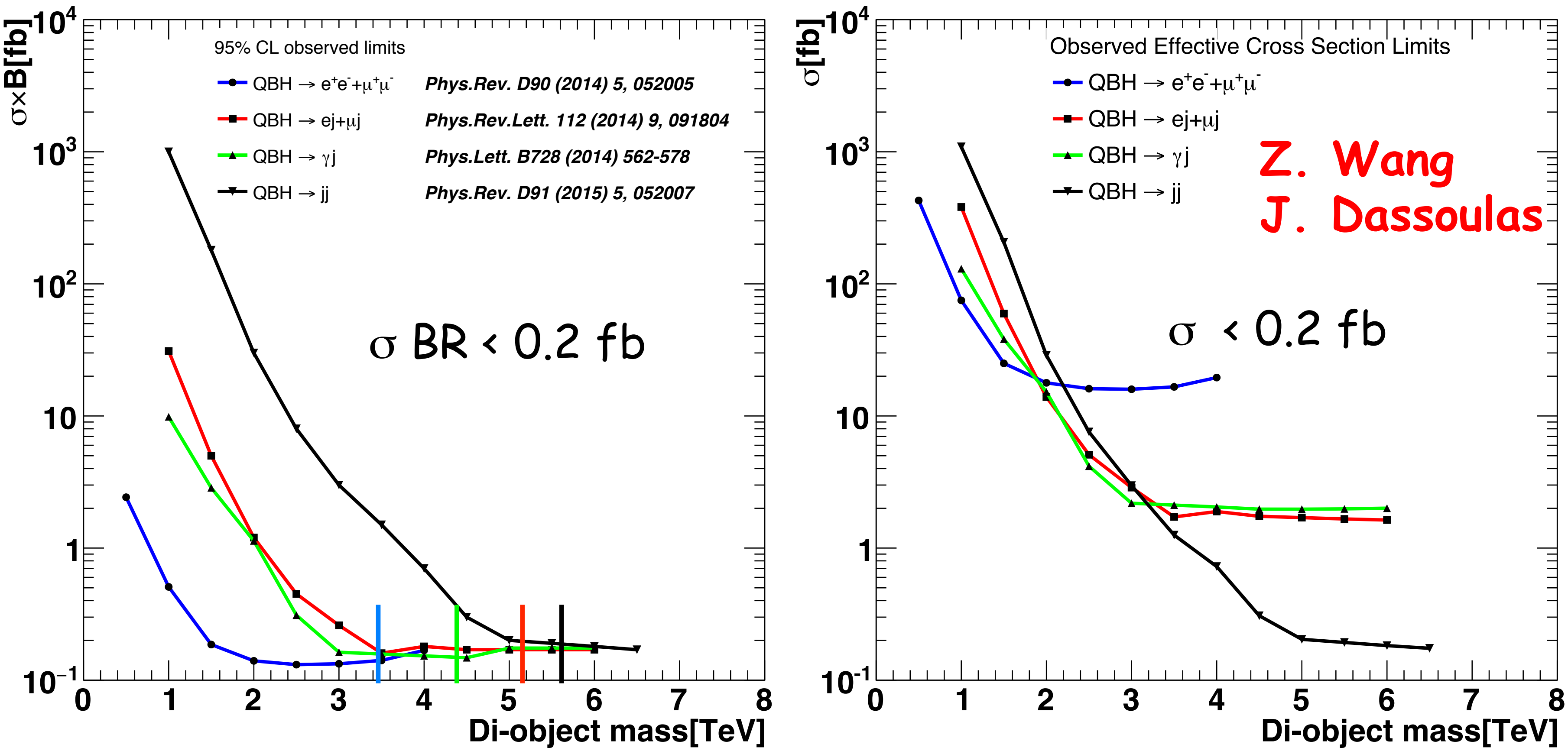
Non-perturbative gravitational states

- 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.

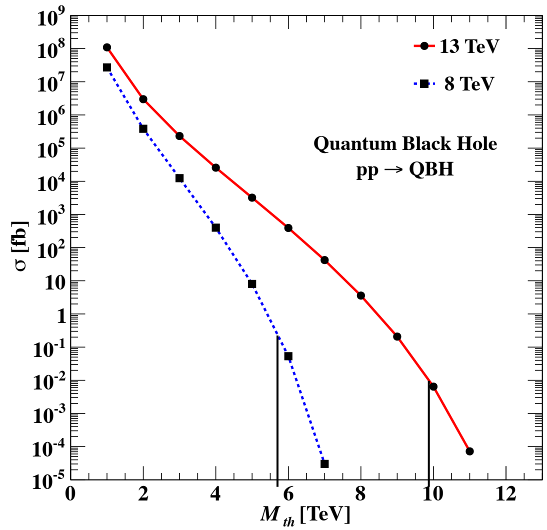
Monte Carlo event generators

- 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



QBH 13 TeV predictions



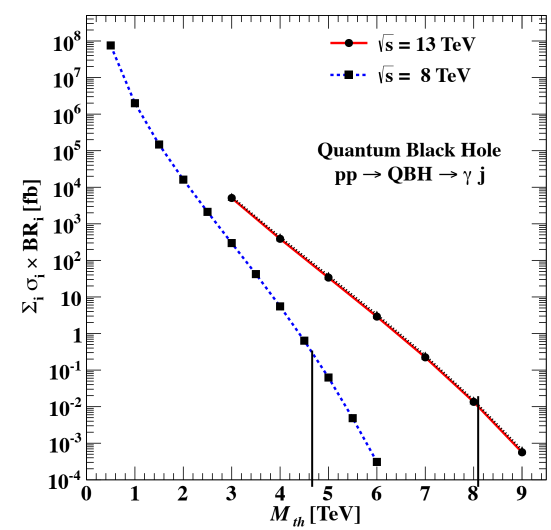
Assume 300 fb^{-1}

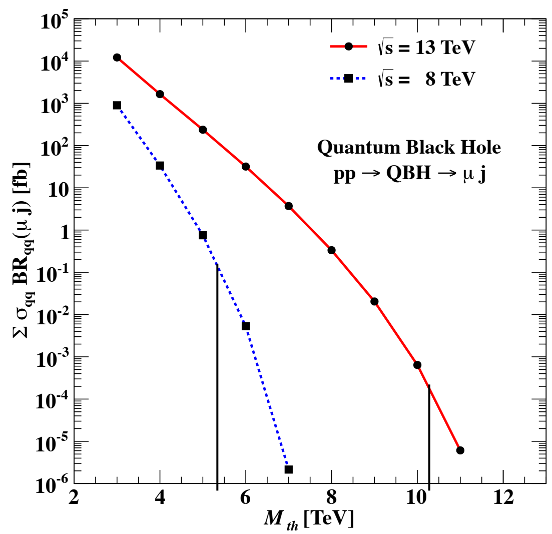
QBH -> jj
5.7-> 10 TeV

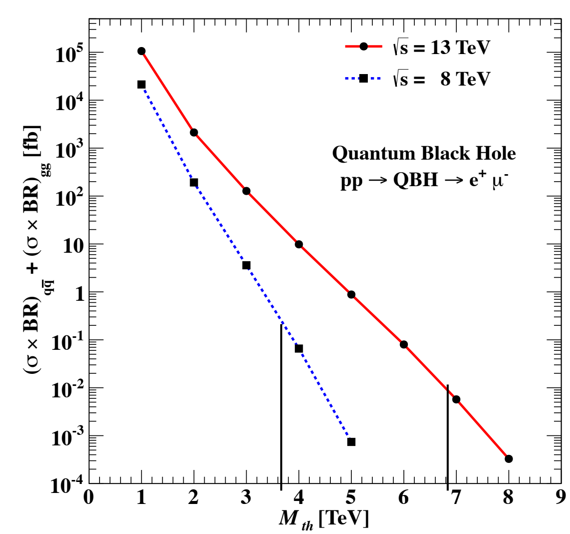
QBH -> μj
5.3 -> 9.2 TeV

QBH -> γj
4.6 -> 8 TeV

QBH -> eμ
3.6 -> 6.8 TeV







Black hole parton cross section

- 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.

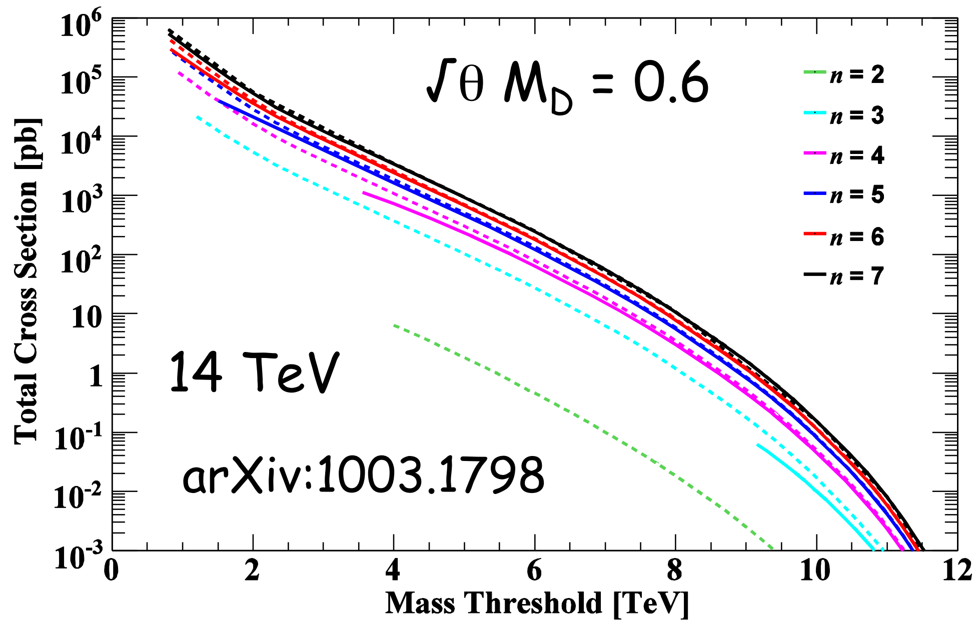
Split-fermion models

- 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-communative geometry

Non-communative geometry inspired black holes

- Smear matter distributions with resolution of non-communativity 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.



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