ARGONNE EXTRA D et al WORKSHOP
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# BLACK HOLE EVAPORATION WITH SEPARATED FERMIONS

(A HOT TALK ABOUT BHs)

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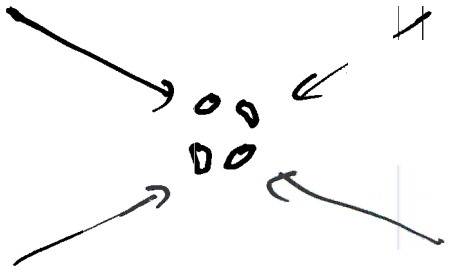
w/ TAO HAN, BOB McELRATH

CLASSICALLY, BLACK HOLES (BHs) EXPECTED TO FORM WHE



SQUEEZE MATTER DENSE ENOUGH SO THAT IT LIES WITHIN ITS SCHWARZSCHILD HORIZON

SUSSKIND & 't HOOFT (93-94) POINTED OUT IF YOU COLLIDE PARTICLES AT ENERGIES $\sqrt{s} \gg M_{Pl}$

A BLACK HOLE IS FORMED

THAT PROMPTLY HAWKING EVAPORATES WITH AN APPROXIMATELY THERMAL SPECTRUM

UNFORTUNATELY, CONGRESS IS UNLIKELY TO ALLOCATE FUNDS FOR A

VVVVVVVVVVVVVVV LHC

TO TEST BH FORMATION & EVAPORATION

# BHs IN ADD

IF WE'RE LUCKY, AND ADD IS RIGHT, THE QUANTUM GRAVITY SCALE COULD BE AS LOW AS A TEV.

LAST YEAR, GIDDINGS-THOMAS & DIMOPOULOS-LANDSBERG OBSERVED THAT BLACK HOLES COULD BE WITHIN REACH OF FUTURE COLLIDERS IF $M_*$ (QUANTUM GRAVITY SCALE) IS LOW ENOUGH.

THE SEMI-CLASSICAL EXPECTATION FOR THE PRODUCTION CROSS SECTION WAS GIVEN:

$$\sigma_{ij \to BH} \sim \pi r_h^2$$

AREA OF BH HORIZON (PROJECTED ON OUR 3-BRANE)

$$\sim (\sqrt{s})^{\frac{2}{D-3}}$$

↑ FOR A BH IN "D" DIMENSIONS

A SPIRITED DEBATE IS ONGOING AS TO THE VALIDITY OF THIS:

| FOR | AGAINST |
| --- | --- |
| GIDDINGS; EARDLEY & GIDDINGS HSU; JEVICKI & THALER; | VOLOSHIN |

IN THIS TALK I WILL FOCUS ON THE BLACK HOLE

EVAPORATION SPECTRUM

NEAR THE END OF A BH'S LIFE

(THIS ACCOUNTS FOR THE ENTIRE LIFE OF A COLLIDER

PRODUCED BH

# EXTRA DIMENSIONAL SETUP

WE IMAGINE SPACETIME CONSISTS OF

$D$ DIMENSIONS $= 3+1$ USUAL

$(D-4)$ EXTRA COMPACTIFIED DIMENSIO

HIGHER-D NEWTON CONSTANT

$$G_D = G_4 \, V_D$$

$\hookrightarrow (2\pi R)^{D-4}$ FOR A TORUS WITH EQUAL SIZES

$\hookrightarrow M_{Pl} = 2 \times 10^{18} \text{ GeV} \equiv \frac{1}{\sqrt{8\pi G_4}}$

WE DEFINE HIGHER-D PLANCK SCALE

$$M_* \equiv \left(\frac{1}{8\pi G_D}\right)^{\frac{1}{D-2}}$$

(DIFFERS FROM SOME OTHER CHOICES BY FACTORS OF $2\pi$)

THIS CHOICE IS WELL MOTIVATED, AS WE WILL SEE.

NEED PROPERTIES OF BH's IN EXTRA DIMENSIONS

WITHOUT A COMPLETE, CALCULABLE QUANTUM GRAVITY THEORY

THE BEST WE CAN DO IS TO CALCULATE SEMI-CLASSICAL PROPERTIES OF BH'S (JUSTIFICATION MUST BE POST FACTO)

MOSTLY INTERESTED IN BH's WITH

$r_h <$ (all radii)

THAT DO NOT DRAMATICALLY DISTORT EXTRA-D GEOMETRY

FINALLY, I WILL NEGLECT THE SPIN OF THE BH.

(WILL NOT AFFECT CONCLUSIONS)

# SEMI-CLASSICAL PROPERTIES OF BH's IN EXTRA-D

[MYERS-PERRY]

SCHWARZSCHILD HORIZON:

$$= \frac{1}{M_*}\left(\frac{M_{bh}}{M_*}\right)^{\frac{1}{D-3}}\left(\frac{2}{(D-2)\,\Omega_{D-2}}\right)^{\frac{1}{D-3}}$$

$$\Omega_{D-2} \equiv \frac{2\pi^{\frac{D+1}{2}}}{\Gamma\left[\frac{D+1}{2}\right]}$$

$\frac{1}{4} \to \frac{1}{2}$

$6 \leq D \leq 11$

GROWS SLOWLY FOR INCREASING BLACK HOLE MASS

TEMPERATURE:

$$= \frac{D-3}{4\pi r_h}$$

$$\simeq M_* \left(\frac{M_{bh}}{M_*}\right)^{\frac{-1}{D-3}}$$

D-DIMENSIONAL NUMERICAL FACTOR

$0.85 \to 1.15$

$4 \leq D \leq 11$

IN FOUR DIMENSIONS

WHEN $\begin{cases} T = M_* = M_{Pl} = 2 \cdot 10^{18}\ \text{GeV} \\ M_{bh} \longrightarrow M_* = M_{Pl}. \end{cases}$

SAME IS TRUE FOR EXTRA-D CASE, $\begin{cases} T = M_* \\ \text{AS} \\ M_{bh} \longrightarrow M_* \end{cases}$

$\Rightarrow$ NO OTHER CHOICE OF DEF'N OF $M_*$ HAS THIS PROPERTY. $\Leftarrow$

LIFETIME

$$\tau \sim \frac{1}{M_*} \left(\frac{M_{BH}}{M_*}\right)^{\frac{D-1}{D-3}}$$

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IN SUMMARY, FOR FIXED $\left(\frac{M_{BH}}{M_*}\right)$, NORMALIZED TO $M_*$,

HIGHER-D BH's ARE:

SMALLER

- HOTTER
- LIVE LONGER

EACH PROPERTY GETS MORE EXTREME AS THE # OF DIMENSIONS INCREASE

# BLACK HOLE EVAPORATION

GIDDINGS - THOMAS EMPHASIZED THAT BH EVAPORATION FROM INITIAL CREATION IN A PARTICLE COLLISION PROCEEDS IN STAGES:

BALDING PHASE

BH SETTLES INTO A SYMMETRICAL (ROTATING) STATE

SPIN-DOWN PHASE

BH PREFERENTIALLY EMITS FERMIONS & GAUGE BOSONS TO SHED ITS ANGULAR MOMENTUM

SCHWARZSCHILD PHASE

BH HAWKING RADIATES, APPROXIMATELY THERMAL

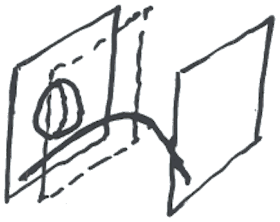
# WHAT DOES A HIGHER-D BH DECAY INTO?

SINCE BH TEMPERATURE $\sim \frac{1}{r_h}$, HIGHER-D BH CAN EMIT BULK KK MODES. DO THEY DOMINATE THE EVAPORATION? NO.

[EMPARAN, HOROWITZ, MYERS]

HEURISTIC ARGUMENT:

- NUMBER OF KK MODES $\sim (T \cdot R)^{D-4}$
- EACH KK MODE, HOWEVER, ONLY PARTIALLY OVERLAPS WITH BH HORIZON



WAVEFCN OVERLAP FOR $(D-4)$ EXTRA DIMENSIONS IS

$$\sim \left(\frac{r_h}{R}\right)^{D-4}$$

- NET RATE INTO BULK MODES

$$(TR)^{D-4}\left(\frac{r_h}{R}\right)^{D-4} = (T r_h)^{D-4} \sim 1$$

$\Rightarrow$ NO ENHANCEMENT INTO BULK MODES

LET'S DO THIS MORE CAREFULLY:

THERMAL EMISSION OF A BLACK BODY HAS A SPECTRUM

$$\frac{dE}{dt} = \frac{E}{e^{E/T} - (-1)^{2s}} \frac{d^{n-1}k}{(2\pi)^{n-1}}$$

INTO PARTICLES WITH SPIN $s$ THAT LIVE IN $n$ DIMENSIONS

LET'S COMPARE SCALAR EMISSION INTO 4 VS. 10 DIMENSIONS:

INTEGRATING THE SPECTRUM

$$\frac{d\mathcal{E}_4}{dt} = \sigma_4 A_4 T^4 \qquad \frac{d\mathcal{E}_{10}}{dt} = \sigma_{10} A_{10} T^{10}$$

WHERE THE $n$ DIMENSIONAL STEFAN-BOLTZMANN CONSTANT IS:

$$\sigma_n = \frac{\Omega_{n-3}}{(2\pi)^{n-1}(n-2)} \Gamma(n)\zeta(n)$$

e.g. $\sigma_4 = \frac{\pi^2}{120} \sim 0.08$, $\sigma_{10} = \frac{\pi^5}{3168} \sim 0.1$

THE RATIO:

$$\frac{\frac{d\mathcal{E}_4}{dt}}{\frac{d\mathcal{E}_{10}}{dt}} = \frac{\sigma_4 A_4 T^4}{\sigma_{10} A_{10} T^{10}} \sim \frac{r_4^2 \cdot \left(\frac{1}{r_4}\right)^4}{r_4^6 \left(\frac{1}{r_4}\right)^{10}} \sim 1$$

ALL OTHER THINGS EQUAL EXTRA D BHs EMIT

ABOUT THE SAME POWER INTO BULK & BOUNDARY FIELDS

BUT!

MANY MORE BOUNDARY FIELDS THAN BULK FIELDS

=> BHs RADIATE MAINLY ON THE BRANE.

# SEPARATED FERMIONS?

PREVIOUS BH EVAPORATION STUDIES ASSUMED ALL SM FIELDS WERE LOCALIZED TO A (SINGLE) 3-BRANE.

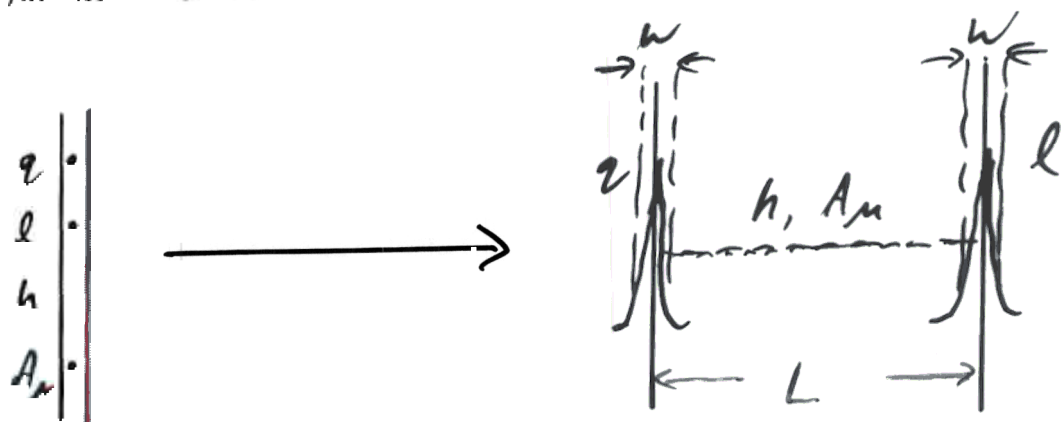
WITH A LOW QUANTUM GRAVITY SCALE, LEADS TO PROBLEMS:

- PROTON DECAY
  FCNC
  NEUTRINO MASSES

IF WE CONSIDER AN EXPLICIT SOLUTION TO $p$ DECAY (IN PARTICULAR), HOW DOES BH PRODUCTION/EVAPORATION CHANGE?

# SEPARATED FERMIONS !

A KAKU HAMED SCHMALTZ SUGGESTED A NOVEL SOLUTION




COULD BE A FAT BRANE OR AN ORTHOGONAL EXTRA DIMENSION

INDUCED PROTON DECAY OPERATOR

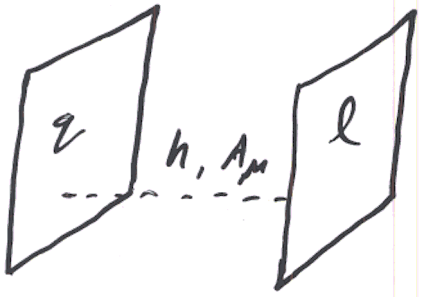
$$\int d^4x \, c \, \frac{qqql}{M_*^2}$$

WHERE $c \sim \exp\left[-\left(\frac{L}{w}\right)^2\right]$

THIS IS ADEQUATE SUPPRESSION FOR $\left(\frac{L}{w}\right) \sim 1$

# QUALITATIVE CHANGES

FOR CONCRETENESS, CONSIDER A SCENARIO:

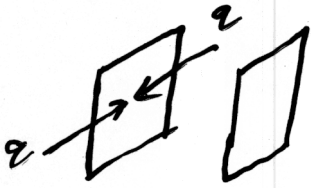



EXTRA ORTHOGONAL DIMENSION WITH GAUGE/HIGGS IN BULK

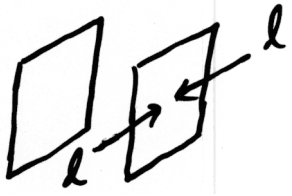
SMALLEST PHYSICALLY SENSIBLE FERMION WIDTH: $w \sim \frac{1}{M_*}$

(FIELD THEORETIC LOCALIZATION SUGGESTS $w \sim \frac{10}{M_*}$)

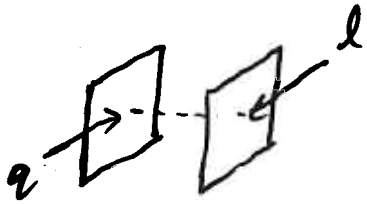
PRODUCTION:




HADRON COLLIDER




LEPTON COLLIDER




HERA

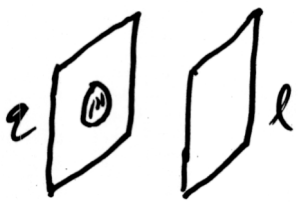
BH PRODUCTION EXPONENTIALLY SUPPRESSED! (FOR $M_{BH}$ NOT TOO FAR ABOVE $M_*$)

QUARK-GLUON OR GLUON-GLUON SCATTERING ALSO INTERESTING, BUT PROBABILITY TO EXTRACT GLUON WITH A LARGE FRACTION

# EVAPORATION

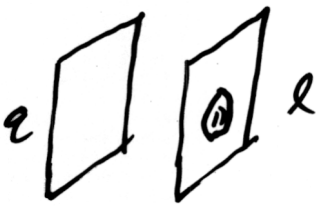
FIRST RECALL THAT HORIZON SIZE $r_h$ GROWS VERY SLOWLY WITH INCREASING $M_{bh}$ ; $r_h$ AT MOST ~ few/$M_*$ FOR BLACK HOLE MASSES OF SAY $(10 \to 100) \cdot M_*$

HADRON MACHINE BH




ONLY DIRECT EVAP. INTO QUARKS (+ GAUGE/HIGGS)

LEPTON MACHINE BH




ONLY DIRECT EVAP. INTO LEPTONS (+ GAUGE/HIGGS)

ESTIMATES OF THE RATIOS OF EMITTED PARTICLE SPECIES:

| | $q$ : | $l$ : | $g$ : | $W^\pm, Z$ : | $h$ : | $\gamma$ |
|---|---|---|---|---|---|---|
| QUARK BRANE BH | 108 | – | 8 | 7 | 1.4 | 1 |
| LEPTON BRANE BH | – | 36 | 8 | 7 | 1.4 | 1 |

↓ AFTER GAUGE BOSON DECAY/FRAGMENT

| | jets : | $l^\pm$ : | invisible : | $\gamma$ |
|---|---|---|---|---|
| Q.B. BH | 113 | 8 | 7.5 | 1 |
| L.B. BH | 17 | 20 | 19 | 1 |

# SCALES

KK EXCITATIONS TO SM GAUGE BOSONS $\Lambda$ CONSTRAINED BY EW PRECISION DATA. BOUND IS ROUGHLY

$$L^{-1} \gtrsim 2 \to 5 \text{ TEV}$$

[e.g. SEE RIZZO-WELLS; DELGATO-POMAROL-QUIROS]

FERMION SEPARATION REQUIRES AT LEAST

$$M_* \gtrsim 10 L^{-1}$$

HENCE

$$M_* \gtrsim 20 \to 50 \text{ TEV}$$

THIS IS GOOD FOR THE MODEL:

- ALEVIATES FCNC PROBLEMS

  $n \leftrightarrow \bar{n}$ INDUCED OPERATOR OK (FOR $M_* \gtrsim 40$ TEV)

- COULD HAVE 2 "gravity-only" DIMENSIONS
  + 1 "gauge/higgs" DIMENSION

  AND AVOID ADELBERGER, SN CONSTRAINTS

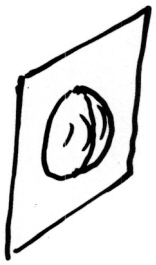
BUT BAD FOR COLLIDER PROSPECTS:

- LHC WOULD (AT BEST) SEE KK RESONANCE(S) OF BULK FIELDS
- NEED VLHC $\gtrsim$ 100 TEV FOR BH PRODUCTION

# BHs WANDERING OFF BRANES?

EMPARAN-HOROWITZ-MYERS ARGUE: NO.

CONSIDER A BRANE WITH STRESS-TENSOR $T_{\mu\nu}$, AND A BH FORMED ON IT:



FOR THE BH SIZE TO REMAIN STATIC, $T_{\mu\nu} \ell^\mu \ell^\nu = 0$

↳ NULL GEODESIC GENERA OF HORIZON

BRANE STRESS-TENSOR $T_{\mu\nu} \propto \eta_{\mu\nu}$

$\Rightarrow$ $\eta_{\mu\nu} \ell^\mu \ell^\nu = 0$

SATISFIED IF RADIAL DIRECTION ORTHOGONAL TO BH HORIZON IS TANGENT TO THE BRANE

SO IF YOU TRIED TO MOVE THE BH, THE BRANE BENDS

AND PROVIDES A RESTORING FORCE, KEEPING THE BH ON THE BRANE.

- MODELS WITH LARGE EXTRA DIMENSIONS COULD TO BHs BEING PRODUCED IN COLLIDER

- BHs DECAY MAINLY TO BRANE FIELDS, DUE LARGER MULTIPLICITY

- SEPARATING QUARKS & LEPTONS SOLVES p LEADING TO DIFFERENT EVAPORATION SPECTRUM THAT DEPENDS ON WHERE BH CREATED

- QUANTUM GRAVITY SCALE MUST BE LARGE, $\gtrsim$ 20 → 50 TEV

TO SATISFY CURRENT EXPT. CONSTRAINTS, IN THIS

→ NEED VLHC TO SEE BH PRODUCTION/EV