Probing Higher Curvature Gravity in Extra Dimensions at Colliders

- JHEP ϕ1 (2005) 028
- hep-ph/0503163

- Higher Curvature Terms :

  $\Rightarrow$ What are they + when are they important ?

- Where do we see them ?

  $\Rightarrow$ Modifications in 'traditional' extra dimensional model signatures...

  - 'Large' Extra Dimensions (ADD) $\Leftrightarrow$ <u>BH</u>
  - 'Warped' Randall-Sundrum model (RS)

    <u>Pheno talk</u>

- Summary + Conclusions

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5/05

$$S = \int d^{4+n}x \, \sqrt{-g} \left\{ \underbrace{\frac{M_*^{n+2}}{2} R - \Lambda}_{\text{Einstein-Hilbert (EH) action}} + ?? \right\} \Leftarrow \text{GRAVITY}$$

$\begin{cases} M_* \equiv \text{fundamental scale} \\ R = \text{Ricci curvature scalar} \end{cases}$ Λ = Cosmological constant

EH is
- The basis of GR in 4d.....
- The basis for ADD/RS models in extra dimensions
- At best, an effective theory below M_* (~ few TeV ??, M_{Pl} ?)

"??" terms from "UV-completion" (strings?) may be important as Energies approach M_* ...

⟹ What can they be ??

- R^2, $(\partial R)^2$, R^{-3}, $R_{AB} R^{BC} R_C{}^A$, ... ??

.... many, many possibilities

- We need guidance !!

• Unitary / ghost-free theory $\Longrightarrow$

no derivatives of the metric > 1^{st} (2^{nd}) in the action (eqs of motion)

LaGrange's Eqs.

• Produces 'benign' modifications to Einstein Eqs:

$$R_{AB} - \frac{1}{2} g_{AB} R + \underline{\underline{L_{AB}}} = \frac{1}{M_*^{n+2}} T_{AB}.$$

$\Rightarrow$ extra terms are symmetric + divergence free...

• String 'Motivation' $\longrightarrow$ lowest-order terms arise from string expansion... [Zwiebach '84], [Zumino '86]

$\Rightarrow$ Unique Solution! The effective action is a sum of <u>Lovelock</u> <u>invariants</u> at low energies...

Lanczos '32, '38
Lovelock '71

$$\boxed{\mathcal{L}_m} \sim \underbrace{\delta^{A_1 B_1 \ldots A_m B_m}_{C_1 D_1 \ldots C_m D_m}}_{\text{totally antisymmetric Kronecker}} R_{A_1 B_1}{}^{C_1 D_1} \ldots\ldots R_{A_m B_m}{}^{C_m D_m}$$

Riemann Curvature Tensor

Too many terms? Not really...

· in $D = 4+n$ **MOST** $\mathcal{L}_m$ are **zero** ! ... only $\mathcal{L}_m$ with $D \geq 2m+1$ are '**dynamical**' = contribute to Einstein's eqs., ie, :

- $D = 9, 10$:
  - $D = 7, 8$:
    - $D = 5, 6$:
      - $D = 4$:
        - $\mathcal{L}_0 = $ a constant (Λ)
        - $\mathcal{L}_1 = R$

        EH !
      - $\mathcal{L}_2 = R^2 - 4R_{AB}R^{AB} + R_{ABCD}R^{ABCD}$ (Gauss - Bonnet)
    - $\mathcal{L}_3 = 8$ terms
  - $\mathcal{L}_4 = 25$ terms...

    ⋮

... etc, etc ...

· EH is just the first two terms of a general expansion ...

... it is the **UNIQUE** Lovelock action in $D=4$!

... in $D=5$, $R + \frac{\alpha}{M_*^2}\mathcal{L}_2 \cdots \Lambda$ is unique (RS)

$\therefore \sum_m \alpha_m \mathcal{L}_m$: often used in literature as toy models to probe quantum/stringy corrections to EH ... in Extra Dimensions ...

(Briggs)

The Lovelock invariants rapidly grow in complexity ...

(Müller-Hoissen)

$$\text{EH}\left\{\begin{aligned} L_{(0)} &= 1, \\ L_{(1)} &= -R, \\ L_{(2)} &= R^2 - 4\,R_{b}{}^{a}\,R_{a}{}^{b} + R_{cd}{}^{ab}\,R_{ab}{}^{cd}, \end{aligned}\right. \qquad \text{(Gauss-Bonnet)}$$

and

$$\begin{aligned} L_{(3)} = &- R^3 + 12\,R\,R_{b}{}^{a}\,R_{a}{}^{b} - 3\,R\,R_{cd}{}^{ab}\,R_{ab}{}^{cd} - 16\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{a}{}^{c} + \\ &+ 24\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ab}{}^{cd} + 24\,R_{b}{}^{a}\,R_{de}{}^{bc}\,R_{ac}{}^{de} + \\ &+ 2\,R_{cd}{}^{ab}\,R_{ef}{}^{cd}\,R_{ab}{}^{ef} - 8\,R_{ce}{}^{ab}\,R_{af}{}^{cd}\,R_{bd}{}^{ef}. \end{aligned}$$

$$\begin{aligned} L_{(4)} = &\, R^4 - 24\,R^2\,R_{b}{}^{a}\,R_{a}{}^{b} + 6\,R^2\,R_{cd}{}^{ab}\,R_{ab}{}^{cd} + 64\,R\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{a}{}^{c} - 96\,R\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ab}{}^{cd} - 96\,R\,R_{b}{}^{a}\,R_{de}{}^{bc}\,R_{ac}{}^{de} - 8\,R\,R_{cd}{}^{ab}\,R_{ef}{}^{cd}\,R_{ab}{}^{ef} + \\ &+ 32\,R\,R_{ce}{}^{ab}\,R_{af}{}^{cd}\,R_{bd}{}^{ef} + 48\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{d}{}^{c}\,R_{c}{}^{d} - 96\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{d}{}^{c}\,R_{a}{}^{d} + 384\,R_{b}{}^{a}\,R_{d}{}^{b}\,R_{e}{}^{c}\,R_{ac}{}^{de} - 24\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{ef}{}^{cd}\,R_{cd}{}^{ef} + \\ &+ 192\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{ef}{}^{cd}\,R_{ad}{}^{ef} + 96\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ef}{}^{cd}\,R_{ab}{}^{ef} - 192\,R_{c}{}^{a}\,R_{e}{}^{b}\,R_{af}{}^{cd}\,R_{bd}{}^{ef} + 192\,R_{c}{}^{a}\,R_{e}{}^{b}\,R_{bf}{}^{cd}\,R_{ad}{}^{ef} - 192\,R_{b}{}^{a}\,R_{ad}{}^{bc}\,R_{fg}{}^{de}\,R_{ce}{}^{fg} + \\ &+ 96\,R_{b}{}^{a}\,R_{de}{}^{bc}\,R_{fg}{}^{de}\,R_{ac}{}^{fg} - 384\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{ag}{}^{de}\,R_{ce}{}^{fg} + 3\,R_{cd}{}^{ab}\,R_{ab}{}^{cd}\,R_{gh}{}^{ef}\,R_{ef}{}^{gh} - 48\,R_{cd}{}^{ab}\,R_{ae}{}^{cd}\,R_{gh}{}^{ef}\,R_{bf}{}^{gh} + \\ &+ 6\,R_{cd}{}^{ab}\,R_{ef}{}^{cd}\,R_{gh}{}^{ef}\,R_{ab}{}^{gh} - 96\,R_{cd}{}^{ab}\,R_{eg}{}^{cd}\,R_{ah}{}^{ef}\,R_{bf}{}^{gh} + 48\,R_{ce}{}^{ab}\,R_{ag}{}^{cd}\,R_{bh}{}^{ef}\,R_{df}{}^{gh} - 96\,R_{ce}{}^{ab}\,R_{ag}{}^{cd}\,R_{dh}{}^{ef}\,R_{bf}{}^{gh}. \end{aligned}$$

$$\begin{aligned} L_{(5)} = &- R^5 + 40\,R^3\,R_{b}{}^{a}\,R_{a}{}^{b} - 10\,R^3\,R_{cd}{}^{ab}\,R_{ab}{}^{cd} - 160\,R^2\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{a}{}^{c} + 240\,R^2\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ab}{}^{cd} + 240\,R^2\,R_{b}{}^{a}\,R_{de}{}^{bc}\,R_{ac}{}^{de} + 20\,R^2\,R_{cd}{}^{ab}\,R_{ef}{}^{cd}\,R_{ab}{}^{ef} - \\ &- 80\,R^2\,R_{ce}{}^{ab}\,R_{af}{}^{cd}\,R_{bd}{}^{ef} - 240\,R\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{d}{}^{c}\,R_{c}{}^{d} + 480\,R\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{d}{}^{c}\,R_{a}{}^{d} - 1920\,R\,R_{b}{}^{a}\,R_{d}{}^{b}\,R_{e}{}^{c}\,R_{ac}{}^{de} + 120\,R\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{ef}{}^{cd}\,R_{cd}{}^{ef} - \\ &- 960\,R\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{ef}{}^{cd}\,R_{ad}{}^{ef} - 480\,R\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ef}{}^{cd}\,R_{ab}{}^{ef} + 960\,R\,R_{c}{}^{a}\,R_{e}{}^{b}\,R_{af}{}^{cd}\,R_{bd}{}^{ef} - 960\,R\,R_{c}{}^{a}\,R_{e}{}^{b}\,R_{bf}{}^{cd}\,R_{ad}{}^{ef} + 960\,R\,R_{b}{}^{a}\,R_{ad}{}^{bc}\,R_{fg}{}^{de}\,R_{ce}{}^{fg} - \\ &- 480\,R\,R_{b}{}^{a}\,R_{de}{}^{bc}\,R_{fg}{}^{de}\,R_{ac}{}^{fg} + 1920\,R\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{ag}{}^{de}\,R_{ce}{}^{fg} - 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• Are the $\mathcal{L}_m$ important in ADD/RS models?

$$S = \int d^{4+n}x \sqrt{-g} \left\{ \frac{M_*^{n+2}}{2} \cdot \left[R + \underset{(D=5,6)}{\frac{\alpha}{M_*^2}\mathcal{L}_2} + \underset{(D=7,8)}{\frac{\beta}{M_*^4}\mathcal{L}_3} + \underset{(D=9,10)}{\frac{\gamma}{M_*^6}\mathcal{L}_4} \right] - \Lambda \right\}$$

• α, β, γ = dimensionless constrants†

• Since $\mathcal{L}_m \sim R^m$, Lovelock 'corrections' are <u>potentially</u> <u>large</u> when R/M_*^2 <u>is big</u> ...

⇒ When does this happen??

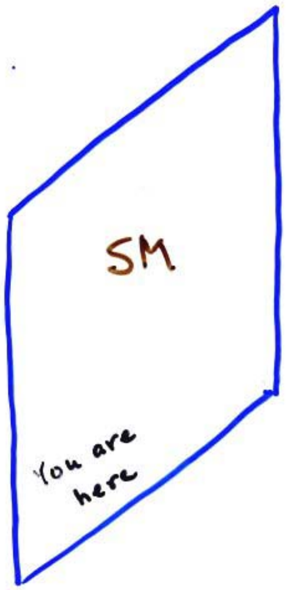
Look at models .... in $\left\{ \begin{matrix} \text{ADD} \\ \text{RS} \end{matrix} \right\}$.. , but first...

† How large are α, β, γ? <u>If</u> PT holds, then:

$$\left\{ \begin{aligned} &\alpha \sim 1/D^2 \sim \text{few} \cdot 10^{-2} \\ &\beta \sim 1/D^4 \sim \text{few} \cdot 10^{-4} \\ &\gamma \sim 1/D^6 \sim 10^{-5} \end{aligned} \right.$$

... keep these values in mind for the $\boxed{\text{ADD}}$ case below...

ADD Basics $\left\{ \begin{matrix} \text{Arkani-Hamed, Dimopoulos +} \\ \text{Dvali} \end{matrix} \right\}$ ('98)



3-brane

- Bulk gravity in $D = 4 + n$ dimensions
- n-extra dims usually compactified on a Torus, ie, "flat" (conformally

$$\Rightarrow \underbrace{\bar{M}_{Pl}^{\,2}}_{\sim G_{Newton}^{-1}} = \underbrace{V_n}_{\text{vol. of compact dims} = (2\pi R)^n} \; M_*^{\,n+2}$$

true fundamental scale $\sim \underline{\underline{\text{TeV}}}$

$$\left\{ \begin{array}{lll} n = 1 & R \sim 10^{13}\,\text{cm} & \text{(too big)} \\ n = 2 & R \sim 100\ \mu\text{m} & \text{(Table top)} \\ \ \ = 3 & \ \ \sim 10^{-9}\,\text{m} & \vdots \\ \ \ \vdots & \ \ \vdots & \vdots \end{array} \right.$$

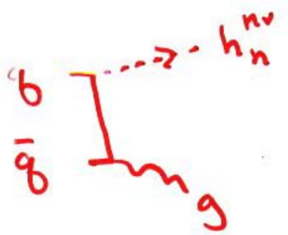
$$\boxed{m_{KK_n}^2 = \frac{\vec{n}^2}{R^2}}$$

→ Tiny masses
→ Tiny spacing

- $$\mathcal{L} = -\frac{1}{\bar{M}_{Pl}} \sum_n h_{\mu\nu}^{(n)} T^{\mu\nu}$$

stress tensor for SM matter

weak coupling!

- 

\- many states appears as $\not{E}_T$

monojet + $\not{E}_T$ at LHC

γ + 'nothing' at ILC

$\boxed{\text{emission signature}}$

The signal is the little guy on top...

Vacavant + Hinchliffe

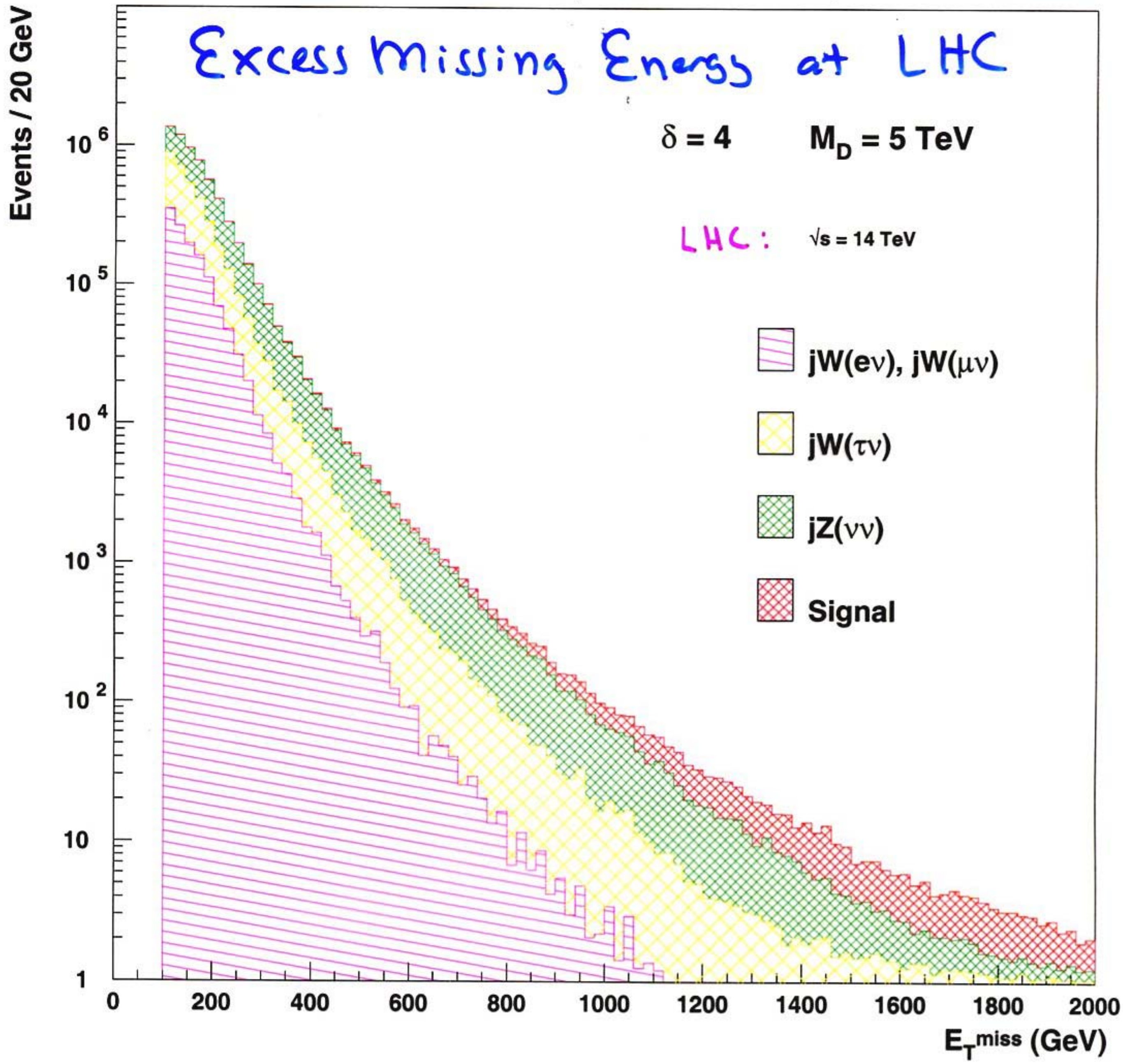
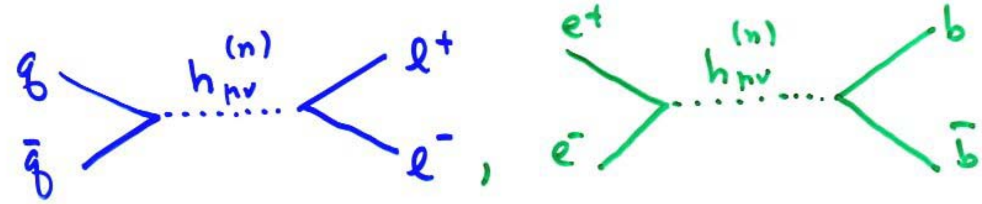


Figure 1: Missing energy spectrum at the LHC.

Understand Your Backgrounds !!

- exchange signature:



dim-8 operators

$$\mathcal{O} \equiv \frac{4\lambda}{M_H^4} T^{(1)}_{\mu\nu} T^{\mu\nu}_{(2)}$$

- These are not influenced by higher-curvature terms $\boxed{\text{EVEN}}$ if not compactified on a T^n torus... $\left[(R_c M_*)^2 \gg 1\right]$

- What's Left? Black Holes!! Why?

  - $\underline{\dfrac{R}{M_*^2}}$ is large near BH's ...

  - BH's in extra dims were studied long ago...

    e.g, Schwartzchild-like soln's...

    - Boulware + Deser '85
    - Wheeler '86
    - Whitt '88
    - Wiltshire '86 +...

- TeV-scale BH
  - Banks + Fischler '99
  - Dimopoulos + Landsbergs '01
  - Giddings + Thomas '01

Reviews:
- Kanti '04
- Hossenfelder: '04

BH at Accelerators: Basic Idea

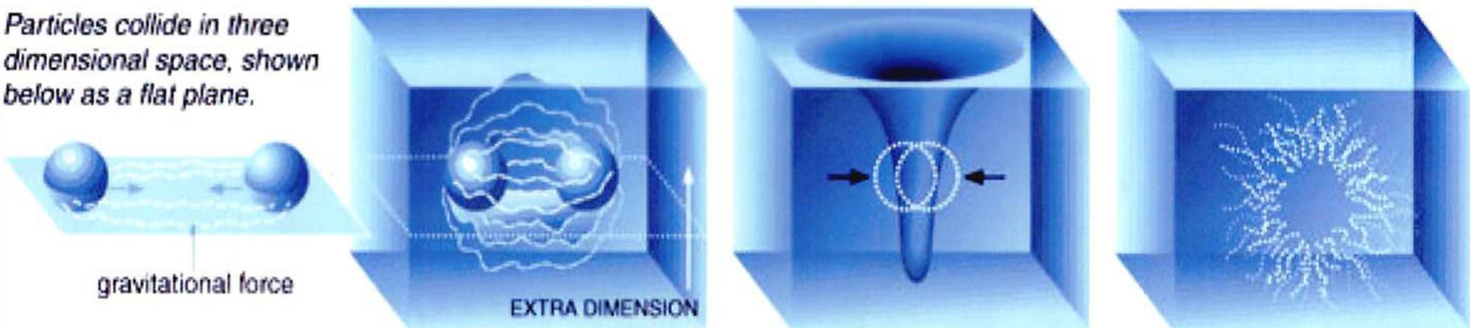
Black Holes on Demand

→ NYT, 9/11/01

The New York Times ON THE WEB

Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:

Particles collide in three dimensional space, shown below as a flat plane.



As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

Lore:

hep-ph/0412265

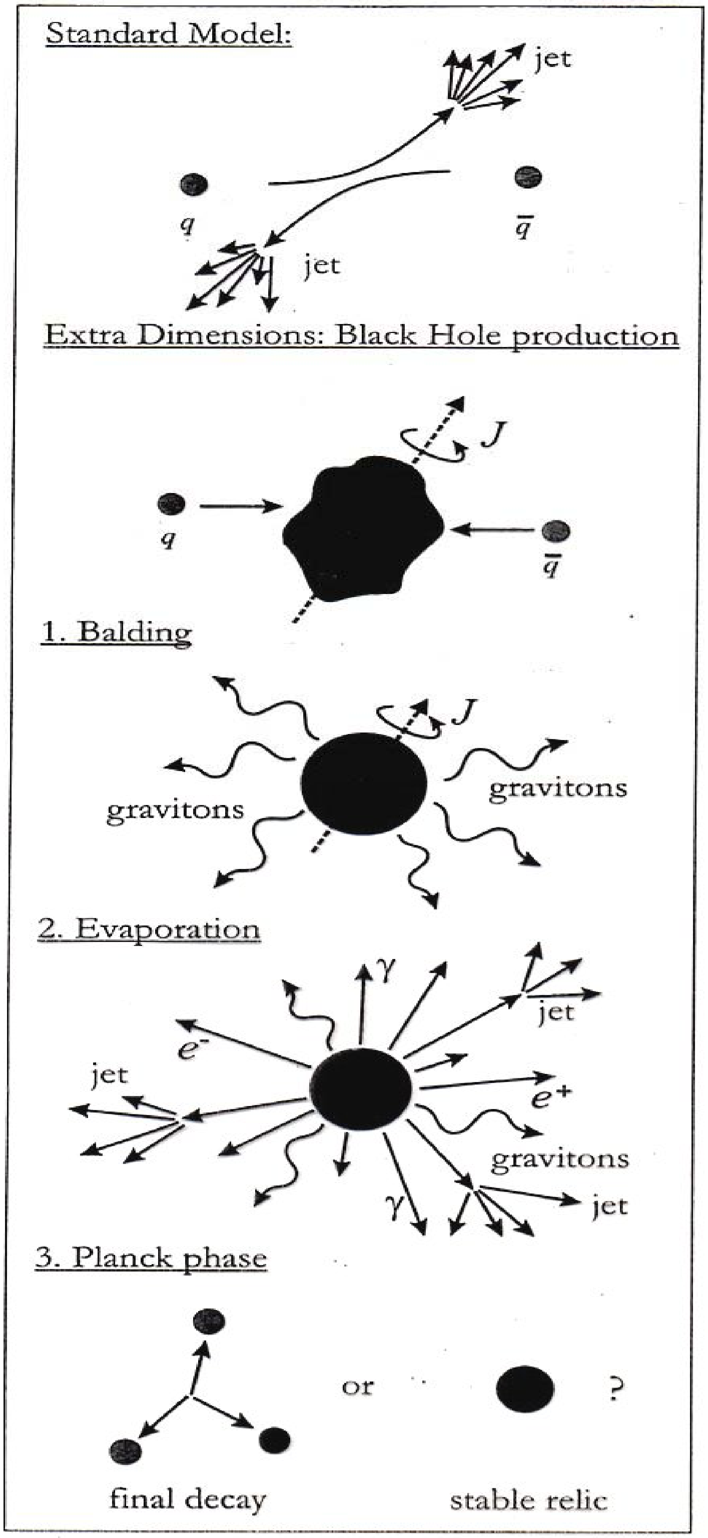


Figure 8: Phases of black hole evaporation.

Once produced, the black holes will undergo an evaporation process whose thermal properties carry information about the parameters M_f and d. An analysis of the evaporation will therefore offer the possibility to extract knowledge about the topology of our space time and the underlying theory.
The evaporation process can be categorized in three characteristic stages [36], see also the illustration in Figure 8:

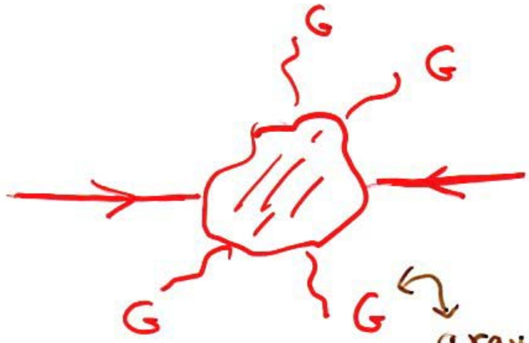
1. BALDING PHASE: In this phase the black hole radiates away the multipole moments it has inherited from the initial configuration, and settles down in a hairless state. During this stage, a certain fraction of the initial mass will be lost in gravitational radiation.

2. EVAPORATION PHASE: The evaporation phase starts with a spin down phase in which the Hawking radiation carries away the angular momentum, after which it proceeds with emission of thermally distributed quanta until the black hole reaches Planck mass. The radiation spectrum contains all Standard Model particles, which are emitted on our brane, as well as gravitons, which are also emitted into the extra dimensions. It is expected that most of the initial energy is emitted in during this phase in Standard Model particles. ✗

3. PLANCK PHASE: Once the black hole has reached a mass close to the Planck mass, it falls into the regime of quantum gravity and predictions become increasingly difficult. It is generally assumed that the black hole will either completely decay in some last few Standard Model particles or a stable remnant will be left, which carries away the remaining energy.

✗ $\tau_{BH} \lesssim 10^{-26}$ sec here

Black Hole Forms



gravitational radiation

$\underline{\sqrt{\hat{s}} > M_*}$

Collide Beams

Step-function Turn-on !!

Issues :

$$\hat{\sigma} = A_n \cdot \pi R_s^2 \sim \frac{1}{M_*^2}\left(\frac{M_{BH}}{M_*}\right)^{\frac{2}{n+1}}$$

Schwartzchild radius

This is huge if $M_* \sim 1\,\text{TeV}$ or so

- What is A_n ? (suppression ?)
- What is $M_{BH}/\sqrt{\hat{s}}$? ("efficiency" ?)

- Yoshino + Rychov (hep-th/0503171) :

  $\Rightarrow$ A_n is 1.5 (D=5), 3.2 (D=11) from detailed sim.

  $\Rightarrow$ $M_{BH}/\sqrt{\hat{s}} \simeq 0.60 - 0.75$

- Cardoso, Berti + Cavaglia (hep-ph/0505125) :

  - multiple techniques to obtain $M_{BH}/\sqrt{\hat{s}}$ ... $\boxed{\text{for } D=5-10}$

    I) 0.40 - 0.65 II) 0.98 - 1.0

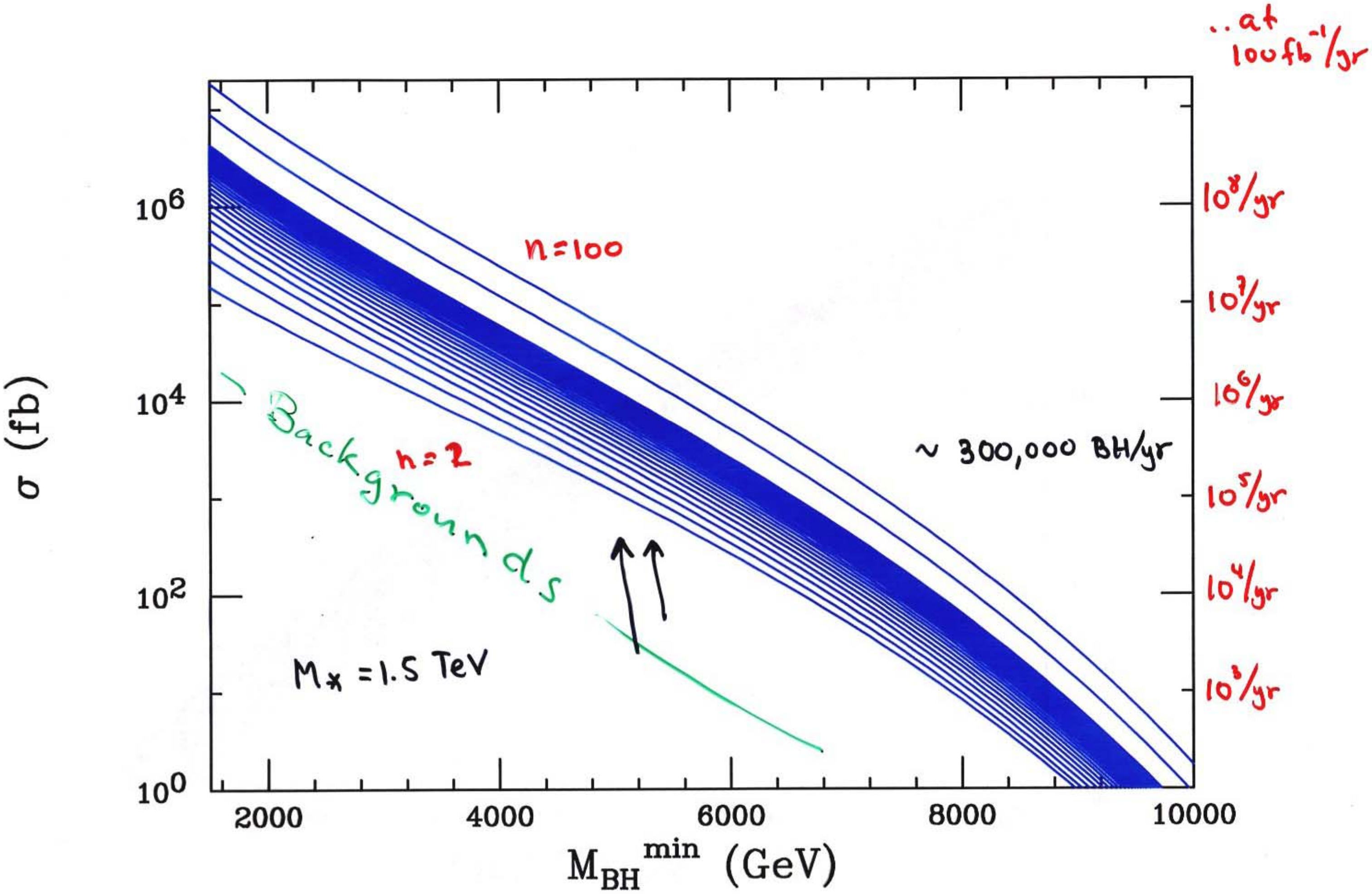
    III 0.90 - 0.92

    hmm...

- Controversy remains + lots of work needs doing..

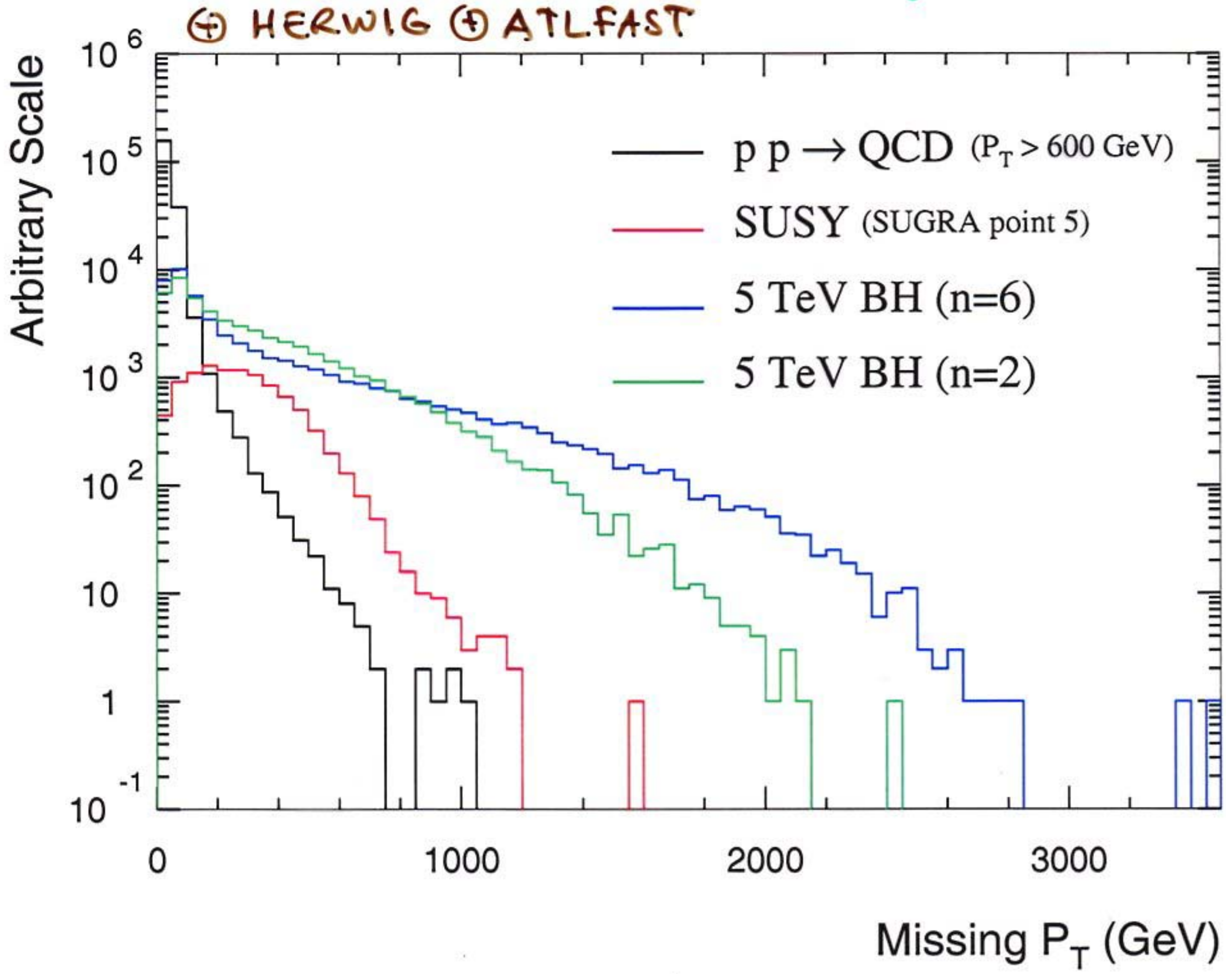
$\Rightarrow$ Here I assume $A_n = 1$, $M_{BH}/\sqrt{\hat{s}} = 1$ as is usually done in collider analyses...

BH's at LHC - big cross section



The unusual nature of BH events should make them relatively easy to spot at the LHC:

CHARYBDIS (Cambridge group)
⊕ HERWIG ⊕ ATLFAST



hep-ph/0411022

It is relatively easy to extract BH properties from kinematic distributions:

LHC { $M_{BH} = 8\,\text{TeV}$, $100\ fb^{-1}$

$\boxed{\text{CHARYBDIS}}$

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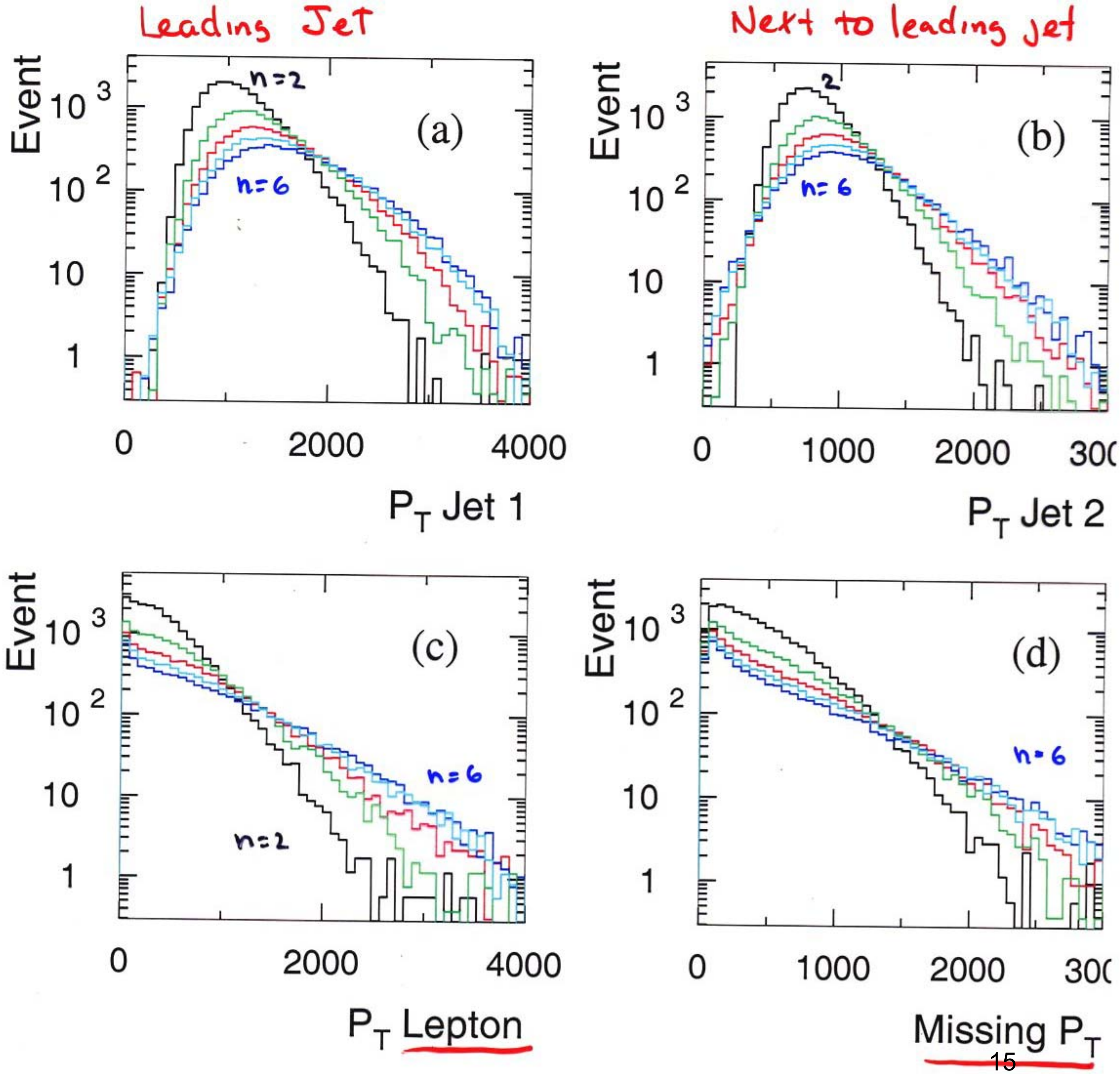
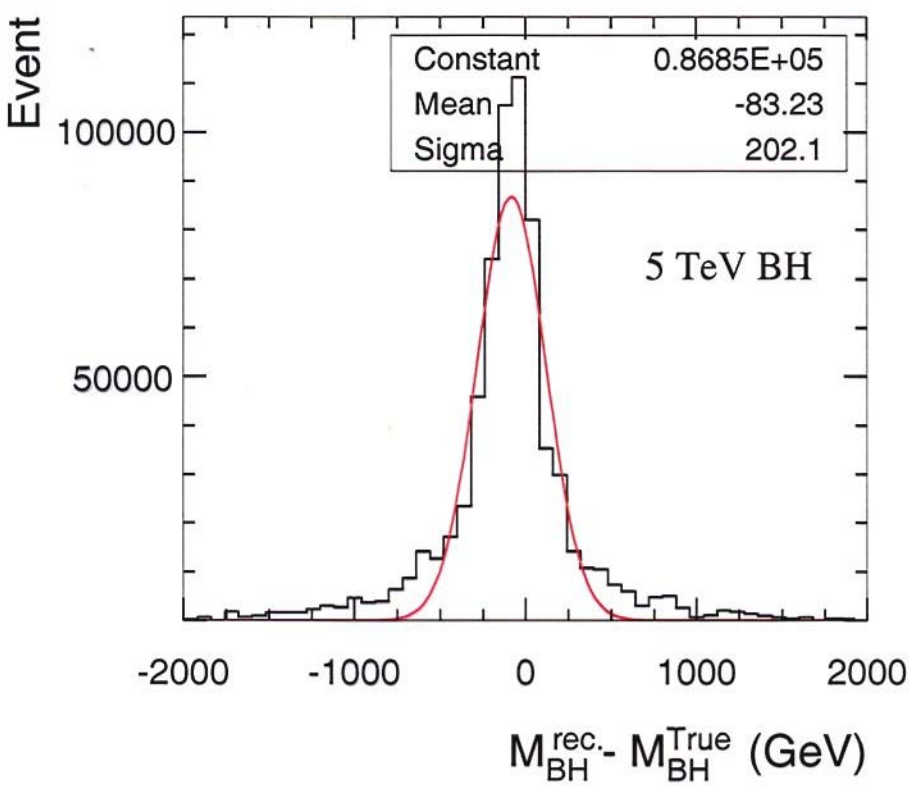


BH mass reconstruction at LHC from visible decay products... quite reasonable...



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Issues II : Do BH decay more to brane or bulk modes (in ADD) ??

Stefan-Bolzmann law

$$\begin{cases} \dfrac{dM}{dt} = N_3 \, R_s^2 \, T^4 \cdot n_{Brane} \\[2ex] \dfrac{dM}{dt} = N_{3+n} \, R_s^{2+n} \, T^{4+n} \cdot n_{Bulk} \end{cases}$$

number of brane (~60) and bulk (1) modes

$$\Rightarrow \frac{\text{Brane}}{\text{Bulk}} \simeq 250 - 720 \; !$$

SM modes dominate ! ✓

<u>now</u>

$$R_s = R_s(\alpha, \beta, \gamma) \; , \quad T_{BH} = T_{BH}(\alpha, \beta, \gamma) \quad \text{etc}$$

$\Rightarrow$ Quantitetive + <u>Qualitetive</u> Changes

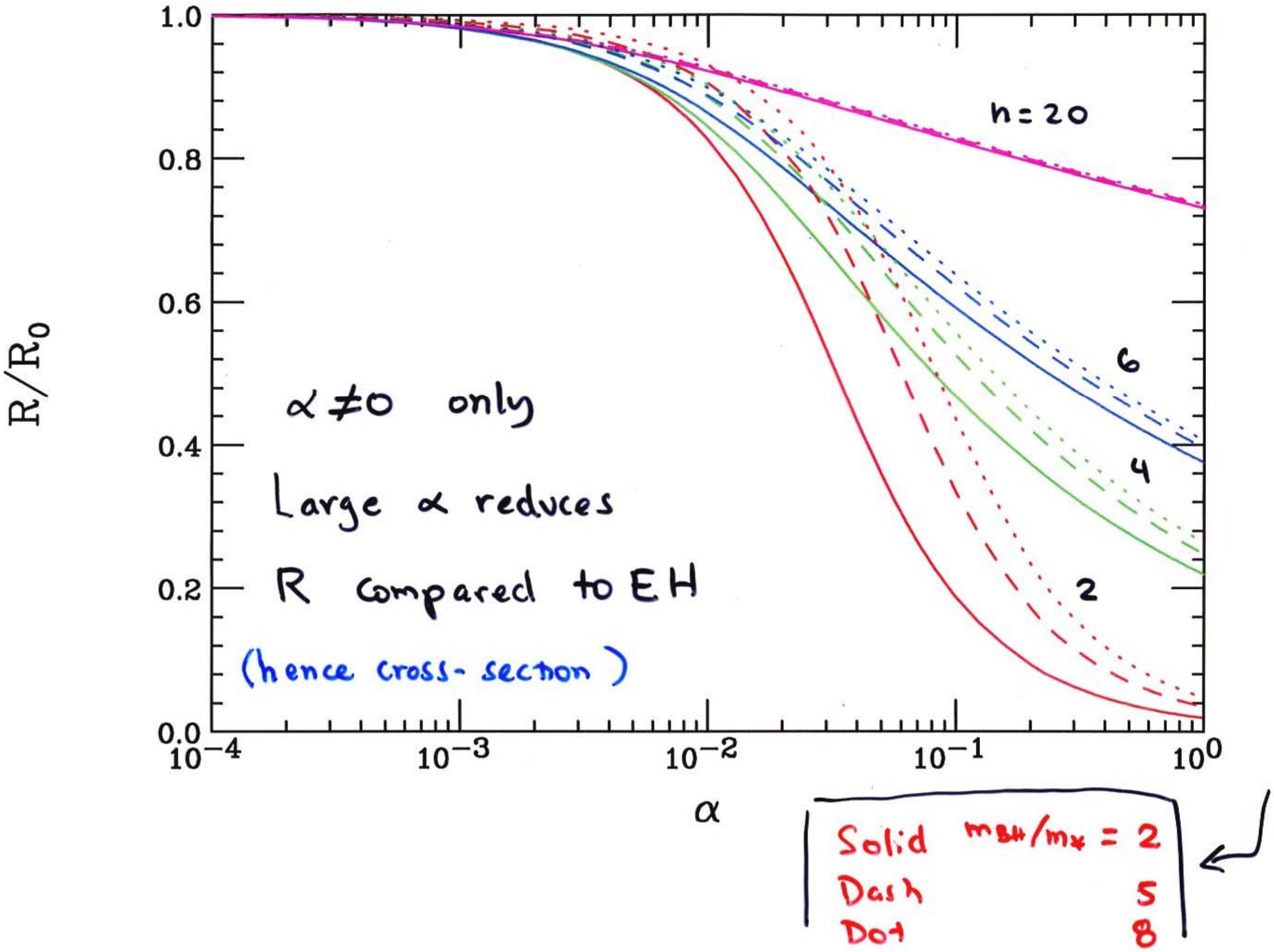
e.g.,

- for $\left.\begin{aligned} n &= 3, \; \beta \neq 0 \\ &= 5, \; \gamma \neq 0 \end{aligned}\right\}$ No BH can form below a critical minimum mass

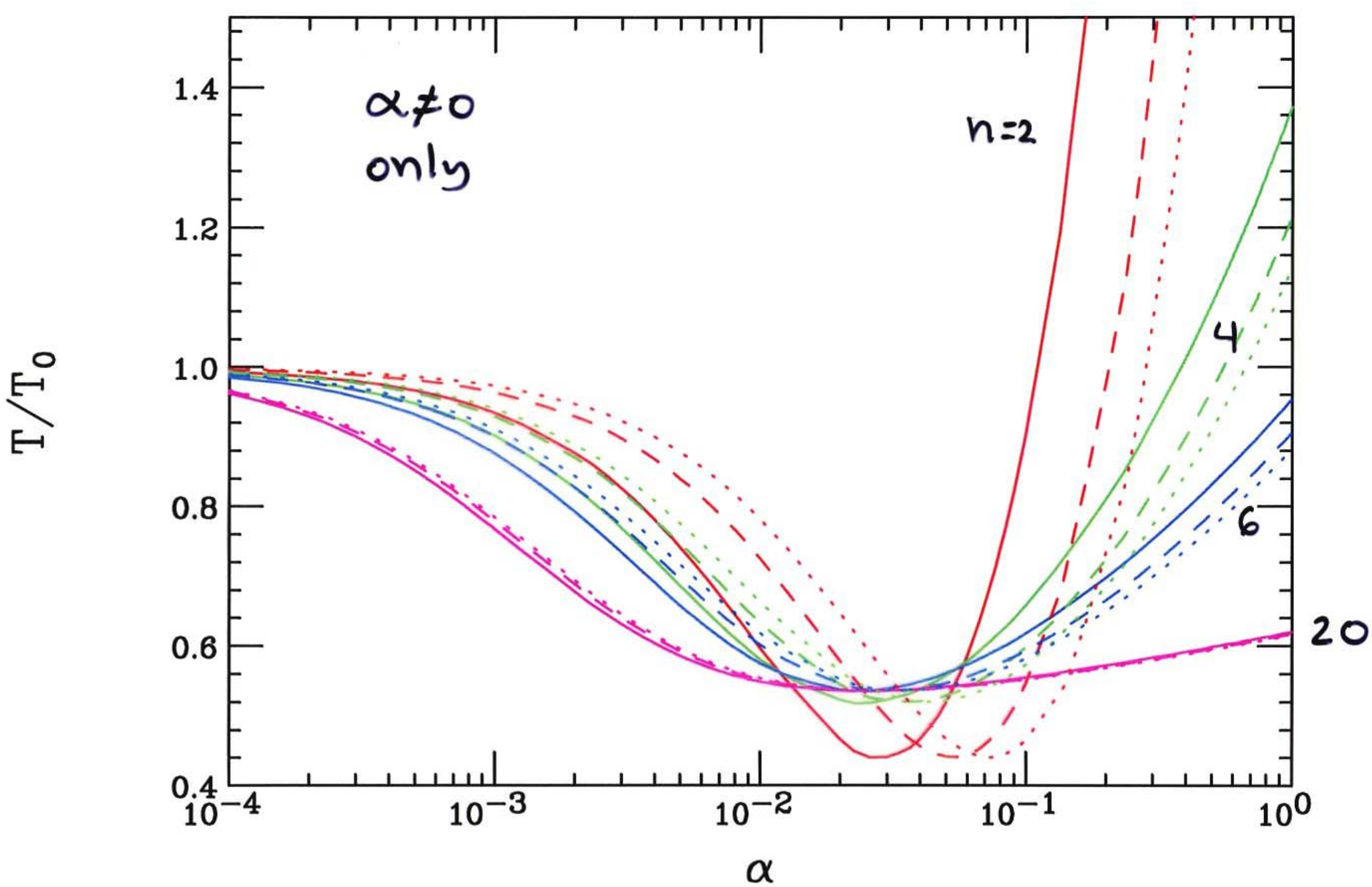
$\rightarrow$ removes <u>unphysical</u> step-function turn-on ...

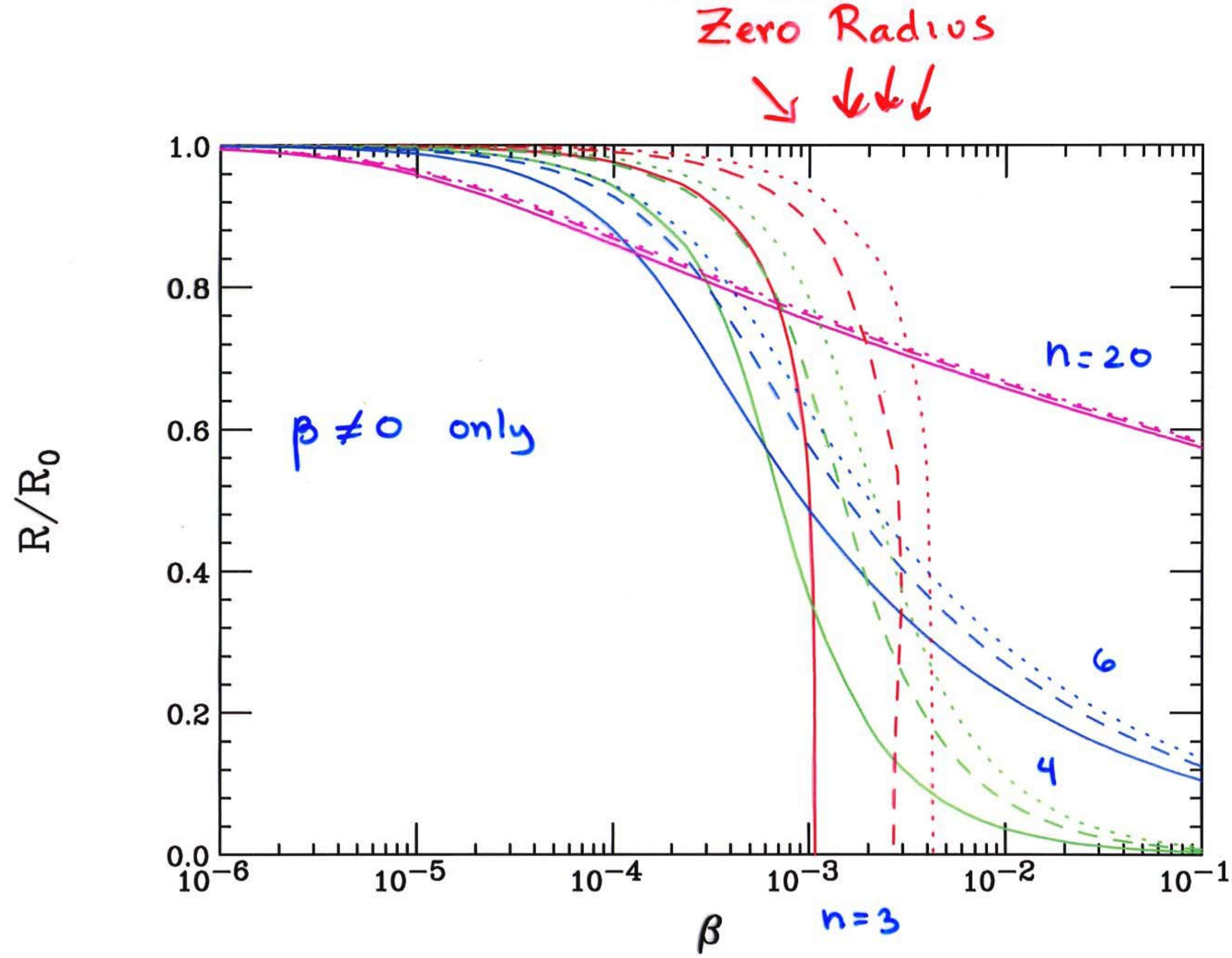
<u>Furthermore</u> for $M_{BH} \simeq M_{crit}$, BH are <u>STABLE</u> in these cases $\Rightarrow$ "Planck phase" info ?

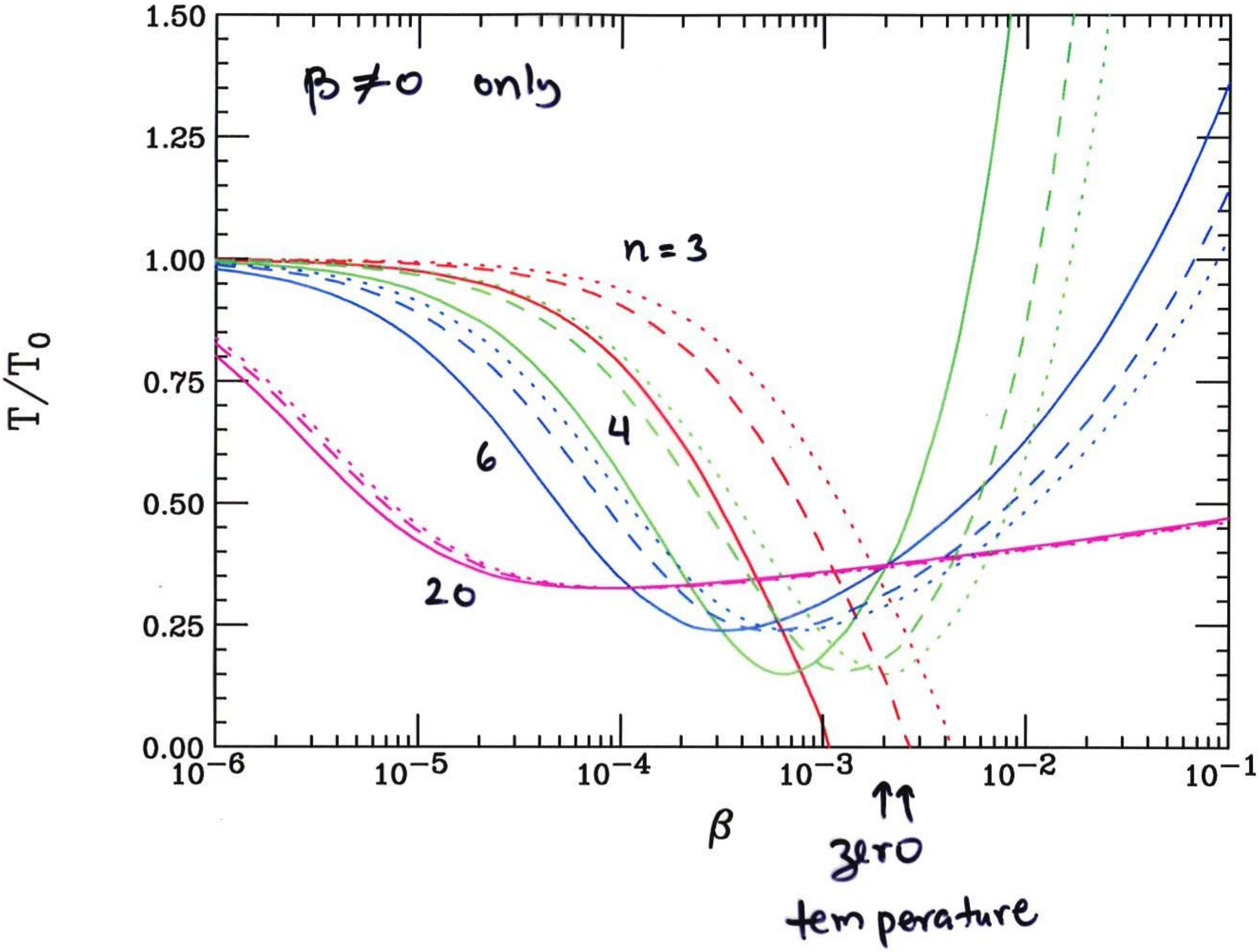
Shift in Schwarzschild radius



O(1) Temperature changes




Zero Radius
1.0
0.8
0.6
0.4
0.2
0.0
R/R$_0$
$\beta \neq 0$ only
n=20
6
4
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
β
n=3


β ≠ 0 only
n = 3
4
6
20
T/T0
β
1.50
1.25
1.00
0.75
0.50
0.25
0.00
10−6
10−5
10−4
10−3
10−2
10−1
zero
temperature

'Simple' Example : $\beta \neq 0$, $\alpha = 0$ w/ $\underline{n=3}$ Then :

$$R_s M_* = \left\{ \frac{M_{BH}/M_*}{5\pi^3/2} - 24\beta \right\}^{1/4} \Longrightarrow$$

Unless $M_{BH} > M_{crit} = \underbrace{60\pi^3 \beta}_{O(1)} M_*$, __no__ BH will form !

$\Longrightarrow$ __Threshold__ !

__Lifetime__ : $\frac{dM}{dt} \sim (\text{Area})(\text{Temp})^4$

$$\sim \frac{(M_{BH} - M_{crit})^{7/2}}{(M_{BH} + 2M_{crit})^4} \Longrightarrow$$

- For any $M_{BH} > M_{crit}$, This is ∞ ! Why ?
- Lovelock BH can __cool__ as they lose mass unlike EH BH..
- Other scenarios That try to capture some 'quantum' BH aspects also lead to __thresholds__ + __long-lived BH__...

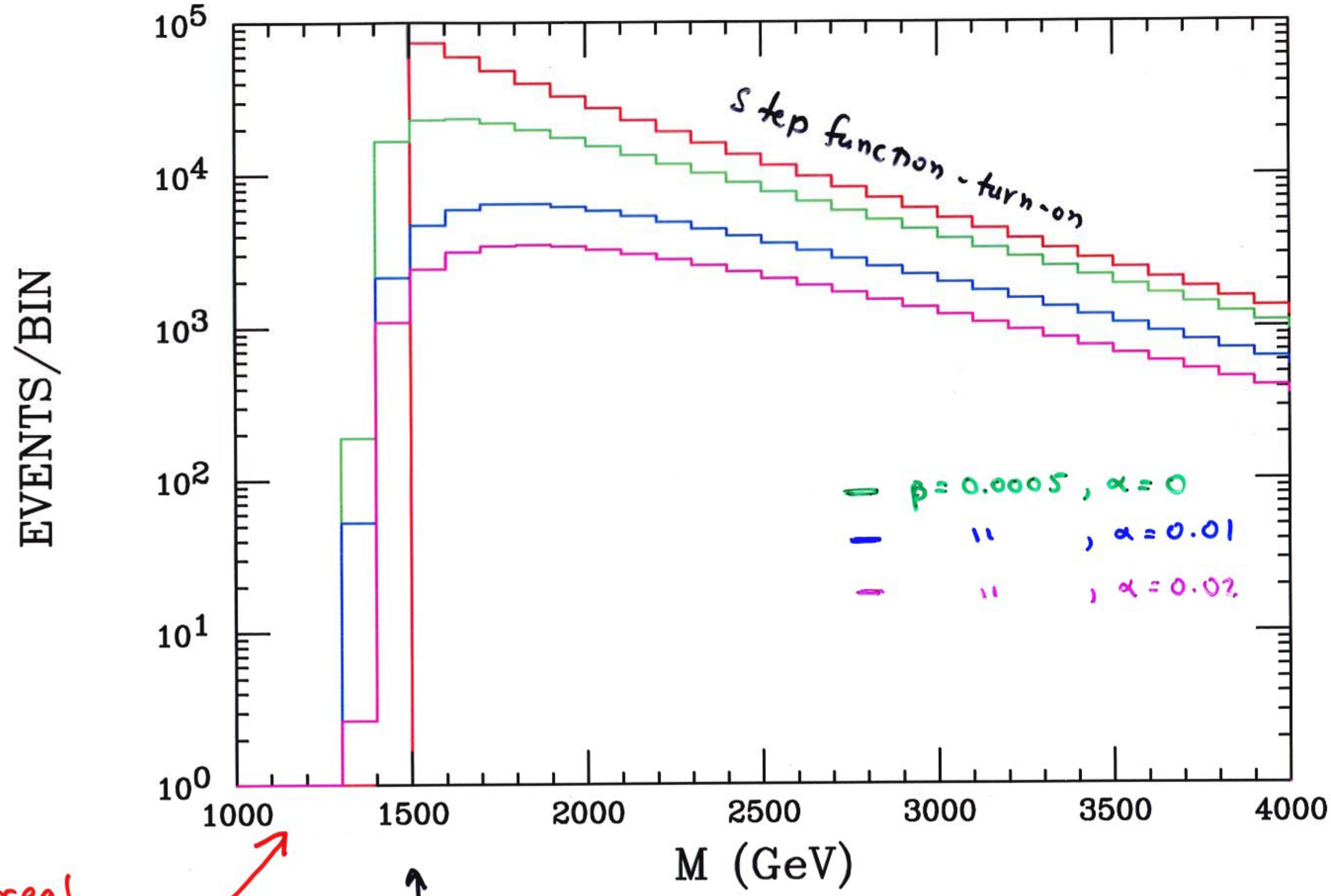
i) running G_N : Bonanno + Reuter, hep-th/0002196

ii) loop QG : Bojowald, Goswami, Maartens + Singh gr-qc/0503041

(iii) finite length models : Cavaglia, Das + Maartens : hep-ph/0305223

Hossenfelder : hep-th/0404232

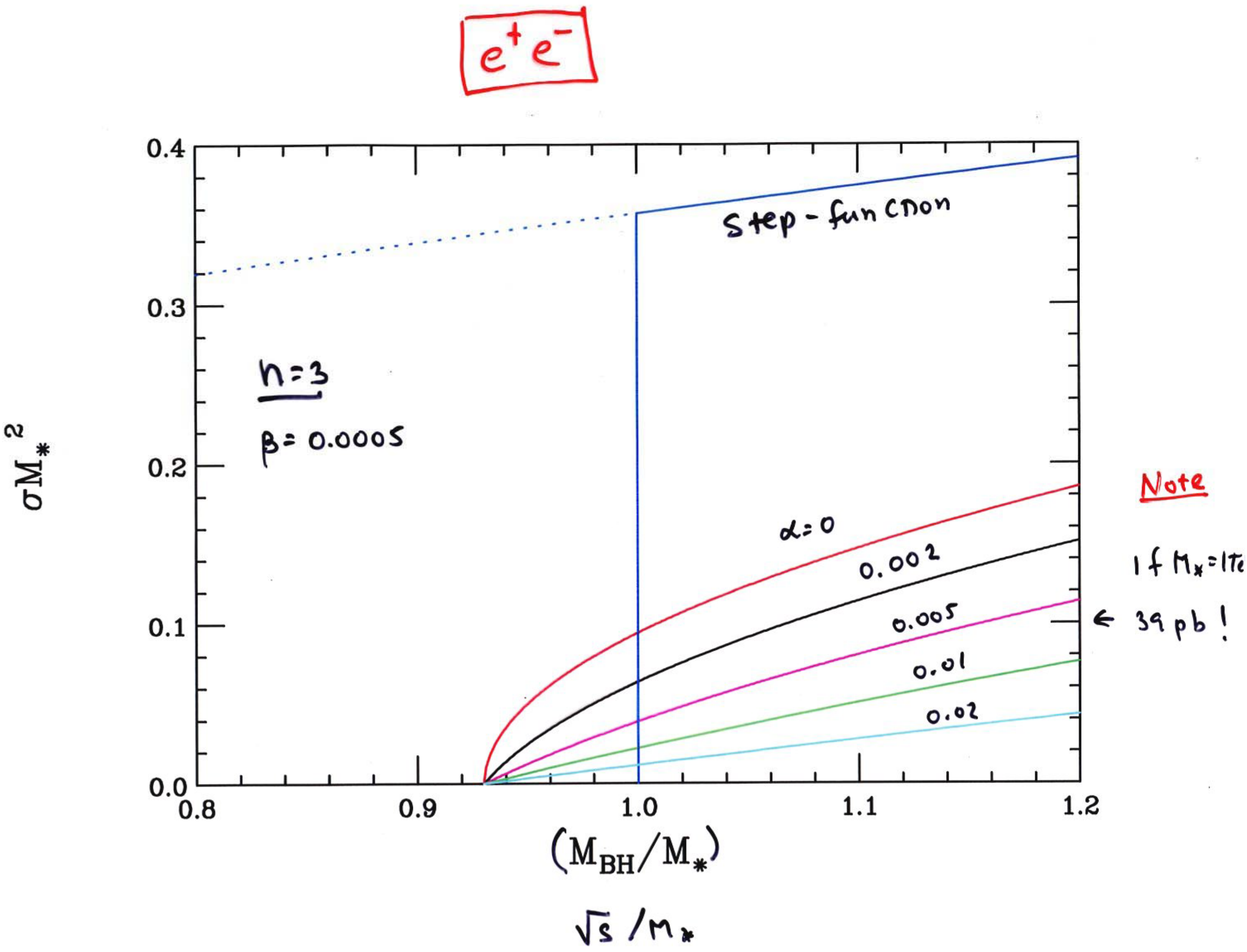
BH at LHC 100 fb^{-1}



a real threshold

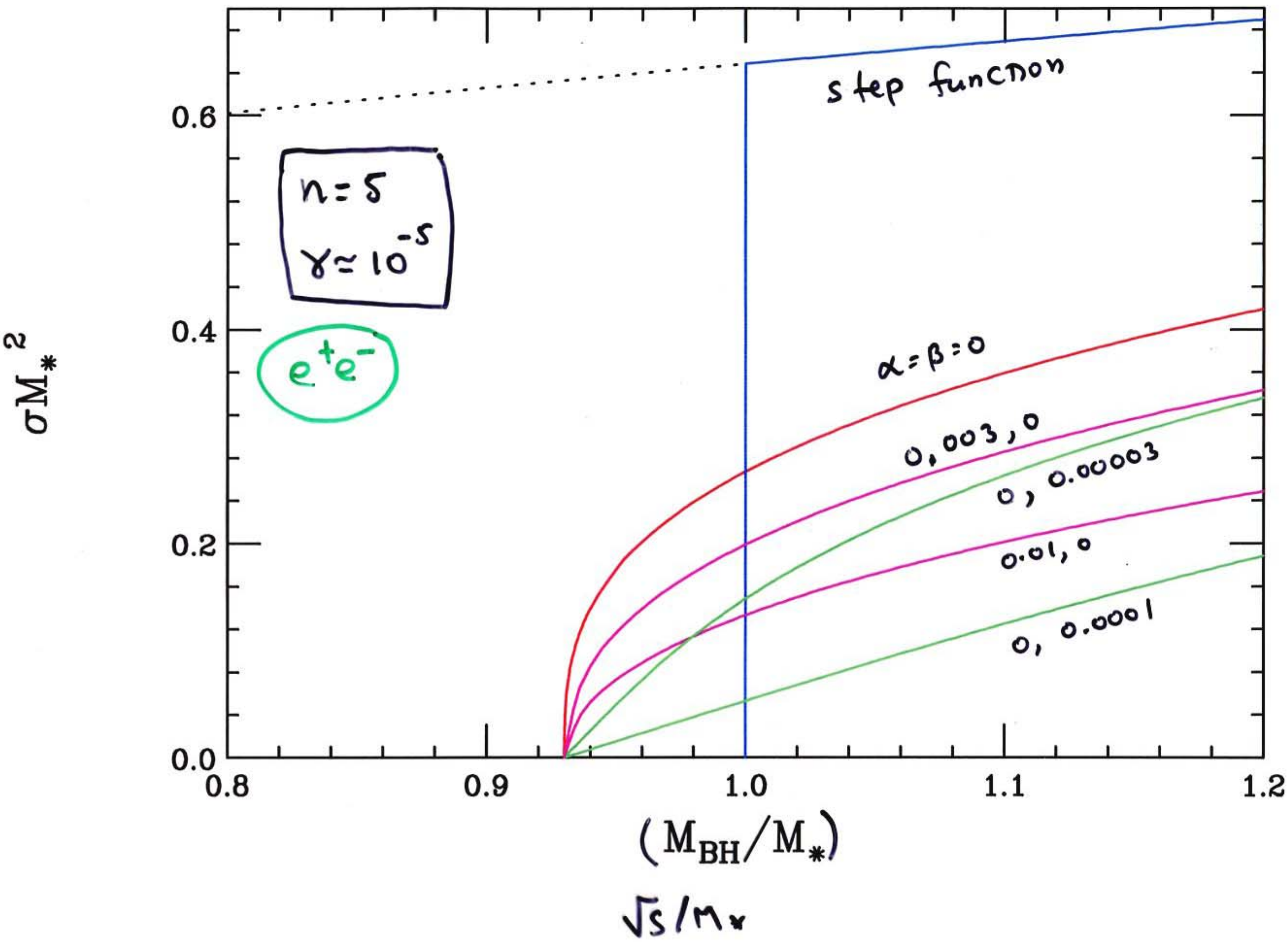
M_* = 1.5 TeV

... need precision to probe parameters

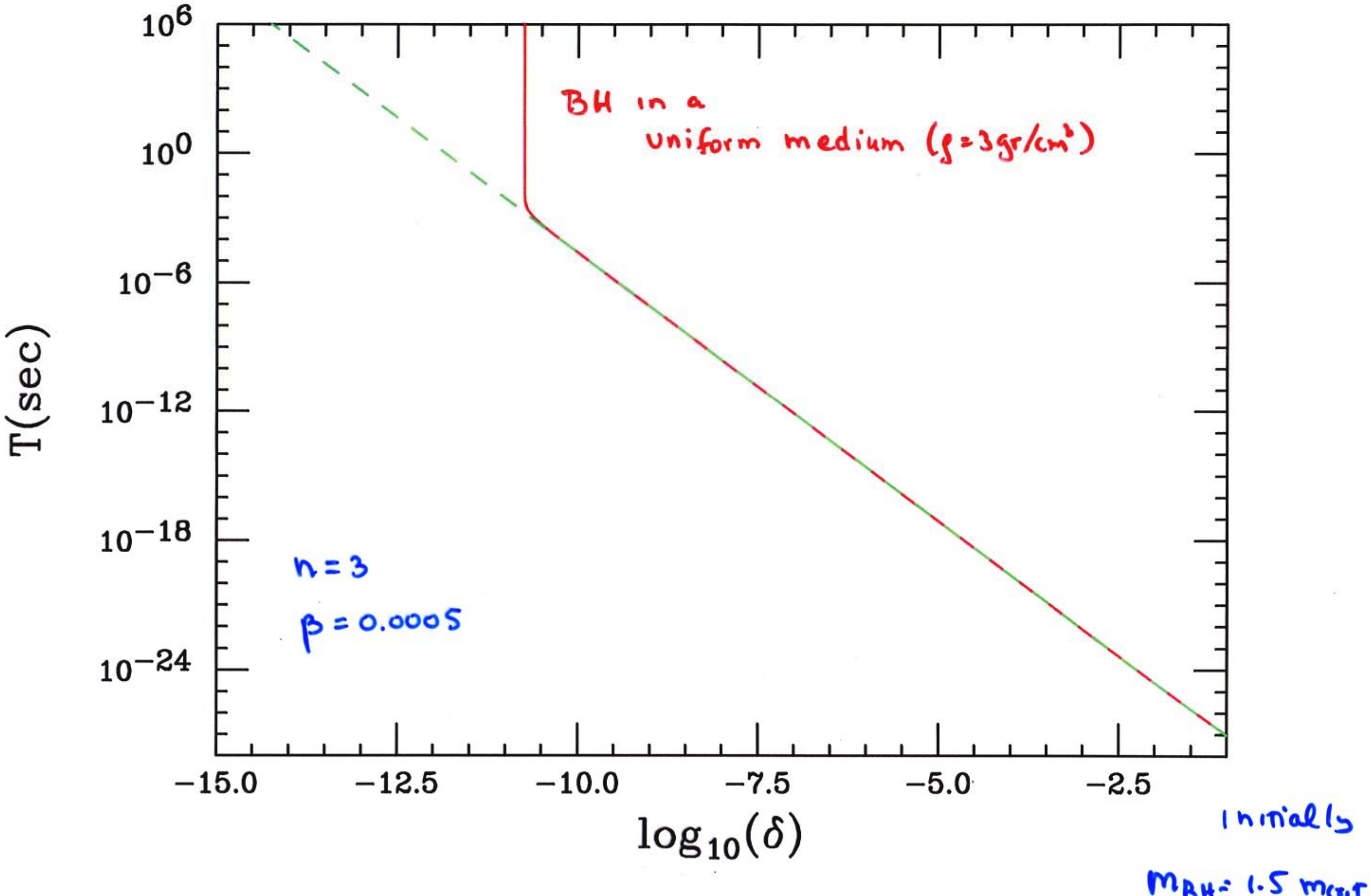


e+e-
0.4
0.3
0.2
0.1
0.0
0.8
0.9
1.0
1.1
1.2
Step - function
n=3
β= 0.0005
σM*²
α=0
0.002
0.005
0.01
0.02
Note
If M*=1Te
← 39 pb !
(M_BH/M*)
√s /M*

Threshold shapes will tell us $(\alpha, \beta\gamma)$ ...

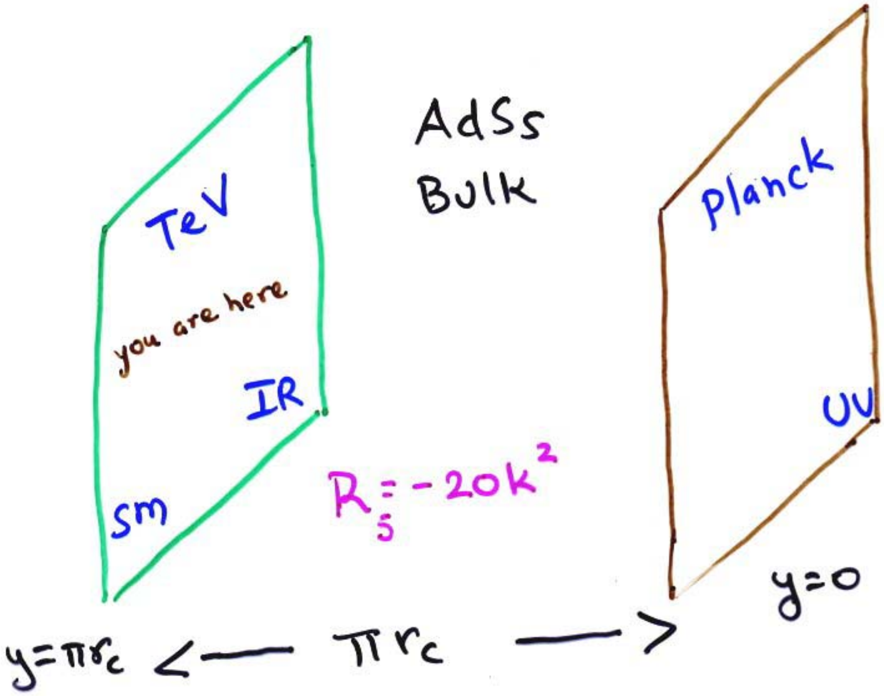


Crude Estimate of BH lifetime ...



$M_{BH} = m_{crit} + \delta$

Randall-Sundrum Basics: 1 extra dim.



- Two 3-branes
- we live on SM brane
- gravity lives everywhere
- compactified on S^1/Z_2

- $ds^2 = \underbrace{e^{-2ky}}_{\text{warp factor}} \eta_{\mu\nu}\, dx^\mu dx^\nu - dy^2$; $\frac{k}{\overline{M}_{Pl}} \simeq 0.01 - 0.1$ $(k \lesssim M_*)$

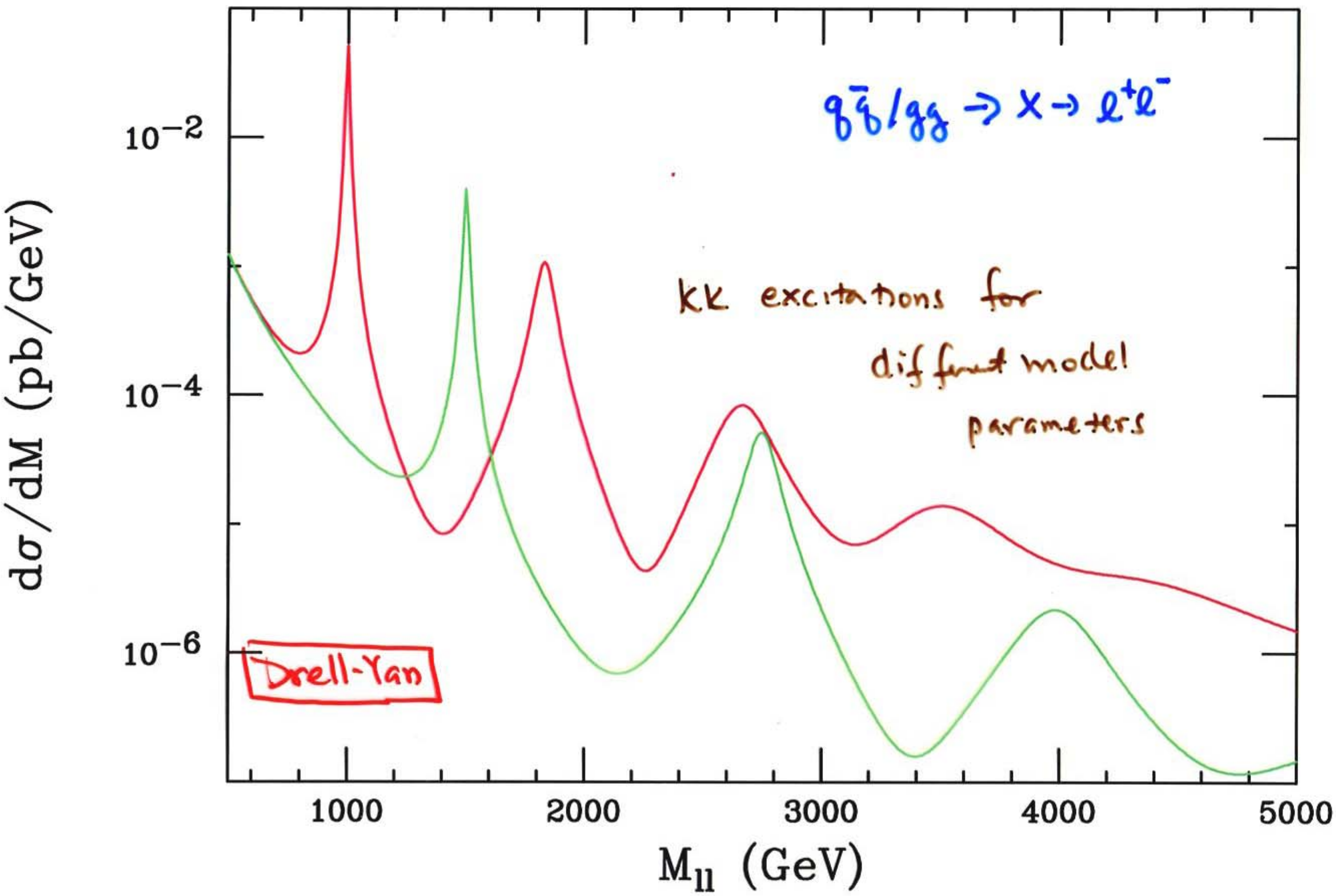
$m_{KK_n} = x_n k\, e^{-k\pi r_c}$; $J_1(x_n) = 0$ ~ few hundred GeV

$\mathcal{L}_{KK} = -\frac{1}{\Lambda_\pi} \sum_n G^{(n)}_{\mu\nu} T^{\mu\nu}_{sm}$, $\Lambda_\pi = \overline{M}_{Pl}\, e^{-kr_c\pi}$

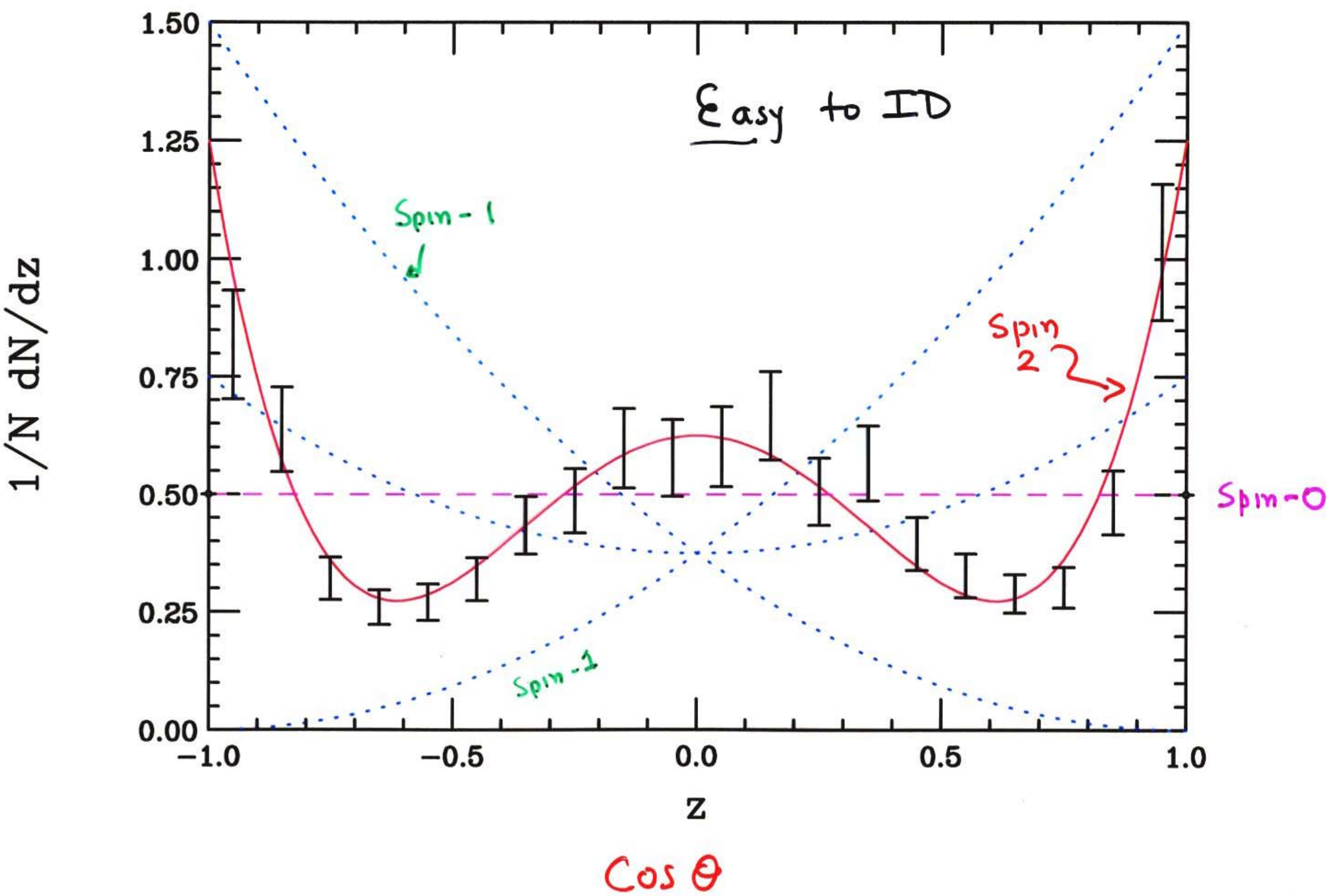
∴ Spin-2 resonances w/ TeV-scale couplings

- couplings identical for all KK levels

- AdS5 bulk → strong curvature ∴ potentially significant higher curvature corrections !! , ie, graviton resonance production at LHC



$f\bar{f} \to \bar{f}'f'$ on a graviton resonance



So in RS , $\langle R \rangle = -20k^2$ thus

$$\frac{\langle R \rangle}{M_*^2} = -20 \frac{k^2}{M_*^2} \qquad \text{w/} \quad k^2 \lesssim M_*^2$$

$\therefore$ potentially large corrections from $\mathcal{L}_2$* ...

$\sim \alpha\, k^2/M_*^2$ [Kim, Kyae & Lee '00]

* recall, in $D=5$ only $\mathcal{L}_2$ is non-zero!

Some differences ... similar to graviton brane kinetic terms

$$\bar{M}_{Pl}^2 = \frac{M_*^3}{k}\left(1 + 4\alpha \frac{k^2}{M_*^2}\right)$$

$$\zeta_1(x_n) + \underbrace{\frac{4\alpha k^2/M_*^2}{1 - 4\alpha k^2/M_*^2}}_{\Omega'''} \zeta_2(x_n) = 0$$

$\boxed{\text{Root Equation}}$ $\downarrow$ KK mass shifts

$J_1 + \lambda Y_1$
Bessel functions

$$\mathcal{L} = -\frac{1}{\Lambda_\pi} \sum \left[\frac{1+2\Omega}{1+2\Omega+\Omega^2 x_n^2}\right]^{1/2} h_{\mu\nu}^{(n)} T^{\mu\nu}$$

$\boxed{\text{Coupling Equation}}$

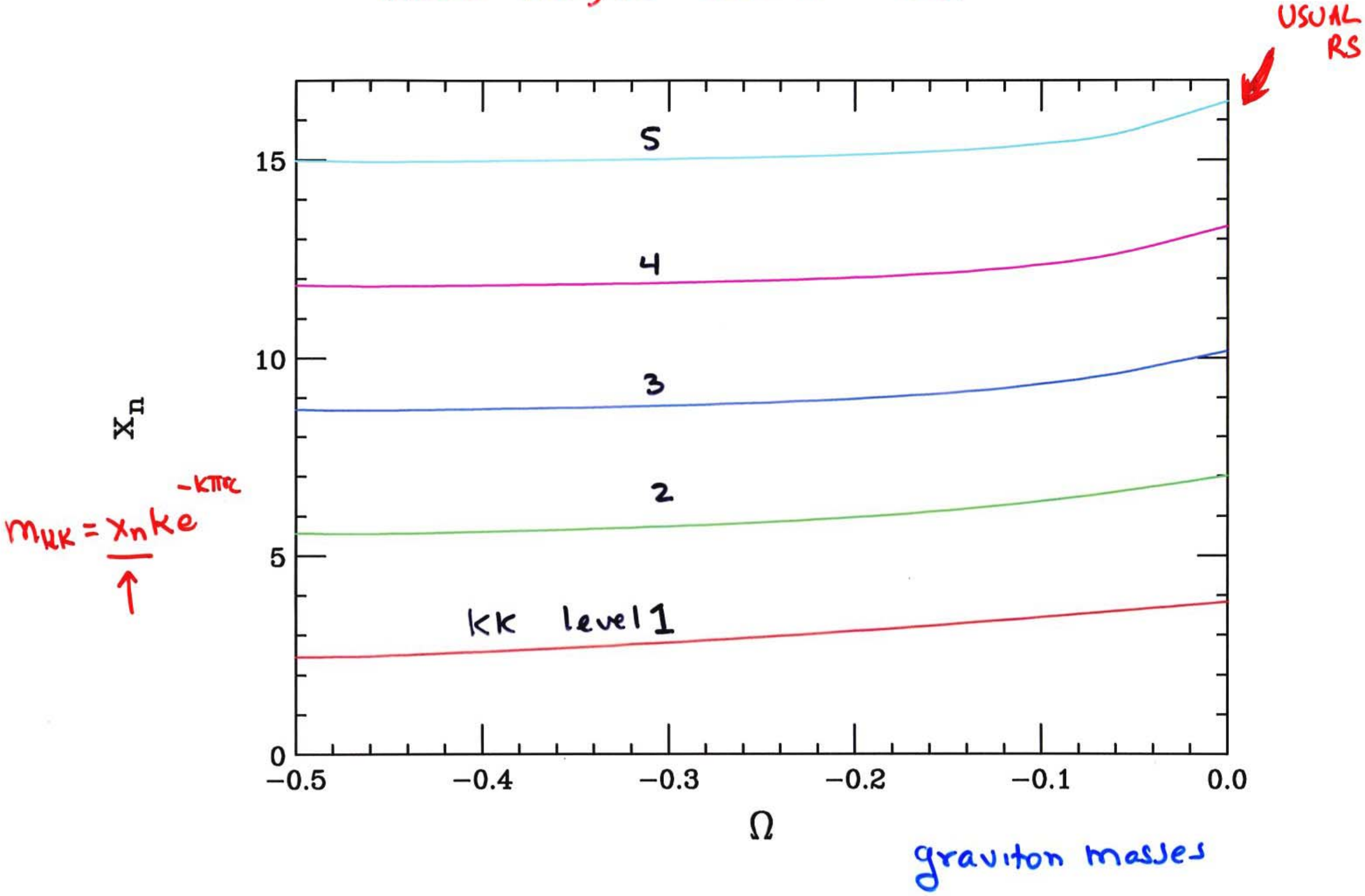
- KK coupling shifts

- $\alpha < 0$ [no tachyons]   { Charmousis + Dufaux '04; Brax, Chatillon + Steer '04 }
- $-\frac{1}{2} \le \Omega \le 0$, $\Omega = 0$ = USUAL RS model!
- couplings are KK level dependent!

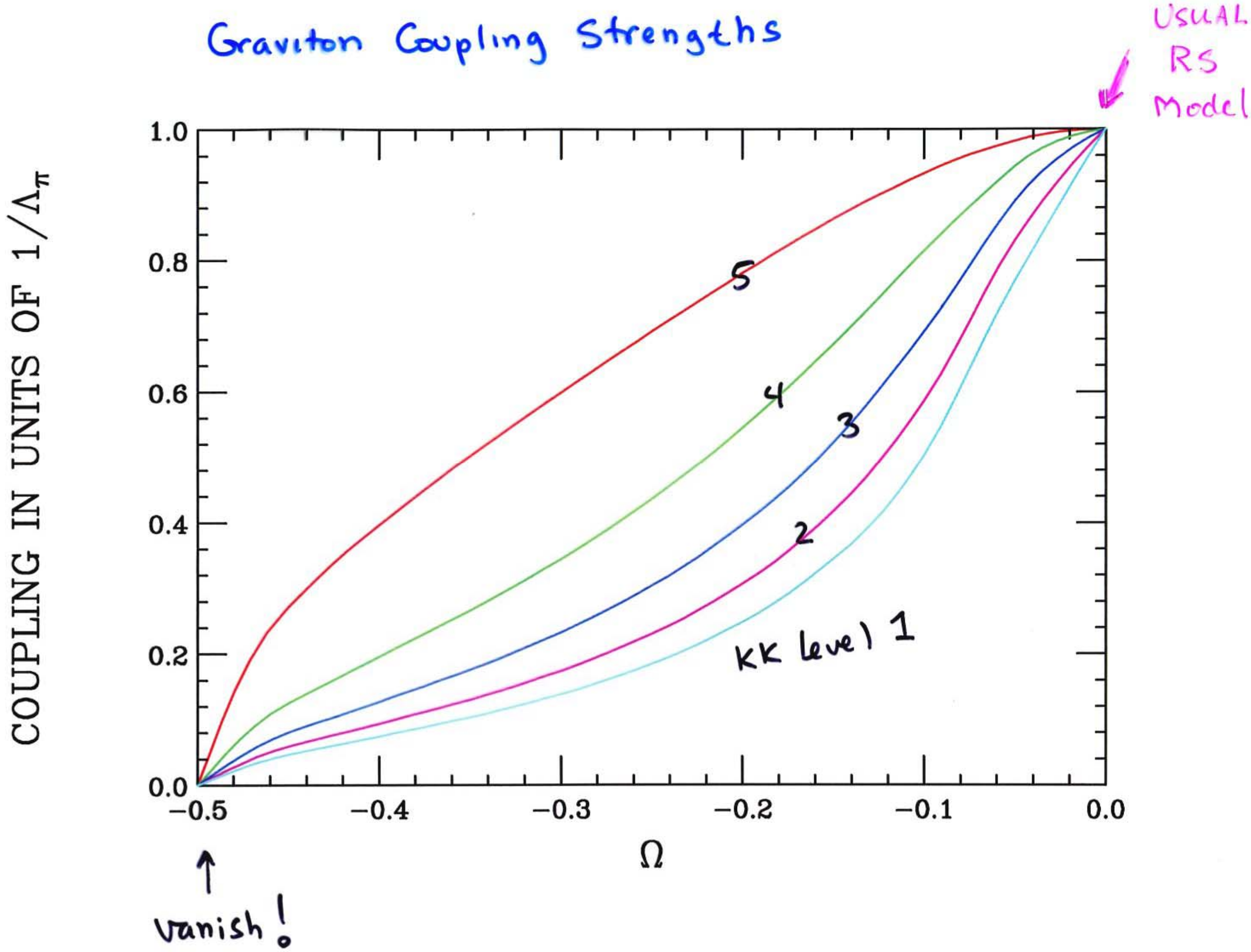
  and vanishing for $\Omega = -\frac{1}{2}$!
- level shifts (weak)
- Can we measure / constrain Ω??

Use m_2/m_1 + Γ_2/Γ_1 ratios : Ω to ± 0.01?

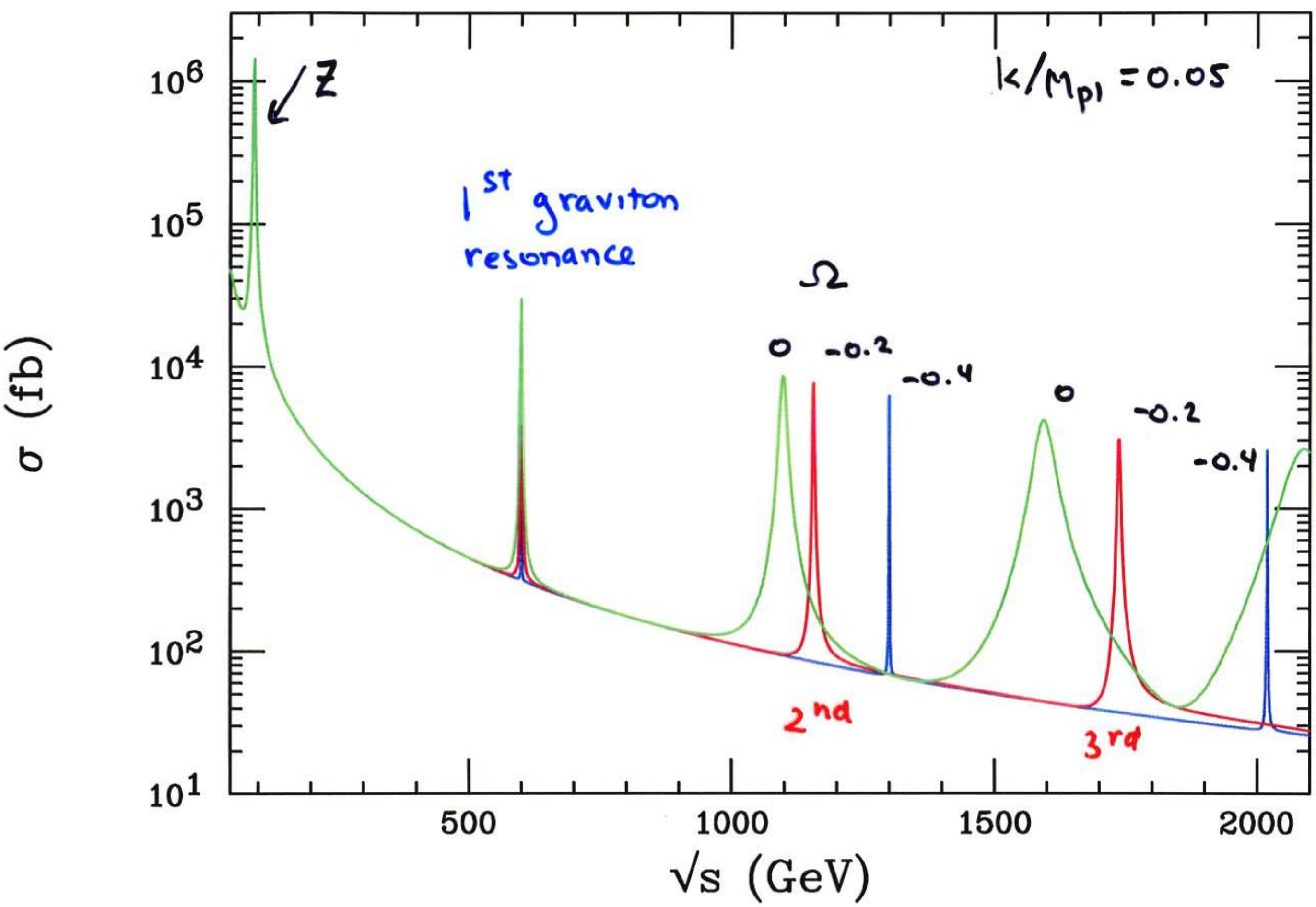
Root shifts due to $\mathcal{L}_2$ in RS



Graviton Coupling Strengths

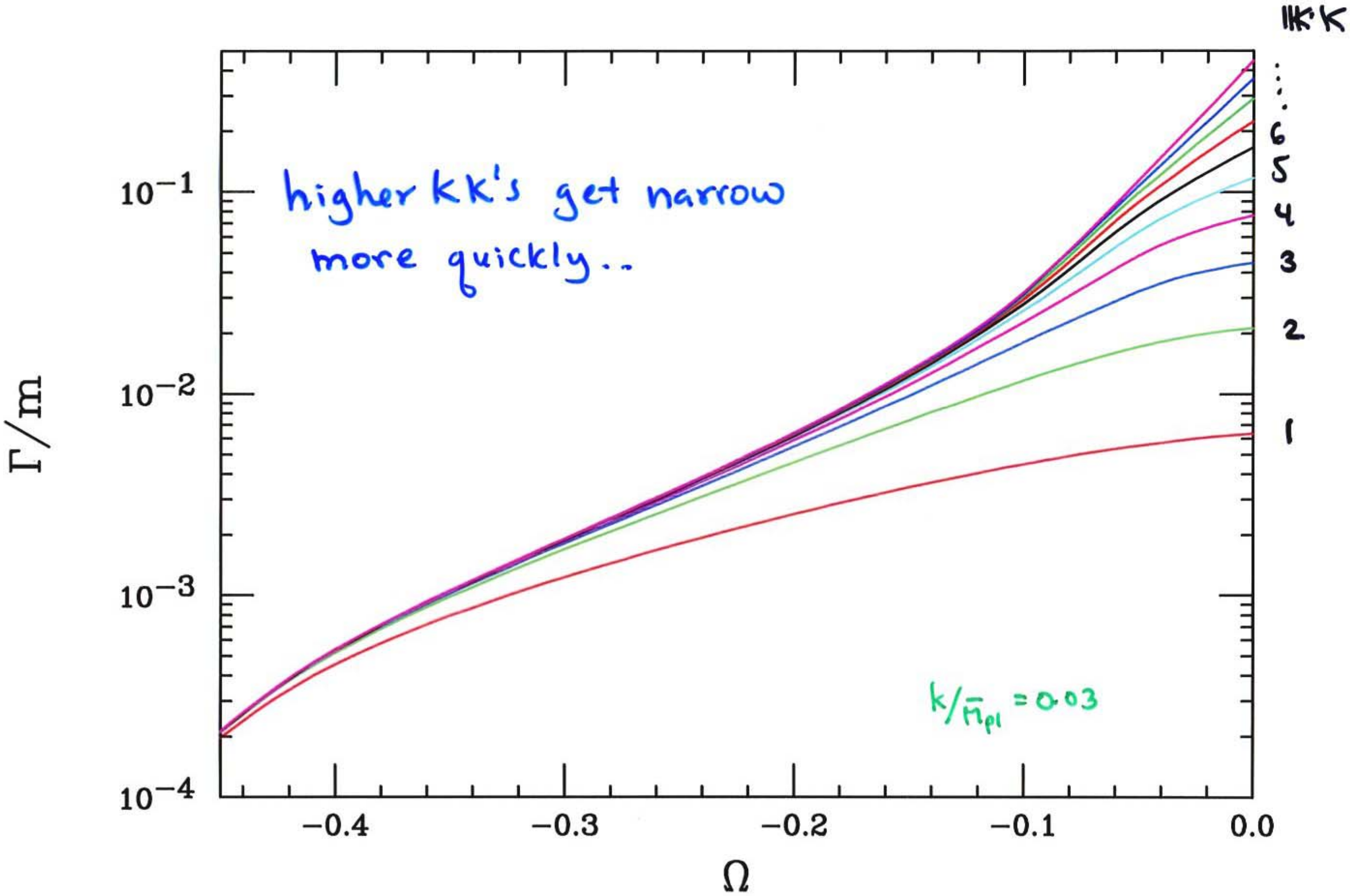


$e^+e^- \rightarrow \mu^+\mu^-$

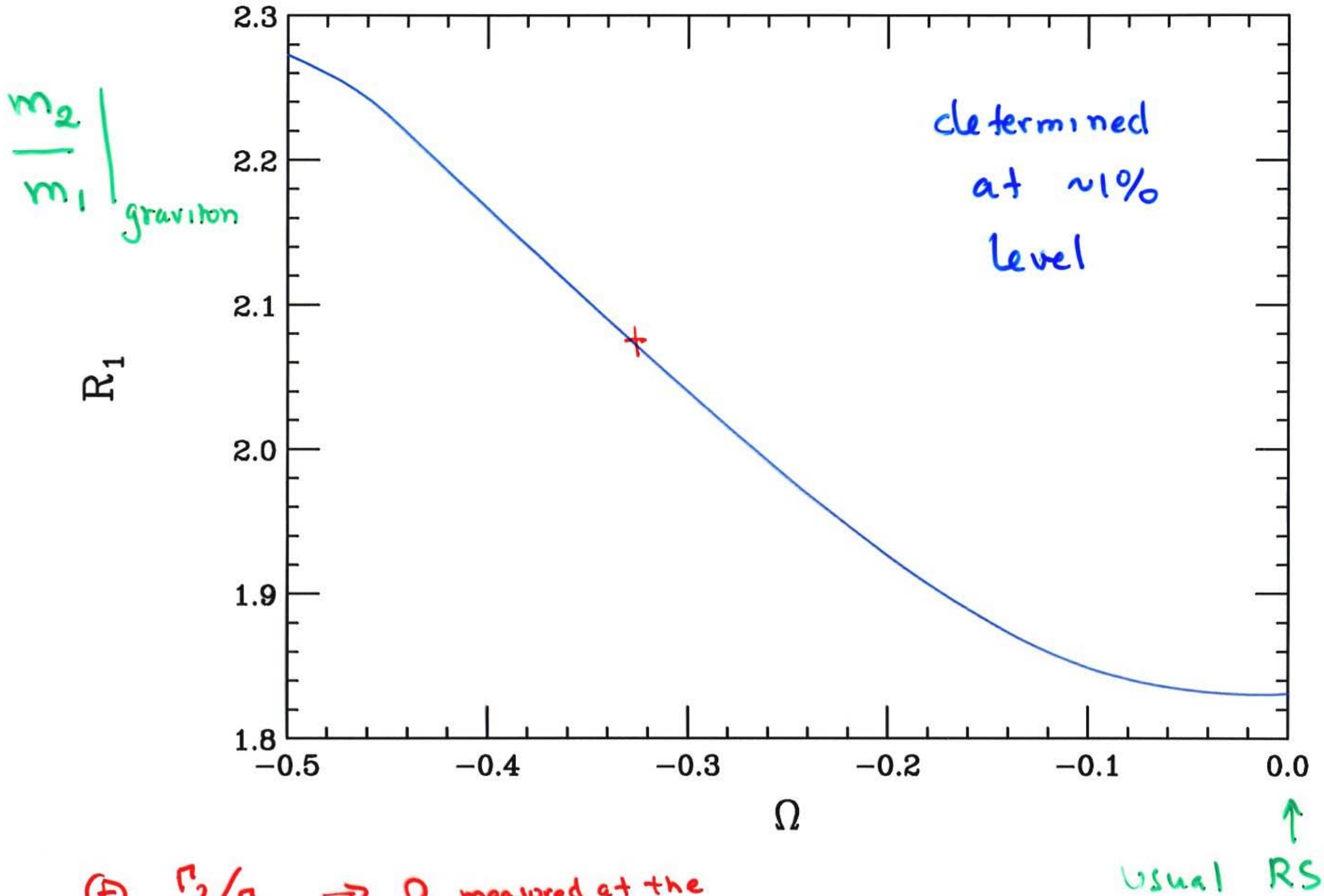


KK spectrum shifted + resonances narrowed

KK's are getting narrow quite quickly



KK mass rations



⊕ $\Gamma_2/\Gamma_1 \Rightarrow \Omega$ measured at the level 0.01 or better!

Summary

- The presence of higher curvature terms in the action for gravity can lead to <u>visible</u> modifications in our favorite Extra Dim theories..

    - KK spectrum + coupling shifts in RS
    - New features in BH production /properties in ADD (thresholds, stability)

- More work needs to be done to elucidate these exciting possibilities... and to find other potential signatures