Higher Curvature Corrections to TeV-Scale Gravity at Colliders

- JHEP01 (2005) 028
- hep-ph/0503163

- Higher Curvature Terms...

  What are they + why are they important ??

- Where do we see them ??

  → Signals in Randall-Sundrum...

  → Signals in ADD...

- Summary + Conclusions

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5/05

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

- EH is at best an effective theory below M_*

basis for $\Rightarrow$ $\begin{cases} \text{GR in 4d} \ldots \\ \text{RS/ADD in extra dims} \end{cases}$

"??" terms from UV completion (strings?) may be important as we approach M_* ... what can they be?

?? R^2, $(\partial R)^2$, $\frac{1}{R^2}$, $R_{AB} R^{BC} R_C{}^A$, ... ??

Many, many possibilities!

- We need some guidance ...
  - Unitary / ghost-free theory
    → no derivatives of metric > 2

[Boulware + Deser]

∴ 'Benign' modifications to Einstein's Eqs

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

... is symmetric, zero covar. derivative, no derivatives of metric higher than 2^{nd}

• String 'motivation' (Zweibach)

Lowest-order corrections to GR in string Expansion... [⇒ Gauss-Bonnet]

⇒ Unique solution : Lovelock invariants !

{Lanczos '32, '38
Lovelock '71

• The effective low energy gravity theory is a sum of Lovelock invariants...

$$\mathcal{L}_m \sim \underbrace{\delta^{A_1 B_1 \dots A_m B_m}_{C_1 D_1 \dots C_m D_m}}_{\text{Totally antisymmetric kronecker}} R_{A_1 B_1}{}^{C_1 D_1} \dots R_{A_m B_m}{}^{C_m D_m}$$

.. in $D = 4+n$ MOST $\mathcal{L}_m$ are Zero !

- Only $\mathcal{L}_m$ with $D \geq 2m+1$ are 'dynamical', ie, contribute to field equations

D=9,10 { D=7,8 { D=5,6 { D=4 {

$$\left.\begin{aligned} \mathcal{L}_0 &= \text{a constant } (\Lambda) \\ \mathcal{L}_1 &= R \end{aligned}\right\} \underline{\text{EH}}$$

$$\mathcal{L}_2 = R^2 - 4R_{AB}R^{AB} + R_{ABCD}R^{ABCD}$$

(Gauss-Bonnet)

$\mathcal{L}_3$ = 8 terms ...

$\mathcal{L}_4$ = 25 terms ..

- EH is just the First Two Terms of a general expansion...

.. it is THE UNIQUE (Lovelock action) in 4d !!

... in 5d $\quad R + \frac{\alpha}{M_*^2}\mathcal{L}_2 - \Lambda \quad$ is unique, etc (RS)

- $\Sigma \alpha_m \mathcal{L}_m$: often used in literature as toy models to probe quantum/strings corrections to EH ...

- What happens in ADD / RS ??

(Briggs)

The Lovelock invariants rapidly grow in complexity ...

EH $\left\{ \begin{aligned} L_{(0)} &= 1, \\ L_{(1)} &= -R, \\ L_{(2)} &= R^2 - 4\,R_{b}{}^{a}\,R_{a}{}^{b} + R_{cd}{}^{ab}\,R_{ab}{}^{cd}, \end{aligned} \right.$ (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} - 15\,R\,R_{cd}{}^{ab}\,R_{ab}{}^{cd}\,R_{gh}{}^{ef}\,R_{ef}{}^{gh} + 240\,R\,R_{cd}{}^{ab}\,R_{ae}{}^{cd}\,R_{gh}{}^{ef}\,R_{bf}{}^{gh} - \\ & - 30\,R\,R_{cd}{}^{ab}\,R_{ef}{}^{cd}\,R_{gh}{}^{ef}\,R_{ab}{}^{gh} + 480\,R\,R_{cd}{}^{ab}\,R_{eg}{}^{cd}\,R_{ah}{}^{ef}\,R_{bf}{}^{gh} - 240\,R\,R_{ce}{}^{ab}\,R_{ag}{}^{cd}\,R_{bh}{}^{ef}\,R_{df}{}^{gh} + 480\,R\,R_{ce}{}^{ab}\,R_{ag}{}^{cd}\,R_{dh}{}^{ef}\,R_{bf}{}^{gh} + \\ & + 640\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{d}{}^{c}\,R_{e}{}^{d}\,R_{c}{}^{e} - 768\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{d}{}^{c}\,R_{e}{}^{d}\,R_{a}{}^{e} - 960\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{e}{}^{c}\,R_{f}{}^{d}\,R_{cd}{}^{ef} + 3840\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{e}{}^{c}\,R_{f}{}^{d}\,R_{ad}{}^{ef} + 1920\,R_{b}{}^{a}\,R_{e}{}^{b}\,R_{d}{}^{c}\,R_{f}{}^{d}\,R_{ac}{}^{ef} - \\ & - 960\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{d}{}^{c}\,R_{fg}{}^{de}\,R_{ce}{}^{fg} - 160\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{a}{}^{c}\,R_{fg}{}^{de}\,R_{de}{}^{fg} + 1920\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{d}{}^{c}\,R_{fg}{}^{de}\,R_{ae}{}^{fg} + 1920\,R_{b}{}^{a}\,R_{d}{}^{b}\,R_{e}{}^{c}\,R_{fg}{}^{de}\,R_{ac}{}^{fg} - \\ & - 3840\,R_{b}{}^{a}\,R_{d}{}^{b}\,R_{f}{}^{c}\,R_{ag}{}^{de}\,R_{ce}{}^{fg} + 3840\,R_{b}{}^{a}\,R_{d}{}^{b}\,R_{f}{}^{c}\,R_{cg}{}^{de}\,R_{ae}{}^{fg} + 1920\,R_{d}{}^{a}\,R_{f}{}^{b}\,R_{e}{}^{c}\,R_{bg}{}^{de}\,R_{ac}{}^{fg} + 3840\,R_{d}{}^{a}\,R_{f}{}^{b}\,R_{g}{}^{c}\,R_{ab}{}^{de}\,R_{ce}{}^{fg} - \\ & - 80\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{ef}{}^{cd}\,R_{gh}{}^{ef}\,R_{cd}{}^{gh} + 320\,R_{b}{}^{a}\,R_{a}{}^{b}\,R_{eg}{}^{cd}\,R_{ch}{}^{ef}\,R_{df}{}^{gh} - 1920\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{ae}{}^{cd}\,R_{gh}{}^{ef}\,R_{df}{}^{gh} + 960\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{ef}{}^{cd}\,R_{gh}{}^{ef}\,R_{ad}{}^{gh} - \\ & - 3840\,R_{b}{}^{a}\,R_{c}{}^{b}\,R_{eg}{}^{cd}\,R_{ah}{}^{ef}\,R_{df}{}^{gh} + 240\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ab}{}^{cd}\,R_{gh}{}^{ef}\,R_{ef}{}^{gh} - 1920\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ae}{}^{cd}\,R_{gh}{}^{ef}\,R_{bf}{}^{gh} + 480\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{ef}{}^{cd}\,R_{gh}{}^{ef}\,R_{ab}{}^{gh} - \\ & - 1920\,R_{c}{}^{a}\,R_{d}{}^{b}\,R_{eg}{}^{cd}\,R_{ah}{}^{ef}\,R_{bf}{}^{gh} - 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\\ & - 1920\,R_{b}{}^{a}\,R_{de}{}^{bc}\,R_{fh}{}^{de}\,R_{ai}{}^{fg}\,R_{cg}{}^{hi} - 1920\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{ac}{}^{de}\,R_{hi}{}^{fg}\,R_{eg}{}^{hi} - 1920\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{ag}{}^{de}\,R_{hi}{}^{fg}\,R_{ce}{}^{hi} + 3840\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{ah}{}^{de}\,R_{ci}{}^{fg}\,R_{eg}{}^{hi} - \\ & - 3840\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{ah}{}^{de}\,R_{ei}{}^{fg}\,R_{cg}{}^{hi} + 1920\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{cg}{}^{de}\,R_{hi}{}^{fg}\,R_{ae}{}^{hi} + 3840\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{ch}{}^{de}\,R_{ei}{}^{fg}\,R_{ag}{}^{hi} - 1920\,R_{b}{}^{a}\,R_{df}{}^{bc}\,R_{gh}{}^{de}\,R_{ei}{}^{fg}\,R_{ac}{}^{hi} + \\ & + 20\,R_{cd}{}^{ab}\,R_{ab}{}^{cd}\,R_{gh}{}^{ef}\,R_{ij}{}^{gh}\,R_{ef}{}^{ij} - 80\,R_{cd}{}^{ab}\,R_{ab}{}^{cd}\,R_{gi}{}^{ef}\,R_{ej}{}^{gh}\,R_{fh}{}^{ij} + 480\,R_{cd}{}^{ab}\,R_{ae}{}^{cd}\,R_{bg}{}^{ef}\,R_{ij}{}^{gh}\,R_{fh}{}^{ij} - 480\,R_{cd}{}^{ab}\,R_{ae}{}^{cd}\,R_{gh}{}^{ef}\,R_{ij}{}^{gh}\,R_{bf}{}^{ij} + \\ & + 1920\,R_{cd}{}^{ab}\,R_{ae}{}^{cd}\,R_{gi}{}^{ef}\,R_{bj}{}^{gh}\,R_{fh}{}^{ij} + 24\,R_{cd}{}^{ab}\,R_{ef}{}^{cd}\,R_{gh}{}^{ef}\,R_{ij}{}^{gh}\,R_{ab}{}^{ij} - 480\,R_{cd}{}^{ab}\,R_{ef}{}^{cd}\,R_{gi}{}^{ef}\,R_{aj}{}^{gh}\,R_{bh}{}^{ij} - 480\,R_{cd}{}^{ab}\,R_{eg}{}^{cd}\,R_{ah}{}^{ef}\,R_{ij}{}^{gh}\,R_{bf}{}^{ij} + \\ & + 960\,R_{cd}{}^{ab}\,R_{eg}{}^{cd}\,R_{ai}{}^{ef}\,R_{bj}{}^{gh}\,R_{fh}{}^{ij} - 1920\,R_{cd}{}^{ab}\,R_{eg}{}^{cd}\,R_{ai}{}^{ef}\,R_{fj}{}^{gh}\,R_{bh}{}^{ij} + 1920\,R_{ce}{}^{ab}\,R_{af}{}^{cd}\,R_{gi}{}^{ef}\,R_{bj}{}^{gh}\,R_{dh}{}^{ij} - 384\,R_{ce}{}^{ab}\,R_{ag}{}^{cd}\,R_{bi}{}^{ef}\,R_{dj}{}^{gh}\,R_{fh}{}^{ij} + \\ & + 1920\,R_{ce}{}^{ab}\,R_{ag}{}^{cd}\,R_{bi}{}^{ef}\,R_{fj}{}^{gh}\,R_{dh}{}^{ij} - 1920\,R_{ce}{}^{ab}\,R_{ag}{}^{cd}\,R_{di}{}^{ef}\,R_{fj}{}^{gh}\,R_{bh}{}^{ij} - 768\,R_{ce}{}^{ab}\,R_{fg}{}^{cd}\,R_{hi}{}^{ef}\,R_{aj}{}^{gh}\,R_{bd}{}^{ij}. \end{aligned}$$

$$S = \int d^{4+n}x \sqrt{-g} \left\{ \frac{M_*^{n+2}}{2} \left[R + \frac{\alpha}{M_*^2} \mathcal{L}_2 + \frac{\beta}{M_*^4} \mathcal{L}_3 + \frac{\gamma}{M_*^6} \mathcal{L}_4 \right] - \Lambda \right\}$$

all Lovelock invariants

- $\alpha, \beta\, \gamma$ = dimensionless constants (not generally $O(1)$)

When are $\mathcal{L}_{m\geq 2}$ important ???

$\Rightarrow$ when $\sim \dfrac{R^{\text{backgrnd}}}{M_*^2}$ is big......

- in RS, $R^{\text{backg'nd}} = \underline{-20\,k^2}$

Recall: $ds^2 = \underline{e}^{-2k|y|} (\eta_{\mu\nu} dx^\mu dx^\nu) - dy^2$ (warp factor $\rightarrow$ curvature!)

$\therefore$ corrections in RS $\underline{\sim \alpha k^2/M_*^2}$!

- recall, we usually demand $20k^2/M_*^2 < 1$ in RS to AVOID large curvature!! [Drop?]

- in ADD? space + 'brane' are flat $[T^n]$

$\rightarrow R^{\text{backgrnd}} = 0$ (usually)

So...

$\Rightarrow$

- ADD relation unaltered: $\bar{M}_{Pl}^2 = V_n M_*^{n+2}$
- Matter - graviton coupling unaltered:

$$S_{SM} = \int d^{4+n}x \sqrt{-g} \cdot \frac{-1}{M_*^{1+\frac{n}{2}}} h_{\mu\nu}^{(n)} T^{\mu\nu}$$

- graviton mass spectrum <u>unaltered</u>

$\therefore$ $\not{E}$ + contact int' signatures <u>as usual</u>

<u>insensitive</u> to $\mathcal{L}_m$! ... but

$\Rightarrow$ $\boxed{\text{Black Holes}}$ <u>do</u> have big $\frac{R^{\text{backg}}}{M_*^2}$!

(Return to this later....)

<u>RS Model</u> : can add on $\mathcal{L}_2$ in $D=5$

$\rightarrow$ general sol'n structure remains but details change [Kim, Kyae + Lee]

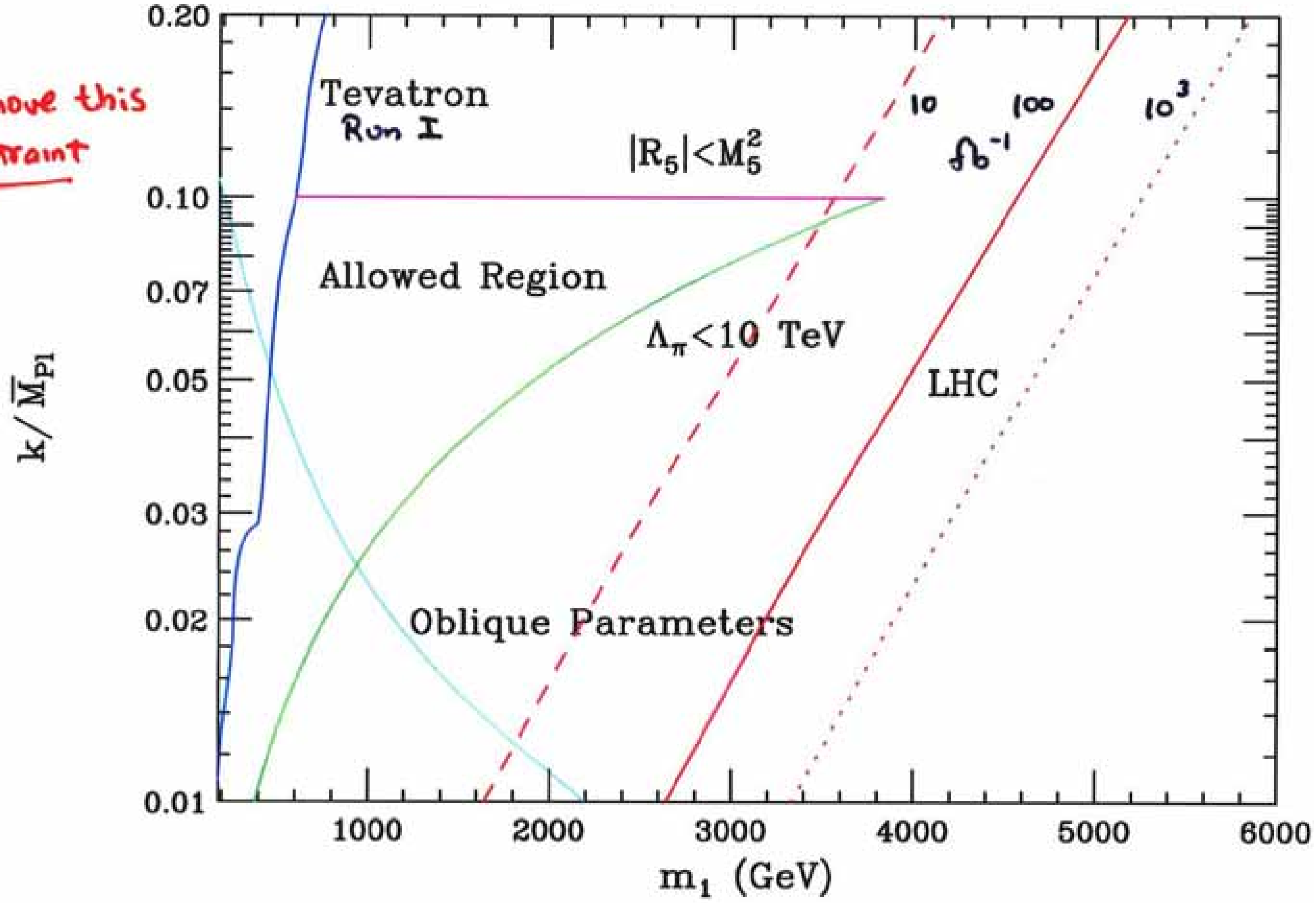
<u>Still</u> $\psi_n(y) = \frac{e^{2\sigma}}{N_n} \mathcal{J}_2\left(\frac{m_n}{k} e^{\sigma}\right)$ $(\sigma = k|y|)$

$\uparrow$

$J_2 + \lambda Y_2$ Bessel functions

The LHC has good RS coverage

Remove this constraint



first graviton KK mass

Some differences .... similar to graviton brane kinetic terms

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

$$J_1(x_n) + \underbrace{\frac{4\alpha k^2/M_*^2}{1-4\alpha k^2/M_*^2}}_{\Omega} J_2(x_n) = 0$$

KK mass shifts

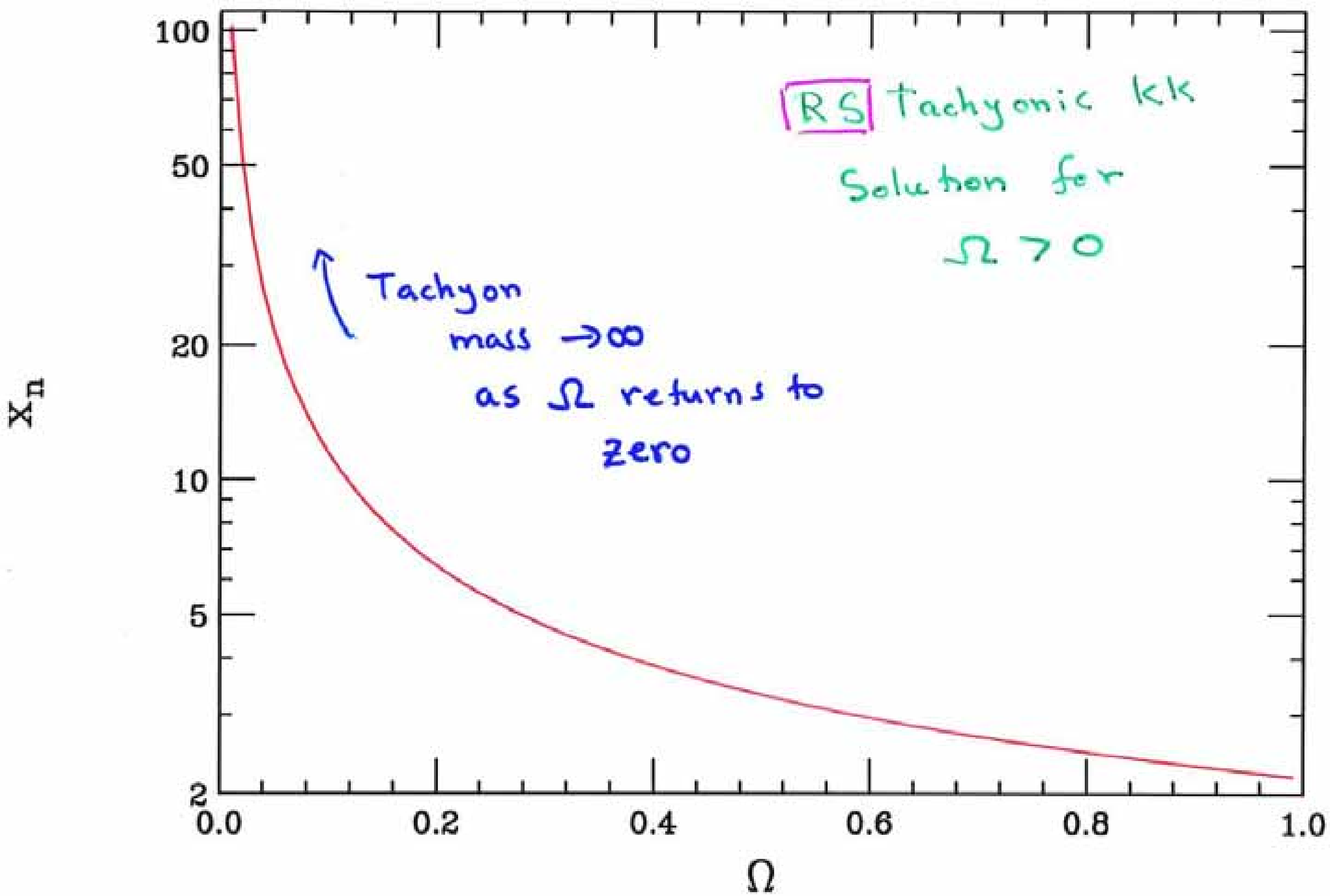
$$\mathcal{L} = \frac{1}{\Lambda_\pi} \sum \left[\frac{1+2\Omega}{1+2\Omega+\Omega^2 x_n^2}\right]^{1/2} h_{\mu\nu}^{(n)} T^{\mu\nu}$$

- KK coupling shifts

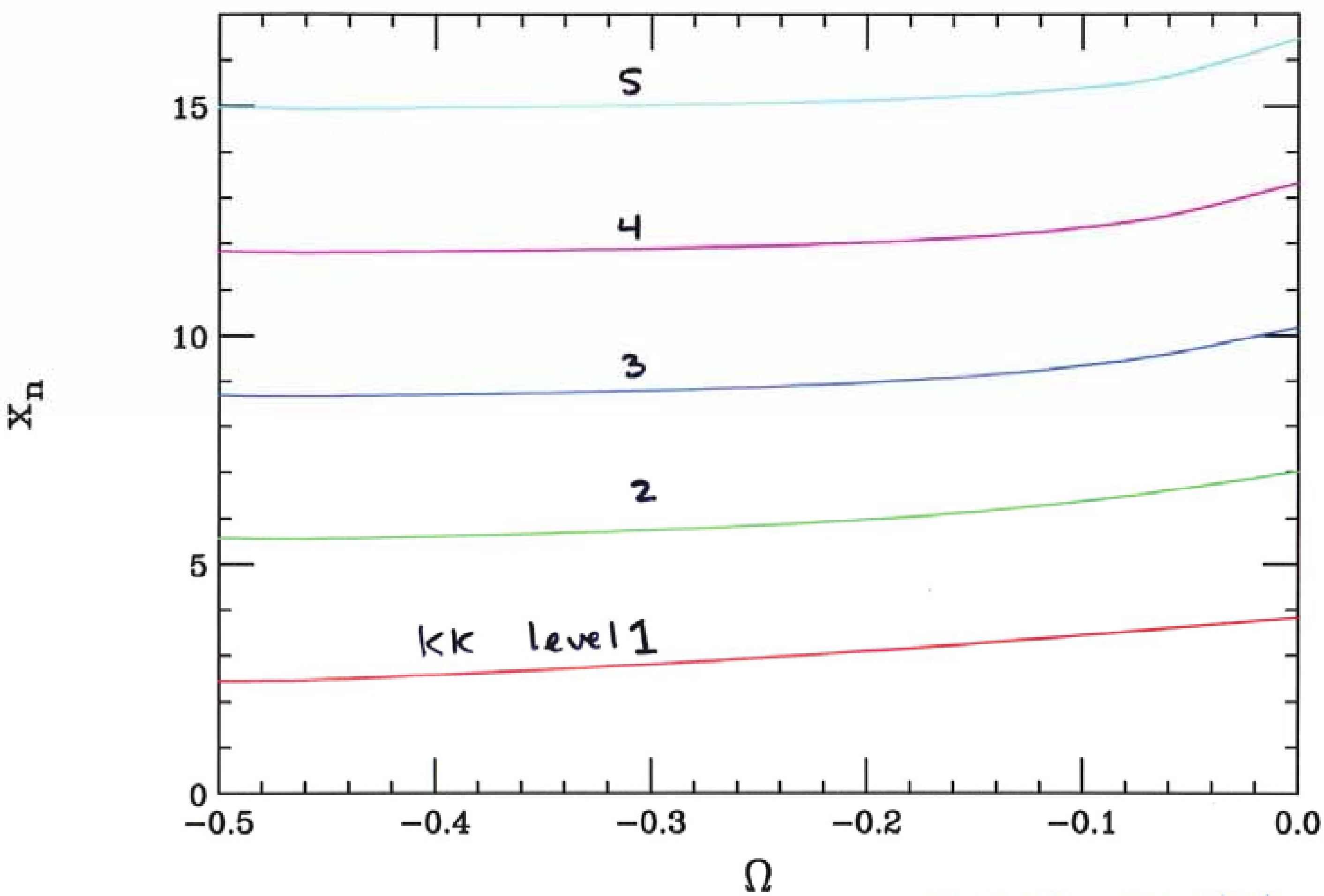
- $\alpha < 0$ [no tachyons] { Charmousis + Dufaux; Brax, Chatillon + Steer }
- $-\frac{1}{2} \leq \Omega \leq 0$, $\Omega = 0$ = USUAL RS model
- couplings are KK level dependent and <u>vanishing</u> for $\Omega = -\frac{1}{2}$!
- level shifts (weak)
- Can we measure / constrain Ω ??

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

$$m^2_{\text{Tachyon}} = -x_n^2 k^2 e^{-2\pi k r_c} < 0$$

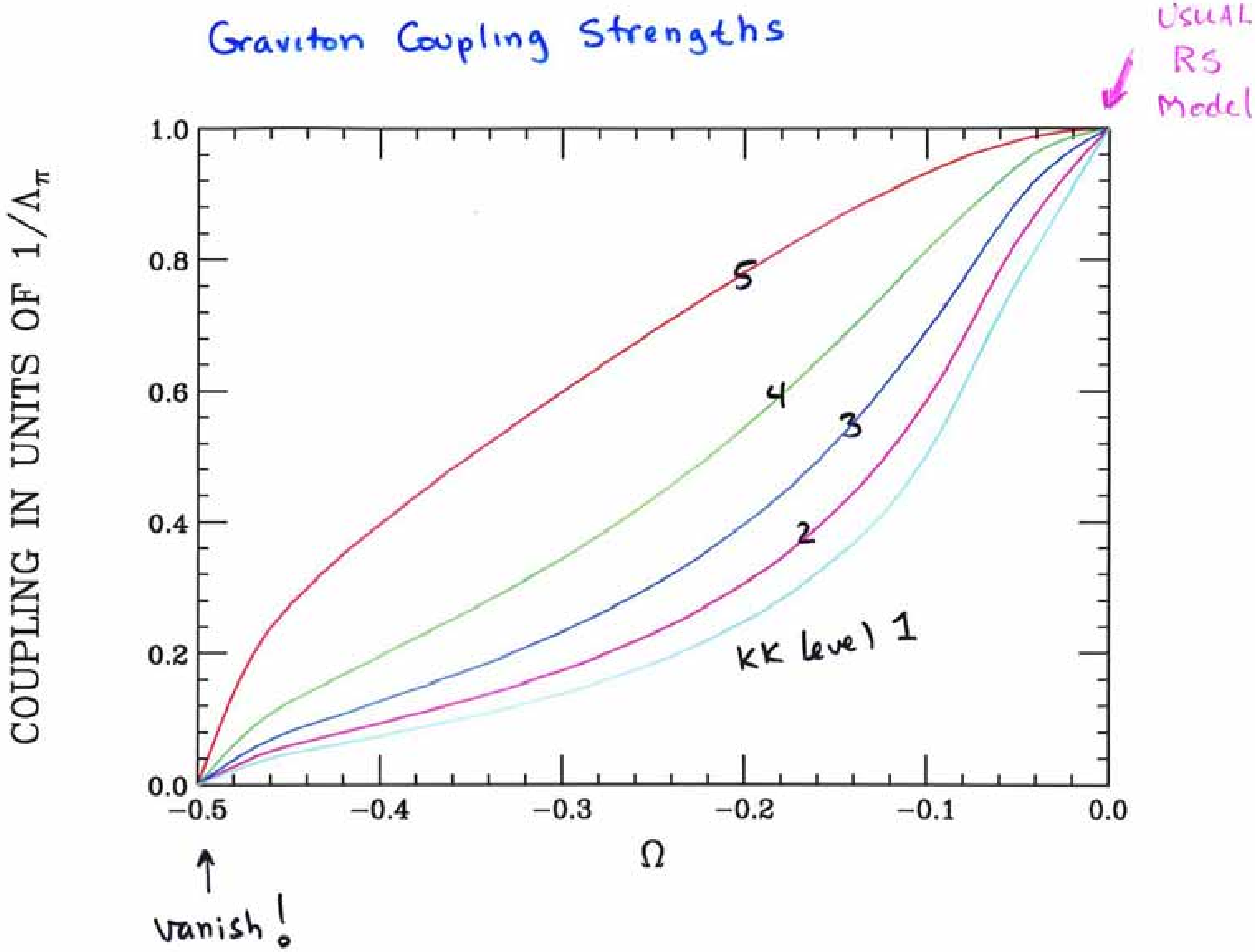


Root shifts due to $\mathcal{L}_2$ in RS

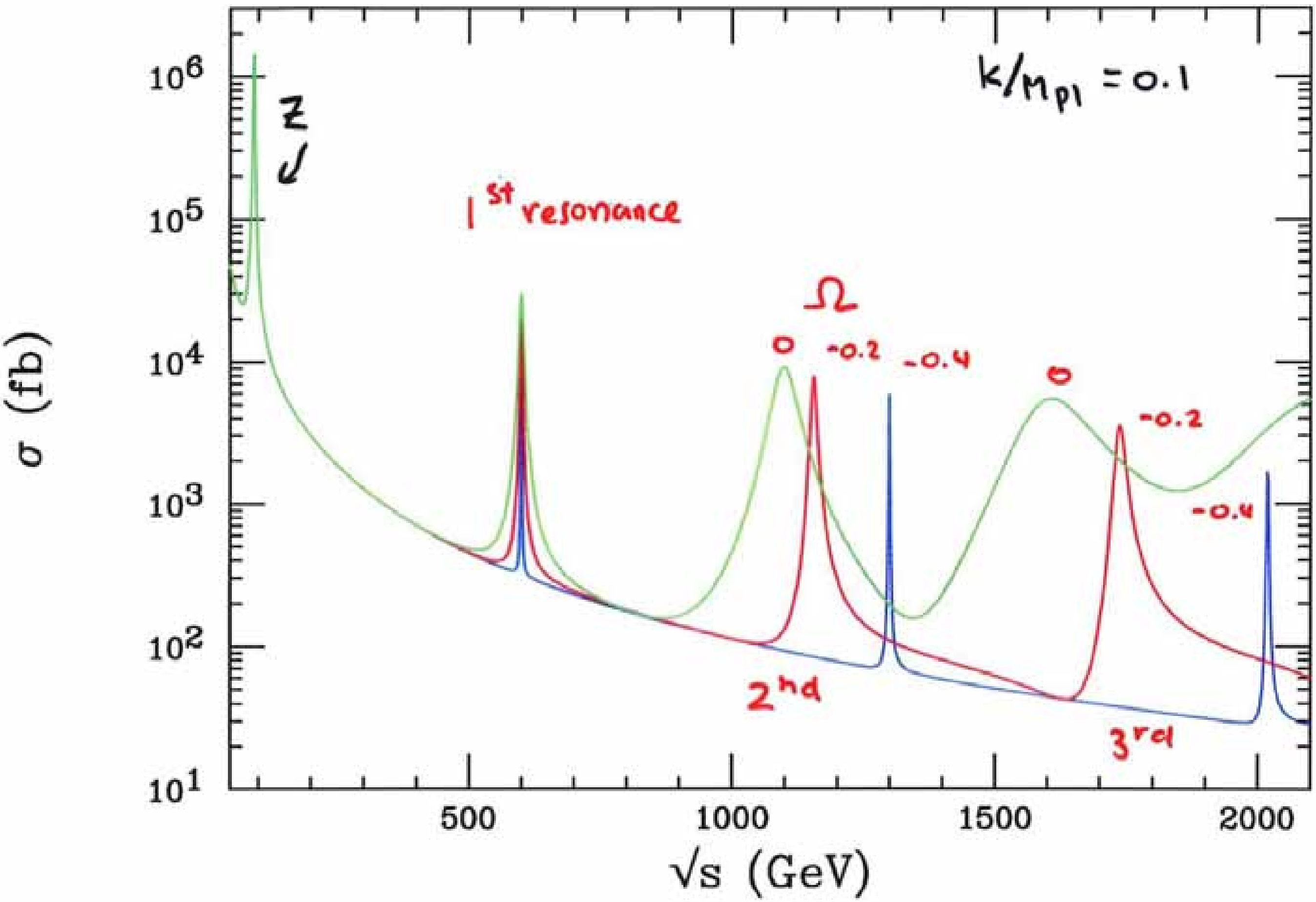


graviton masses

Graviton Coupling Strengths

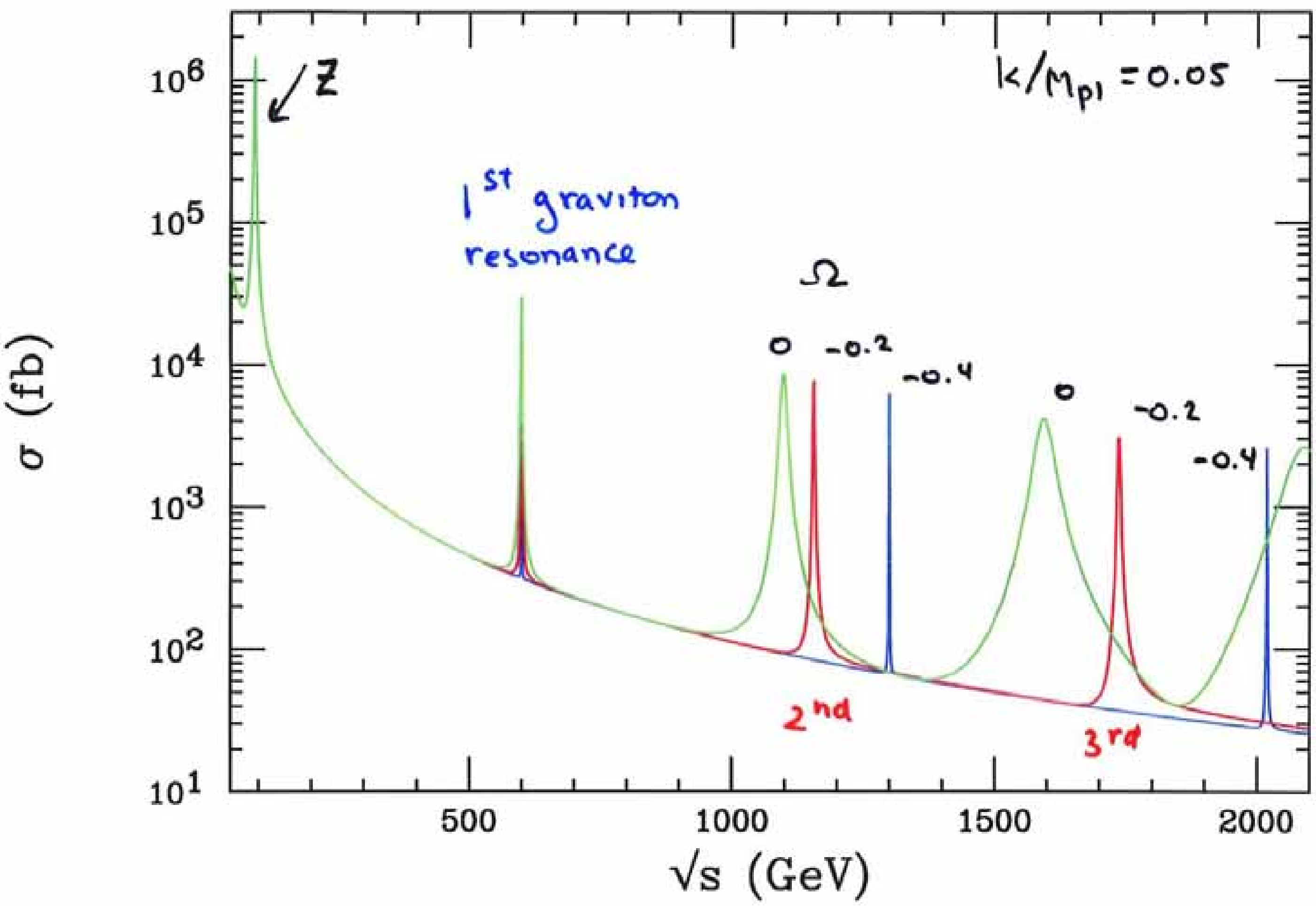


$e^+e^- \to \mu^+\mu^-$



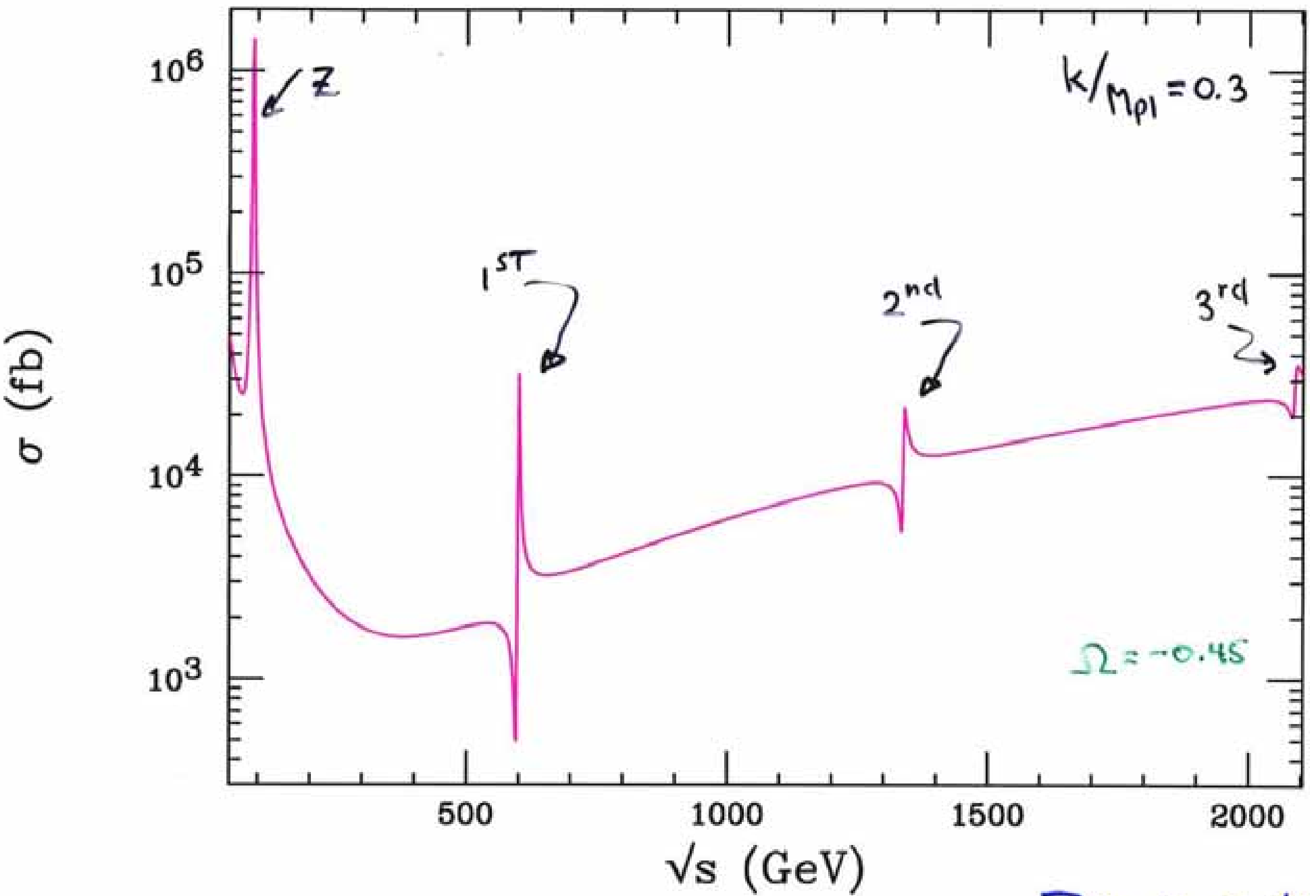
mass shifted + narrowed ..

$e^+e^- \to \mu^+\mu^-$



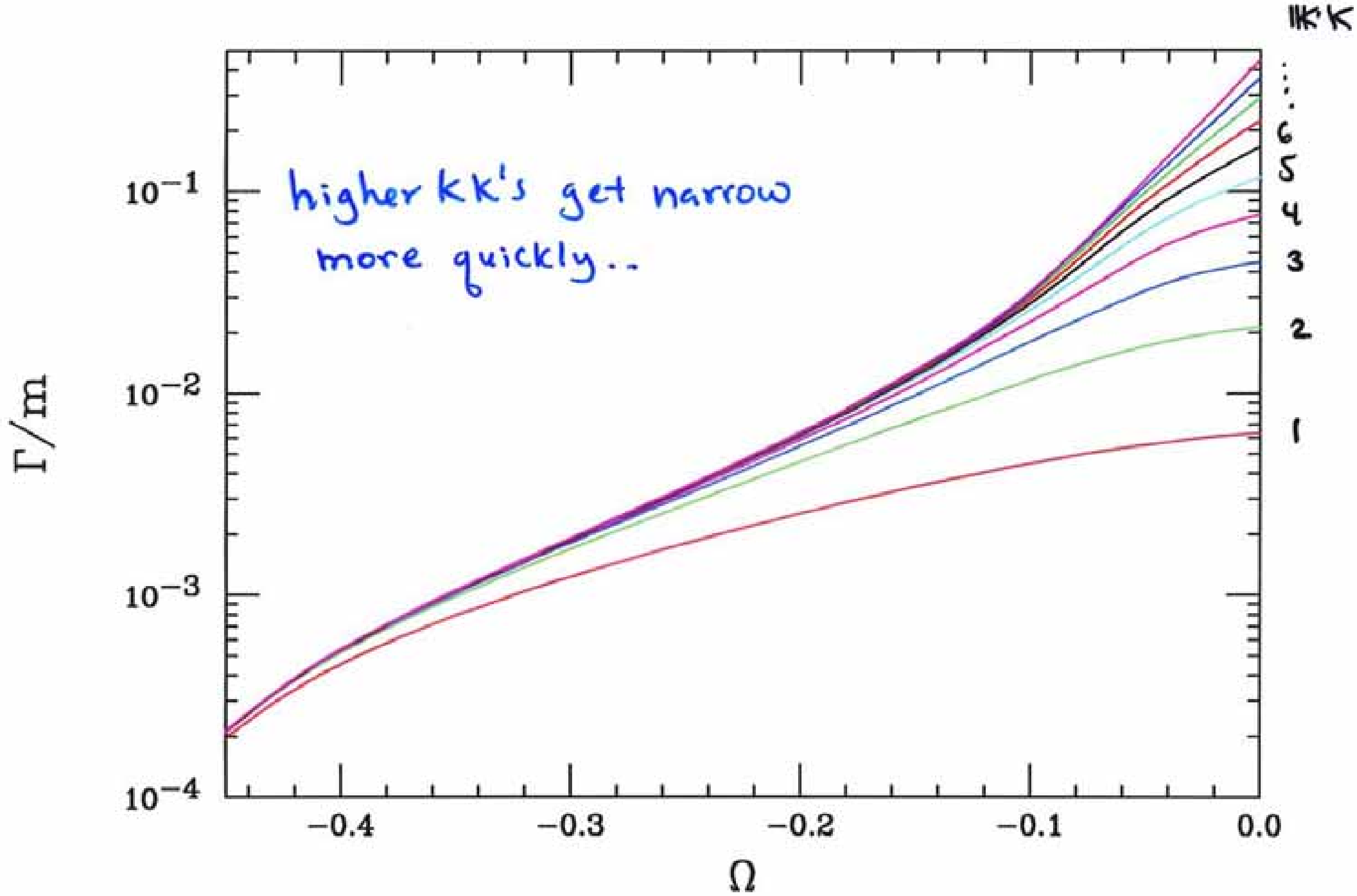
K.K spectrum shifted + resonances narrowed

$e^+e^- \to \mu^+\mu^-$

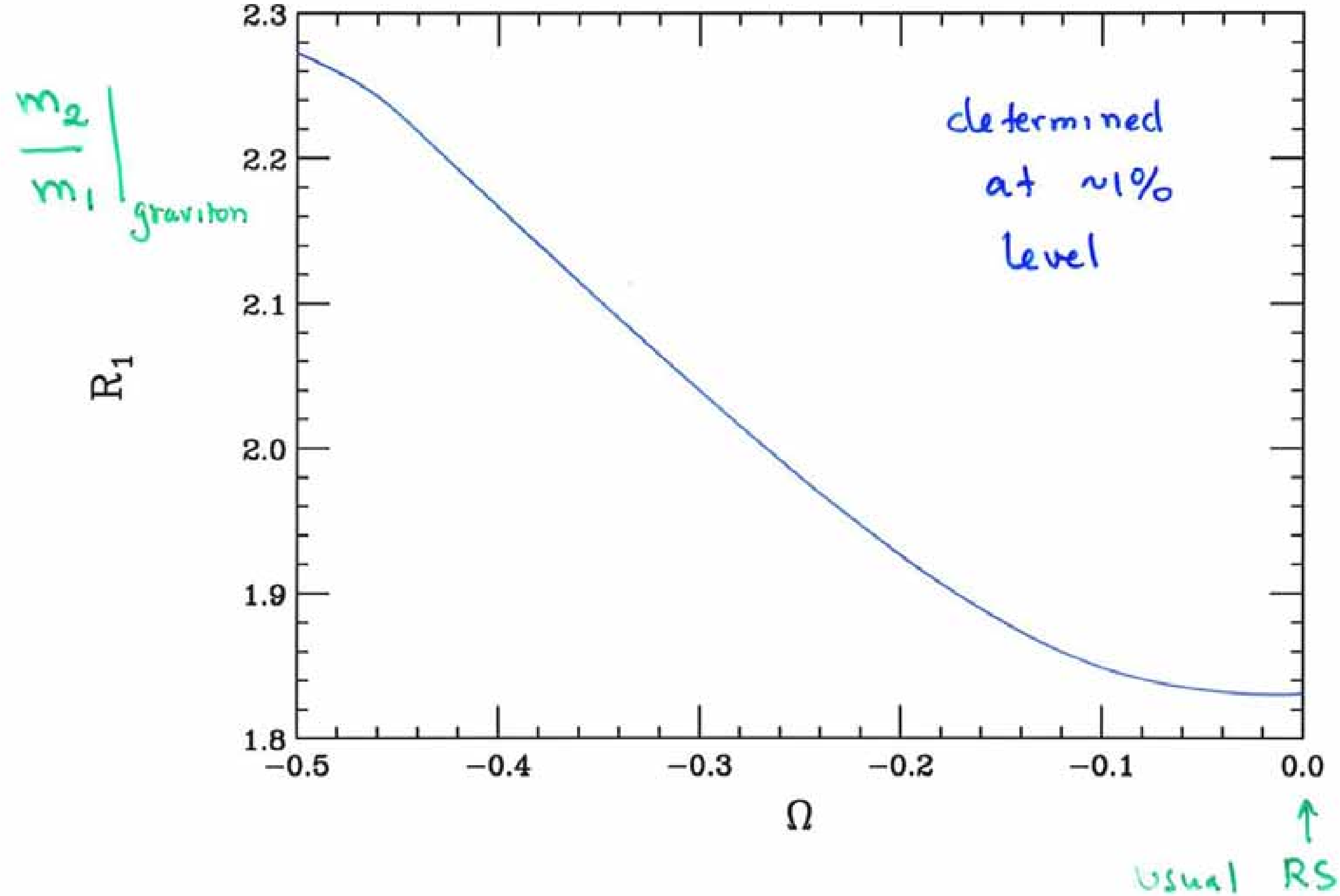


... This is a traditionally excluded region of parameter space

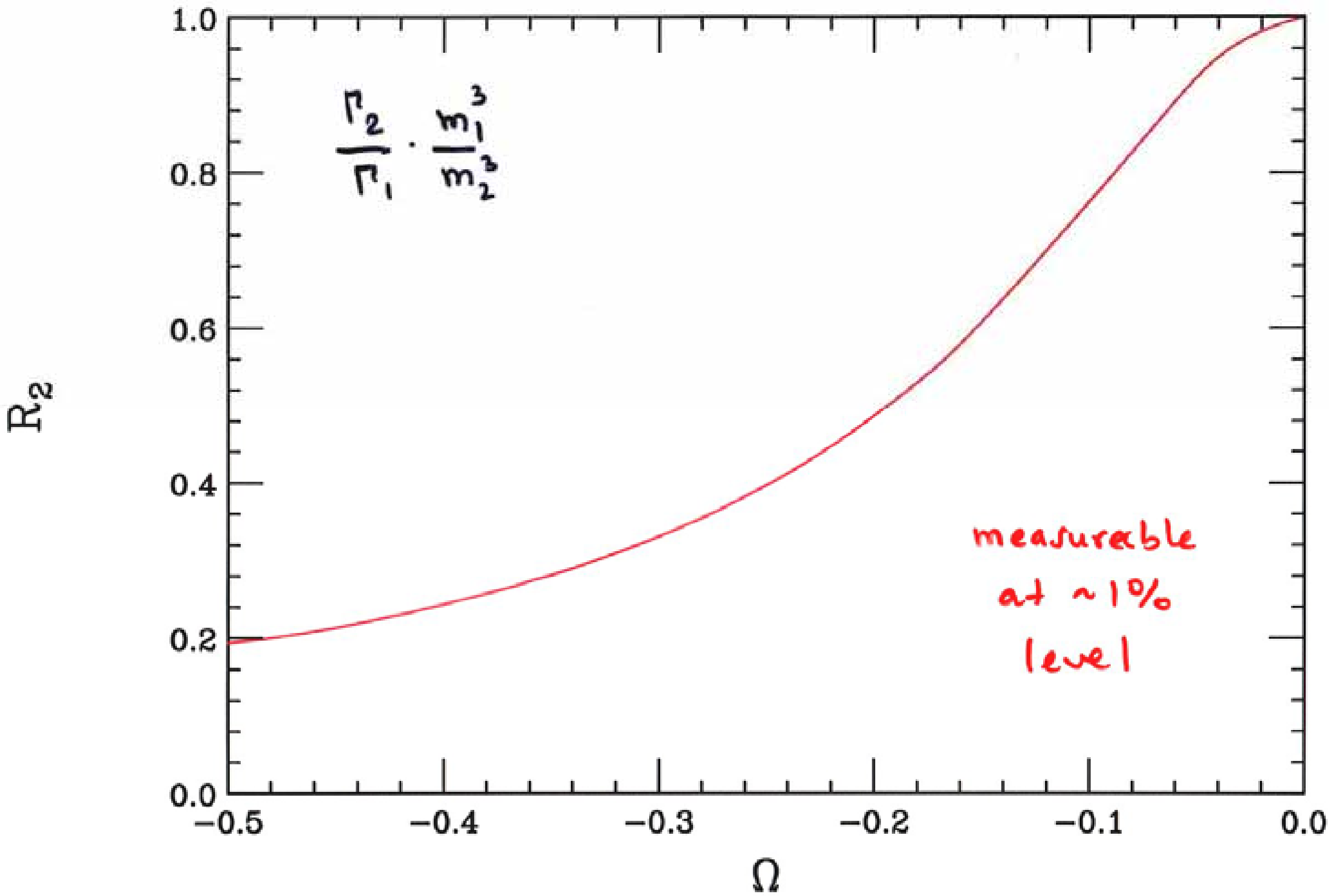
KK's are getting narrow quite quickly



KK mass ratios

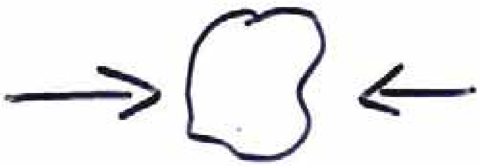


Scaled width ratios



ADD

- modification of BH properties



$$\hat{\sigma} \simeq \pi R_s^2 \, \delta(\hat{s} - M_*^2)$$

↳ decays by 'Hawking radiation' very rapidly into SM particles

$$\langle S \rangle \sim 10$$

- $R_s \, (m_{BH}/M_*, n) \;\; [\alpha, \beta, \gamma]$
- $T \, (m_{BH}/M_*, n) \;\; [\alpha, \beta, \gamma]$

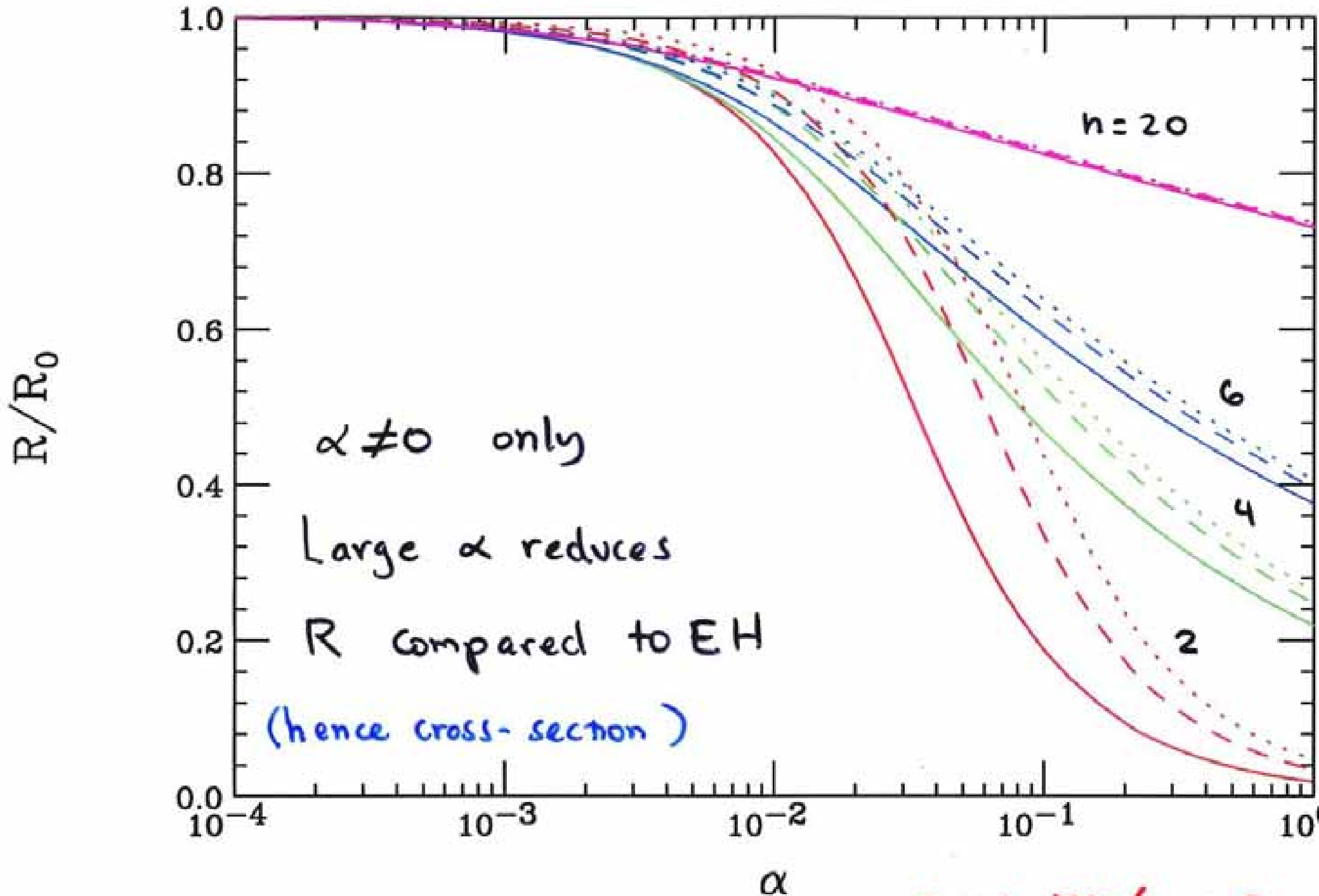
⋮ etc

Quantitative + Qualitative Changes

- R, T vary w/ α, β, γ for fixed n, $\frac{m_{BH}}{M_*}$
- $\left.\begin{array}{l} \text{for } n=3, \ \beta \neq 0 \\ \quad\;\, = 5, \ \gamma \neq 0 \end{array}\right\}$ **No BH** can form below a critical minimum mass

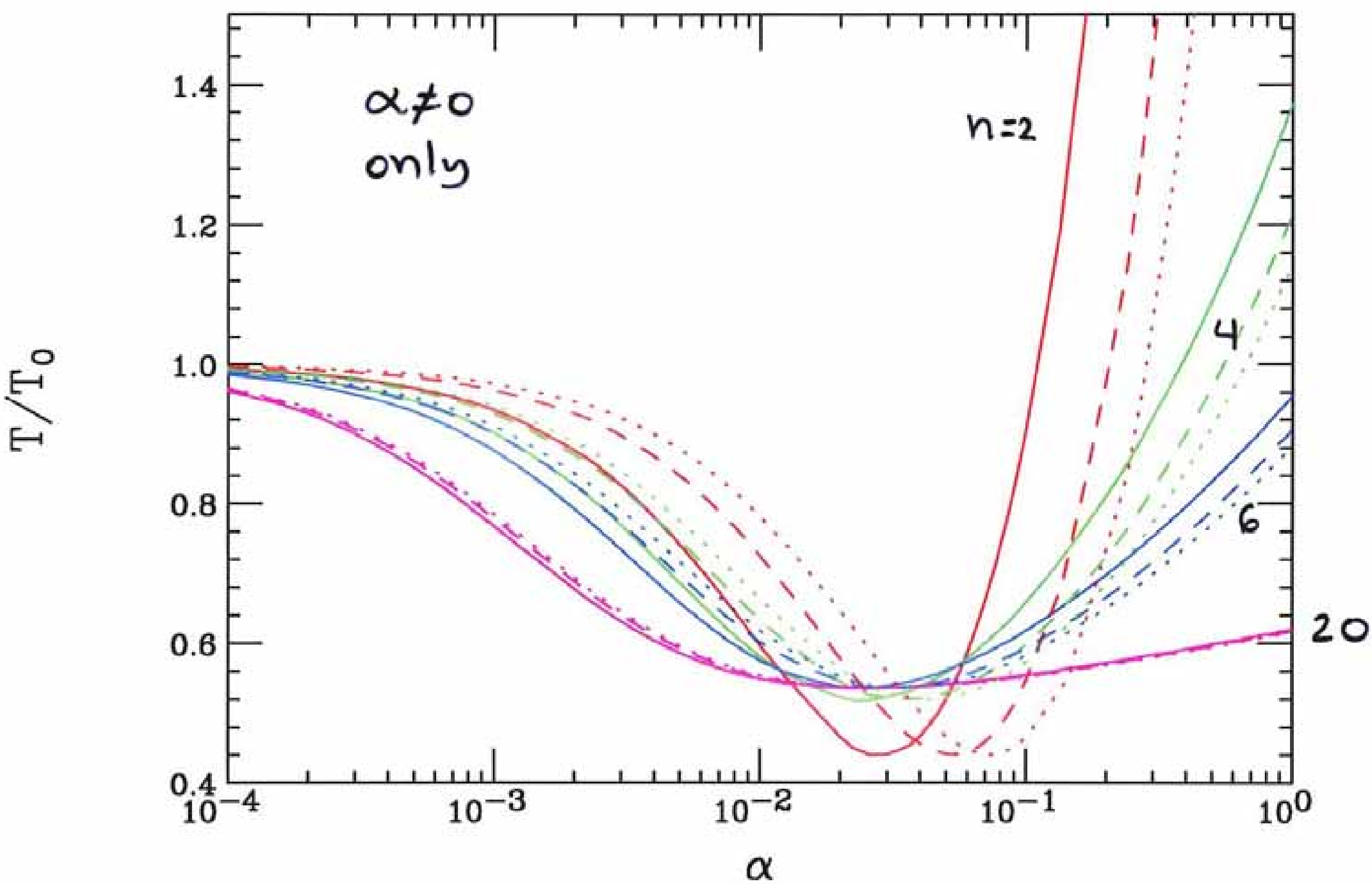
Furthermore, for $M_{BH} \simeq M_{crit}$ BH are STABLE in these cases

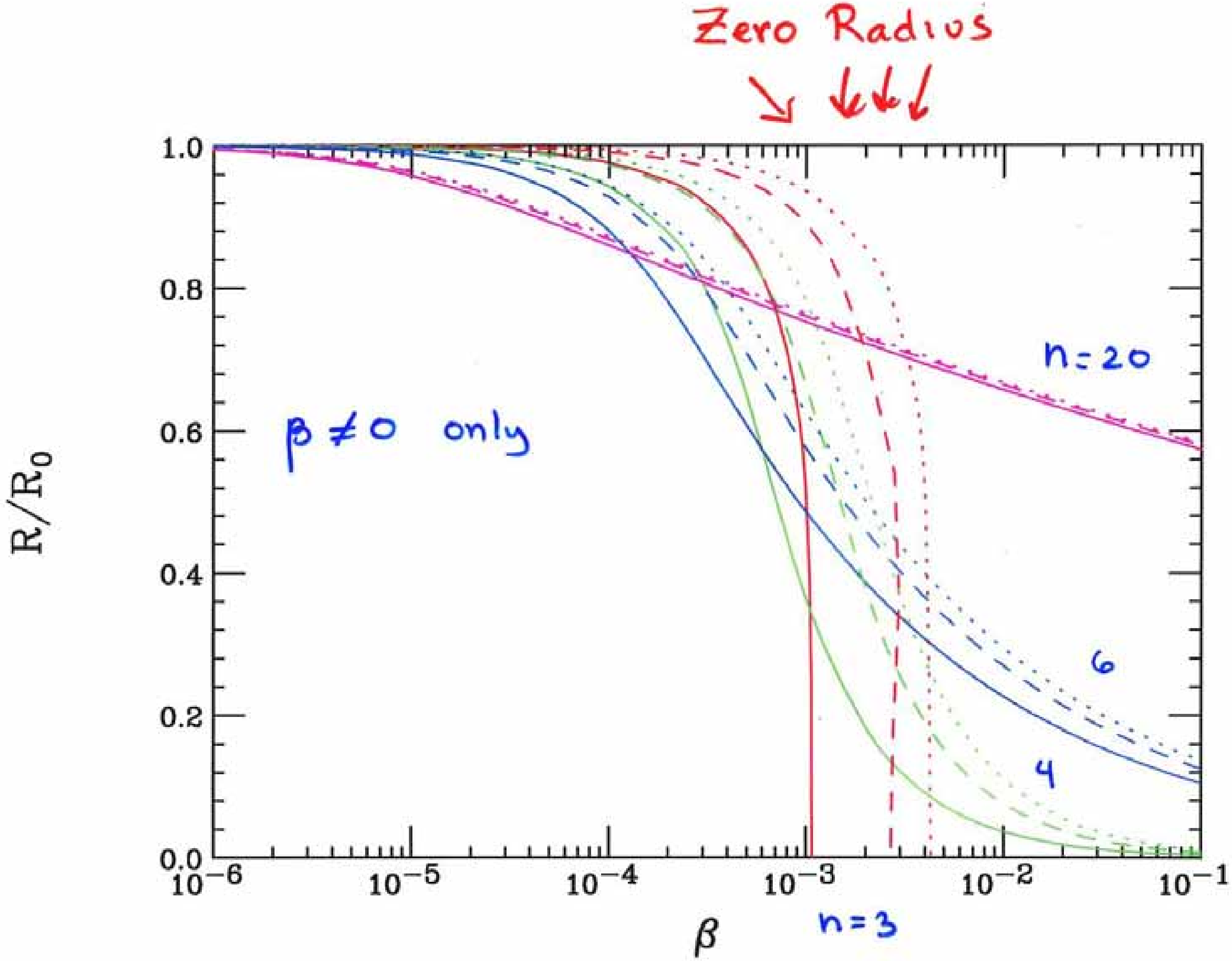
Shift in Schwarzschild radius

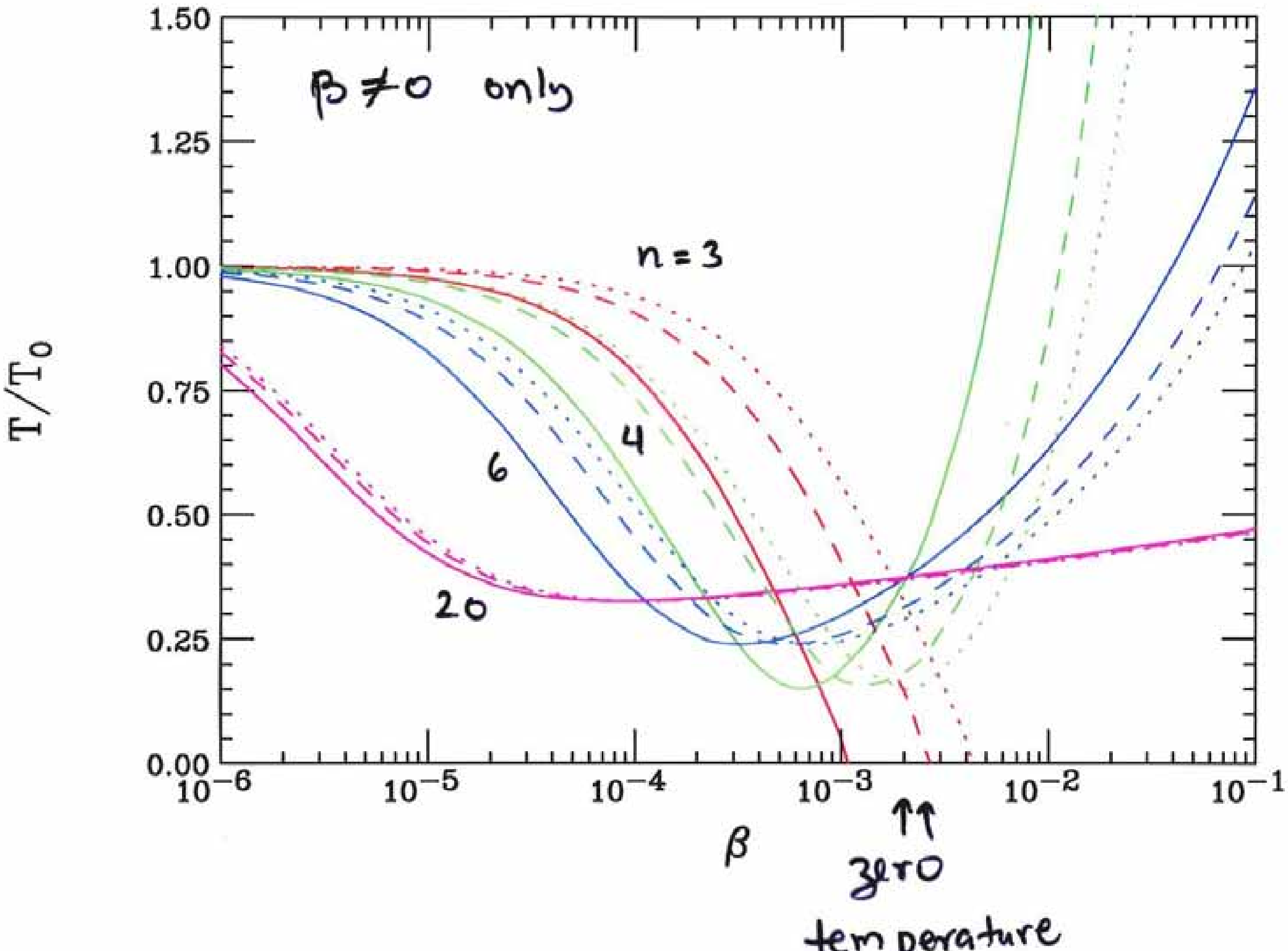


Solid $m_{BH}/m_* = 2$
Dash 5
Dot 8

O(1) Temperature changes




Zero Radius
1.0
0.8
0.6
0.4
0.2
0.0
R/R_0
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
β
$\beta \neq 0$ only
n=20
6
4
n=3



$\beta \neq 0$ only
n = 3
4
6
20
T/T0
β
zero
temperature
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

For $\underline{n=3}$, $\underline{\beta \neq 0}$

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

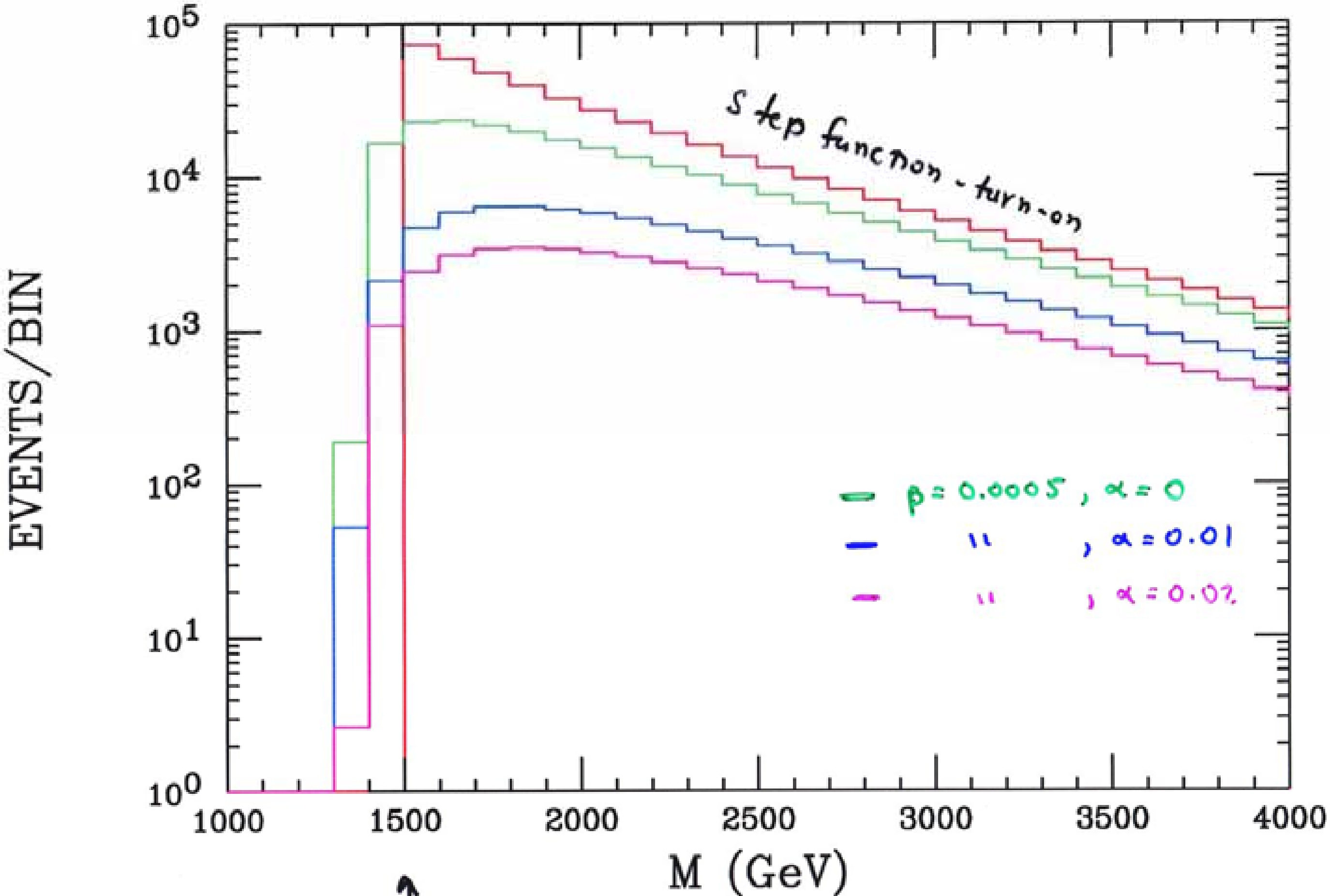
$\therefore$ unless $M_{BH} > 60\pi^3 \beta M_*$ <u>NO</u> BH forms...

<u>Lifetime</u> : $\frac{dm_{BH}}{dt} \sim (\text{Area})(\text{Temp})^4$ (BB-radiation)

$$\sim \frac{(M_{BH} - 60\pi^3 \beta M_*)^{7/2}}{(M_{BH} + 120\pi^3 \beta M_*)^4}$$

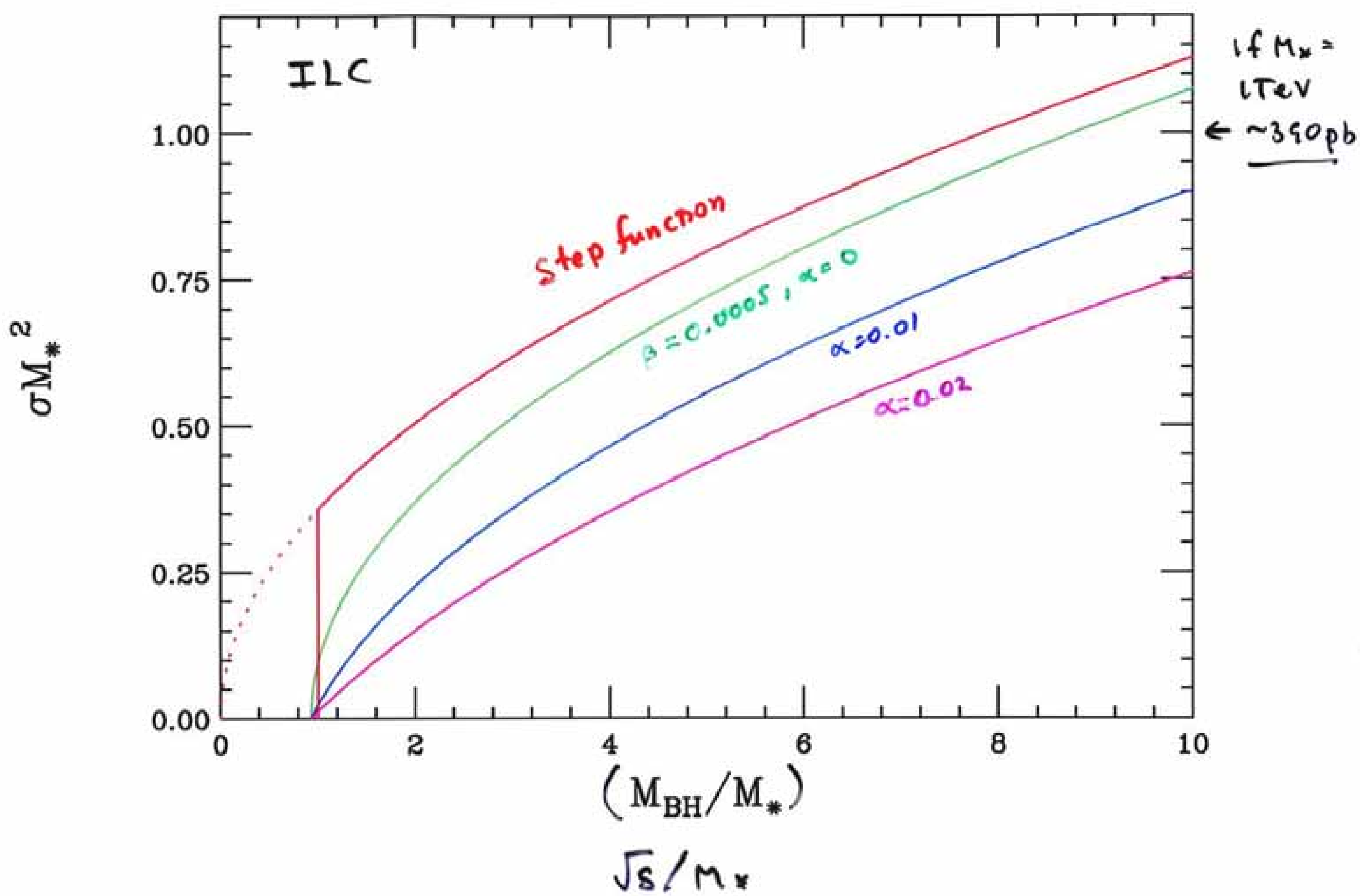
- For any $M_{BH} > m_{crit} = 60\pi^3 \beta M_*$, the lifetime is ∞ long.
- These BH $\boxed{\text{cool}}$ as they lose mass, so loss is reduced
- Make a BH with $M_{BH} > m_{crit}$, it will radiate until $M_{BH} \sim m_{crit}$ is reached
- σ_{BH} now have <u>THRESHOLDS</u> .. the turn-on at M_* is <u>no longer</u> a <u>STEP FUNCTION</u> !

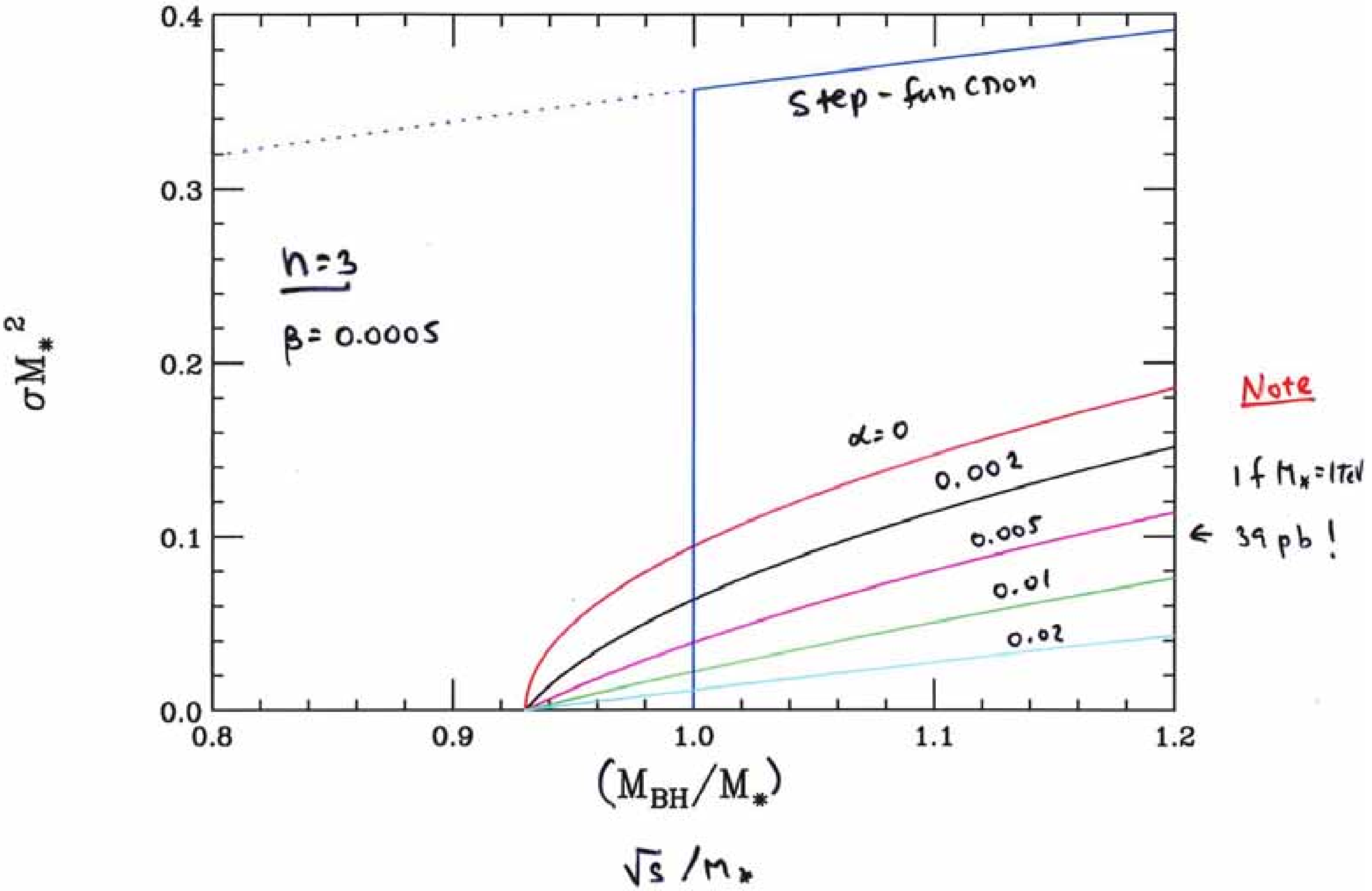
BH at LHC $100 \; fb^{-1}$



$M_* = 1.5$ TeV

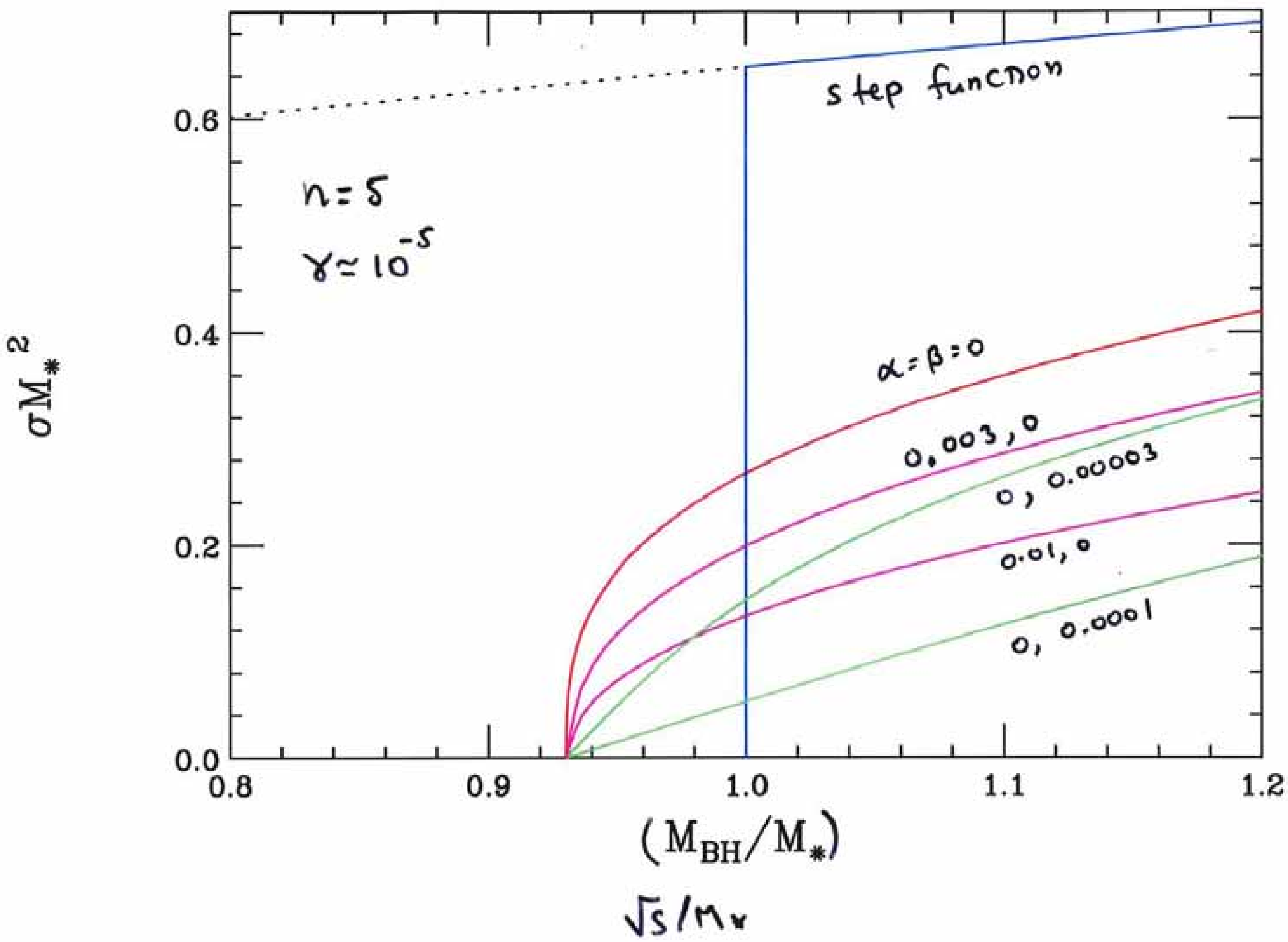
... need precision to probe parameters


ILC
Step function
β=0.0005, α=0
α=0.01
α=0.02
if M* = 1TeV
← ~390pb
σM*²
0.00
0.25
0.50
0.75
1.00
0
2
4
6
8
10
(M_BH/M*)
√s/M*

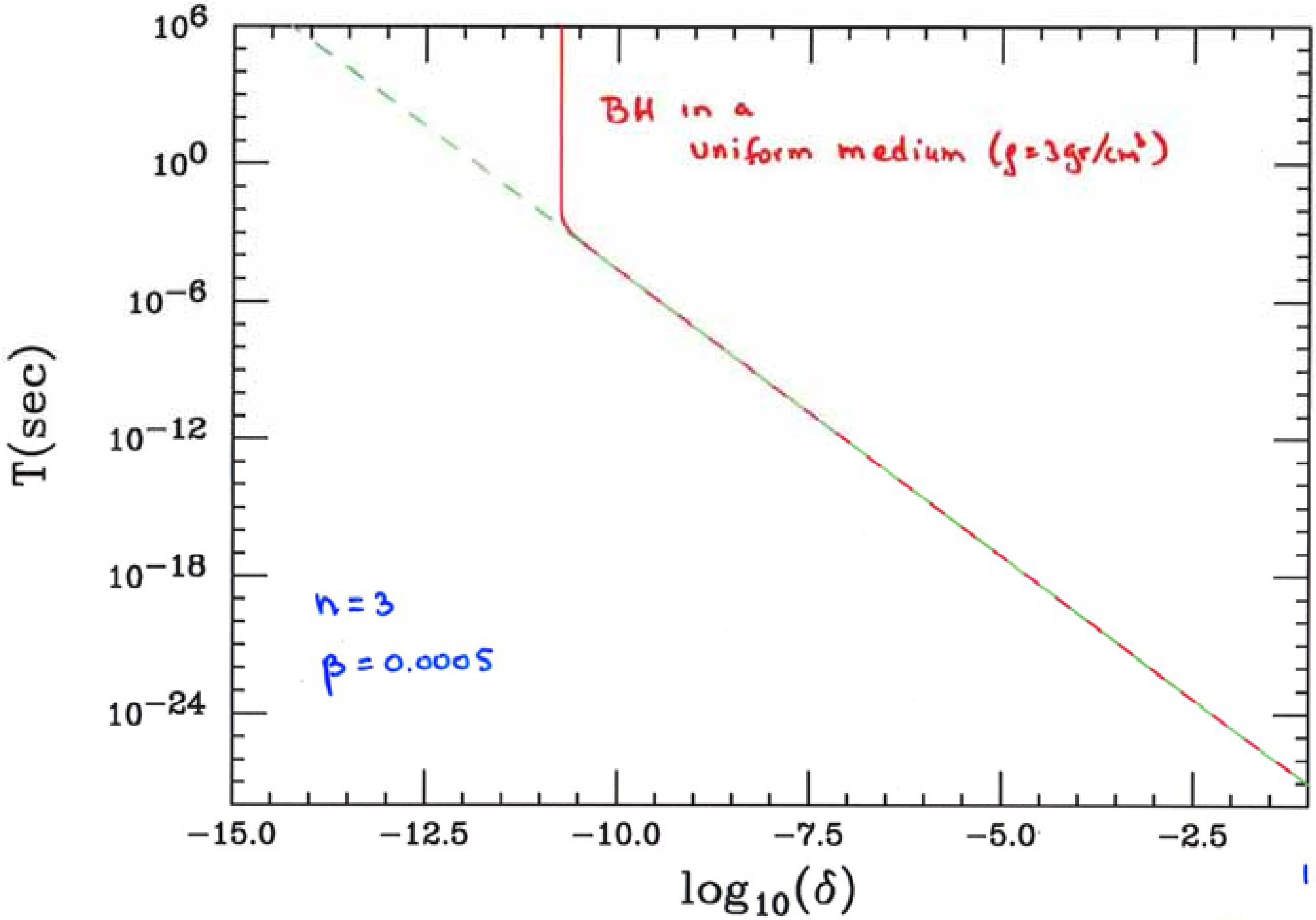


0.4
0.3
0.2
0.1
0.0
0.8
0.9
1.0
1.1
1.2
$\sigma M_*^{\,2}$
(M_{BH}/M_*)
$\sqrt{s}/M_*$
Step - function
n=3
β= 0.0005
α=0
0.002
0.005
0.01
0.02
Note
1 if M_*=1TeV
← 39 pb !

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



Crude Estimate of BH lifetime...



Initially

$M_{BH} = 1.5\, m_{crit}$

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

Summary

- The presence of higher curvature terms in the action for gravity can lead to visible 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