Exotic Physics at VLHC

⇒ What we consider the bizarre + unusual may BE the VLHC physics program ...

- Extra Dimensions
  - TeV^{-1}: KK gauge excitations
  - ADD: $\not{E}$ ⊕ contact ints
  - RS: graviton resonances

⇒ not just discovery - but a detailed exploration

- Black Holes
  - huge σ's
  - Ifs / ands / buts
  - other phenomena: { stringballs, p-branes }

  uncertainties + alternatives

- Really strange
  - non-com. co-ords → new interactions
  - Lorentz violation,
  - String excitations, ... ??

- Conclusions / Summary

TGRizzo
10/03

VLHC Signatures for ED

- many models, many possibilities
- not just a matter of discovery

  BUT an opportunity to explore the details of the model

* .: TeV^{-1} : KK excitations of $SU(2)_c \times U(1)$ GB $\rightarrow$ 'resonances' in Drell-Yan

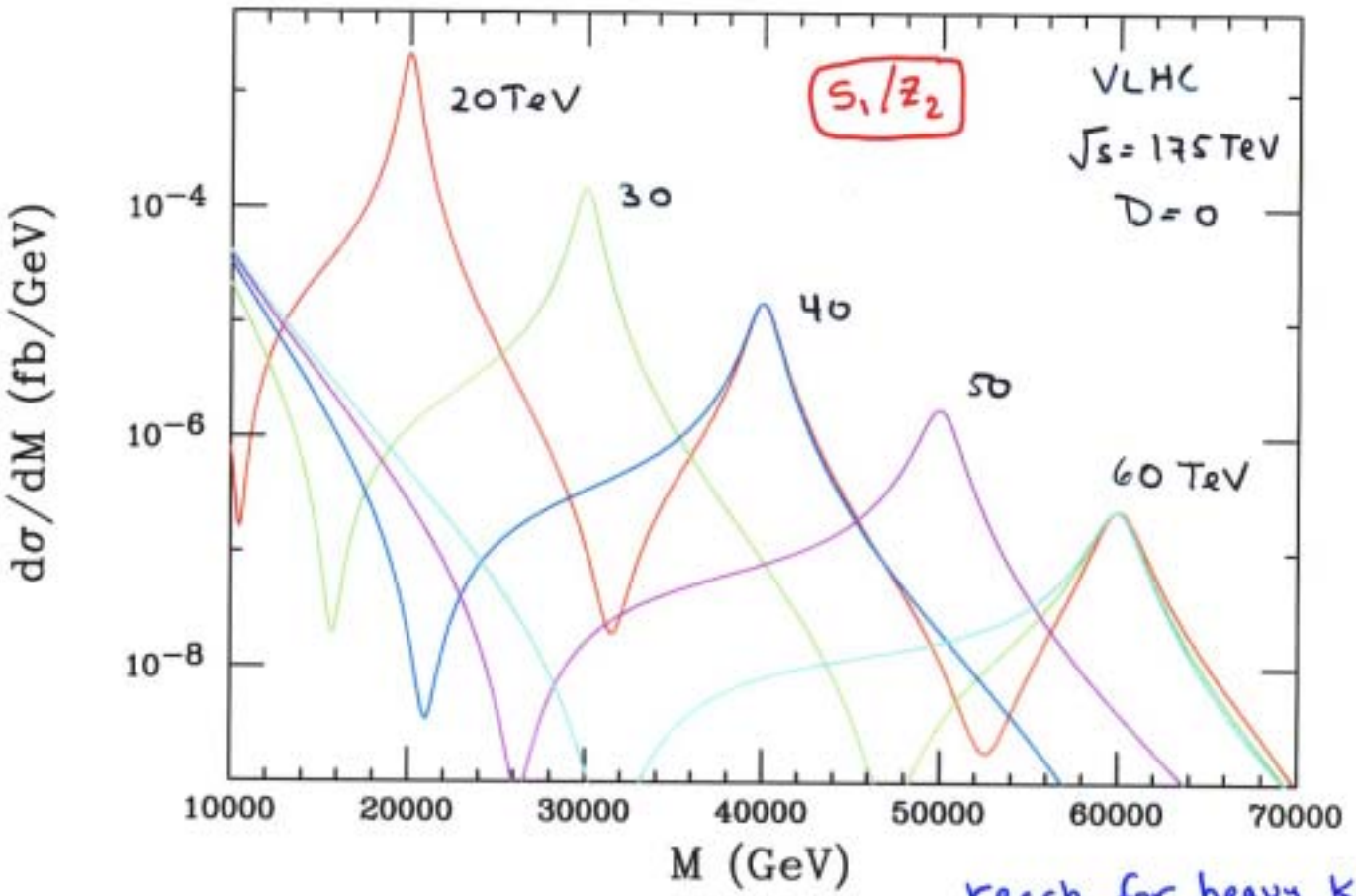
$\Rightarrow$ a series of KK resonances is the hallmark signature of ED... ‡

. Important to see the 'whole' spectrum + not just the first KK .. $\rightarrow$ { # of extra dims + compactification geometry

* Discovery reach @ VLHC $\boxed{\approx 55 \text{ TeV}}$ in DY

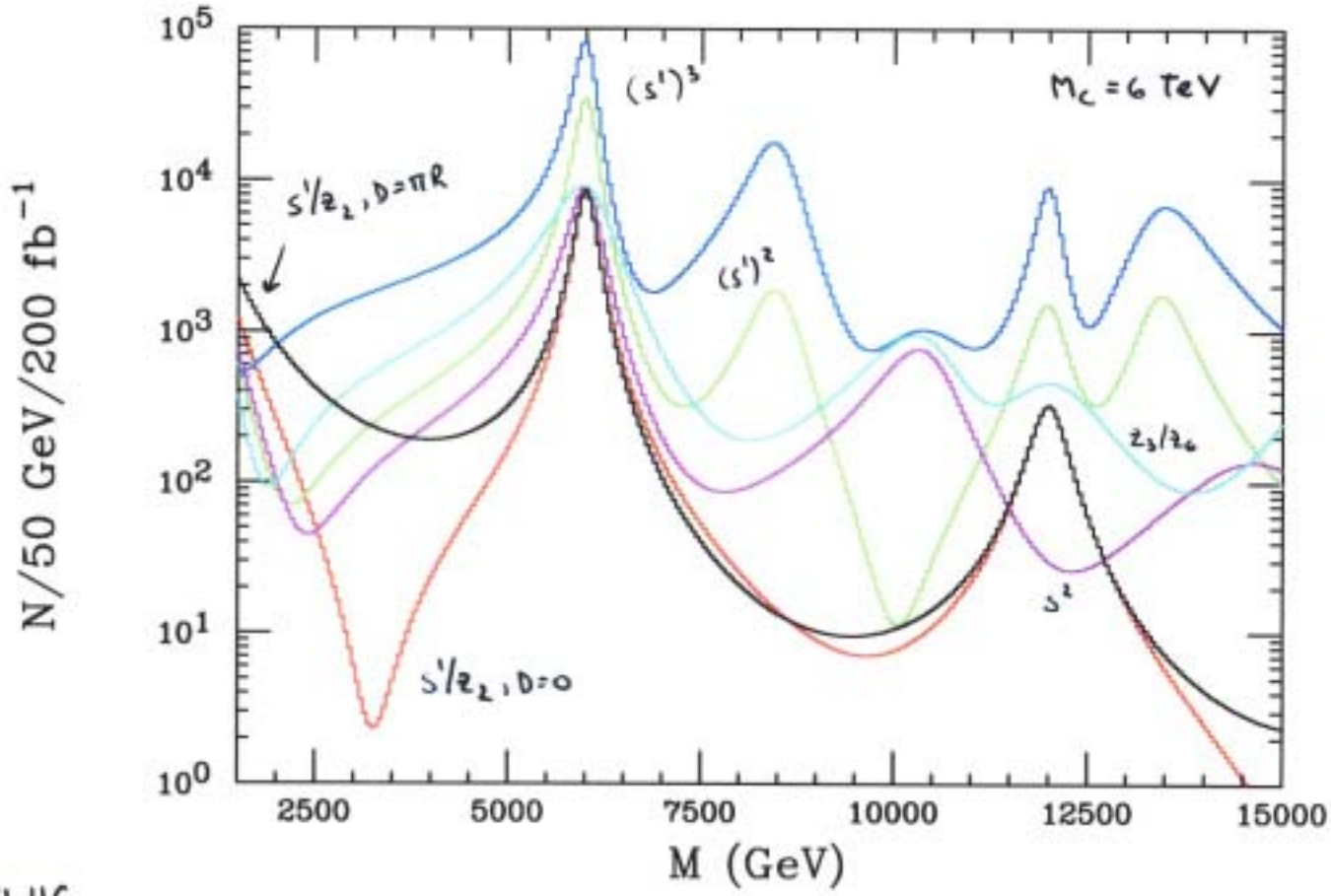
‡ $M_n \equiv M_c \, f(n)_G$ depends on n + compactification manifold

$\gamma^{(1)}/Z^{(1)}$ in Drell-Yan..



reach for heavy KK's
≃ 55 TeV

Drell-Yan KK excitations

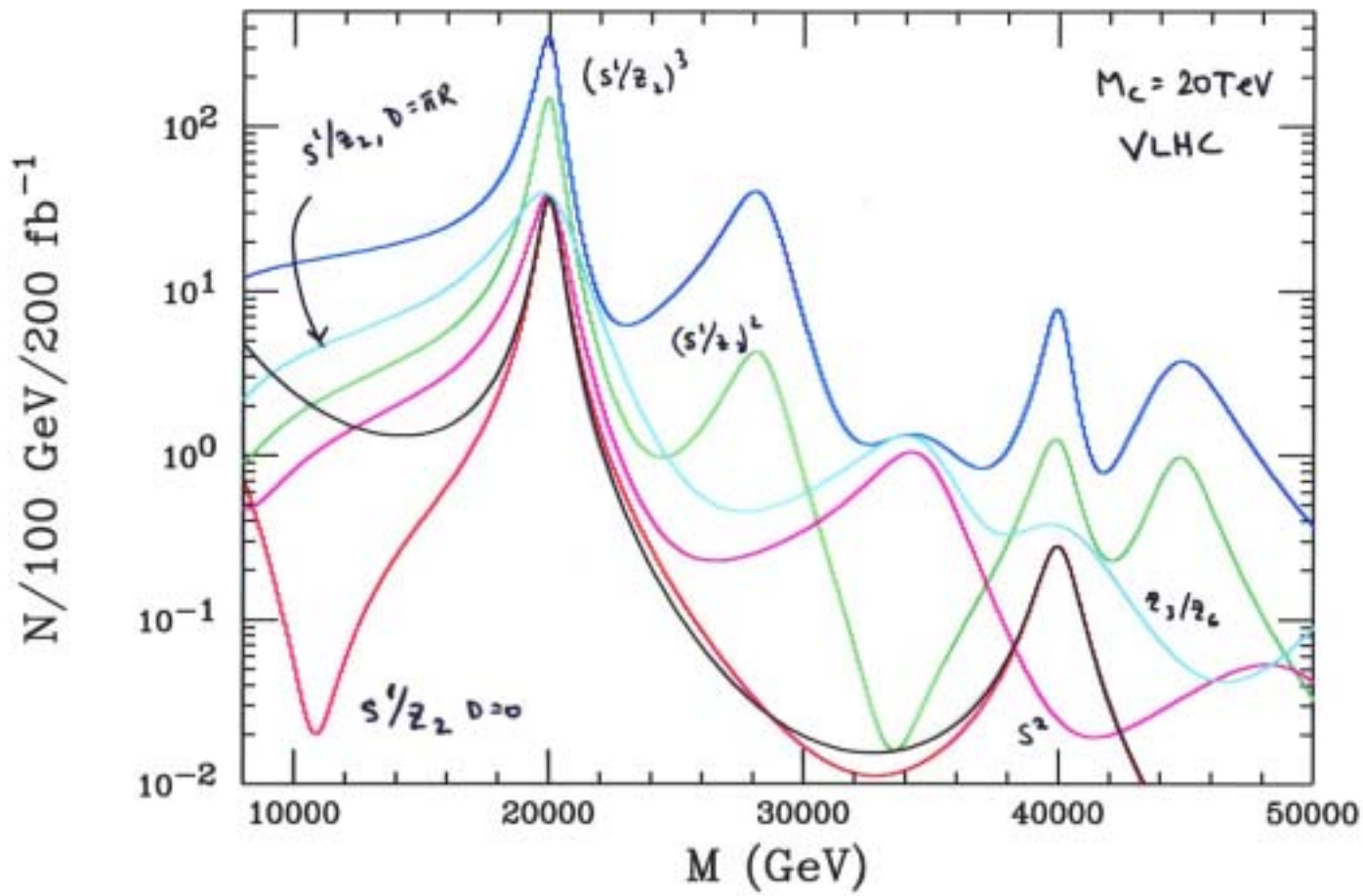


VLHC

$\sqrt{s} = 175$ TeV

Perhaps MORE important to explore the spectrum of KK's...

Drell-Yan KK excitations



$\sqrt{s} = 175$ TeV

ADD

Arkani-Hamed
Dimopoulos
Dvali

$$M_{Pl}^2 = V_n \, M_*^{n+2}$$

$\gtrsim$ TeV

→ finely spaced graviton spectrum

∴ $\gamma/j + \not{E}$ from graviton tower emission

∴ contact int's from graviton exchange

e.g., contact int's produce shoulder in DY ... { probes cut-off scale in KK summation $M_H \sim M_*$

⇒ { DY VLHC reach is $\boxed{45 \sim 60 \text{ TeV}}$ in M_H for $\sqrt{s} = 175 - 200$ TeV $L = 0.2 - 1 \text{ ab}^{-1}$

Randall - Sundrum (RS)

$$\Lambda_\pi = \bar{M}_{Pl} \, e^{-\pi k r_c}$$

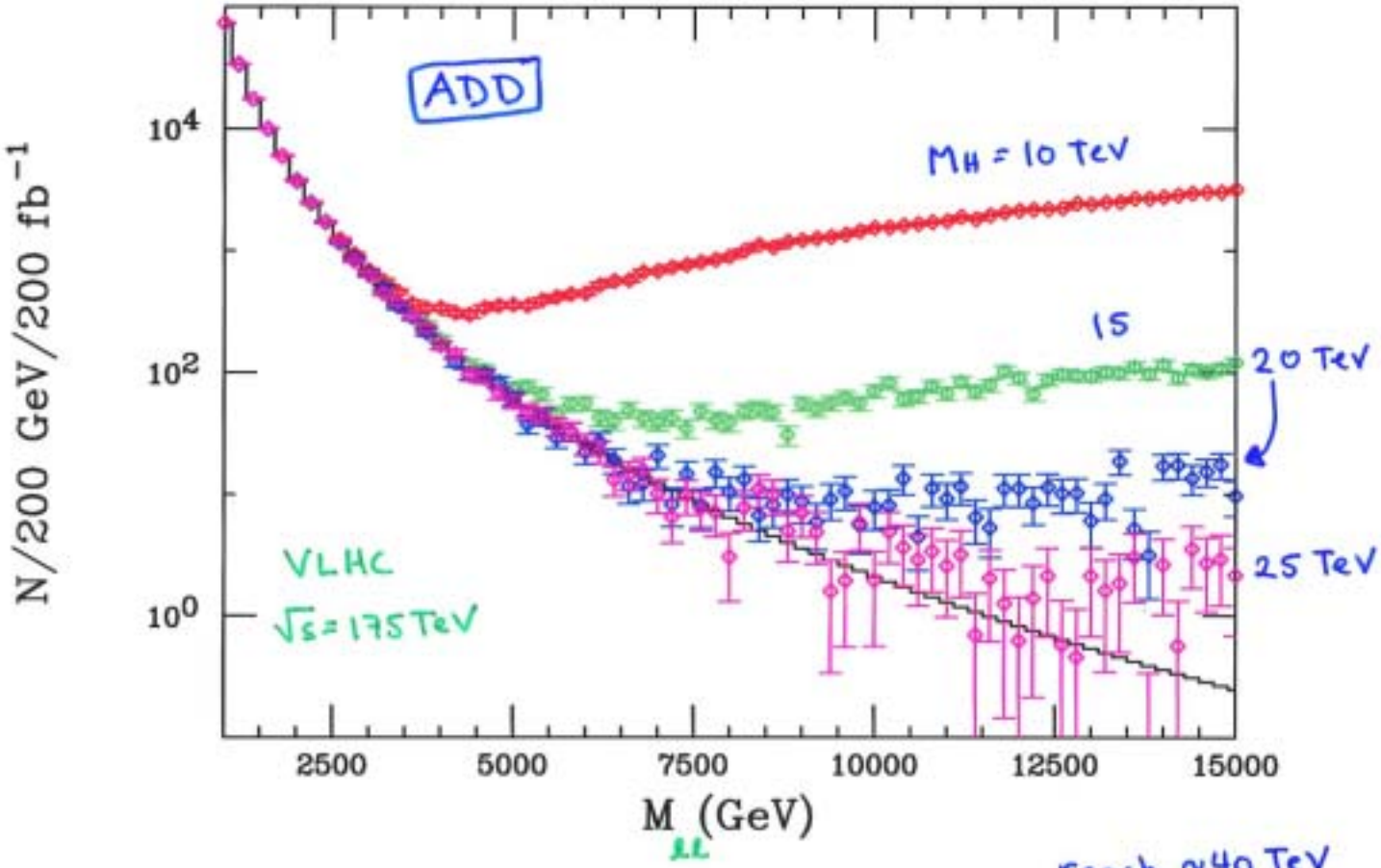
- m_n = roots of Bessel functions

~ TeV masses w/ ~ 1/TeV couplings

→ graviton resonances

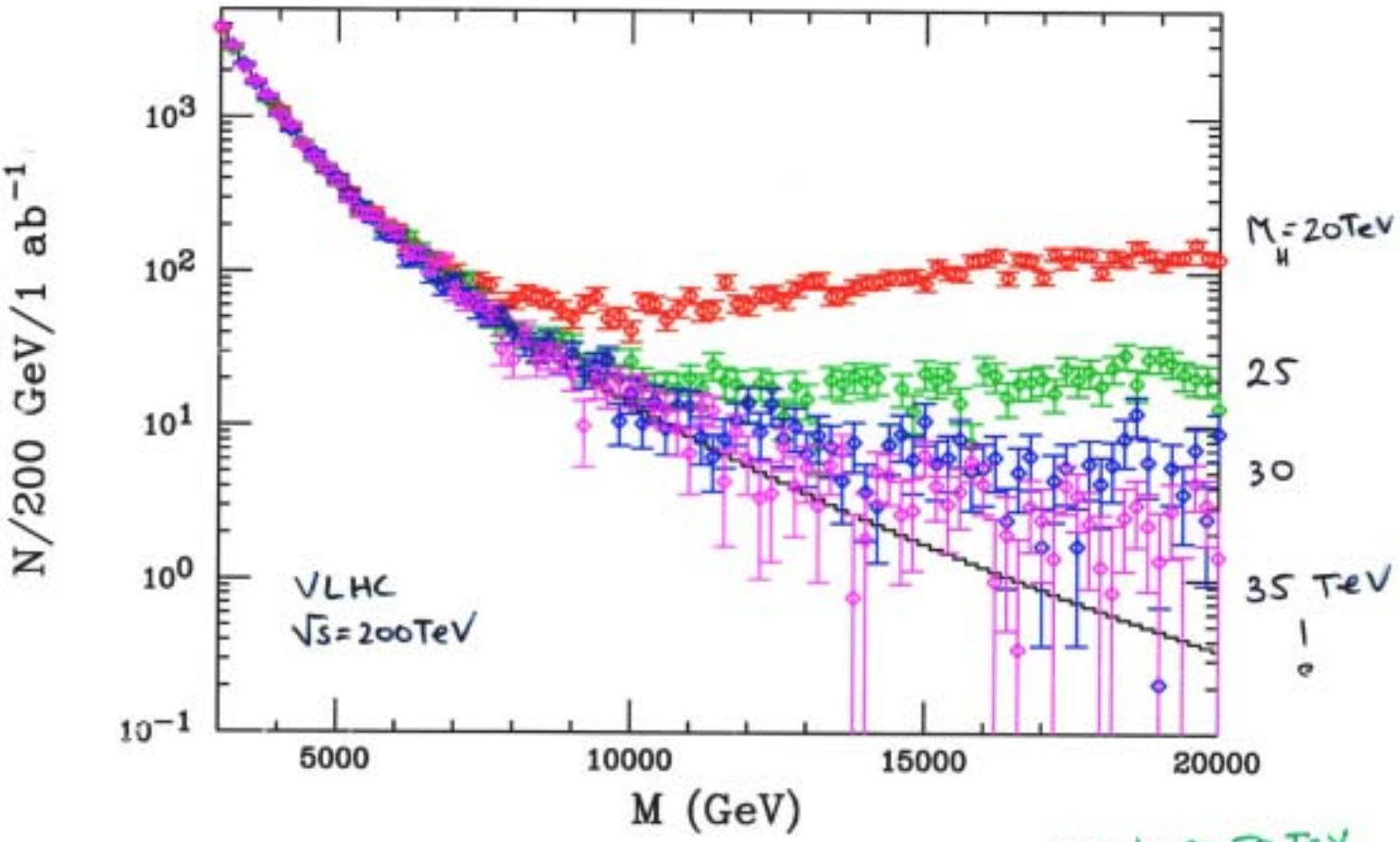
many variants on basic model

Drell-Yan $q\bar{q} \oplus gg \to e^+e^- X$



reach $\simeq$40 TeV
-45 TeV

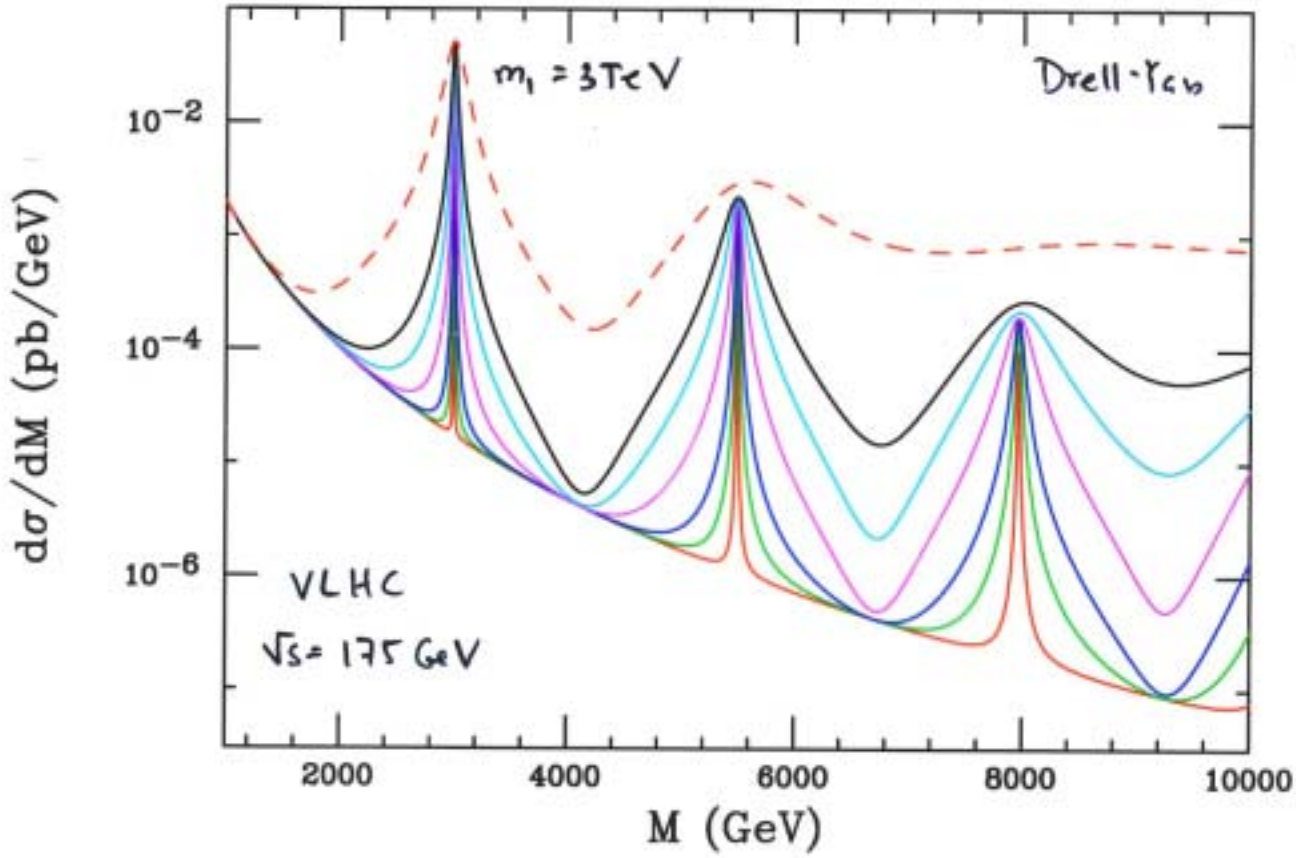
ADD model Drell-Yan



reach ≃ 50 TeV
-60 TeV

Randall - Sundrum graviton resonances

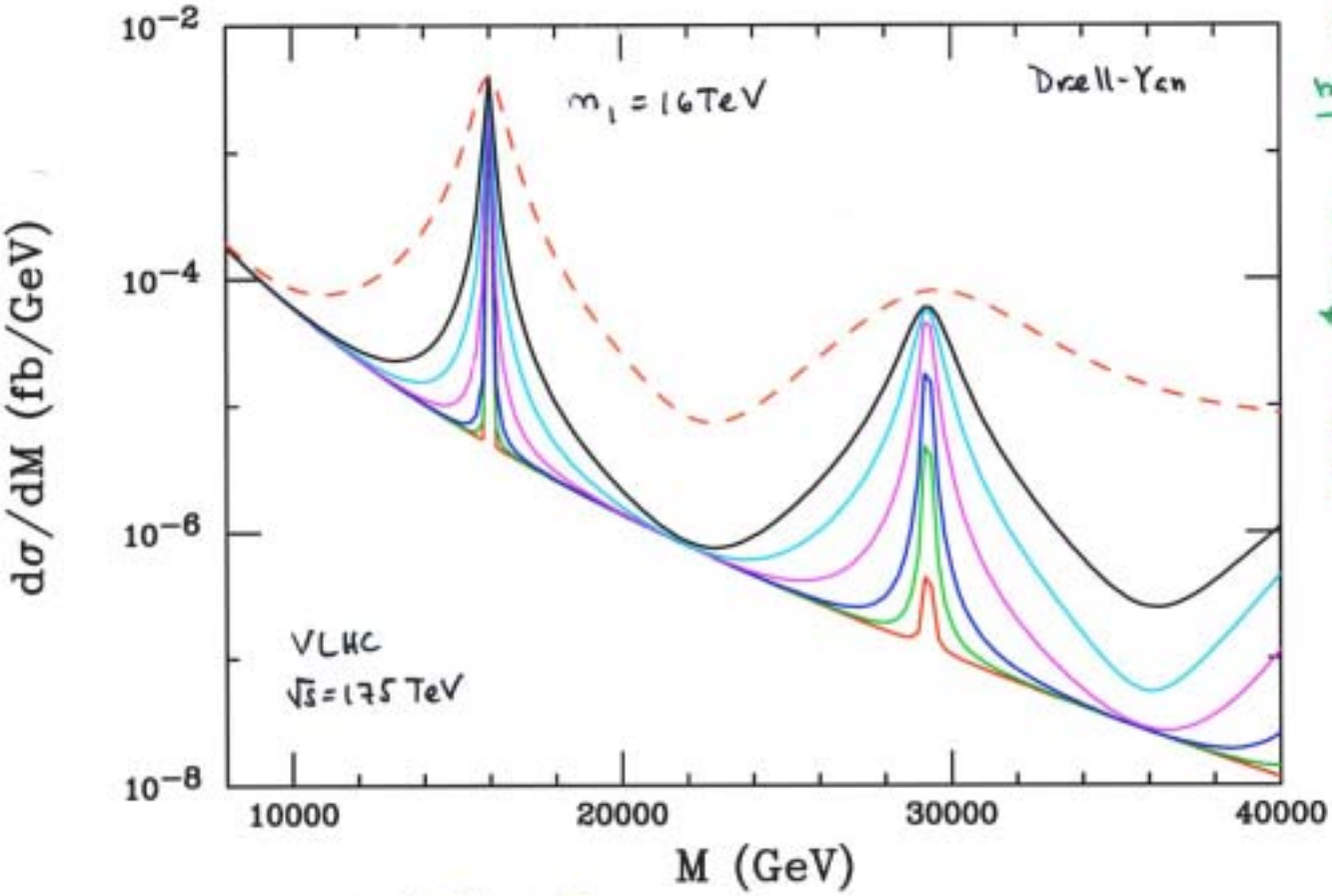
Is it really RS ????



no smearing

$0.01 \leq \frac{k}{\bar{M}_{pl}} \leq 0.2$

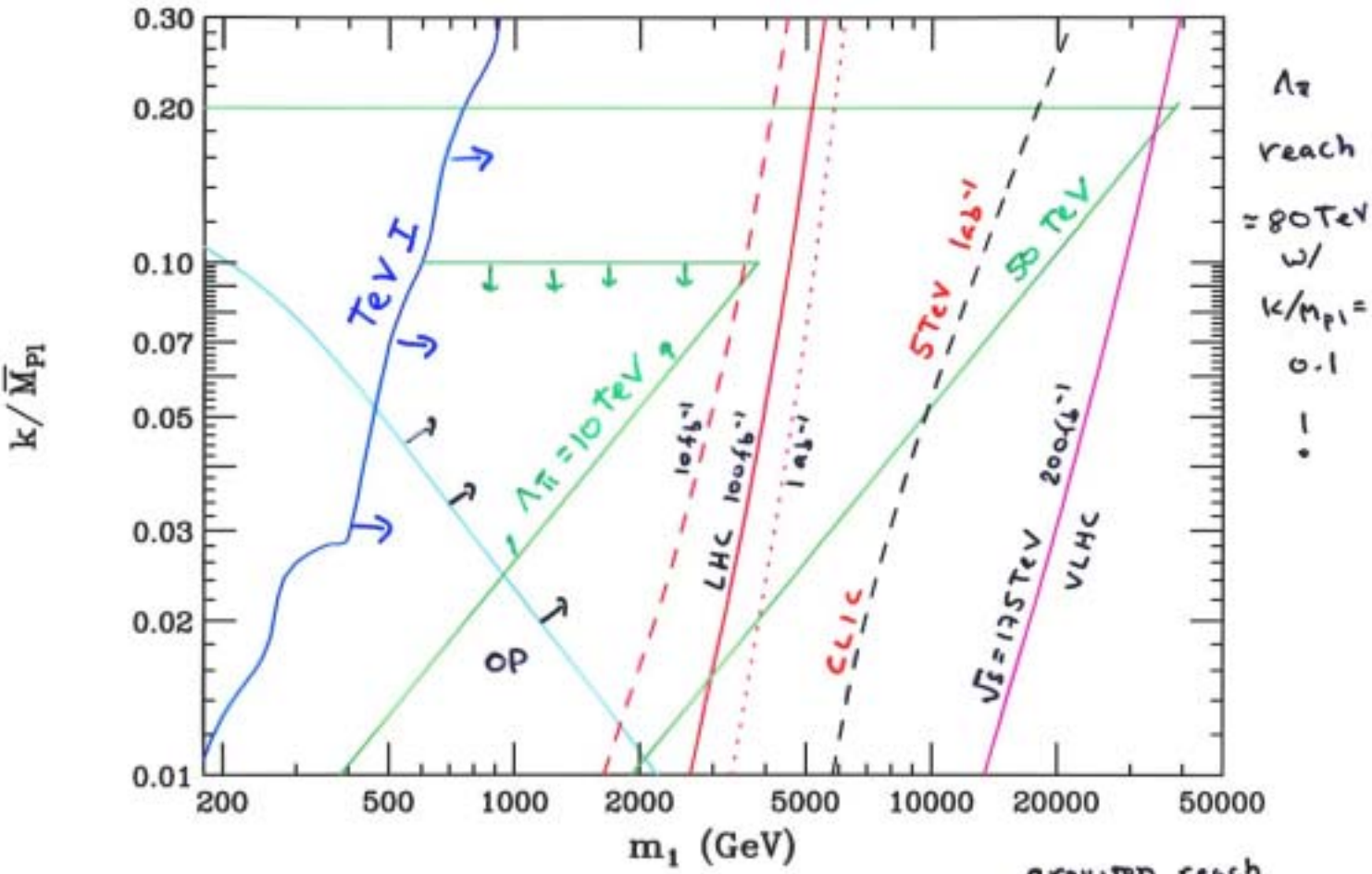
RS gravitons



See multiple peaks - measure peak σ's + Γ's as well as masses

$0.01 \leq C \leq 0.2$

Standard RS model coverage



graviton reach is ≃ 32 TeV

- important AGAIN to see more than the first resonance

$\rightarrow$ brane terms, ...
$\rightarrow$ > 5 dims, ...

} modifications in graviton spectrum

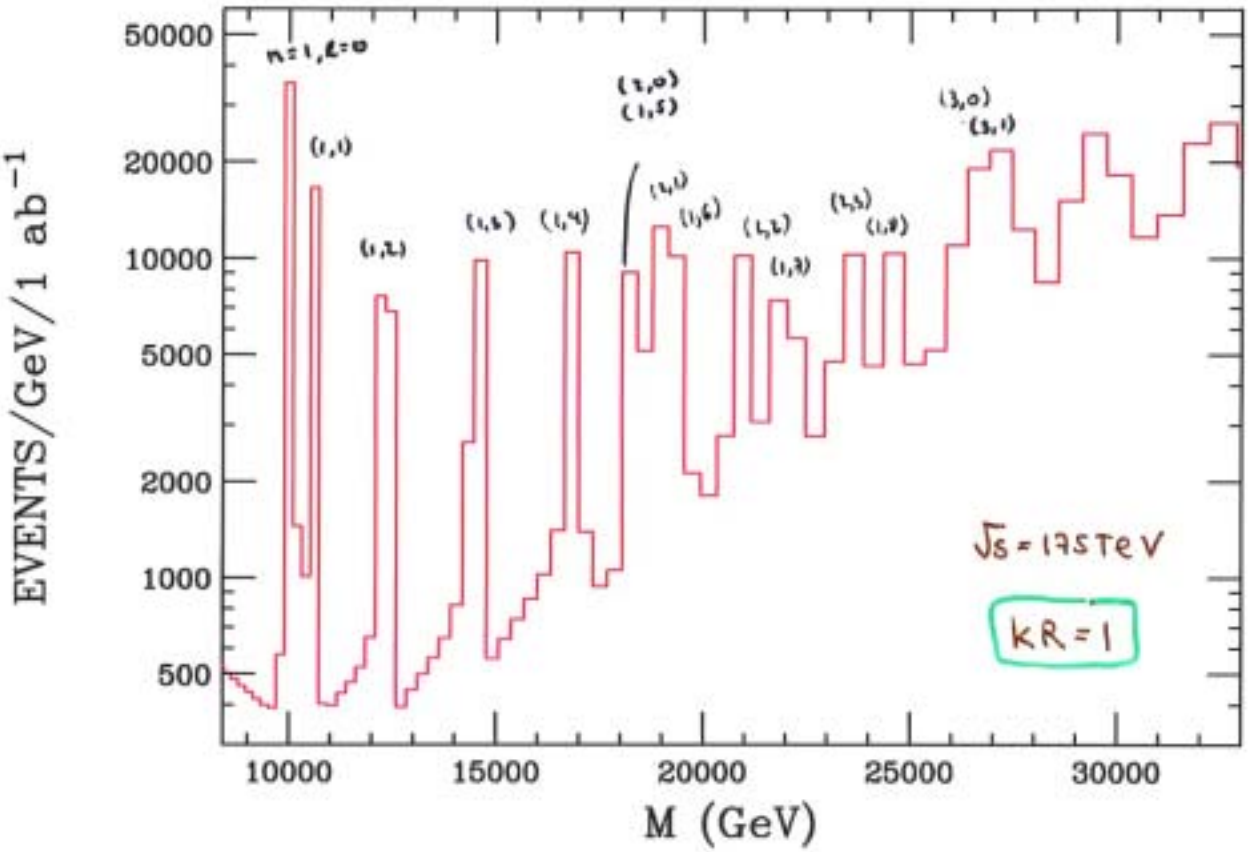
RS reach of VLHC up to $\Lambda_\pi = 80$ TeV

for $k/\bar{M}_{pl} = 0.1$ $\simeq$ 8 times > than LHC

.. a fun mess!

RS ⊗ S^1/Z_2

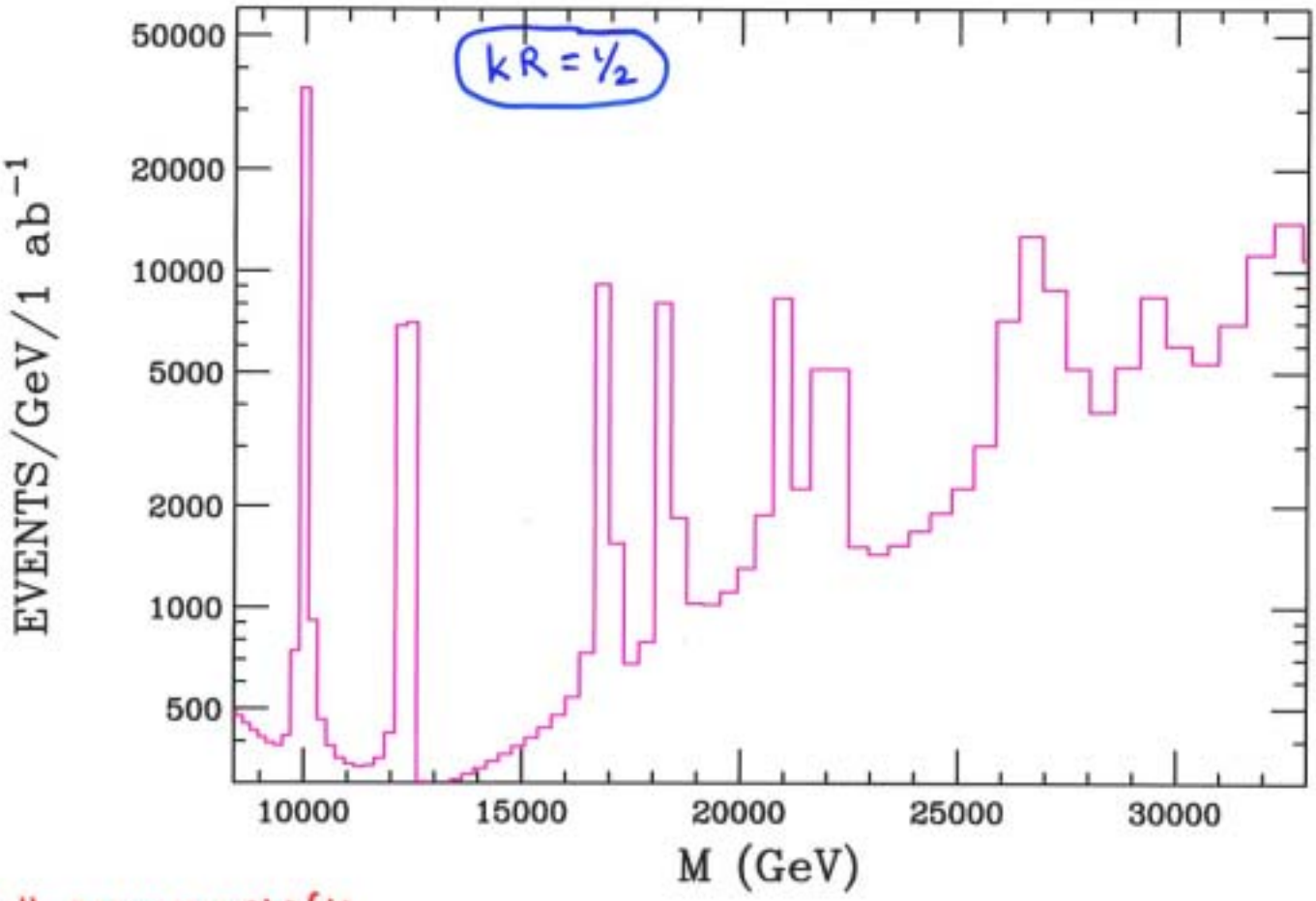
$k/m_{pl} = 0.03$



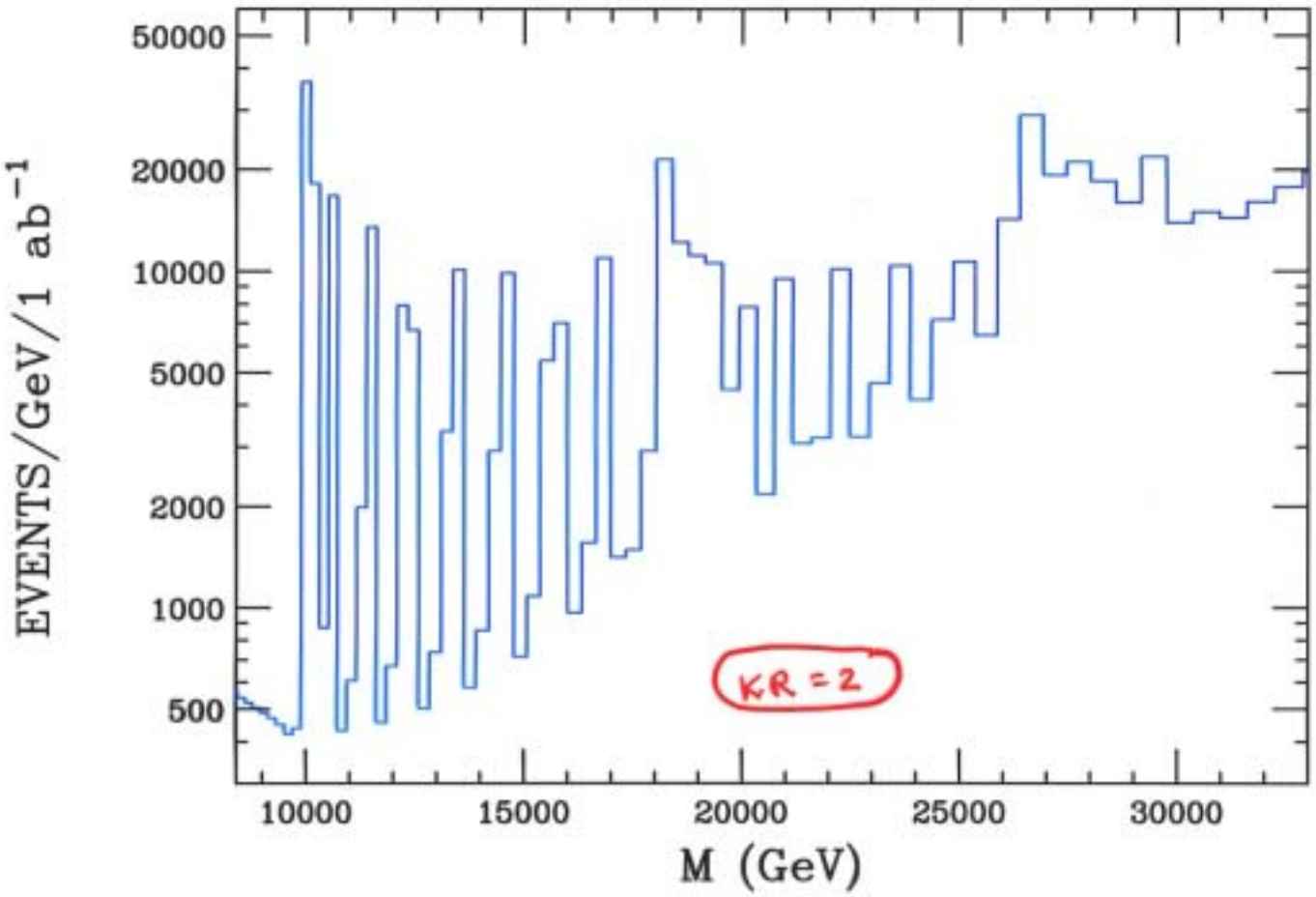
Huge numbers of resonances !!

≥ 17 resonances here

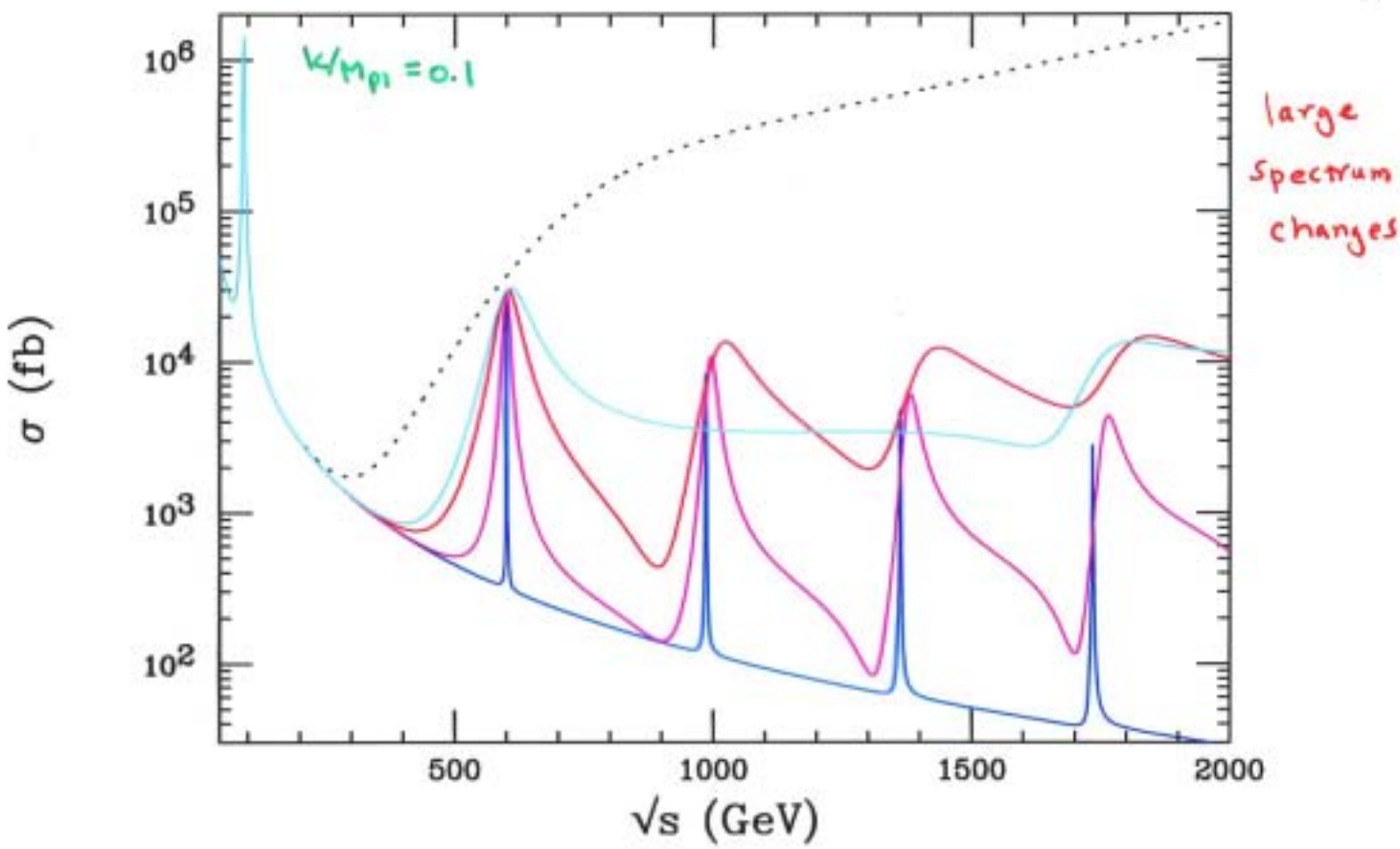
important to see big part of spectrum....



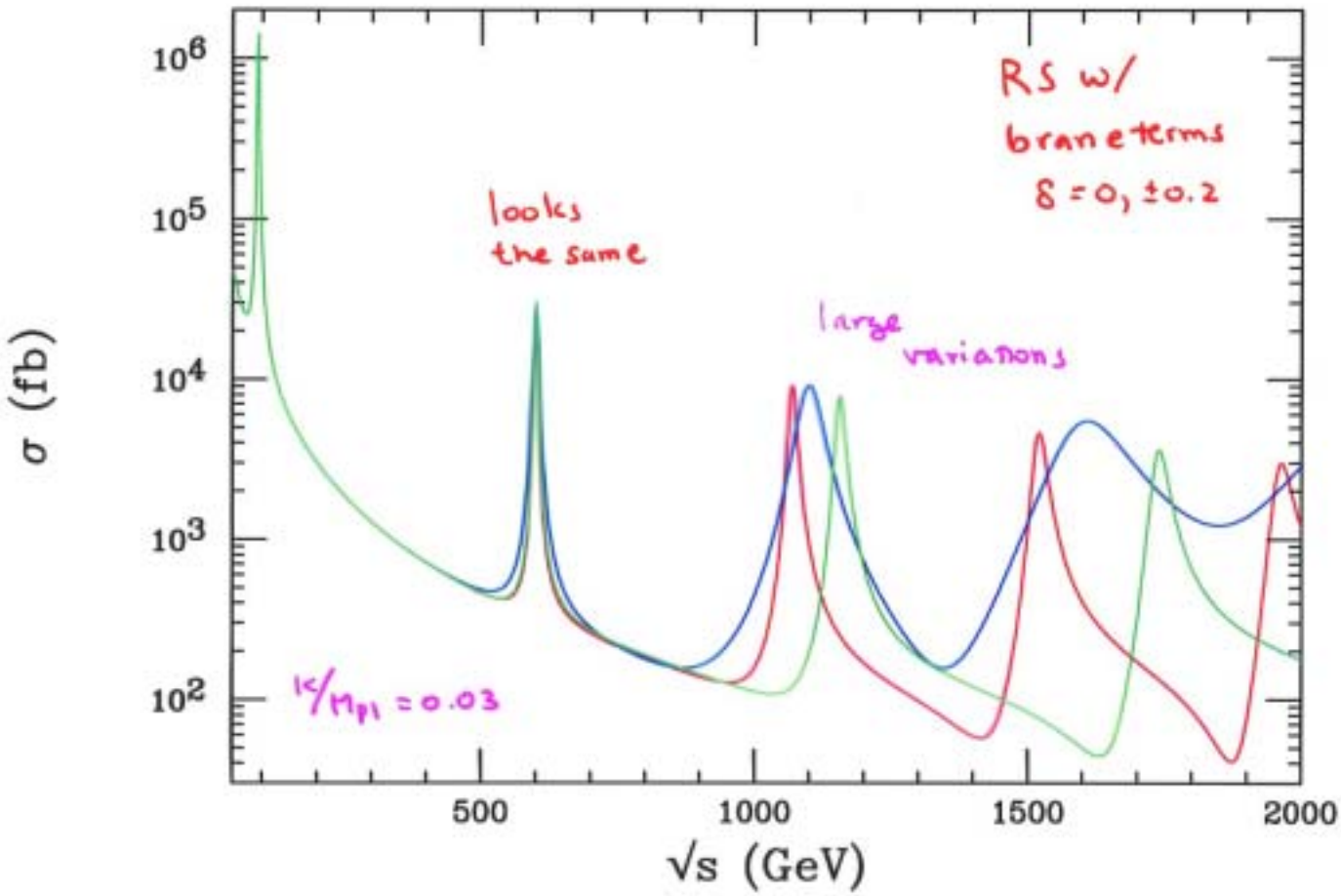
Small parameter shifts significantly change spectrum


EVENTS/GeV/1 ab^{-1}
50000
20000
10000
5000
2000
1000
500
10000
15000
20000
25000
30000
M (GeV)
KR = 2

RS w/ brane terms



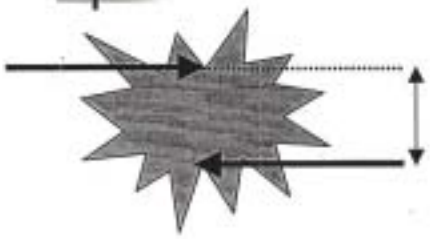
don't just find first evidence - check the spectrum!



THE Paradigm

Black Hole

M_p : Planck scale
n : extra dimenstions
M_{BH} : BH mass



d < R_s $$R_S = \frac{1}{\sqrt{\pi} M_P}\left[\frac{M_{BH}}{M_P}\left(\frac{8\Gamma(\frac{n+3}{2})}{n+2}\right)\right]^{\frac{1}{1+n}}$$

$R_s = \sim 10^{-20}$(m) < $R_n \sim 10^{11}$m(n=1) – $\sim 10^{-17}$m(n=7)

- When an impact parameter (d) is smaller than Schwarzschild radius (R_s), a BH is produced.
- A geometric cross section of BHs is

$$\sigma(M_{BH}) \sim \pi R_S^2 = \frac{1}{M_P^2}\left[\frac{M_{BH}}{M_P}\left(\frac{8\Gamma(\frac{n+3}{2})}{n+2}\right)\right]^{\frac{2}{1+n}}$$

→ $\sigma \sim O(100)$pb → Large cross section! (~10^5event/yr@LowL.)

S.Dimopoulos, G.Landsberg
PRL **87** (2001) 161602

stolen from ⇒ J. Tanaka

Giddings + Thomas
PRD 65 056010 '02

Watch out for different definitions!

$$M_{DL}^{2+n} = G_{4+n}^{-1}$$

$$M_{GT}^{2+n} = \frac{(2\pi)^n}{4\pi\, G_{4+n}}$$

$$M_{GRW}^{2+n} = \frac{(2\pi)^n}{8\pi\, G_{4+n}}$$

$$M_{HLZ}^{2+n} = \frac{(2\pi)^n}{\frac{2\pi^{n/2}}{\Gamma(n/2)} \cdot G_{4+n}}$$

$$\vdots$$

etc. etc...

You get the idea....

IFS / ANDS / BUTS re BH

- BH formation takes place with high $\vec{L}$ + non-trivial Q

  $R_{Horizon} \neq R_{Schw.}$ → Balding Phase to Kerr solution

- Not all of the partonic Energy goes into BH production – losses due to, eg, grav. radiation : $\epsilon \approx 70\%$, n-dependent

- Semiclassical treatment only applies when $M_{BH}/M_x \gg 1$ (3, 5, 10, 100 ??)
  (large entropy → semi-classical validity)

- Decay not-trivial : after Balding, Hawking phase "reasonably well" understood including Quant. Corrts ('greybody' factors)

- Planck phase remenant : $M_x \approx M_{BH}$ what happens ?

⇒ Simulation issues (Tanaka + Parker @ 4th Atlas physics workshop)

Particle Emission Probabilities

- Relative emission probabilities for different spins:

	$s = 0$	$s = \frac{1}{2}$	$s = 1$
$n = 0$	1.0	0.37	0.11
$n = 1$	1.0	0.69	?
$n = 2$	1.0	0.75	?
$n = 6$	1.0	0.58	?
'Black body'	1.0	0.75	1.0

- These allow relative emission probabilities for different particle species to be calculated:

	q	$l^{\pm}$	ν	g	γ	Z	$W^{\pm}$	H
$n = 0$	66.5	11.1	5.5	4.5	0.6	3.1	6.2	2.5
'Black body'	56.5	9.4	4.7	16.8	2.1	3.1	6.3	1.0

"greybody" factors 'distort' the weights of spin-0, ½ & 1 final states in BH decay by O(1) corrections

Parker

Tanaka

Simulation

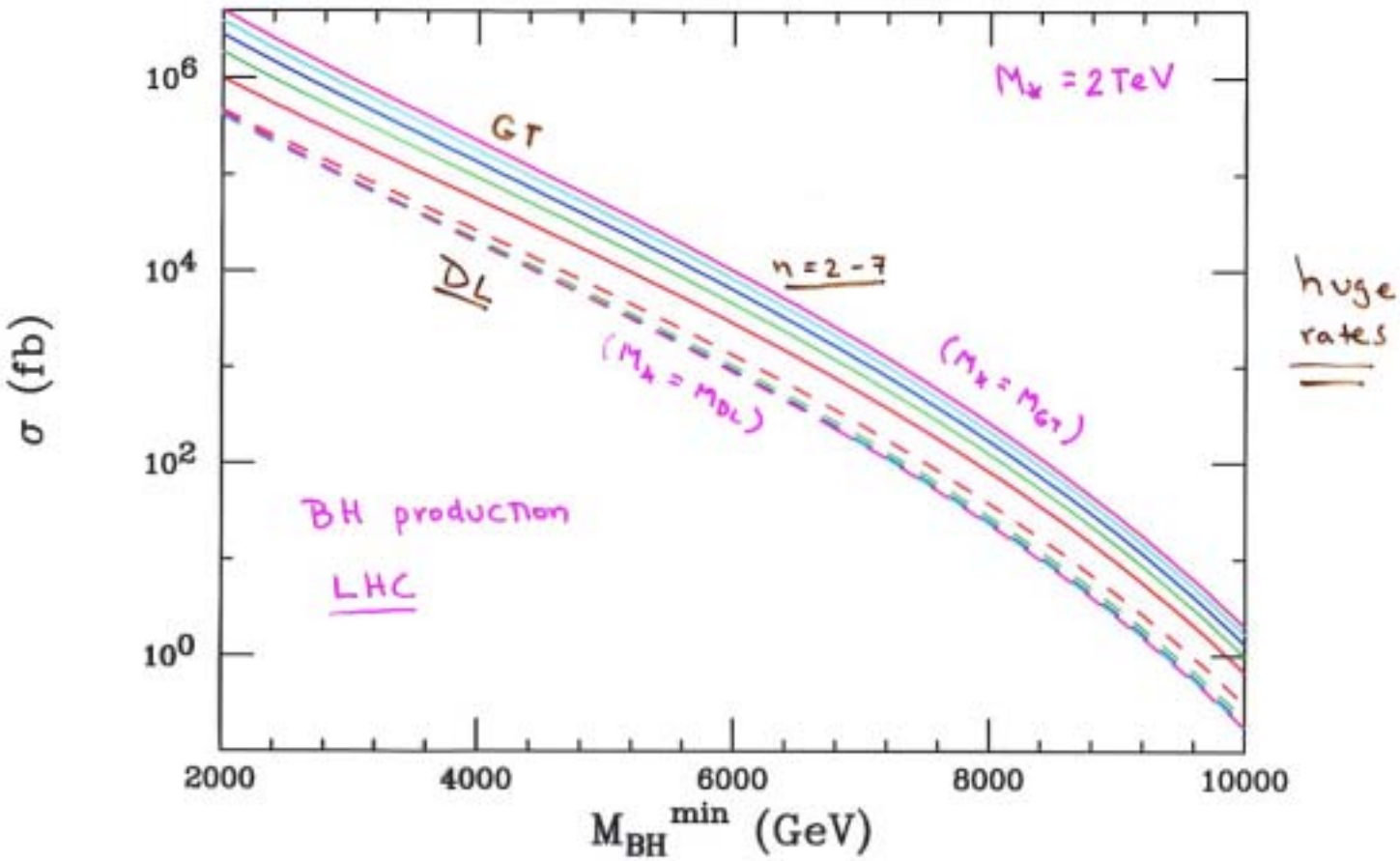
- Signal samples BH → PYTHIA → ATLFAST
  - We have developed ***our original BH generator***.
  - Initial state parton showers, hadronisation and decay are performed using PYTHIA 6.2.
  - Q^2_{ren}=(Generated BH mass)^2
- Background samples
  - jj, Wj, Zj, bb, tt, WZ, WW, ZZ, γj, γV, $\gamma\gamma$
    "j" = quark, lepton, gluon by PYTHIA 6.2.

All samples are processed through the *ATLFAST*. (Low luminosity condition)

A toy model ...

- PDF = CTEQ5L

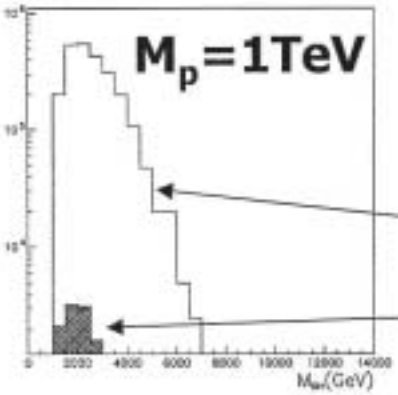
BH's → huge rates at LHC



Tanaka

Mass Distributions

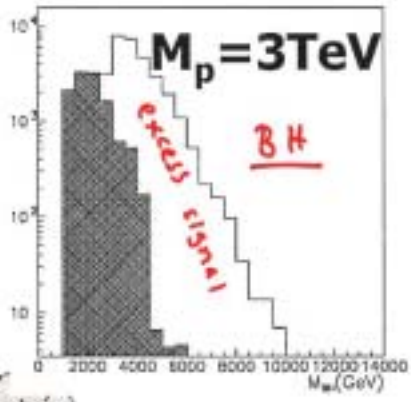
n=3, $\int L$ = 30 fb^{-1}

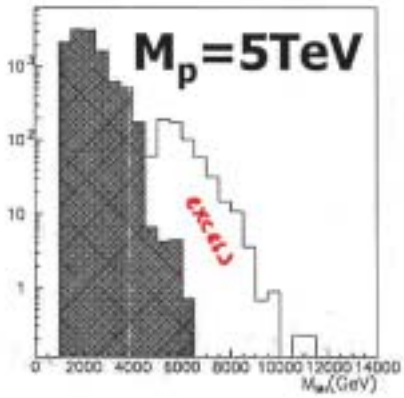


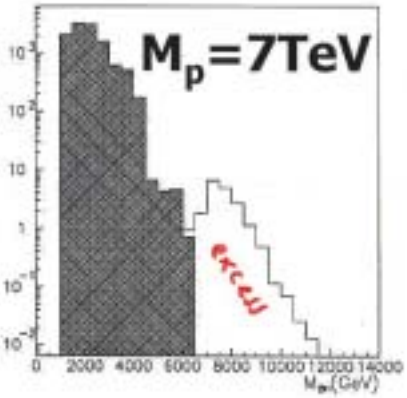
- As M_p becomes larger, the excess of events becomes smaller.

Signal+Background

Background

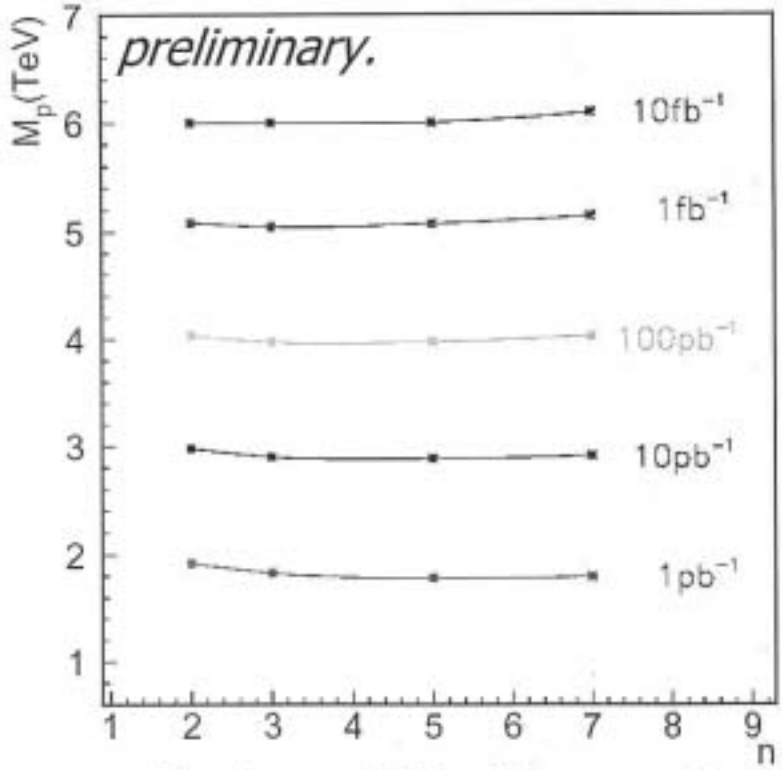






Tanaka

Discovery Potential



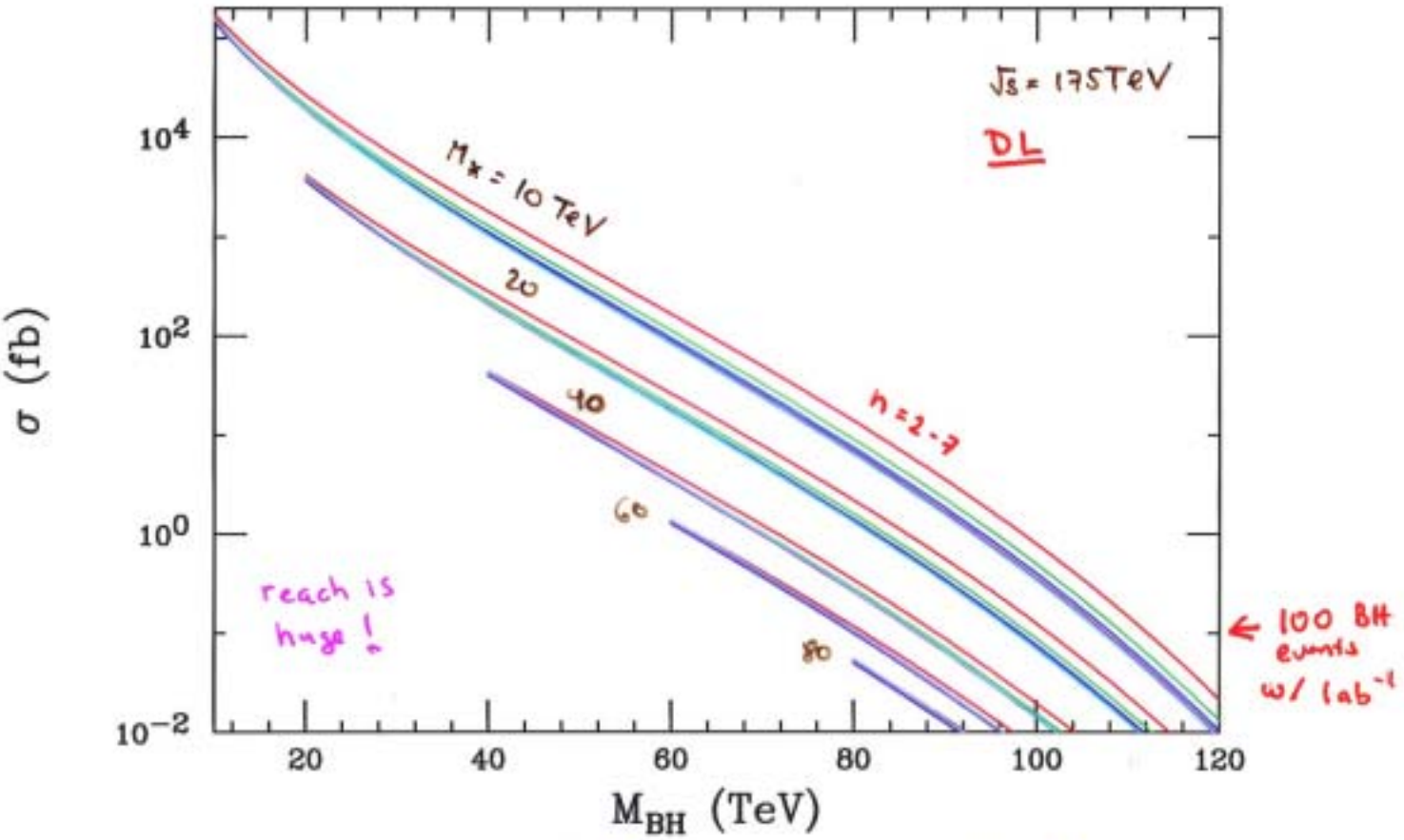
Contour of 5σ discovery in (M_p,n) plane

- Discovery potential depends almost only on M_p.
- **M_p < 4TeV**
  - BH will be discovered with $\int \mathcal{L}$ **= 100 pb^{-1}**, which corresponds to **~ 1 day !**

≈ 30 events !!

BH production at VLHC

rates big
even for large M_*



Reach $\approx$ M_* = 80 TeV

"Easy" to modify TeV-scale type models to suppress BH production...

Finite-length models: Cavaglia, Das + Maartens hep-ph/0305223

$$\Delta x \, \Delta p \geq \hbar \left\{ 1 + (\alpha' \ell_{PL} \Delta p / \hbar)^2 \right\} \quad \text{(string/NC)}$$

α': $O(1)$ parameter; ℓ_{PL}: Planck length

$$\boxed{r_{schw} \geq \alpha \, \ell_{Pl}} \rightarrow M_{BH} \geq f(n) M_*$$

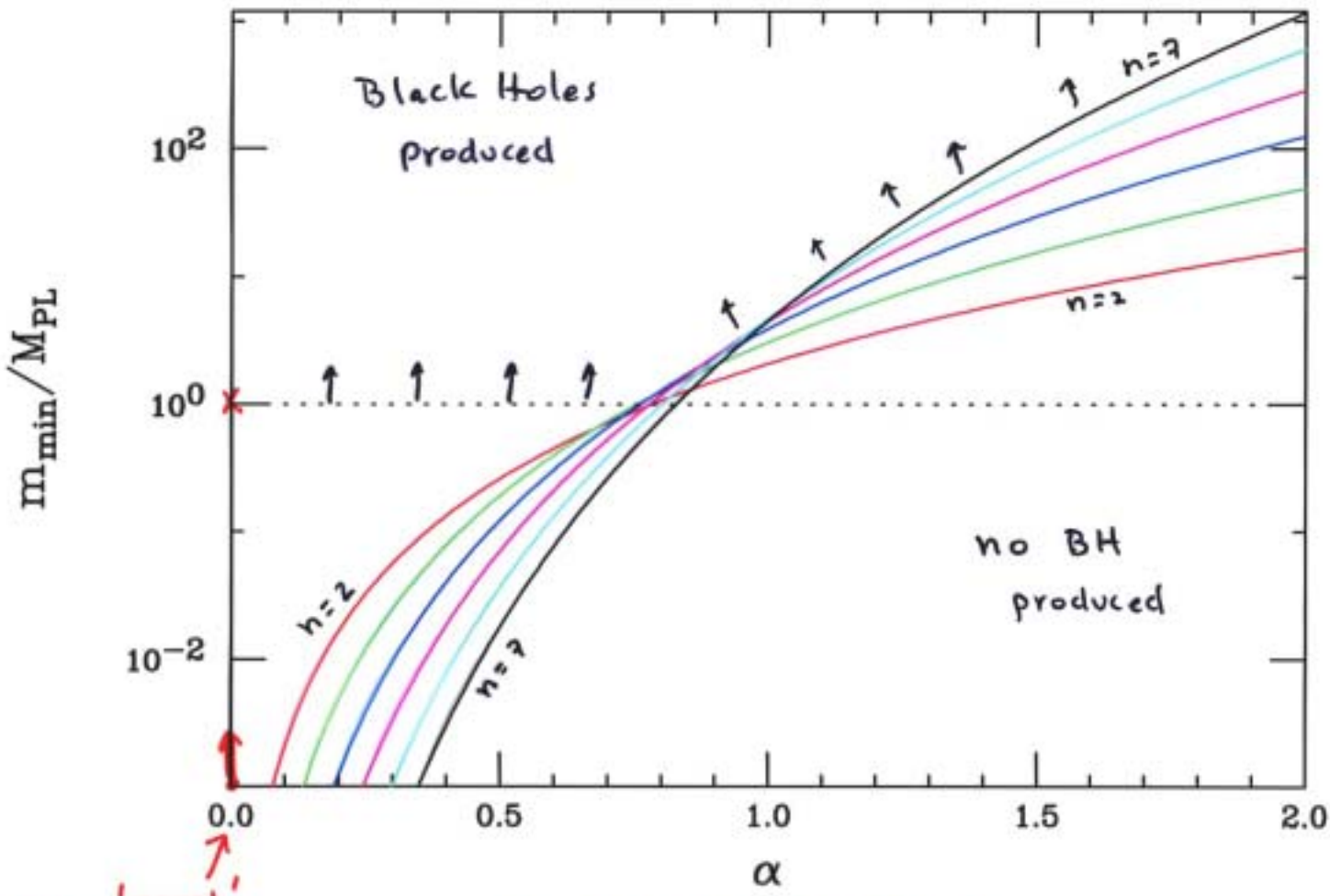
→ For $\alpha \sim O(1)$ + $M_* \sim 1$ TeV

EVEN VLHC will <u>not</u> see <u>BH production</u>!

⇒ raises $M_{BH}^{min}(M_*)$ + cuts off $\underline{\sigma}$ integrations for any n

large σ_{BH} not a 'done deal'...

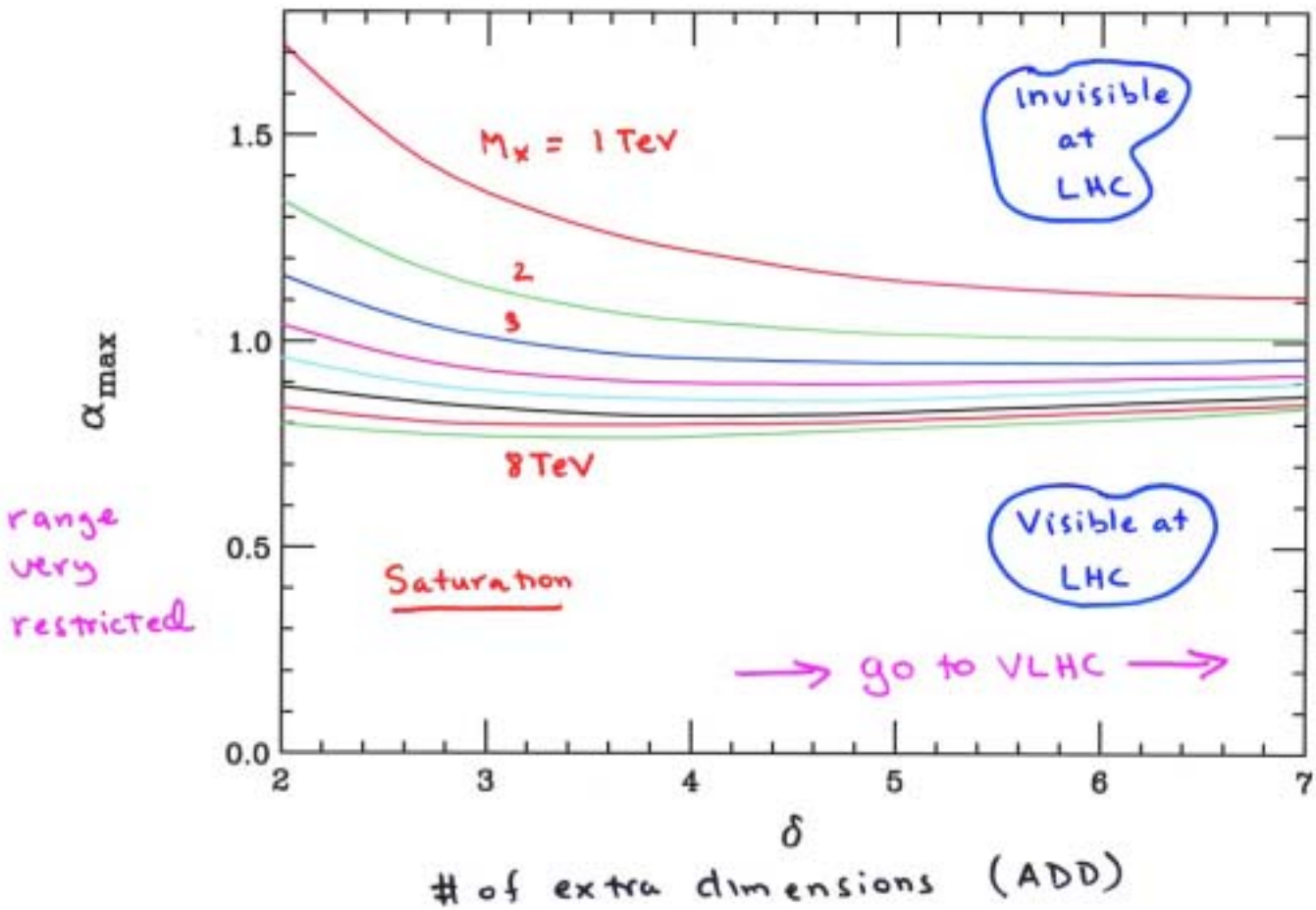
minimum BH mass in finite-length model



$\alpha = 0$ 'usual' case

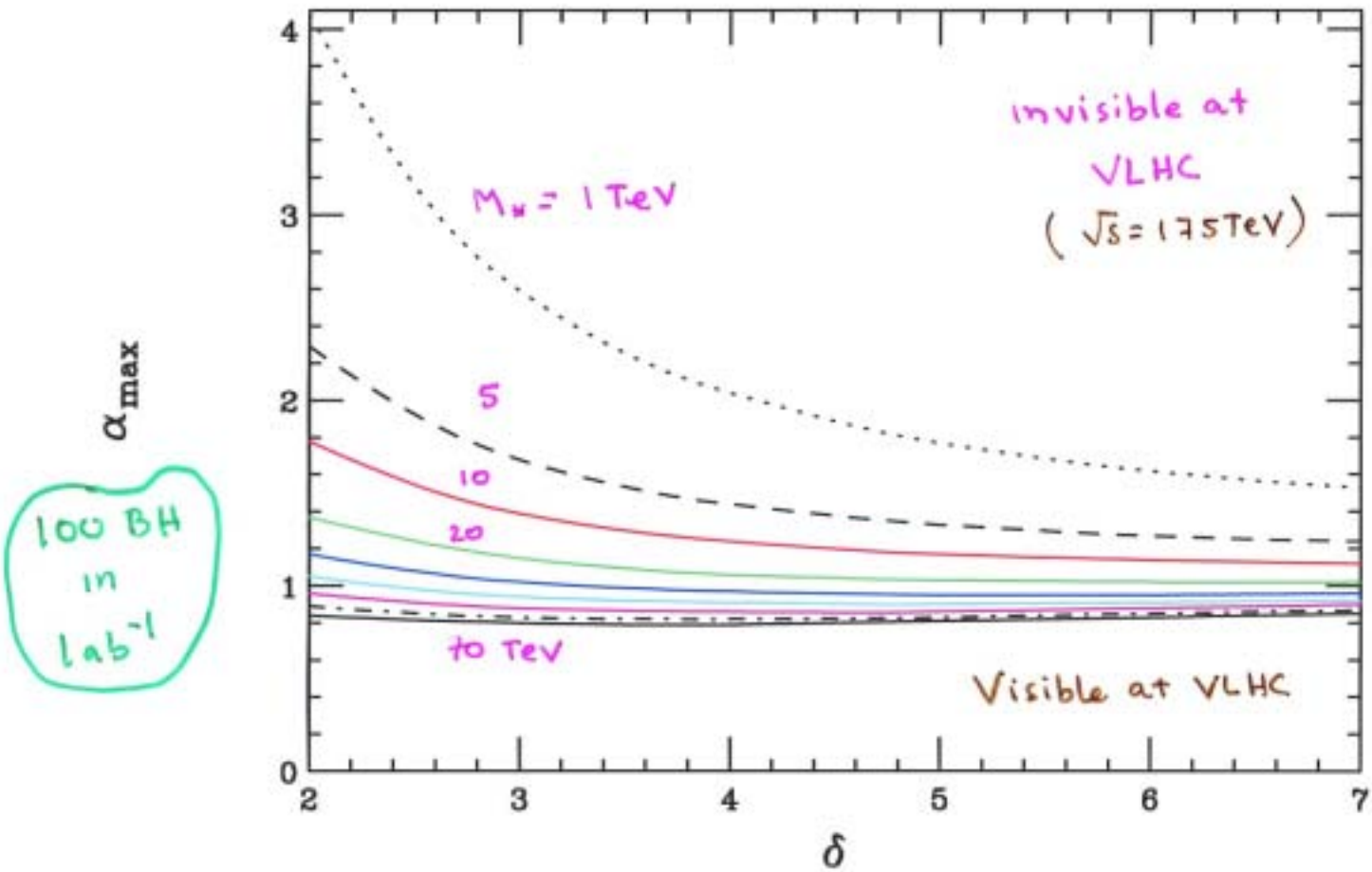
$O(1)$ length parameter

Upper bound on α from LHC BH visibility (100 BH's in 200 fb^{-1})



range restricted <u>even</u> for $M_* = 1$ TeV

- even for VLHC



Beyond BH

$\Rightarrow$ String Balls + p-branes

- Dimopoulos + Emparan hep-ph/0108060
- Ahn, Cavaglia + Olinto hep-ch/0201042
- Cheung, hep-ph/0205033
- Cavaglia, hep-ph/0210296

Below $M_{BH} = M_s/g_s^2$ the BH becomes a highly excited 'jagged' string state

a String Ball

such that

$$\sigma_{SB} = \sigma_{BH}\big|_{M = M_s/g_s^2}$$

Claim:

match at boundaries

$$M_s \ll M_{SB} \leq \frac{M_s}{g_s} \quad : \quad \sigma \sim \frac{M_{SB}^2}{M_s^4}$$

Saturates unitarity at upper end

$$\frac{M_s}{g_s} \leq M_{SB} \leq \frac{M_s}{g_s^2} \quad : \quad \sigma \sim \frac{1}{M_s^2}$$

$$M_s/g_s^2 \leq M_{BH} \quad : \quad \sigma \sim \sigma_{BH} \text{ above}$$

and $M_X^{n+2} \simeq M_s^{n+2}/g_s^2$ $\quad (g_s^2 \ll 1)$ weak coupling

- SB decay ~ BH decay qualitatively

- Even stranger is the possibility of making p-branes

(The BH is just a $p=0$ brane ....)

$$\frac{\sigma(pB)}{\sigma(BH)} = \left(\frac{M}{M_*}\right)^{\frac{2p}{(n+1)(n-p+1)}} \underbrace{\mathcal{N}(n,p)}_{\text{a messy numerical factor } \sim O(1)}$$

.... in the case where all dims are $\sim M_*^{-1}$ in size

by the same geometrical arguments. ...

$\Longrightarrow$ Since $M_{\substack{pB \\ BH}} > M_*$, $\sigma(pB) \gtrsim \sigma(BH)$ ....

e.g, VLHC $\sqrt{s} = 200\,\text{TeV}$ $\underline{M_{SB}^{min} = 2M_*}$, $\underline{M_{\substack{BH \\ pB}} = 5M_*}$

$\underline{n=5}$

$\underline{M_* = 15\,\text{TeV}}$

$\Rightarrow$ $\sigma_{BH} = 0.43\,\text{pb}$, $\sigma_{SB} = 180\,\text{pb}$, $\sigma_{pB} = 1.3\,\text{pb}$

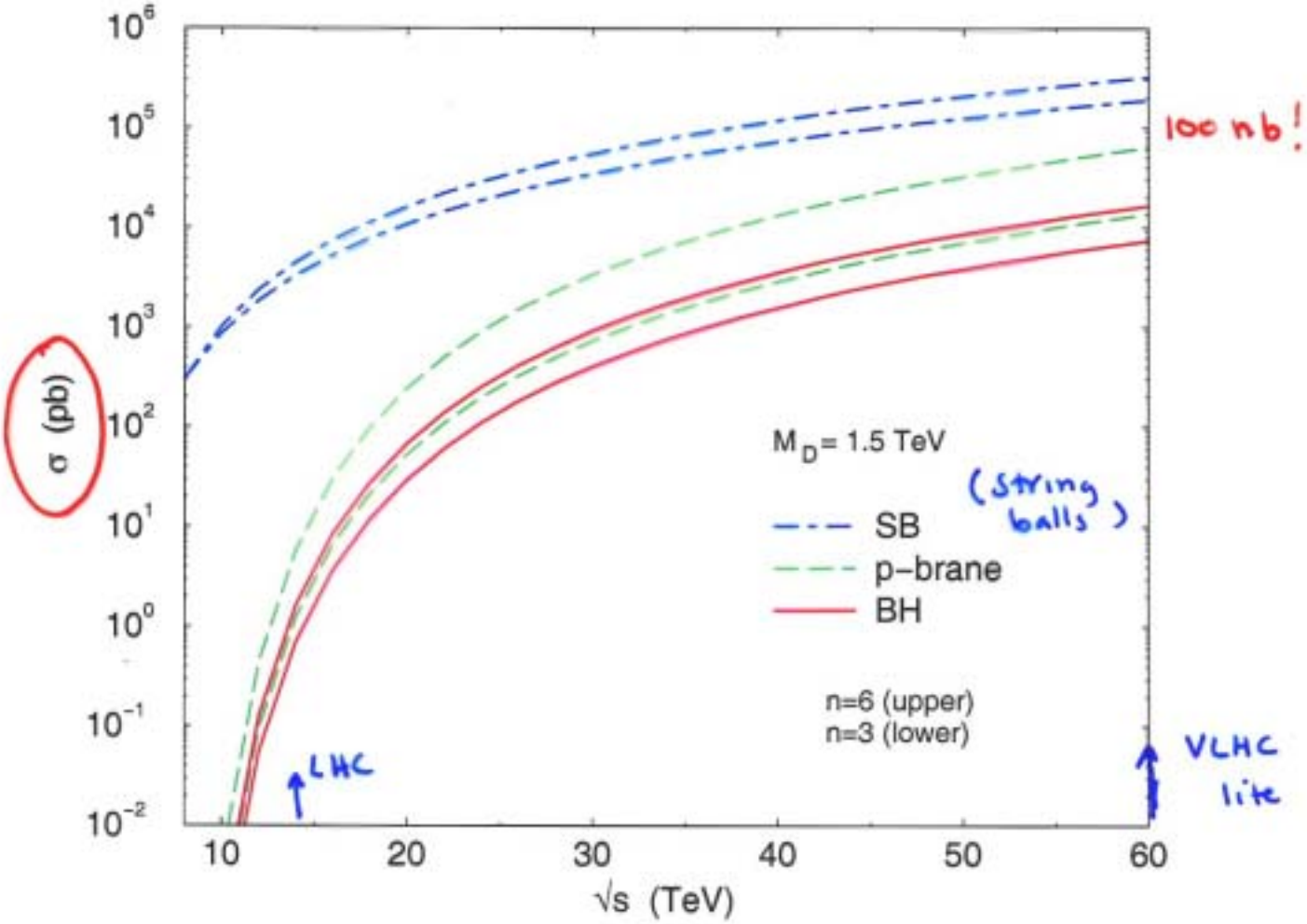
for			
	$\shortparallel$		
$M_* = 25\,\text{TeV}$	0.25 fb	6.6 pb	0.78 fb

Though BH's have large σ's,

other Extra-dim objects may have

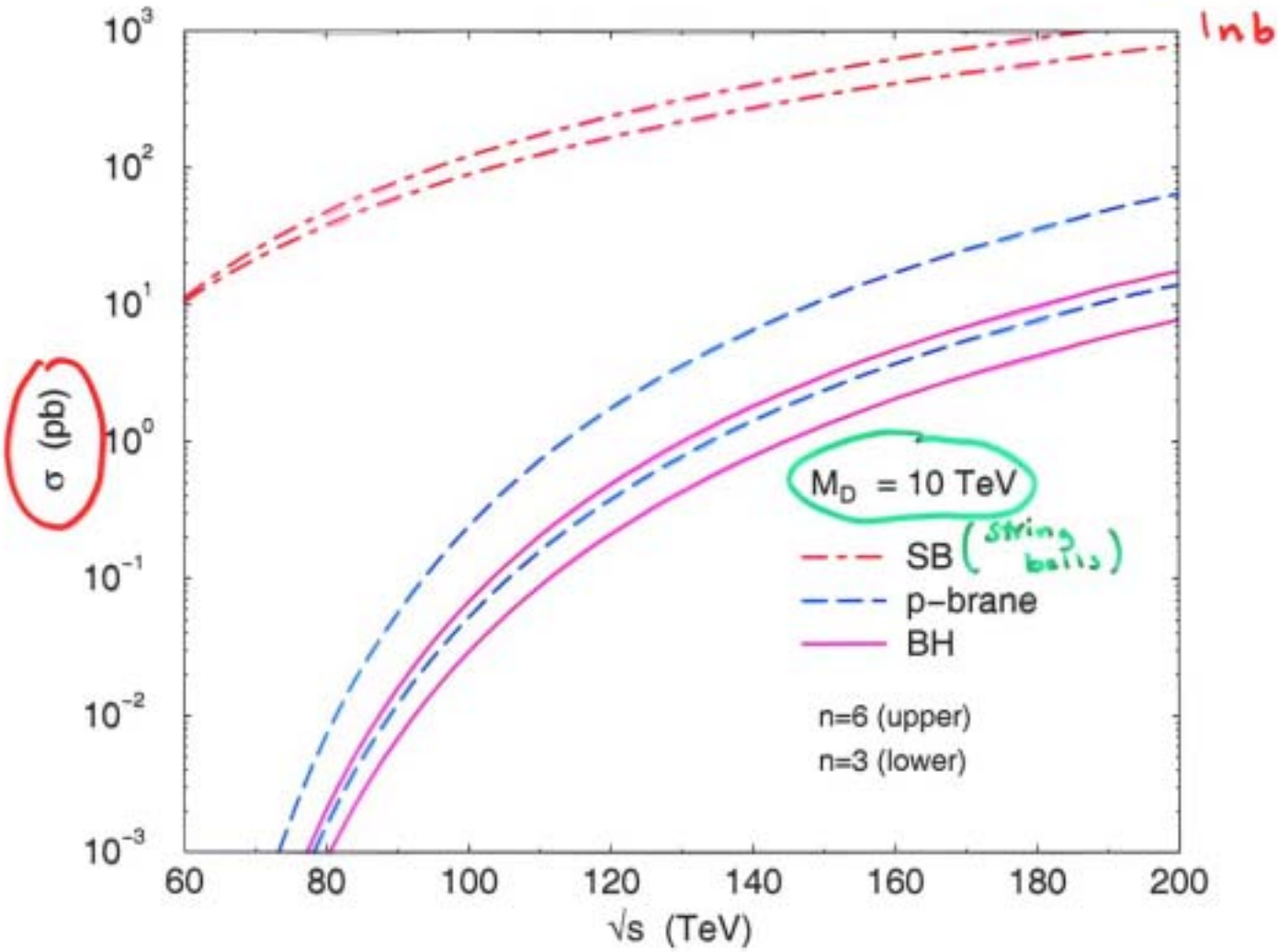
larger ones....

K. Cheung



... this persists at VLHC energies

K. Cheung



Really Strange

non-commutative SPACE-TIME :

$$[\hat{x}_\mu, \hat{x}_\nu] = i\,\theta_{\mu\nu} \sim M_{NC}^{-2}$$

→ NON C. QED, QCD, SM
→

→ new interactions not allowed in SM (at all)

e.g, $Z \to \gamma\gamma$ ‡

<u>VLHC</u> : modification of $q\bar{q}g$, $3g$, $4g$ vertices

e.g, $\sim \theta\, FFF$ terms $\sqrt{s} \lesssim m_0$

modifies jet production ...

- Has <u>not</u> been studied in detail for colliders....

‡ due to Lorentz violation

Summary + Conclusions

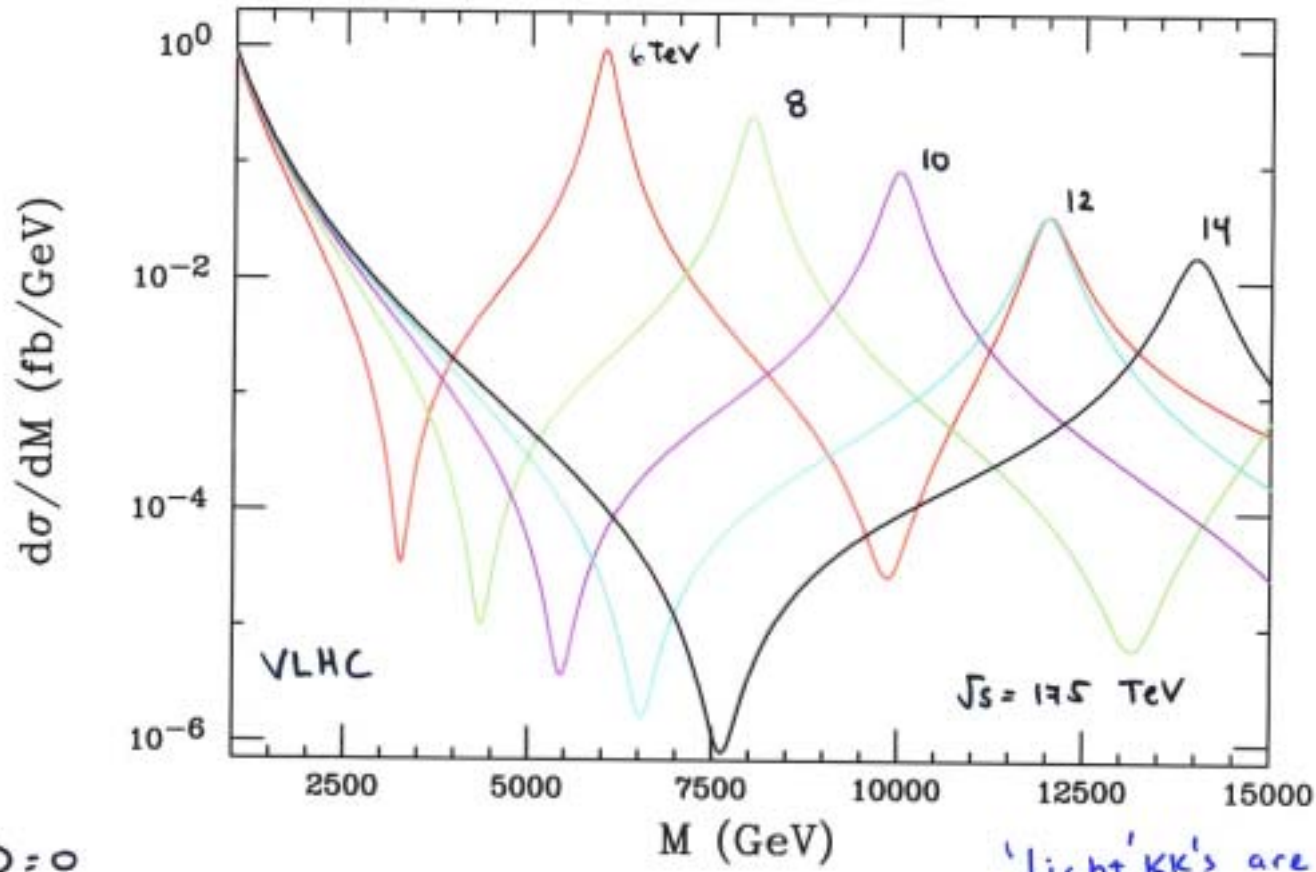
- The VLHC has an enormous capability to find + explore new exotic phenomena...

- Important to go beyond the discovery of a first graviton or KK gauge resonance

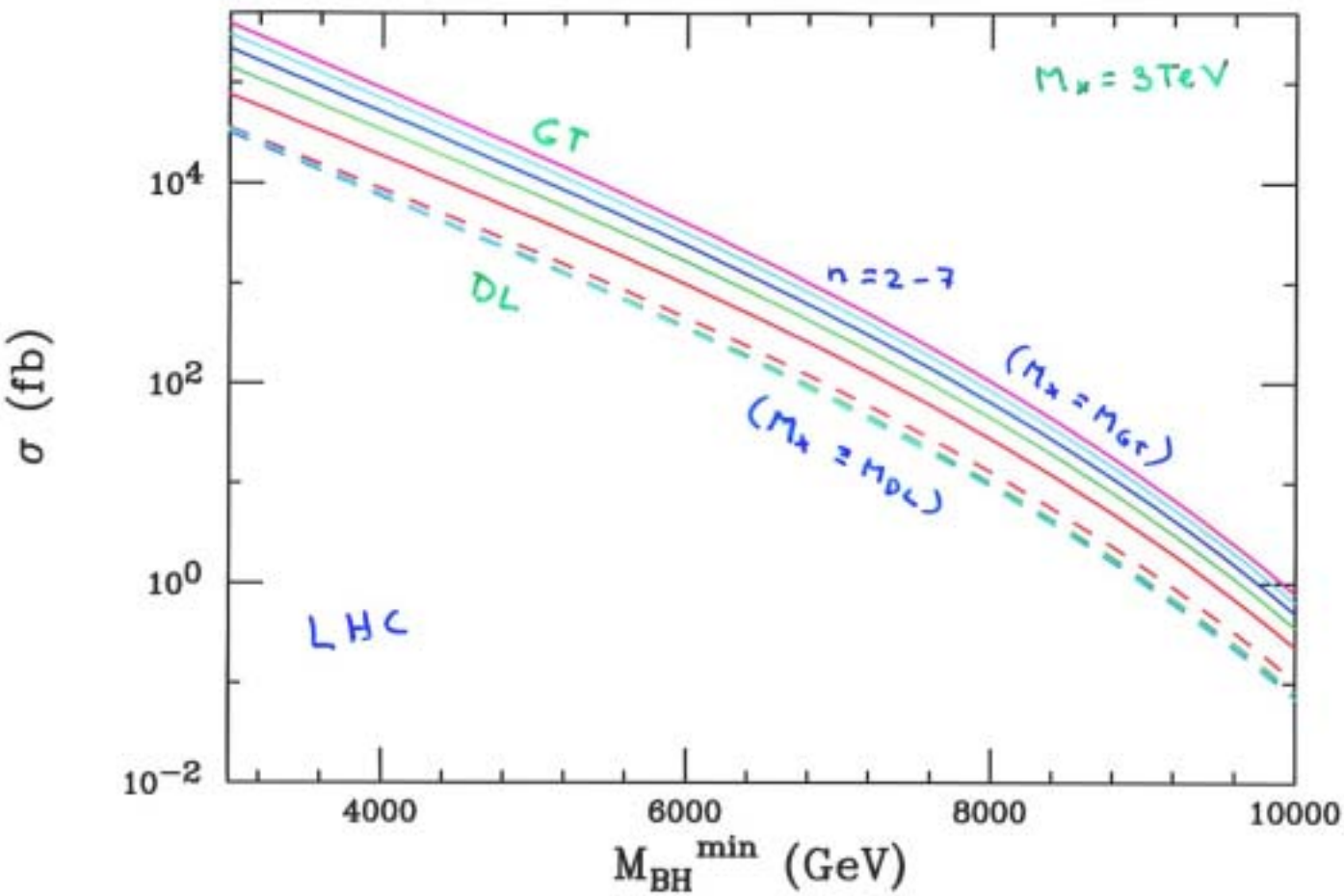
The REAL physics may be in what comes later ....

⇒ The VLHC will allow us to do this ...

$\gamma^{(n)}/Z^{(1)}$ KK resonances in Drell-Yan S^1/Z_2



D = 0
1 extra dimension

'light' KK's are easy
– see the spectrum

BH's at LHC - big rates