

Exotic Physics at VLHC

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

- Extra Dimensions {
 - TeV⁻¹: KK gauge excitations
 - ADD: ~~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

TG Rizzo
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

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

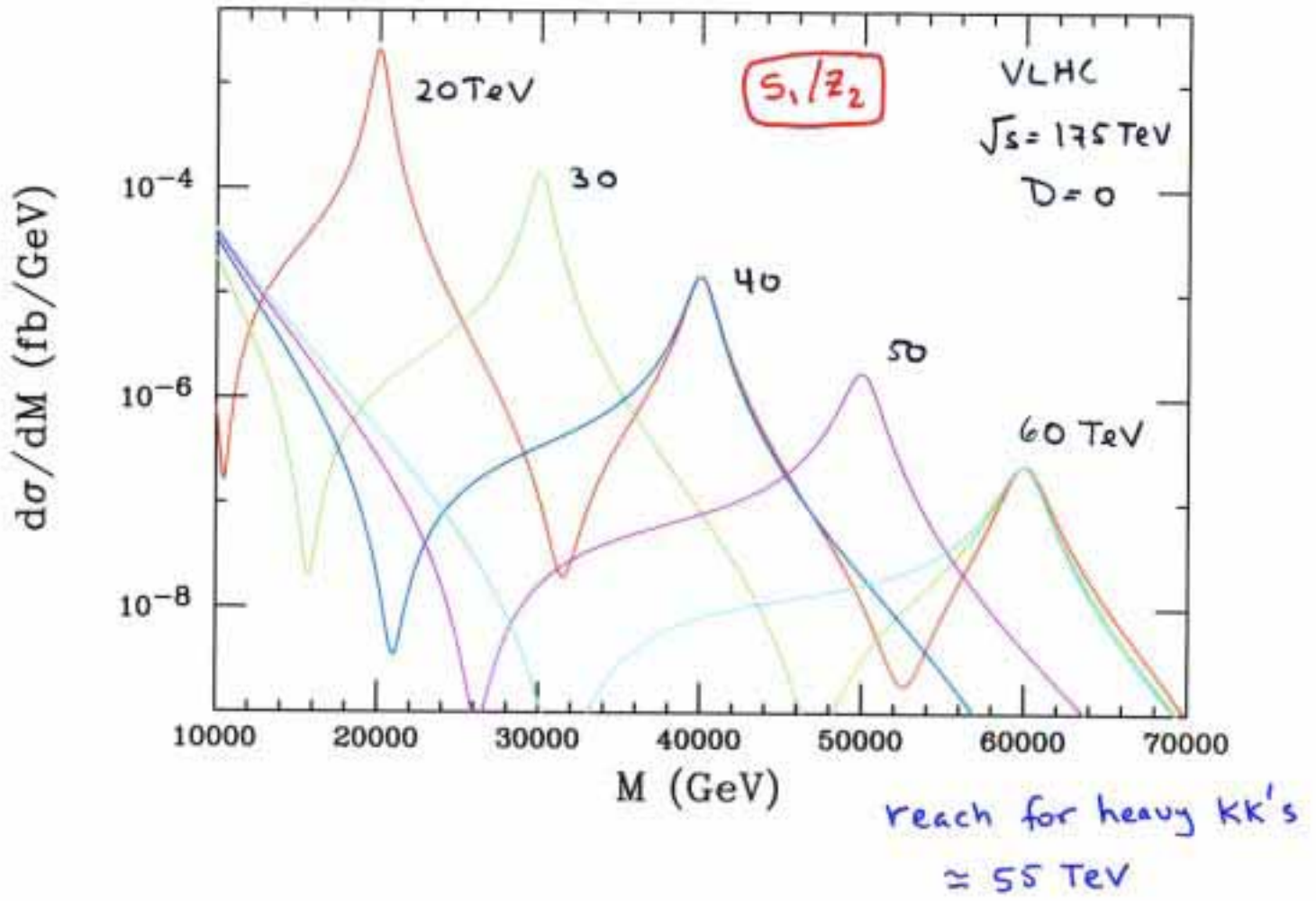
\Rightarrow a series of KK resonances is the hallmark signature of ED... †

• Important to see the 'whole' spectrum
+ not just the first KK... \rightarrow $\left\{ \begin{array}{l} \# \text{ of extra dims} \\ \text{Compactification geometry} \end{array} \right.$

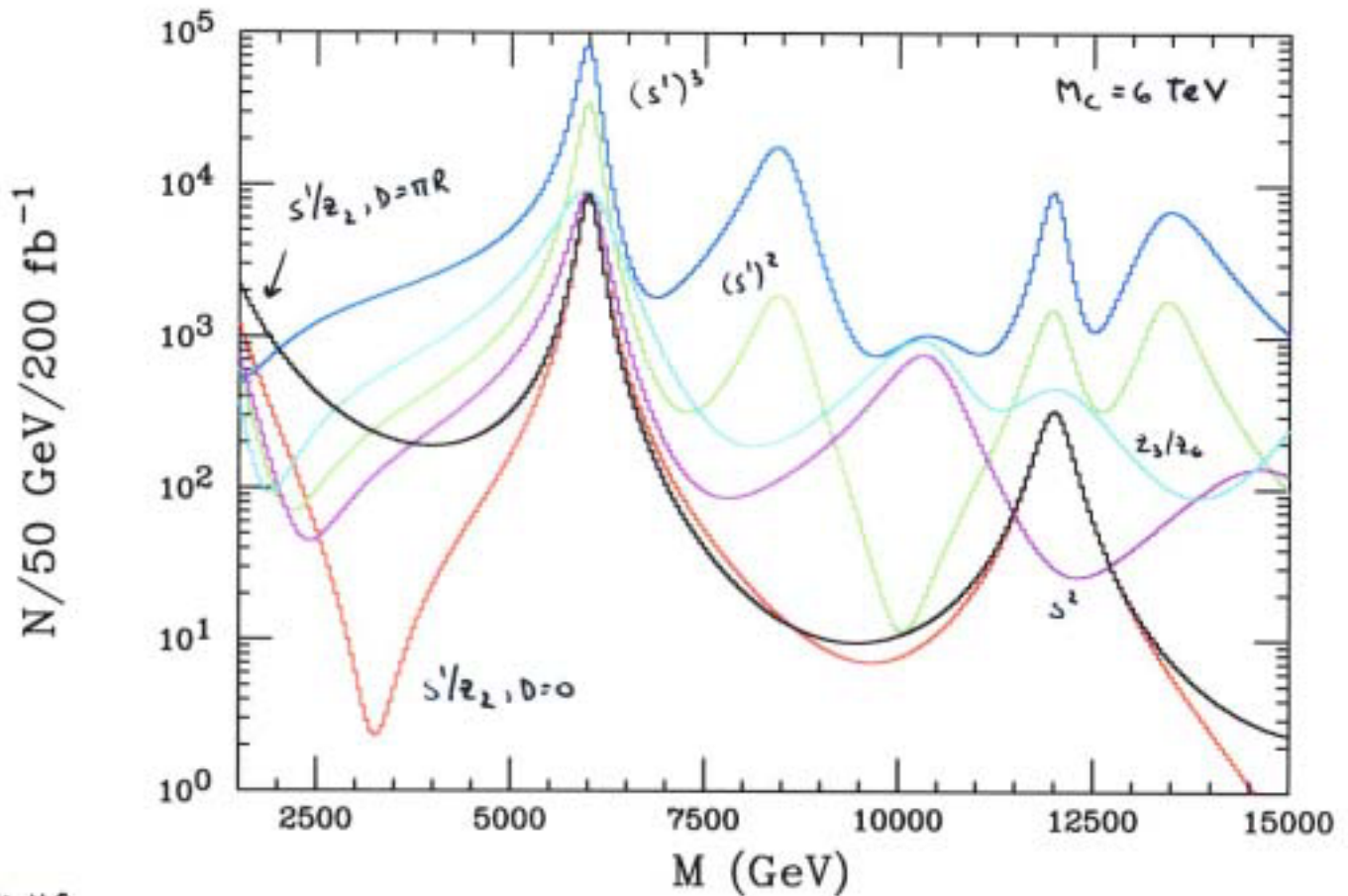
* Discovery reach @ VLHC $\approx 55 \text{ TeV}$
in DY

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

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



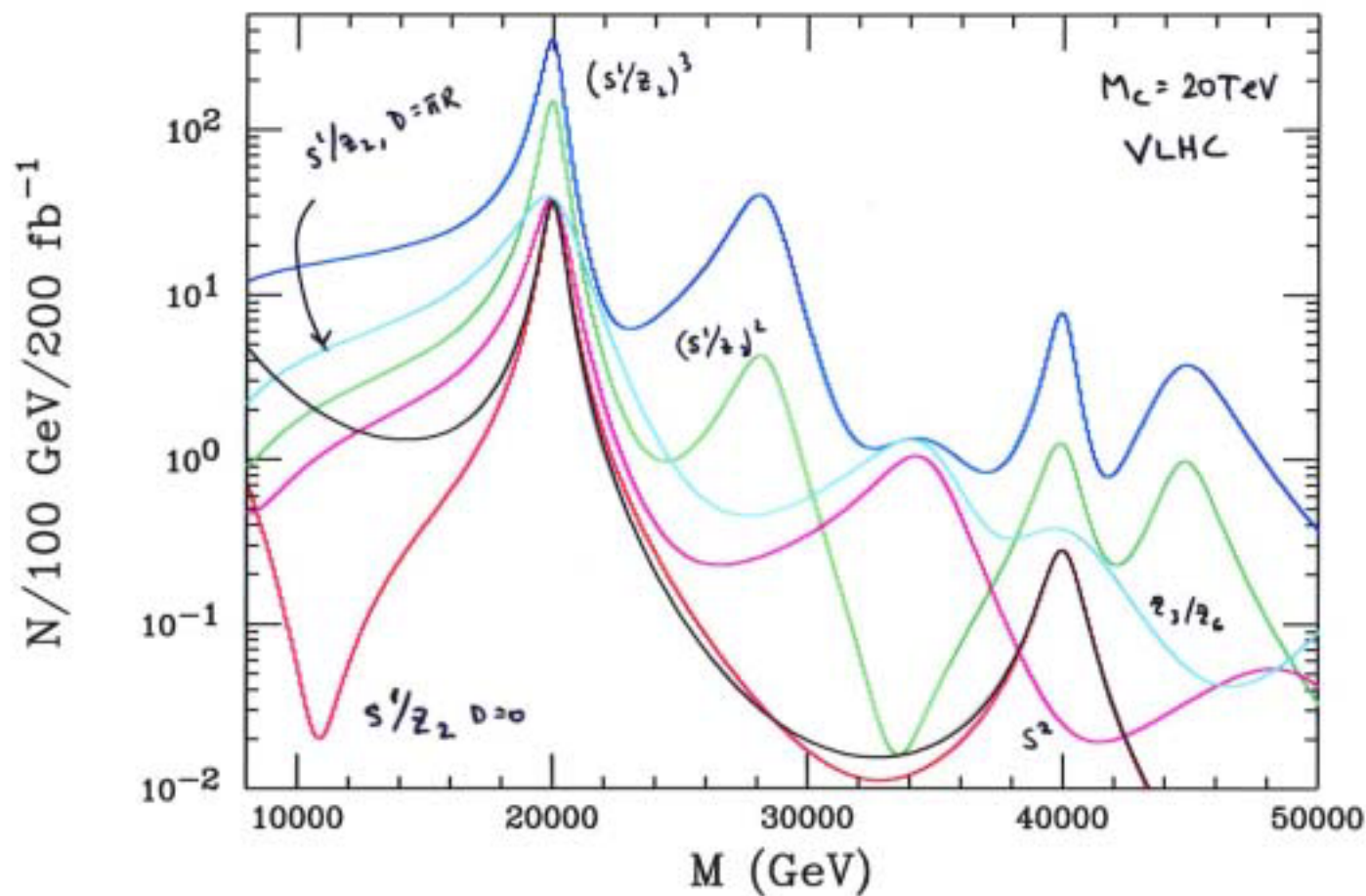
Drell-Yan KK excitations



VLHC
 $\sqrt{s} = 175 \text{ TeV}$

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

Drell-Yan KK
excitations



$\sqrt{s} = 17.5 \text{ TeV}$

ADD

Arkani-Hamed
Dimopoulos
Dvali

$$\frac{M_{\text{pl}}^2}{V_n} = M_*^{n+2} \approx \text{TeV}$$

→ finely spaced graviton spectrum

∴ $\gamma/\nu + \cancel{e}$ 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 $45 \sim 60 \text{ TeV}$ in M_H for
 $\sqrt{s} = 175 \sim 200 \text{ TeV}$ $L = 0.2 \sim 1 \text{ ab}^{-1}$

Randall - Sundrum (RS)

$$\Lambda_{\pi} = \bar{M}_{\text{pl}} e^{-\pi k r_0}$$

• $m_n =$ roots of Bessel functions

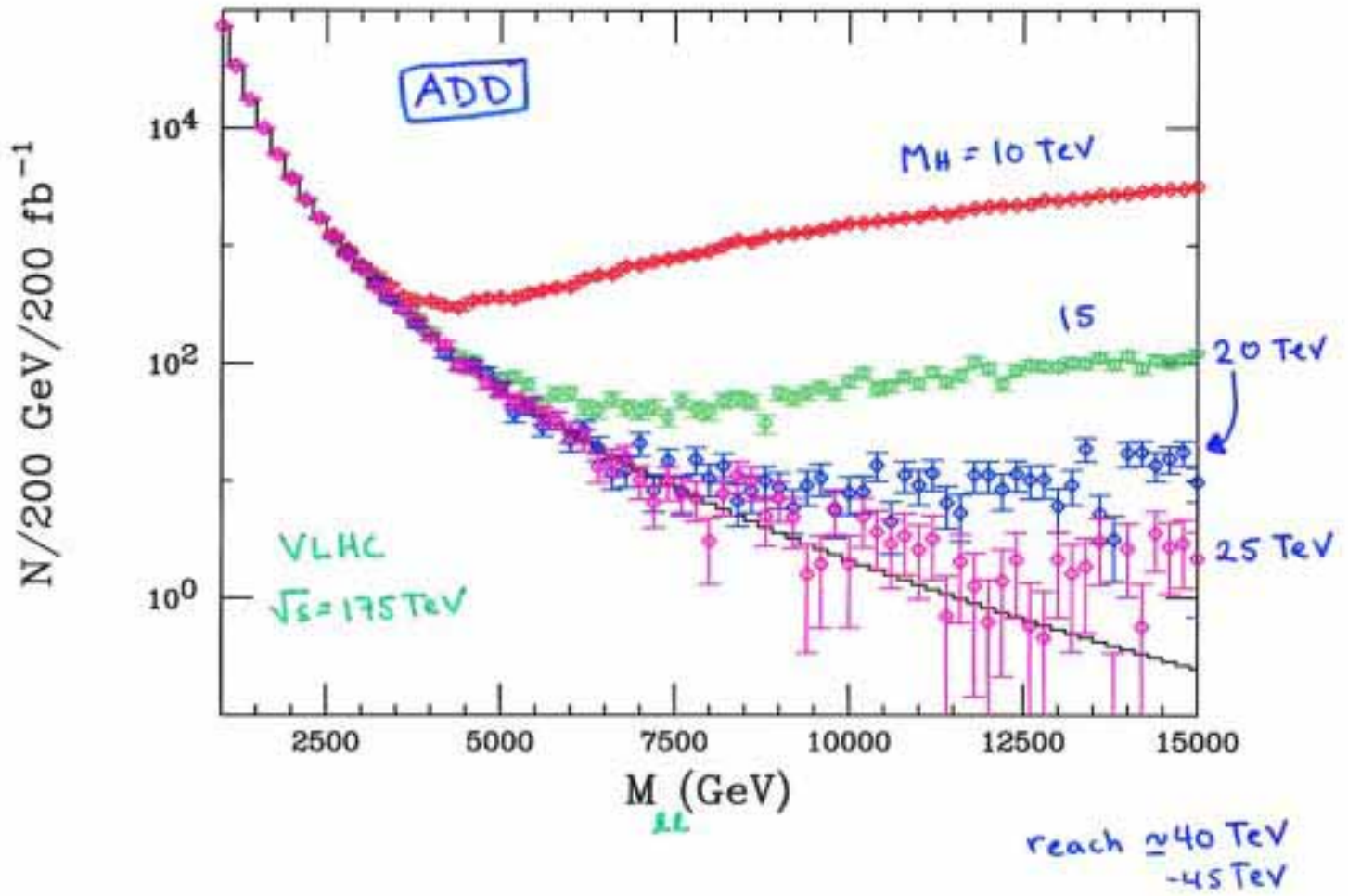
~ TeV masses w/ $\sim 1/\text{TeV}$ couplings

→ graviton resonances

many variants on basic model

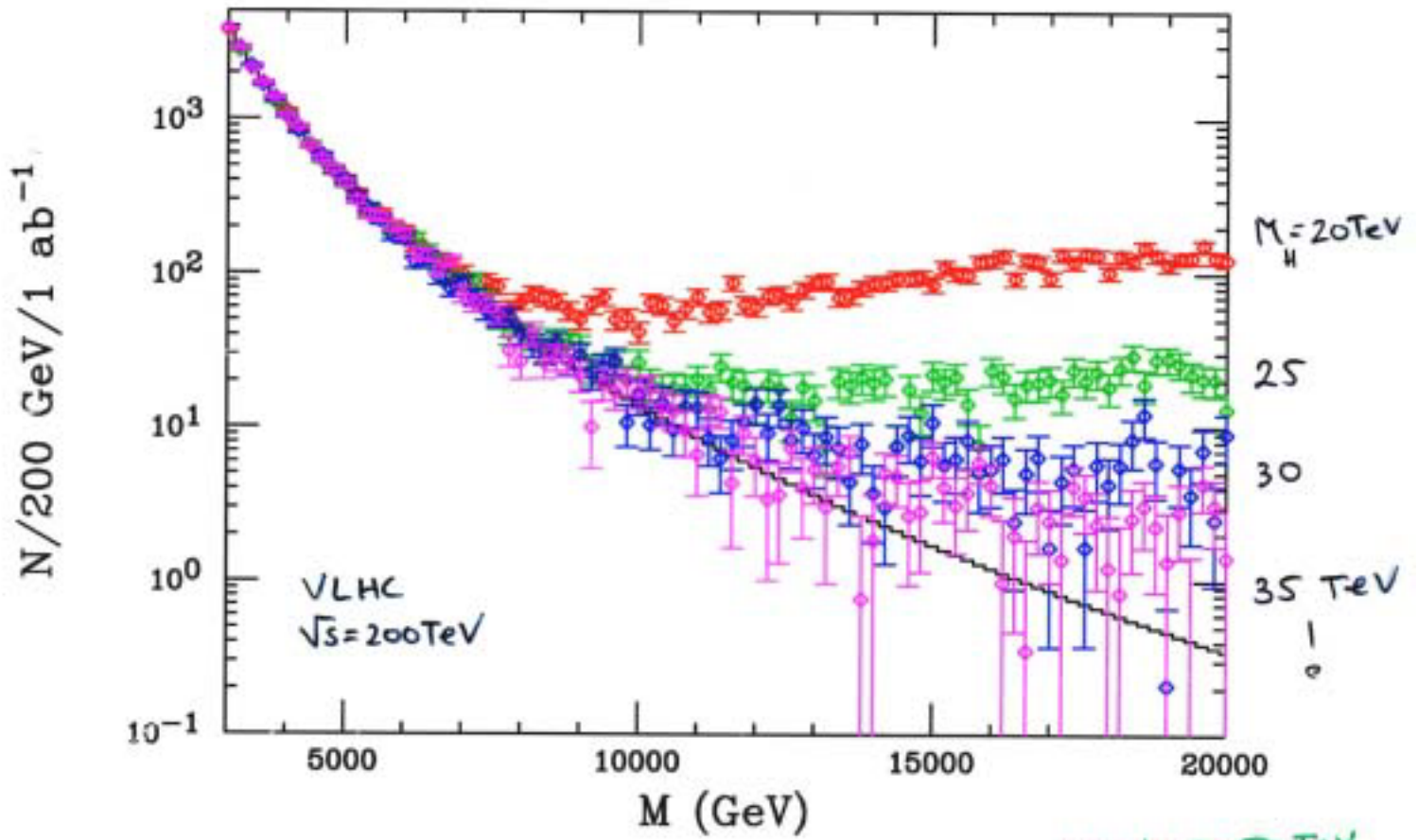
Drell-Yan

$q\bar{q} \rightarrow e^+e^- X$



ADD model

Drell-Yan

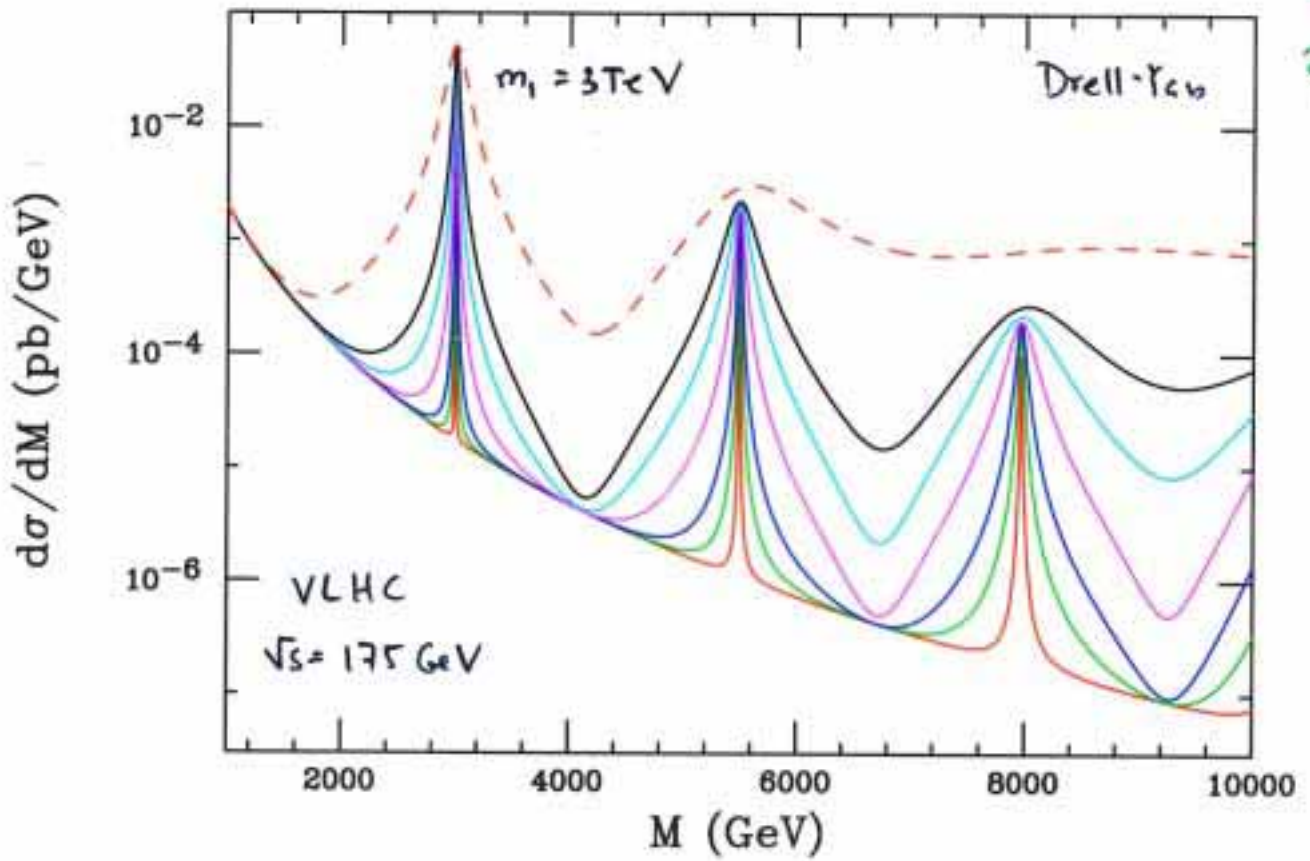


reach $\approx 50 \text{ TeV}$
 -60 TeV

Randall - Sundrum graviton resonances

Is it really

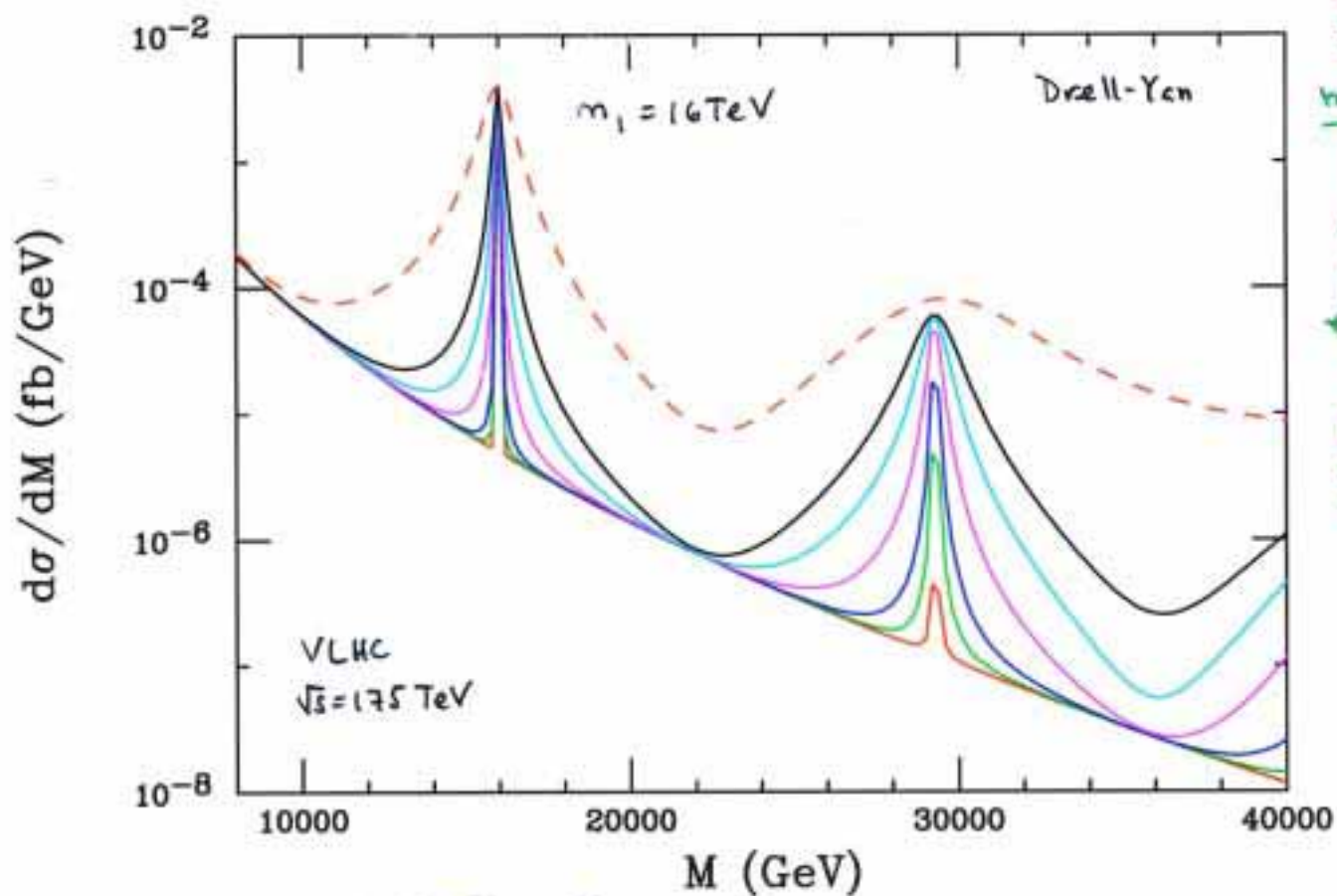
RS
????



no smearing

$$0.01 \leq \frac{k}{M_{pl}} \leq 0.2$$

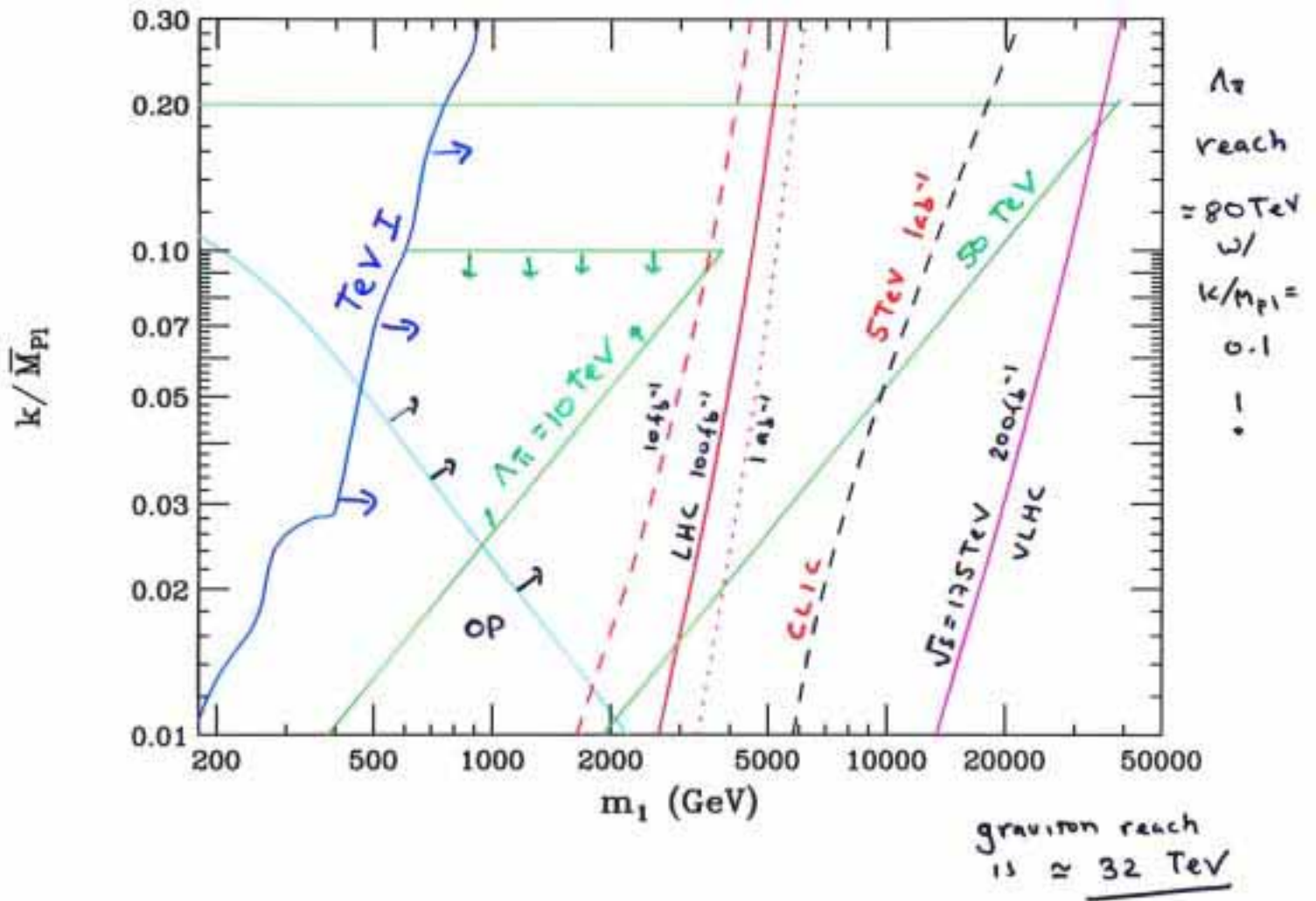
RS gravitons



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

$$0.01 \leq C \leq 0.2$$

Standard RS model coverage



• Important AGAIN to see more than the first resonance

→ brane terms, ... } modifications in
→ > 5 dims, ... } graviton spectrum

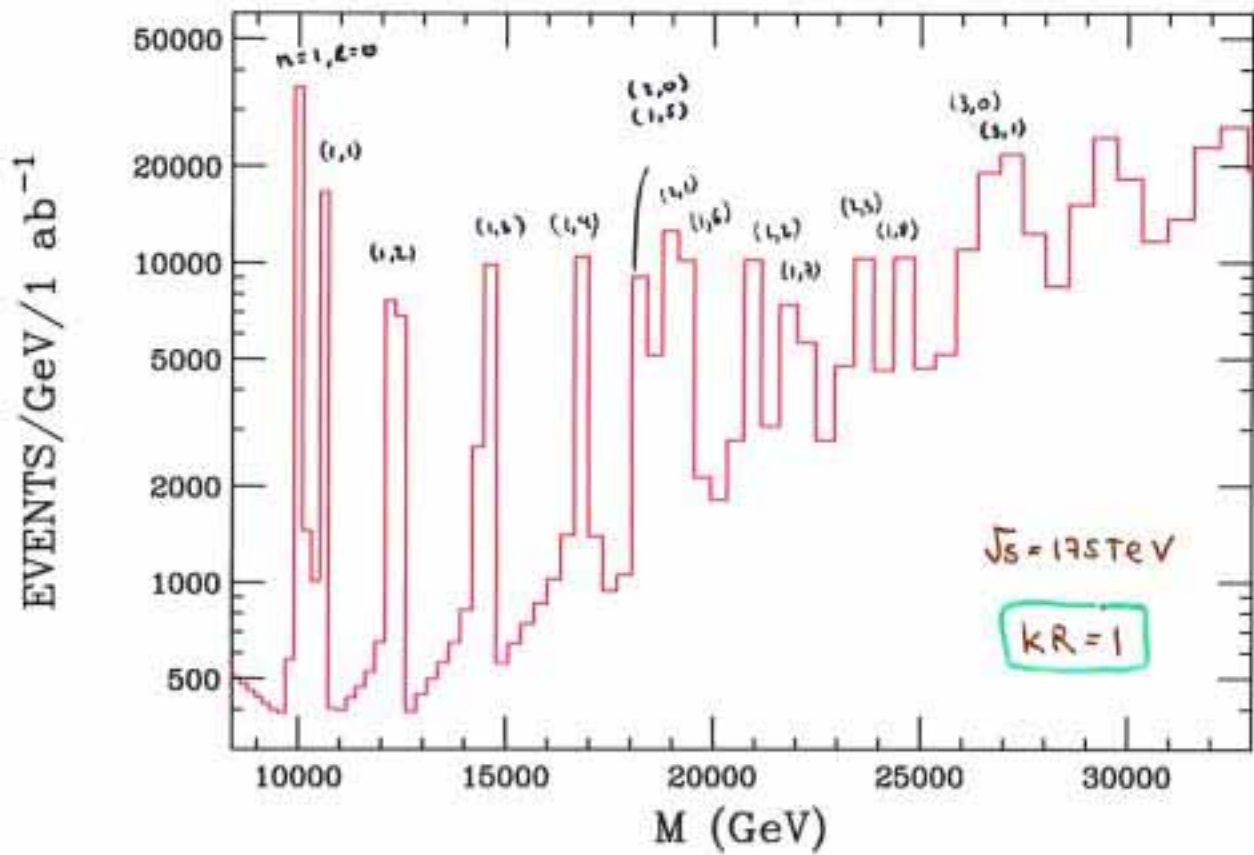
RS reach of VLHC up to $\Lambda_{\pi} = 80 \text{ TeV}$

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

... a fun
mess!

RS @ S/Z_2

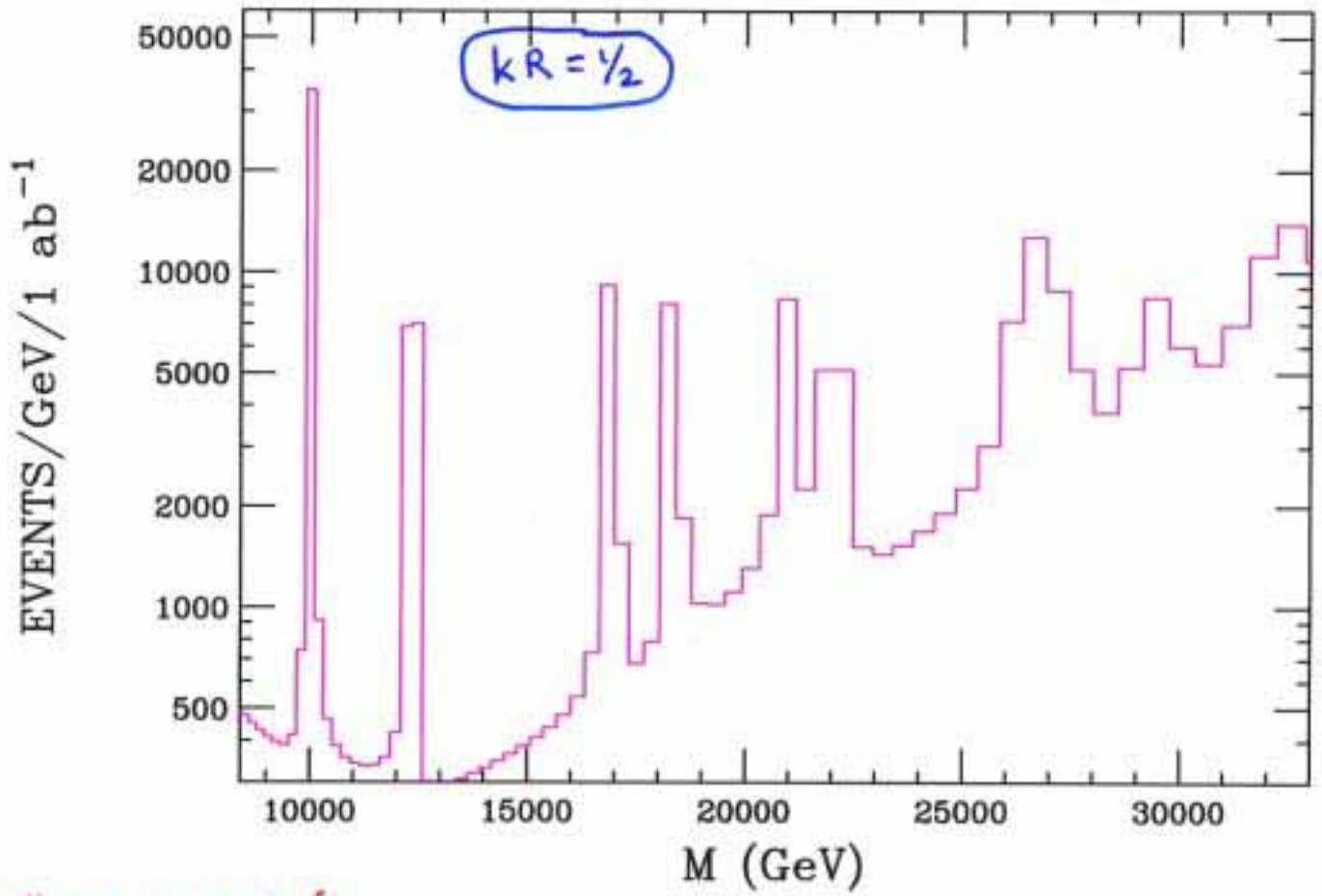
$k/m_{\pi 1} = 0.03$



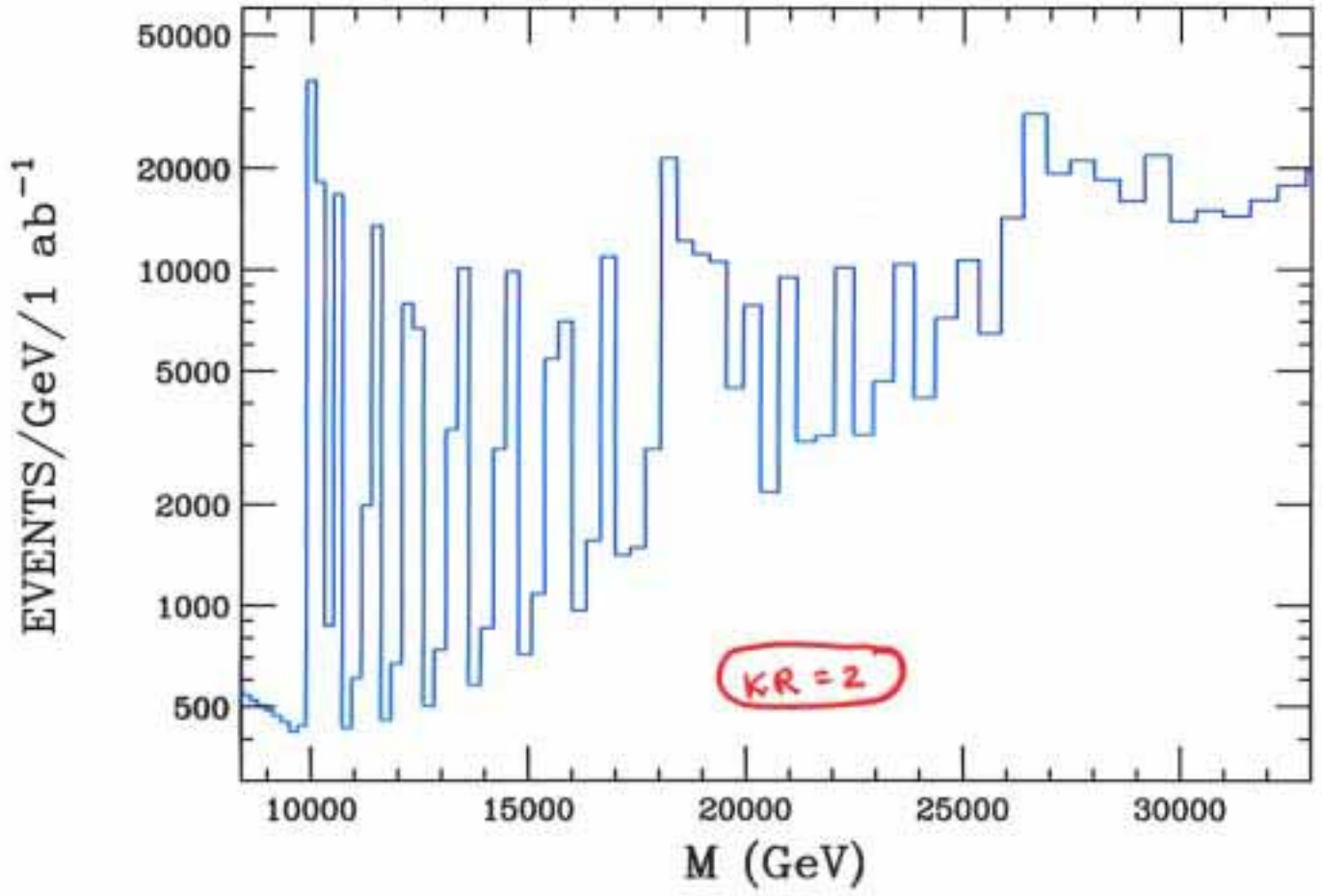
Huge
numbers
of
resonances
!!

≥ 17 resonances
here

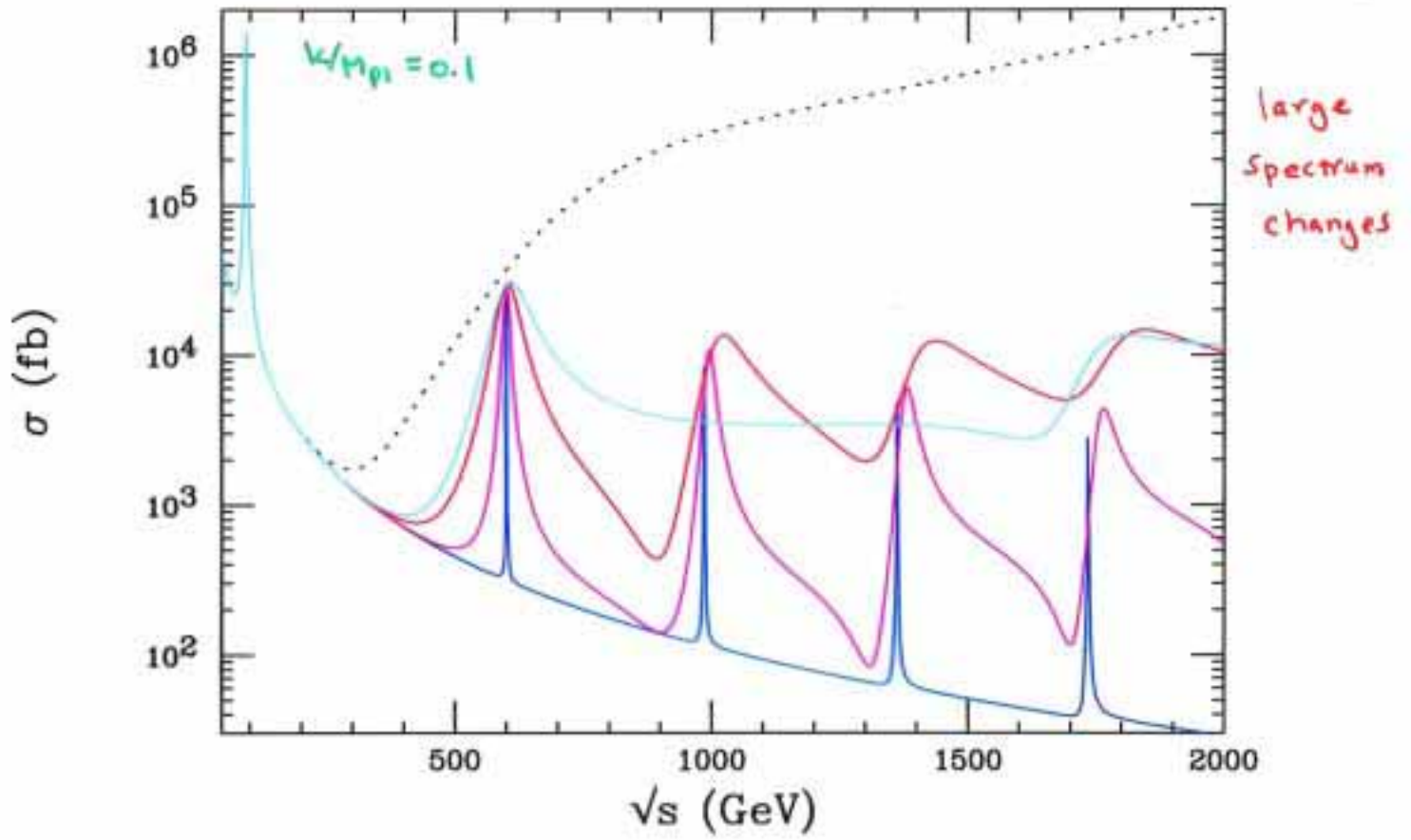
important to see big part of spectrum....



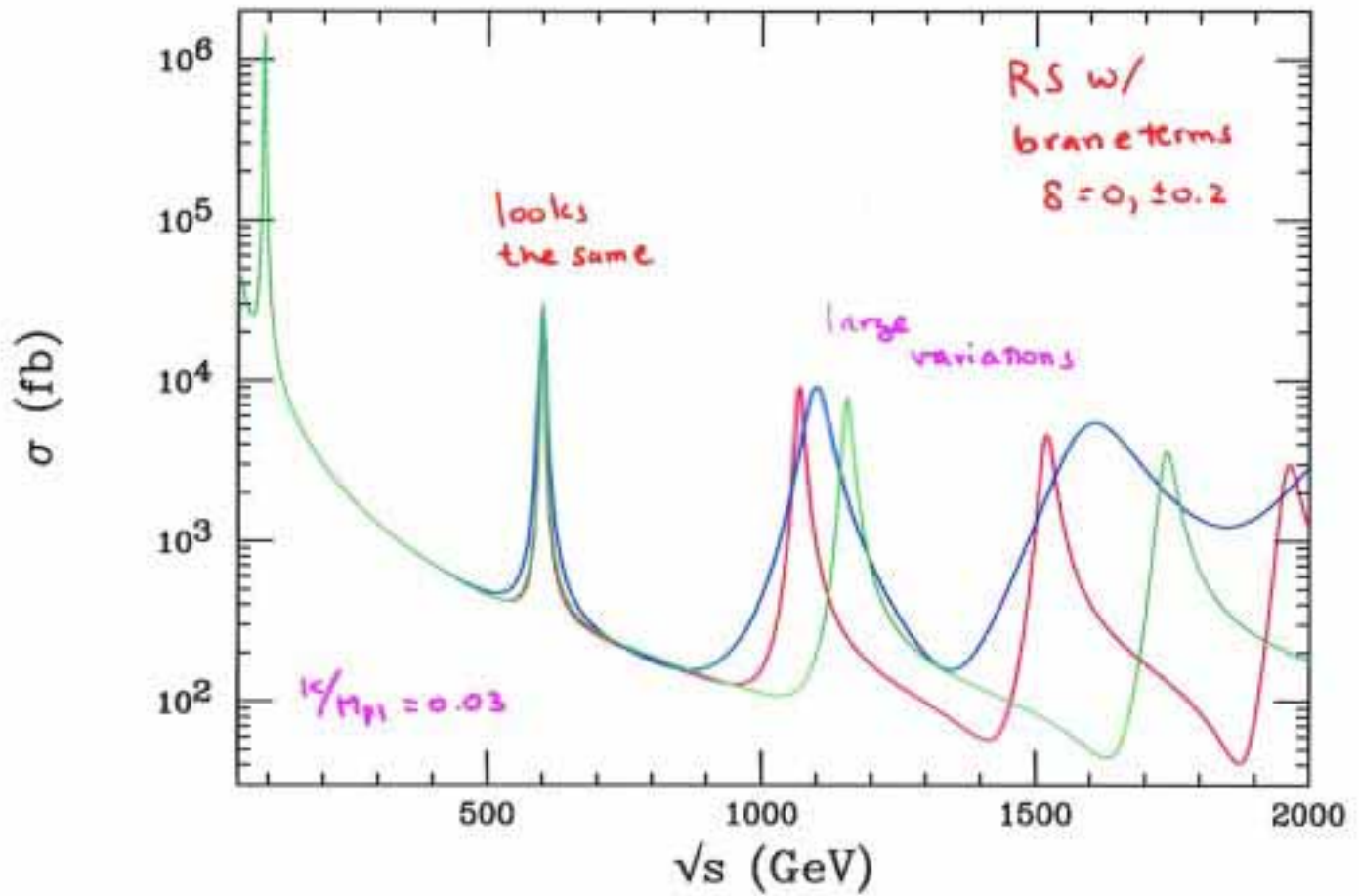
Small parameter shifts
Significantly change
Spectrum



RS w/brane terms



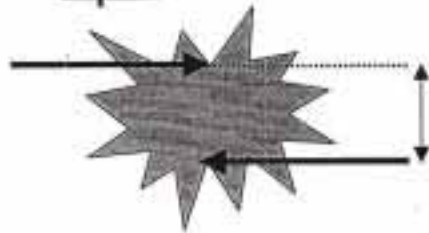
don't just find first evidence - check the spectrum!



THE Paradigm

Black Hole

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



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

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

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

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

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



stolen from

⇒ J. Tanaka

4th ATLAS Physics Workshop

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

24th May 2003@Athens

4

Giddings & Thomas
 PRD **65** 056010 '02

Watch out for different definitions!

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

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

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

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

⋮

etc. etc. ...

You get the idea....

IFS / ANDS / BUTS re BH

- BH formation takes place with high \vec{L}
+ non-trivial Q
 $R_{\text{Horizon}} \neq R_{\text{Schw.}}$ ↓ Balding Phase
to Kerr solution

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

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

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

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

\Rightarrow Simulation issues (Tanaka + Parker e. 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

"graybody" factors 'distort' the weights of spin-0, 1/2 + 1 final states in BH decay by O(1) corrections



Parker



Simulation

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

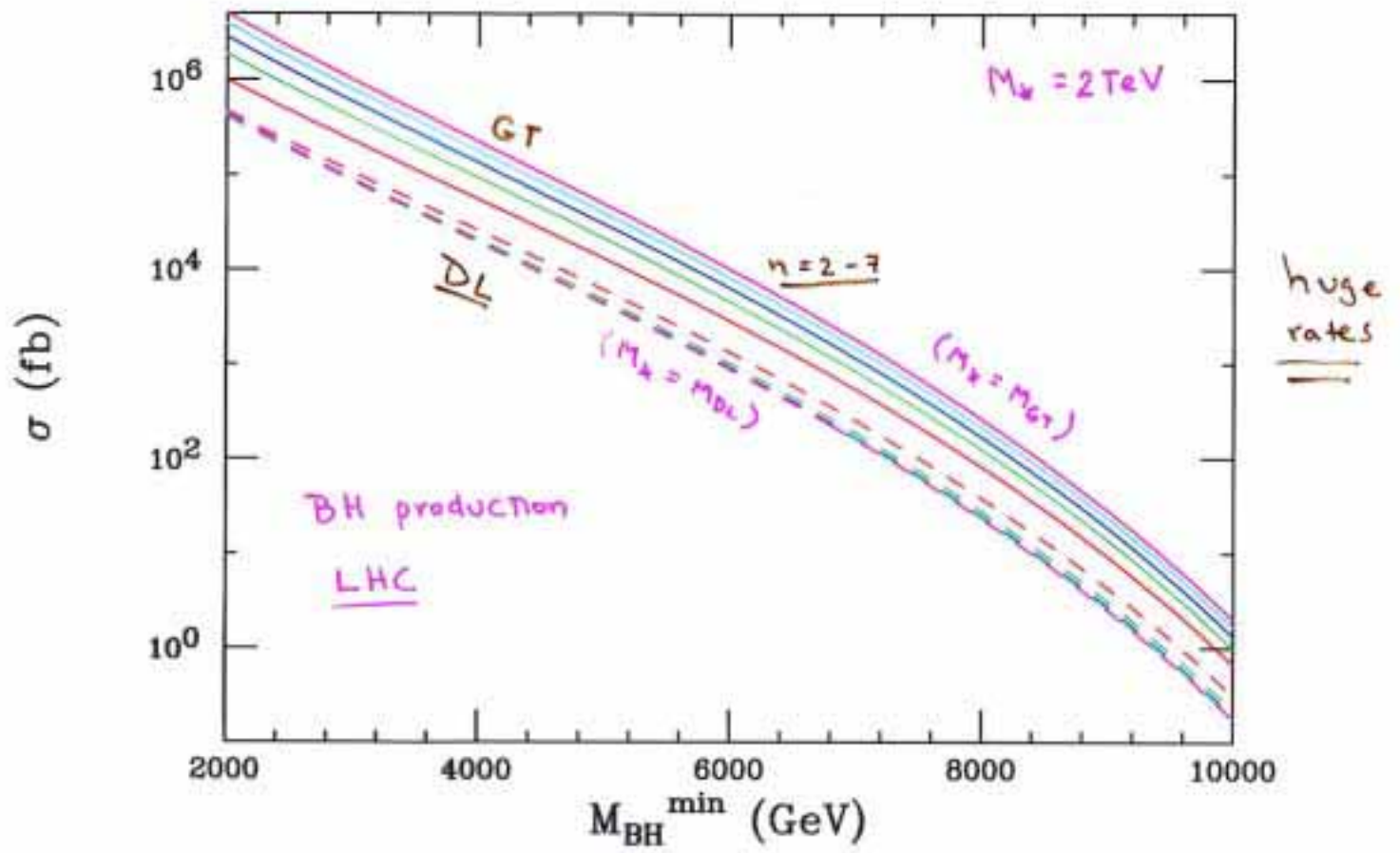
All samples are processed through the *ATLFast*.
(Low luminosity condition)

- PDF = CTEQ5L

A toy model ...



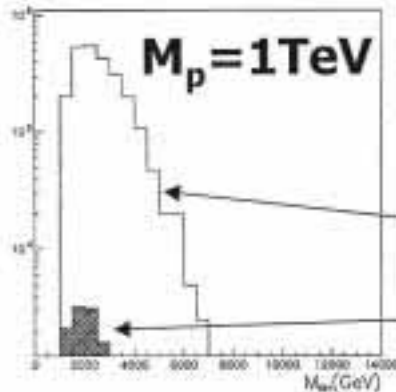
BH's \rightarrow huge rates at LHC





Mass Distributions

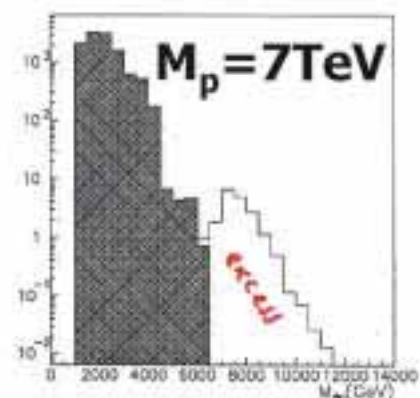
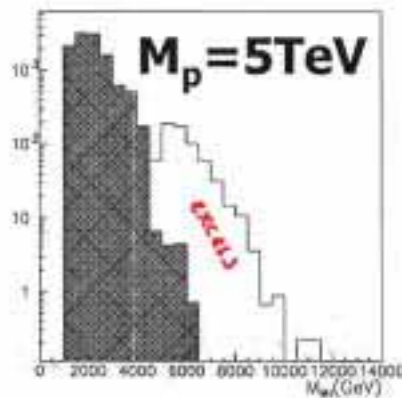
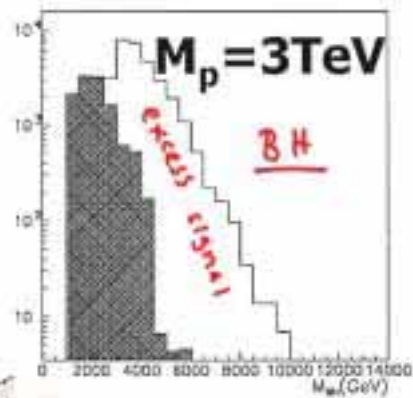
$$n=3, \int L = 30 \text{ fb}^{-1}$$



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

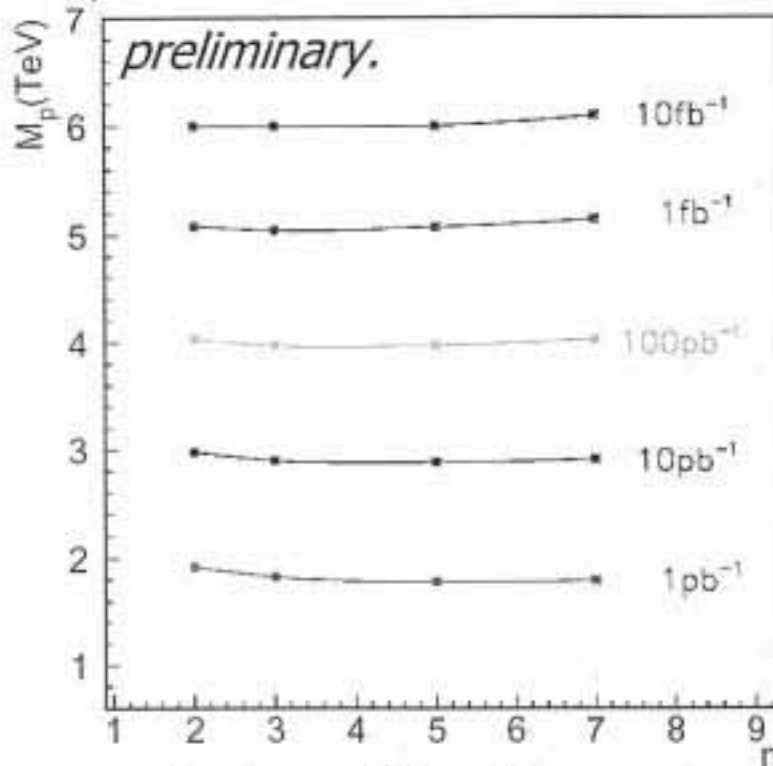
Signal+Background

Background





Discovery Potential



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

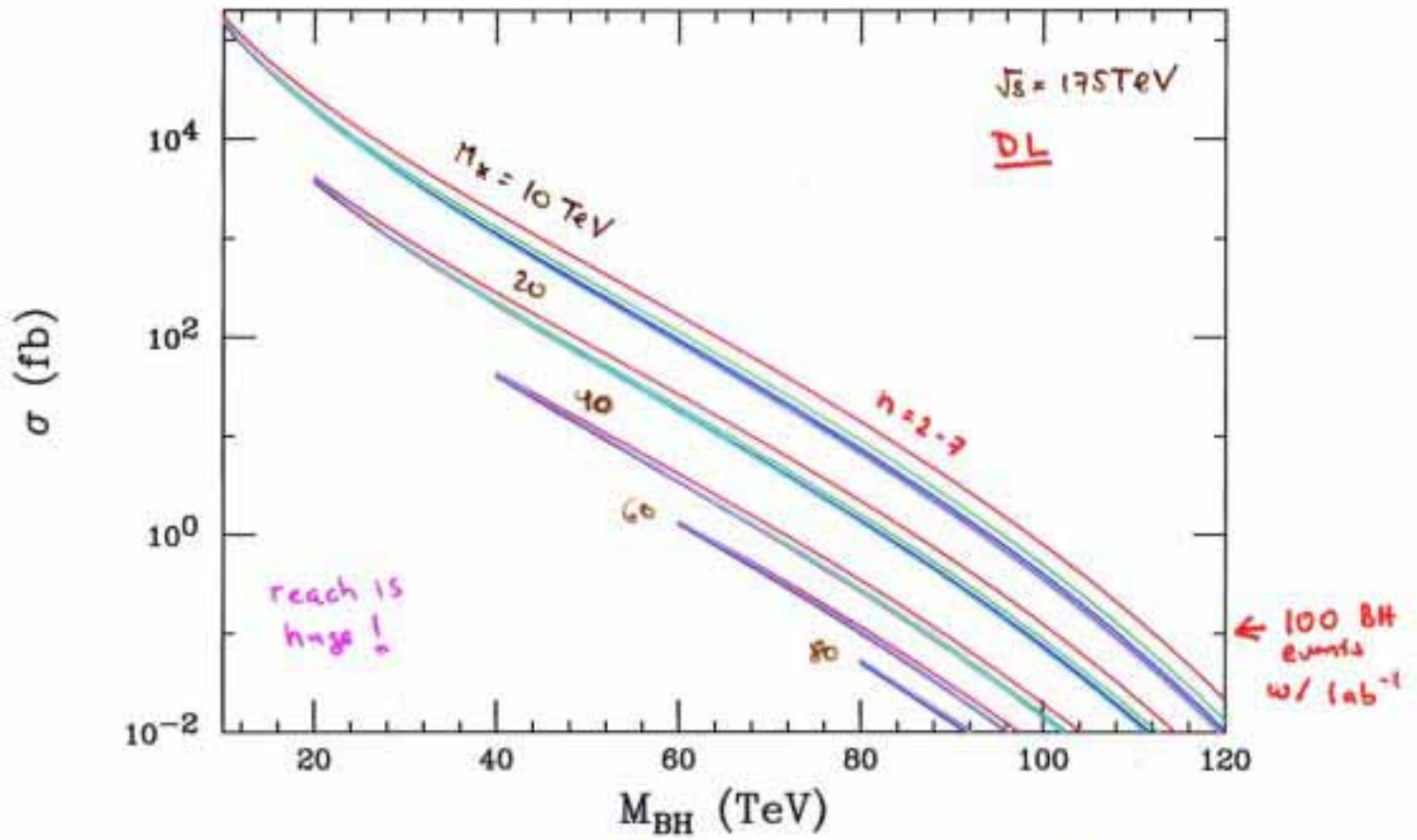
$\approx 30 \text{ events} !!$

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



BH production at VLHC

rates big
even for large M_x



Reach $\approx M_x = 80$ TeV

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

Finite-length models: Cavaglia, Das & Martens
hep-ph/0305223

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

α' parameter Planck length

$$r_{schw} \geq \alpha l_{pl} \rightarrow M_{BH} \geq f(n) M_n$$

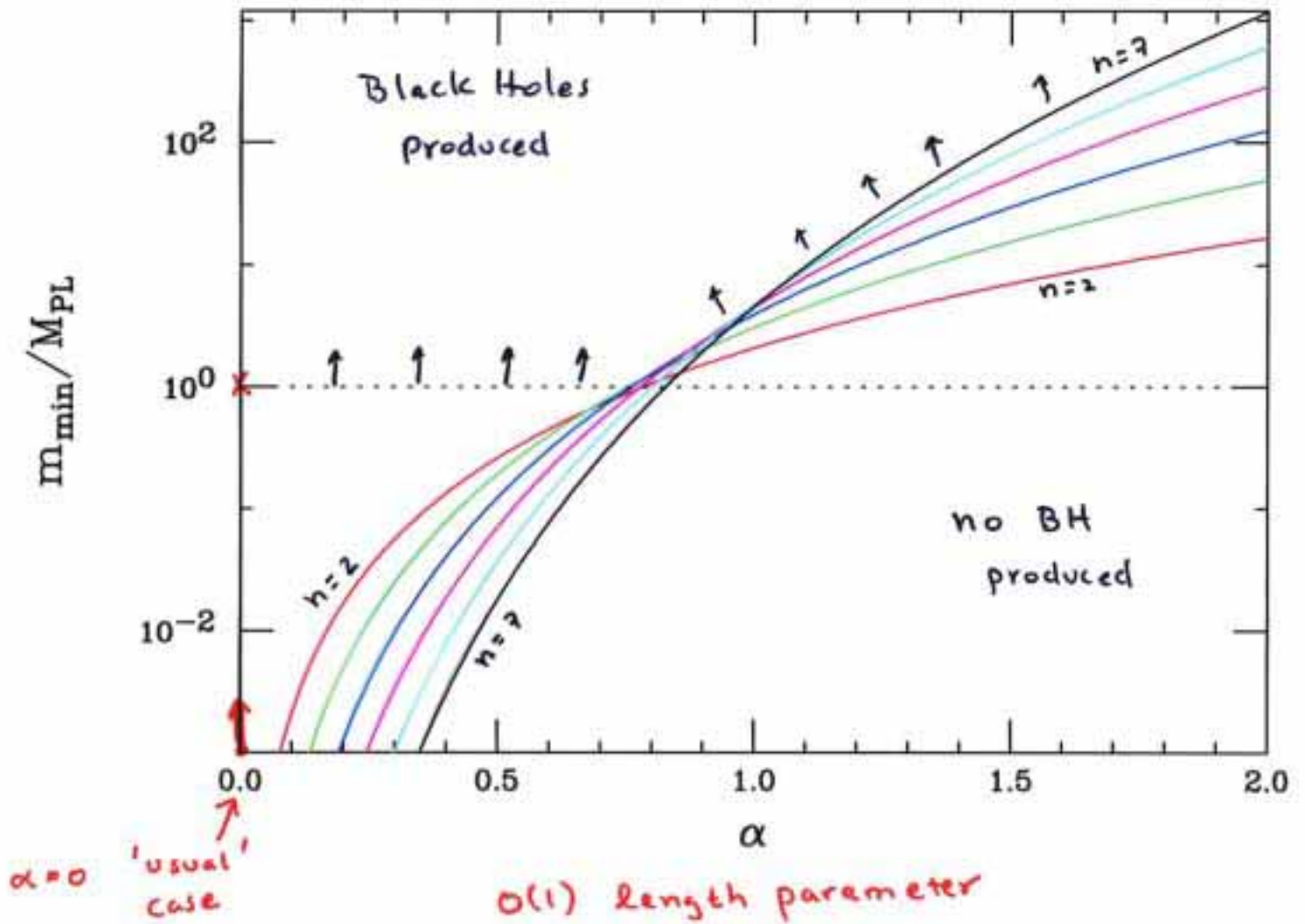
→ For $\alpha \sim 0(1)$ + $M_n \sim 1 \text{ TeV}$

EVEN VLHC will not see BH production!

⇒ raises $M_{BH}^{\min}(M_n)$ + cuts off σ integrations for any n

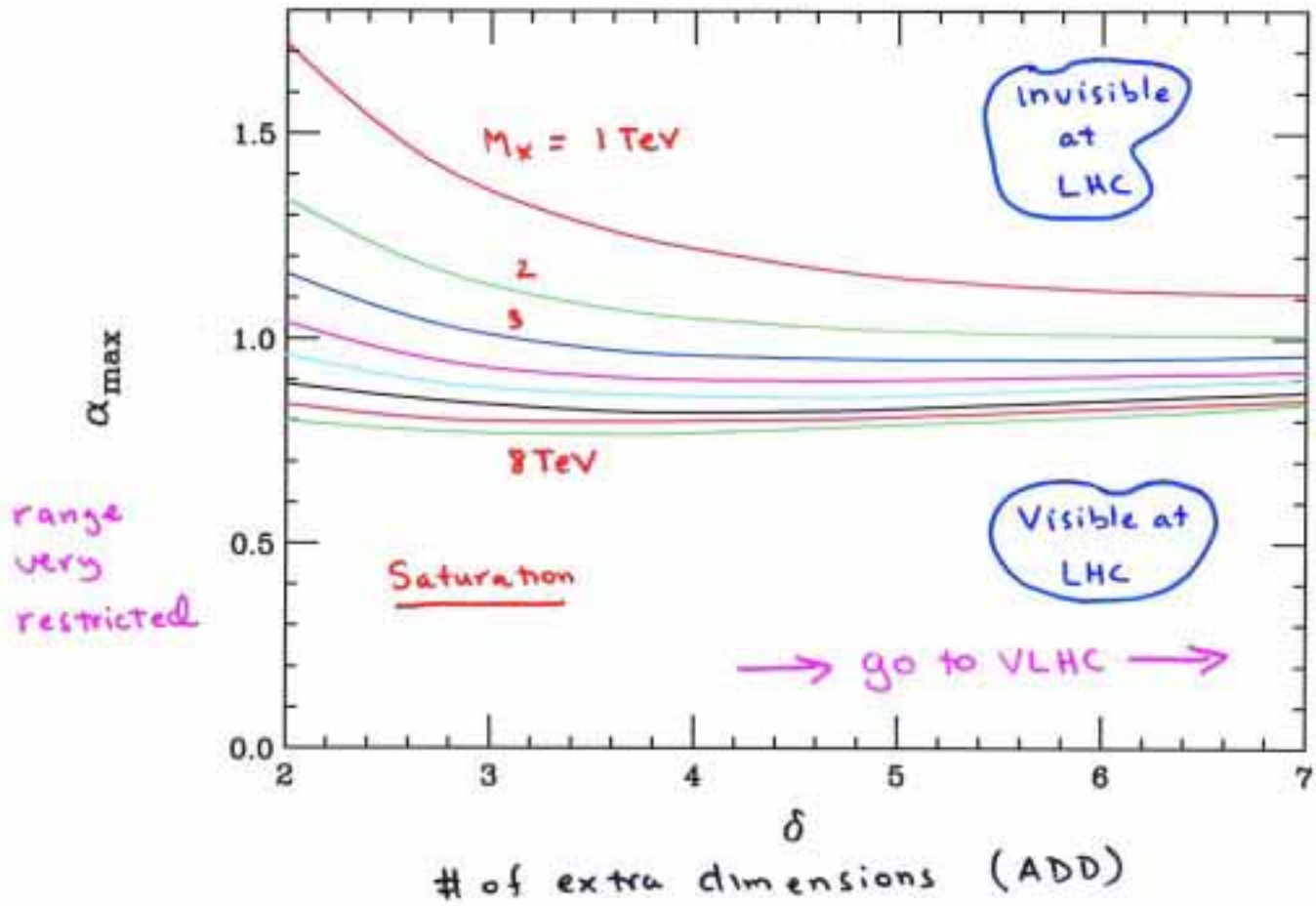
large σ_{BH} not a 'done deal'...

minimum BH mass in finite-length model



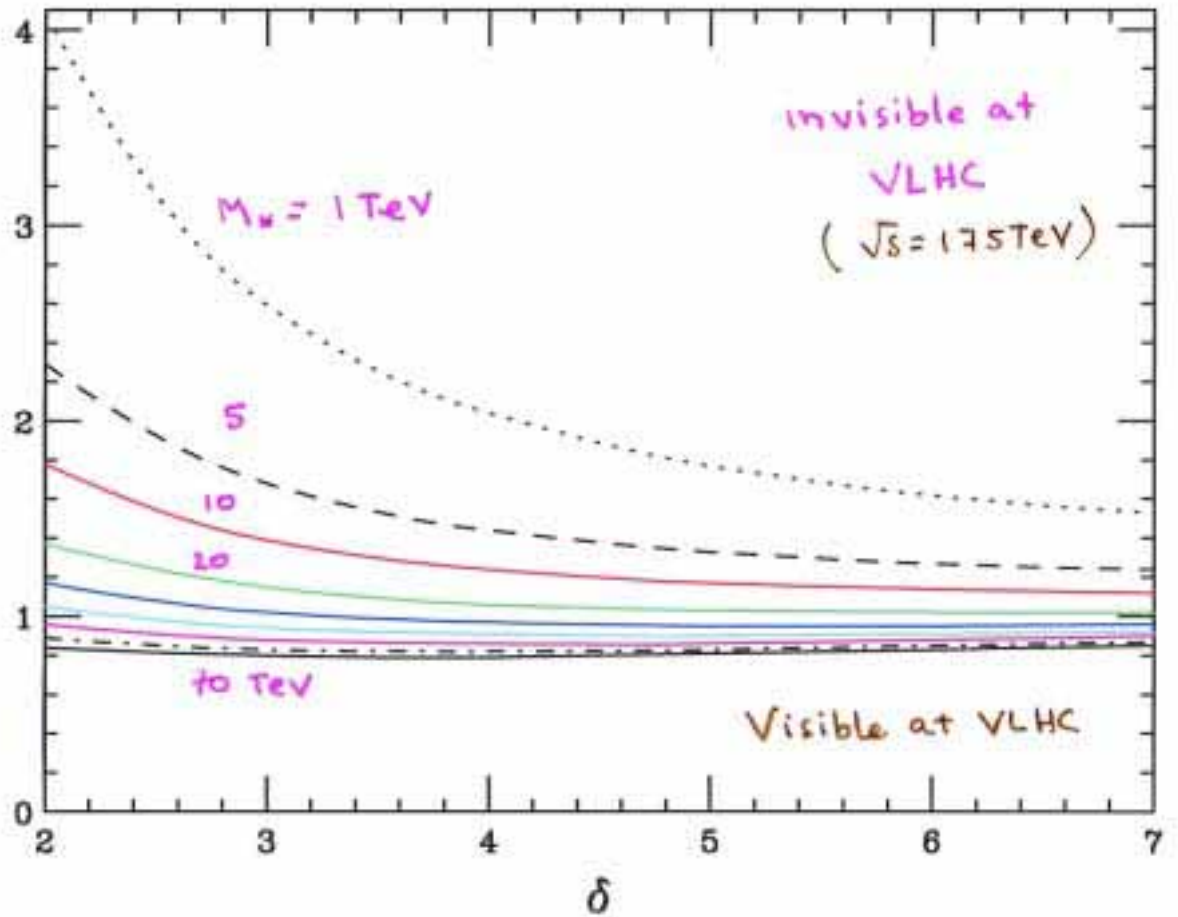
Upper bound on α from LHC
BH visibility

(100 BH's in 200fb^{-1})



range restricted even for $M_* = 1 \text{ TeV}$
- even for VLHC

α_{max}
100 BH
in
 lab^{-1}



Beyond BH

⇒ String Balls +
p-branes

- Dimopoulos + Emparan
hep-ph/0108060
- Ahn, Cavaglia + Olesen
hep-th/0201042
- Cheung, hep-ph/0205022
- Cavaglia, hep-ph/0210246

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

such that

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

Claim:

match
at
boundaries

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

Saturates
unitarity
at upper
end

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

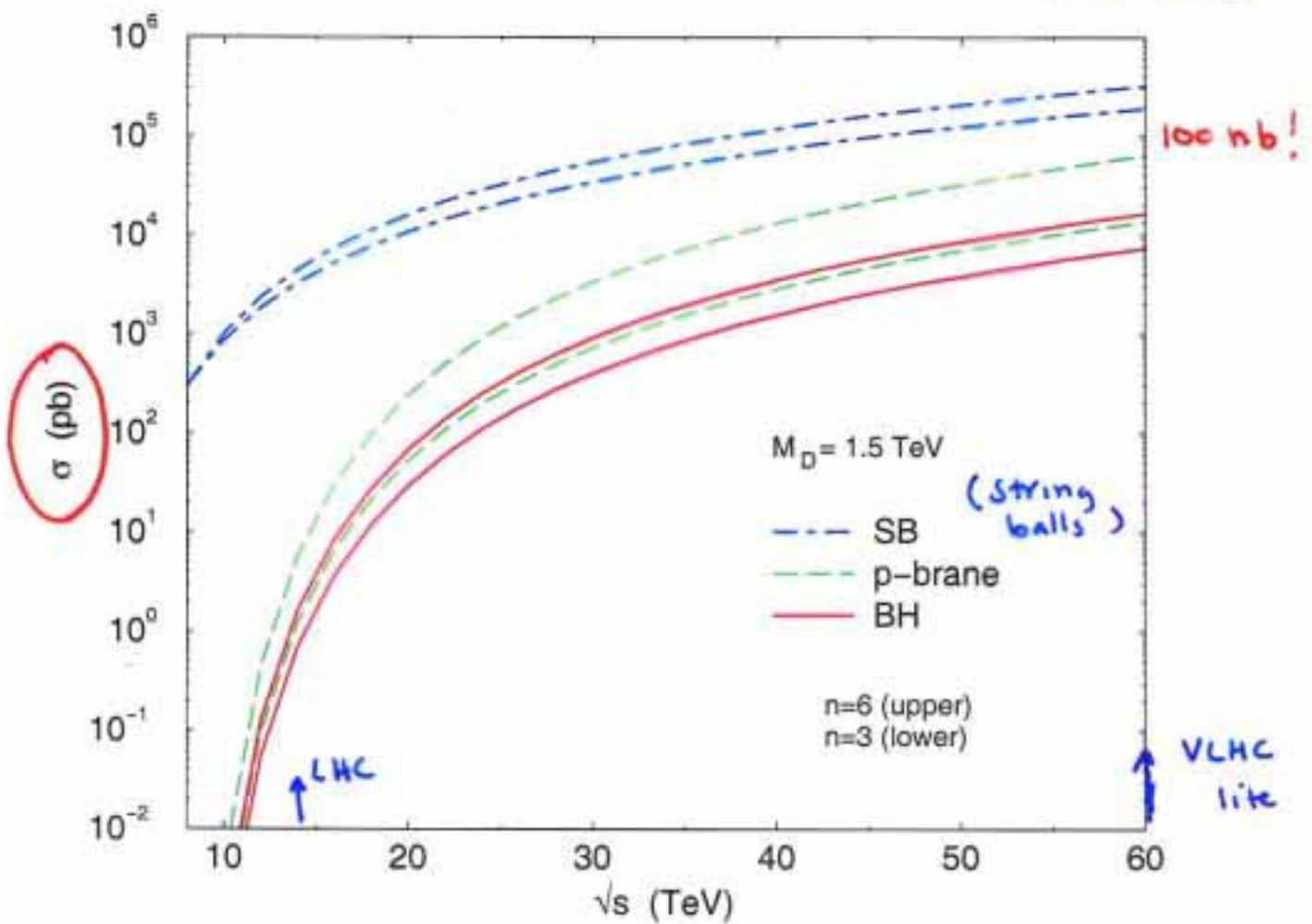
$$M_s/g_s^2 \leq M_{BH} : \sigma \sim \sigma_{BH} \text{ above}$$

and $M_x^{n+2} \approx M_s^{n+2}/g_s^2$ ($g_s^2 \ll 1$)
weak coupling

- SB decay \sim BH decay qualitatively

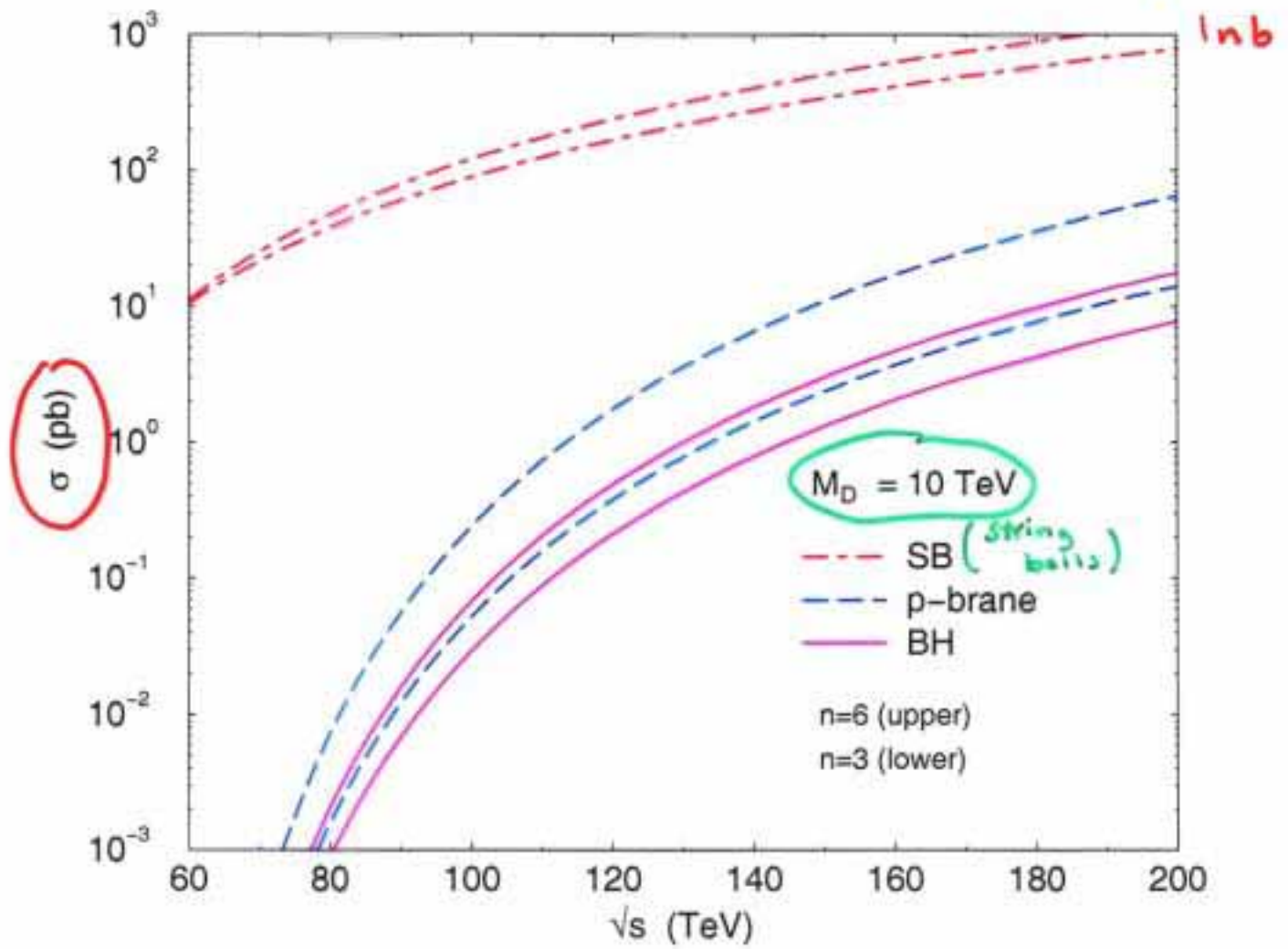
Though BH's have large σ 's,
other Extra-dim objects may have
larger ones....

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., $Z \rightarrow \gamma\gamma \#$

VLHC : modification of $g\bar{g}g, 3g, 4g$
vertices

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

modifies jet production ...

- Has not been studied in detail for colliders....

due to Lorentz violation

Summary + Conclusions

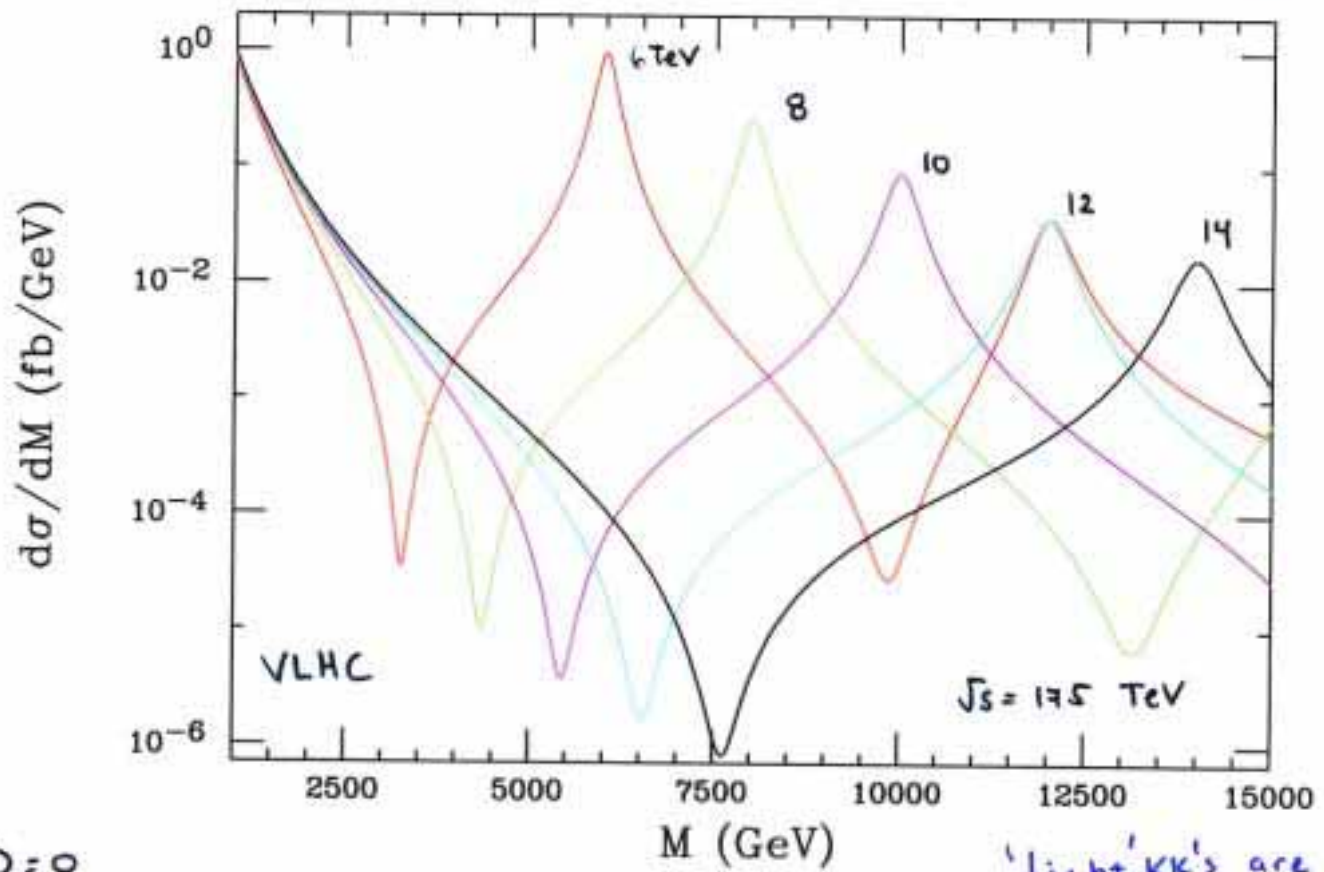
- The VLHC has an enormous capability to find + explore new exotic phenomena...
- Important to go beyond the discovery of a first graviton or KK gauge resonance

The REAL physics may be in what comes later

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

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

S/Z_2



$D=0$
1 extra dimension

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

BH's at LHC - big rates

