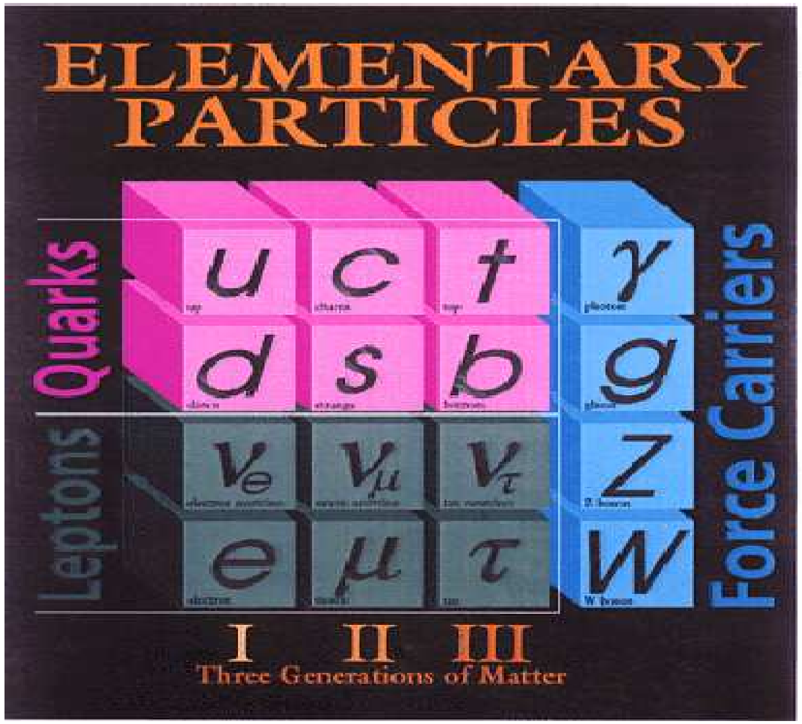
Why go beyond the SM

Unanswered theoretical problems

(1) Flavor problem: Why THREE families? How they get masses?? And the mass pattern? Experimentally, invisible Z^0 width implies only 3 light neutrinos: $Z \to \nu_e \bar{\nu}_e\ ,\ \nu_\mu \bar{\nu}_\mu\ ,\ \nu_\tau \bar{\nu}_\tau$



Theoretical problems...

(2) Grand Unification

- It would be nice to unify all four interactions into a single theory.
- So far the EM, weak, and strong couplings can unify in a number of supersymmetric GUT theories.
- To unify with gravity we need string theories.

(3) Large Hierarchy: $M_{\text{Planck}} \gg M_W$.

- New physics is needed to stabilize the hierarchy, e.g., Supersymmetry.

Recent developments in string theories and extra dimensions.
Transform the hierarchy into geometry stabilization.

(***) Someone may ask if SUSY or Extra Dimensions, in fact, solve or create more problems !!

Extra Dimensions

- Why we need extra dimensions.
- Highlights of sub-Planckian signatures.
- Trans-Planckian signals: production and decays.
- Black holes, string balls, p-branes.

References:

(1) S. Giddings, S. Thomas, PRD65:056010 (2002)
(2) S. Dimopoulos, G. Landsberg, PRL 87, 161602 (2001)
(3) S. Dimopoulos, R. Emparan, Phys. Lett. B526, 393 (2002)
(4) K. Cheung, PRL 88, 221602 (2002), hep-ph/0110163
(5) K. Cheung, hep-ph/0205033
(6) E. Ahn, M. Cavaglia, A. Olinto, hep-th/0201042
(7) K. Cheung and C. Chou, hep-ph/0205284.

Extra Dimensions

- Huge difference between M_{EW} and M_{Pl}.
- New physics at $\sim$ TeV, e.g. SUSY.
- New ideas using extra dimensions can bring M_{Pl} down to TeV.

Let n total extra dimensions, m small, $n-m$ large.

- The observed 4D Planck scale $M_{\rm Pl} \sim 10^{19}$ GeV is a derived quantity

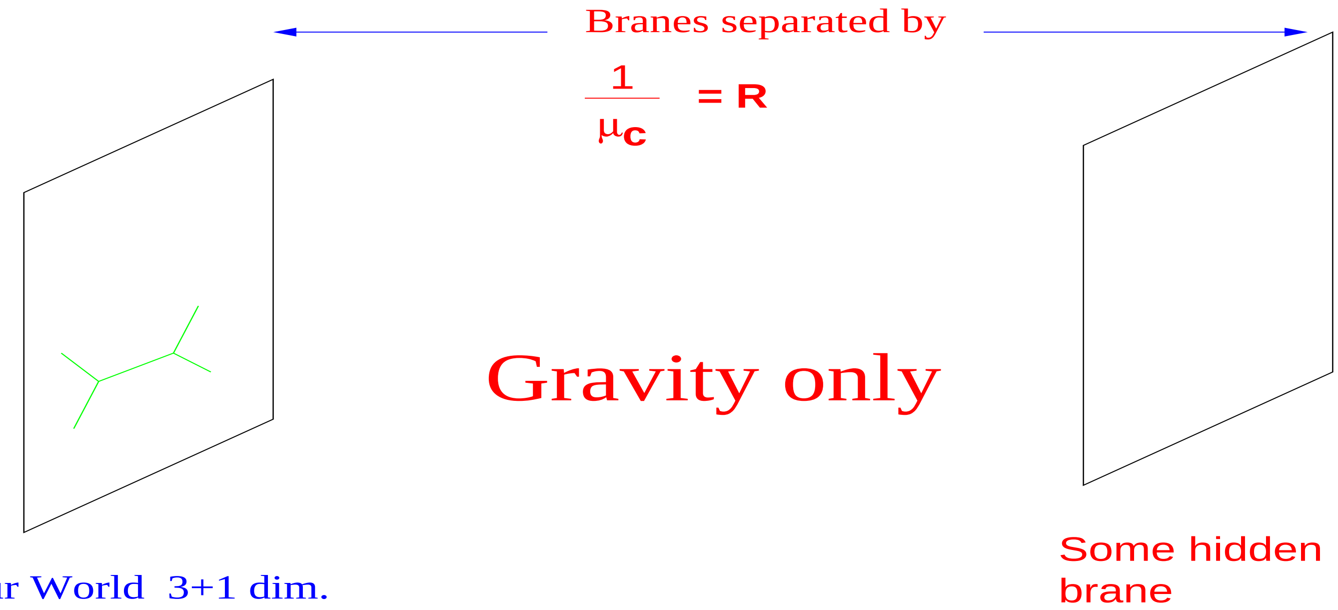
$$\boxed{M_{\rm Pl}^2 = M_*^{2+n}\, V_m\, V_{n-m}}$$

$$V_m = L_m^m = \left(\frac{l_m}{M_*}\right)^m \;;\quad V_{n-m} = L_{n-m}^{n-m} = \left(\frac{l_{n-m}}{M_*}\right)^{n-m}$$

$$\boxed{M_{\rm Pl}^2 \sim M_*^2\;\, l_{n-m}^{n-m}}$$

- Some conventions used M_D instead of M_*: $M_D^{n+2} = \frac{(2\pi)^n}{8\pi}\, M_*^{n+2}$

ADD model



Proposed by Arkani et al. the size of the extra dimensions can be as large as $R \lesssim 1$ mm.

$$\mu_c \equiv R^{-1} \gtrsim 10^{-4}\ \text{eV} \ll M_{\rm EW}$$

$$M_{\rm Pl}^2 \sim M_D^{n+2}\, R^n \qquad \text{(Gauss)}$$

- $M_{*,D}$ is the fundamental Planck scale, as low as TeV.

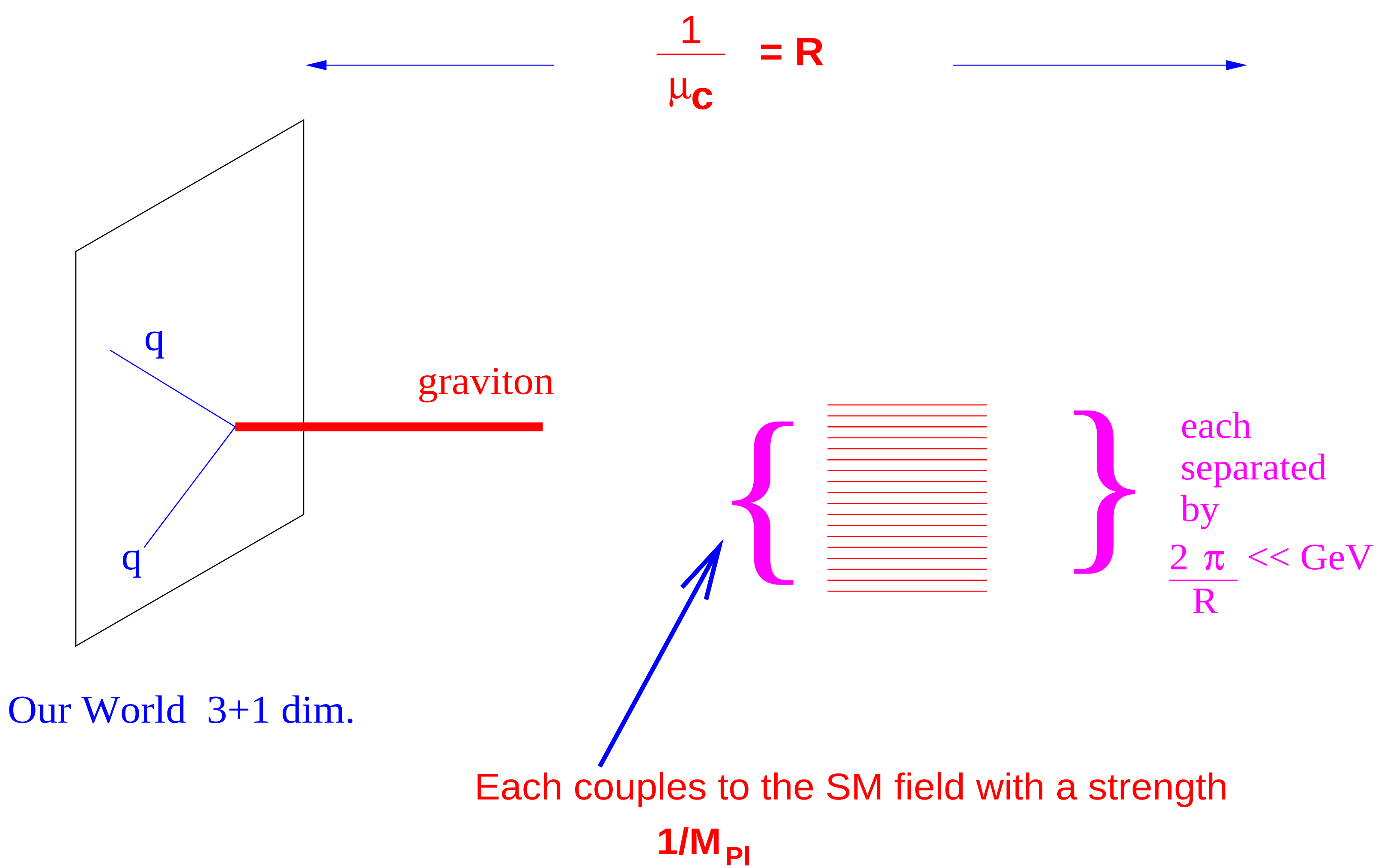
Solve the hierarchy.

- Allow only gravity in the bulk.

In 4-D, the graviton becomes towers of Kaluza-Klein states

$$M_n = \frac{2\pi n}{R}$$

- SM particles confined to a brane.



- Effectively, interaction $\sim \frac{1}{M_D} = (1\mathrm{TeV})^{-1}$.

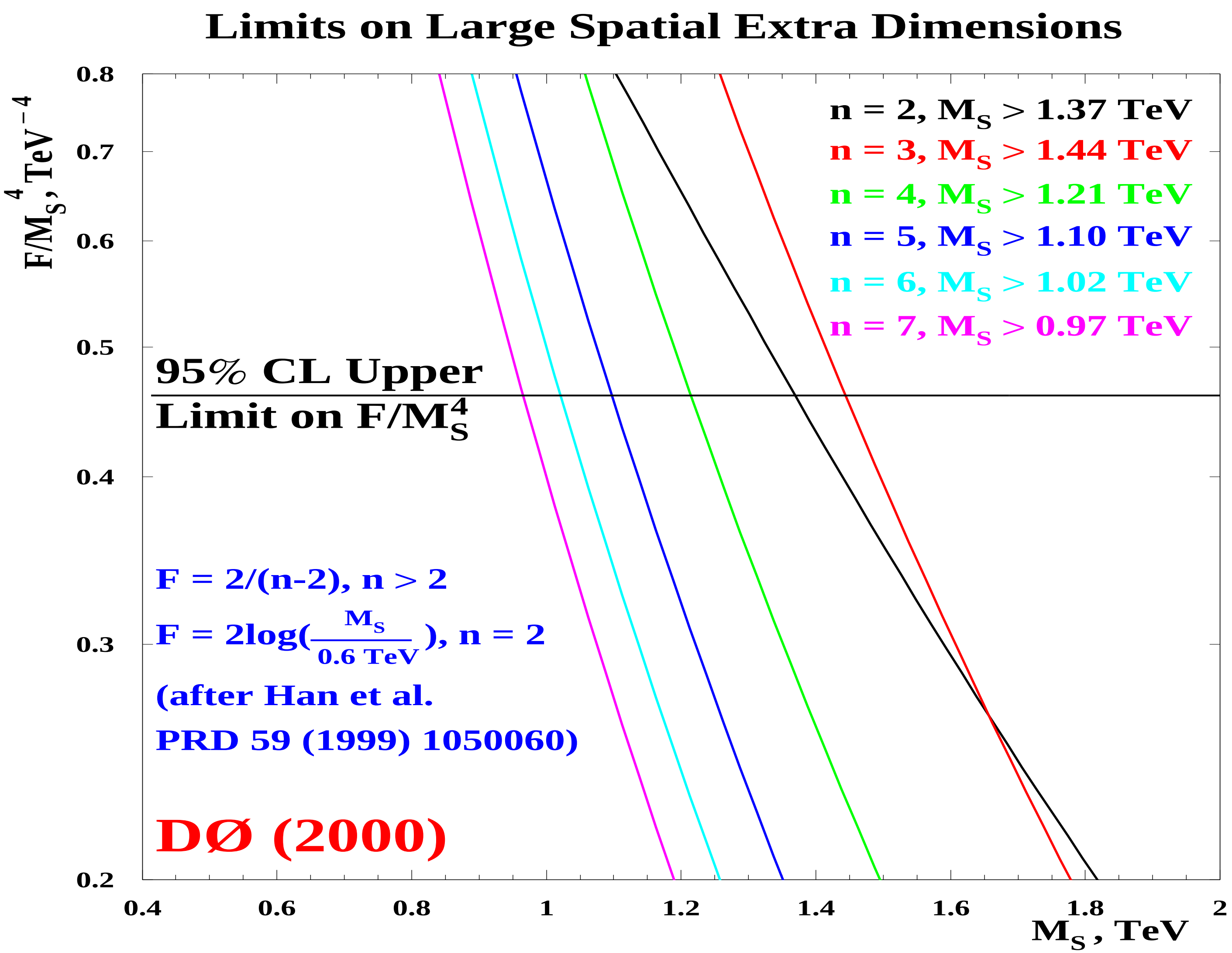
Sub-Planckian Physics

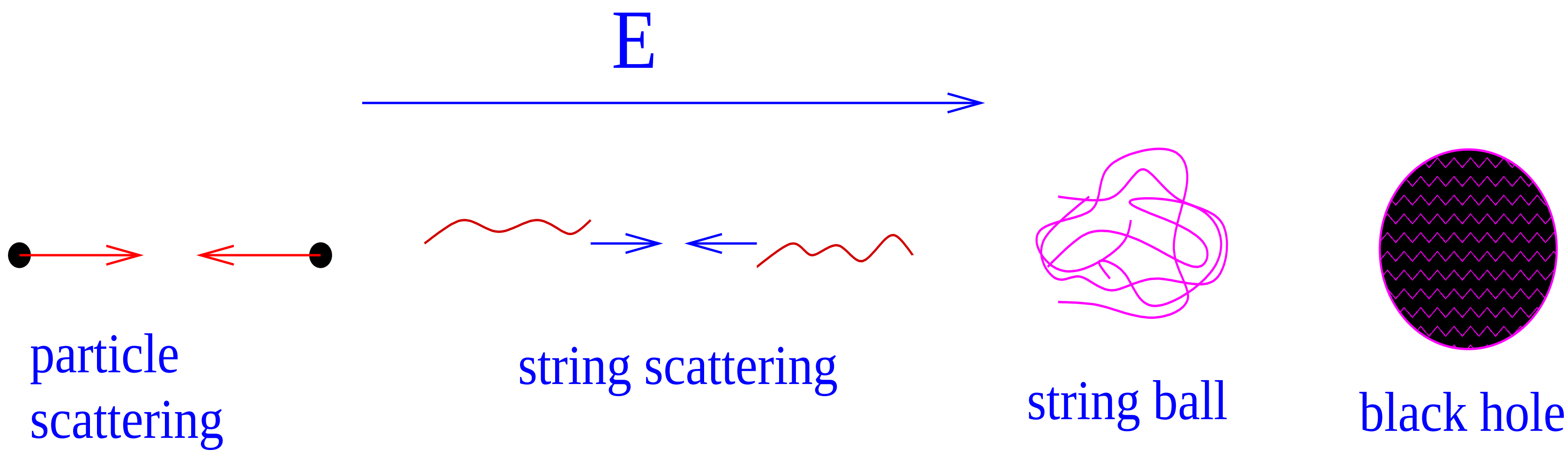
- Graviton emission into extra dimensions.
- Graviton exchange processes: interference with the SM.
- Exponential suppression to scattering amplitudes when close to the string scale.

Trans-Planckian Physics

- Black holes
- String balls
- p-branes

The energy scale is $\gg M_D, M_s$


Limits on Large Spatial Extra Dimensions
0.8
0.7
0.6
0.5
0.4
0.3
0.2
F/M_S^4, TeV^{-4}
n = 2, M_S > 1.37 TeV
n = 3, M_S > 1.44 TeV
n = 4, M_S > 1.21 TeV
n = 5, M_S > 1.10 TeV
n = 6, M_S > 1.02 TeV
n = 7, M_S > 0.97 TeV
95% CL Upper
Limit on F/M_S^4
F = 2/(n-2), n > 2
$F = 2\log(\frac{M_S}{0.6\ \text{TeV}})$, n = 2
(after Han et al.
PRD 59 (1999) 1050060)
DØ (2000)
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
M_S, TeV


E
particle
scattering
string scattering
string ball
black hole

Black Holes

A BH is characterized by

- mass $M_{\rm BH} \Rightarrow R_{\rm BH}, S_{\rm BH}, \tau$,
- Charge Q,
- Angular Momentum $J(=0)$.

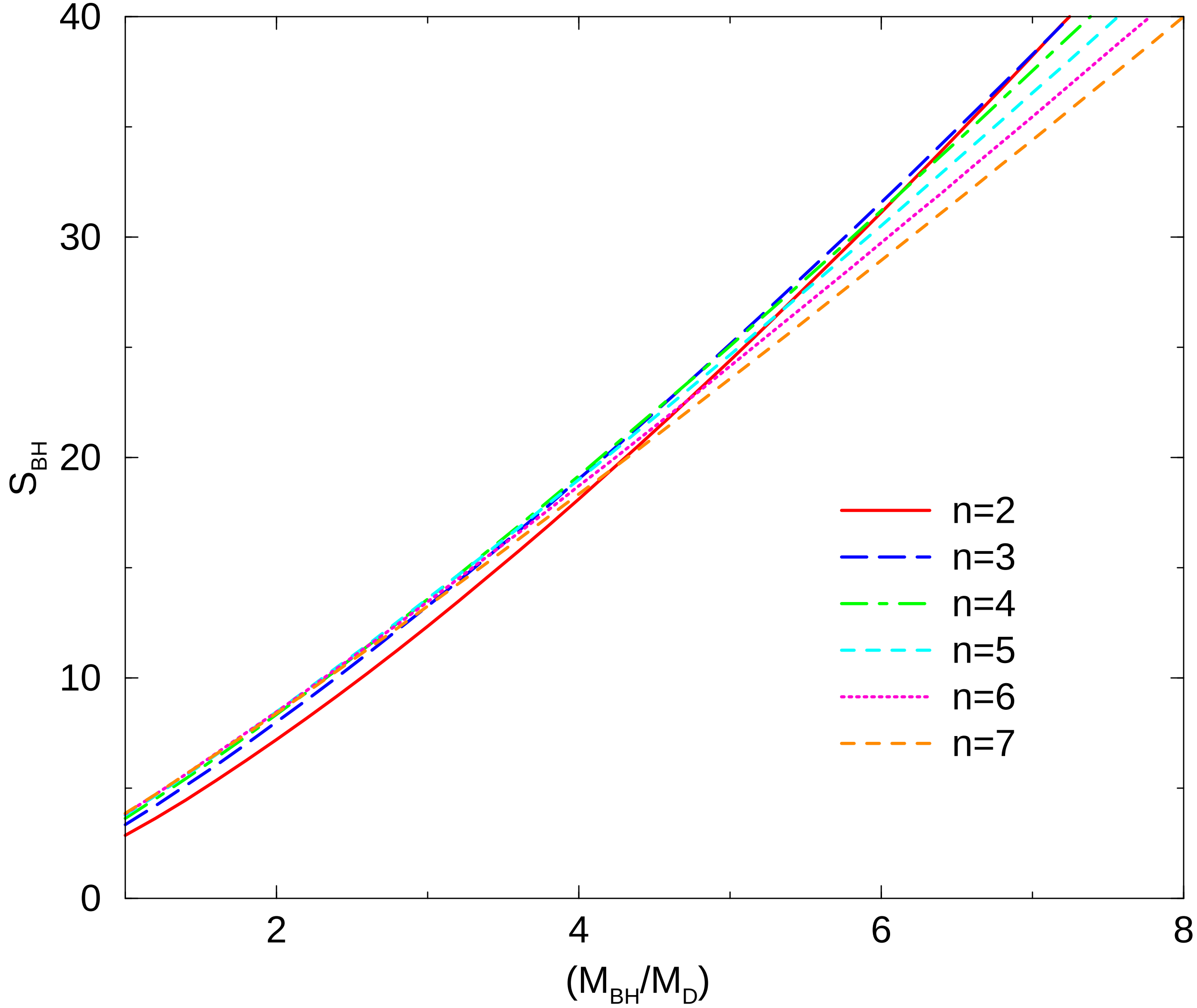
Minimum $M_{\rm BH} \sim$ a few $\times M_D$, in order that large entropy is fulfilled.

$$R_{\rm BH} = \frac{1}{M_D} \left(\frac{M_{\rm BH}}{M_D}\right)^{\frac{1}{n+1}} \left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma(\frac{n+3}{2})}{n+2}\right)^{\frac{1}{n+1}}$$

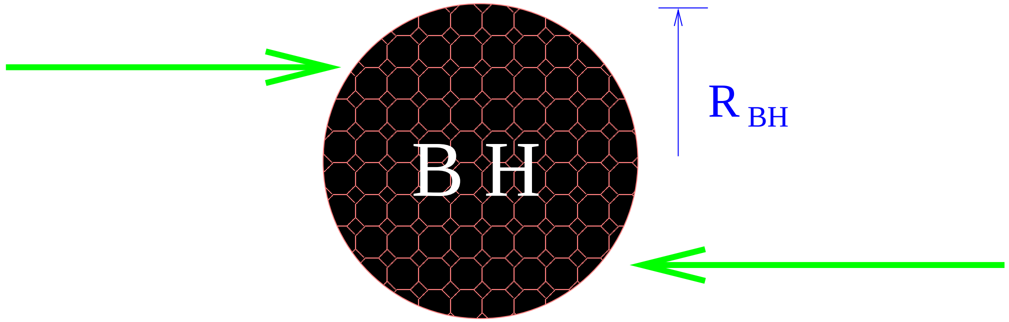
$$S_{\rm BH} = \frac{4\pi}{n+2} \left(\frac{M_{\rm BH}}{M_D}\right)^{\frac{n+2}{n+1}} \left(\frac{2^n \pi^{\frac{n-3}{2}} \Gamma(\frac{n+3}{2})}{n+2}\right)^{\frac{1}{n+1}} .$$

$M_{\rm BH} \gtrsim 5 M_D$ for $S_{\rm BH} \gtrsim 25$

Entropy $S_{\rm BH}$ versus $(M_{\rm BH}/M_D)$



Production cross sections

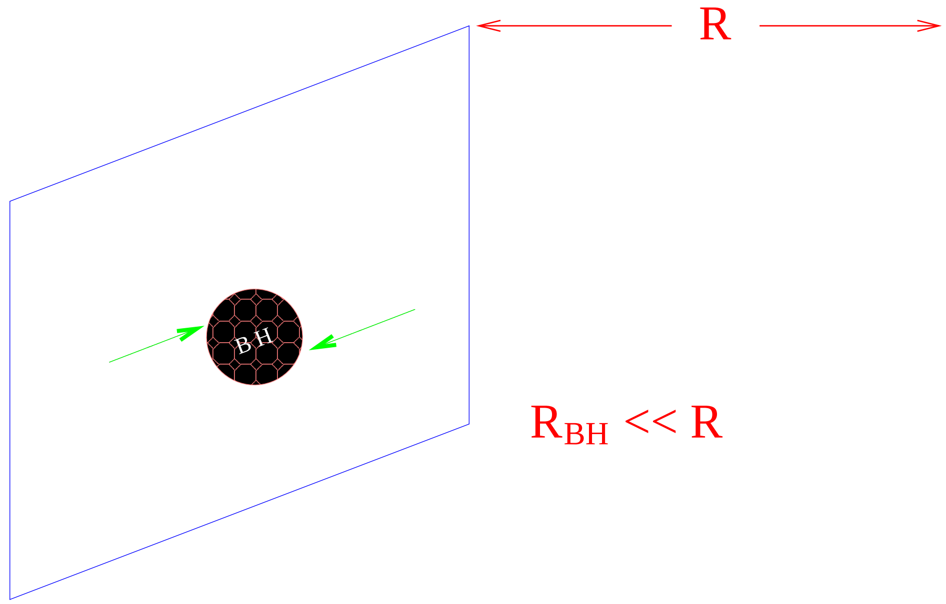


$$\sigma(M_{\rm BH}^2) \approx \pi R_{\rm BH}^2$$

$$2 \to 1: \ \hat\sigma(\hat s) = \int d\left(\frac{M_{\rm BH}^2}{\hat s}\right) \pi R_{\rm BH}^2 \, \delta\left(1 - M_{\rm BH}^2/\hat s\right) = \pi R_{\rm BH}^2 \, .$$

$$2 \to k: \ \hat\sigma(\hat s) = \int_{(M_{\rm BH}^2)_{\rm min}/\hat s}^{1} d\left(\frac{M_{\rm BH}^2}{\hat s}\right) \pi R_{\rm BH}^2 \, .$$

Decay Signature of BH



- λ corresponding to the Hawking temp. much larger than $R_{\rm BH}$, BH evaporates like a s-wave point source. Equally into brane and bulk modes. No reason to expect:

$$\text{BH} \to \text{graviton} \to \text{extra dimensions}$$

$$R_{\rm BH} \ll R$$

A BH decays “blindly”. The main phase is the Hawking Evaporation, according to the degrees of freedom.

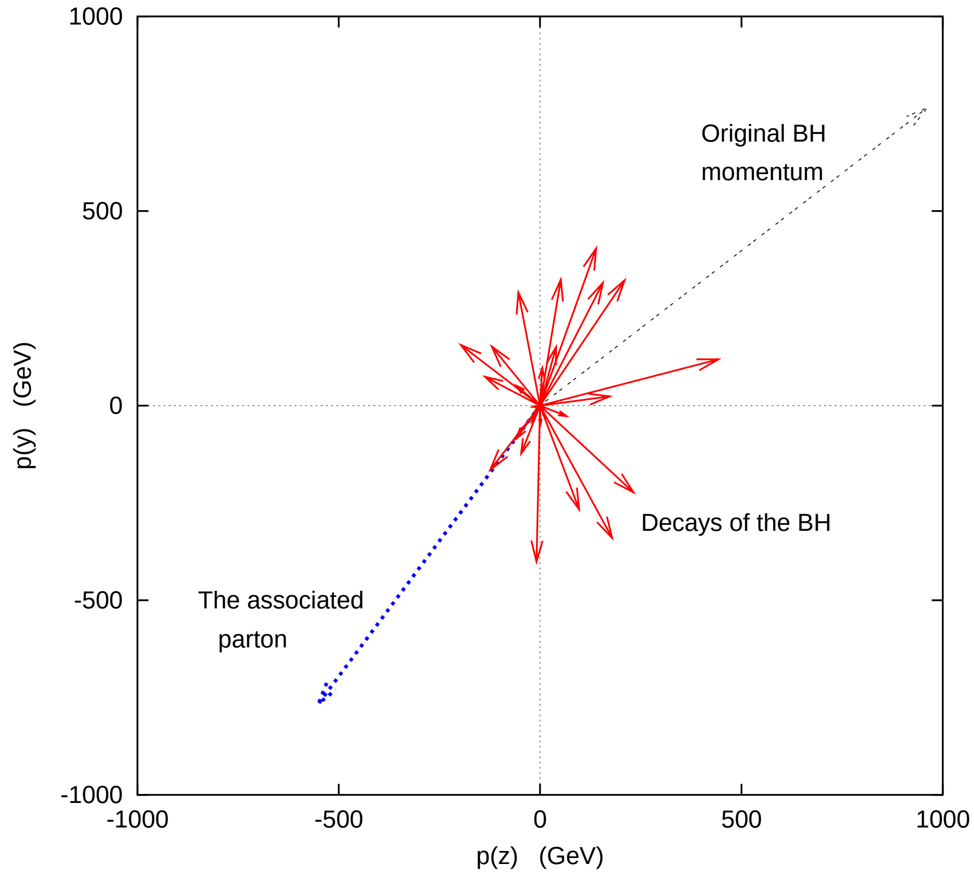
$$Z, W, H, \gamma, g, G; \;\; u, d, s, c, b, t; \;\; e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau = 30 : 72 : 18$$

Hadronic : leptonic $\sim 5 : 1$

A nonrotating BH decays isothermally. E.g., a BH with $M_{\rm BH} \sim$ a few TeV decays into $\sim 30 - 50$ particles. Each has about a few 100 GeV, like

A spherical fireball

A typical BH event with a large p_T



Two sides: 1^0 a few energetic partons $\Rightarrow$ provide tags.

2^0 the BH decay, a boosted "fireball".

String Balls

- Dimopoulos and Emparan pointed out that when a BH reaches a minimum mass, it transits into a state of highly excited and jagged strings – string balls (SB).

$$M_{\rm BH}^{\rm min} = M_s/g_s^2$$

- SBs are the stringy progenitors of BHs.

- BH Correspondence principle: properties of a BH with a mass $M_{\rm BH}$ match those of a string ball of a string theory with $M_s/g_s^2 = M_{\rm BH}$.

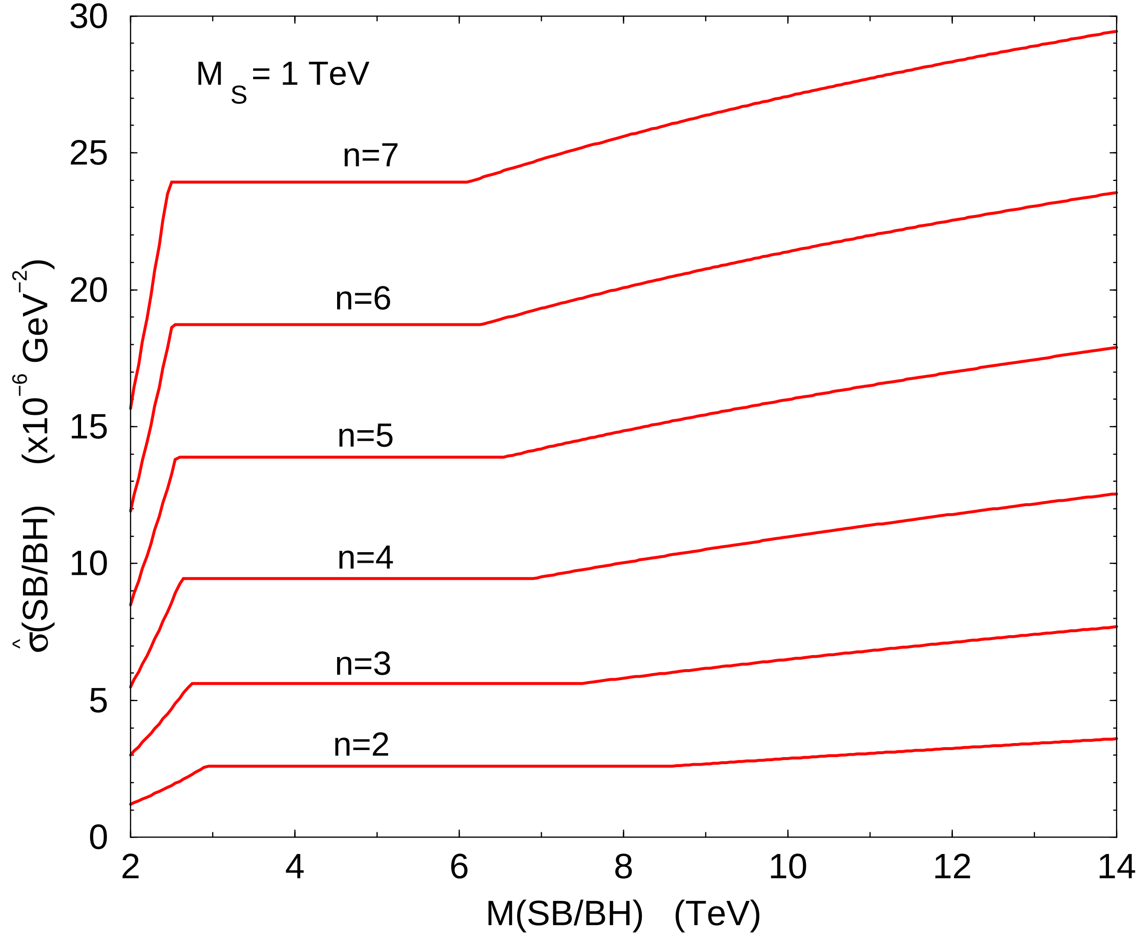
$$\sigma(SB)|_{M_{SB}=M_s/g_s^2} = \sigma(BH)|_{M_{BH}=M_s/g_s^2}$$

Production cross sectons

$$\hat{\sigma}(\mathrm{SB/BH}) = \begin{cases} \frac{\pi}{M_D^2} \left(\frac{M_{\mathrm{BH}}}{M_D}\right)^{\frac{2}{n+1}} [f(n)]^2 & \frac{M_s}{g_s^2} \le M_{\mathrm{BH}} \\ \frac{\pi}{M_D^2} \left(\frac{M_s/g_s^2}{M_D}\right)^{\frac{2}{n+1}} [f(n)]^2 = \frac{\pi}{M_s^2} [f(n)]^2 & \frac{M_s}{g_s} \le M_{\mathrm{SB}} \le \frac{M_s}{g_s^2} \\ \frac{\pi g_s^2 M_{\mathrm{SB}}^2}{M_s^4} [f(n)]^2 & M_s \ll M_{\mathrm{SB}} \le \frac{M_s}{g_s} \end{cases}$$

- When the energy is above M_s but below M_s/g_s, the scattering is between two strings. The amplitude $\sim \hat{s}/M_s^4$.
- When the energy reaches M_s/g_s, saturation of unitarity sets σ constant until it hits the correspondence point.

$\hat{\sigma}$ (SB/BH) versus $M_{\mathrm{BH/SB}}$



$M_s = 1$ TeV. Correspondence point at $M_s/g_s^2 = 5M_D$

Decay Signature of SB

- Highly excited long strings

emit massless quanta with a thermal spectrum at the *Hagedorn* temperature.

Hagedorn temp. of an excited string matches the Hawking temp. of a BH at $M_{\rm BH}^{\rm min}$.

- At $M_{\rm SB} \sim M_s/g_s^2$, wavelength $\lambda \equiv 2\pi/T$ is larger than $R_{\rm SB}$. The string ball is like a point source and emits in s-waves

$\Rightarrow$ equally into brane and bulk modes.

- When $M_{\rm SB}$ gets below M_s/g_s^2, the SB likely to puffs up to a *random-walk size* $\approx$ the λ of the emissions. Therefore, it makes more use of the angular momentum states provided by the extra dim.

$\Rightarrow$ more into the bulk modes, but only temporary

- When the SB decays further, it shrinks back to l_s, and emits as a point source again.
- Most of time, SB decays into visible quanta.

p Branes

A BH is considered a 0-brane, so p-branes, in principle, can also be produced.

- Consider an uncharged, static p-brane with mass $M_{p\mathrm{B}}$. The p-brane wraps on $r(\leq m)$ small extra dim. and on $p-r(\leq n-m)$ large extra dim.

- The radius of the p-brane is

$$R_{p\mathrm{B}} = \frac{1}{\sqrt{\pi} M_*} \gamma(n,p) \, V_{p\mathrm{B}}^{\frac{1}{1+n-p}} \left(\frac{M_{p\mathrm{B}}}{M_*} \right)^{\frac{1}{1+n-p}}$$

$$V_{p\mathrm{B}} = l_{n-m}^{p-r} \, l_m^r \approx \left(\frac{M_{\mathrm{Pl}}}{M_*} \right)^{\frac{2(p-r)}{n-m}} ,$$

$$\gamma(n,p) = \left[8\Gamma \left(\frac{3+n-p}{2} \right) \sqrt{\frac{1+p}{(n+2)(2+n-p)}} \right]^{\frac{1}{1+n-p}}$$

- $R_{p\mathrm{B}} \to R_{\mathrm{BH}}$ in the limit $p=0$.

Production of p Branes

- $\sigma(p\mathrm{B}) \sim \sigma(\mathrm{BH})$, based on a naive geometric argument.

$$\hat{\sigma}(M_{p\mathrm{B}}) = \pi R_{p\mathrm{B}}^2$$

- $R_{p\mathrm{B}}$ of a p-brane is suppressed by some powers of the volume $V_{p\mathrm{B}}$ wrapped by the p-brane. Minimum $V_{p\mathrm{B}} = 1$ occurs when the p-brane wraps entirely on the small extra dimensions only,

$$r = p$$

- Compare $\sigma(\mathrm{BH})$ with $\sigma(p\mathrm{B})$

$$R \equiv \frac{\hat{\sigma}(M_{p\mathrm{B}}=M)}{\hat{\sigma}(M_{\mathrm{BH}}=M)} = \left(\frac{M_*}{M_{\mathrm{Pl}}}\right)^{\frac{4(p-r)}{(n-m)(1+n-p)}} \left(\frac{M}{M_*}\right)^{\frac{2p}{(1+n)(1+n-p)}} \left(\frac{\gamma(n,p)}{\gamma(n,0)}\right)^2$$

The ratio $R \equiv \hat{\sigma}(M_{p\mathrm{B}} = M)/\hat{\sigma}(M_{\mathrm{BH}} = M)$

	$p = 0$	$p = 1$	$p = 2$	$p = 3$	$p = 4$	$p = 5$
$n = 2$	1					
$n = 3$	1	1.77				
$n = 4$	1	1.41	2.46			
$n = 5$	1	1.25	1.72	3.02		
$n = 6$	1	1.17	1.42	1.94	3.46	
$n = 7$	1	1.12	1.27	1.54	2.10	3.78

$n - m \geq 2$, $M_D = 1.5$ TeV and $M_{\mathrm{BH}} = 5M_D$, $r = p = m$.

Decay of p-Branes

Not well understood.

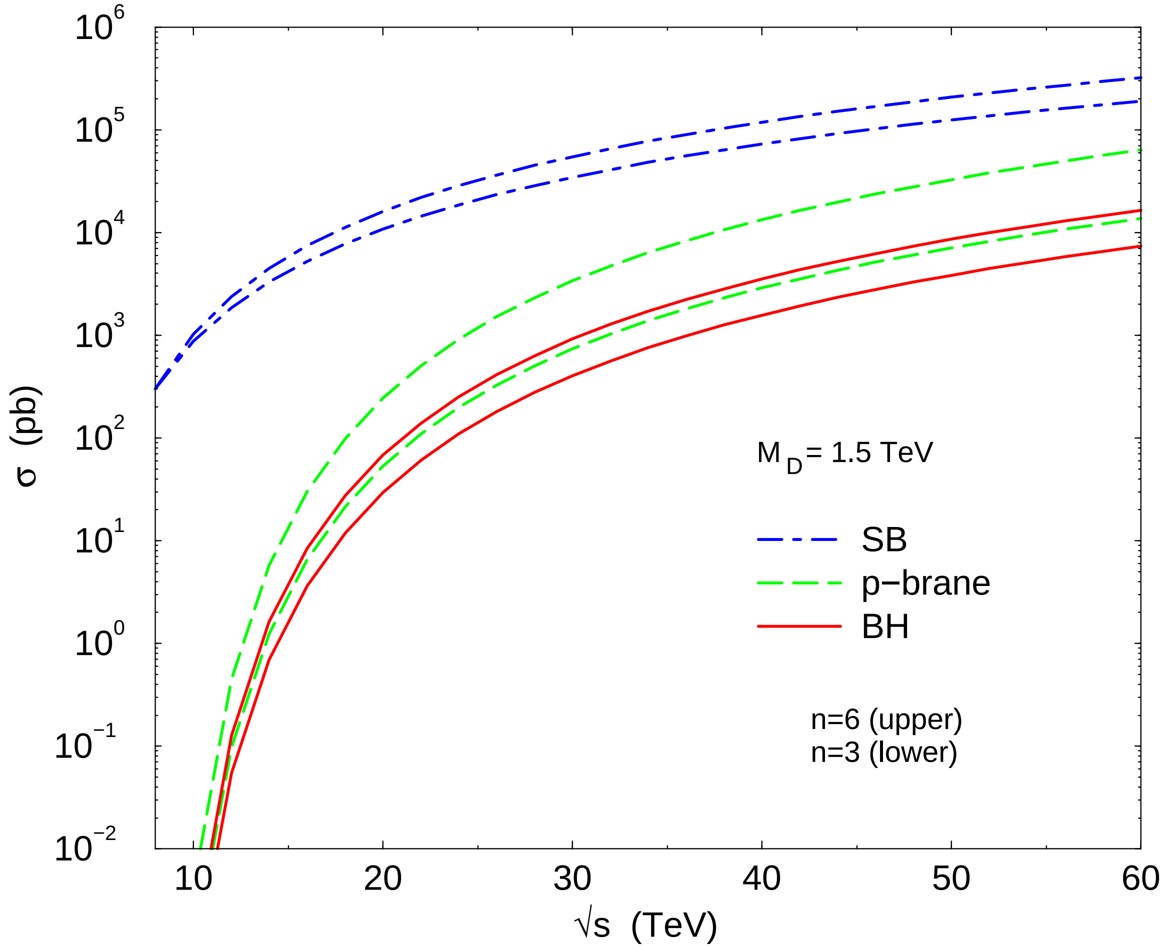
- One possibility is decay into lower dimensional branes, leading to

Cascade of branes.

- Size $R_{p\mathrm{B}}$ is much smaller than the extra dim. We expect it decays like a point source in s-waves.

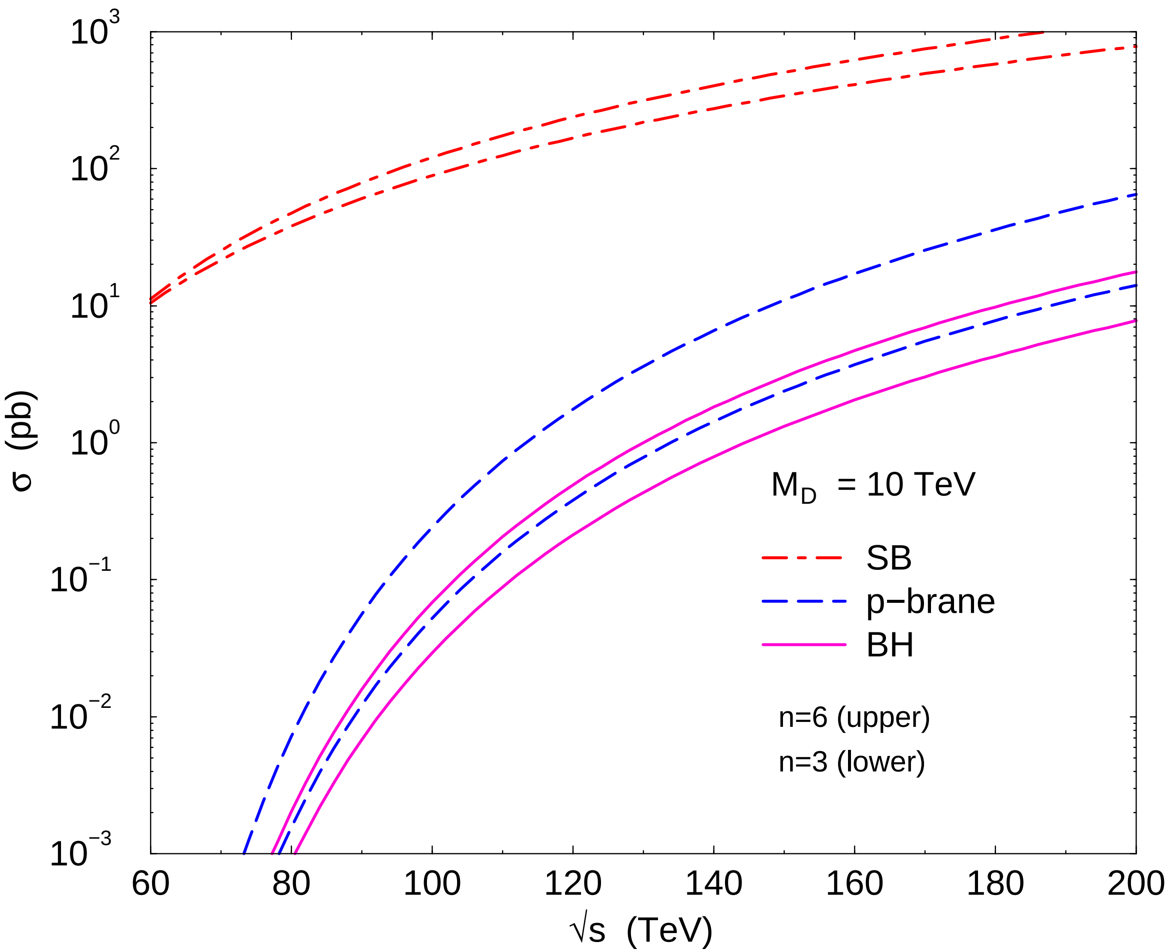
Decay mainly into brane particles.

pp Collisions



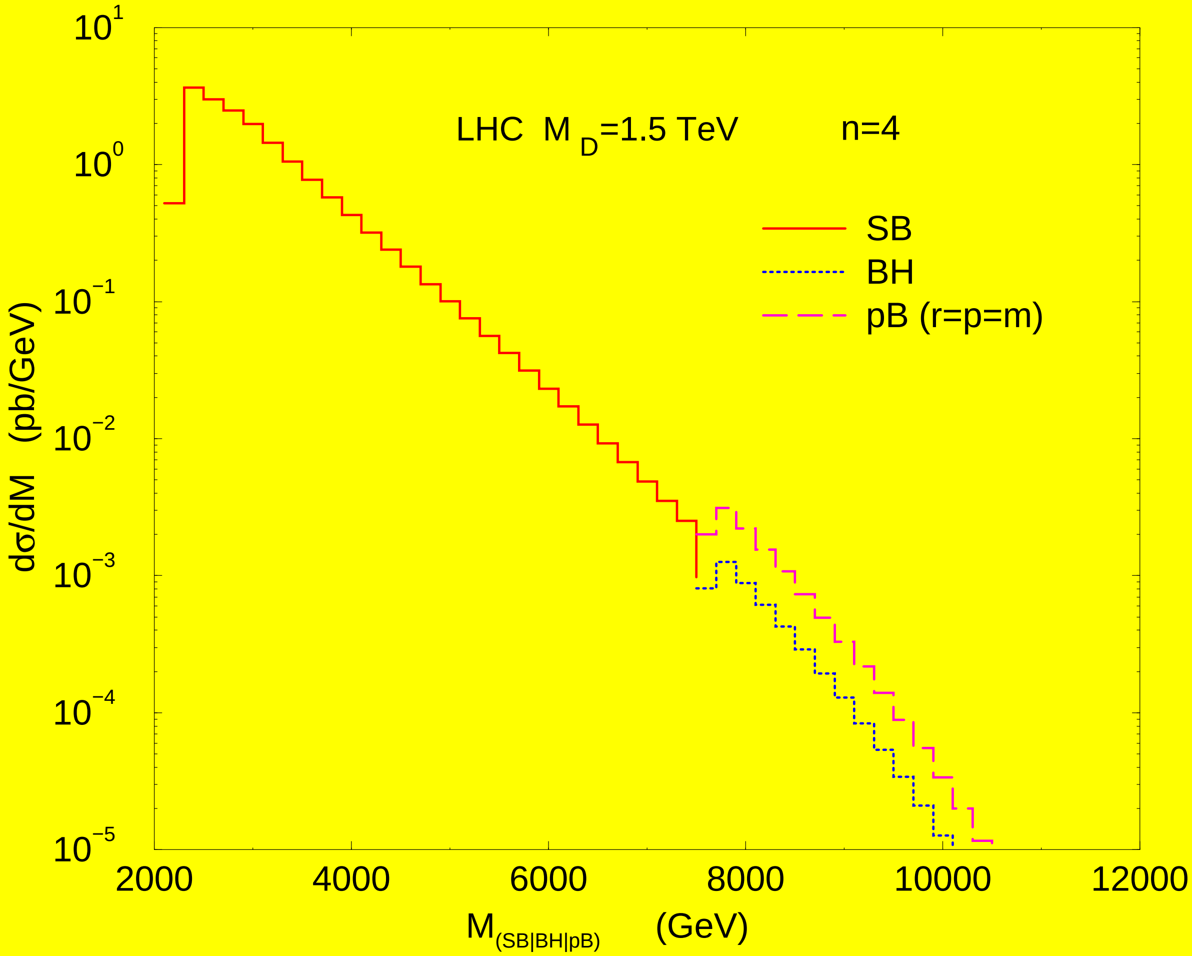
$M_D = 1.5$ TeV, $M_{\rm BH}^{\rm min} = 5 M_D$, $M_{\rm SB}^{\rm min} = 2 M_s$.

pp Collisions



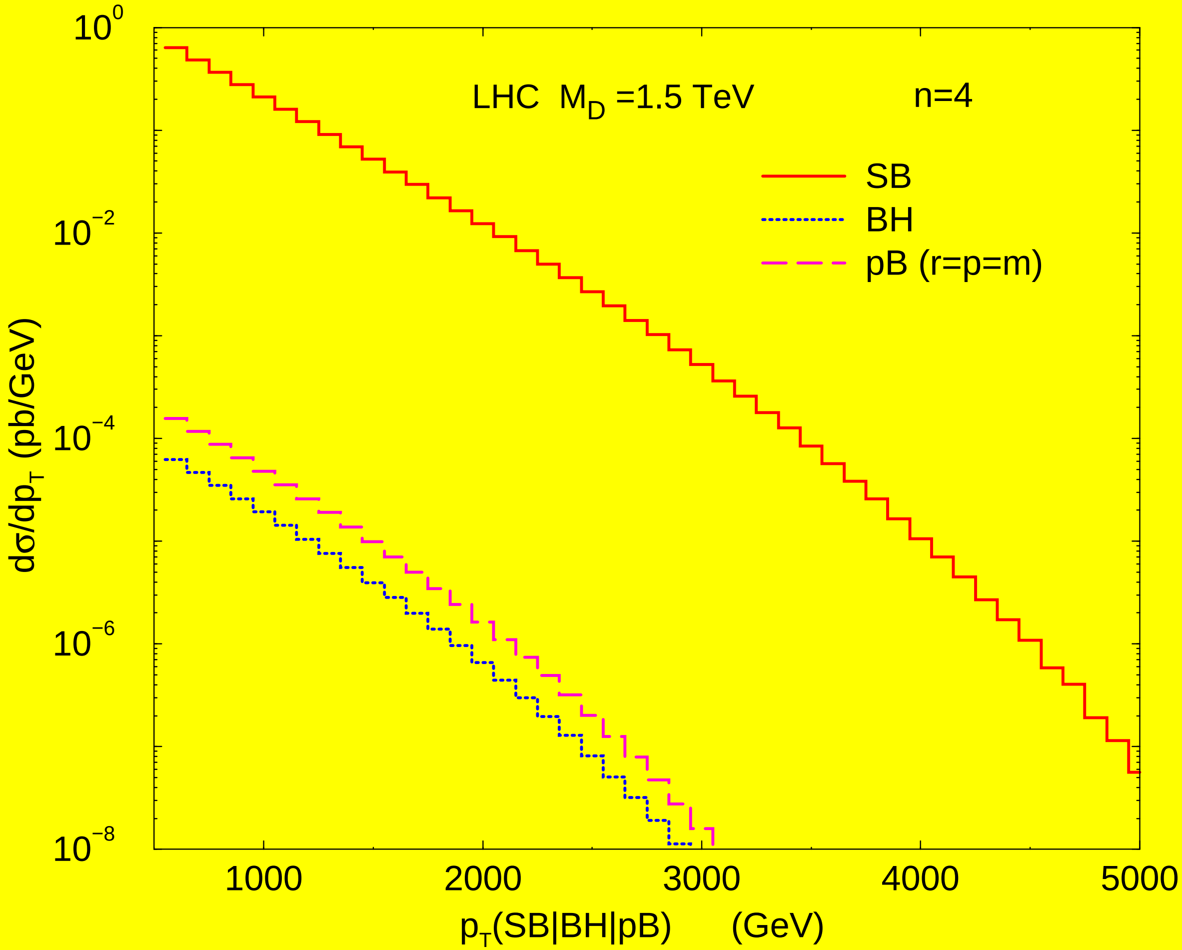
$M_D = 10$ TeV, $M_{\rm BH}^{\rm min} = 5M_D$, $M_{\rm SB}^{\rm min} = 2M_s$.

Differential cross section $d\sigma/dM$



$M_D = 1.5$ TeV, $M_{\rm BH}^{\rm min} = 5M_D$, $M_{\rm SB}^{\rm min} = 2M_s$.

Differential cross section $d\sigma/dp_T$



$M_D = 1.5$ TeV, $M_{\rm BH}^{\rm min} = 5M_D$, $M_{\rm SB}^{\rm min} = 2M_s$.

Conclusions

- Present limits are around $M_D \sim 1 - 1.4$ TeV for the fundamental Planck scale.
- Trans-Planckian physics becomes very interesting, e.g., black holes.
- LHC and VLHC will be ideal places to study BH, SB, p-branes.
- Including spinning black hole the production increases by about a factor of 2.
- Decay spectrum of the BH (spinning) deserves more studies.