WARNING !!

Substitute teacher: don't expect too much

The Standard Model is so successful and healthy

Ooops:

R_b, R_c

CDF high E_T jets

HERA high-Q^2 events

CDF $e^+e^-\gamma\gamma \not{E}_T$ event

$\sin^2\theta_w$

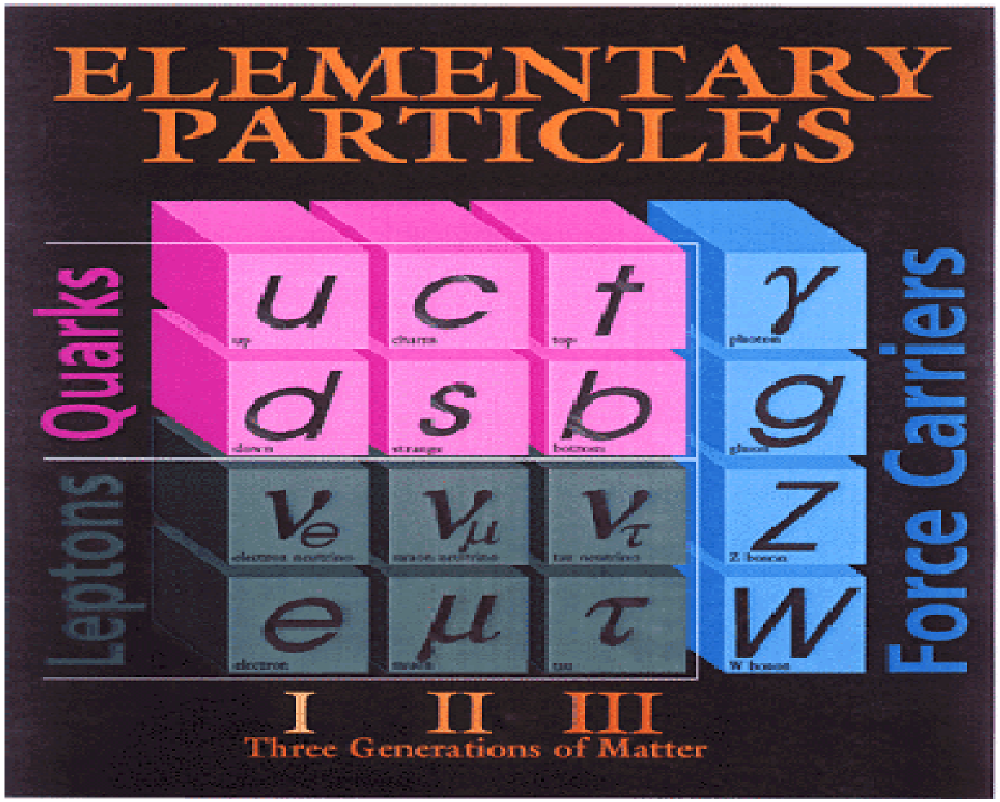
ν mass

$g-2$

Why physicists are still not happy?

Open Questions

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



Open Questions ...

(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.

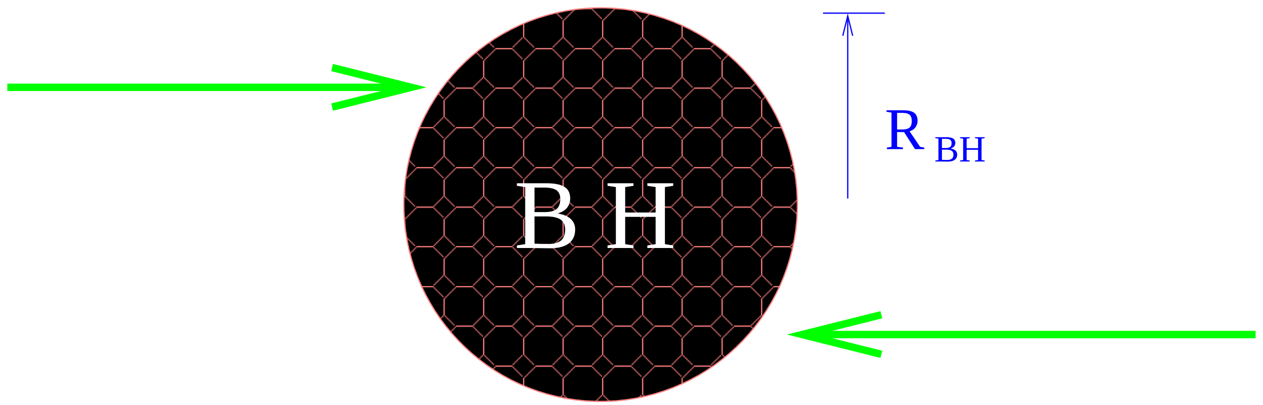
• To unify with gravity we need string theories.

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

• New physics is needed to stabilize the hierarchy, e.g., SUSY.

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

Collider tests of Large Extra Dimensions



Spring School 2002

Kingman Cheung

Outline

- 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)

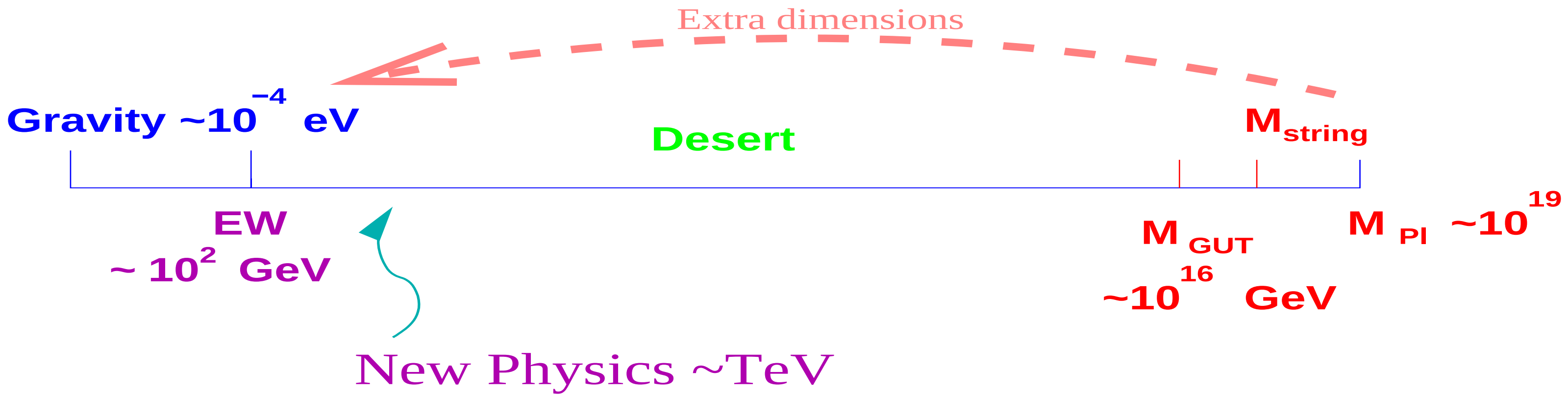
(3) S. Dimopoulos, R. Emparan, Phys. Lett. B526, 393 (2002)

(4) K. Cheung, hep-ph/0110163

(5) E. Ahn, M. Cavaglia, A. Olinto, hep-th/0201042

(6) J. Feng, A. Shapere, PRL 88:021303 (2002)

Extra Dimensions



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

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

- The observed 4D Planck scale $M_{\rm Pl}$ is a derived quantity

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

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

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

- 4D Planck scale is related to the string scale M_s

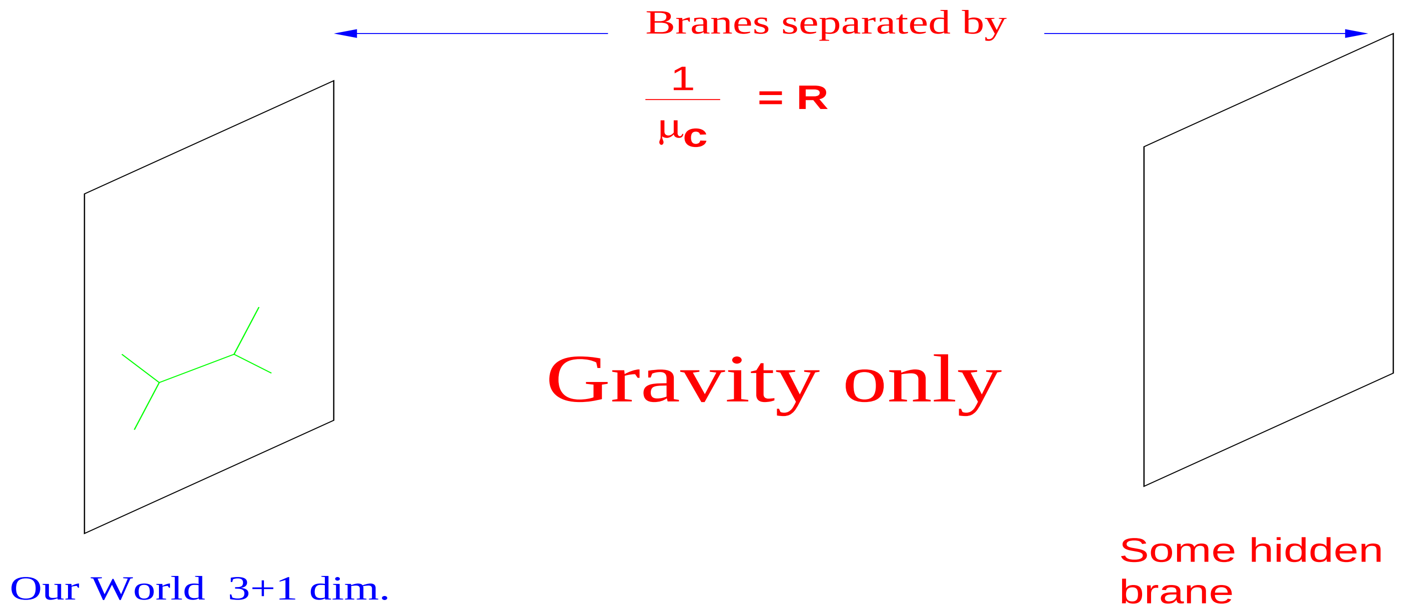
$$M_{\rm Pl}^2 \sim \frac{M_s^{2+n}}{g_s^2}\, V_m\, V_{n-m}$$

- The fundamental Planck scale and string scale are related by

$$M_*^{2+n} \sim \frac{M_s^{2+n}}{g_s^2}\;.$$

- 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.

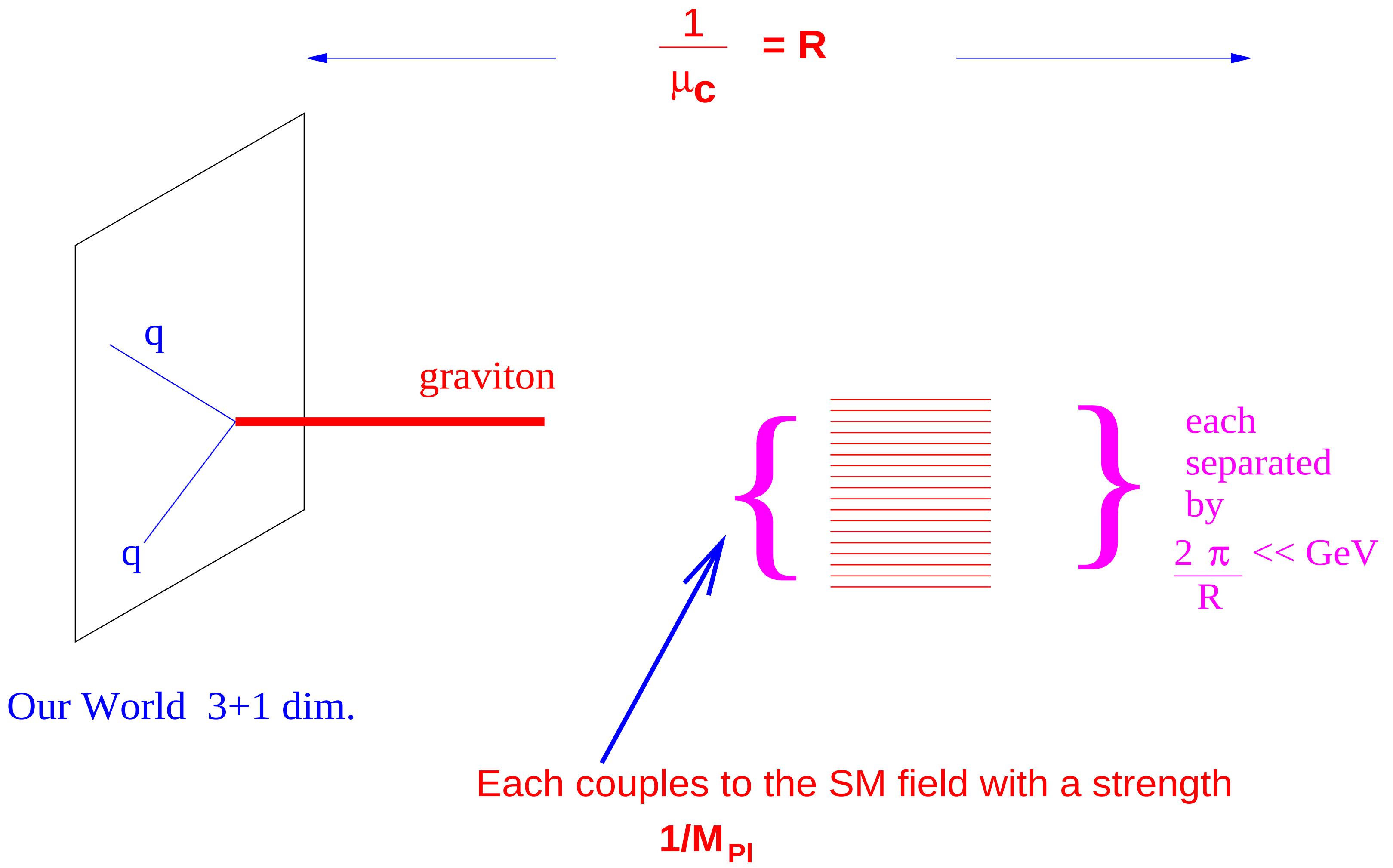
Solve the hierarchy.

- 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 $\gg M_D, M_s$

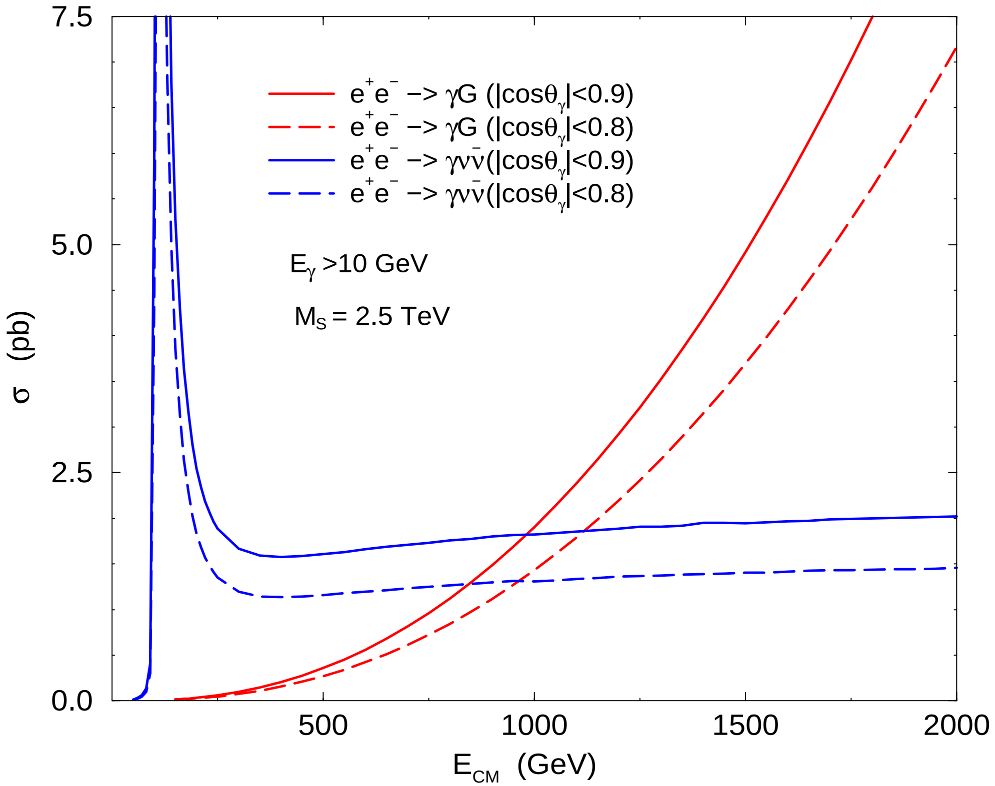
Other interesting scenarios

- Randall-Sundrum model, a special warped metric instead of a flat one. It requires only a smaller extra dimensions to explain the hierarchy.
- Put the gauge boson and/or Higgs into the bulk (K. Dienes et al. model). They achieve a much lower GUT scale. In this case, the compactification scale $\gtrsim 6 - 7$ TeV.
- A fat brane on which the fermions are localized at different positions to explain the fermion mass (John's talk.)
- A sterile neutrino in the bulk. The large bulk volume naturally gives small neutrino mass.
- The whole SM in the bulk (Hsin-chia's talk.)
- Supersymmetry model building. E.g. Anomaly-mediated SUSY breaking, gaugino-mediated SUSY breaking.

Sub-Planckian

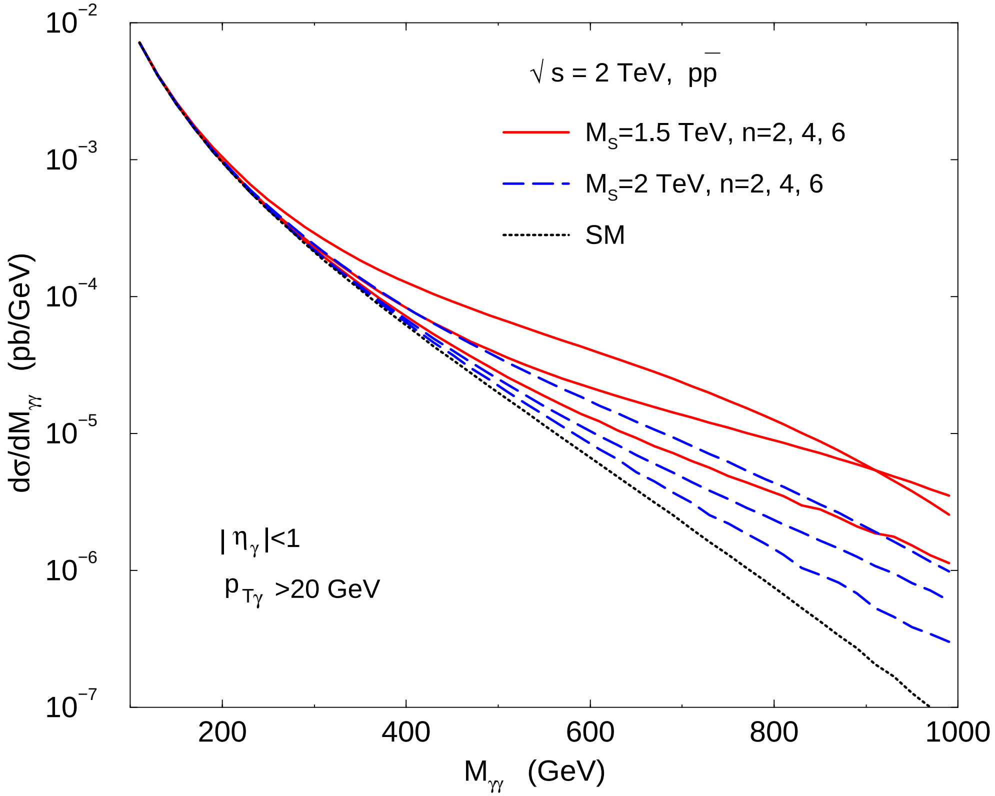
Novel signatures

$e^+e^- \to \gamma G, ZG$: Single-photon (Z) plus missing E_T.



Cheung and Keung

$$\gamma\gamma \to \gamma\gamma\,, \qquad p\bar{p} \to \gamma\gamma, \ell^+\ell^-$$



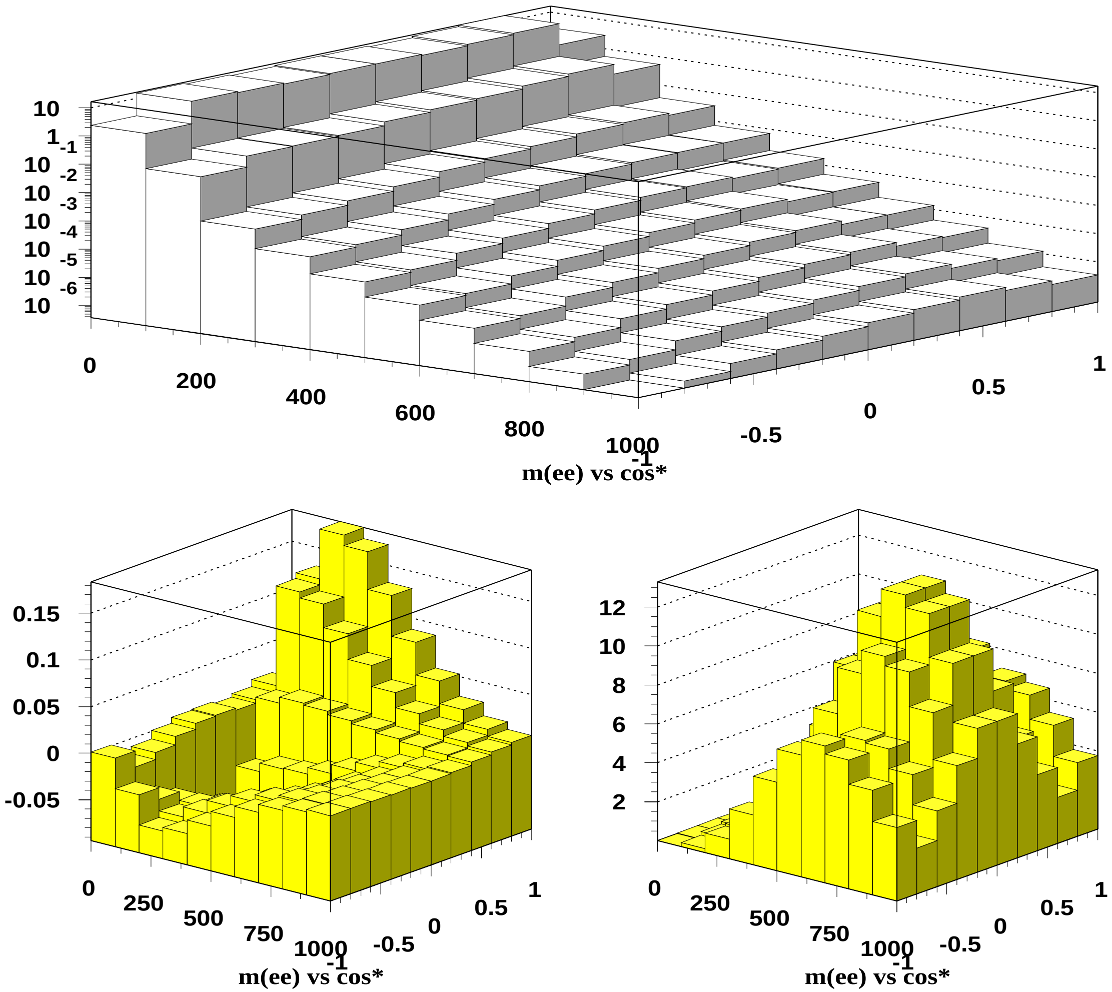
Cheung

Recent experimental results

Tevatron

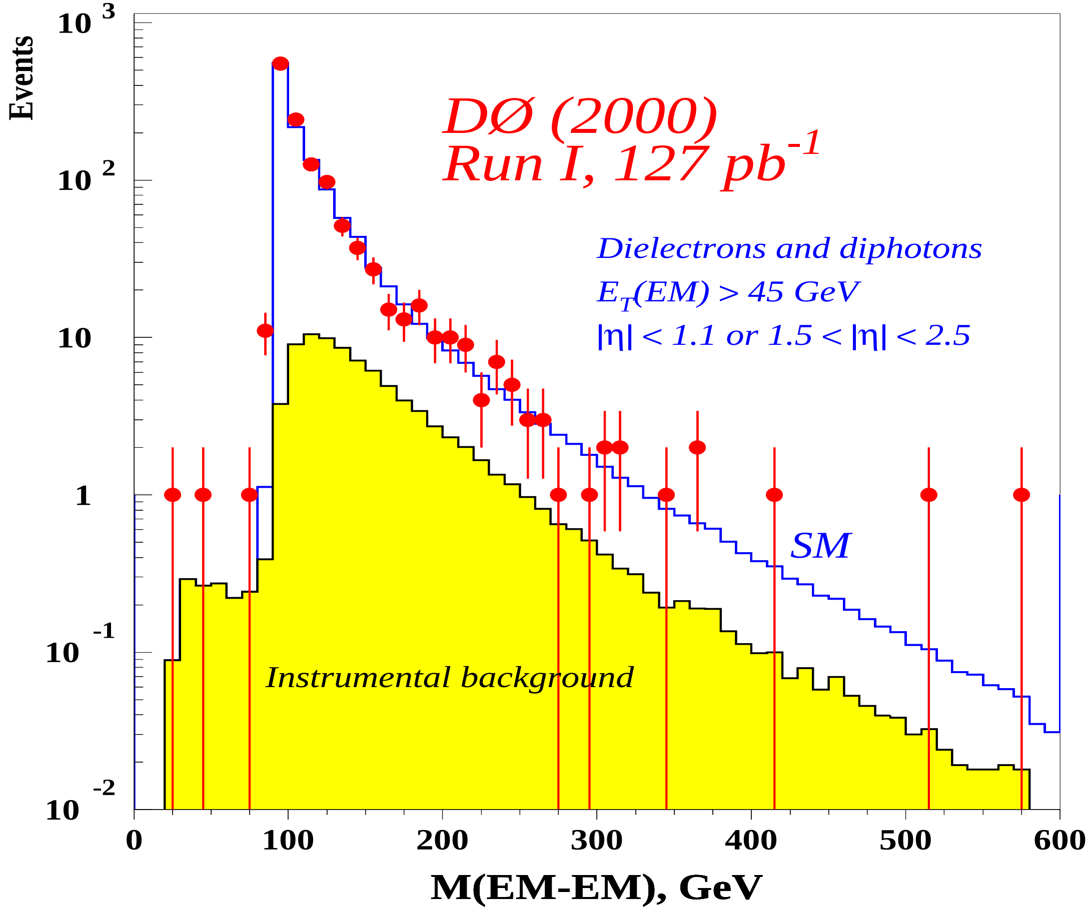
- Large extra dimensions

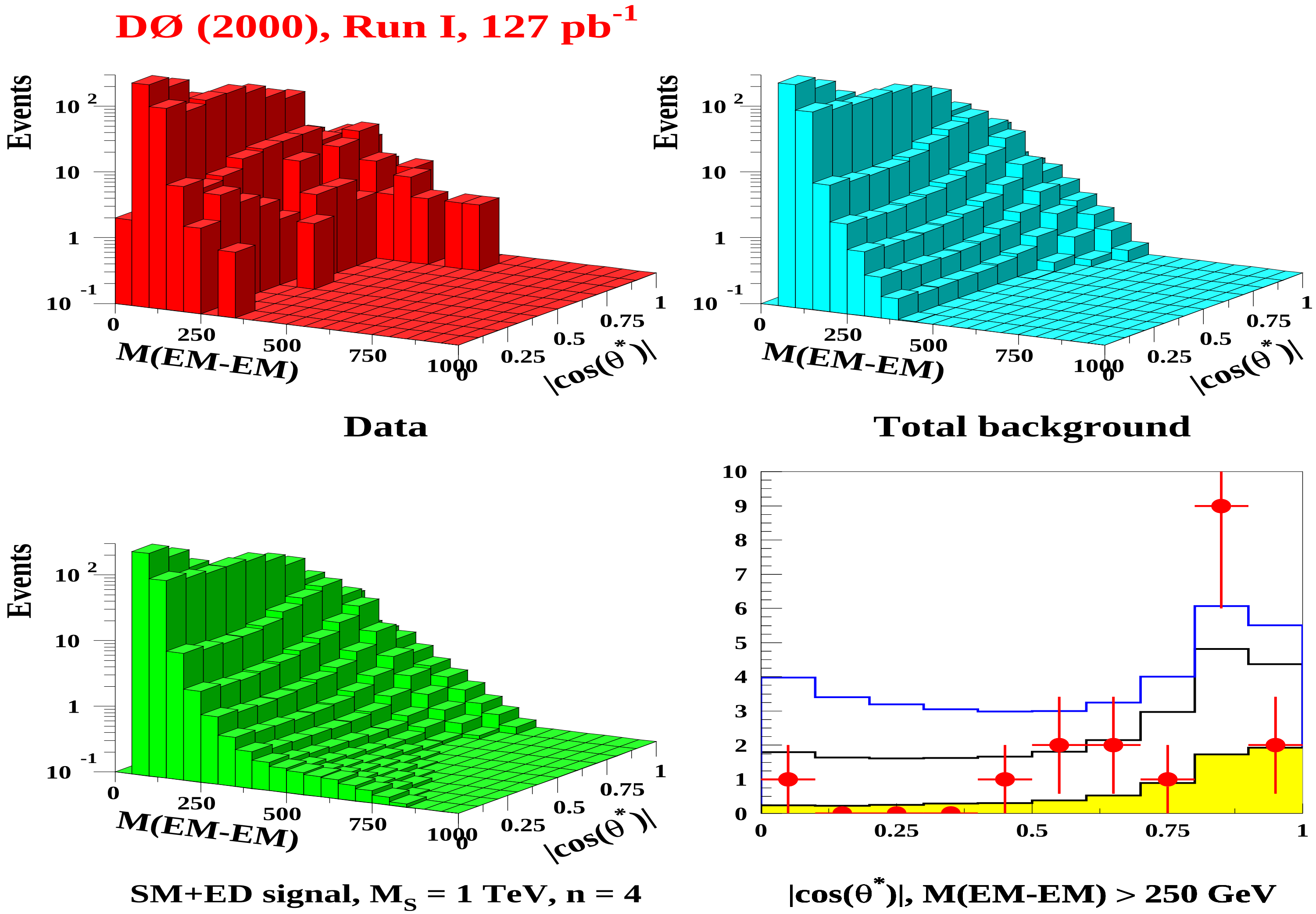
Diphoton and dilepton production are useful probes of extra dimensions (Cheung).
Use the double differential distribution to maximize the effects (Cheung+Landsberg)

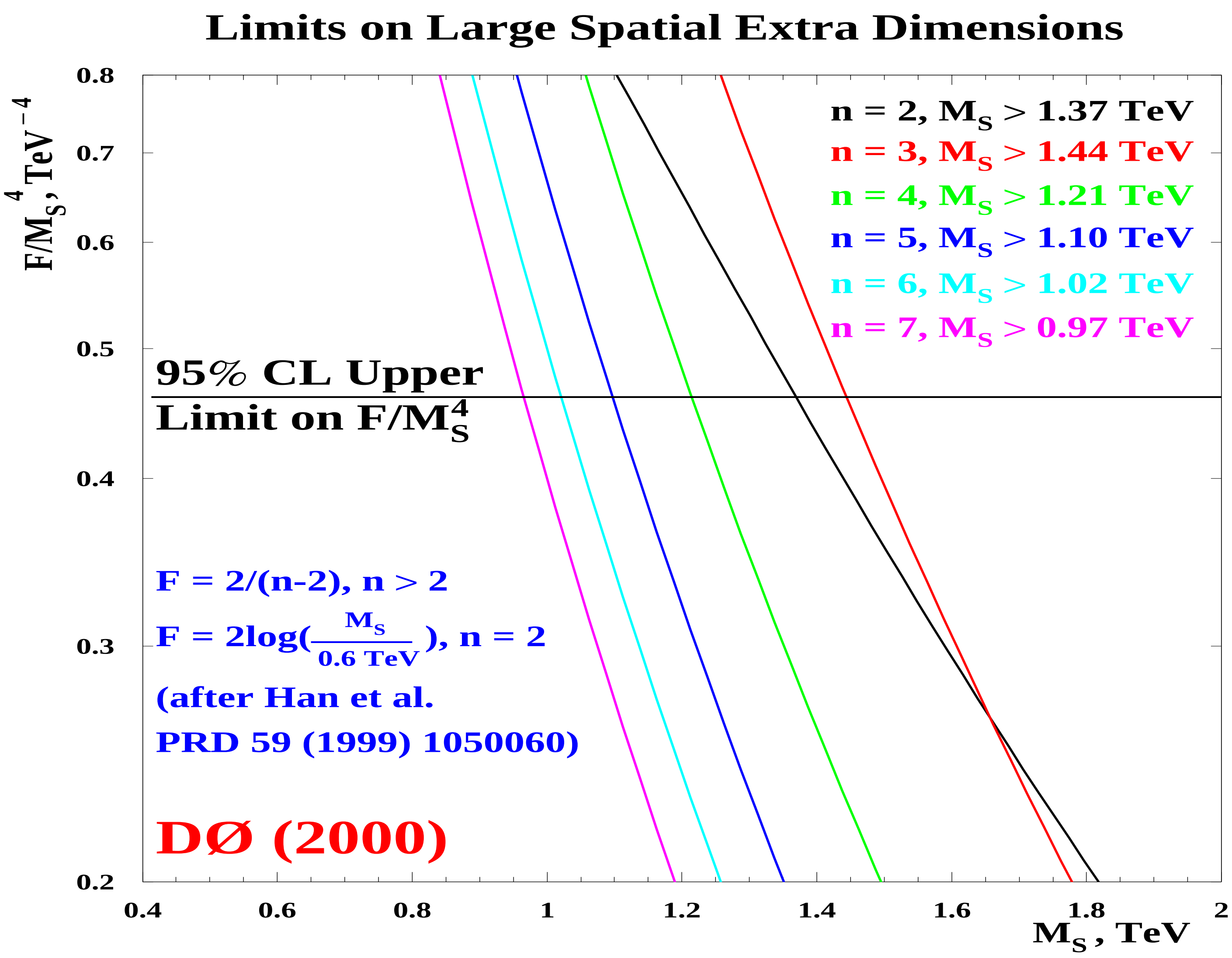

10
1
10 -1
10 -2
10 -3
10 -4
10 -5
10 -6
0
200
400
600
800
1000
-1
-0.5
0
0.5
1
m(ee) vs cos*
0.15
0.1
0.05
0
-0.05
0
250
500
750
1000
-1
-0.5
0
0.5
1
m(ee) vs cos*
12
10
8
6
4
2
0
250
500
750
1000
-1
-0.5
0
0.5
1
m(ee) vs cos*

DØ used the dilepton and diphoton production to search for the effect of large extra dimensions.

Comparison of the data with the SM predictions




DØ (2000), Run I, 127 pb-1
Events
M(EM-EM)
|cos(θ*)|
Data
Total background
SM+ED signal, MS = 1 TeV, n = 4
|cos(θ*)|, M(EM-EM) > 250 GeV


Limits on Large Spatial Extra Dimensions
F/M_S^4, TeV^-4
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
M_S , TeV
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 = 2log(M_S / 0.6 TeV), n = 2
(after Han et al.
PRD 59 (1999) 1050060)
DØ (2000)

Trans-Planckian

Black Holes

A BH is characterized by

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

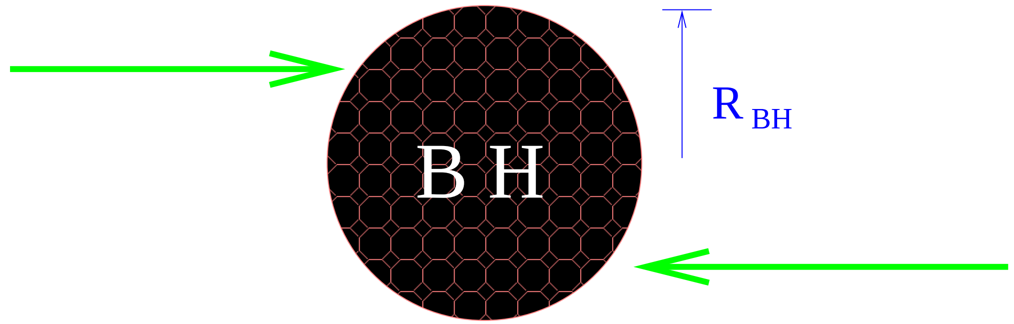
Minimum $M_{\rm BH} \sim$ a few $\times M_D$, in order that large entropy is fulfilled.

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

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

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

Production cross sections



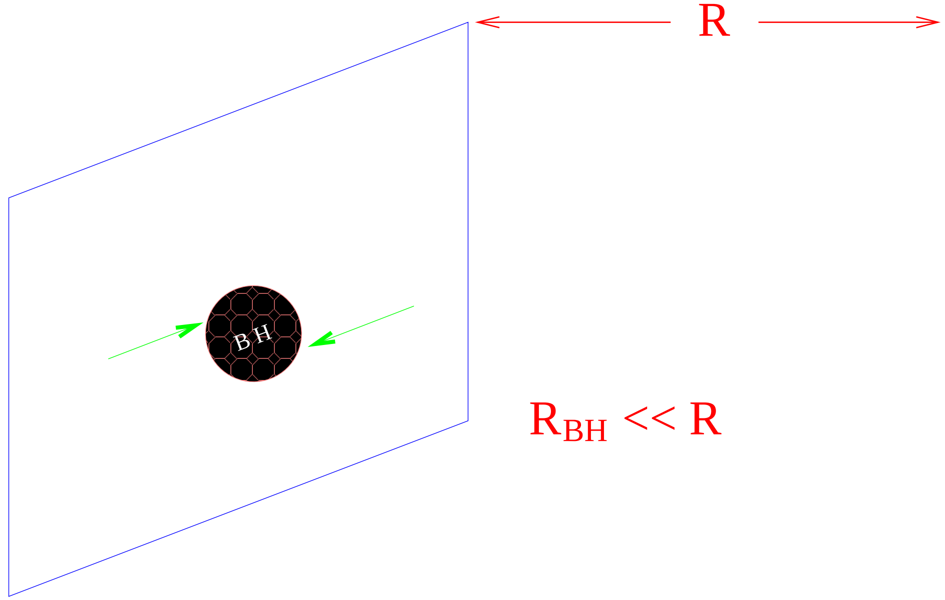
$$\sigma(M^2_{\rm BH}) \approx \pi R^2_{\rm BH}$$

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

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

Voloshin's suppression factor: $\exp\left(-\frac{S_{\rm BH}}{n+1}\right)$

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:

BH $\rightarrow$ graviton $\rightarrow$ extra dimensions

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

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

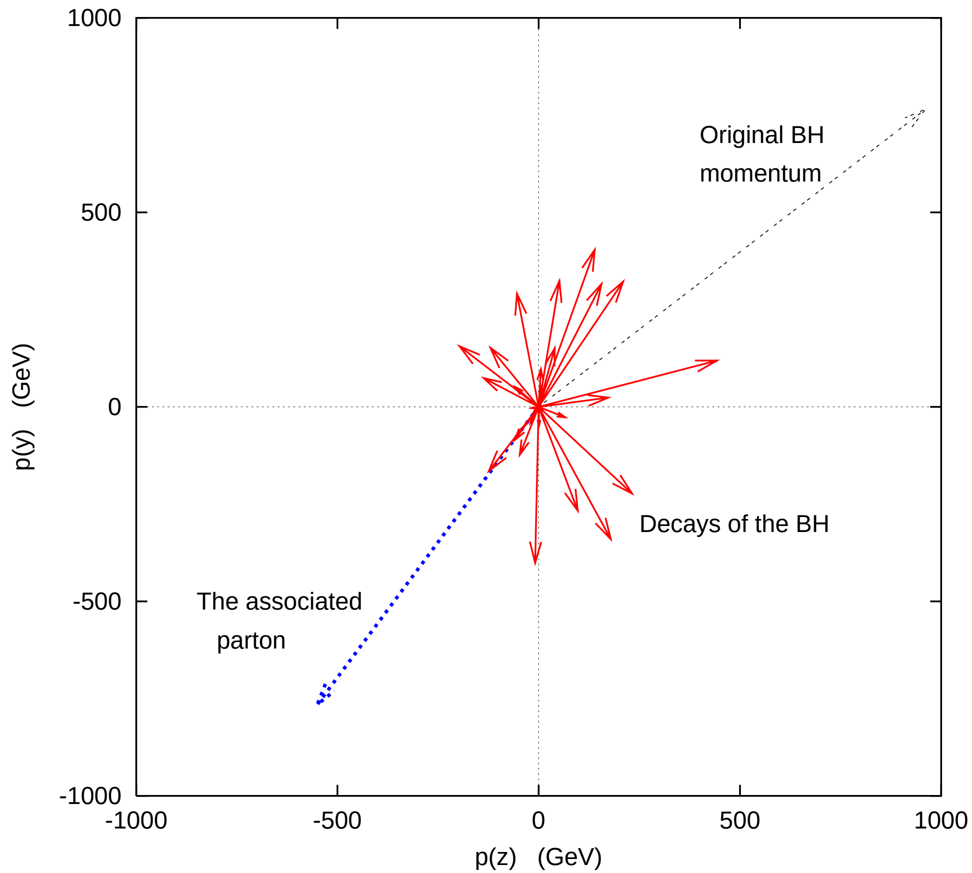
$$Z, W, H, \gamma, g; \;\; u, d, s, c, b, t; \;\; e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau = 25 : 36 : 9$$

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

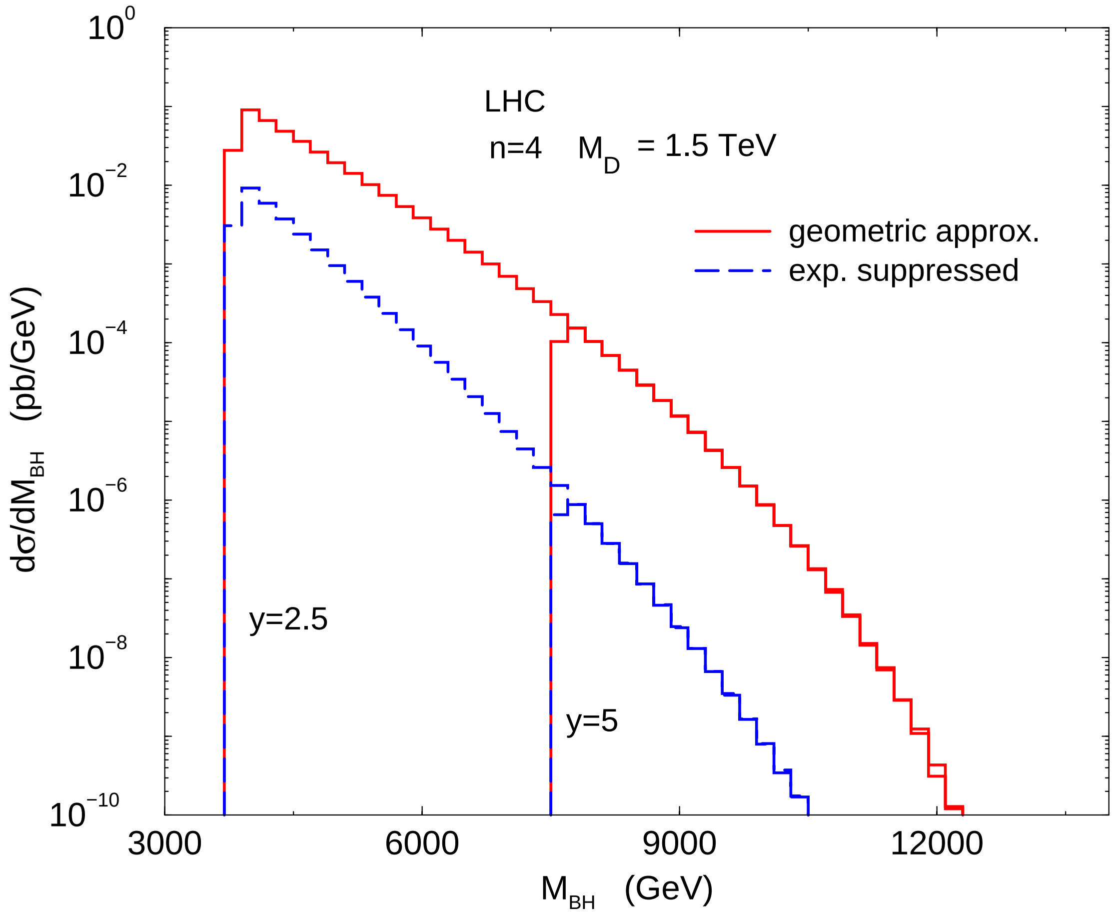
A spherical fireball

A typical BH event with a large p_T



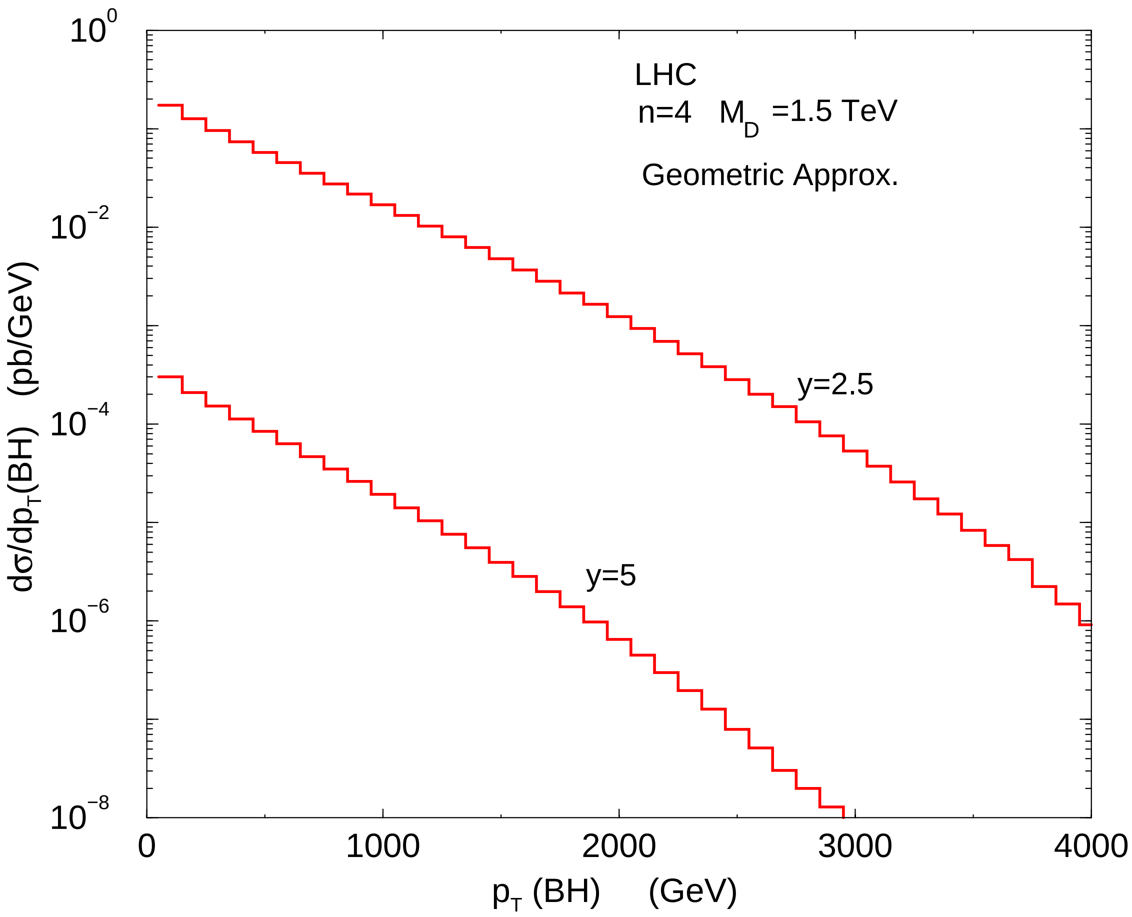
Two sides: 1^0 a few energetic partons $\Rightarrow$ provide tags.
2^0 the BH decay, a boosted "fireball".

Mass spectrum



$$M_{\rm BH}^{\rm min} = y M_D$$

p_T spectrum



$$M_{\rm BH}^{\rm min} = y M_D$$

Cross section in pb $2 \to 2$ ($2 \to 1$)

	$n = 4$	$n = 5$	$n = 6$
$M_D = 1.5$ TeV			
$y = 1$	571 (8650)	820 (12400)	1090 (16600)
$y = 2$	62.8 (831)	87.1 (1150)	113 (1490)
$y = 3$	6.3 (105)	8.6 (142)	10.9 (180)
$y = 4$	0.49 (11.8)	0.65 (15.7)	0.82 (19.8)
$y = 5$	0.024 (0.97)	0.032 (1.3)	0.039 (1.6)
$M_D = 3$ TeV			
$y = 1$	11.9 (157)	17.3 (228)	23.1 (305)
$y = 2$	0.09 (2.2)	0.13 (3.1)	0.17 (4.1)
$y = 3$	1.0×10^{-4} (0.0084)	1.4×10^{-4} (0.011)	1.8×10^{-4} (0.015)
$y = 4$	1.1×10^{-10} (2.6×10^{-7})	1.4×10^{-10} (3.5×10^{-7})	1.8×10^{-10} (4.5×10^{-7})
$y = 5$	-	-	-

$$M_{\rm BH}^{\rm min} = y M_D$$

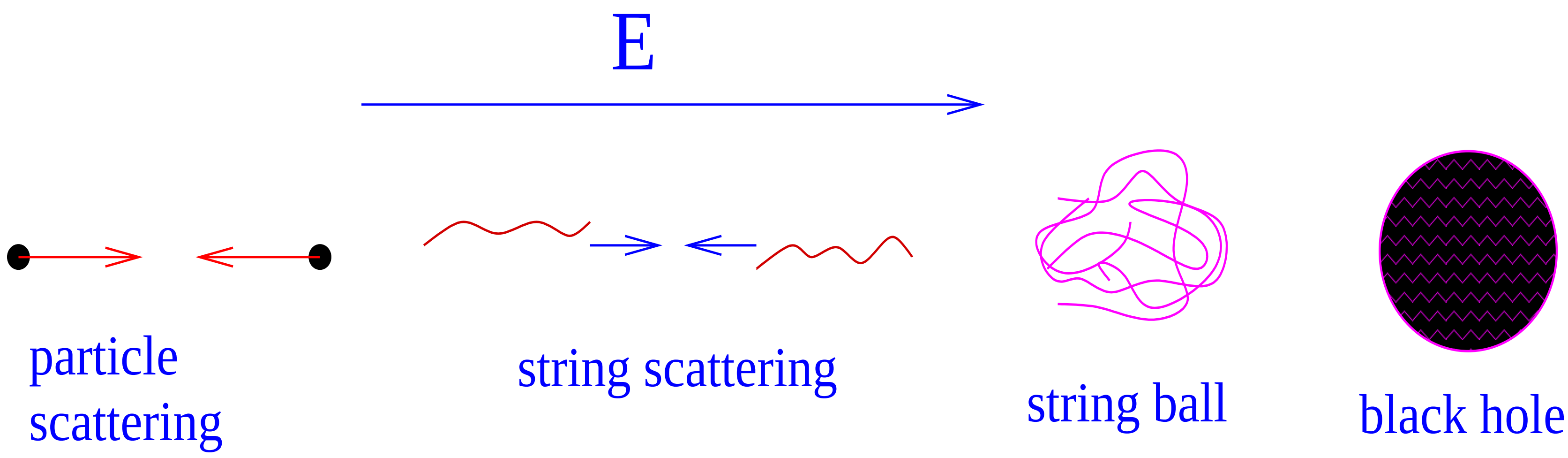
String Balls

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

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


E
particle scattering
string scattering
string ball
black hole

Production cross sectons

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

- 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.

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.

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

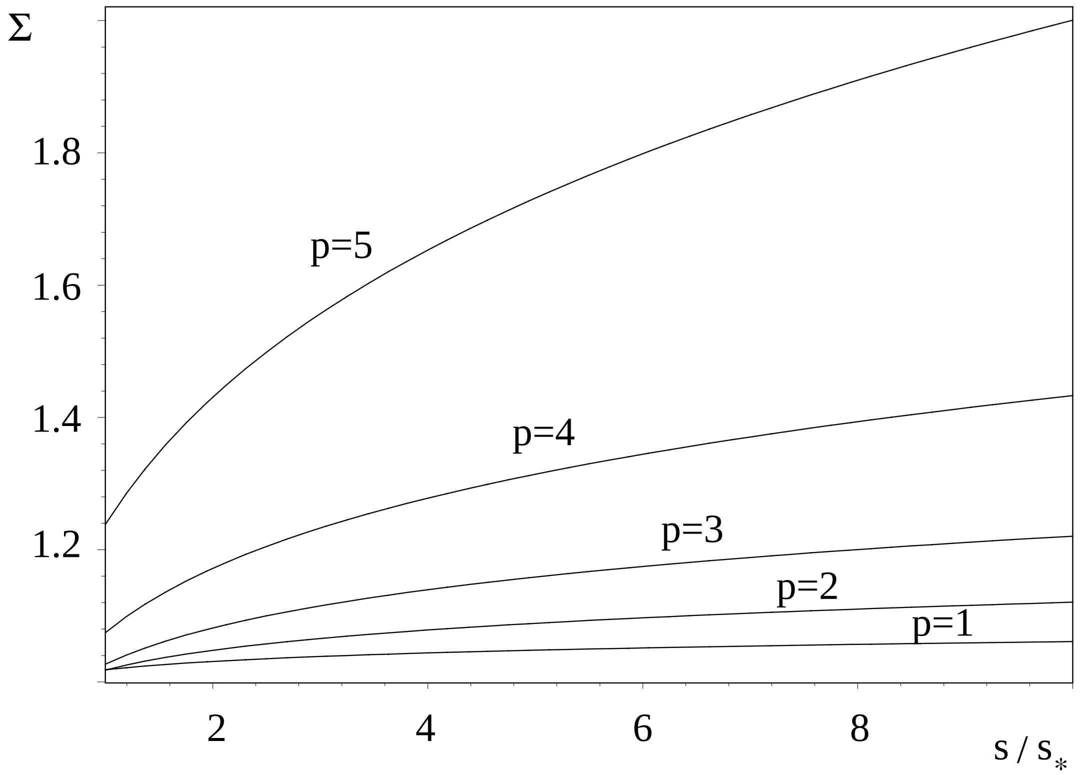
- $R_{p\mathrm{B}}$ of a p-brane is suppressed by some powers of the volume $V_{p\mathrm{B}}$ wrapped by the p-brane. Minimum $V_{p\mathrm{B}} = 1$ occurs when the p-brane wraps entirely on the small extra dimensions only,

$$r = p$$

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

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

Production ratio of p-brane to BH



$n = 7$, $m = 5$

Ahn, Cavaglia, Olinto

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

	$p=0$	$p=1$	$p=2$	$p=3$	$p=4$	$p=5$	$p=6$	$p=r+1=6$
$n=2$								
$n=3$								
$n=4$								
$n=5$								
$n=6$								

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.

Comparison of production cross sections at LHC and VHC

In Progress ... ...

Production via UHE Cosmic Rays

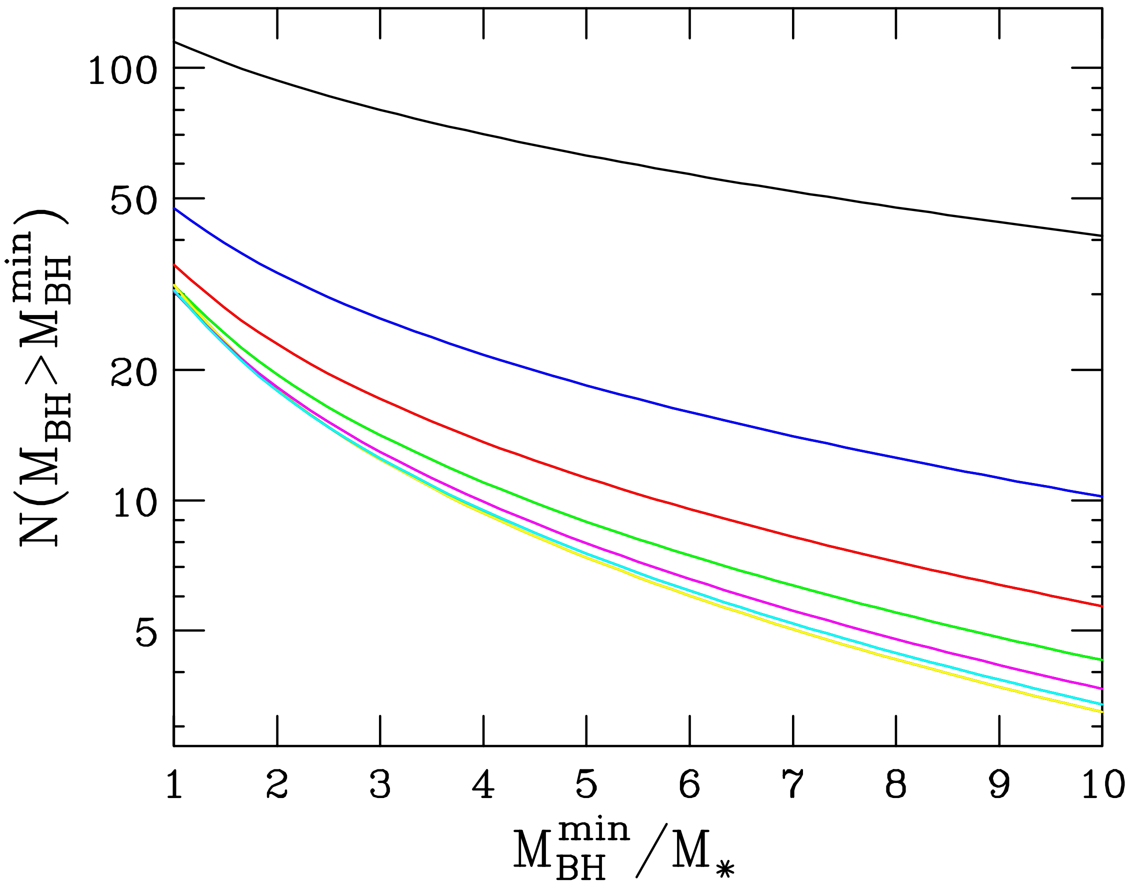
- UHECR as a beam, atmosphere as the target.

$$E_p \sim 10^{13} - 10^{21} \text{ eV}$$

$$pN \longrightarrow BH \longrightarrow \text{Giant Air shower}$$

$$\nu N \longrightarrow BH \longrightarrow \text{horizontal air shower}$$

BH production rate



# of BH detected by the ground array in 5 Auger site-years for $n = 1 - 7$ from above.

Feng, Shapere

Conclusions

- There have been extensive studies of sub-Planckian collider signatures for large extra dimensions.
- Experimentally, there are already some limits around $M_D \sim 1 - 1.4$ TeV for the fundamental Planck scale.
- Studies of trans-Planckian signatures just began.
- We are going to see how LHC or VHC will perform in search for BH, SB, p-branes. On the other hand, the UHECR will provide the ever highest energy beam.

Nima is stepping into the room.

Just kidding !!