Super-Planckian scattering at the LHC

Seongchan Park, CNU

ACP seminar
Aug. 24. IPMU

S. Park, Phys.Lett. B701 (2011) 587-590

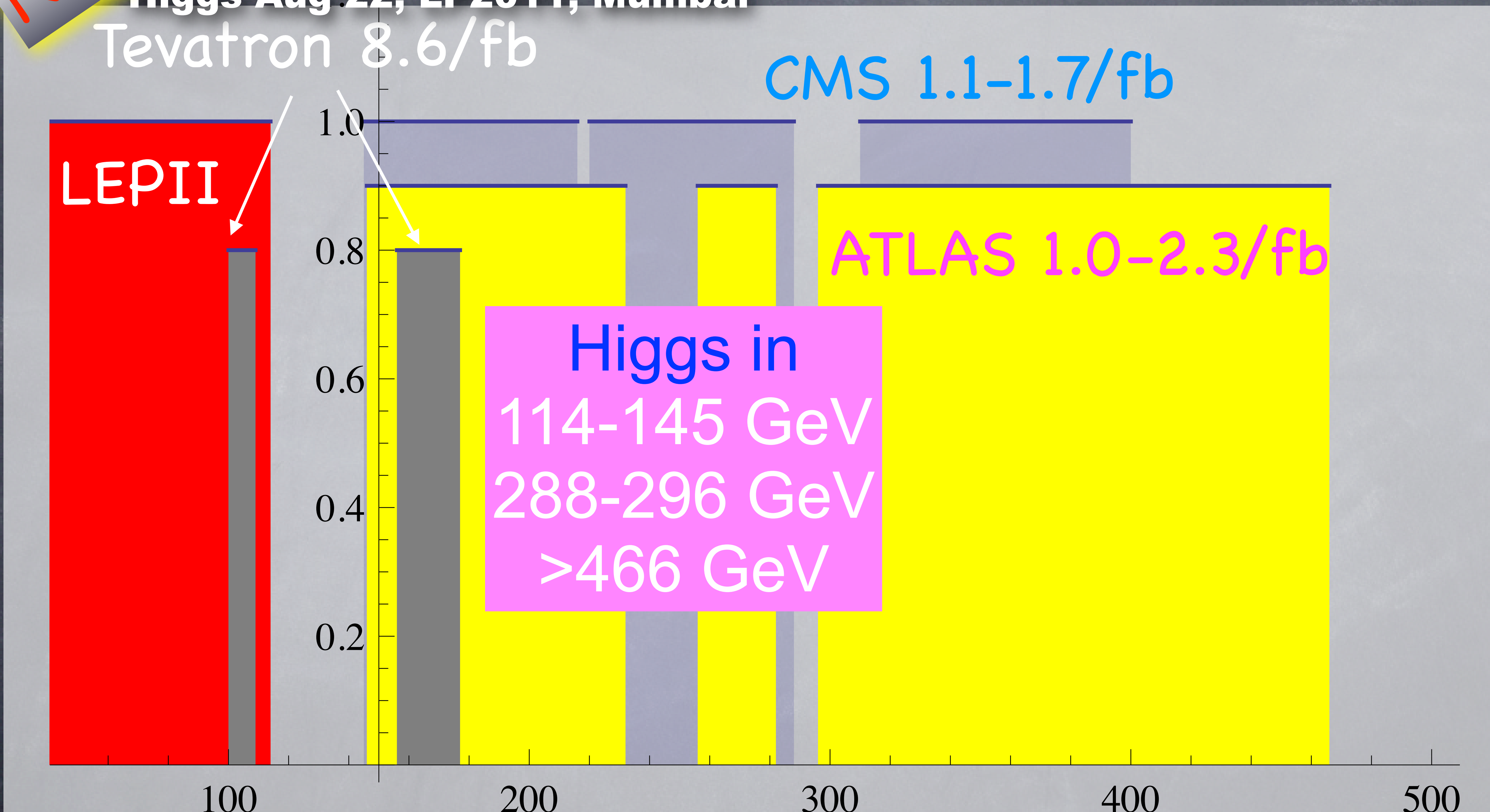
Outline

- Large volume compactification, RS,ADD,CHS
- Trans-Planckian scattering, Black hole production
- BH signature
- The recent CMS result on BH, critical comment/ Future

NEW!

We live in the LHC era

Higgs Aug 22, LP2011, Mumbai



114-145 GeV　　288-296GeV　　>466GeV

m(Higgs)~100 GeV

experiment

Higgs in
114-145 GeV
288-296 GeV
>466 GeV

theory

$$m_H^2 = m_{\text{tree}}^2 + \frac{\lambda_t^2}{16\pi^2}\Lambda_{\text{NP}}^2$$

Hierarchy Problem

A delicate Fine tuning is required if

$$\Lambda \gg 100\text{GeV}$$

Some well known (Stringy) solutions

SUSY

$$m_H^2 \sim m_{\rm soft}^2 \ll \Lambda^2$$

XD

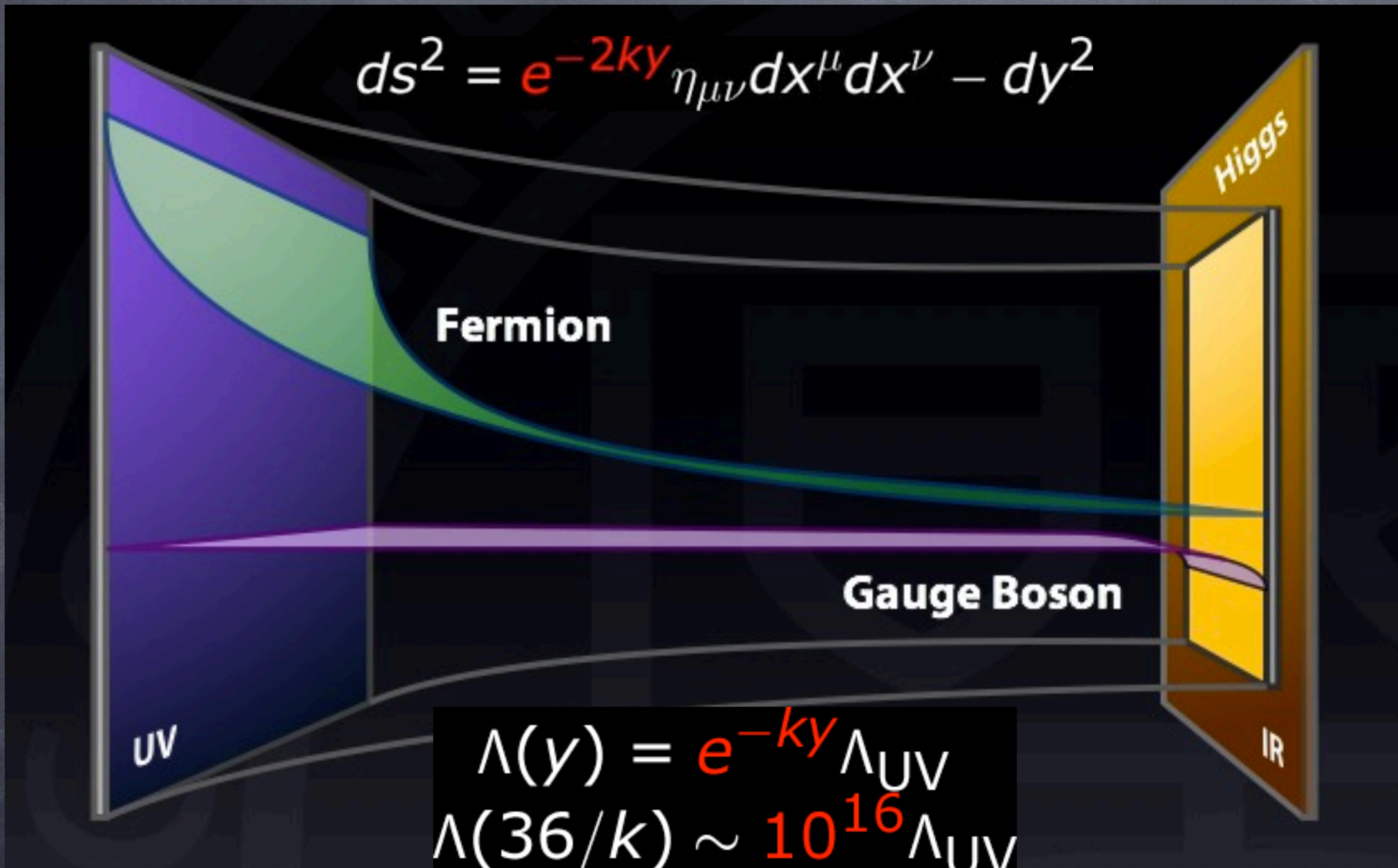
$$\Lambda_{\rm NP} \sim {\rm TeV}$$

LHC: squarks, gluinos

KK states
strong dynamics

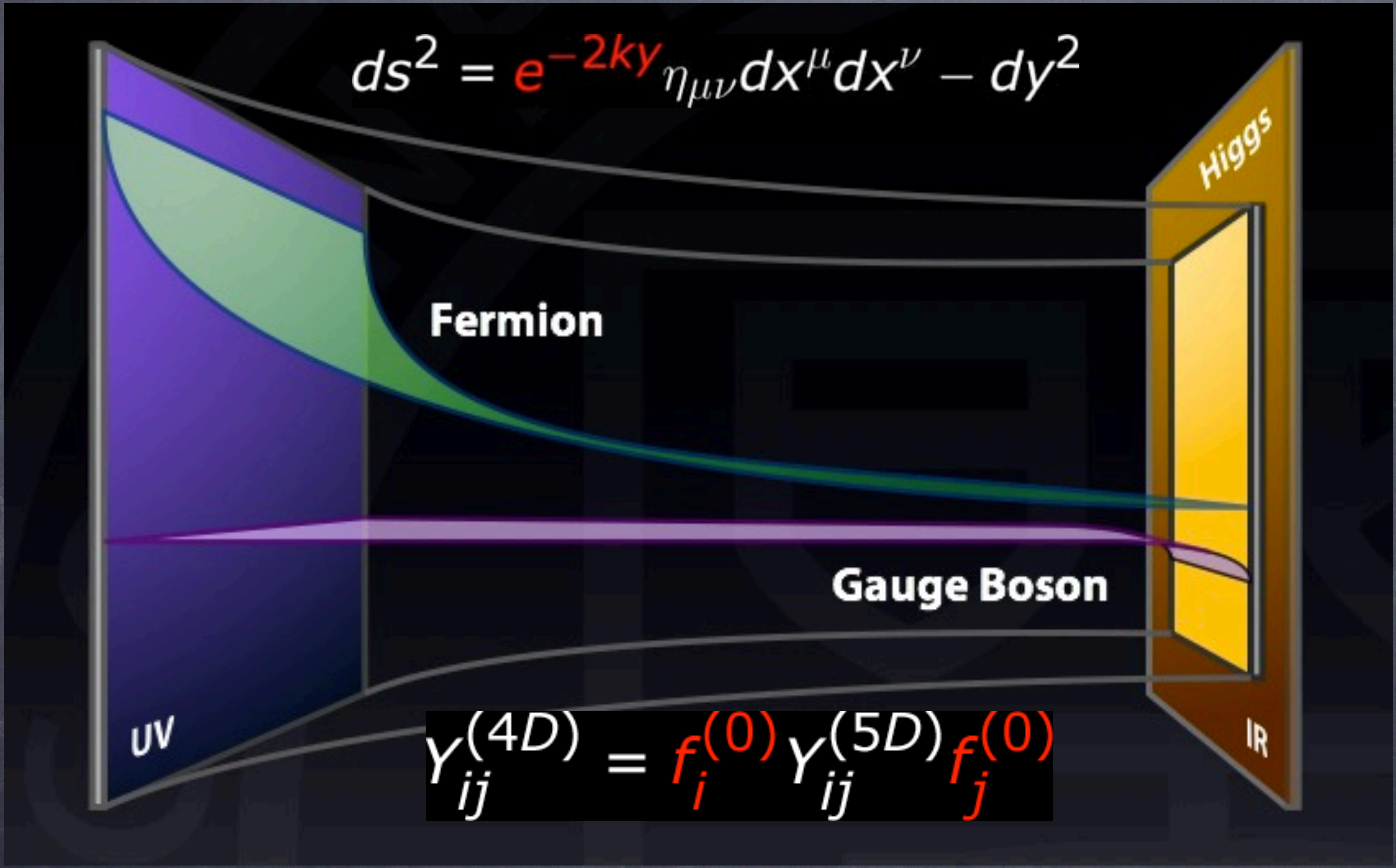
this talk

Randall-Sundrum



Randall, Sundrum (99); Davoudiasl, Hewett, Rizzo (99); Grossman, Neubert (00); Gherghetta, Pomarol (00); **Bulk Higgs:** Agashe, Contino, Pomarol (04); Davoudiasl, Lille, Rizzo (05)

Randall-Sundrum



Flavor: Huber, Shafi (03); Burdman (03); Kalil, Mohapatra (04); Agashe, Perez, Soni (04); Chen (05); Agashe, Blechman, Petriello (06); Davidson, Isidori, Uhlig (07); Csáki, Falkowski, Weiler (08) Chen, H.B. Yu (08); Chen, Mahanthappa, F. Yu (09) , ...

Large Torus compactification: ADD

$$S = \frac{M_{\rm Pl}^2}{2}\int d^4x\sqrt{g}R + \int d^4x\sqrt{g}\mathcal{L}_M$$

$$1/8\pi G = M_{\rm Pl}^2 \qquad [R] = L^{-2} = M^2$$

$$S = \frac{M_D^{2+n}}{2}\int dx^{4+n}\sqrt{g_D}R_D$$

factorizable geometry

$$\frac{M_D^{2+n}}{2}\int d^n y\sqrt{g}\int d^4x\sqrt{g_4}R + \cdots$$

$$\frac{M_{\rm Pl}^2}{2} = \frac{M_D^{2+n}}{2}[Vol]$$ of extra dimension

High Planck Energy is due to "large volume" of extra dimension

What we expect to see-(1)

"small mass gap"

$$\Delta m \sim m_{\mathrm{KK}} = k e^{-kL}$$

$$\Delta m \sim [Vol]^{-1/n}$$

Light KK-excitations (~TeV):

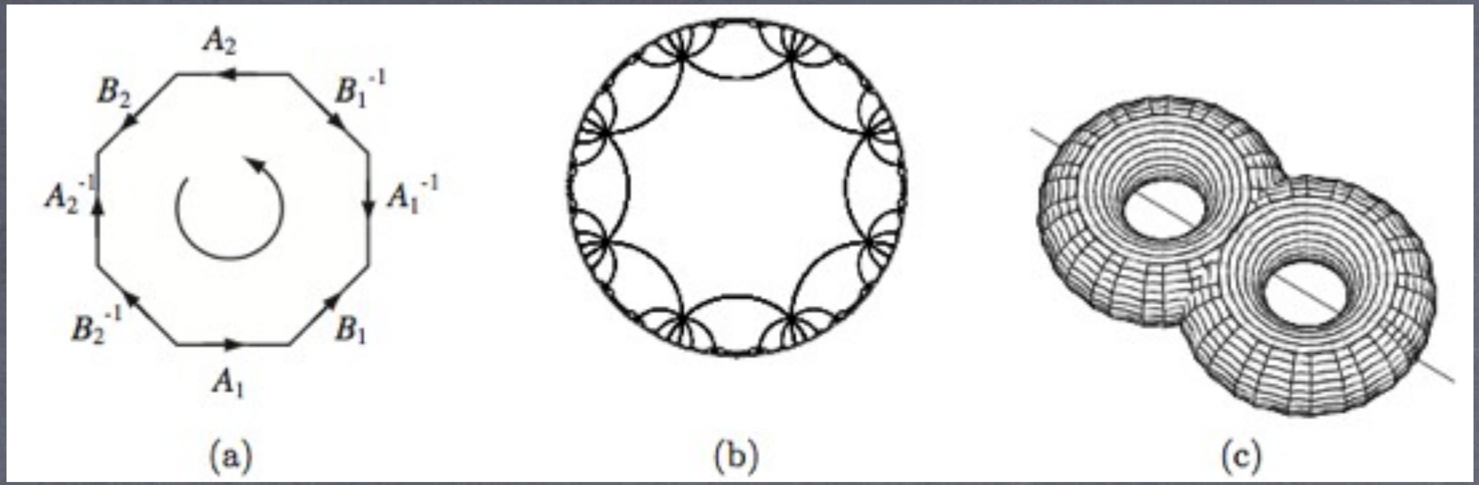
KK-graviton, KK-Z, KK-W, etc..

G+gamma, jj, ll .. @LHC

$$m_{\mathrm{KK}} \geq 1.1\mathrm{TeV}$$

(NOTE) not always the case e.g. CHS

[Orlando, Park 2010]



Compact Hyperbolic Space

{ Mostow Rigidity theorem (d>2)

[G. Mostow, 1968]

Selberg conjecture $k_1\ell \geq 1/2$

[A. Selberg, 1965]

proved up to $k_1\ell \geq \sqrt{171/784} \approx 0.22$

[W. Luo, Z. Rudnick, and P. Sarnak, 1995]

(by number theory)

Maximally Symmetric Spaces

n-maximally symmetric Einstein space in R^{n+1}

$$\epsilon_0 X_0^2 + X_1^2 + \cdots + X_{n-1}^2 + \epsilon_n X_n^2 = \epsilon L^2$$

$(\epsilon_0, \epsilon_n, \epsilon)$	curvature
$AdS_n = (-1, -1, -1)$	<0
$dS_n = (-, +, +)$	>0
$S^n = (1, 1, 1)$	>0
$H_n = (-1, 1, -1)$	<0

$$\left.\begin{array}{c} R = \frac{\epsilon}{L^2} n(n-1) \\ R_{\mu\nu} = R g_{\mu\nu}/n \\ R_{\mu\nu\rho\sigma} = R(g_{\mu\sigma}g_{\nu\rho} - g_{\mu\rho}g_{\nu\sigma})/n(n-1) \end{array}\right\} \propto \epsilon$$

Compact Hyperbolic space

$$H_n = \frac{SO(1,n)}{SO(n)} \quad \xrightarrow[\text{“Lattice”}]{\Gamma \in SO(1,n)} \quad H_n/\Gamma$$

CHS

H_n/Γ

- Mostow Rigidity theorem (d>2)

  [G. Mostow, 1968]

- Selberg conjecture $k_1 \ell \geq 1/2$

  [A. Selberg, 1965]

proved up to $k_1 \ell \geq \sqrt{171/784} \approx 0.22$

[W. Luo, Z. Rudnick, and P. Sarnak, 1995]

(by number theory)

Mostow theorem

1. The geometry of a finite volume hyperbolic manifold of dimension greater than two is determined by its fundamental group

2. once we have fixed the curvature and the volume, there are no more moduli.

**The theorem is not valid in $d = 2$ dimensions. In fact, a Riemann surface of genus $g > 1$ (which can always be represented as quotients H_2/Γ, $\Gamma \subset SO(1, 2)$), has a $6(g - 1)$-dimensional moduli space.

two independent length scales of H_d/Γ

ℓ_c

:local length scale, curvature
appears in EOM
~1/[Mass Gap]

$$k_1 \ell \geq 1/2$$

ℓ_Γ

:global length scale, volume
appears in the quotient group
of the compactification

$$V[H_d/\Gamma] = \ell_c^d e^{\alpha \ell_\Gamma / \ell_c}$$

CHS in an M-theory solution

[Orlando, SCP 006]

$$AdS_{7-d} \times H^d/\Gamma \times S^4$$

$V[H_d/\Gamma] = \ell_c^d e^{\alpha \ell_\Gamma / \ell_c}$

- Large volume = Hierarchy solved
- No light KK-state expected

$k_1 \ell \geq 1/2$

Compact hyperbolic extra dimensions: a M-theory solution and its implications for the LHC.
Domenico Orlando, Seong Chan Park (Tokyo U., IPMU). IPMU10-0096. Jun 2010. 17 pp.
Published in **JHEP 1008 (2010) 006**
e-Print: **arXiv:1006.1901 [hep-th]**

What we expect to see (2)

"Low scale gravity"

$$M_D < \sqrt{s}$$

Trans-Planckian scattering

*Gravity dominance ['t Hooft 1986]

*Black hole production [T. Banks, Fischler 1999], [Dimopoulos, Landsberg 2001], [Giddings Thomas 2002]

LHC

A super-Planckian machine?

- E=7TeV in pp frame (will be 14TeV in 2 yrs)
- P={u,d,s,c,b,g}
- Partons carry a fraction of 7TeV (pdf suppression): $E_{ij} = E F_{i/P} F_{j/P}$ .. Say, E/5 of the energy is available.
- Possible to have $E > \Lambda \sim$ TeV

Heisenberg's microscope

If one wants to be clear about what is meant by "position of an object," for example of an electron..., then one has to specify definite experiments by which the "position of an electron" can be measured; otherwise this term has no meaning at all.

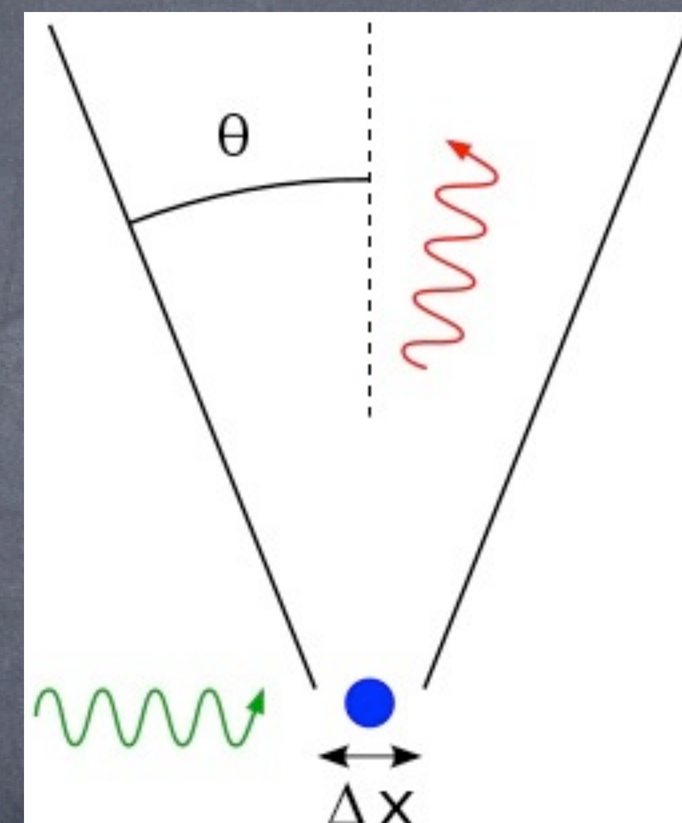
--Heisenberg, in uncertainty paper, 1927

...if the scattering energy is exceedingly greater than the Planck energy, black hole starts to form

G. 't Hooft 1987

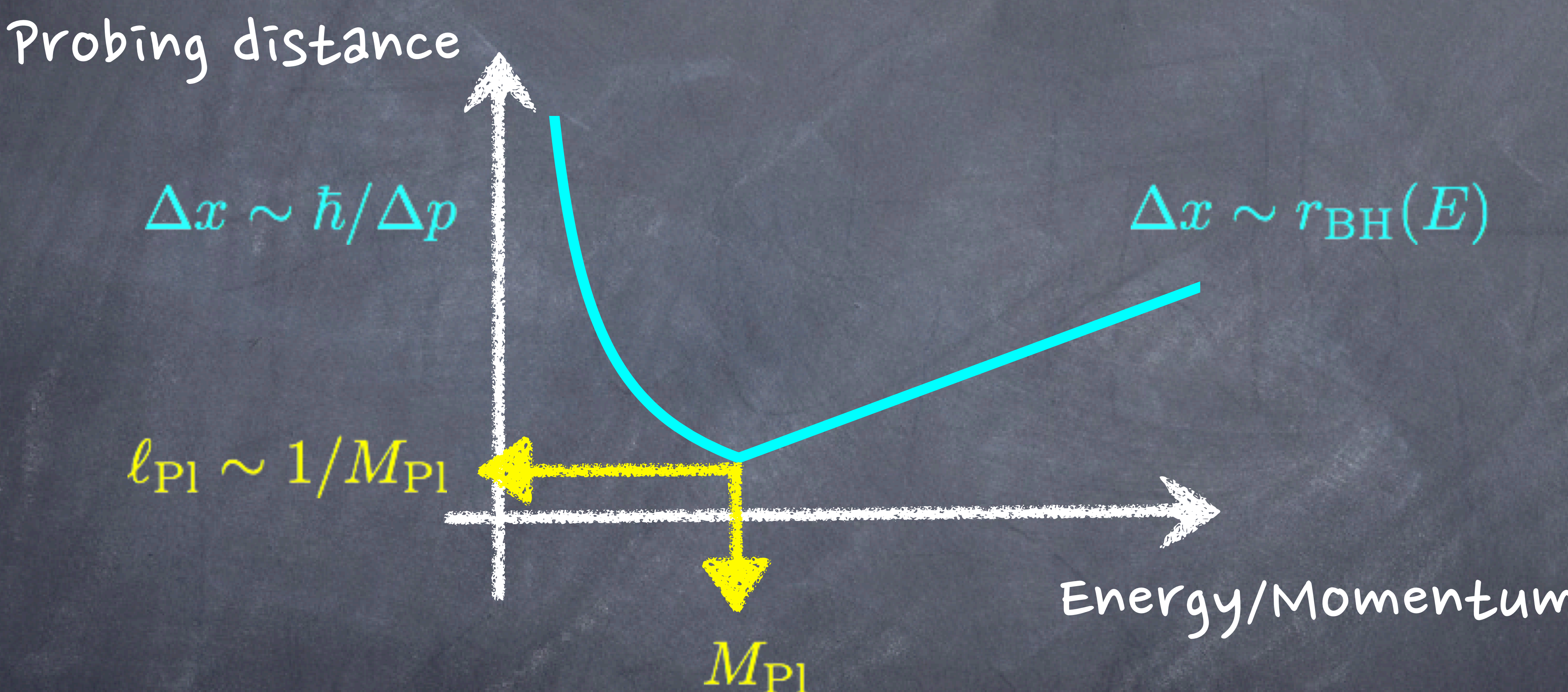
$$E \gg M_{\rm Pl} c^2$$

$$\Delta x \sim \lambda \sim \hbar/\Delta p$$



a baby black hole forms

‘t Hooft-Heisenberg’s uncertainty principle



$$[x, p] = i(1 - \alpha p)$$

T. Yoneya (1989)

Trans-Planckian Scattering

initial state

$$E_{\rm CM} > M_P$$

what's the final state?

Trans-Planckian Scattering

A naive effective field theory approach fails

$$\mathcal{L}_{\rm eff} \ni \psi\psi\psi\psi/M_{\rm P}^2$$

becomes non-unitary at E>MP

Relevant scales

$$\ell_{\mathrm{de-Broglie}} \sim 1/E$$

$$\ell_{\mathrm{Planck}}$$

$$\ell_{\mathrm{EventHorizon}} \sim (GE)^{1/(D-3)}$$

$$b \sim J/E$$

$$\ell_c$$

Black hole forms

$$b < \ell_H$$

$$\ell_H \gg \ell_P$$

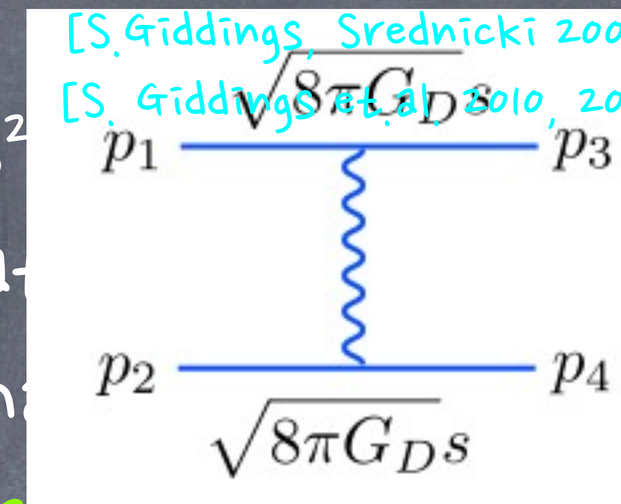
$$b > \ell_H \gg \ell_P$$

$$\ell_c > b > \ell_H >> \ell_p$$

Trans-Planckian scattering

[D. Gross et.al. 1987, 1988]
[G.Veneziano 1992, 1993, 2010]
[R. Rattazzi 2004]
[S.Giddings, Srednicki 2008]
[S. Giddings et.al. 2010, 2011]

$\sqrt{s} \gg M_D$



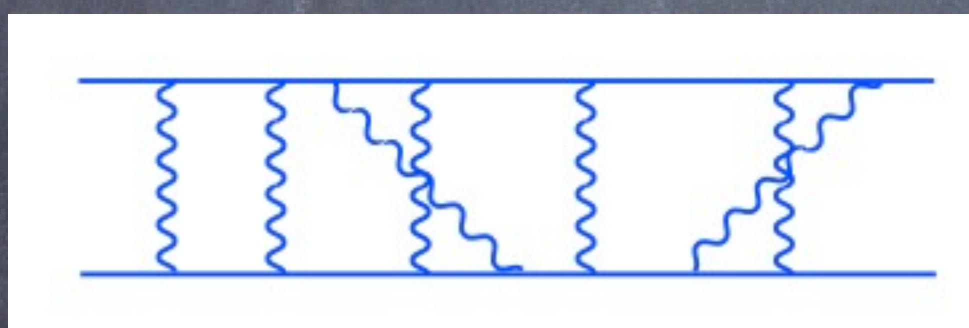
$b \gg 1/M_P$

:small QG effect (R/M_P^2

Born approximat

Eikonal approxim

black hole formation



cal, quasi-quantum description holds!

$b \sim 1/M_P$

:QG [string] domain

non-perturbative

Not much things we know

2->2 dominance (?)

Small curvature perturbation is valid for trans-Planckian BH

Einstein-Hilbert

$$S = \int d^4x \sqrt{g} \frac{M^2}{2} \left(R + O(\frac{R^2}{M^2}) \right)$$

includes higher derivative terms (>2)

$$O(R^2) = aR^2 + bR^{\mu\nu\rho\sigma}R_{\mu\nu\rho\sigma} + cR^{\mu\nu}R_{\mu\nu}$$

$$\frac{R}{M^2} \sim \frac{1}{r_H^2 M^2} \ll 1, \quad E \gg M$$

$$(a, b, c) = (1, 1, -4)$$ Gauss-Bonnet

$$r_H \sim E/M^2$$

Ghost-Free, D>4 [B. Zwiebach 1985]

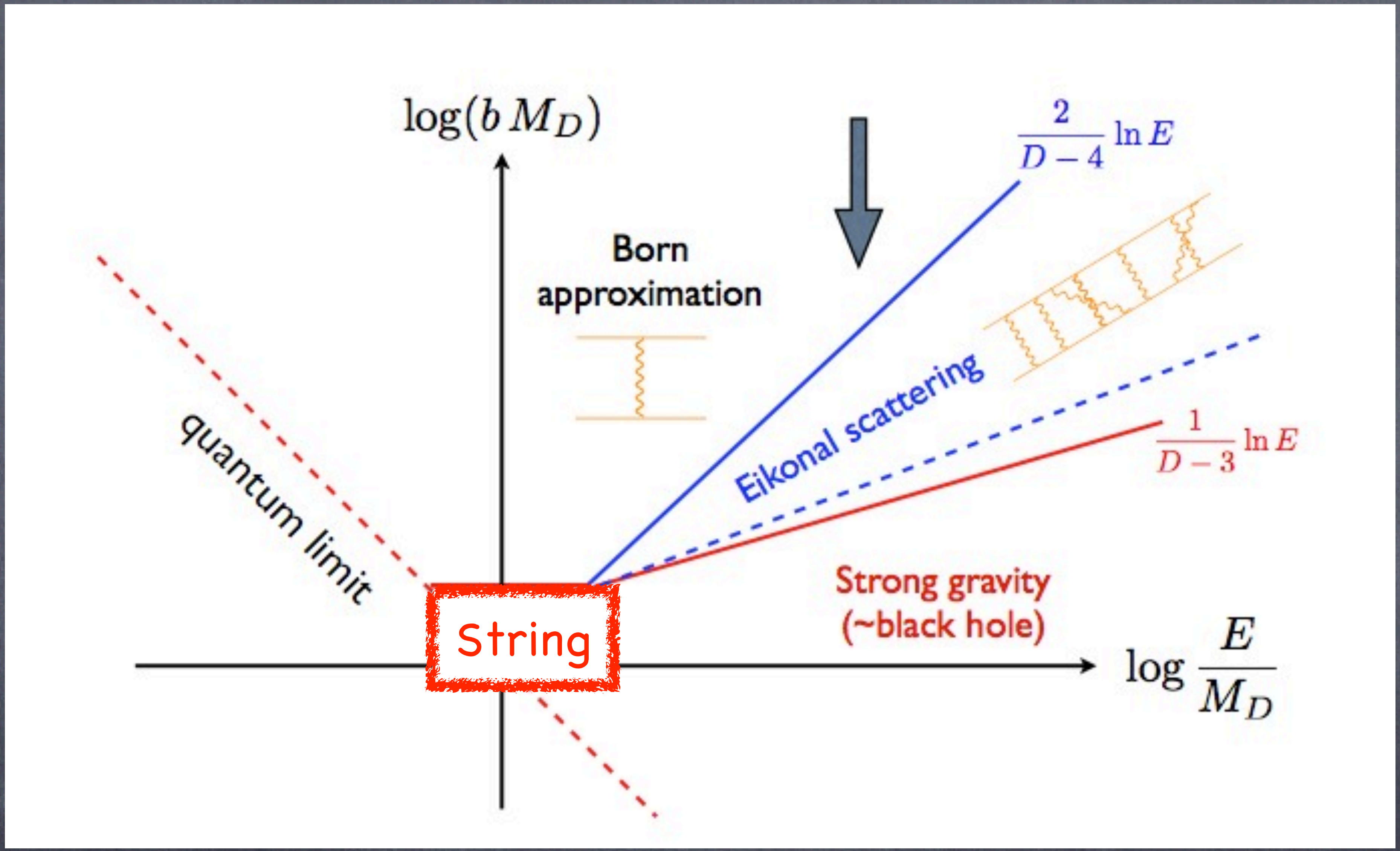
Heterotic string
6D Calabi-Yau compactification of M-theory

for BH in D>4

$$S_G = \int d^D x \sqrt{-g} \frac{M_D^{D-2}}{2} R \left[1 + \Delta\right],$$

$$\Delta \sim \frac{R}{M_D^2} \sim \frac{1}{r_{BH}^2 M_D^2} \sim \left(\frac{M_D}{M}\right)^{\frac{2}{D-3}}$$

if $M \gg M_D$, QG correction is small



$\log(b\,M_D)$
Born
approximation
$\frac{2}{D-4}\ln E$
Eikonal scattering
$\frac{1}{D-3}\ln E$
quantum limit
String
Strong gravity
(~black hole)
$\log\frac{E}{M_D}$

validity domain of semiclassical approximation

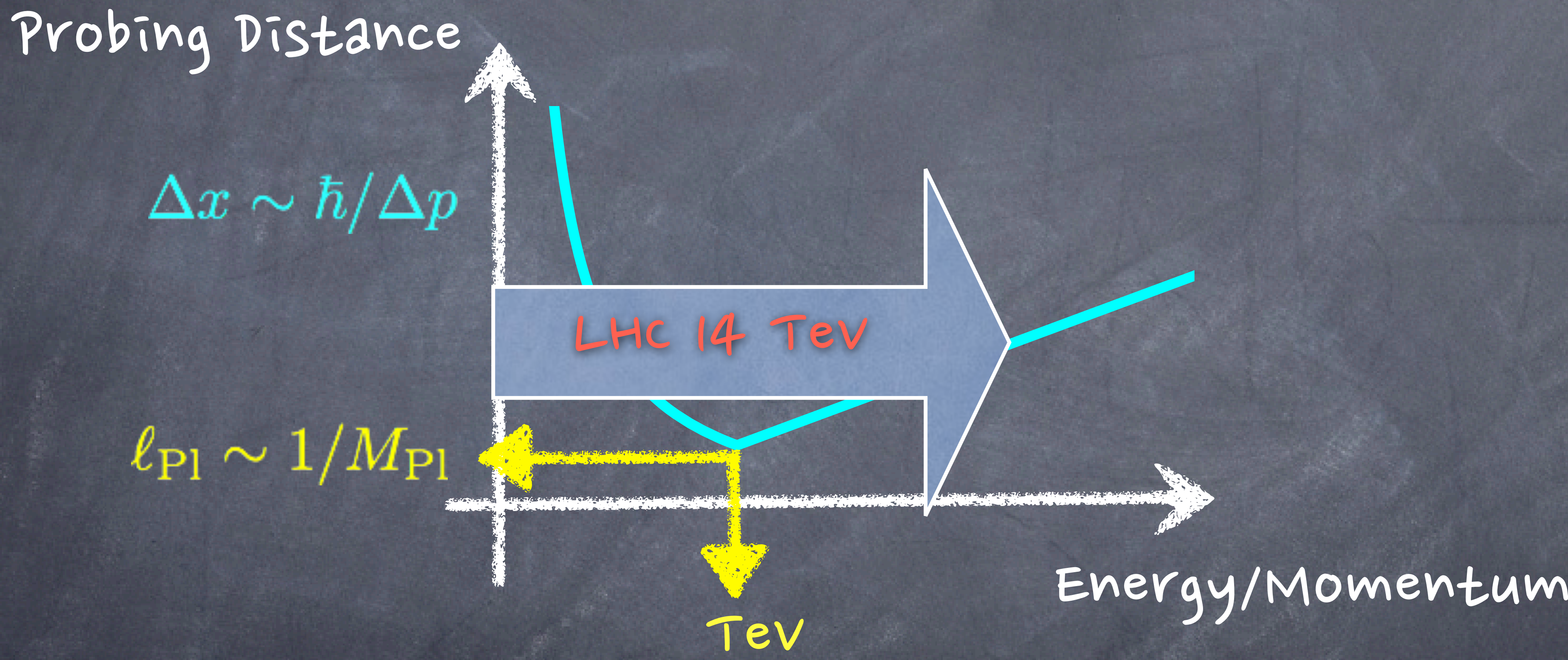
Higher dimensional

$$\ell_D \ll \underbrace{}_{\text{QG irrelevant}} r_{\rm BH} \overbrace{\ll}^{\text{Higher dimensional}} r_c$$

QG irrelevant

- Reliable calculation available
- Large entropy (= Large surface area)

BH @ LHC



Probing Distance
$\Delta x \sim \hbar/\Delta p$
LHC 14 TeV
$\ell_{\rm Pl} \sim 1/M_{\rm Pl}$
TeV
Energy/Momentum

BH(D>4) Signal

[Ida-Oda-SCP 2003,2005,2006]

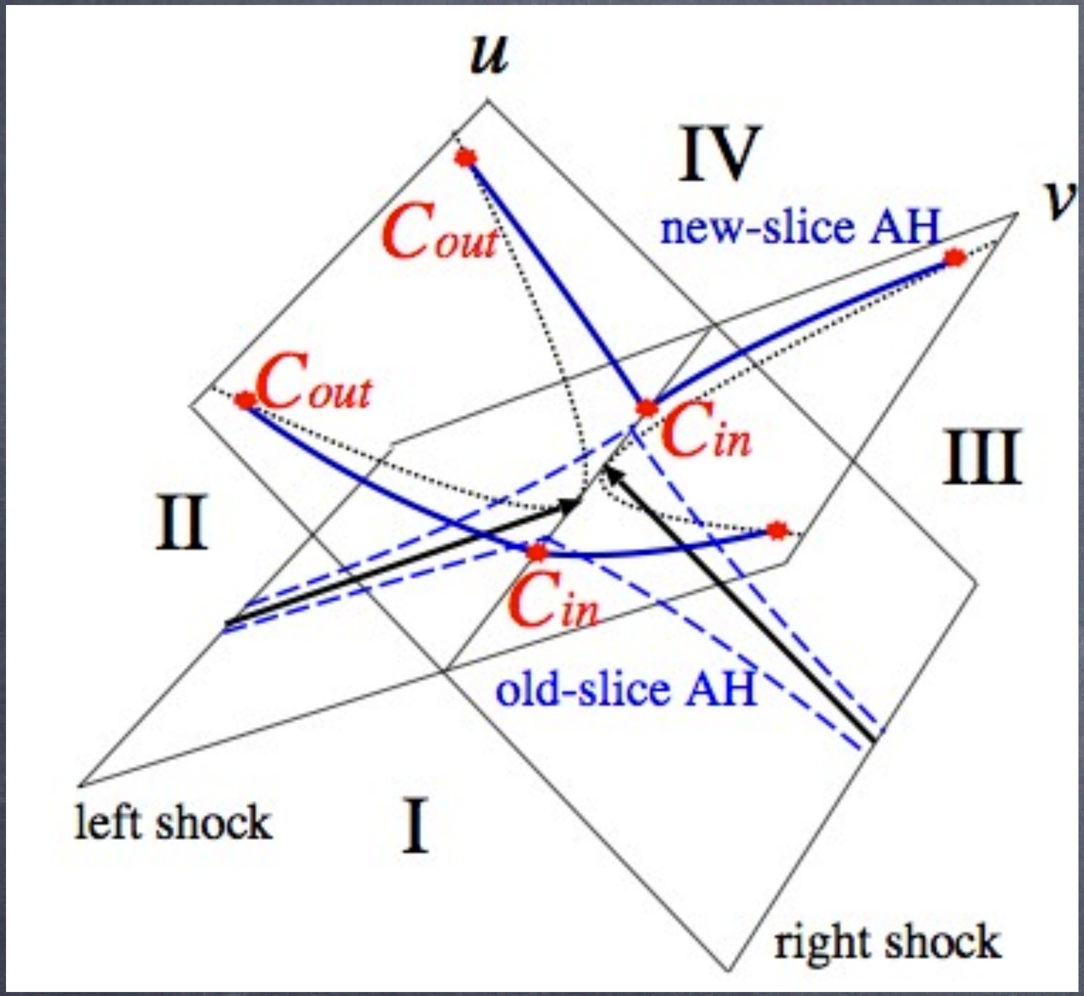
- BH decays through Hawking radiation: Thermal radiation with Large multiplicity (large entropy >10).
- T > TeV, all kinds of SM particles will come out.
- Doesn't depend on the flavor but spin of radiated particle; details are determined by Greybody factor. (vector>spinor>scalar)
- gluon > quark (>photon) > lepton, neutrino> Higgs

MC for BH events

- Two MC simulation codes are used by the LHC
  - BlackMax2.0 (case western, SUNY buffalo, oxford, London): CMS
  - CHARYBDIS2.0 (cambridge): ATLAS
- Both are based on [Yoshino et.al. 2003, 2005] (for production), [Ida-Oda-SCP 2003, 2005, 2006] (for decay).
- Valid in semi-classical domain.

Yoshino-Rychkov

[Yoshino-Nambu 2003]
[Yoshino-Rychkov 2005]



*initial:

infinitely boosted BH (Aichelberg-Sexl sol.)

*final:

formation of AH

*Theorem: BH forms when AH forms

*An active topic in NR

[Pretorius et.al. 2008, 2010]
[Shibata et.al. 2008, 2010, 2011]

Ida-Oda-SCP

Observer a distance

Greybody factor

black hole looks grey"

emission rate

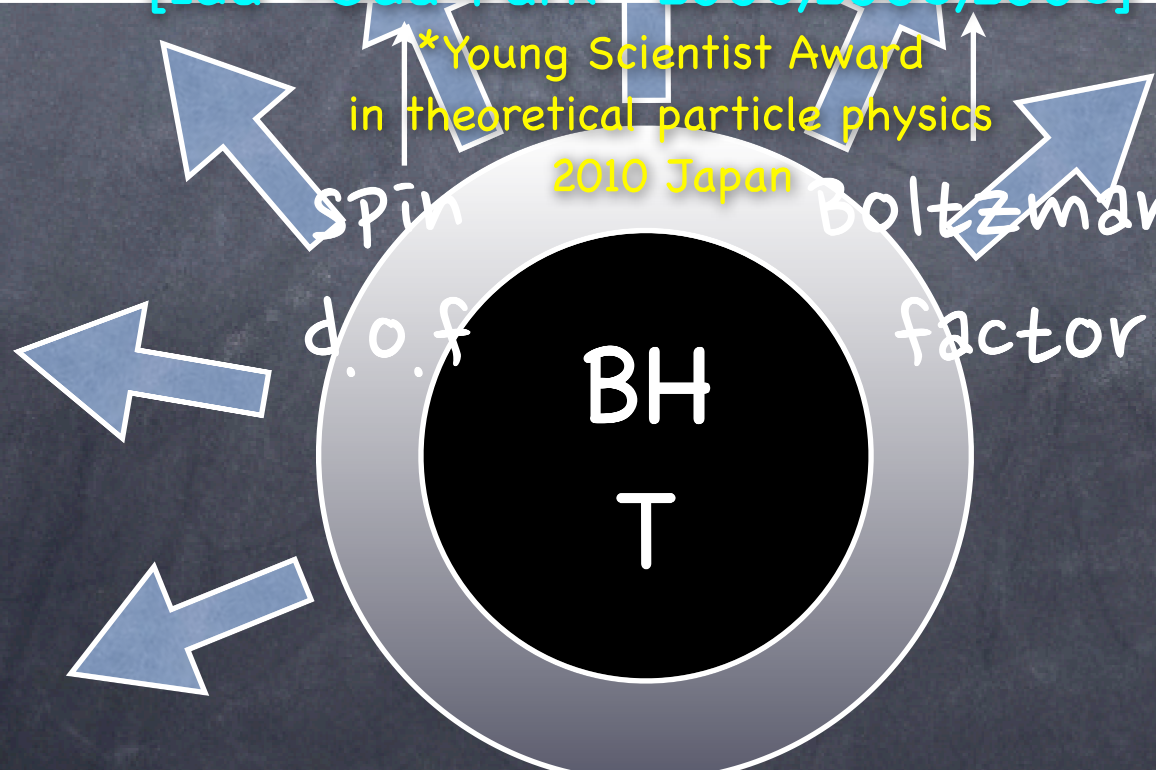
$$-\frac{dE_{s,l,m}}{dt} = \frac{g_s}{2\pi}\int d\omega \frac{{}_s\Gamma_{lm}\,\omega}{e^{(\omega - m\Omega)/T} \mp 1}$$

[Ida*-Oda-Park* 2003,2005,2006]

*Young Scientist Award
in theoretical particle physics
2010 Japan

spin d.o.f

Boltzmann factor



Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for microscopic black hole signatures at the Large Hadron Collider ☆

CMS Collaboration *

CERN, Switzerland

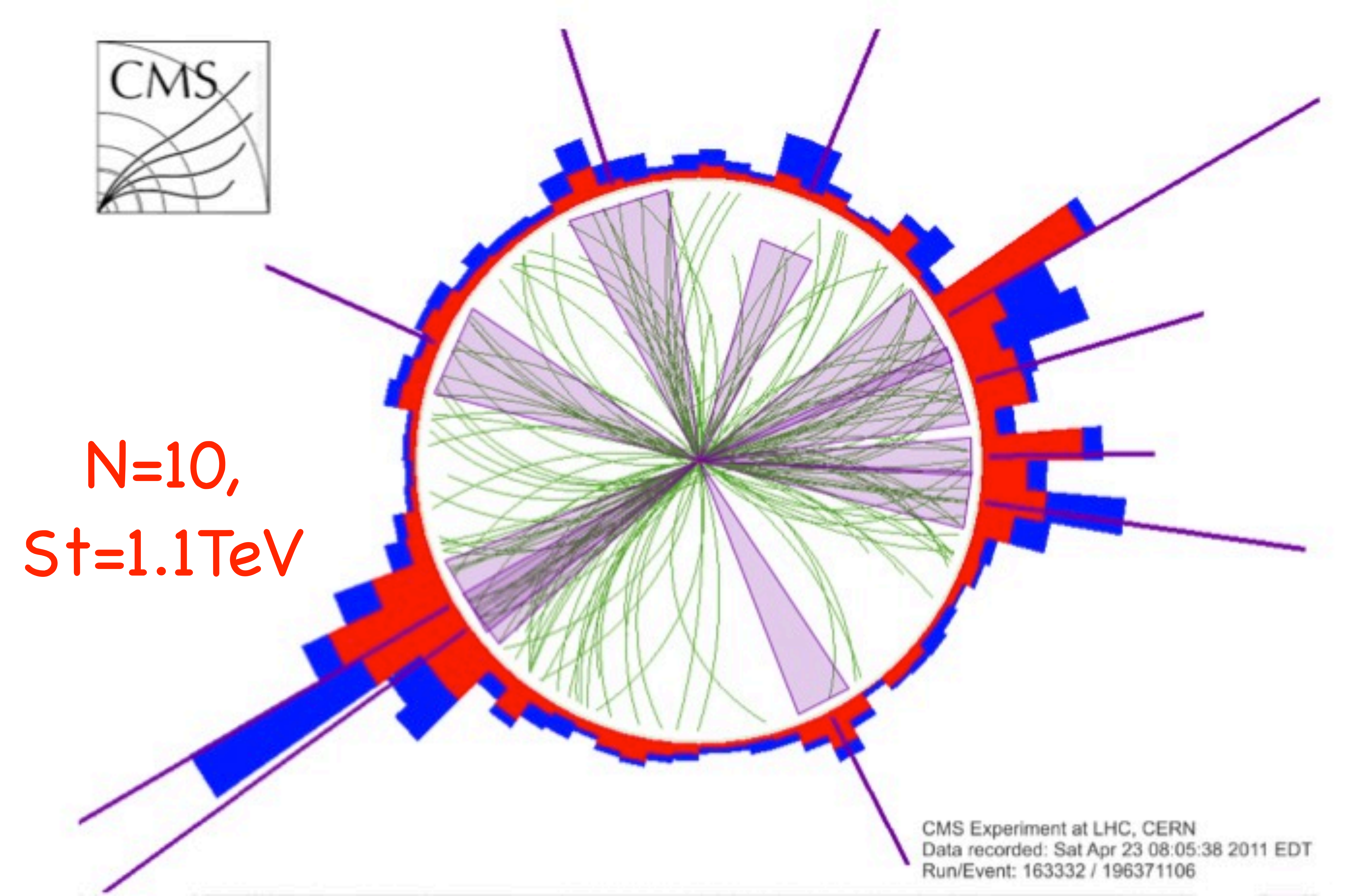
A B S T R A C T

A search for microscopic black hole production and decay in pp collisions at a center-of-mass energy of 7 TeV has been conducted by the CMS Collaboration at the LHC, using a data sample corresponding to an integrated luminosity of 35 pb^{-1}. Events with large total transverse energy are analyzed for the presence of multiple high-energy jets, leptons, and photons typical of a signal expected from a microscopic black hole. Good agreement with the standard model backgrounds, dominated by QCD multijet production, is observed for various final-state multiplicities and model-independent limits on new physics in these final states are set. Using simple semi-classical approximation, limits on the minimum black hole mass are derived as well, in the range 3.5–4.5 TeV. These are the first direct limits on black hole production at a particle accelerator.

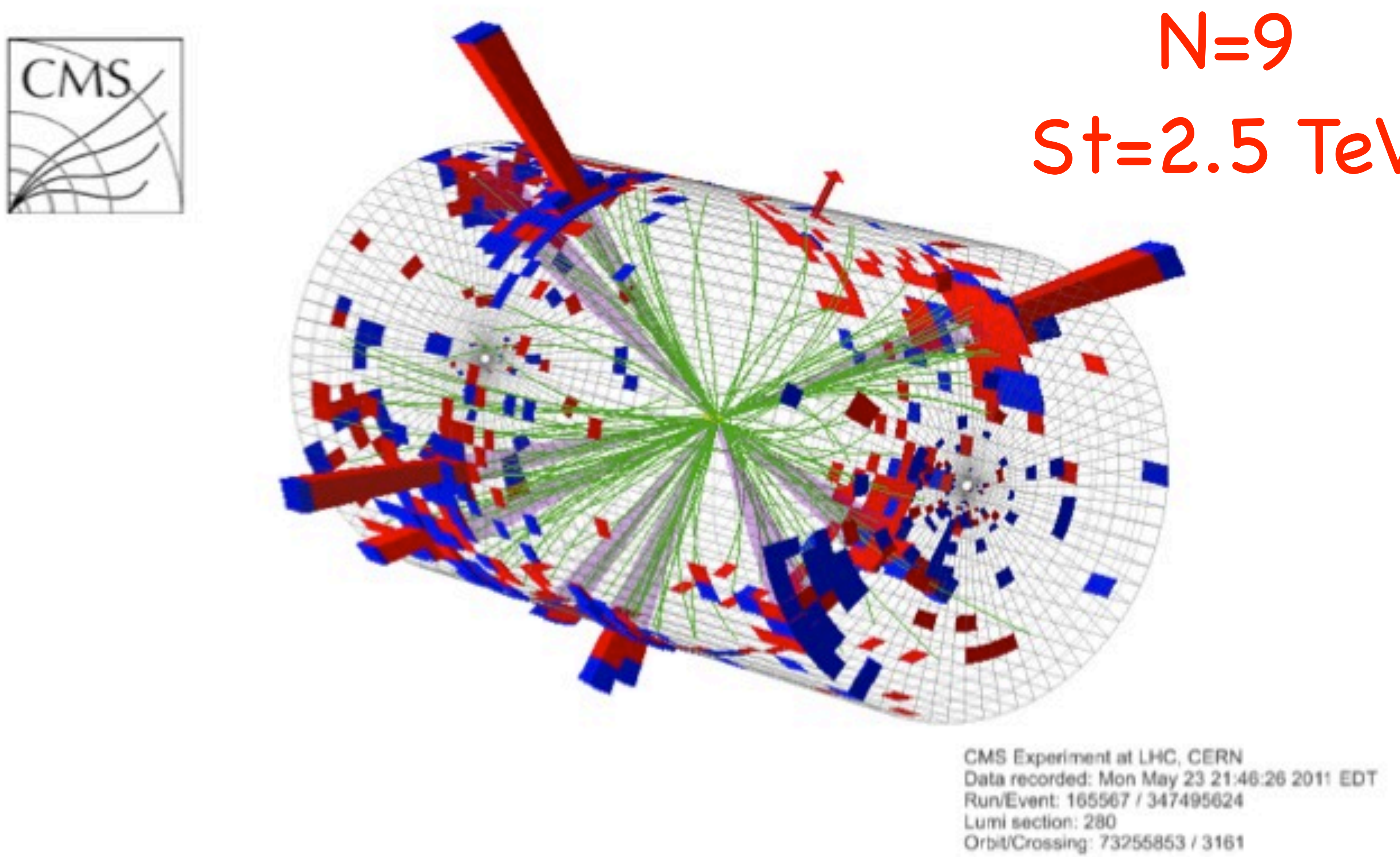
**also see LHC analysis
(with 1.1/fb) 2011 July 21 @EPS
(with 2/fb) 2011 Aug @LP11??

BH Candidate event (1)

N=10,
St=1.1TeV

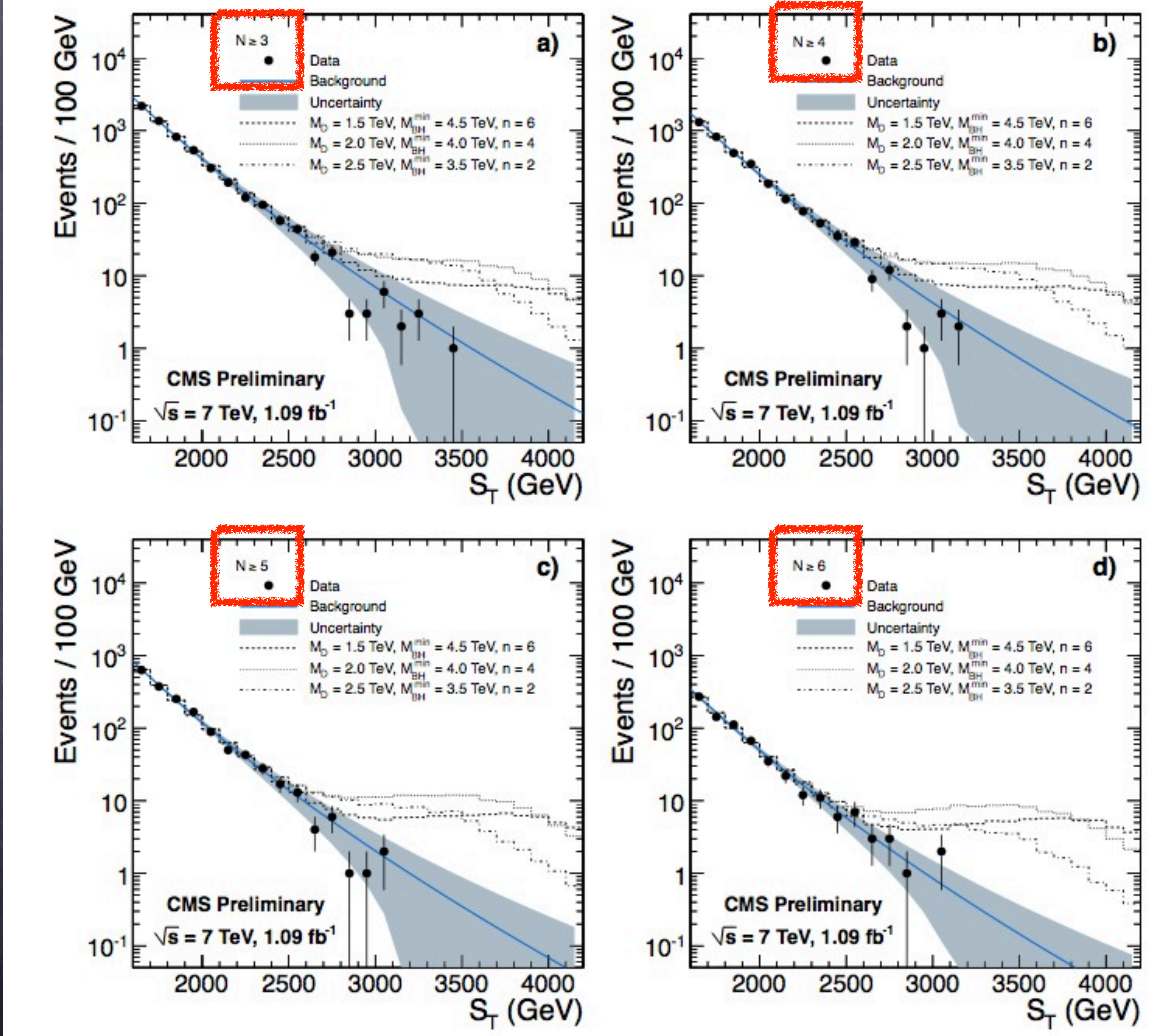


BH Candidate event (2)



N=9
St=2.5 TeV

Figure 4: A 3D event display of a $N = 9$ black hole candidate with $S_T = 2.5$ TeV (Run 165567, Event 347495624).


N ≥ 3
Data
Background
Uncertainty
M_D = 1.5 TeV, M_BH^min = 4.5 TeV, n = 6
M_D = 2.0 TeV, M_BH^min = 4.0 TeV, n = 4
M_D = 2.5 TeV, M_BH^min = 3.5 TeV, n = 2
a)
CMS Preliminary
√s = 7 TeV, 1.09 fb-1
Events / 100 GeV
S_T (GeV)
N ≥ 4
b)
N ≥ 5
c)
N ≥ 6
d)

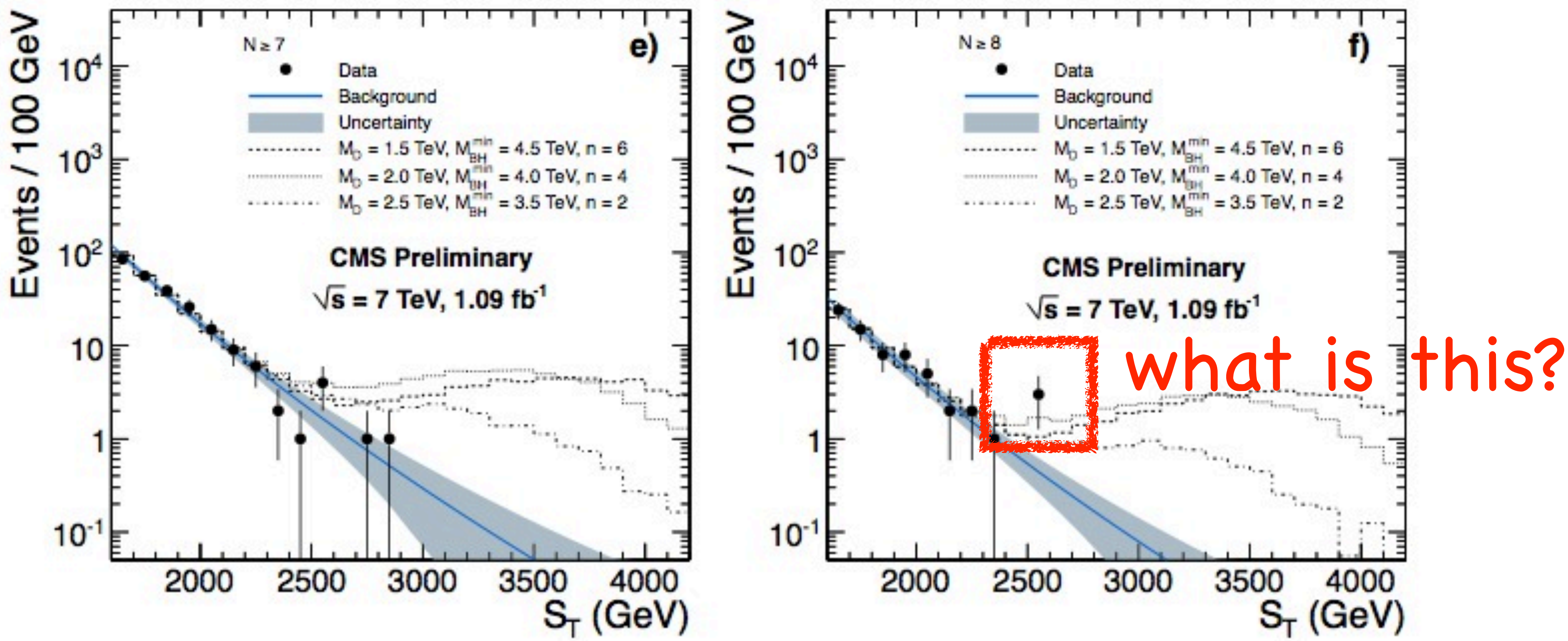


Figure 2: Total transverse energy, S_T, for events with: a) $N \geq 3$, b) $N \geq 4$, c) $N \geq 5$, d) $N \geq 6$, e) $N \geq 7$, and f) $N \geq 8$ photons, electrons, muons, or jets in the final state. in the final state. Data are depicted as points with error bars; shaded band is the background prediction (solid line) with its uncertainty. Also shown are black hole signals for three different parameter sets.

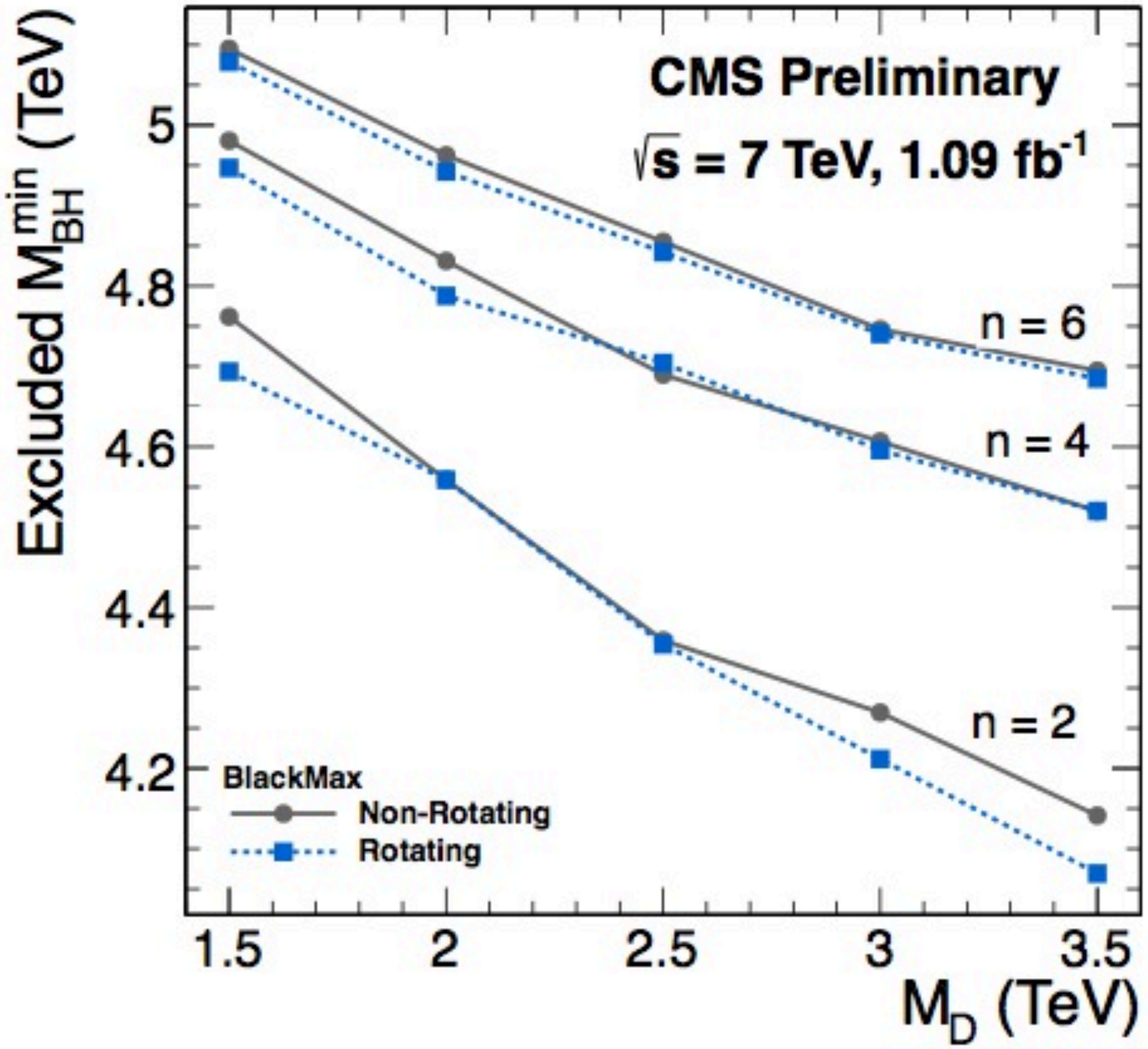


Figure 7: Limits on the black hole model parameters for several benchmark scenarios. The areas below each curve are excluded by this search.

CMS summary

Lower bound of BH mass

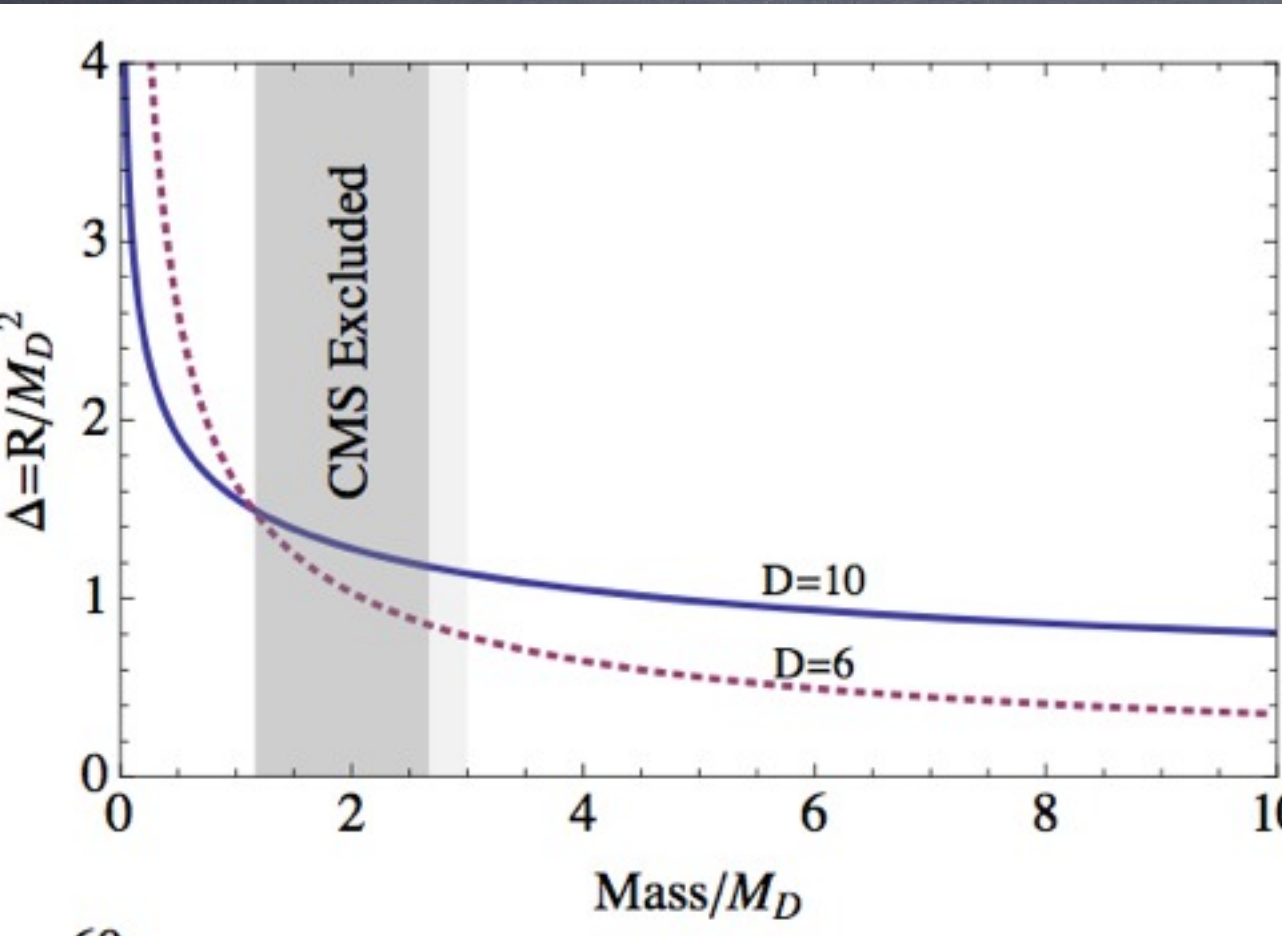
$$\left(\frac{M}{M_D}\right)_{\mathrm{CMS}} \in \left[\frac{3.5}{3.0}, \frac{4.0}{1.5}\right]_{D=6},$$
$$\in \left[\frac{4.0}{3.5}, \frac{4.5}{1.5}\right]_{D=10},$$

or

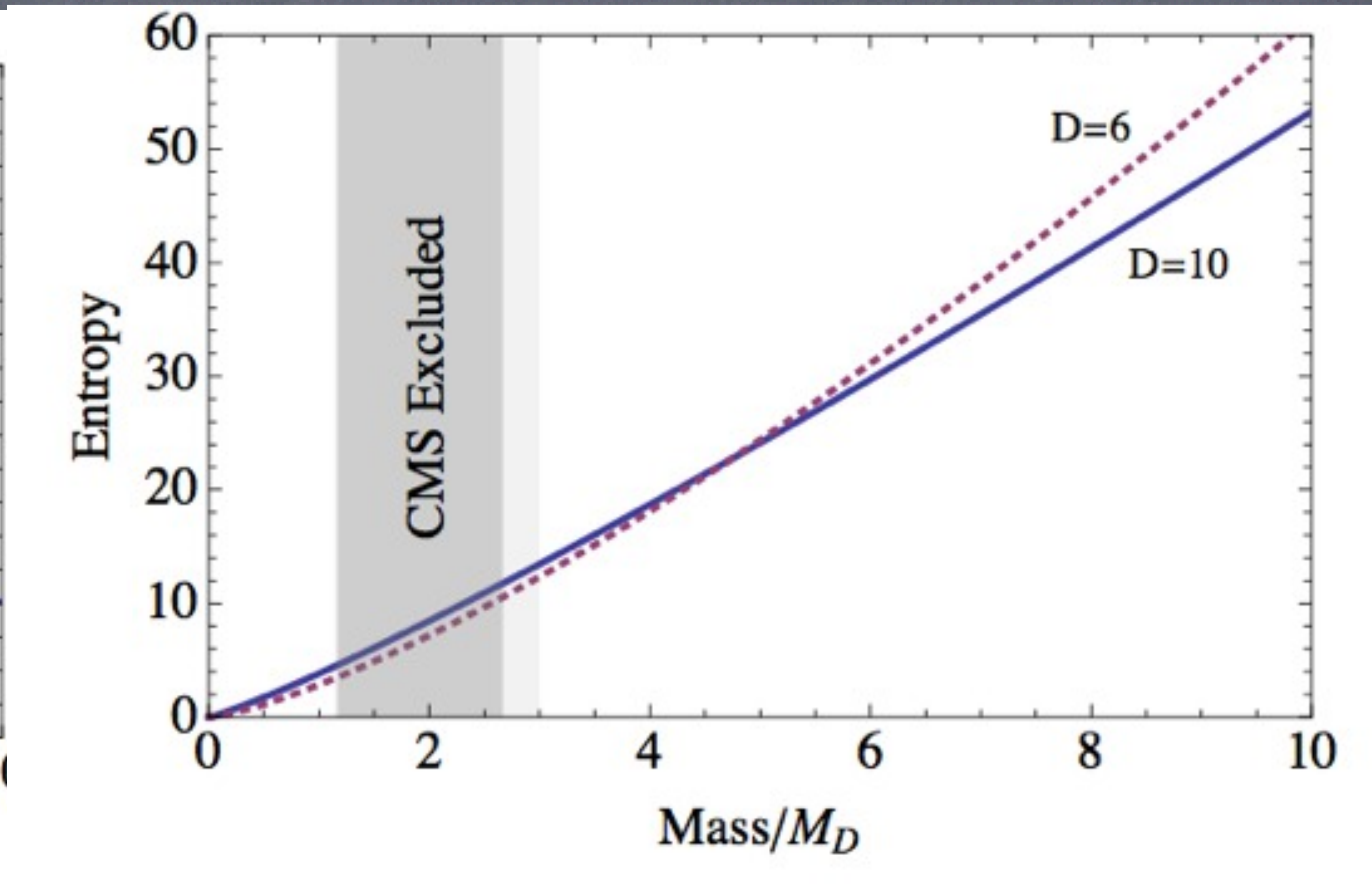
$$(r_{BH})_{\mathrm{CMS}} \in [0.9, 2.1]\,\ell_6,$$
$$\in [0.9, 2.4]\,\ell_{10}.$$

Do not belong to semi-classical domain! :-(

QG correction



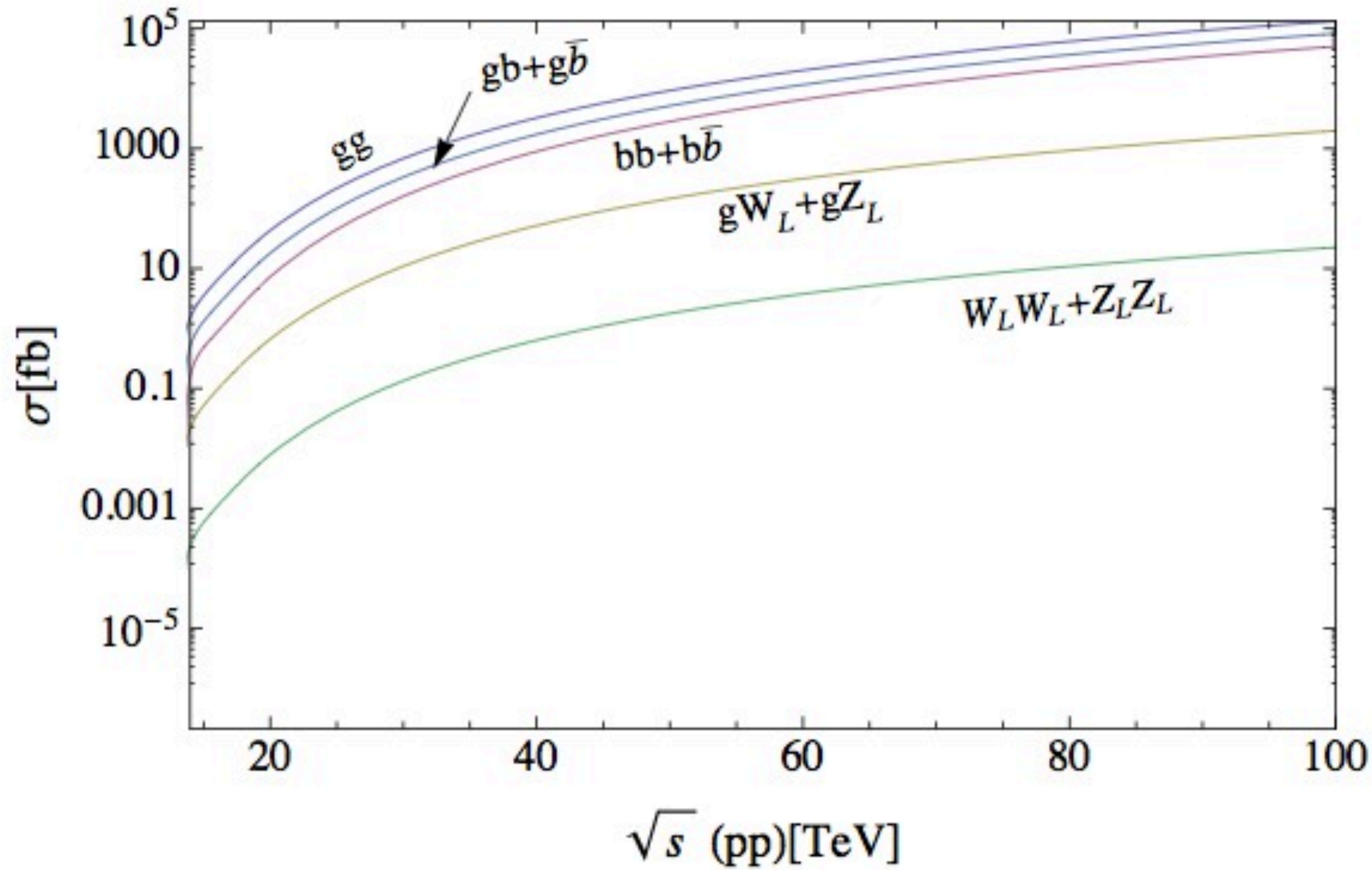
Entropy



$\Delta > 100\%$

$Entropy < 10$

Model dependence: RS with bulk SM



D. Orlando, S. C. Park, JHEP 1008, 006 (2010).

conclusion & future prospects (1/3)

- Tev gravity realized with large volume compactification (ADD, RS, CHS ..): hierarchy problem solved.
- Two ways to see LED: Low mass gap (~1/vol) or strong gravity
- The LHC can be the first BH factory (still valid!)

conclusion & future prospects (2/3)

- caution! The first result(7 Tev run) is out of the validity range of semi-classical approximation.
- Model independent "bound" can be useful in the future.
- Future runs with 14 Tev or higher (100 Tev) are more interesting for BH search.

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conclusion & future prospects (3/3)

- Scattering at E~MP with a definite QG theory.
- AdS/CFT ∴ BH~Thermal state in CFT. Glueball? string ball?
- The final state of BH at M~MP.