Black Holes at Accelerators: Problems and Perspectives

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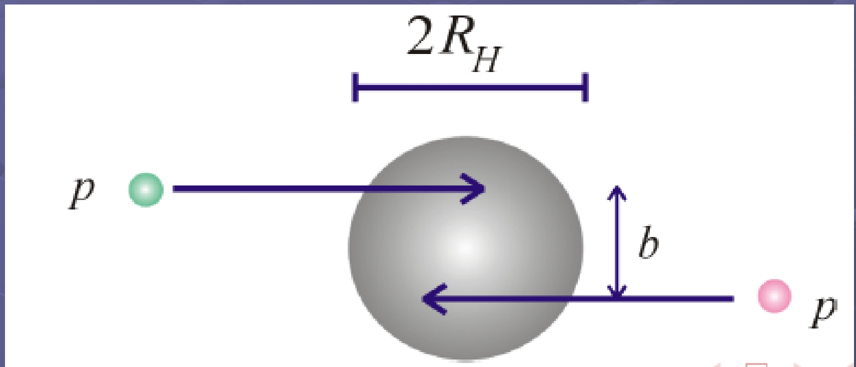
International Workshop "Bogoliubov readings", Dubna, 22 September 2010

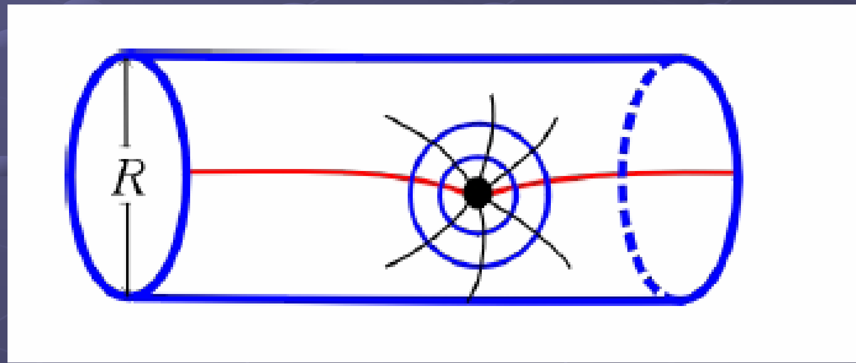
Black Hole formation in TeV-scale gravity

In large extra dimension models

- Gravity stronger at small distances
- Horizon radius larger
- For M ~ TeV it increases from 10^{-38} fm to 10^{-4} fm

For these BH R_h<< R and they have approximately higher dimensional spherical symmetry



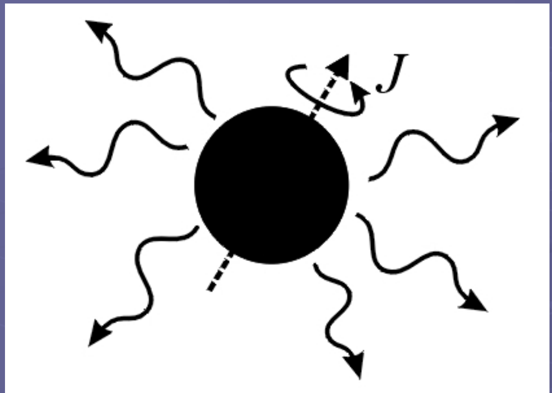


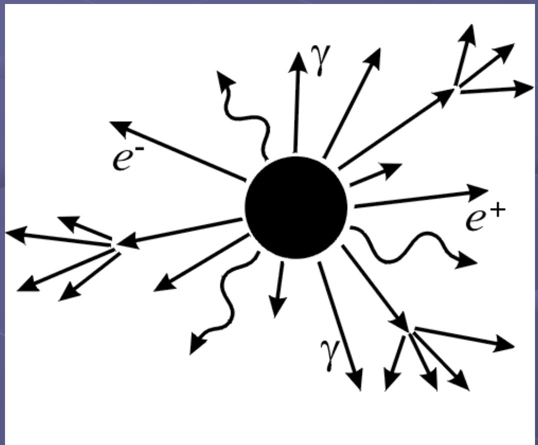
Pictures by Sabine Hossenfelder

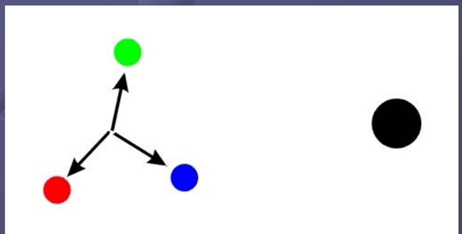
At the LHC partons can come closer than their Schwarzschild horizon

black hole production

Evolution stages for BH



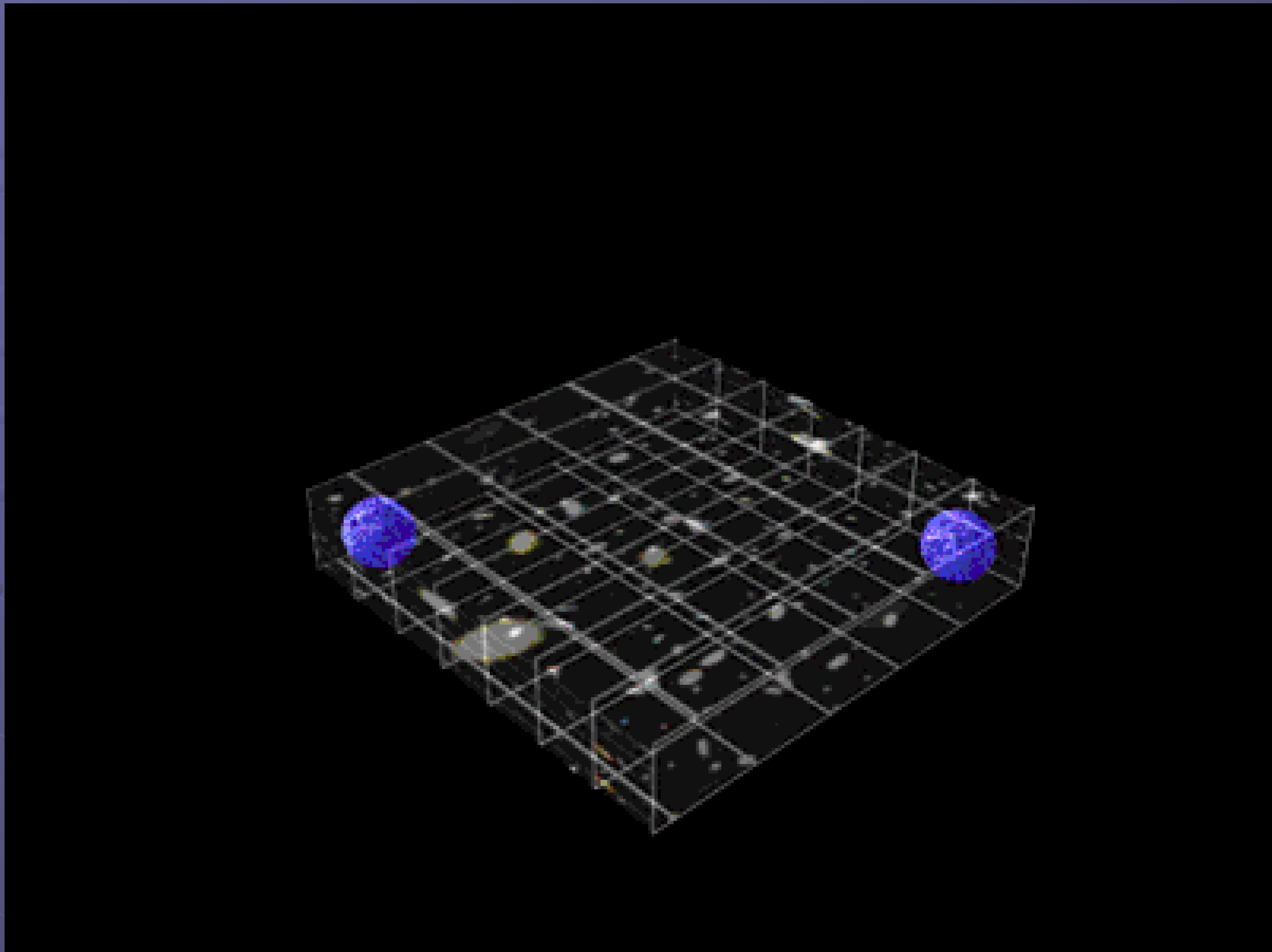




I. **Balding phase**
Asymmetric production, but "No hair" theorem: BH sheds its high multipole moments for fields (graviton and GB emitting classically), as electric charge and color.
Characteristic time is about $t \sim R_S$
Result: BH are classically stable objects

II-III. **Hawking radiation phases (short spindown + more longer Schwarzschild)**
Quantum-mechanical decay trough tunneling, transition from Kerr spinning BH to stationary Schwarzschild one. angular momentum shedding (up to ~ 50% mass loss). Corrections with Gray Body Factors
After this – thermal decay to all SM particles with black body energy spectra. Accelerating decay with a varying growing temperature. No flavor dependence, only number of D.o.f.– "democratic" decay

IV. **Planck phase: final explosion** (subj for QGr)
BH remnant (non-detectable energy losses), N-body decay, Q, B, color are conserved or not conserved



BH production in pp collisions: some well-known formulas

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

Schwarzschild raduis of a multidimensional BH
(R.C. Myers and M.J. Perry, Ann. Phys. 172, 304, 1986)

$$R_S \sim M_D^{-1}(E/M_D)^{1/D-3}, \quad D = 4+n$$

$$\frac{d\sigma_{\rm BH}}{dM_{\rm BH}} = \frac{dL}{dM_{\rm BH}}\hat{\sigma}(ab\to {\rm BH})\Big|_{\hat{s}=M_{\rm BH}^2}$$

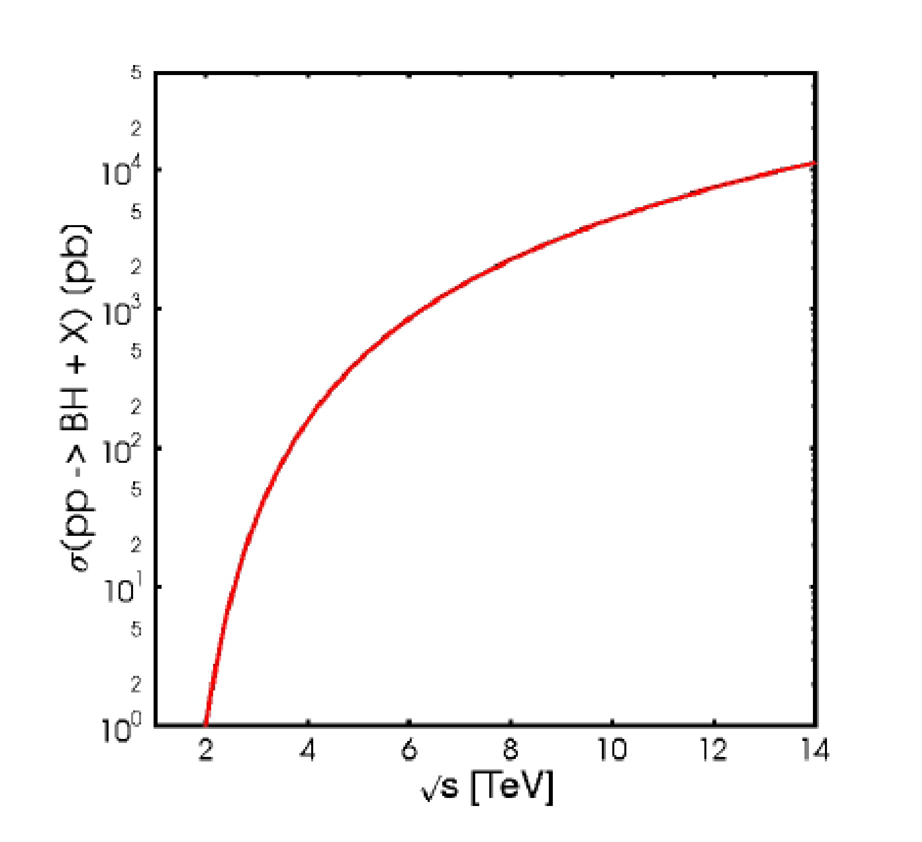
$\hat{\sigma}(ab\to {\rm BH}) \to \pi R_S^2$

BH production cross section
(S. Dimopoulos, G. Landsberg, Phys.Rev.Lett.87:161602, 2001 hep-ph/0106295v1)

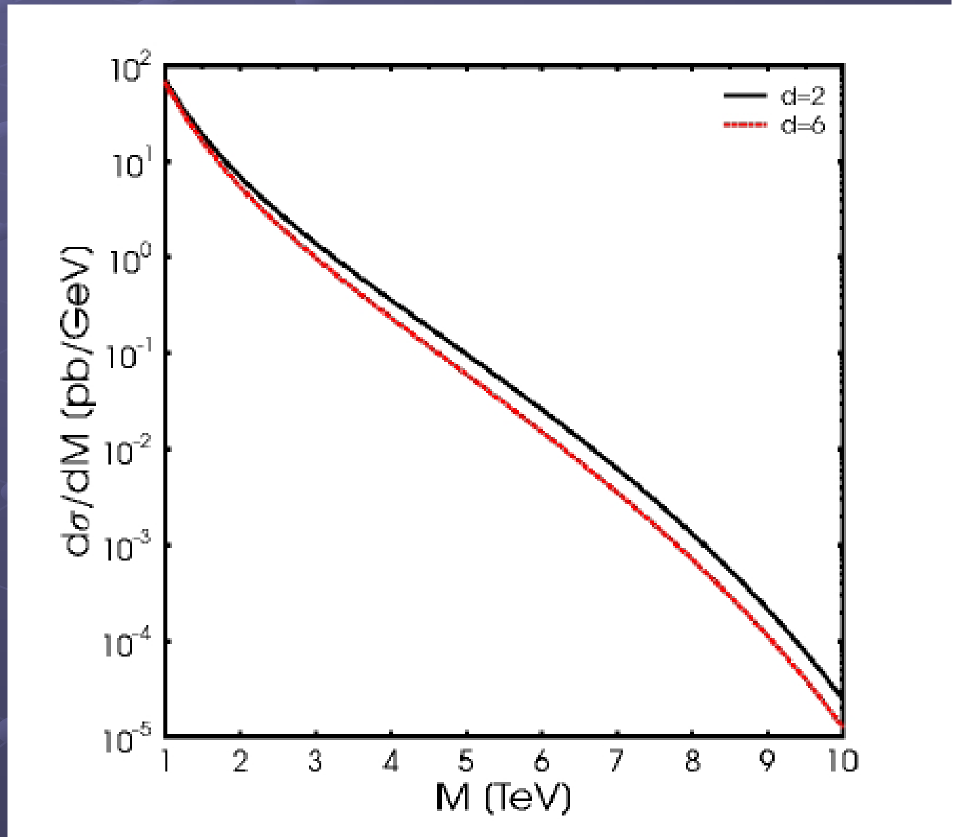
$$\frac{dL}{dM_{\rm BH}} = \frac{2M_{\rm BH}}{s}\sum_{a,b}\int_{M_{\rm BH}^2/s}^{1}\frac{dx_a}{x_a}f_a(x_a)f_b\left(\frac{M_{\rm BH}^2}{sx_a}\right)$$

PDF's: f_a, f_b

BH Production in pp collisions at the LHC



Increasing cross section, **no suppression** from small couplings



Hawking evaporation of BH

$$T_H = M\left(\frac{M}{M_{BH}}\frac{n+2}{8\Gamma\left(\frac{n+3}{2}\right)}\right)^{\frac{1}{n+1}} \times \frac{n+1}{4\sqrt{\pi}} = \frac{n+1}{4\pi R_S}$$

Hawking temperature

(R.C. Myers and M.J. Perry, Ann. Phys. 172, 304, 1986)

$$T_{\mathrm{H}} \propto M^{-1/(D-3)}$$

Multiplicity of produced particles in BH decay

$$\langle N\rangle = \langle M_{BH}/E\rangle$$

Planckian spectrum (black body)

$$\left\langle\frac{1}{E}\right\rangle = \frac{1}{T_H}\frac{\int_0^\infty dx \frac{1}{x}\frac{x^2}{e^x \pm c}}{\int_0^\infty dx \frac{x^2}{e^x \pm c}} = \frac{a}{T_H}$$

where $x = E/T_H$

$$\langle N\rangle = \frac{2\sqrt{\pi}}{n+1}\left(\frac{M_{\mathrm{BH}}}{M}\right)^{\frac{n+2}{n+1}}\left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)^{\frac{1}{n+1}}$$

Grey Body Factors for BH Decay

$$\frac{dN_{s,l,m}}{d\omega dt} = \frac{1}{2}\frac{\Gamma_{s,l,m}}{\exp[\omega/T_{\rm H}]\mp 1}$$

$$T_{\rm H} = \frac{n+1}{4\pi r_h}$$

Grey body factors

particle's spin	c_i	Γ_i
0	1	0.80
$\frac{1}{2}$	90	0.66
1	27	0.60

Papers on GBF:

P. Kanti, J. March-Russell, I. Olasagasti K. Tamvakis, 2002;
G. Duffy, C. Harris, P. Kanti and E. Winstanley, 2005;
M. Casals, P. Kanti and E. Winstanley, S. R. Dolan, 2006-2007
D. Ida, K.-y. Oda and S. C. Park, 2003-2006

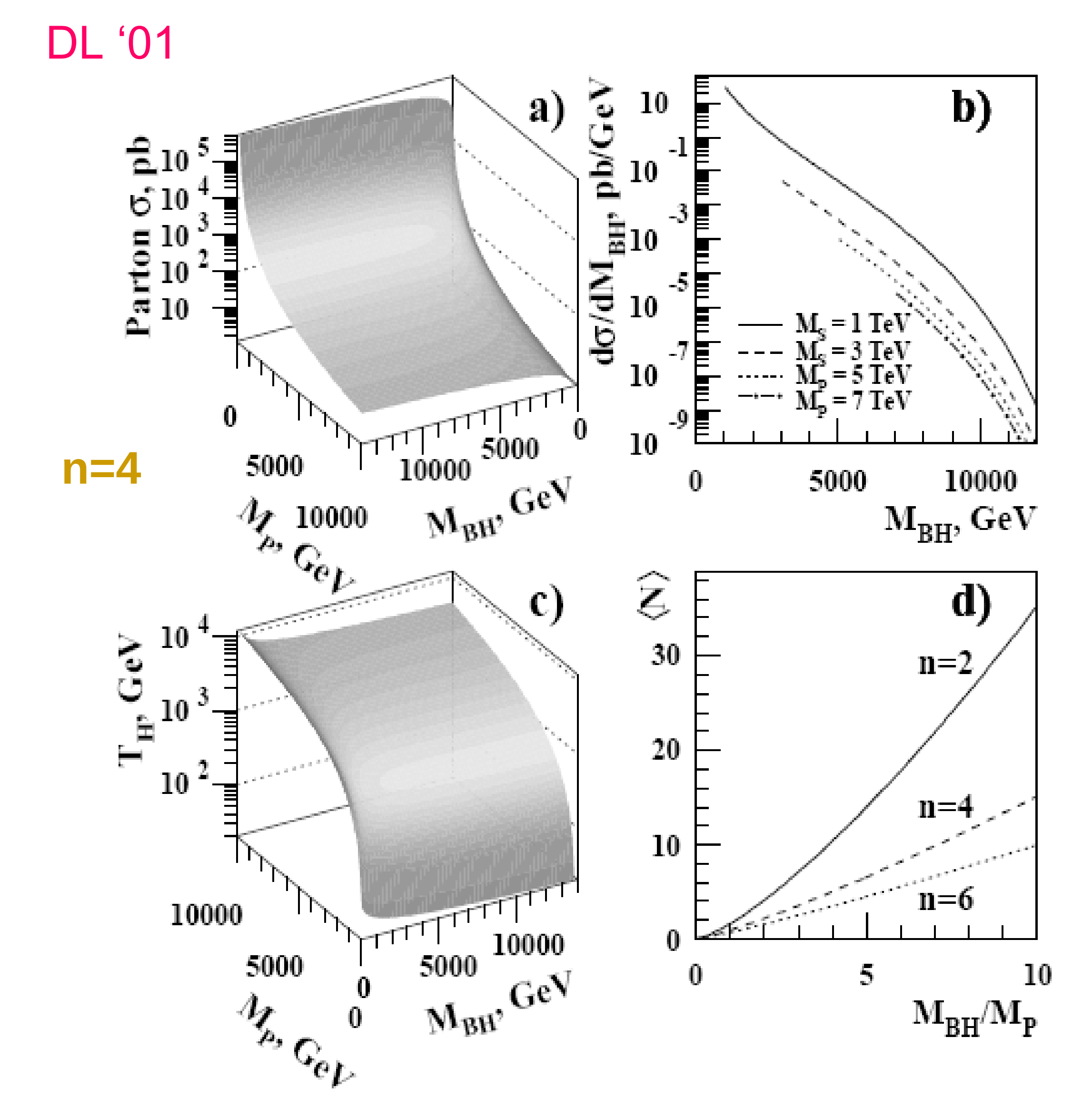
$$\frac{dN_{e^-}}{d\omega dt} = 2\sum_{l,m}\frac{dN_{1/2,l,m}}{d\omega dt}$$

D.o.F. for e-

$$\frac{dN_{W^-}}{d\omega dt} = 2\sum_{l,m}\frac{dN_{1,l,m}}{d\omega dt} + \sum_{l,m}\frac{dN_{0,l,m}}{d\omega dt}$$

D.o.F. for GB

BH production in pp collisions at the LHC



For the LHC energies:

a) Parton-level production cross section

b) Differential cross section

c) Hawking temperature

d) Average decay multiplicity for Schwarzschild BH

(S. Dimopoulos, G. Landsberg, Phys.Rev.Lett.87:161602, 2001, hep-ph/0106295v1)

Entropy, BH decay and $M_{min}(BH)$

BH Entropy

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

(R.C. Myers and M.J. Perry, Ann. Phys. 172, 304, 1986)

S_{BH} must be large enough to reproduce thermal BH decay

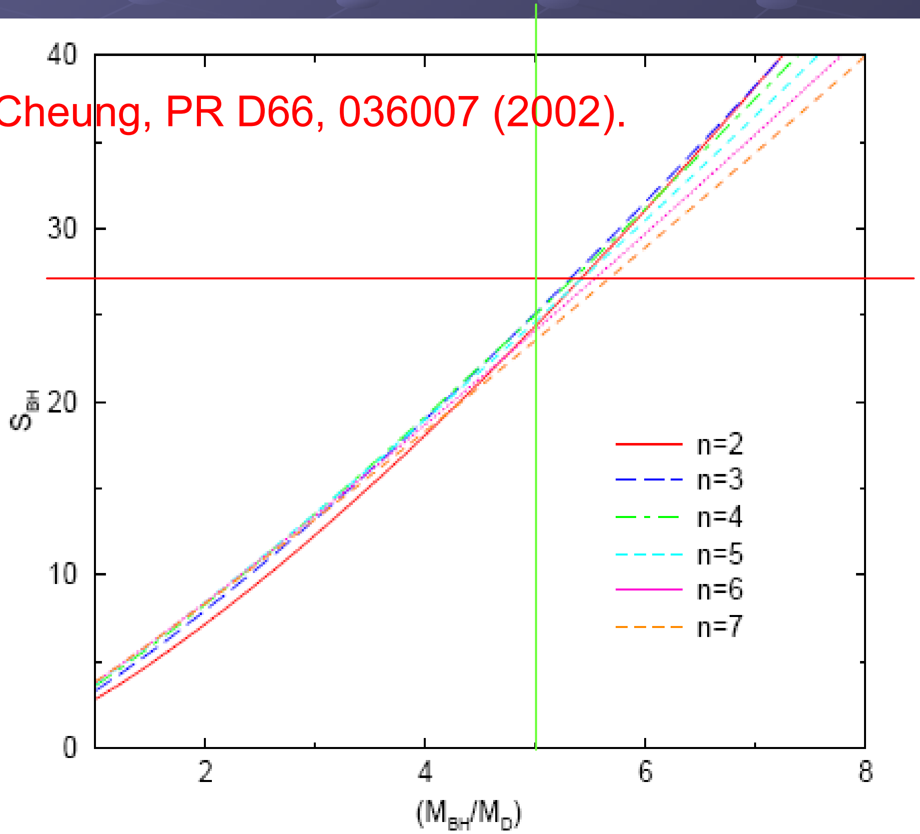
$$1 << \frac{1}{\sqrt{S_{\rm BH}}} \Rightarrow S_{\rm BH} > 25$$

(S.B. Giddings, hep-ph/0110127v3, K. Cheung, Phys. Rev. Lett. 88, 221602, 2002)

$$M_{\rm BH}^{\rm min} \geq 5M$$

Democratic decay blinded to flavor: probabilities are the same for all species (violation of some conservation laws)

K. Cheung, PR D66, 036007 (2002).



D.o.f. counting and "democracy" of decay

$$\begin{array}{ccccccccccccccccc} Z, & W^\pm, & \gamma, & g, & H; & e^\pm, & \mu^\pm, & \tau^\pm, & \nu_e, & \nu_\mu, & \nu_\tau; & u, & d, & s, & c, & b, & t \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \\ 3 & 6 & 2 & 16 & 1 & 4 & 4 & 4 & 2 & 2 & 2 & 12 & 12 & 12 & 12 & 12 & 12 \end{array}$$

$$l^\pm \;\to\; 2\left|+\frac{1}{2};\ -\frac{1}{2}\right.$$

$$\underbrace{u, d, s, c, b, t}_{6\times4\times3}$$

$6\times4\times3$: $\downarrow$ *flavor*, $\downarrow$ *color*

(Gauge+Higgs) : (Leptons) : (Quarks) = 28 : 18 : 72

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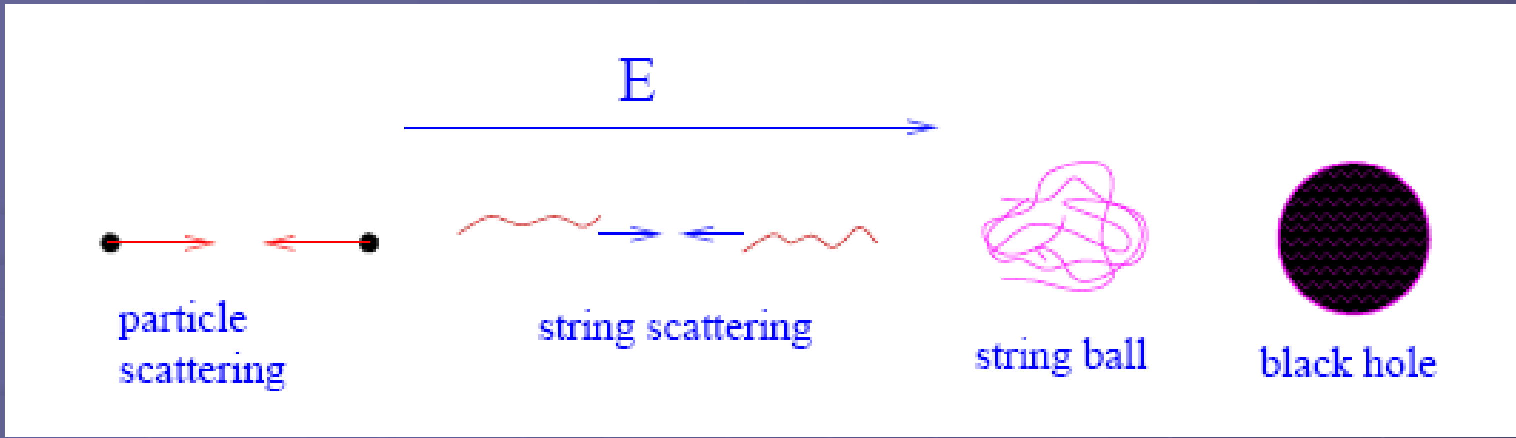
The ratio of hadronic/leptonic is 5 : 1

Black Hole or String Ball?



Picture by Kingman Cheung

M_{BH} >> M_D : semiclassical well-known description for BH's.

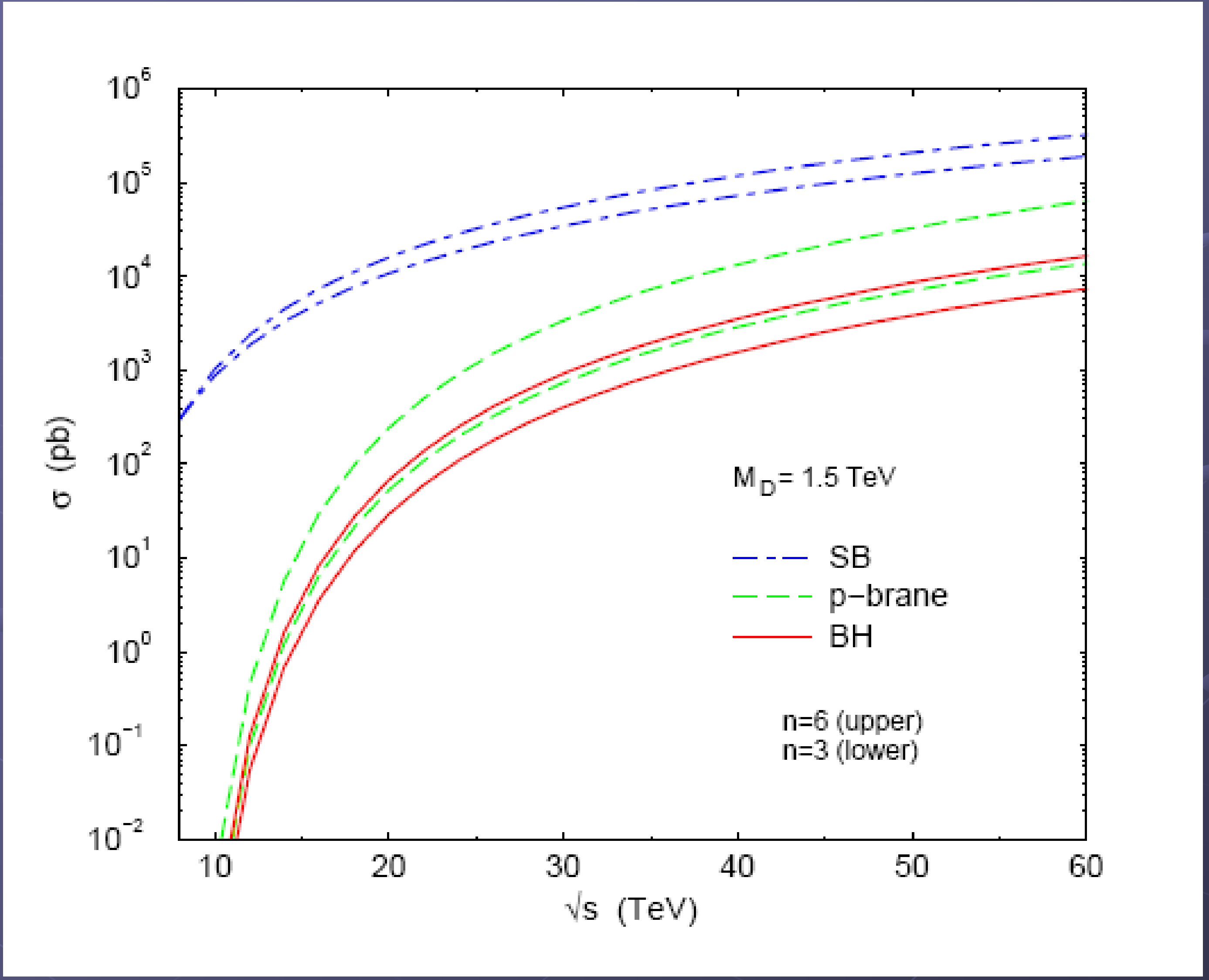
What happens when M_{BH} approach M_D?
BH becomes "stringy", their properties become complex.

Matching:

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

S. Dimopoulos and R. Emparan, Phys. Lett. B526, 393 (2002), hep-ph/0108060

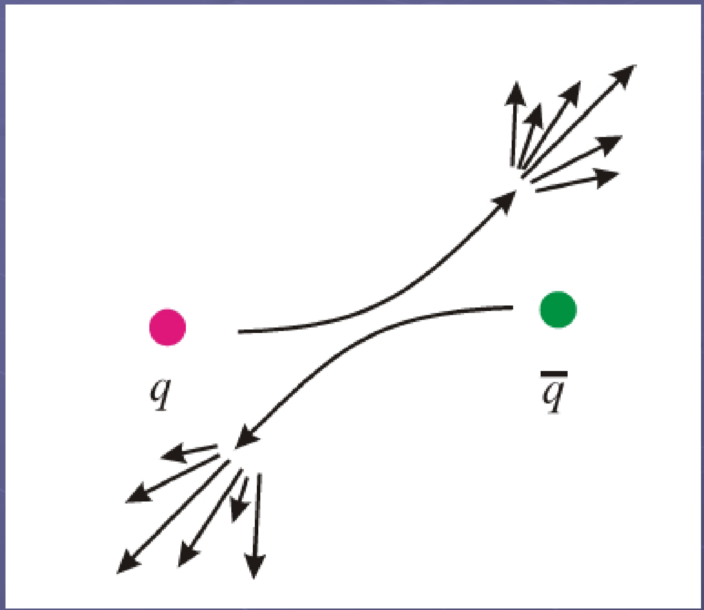
Production cross section for BH, SB and p-brane



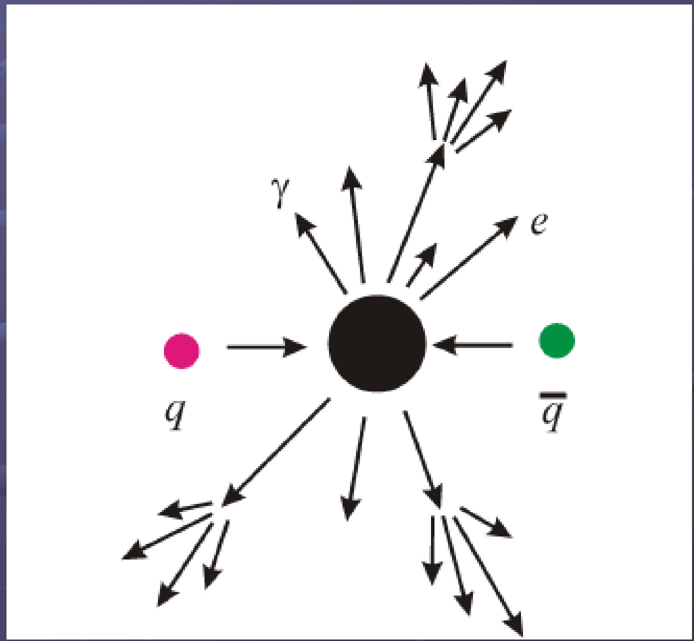
K. Cheung, PR D66, 036007 (2002), hep-ph/0305003

Final state of the SM process vs typical BH decay spectra

SM



BH decay



Pictures by Sabine Hossenfelder

Multi-jet and hard leptons events, spherical, typical temperature about 200 GeV

BH Experimental Signatures

- Potentially large cross sections, approaching 10^3 fm or more
- An increase of cross sections with energy, according to an absense of gauge coupling suppression (will be hard to see at the LHC)
- Relatively high sphericity for final states
- High multiplicity as proportional to the BH entropy of particles produced (primaries)
- Hard trasverse leptons and jets, in significant numbers
- Approximately thermally determined ratios of species (democratic decay)
- Suppression of highest-energy jets
- Decrease of decay primary (lepton/parton) energy with total event transverse energy (resulting from decreasing Hawking temperature with mass)

Part II. Optimism Is fading…

BH not as spectacular as advertized!!

- BH Production near the threshold and careful counting
- Conventions on a fundamental mass
- Inelasticity for BH formation at the LHC and in the UHECR
- Minimal M for a sensible definition of a BH
- LHC unlikely to make classical BH with thermal decay spectra.
  So, what can we see, then?
- Two-body final states and QG

… but it is not the end of the story

Conventions on a fundamental mass

$$S = \frac{1}{8\pi G_D}\int d^D x\sqrt{-g}\,\frac{1}{2}\Re + \int d^D x\sqrt{-g}\,L$$

Just numerical coefficients

At least three definitions:

But: there is essential difference between M about 1 TeV and 2 TeV for the LHC!

$$M_P^{D-2} = \frac{(2\pi)^{D-4}}{4\pi G_D}$$

$$M_P = 2^{\frac{1}{D-2}} M_D$$

$$M_D^{D-2} = \frac{(2\pi)^{D-4}}{8\pi G_D}$$

$$M_{\rm DL}^{D-2} = \frac{1}{G_D}$$

$$M_P^{D-2} = 2^{D-6}\pi^{D-5} M_{\rm DL}^{D-2}$$

D=6 $M_p = 1.3 M_{DL}$

D=10 $M_p = 2.9 M_{DL}$

At what energy can we safely speak about "true" BH production?

Clearly E > M_D. But how much large?

Criteria for a Black Hole?

- $M_{BH}>M$
  - As advertised, not even convention independent
- $2\pi/(M/2)<R_S$
  - More stringent version of above
  - ADD (n=6) $M_{BH}>4M$—almost at experimental limit
  - RS $M_{BH}>16M$—if taken seriously, bhs already out of reach

From the talk by Lisa Randall at String'2007

Inelasticity in BH production and X_{min}

$$\sigma^{pp}(s, x_{\min}, d, M) = \int_0^1 2z\,dz \int_{\frac{(x_{\min M})^2}{y^2 s}}^1 du \int_u^1 \frac{dv}{v} F(n)\pi r_s^2(us, n, M) \times \sum_{i,j} f_i(v,Q) f_j(u/v,Q)$$

$$x_{\min} = M_{BH}^{\min}/M \quad ; \quad y \equiv M_{BH}/\sqrt{\hat{s}} \quad ; \quad z = b/b_{\max}$$

What part of initial collision energy actually was trapped in BH formation process?

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inelasticity (pp → BH + X) – function of n,b

TSM

$(I): \quad M = 0{,}6E\,, \quad b < 0{,}5R_S \quad ; \quad M = 0\,, \quad b > 0{,}5R_S$

$(II): \quad M = 0{,}7E\,, \quad b < 0{,}5R_S \quad ; \quad M = 0\,, \quad b > 0{,}5R_S$

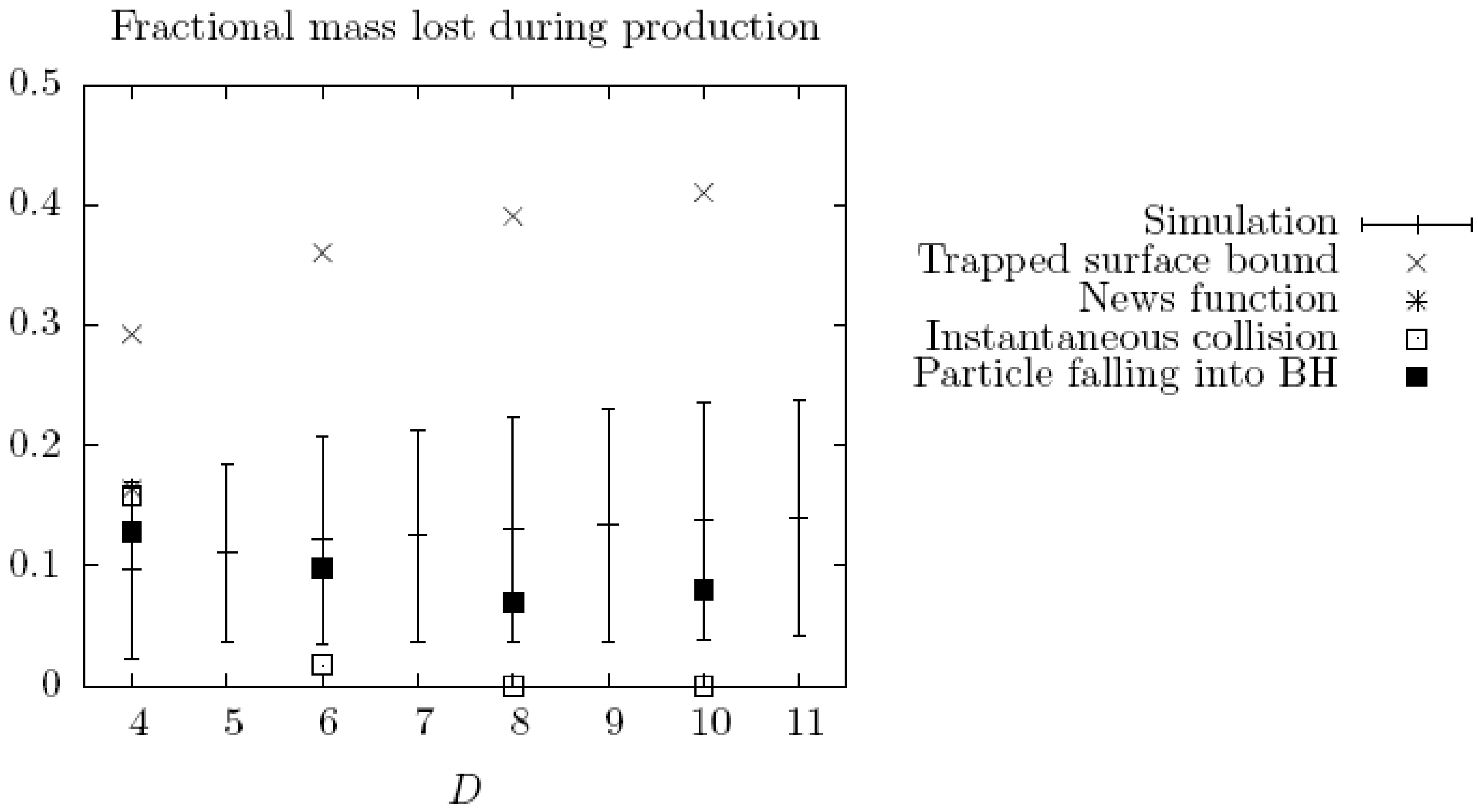
10^{34} ⇒

$(I): \; \sigma = 1{,}8 \times 100\, fb$

$(II): \; \sigma = 1{,}8 \times 1000\, fb$

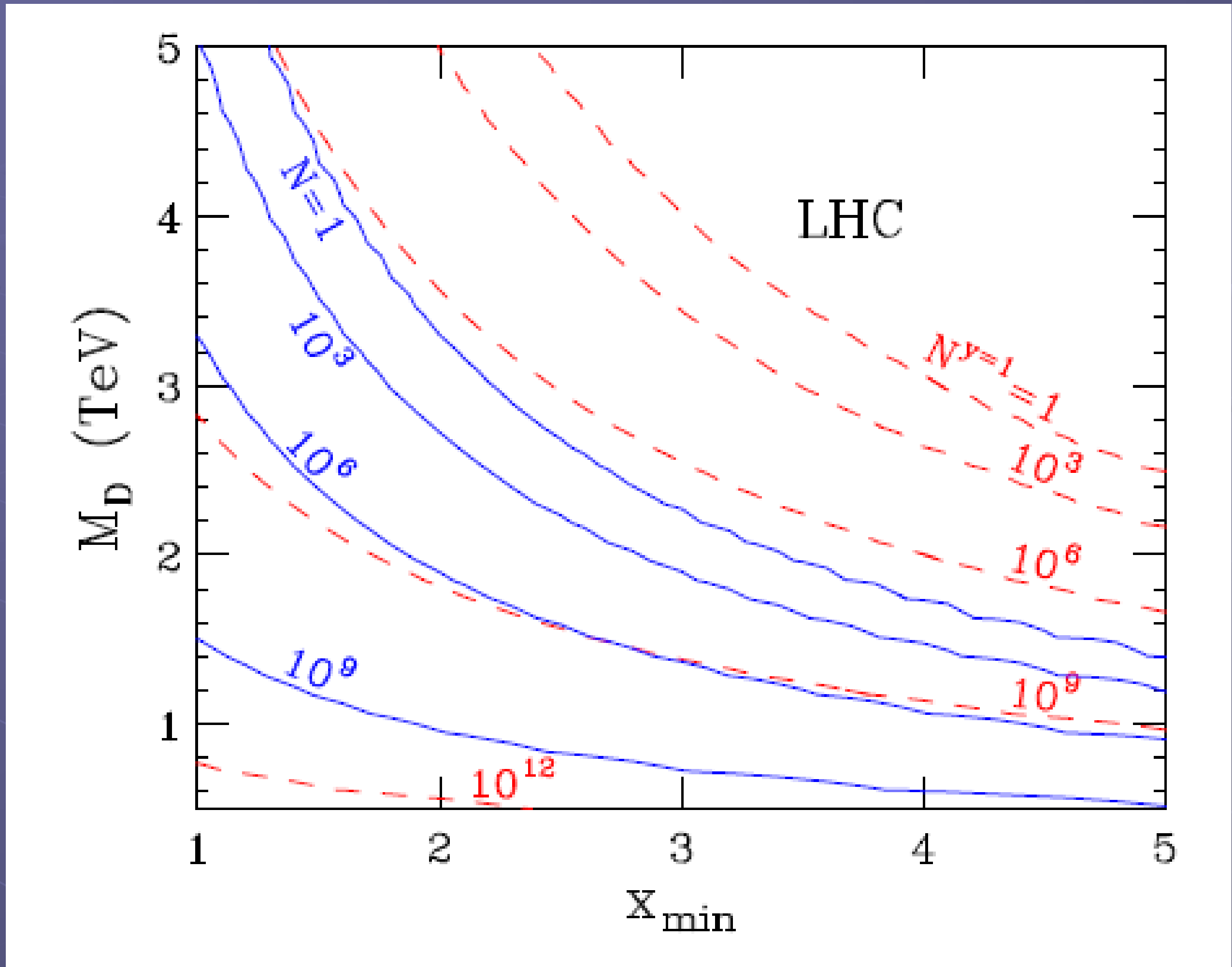
H. Yoshino and Y. Nambu, Phys. Rev. D 67, 024009 (2003), gr-qc/0209003;
L. A. Anchordoqui, J.L. Feng, H. Goldberg, and A.D. Shapere, hep-ph/0311365
H. Yoshino, V.S. Rychkov, Phys. Rev. D71, 104028 (2005), hep-th/0503171

Mass loss during BH formation in different models



J. A. Frost, J. R. Gaunt, M. O.P. Sampaio, M. Casals, S. R. Dolan, M. A. Parker, and B. R. Webber, *arXiv:0904.0979*

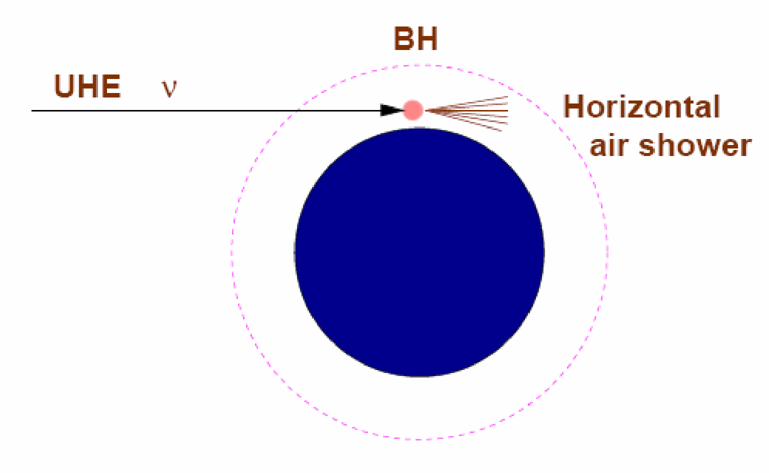
Inelasticity by TSM and predictions for the LHC



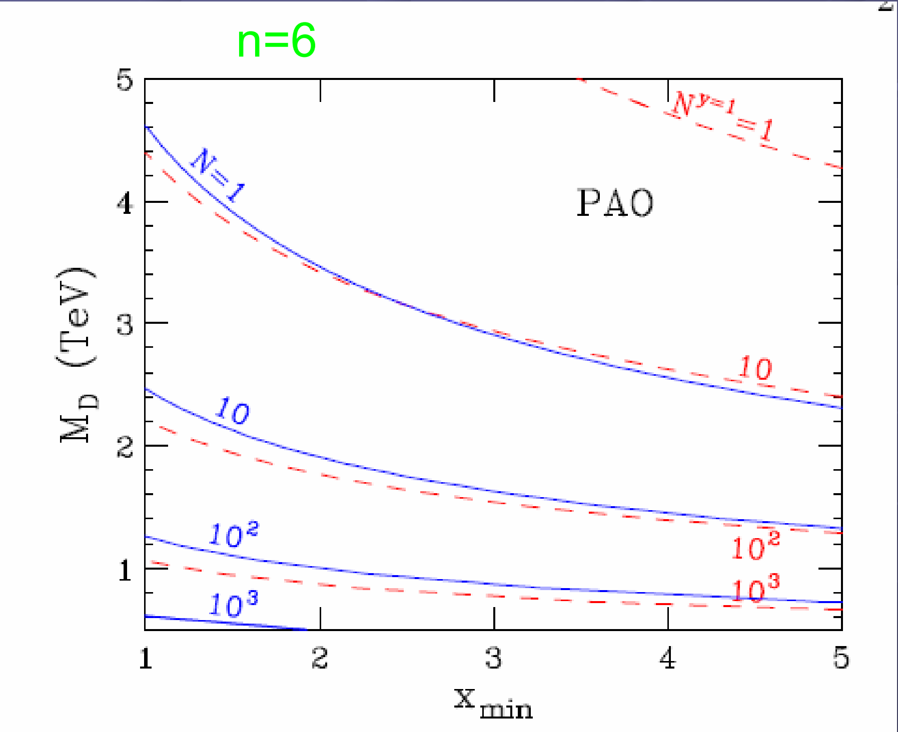
L.A. Anchordoqui, J.L. Feng, H. Goldberg, A.D. Shapere, Phys.Lett. B594 (2004), hep-ph/0311365

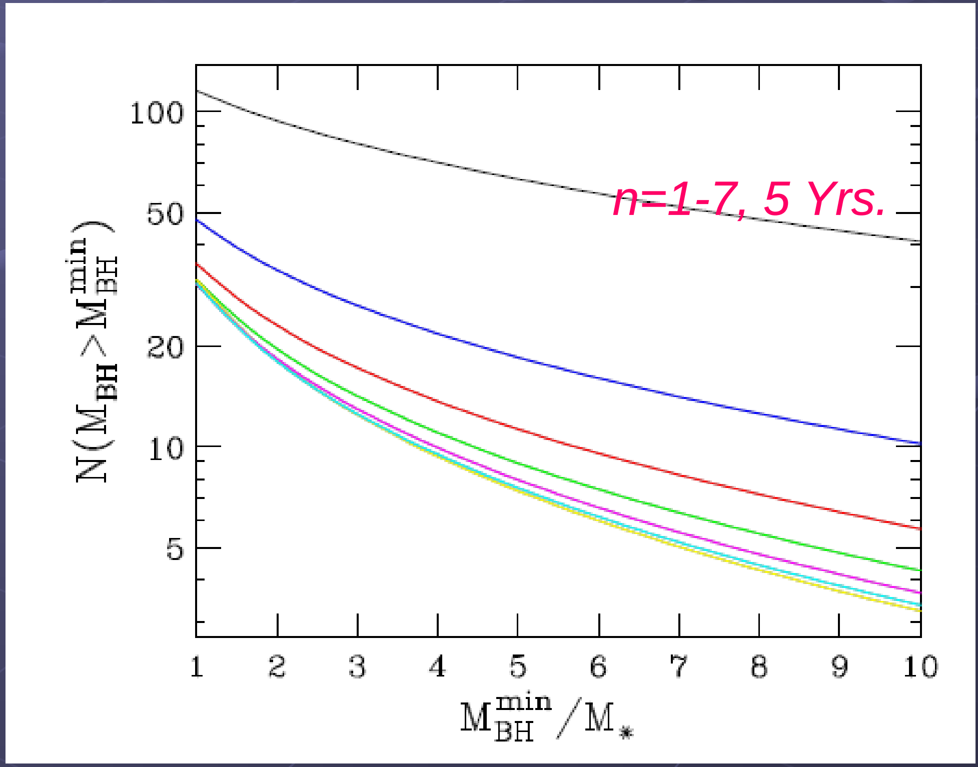
BH production in UHECR

BH Production in UHECR

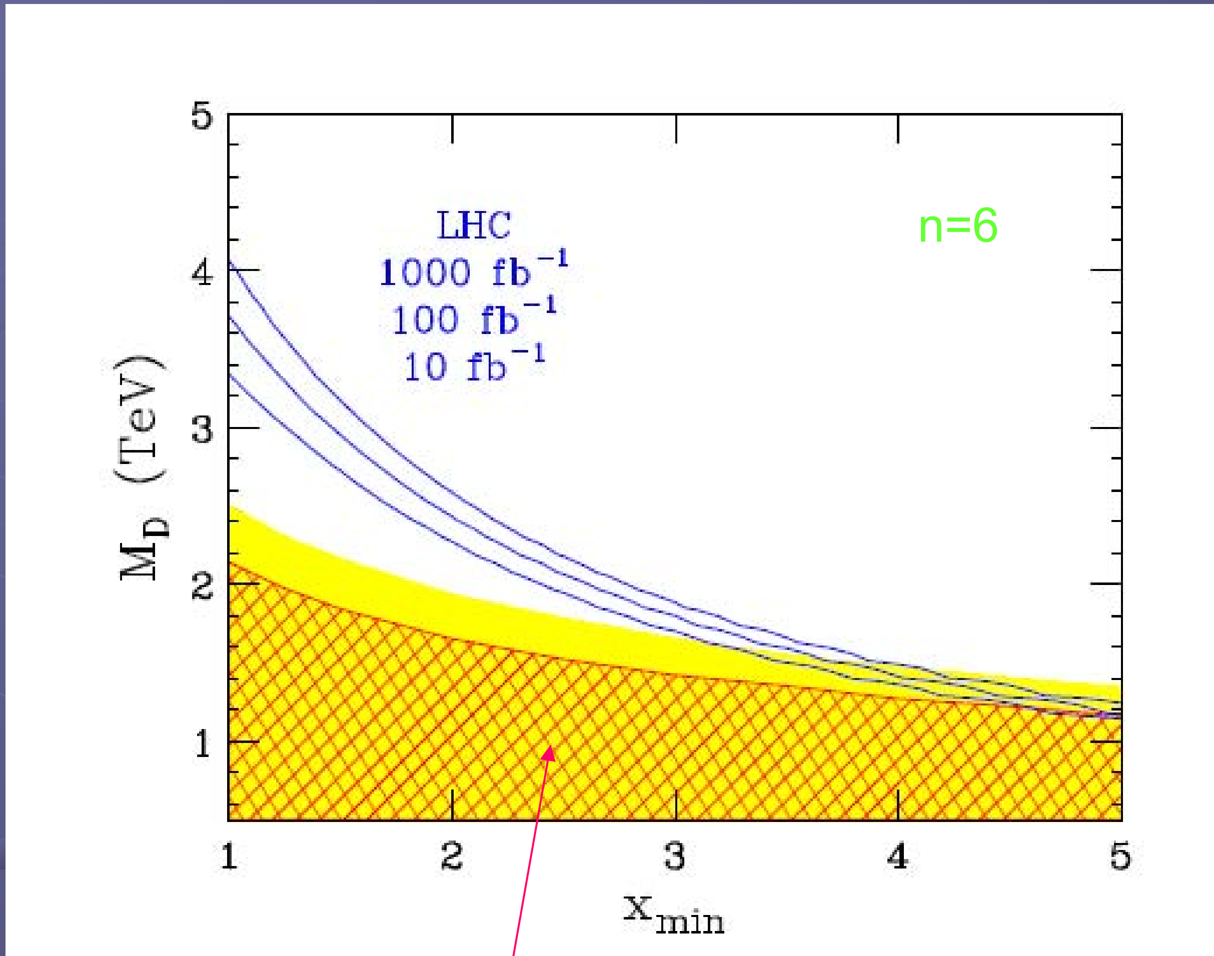


Pierre-Auger Observatory





The discovery reaches for the LHC



PAO didn't see BH pruduction in HAS.

It means what PAO didn't see the signal in HAS

- Suppression of ν fluxes in ED
 B conservation in νp

We need wait for the LHC!

This region tested by PAO 5 Years (not excluded hardly)

L.A. Anchordoqui, J.L. Feng, H. Goldberg, A.D. Shapere, Phys.Lett. B594 (2004), hep-ph/0311365

Simulation of BH production and decay: event generators

Black Hole Event Generators

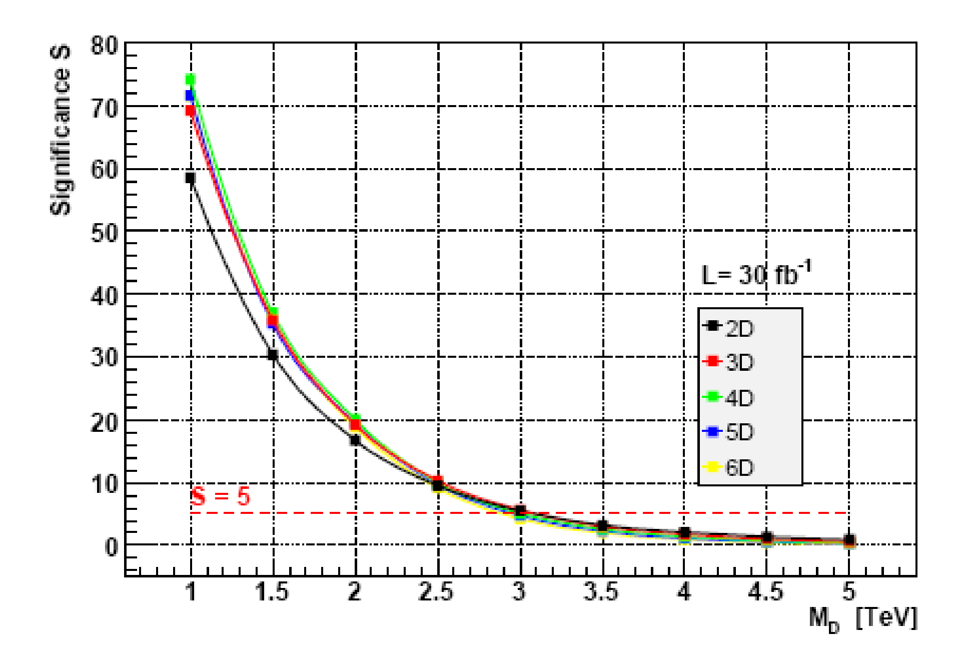
CHARYBDIS 1.003 (August 2006)
C.M. Harris, P. Richardson and B.R. Webber
"CHARYBDIS: A Black Hole Event Generator", JHEP 0308:033, hep-ph/0307305, 2003
http://www.ippp.dur.ac.uk/montecarlo/leshouches/generators/charybdis/

CHARYBDIS2 (April 2009)
J. A. Frost, J. R. Gaunt, M. O.P. Sampaio, M. Casals, S. R. Dolan, M. A. Parker, and B. R. Webber, *arXiv:0904.0979*
http://projects.hepforge.org/charybdis2/

CATFISH 1.1 (October 2006),
M. Cavaglia, R. Godang, L. Cremaldi and D. Summers, "CATFISH: A Monte Carlo simulator for black holes at the LHC", *arXiv: hep-ph/0609001*
http://www.phy.olemiss.edu/GR/catfish/catfish-v1.01.docu.pdf

BlackMax (April 2008, the latest version – March 2010)
De-Chang Dai, G. Starkman, D. Stojkovic, C. Issever, E. Rizvi, J. Tseng
"BlackMax: A black-hole event generator with rotation, recoil, split branes and brane tension", *Phys.Rev. D77:076007, 2008, arXiv:0711.3012v4*
http://projects.hepforge.org/blackmax/

CHARYBDIS1 Gen.: Analysis and results for the CMS

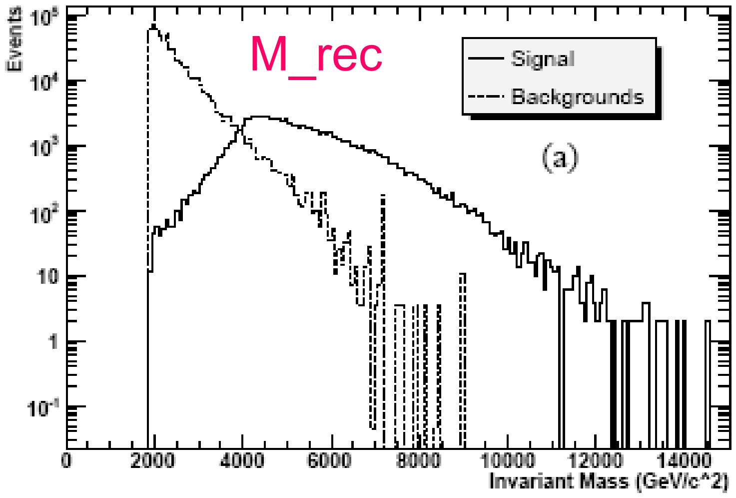


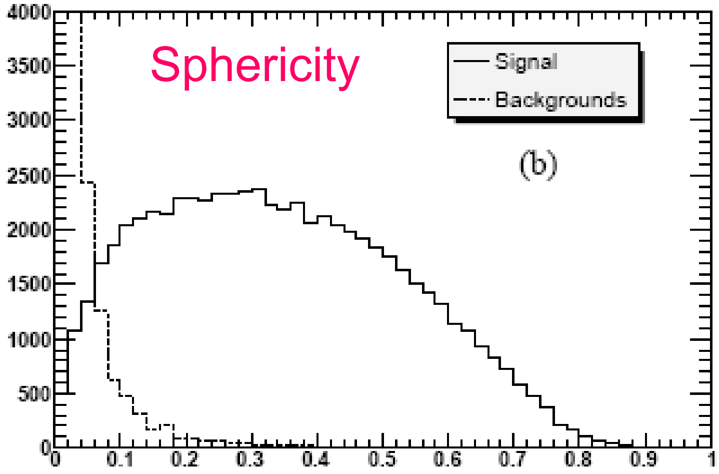
CMS PTDR Vol. II, 2007

Hard jets, leptons and γ's

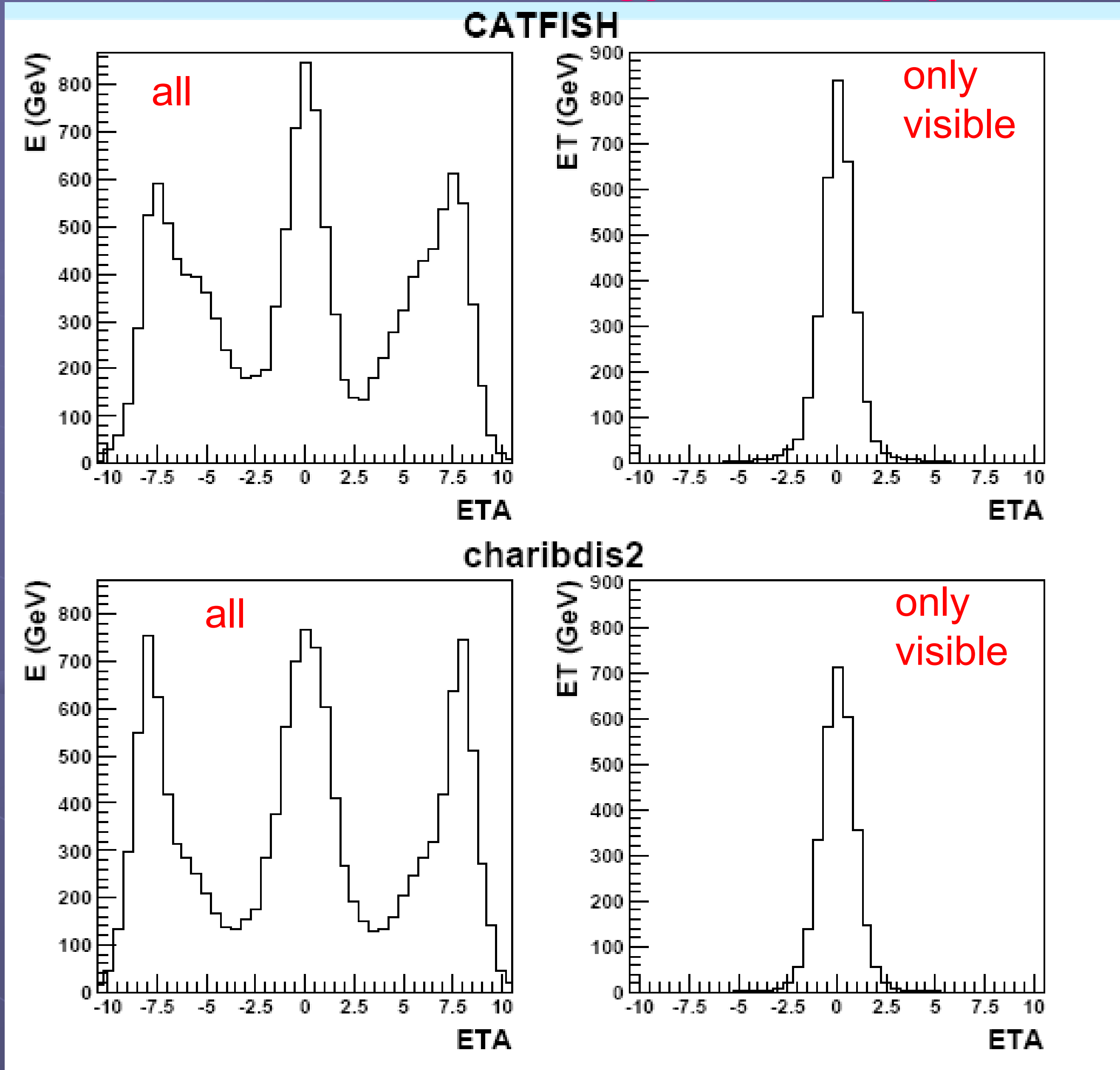
$L = 30\ fb^{-1}$

As a benchmark:
2 TeV/c^2 fundamental Planck scale
4 TeV/c^2 – 14 TeV/c^2 BH mass
n=3 number of ED





Total vs visible energy of decay products



Sqrt(s)=14 TeV, n=6, M=1 TeV, M_{BH}=5 TeV

Cut on eta: |η|<3 can be applied

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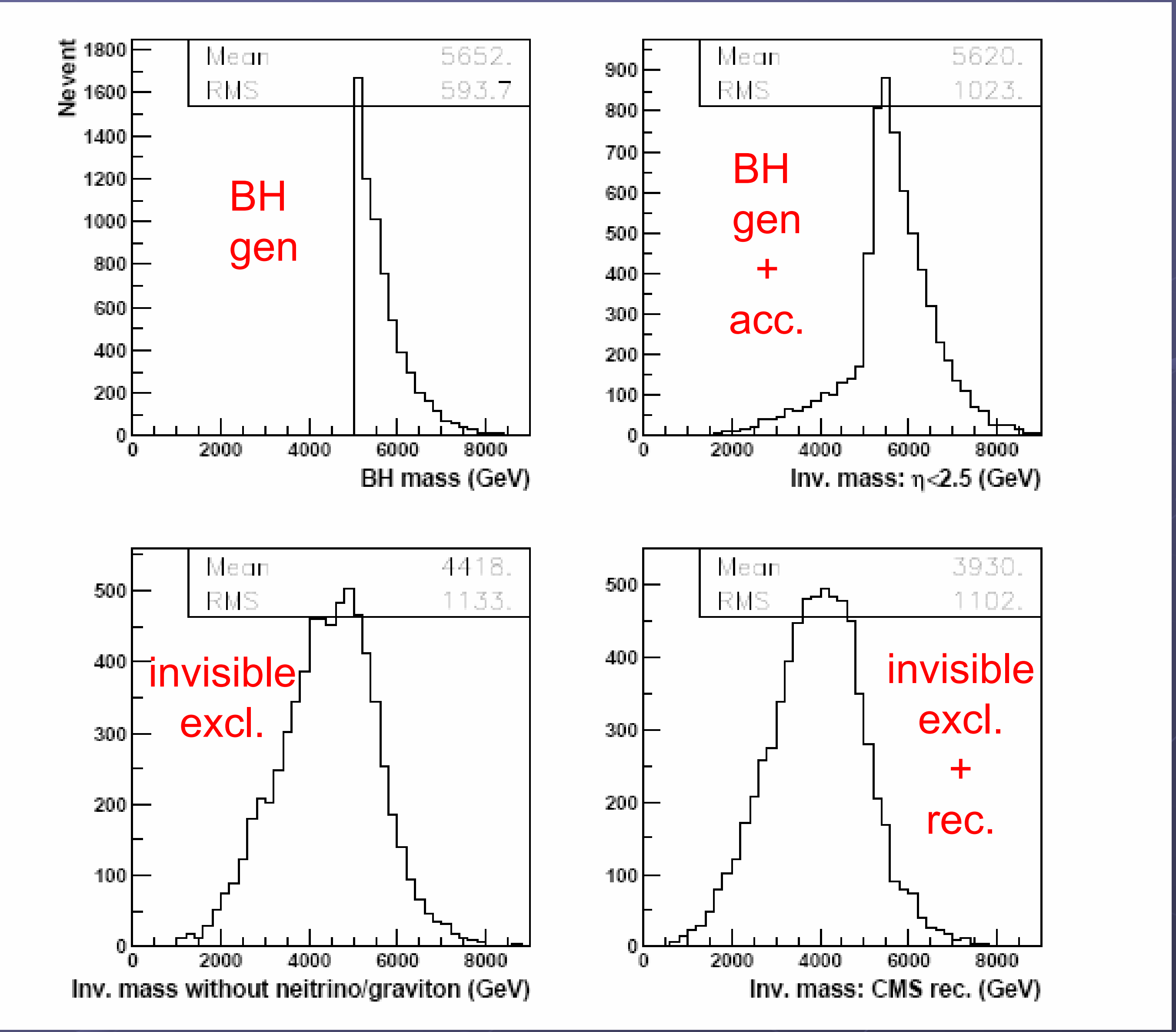
Invariant mass of decay products (visible only + kin. cuts + acceptance)



Sqrt(s) = 14 TeV,
n = 6, M =1 TeV,
M_{BH} = 5 TeV

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Invisible energy (from neutrinos and gravitons), in percents of total energy, Charybdis2

Table 1. Particles from BH used.

M_{BH} (GeV)	n=7	n=8	n=9	n=10
> 5000	21.7	23.9	24.8	27.0
> 7000	24.5	27.2	28.1	29.9
> 10000	27.9	30.8	31.3	32.0

Table 2. Particles with $|\eta| < 2.5$ used.

M_{BH} (GeV)	n=7	n=8	n=9	n=10
> 5000	20.8	22.8	23.4	24.5
> 7000	23.8	24.9	27.2	28.9
> 10000	27.0	28.9	30.2	31.4

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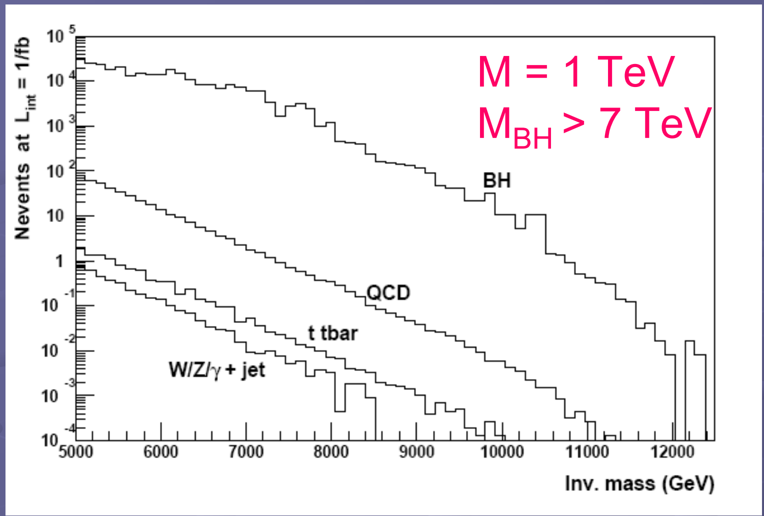
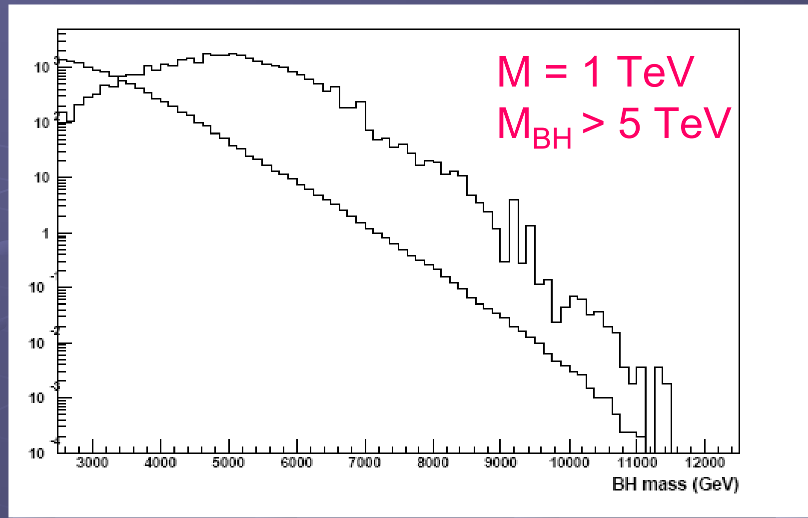
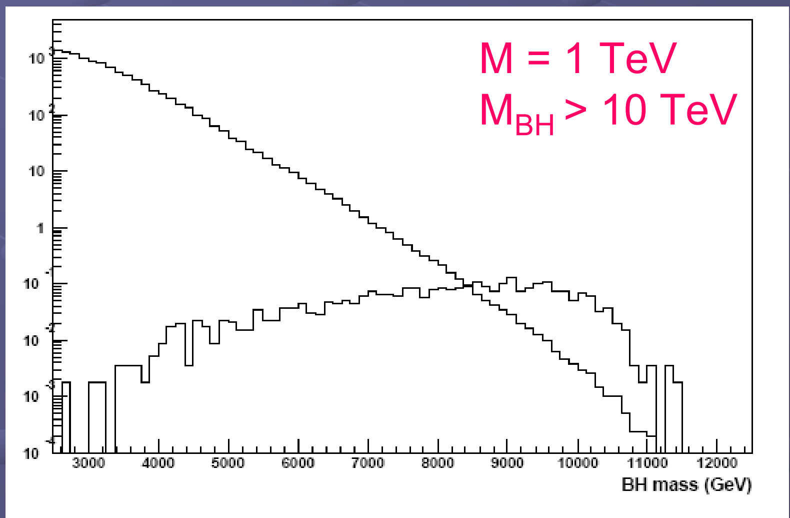
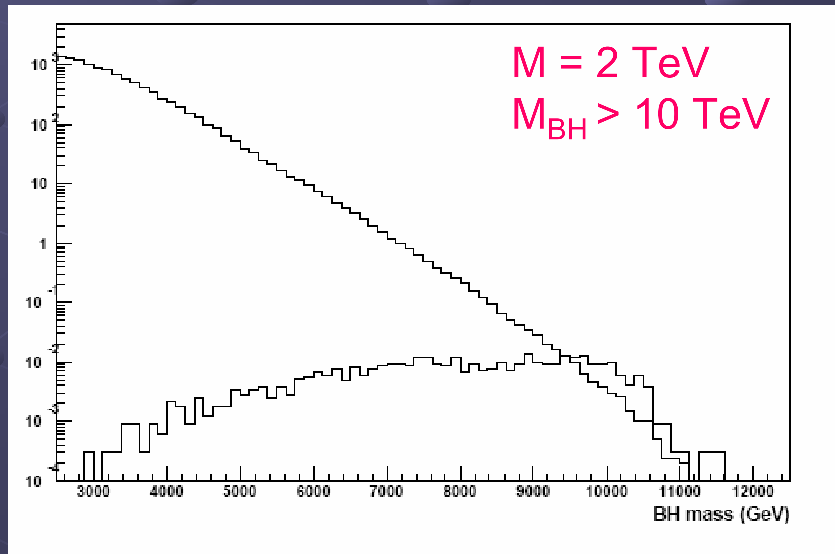
Charybdis2: S&B Sphericity for different fundamental scales and Xmin









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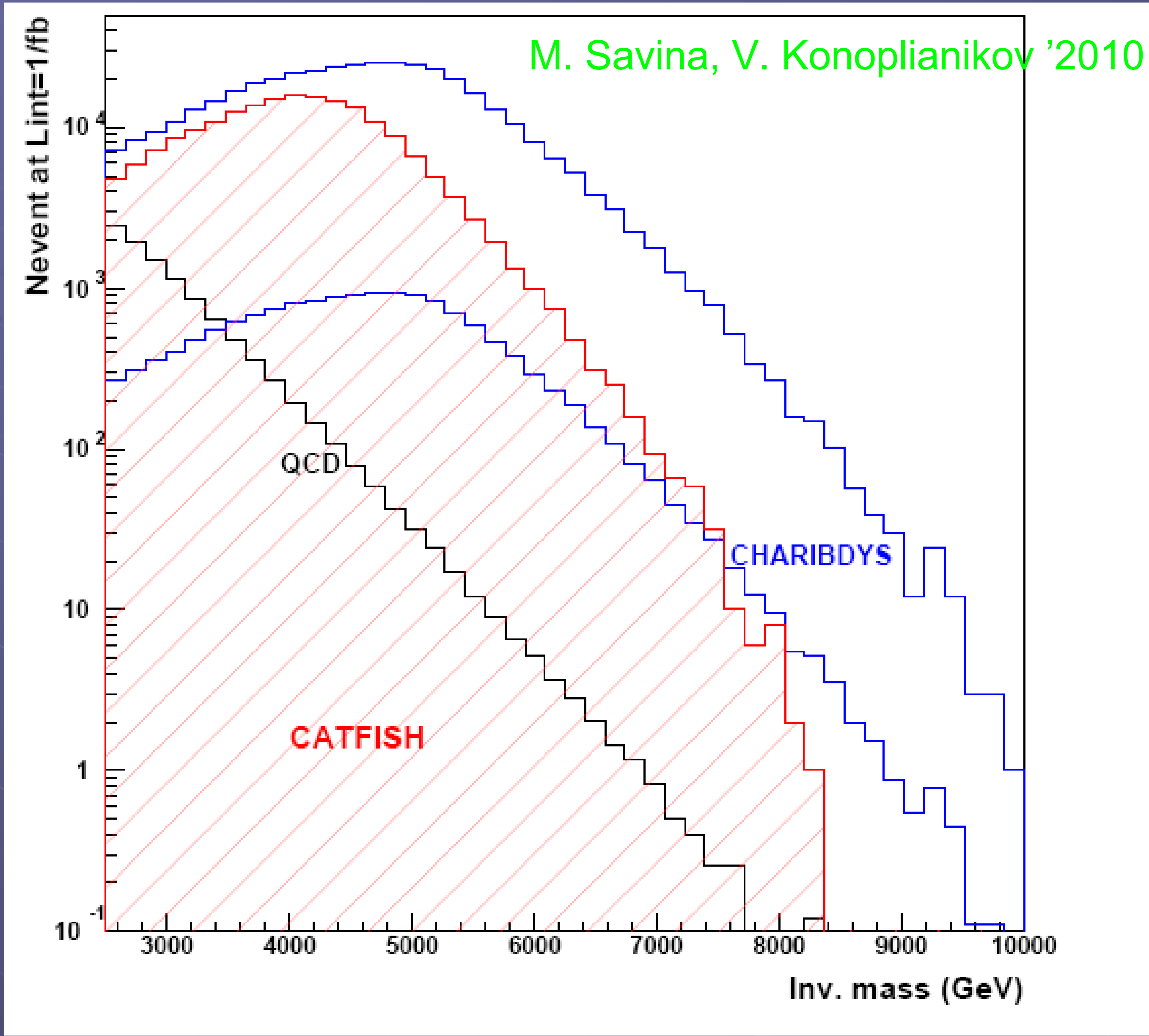
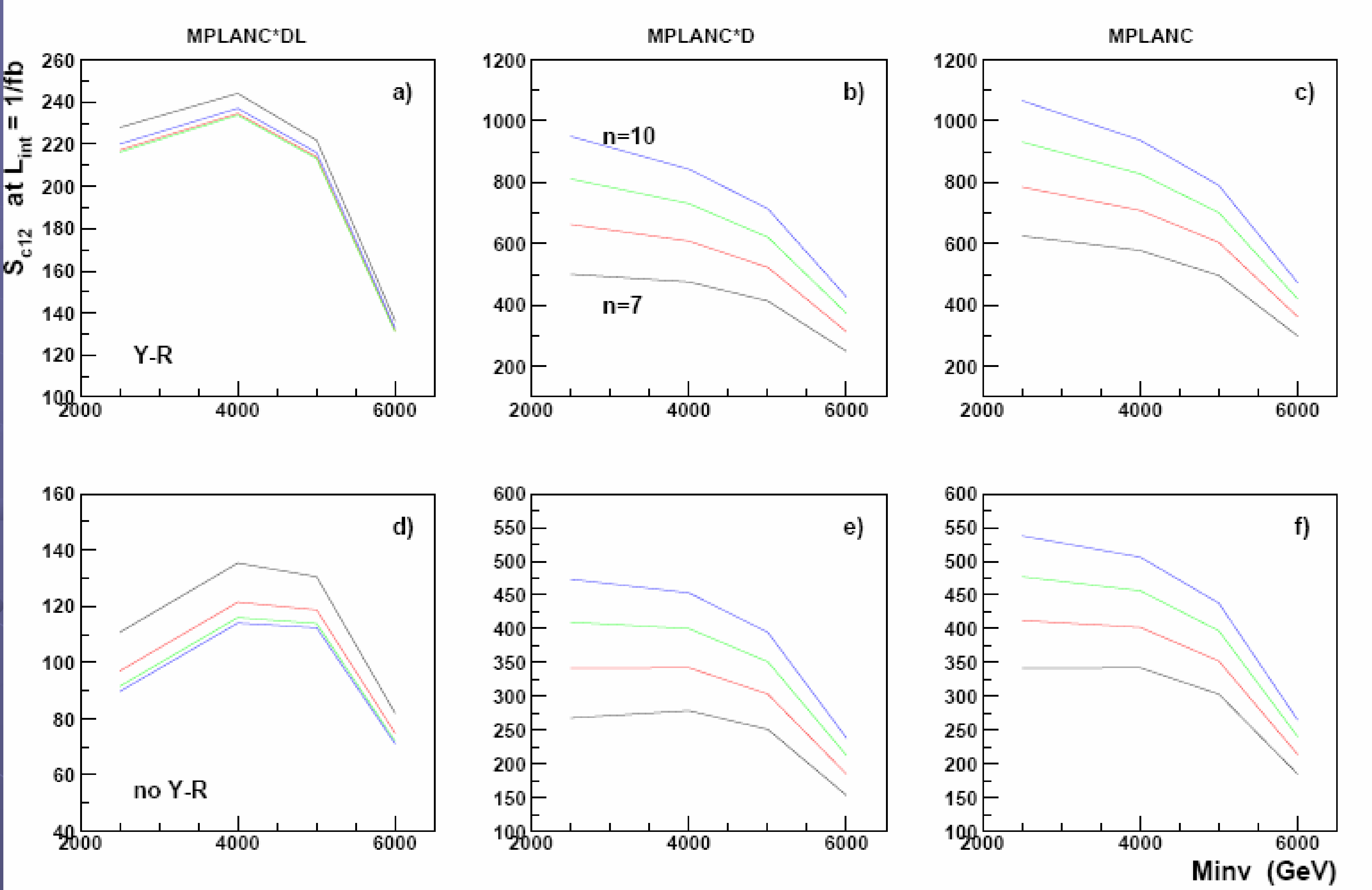
CatFish (red) vs Charybdis (blue)



Charybdis2: S_{12} vs minimal visible mass, for different M def.



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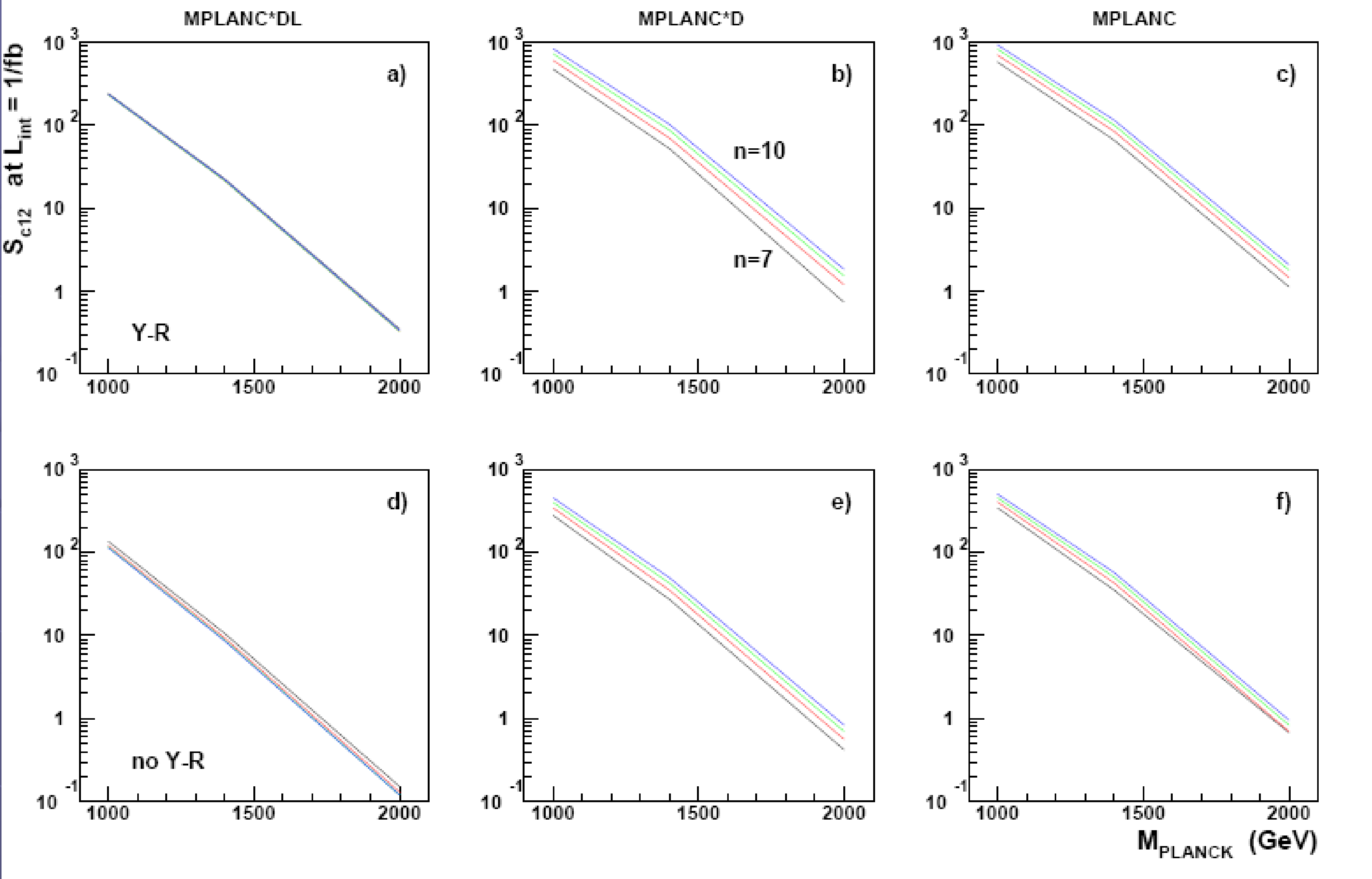
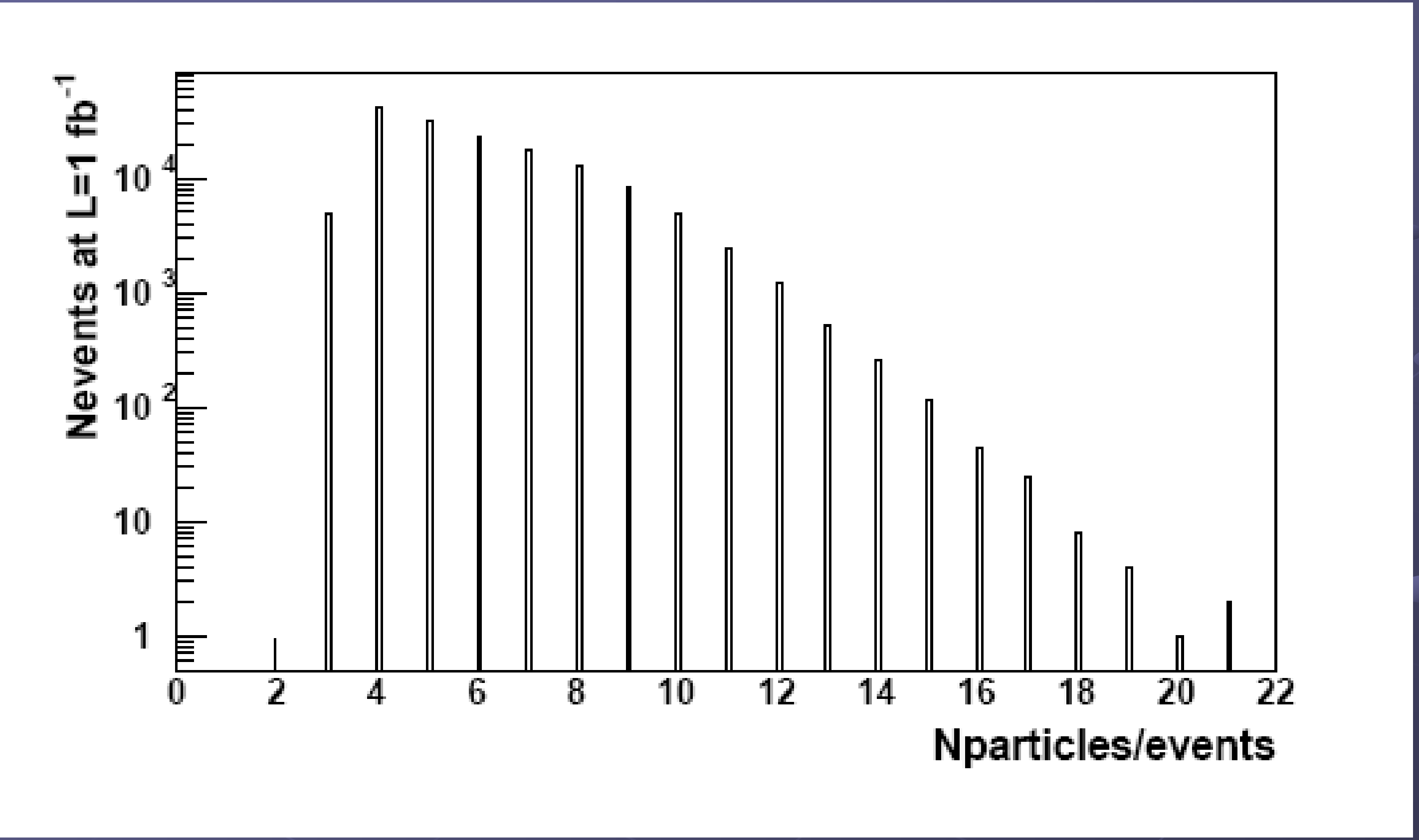
Charybdis2: S_{12} vs Planck mass, for different M def.



M. Savina, V. Konoplianikov '2010

Charybdis2: number of partons in BH events



Resume (not hard and final, because too many calculations and theoretical Investigation are waiting to be done in this field)

- Black Holes is not a such spectacular signature as commonly advertized earlier (from the very first papers in 1998).
- Likely the LHC will not be able to observe classical thermal BH decays.
- Careful counting pushes the minimal value of BH mass to higher energies what make observation of BH hopeless at the LHC
  (important moment: there are alternative point of views on this problem, not just one possible).
- In any case for TeV scale gravity near the threshold we will see signatures of QG (if one of them are realized by Nature).
- We can’t calculate its and make quantitative prediction. But these signatures can be distinguished from other possible new physics (by high transversality for final states).