

Title: Phenomenology of black holes in particle colliders and cosmic ray showers

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Abstract: If large extra dimensions exist, microscopic black holes may be created in TeV particle colliders and in Earth's atmosphere by the collisions of ultrahigh-energy cosmic rays with atmospheric nuclei. The decay of these black holes could soon be observed at the Large Hadron Collider or the Pierre Auger Observatory. Monte Carlo codes have been developed to simulate these events. In this talk I will introduce two of these codes (CATFISH for the LHC and GROKE for the PAO), and discuss how mini black holes can be distinguished from standard model or susy events.



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# **Phenomenology of black holes in particle colliders and cosmic ray showers**

**Marco Cavaglià**

*University of Mississippi*



# Braneworlds

(Arkani-Hamed, Dimopoulos & Dvali 1998; 1999; Antoniadis, Arkani-Hamed & Dvali 1998)

- ◆ The space time is  $D$ -dimensional ( $D>4$ )
- ◆ SM fields are confined on a 3-brane in a higher-dimensional space time
- ◆ Only gravity propagates in the  $n=D-4$  extra dimensions





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# Fundamental scale of gravity may be at the TeV scale

## Perturbative effects (Energy $\lesssim M_D$ )

(Giudice et al. 1998; Mirabelli et al. 1998; Han et al. 1998; Hewett 1999)

- ◆ Kaluza-Klein modes
- ◆ Graviton production
- ◆ ...

## Nonperturbative effects (Energy $\gtrsim M_D$ )

(Banks & Fischler 1999; Amati et al. 1987)



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# Micro-black hole formation

(Giddings & Thomas 2001; Landsberg & Dimopoulos 2001)

- ◆ Scattering of two particles with c.o.m.  $E \gtrsim \text{TeV}$  scale and impact parameter  $\lesssim \text{TeV}^{-1}$  forms a BH
- ◆ BH is unstable and decays → can be observed
- ◆ Decay signatures very distinctive
- ◆ Process may leave a remnant

(Koch, Bleicher & Hossenfelder 2005)



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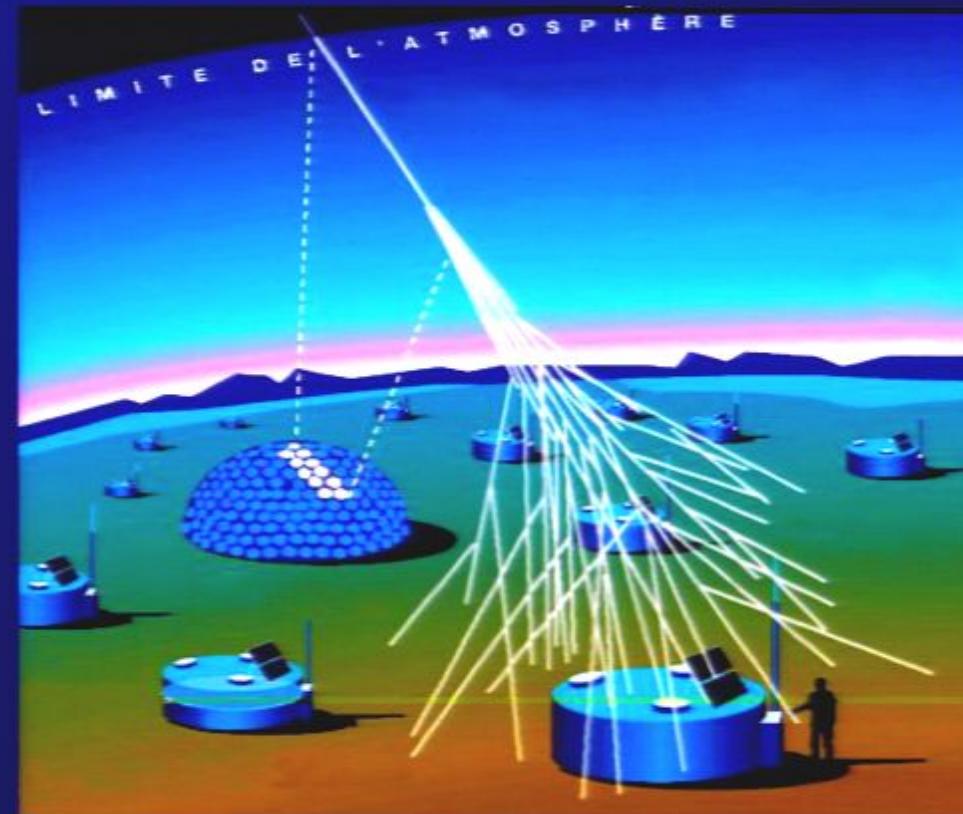
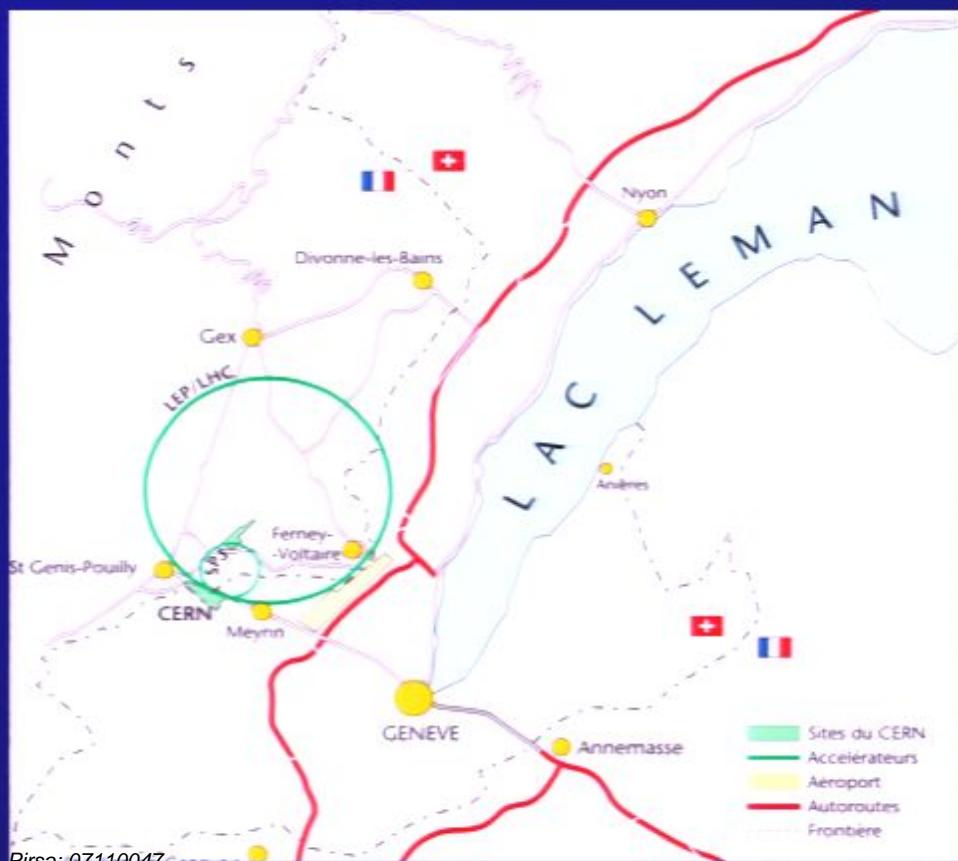
(Koch, Bleicher & Hossenfelder 2005)



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# How do we probe micro-BHs?

UHECRs: CM energy  $\sim 400$  TeV



LHC: CM energy = 14 TeV



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# Cross section rough estimate

(Landsberg & Dimopoulos 2001; Giddings & Thomas 2002)

$$\sigma_{bh}(s; n) \approx \pi r_s^2 \approx \frac{1}{s_D} \left[ \frac{2^n \pi^{\frac{n-3}{2}} \Gamma((n+3)/2)}{(2+n)} \right]^{\frac{2}{n+1}} \left( \frac{s}{s_D} \right)^{\frac{1}{n+1}}$$



Black disk

- ◆ Uncharged, non-rotating, spherically symmetric BH
- ◆ Cross section = black disk (semiclassical regime)
- ◆ Form factor = 1



# Experiments compared

- ◆ UHECR (neutrino-proton to BH):

$$\sigma_{\nu p \rightarrow bh}(s; n) \approx \sum_i \int_0^1 dx f_i(x, Q) \sigma_{bh}(xs; n)$$

- ◆ LHC (proton-proton to BH):

$$\sigma_{pp \rightarrow bh}(s; n) \approx \sum_{ij} \int_0^1 dx \int_x^1 \frac{dy}{y} f_i(y, Q) f_j(x/y, Q) \sigma_{bh}(xs; n)$$

- ◆ Lepton collider (eg, muon-muon to BH):

$$\sigma_{\mu\mu \rightarrow bh}(s; n) \approx \sigma_{bh}(s; n)$$



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# Phenomenology

(Giddings & Thomas 2002)

- ◆ Very large and steep cross section
- ◆ Visible transverse energy / High sphericity events
- ◆ High multiplicity events (hadronic jets + leptons  
+ hard quanta at the end of decay)
- ◆ Ratio of hadronic to leptonic activity  $\sim 5:1$
- ◆ Large missing energy
- ◆ Suppression of hard perturbative scattering processes

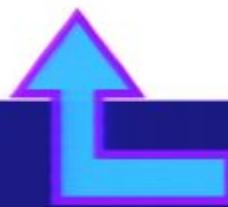


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# Uncertainties

- ◆ Collisional energy loss / inelasticity effects
- ◆ Minimal BH formation mass
- ◆ Rotation, recoil?
- ◆ Charge effects, QCD effects
- ◆ Hawking phase, greybody factors
- ◆ Quantum gravity effects, thermal fluctuations



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# Inelasticity

(Yoshino & Nambu, 2003, Yoshino & Rychkov 2005, Cardoso, Berti & Cavaglià, 2005)

$$\sigma_{vp \rightarrow bh}(s; n) \approx \sum_i \int_0^1 2z dz \int_{x'_{\min}}^1 dx f_i(x, Q) \sigma_{bh}(xs; n)$$

$$x'_{\min} = x_{\min} / y(z)^2 \quad \text{Fraction of trapped energy}$$

$$\sigma_{bh}(s; n) = F(n) \frac{1}{s_D} \left[ \frac{2^n \pi^{\frac{n-3}{2}} \Gamma((n+3)/2)}{(2+n)} \right]^{\frac{2}{n+1}} \left( \frac{s}{s_D} \right)^{\frac{1}{n+1}}$$

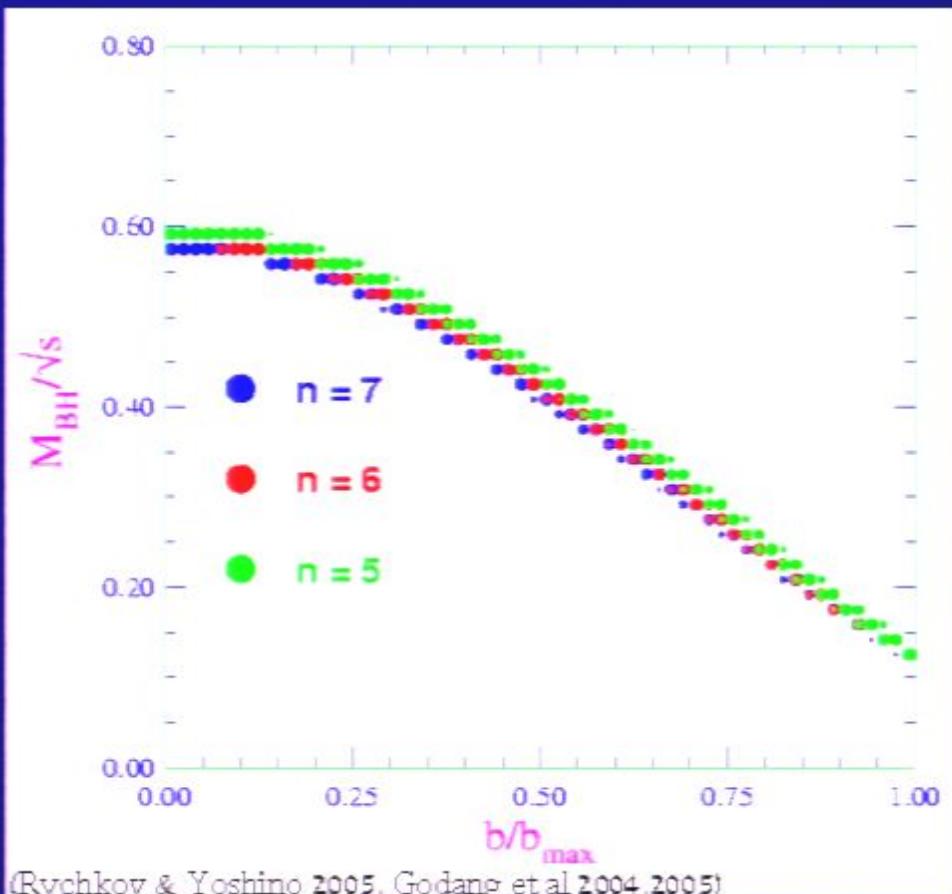


Form factor

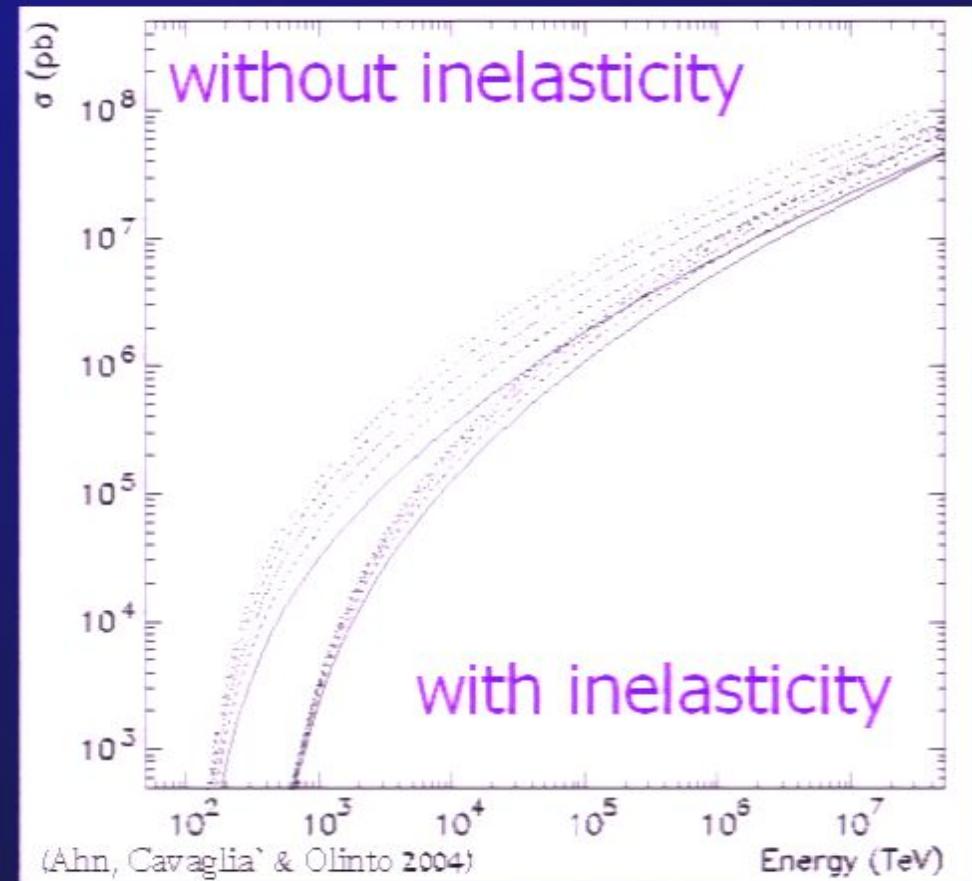


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# Gravitational loss effects



(Rychkov & Yoshino 2005, Godang et al 2004, 2005)



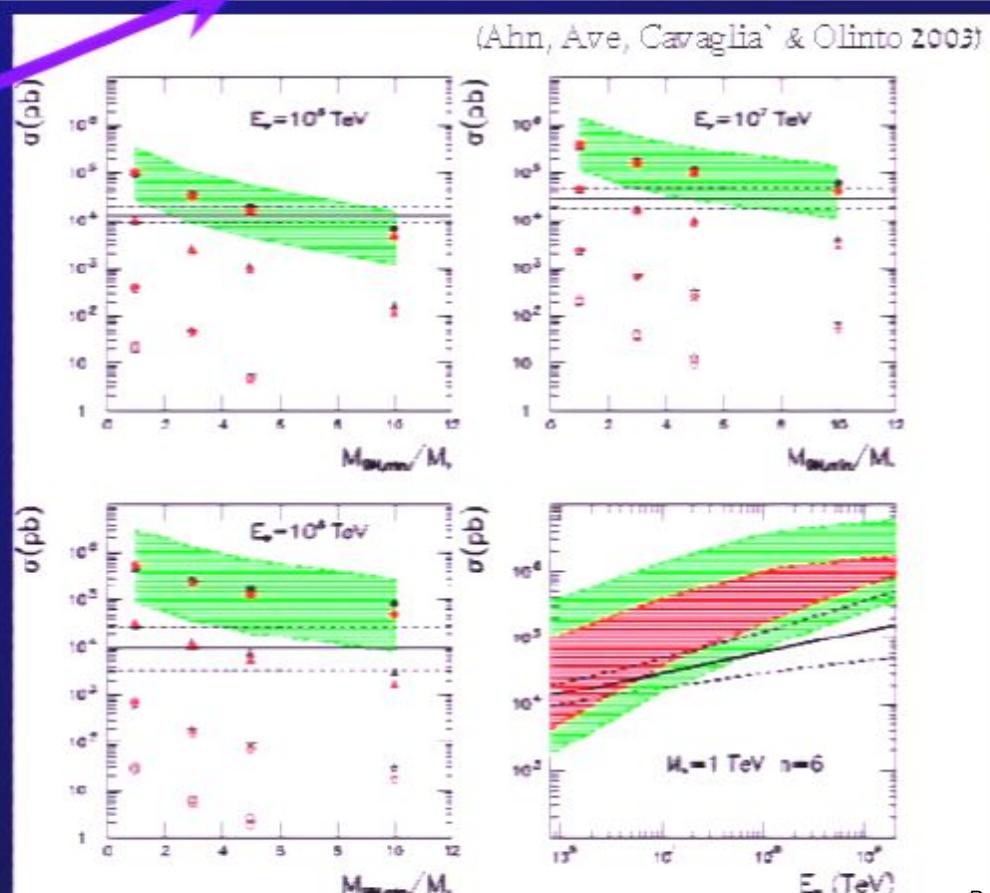
(Ahn, Cavaglia\* & Olinto 2004)



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# Minimal BH formation mass

$$\sigma_{\nu p \rightarrow bh}(x_m, s; n) \approx \sum_i \int_0^1 2z dz \int_{x_{\min}}^1 dx f_i(x, Q) \sigma_{bh}(xs; n)$$





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# Greybody factors & multiplicity

(Cavaglia` 2003, Cardoso, Cavaglia` & Gualtieri 2006a, 2006b)

$$N = \frac{(n+1)S}{4\pi} \frac{\sum_i c_i R_i \Gamma_{R_i}}{\sum_j c_j P_j \Gamma_{P_j}}$$

↓ Degrees of freedom

← Greybody (number emissivity)

$$N_i = N \frac{c_i R_i \Gamma_{R_i}}{\sum_j c_j R_j \Gamma_{R_j}}$$

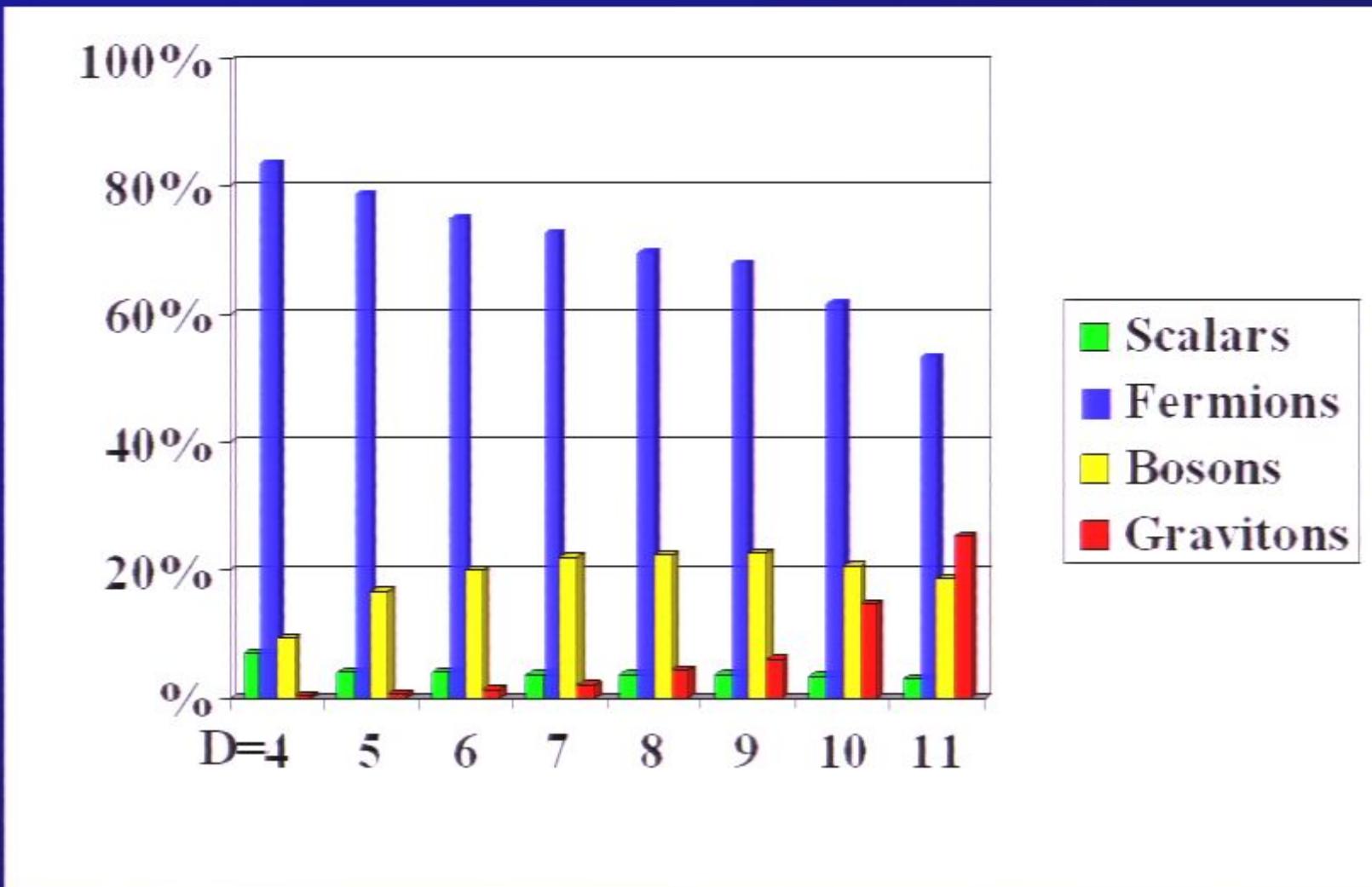
↑ Greybody (power emissivity)

Do BHs really decay on the brane?



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# Minimal Standard Model



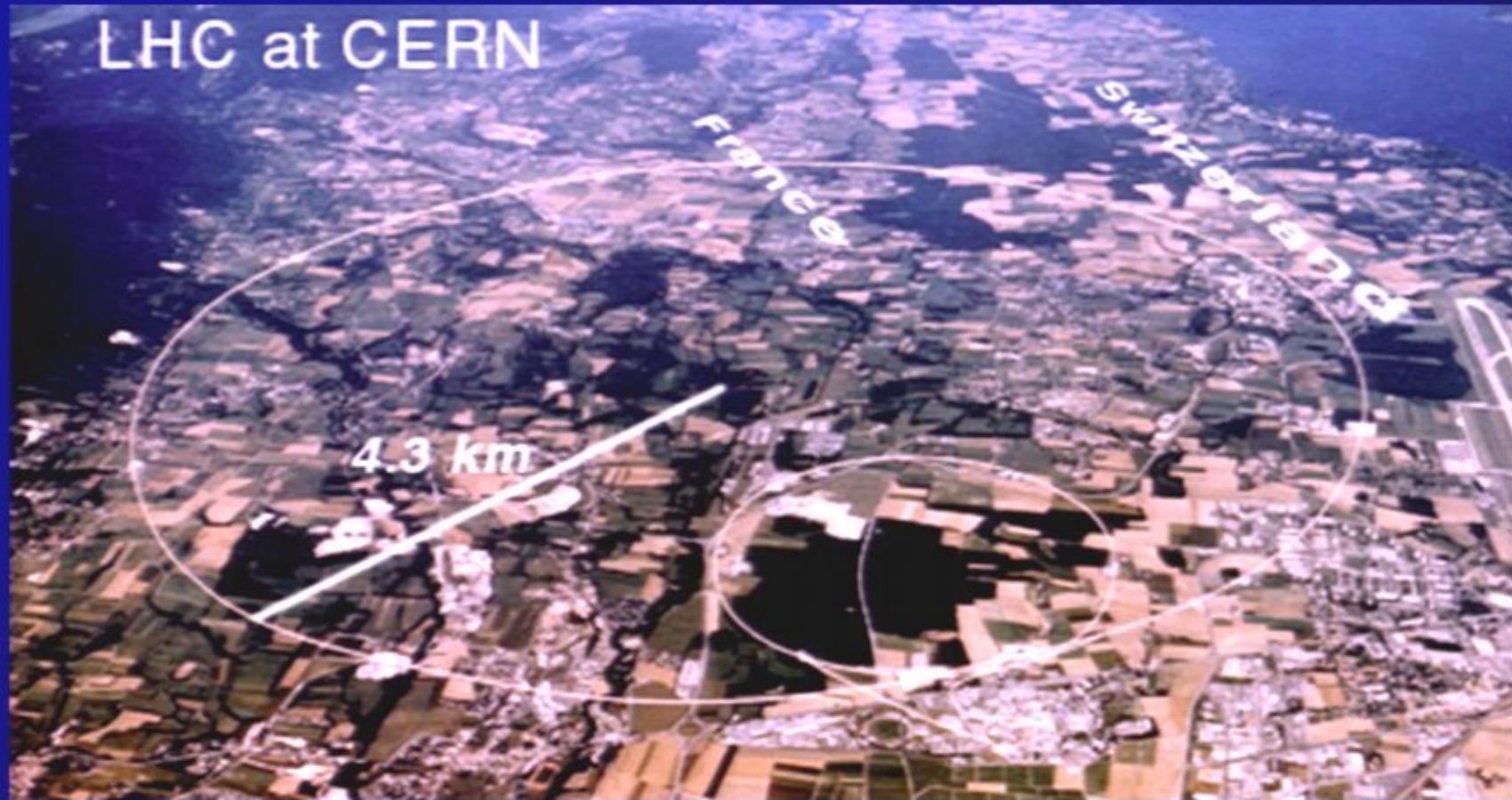


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# Gravity at the LHC



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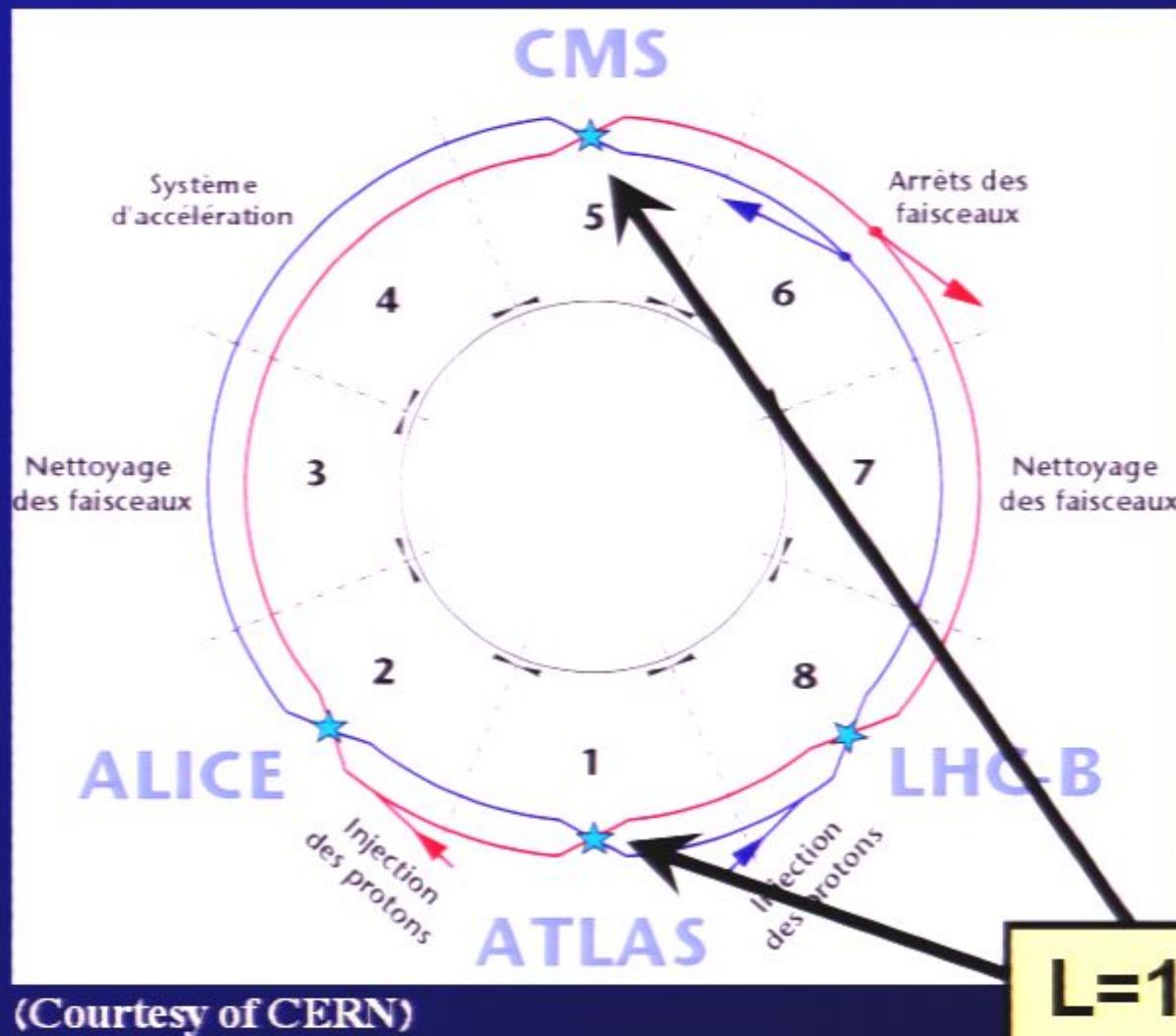
(Courtesy of CERN)

(End of commissioning: 2008)



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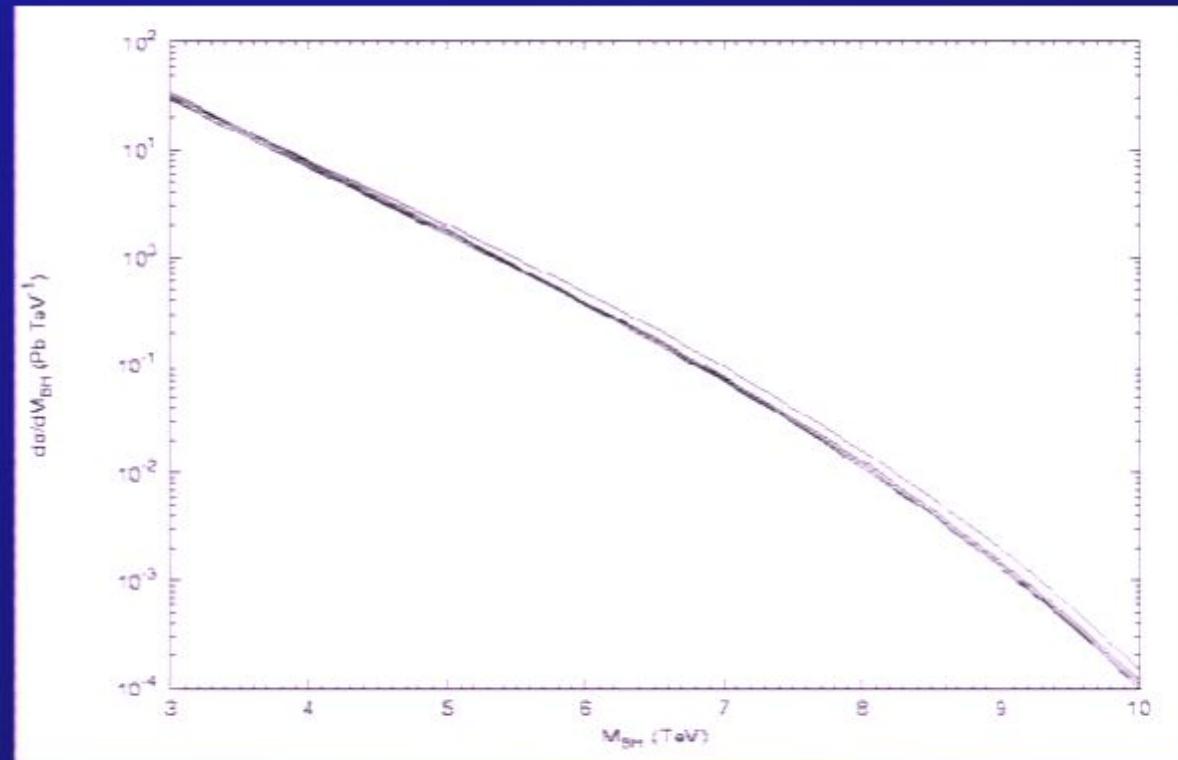
# LHC Collision points





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# Differential cross section

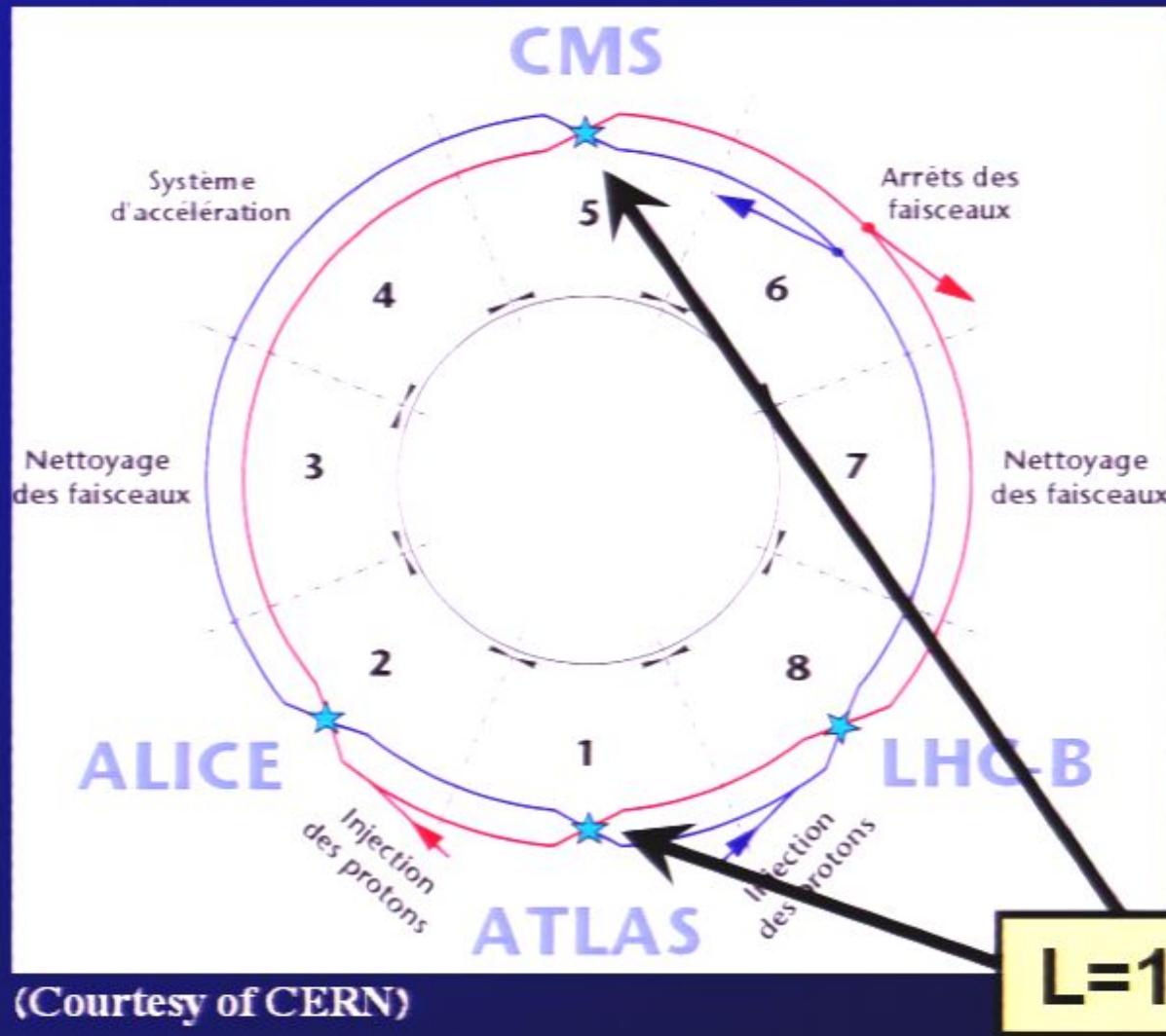


$$\frac{d\sigma_{pp \rightarrow bh}(x, s; n)}{dM_{BH}} \approx \int_x^1 \frac{dy}{y} f_i(y, Q) f_i(x/y, Q) \sigma_{bh}(xs; n)$$



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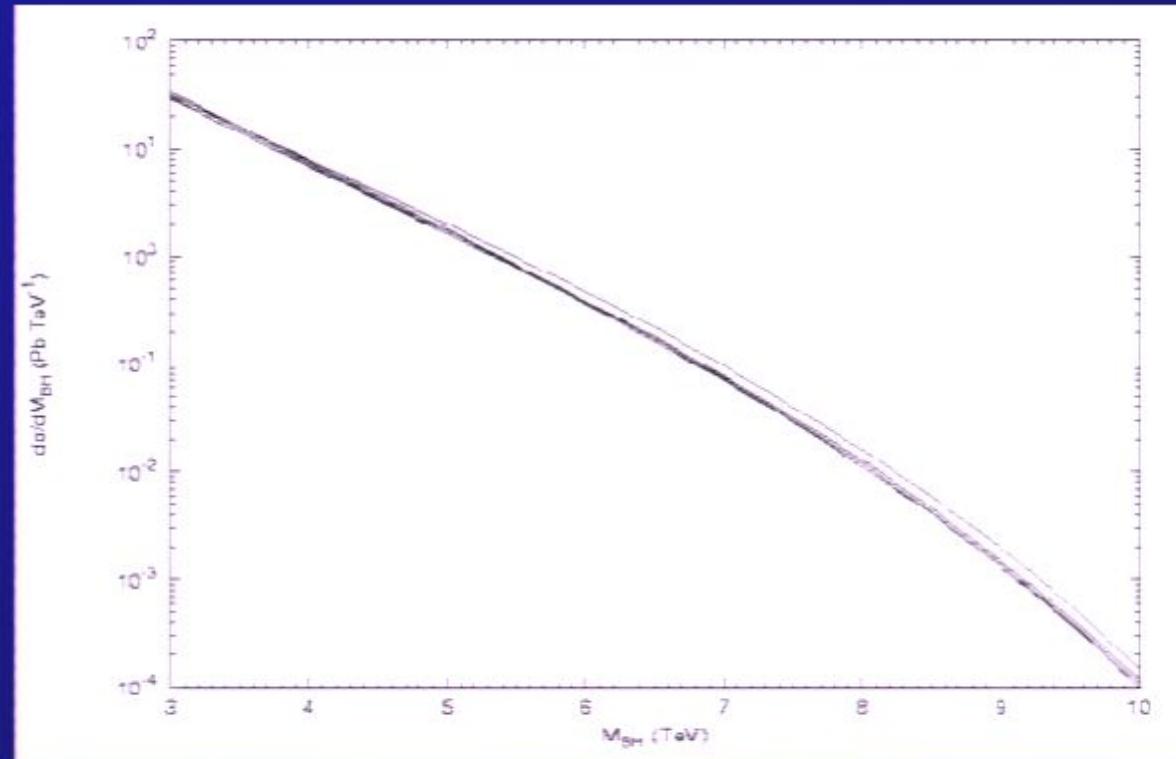
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# Differential cross section



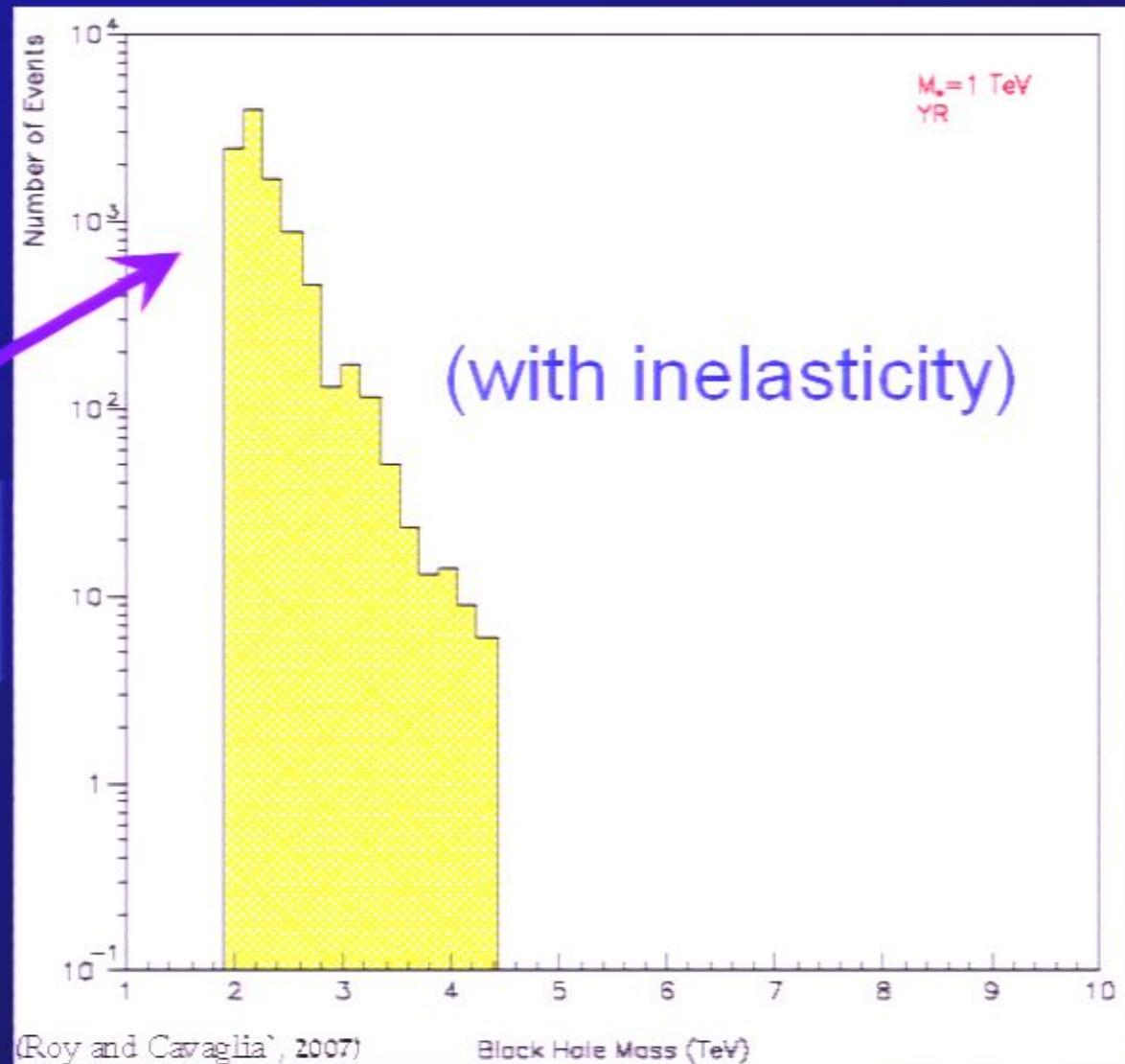
$$\frac{d\sigma_{pp \rightarrow bh}(x, s; n)}{dM_{BH}} \approx \int_x^1 \frac{dy}{y} f_i(y, Q) f_i(x/y, Q) \sigma_{bh}(xs; n)$$



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# BH mass distribution

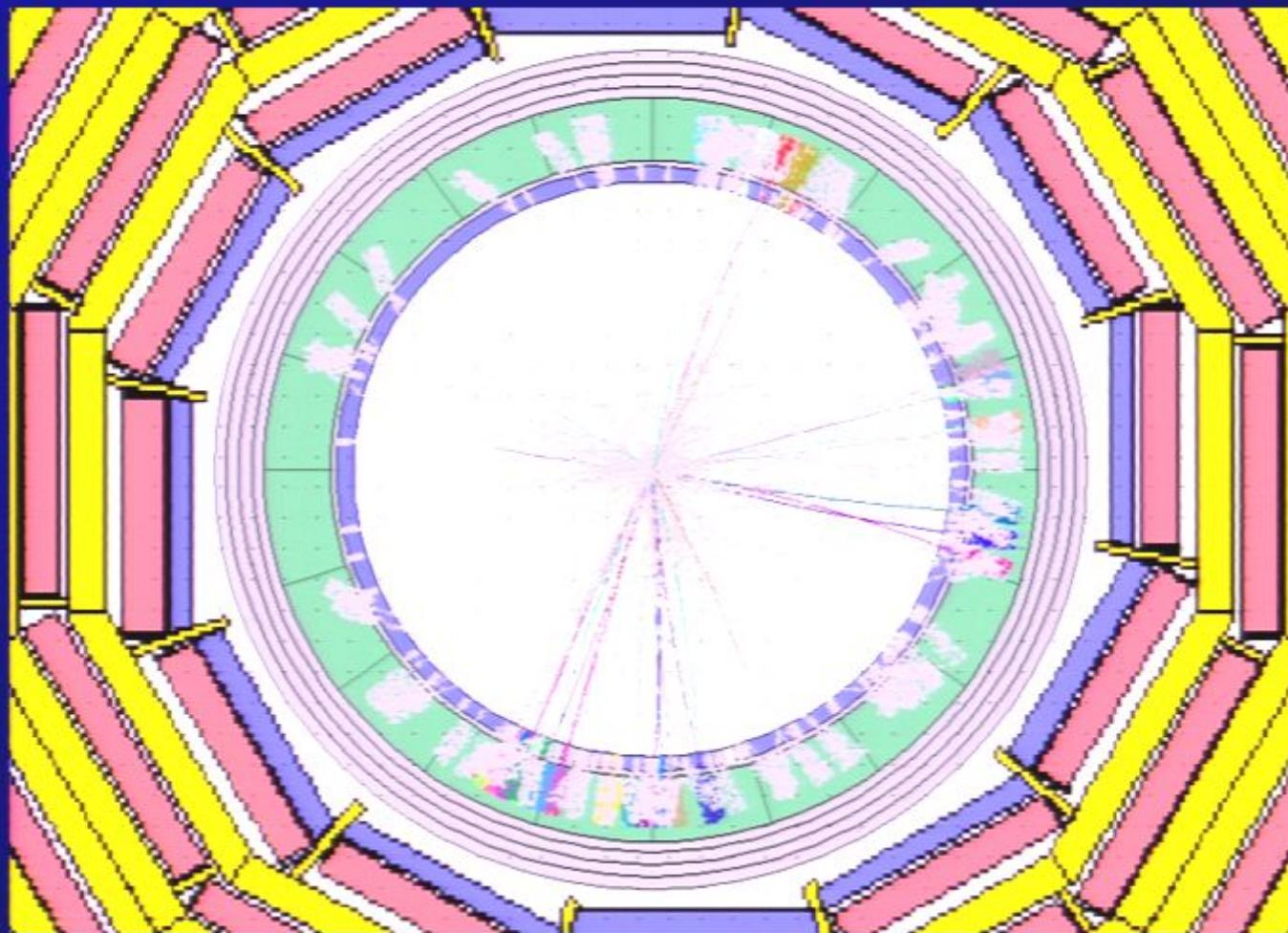
Min. mass  
cutoff





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# A simulated event



(Visualization by P. Sonnek)



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# Welcome to the Catfish website

You are visitor number: **1217**

(Background image courtesy of CERN)

Webmaster: [Marco Cavaglià](#)

Last Modified: Friday, 01-Sep-2006 10:55:05 CDT

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# CATFISH: Collider grAviTational Field Simulator for black Hole

- ◆ Mass of the BH = CM energy (14 TeV) - beam remnant - inelasticity
- ◆ Multiplicity with statistics, counting of d.o.f. and exact greybody factors
- ◆ Isotropic distribution of emitted quanta
- ◆ Final N-body decay when  $\sim M_D$  is reached
- ◆ Conservation of charge/momentum  
B/L not conserved
- ◆ Allows for spacetime minimum length/remnant





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# CATFISH output

	<b>p<sub>x</sub></b>	<b>p<sub>y</sub></b>	<b>p<sub>z</sub></b>	<b>E</b>
Graviton	-0.653E+02	-0.453E+03	-0.207E+03	0.502E+03
Graviton	0.639E+02	0.448E+03	0.208E+03	0.498E+03
p+	0.841E+00	0.659E+00	0.246E+04	0.246E+04
nbar0	-0.412E-02	-0.123E+00	0.248E+02	0.249E+02
n0	-0.295E+00	-0.528E+00	0.207E+02	0.207E+02
pi-	-0.214E+00	0.613E+00	0.114E+03	0.114E+03
pi-	-0.388E+00	-0.289E+00	-0.175E+00	0.533E+00
pi+	0.526E+00	0.904E+00	-0.153E+00	0.107E+01
K-	0.285E+00	-0.409E+00	-0.462E+01	0.468E+01
K-	-0.103E+01	0.519E+00	-0.526E+02	0.526E+02
pi+	0.231E+00	-0.563E-03	-0.505E+02	0.505E+02
pi-	0.679E+00	-0.362E+00	-0.222E+03	0.222E+03
pi+	-0.248E+00	0.360E+00	-0.798E+02	0.798E+02
pi-	-0.297E+00	-0.167E+00	-0.553E+03	0.553E+03
pi+	0.121E+01	0.133E+01	-0.735E+03	0.735E+03
n0	0.657E+00	0.867E+00	-0.213E+04	0.213E+04
pi-	-0.130E+00	0.404E+00	0.644E+00	0.783E+00
gamma	-0.254E+00	-0.752E-01	0.522E+00	0.586E+00
gamma	-0.336E+00	-0.806E-01	0.401E+00	0.529E+00
gamma	0.942E-02	0.245E-01	0.172E+00	0.174E+00
gamma	0.378E+00	0.573E+00	0.168E+01	0.182E+01
nbar0	-0.379E+00	-0.106E+00	0.612E+01	0.621E+01
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pi-	-0.599E-01	-0.250E+00	0.205E+01	0.207E+01
gamma	0.365E-01	-0.444E-01	0.284E+01	0.284E+01
gamma	-0.148E-01	0.833E-01	0.397E+01	0.397E+01



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# CATFISH output

BH

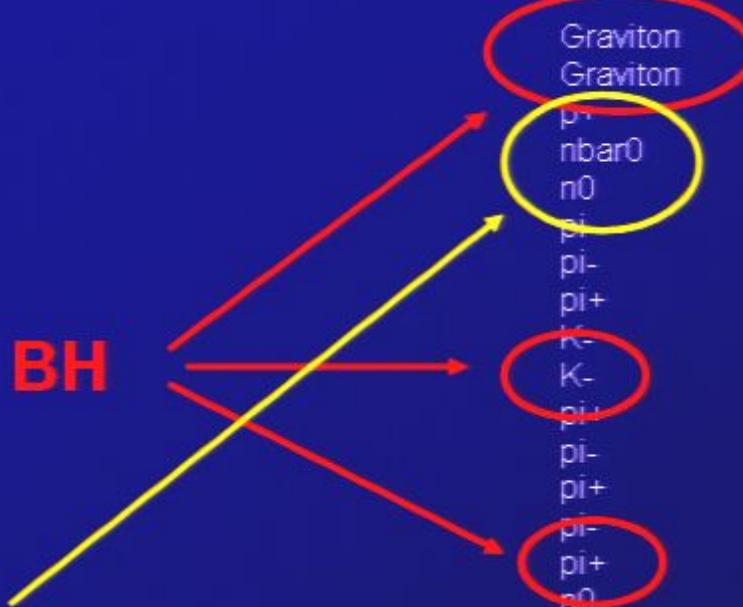
Graviton  
Graviton  
p+  
nbar0  
n0  
pi-  
pi-  
pi+  
K-  
K-  
pi+  
pi-  
pi+  
pi-  
pi+  
pi-  
n0  
pi-  
gamma  
gamma  
gamma  
gamma  
nbar0  
pi+  
gamma  
gamma  
pi-  
gamma  
gamma

	$p_x$	$p_y$	$p_z$	E
Graviton	-0.653E+02	-0.453E+03	-0.207E+03	0.502E+03
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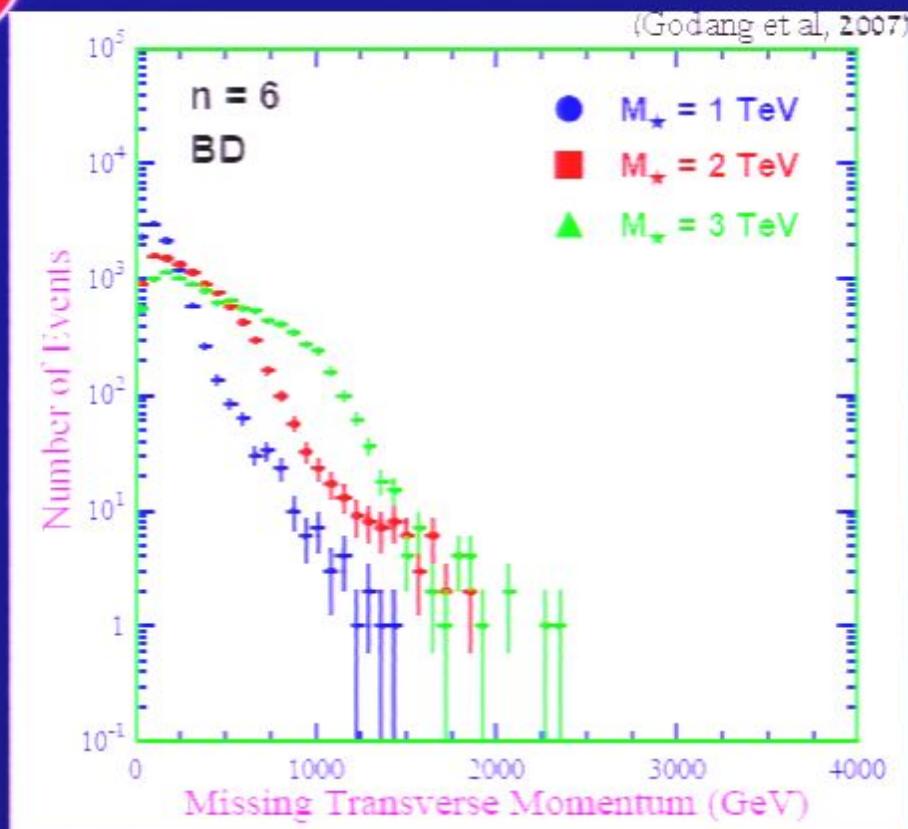
# CATFISH output



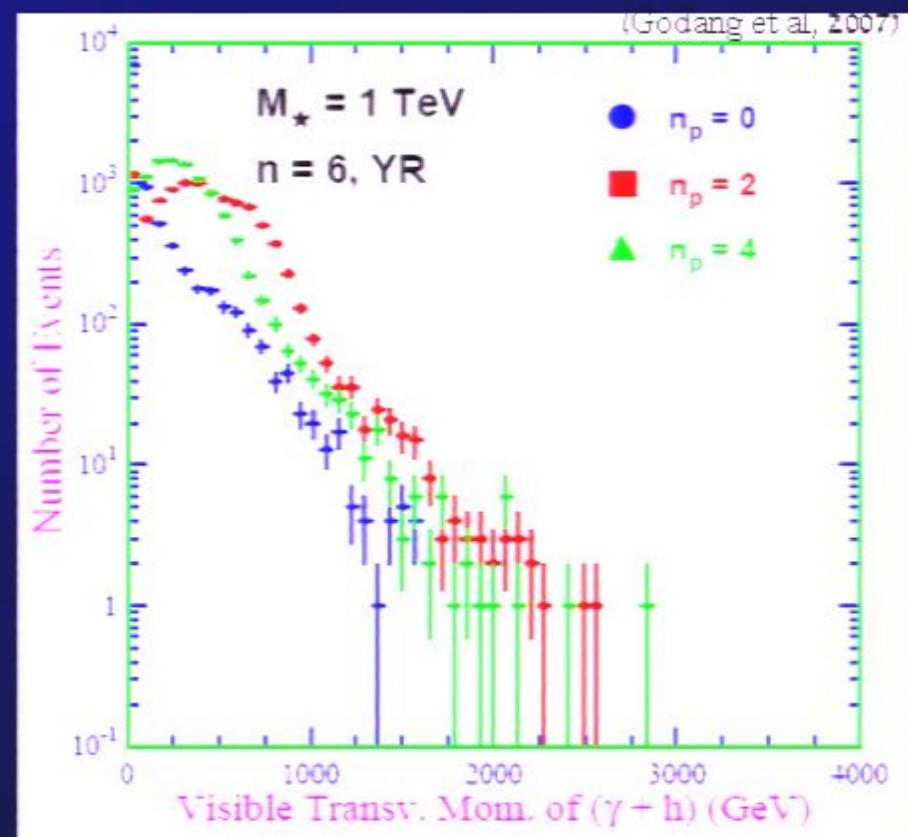
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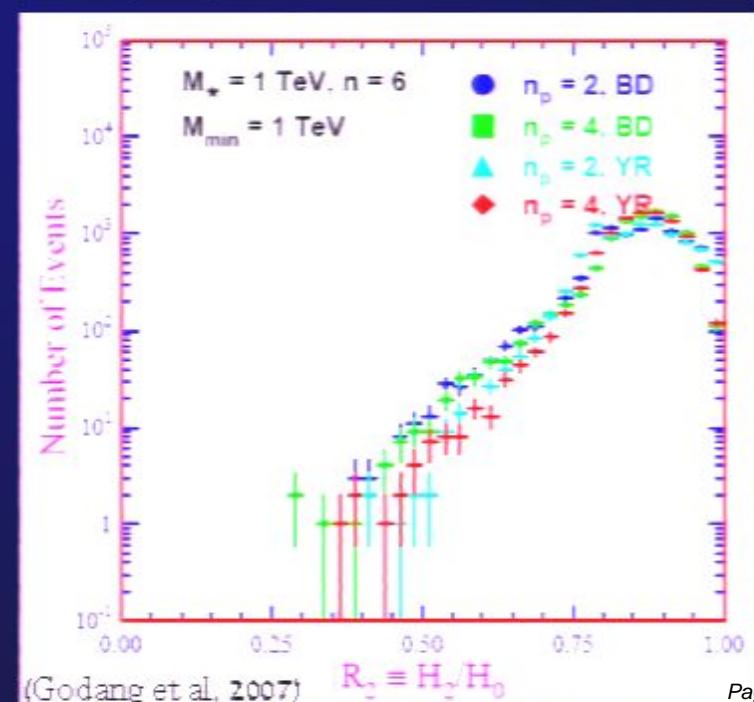
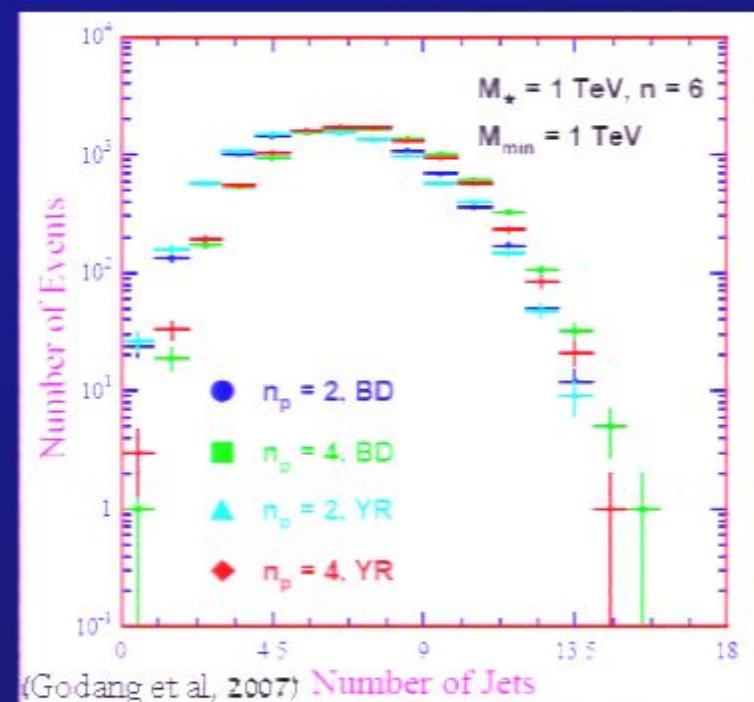
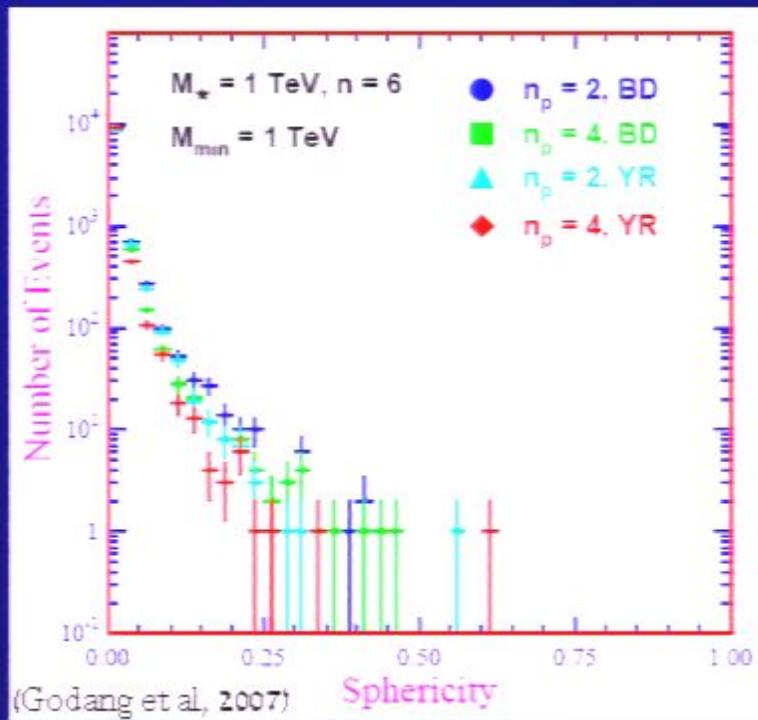
# Analysis



## Missing and visible transverse momentum



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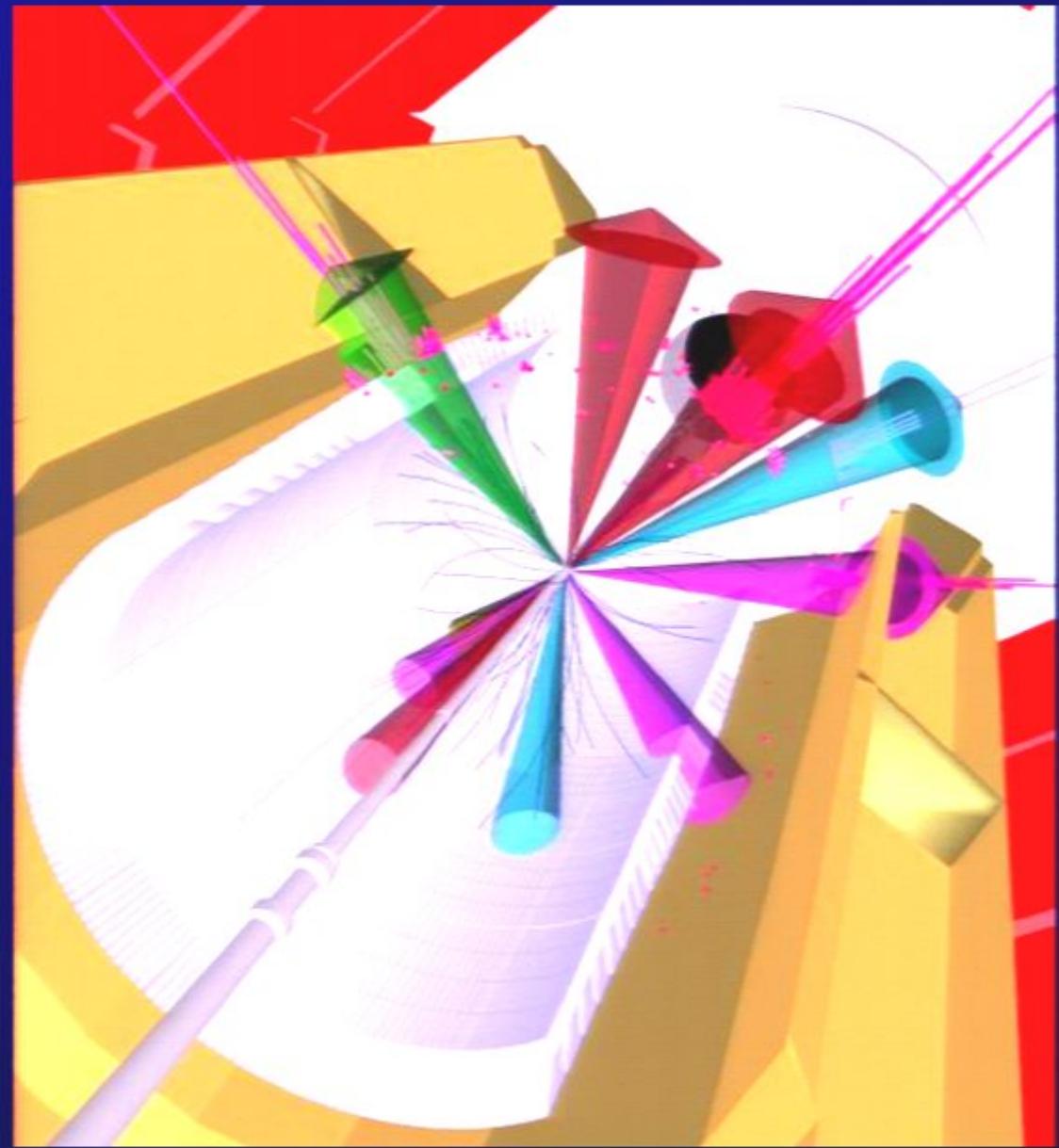
## Sphericity, jets and Fox-Wolfram moment



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# A lot of transverse momentum!

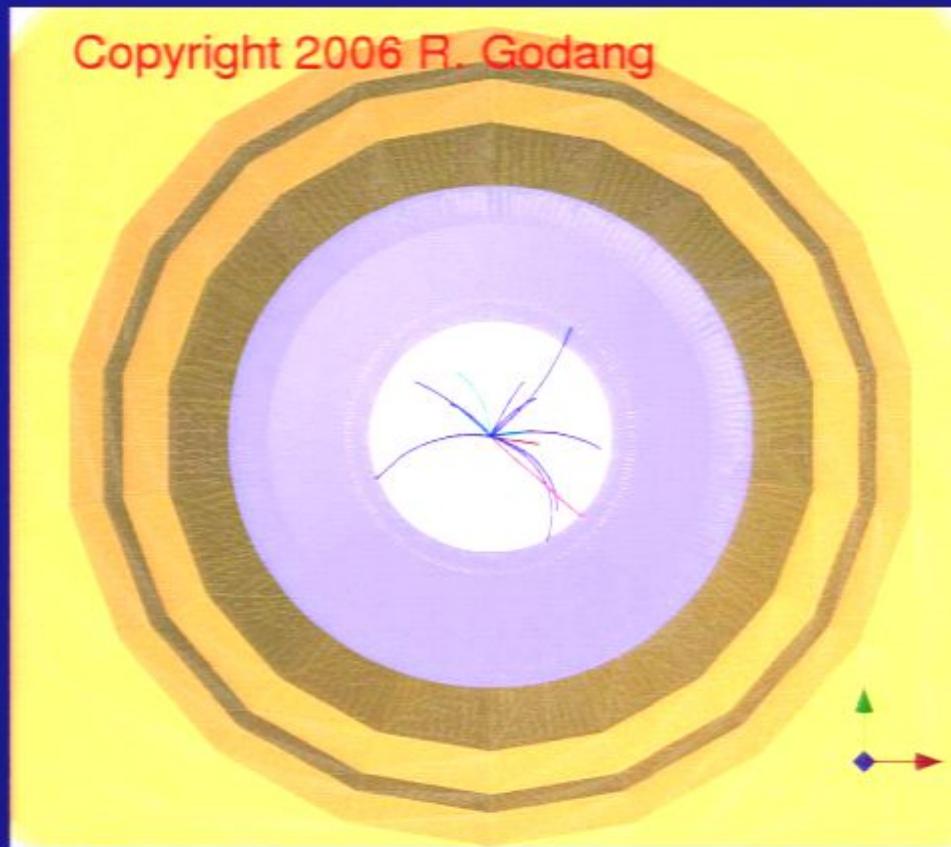
**Simulation based on  
CMS detector response  
using IGUANACMS**



(Visualization by R. Godang)

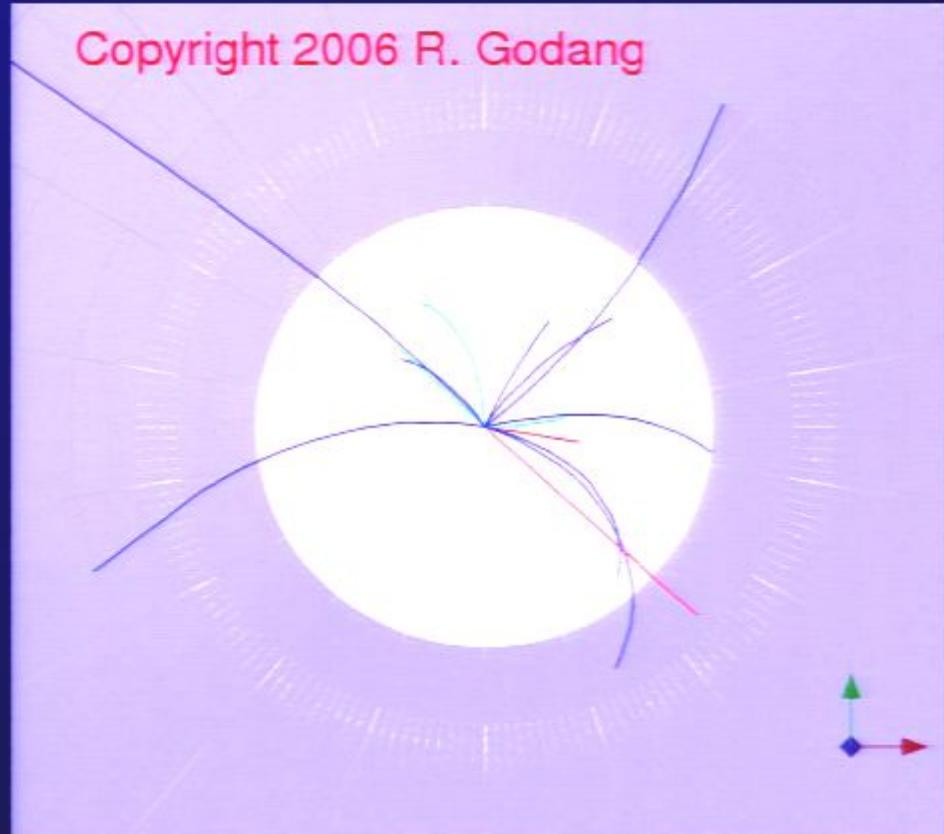


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**White: CMS tracker**  
**Blue: EM calorimeter**  
**Yellow: Hadron calorimeter**

## Simulation based on CMS detector response using IGUANACMS





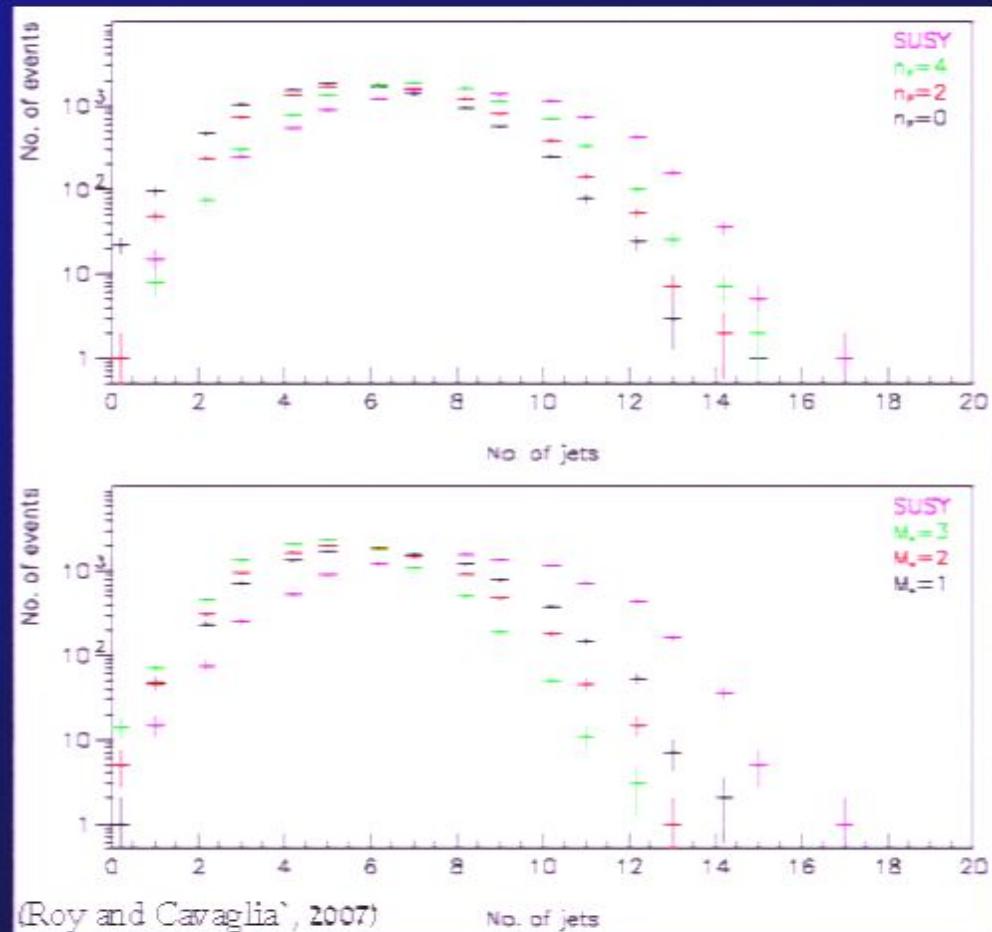
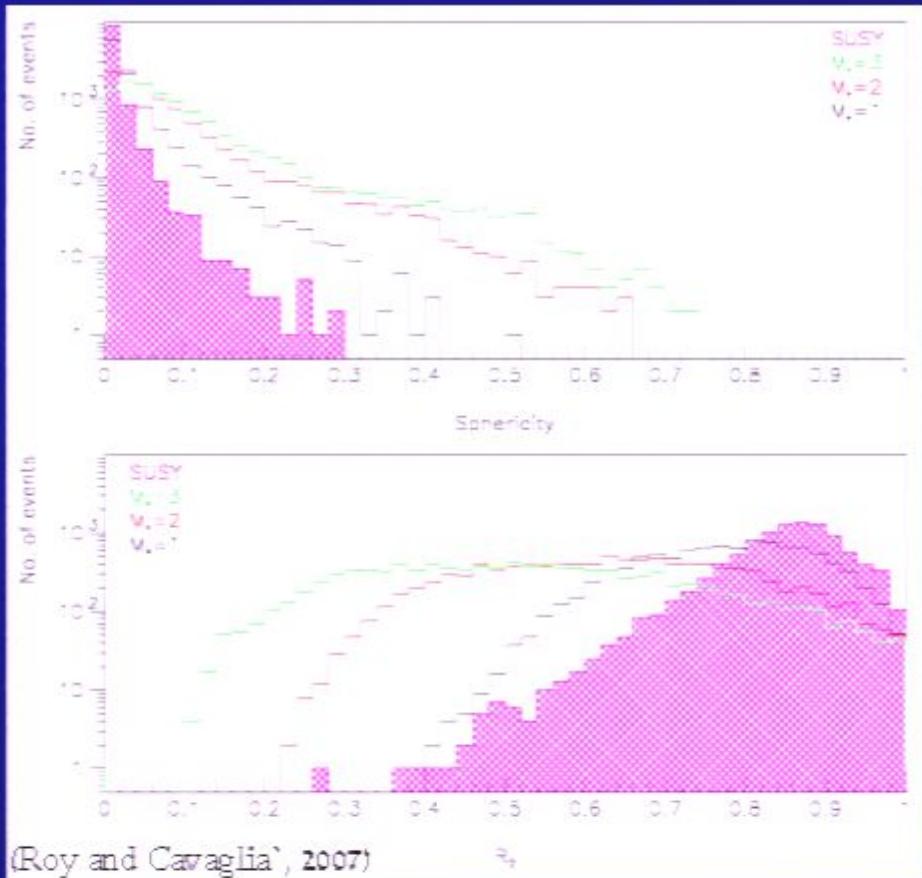
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# BHs versus SUSY



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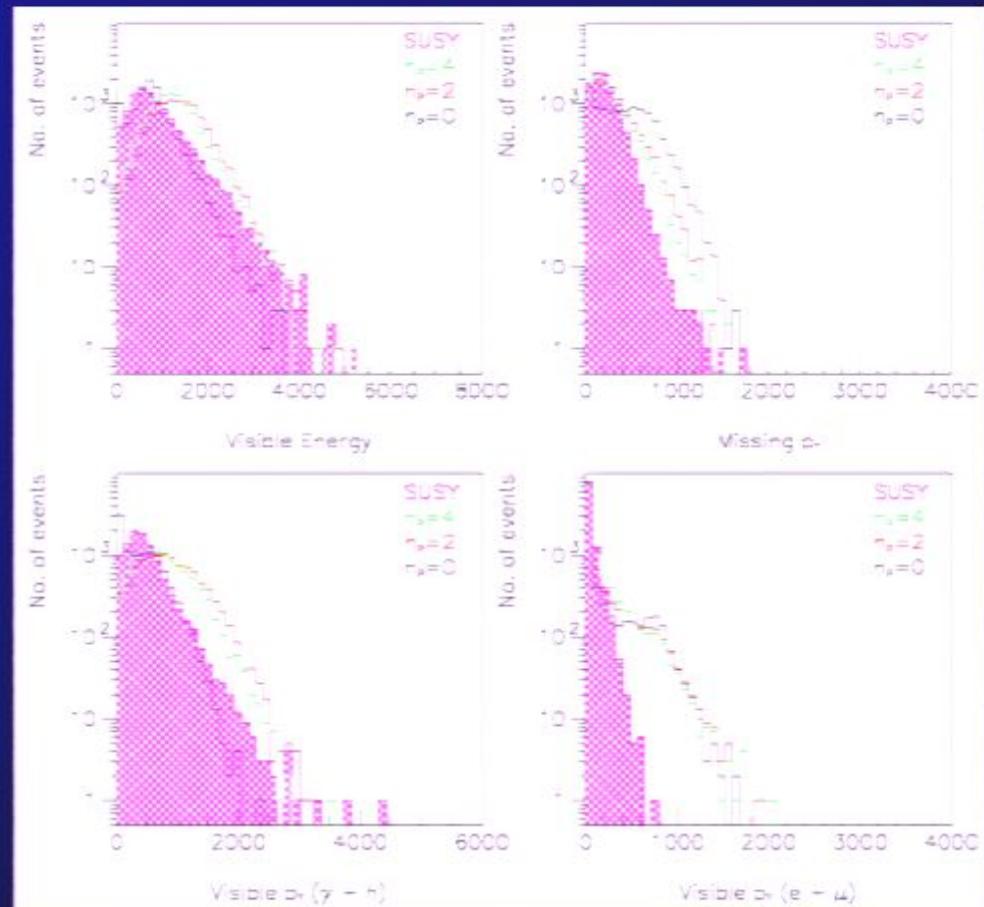
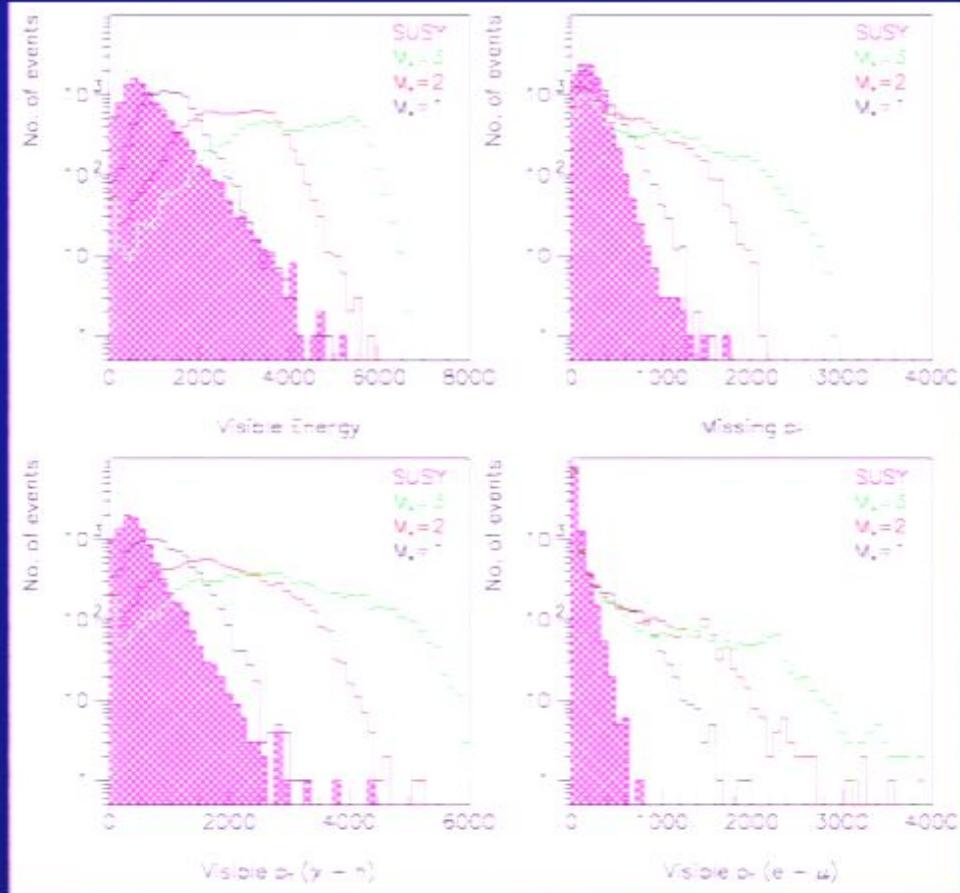
# Event-shape variables and jets





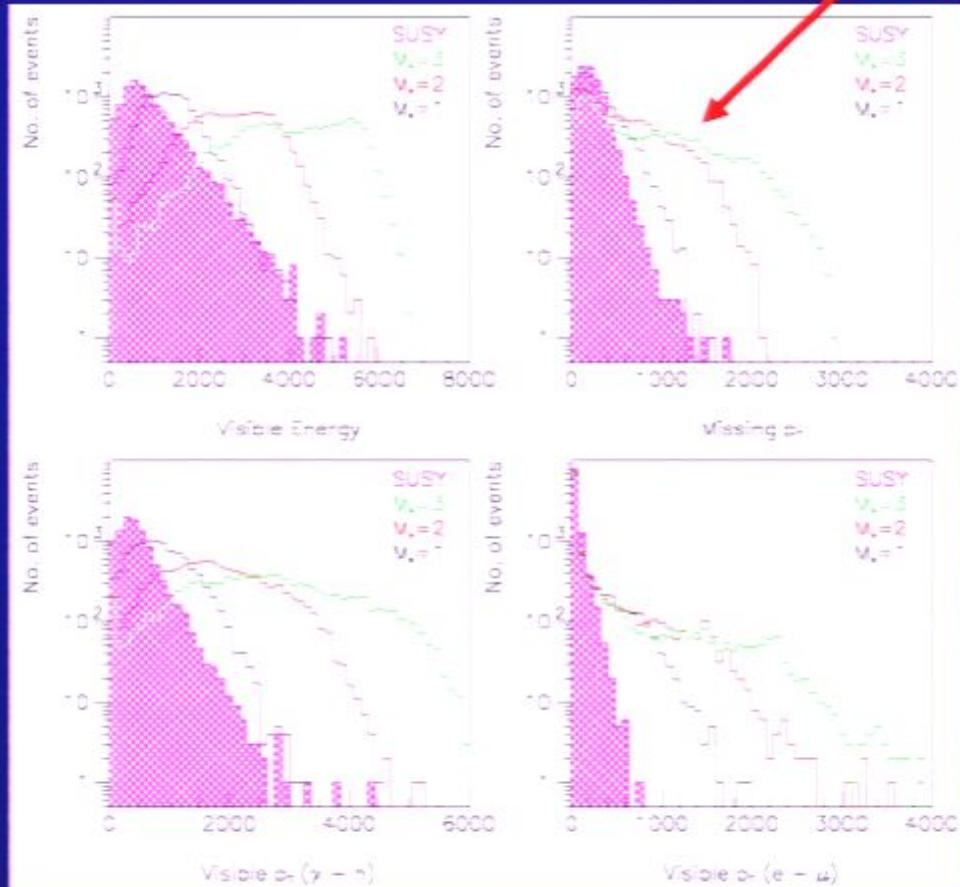
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# Missing energy and $P_T$

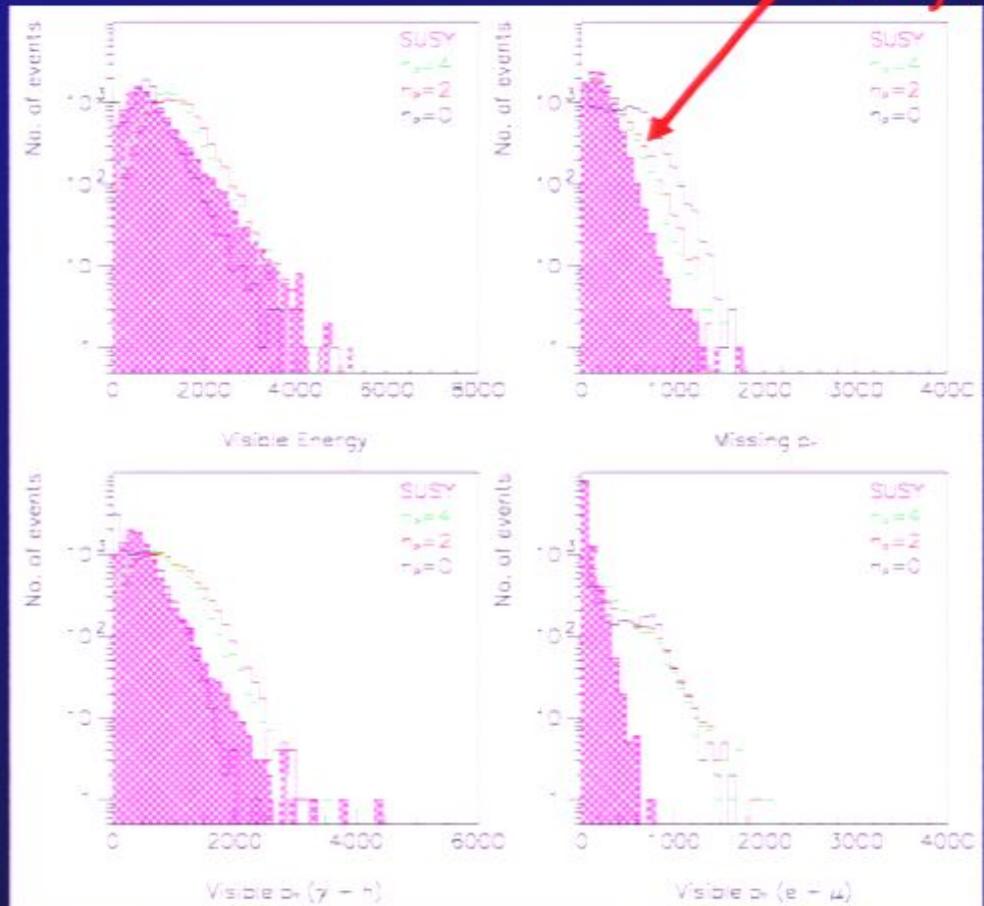




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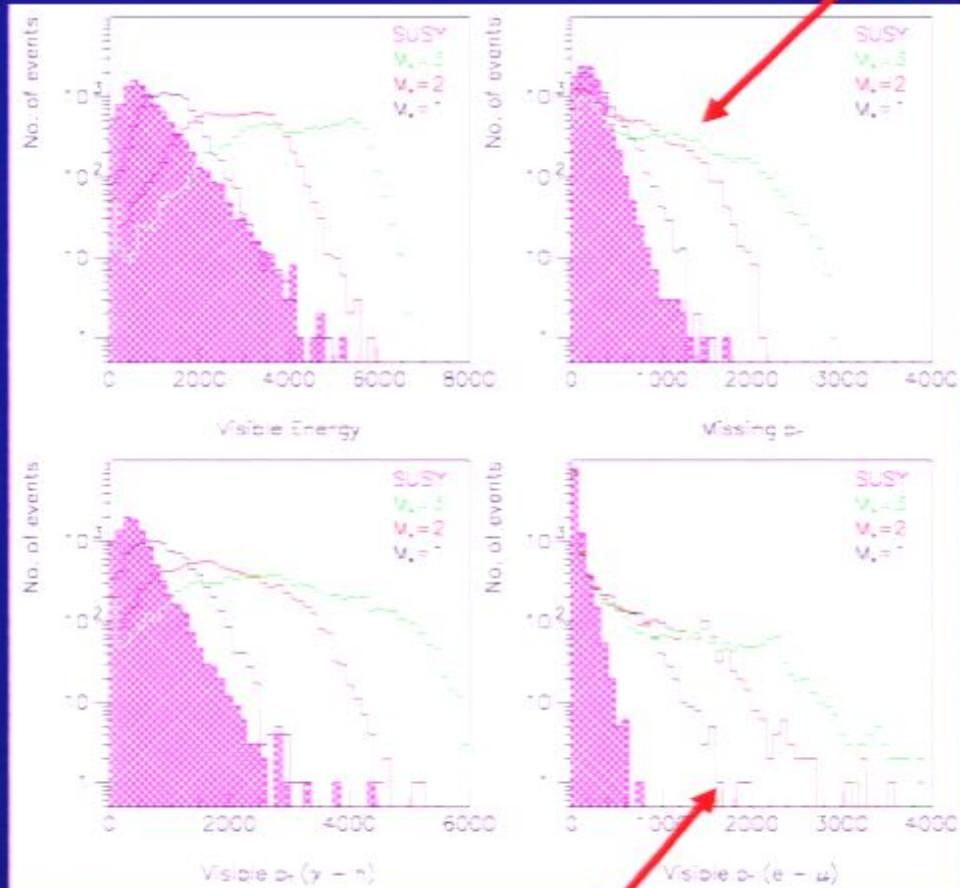


# Missing energy and $P_T$





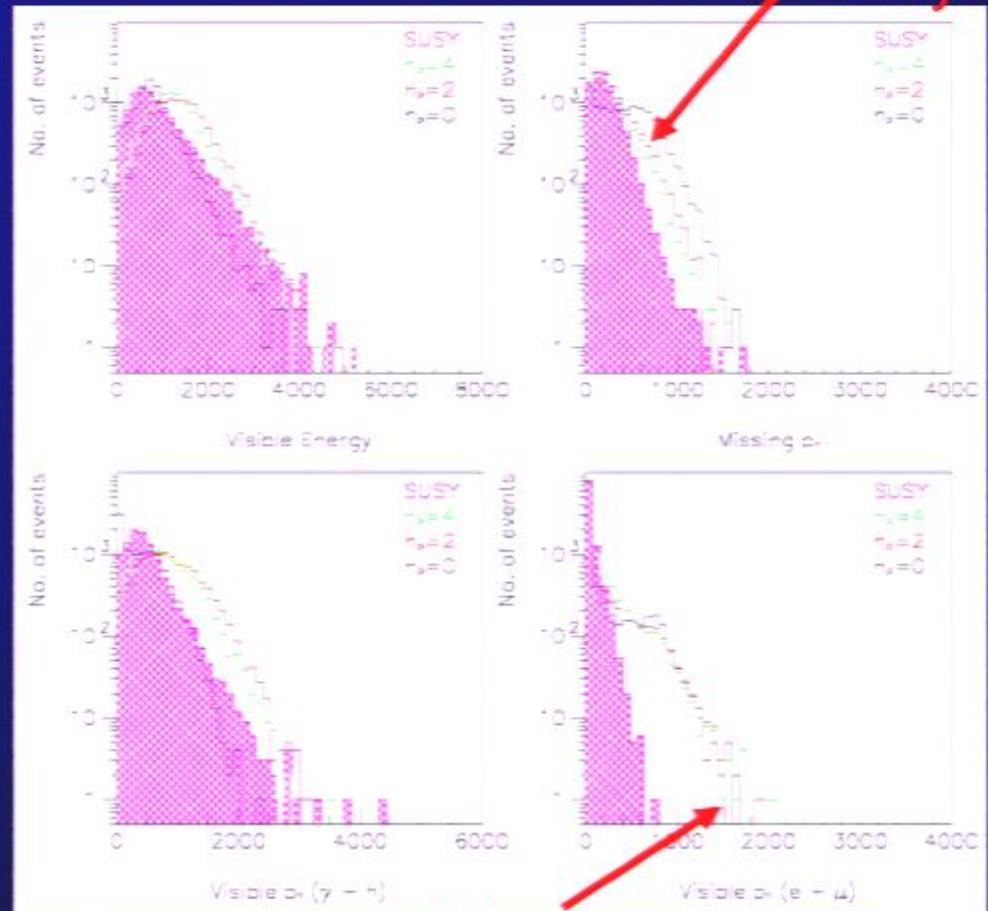
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very easy

# Missing energy and $P_T$

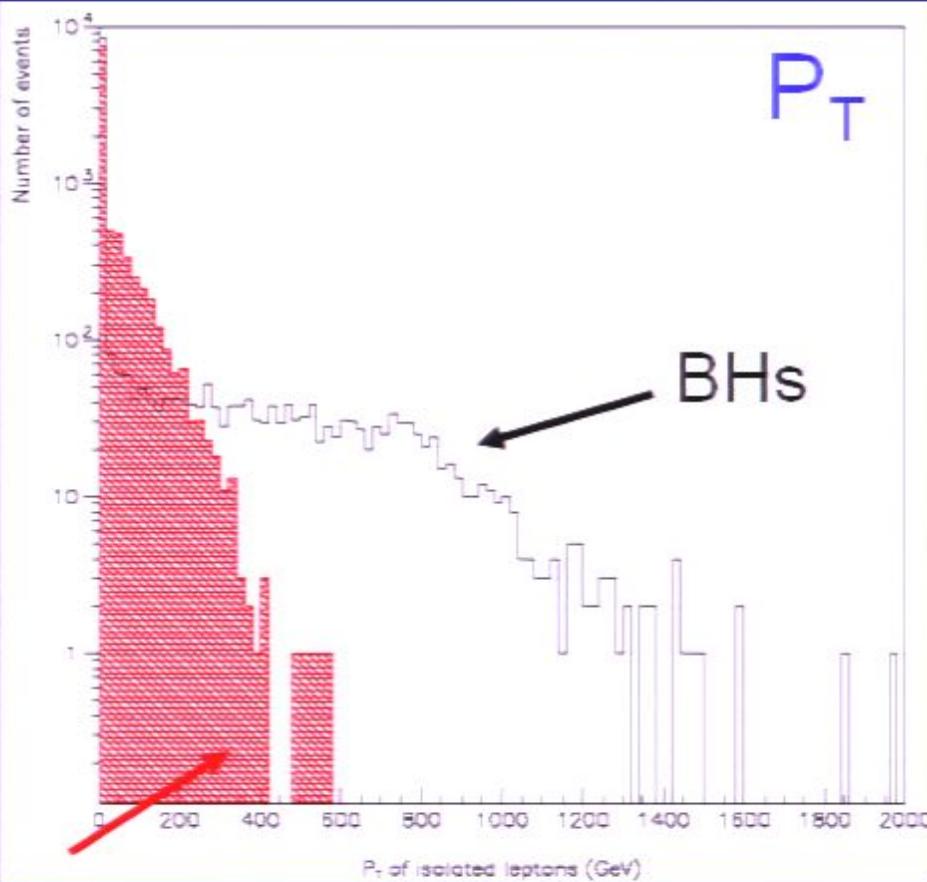
not so easy...



still easy...



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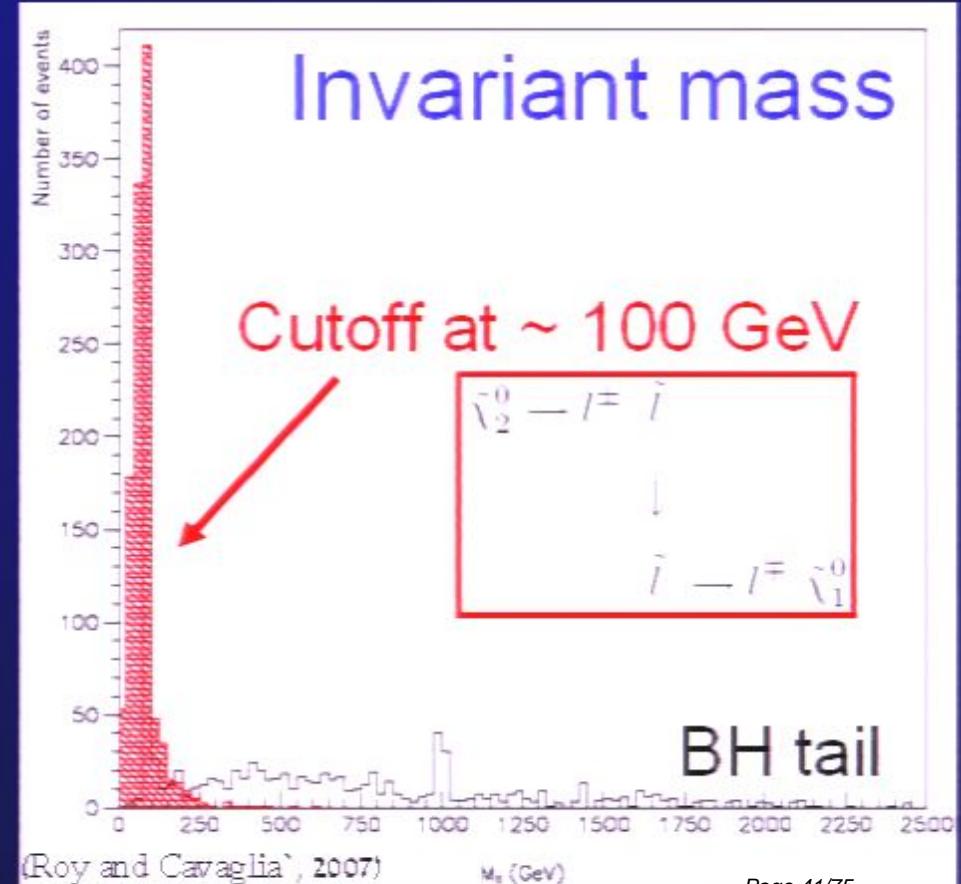


SUSY

- ◆  $P_T \geq 15 \text{ GeV}$
- ◆  $\eta_{||} < 2.5$
- ◆  $P_T < 7 \text{ GeV}$  in  $R = 0.2$

Pirsa: 07110047

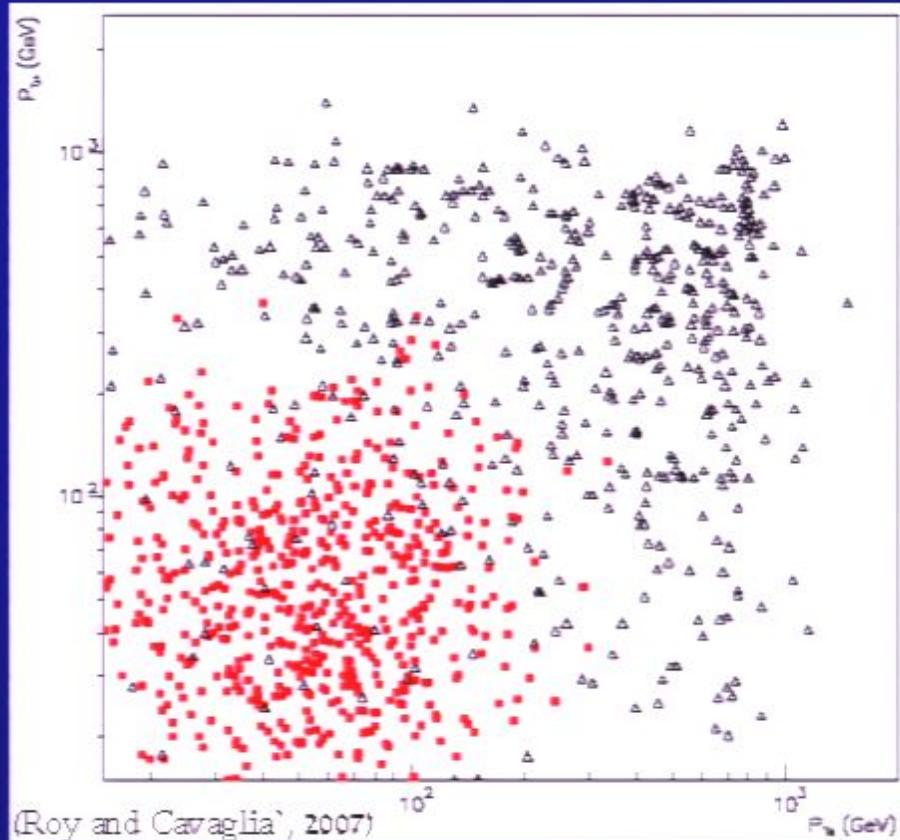
## Dilepton events



BH tail



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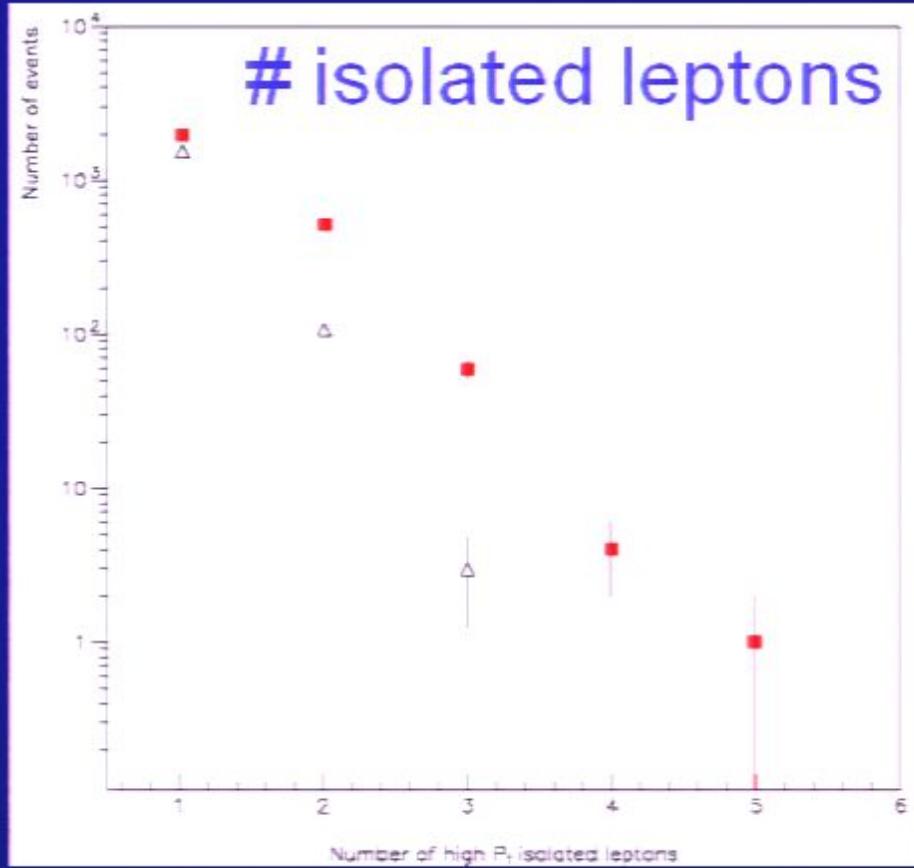


# Dilepton flavor and charge

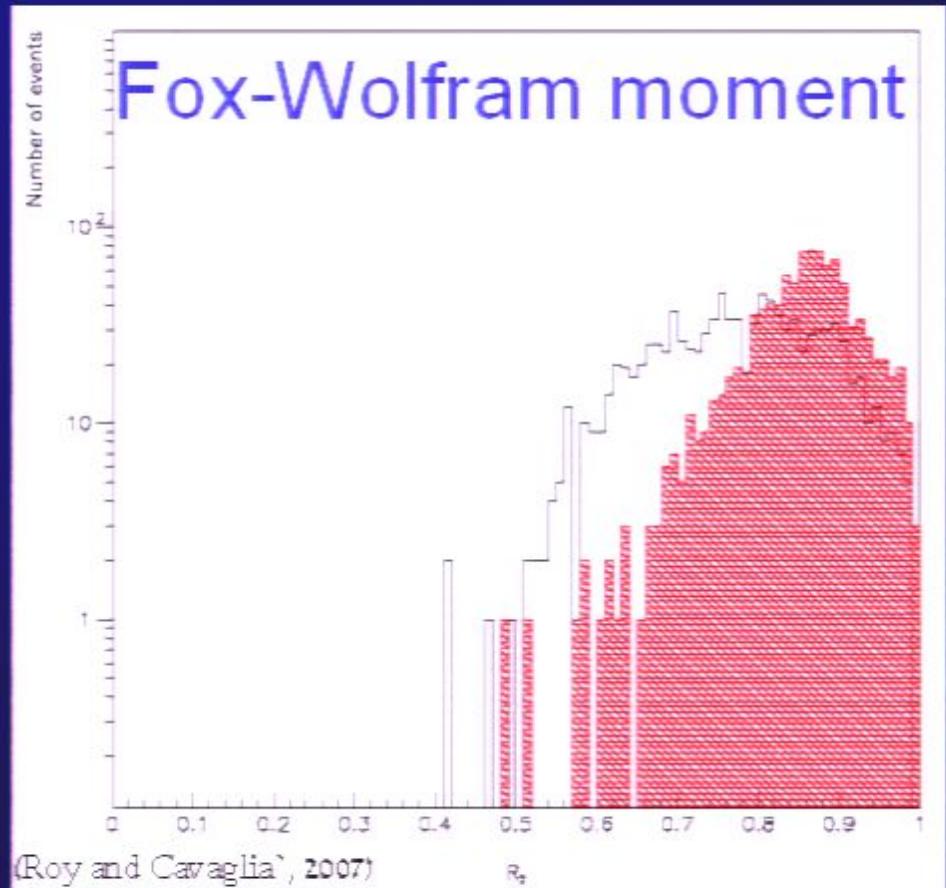
High $P_T$ isolated dileptons	SUSY %	BH %	
OSSF	768	73	523
SSSF	65	6	103
OSOF	169	16	341
SSOF	52	5	87



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## Multilepton events





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# Gravity at the Pierre Auger Observatory

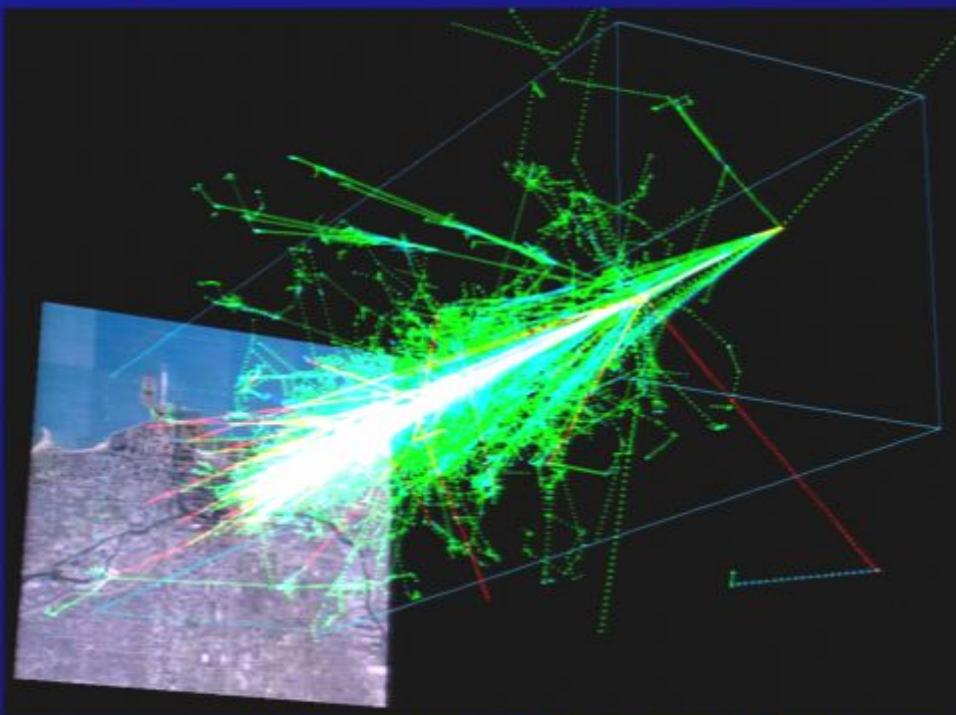


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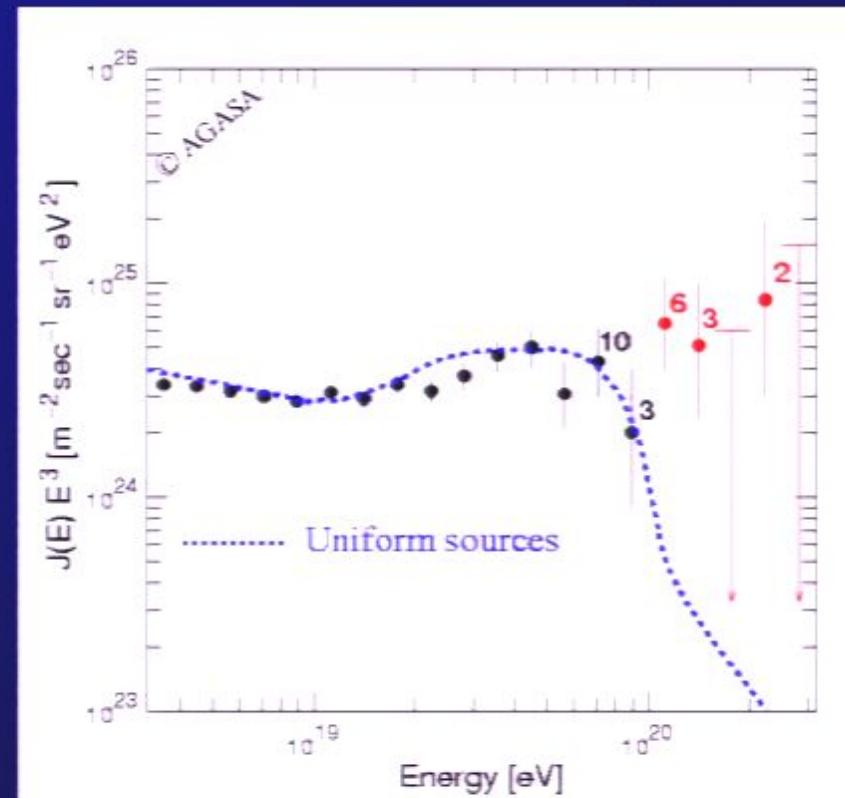
# Ultra High Energy Cosmic Rays

Primary energy  $\gtrsim 10^{20}$  eV

Composition: hadrons,  $\nu$ 's



(Courtesy of University of Chicago)



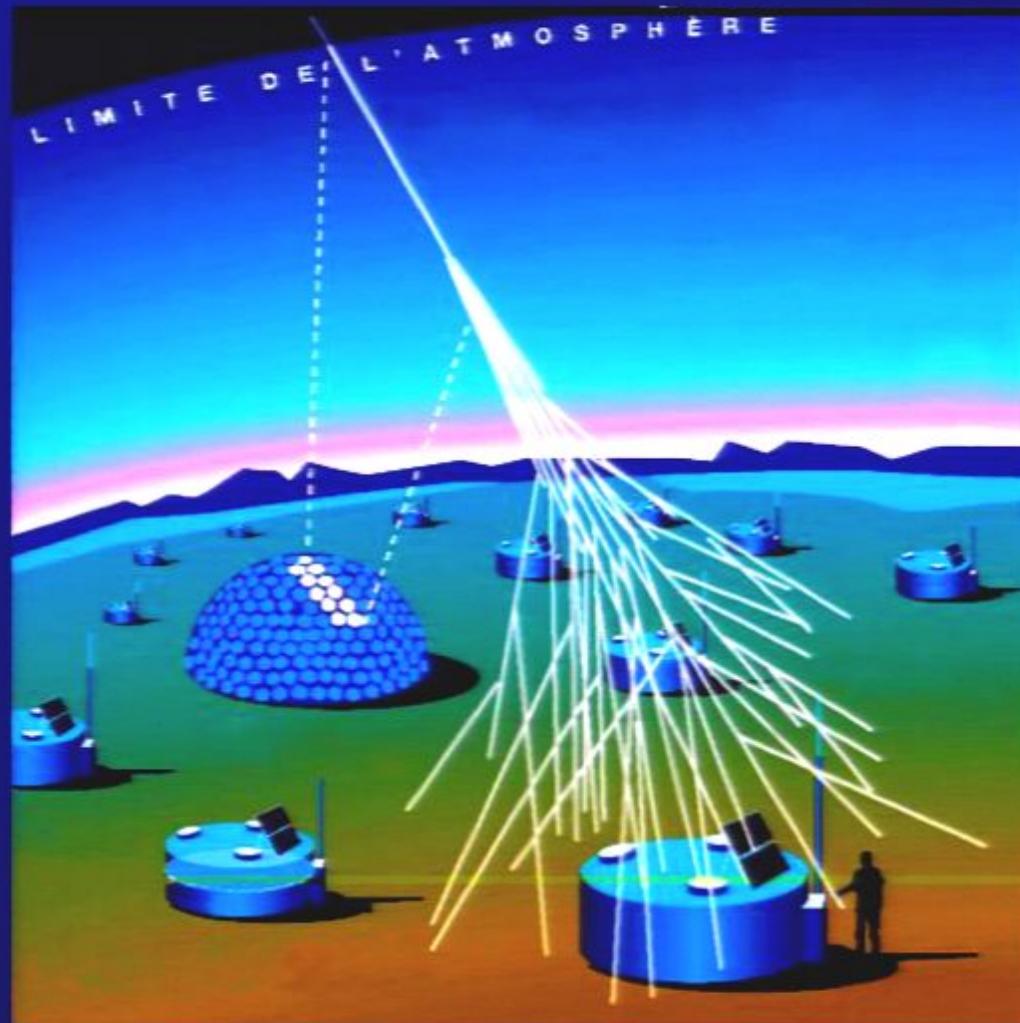
(Courtesy of Agasa)



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# Pierre Auger Observatory

Hybrid  
Detector





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# Ground



(Courtesy of Auger project)



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# Ground



(Courtesy of Auger project)



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# Fluorescence

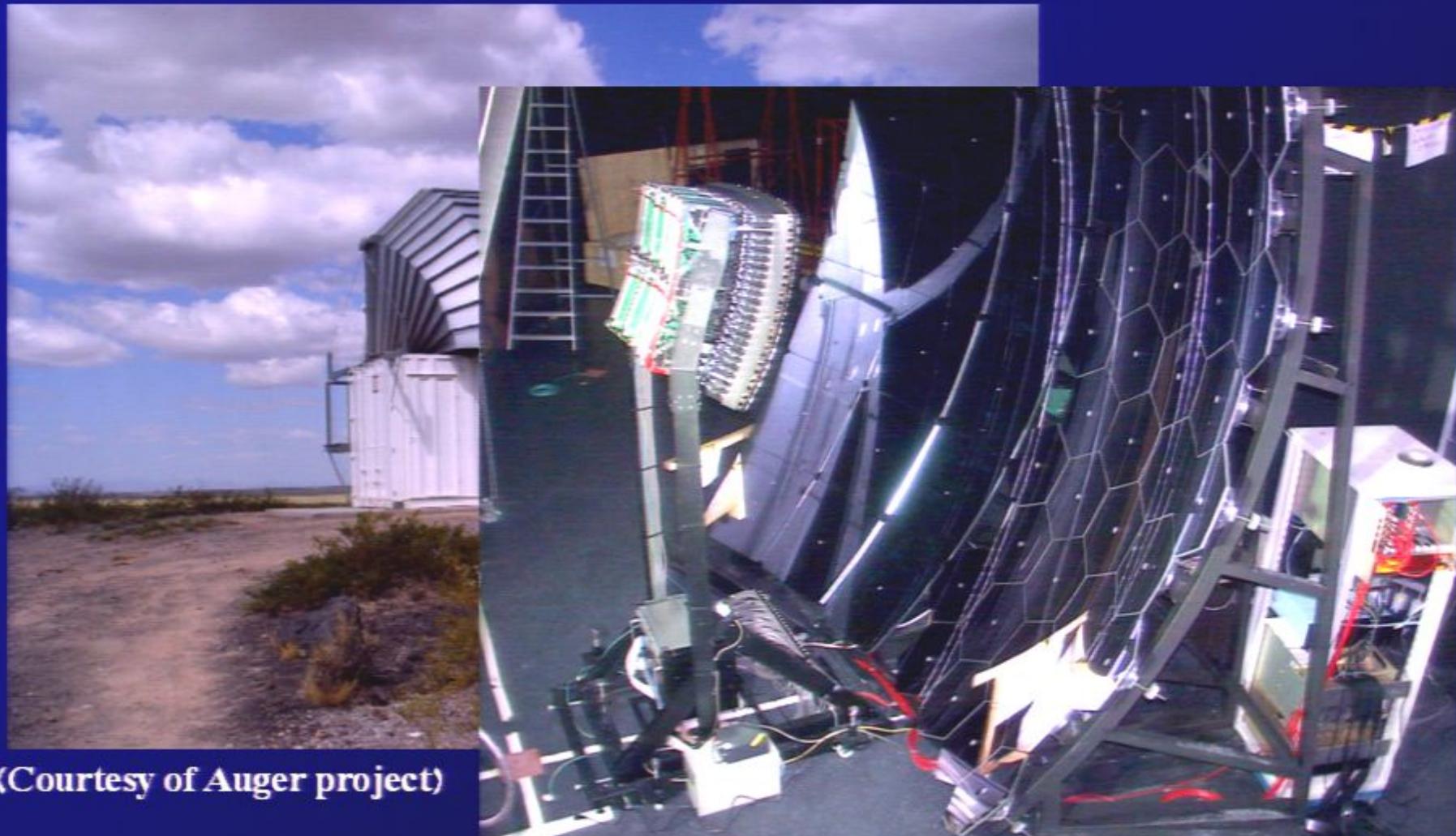


(Courtesy of Auger project)



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# Fluorescence



(Courtesy of Auger project)



# Experimental signatures in airshowers

- ◆ Large cross section  
(Landsberg & Dimopoulos 2001; Giddings & Thomas 2001)
- ◆ Excess of horizontal showers  
(Feng & Shapere, 2002)
- ◆ Hadronic-like showers  
(Ahn, Ave, Cavaglia` & Olinto, 2003; Ahn & Cavaglia`, 2006)
- ◆ Tau double bang  
(Ahn, Ave, Cavaglia` & Olinto, 2003, Cardoso et. al 2004)



## Groke: The black hole air shower generator

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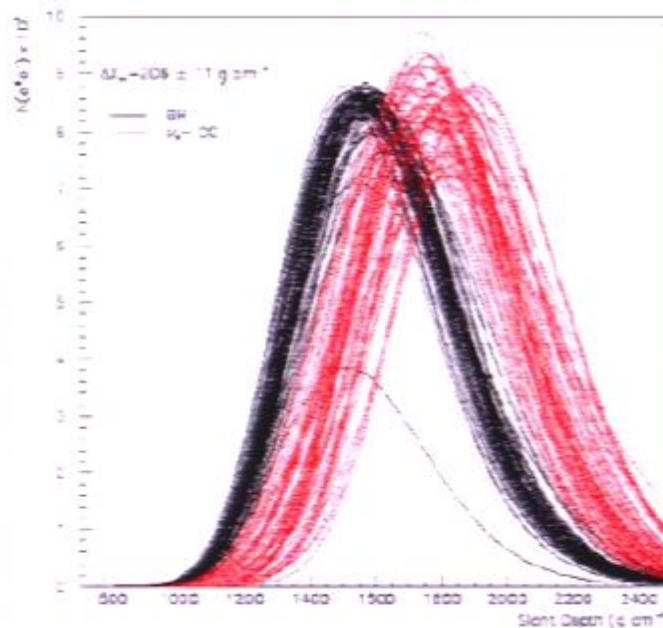
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# Welcome to the Groke website



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# Groke: The Monte Carlo for airshowers

- ◆ Mass of the BH from differential cross section, inelasticity.
- ◆ Multiplicity with statistics, counting of d.o.f. and greybody factors
- ◆ Initial- and final-state radiation, fragmentation, beam remnant (**PYTHIA**)
- ◆ Secondaries generated with **AIRES** (same interaction point except tau's)
- ◆ Zenith angle: 70°, First interaction point: 10 Km
- ◆ CC- $\nu_e$  dominates (CC- $\nu_m/\nu_t$ : invisible high-energy m/t, NC: smaller cross section/invisible  $\nu$ )

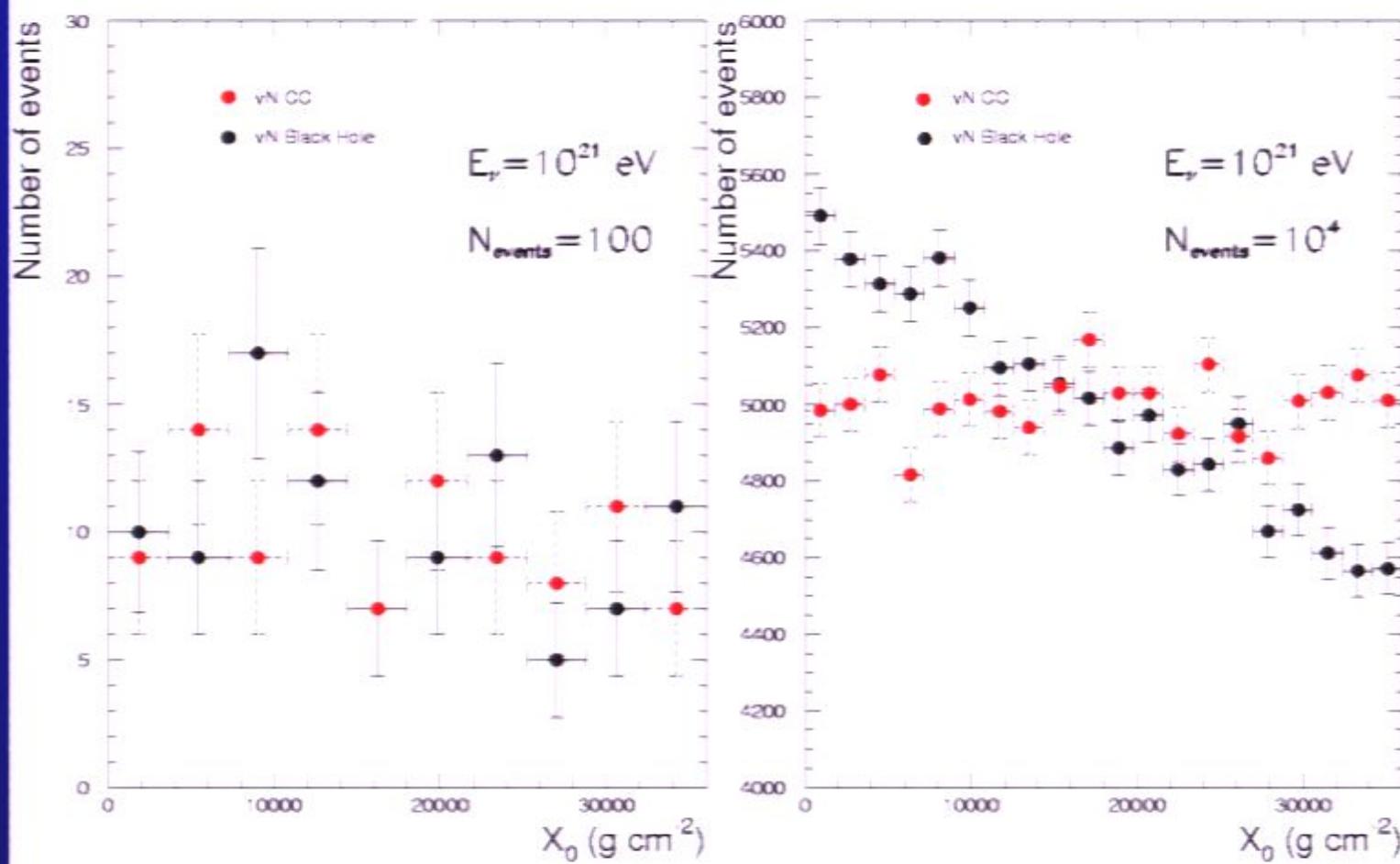




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# Excess of horizontal showers

(Ahn, Ave, Cavaglia` & Olinto 2003)





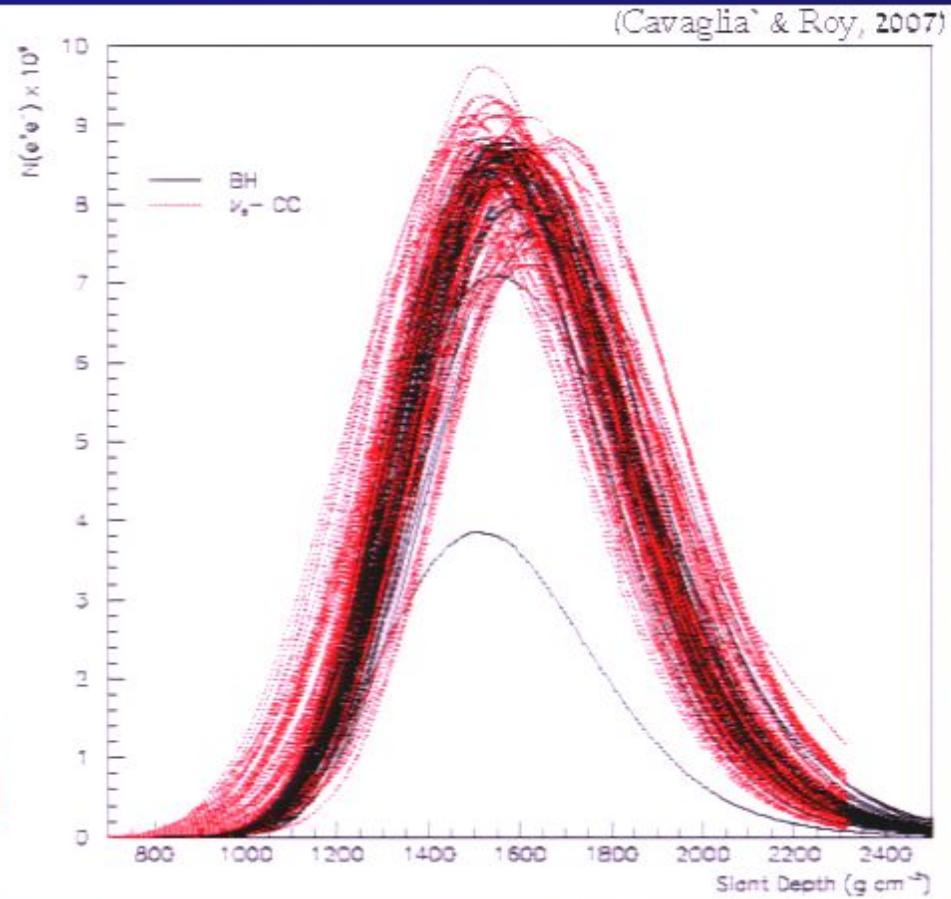
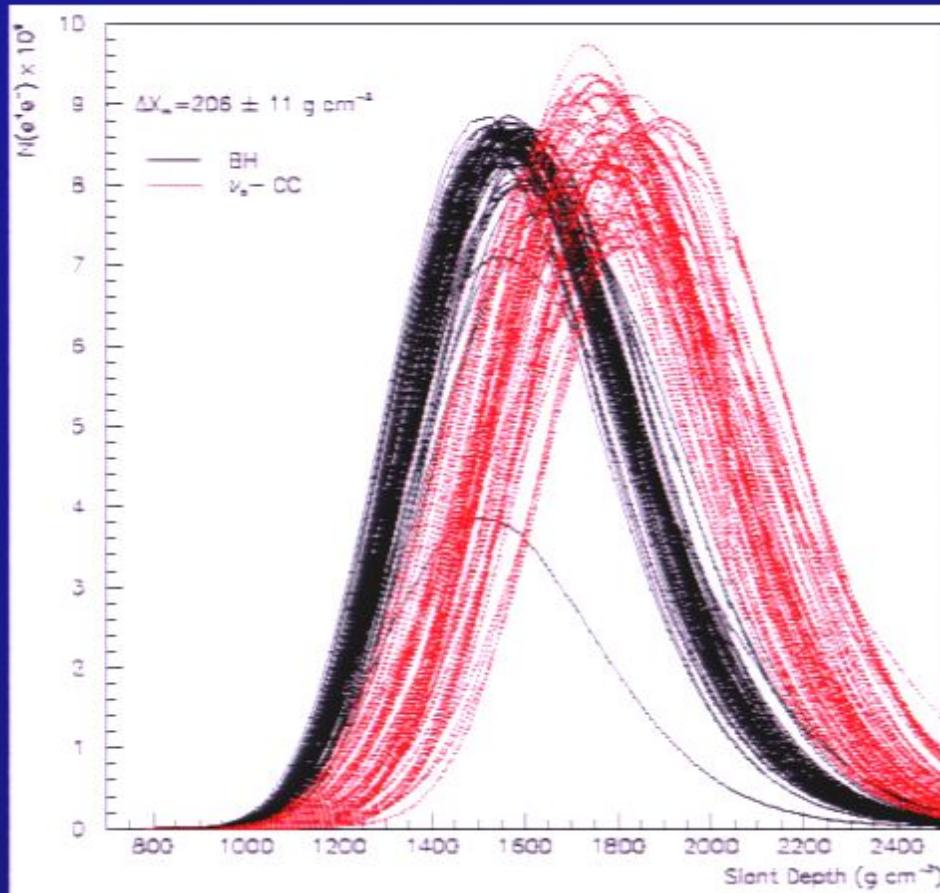
# BH vs. SM airshowers

	Black hole	SM $\nu_e$ -CC
Muon content	High	Low
Development	Quick	Slow
Peak fluctuations	Small	Large
Average total energy	Varying	Stable



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# Shower profile



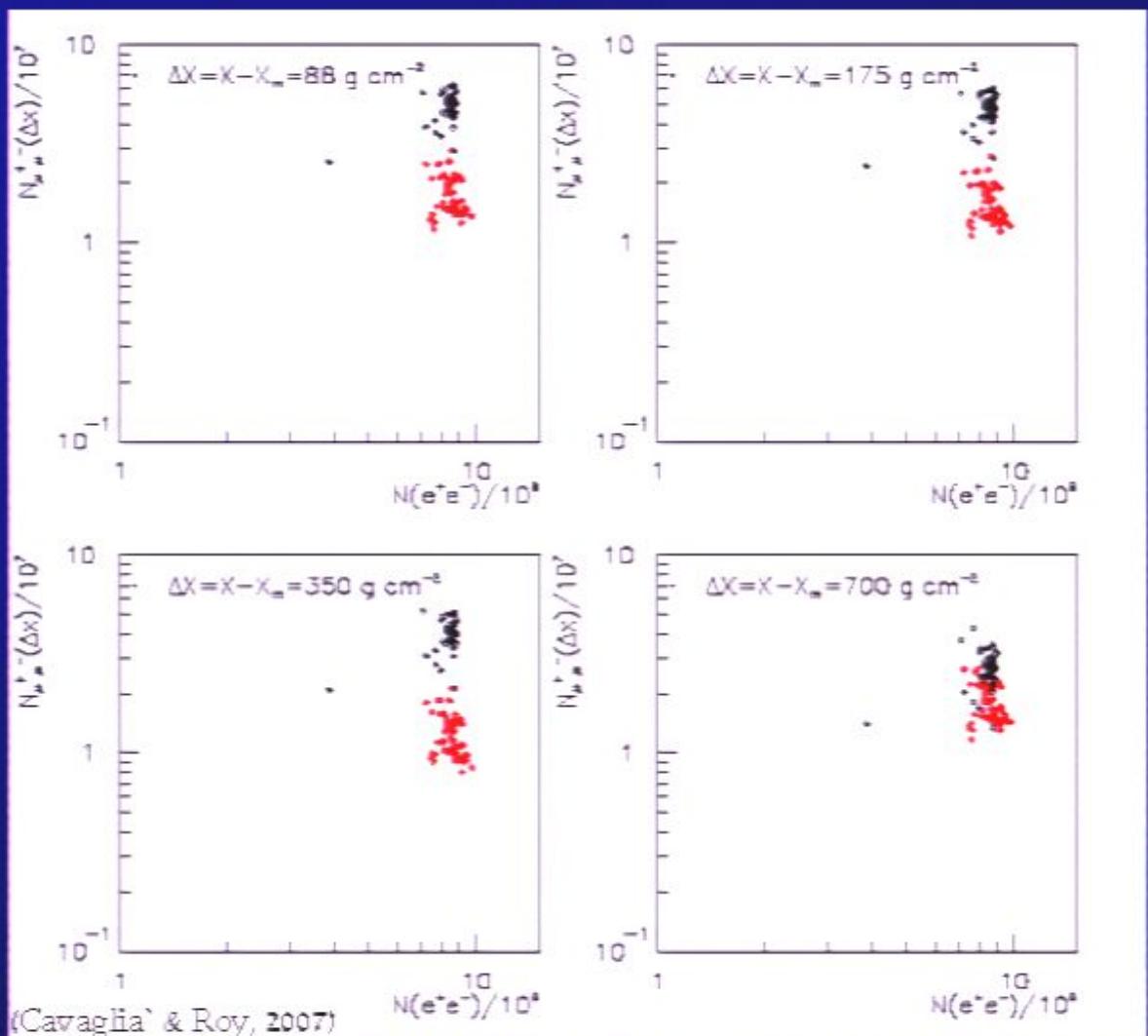
$$X_m = X_0 + A \log_{10} \left[ \frac{E_\nu}{N T eV} \right] + B \quad A \approx 60 \text{ g cm}^{-2} \quad B \approx 311 \text{ g cm}^{-2}$$



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# Ground: $\mu^+ \mu^-$ at $X_m + \Delta X$ vs. $e^+ e^-$ at $X_m$

BH  
showers  
are  $\mu$ -rich



(Cavaglià &amp; Roy, 2007)

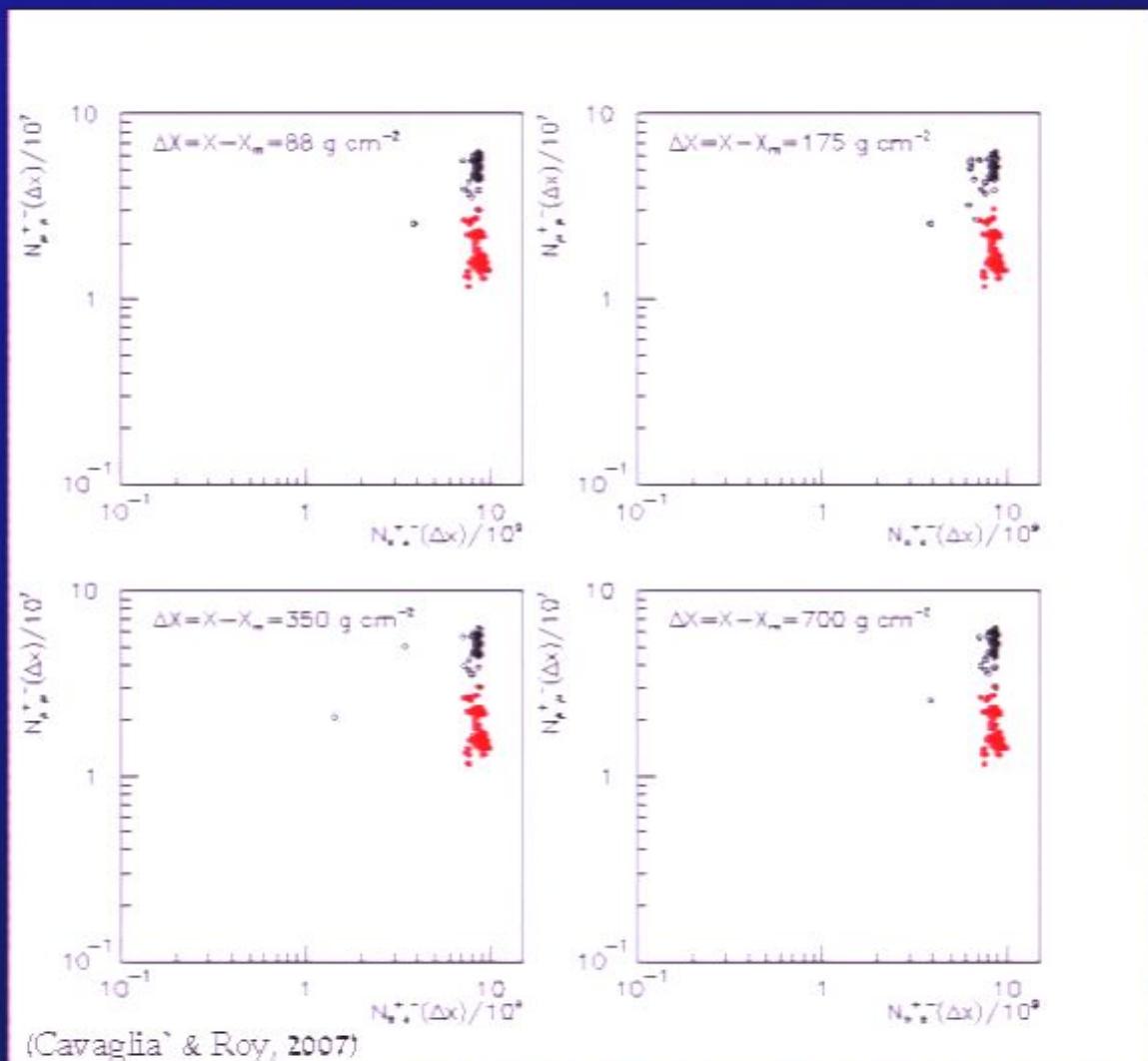


(Ahn, Ave, Cavaglià & Olinto 2003-2004)

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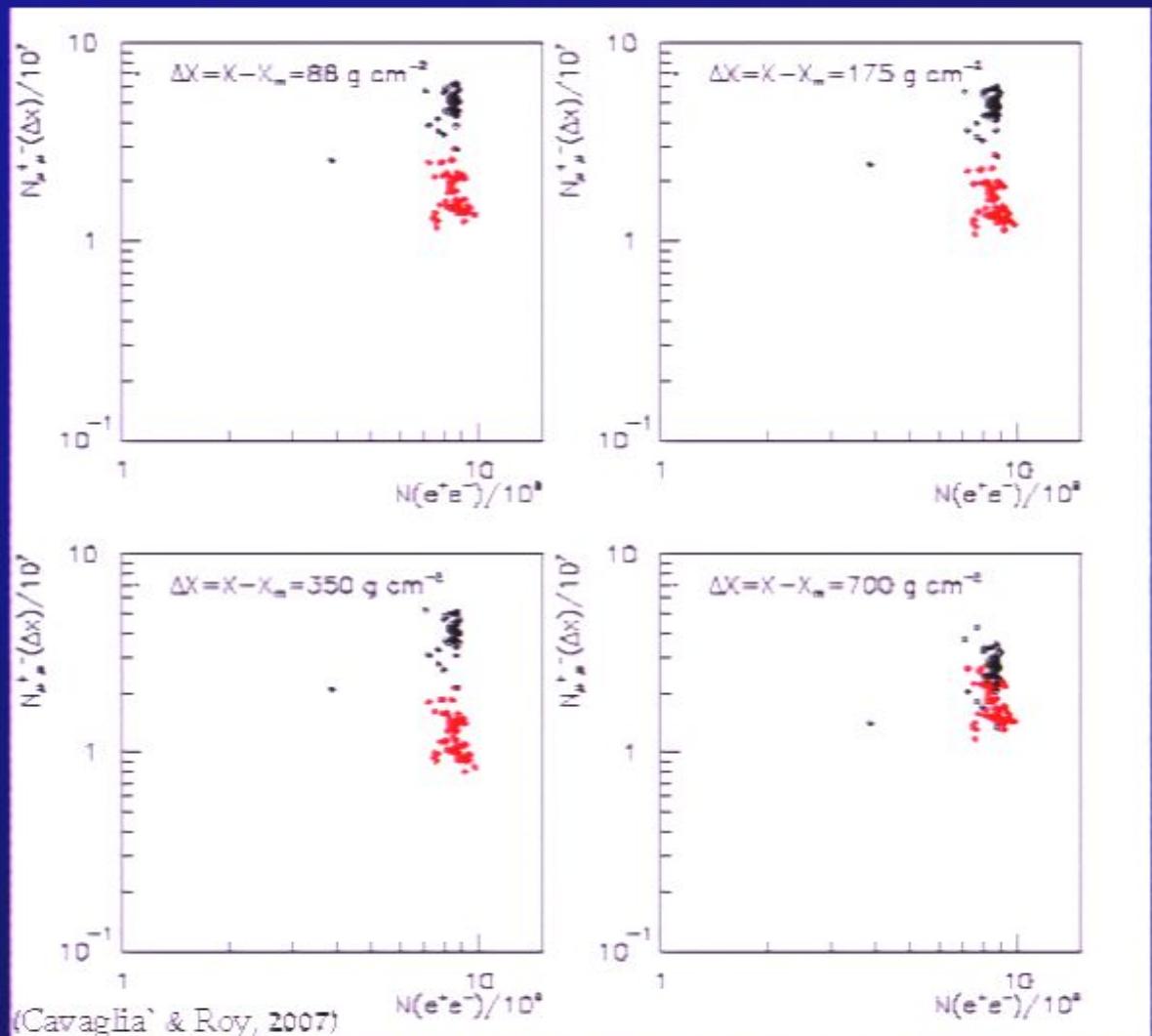


(Ahn, Ame, Cavaglià & Olinto 2003-2004)

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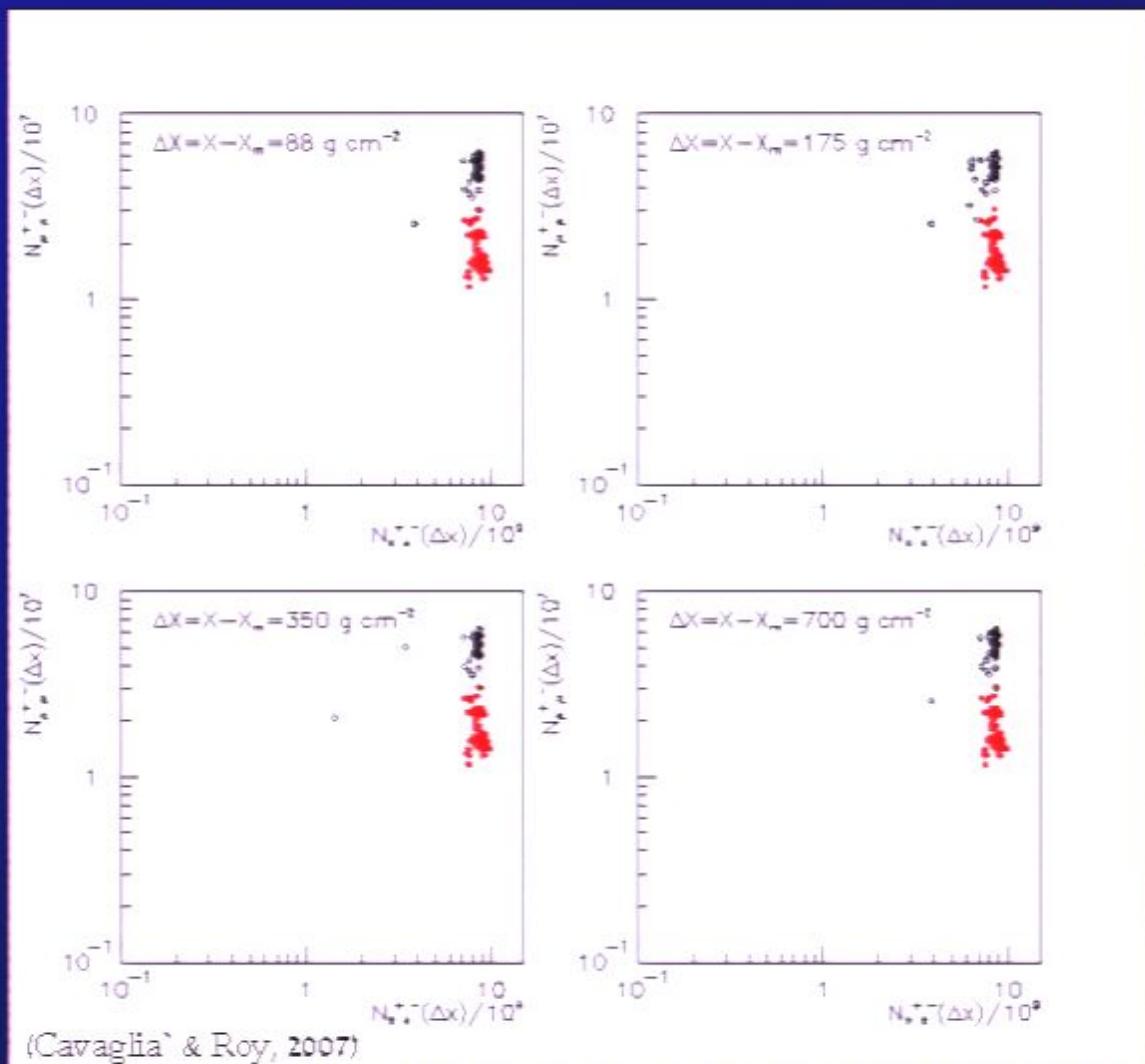




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# Ground: $\mu^+ \mu^-$ vs. $e^+ e^-$ at $X_m + \Delta X$

BH  
showers  
are  $\mu$ -rich





# Effect of BH parameters

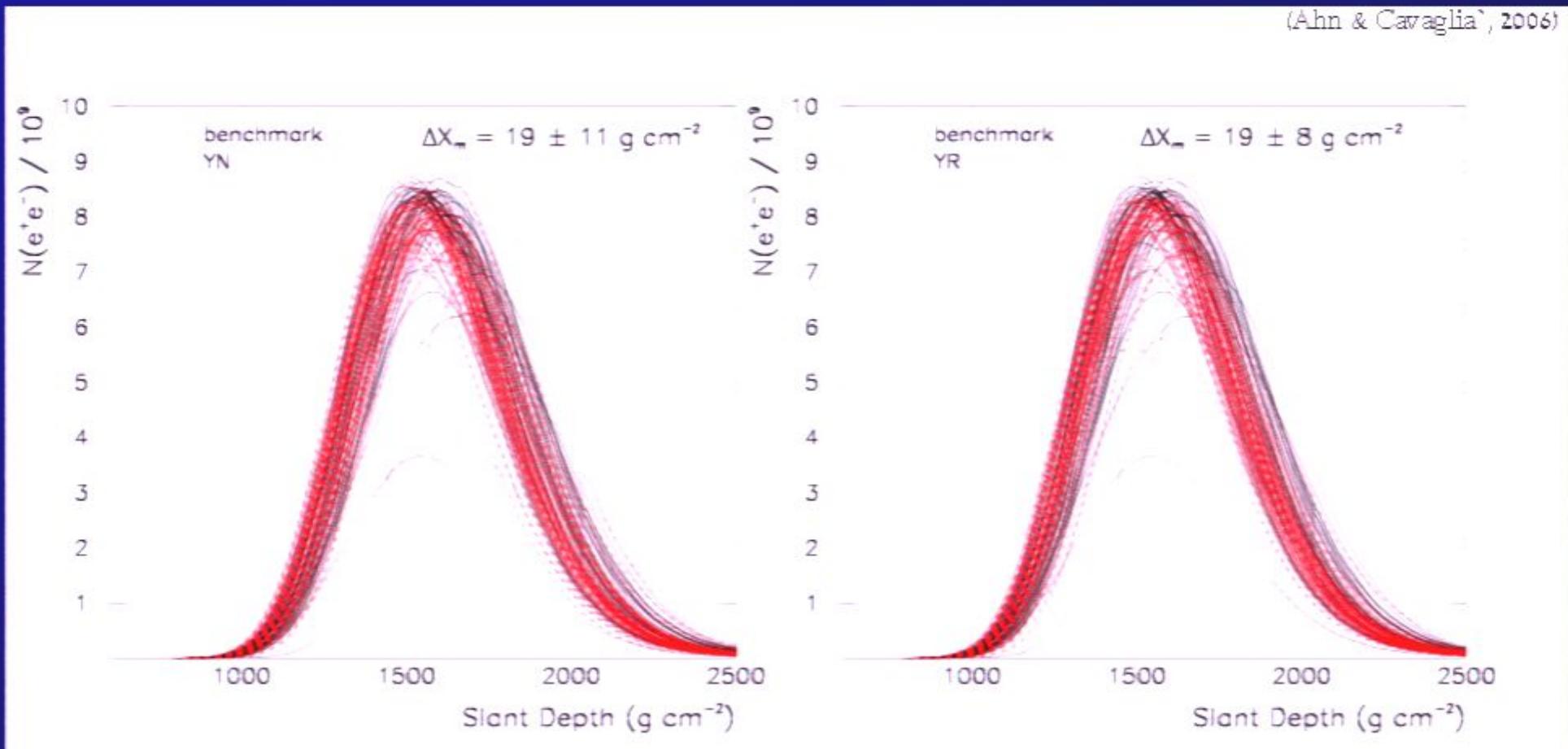
	Benchmark
Planck mass	1 TeV
No. of extra dimensions	6
Formation model	Black disk
Minimum-allowed mass	$2M_D$
Quantum threshold	$1M_D$
No. of final hard quanta	2
Momentum transfer	$r^{-1}(M)$
EM charge conservation	YES
Minimum spacetime length	0



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# Can we detect graviton loss?

(Ahn & Cavaglià, 2006)

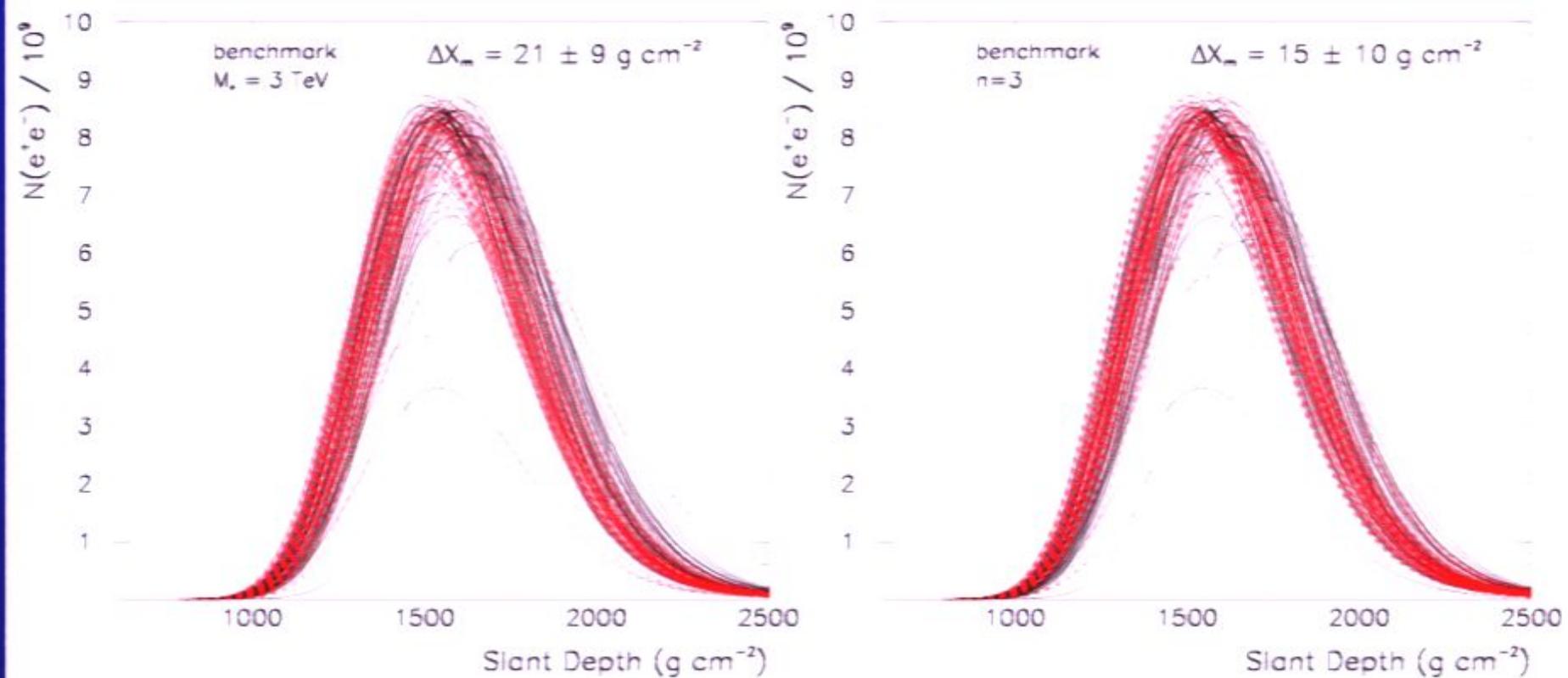




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# Can we measure $n$ or Planck mass?

(Ahn & Cavaglià, 2006)

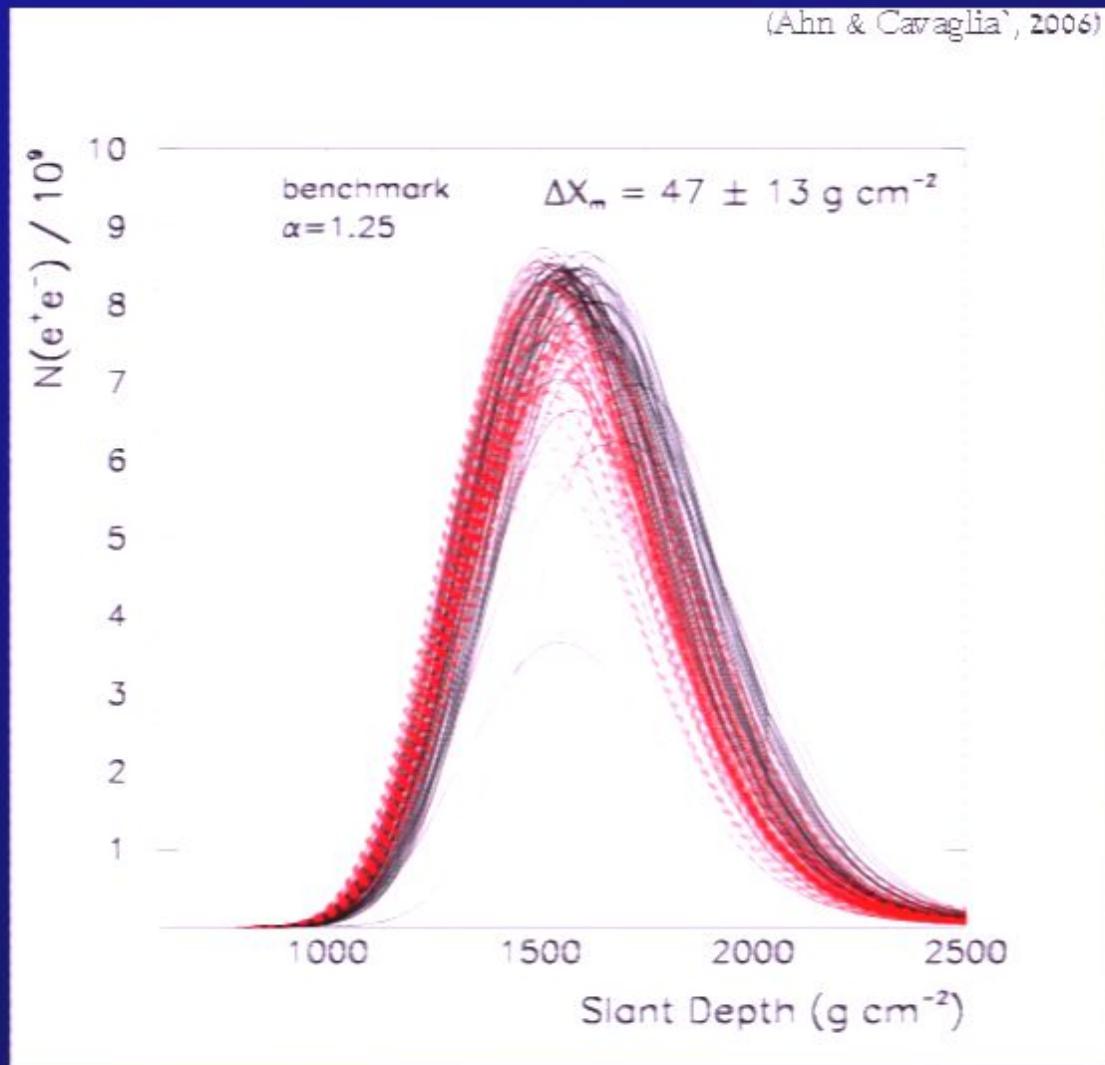




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# Can we detect a minimum length?

(Ahn & Cavaglia', 2006)



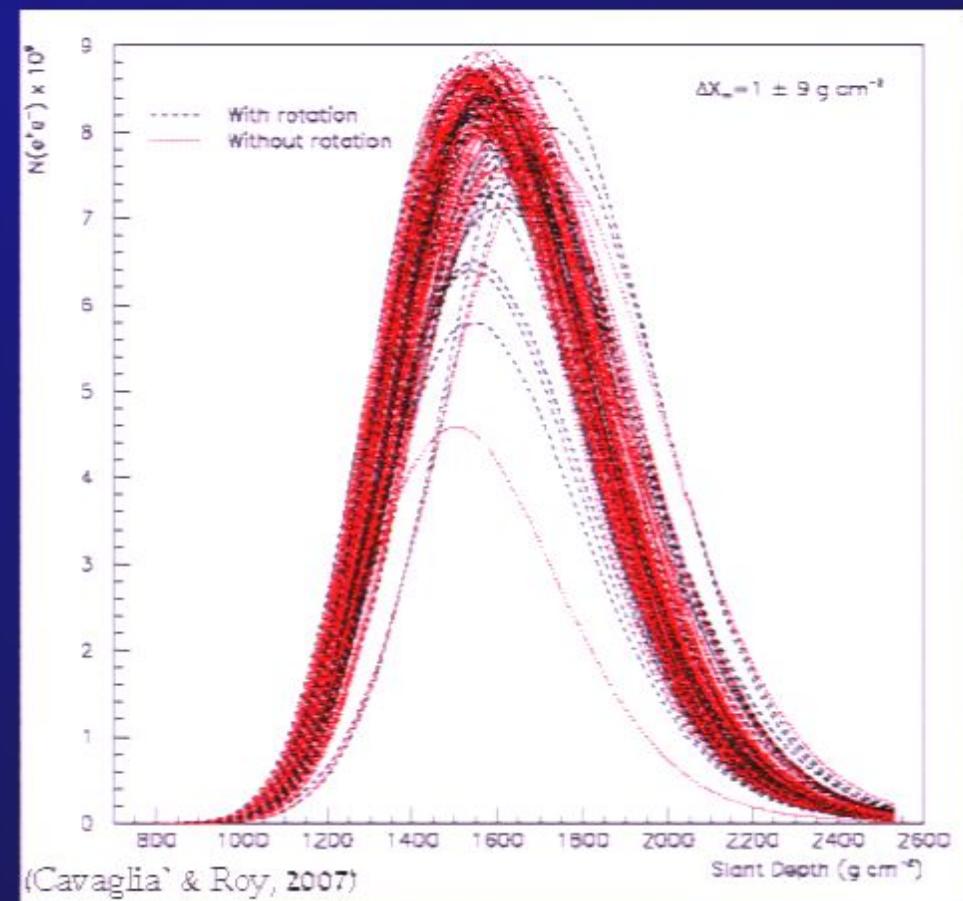
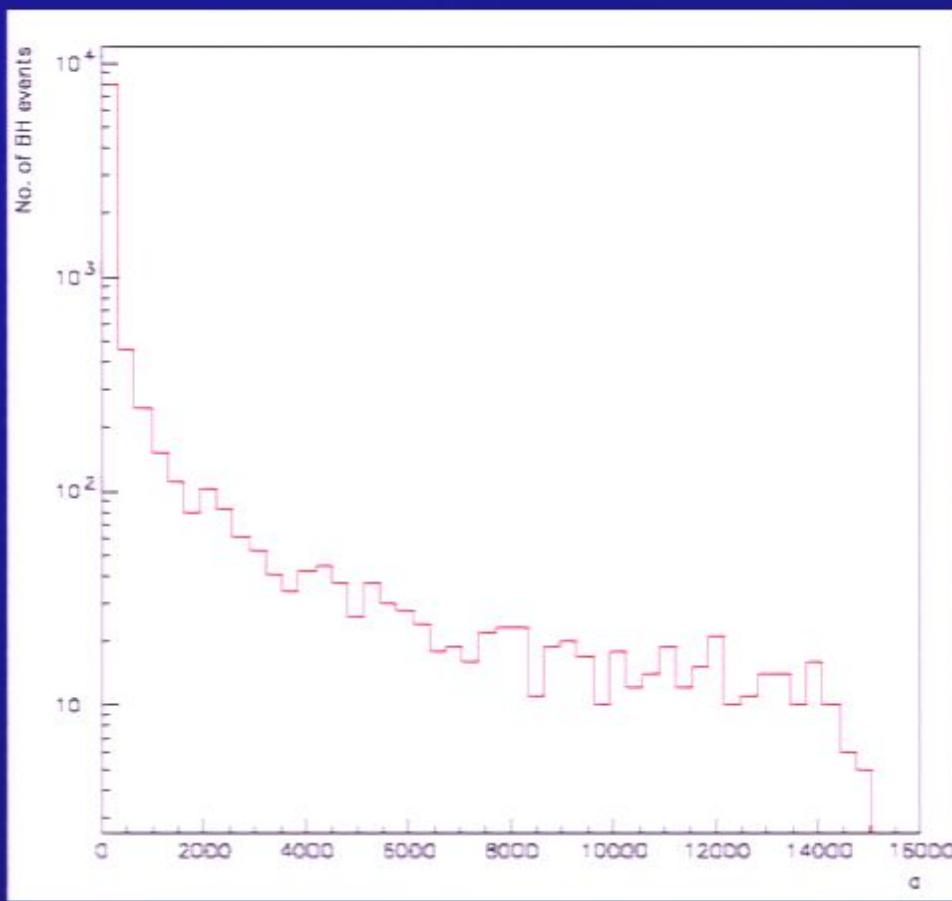


# Summary of BH parameters

	$X_m \pm \text{rms error}$
None (benchmark)	$1566 \pm 6$
$M_D = 3 \text{ TeV}$	$1545 \pm 6$
$n = 3$	$1551 \pm 5$
$M_{\min} = 10 \text{ TeV}$	$1546 \pm 6$
$Q_{\min} = 2 \text{ TeV}$	$1559 \pm 7$
Neutral remnant	$1549 \pm 6$
Charged remnant	$1564 \pm 6$
YN model	$1547 \pm 6$
YR model	$1547 \pm 5$
$ l_{\min}  = 2.5/M_D$	$1519 \pm 4$



# What about rotation?



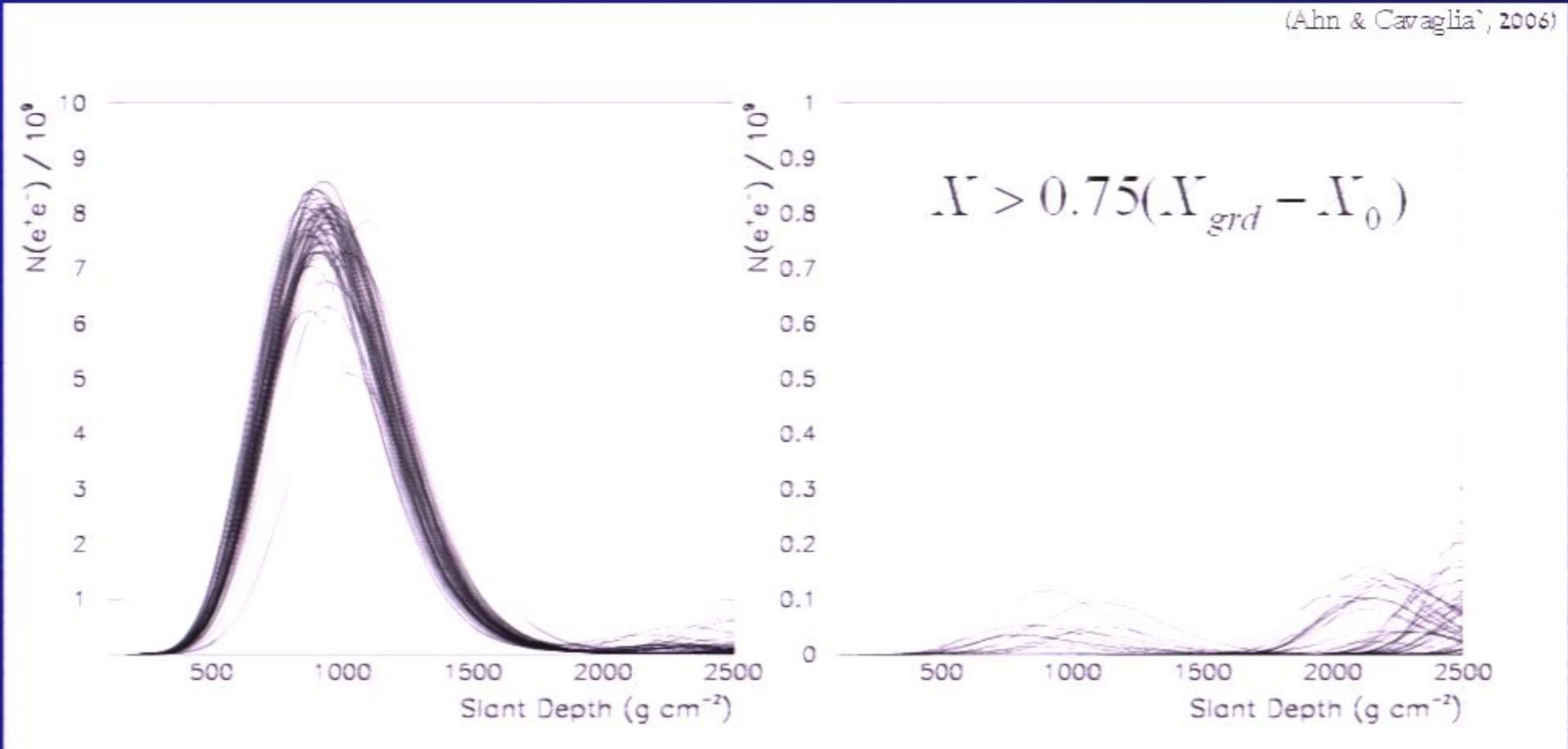
Most of the BH are slow rotating → Graviton emissivity  $\times 10$



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# Tau double bang

(Ahn & Cavaglia, 2006)





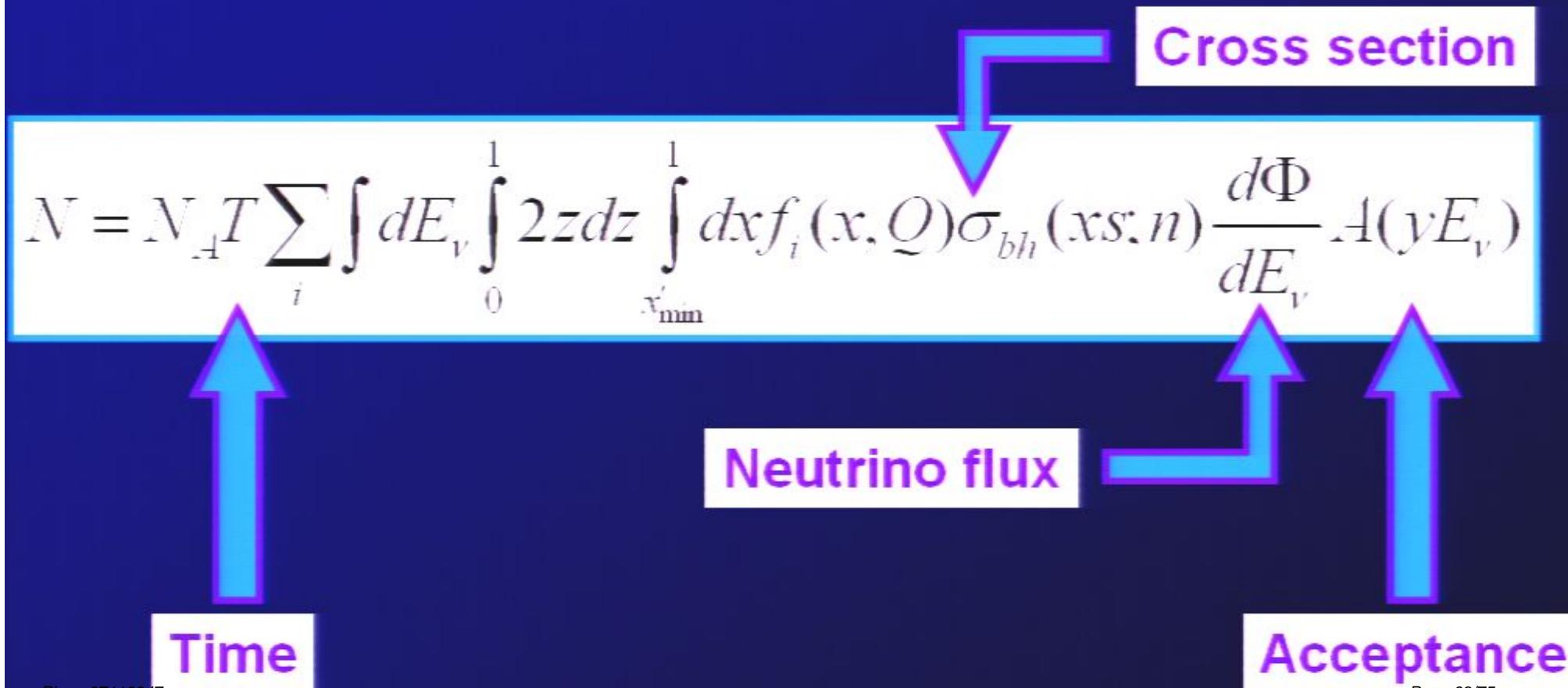
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# A few words on experimental bounds



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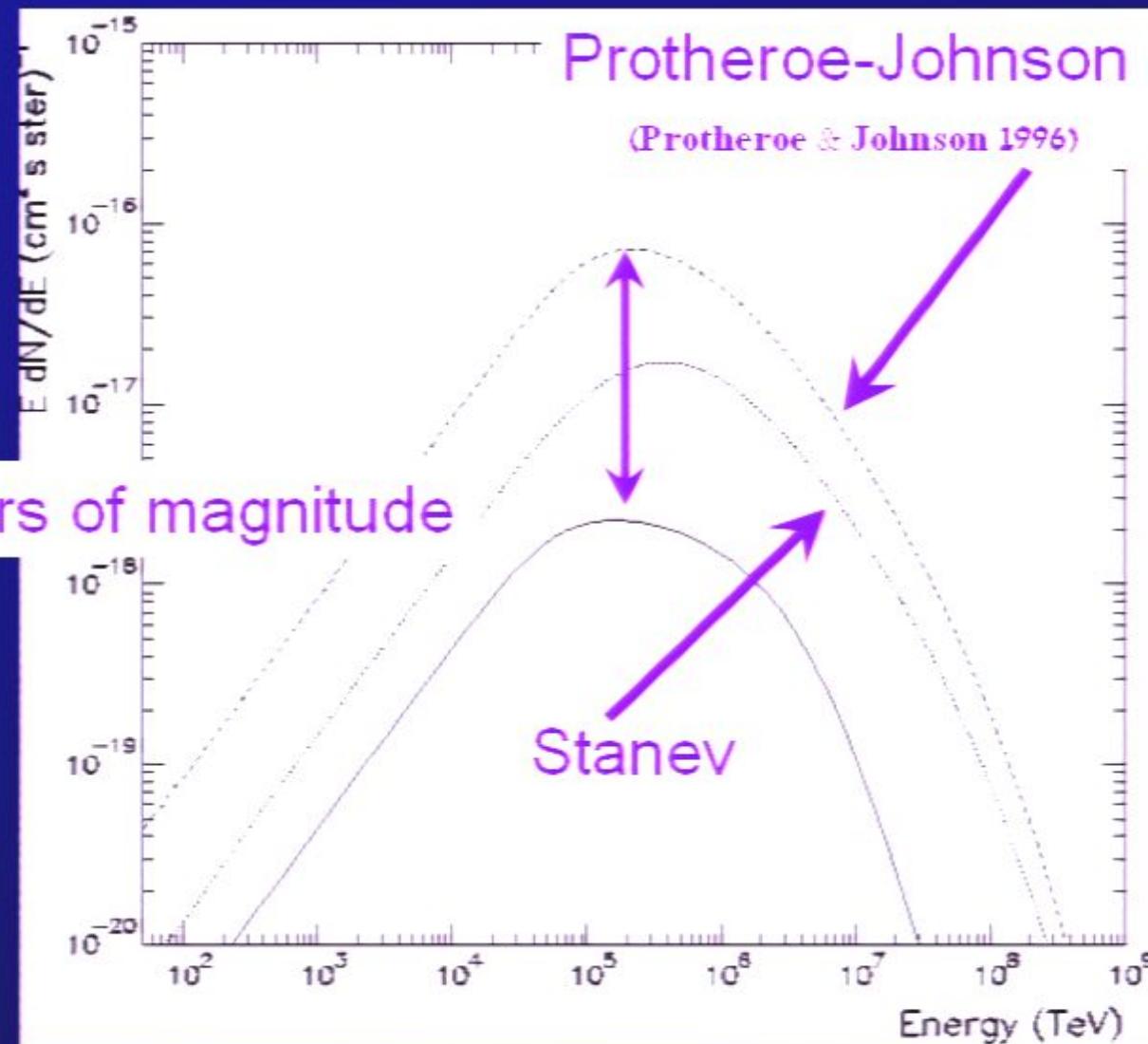
# Experimental constraints from BH-induced air showers





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# Neutrino flux uncertainty





# Realistic bounds on $M_D$ :

$M_D \approx 0.2 - 0.5$  for  $n=2 \dots 6$

**Less stringent than collider bounds**



# Conclusion

- ◆ Something must happen at the TeV scale: Maybe gravity?
- ◆ Possible observation of strong gravitational effects at:
  - Particle colliders
  - Cosmic ray observatories
- ◆ If not, constraints on the Planck scale.  
If yes, new physics!
- ◆ Possible tests of strong gravitational effects (Hawking radiation, minimum length)
- ◆ Other nonperturbative gravitational objects (string balls, branes, etc...)



"The last I heard, Cavaglià was working on a model black hole in his lab."



# Recent bibliography

- ◆ A. Roy and MC, arXiv:0710.5490
- ◆ MC and A. Roy, Phys. Rev. D76, 044005 (2007)
- ◆ R. Godang, MC, L. Cremaldi and D. Summers, JHEP 0706, 055 (2007)
- ◆ R. Godang, MC, L. Cremaldi and D. Summers, Comp. Phys. Comm. 177, 506 (2007)
- ◆ E.-J. Ahn and MC, Phys. Rev. D73, 042002 (2006)
- ◆ CATFISH web page: <http://www.phy.olemiss.edu/GR/catfish>
- ◆ GROKE web page: <http://www.phy.olemiss.edu/GR/groke>



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No Signal  
VGA-1