FRIENDLY BLACK HOLES AT THE MUON COLLIDER

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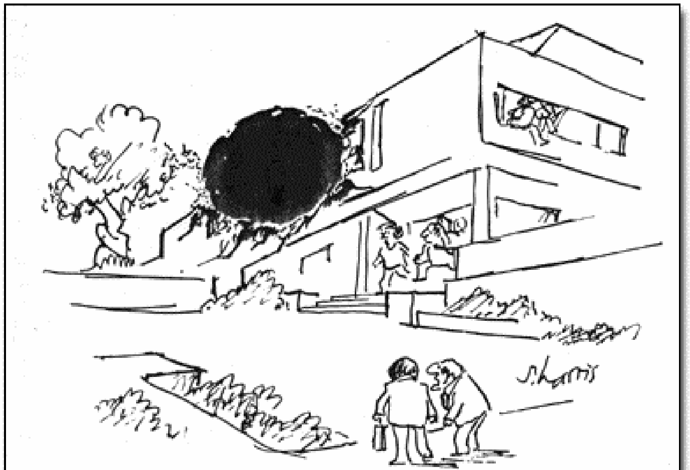
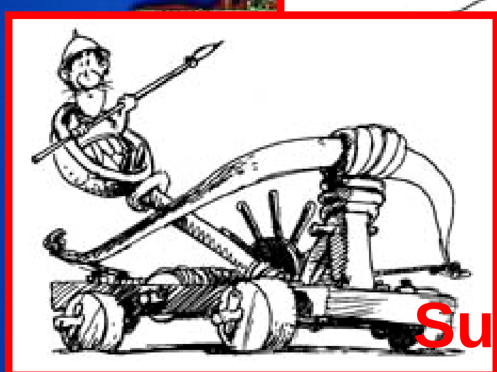


"The last I heard, Medwick was working on a model black hole in his lab."

Hierarchy problem

Observed Planck scale: $M_{Pl} \sim 10^{19}$ GeV



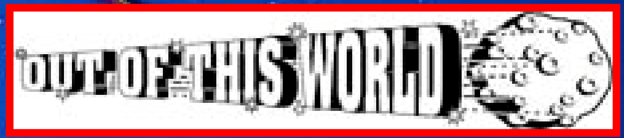
Susy? Running couplings?

Observed EW scale: $M_{EW} \sim 10^{2}$ GeV

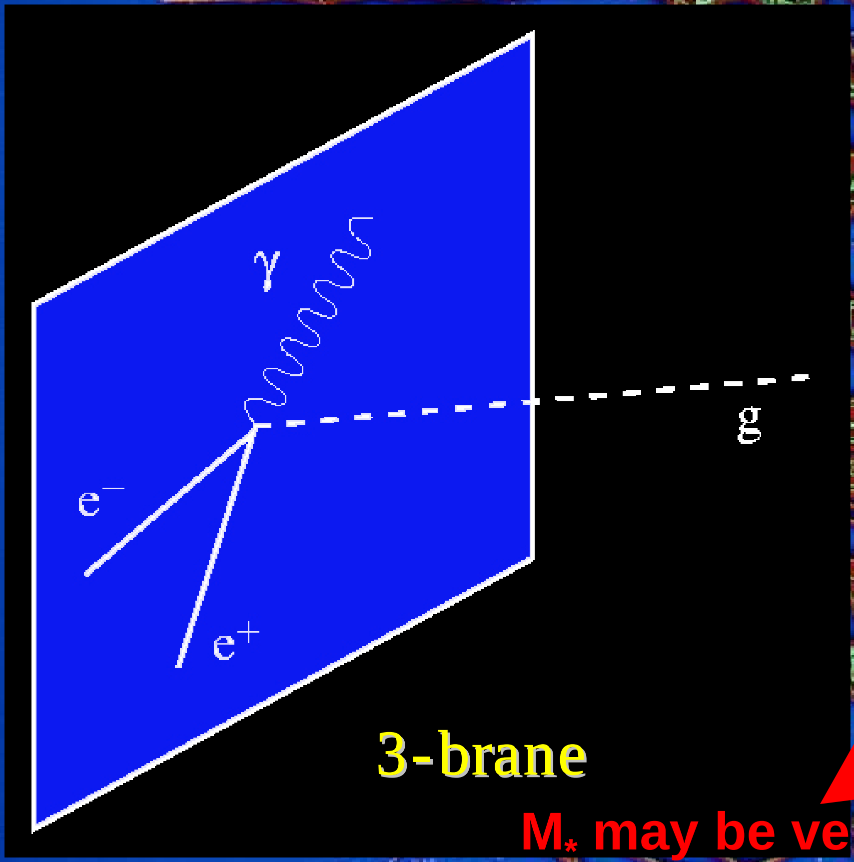
The approach “from below”

(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**



Brane Universe



$$S = \frac{M_*^{n+2}}{16p}\int d^{n+4}x\sqrt{-g}\,R(g)$$

$$G_{n+4} = G_4 V_n$$

$$M_{Pl}^2 = M_*^{n+2} V_n$$

M_* may be very small!!

How do we probe extra-dimensions?

Gravitational effects at the TeV scale

Perturbative effects (Energy $\lesssim M_*$)

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

- **Kaluza-Klein modes**
- **Virtual graviton exchange**

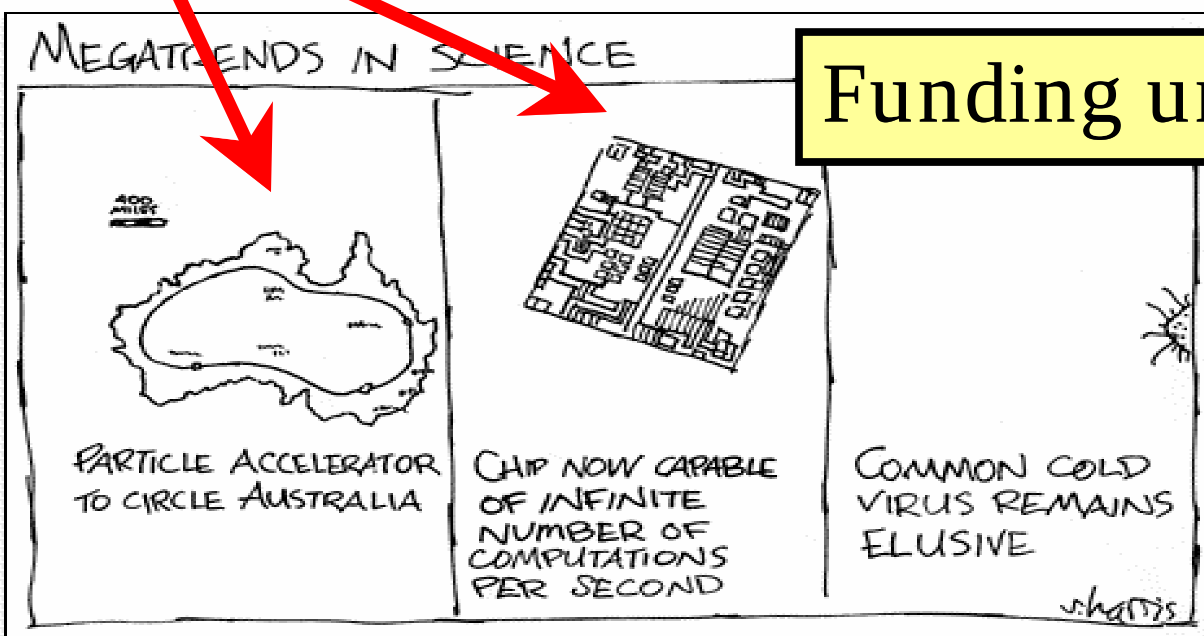
Nonperturbative effects (Energy $\gtrsim M_*$)

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

All depends on M_*...

If M_* is ~ 10^{16} TeV…

…experimental quantum gravity requires:



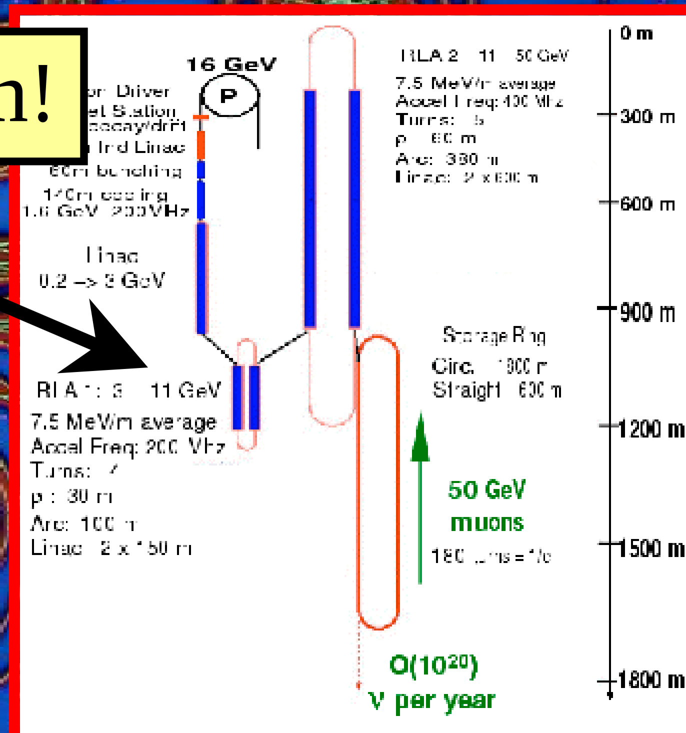
Funding unlikely!

But

If M_* is ~ TeV…

…quantum gravity becomes strong at ~ TeV

This may be enough!



Experimental constraints

- **Cavendish experiments: n=2, M_*>1.6 TeV**
  (Adelberger et al. 2002)
- **Particle collider experiments: M_*/TeV larger than**
  (see e.g. Giudice & Strumia 2002; Peskin 2000)

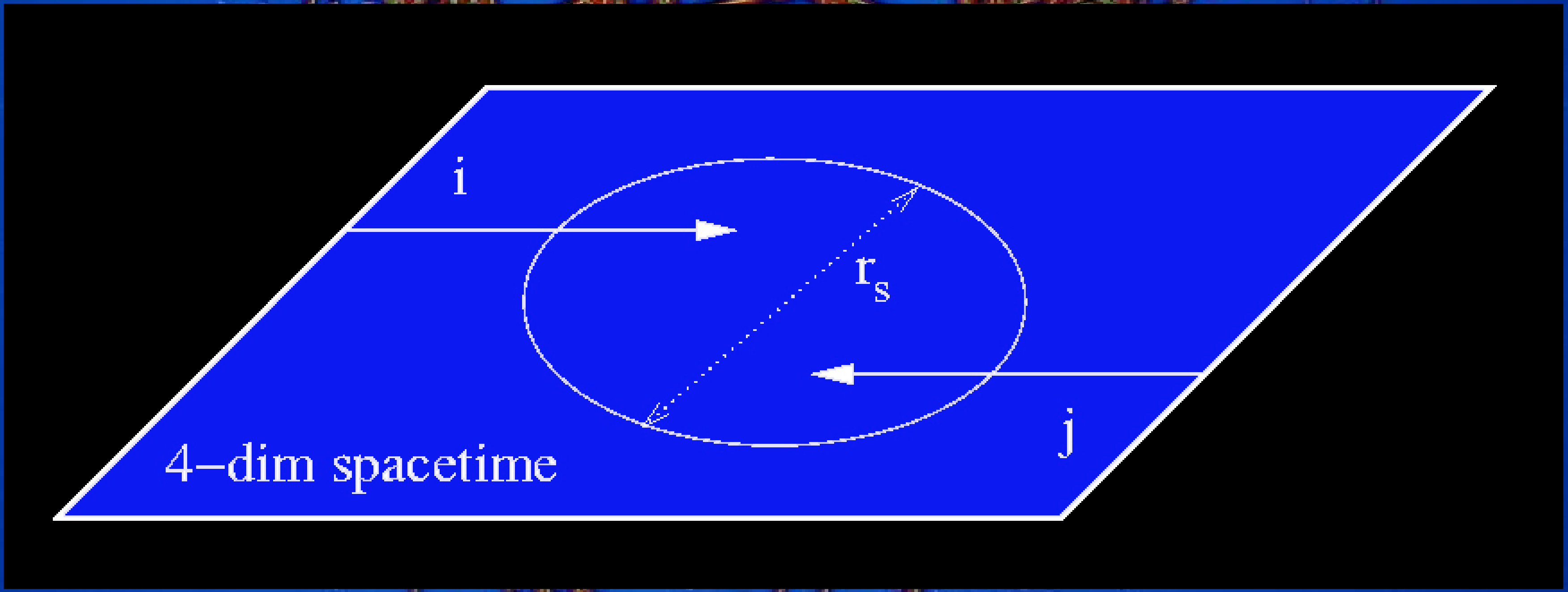
	n=2	n=4	n=6
LEP II	0.90	0.33	0.18
Tevatron	0.86	0.39	0.27
LHC	9.4	3.4	2.1

- **Astrophysics and cosmology: M_*/TeV larger than**
  (see e.g. Cullen & Perelstein 1999)

	n=2	n=3	n=4
SN1987A	38-63	2.2-3.9	0.45
Neutron stars	1260	33	
CMBR	65-750	4-32	0.7-4
CγBR	83-263	2.8-7.6	
UHECR		0.2-0.3	0.2-0.3

Nonperturbative effects:

Scattering of two particles with C-o-M energy > TeV and impact parameter $b < r_s$



Black hole forms!

Cross section

(Landsberg & Dimopoulos 2001; Giddings & Thomas 2002)

$$\sigma_{bh}(s;n) \approx \pi r_s^2 \approx \frac{1}{s_*}\left[\frac{8\Gamma((n+3)/2)}{(2+n)}\right]^{\frac{2}{n+1}}\left(\frac{s}{s_*}\right)^{\frac{1}{n+1}}$$

where

$$M = \sqrt{s} \qquad M_* = \sqrt{s_*}$$

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

If M ~ TeV Þ r_s ~ TeV^{-1}

- **UHECR (neutrino-proton to BH):**

$$s_{np \to bh}(s;n) \approx \sum_i \int^1 dx\, f_i(x,Q) s_{bh}(xs;n)$$

- **LHC (proton-proton to BH):**

$$s_{pp \to bh}(s;n) \approx \sum_{ij} \int^1 dx \int_x^1 \frac{dy}{y} f_i(y,Q)\, f_i(x/y,Q) s_{bh}(xs;n)$$

- **Muon collider (muon-muon to BH):**

$$s_{mm \to bh}(s;n) \approx s_{bh}(s;n)$$

Experimental signatures:

- **Very large and steep cross section**
  (Landsberg & Dimopoulos 2001; Giddings & Thomas 2002)
- **Visible transverse energy / High sphericity events**
  (Giddings & Thomas 2002)
- **High (?) multiplicity events (hadronic jets + leptons + hard quanta at the end of decay)**
  (Giddings & Thomas 2002; Cavaglia` 2003)
- **Ratio of hadronic to leptonic activity ~ 5:1**
  (Giddings & Thomas 2002; Han et al. 2002; Cavaglia` 2003)
- **Possible large missing energy**
  (Cavaglia`, Das & Maartens 2003)
- **Suppression of hard perturbative scattering processes**

Example

$M_* = 1$ TeV, $n = 6$, $M_{BH} = 12$ TeV

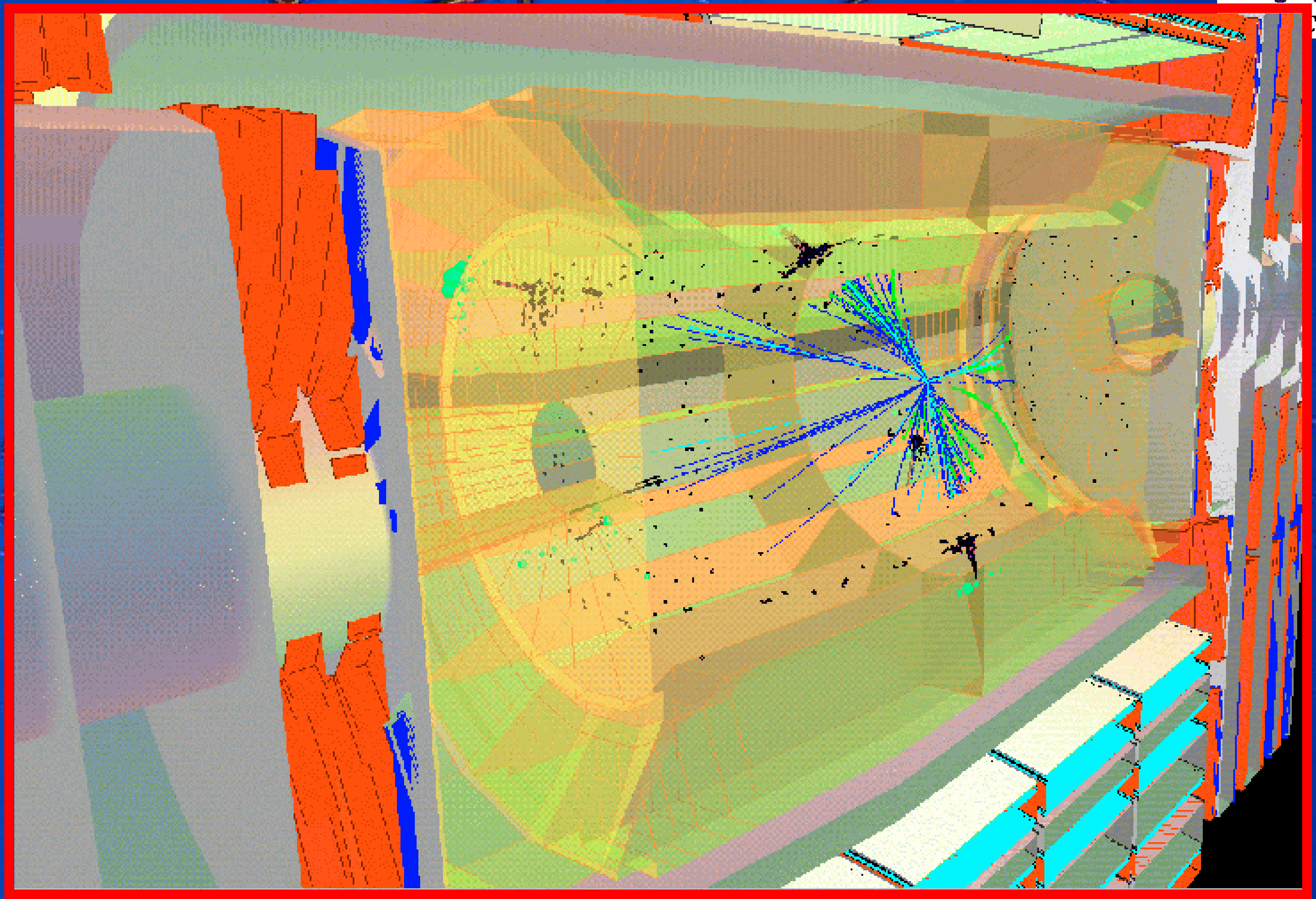
quark	5	gluon	1
charged *l*.	1	W	0
neutrino	0	Z	0
Higgs	0	graviton	0
photon	0		

Quarks and gluon hadronize. H-to-L ratio ~ 5:1

Cross section uncertainties

- **Nonrelativistic limit estimates**
- **Classical photon capture / plunging estimates**
  (Berti, Cavaglia` & Gualtieri 2003)
- **Collisional energy loss/inelasticity**
  (Yoshino & Nambu, 2003)
- **Angular momentum correction**
  (Yoshino & Nambu 2003)
- **Charge effects**
  (Casadio & Harms 2002)
- **Minimal BH formation mass**
  (Cavaglia`, Das & Maartens 2003)

BH event at CMS



(Model of Landsberg & Dimopoulos, Herwig implementation by C. Harris & P. Richardson, generated by A. de Roeck, simulated & visualised by S. Wynhoff)

The LHC vs the Muon Collider

Muon Collaboration

LHC: Center-of-mass energy (pp) = 14 TeV

“ “ (PbPb) = 5.5 TeV

mC: Center-of-Mass energy = 4 TeV

VLHC: Center-of-Mass energy = up to 100 TeV

Disadvantage!

VLmC: Center-of-Mass energy = up to 200 TeV

Cross section at the LHC:

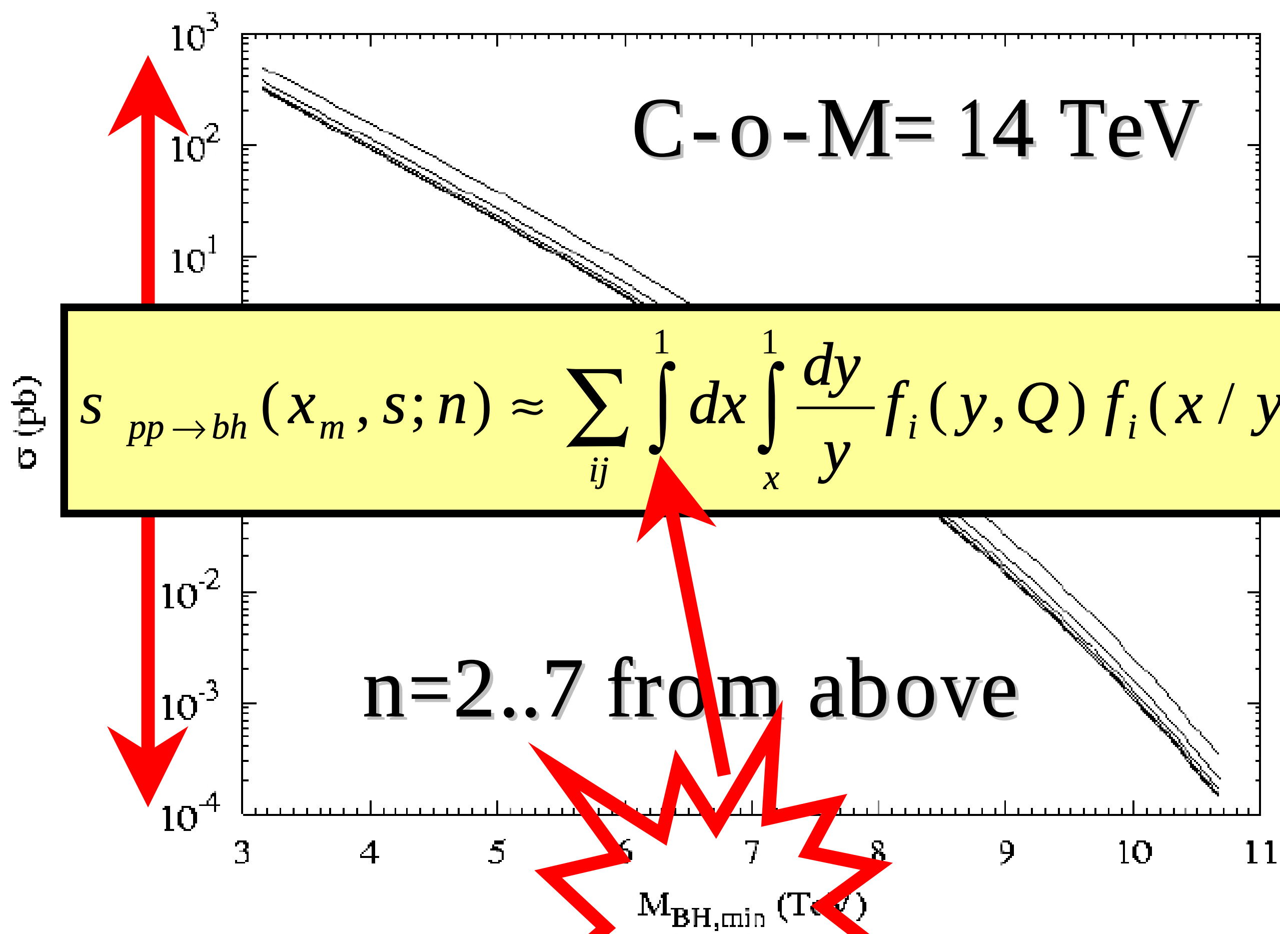
Up to 10^4 pb

Cross section at the 4-TeV Muon collider:

$\sigma \approx 10^2$ pb

Disadvantage!

BH cross section at the LHC:



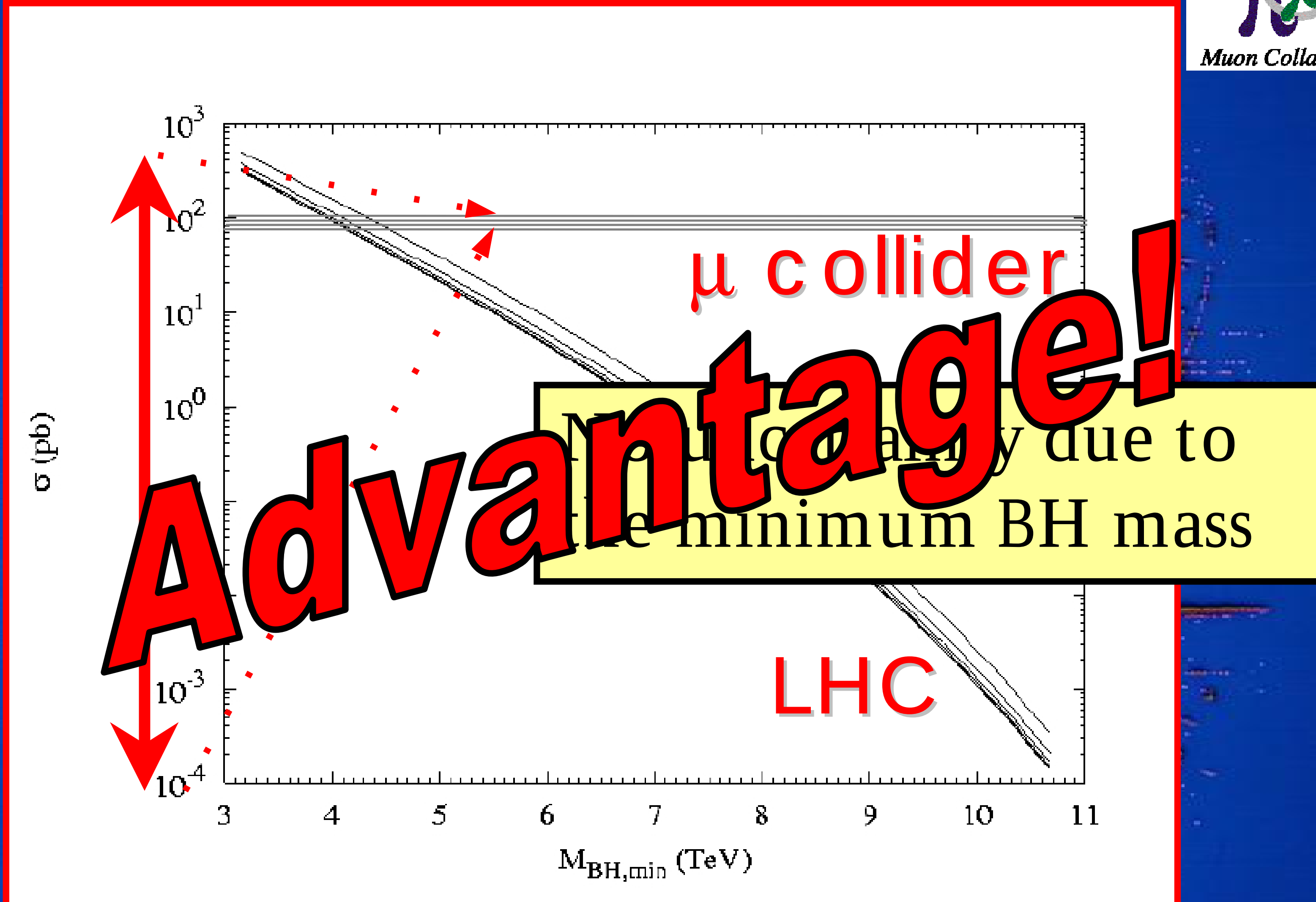
$$s_{pp\to bh}(x_m, s; n) \approx \sum_{ij} \int^{1} dx \int_{x}^{1} \frac{dy}{y} f_i(y,Q)\, f_i(x/y,Q)\, s_{bh}(xs;n)$$

BH cross section at the muon collider:

$$s_{mm \to bh}(s;n) \approx \int^{1} d^{2}e \; f(e_1) f(e_2) s_{bh}[s(e_1, e_2); n]$$

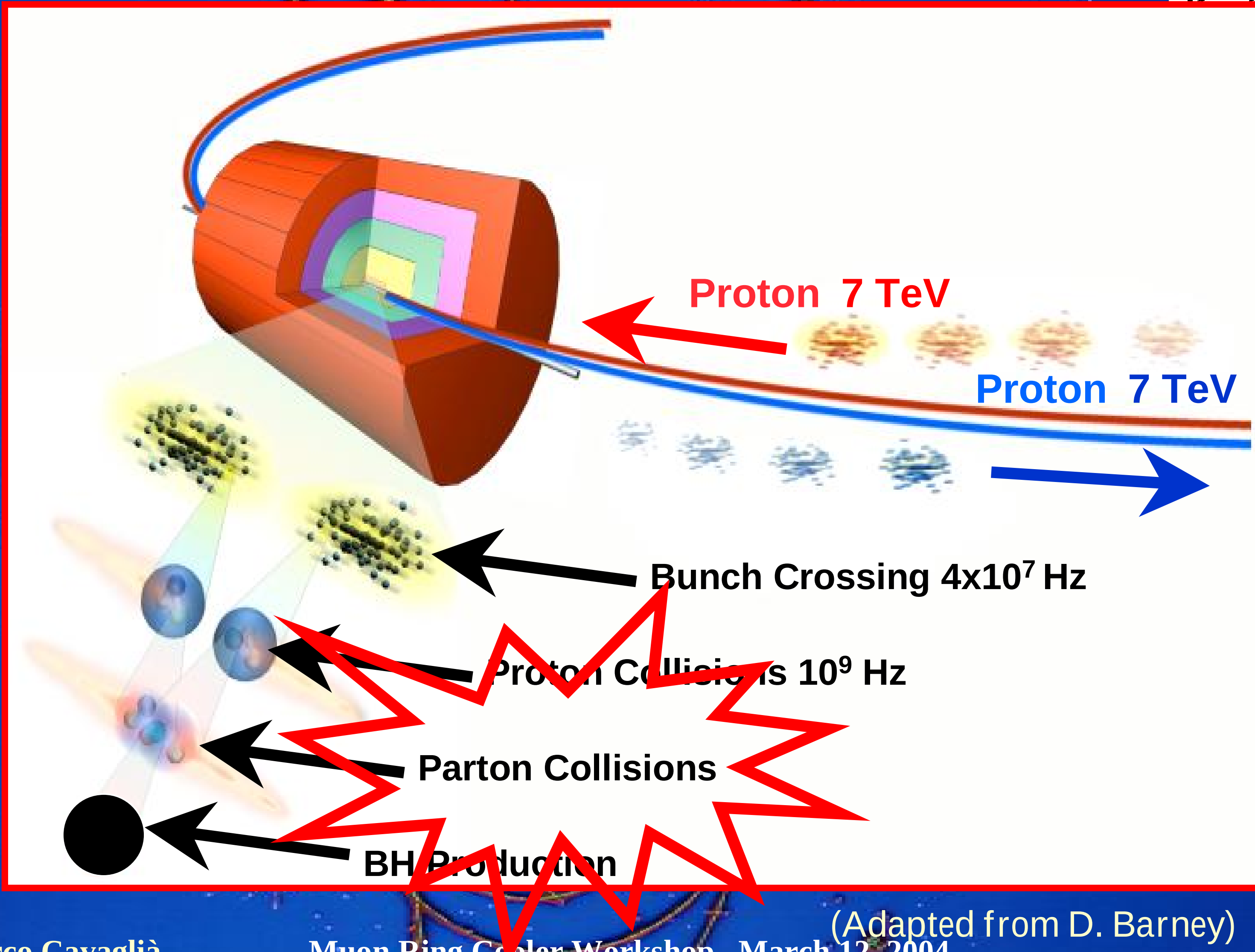
$$f(e_1) \approx d\left(e_1 - e_0\right), \qquad f(e_2) \approx d\left(e_2 - e_0\right)$$

If $\varepsilon_m << \varepsilon_0$, the cross section does not depend on the minimum BH mass

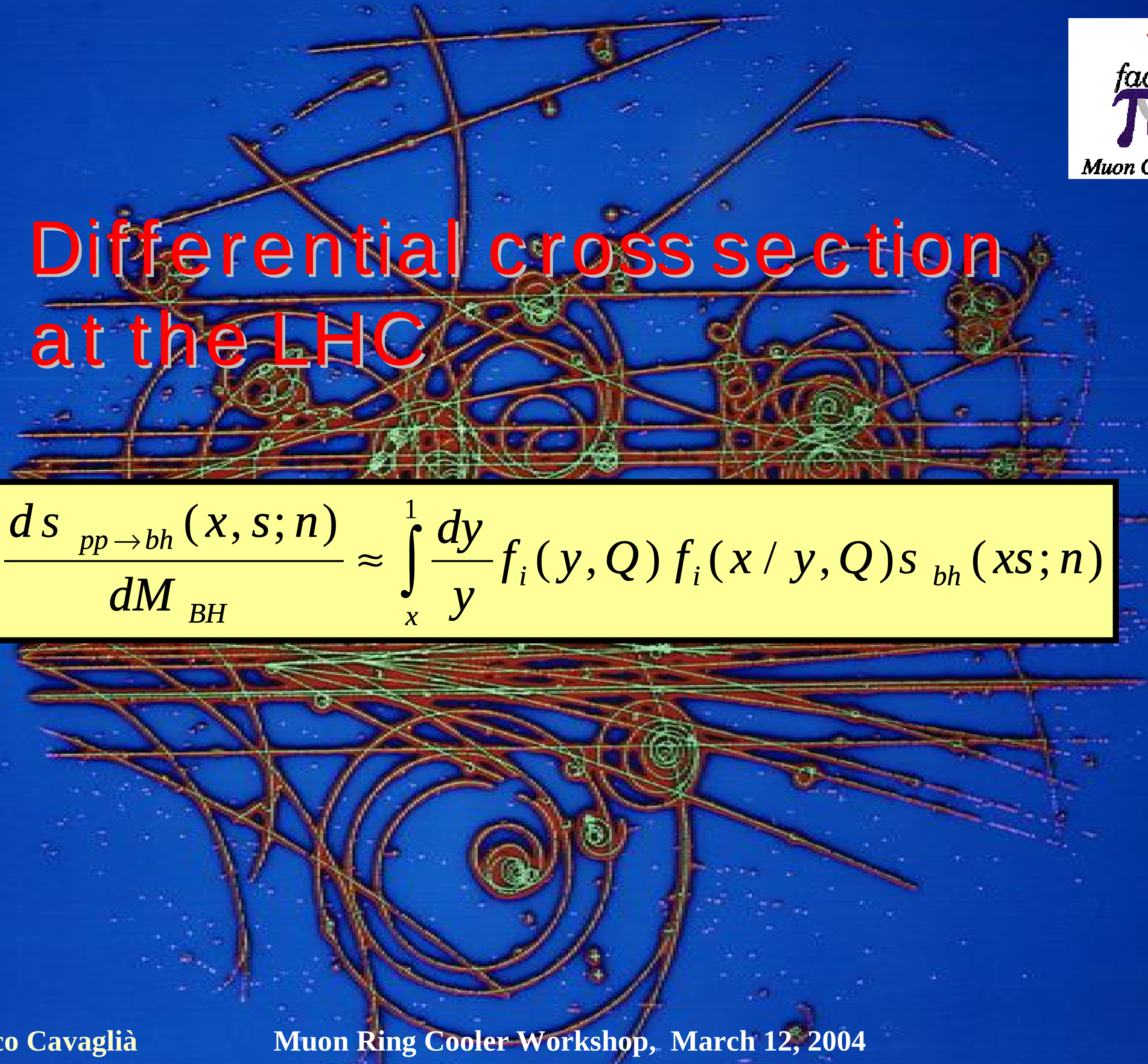


Advantage!
μ collider
LHC
due to
minimum BH mass
σ (pb)
10^3
10^2
10^1
10^0
10^{-3}
10^{-4}
3
4
5
6
7
8
9
10
11
$M_{BH,min}$ (TeV)

BH collisions at LHC



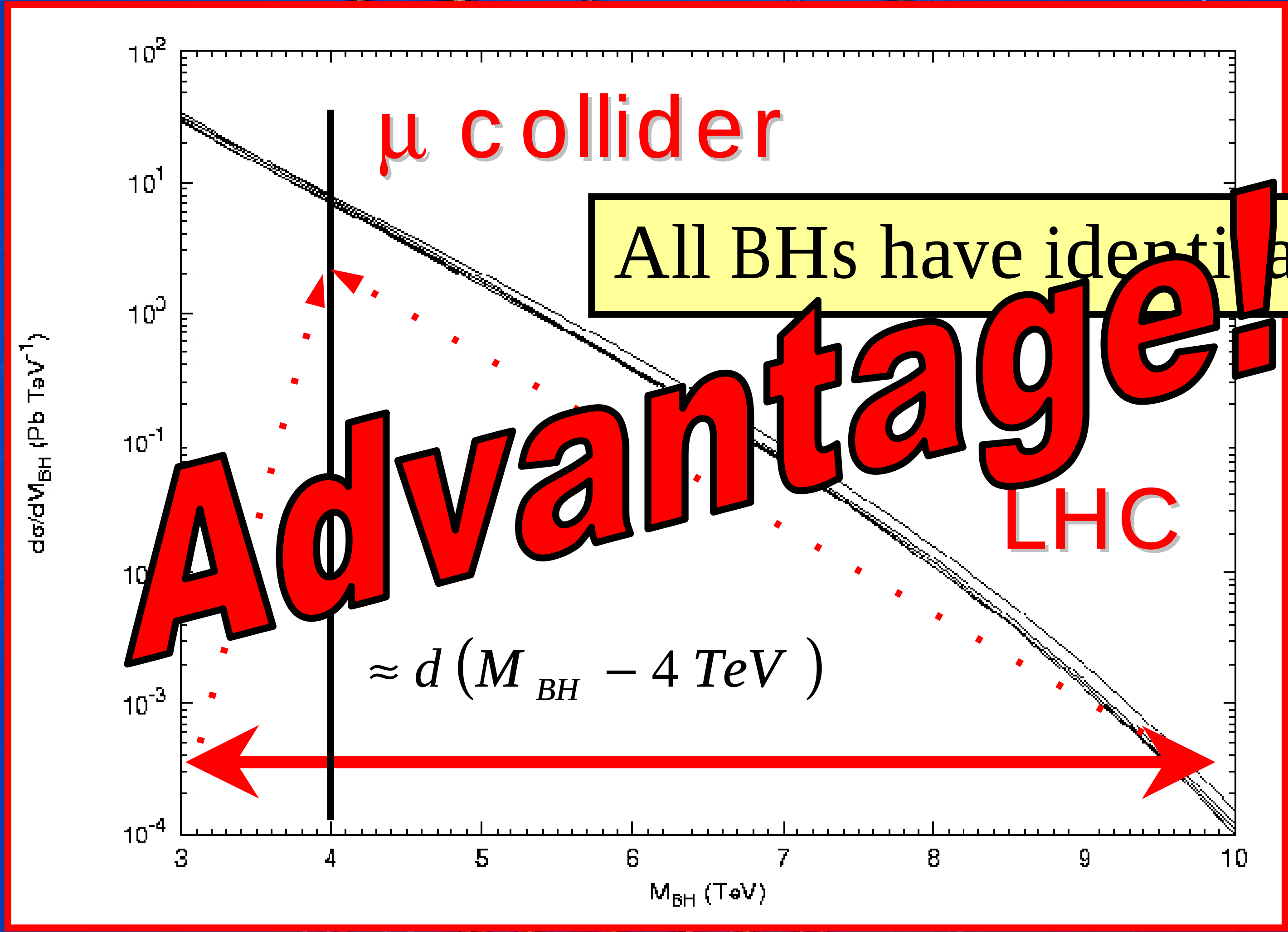
(Adapted from D. Barney)



Differential cross section at the LHC

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

Distribution of BH masses



What we (want to) do:

- Compute the cross section taking into account the beam profile
- Systematical analysis of the parameter space
- Write an improved montecarlo for BH events at the LHC and at the muon collider
- Simulate BH events at the LHC and at the muon collider
- Analysis and comparison

Conclusion

Muon Collaboration

- If large extra dimensions exist Þ Planck scale ~ TeV
- Nonperturbative quantum gravity effects at E ~ TeV
- Creation of black holes & branes at the muon collider!
- If not, constraints on the Planck scale. If yes, new physics at the TeV scale
- Possible tests of strong gravitational effects:
  - Hawking radiation
  - Generalized uncertainty principle