Quantum black holes at the LHC

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Frameworks for Quantum Black Holes (QBHs) at 1 TeV

- Large extra-dimensions
- Large hidden sector (and 4 dimensions)
- Common feature: gravity becomes strong at 1 TeV and QBHs could be produced at colliders

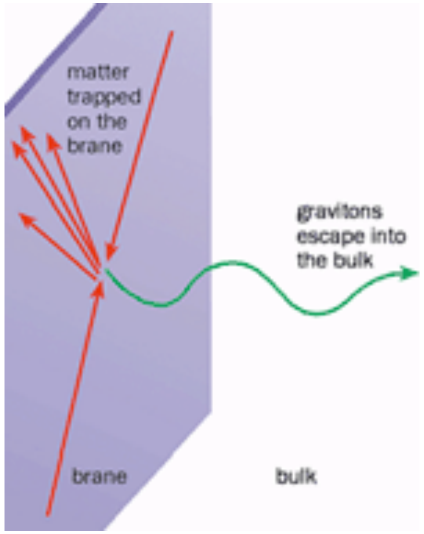
TeV gravity extra-dimensions

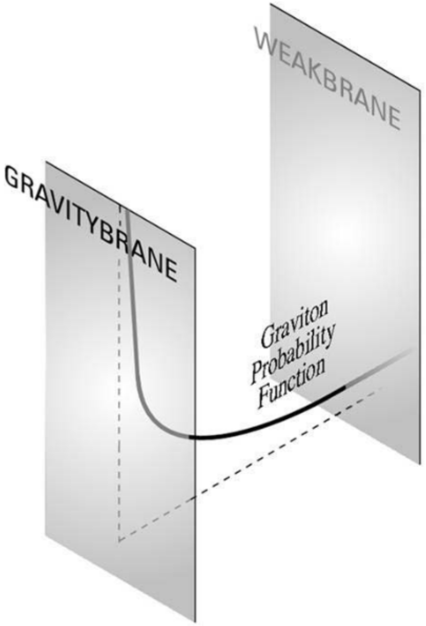
$$\int d^4x\, d^{d-4}x' \sqrt{-g}\ (M_*^{d-2}\mathcal{R} + \cdots\ ) \qquad M_P^2 = M_*^{d-2}V_{d-4}$$

where M_P is the effective Planck scale in 4-dim

ADD brane world

RS warped extra-dimension



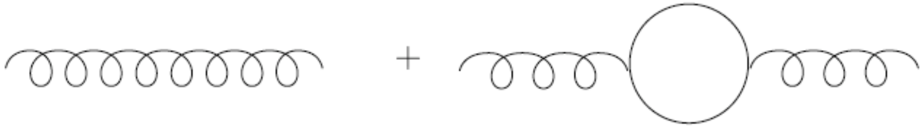


Running of Newton's constant

- Consider GR with a massive scalar field

$$S=\int d^4x\sqrt{-g}\left(-\frac{1}{16\pi G}R+\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-\frac{m^2}{2}\phi^2\right)$$

- Let me consider the renormalization of the Planck mass:



$$M(\mu)^2 \;=\; M(0)^2-\frac{\mu^2}{12\pi}\left(N_0+N_{1/2}-4N_1\right)$$

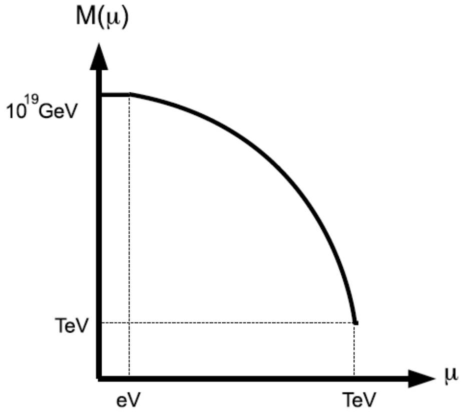
- Can be derived using the heat kernel method (regulator preserves symmetries!)
- Gravity becomes strong if:

$$M(\mu_*)\sim\mu_*$$

A large hidden sector!

XC, Hsu & Reeb (2008)

- Gravity can be strong at 1 TeV if Newton's constant runs fast somewhere between eV range and 1 TeV.



- Strong gravity at μ_*=1 TeV takes N=10^{33} fields.
- We assume that these new fields only interact gravitationally with the standard model.
- This will reproduce a lot of the phenomenology of models with large extra-dimensions

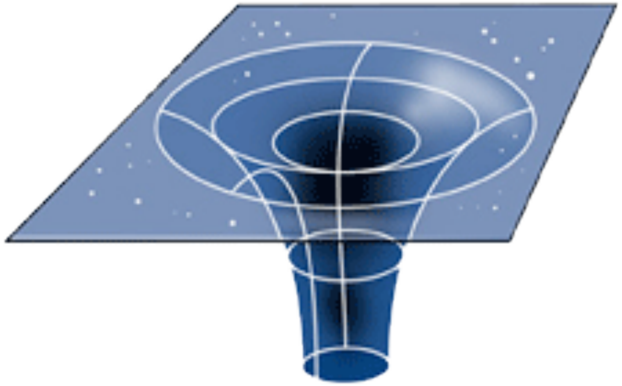
A brief review on the formation of black holes

When does a black hole form?

This is well understood in general relativity with symmetrical distribution of matter:

$$c^2 d\tau^2 = \left(1 - \frac{r_s}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - \frac{r_s}{r}} - r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$r_s = \frac{2GM}{c^2}$$



But, what happens in particle collisions at extremely high energies?

Small black hole formation

(in collisions of particles)

- In trivial situations (spherical distribution of matter), one can solve explicitly Einstein's equations e.g. Schwarzschild metric.
- In more complicated cases one can't solve Einstein equations exactly and one needs some other criteria.
- Hoop conjecture (Kip Thorne): if an amount of energy E is confined to a ball of size R, where R < E, then that region will eventually evolve into a black hole.

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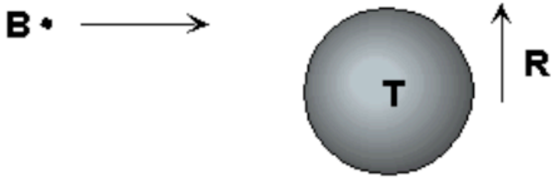
- Hoop conjecture (Kip Thorne): if an amount of energy E is confined to a ball of size R, where R < E, then that region will eventually evolve into a black hole.
- Cross-section for semi-classical BHs (closed trapped surface constructed by Eardley & Giddings, (semi-classical: Hsu)):

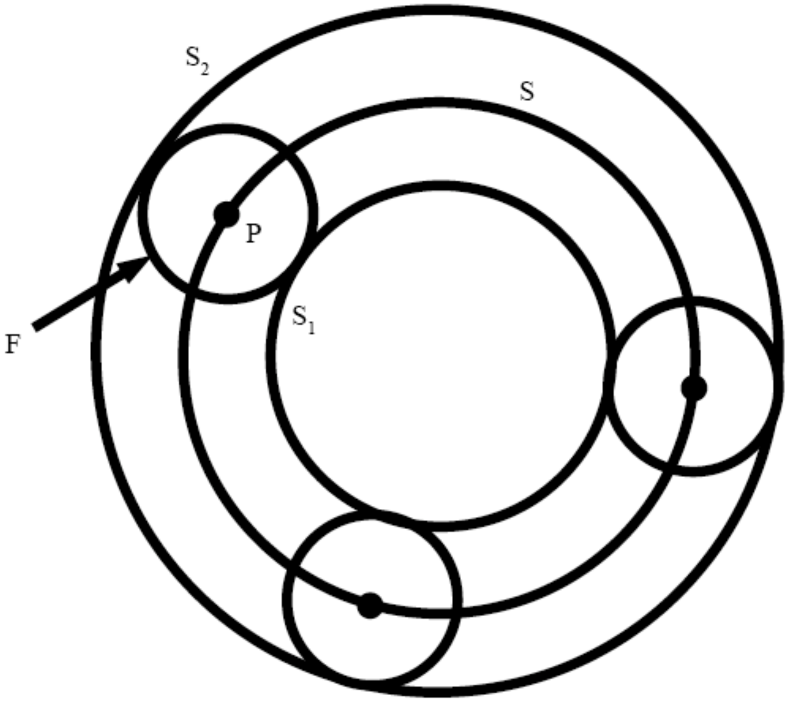
$$\hat{\sigma} \approx \pi r_s^2 \qquad r_s(M_{\mathrm{BH}}) = \frac{1}{M_D}\left[\frac{M_{\mathrm{BH}}}{M_D}\right]^{\frac{1}{1+n}}\left[\frac{2^n \pi^{(n-3)/2}\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{1+n}}$$



The cross section for point-like particles colliding with a sphere is just the area of the sphere projected onto the transverse plane, that is, a circular disk of radius R.

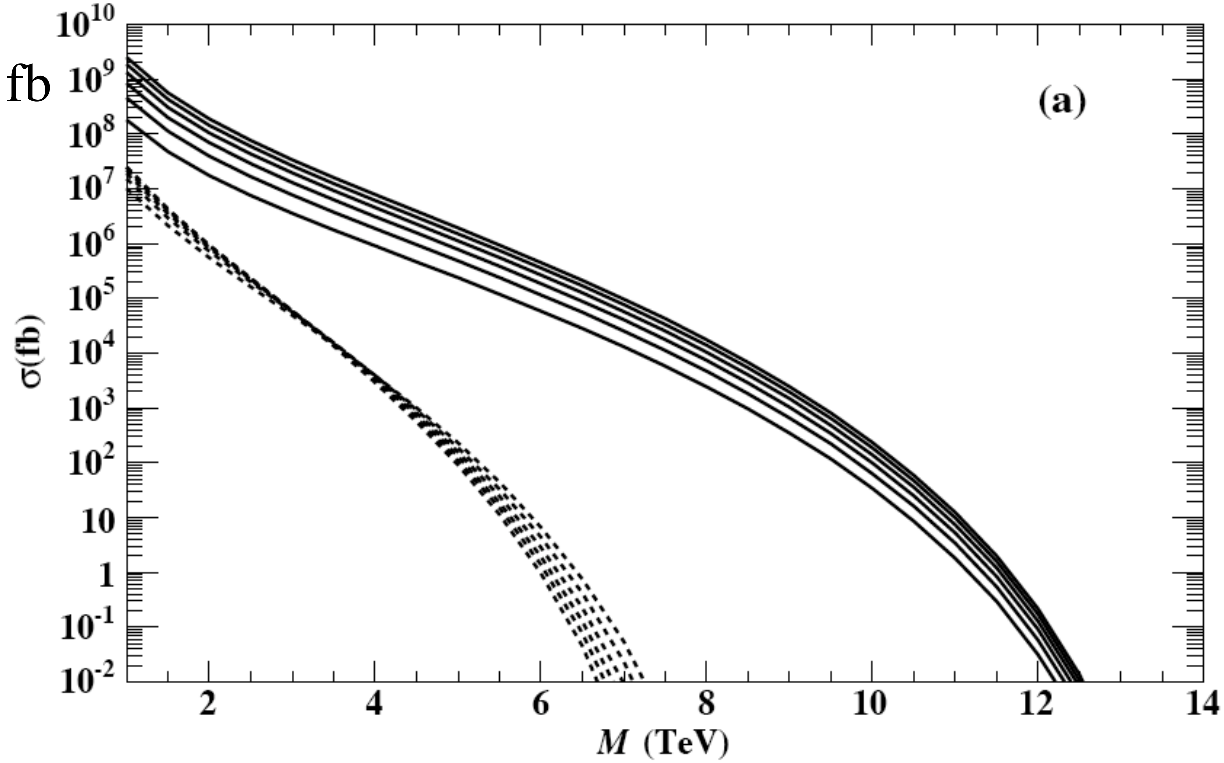
$$r_s = \frac{2GM}{c^2}$$

- A CTS is a compact spacelike two-surface in space-time such that outgoing null rays perpendicular to the surface are not expanding.



- At some instant, the sphere S emits a flash of light. At a later time, the light from a point P forms a sphere F around P, and the envelopes S_1 and S_2 form the ingoing and outgoing wavefronts respectively. If the areas of both S_1 and S_2 are less than of S, then S is a closed trapped surface.

Small BHs @ LHC (studied by Anchordoqui et al. and many other people, this plot is from Gingrich, hep-ph/0609055)



σ(pp->BH+X), M_D=1 TeV

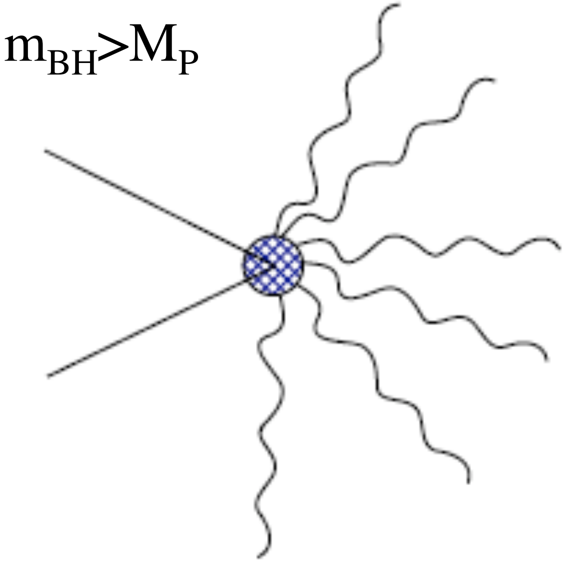
$$\sigma \sim \frac{1}{M_D^2}\left(\frac{\sqrt{s}}{M_D}\right)^{\frac{2}{1+n}}$$

For partons, σ increases with energy but note that PDFs go so fast to zero that they dominate. In other words quantum black holes dominate!

This shows the significance of the inelasticity in BH production

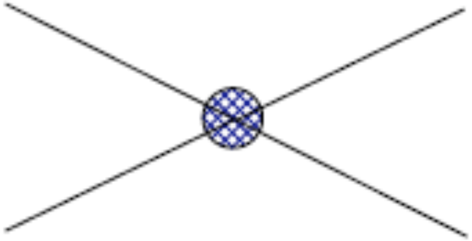
Semi-classical (thermal) versus quantum black hole: calculate the entropy!

$m_{BH} > M_P$



thermal black hole
large entropy

$m_{BH} \sim M_P$



quantum black hole
small entropy

$$S = \frac{1+n}{2+n}\frac{M_{BH}}{T_{BH}}$$

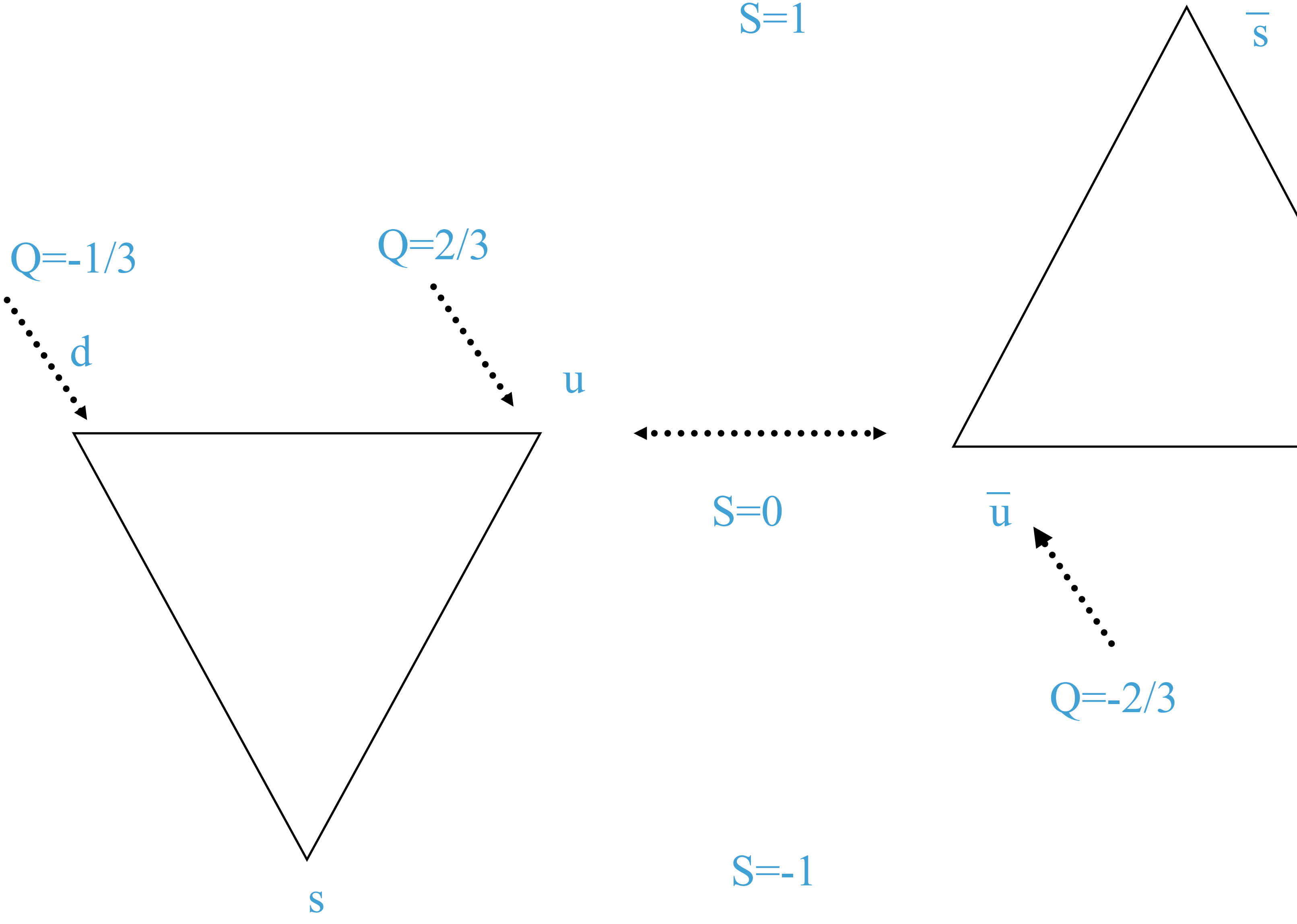
$$\langle N \rangle \propto \left(\frac{M_{BH}}{M_\star} \right)^{\frac{n+2}{n+1}}$$

Keep in mind that E-G construction only works for $m_{BH} >> M_P$

Assumptions on Quantum Black Holes decays

- Gauge invariance is preserved (conservation of U(1) and $SU(3)_C$ charges)
- Quantum Black Holes do not couple to long wavelength and highly off-shell perturbative modes.
- Global charges can be violated. Lepton flavor is not conserved. Lorentz invariance could be broken or not.
- Gravity is democratic.
- We can think of quantum black holes as gravitational bound states.
- Cross-sections are given by the Eardley-Giddings construction (justify by recent results by Veneziano et al. who are finding black holes precursors using perturbation theory).
- These considerations apply to our model but also to ADD and RS.

The Quark Model



S=1

$\bar{s}$

Q=-1/3

Q=2/3

d

u

S=0

$\bar{u}$

$\bar{d}$

Q=-2/3

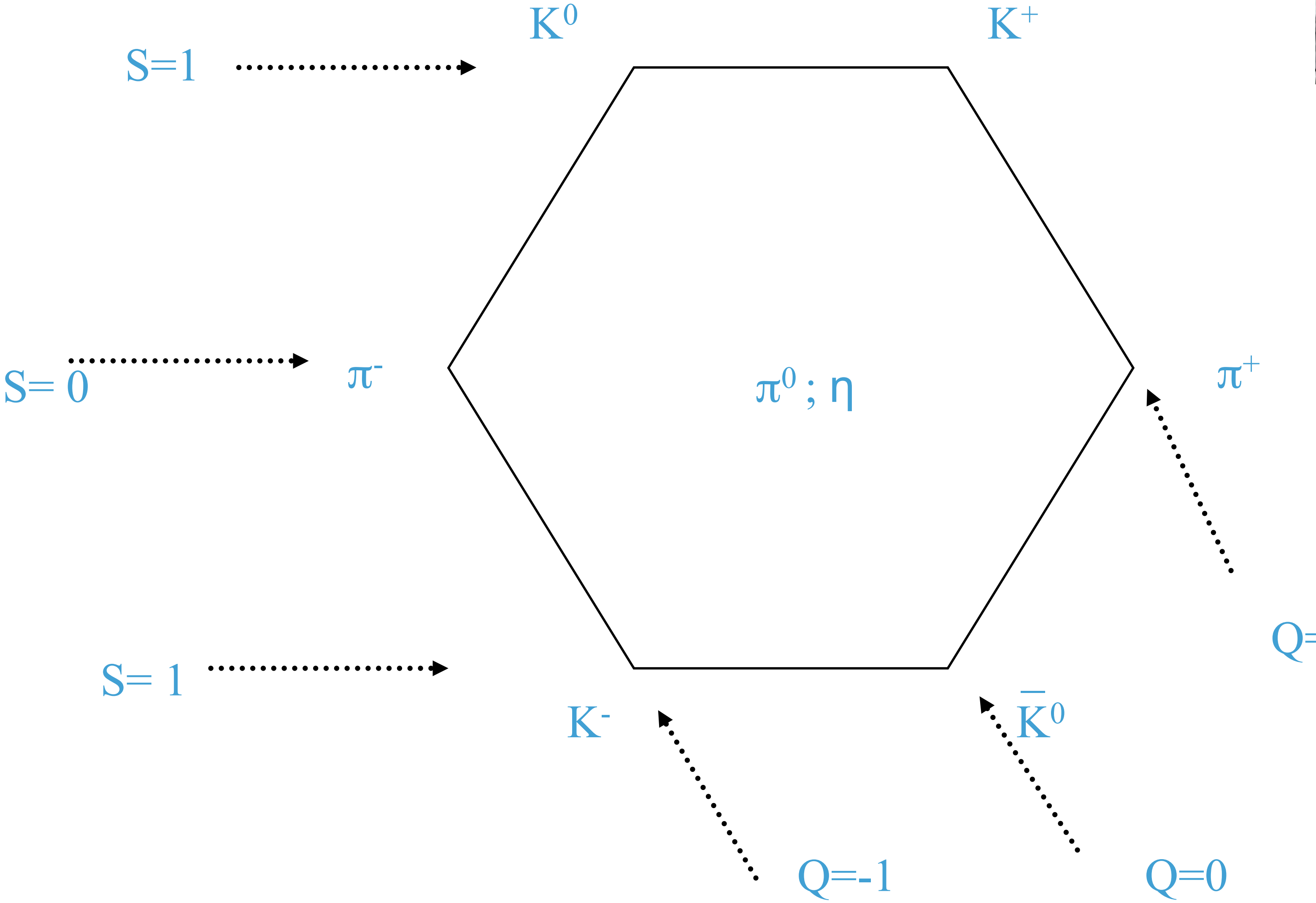
Q=-1/3

s

S=-1

THE EIGHTFOLD WAY

The Meson Octet



K^0 K^+

S=1

S= 0 π^- π^0 ; η π^+

S= 1

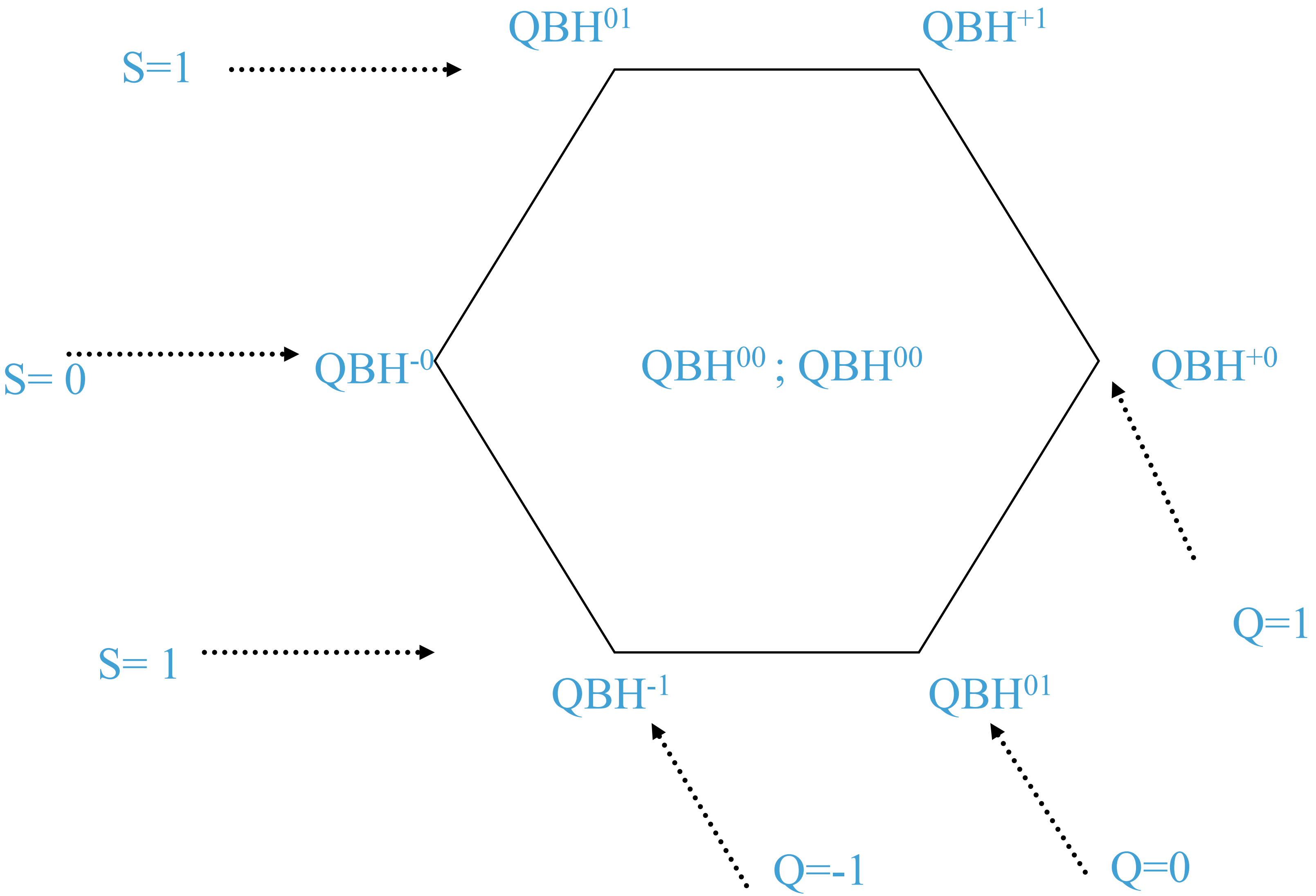
K^- $\bar{K}^0$

Q=1

Q=-1 Q=0

THE EIGHTFOLD WAY FOR QUANTUM BLACK HOLES

The Quantum Black Hole Octet



S=1

QBH^{01}

QBH^{+1}

S= 0

QBH^{-0}

QBH^{00} ; QBH^{00}

QBH^{+0}

Q=1

S= 1

QBH^{-1}

QBH^{01}

Q=-1

Q=0

QCD for Quantum Black Holes

- Quantum Black Holes are classified according to representations of $SU(3)_C$.
- For LHC the following Quantum Black Holes are relevant:

$$\mathbf{3} \times \overline{\mathbf{3}} = \mathbf{8} + \mathbf{1}$$

$$\mathbf{3} \times \mathbf{3} = \mathbf{6} + \overline{\mathbf{3}}$$

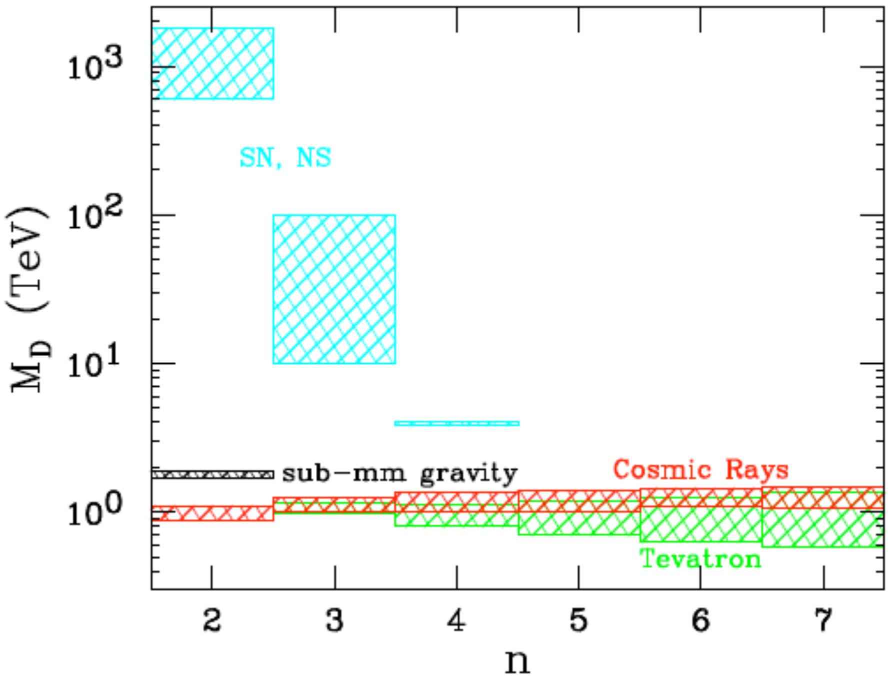
$$\mathbf{3} \times \mathbf{8} = \mathbf{3} + \overline{\mathbf{6}} + \mathbf{15}$$

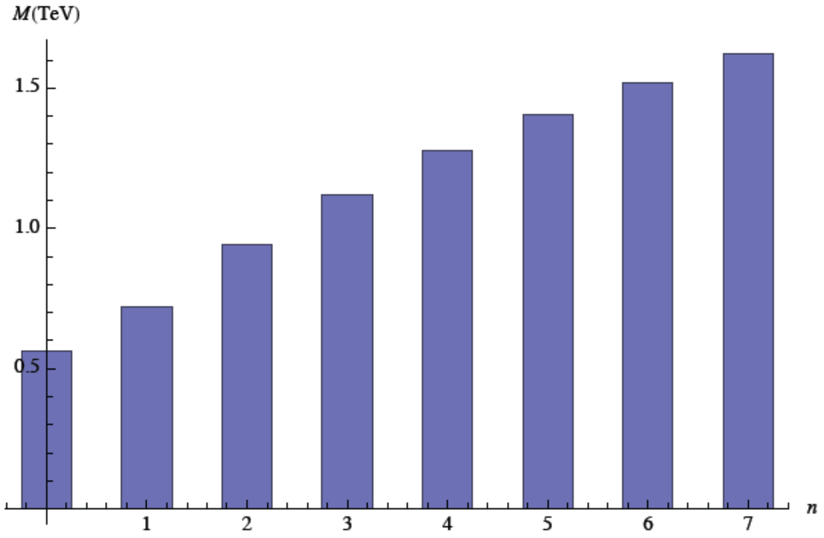
$$\mathbf{8} \times \mathbf{8} = \mathbf{1}_S + \mathbf{8}_S + \mathbf{8}_A + \mathbf{10} + \overline{\mathbf{10}}_A + \mathbf{27}_S$$

- They can have non-integer QED charges.
- They can carry a $SU(3)_C$ charge.

Bounds from cosmic rays:
depend on the composition of most energetic cosmic rays

- AGASA provides the tightest bound on TeV extra-dimensions with n>5 (Anchordoqui et al. hep-ph/0307228)
- In 4 dimensions, M_4>550 GeV





TeV QBHs @ LHC

- At the LHC we could get up to σ(pp -> QBH + X) ~ 10^5 fb for a reduced Planck scale of ~ 1 TeV. For a luminosity of 100 fb^{-1}, we expect 10^7 events at the LHC (for RS σ(pp -> QBH + X) ~ 2.10^6 fb and ADD with n=6 σ(pp -> QBH + X) ~ 10^7 fb)
- Very interesting signatures pp -> QBH -> lepton+ jet
- Gravity is democratic: lepton can be e, μ or τ
- A lot of two jets back to back events (dominant decay mode for QBH at LHC)

A few technical details

- Inclusive cross-sections (using Eardley & Giddings):

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

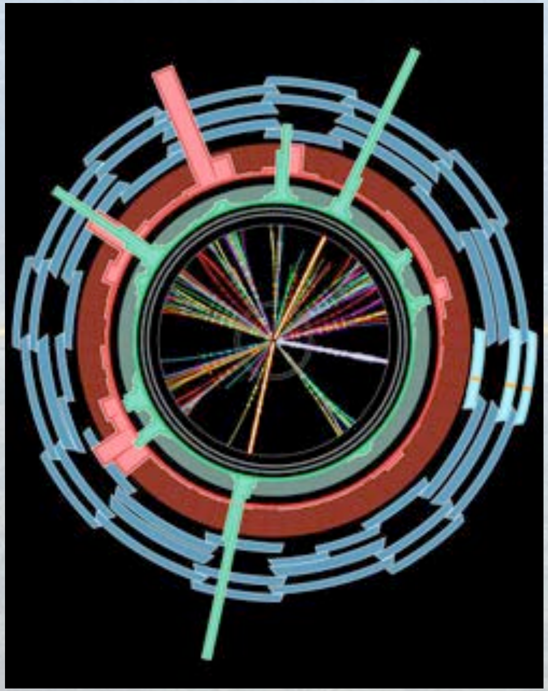
- cross-section for the production of one specific QHB:

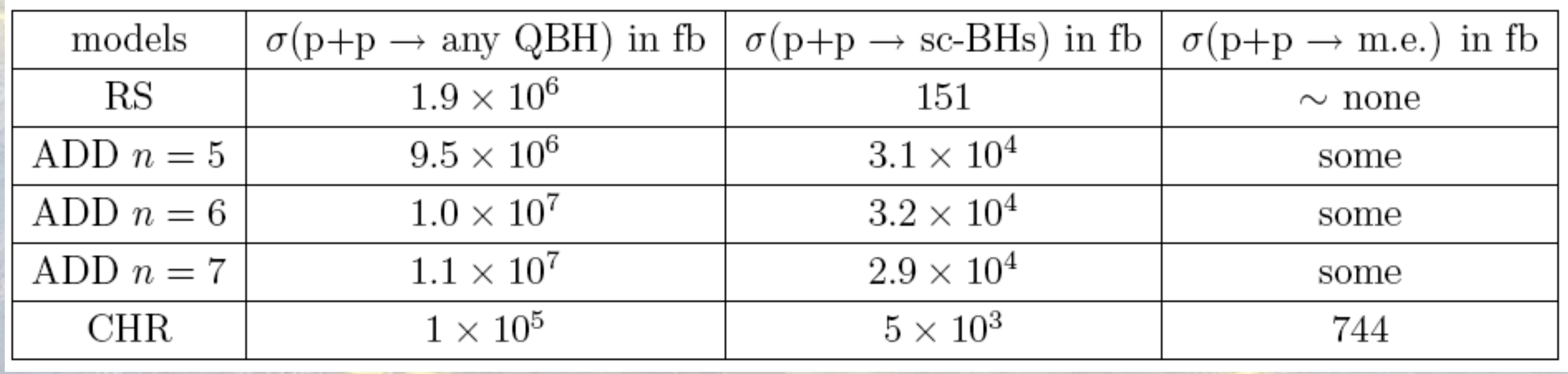
$$\sigma^{pp}(s, x_{min}, n, M_D) = \int_0^1 2z dz \int_{\frac{(x_{min} M_D)^2}{y(z)^2 s}}^1 du \int_u^1 \frac{dv}{v} \times F(n) \pi r_s^2(us, n, M_D) \left(\frac{1}{9} \sum_{i,j=q,\bar{q}} f_i(v, Q) f_{\bar{j}}(u/v, Q) + \frac{1}{64} f_g(v, Q) f_g(u/v, Q) \right)$$

QBH_1^0

cross-sections @ LHC

XC, Gong & Hsu (2008)

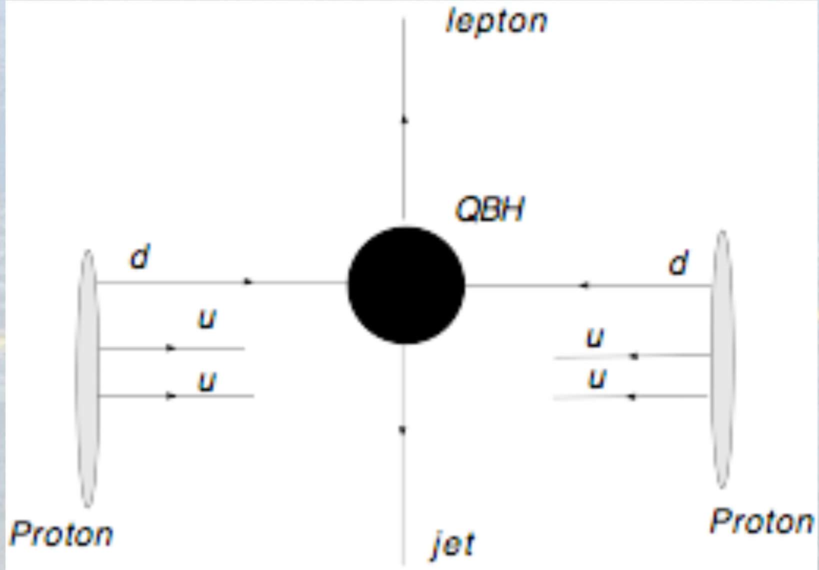


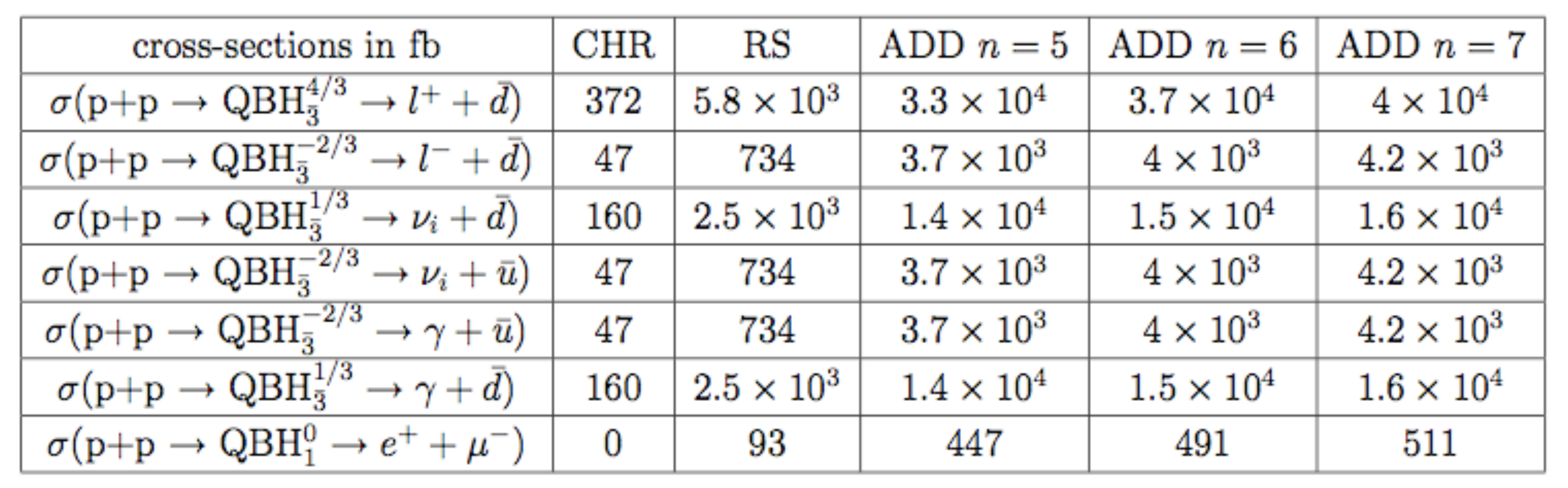


models	σ(p+p $\rightarrow$ any QBH) in fb	σ(p+p $\rightarrow$ sc-BHs) in fb	σ(p+p $\rightarrow$ m.e.) in fb
RS	1.9×10^6	151	$\sim$ none
ADD $n = 5$	9.5×10^6	3.1×10^4	some
ADD $n = 6$	1.0×10^7	3.2×10^4	some
ADD $n = 7$	1.1×10^7	2.9×10^4	some
CHR	1×10^5	5×10^3	744

cross-sections @ LHC

XC, Gong & Hsu (2008)





cross-sections in fb	CHR	RS	ADD $n = 5$	ADD $n = 6$	ADD $n = 7$
$\sigma(\mathrm{p+p} \to \mathrm{QBH}_{\bar{3}}^{4/3} \to l^+ + \bar{d})$	372	5.8×10^3	3.3×10^4	3.7×10^4	4×10^4
$\sigma(\mathrm{p+p} \to \mathrm{QBH}_{\bar{3}}^{-2/3} \to l^- + \bar{d})$	47	734	3.7×10^3	4×10^3	4.2×10^3
$\sigma(\mathrm{p+p} \to \mathrm{QBH}_{\bar{3}}^{1/3} \to \nu_i + \bar{d})$	160	2.5×10^3	1.4×10^4	1.5×10^4	1.6×10^4
$\sigma(\mathrm{p+p} \to \mathrm{QBH}_{\bar{3}}^{-2/3} \to \nu_i + \bar{u})$	47	734	3.7×10^3	4×10^3	4.2×10^3
$\sigma(\mathrm{p+p} \to \mathrm{QBH}_{\bar{3}}^{-2/3} \to \gamma + \bar{u})$	47	734	3.7×10^3	4×10^3	4.2×10^3
$\sigma(\mathrm{p+p} \to \mathrm{QBH}_{\bar{3}}^{1/3} \to \gamma + \bar{d})$	160	2.5×10^3	1.4×10^4	1.5×10^4	1.6×10^4
$\sigma(\mathrm{p+p} \to \mathrm{QBH}_{1}^{0} \to e^+ + \mu^-)$	0	93	447	491	511

Exclusive cross-sections

- Branching ratios are obtained by counting the number of possible final states assuming that gravity is democratic (typically 1/100 for SM).

- Implementation in Monte-Carlo programs: code is being developed as we speak by Gingrich.

Black holes have already been spotted in Belgium

This is a pub
called “black hole”
close to my
in-laws’ place.

So far Belgium has not imploded…

despite black holes

Conclusions

- There are different options for TeV quantum gravity.
- Quantum gravity could be around the corner even in 4 dimensions: this is really an experimental question.
- Unique opportunity to learn about gravity at short distances and in particular about black holes.
- Gravity is still a fascinating playground.
- LHC phenomenology would be extremely rich.
- Exciting flavor physics in quantum black holes scenarios.

Thanks for your attention