# Noncommutative geometry inspired black holes in higher dimensions at the LHC

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# Introduction

- Embed model of noncommutative geometry inspired black holes into peridium of large extra dimension.
- Relate noncommutativity scale to higher-dimensional Planck scale.
- One of the main consequences is the prediction of a black hole remnant.
- Mass of remnant can be well above the Planck scale.
- Experimental signatures quite different from usual black hole studies at LHC.
- Discovery would result in additional mass threshold above Planck scale at which new physics occurs.

# Noncommutivity

- Concept of quantization of spacetime considered to help regulate short-distance behaviour of point interactions.
- Geometry and noncommutative algebras developed in theory of noncommutative geometry.
- String theory and M-theory interested in generalization of quantum field theory to noncommutative coordinates.

Treat coordinates as operators in $D$ dimensions

$$\left[\hat{x}^A, \hat{x}^B\right] = i\theta^{AB} \equiv i\frac{\epsilon^{AB}}{\Lambda_{\mathrm{NC}}^2}$$

$\Lambda_{\mathrm{NC}}$ scale associates with noncommutative

# Effective Theory of Quantum Gravity

- Noncommutative equivalent of general relativity not yet mature enough to allow phenomenological studies.
- Formulate model in which general relativity in usual commutative form, but smear matter distributions on a length scale of $O(1/\Lambda_{NC})$.
- Effective approach could be considered as improvement to semiclassical gravity.

Smeared matter distribution

$$\rho = \frac{m}{(4\pi\theta)^{(n+3)/2}} e^{-r^2/(4\theta)}$$

We take $\sqrt{\theta} = 1/\Lambda_{NC}$

$D - 1 = n + 3$ space dimensions

# Black Hole Production

- Replace delta-function mass distributions with smeared distributions in energy-momentum tensor.
- Solve for spherically symmetric and static metric.

$$\frac{m}{M_D} = \frac{k_n}{P\left(\frac{n+3}{2}, \frac{r_g^2}{4\theta}\right)} (r_g M_D)^{n+1}$$

Gravitational radius not in closed form

$$k_n = \frac{n+2}{2^n \pi^{(n-3)/2} \Gamma\left(\frac{n+3}{2}\right)}$$

$$P\left(\frac{n+3}{2}, \frac{r_g^2}{4\theta}\right) = \frac{1}{\Gamma\left(\frac{n+3}{2}\right)} \int_0^{r_g^2/(4\theta)} dt\, e^{-t} t^{(n+3)/2-1}$$

Regularized incomplete gamma function from below

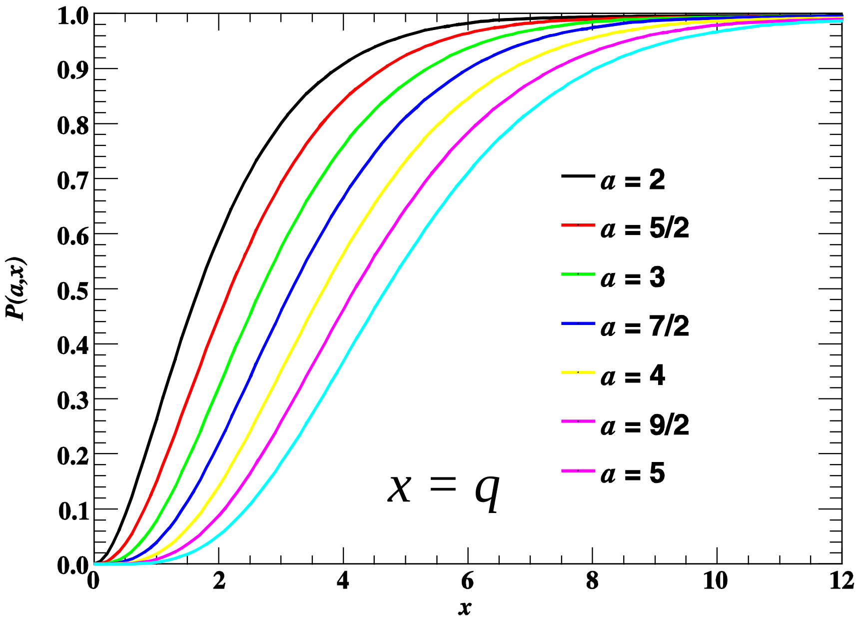
# Incomplete Gamma Function

Since $n$ integer, simpler notation

$$F_a(q) \equiv P\left[(n+3)/2, r_g^2/(4\theta)\right]$$

$$a = (n+3)/2$$

$$q = r_g^2/(4\theta)$$




- Can not approximate $F_a(q)$.
- Solve for $r_g$ numerically.
- There is a minimum mass $m_{\min}$.
- Gravitational radius is double valued (two horizons) for $r_g > (r_g)_{\min}$.
- We need only consider outer gravitational radius.
- Insensitive to type of distribution function if $r_g > 1/\Lambda_{NC}$

# Parameters Space

- $1 < m_{\min}/M_D < 14/M_D$
- Minimize gravitational radius and solve for mass.

| $n$ | $M_D$ (TeV) |
|---|---|
| 2 | 4 |
| 3 | 1.2 |
| 4 | 0.94 |
| 5 | 0.86 |
| 6 | 0.83 |
| 7 | 0.80 |

$$F_a(q_0) - \frac{2q_0^a e^{-q_0}}{(n+1)\Gamma(a)} = 0$$

$$\sqrt{q_0}/2 = (r_g)_{\min}/\sqrt{\theta}$$

| $n$ | $(r_g)_{\min}/\sqrt{\theta}$ | $(m_{\min}/M_D)(\sqrt{\theta}M_D)^{-(n+1)}$ | $\sqrt{\theta}_{\min}M_D$ | $\sqrt{\theta}_{\max}M_D$ |
|---|---|---|---|---|
| 2 | 2.51 | 65.2 | 0.248 | 0.377 |
| 3 | 2.41 | 58.8 | 0.361 | 0.667 |
| 4 | 2.34 | 48.6 | 0.460 | 0.789 |
| 5 | 2.29 | 37.9 | 0.546 | 0.869 |
| 6 | 2.26 | 28.2 | 0.621 | 0.929 |
| 7 | 2.23 | 20.3 | 0.686 | 0.982 |

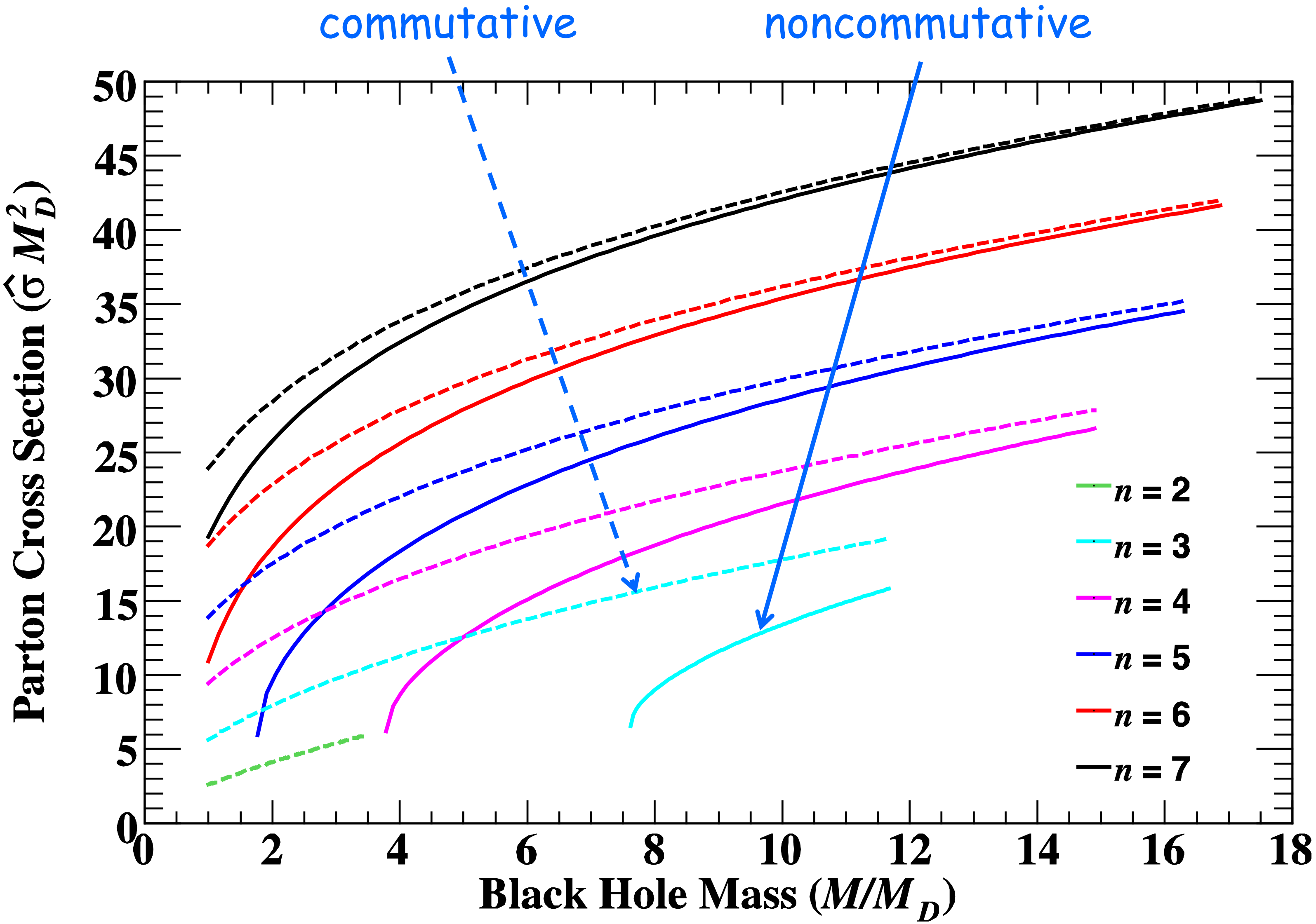
# Restrict Parameter Space

- 3 Parameters: $n$, $M_D$, $\sqrt{\theta}$
- Restricted by experimental lower bounds on $M_D$ and maximum LHC energy reach.
- Pick $\sqrt{\theta} M_D = 0.6$

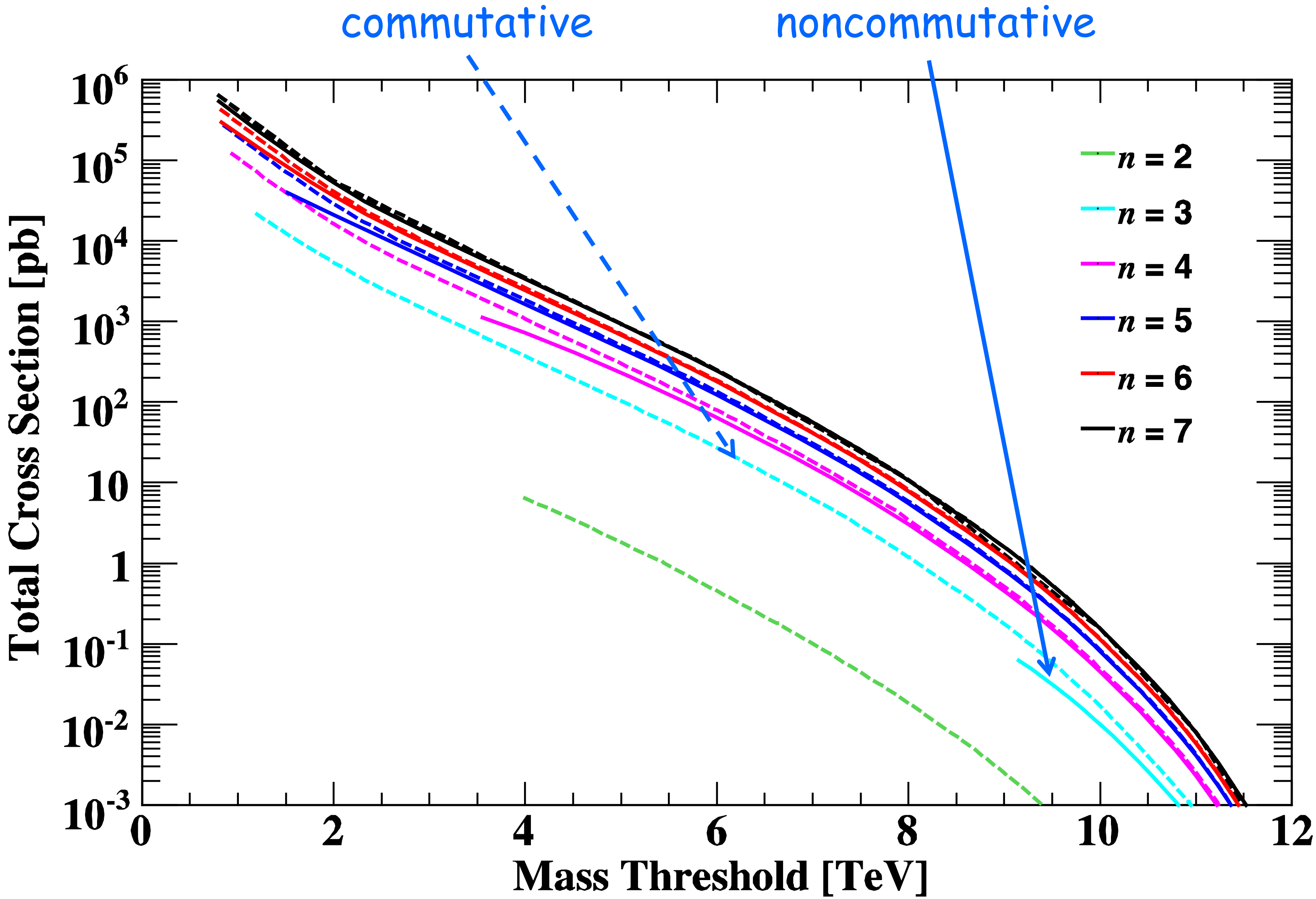
| $n$ | $(r_g)_{\min} M_D$ | $m_{\min}/M_D$ |
|---|---|---|
| 2 | 1.51 | 14.09 |
| 3 | 1.45 | 7.62 |
| 4 | 1.40 | 3.78 |
| 5 | 1.38 | 1.77 |
| 6 | 1.35 | 0.79 |
| 7 | 1.34 | 0.34 |

- $n \leq 2$, minimum mass above LHC energy reach.
- $n \geq 6$, minimum mass below Planck scale.
- $3 \leq n \leq 5$, minimum mass within LHC energy reach.

# Parton Cross Section



# Proton Cross Section



# Black Hole Decays

Assume thermal decays over most of mass range.

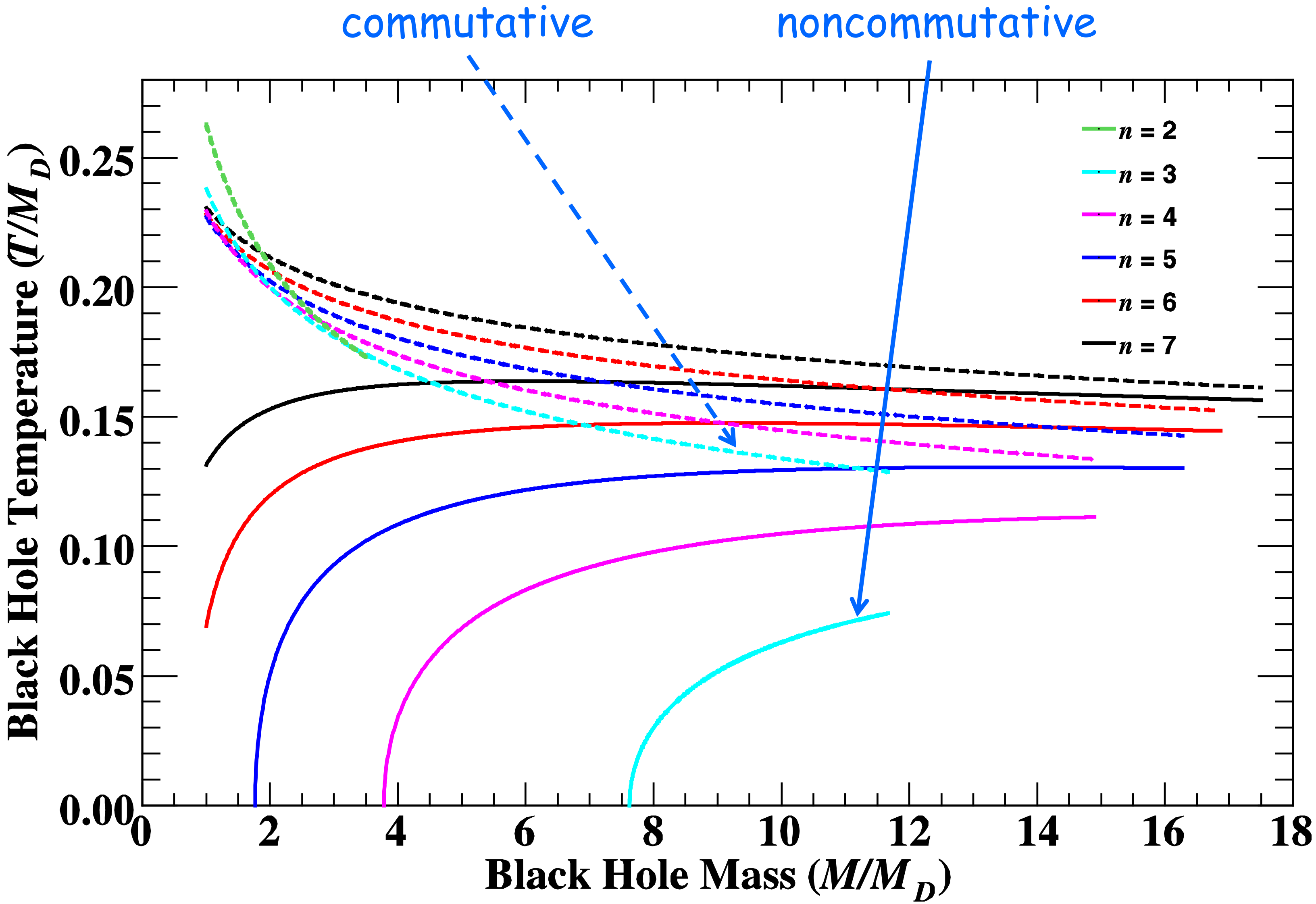
$$T = \frac{n+1}{4\pi r_g M_D}\left[1 - \frac{2q^{(n+3)/2}e^{-q}}{F_n(q)(n+1)\Gamma\left(\frac{n+3}{2}\right)}\right]$$

- Black hole cold, so use canonical ensemble approach to decay.
- No need to invoke a terminal-decay phase near end of decay.

  - Decay lifetime infinite as BH approaches minimum radius.
  - Temperature vanishes when radius at minimum.
  - Heat capacity also vanishes at minimum radius.

    $\rightarrow$ take black hole remnant to be stable.
    - Remnant mass can be above Planck scale.

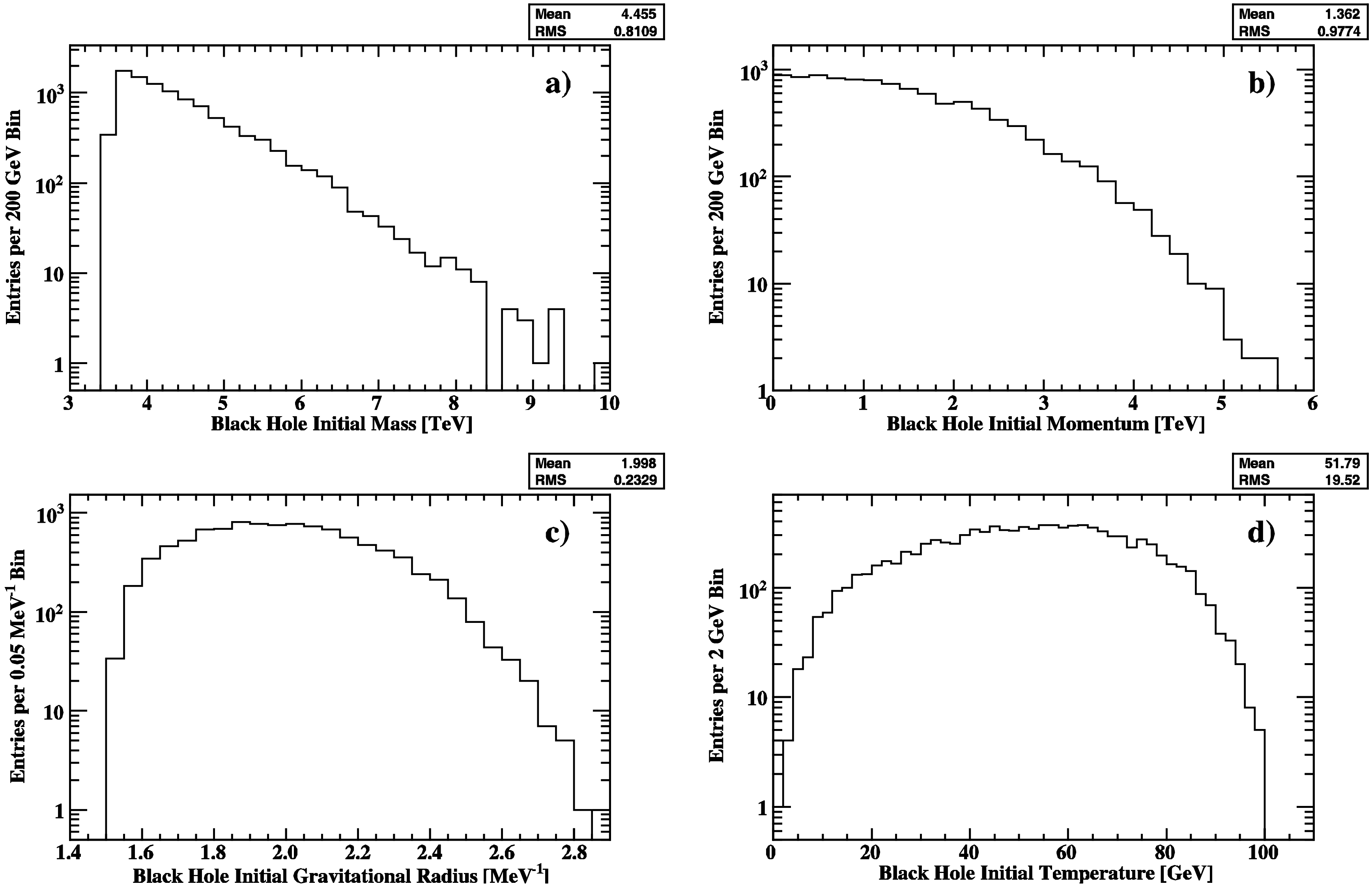
# Temperature



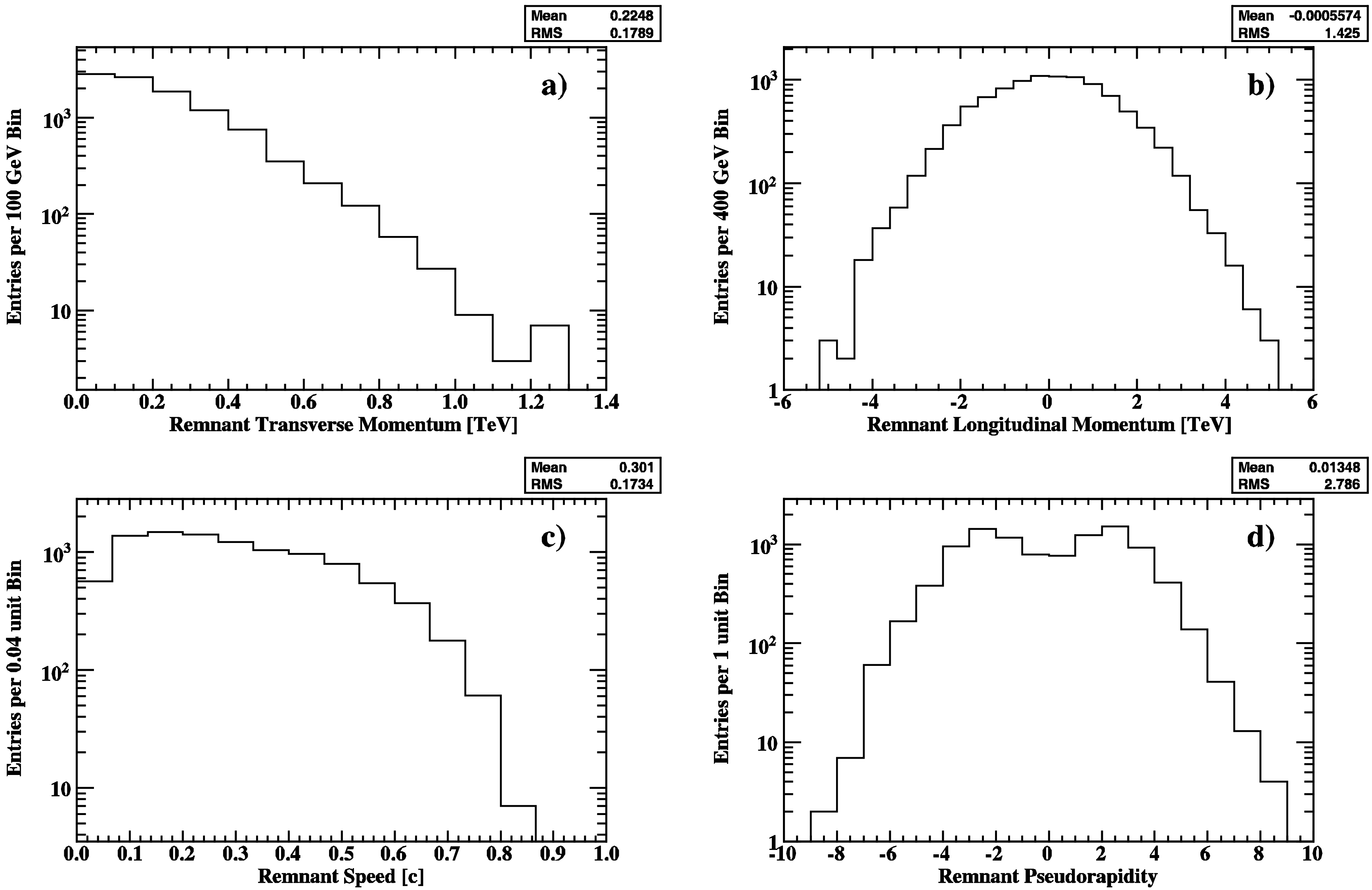
# Results

- Use CHARYBDIS:
  - Modify cross section (solve for radius numerically each time).
  - Modify temperature (solve for radius numerically each time).
  - Set minimum mass to $\max(M_D, m_{\min})$ for production and decay.
  - Use remnant final state option:
    - Baryon number 0
    - Charge -1, 0, +1.
    - Modify to have fixed decay mass.
  - Add cutoff of decay within 100 MeV of remnant mass.
- Consider interesting case: $n = 4$, $M_D = 0.94$ TeV, $\sqrt{\theta} = 0.64$ TeV$^{-1}$.
  - Remnant mass 3.6 TeV

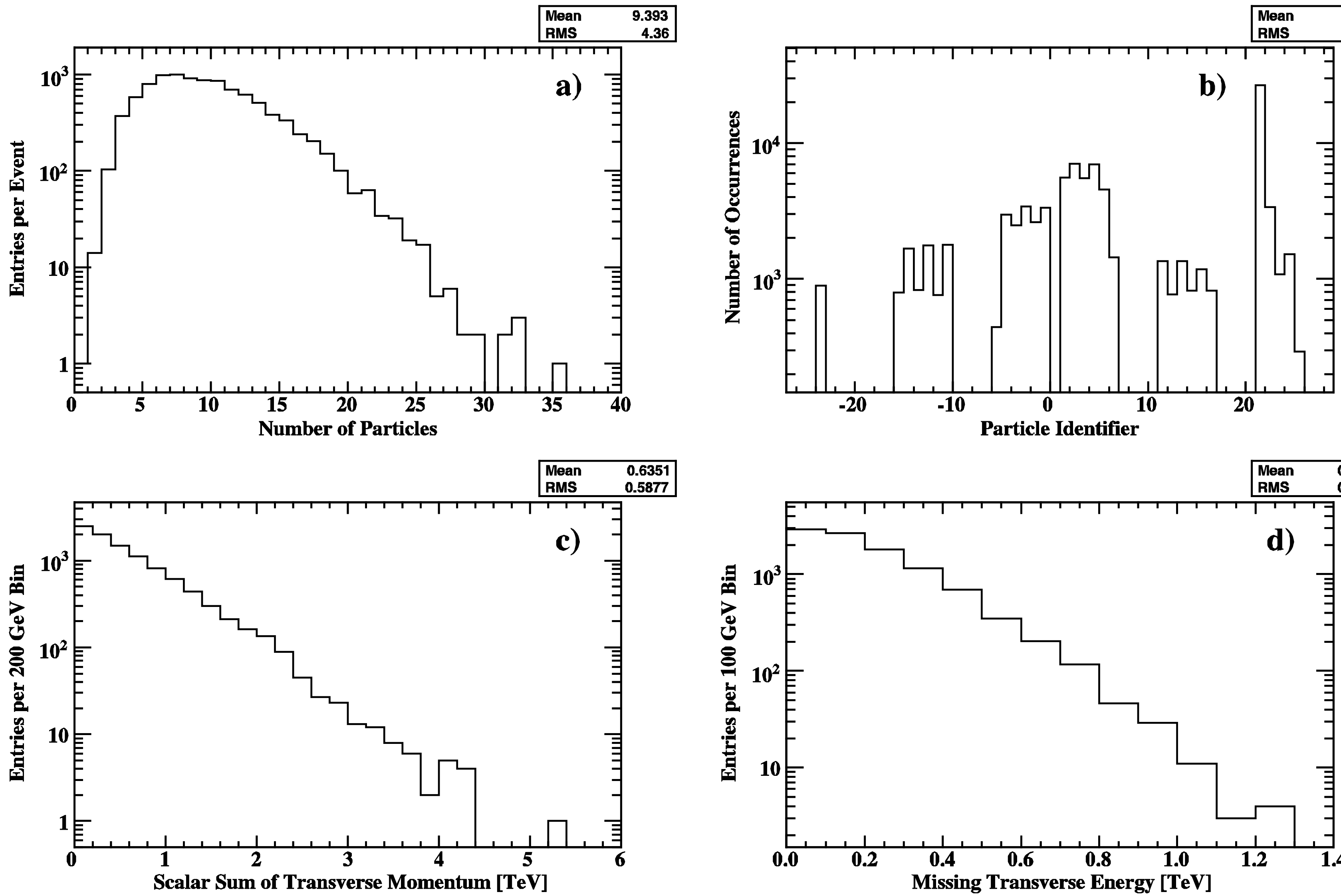
# Initial Black Hole Characteristics



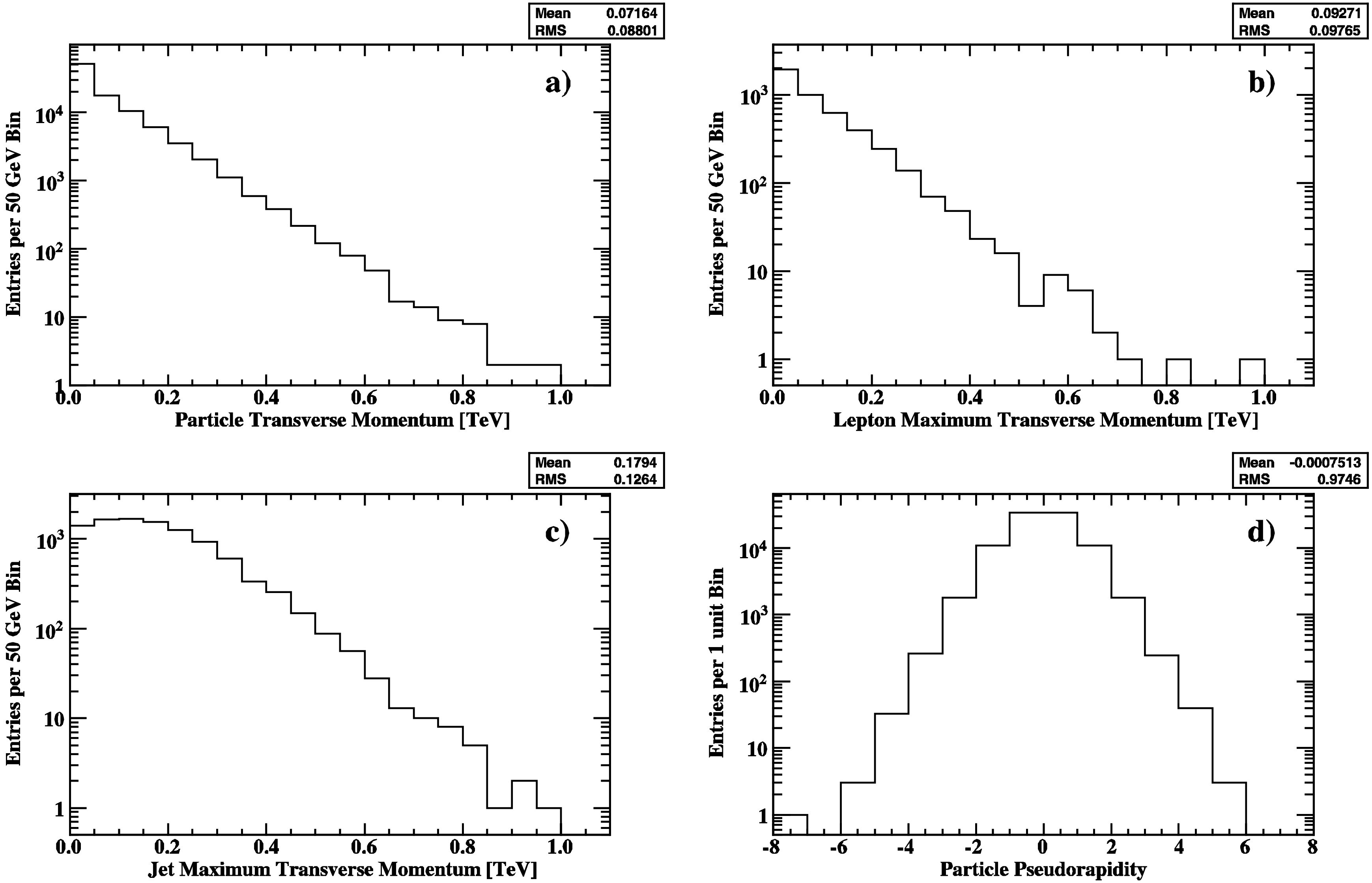
# Remnant Characteristics



# Event Characteristics



# Particle Characteristics



# Conclusions and Comments

- Summary of signatures:
  - Remnant non-relativistic and about half have $|\eta| > 2.5$.
  - Multiplicity still high and most particles in detector.
  - Lots of low-$p_T$ particles.
  - Sum of scalar transverse momentum not useful cut variable.
  - Missing-$E_T$ not particularly high.
- Search strategies:
  - Final state dominate by remnant.
  - Signature very different from high-$p_T$ semiclassical black holes, or gravitational scattering and 2-body decays of quantum black holes.
  - Perhaps need to re-think search strategies.
  - Triggering would need to be reexamined.
  - Study of direct detection of charged remnant needs full detector simulation.

# Pontification: Mass Thresholds

- Mathematically ADD commutative geometry classical black holes can have zero radius and zero mass (infinite temperature).
- To ensure validity of predictions of semiclassical gravity a lower-mass threshold is usually imposed.
- Non-physical threshold often has more of an impact on anticipated signatures than the physical parameters $n$ and $M_D$, or the decay assumptions.
- However, in real data there should also be nonperturbative gravitational objects produced below this threshold (domain of quantum gravity).
- A perfectly efficient search with no acceptance restrictions would allow all quantum black holes to be observed.
- Clearly, the MC simulations would not accurately simulate the data.
- Noncommutative inspired black holes could offer a way out of this difficulty:
  - A physical lower-mass threshold above the Planck scale eliminates the need for a nonphysical model-dependent mass threshold.

# Pontification: Extension of Validity

- Usually transition from semiclassical gravity to quantum gravity regimes.
- This model allows transition from commutative semiclassical gravity to noncommutative gravity regimes, before full UV complete quantum gravity effects take over.
- However, noncommutative gravity only an effective theory.

- For details, approximations, justifications, and citations see JHEP 1105:022,2010