Black holes at LHC

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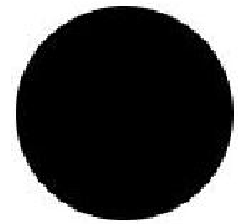
- ♣ *Introduction to BH Production and Decay*
- ♣ *Simulation of Black Holes (BH)*
- ♣ *Experimental Search*
- ♣ *Finding the number of extra-Dimension*
- ♣ *Summary*

A massive object $\xrightarrow{\text{undergoes}}$ gravitational collapse



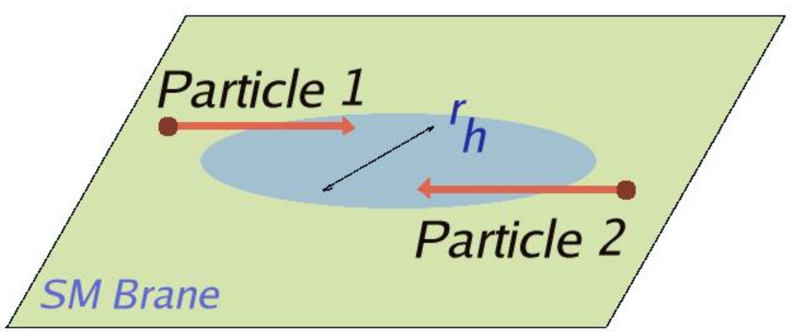
Black Hole (BH) $\longrightarrow$ Event Horizon at radius r_h

Beyond the event horizon nothing can escape (not even light)

♣ In Extra Dimensions $\longrightarrow$ Gravity can operate in the bulk
$\longrightarrow$ SM fields confined to a 3D brane

In $(n+4)$ Dimensions 4−dimensional Planck Scale $\sim 10^{18}$ GeV $\longrightarrow$ **$M_p \sim$ TeV**

$\longrightarrow$ gravity $\times 10^{38}$ stronger!



Quantum sized BH @ LHC

$$r_h \sim \frac{1}{M_p}\left(\frac{M_{BH}}{M_p}\right)^{\frac{1}{n+1}}$$

$M_{\rm BH} \sim$ 5 TeV $\longrightarrow r_h \sim 10^{-19}$ m $\quad (10^{-4}$ fm)

▷ Semiclassical approach: $M_{BH} \gg M_P$

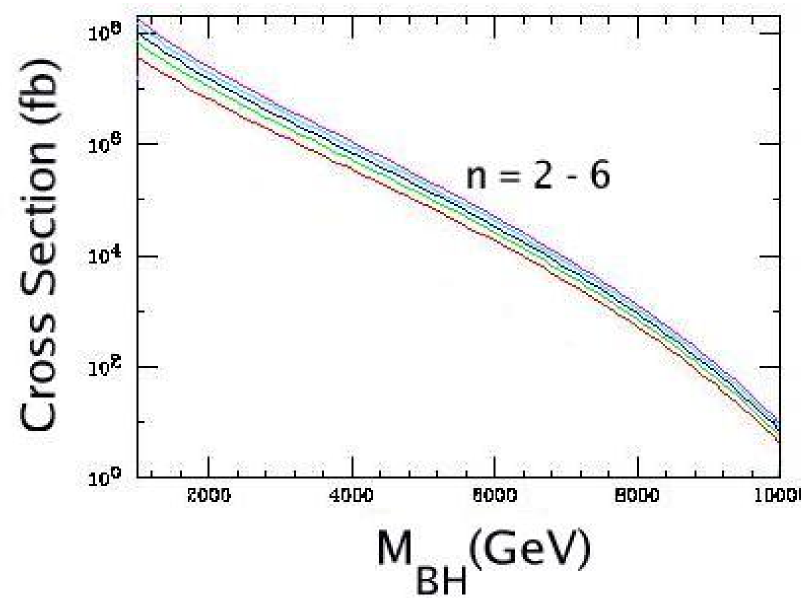
- For $M_{BH} \rightarrow M_P$ semiclassical approach breaks down $\rightarrow$ quantum gravity
- Experimental motivation: $M_{BH} \geq 5M_P$

▷ Semiclassical (geometrical) cross section

$$\sigma \approx \pi r_h^2$$

$$\sigma \sim \begin{cases} \text{nb} & : \text{ for } M_p = \text{ 2 TeV }, \; n = 7 \\ \text{100 fb} & : \text{ for } M_p = \text{ 6 TeV }, \; n = 3 \end{cases}$$

($M_p = 1$ TeV)



BH production rate @ LHC $\sim$ 1 Hz

$\longrightarrow$ LHC $\equiv$ BH Factory!

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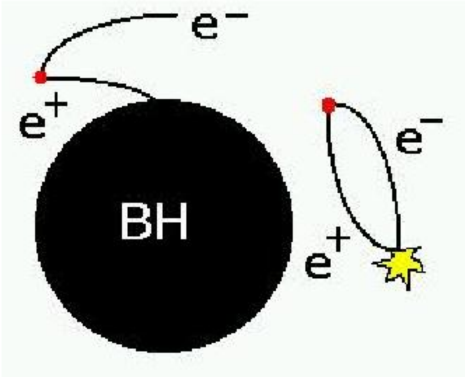
BH $\longrightarrow$ emit particles by Hawking evaporation

$$T_H \sim \frac{n+1}{r_h} \sim M_p \left(\frac{M_p}{M_{\text{BH}}}\right)^{\frac{1}{n+1}}$$



BH $\xrightarrow{\text{decay}}$ jets + leptons + γ + ...

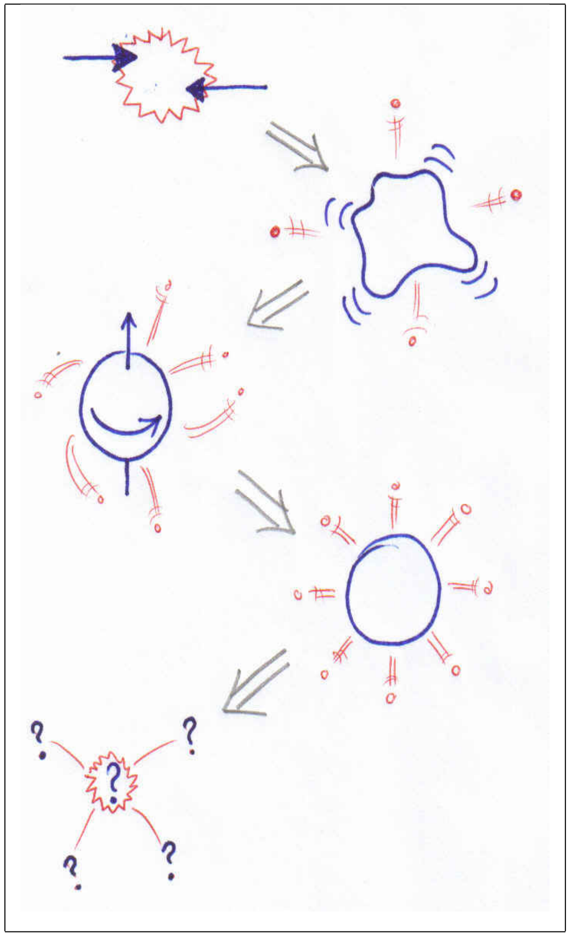
Event Multiplicity : $< N > \approx \left\langle \frac{E}{2T_H} \right\rangle \gg 1$

$M_{\text{BH}} \sim$ 5 TeV $\longrightarrow T_H \sim 10^{12}$ K $\longrightarrow$ few hundred GeV

BH Decay Phases

BH decay

- **Balding** → emission of graviton
  - + gluons
  - → Kerr solution
  - → not well studied in $(4+n)-D$
- **Hawking Evaporation** (well modelled)
  - **Spin down**
    - → shed away J
    - → Hawking rad.
  - **Swcharzschild**
    - → $J=0$
    - → Visible SM particle
- **Planck Phase** → $\mathrm{M_{BH}} \sim \mathrm{M_p}$
  - → emission of Planck scale quanta
  - → not well understood



Hawking Evaporation Phase → Account for the majority of the BH mass loss

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Simulation of BH decay

CHARYBDIS
generator

C. M. Harris, P. Richardson, and B. R. Weber - JHEP **08** (2003) 033 [hep-ph/0307305]

- Simulate the BH in pp colliders → Interfaced → *HERWIG* or PYTHIA.

- ▷ Assumes the semiclassical cross section $\sigma \approx \pi r_h^2$.
- ▷ *Spinless* Black Hole.
- ▷ Includes the BH *Recoil* against emitted particles.

▷ *Time dependence* of $T_H(t)$.

▷ Model only the *Hawking Evaporation* Phase.

▷ BH $\longrightarrow$ *SM* particles on the *brane*.

▷ Includes the *Greybody Factors*

$\longrightarrow$ Modify the spectrum from that of a perfect thermal black body.

$\longrightarrow$ They differ for different spins in different numbers of dimensions,

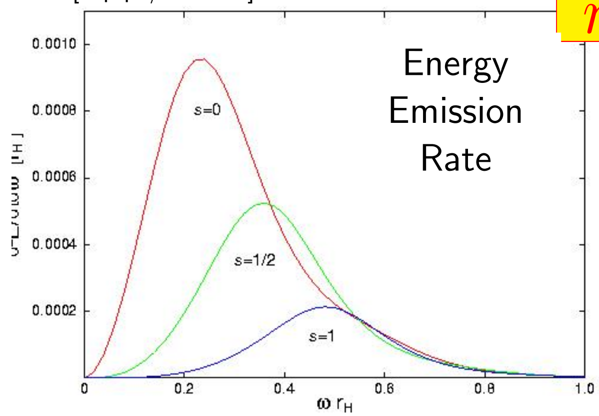
$\longrightarrow$ The relative ratios of scalars/fermions/gauge bosons will be different.

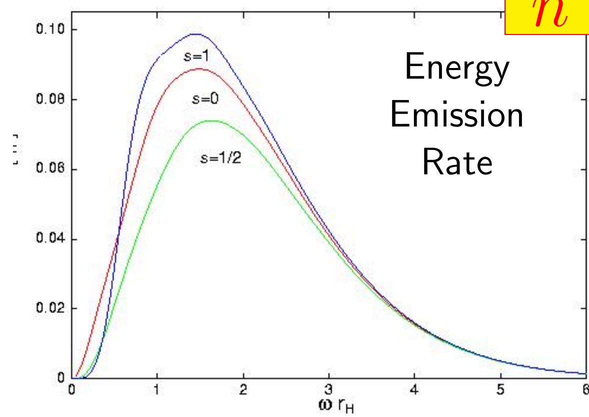
▷ Numerical solutions in (4+n) dimension

$\longrightarrow$ C. Harris & P. Kanti, JHEP **10** (2003) 014 [hep-ph/0309054]

See P. K. talk

[hep-ph/0309054]





Flux Emission Ratio

n	$s=0$	$s=\frac{1}{2}$	$s=1$
0	**1.0**	**0.37**	**0.11**
1	1.0	0.70	0.45
2	**1.0**	**0.77**	**0.69**
3	1.0	0.78	0.83
4	1.0	0.76	0.91
5	1.0	0.74	0.96
6	**1.0**	**0.73**	**0.99**
7	1.0	0.71	1.01
Blackbody	**1.0**	**0.75**	**1.0**

Power Emission Ratio

n	$s=0$	$s=\frac{1}{2}$	$s=1$
0	**1.0**	**0.55**	**0.23**
1	1.0	0.87	0.69
2	**1.0**	**0.91**	**0.91**
3	1.0	0.89	1.00
4	1.0	0.87	1.04
5	1.0	0.85	1.06
6	**1.0**	**0.84**	**1.06**
7	1.0	0.82	1.07
Blackbody	**1.0**	**0.87**	**1.0**

The grey-body factors must be taken into account in any attempt to determine the number of extra dimensions by studying the energy spectrum of particles emitted from a black hole.

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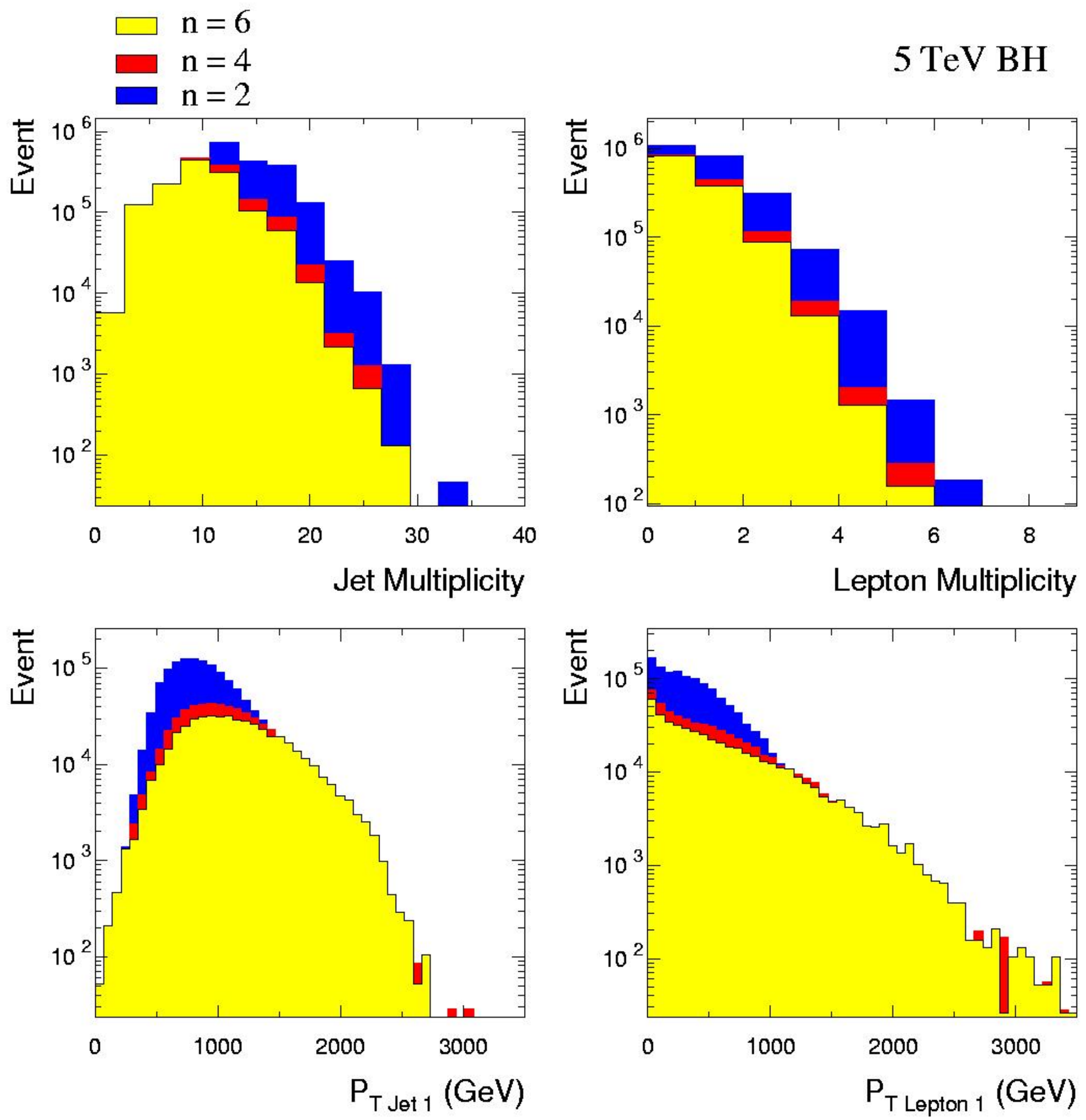
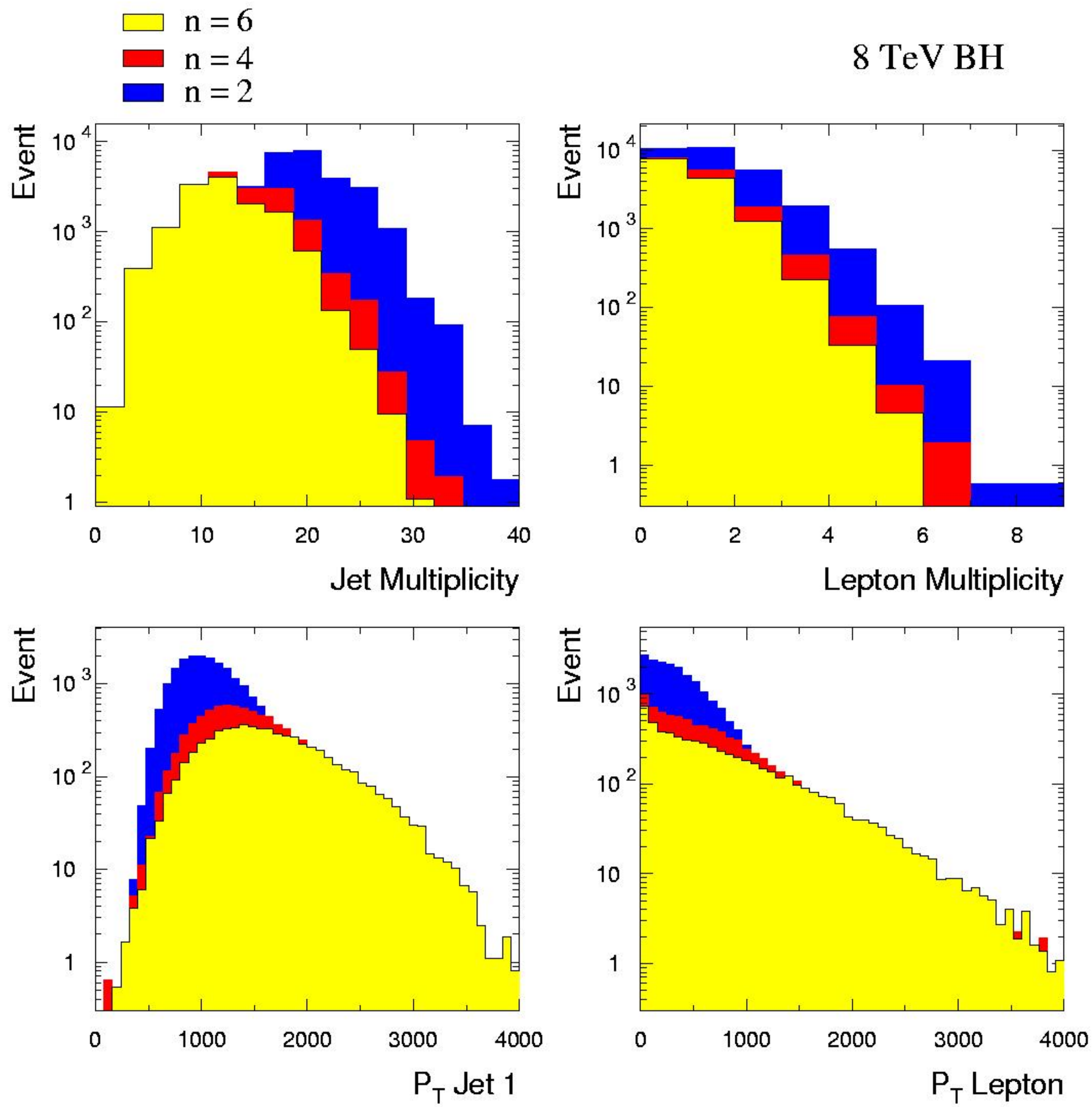
▷ The generated events are passed through the ALTFAST.

Experimental Signatures

- ▷ Large cross section
- ▷ Large E_T
- ▷ Large Multiplicity
- ▷ High sphericity even



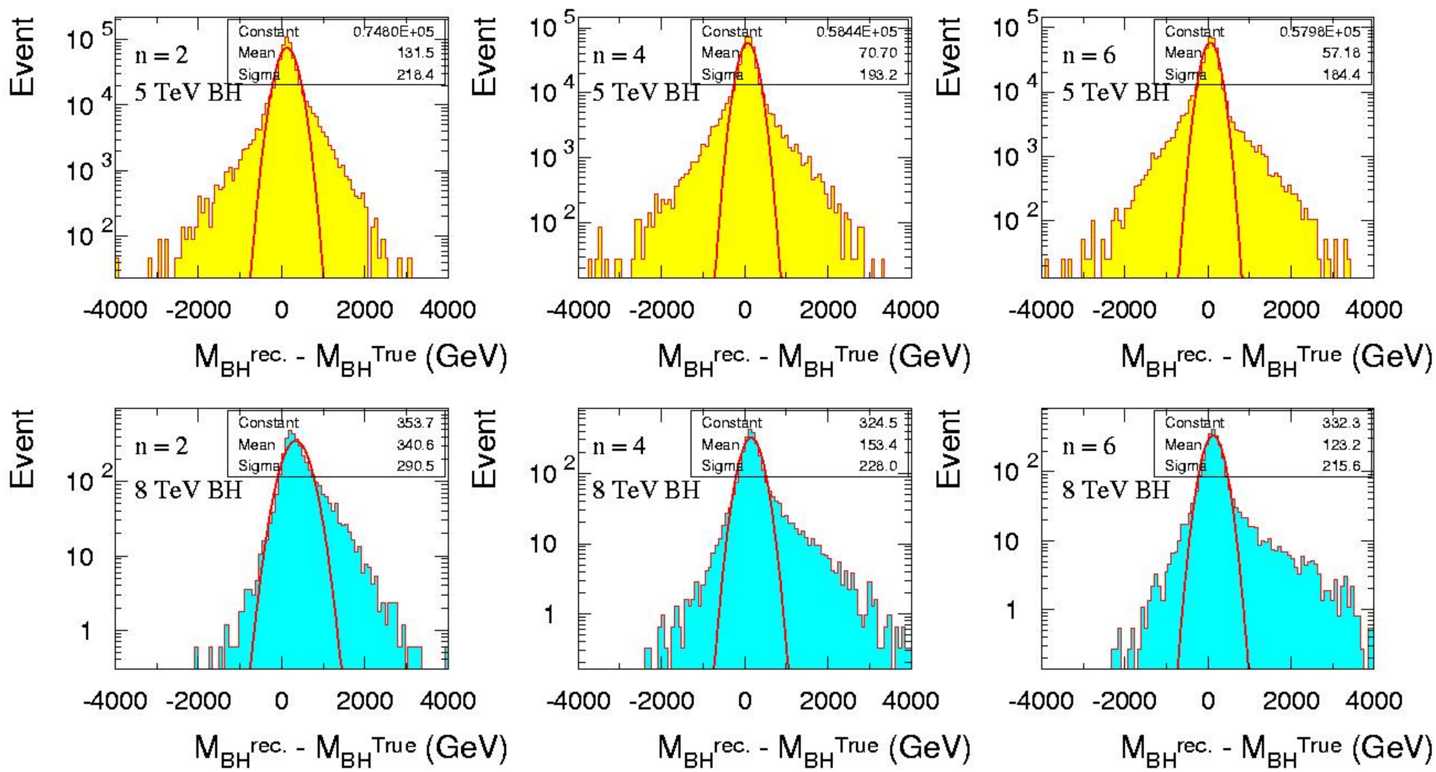

n = 6
n = 4
n = 2
8 TeV BH
Event
Jet Multiplicity
Lepton Multiplicity
P_T Jet 1
P_T Lepton

Mass Reconstruction

Event Selection:

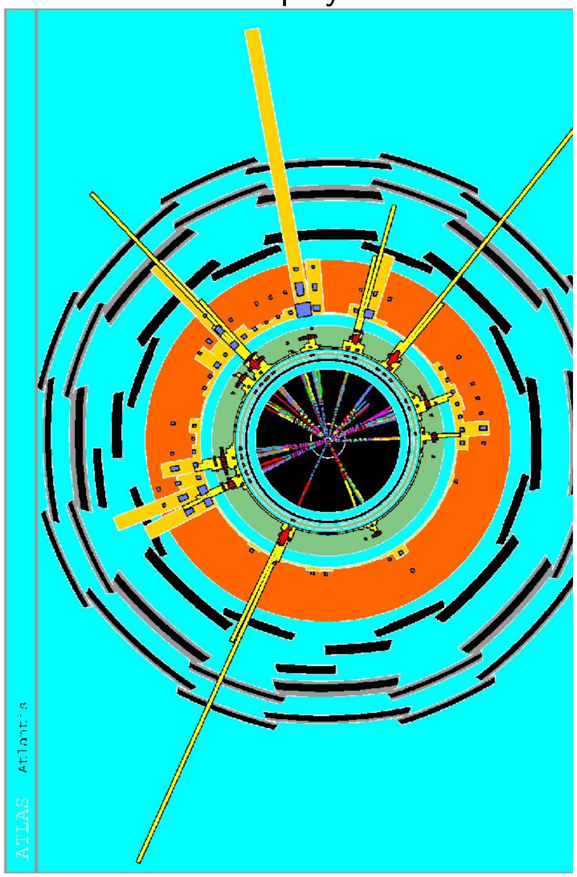
- ▷ # of jets ≥ 4
- ▷ $P_{t\,\mathrm{jet}\,1,2,3} > 500$, 400 , 300 GeV.
- ▷ Particles with $|\eta| < 2.5$.
- ▷ $\not{P}_T < 100$ GeV

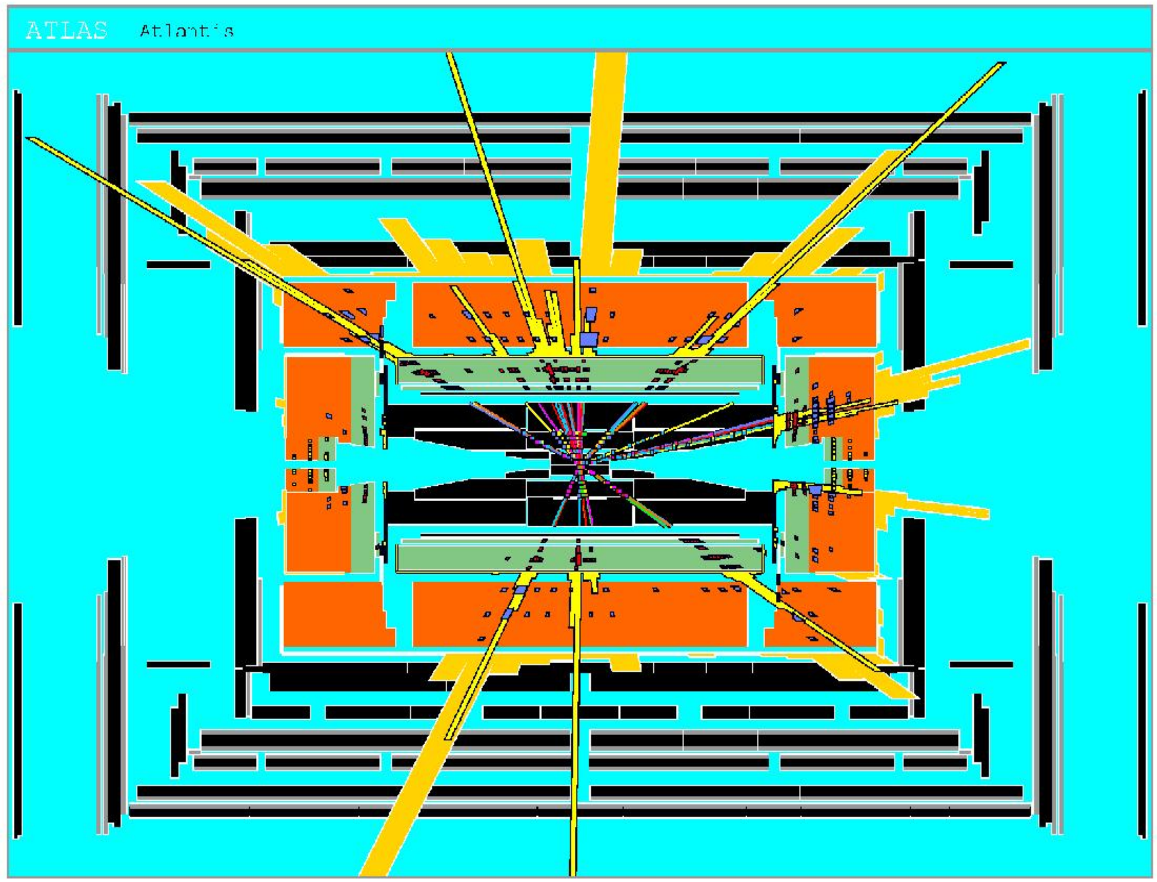
Topology		Mass Resolution (GeV)	Efficiency (%)
5 TeV black hole	$n = 2$	202.1	26.1
	$n = 4$	188.4	30.0
	$n = 6$	184.4	31.9
8 TeV black hole	$n = 2$	293.9	13.2
	$n = 4$	234.0	17.8
	$n = 6$	226.4	19.3



Visualisation of 8 TeV Black Hole Event using the Atlantis Event Display

Atlantis event display



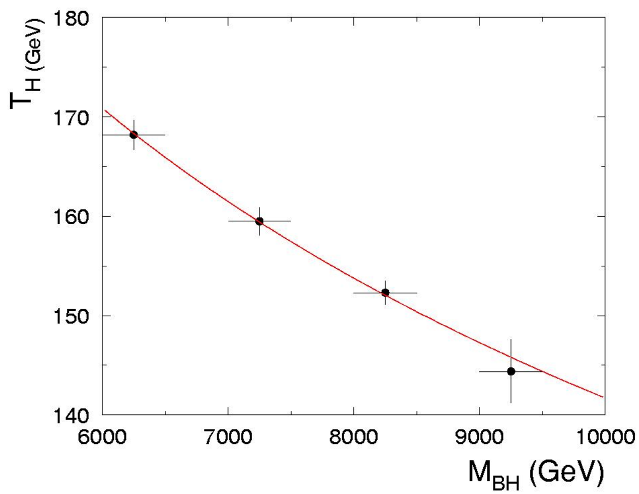


8 TeV Black Hole	n = 6	$M_p = 1$ TeV

Problem of Determination of n with Standard Method

♣ It is assumed that the BH spends most of its time near the initial T_H.

- Ignore the time variation of T_H → Use e, γ spectrum → Estimate T_H.
- From $\log(T_H) \sim \frac{-1}{n+1}\log(M_{BH})$ → Find n .



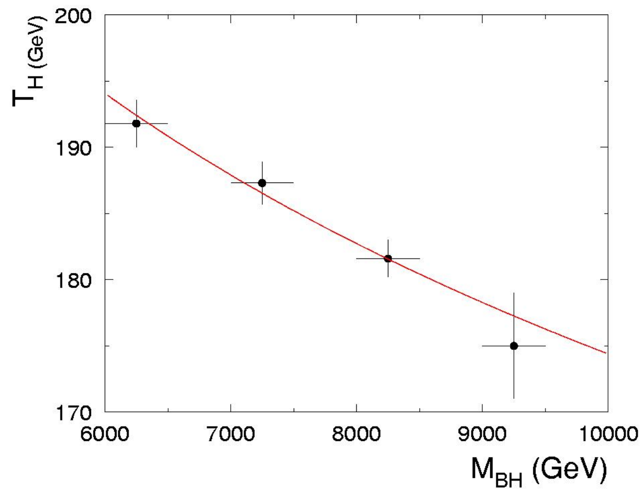
For

$n = 2$ and $M_p = 1$ TeV

[with fixed T_H]

Fit gives

$n = 1.7 \pm 0.3$



For

$n = 2$ and $M_p = 1$ TeV

[with time variation $T_H(t)$]

Fit gives

$n = 3.8 \pm 1.0$

It is not possible to ignore the time variation of T_H.

▷ Other issues: Recoil of BH - Grey body factors ($\longrightarrow$ change the spectrum)

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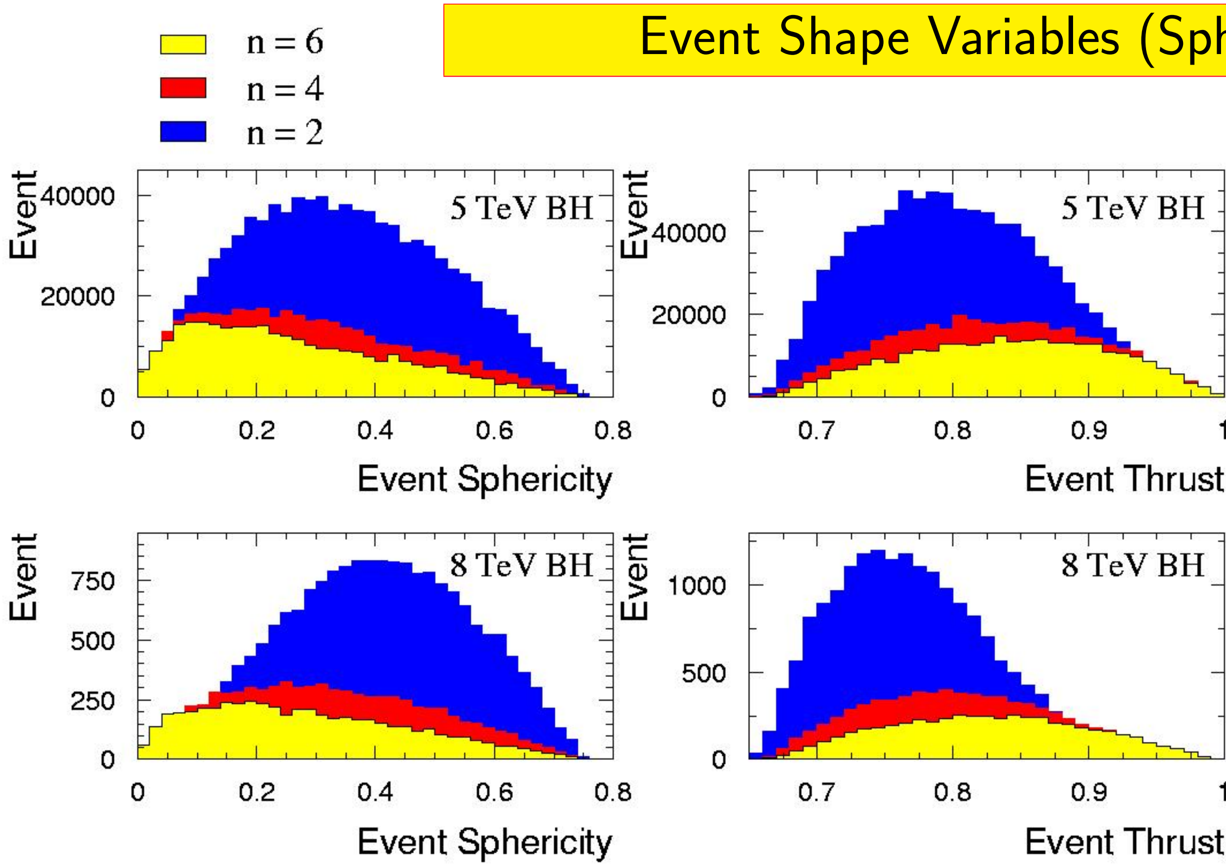
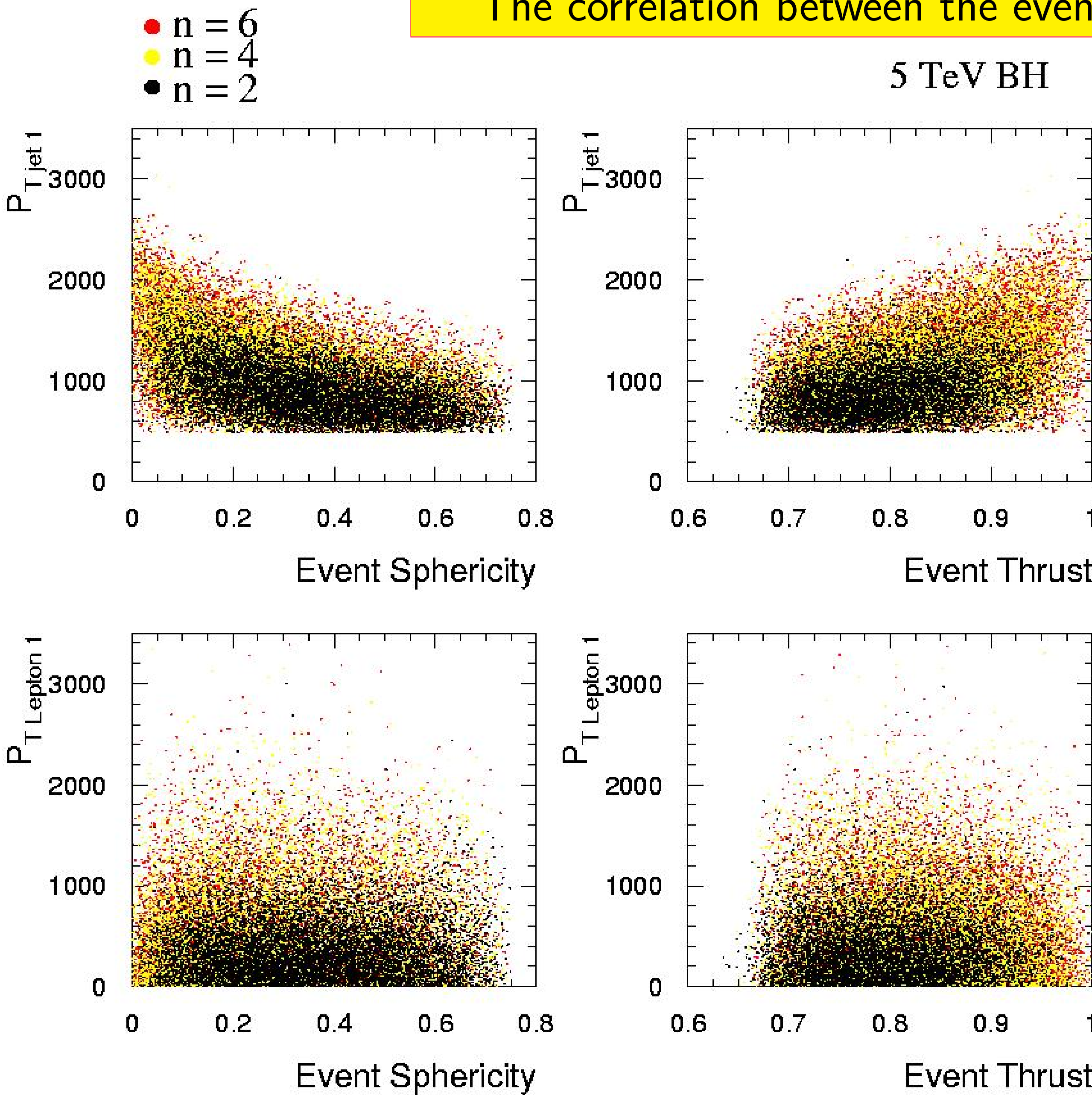
▷ Find a (kinematic) variable of the BH which *depends* (strongly) on n $\longrightarrow$ measure directly the true number of space dimensions.

Event Shape Variables (Sphericity & Trust)

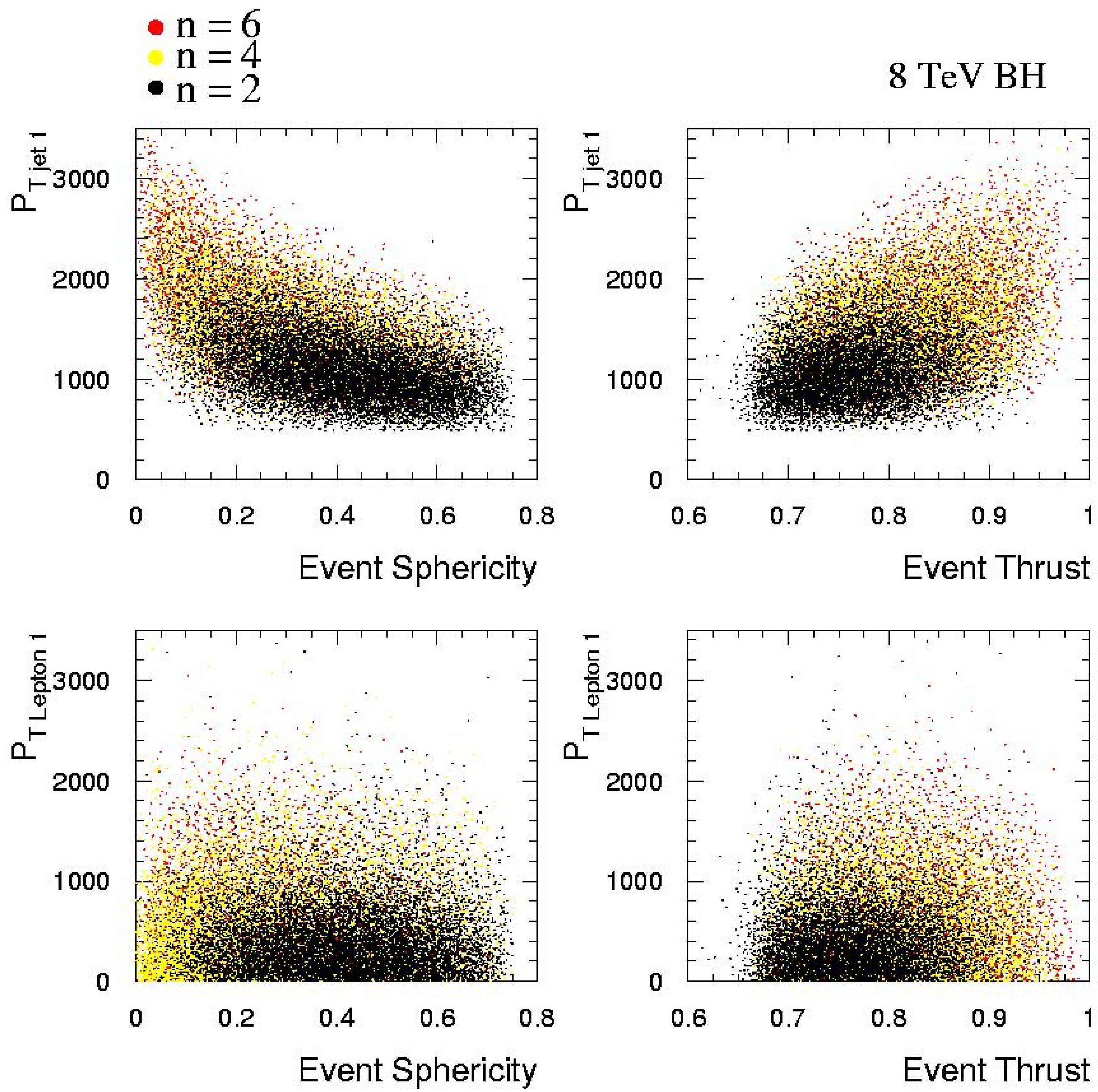


Topology		Trust	Sphericity
5 TeV BH	$n=2$	0.80	0.35
	$n=4$	0.83	0.28
	$n=6$	0.84	0.27
8 TeV BH	$n=2$	0.77	0.40
	$n=4$	0.81	0.32
	$n=6$	0.83	0.29

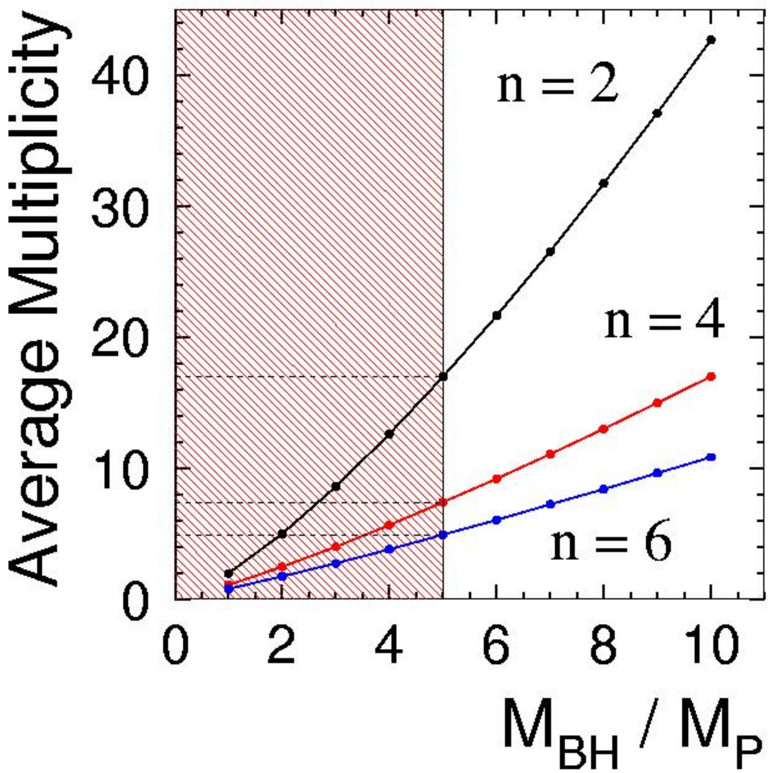
The correlation between the event shape & P_T



The rate of change of variables with n decreases at large n making it hard to distinguish them from one another.

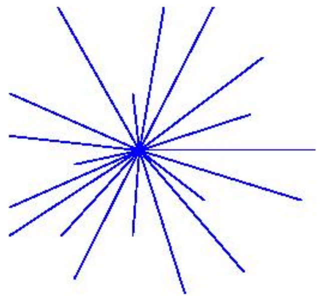
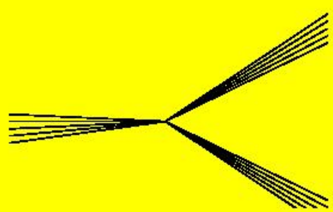

n = 6
n = 4
n = 2
8 TeV BH
$P_{T\,jet\,1}$
Event Sphericity
Event Thrust
$P_{T\,Lepton\,1}$
0
1000
2000
3000
0.2
0.4
0.6
0.8
0.7
0.9
1

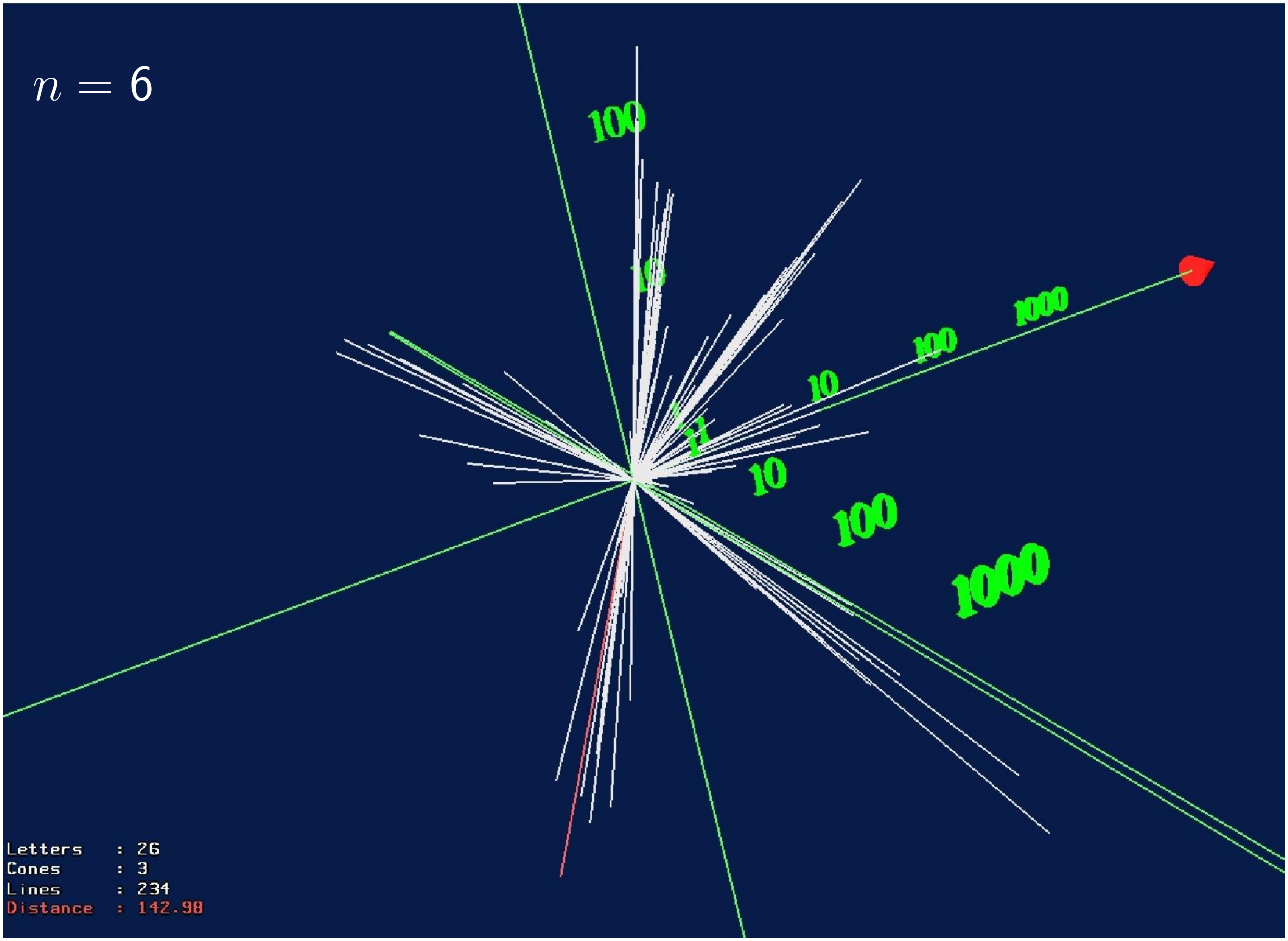
For large n the multiplicity gets too low



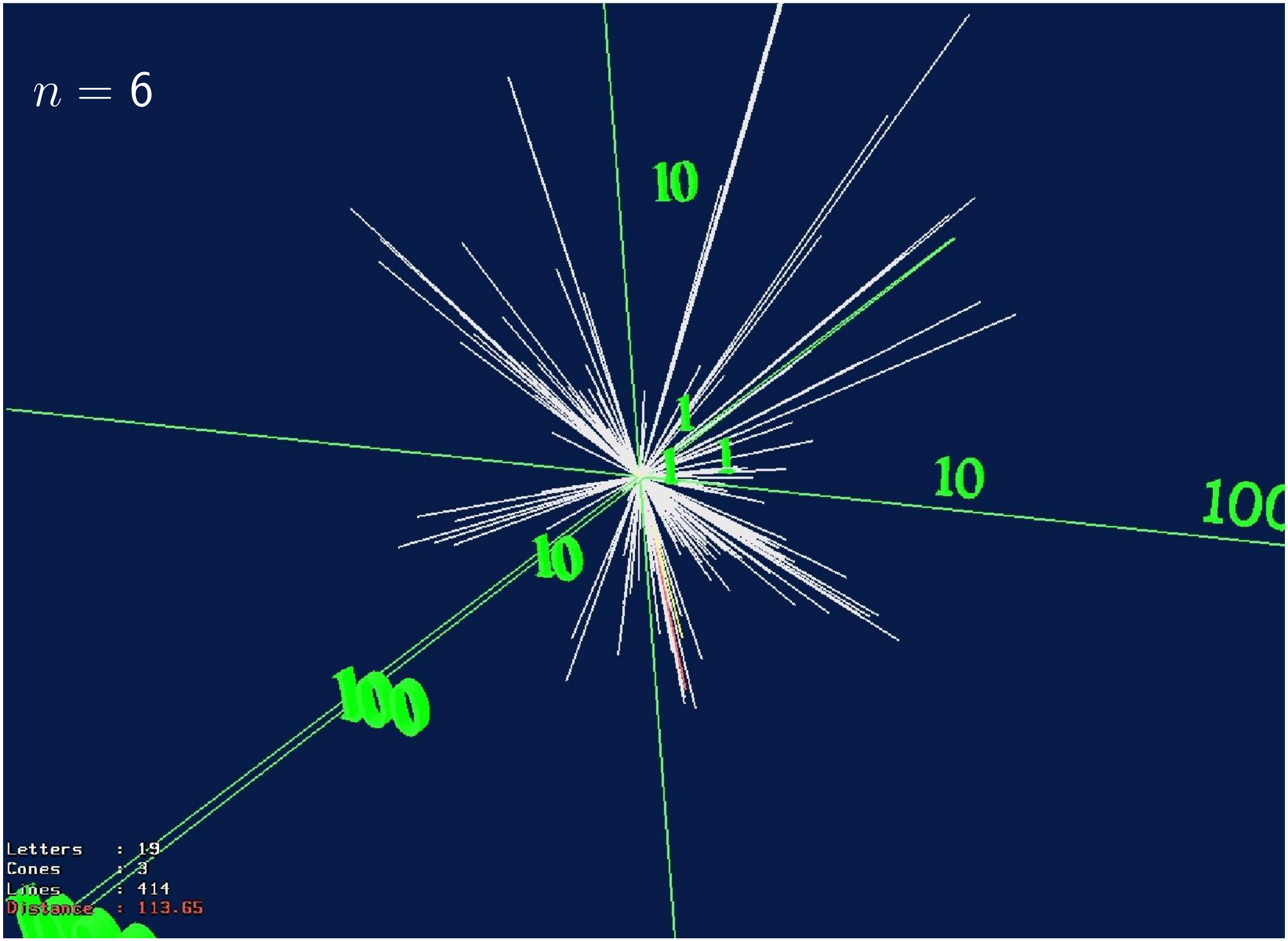
- For the *majority* of the decay (Semi-classical regime):
  - ▷ Average Multiplicity $>> 1$
  - ▷ $M_{BH} >> M_p$
  - ▷ $M_{BH} >> T_H$.
- These conditions start *breaking down* towards the *end of the* decay. (Theoretically invalid regime)

- *Most* of the *problems* are for the low multiplicity events $\longrightarrow$ higher dimensional BH $\rightarrow$ lower sphericity

Particle Trajectory	T Thrust	O Oblateness	S Sphericity	A Apalnarity
	$\rightarrow \frac{1}{2}$	$\rightarrow 0$	$\rightarrow 1$	$\rightarrow \frac{1}{2}$
	$\rightarrow 1$	$\rightarrow 0$	$\rightarrow 0$	$\rightarrow \frac{1}{2}$
	$\sim \frac{3}{4}$	$\sim \frac{1}{4}$	$\sim \frac{1}{2}$	$\rightarrow 0$
5 TeV BH , $n = 2$	0.80	0.20	0.35	0.12
5 TeV BH , $n = 6$	0.84	0.23	0.27	0.07
8 TeV BH , $n = 2$	0.77	0.16	0.40	0.17
8 TeV BH , $n = 6$	0.83	0.22	0.29	0.08



- 10 jets , M_{BH} = 5180.7 GeV , $E_{T\ \mathrm{jet}\ 1}$ = 1410.7 GeV , $E_{T\ \mathrm{jet}\ 2}$ = 834.7 GeV
- Circularity = 0.31 , Thrust = 0.67 , Oblateness = 0.28 , Aplanarity = 0.13



- 8 jets , M_{BH} = 5148.5 GeV , $E_{T\ \mathrm{jet}\ 1}$ = 1373.9 GeV , $E_{T\ \mathrm{jet}\ 2}$ = 1325.6 GeV
- Circularity = 0.60 , Thrust = 0.60 , Oblateness = 0.085 , Aplanarity = 0.36

Summary

- The quantum sized black holes can be produced at energies higher than the Planck mass at the LHC $\longrightarrow$ very spectacular events:
  $\longrightarrow$ Large Mulitiplicity, E_T, sphericity

- Mass Resolution 180 – 300 GeV $\longrightarrow$ for $M_{\mathrm{BH}} = 5$ – 8 TeV.

- The kinematic variables depend weakly on n for higher number of large extra dimensions.

  It is possible to distinguish lower number of n, $e.g.\ n = 2$ or 3 at the LHC
  $\longrightarrow$ harder for higher values of n.

- To extract the value of n from a BH signature,
  $\longrightarrow$ it is not possible to ignore the time variation of T_H,
  $\longrightarrow$ should take into the account the Grey body factors.

▷ With thanks to: Chris Harris , Peter Richardson and the Cambridge SUSY Working group