# Hadrons as Signature of Black Hole Production at the LHC

Ina Sarcevic

University of Arizona

ina@physics.arizona.edu

- Possibility that we live in $4 + n$ spacetime dimensions has profound implications. If gravity propages in these extra dimensions, the fundamental Planck scale, $M_P$, at which gravity becomes comparible in strength to other forces, may be far below $M_{Pl} \sim 10^{19}$ GeV, in TeV range, leading to a host of potential signatures for high energy physics $\Rightarrow$ one of the most striking consequences of low-scale gravity is the possibility of black hole creation in high-energy particle collisions.

- Most gravitation processes, such as those involving graviton emission and exchange, analyses rely on a perturbative description that breaks down for energies of $M_P$ and above.

- In contrast, black hole properties are best understood for energies above $M_P$, where semiclassical and thermodynamic descriptions become increasingly valid.

- *Particle scattering at super-Planckian energies is dominated in the s-channel by black hole production. Thus, black holes provide a robust probe of extra dimensions and low-scale gravity, as long as particle collisions with energies above $M_P$ are available.*

- *Copious production of microscopic black holes is one of the least model-dependent predictions of TeV-scale gravity scenarios.*

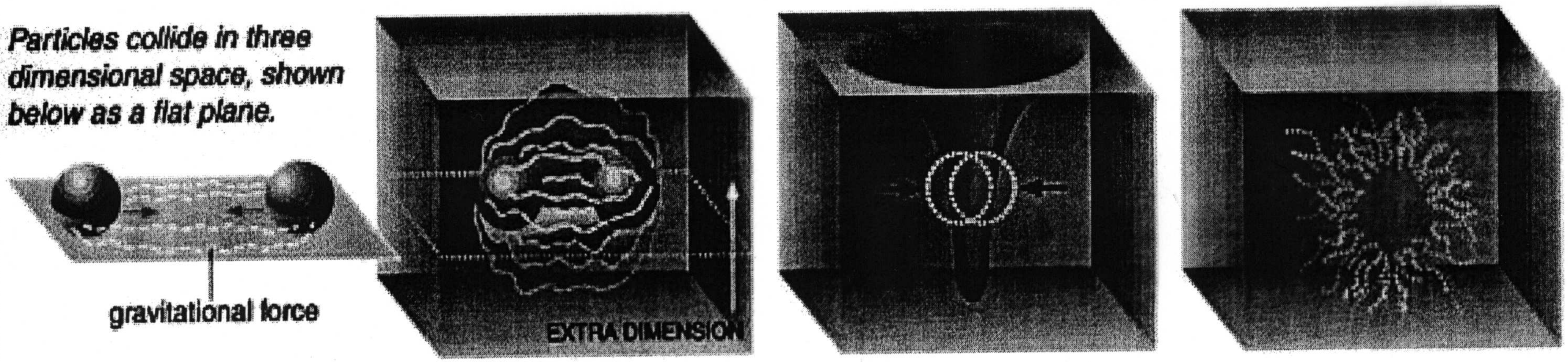
- *LHC will provide energy up to 14 TeV. Black holes with masses of this order can be produced in $pp$ collisions. These masses should be high enough above the Planck scales, $M_P$, for the semi-classical description to be valid. LHC might be called the* **black hole factory**.

The New York Times ON THE WEB

# Black Holes on Demand

**Scientists are exploring the possibility of producing miniature black holes on demand by smashing particles together. Their plans hinge on the theory that the universe contains more than the three dimensions of everyday life. Here's the idea:**

*Particles collide in three dimensional space, shown below as a flat plane.*




As the particles approach in a particle accelerator, their gravitational attraction increases steadily.

When the particles are extremely close, they may enter space with more dimensions, shown above as a cube.

The extra dimensions would allow gravity to increase more rapidly so a black hole can form.

Such a black hole would immediately evaporate, sending out a unique pattern of radiation.

## Black Holes in General Relativity

- Schwarzschild solution to Einstein's general relativity equations applied to a static massive object $\Rightarrow$ any physical object whose radius is less than $R_S$, will become a black hole with the event horizon at $R_S$.

- According to Hawking, black holes are unstable semiclassically and evaporate, i.e. decay into thermal spectrum of particles.

- As the BH evaporates, its mass becomes smaller and the Hawking temperature increases.

## Black Holes in Higher Dimensional Space-Time

- **Static BH solution in N+1 dimensions is a generalization of familiar Schwarzschild solution**

*Myers and Perry, Annals of Phys.* **172** *(1986).*

- **BH radiates mainly on the brane**

*Emparan, Horowitz and Myers, PRL 85 (2000).*

- **The energy radiated in $n$ dimensions by a $d$-dimensional black hole with temperature $T$ is**

$$\frac{\mathrm{d}E_n}{\mathrm{d}t} = \int \frac{\mathrm{d}^{n-1}k}{(2\pi)^{n-1}} \frac{E}{e^{E/T}-1} (\Omega_{n-2} r_S^{n-2}) =$$
$$\frac{1}{(2\pi)^{n-1}} \int \frac{E^{n-1}\mathrm{d}E}{e^{E/T}-1} \Omega_{n-2} (\Omega_{n-2} r_S^{n-2}) =$$

$$\frac{1}{(2\pi)^{n-1}} \Gamma(n)\zeta(n) T^n \Omega_{n-2} (\Omega_{n-2} r_S^{n-2})$$

**where**

$$T = \frac{d-3}{4\pi r_S} \qquad \Omega_{n-1} = \frac{2\pi^{n/2}}{\Gamma(n/2)}$$

- **The black hole is a $d$-dimensional object and it radiates in all dimensions with a rate $\mathrm{d}E_n/\mathrm{d}t$. However, Standard Model fields are four dimensional fields that live on the brane, thus the rate of emission on the brane is $\mathrm{d}E_4/\mathrm{d}t$.**

- **The ratio of emission rates in $4$ dimensions and in $n$ dimensions is:**

$$\frac{\mathrm{d}E_4/\mathrm{d}t}{\mathrm{d}E_n/\mathrm{d}t} \sim 10$$

**thus most of the radiation is on the brane, in SM particles.**

# Black Hole Production and Decay

- In a high energy parton-parton collision, when the impact parameter is smaller than the Schwarzschild radius in $d$ dimensions, a $d$-dimensional black hole is formed with the geometrical cross-section,

$$\sigma_{BH} = \pi r_S^2 (M_{BH} = \sqrt{\hat{s}}) \theta(\sqrt{\hat{s}} - M_{BH}^{min})$$

where $r_S$ is Schwarzschild radius in $d$ dimensions given by

$$r_S = \frac{1}{\sqrt{\pi}} \frac{1}{M_P} \left[ \frac{M_{BH}}{M_P} \left( \frac{8\Gamma(\frac{n+3}{2})}{n+2} \right) \right]^{\frac{1}{n+1}}$$

and $\sqrt{\hat{s}}$ is the center of mass energy of parton-parton collision.

- **The cross-section for black hole production in $pp$ collisions, for example, is obtained by folding in the parton densities:**

$$\sigma(pp \rightarrow BH + X) = \frac{1}{s}\sum_{ab}\int_{M^2_{BH,min}}^{s} dM^2_{BH} \times \int_{x_{1,min}}^{1} \frac{dx_1}{x_1} f_a(x_1, Q^2)\hat{\sigma}_{BH} f_b(x_2, Q^2)$$

**$x_1$ and $x_2 = M^2_{BH}/(x_1 s)$ are the momentum fractions of the initial partons, $x_{1,min} = M^2_{BH}/s$, $Q^2 = 1/r^2_S$.**

**We use CTEQ6M for the parton distribution functions.**

- Radiation rate into Standard Model particles is given by a thermal distribution in 4 dimensions:

$$\frac{dE}{dt} = \frac{1}{(2\pi)^3} \sum_i \int \frac{\omega g_i \sigma_i d^3k}{e^{\omega/T_{BH}} \pm 1}$$

with the black hole temperature, $T_{BH} = \frac{d-3}{4\pi r_S}$, $g_i$ ia a statistical factor, acounting for the number of degrees of freedom that can be produced. The sign $+$ is for fermions and $-$ for bosons, $\sigma_i$ are the gray body factors which depend on the spin of each particle.

**$\sigma_{i,s} = \Gamma_s A_4$, where $\Gamma_s$ are constant ($\Gamma_{1/2} = 2/3, \Gamma_1 = 1/4, \Gamma_0 = 1$).**

**A black hole acts as an absorber with a radius somewhat larger than $r_S$, such that $A_k$ can be written as :**

$$A_k = \Omega_{k-2} \left(\frac{d-1}{2}\right)^{\frac{d-2}{d-3}} \left(\frac{d-1}{d-3}\right)^{\frac{k-2}{2}} r_S^{k-2}$$

**where**

$$\Omega_k = \frac{2\pi^{\frac{k+1}{2}}}{\Gamma(\frac{k+1}{2})}.$$

*Emparan, Horowitz, Myers, PRL* **85** *(2000).*

- For the emission into gravitons, which are $d$-dimensional, the rate is given by:

$$\frac{dE}{dt} = \frac{1}{(2\pi)^{d-1}} \sum_i \int \frac{\omega g_i \sigma_i d^{d-1}k}{e^{\omega/T_{BH}} - 1}$$

where $\sigma_i \sim A_{d-1}$. This rate is much smaller than emission rate into SM particles.

- The lifetime of the black hole is then obtained by integrating rate equation and, assuming no mass evolution during the decay, is given by:

$$\tau_{BH} = M_{BH}\Big[\frac{\pi^2}{30}\Big(\sum_f \frac{7}{8} g_f \sigma_f + \sum_b g_b \sigma_b\Big) T_{BH}^4\Big]^{-1}$$

## Assumptions:

- To avoid stringy effects and be able to use semi-classical approach we consider $M_{BH} >> M_P$
- Decay: BH evaporation at the original temperature
- BH radiates mainly on the brane
- Most of the decay is hadronic
- Typical lifetime $10^{-27}$ s.
- Lack of knowledge of quantum gravity effect close to the Planck scale $-$ theoretical input needed
- Greybody factors in $\omega r_S << 1$ approximation ( *Kanti and March-Russell (2003)*

# Hadron spectrum

The cross section for inclusive charged hadron production from the partons produced in the black hole decay:

$$E\frac{d\sigma^h}{d^3p} = \frac{1}{s}\sum_{a,b,c}\int_{M^2_{BH,min}}^{s} dM^2_{BH}\int_{x_{1,min}}^{1}\frac{dx_1}{x_1}\int_{z_{min}}^{1}\frac{dz}{z^2}$$
$$\times \quad f_a(x_1,Q^2)\sigma_{BH}f_b(x_2,Q^2)E_c\frac{dN_c}{d^3p_c}D_c^h(z,Q_f^2),$$

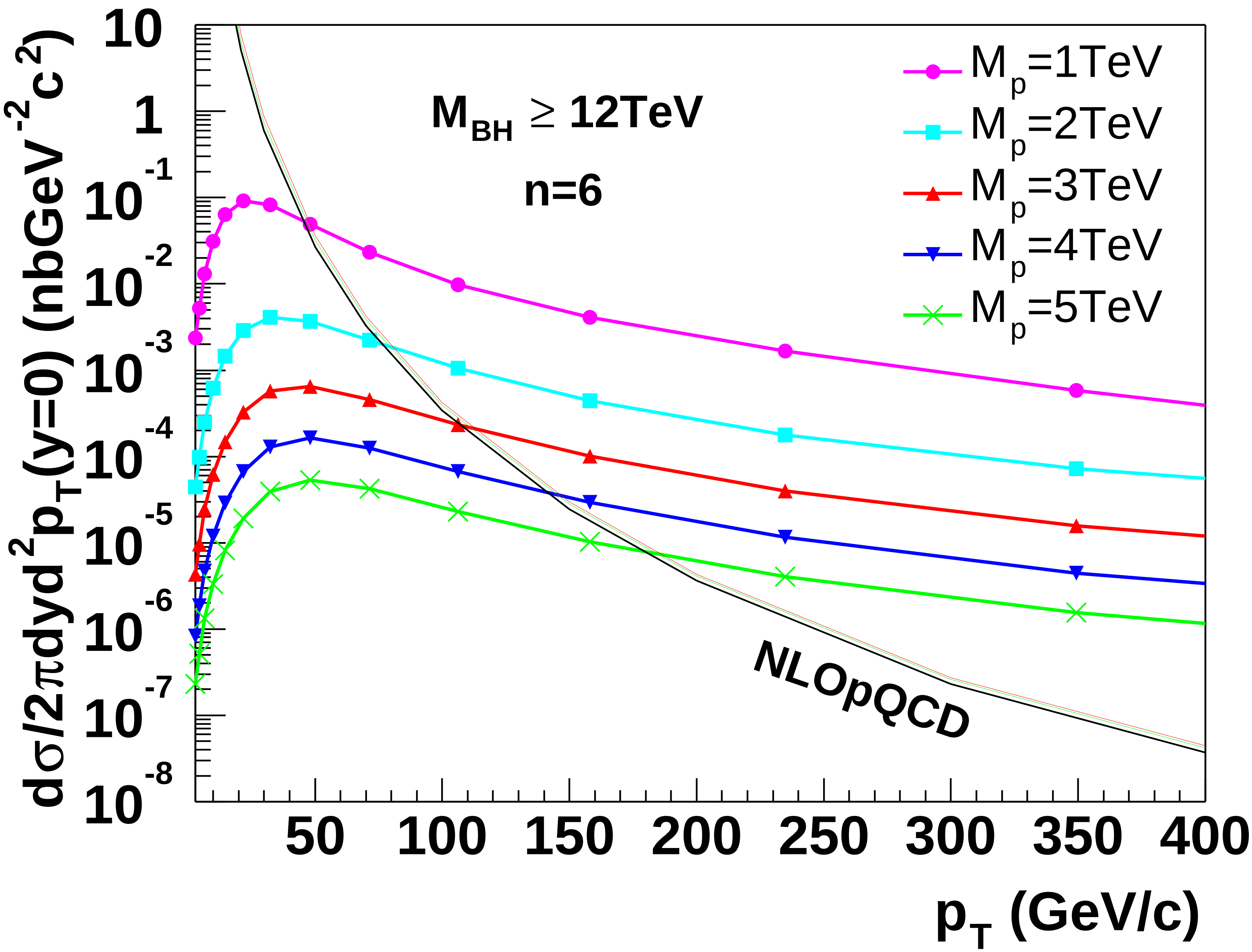
where $z_{min} = 2p/\sqrt{s}$ and $z = p/p_c$ and the decay distribution is:

$$E_c\frac{dN}{d^3p_c} = \frac{1}{(2\pi)^3}\frac{p_c^\mu u_\mu \gamma g_c \sigma_c \tau_{BH}}{e^{p_c^\mu u_\mu/T_{BH}} \pm 1},$$

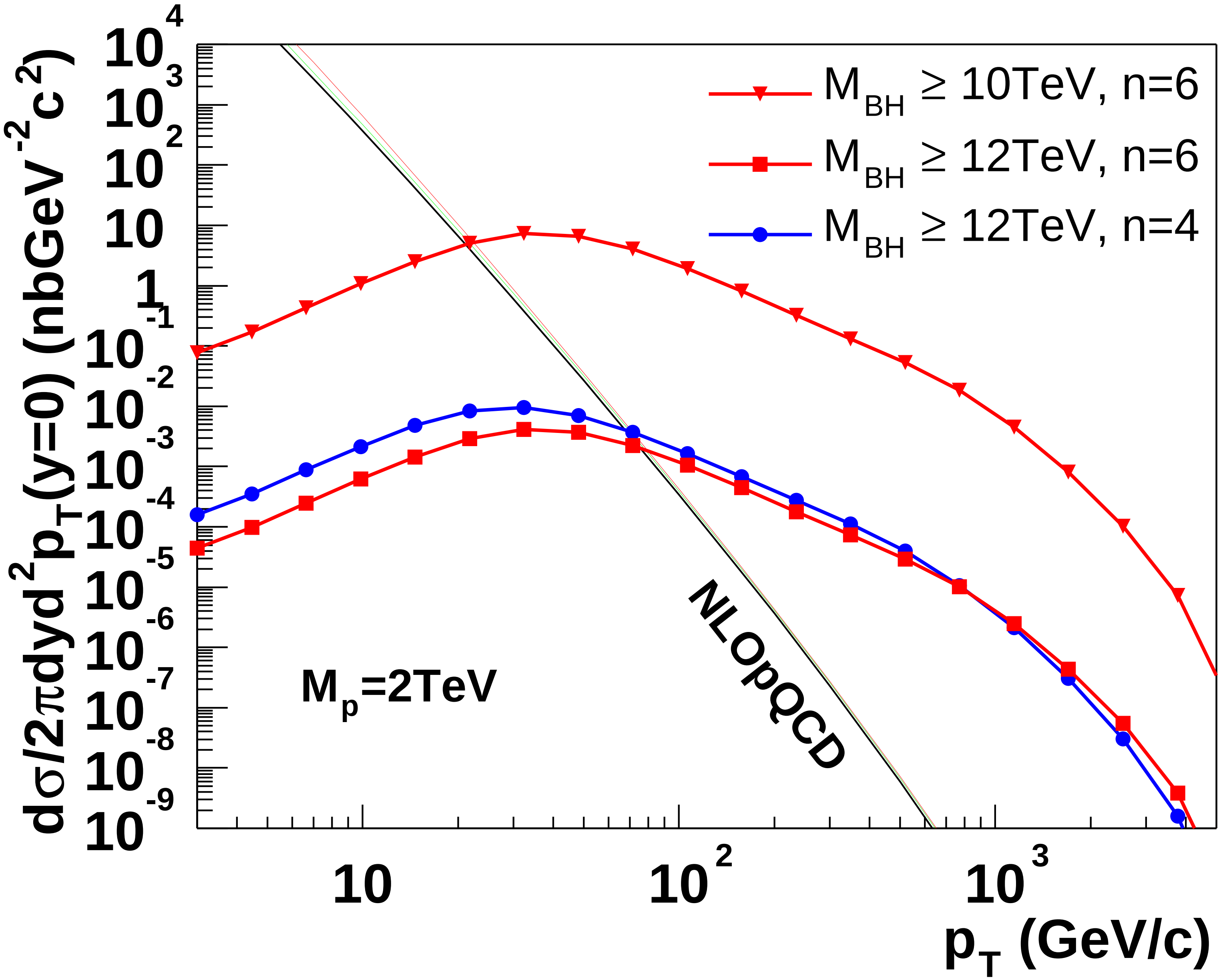
where $\gamma$ is the Lorentz gamma factor and $u = (\gamma, 0, 0, (x_1 - x_2)\sqrt{s}/(2M))$ takes into account that the black hole is not produced at rest. Here $p$ and $E$ refer to hadrons, while $p_c$ and $E_c$ are for partons.

- We choose $Q_f^2 = p_T^h$ in the fragmention functions, $D_c^h(z, Q_f^2)$ and we use KKP fragmentation functions, which are parametrized in the range of $0.1 \leq z \leq 1.0$ and $1.4 \leq Q_f \leq 100$ GeV. For the large $Q_f$, we evolve the KKP fragmentation function from the scale $Q_f = 100$ GeV up to the desired values (in this case up to $\sim 10$ TeV) using DGLAP equations

- For the $z < 0.1$ range, we use small-$z$ fragmentation function by Fong and Webber which is based on the coherent parton branching formalism, which correctly takes into account the leading and next-to-leading soft gluon singularities, as well as the leading collinear ones.




Inclusive charged hadron distribution from 10D black holes in $pp$ collision at $\sqrt{s} = 14$ TeV compared to QCD background.




Cross section for inclusive charged hadron production from black holes in $pp$ collision at $\sqrt{s} = 14$ TeV for $n = 4$ and $n = 6$.

- **Dependence on the number of extra dimensions is weak.**

- **The QCD background is obtained with different choices of the scale used in the structure and fragmentation functions (**$p_T, p_T/2, 2p_T$**). The dependence on this scale is very weak in the high transverse momentum region.**

- Transverse momentum dependence of the hadrons does not change much when changing $M_P$ or $M_{BH}^{min}$, but the overall rate of hadrons produced does.

- At the parton level changing $M_P$ or $M_{BH}^{min}$, the temperature of the black hole is modified and consequently the spectrum of the emitted particles is different. Hadronization washes out most of the effect.

- We cannot get a direct determination of the temperature of the black holes from the hadron spectrum.

- Look at the spectrum of photons and electrons in the black hole event, which preserves the black body radiation type of spectrum, but is considerably lower than the hadron signal because photons and electrons are only a small fraction of the particles produced in the black hole evaporation.

- Consider black holes with lower masses in order to obtain a detectable signal.

**Black hole events will be easily detected in the hadron spectra at high $p_T$. The values of $p_T$ for which the signal becomes higher than the background would give an indication on the values of $M_P$ and $M_{BH}$ that this signal corresponds to.**

## Black Holes in Pb+Pb Collisions

- To compute the spectra in the case of Pb+Pb collisions, we take into account nuclear effects, such as the Glauber profile density $T_{AA}(b) = \int d^2r T_A(r) T_A(|b-r|)$, where $T_A(r) = \int dz \rho(r,z)$.

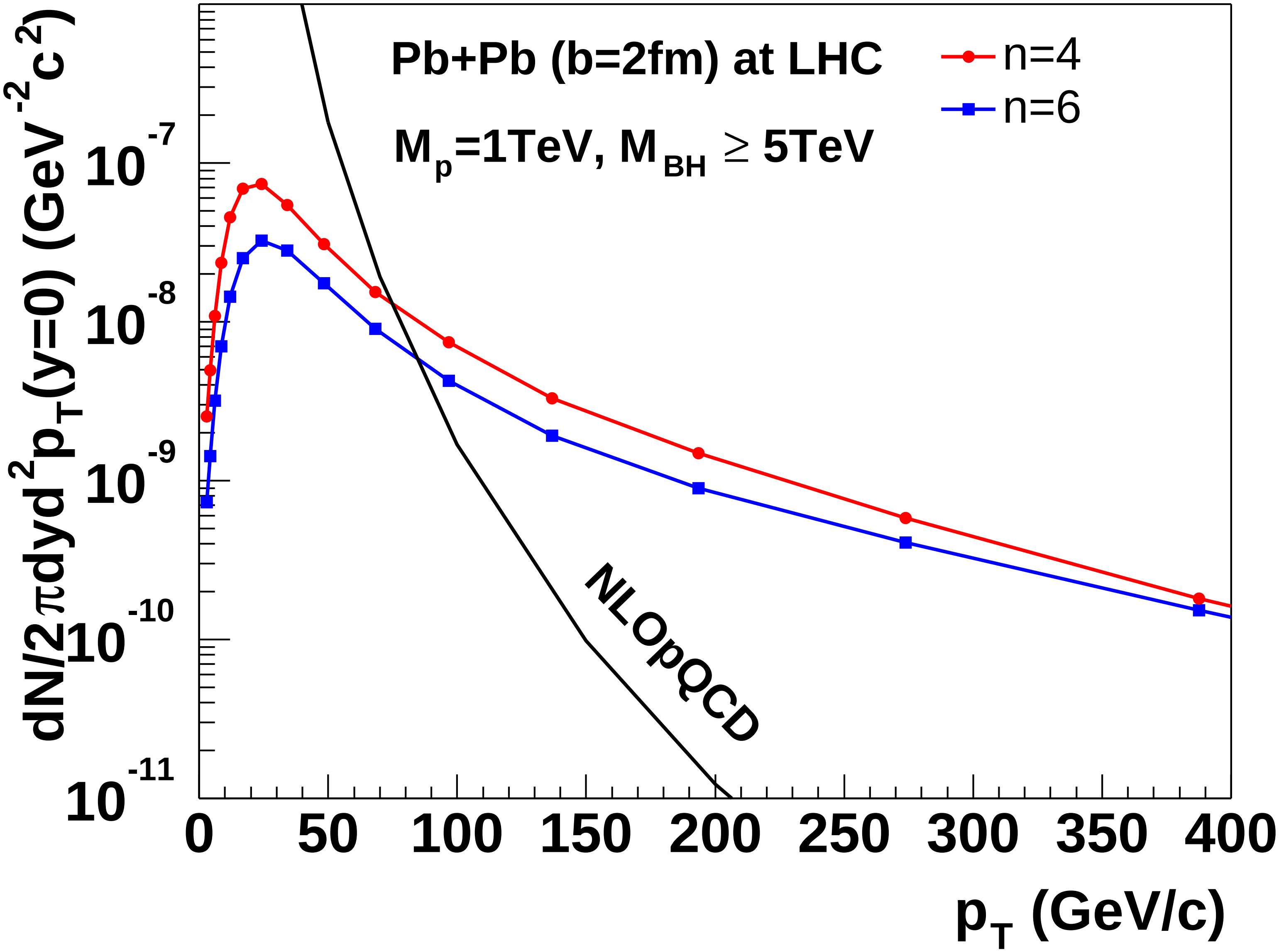
- Since $\sqrt{s_{NN}} = 5.5$ TeV, only lower mass black holes can be produced and a smaller parameter space can be probed. Nuclear modification of parton distribution is getting smaller when we go to larger scale from $Q^2 = 2.25$ GeV$^2$ up to $Q^2 = (30\text{TeV})^2$.

- **The modified fragmentation function $D_c^h(z, Q_f^2)$ is given by**

$$D_c^h(z, \Delta L, Q^2) = \frac{1}{z} \sum_{n=0}^{N} P_c(n) \Big[ z_n^c {D^0}_c^h(z_n^c, Q^2) + \sum_{m=1}^{n} z_m^c {D^0}_g^h(z_m^c, Q^2) \Big]$$

**where $z_n^c = zE^c/E_n^c$, $z_m^c = E/\epsilon_m^c$, $E_{n+1}^c = E_n^c - \epsilon_n^c$ and $P_c(n)$ is a Poisson distribution.**

- **Energy loss has significant effects at $p_T$ below 10 GeV in the QCD spectrum at LHC.**




Transverse momentum distribution for charged particle at mid-rapidity from black hole decay in Pb+Pb collision at LHC. pQCD calculation with the scale $Q = Q_f = p_T$ is also shown.

- **There is a possibility to have** *enhanced* **particle yield around $p_T \sim 10$ GeV/c, because the hadron spectra is much flatter than that of the QCD spectra and feedback from the emitted gluons could be non-negligible. In this case the black hole signal could be also identified in the lower $p_T$ region, in addition to the high $p_T$ one.**

- **Interactions of the black hole with the surrounding particles and possible absorption of these particles by the black hole, would affect the decay of the black hole.**

# Conclusions

- **Hadrons from Black Holes are detectable at the LHC; they dominate at transverse momentum $p_T \geq 30 - 100$ GeV over QCD processes.**

- **Our results are conservative, as they only take into account very high mass black holes. Including black holes with lower masses gives even stronger signals. The value of $p_T$ at which the signal becomes bigger than the background is determined by $M_P$ and $M_{BH}$ considered.**

- For high rapidity (figs. shown for $y = 0$), QCD background is much smaller, while the Black Hole signal is the same for all rapidities. Looking at the high rapidity region would enhance the signal to background ratio even further.

- Charged hadron distributions in p-p and Pb-Pb collisions at the LHC provide unique probe of Black Hole production and the physics of extra dimensions for Planck scale up to 5 TeV and for any number of extra dimensions.