Search for the multidimensional black holes in TeV-scale gravity models with the CMS detector

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Novosibirsk
March 10, 2020

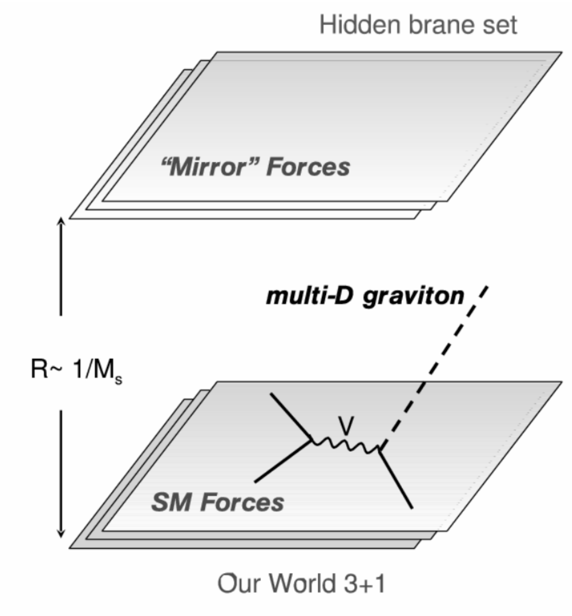
TeV scale gravity models

ADD model

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, 1998

Large compact ED with a radius *R*

Flat space, $M^4 \times X^n$
$n = 2 \div 6$

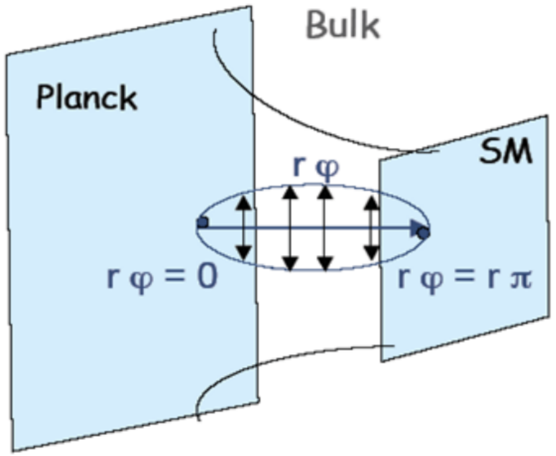


RS1 model

L. Randall, R. Sundrum, 1999

Space with warped geometry: a slice of AdS_5 with two branes at the ends

One small ED **$n=1$**

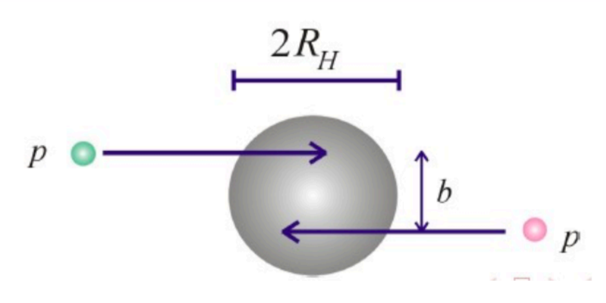


Black hole production

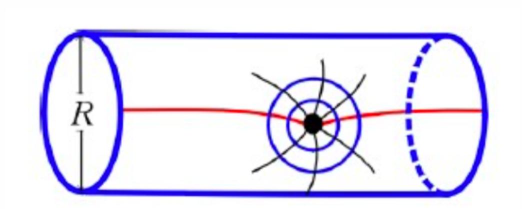
Thorne's hoop conjecture

$$b < 2r_h(n, M, J)$$

Two colliding ultrarelativisric particles.



BH radius less than compactification radius of extra dimension.



BH evolution stages:

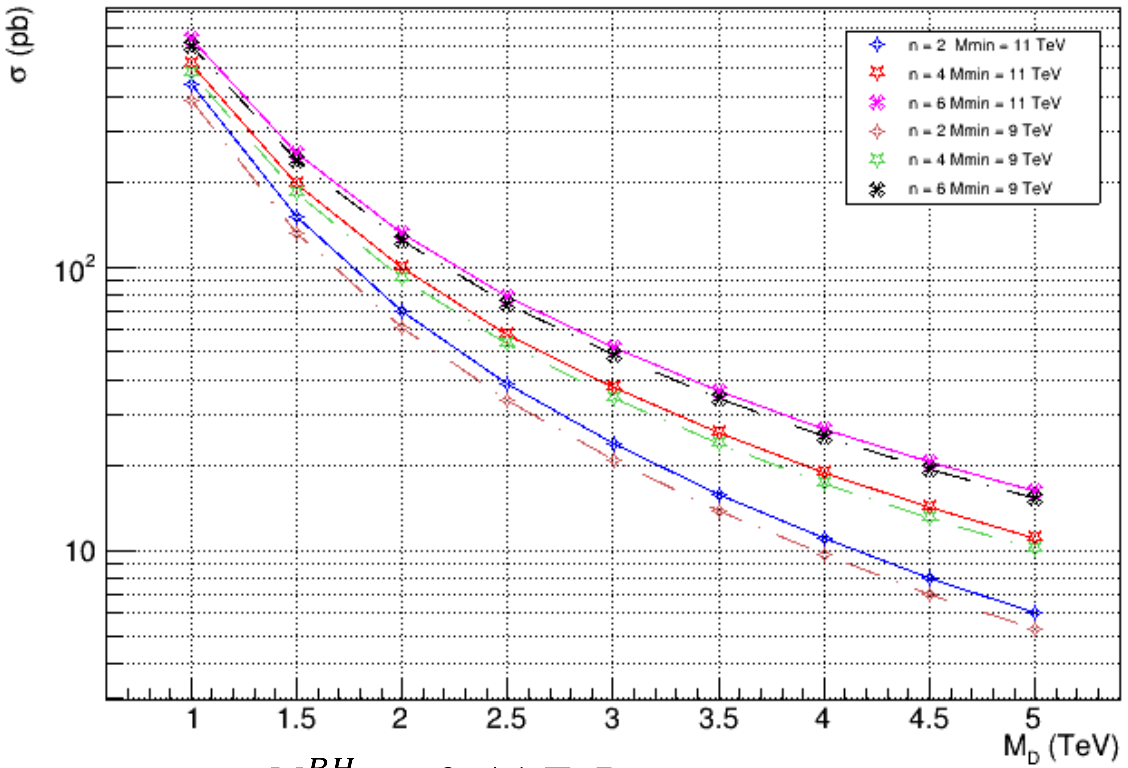
- Balding phase sheds its asymmetries through the emission of gravitational radiation and also loses any gauge field charges arising from the particles which formed it;
- Spin-down phase loses both mass and angular momentum, at the end is no longer rotating;
- Swarzschild stage & Hawking radiation relative probability for the emission ⟹ grey-body factors (depend on charge, spin, mass, momentum).
- Final Planck stage “usual” decay on a few “fragments”, non-observable stable remnant, B, L, B+L ...non-conservation.

R.C. Myers and M.J. Perry, Ann. Phys. 72, 304, 1986

BH characteristics

The cross section as “a black disk" area:

$$\sigma_{BH} = \pi r_S^2$$



$$M_{min}^{BH} = 9, 11 \text{ ТэВ}$$

Schwarzschild radius of BH:

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

Entropy:

$$S_{BH} = \frac{4\pi}{n+2}\left(\frac{M_{BH}}{M_D}\right)^{\frac{n+2}{n+1}}\left(\frac{2^n \pi^{\frac{n-3}{2}}\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)^{\frac{1}{n+1}} = \frac{1+n}{2+n}\frac{M_{BH}}{T_H}$$

Hawking temperature:

$$T_H = M_D\left(\frac{M_D}{M_{BH}}\frac{n+2}{8\Gamma\left(\frac{n+3}{2}\right)}\right)^{\frac{1}{n+1}}\frac{n+1}{4\sqrt{\pi}} = \frac{n+1}{4\pi r_S}$$

$$D = 10 = d + n, \qquad d = 1 \dots 4, \qquad n = 10 - d$$

In RS1 model under condition: $r_S \ll 1/k e^{-k r_c}$

In the energy region $\tilde{M} < E < (M/k)^2 \tilde{M}$

we can describe RS-type BHs as ADD-type BHs for *n=1*

Additional restrictions by an entropy for BH of RS type ($x_{min} > 16$)

BH production cross section at colliders

Simple estimation:

All the initial energy was trapped under a horizon. An elementary (hard) BH production cross section is defined by simple geometrical formula ⟶

in pp-collisions at the LHC differential cross section in the LO approximation can be written as

$$\frac{d\sigma(pp \to BH + X)}{dM_{BH}} = \frac{dL}{dM_{BH}} \hat{\sigma}(ij \to BH)|_{\hat{s}=M_{BH}^2}$$

$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s} \sum_{i,j} \int_{M_{BH}^2/s}^{1} \frac{dx_i}{x_i} f_i(x) f_j\left(\frac{M_{BH}^2}{s x_i}\right)$$

$$\hat{s} = x_i x_j s$$

It is also possible that some part of initial collision energy will leak away during horizon formation. The process is known as Yoshino-Rychkov mechanism.

$$M_{BH} = \sqrt{\hat{s}} \Longrightarrow M_{BH} = y\sqrt{\hat{s}} \qquad y < 1$$

$$\sigma^{pp}\left(\sqrt{\hat{s}}, x_{min}, n, M_D\right) = \int_0^1 2z dz \int_{\frac{x_{min} M_D^2}{y^2 s}}^{1} \frac{dv}{v} f(n) \pi r_s^2\left(u\sqrt{\hat{s}}, n, M_D\right) \sum_{i,j} f_i(v, Q^2) f_j\left(\frac{u}{v}, Q^2\right)$$

where

$$x_{min} = \frac{M_{min}^{BH}}{M_D} \qquad y = \frac{M_{BH}}{\sqrt{\hat{s}}} \qquad z = b/b_{max}$$

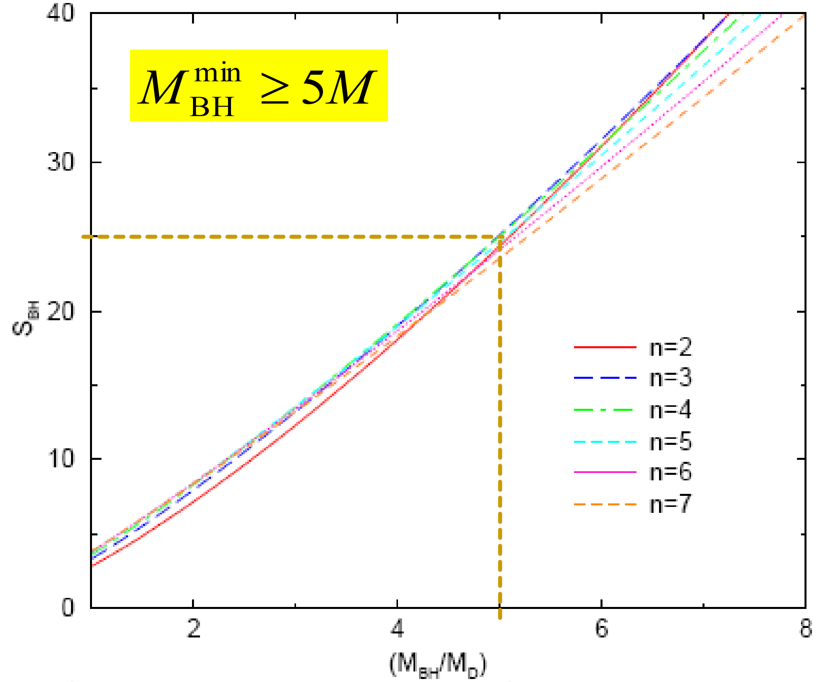
Criteria of semiclassical approach for BH

Semiclassical BHs

⇕

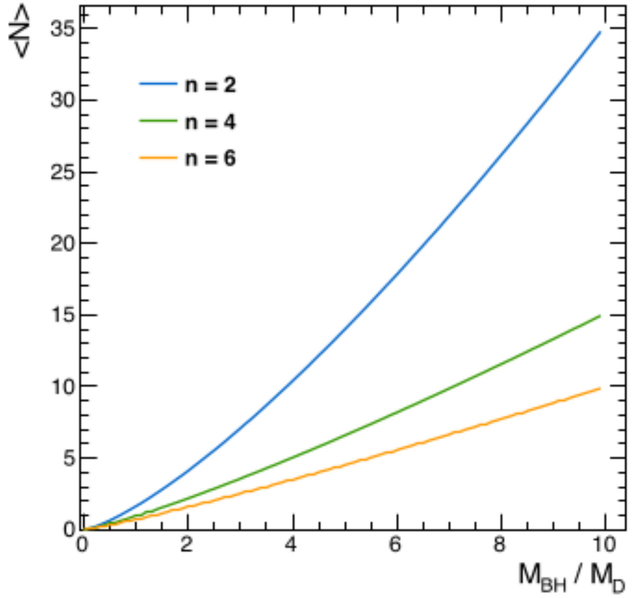
sufficiently large entropy

$$S_{BH} \approx \frac{1}{n+2}\left(\frac{M_{BH}}{M_D}\right)^{\frac{n+2}{n+1}}$$



S_{BH} must be large enough to satisfy a number of BH thermal evolution conditions, say,

$$T_H\left|\frac{\partial T_H}{\partial M}\right| << T_H \quad \Leftrightarrow \quad \frac{1}{\sqrt{S_{BH}}} << 1 \Rightarrow S_{BH} > 25$$



More conditions:

- The lower limit of BH production ("quantum threshold") that gives

  $\lambda_C(E = \frac{\hat{s}}{2}) < r_S$ $x_{min}>4.1$ (ADD) $x_{min}>16$ (RS1) $x_{min} \equiv \frac{M_{min}}{M_D}$

- The energy of an each emitted d.o.f. is much smaller than M_{BH} ($dM/dN << M_{BH}$)

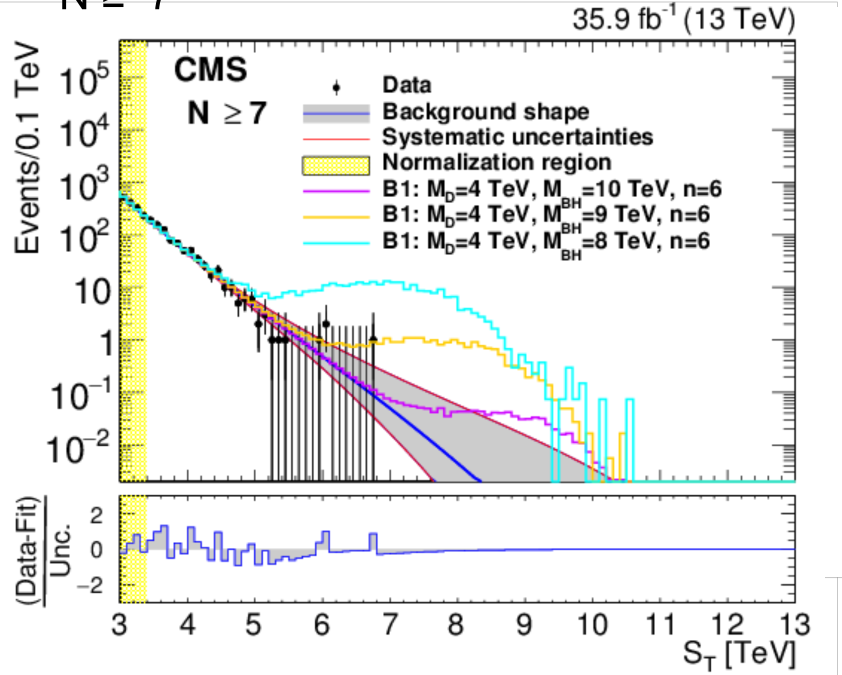
- Life time criteria for BHs ($\tau M >> 1$) etc.

The CMS experimental limits for M_{min}^{BH} in the multijet channel, LHC RUN2

Multijet events, S_T observable $S_T = \sum_{i=1}^{N_{jet}} E_T^i + E_T^{miss}$

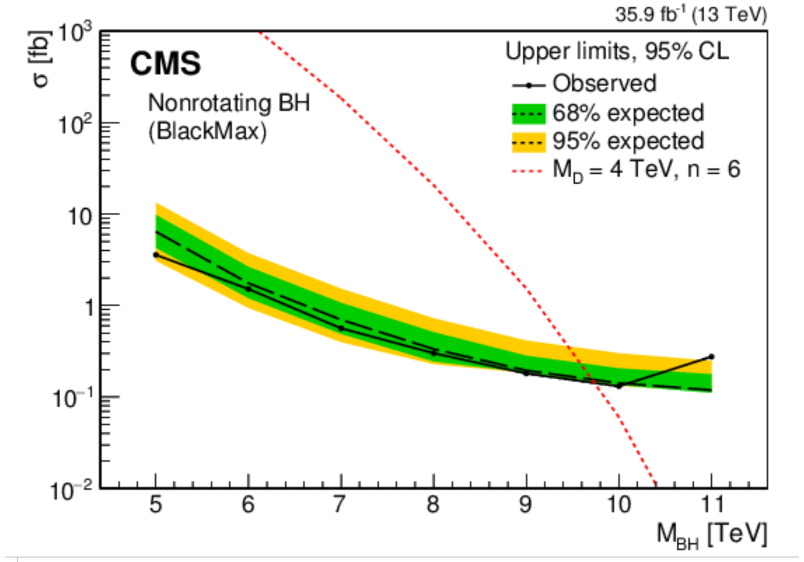
The CMS Collab., JHEP 11 (2018) 042 & PLB 774 (2017) 279

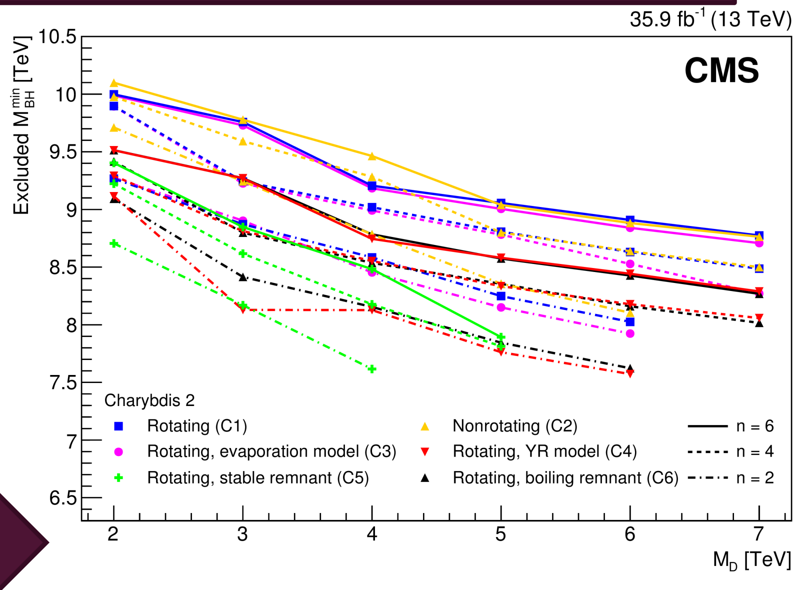
S_T distribution for final state multiplicities N ≥ 7

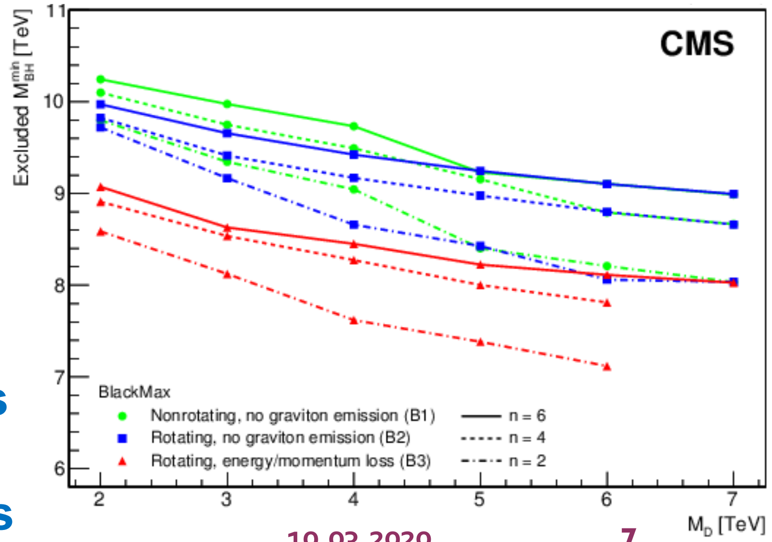


The shape of QCD multijet background is invariant for different multiplicities

Upper model-independent limit on cross section for multijet events, N ≥ 6







Minimal masses of semiclassical BHs are excluded up to 10.1 TeV in dependence on n and model details

Near-threshold transition of BHs to string balls

Model approach:

L. Susskind, hep-th/9309145.
G. T. Horowitz and J. Polchinski, PRD 55, 6189 (1997)

- "String balls" in ST version with a weak-coupling regime at energies of the order of TeV (manifestation of string physics at the LHC)

- **The idea:**
  near-threshold transition of BH produced to a string ball under conditions (a correspondence principle): at the transition point the entropy, mass, angular momentum of the SB and BH are equal.

$$S_{string} \sim \sqrt{\alpha'} M_{SB} = \frac{M_{SB}}{M_S},$$

$$S_{BH} = \frac{4\pi}{n+2} f(n) \left(\frac{M_{BH}}{M_D}\right)^{\frac{n+2}{n+1}} \sim \frac{4\pi}{n+2} f(n) \frac{1}{g_S^2} \left(\frac{g_S^2 M_{BH}}{M_S}\right)^{\frac{n+2}{n+1}}$$

- Can be realized when $M_D^{n+2} = M_S^{n+2}/g_S^2$

- Three regulating parameters – M_S, M_D, g_S, minimal BH mass is not arbitrary $M_{BH}^{\min} = M_s/g_s^2$

Near-threshold transition BH/SB, the CMS experimental limits, RUN2 LHC

Competitive regimes

$$M_S < M_D < \frac{M_S}{g_S} < \frac{M_S}{g_S^2}$$

$$M_D^{n+2} = M_S^{n+2}/g_S^2$$

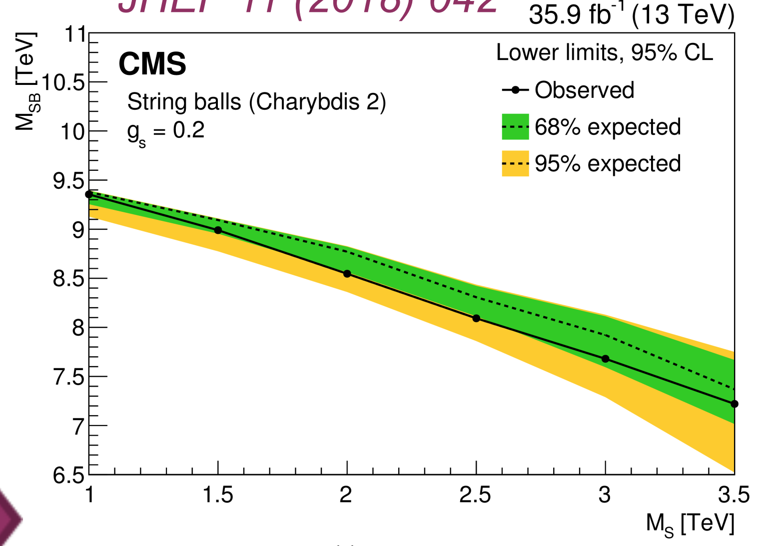
$$M_{BH}^{\min} = M_s/g_s^2$$

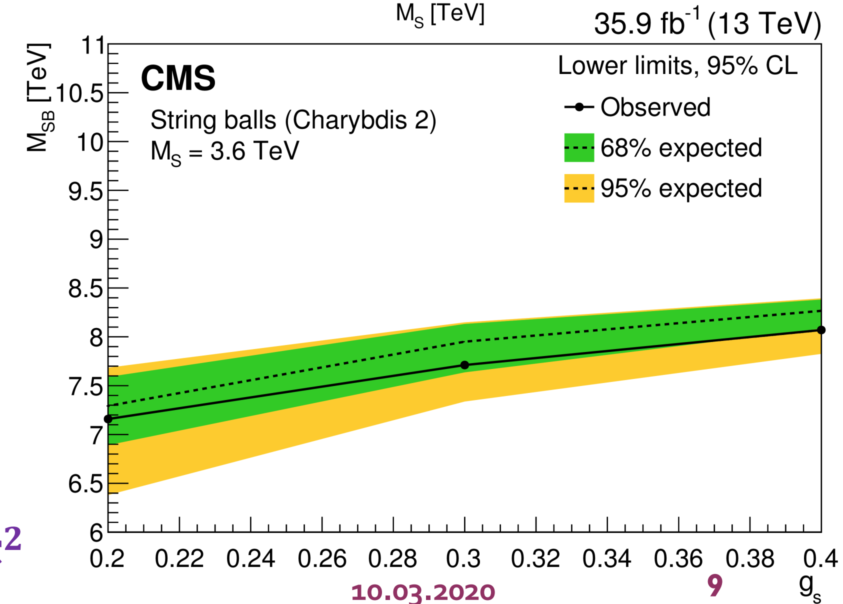
SB simulation – cross section matching
in the point of transition (xsecs are equal):

$$\sigma(SB)\Big|_{M_{SB}=M_s/g_s^2} = \sigma(BH)\Big|_{M_{BH}=M_s/g_s^2}$$

$$\sigma(SB/BH) = \begin{cases} \frac{\pi}{M^2}\left(\frac{M_{BH}}{M}\right)^{\frac{2}{n+1}}[f(n)]^2; & \frac{M_s}{g_s^2} \le M_{BH} \\ \frac{\pi}{M^2}\left(\frac{M_s/g_s^2}{M}\right)^{\frac{2}{n+1}}[f(n)]^2 = \frac{\pi}{M_s^2}[f(n)]^2; & \frac{M_s}{g_s} \le M_{SB} \le \frac{M_s}{g_s^2} \\ \frac{\pi g_s^2 M_{SB}^2}{M_s^4}[f(n)]^2; & M_s << M_{SB} \le \frac{M_s}{g_s} \end{cases}$$

JHEP 11 (2018) 042

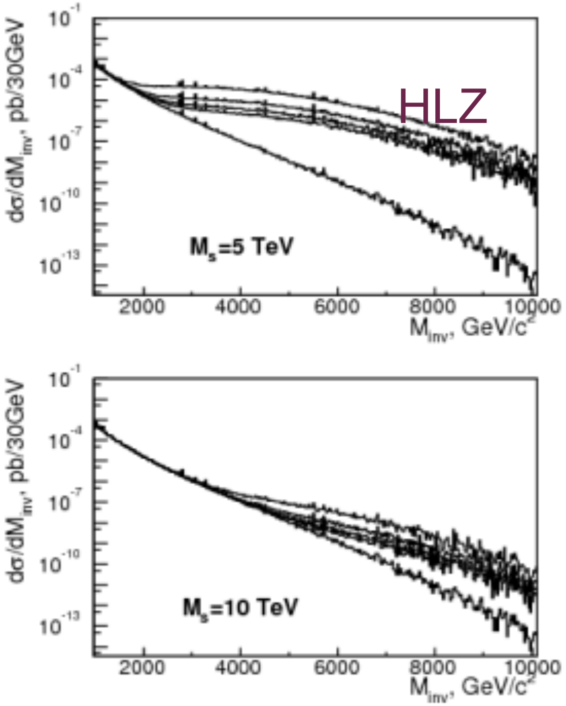




SB masses M_{min}^{SB} are excluded up to 7.1 −9.4 TeV/c²

Search for KK-gravitons in TeV-scale models: effective description (EFT approach)

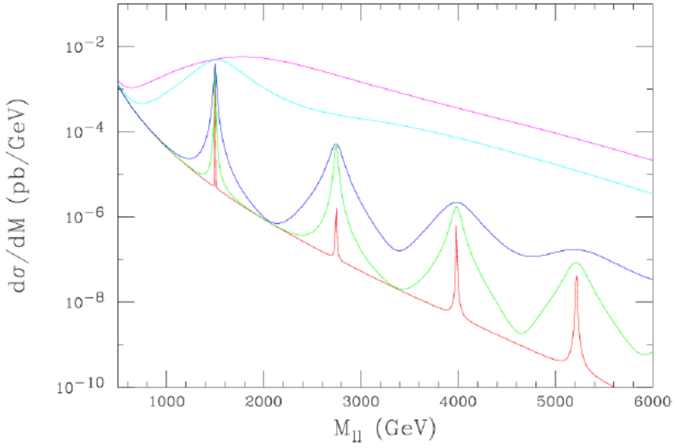
Non-resonant graviton production in the ADD model



Different matrix element parametrizations:

- HLZ (M_S,n)
- GRW (Λ_T)
- Hewett (M_D, λ=±1)

Heavy graviton resonance production in the RS1 model



A resonance mass:

$$m_n = k\beta_n e^{-\pi kR}$$

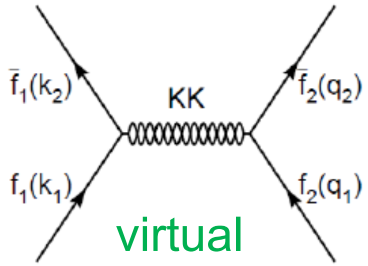
A resonance width:

$$\Gamma = \rho m_n \beta_n^2 \left(\frac{k}{M_{Pl}}\right)^2$$

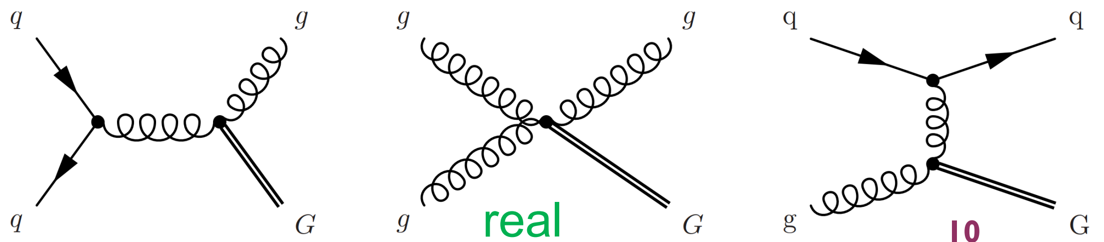
c (coupling constant)

Possible contributions to all SM processes, in particular:

- virtual contributions of KK modes to Drell-Yan process, photon and jet pair production (resonant and non-resonant type)
- dijet angular distributions (non-resonant type)



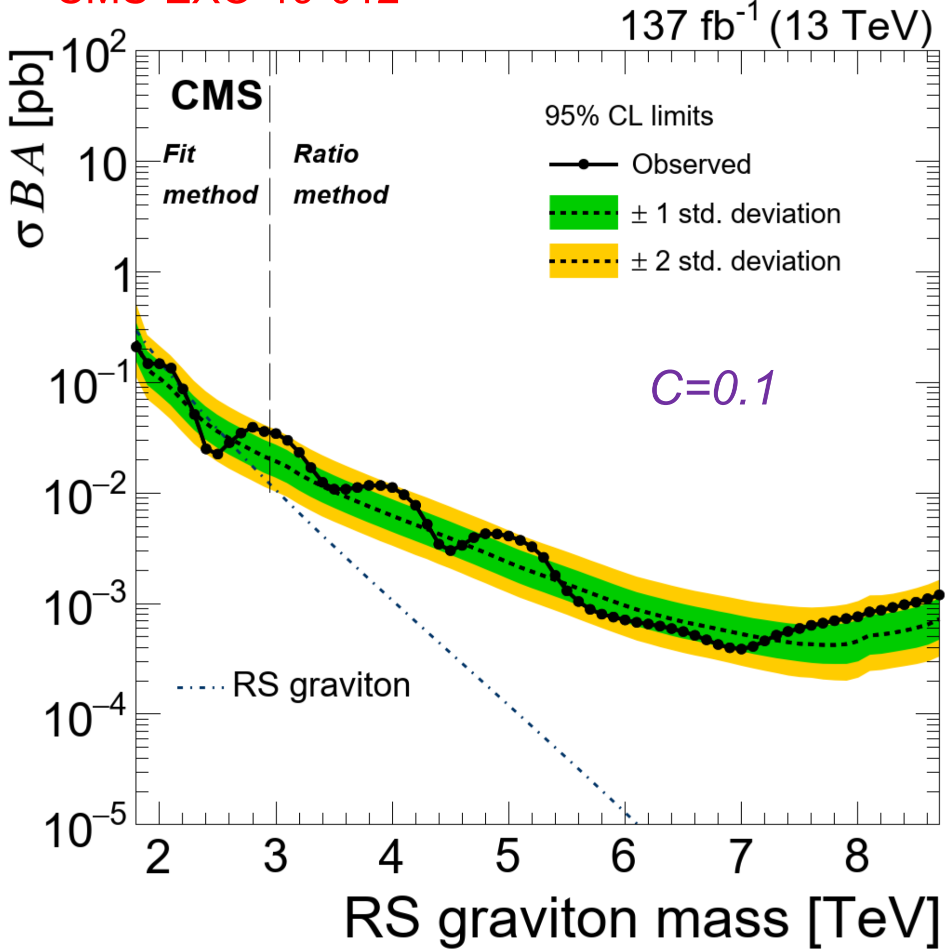
- KK mode direct production: a single hard probe (jet/V/γ) + missing E_T



Search for KK-gravitons at the LHC: observables

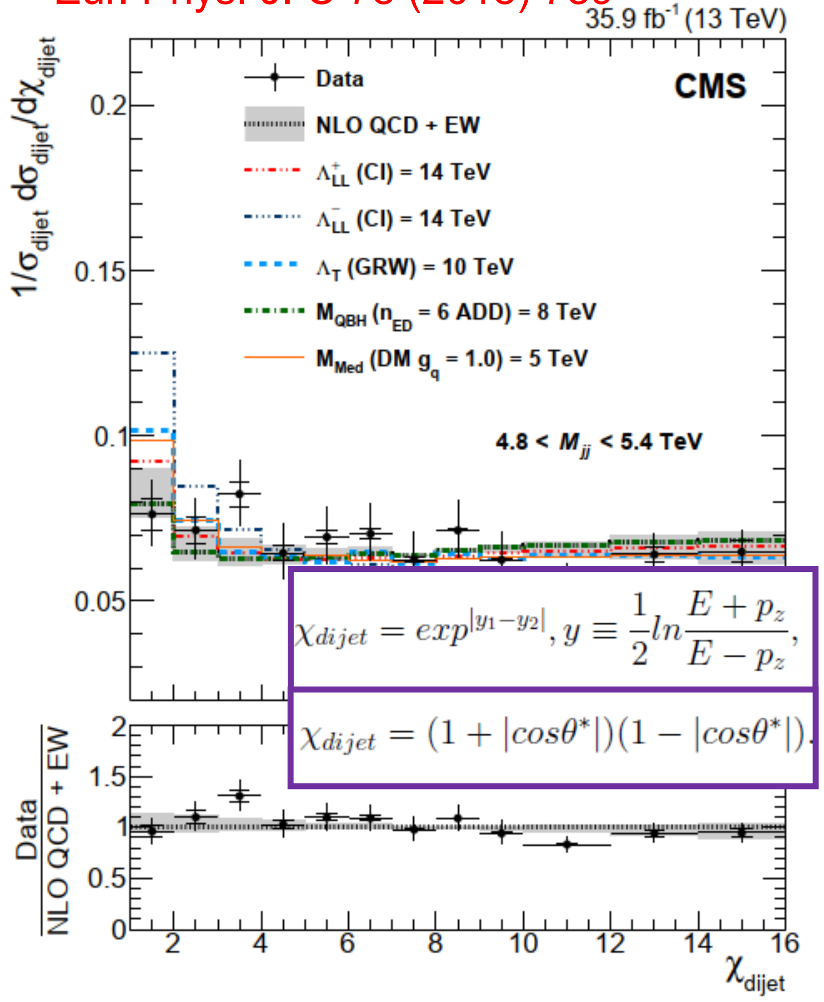
Virtual contributions of KK modes to jet pair production (RS1)

CMS-EXO-19-012



Dijet angular distributions (ADD)

Eur. Phys. J. C 78 (2018) 789



$$\chi_{dijet} = exp^{|y_1 - y_2|}, y \equiv \frac{1}{2} ln \frac{E + p_z}{E - p_z},$$

$$\chi_{dijet} = (1 + |cos\theta^*|)(1 - |cos\theta^*|)$$

The CMS experimental limits on M_D from KK-graviton searches, LHC RUN2

Excluded masses and scales in TeV, CMS

	Diphoton *PRD 98 (2018) 092001* *[36 fb^{-1}]*	Dijet *JHEP* *[137 fb^{-1}]*	Dilepton *JHEP 04 (2019)114* *[36 fb^{-1}]*	Dijet ang. distr. EPJ C **78** (2018) 789 *[36 fb^{-1}]*
Non-resonant				
ADD (GRW), Λ_T	**7.8**	**-**	**6.7**	**10.1**
ADD (Hewett), M_S, $\lambda = +1$	**7.0**	**-**	**6.0**	
ADD (HLZ), M_S, $n = 3$	**9.3**	**-**	**8.0**	**12.0**
ADD (HLZ), $M_S, n = 6$	**6.6**	**-**	**5.7**	**8.5**
Resonant				
RS1, m_G, $k/M_{Pl} = 0.01$	**2.3**		**2.05**	**-**
RS1, m_G, $k/M_{Pl} = 0.05$			**3.50**	**-**
RS1, m_G, $k/M_{Pl} = 0.1$	**4.1**	**2.6**	**4.05**	**-**

Result consistency on KK modes and BH:

- ❖ Semiclassical BH masses are excluded up to **10.1** TeV/c^2 in dependence on a number of ED n and model details.
- ❖ String ball masses are excluded up to **7.1 – 9.4** TeV/c^2
- ❖ For KK modes of graviton in two different multidimensional scenarios, ADD and RS1 obtained lower limits on M_S or Λ_T of:
  - ➢ **8.5 – 12.0** TeV in the ADD model;
  - ➢ from **2.3** TeV/c^2 (c=0.01) up to **4.1** TeV/c^2 (c=0.1) for the mass of the first graviton resonance M_G^{KK} (connected directly with M_D) in the RS1 model.

Classical approach

$$M^{BH}_{\min} = 4.1 M_D \quad \text{for ADD BH}$$
$$M^{BH}_{\min} \geq 16 M_D \quad \text{for RS1 BH}$$

⬇

Semiclassical BH production lookes inaccessible at the LHC c.m.s. energy up to 14 TeV

⬇

“Quantum” black holes etc.?

Quantum black holes

X. Calmet, Wei Gong, and S. D. H. Hsu, PLB 668 (2008) 20;
P. Meade and L. Randall, JHEP 05 (2008) 003.

Model approach:

- Small multidimensional BH produced near the fundamental gravity scale threshold.
- Clearly non-classical ⟹ "quantum" BH ⟹ BH in non-equilibrium thermal states,
  small entropy, a few-body decay (into 2-3 particles)
- "A memory" of initial states – final BH states as color and electric charge representations.

- **A large Compton length** such that it becomes larger than the QBH size ("quantum").

$$\lambda_C^{QBH} = \frac{2\pi}{M_{QBH}} \geq r_S$$

- Can be simulated by analogy with semiclassical BH using the same formulas (upper limits for xsecs) in the mass region

$$\left(\frac{1}{f(n)}\right)^{\frac{n+1}{n+2}} \leq \frac{M_{QBH}}{M_D} \leq \left(\frac{2\pi}{f(n)}\right)^{\frac{n+1}{n+2}}$$

(approx. $M_D \leq M_{QBH} \leq 2.7\ M_D$)

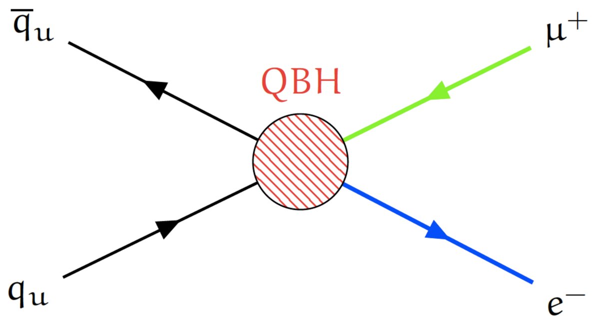
- **Can be FV final states! (and/or electric charge non-conservation)**

QBH event generator *Comput. Phys. Commun. 181, 1917 (2010)*

The CMS experimental limits on QBH search, RUN2 LHC

Experimental signatures:

- Dijet angular distributions
- FV two-body final states
- Q non-conservation (?) in two-body final states…



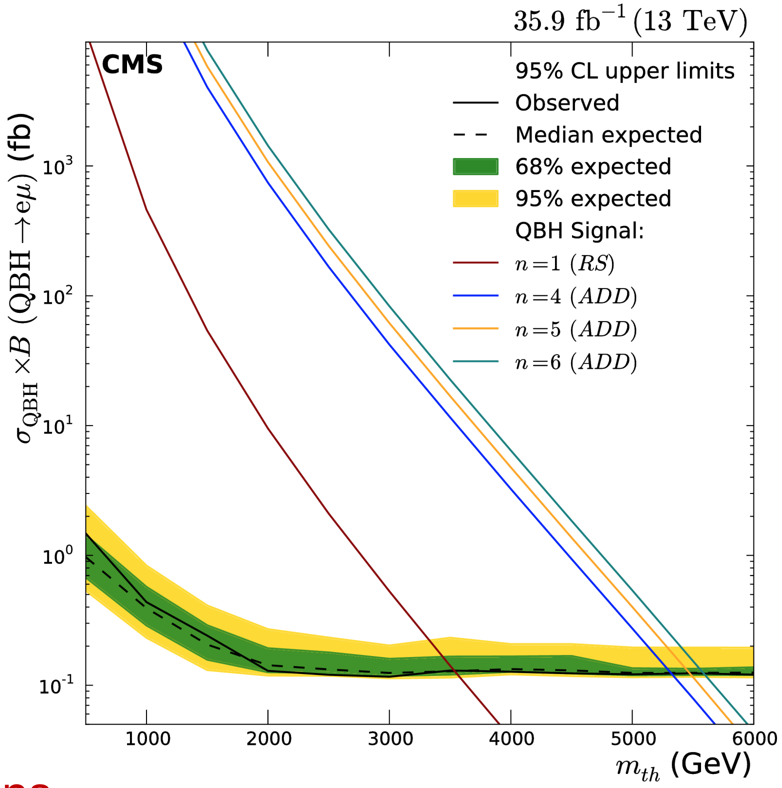
Initial states can be: qqbar, gg, gq(qbar)

Final states can be: FV or FC lepton(quark) pairs

❑ LFV channel – eμ

JHEP 04 (2018) 073

n	Limit on M_{th}
4 (ADD)	5.3 TeV
5 (ADD)	5.5 TeV
6 (ADD)	5.6 TeV
1 (RS1)	3.6 TeV



❑ Dijet angular distributions

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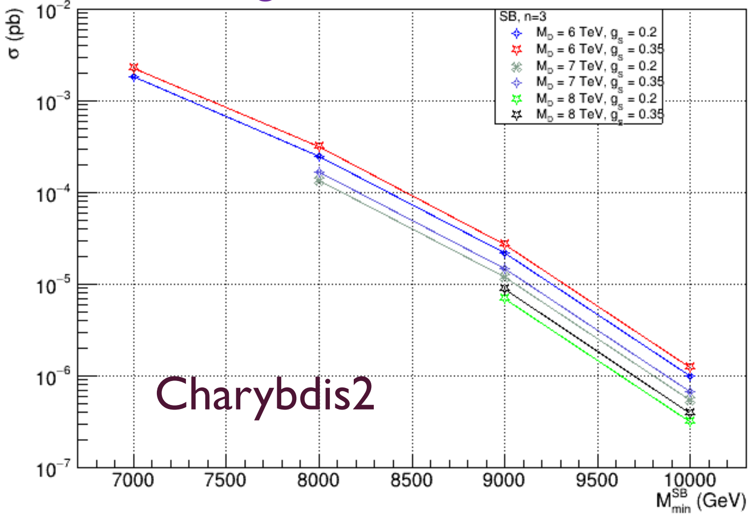
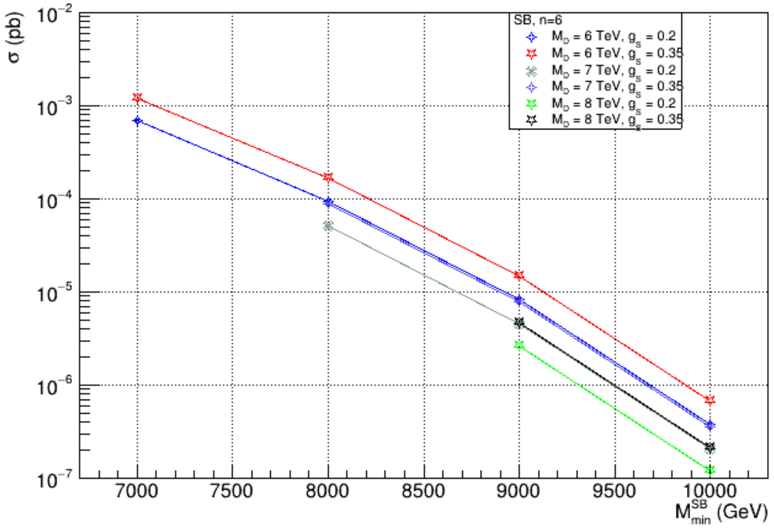
QBH masses are excluded up to 5.9 ÷ 8.2 TeV

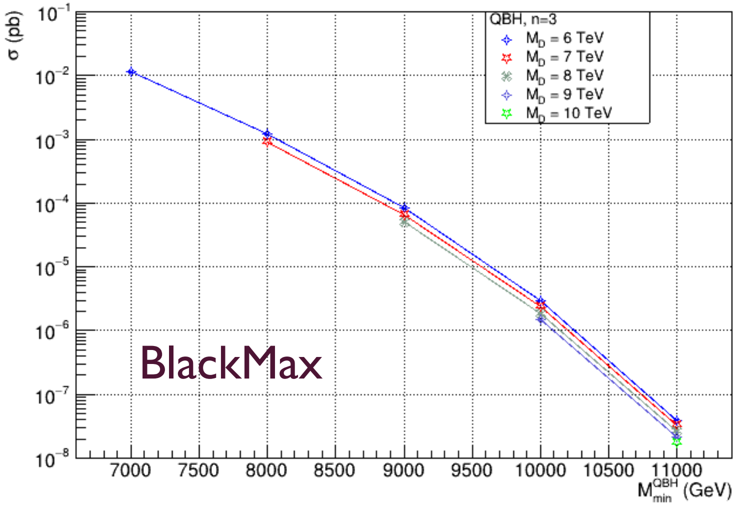
Simulation of near-threshold objects for actual parameter values

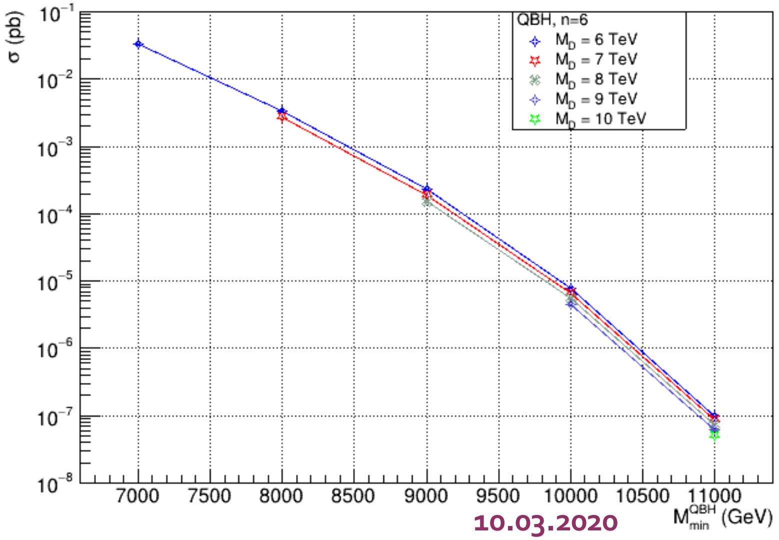
String ball cross sections





Quantum black holes



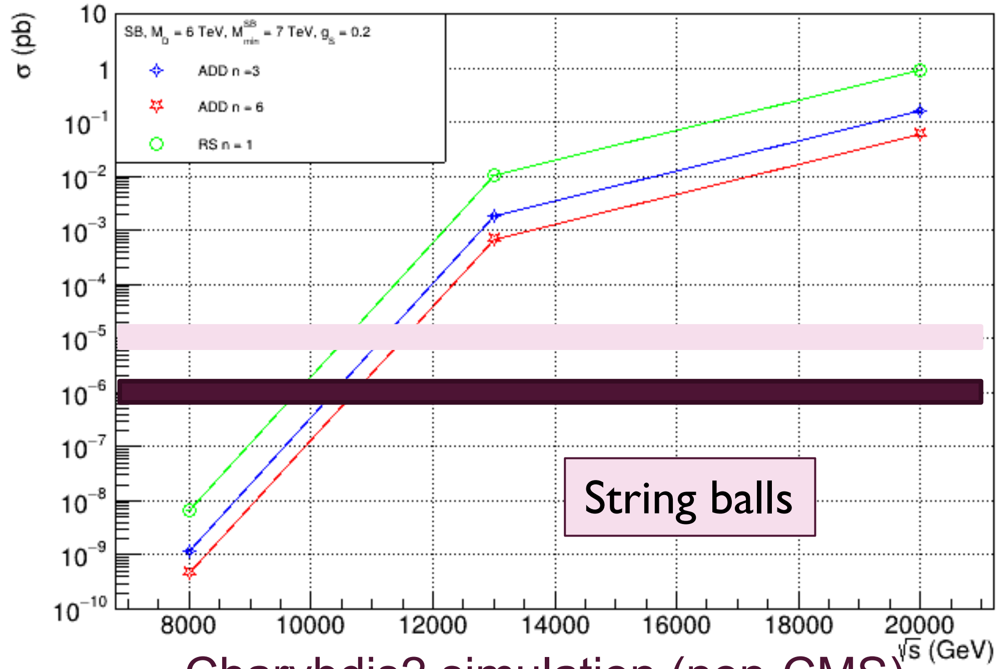


RUN 3 expectations for near-threshold objects observation

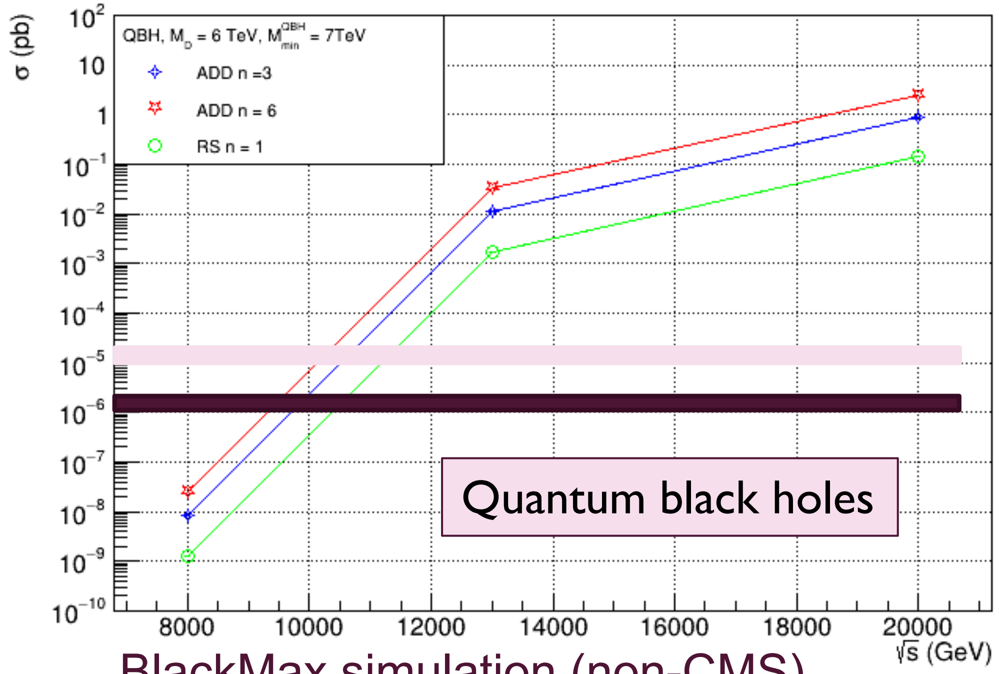
RUN 3 period	2021-2024
Collision energy, pp	13(14?) TeV
Full statistics	300 fb^{-1}

RUN 3 LHC
HL-LHC

Energy dependence of QBH and SB production cross sections



Charybdis2 simulation (non-CMS)



BlackMax simulation (non-CMS)

Summary and outlook 1

- TeV-scale gravity models predict the existence of two type physics phenomena – KK modes of graviton and microscopic multidimensional black holes and(or) other objects of strong gravity (string balls, “quantum” black holes). During the LHC Run1 & Run2 connected searches were actively performed by the CMS Collaboration.

- No signals of new physics under study were observed, lower limits on a fundamental gravity scale and object masses were set up to:
  - 7.1 ÷ 10.1 TeV/c^2 for semiclassical BH masses (multijet events);
  - 7.1 ÷ 9.4 TeV/c^2 for SB masses (multijet events);
  - 5.9 ÷ 8.2 TeV/c^2 (2jet ang. distr.), 3.6 ÷ 5.3 TeV/c^2 (LFV dileptons) for QBH masses;
  - *8.5* ÷ 12.0 TeV for a fundamental gravity scale in the ADD model M_D (2jet ang. distr.);
  - 2.3 ÷ 4.1 TeV/c^2 for the first KK mode mass $m_G^{(1)}$ in the RS1 model (2jet/2l/2γ).

Limits are in a good agreement with each other

Summary and outlook 2

- As limits set during the LHC RUN2 is high for LHC energy, we do not expect to observe semiclassical BH during RUN3, therefore the searches for near-threshold objects seems to be more perspective.

QBH in our case.

- Angular distribution of dijets and two-particle final states with flavor violating combinations are more appropriate.
- We plan to do future analysis with dilepton final states with LFV during the LHC RUN3.

THANKS FOR YOUR ATTENTION!

BACKUP SLIDES

R.C. Myers and M.J. Perry, Ann. Phys. 72, 304, 1986

Myers-Perry solution

$$D = 10 = d + n, \qquad d = 1 \ldots 4, \qquad n = 10 - d$$

$$ds^2 = \left(1 - \frac{\mu r^{1-n}}{\Sigma(r,\theta)}\right) dt^2 - sin^2\theta \left(r^2 + a^2 \left(1 + sin^2\theta \frac{\mu r^{1-n}}{\Sigma(r,\theta)}\right)\right) d\phi^2 + 2a sin^2\theta \frac{\mu r^{1-n}}{\Sigma(r,\theta)} dt d\phi - \frac{\Sigma(r,\theta)}{\Delta} dr^2 -$$
$$-\Sigma(r,\theta) d\theta^2 - r^2 cos^2\theta d^n\Omega$$

$$\Sigma = r^2 + a^2 cos^2\theta \qquad \Delta = r^2 + a^2 - \mu r^{1-n}$$

BH mass:

$$M = \frac{(n+2)A_{n+2}}{16\pi G_D}\mu$$

Angular momentum:

$$J = \frac{2Ma}{n+2}$$

Area of (n+2)-sphere surface of unit radius:

$$A_{n+2} = \frac{2\pi^{(n+2)/2}}{\Gamma(\frac{n+3}{2})}$$

Multidimensional gravitational constant G_D:

$$G_D = \frac{(2\pi)^{n-1}}{4M_D^{d+2}}$$

$$S = \int \left(\frac{1}{16\pi G} R + \mathcal{L}\right) \sqrt{-g} d^D x$$

$$M_P^{D-2} = \frac{(2\pi)^{D-4}}{4\pi G_D} \qquad \text{GT}$$

$$M_D^{D-2} = \frac{(2\pi)^{D-4}}{8\pi G_D} \qquad \text{GRW (PDG)}$$

$$M^{D-2} = \frac{1}{G_D} \qquad \text{DL}$$