Quantum black holes and their lepton signatures at the LHC

Alexander Belyaev

Southampton University & Rutherford Appleton LAB

Black Holes and their Analogues: 100 years of General Relativity

in honor of Kirill Bronnikov's 70th birthday

Ubu, Brazil, April 16th, 2015

OUTLINE

Based on arXiv:1412.2661, AB and Xavier Calmet

- Introduction -
  QBH as a link between GR and QFT
- QBH at the LHC
  - Our approach
  - Model implementation
  - LHC potential to probe QBH in XD models
- Conclusions

Planckian (Quantum) Black Holes: QBH

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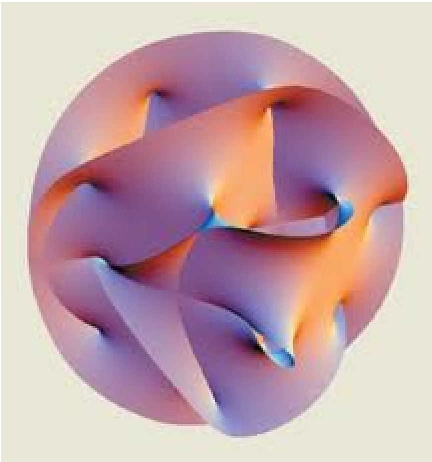
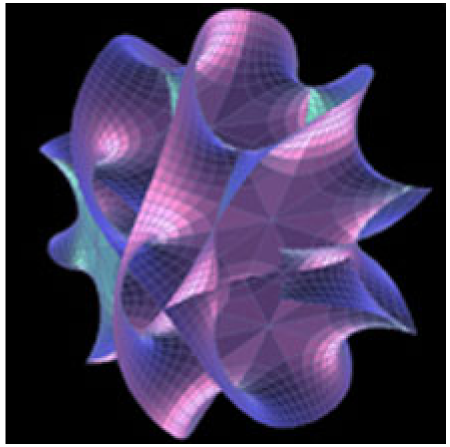
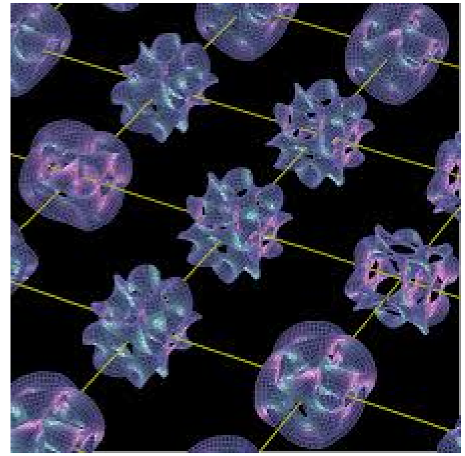
  - In three-dimensional gravity, the minimal mass of microscopic black hole is $M_{PL} = 10^{19}$ GeV
  - To reach Planck length and Plank Mass with current technologies one should build collider with about 1000 light years in diameter!
- Luckily, in some scenarios involving (large) extra dimensions of space, the Planck mass can be as low as the TeV range

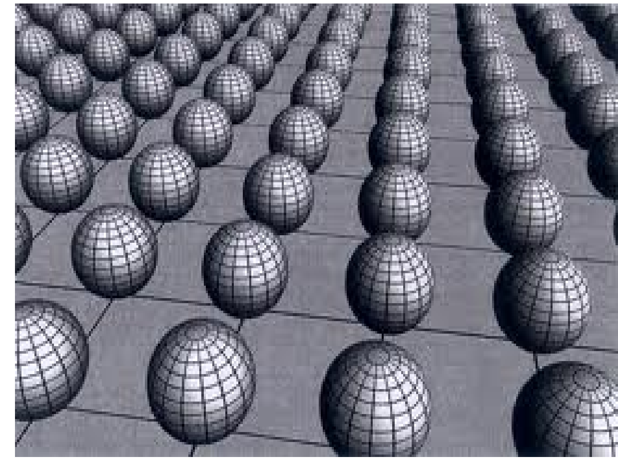
  In this case QBH will be accessible at the LHC - this talk

eXtra Dimensions (XD)









Motivations

- String theory, the best candidate to unify gravity & gauge interactions, is only consistent in 10 D space-time
- Extending symmetries: Internal symmetries - GUTs, technicolour...; Fermionic spacetime- SUSY; Bosonic spacetime - Extra dimensions
- The presence of XD could have an impact on scales << M_{planck} (started with ADD)
  The question is what is the size and the shape of XD ?!

New perspectives of XD

- The nature of electroweak symmetry breaking
- The origin of fermion mass hierarchies
- The supersymmetry breaking mechanism
- The description of strongly interacting sectors (provide a way to model them)
- ....

Brief History

- 1914: Nordstrom tried to unify gravity and electromagnetism in 5D
  (A_μ -> A_M, where M = 0,1,2,3,4)

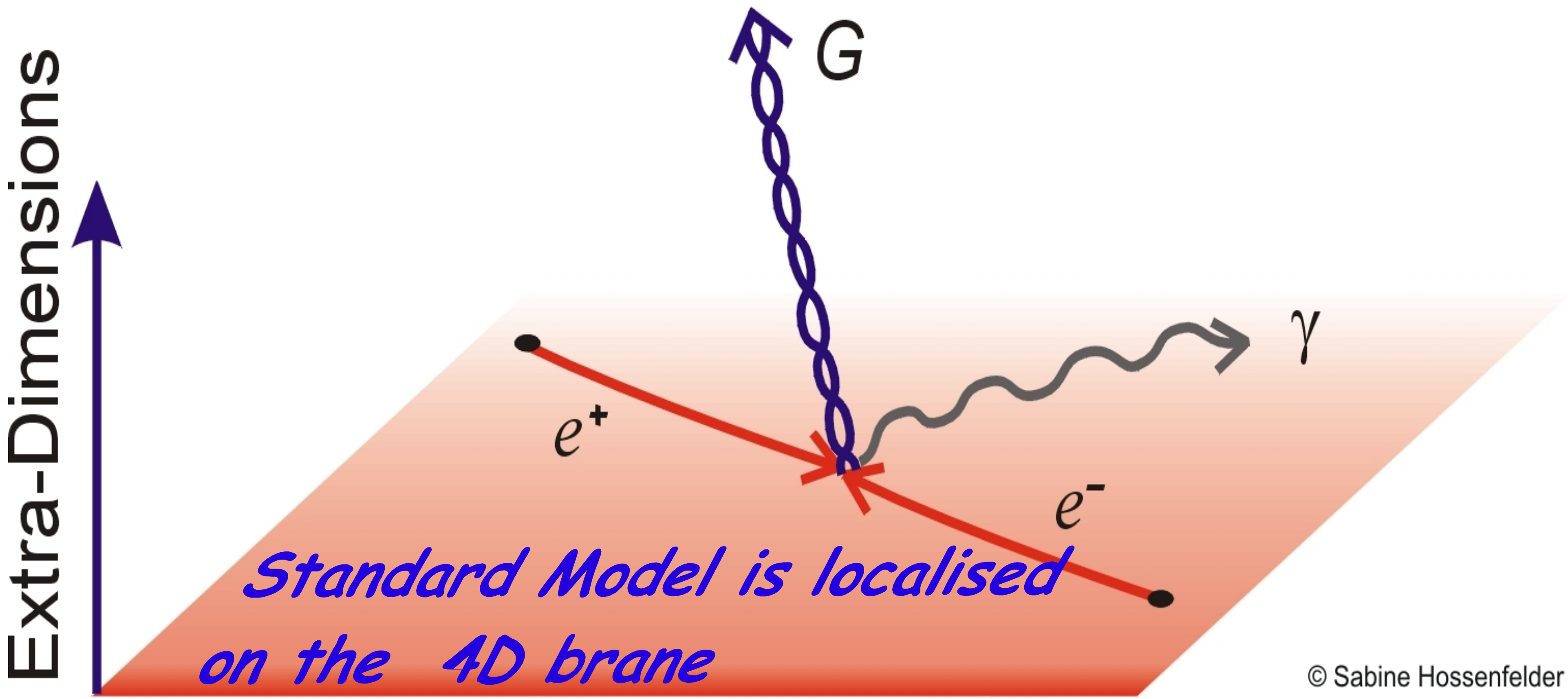
- 1920's: Kaluza and Klein tried using Einstein's equations in 5D ($g^{\mu\nu}$ -> g^{MN} ~ $g^{\mu\nu}$, $g^{\mu 4}$, g^{44})

- 1970's: Development of superstring theory and supergravity required extra dimensions

- 1998: Arkani-Hamed, Dimopoulos, and Dvali propose Large Extra Dimensions (ADD) as a solution to the Hierarchy /Fine tuning problem of the Standard Model

The idea of ADD

- The Standard Model has been tested to r ~ 10^{-16} mm, Gravity has been tested to r ~ 1 mm only



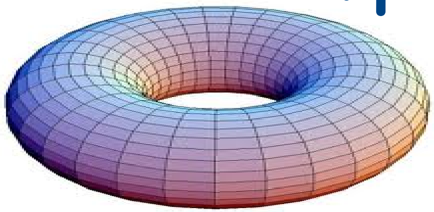
The idea of ADD

- The Standard Model has been tested to r ~ 10^{-16} mm,
  Gravity has been tested to r ~ 1 mm only
- 4D –> (4 + n)D
  The effective D = 4 action is

$$\frac{M_{\rm f}^{2+n}}{2}\int d^4x \int_0^{2\pi R} d^n Z\,\sqrt{G}\,R_{4+n} \longrightarrow \frac{1}{2}M_{\rm f}^{2+n}\,V_n\int d^4x\,\sqrt{g}\,R$$

In case of toroidal compactification of equal radii, R

$$V_n = (2\pi R)^n$$



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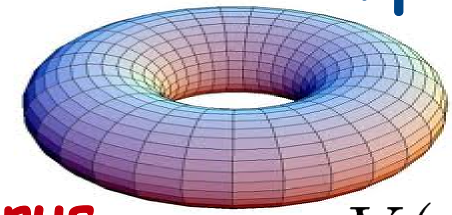

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r>>R ⇒ the torus effectively disappear

$$V(r)=-G_N\frac{m_1m_2}{r}=-\frac{m_1m_2}{M_P^2 r}$$

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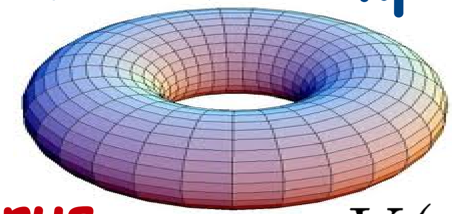

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$$V(r) = -G_N \frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_P^2 r}$$

r<<R ⇒ observer is able to feel the bulk

$$V(r) = -G_* \frac{m_1 m_2}{r} = -\frac{m_1 m_2}{M_f^{2+n} r^{1+n}}$$

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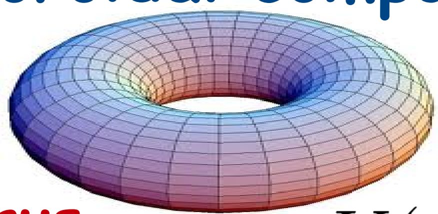

$$M_P^2=M_f^{2+n}V_n$$

r>>R ⇒ the torus effectively disappear

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$$V(r)=-G_N\frac{m_1m_2}{r}=-\frac{m_1m_2}{M_P^2r}$$

$$V(r)=-G_*\frac{m_1m_2}{r}=-\frac{m_1m_2}{M_f^{2+n}r^{1+n}}$$

Fundamental quantum gravity scale

The current status of ADD

So, $M_P^2 = M_f^{n+2}(2\pi R)^n$ and respectively,

$$R = \frac{1}{2\pi}\frac{1}{M_f}\left(\frac{M_P}{M_f}\right)^{\frac{2}{n}} [\mathrm{GeV}^{-1}] \times 0.197 [\ \mathrm{GeV\ m}]$$

How big are these dimensions are?

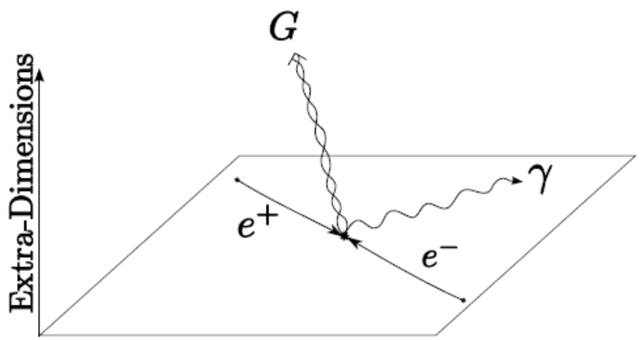
Let us assume $M_f \sim 1$ TeV, then

$$R \sim \begin{cases} 10^{15}\ \mathrm{mm} & n=1 \\ 1\ \mathrm{mm} & n=2 \\ 10^{-6}\ \mathrm{mm} & n=3 \\ \vdots & \end{cases}$$

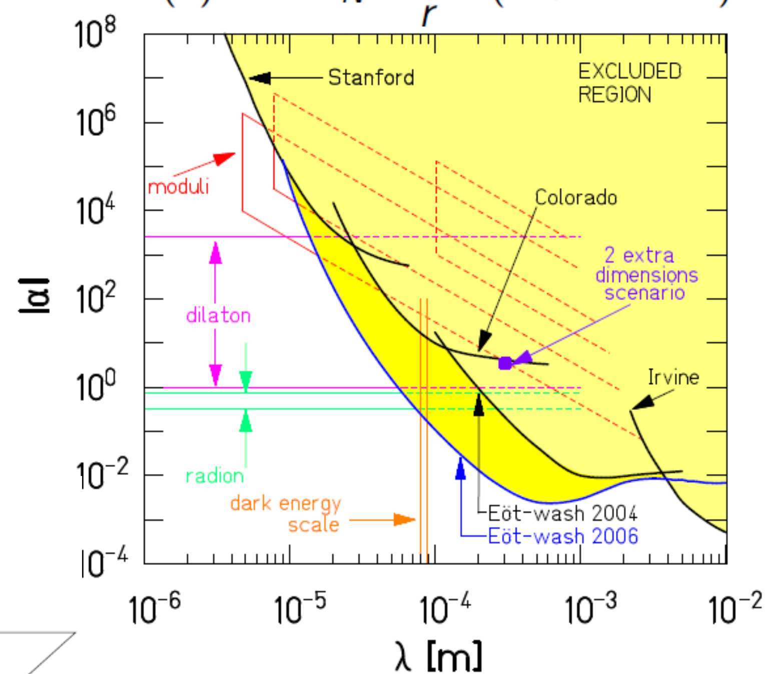
✕ ✕ **Already ruled out**

Collider signature:

$$pp \to jet + \not{E}_T$$



$$V(r) = -G_N\frac{m_1 m_2}{r}(1+\alpha e^{-r/\lambda})$$



The current bound is $R < 37\ \mu\mathrm{m}$

For $n = 2$ this means that $M > 1.4$ TeV

Summary of ADD ("flat scenario")[1998]

- gravity propagates in the compact & non-compact dimension
- the Einstein action

$$S_E = \frac{1}{8\pi G}\int d^D x\sqrt{-g}\,\frac{1}{2}\mathcal{R}$$

- implies the relation between the four-dimensional and D-dimensional Newton's constants

$$G_N = \frac{G_D}{V_{D-4}}$$

- The reduced fundamental Planck scale is generally related to the D-dimensional Newton's constant as

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

Rundal Sundrum ("warp scenario")[1999]

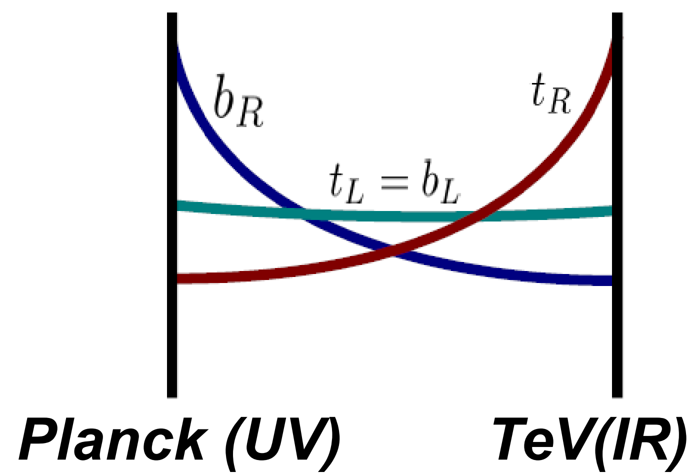
- a warped geometry is described by a metric of the form

$$ds^2 = e^{2A(y)} dx_4^2 + g_{mn}(y) dy^m dy^n$$

- where $dx_4^2 = \eta_{\mu\nu} dx^\mu dx^\nu$ is the 4D Minkowski line element

  y^n parameterise the XD of space-time, with metric g_{mn}
- The function e^A is the warp factor, defining 4D massscales
- gravity propagates in the compact & non-compact directions
- The 4D Newton's constant is related to the the D dimensional one by

$$G_N^{-1} = G_D^{-1} \int d^{D-4} y \sqrt{g}\, e^{2A}$$



- 4D Planck scale M_D exponentially suppressed by the warp factor

$$M_D = M_{PL} exp(-\pi k R)$$

where k, R are related to $A(y)$

QBH at colliders – features and assumptions

- high energy processes on the brane at scales of order or fundamental Planck Mass, M_P ~ TeV in ADD/RS models can probe strong gravitational effects including QBH formation
- The lowest scale at which BH can be produced is M_P, which means that this BH will be essentially non-termal, i.e. QBH
- Since QBH properties are not well understood, the best we can do is to use semi-classical limits:
  - Schwarzschild radius RS in (3+n) spacial dimensions:

$$R_S(M_{\mathrm{BH}}) = \frac{1}{M_D}\left[\frac{M_{\mathrm{BH}}}{M_D}\Gamma\left(\frac{n+3}{2}\right)\frac{2^n\pi^{\frac{n-3}{2}}}{n+2}\right]^{\frac{1}{n+1}}$$

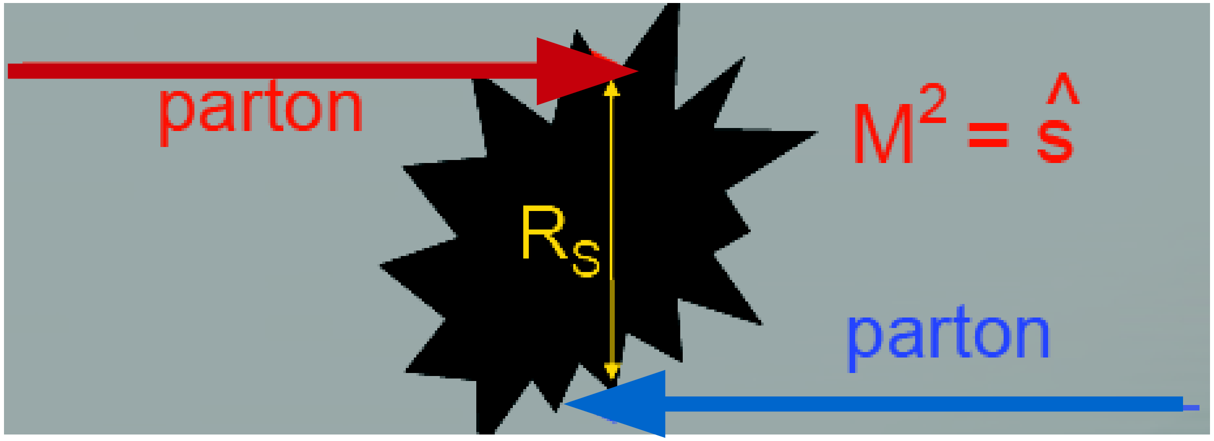
[Meyrs,Perry 1986]

- Hawking temperature $T_H = \dfrac{n+1}{4\pi R_S}$ ~1 TeV

[Dimopolous,Landsberg 2001; Giddings, Thomas, 2002]

QBH at colliders – production

- we assume that the cross section for QBH's can be extrapolated from the classical and semi-classical cases, i.e. that it is given by the geometrical formula $\sigma = \pi r_s^2$
  [Eath & Payne 1992; Eardley & Giddings 2002]
- Cross section, given by disk approximation



$\sigma \sim \pi R_s^2 \sim 1\ \mathrm{TeV}^{-2} \sim 10^{-38}\ \mathrm{m}^2 \sim 100\ \mathrm{pb}$

is comparable with that of the top-quark pair production!

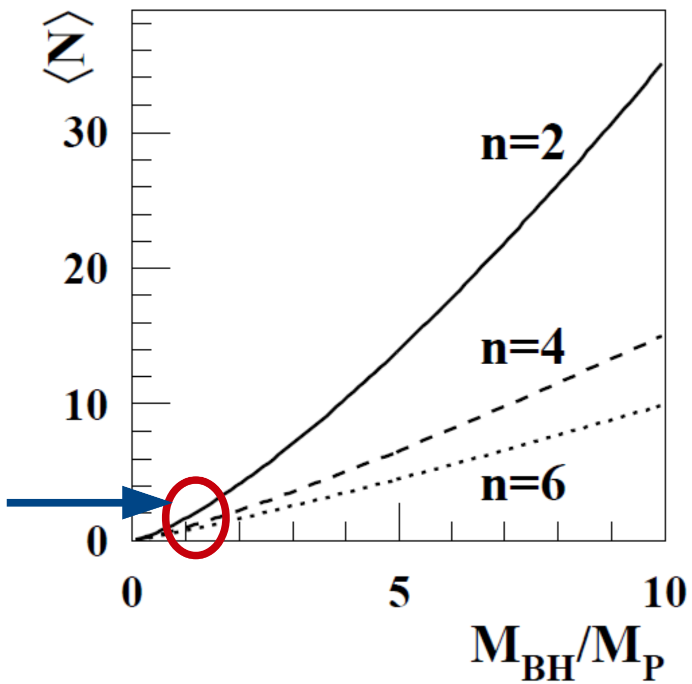
QBH at colliders – evaporation (decay)

- Evaporation (decay) multiplicity of QBH

$$\langle N \rangle = \frac{2\sqrt{\pi}}{n+1}\left(\frac{M_{\rm BH}}{M_P}\right)^{\frac{n+2}{n+1}}\left(\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right)^{\frac{1}{n+1}}$$

- In 4D $\langle N \rangle \approx \frac{M_{\rm BH}}{2T_H}$

- So indeed, QBH will rather explode into just a few particles resembling strong gravitational re-scattering.



[Dimopoulos & Landsberg 2001]

- It is thus tempting to treat QBH as particle, carrying the quantum numbers of the particles which created them.

QBH at colliders – the approach (1)

- Calmet, Fragkakis and Gausmann (2011) proposed a field theoretical model to describe the interactions of QBHs

- It assumes that QBHs can be treated as quantum fields, classified according to representations of the Lorentz group.

- Furthermore, they are classified according to their transformations under the gauge groups of the SM. This fixes their interactions with matter.

- In a proton-proton collider, quantum black holes would be produced from the collisions of quarks and gluons

QBH at colliders – the approach (2)

- We are thus particularly interested in the QBHs carrying QCD and QED quantum numbers and with spins 0,1/2 and 1 since these should be the lowest lying states.
- Generically speaking, quantum black holes form representations of SU(3)c and carry a QED charge.
- We consider process of two partons p_i and p_j forming a quantum black hole in the c representation of $SU(3)_c$ and charge q as: $p_i\ p_j \to QBH_c^q$

QBH at colliders - details of the calculations(1)

$$\sigma(pp \to QBH) = \sum_{i,j} \int dx_1 dx_2 f_i(x_1) f_j(x_2) \sigma(ij \to QBH)$$

- Continuous QBH mass = $\sqrt{s}$ invariant mass of two partons
- In 4D case (just for the sake of simplicity) [running of the gravitational coupling constant can be radically affected by a hidden sector with a large number of particles - analogous to KK modes - Calmet, Hsu, reeb, 2008]
  we have

$$r_s(s, \overline{M}_{PL}) = \frac{\sqrt{s}}{4\pi \overline{M}_{PL}^2} \quad \text{and} \quad \sigma = \frac{1}{16\pi} \frac{s}{\overline{M}_{PL}^4} \Theta(\sqrt{s} - \overline{M}_{PL})$$

QBH at colliders - details of the calculations(2)

- Let us consider production of spinless QBH in the collision of two fermions (quarks for example)
- Recalling that σ ~ s, one can use 4-fermion contact interaction to describe this cross section behaviour as a function of s:

$$\mathcal{L}_{cont} = \frac{g_c}{\Lambda^2}\bar{\psi}_i\psi_i\bar{\psi}_j\psi_j$$

- which gives $|M|^2 = \frac{g_c^2}{\Lambda^4}$ for qq->qq scattering

and the respective total cross section (for massless fermions)

- $\sigma = \frac{1}{16\pi s}|M|^2 = \frac{g_c^2}{16\pi}\frac{s}{\Lambda^4}$ which reproduces the QBH cross section

for $g_c = 1$ and $\Lambda = \overline{M}_{PL}$!

Implementation into CalcHEP (1)

- **CalcHEP – Calculator for High Energy Physics**
  [AB,Pukhov,Christensen '04, created by Pukhov etal in '89 as a CompHEP]

- **Uses the model written in the form of Feynman Rules for any theory (including effective ones) and**

  - Evaluates Matrix element square Analytically
  - Evaluates total and differential CS numerically
  - Simulate events which can be used in further analysis and in further (detector simulations) by CMS, ATLAS and other experimental collaboration
  - One of the leading packages for the LHC physics
  - Very convenient/user-friendly GUI and online help

Implementation into CalcHEP (2)

- QBH model was implemented as contact interactions

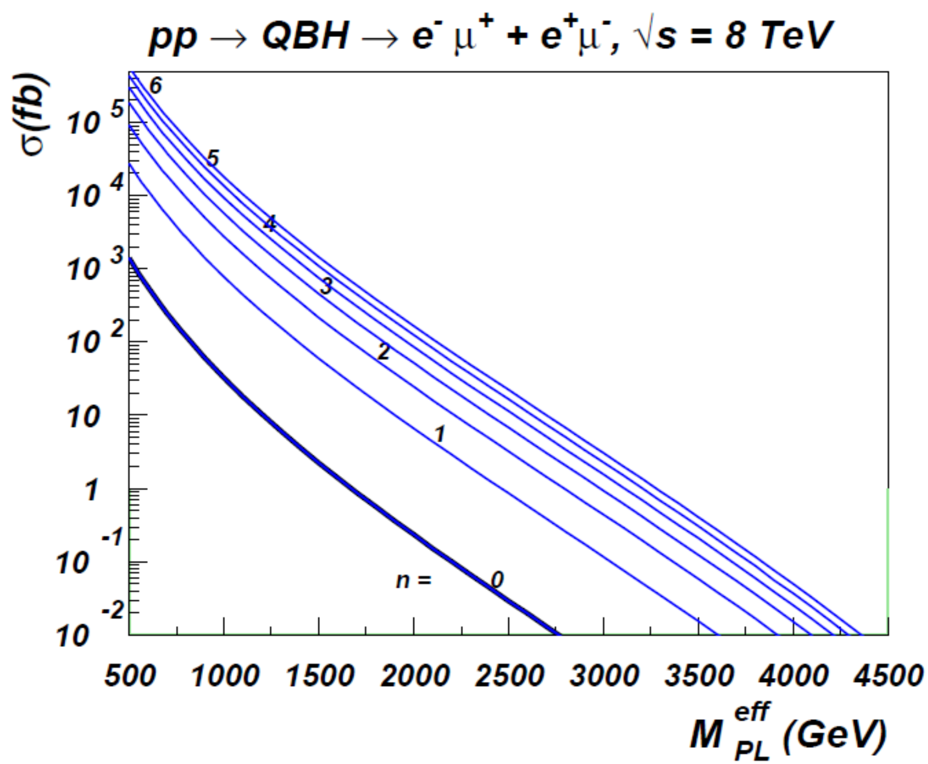
$$\mathcal{L}^{X}_{cont} = g_c \left(\sum_{leptons} \bar{\psi}^{\ell}_i \psi^{\ell}_j X + \sum_{quarks} \bar{\psi}^{q}_i \psi^{q}_j X \right)$$

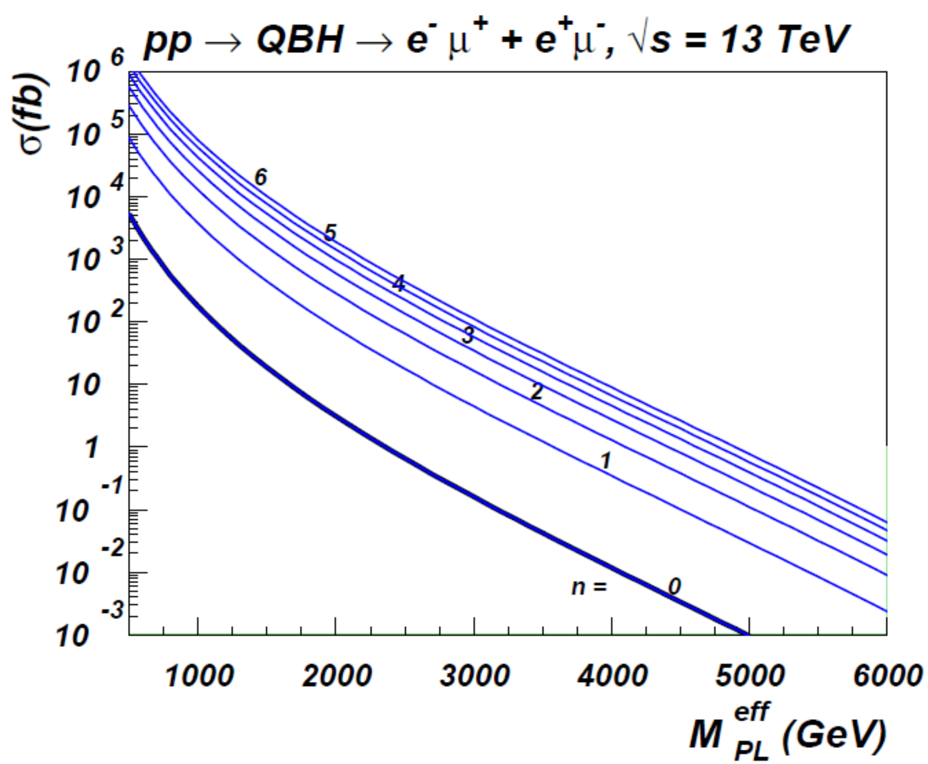
  to take into account all quak and lepton combinations, where i, j are lepton and quark flavour indices, propagator of X "contact" field is $\frac{i}{M^2_{PL}}$

- $g_c = (n_l + 3n_q)^{-1/4}$ is the normalisation factor accounting number of lepton, n_l = 9 and quark, n_q = 18 combinations, including the quark colour factor
- This Lagrangian exactly reproduces the cross section of the spinless neutral QBH production and decay in the 2->2 fermion process as a function of s

QBH Production rate at the LHC for di-lepton signature

- Why di-lepton signature?
  - very "clean" (low background) , especially for $e\mu$ signature
  - Best energy resolution
  - High (~ 90%) lepton ID efficiency





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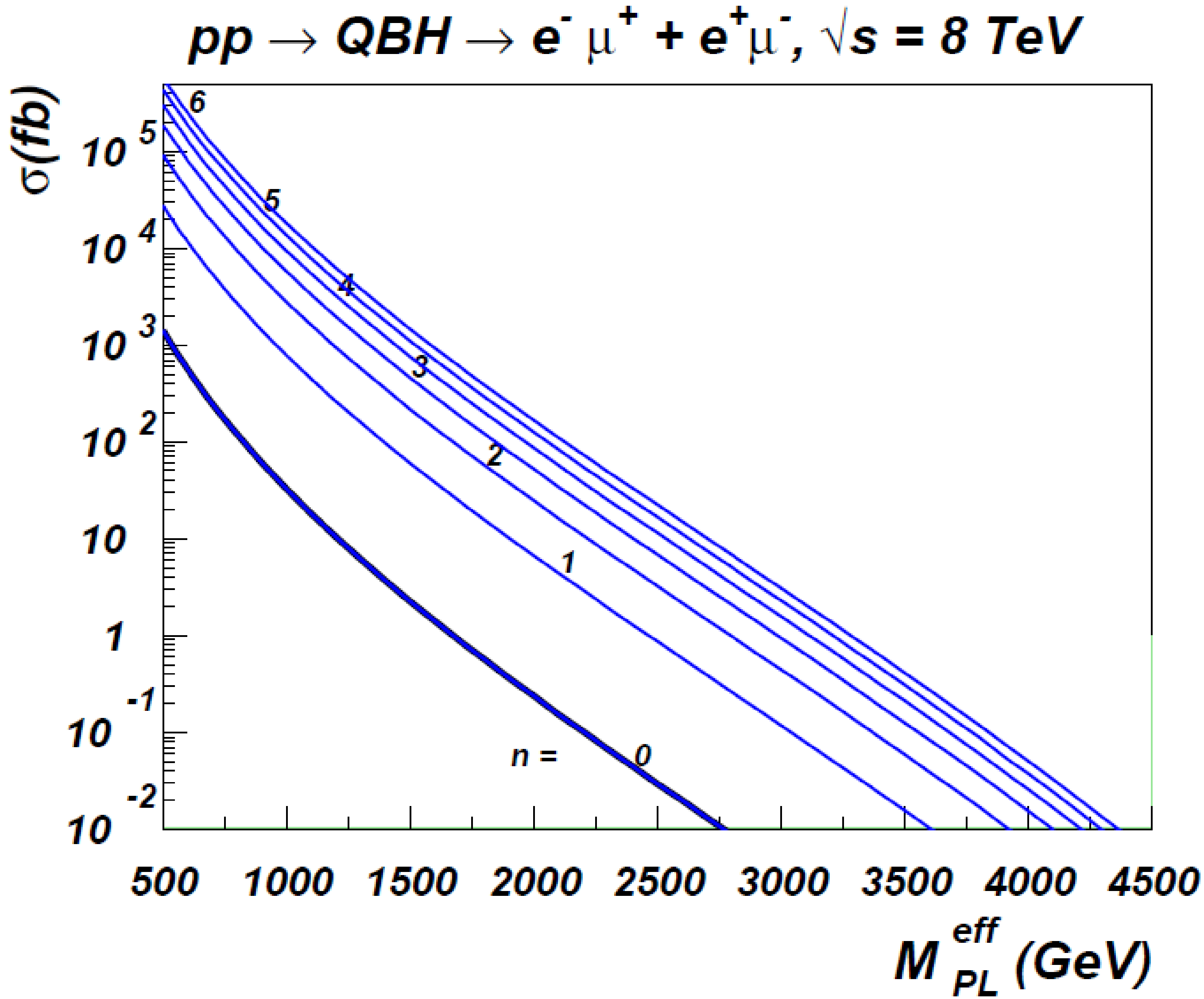

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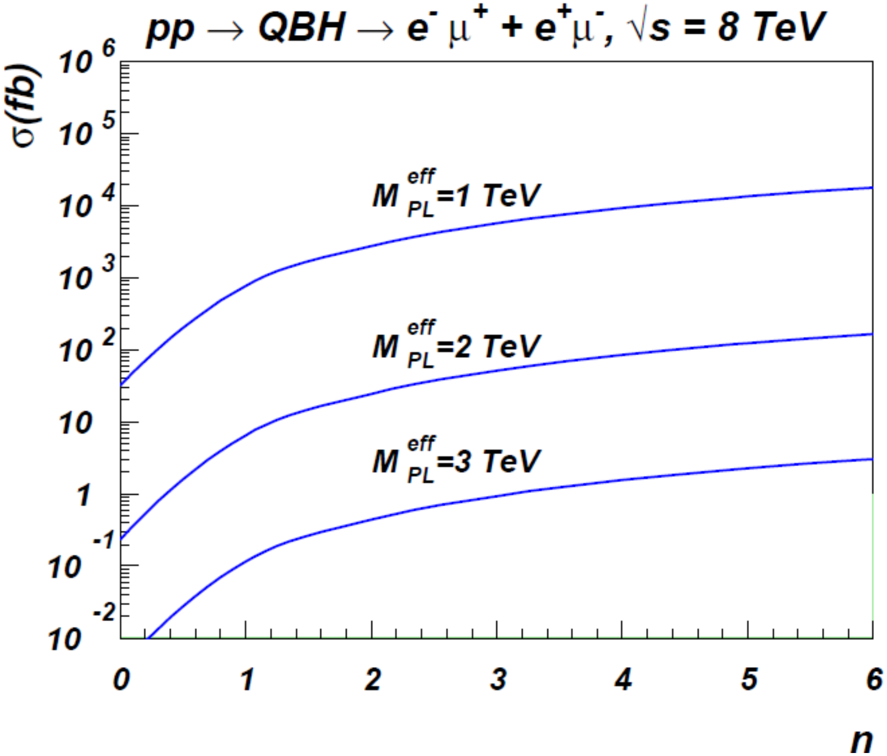
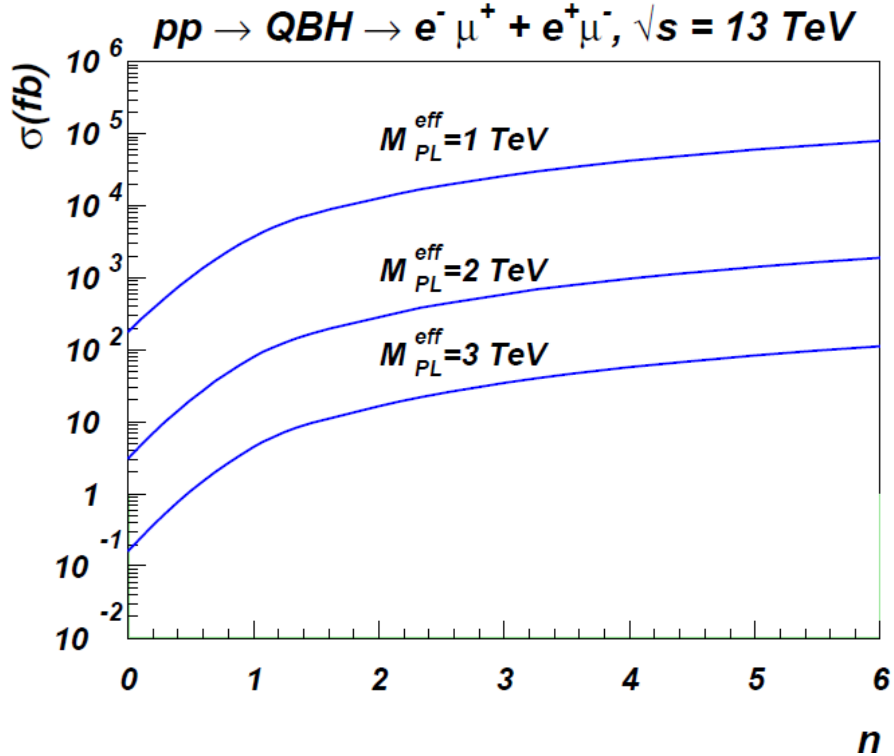


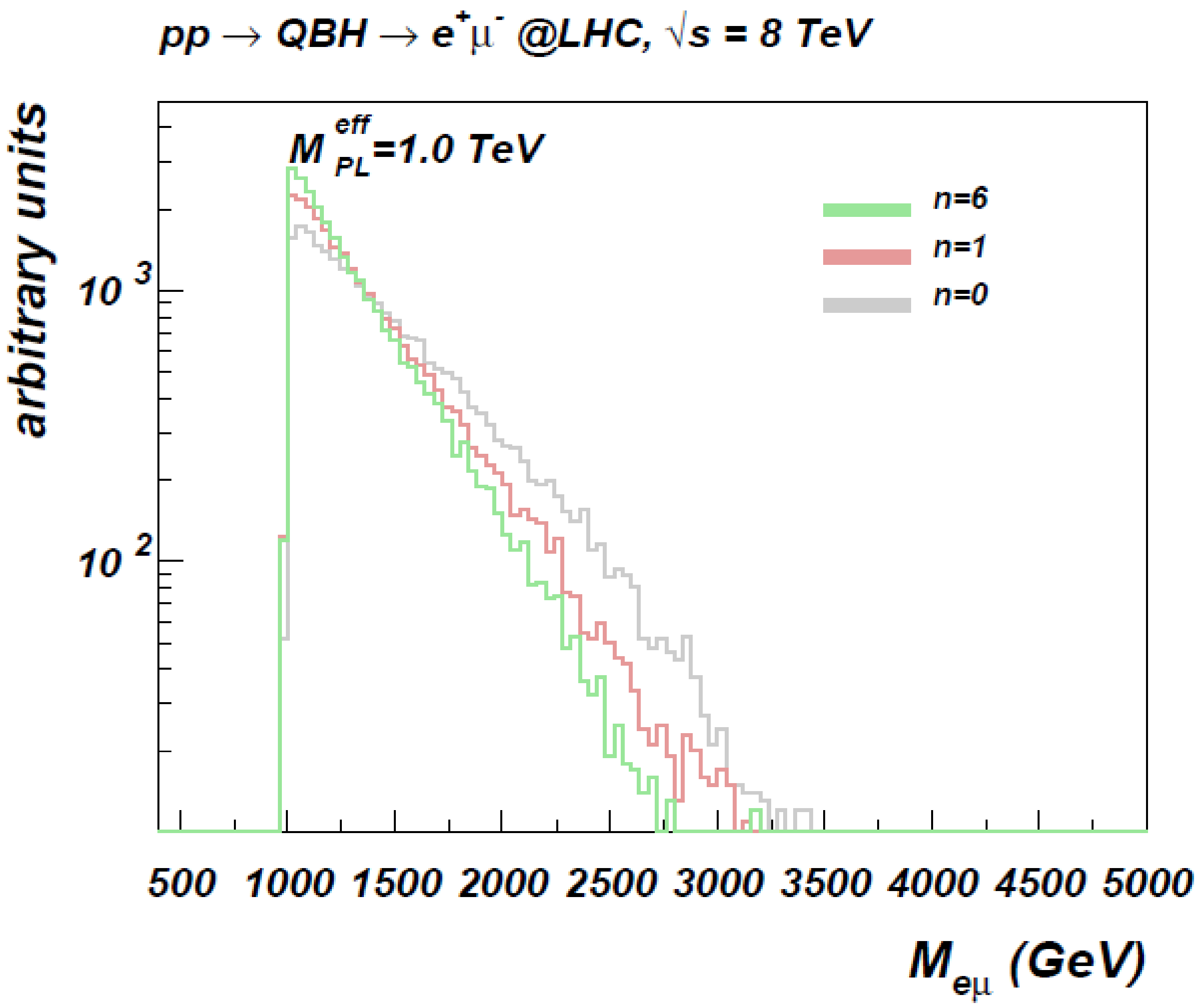


cross section of pp -> QBH -> eμ process in fb

	$\overline{M}_{PL}$ (TeV)	n=0	n=1	n=2	n=3	n=4	n=5	n=6
LHC@8TeV	1.0	32.3	782.	2760.	5730.	9370.	13500.	18100.
	2.0	0.235	6.60	24.5	51.8	85.7	124.	166.
	3.0	0.00388	0.116	0.439	0.939	1.56	2.28	3.06
LHC@13TeV	1.0	177.	373.	12800.	26000.	42200.	60500.	80400.
	2.0	3.11	79.7	286.	596.	980.	1420.	1890.
	3.0	0.161	4.48	16.5	34.8	57.4	83.5	112.

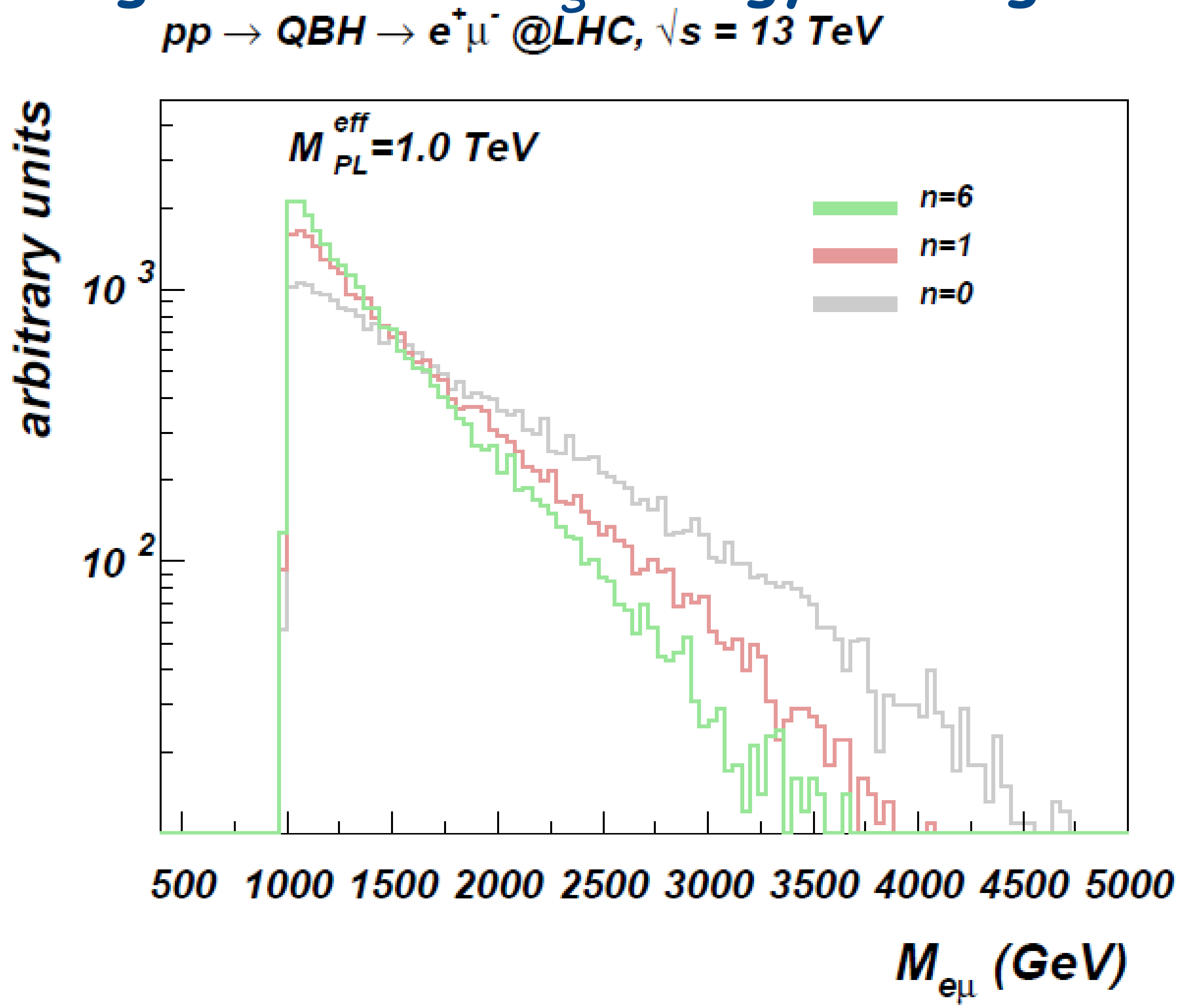
Di-lepton invariant mass distribution

- It does not look like a resonance(!), the fall of parton densities is (much) more steep with the energy than the increase of the parton-level cross section(!)



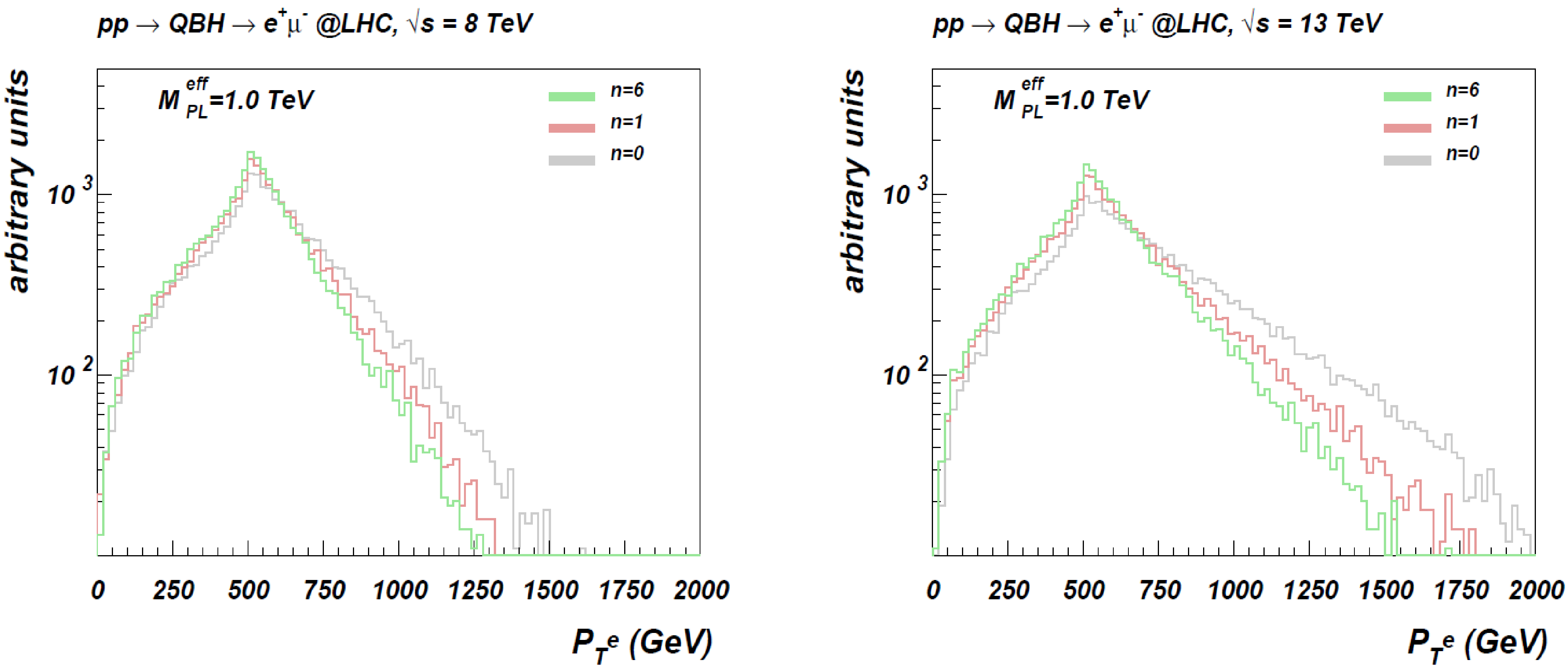
Di-lepton invariant mass distribution

- As far as more phase space is available at 13 TeV LHC, one can see the difference in the tail for dirrerent # of XD reflecting non-trivial R_S energy scaling



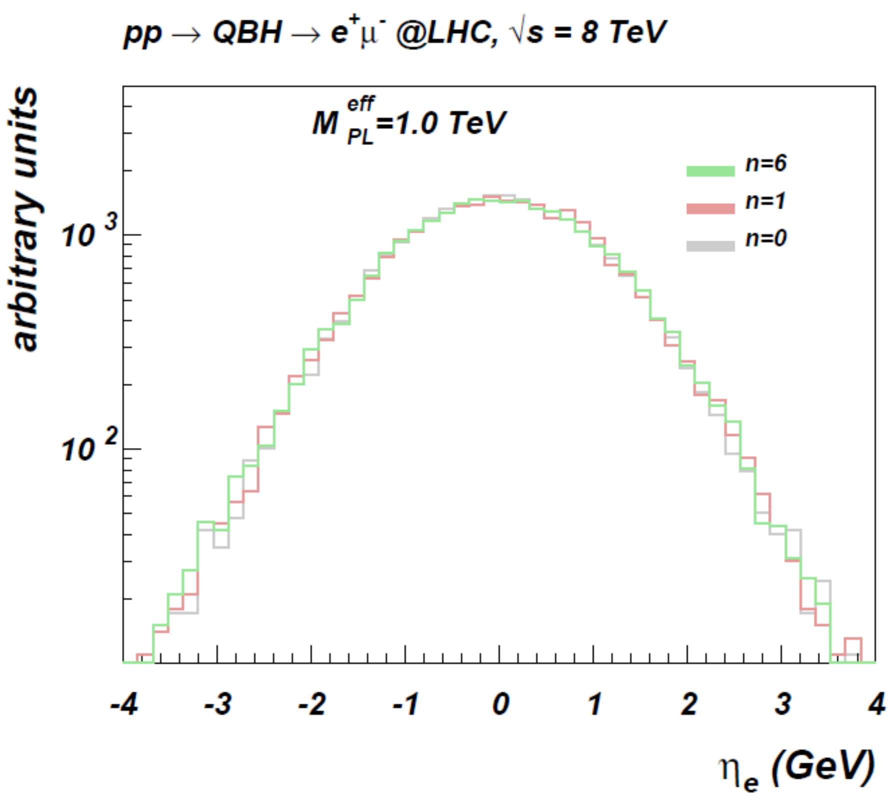
Lepton transverse momentum

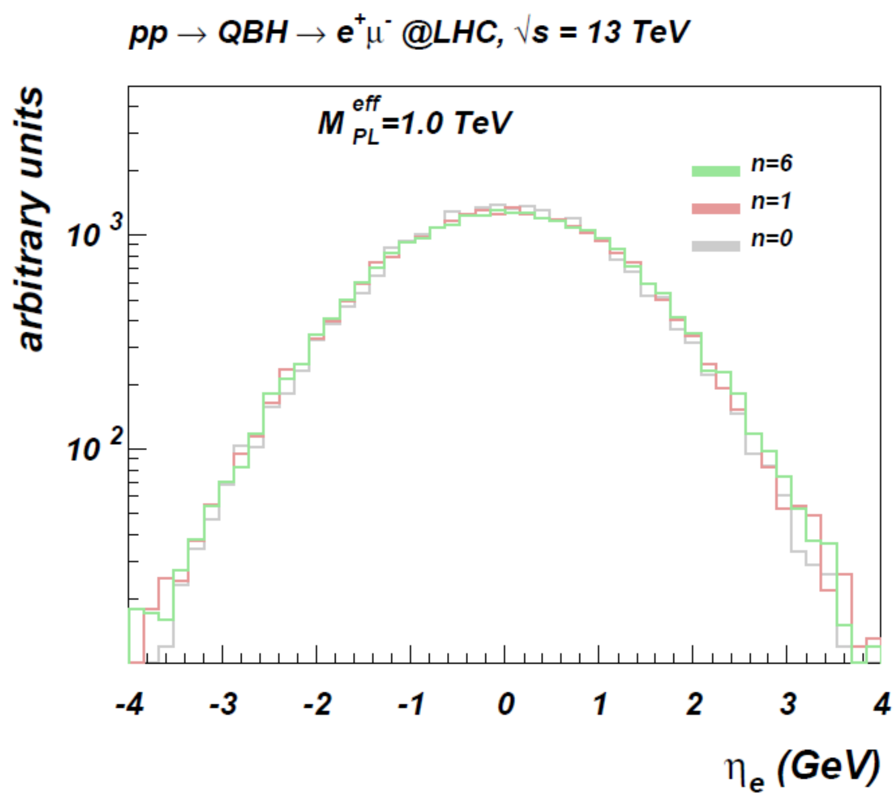
- High enough to fall into the acceptance region, P_T>20 GeV



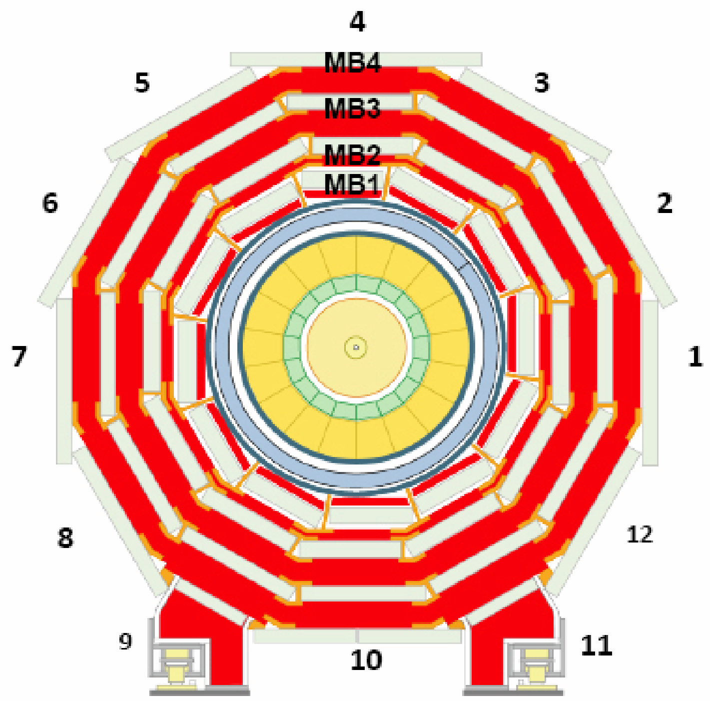
Lepton pseudo-rapidity

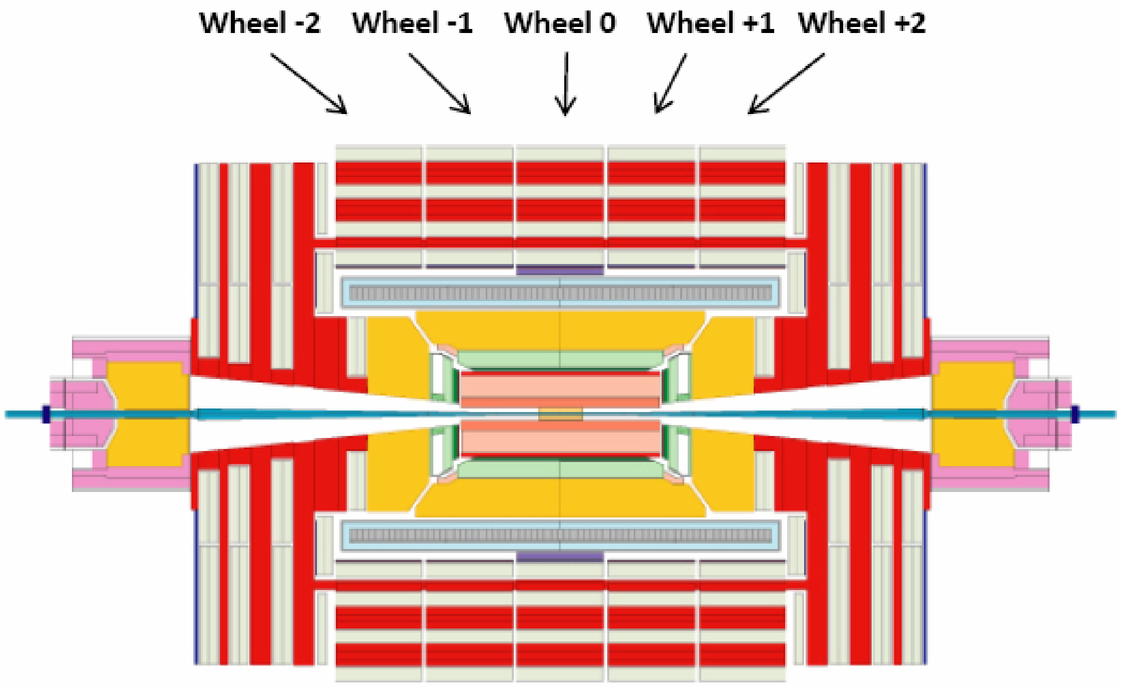
- central enough to fall mostly into the acceptance region, $|\eta_T|< 2.5$





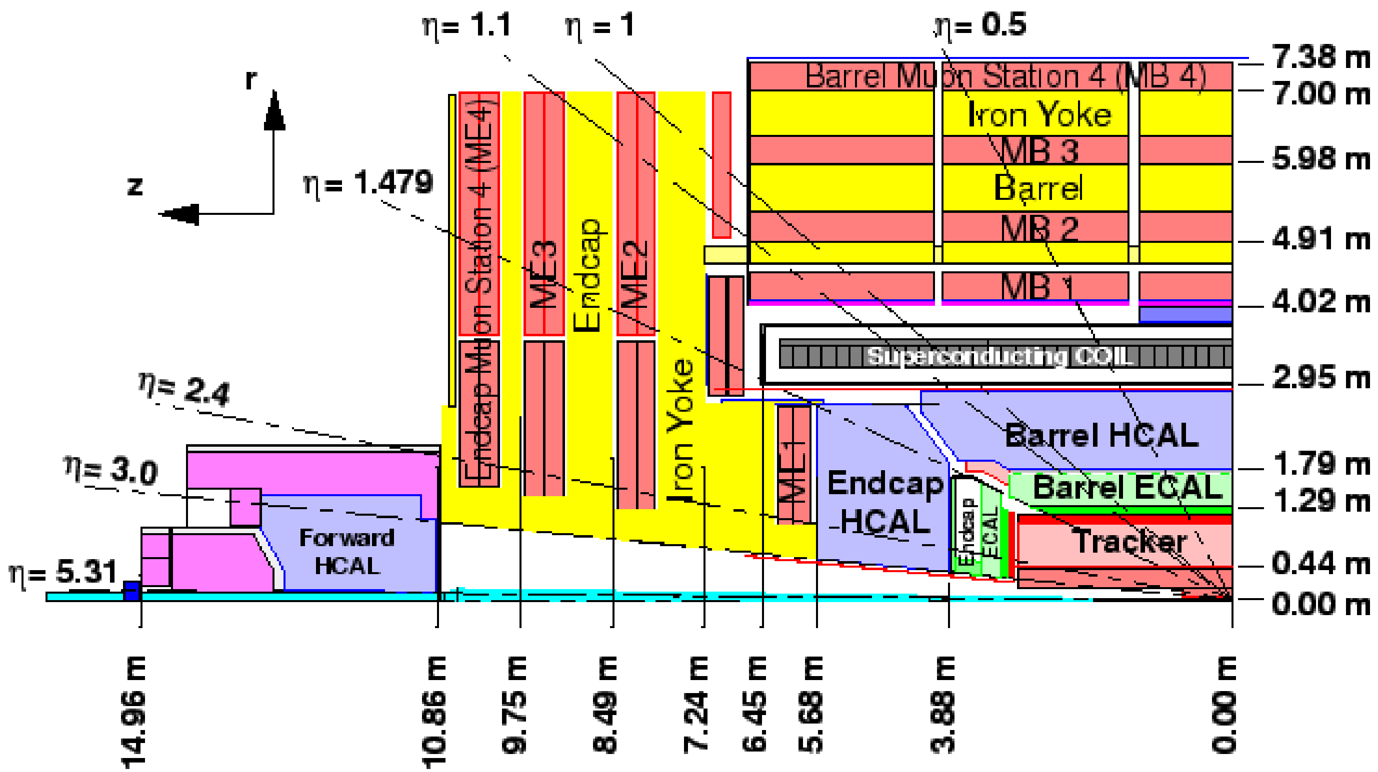
CMS detector





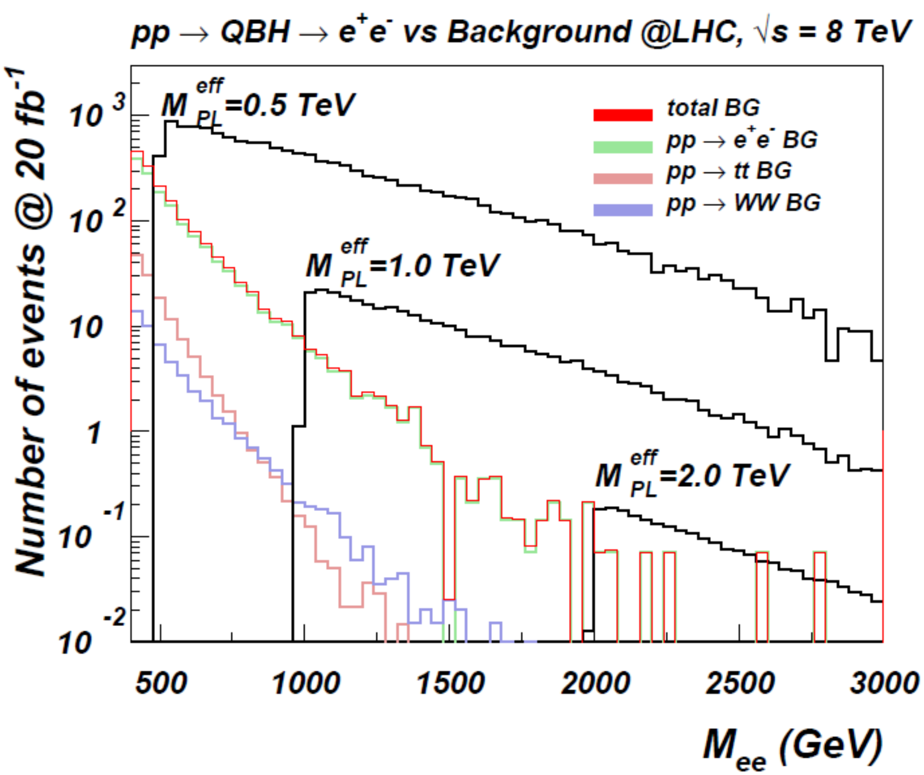
Pseudo-rapidity
CMS detector - Longitudianl view

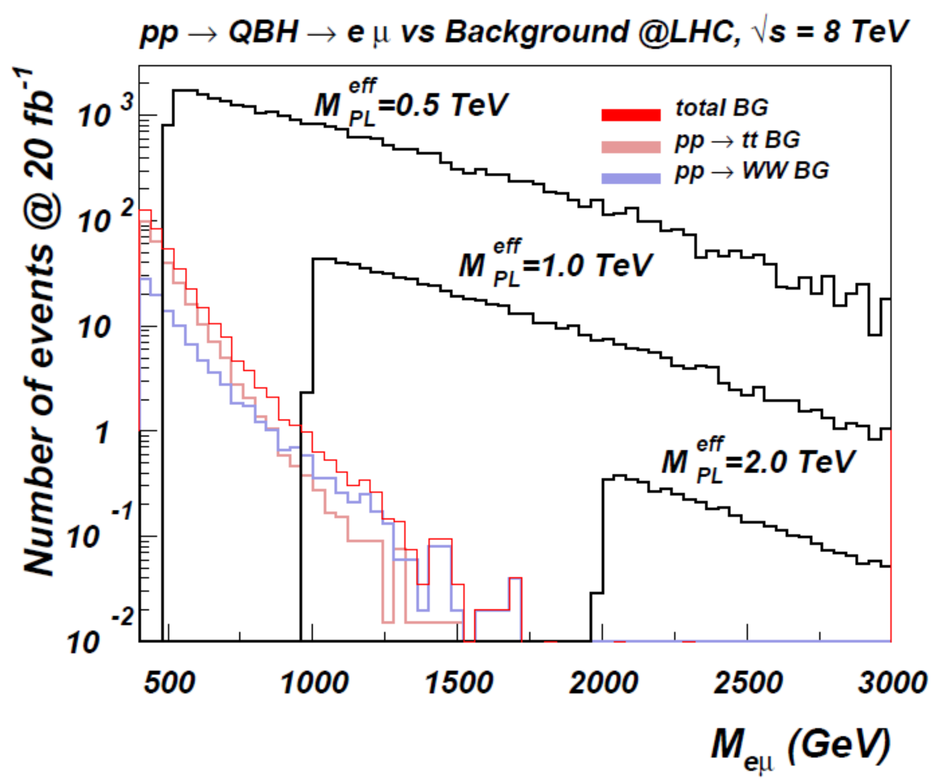
$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_{\rm L}}{|\mathbf{p}| - p_{\rm L}}\right) = \operatorname{artanh}\left(\frac{p_L}{|\mathbf{p}|}\right)$$



Signal vs Background @ 8 TeV

- For ee or μμ signatures - Drell-Yan process is dominant BG
- For eμ signature – the leading BG comes form tt production, but it is negligible!





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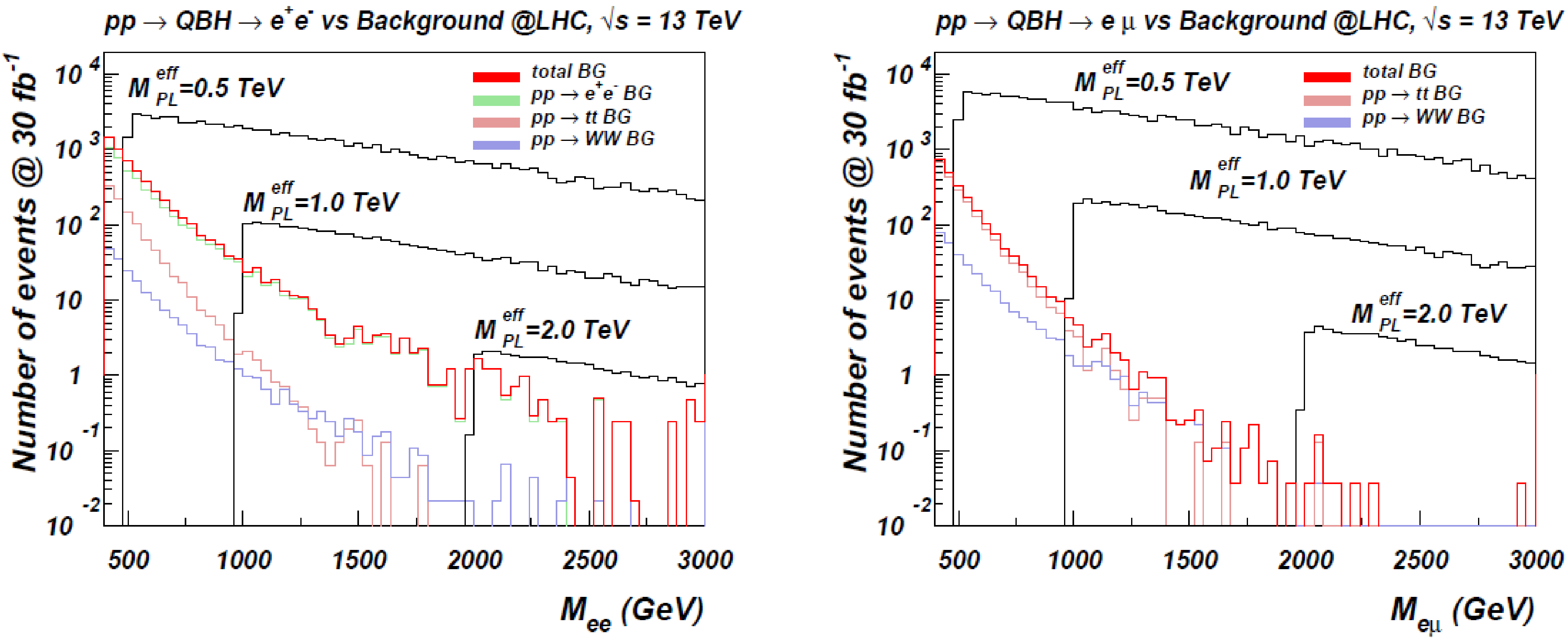
- For ee or μμ signatures - Drell-Yan process is dominant BG
- For eμ signature – the leading BG comes form tt production, but it is negligible!



Simulation and selection details

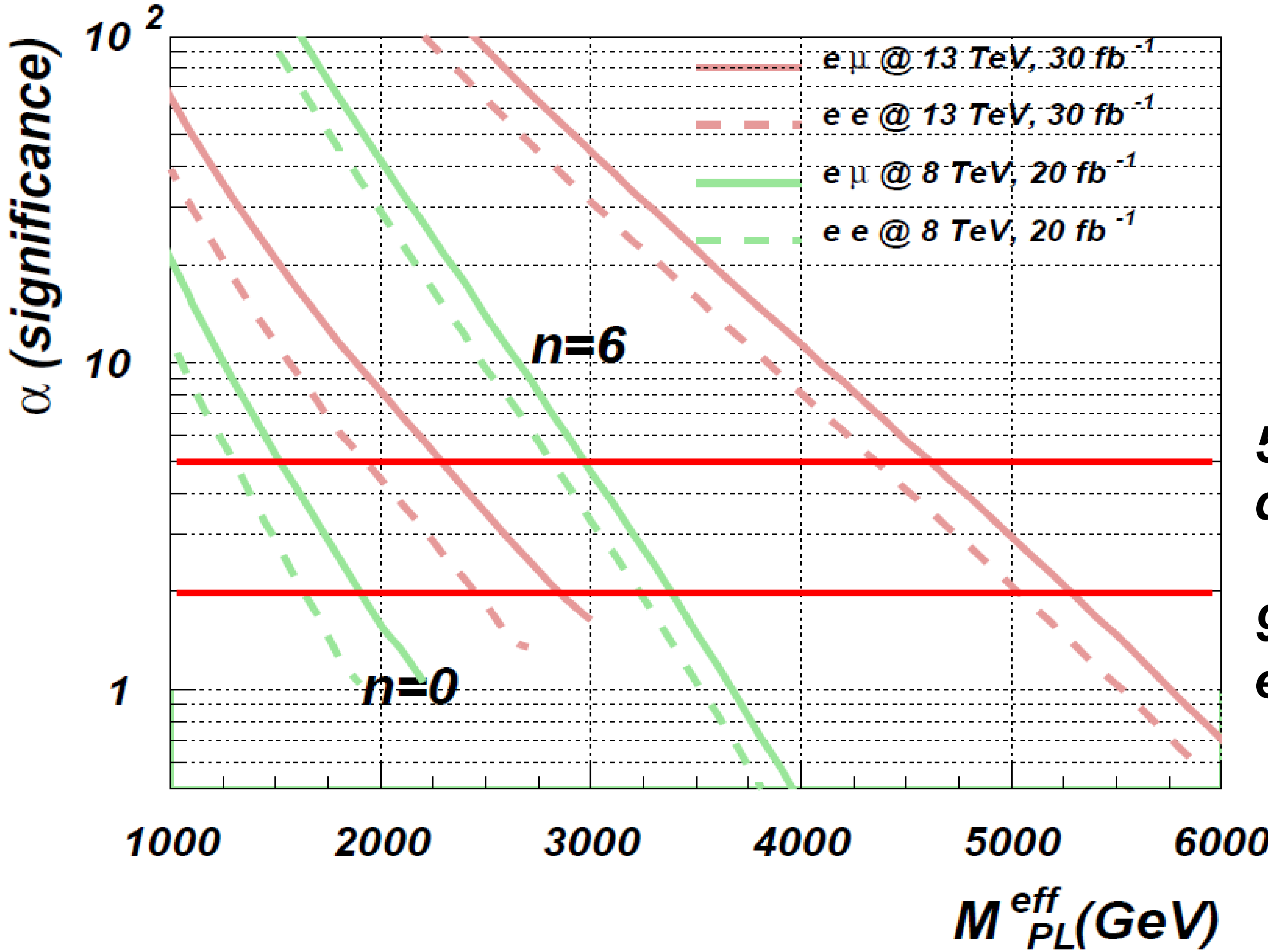
- parton-level analysis, but we take into account realistic electromagnetic energy resolution, using a value of $0.15/\sqrt{E(GeV)}$ typical for the ATLAS and CMS detectors

- We also suggest the simple analysis cut $M_{e\mu}(M_{ee}) > 1.1 \times \overline{M}_{PL}$ noting that the acceptance efficiency will be very similar for different n models

- For both criteria, exclusion and discovery, we use the following formula for statistical signal significance

$$\alpha = 2(\sqrt{N_S + N_B} - \sqrt{N_B})$$

LHC sensitivity@8TeV & 13 TeV



5σ discovery level

95%CL exclusion level

LHC sensitivity@8TeV & 13 TeV

- With the signature suggested M_P in XD models can be tested up to ~ 6 TeV via QBH production!

		LHC@8TeV		LHC@13TeV	
CL	n	e^+e^-	$e\mu$	e^+e^-	$e\mu$
95%CL	0	1920 GeV	2240 GeV	3360 GeV	3780 GeV
5σ	0	1550 GeV	1810 GeV	2790 GeV	3180 GeV
95%CL	6	3540 GeV	3680 GeV	5510 GeV	5750 GeV
5σ	6	3140 GeV	3300 GeV	4850 GeV	5100 GeV

Pheno vs Experimental results

- Results are consistent with very recent CMS limits, which confirms reliability of the simulations and projections fo r the LHC@13 TeV

OUR RESULTS

		LHC@8TeV	
CL	n	e^+e^-	$e\mu$
95%CL	0	1920 GeV	2240 GeV
5σ	0	1550 GeV	1810 GeV
95%CL	6	3540 GeV	3680 GeV
5σ	6	3140 GeV	3300 GeV

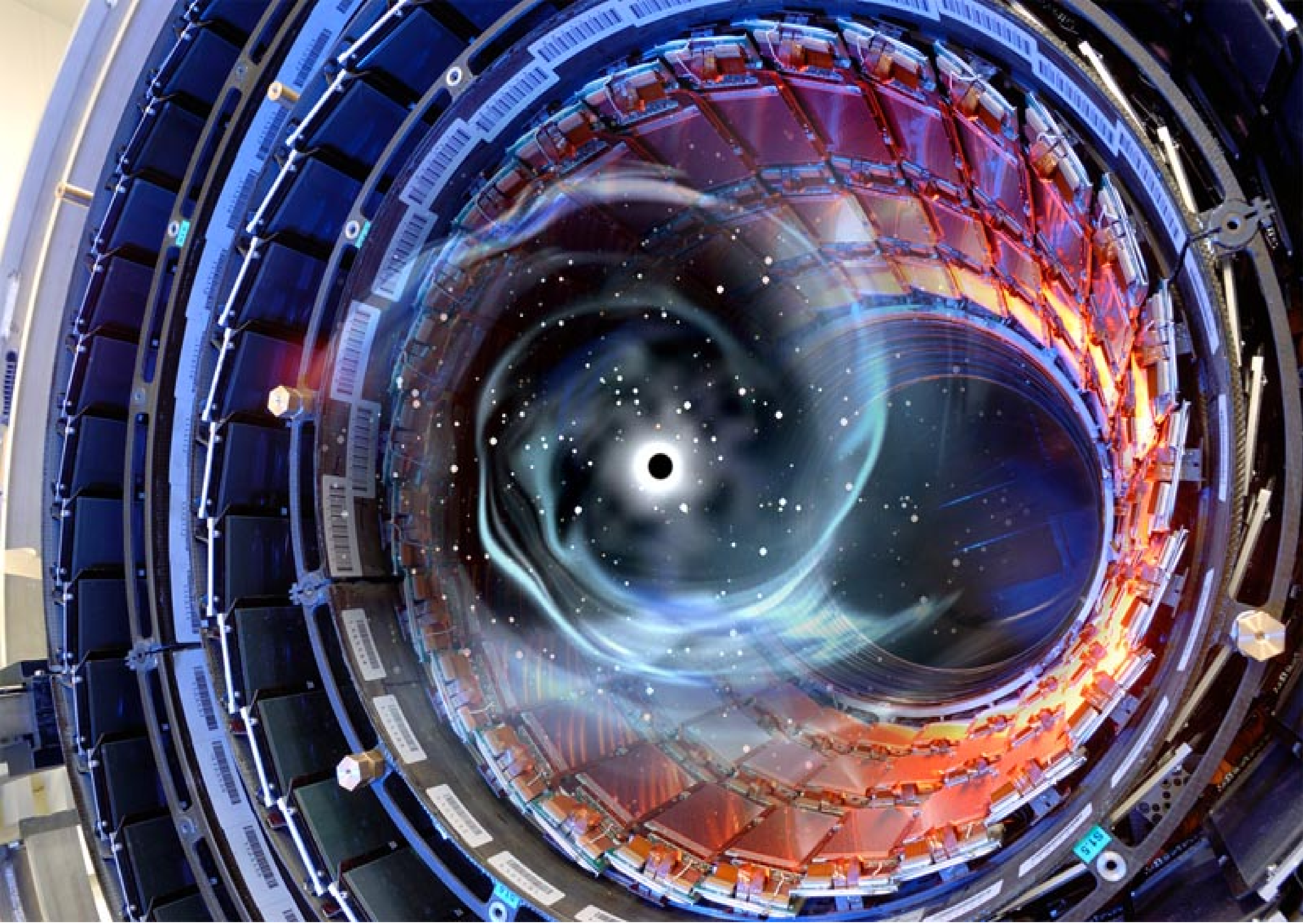
CMS PAS EXO-13-002

Theoretical Model	Mass Limit (TeV)
QBH n=0	1.99
QBH n=1 (RS)	2.36
QBH n=1 (PDG)	2.81
QBH n=2	3.15
QBH n=3	3.34
QBH n=4	3.46
QBH n=5	3.55
QBH n=6	3.63

Conclusions

- QBH – could provide a crucial link between GR and QFT if we could explore them at the LHC
- We have proposed an effective Lagrangian to describe QBH production at the LHC
- The model is implemented into CalcHEP and is publicly available at HEPMDB – High Energy Physics Model Database http://hepmdb.soton.ac.uk/hepmdb:1113.0146
- Di-lepton signature has been suggested and explored
- Model/generator as been already used by CMS for LHC@8TeV data

- LHC@13 has an impressive potential to test M_P in XD models upto ~ 6 TeV



THANK YOU!