Black Holes at the LHC

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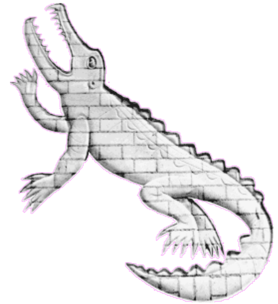
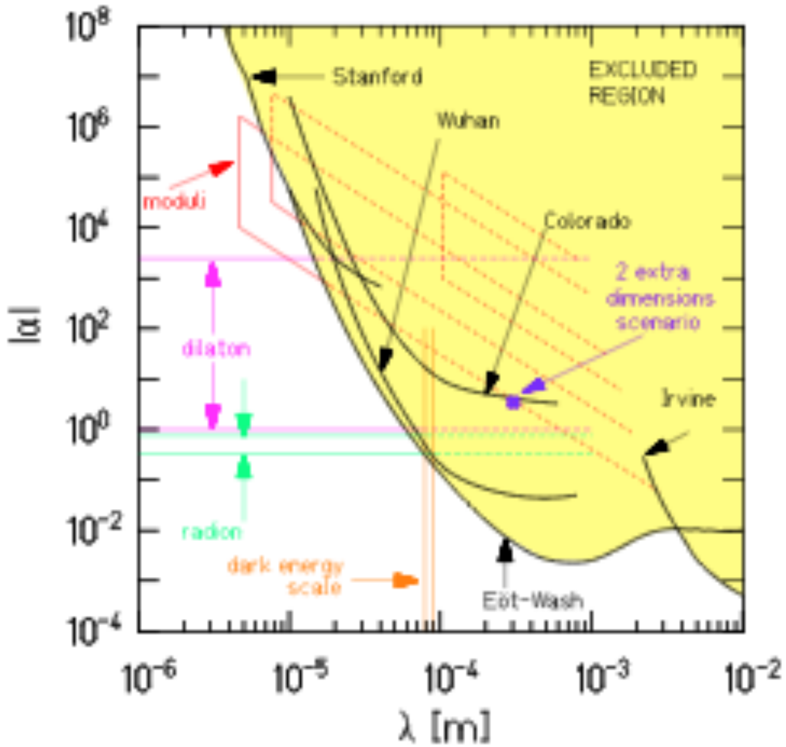
Introduction

- Workshop aims to write a "White Paper" to document state of the art in BH/NR studies and suggest future directions
- This talk will summarise the main experimental results, and show the main strategies experimenters use in searching for BH and TeVG at LHC
- Vicki Moeller will give a detailed talk on one ATLAS analysis – so no details here.
- Last section will raise issues which I hope will be of interest for discussion



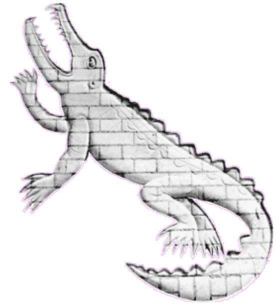
Motivation



- Number of space dimensions constrained by inverse-square law.
- Definitely 3 at scales >10^{-4} m
- No information on space-time geometry at smaller scales.

Figure 10: Constraints on Yukawa violations of the gravitational $1/r^2$ law for $\lambda \leq 1$ cm. The shaded region is excluded at the 95% confidence level. Heavy lines labeled Eöt-Wash, Irvine, Wuhan, Colorado and Stanford show experimental constraints from Refs. [61, 62], [69, 70], [59], [71] and [72, 73], respectively. Lighter lines show various theoretical expectations summarized in Ref. [2].

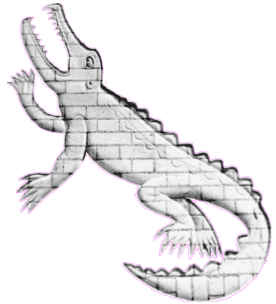
Prog. Part. Nucl. Phys 62, 102 (2009)

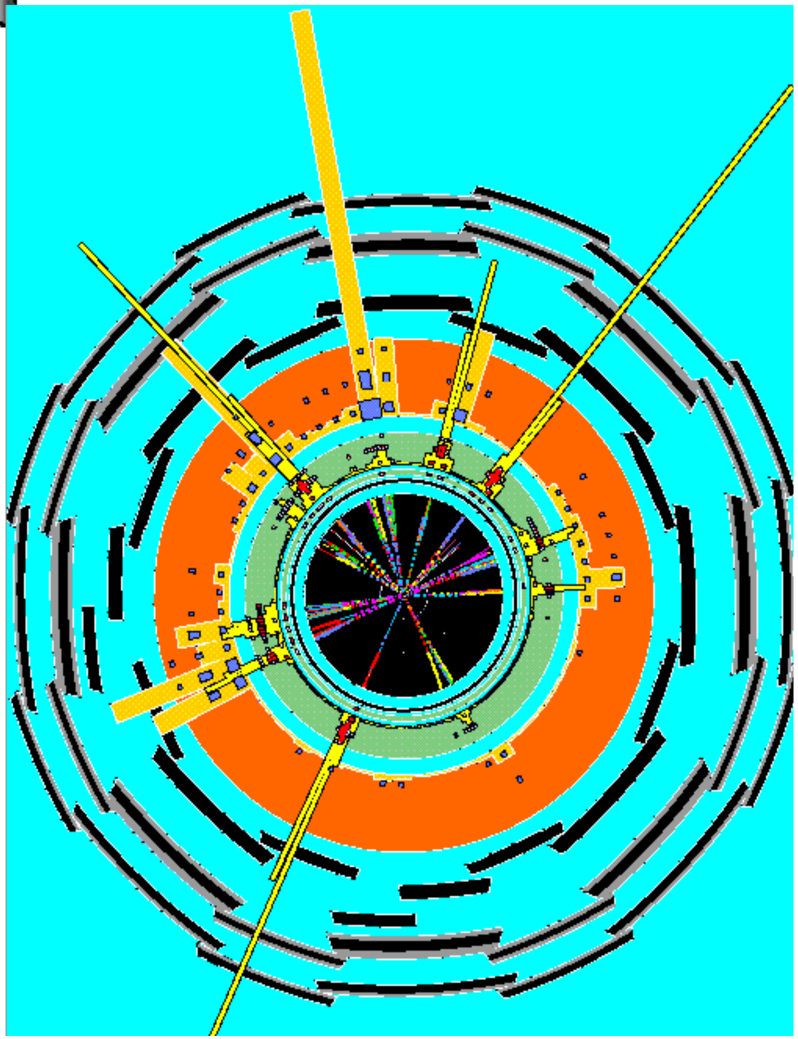


- ADD, RS etc have proposed geometries with compact dimensions within these bounds
- Allow bulk Planck scale M_D in TeV range
- Resolve (*) hierarchy problem and stabilise Higgs mass
- Predict strong gravity effects
  - Gravitational two-body scattering (eg mono-jets)
  - Production of KK modes (eg graviton resonances)
  - Formation of non-perturbative states (eg string-balls)
  - Formation of small black holes (my topic today).

(*) ADD models introduce a new unexplained scale for the compactification radius. ADD and RS do not explain the difference between normal and compact dimensions.

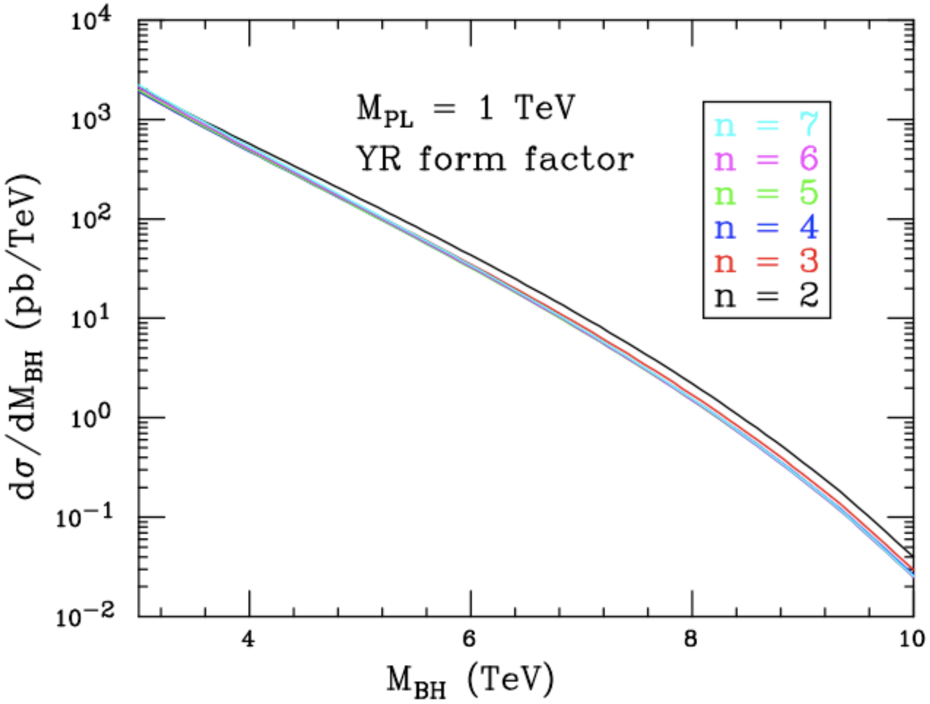
BH production and decay





- Classical production model, $\sigma \sim R_{BH}^2$
- Semi-classical decay model via Hawking radiation, corrected by grey-body factors, valid for $M_{BH} \gg M_D$.
- Final decay of remnant by ad-hoc process – quantum gravity regime, with $M_{BH} \sim M_D$

BH production cross-sections



➡ Several 5 TeV BH per minute at LHC!

Classical approximation to cross-section (Controversial…)

Almost independent of n

Very large rates for n=2-6

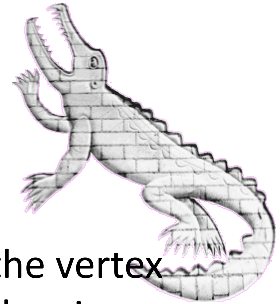
See hep-ph/0111230

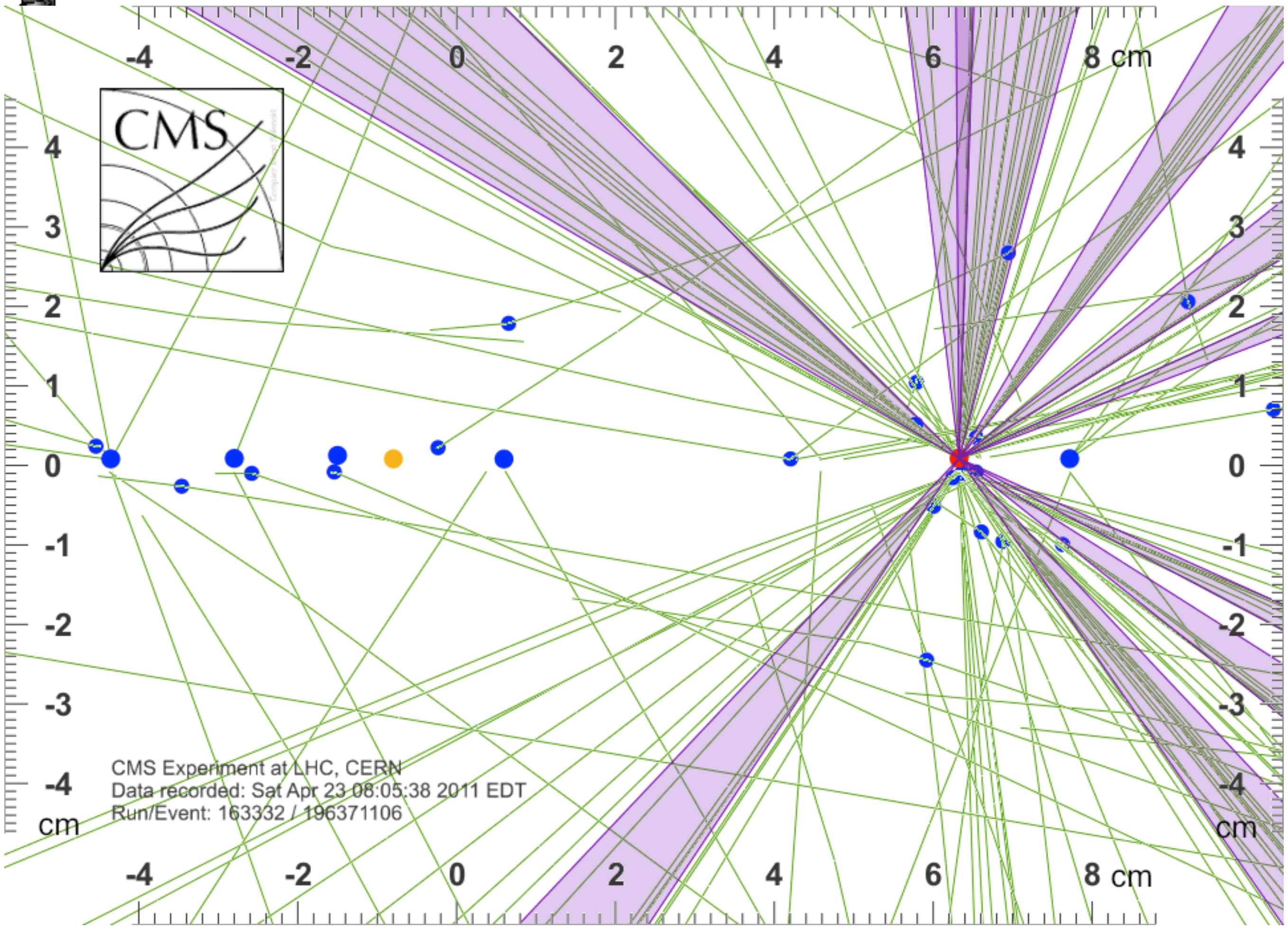
$$\sigma_{BH} \sim \pi r_h^2$$

Signatures

- Hawking radiation is democratic – gravity couples to energy/momentum, not gauge quantum numbers: use all classes of particles (objects).
- Expect relatively high multiplicity – but beware spin effects, and modelling of remnant decay.
- Expect excess of events at high mass /high Sum(pT)
  - But beware of graviton emission in formation and decay
  - Search in multiobject channels
- Expect high rate of leptons compared to QCD
  - Select events with leptons, measure rate or fraction
  - Select events with like-sign dileptons to suppress SM backgrounds

Pileup



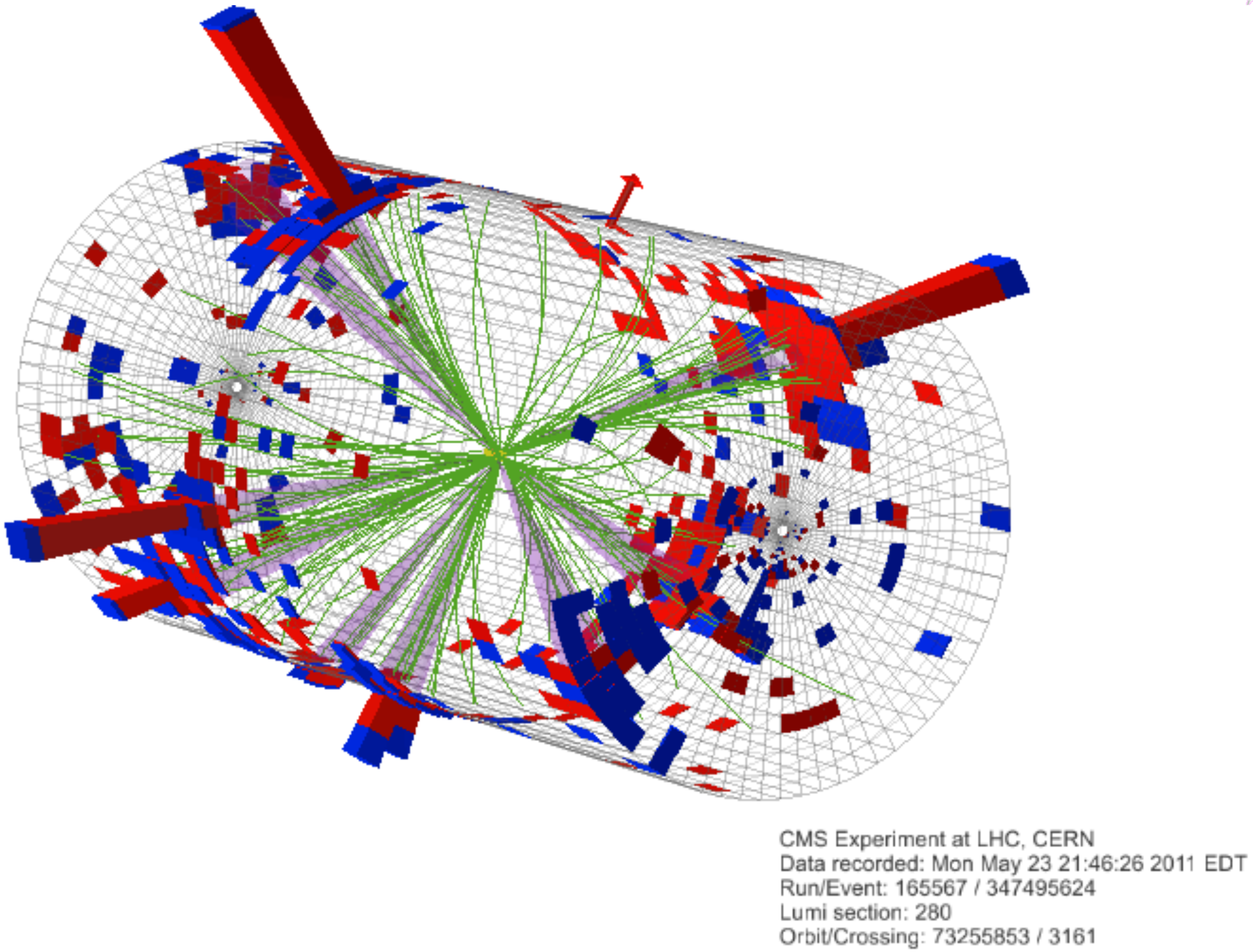


Zoom on the vertex region in the view parallel to the beam-line. All the jets clearly come from the same, primary vertex (red dot), despite a number of pile-up vertices (blue dots). Nominal beamspot position is shown with an orange dot.

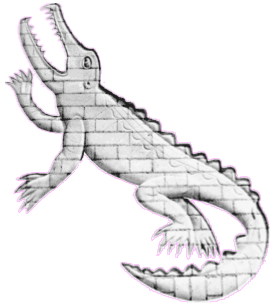
Info: run/event/lumisection = 163332/196371106/295; ST = 1.1 TeV

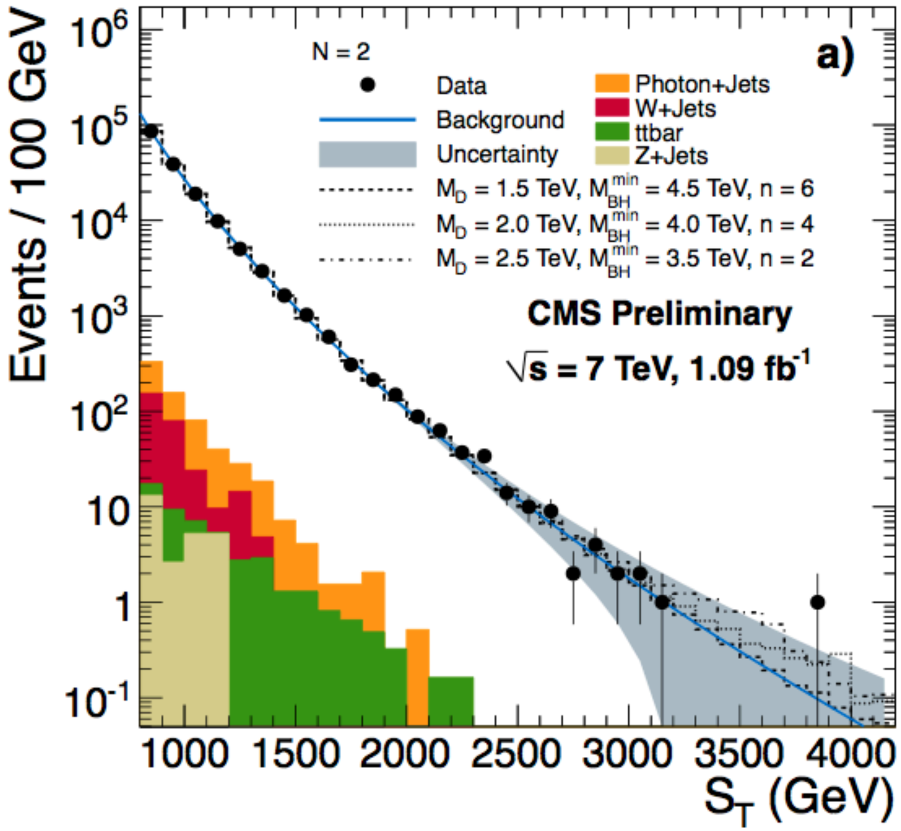
- At LHC luminosity is so high that there are many soft pileup events in each beam crossing. Check all objects come from one vertex.

Experimental results



CMS 2011 – large E_T search

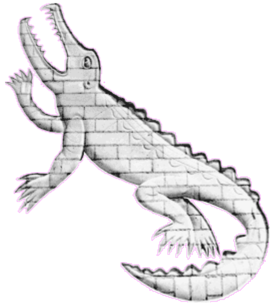


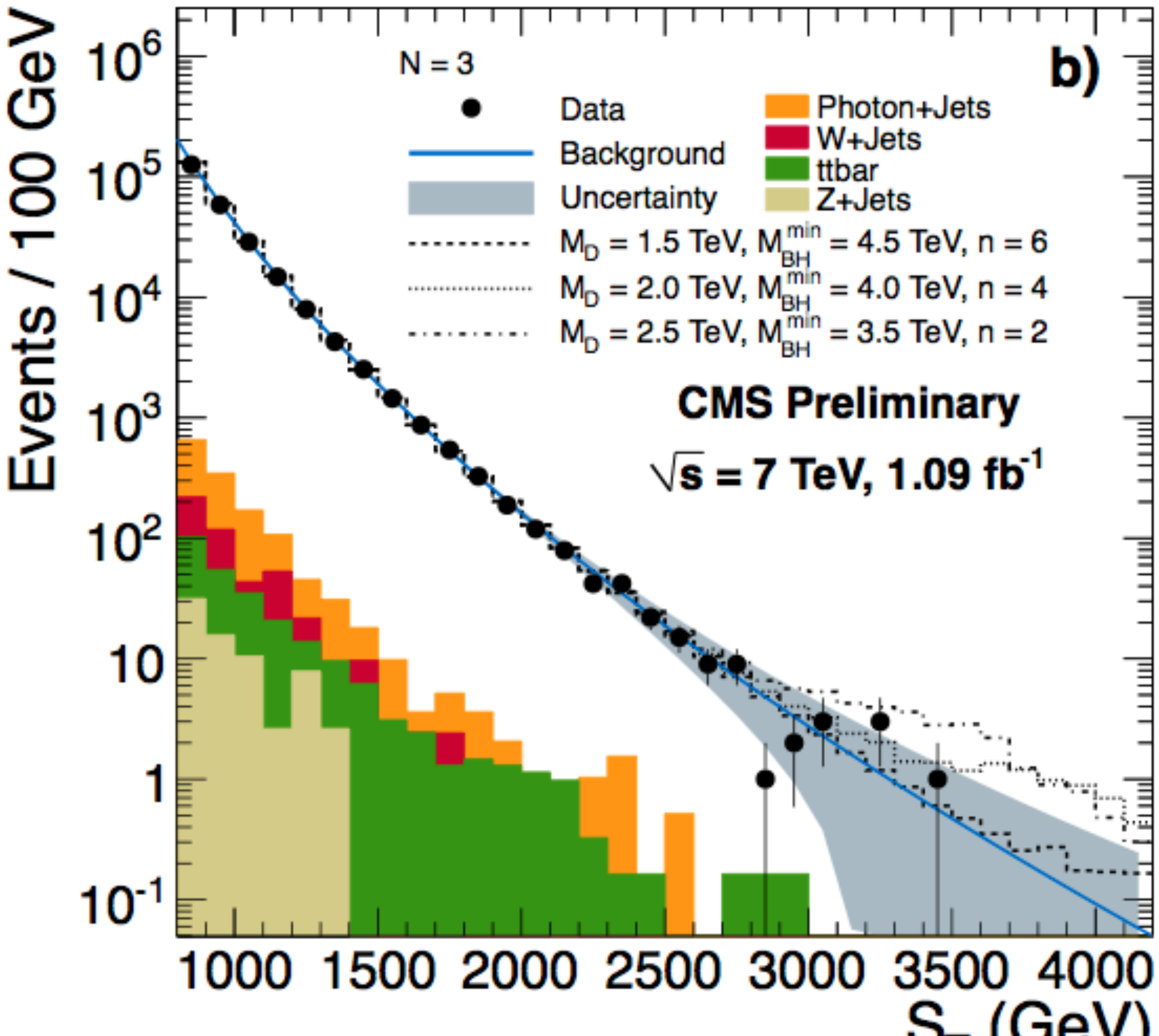


- Total transverse energy S_T, for events with the multiplicity of N = 2 objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction obtained from data (solid line) with its uncertainty. Non-multijet backgrounds are shown as colored histograms. Also shown is the predicted black hole signal for three different parameter sets.

Search for Black Holes in pp Collisions at √s = 7 TeV with 1 fb^{-1} Data Set
CMS PAS EXO-11-071

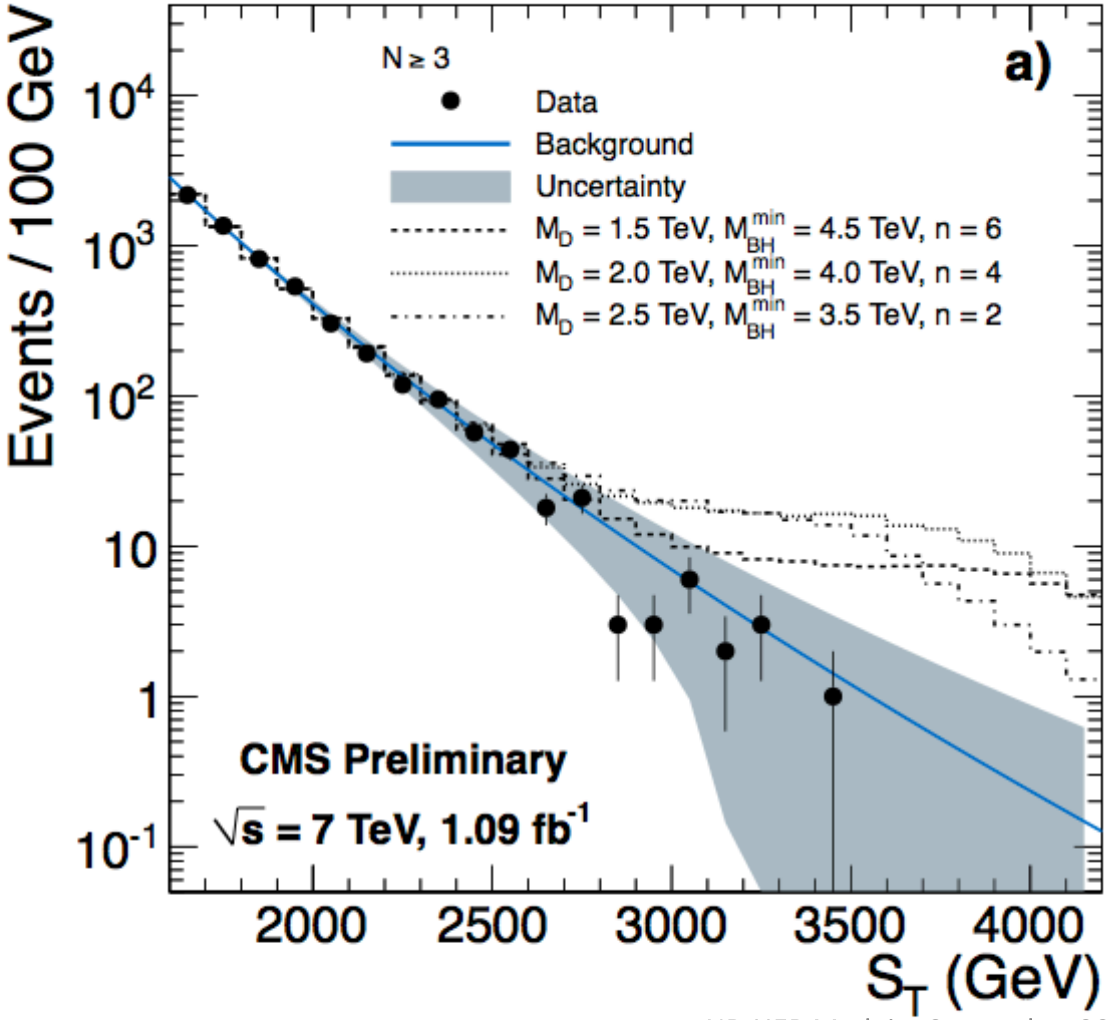
CMS 2011 – large E_T search





Total transverse energy S_T, for events with the multiplicity of N = 3 objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction obtained from data (solid line) with its uncertainty. Non-multijet backgrounds are shown as colored histograms. Also shown is the predicted black hole signal for three different parameter sets.

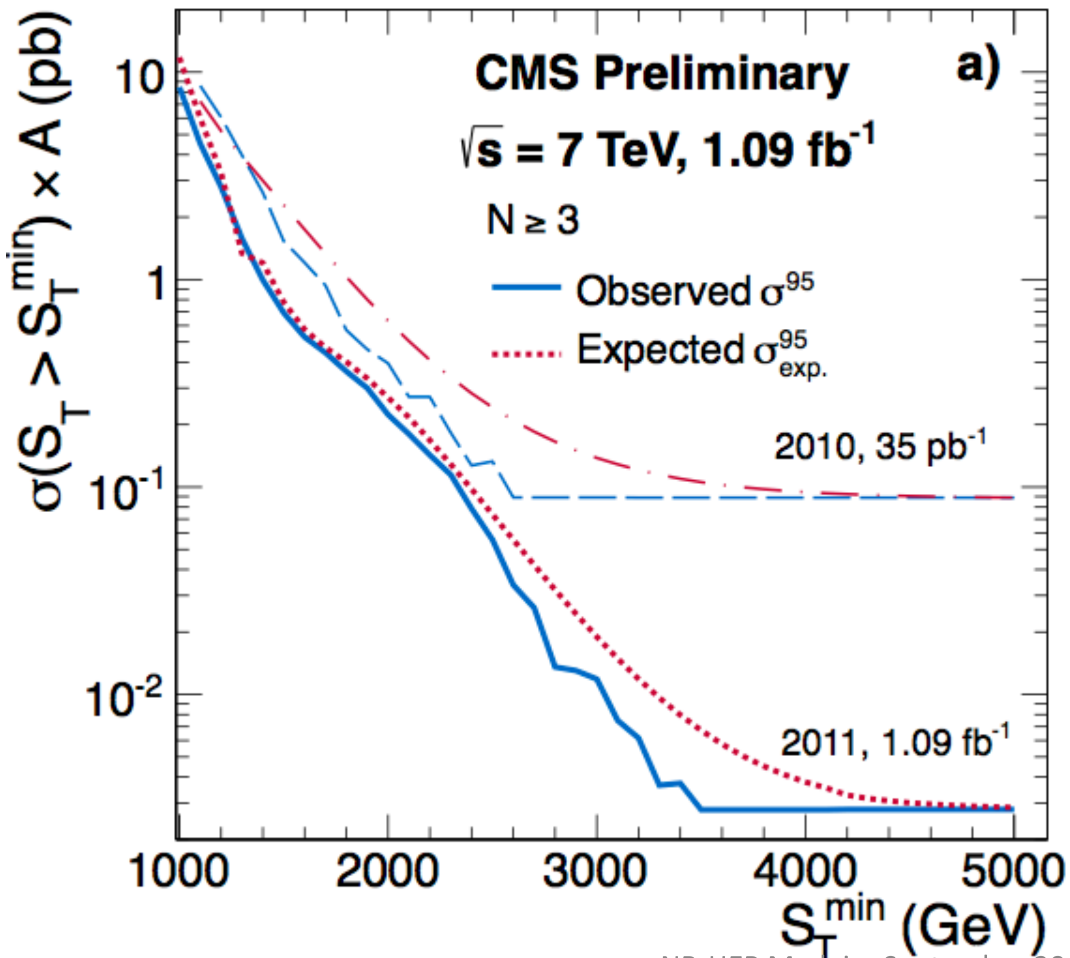
CMS 2011 – large E_T search



Total transverse energy S_T, for events with the multiplicity of N >= 3 objects in the final state. Data are depicted as solid circles with error bars; the shaded band is the background prediction obtained from data (solid line) with its uncertainty. Non-multijet backgrounds are shown as colored histograms. Also shown is the predicted black hole signal for three different parameter sets.

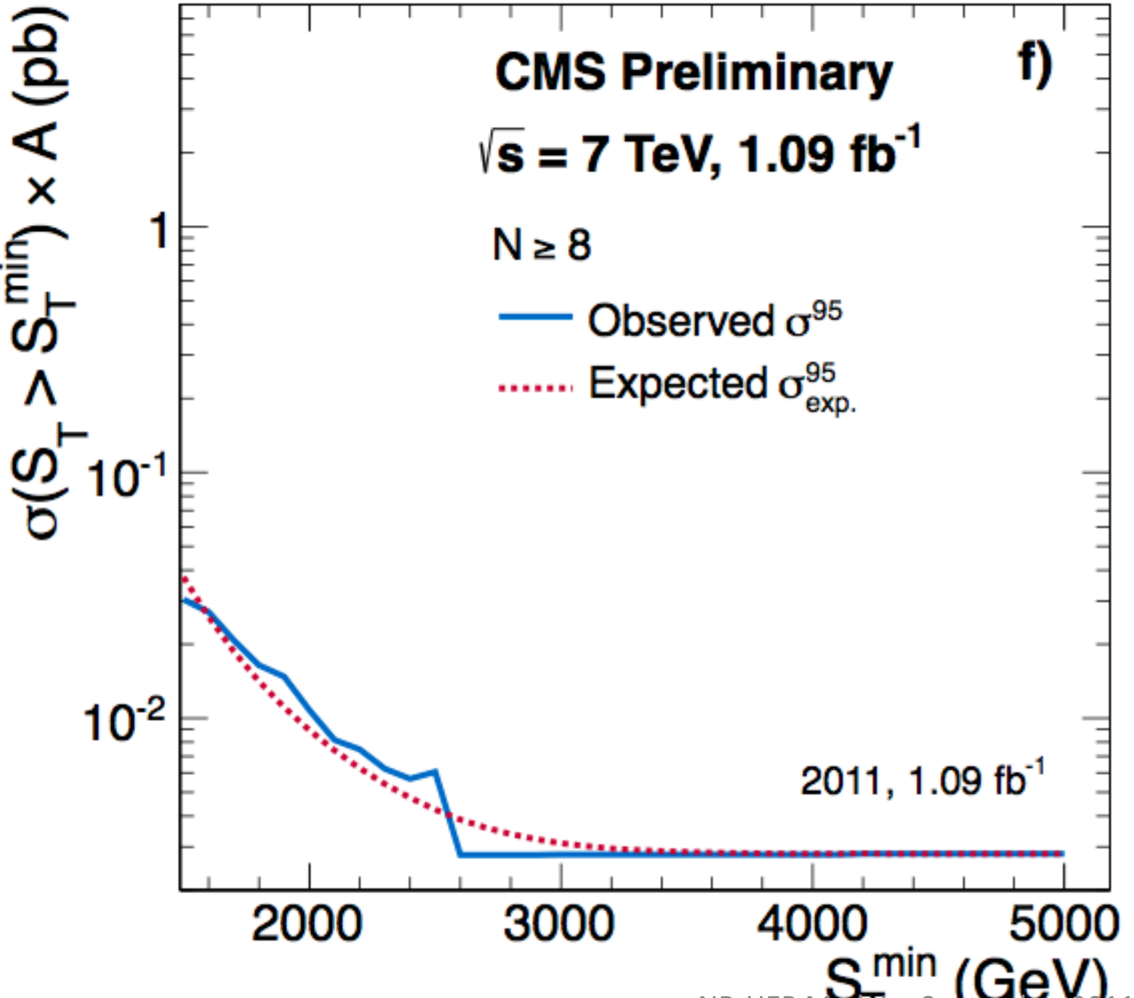
CMS 2011 – large E_T search

- Model independent result: cross-section x acceptance limits



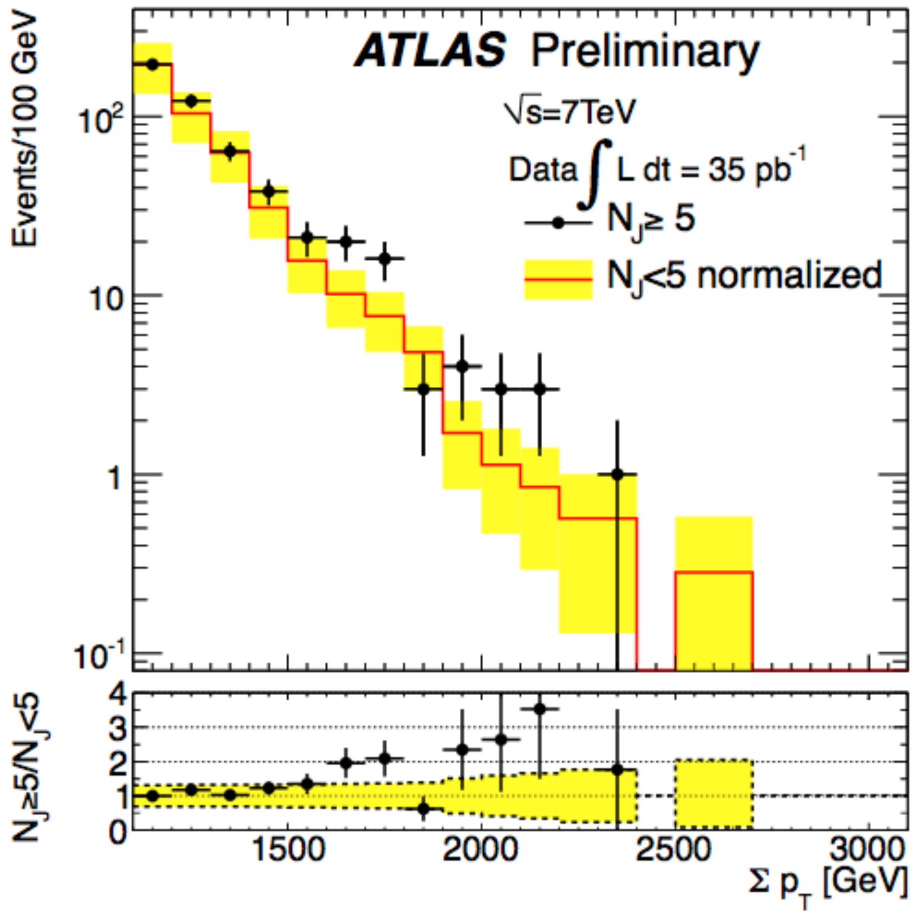
Model-independent 95% confidence level upper limits on a signal cross section times acceptance for nominal signal acceptance uncertainty of 5% for counting experiments with $S_T > S_T^{min}$ as a function of S_T^{min} for N >= 3. The blue (red) lines correspond to an observed (expected) limit for nominal signal acceptance uncertainty of 5%.

CMS 2011 – large E_T search



Model-independent 95% confidence level upper limits on a signal cross section times acceptance for nominal signal acceptance uncertainty of 5% for counting experiments with $S_T > S_T^{min}$ as a function of S_T^{min} for N >= 8. The blue (red) lines correspond to an observed (expected) limit for nominal signal acceptance uncertainty of 5%.

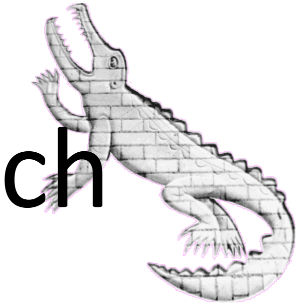
ATLAS 2010 – multijet search

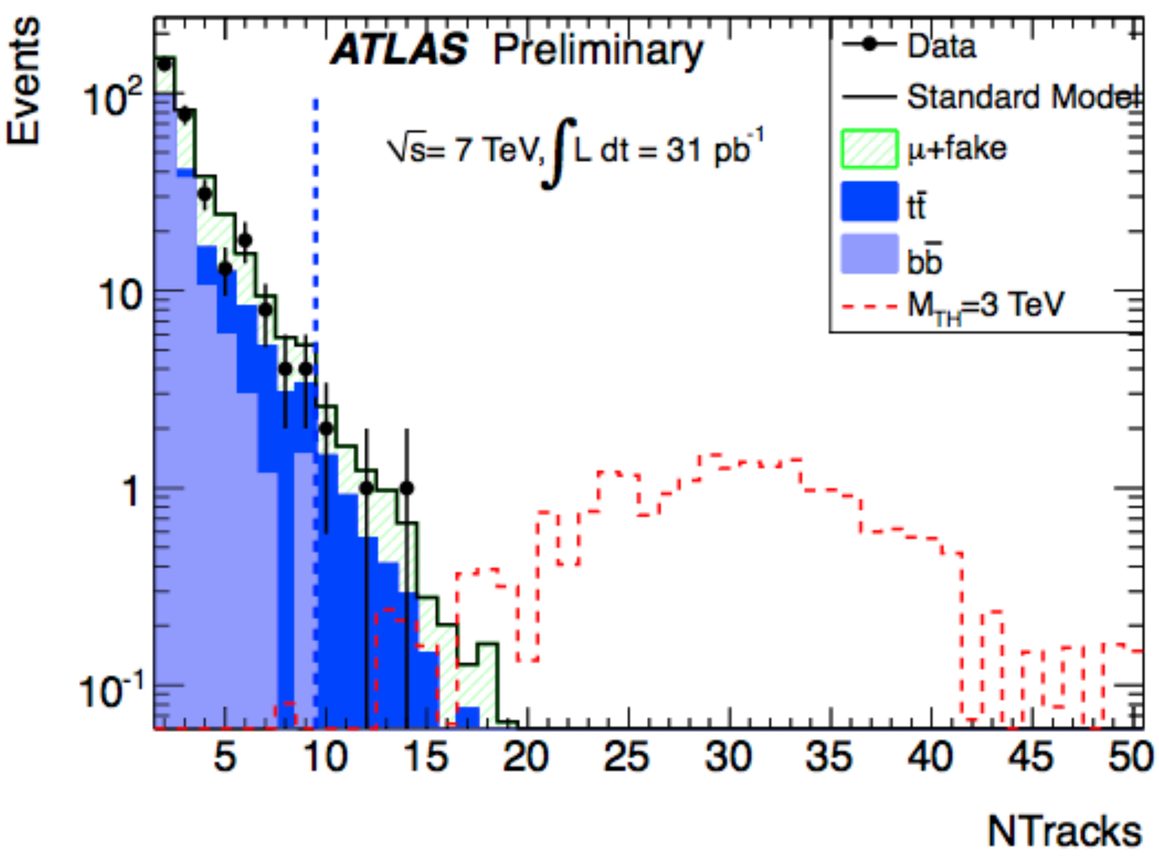


Scalar sum of jet transverse momentum, Sum(p_T), for observed events with less than five jets (histogram) and events with greater than or equal to five jets (dots). The histogram is normalised to the number of events in the region 1.1 < Sum(p_T) < 1.2 TeV. The yellow band represents the total uncertainty, including the statistical uncertainties and the systematic uncertainties added in quadrature.

Search for Microscopic Black Holes in Multi-Jet Final States with the ATLAS Detector at sqrt(s) = 7 TeV ***ATLAS-CONF-2011-068***

ATLAS 2010 – like-sign μμ search





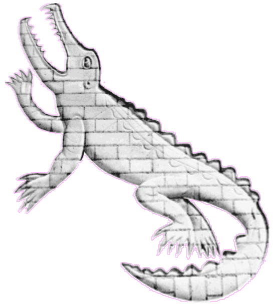
The track multiplicity distribution for all same-sign dimuon events. We select the region with Ntracks >= 10 as the signal region. The background histograms are stacked. The signal expectation for a non-rotating black hole model with parameters M_D = 630 GeV, M_{TH}=3 TeV, and one extra dimension is overlaid for illustrative purposes.

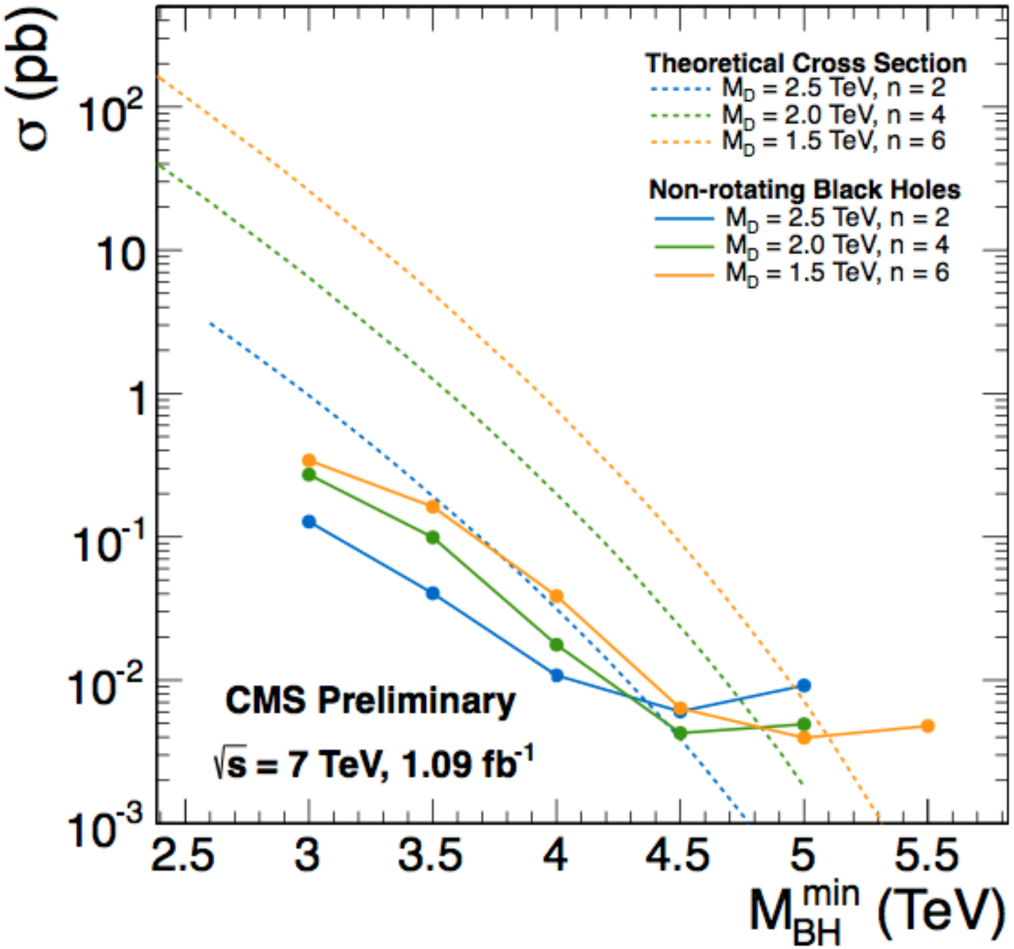
Interpretation

- The results above are solid and uncontroversial.
- Interpretation is more difficult, since the theoretical models break down in the region probed by experiment.
- Theorists using model-independent limits to test their scenarios need to know experimental acceptance
- Experimentalists wanting to rule out theories need predicted cross-sections near M_D.
- Modelling near M_D is more sensitive to remnant decay assumed than to Hawking radiation.
- Also sensitive to gravitational radiation, which lowers mass of observed final state.

Difficult issue for both sides!

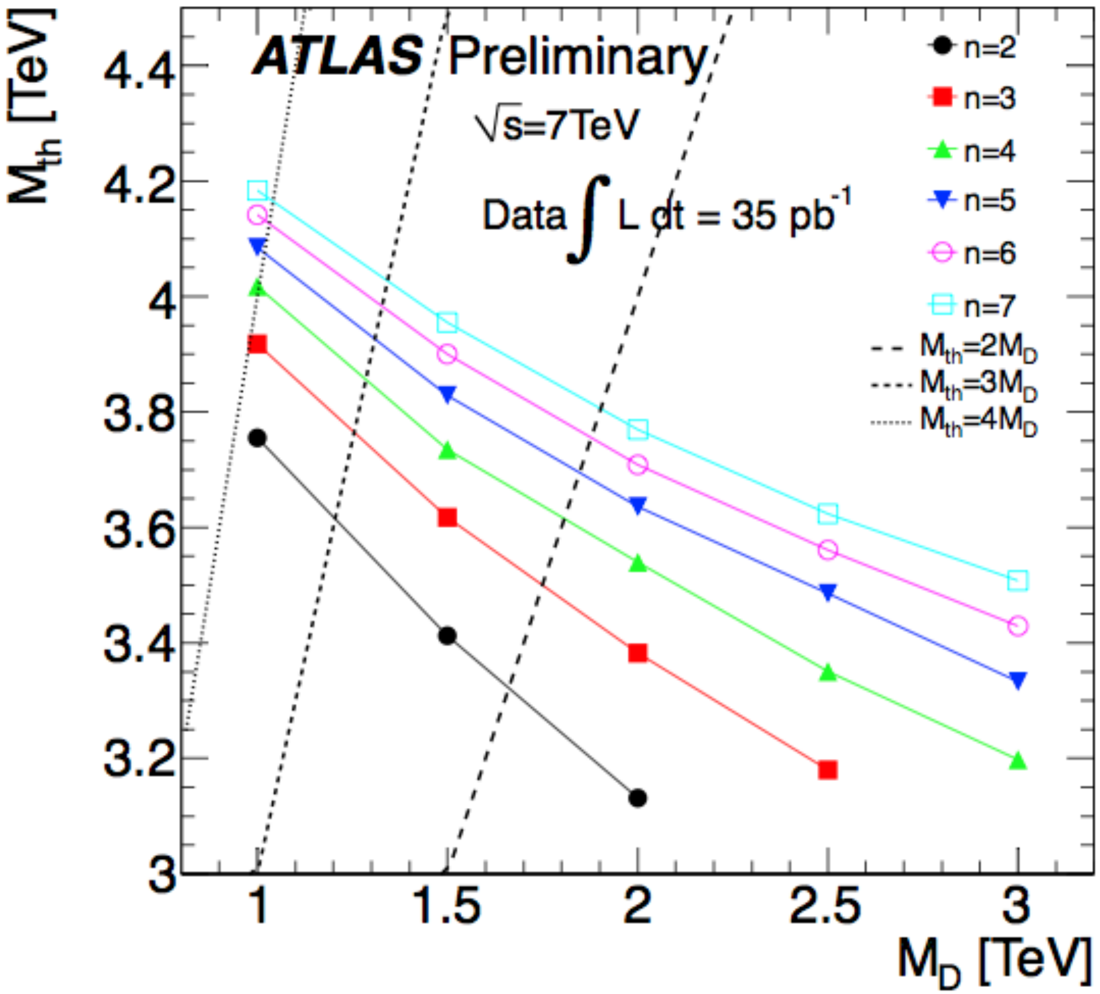
CMS limit setting





Cross section limits at 95% confidence level from the counting experiments optimized for various black hole parameter sets compared with signal production cross section. Colored solid lines show experimental cross section limits, while dotted lines represent corresponding signal cross sections. The corresponding expected limits are 4.4, 4.8, and 5.1 TeV.

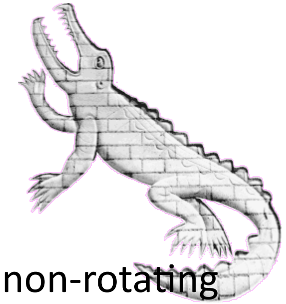
ATLAS 2010 multijet search

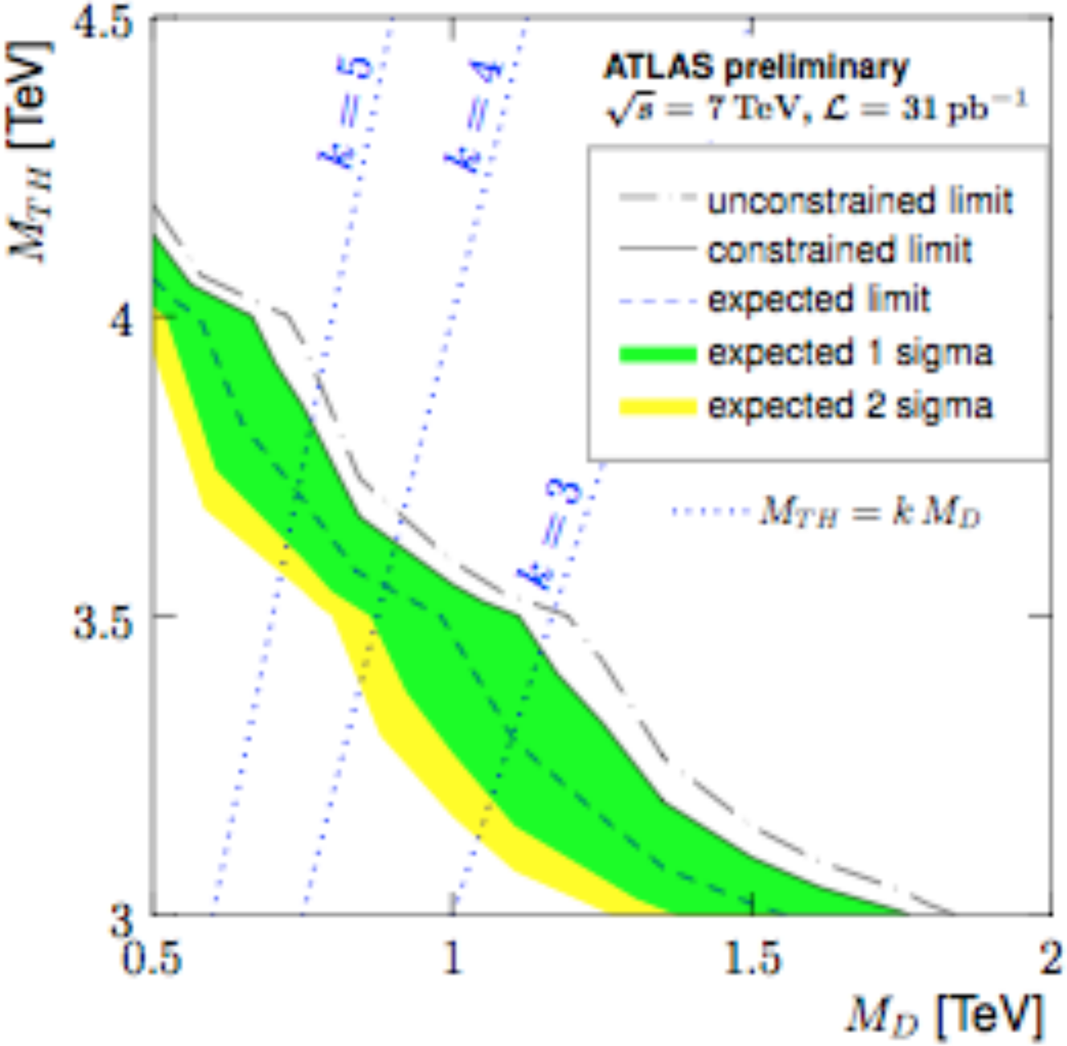


Contour plots of the observed limits on the Planck scale (M_D) versus threshold mass (M_{th}): observed limits. The curves are labelled by the number of extra dimensions n. CTEQ6.6 PDFs are used for the signal contribution. Lines of fixed ratio M_{th}/M_D = 2, 3, and 4 are also shown.

Want M_{th}>>M_D for valid theory

ATLAS 2010 dimuon search

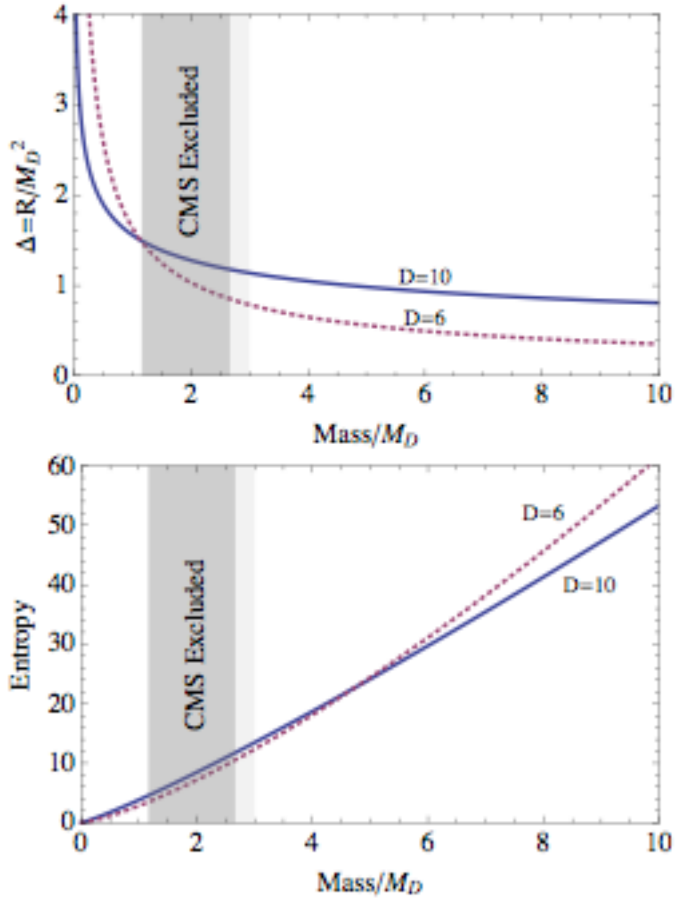




95% C.L. exclusion contours for non-rotating black holes taking into account all statistical and systematic uncertainties. The figure is for models with six extra dimensions and corresponds to signal generations with the CTEQ66 PDF set. The dashed blue line shows the expected exclusion contour with the 1 and 2 σ uncertainty in green and yellow respectively. The solid black line shows a constrained limit at the 1 σ boundary of the estimated sensitivity, which is quoted as the final result. The region below the contour has been excluded by this analysis. The dash-dotted line is the unconstrained limit derived from data. It lies within the 2 σ band of the expected limit, however this yellow band is not shown on that side of the sensitivity contour. The figures show lines of constant slope equal to 3,4, and 5. Only slopes much larger than 1 correspond to physical models.

Theoretical validity

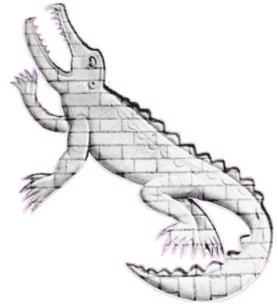
SC Park arXiv:1104.5129



"For the consistency of the perturbative expansion, it is required that the correction term should be significantly smaller than the leading order term ($\Delta \ll 1$) and entropy should be large ($S \gg 1$). However, the CMS exclusion range (vertical columns in gray), the correction is as large as or even larger than the leading order term. Also the entropy of black hole is still less than 10 or so so that we cannot tell that the calculation is trustworthy in semi-classical sense. Within this parameter space, all the MC simulations suffer from large quantum corrections of the order of ~ $O(M_D/M)^{p>0}$ which can lead a significant change in the final result."

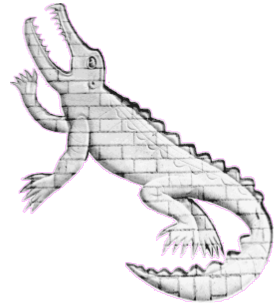
- FIG. 1. entropy(bottom) are plotted for higher dimensional black hole (D = 6(dotted), D = 10(solid)). The vertical column in gray is the CMS exclusion region: M/M_D = [3.5/3.0(4/3.5), 4.0/1.5(4.5/1.5)] for D = 6 (10), respectively. The higher order curvature term, Δ, (top)…

CMS response (2011 paper)



- *"We would like to emphasize that the semi-classical approximation used for deriving the cross section within these benchmark scenarios is expected to break down for most of the points probed. Thus, these limits should be treated as indicative, rather than precise. Apparently, this point has not been emphasized enough in our earlier publication [6] and some authors considered this to be a weakness of our analysis [26]. Given that there is no alternative quantitative calculations in the regime where the semiclassical approximation breaks down and also exponential change of the production cross section with the black hole mass, which results in rather significant changes in the model to translate to rather moderate changes in the mass limit, we still choose to show these limits with the above caveat. The main result of our analysis remains to be the model-independent limits, which the author of Ref. [26] has unfortunately missed."*

What do we need?

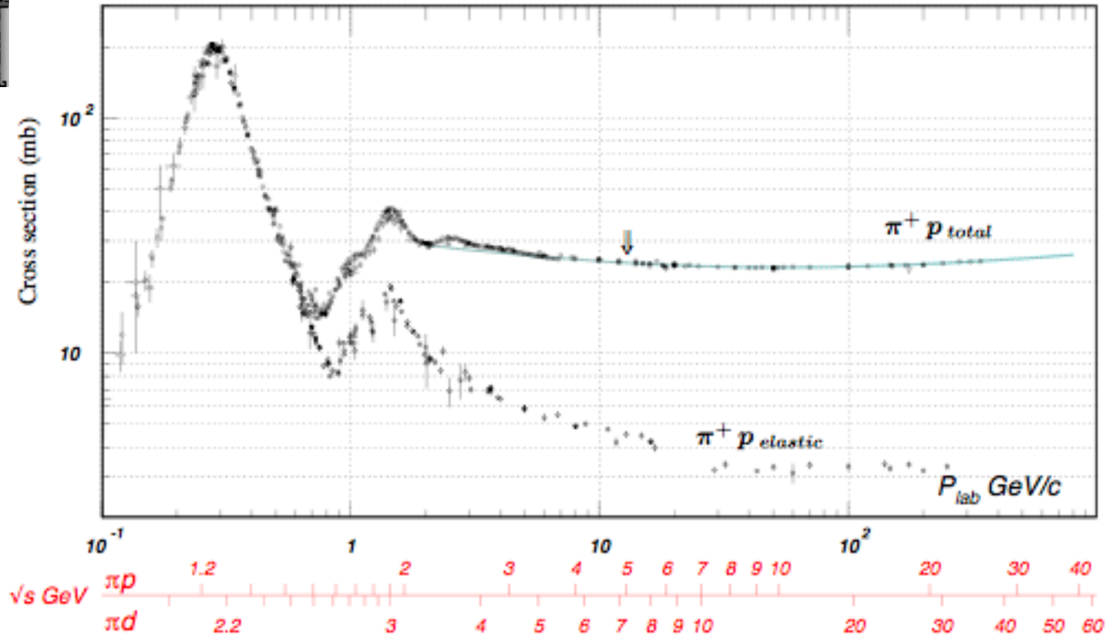


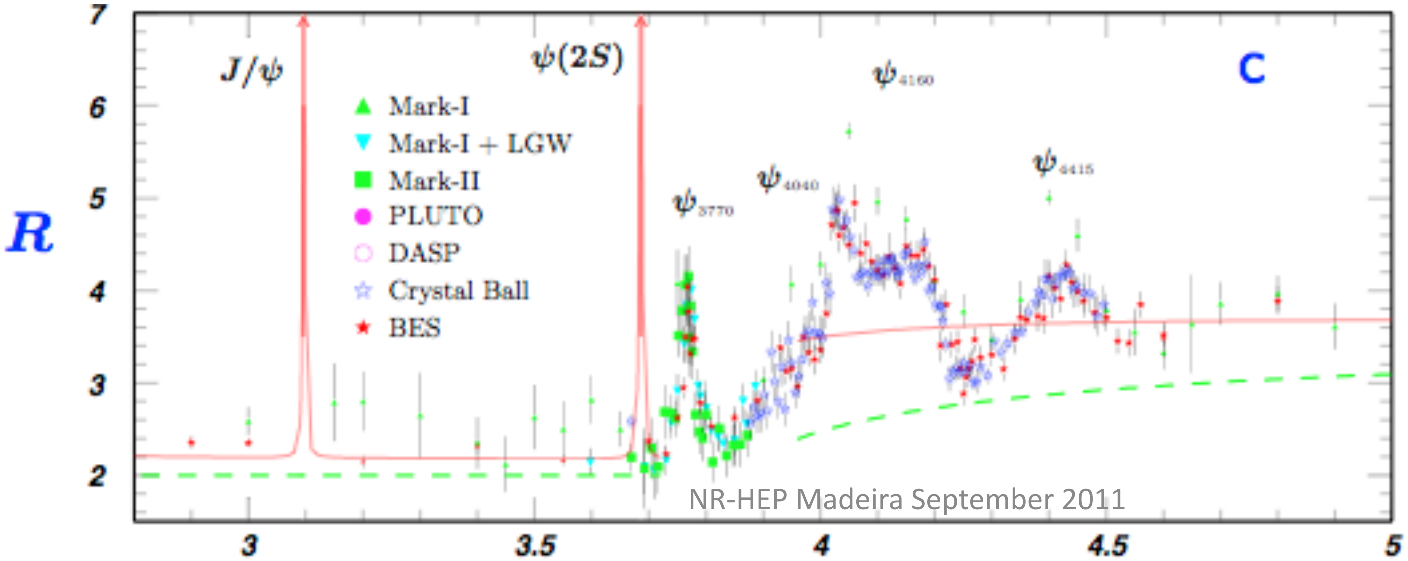
- We can all agree with statements from both papers:
  - *all the MC simulations suffer from large quantum corrections of the order of* $\sim O(M_D/M)^{p>0}$ *which can lead a significant change in the final result.*
  - *The main result of our analysis remains to be the model-independent limits…*

Need theory for TeVG (not BH) which is applicable in the region that the LHC can access.

Experimentalists should always publish physical data and, if possible, model independent constraints. Cross-section limits are more valuable than model exclusions.

Previous new scales

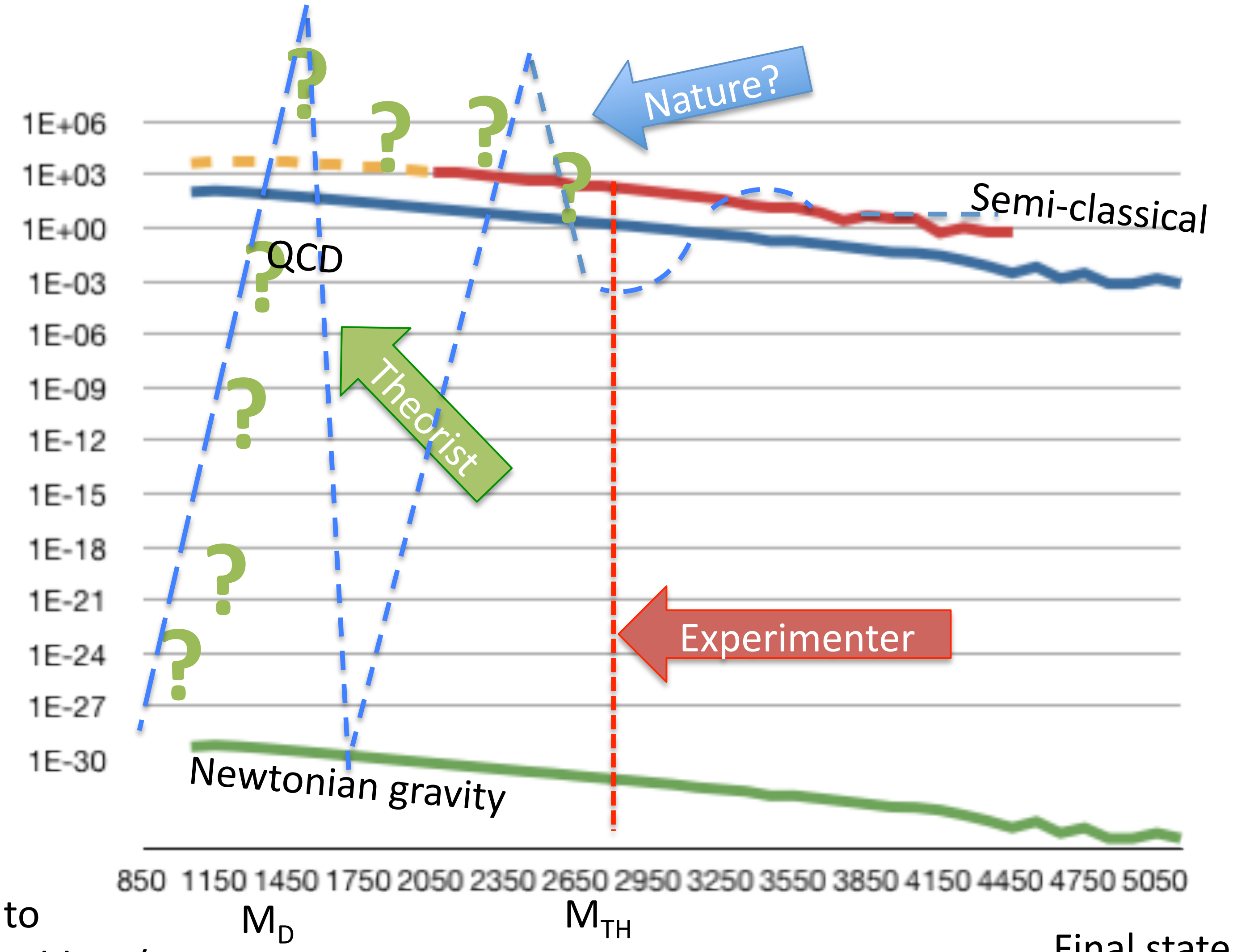




- Past experience shows that large effects can be seen near threshold of new physics.
- Can we provide any generic constraints?

Gravitational cross section at LHC

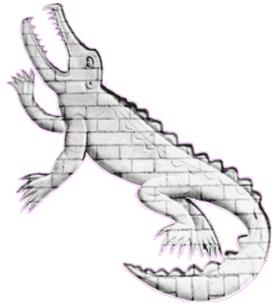
Cross-section (pb)
Log scale



Final state mass

Thanks to
Bryan Webber /
Marco Sampaio

Discussion points

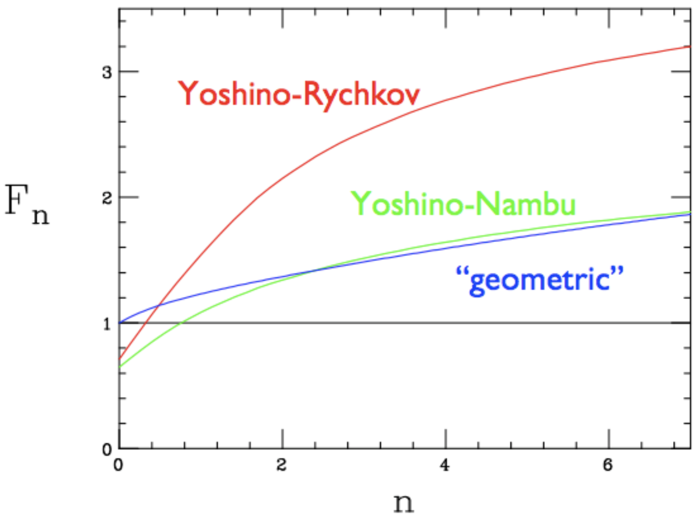


- If experimentalists publish cross-section x acceptance (perhaps map of acceptance vs p_T and η) is this useful to modellers?
- How far do we have to go before the semi-classical calculations are valid? Will 14 TeV be enough? Are there already corners of parameter space which we should emphasise?
- Can the theory provide any useful constraints in the current LHC regime?

Backup

Black hole cross section uncertainties

See nice review by Gingrich
hep-ph/0609055



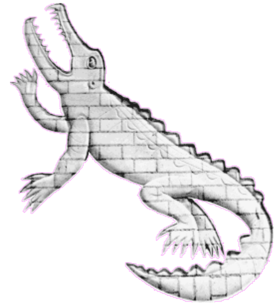
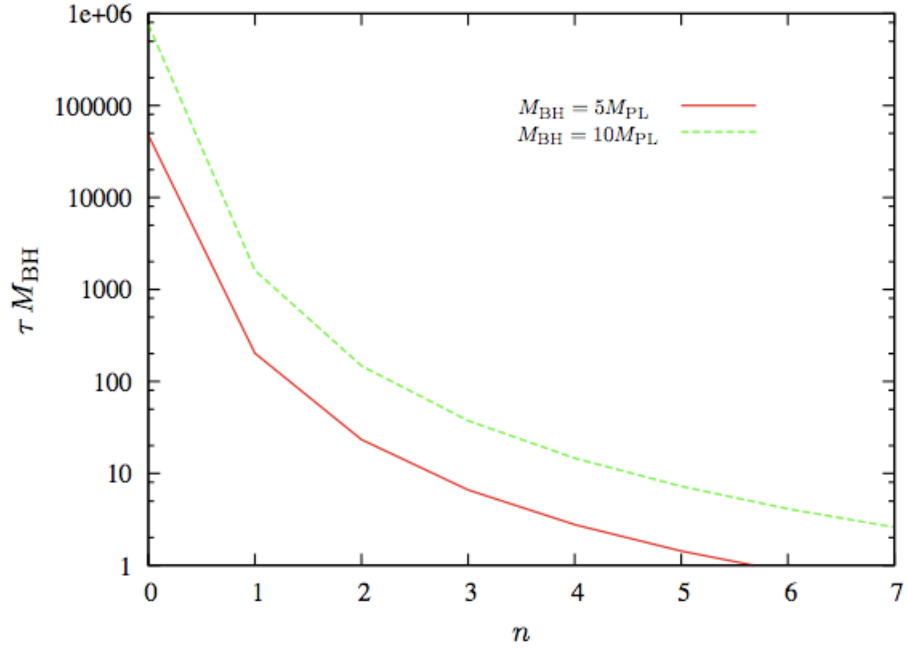
➡ H Yoshino & Y Nambu, gr-qc/0209003
➡ H Yoshino & VS Rychkov, hep-th/0503171

Form factors increase cross-section

"Trapped energy" inside event horizon is less than available parton energy -> decreases cross-section by large factor near threshold at M_{PL}

Lower limits on cross-section have been calculated from GR

Conclude - there is considerable uncertainty and cross-section probably smaller than semi-classical approximation

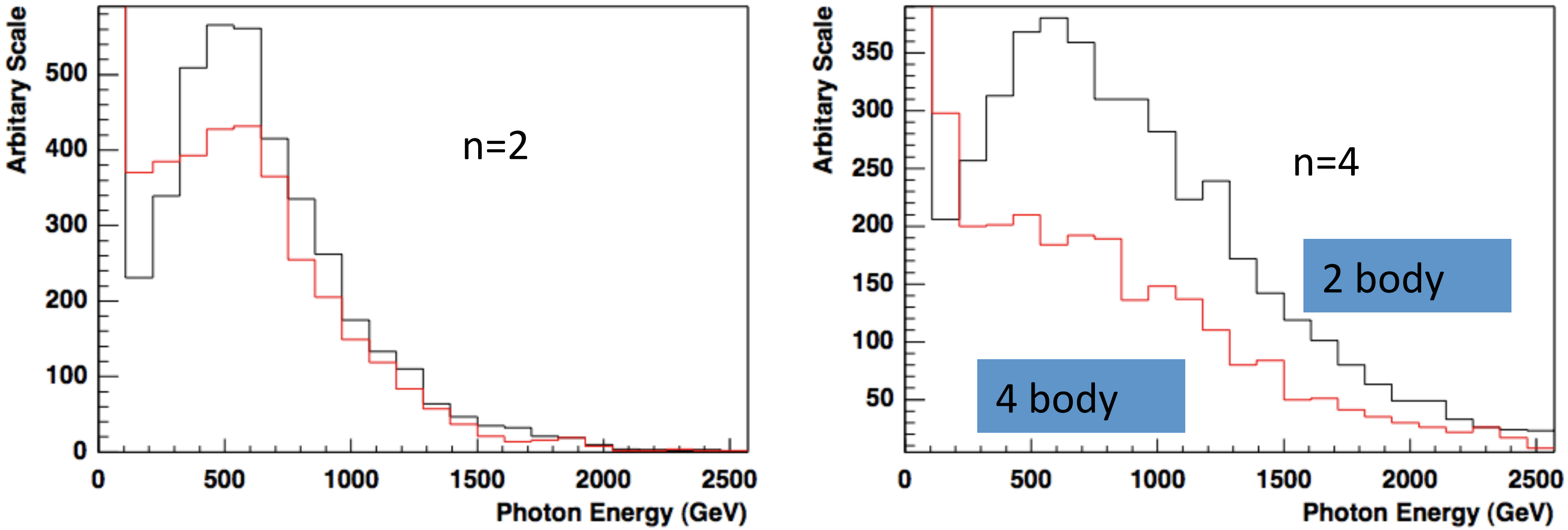



$$\left(M_{\rm BH} = 5\ {\rm TeV} \Rightarrow M_{\rm BH}^{-1} \sim 10^{-28}\ {\rm s}\right)$$

N.B. $\tau M_{\rm BH} \sim 1$ at large n

Black hole no longer well-defined?

Effect of decay of remnant



Remnant is the final stage of decay when QG regime is reached, as M_{BH} drops to M_{PL}

Generator can choose 2 or 4 body decay mode for remnant.

Large effect in final energy spectrum in some cases.