ADD gravitons & black holes at the LHC

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Exotics WG

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ADD gravitons - introduction

- Arkani-Hamed, Dimopoulos, Dvali model introduces n compactified LEDs with radius R to solve the Hierarchy problem where gravitation unifies with the other forces at a lowered, ~TeV order scale

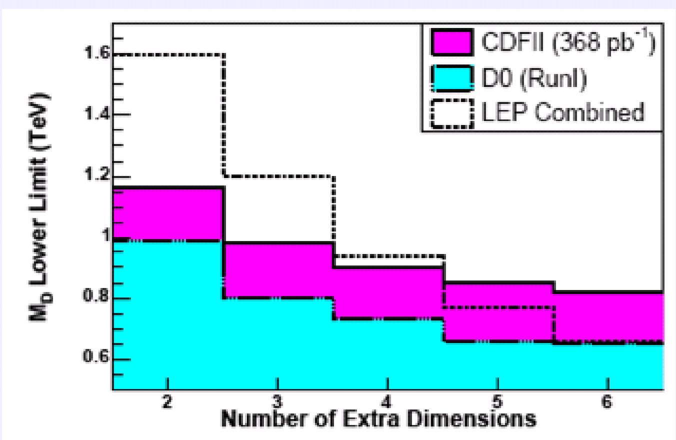
$$M_4^2 = M_{4+n}^{2+n} R^n$$

•,Only gravitons probe the bulk space while others are confined to the 3-brane. Hence, a KK tower of graviton modes: 0-mode is massless; higher modes are massive spin-2 particles that can couple to SM matter. Following consequences are possible:

- Direct graviton emission

$$q\bar{q}/gg \rightarrow g/\gamma G_{KK}^{ADD}, \quad gq \rightarrow qG_{KK}^{ADD}$$

LEP & Tevatron constraints on $M_{(4+n)}$ from jet+G channel



- Virtual graviton exchange:

$$q\bar{q} \rightarrow \gamma/Z^0/G_{KK}^{ADD} \rightarrow ll/\gamma\gamma/jj$$

Find the deviation from SM caused by virtual graviton exchange

%95CL lower limits on $M_{(4+n)}$ for LED with 200pb^{-1} D0 Run II diEM sample and the combined limit for Run I and II

	GRW	HLZ						Hewett
		n=2	n=3	n=4	n=5	n=6	n=7	λ=+1
Run II	**1.36**	1.56	1.61	1.36	1.23	1.14	1.08	1.22
Run I+II, combined	**1.43**	1.67	1.70	1.43	1.29	1.20	1.14	1.28

ADD graviton emission in γ+MET channel: I

$q\bar{q}/gg \rightarrow \gamma G_{KK}^{ADD}$

J.Weng, G.Quast, C.Saout, A.de Roeck, M.Spiropulu, CMS-NOTE 2006/129

Signatures:

A single high-p_T photon in the central η region.

High missing p_T back-to-back with the photon in the azimuthal plane

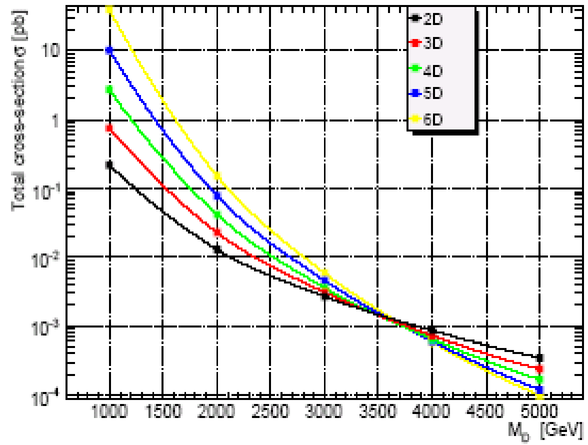
Not strongly dependent on ADD model parameters.

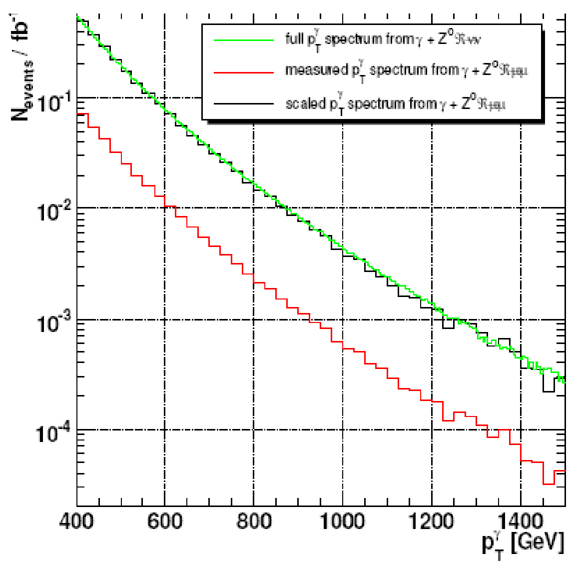
Trigger: Single photon (L1+HLT), E > 80GeV, %100

Event selection:

$E_{Tmiss} > 400$ GeV
$p_T > 400$ GeV
$\Delta\Phi(E_{Tmiss}, \gamma) > 2.5$
$|\eta| < 2.4$
Track veto > 40 GeV
γ likelihood > 0.2

Signal cross section: PYTHIA





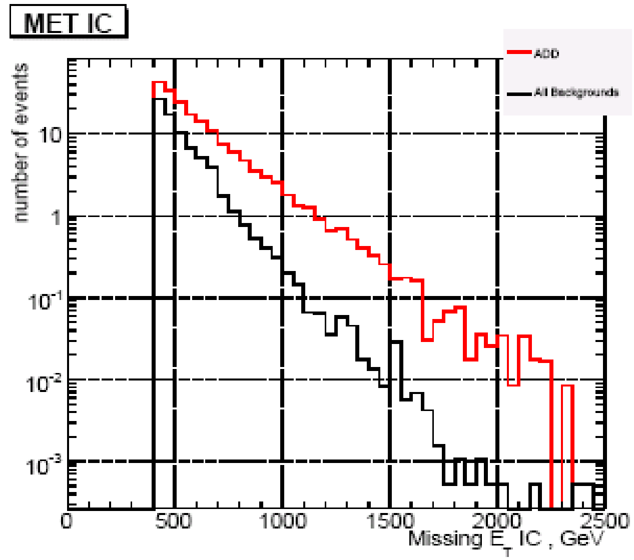
Background	σ for $\hat{p_T} > 400$ GeV
$Z^0\gamma \rightarrow \nu\bar{\nu} + \gamma$	2.16 fb
$W^{\pm} \rightarrow e\nu$	18.2 fb
$W^{\pm} \rightarrow \mu\nu$	18.2 fb
$W^{\pm} \rightarrow \tau\nu$	18.2 fb
$W^{\pm}\gamma \rightarrow e\nu+\gamma$	0.83 fb
γ+Jets	2.50 pb
QCD	2.15 nb
di-γ born	5.20 fb
di-γ box	0.14 fb
Z^0 + jets	0.69 pb

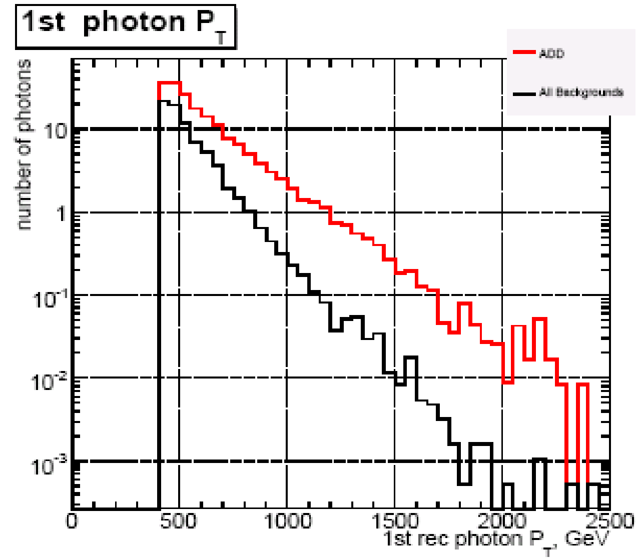
Estimation of γ+Z(→ νν) background from γ+Z(→μμ) processes.

ADD graviton emission in γ+MET channel: II

M_{4+n} = 2.5TeV,
n = 2

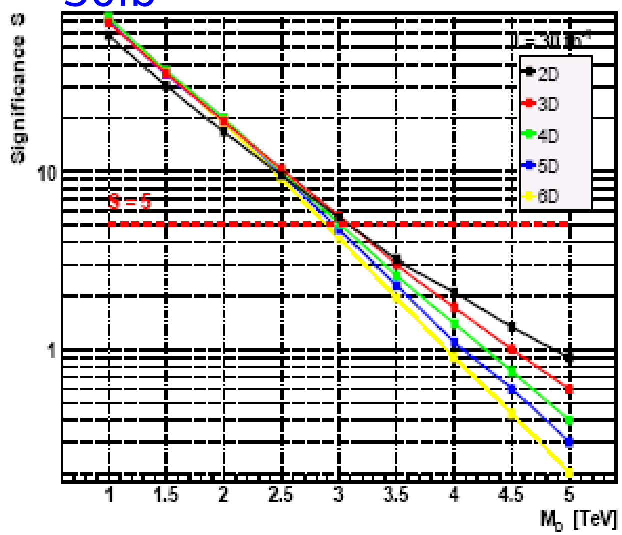
PYTHIA+CMKIN +FAMOS



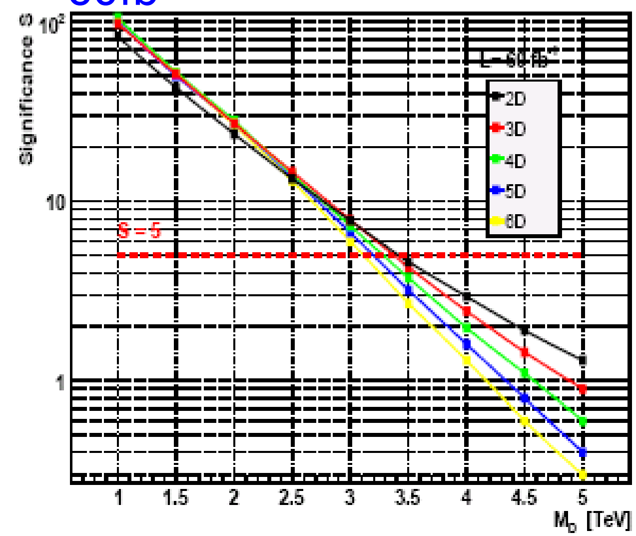


Significances:

30fb^{-1}



60fb^{-1}

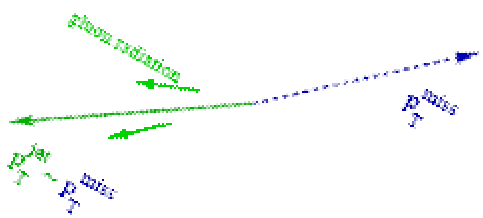


ADD graviton emission in jet+MET channel: I

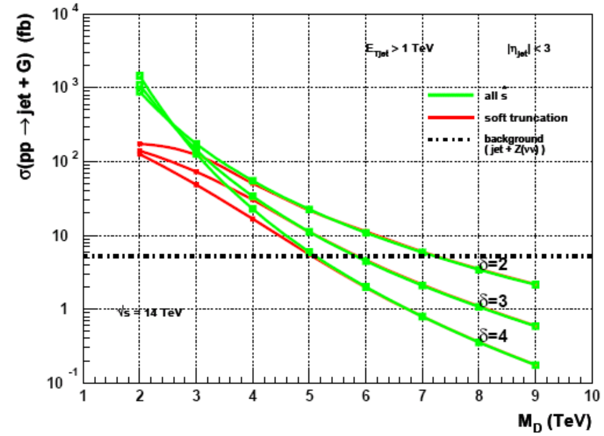
L.Vacavant, I.Hinchliffe, ATLAS-PHYS-2000-016

$$qg \rightarrow qG^{ADD}_{KK}\ ,\ \ gg/q\bar{q} \rightarrow gG^{ADD}_{KK}$$

Signature: Monojet back-to-back in azimuth with missing p_T. Additional jets come from ISR/FSR



S&B cross sections for jets with E_T > 1 TeV -:ISAJET



Backgrounds:

- Jet + Z(→νν)
- jet + W(→τν)
- jet + W(→μν)
- jet + W(→eν)

Trigger:

Single jet + MET

jet: |η| < 3.2, p_T > 50 GeV

p_{Tmiss} > 50 GeV (low L)

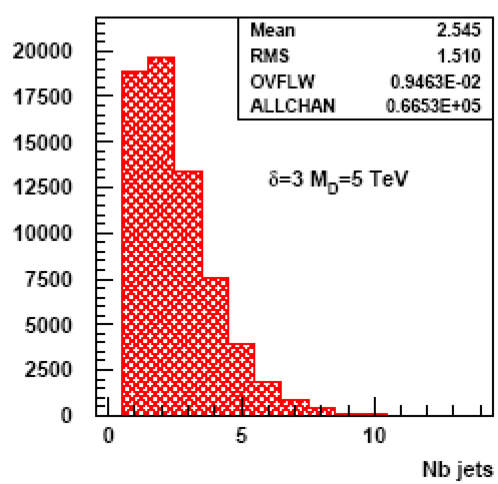
p_Ts -> 100 GeV for high L

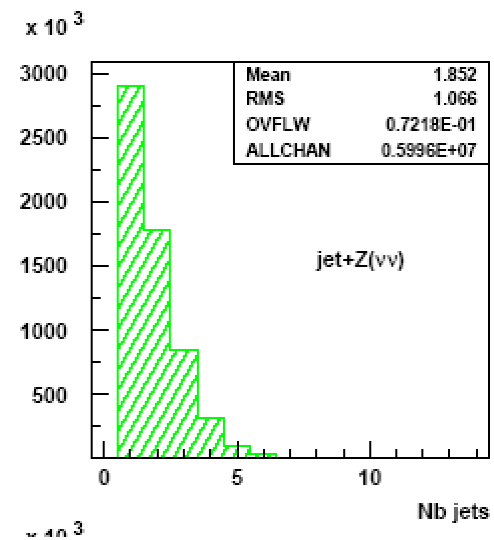
Event selection:

Lepton veto:

Electrons: p_T > 5 GeV, |η| < 2.5

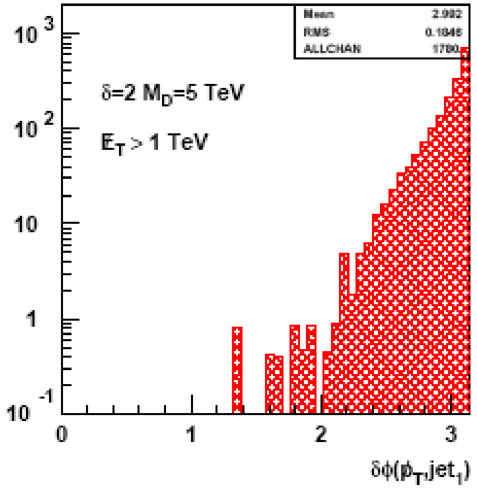
Muons: p_T > 6 GeV, |η| < 2.5

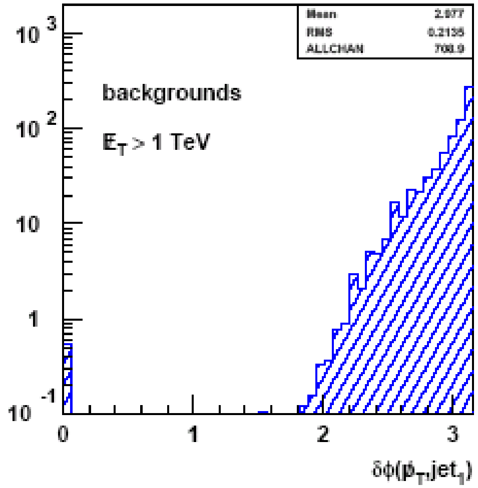


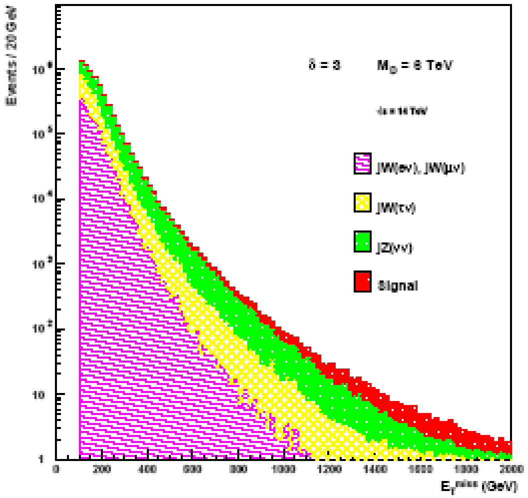


# of jets: ISAJET + ATLFAST

ISAJET + ATLFAST







δ	M_D	Low luminosity, $30 fb^{-1}$			High luminosity, $100 fb^{-1}$		
		S	$S/\sqrt{B}$	$S/\sqrt{7B}$	S	$S/\sqrt{B}$	$S/\sqrt{7B}$
2	4	1036.4	81.6	30.8	3542.2	150.2	56.8
	5	417.0	32.9	12.4	1426.9	60.4	22.8
	6	205.9	16.3	6.2	700.6	29.6	11.2
	7	111.3	8.8	3.3	379.4	16.1	6.1
	8	65.3	5.2	2.0	222.5	9.4	3.5
3	4	641.8	50.6	19.1	2168.4	92.0	34.8
	5	211.5	16.6	6.3	706.0	30.0	11.3
	6	85.1	6.8	2.6	287.5	12.1	4.6
	7	39.3	3.1	1.2	134.0	5.7	2.2
4	4	436.2	34.3	13.0	1473.4	62.5	23.6
	5	113.0	8.8	3.3	383.4	16.3	6.2
	6	37.8	2.9	1.1	128.5	5.4	2.0

Remaining signal events after the selection cuts + E_{Tmiss} > 1TeV, and statistical significance

B estimation via normalization is 7 times smaller then expected due to calibration effects, hence $S/(7B)^{1/2}$ is also used as a worst case scenario.

ADD graviton contribution in dimuon channel: I

$$q\bar{q} \to \gamma/Z^0/G_{KK}^{ADD} \to \mu\mu$$

I.Belotelov, I.Golotvin, A.Lanyov, E.Rogalev, M.Savina, S.Shmatov, D.Bourikov, CMS-NOTE 2006/076

Signatures:

Two high-p_T muons.

Trigger:

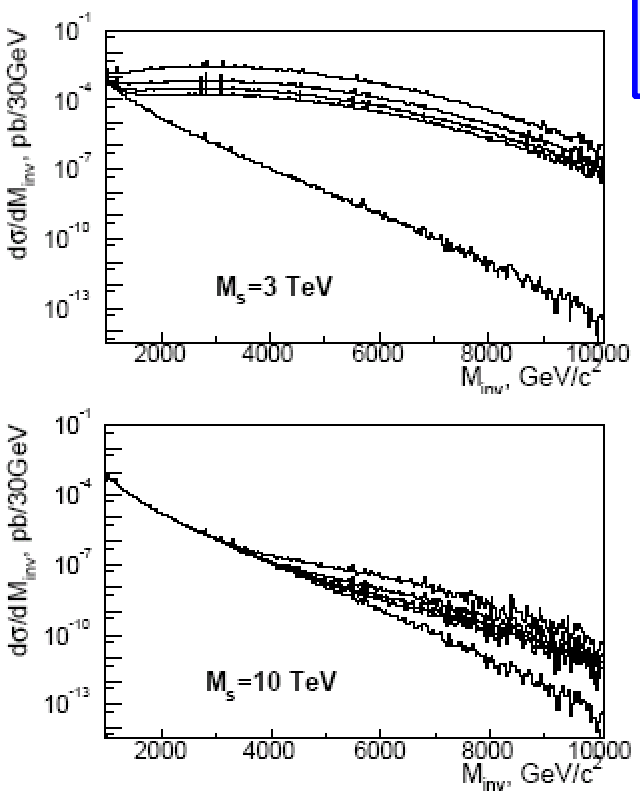
Single muon & dimuon (L1+HLT)
p_T>7GeV($\mu\mu$), 19GeV(single μ)
Efficiency > %98

Event selection:

$M(\mu\mu)_{inv} > M_{min}$
Different M_{min} for different M_{4+n}:
M_{min} = 1TeV for M_{4+n} = 3TeV
M_{min} = 1.5TeV for M_{4+n} = 5TeV

LO DY cross section

M_S, TeV/c^2	3.0	4.0	5.0	7.0
$n=3$	1.5×10^3	160	32.1	8.1
$n=6$	103	11.4	10.1	6.4



Backgrounds:

For $M(\mu\mu)_{inv}$>1TeV

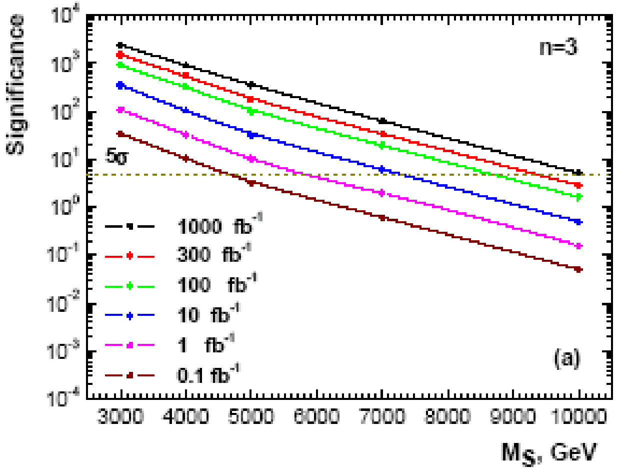
ZZ/WZ/WW:
σ = 2.59x10^{-4} fb^{-1}
tt:
σ = 2.88x10^{-4} fb^{-1}

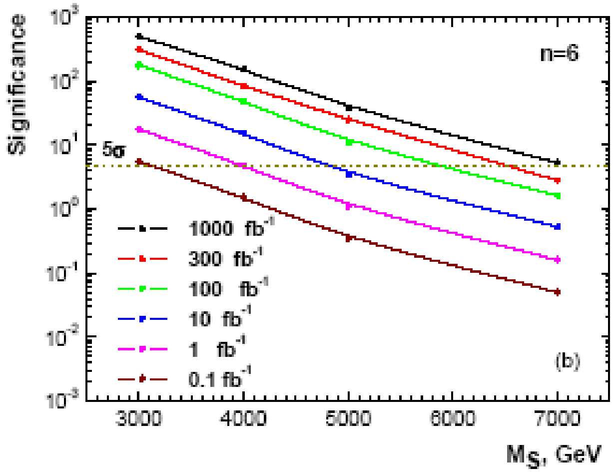
Landsberg code + STAGEN + PHYTIA + ORCA + OSCAR

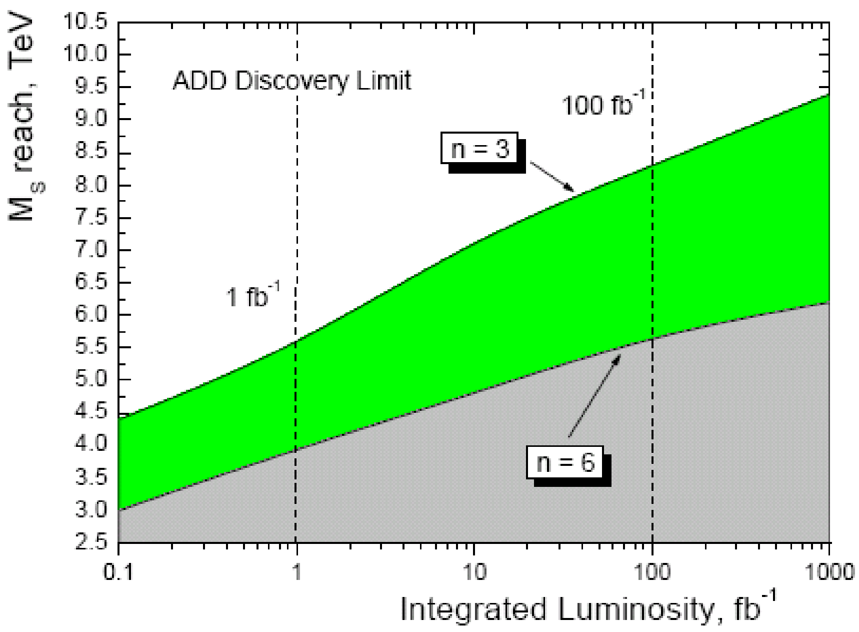
Bottom to top:
SM, n = 6,5,4,3

ADD graviton contribution in dimuon channel: II

Significance:







5σ limit on M_{4+n} for the number of extra dimensions n = 3,4,5,6

ADD graviton contribution in $\gamma\gamma/ll$ channels: I

V.Kabachenko, A. Miagkov, A. Zenin ATLAS-PHYS-2001-012

$$q\bar{q}/gg \rightarrow \gamma/Z^{o}/G_{KK}^{ADD} \rightarrow \gamma\gamma/ll$$

Signature: Two photons or leptons

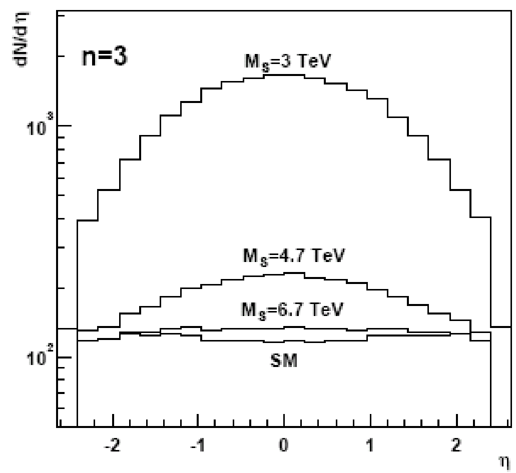
Trigger:

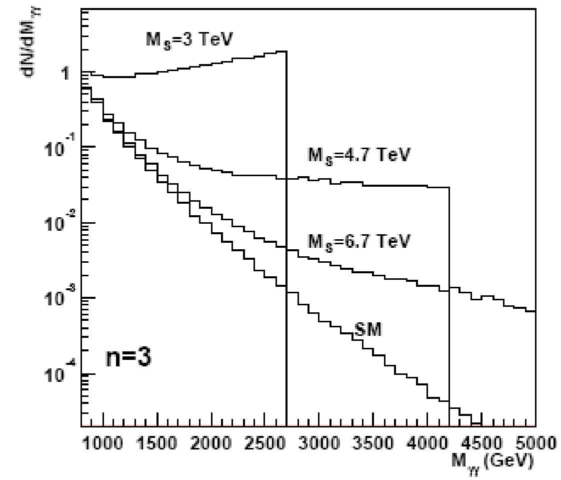
-

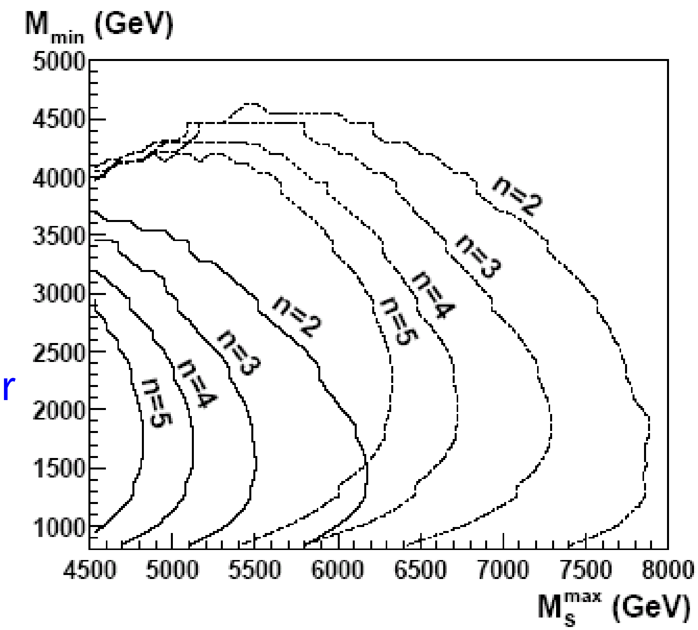
Event selection:

$M(\gamma\gamma/ll)_{inv} < 0.9M_{4+n}$
$M(\gamma\gamma/ll)_{inv} > M_{min} > 0.8TeV$
$p_T(\gamma/l) > 50GeV$
$|\eta| < 2.5$

ATLFAST







Diphoton production, maximal reach at 5σ level in the scale M4+n as a function of the lower cut M_{min}. Solid lines: $10fb^{-1}$, dashed lines $100fb^{-1}$.

Higher-dimensional black holes - introduction

FORMATION

Schwarzschild radius

4+n d

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

4d

$$r_4 = \frac{1}{M_4} \left(\frac{M_{BH}}{M_4} \right) = \frac{1}{M_{4+n}} \left(\frac{M_{BH}}{M_{4+n}} \right) \frac{1}{(M_{4+n} R)^n}$$

$$r_4 < r_{4+n} < R$$

RADIATION

4d | 4+n d

$$T_4 = \frac{dE}{dS}$$

$$T_{4+n} = \frac{dM}{dA}$$

Hawking temperature

$$T_4 > T_{4+n}$$

$$T_4 = \frac{dE}{dS}$$

$$T_{4+n} \sim M_{4+n} \left(\frac{M_{4+n}}{M_{BH}} \right)^{\frac{1}{n+1}}$$

Lifetime

$$\tau_4 < \tau_{4+n}$$

$$\tau_4 \sim \frac{1}{M_4} \left(\frac{M_{BH}}{M_4} \right)^3$$

$$\tau_{4+n} \sim \frac{1}{M_{4+n}} \left(\frac{M_{BH}}{M_{4+n}} \right)^{\frac{n+3}{n+1}}$$

BH production – cross sections

For $M_{BH} >> M_{4+n}$, parton level BH formation cross section is given by semi-classical arguments through a geometrical approach:

$$\sigma(s = M_{BH}^2) = F_n \pi r_{4+n}^2 = \frac{F_n}{M_{4+n}^2} \left(\frac{M_{BH}}{M_{4+n}} \frac{8\Gamma((n+3)/2)}{n+2} \right)^{\frac{2}{n+1}}$$

where F_n is the formation factor. However, the definition of F_n is yet uncertain. σ_{BH} **dominates in high energies.**

For $M_{BH} \sim M_{4+n}$ quantum gravity effects come into play.

Differential production croos section in pp collisions is calculated using parton luminosity approach:

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

$$\frac{dL}{dM_{BH}} = \frac{2M_{BH}}{s} \sum_{a,b} \int_{M_{BH}^2/s}^{1} \frac{dx_a}{x_a} f_a(x_a) f_b\left(\frac{M_{BH}^2}{s x_a}\right)$$

where $f_i(x_i)$ are the PDFs.

Hawking radiation and multiplicity

f:flux, N: multiplicity, $x = E/T_H$

$$\frac{df}{dx} \sim \frac{x^3}{e^x + c}$$

$$\frac{dN}{dE} \sim \frac{1}{E}\frac{df}{dE} \sim \frac{x^2}{e^x + c}$$

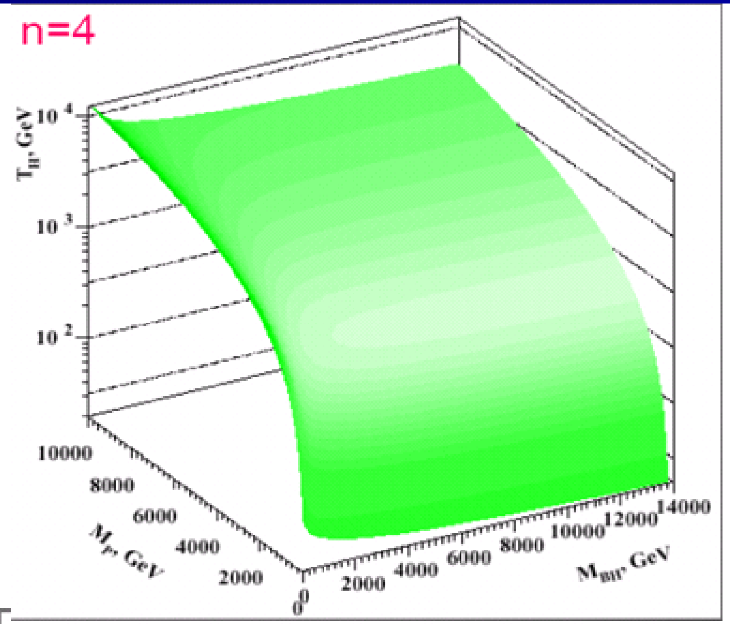
$$\left\langle \frac{1}{E} \right\rangle = \frac{1}{T_H} \frac{\int_0^\infty dx \frac{x^2}{e^x+c}}{\int_0^\infty dx \frac{1}{x}\frac{x^2}{e^x+c}} = \frac{a}{T_H}$$

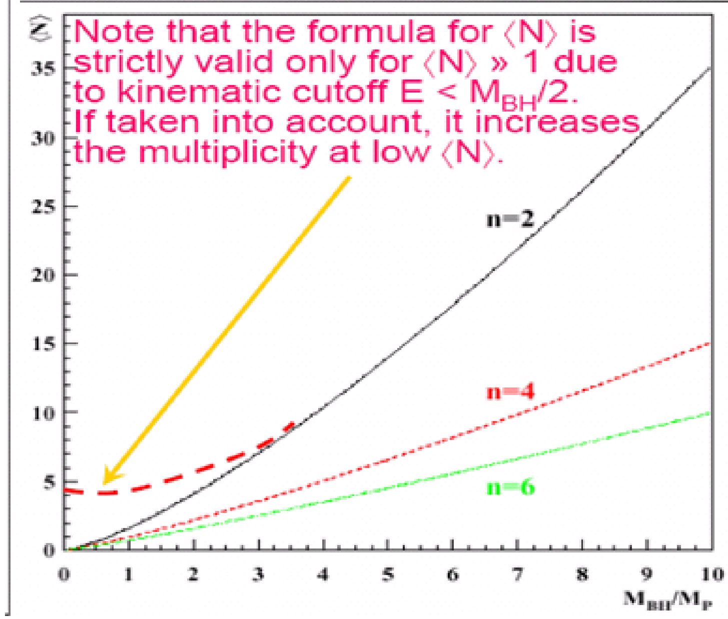
Use $a = 0.5$ for Boltzman statistics.

$$\langle N \rangle = \left\langle \frac{M_{BH}}{E} \right\rangle = \frac{M_{BH}}{2T_H}$$

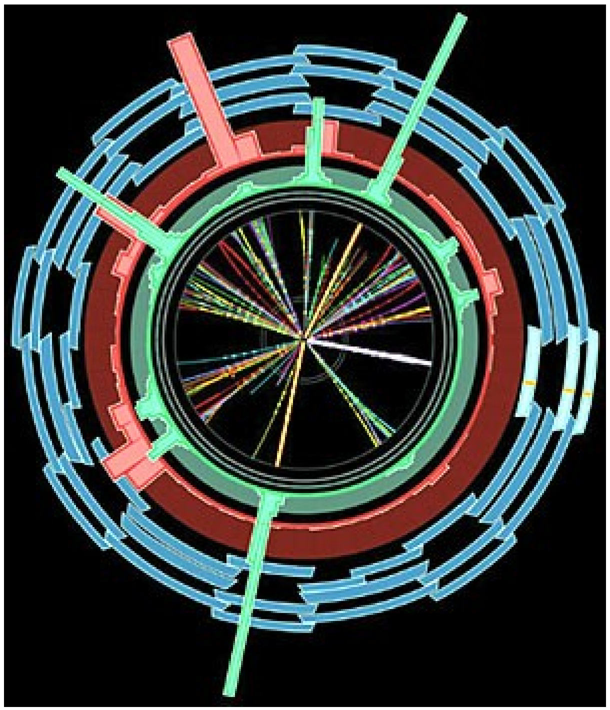
BHs decay democratically to all SM particles

Landsberg, Dimopoulos, PRL 87, 161602 (2001)

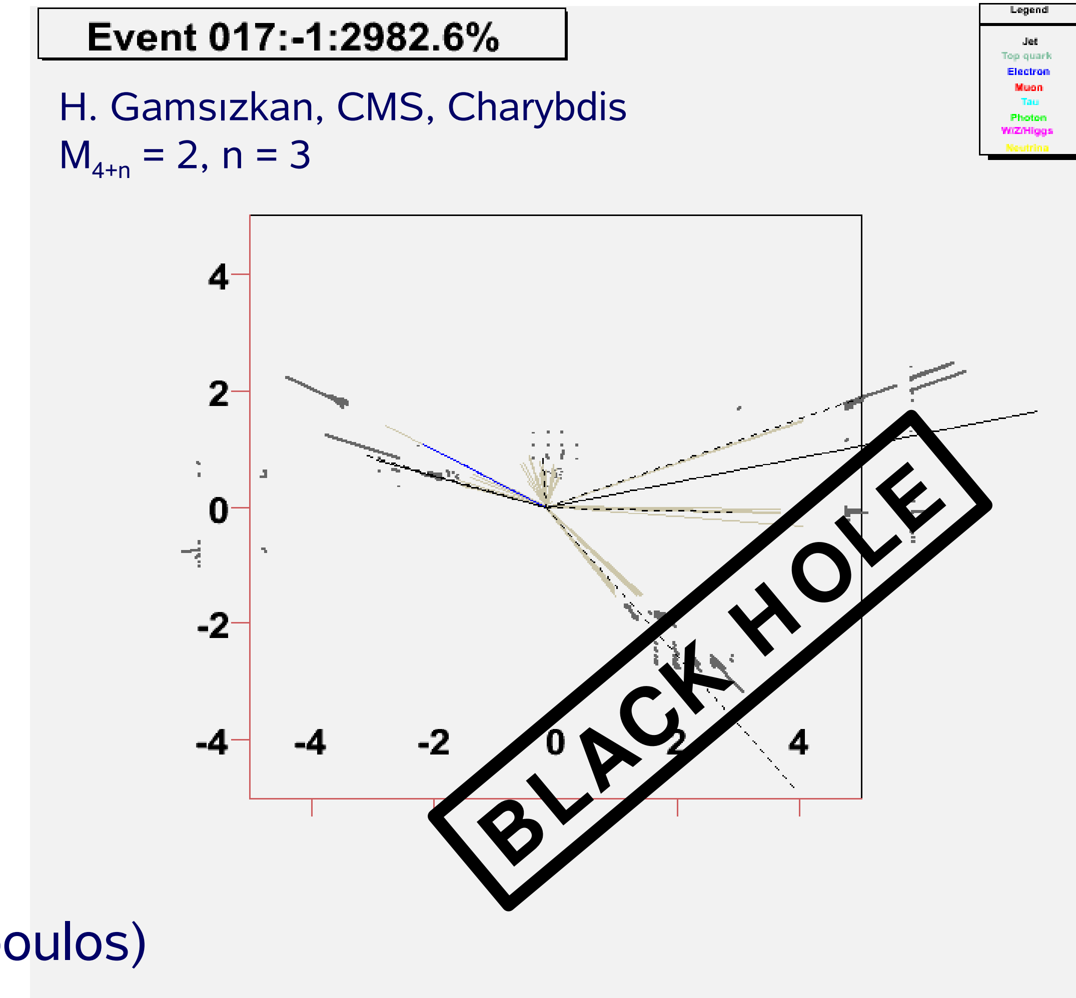




Reconstructing BHs at the LHC



ATLAS



BH event generators:

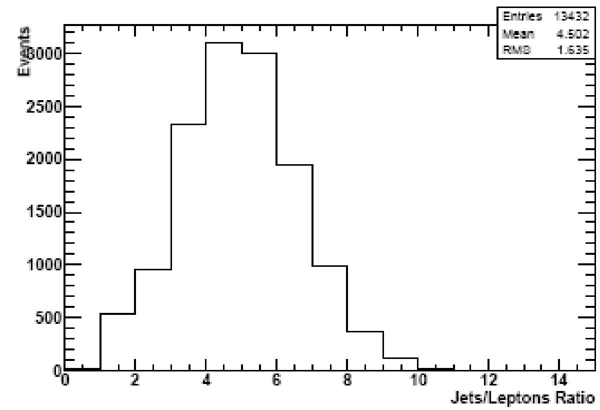
- TRUNOIR (Landsberg, Dimopoulos)
- Unnamed MC by Japan group
- Charybdis (Harris, Richardson, Webber)
- Catfish (Cavaglia, Cremaldi, Godang, Summers)

BH signatures

H.Gamsızkan, A.de Roeck, S.Sekmen, M.T.Zeyrek, CMS-AN 2006/088

Signature: Due to thermal decay, BHs have high sphericity, high Σp_T and high multiplicity compared to SM events – and due to democratic decay, jets/leptons ratio ~ 5 : 1

Backgrounds: tt+jets, W/Z+jets, QCD, WW+jets



Trigger:>4 jets, softest having E_T > 120 GeV (efficiency > %93). BHs can be tagged efficiently by requiring a prompt photon or lepton.

Event selection:

M_{BH}(reco) > 2 TeV

Multiplicity > 4

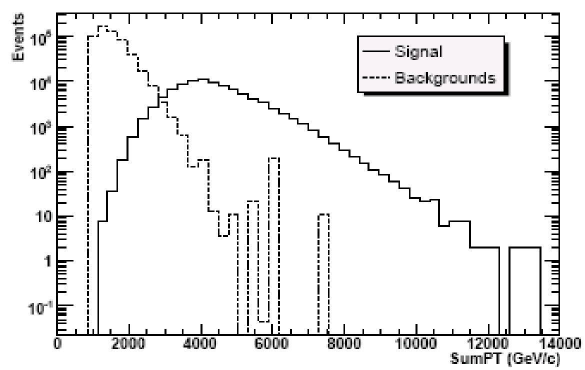
E(xi) < $M_{BH}/2$

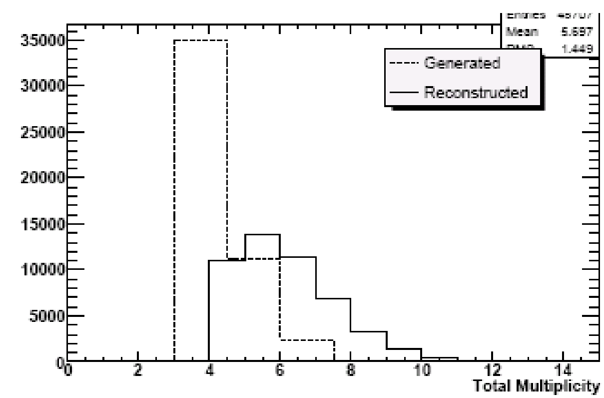
Sphericity < 0.28

M_{4+n} = 2, n = 3, M_{BH} = 4-14,
$\sigma = 18.85$ pb
Charybdis+ORCA+OSCAR

$$\sum p_T = \sum_{i<4} |p_T(jet_i)|$$

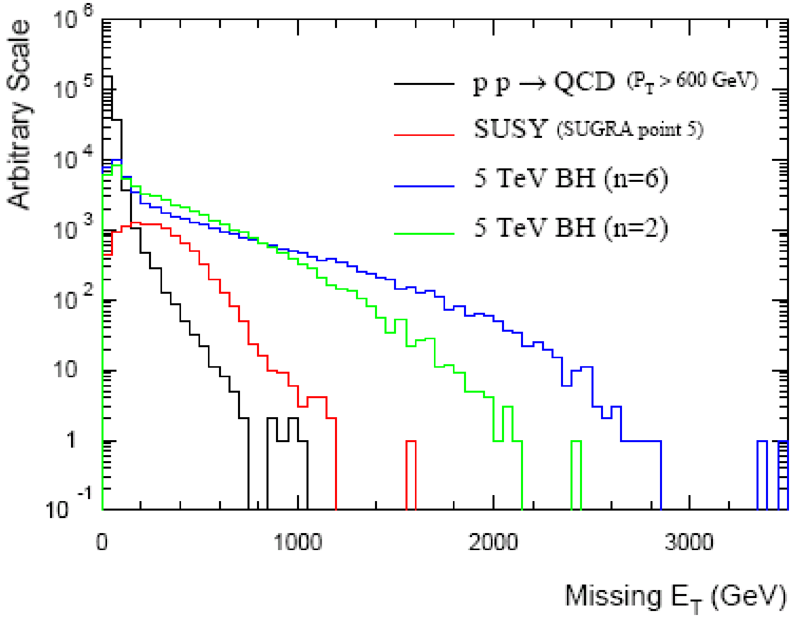
(4 hardest jets)

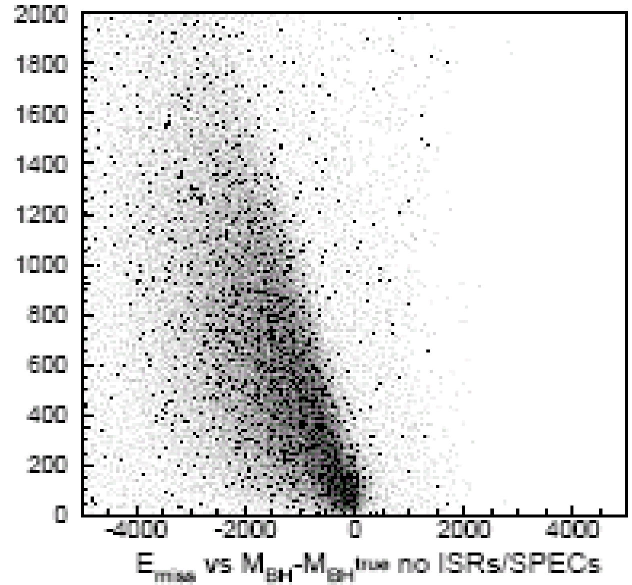




BH signatures: High missing energy

BHs would have high missing E_T due to high energies of democratically emitted neutrinos.





Harris, Palmer, Parker, Richardson, Sabetfakhri, Webber, ATLAS, JHEP 0505 (2005) 053
Charybdis + ATLFAST

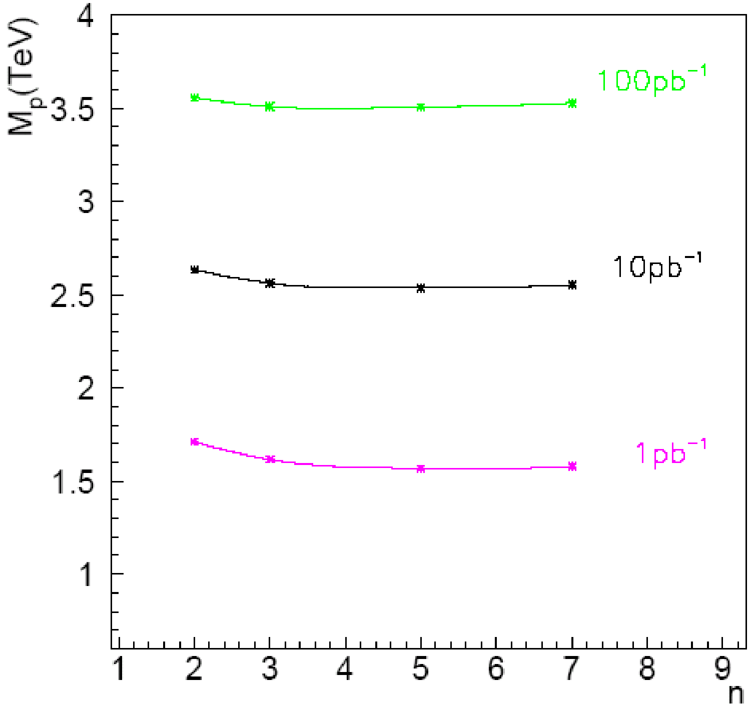
Tanaka, Yamamura, Asai, Kanzaki, ATLAS, Eur. Phys. J. C41 (2005) 19-23
Unnamed MC
M_{4+n} = 1, n = 3, M_{BH} = 1-14

Most analyses use E_{Tmiss} > 100 GeV cut.

BH significance

$M_{(4+n)}$	min M_{BH}	4+n	Cross section (pb)	Luminosity to reach 5σ (fb^{-1})
2	4	7	18.85	3.71×10^{-3}
2.5	5	7	2.661	1.20
1	1	6	27980	6.50×10^{-6}
1	1	8	23510	8.50×10^{-6}
1	1	10	24910	8.50×10^{-6}
1	2	6	3086	1.95×10^{-5}
1	2	8	2282	2.95×10^{-5}
1	2	10	2284	3.15×10^{-5}
2	2	6	486.1	1.52×10^{-4}
2	2	8	432.4	1.82×10^{-4}
2	2	10	468.3	1.74×10^{-4}
2	3	6	93.06	5.79×10^{-4}
2	3	8	75.54	8.74×10^{-4}
2	3	10	78.7	8.88×10^{-4}
2	4	6	23.3	2.30×10^{-3}
2	4	10	17.73	5.29×10^{-3}
3	3	6	31.56	2.47×10^{-3}
3	3	8	28.55	2.96×10^{-3}
3	3	10	31.15	2.74×10^{-3}
3	4	6	7.904	1.45×10^{-2}
3	4	8	6.638	2.38×10^{-2}
3	4	10	7.017	2.32×10^{-2}
4	4	6	3.67	1.21
4	4	8	3.328	1.81
4	4	10	3.636	2.10

Gamsızkan et.al., CMS-AN 2006/088,
Charybdis + FAMOS

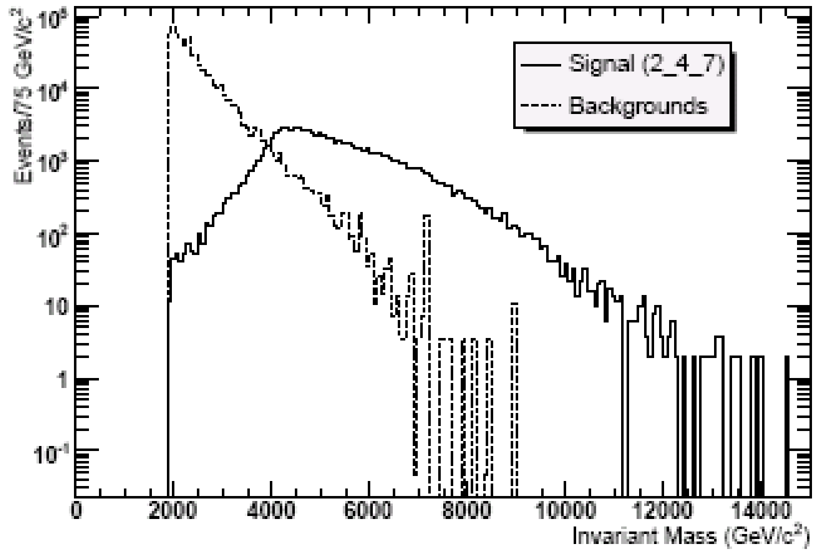


Tanaka, et.al., ATLAS,
Eur. Phys. J. C41 (2005) 19-23
Unnamed MC + ATLFAST
$M_{BH} = M_{4+n}$ + 1 to 14

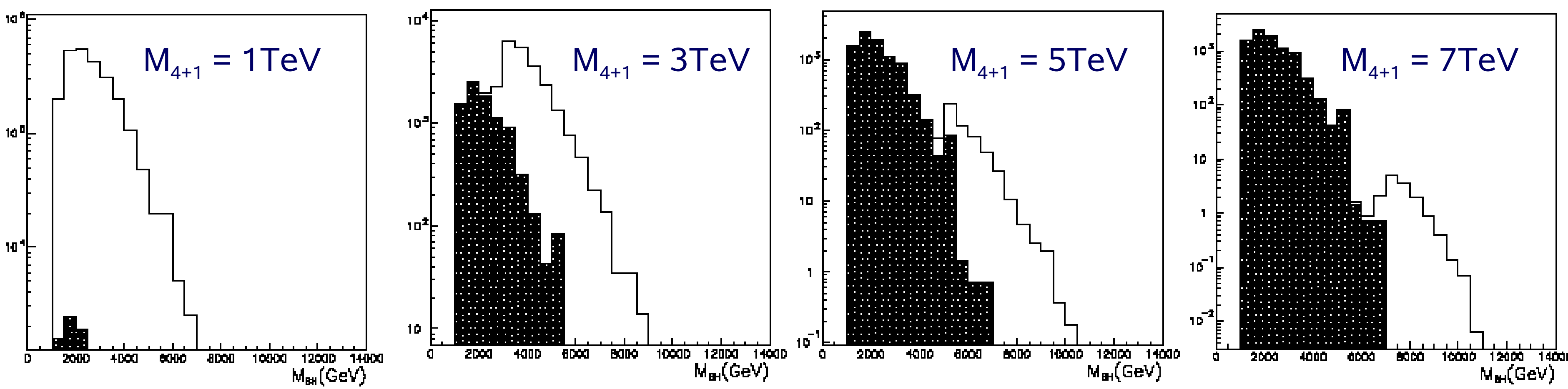
BH invariant mass

$$M_{BH} = \sqrt{(\sum_i p_i)^2}$$

Gamsızkan et.al., CMS-AN 2006/088
Charybdis + ORCA + OSCAR
M_{4+n} = 2, n = 3, M_{BH} = 4-14



Tanaka et.al., ATLAS,
Unnamed MC,
n = 3, M_{BH} = 1-14,
solid line: S+B, cross-hatched: B only

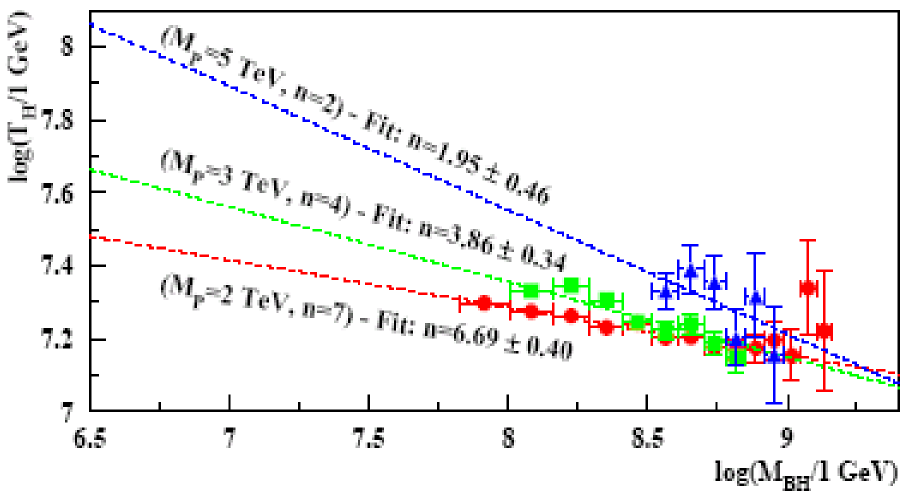


Learning about spacetime

Take the logarithm of both sides of T_H:

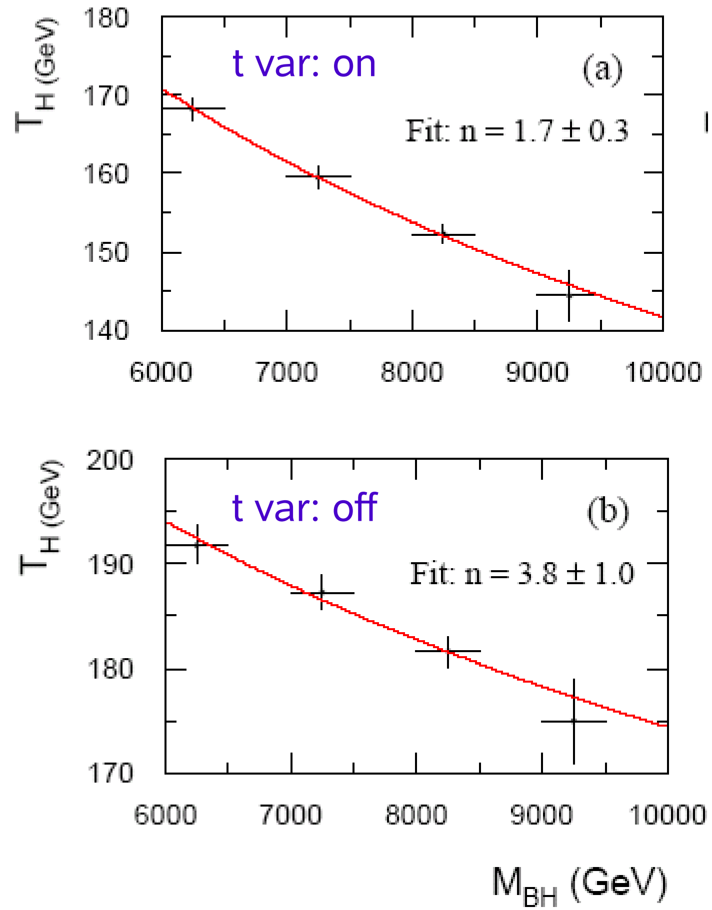
$$log(T_H) = \frac{-1}{n+1} log(M_{BH}) + const$$

Plot M_{BH} vs. T_H and fit to a line. Find n from the slope.



Landsberg, Dimopoulos, PRL 87, 161602 (2001)

But, including time variation leads to problems!



Harris et al, ATLAS, Charybdis, $M_{4+n} = 1$, $n = 2$

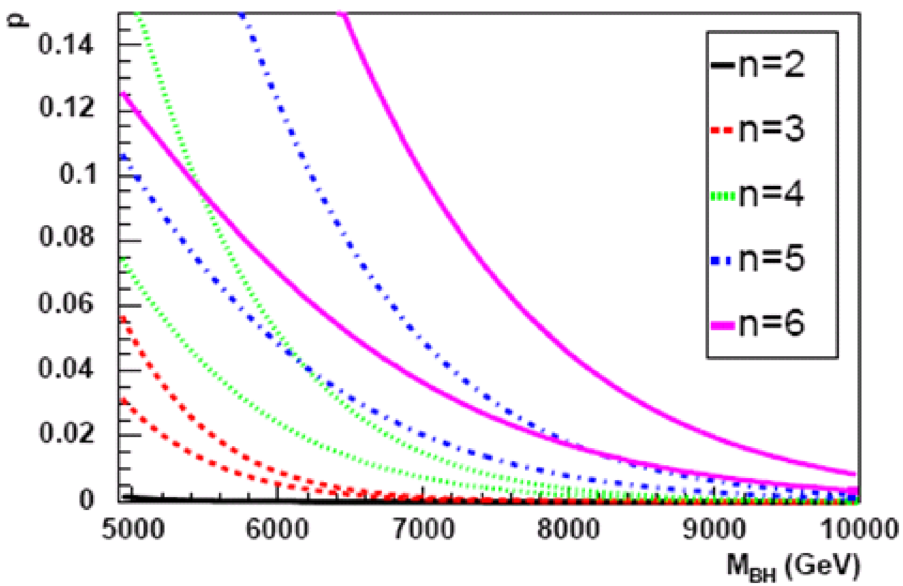
Harris et al tried a method in which they determined the order of particles emitted, reconstructed M_{BH} and T_H after each emission.

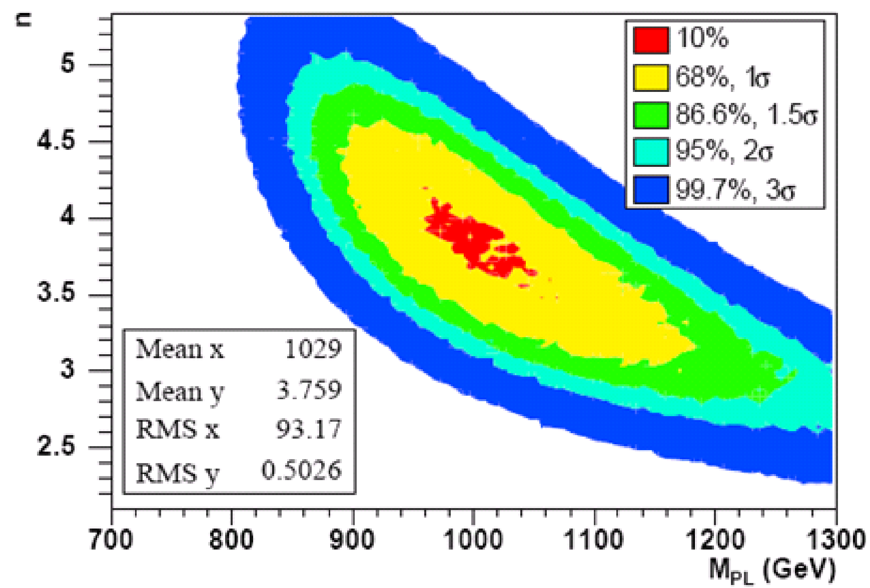
Learning about spacetime

Harris et al, ATLAS, Charybdis, $M_{4+n} = 1$, $n = 2$

To find n: Plot the fraction p of events which emit particles with energy $E_{cut} = M_{BH}/2 - d$. This fraction is srongly dependent on n.

To find $M_{(4+n)}$: Make use of cross sections since they strongly depend on $M_{(4+n)}$ but their n-dependence is negligible.





Theoretical upper and lower limits on p:

$$p_{lower} = k \int_{E_{cut}}^{M_{BH}/2} P\,dE \qquad p_{upper} = k \int_{E_{cut}}^{\infty} P\,dE$$

The final fit!
Combines "n" determination from p parameter and "$M_{(4+n)}$" determination from cross sections

CONCLUSIONS

Both direct ADD gravition production and ADD graviton contribution to DY processes can be observed with sufficient significance for moderate values of M4+n

Copious BH production might be possible at the LHC, and if this is realized, BHs will be identified by their significant signature. By looking at BH decay products, BH mass, Hawking temperature and spacetime properties might be reconstructed.