The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1970-12

Signaling the Arrival of the LHC Era

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Beyond the Standard Model at the LHC - III

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Examples of non-SUSY signatures

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Early discovery

Conditions for new physics to be visible in ffirst LHC year (max 1 fb$^{\times 1}$)

≪Cross-section O(100 fb) for leptonic signatures

≪Small SM backgrounds

≪Clear kinematic signature (peak, edge). No need for counting experiment

≪Signature visible also with not completely understood detector

Examples of well studied and well motivated candidates:

≪Multi-lepton+jets+$\not{E}_T$ SUSY signals with correlated-ffavour edge,already considered in previous lectures

≪High mass resonances decaying into two leptons, appearing in many BSM extensions, including Little Higgs, Extra Dimensional models, TechniColour

≪Mini Black Holes in theories with extra-dimensions, events with large cross-sections and particle multiplicities in ffinal state

Typically very clear signatures, but probing ‘extreme cases’ of requirements on detector performance:

≪Lepton performance for in region of high p_T ($>$500 GeV):

– Very far from the 50-100 GeV region were detector calibration optimised

– Difficult to ffind appropriate control samples in data

≪Reconstruction of events in environment with very high particles multiplicities and very high energy deposit in the calorimeters

For reliable answers need careful simulation work including detector geometry as-installed, material distortions and residual miscalibration/misalignment effects

Phenomenology of high mass lepton resonances

Resonances in lepton-lepton invariant mass distribution happens through s-channel exchange of new particles coupling both to partons and to leptons

≪Gauge boson resonances

– Extended Gauge groups. Examples:

$\leq$SSM: gauge boson with same coupling as SM Z. No theoretical motivation, useful benchmark

$\leq E_6$ models: effective $SU(2)_L \leq U(1)_Y \leq U(1)'$ from breaking of E_6 group

$\leq E_6 \to SU(3)_C \leq SU(2)_L \leq U(1)_Y \leq U(1)_\eta \leq U(1)_\eta$

$\leq$Lightest Z': $Z' = \cos\eta_{E6} Z'_\eta \leq \sin\eta_{E6} Z'_\eta$. η_{E6} value deffines models: Z_η, Z_η, Z_η

$\leq$L-R symmetric models:

$\leq SO(10) \to SU(3)_C \leq SU(2)_L \leq SU(2)_R \leq U(1)$. Model parameter: $\eta = g_R/g_L$

$\leq$Little Higgs models

– Kaluza-Klein excitations of η/Z in models with $SU(2) \leq U(1)$ gauge groups in ED bulk

Couplings of $\leq$ weak strength, with model-dependent scale factor

Natural width typically order a few % of resonance mass

Direct limits from Tevatron 850-950 GeV depending on model

Indirect limits from EW constraints 500-1800 GeV

For KK models with gauge interaction in bulk $m(Z') \gtrless$4 TeV from EW ffits

≪Graviton resonances:

Kaluza Klein (KK) excitations of graviton in models with warped space-time geometry

$\leq$Coupling of gravitational force, but enhanced by warp factor

$\leq$No bounds from EW constraints

$\leq$Distinctive polar angle distribution of decay

Model-dependent limits ranging from several hundred GeV to 1 TeV

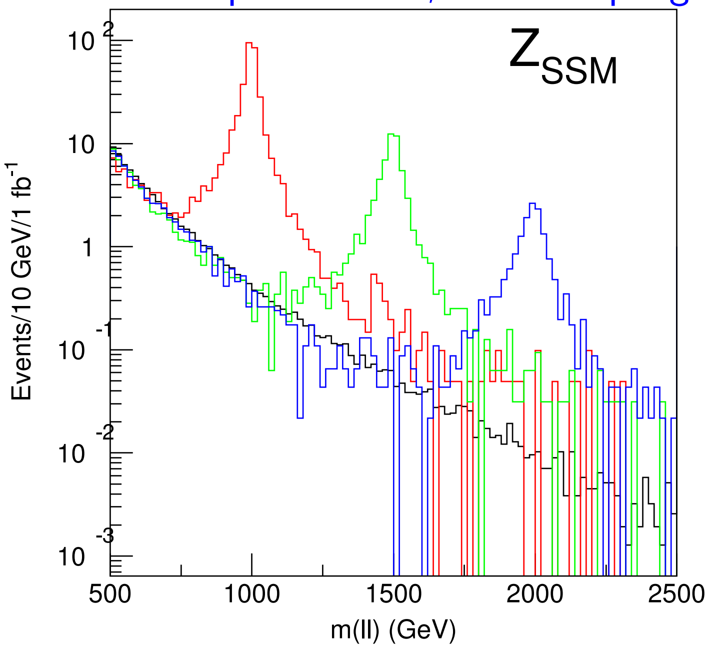
≪Technihadron resonances:

Technihadrons bound together by QCD-like forces are predicted by Technicolor theories. Signifficant BR in fermion-antifermion pairs for vector technihadrons

For TechniColor Strawman Model, and a particular choice of paramters, CDF limits of 280 GeV

Z' at generator level

Consider "Sequential" Z', same couplings as Standard Model



Drell-Yan background $\leq$ 2 orders of magnitude lower than signal in peak

Natural width Δ: $\Delta/M \leq 0.03$

$\leq$Experimental Resolution for $Z^{\rightarrow}e^{+}e^{-} < 1\%$

$\leq$ independent of mass

$\leq$Experimental Resolution for $Z^{\rightarrow}\eta^{+}\eta^{-} \leq 6 \leq 10\%$

for $m(Z')$ between 1 and 3 TeV

Cross-section for the full $\eta/Z/Z'$ system from $m(\ell\ell) > 500$ GeV

Number of events calculated within $\leq 2\Delta$ of peak value

Mass (GeV)	η ×BR fb	Nev Sig Ev/fb	Nev DY Ev/fb
1000	492	275	2.5
1250	245	112	1.05
1500	157	50	0.5
1750	124	25	0.24
2000	109	13	0.12

Example: ATLAS $Z' \to e^+e^{\ll}$ analysis

Recent analysis based on detailed detector simulation

Use Z_η model as benchmark, 3 masses 1,2 and 3 TeV

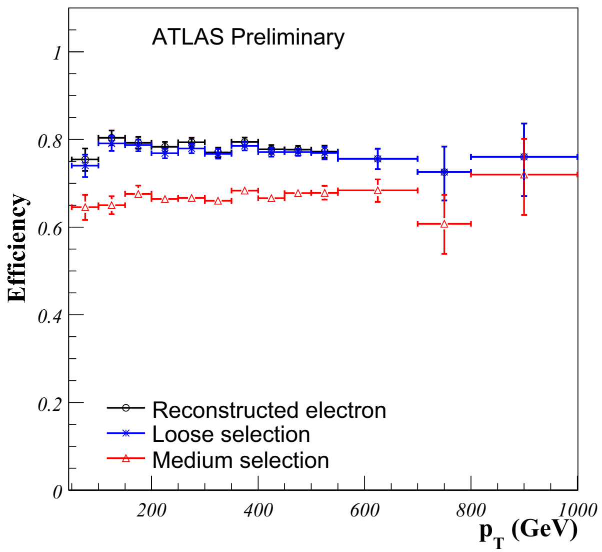
For a 1 (3) TeV mass 86% (95%) of the events have 2 electrons within $|\eta| < 2.5$. Require:

$\leq$The events passes the trigger requiring one electron with $p_T > 60$ GeV

$\leq$Two clusters matched to a track

$\leq$Two reconstructed *loose* electrons, at least one with $P_T > 65$ GeV, with opposite charge

Efficiency for signal is $\leq$42 (34)% for $m = 1(3)$ TeV

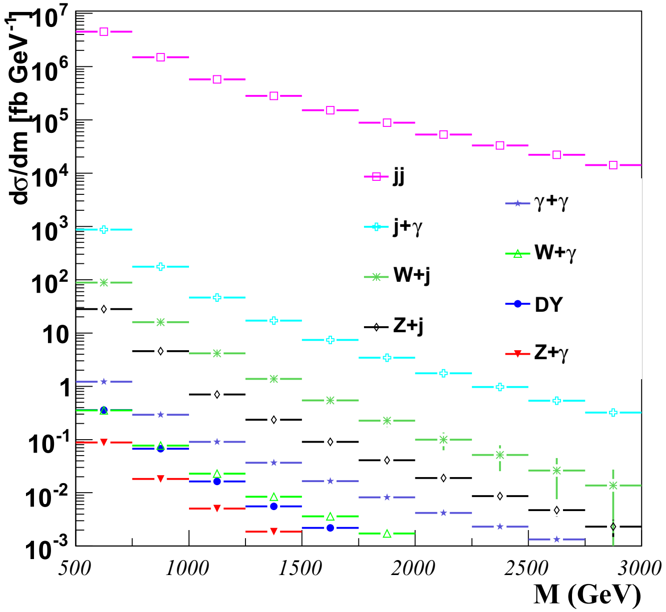


Efficiency for electron reconstruction at high p_T

Loose selection: based on hadronic leakage and selction shape variables, excellent rejection against high energy pions and wide showers

Medium selection: exploit ffine granularity of ffirst EM compartment, and apply stricter cluster-track matching. Additional rejection against $\eta^0 \to \eta\eta$

Background studies



Irreducible background is Drell-Yan

Reducible backgrounds, where jet(s) or photon(s) fake an electron in the detector

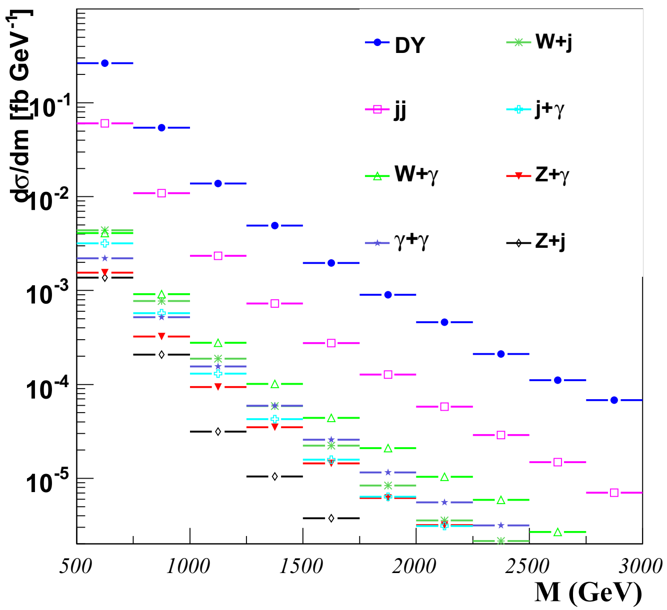
Overwhelming cross-section before identiffication and kinematic cuts

Apply to each leg rejection factor for applied loose e-id cuts:

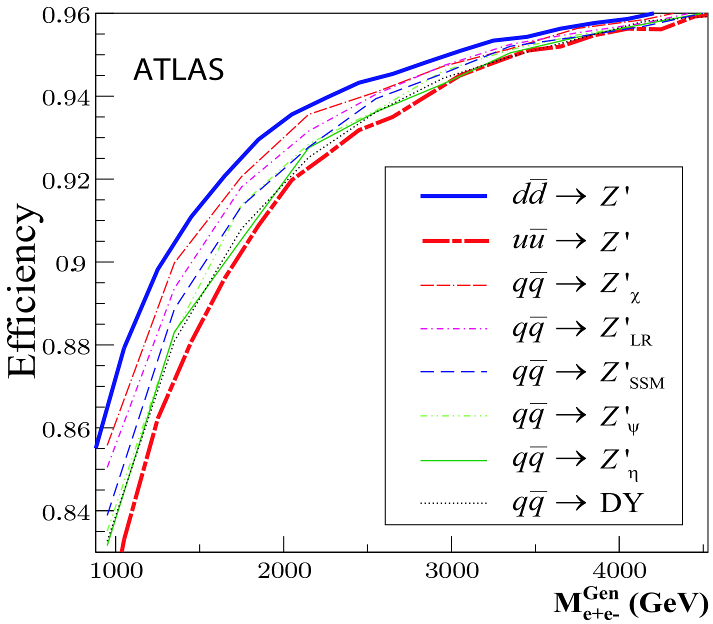
$\leq R_{e-jet} = 4 \leq 10^3 \leq R_{e-\eta} = 10$

And apply kinematic cuts

Total contribution less than 30% of irreducible DY



Signal reach

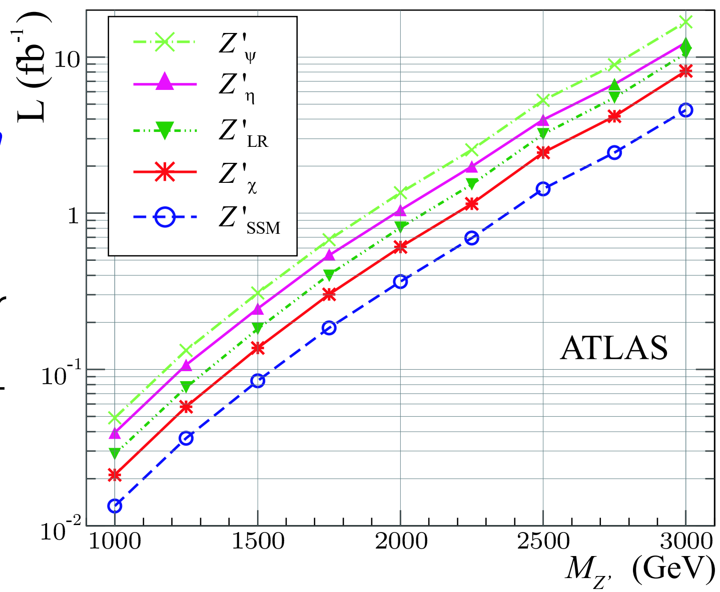


Different models have different couplings to u and d quarks

Different acceptances for kinematic cuts, to be taken into account in the evaluation of signal reach

Plot for different models luminosity needed for 5η discovery

Only statistical error. Dominating sytematic error from theoretical uncertainties on Drell-Yan cross-section: from $\leq 8.5\%$ to $\leq 14\%$.



Width and leptonic cross-section

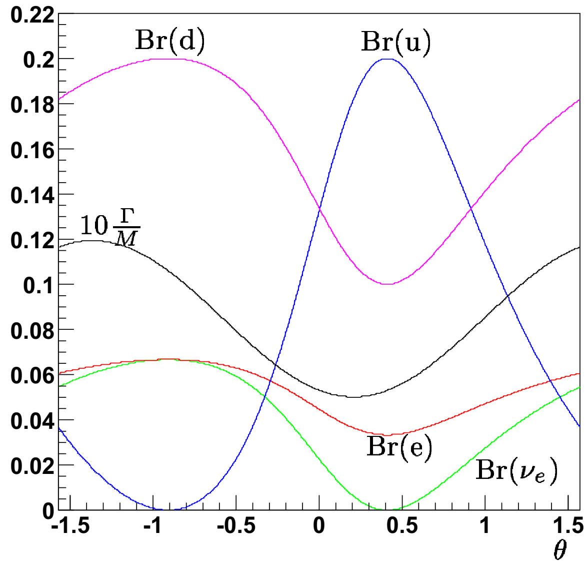
After discovery of peak, focus on variables allowing discrimination of models.

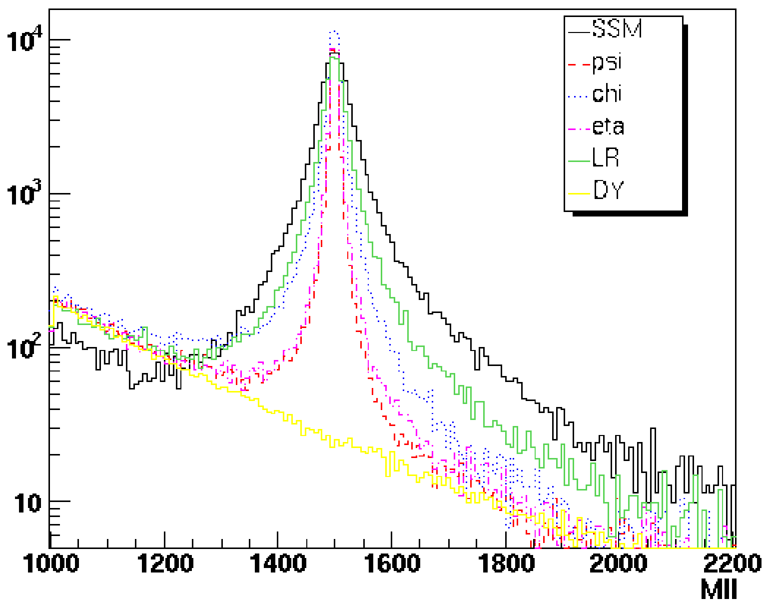
Consider partial decay widths and asymmetries

Partial decay widths

$$\Delta(Z' \to f\,f) = N_c \frac{g^2}{cos^2\eta_W} \frac{1}{48\eta}(g_V^2 + g_A^2)M$$

Width/branching ratio variations in E_6 models, assuming no exotic decays





Resonance shape for different models (arbitrary normalisation)

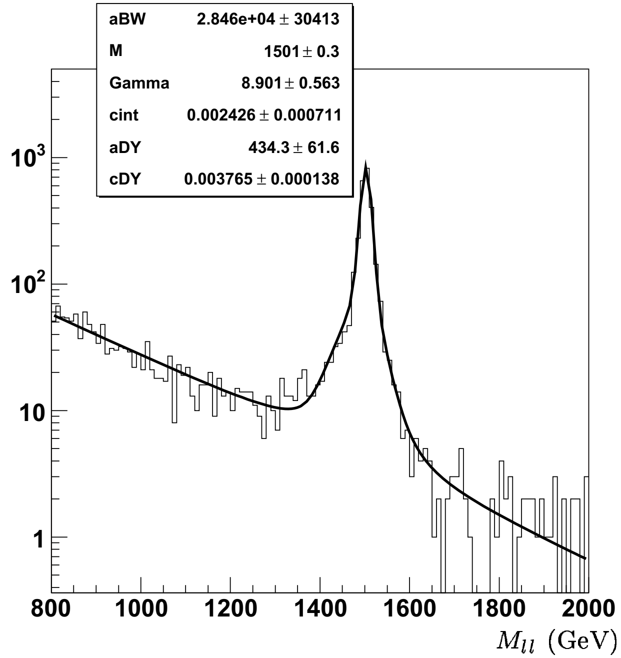
Measure $\eta_{ee} \leq \Delta$ insensitive to possible decays into exotic particles

Width and cross-section measurement

Natural width of Z' and $\eta_{ll} \leq \Delta$

		Γ/M	$\eta_{ll} \times \Gamma$(fb×GeV)
	SSM	0.030	3500
	η	0.005	180
$M = 1.5$ TeV	η	0.012	830
	η	0.006	220
	LR	0.020	1500

Natural width $\gtrless$ experimental width (≤ 0.007).



Breit-Wigner convoluted with exponential (PDF) and parametrisation of experimental resolution

Measure $\eta_{ll} \leq \Delta$ with 5-10% statistical error with 100 fb^{-1} for $M = 1.5$ TeV

Normalize to Z peak. Results will be dominated by systematic uncertainties. e.g.:

$\leq$Knowledge of detector resolution

$\leq$Acceptance estimate (model dependent)

$\leq$DY shape: PDF's, lepton linearity, higher order corrections

TeV$^{\ll 1}$ Extra Dimensions

Standard ADD model:

EW precision measurement test SM gauge fields to distances $\ll 1/$TeV $\Rightarrow$ SM fields can not propagate in "Large" ED and are localized on a brane

Variation on the model: "asymmetric" models where different ED have different compactification radii. Two types of ED:

≪"large" ED where only gravity propagates

≪"small" ($R \ll 1/$ TeV) extra dimensions where both gravity and SM fields propagate

This scheme could be pictured as a "thick" brane in side wihci SM fields propagate, immersed in the usual "large" ADD bulk

Various models, depending on which SM fields propagate in the bulk:

≪Only gauge fields: describe it today

≪Both fermion and gauge fields (UED)

General signature for models with compactified ED: regularly spaced Kaluza Klein excitations of fields propagating in the bulk

KK mass spectra and couplings given by compactification scheme and number of ED

In case of one "small" ED with radius $R_c \ll 1/M_c$:

≪Excitations equally spaced with masses:

$$M_n^2 = M_0^2 + n^2 M_c^2$$

≪Couplings equal to $\sqrt{2} \ll$ gauge couplings

Minimum excitation mass compatible with EW precision measurement: 4 TeV

Consider excitations for all SM bosons:

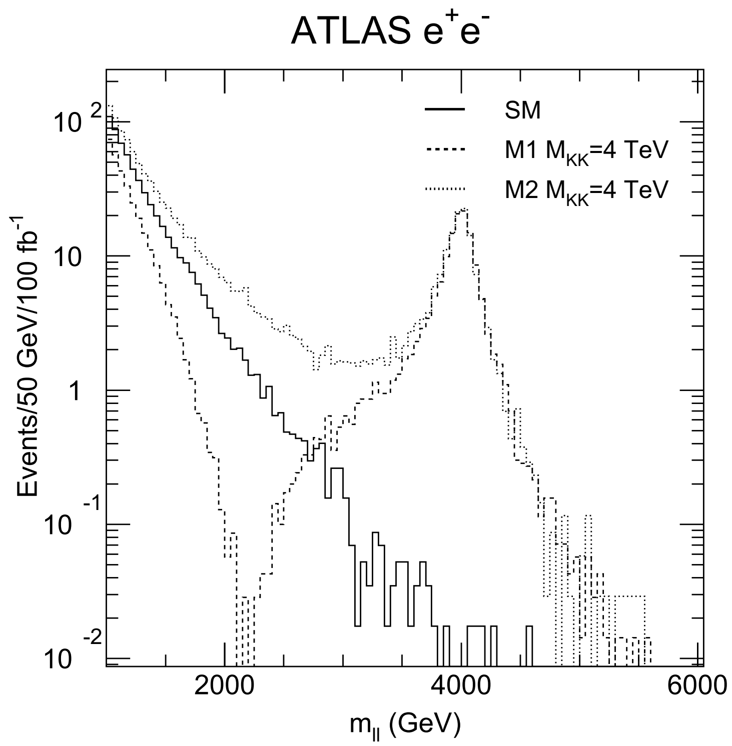
≪Z/η, discovery channel: decay into $\ell^+\ell^\times$

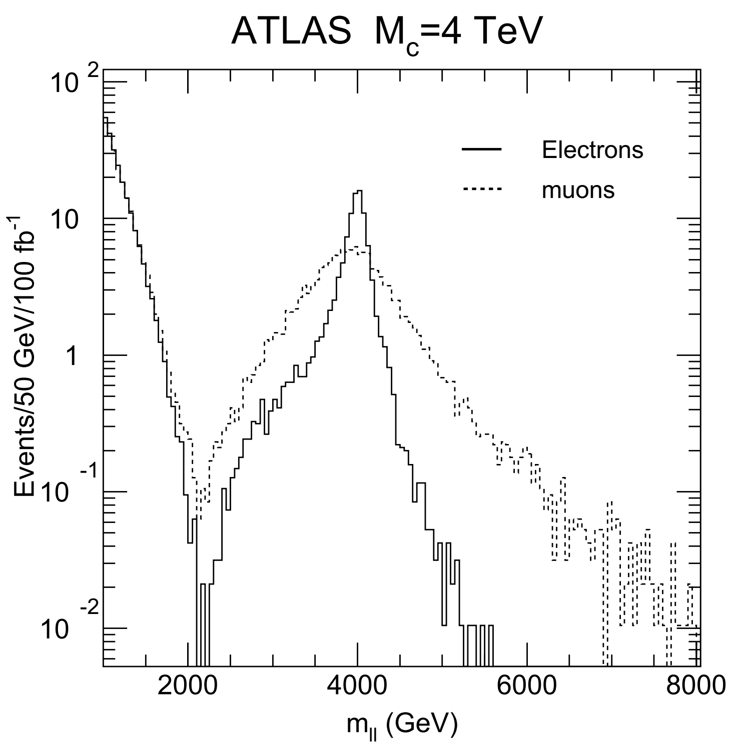
≪W, discovery channel: decay into $\ell\eta$

Old exploratory work in parametrized simulation

Minimum excitation mass considered: 4 TeV: natural width

$\ll 2 \ll \Lambda(W) \ll (M_c/100)$ GeV$\ll 200$ GeV

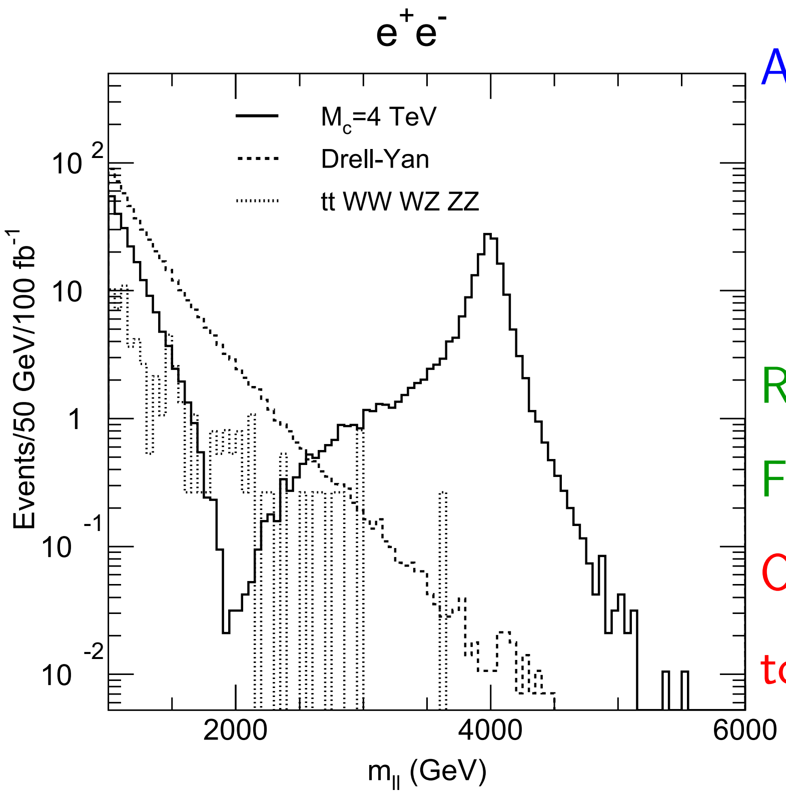




Natural width dominates for $e^+e^\times$. Detailed knowledge of electron resolution not needed as long as $\eta(E)/E$ better better than 2-3%.

Experimental width dominates for $\eta^+\eta^\times \Rightarrow$ use muons only for discovery, not for measurements

Data analysis: Z/γ



Analysis requirements:

$\leq$Two leptons with $P_t > 20$ GeV in $|\eta| < 2.5$

$\leq m_{\ell\ell} > 1$ TeV

Reducible backgrounds: $t\bar{t}$, WW, WZ, ZZ

For $m(e^+e^\times) > 1000$ GeV $\ll$60 background events

Observe characteristic depletion w.r.t Drell-Yan due to interference effects

Resonance includes excitation of both η and Z, two resonances can not be resolved

Evaluate number of events in peak as a function of mass of first excitation (M_{kk})

Require: $S/\sqrt{B} > 5$ and > 10 events in peak, summed over two lepton flavours

Reach for 100 fb$^{\times 1}$: $\ll 5.8$ TeV - Only statistical

In no case second KK peak observable

Data analysis: W

Analysis requirements:

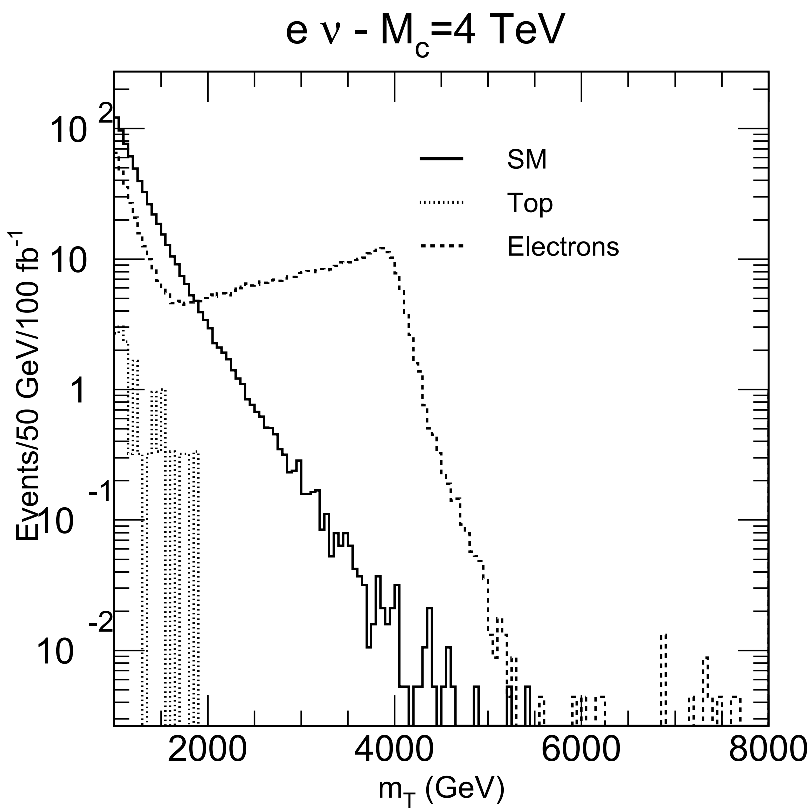
$\leq$One lepton with $P_t > 200$ GeV in $|\eta| < 2.5$

$\leq \not{E}_T > 200$ GeV

$\leq m_T(\ell\eta)) > 1$ TeV

Where $m_T = \sqrt{2p_T^{\ell} p_T^{\eta}(1 \leq \cos\Delta\eta)}$

If no new physics 500 events from offishell SM W (100 fb$^{\times 1}$)



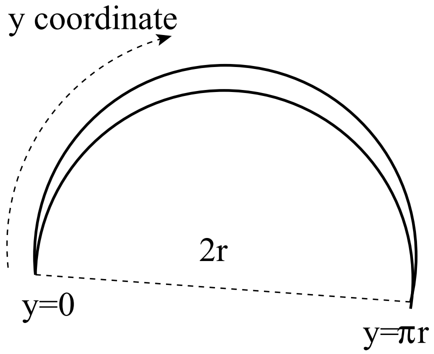
Reducible backgrounds considered: $t\bar{t}, WW, ZZ$

For $m_T(\ell\eta) > 1$ TeV $\ll$75 background events, dominated by WW and WZ

With moderate jet veto at 100 GeV, background reduced to $\ll 20$ events, but bias for study of Jacobian shape

Reach for 100 fb$^{\times 1}$: $\ll 5.8$ TeV - Only statistical

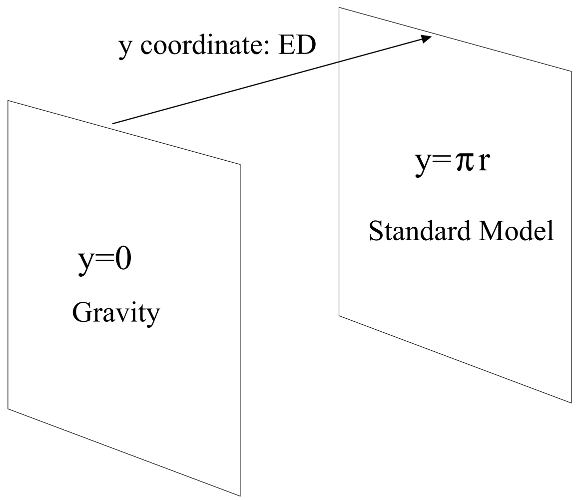
Randall-Sundrum model



One additional dimension in which gravity propagates

ED compactified on S^1/Z_2 (circle folded on itself ≪orbifold)

Two branes at extremal values of compactification:



≪Planck brane: y=0, where gravity localized

≪Tev-brane where SM fields (us) constrained

Metric for this scenario is non-factorizable:

$$ds^2 = e^{\times 2ky}\eta_{\eta\eta}dx^\eta dx^\eta \ll dy^2\,, \qquad (1)$$

Exponential term: "warp factor". Parameter k of order Planck scale governs curvature of space R_5. $R_5 = \ll 20k^2$

5D Plank scale M_5 must be larger than inverse radius of curvature $|R_5| < M_5^2$, otherwise physics dominated by quantum gravity effects

Solving Einstein's equation obtain for reduced 5-dim scale $\overline{M}_5 \ll M_5/\sqrt{8\eta}$:

$$\overline{M}_{\rm Pl}^2 = \frac{\overline{M}_5^3}{k} \tag{2}$$

The bound $|R_5| < M_5^2$ thus becomes $k/\overline{M}_{\rm Pl} \lesssim 0.1 \Rightarrow$ Very small hierarchy

The scale of all physical processes on the TeV brane described by:

$$\Lambda_\eta \ll \overline{M}_{\rm Pl} e^{\times k R_c \eta}$$

$\Lambda_\eta \ll 1$TeV then implies $kR = 10$.

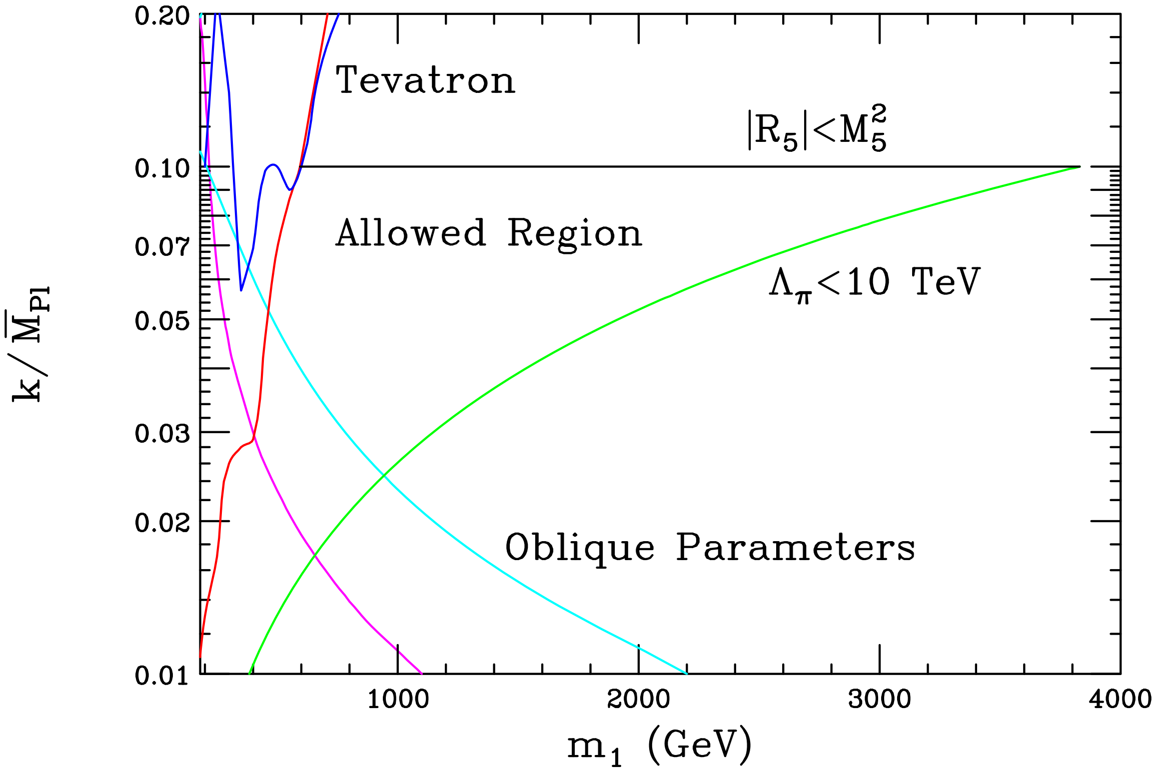
Model deffined in terms of:

$\ll \Lambda_\eta \quad \ll k/\overline{M}_{Pl}$.

By requiring:

$\Lambda_\eta < 10$ TeV (hierarchy)

closed region in $(m_1,\ \ k/\overline{M}_{Pl})$ plane, with $m_1 = 3.83\frac{k}{\overline{M}_{Pl}}\Lambda_\eta$



Randall-Sundrum phenomenology: Narrow graviton states

Masses of KK graviton obtained from Bessel expansion, replacing Fourier expansion of flat geometry. Mass m_n of excitation $G^{(n)}$ at:

$$m_n = x_n k e^{\times k\eta r_c} = x_n \frac{k}{M_{Pl}} \Lambda_\eta$$

where x_n are the roots of the first order Bessel function. $x_1 = 3.83$

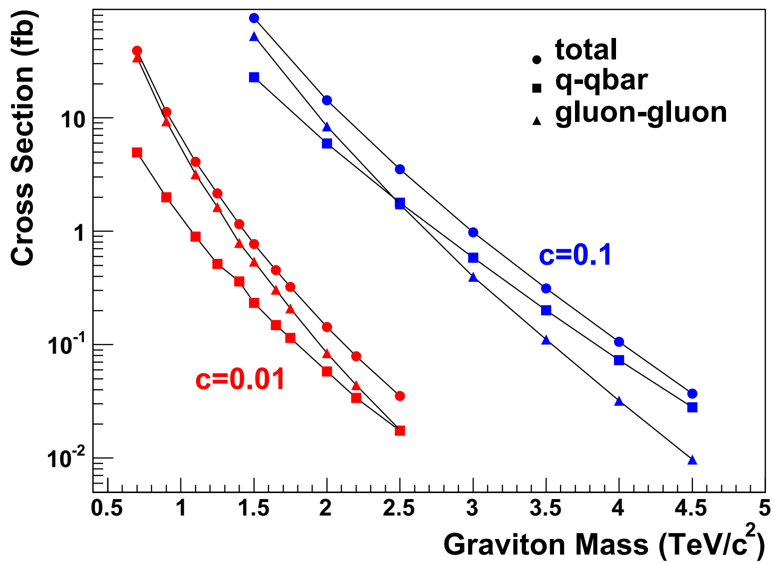
$\Rightarrow$ ≪TeV scale for mass of first excitation, accessible to LHC

Couplings of $G^{(n)}$ to SM fields $\ll 1/\Lambda_\eta$, widths and cross-sections as for Z':

≪sizable cross-section at the LHC

≪Narrow resonances

Coupling driven by factor $c = k/M_{Pl}$



$G(1) \rightarrow e^+e^{\ll}$ in CMS (full simulation)

Graviton couples to all SM particles

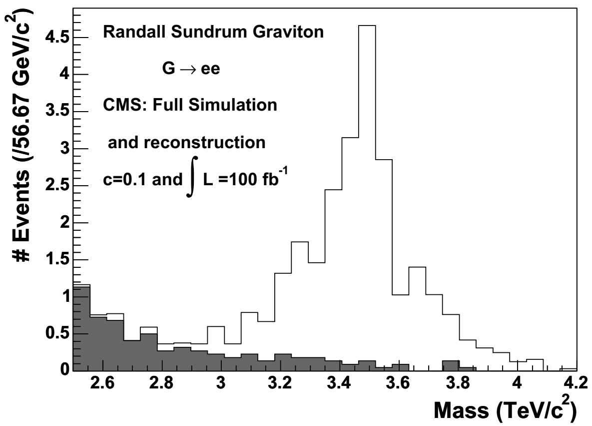
Most favourable channel $G(1) \rightarrow e^+e^{\times}$:

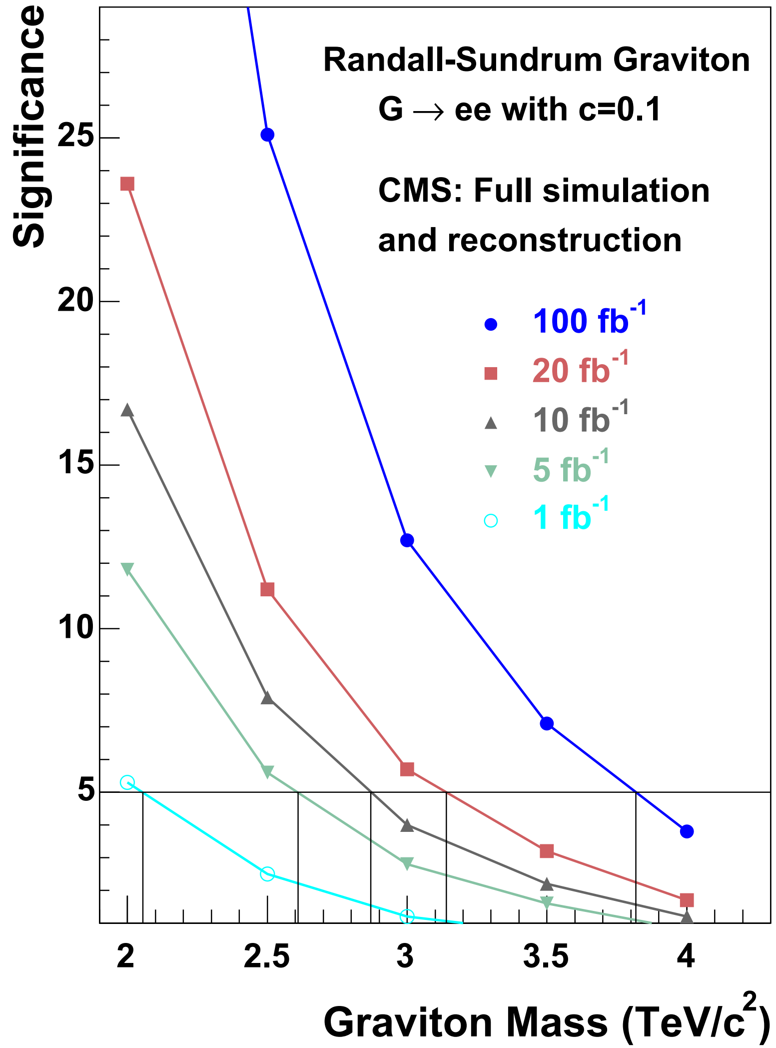
≪Optimal experimental resolution

≪Minimal background

Study achievable signiffcance as a function of mass of ffrst excited state

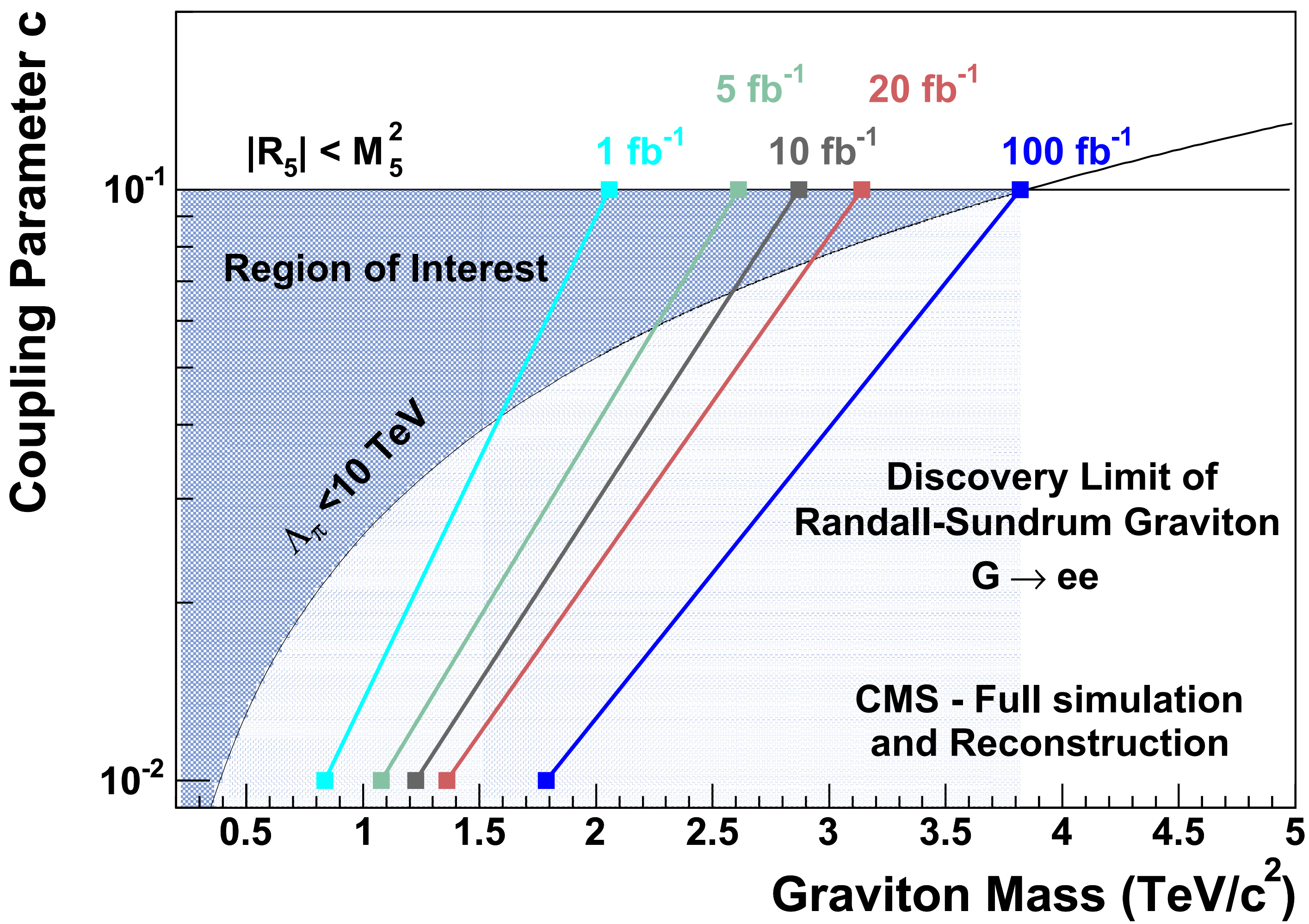
Use $c = 0.1$ and $c = 0.01$ for couplings





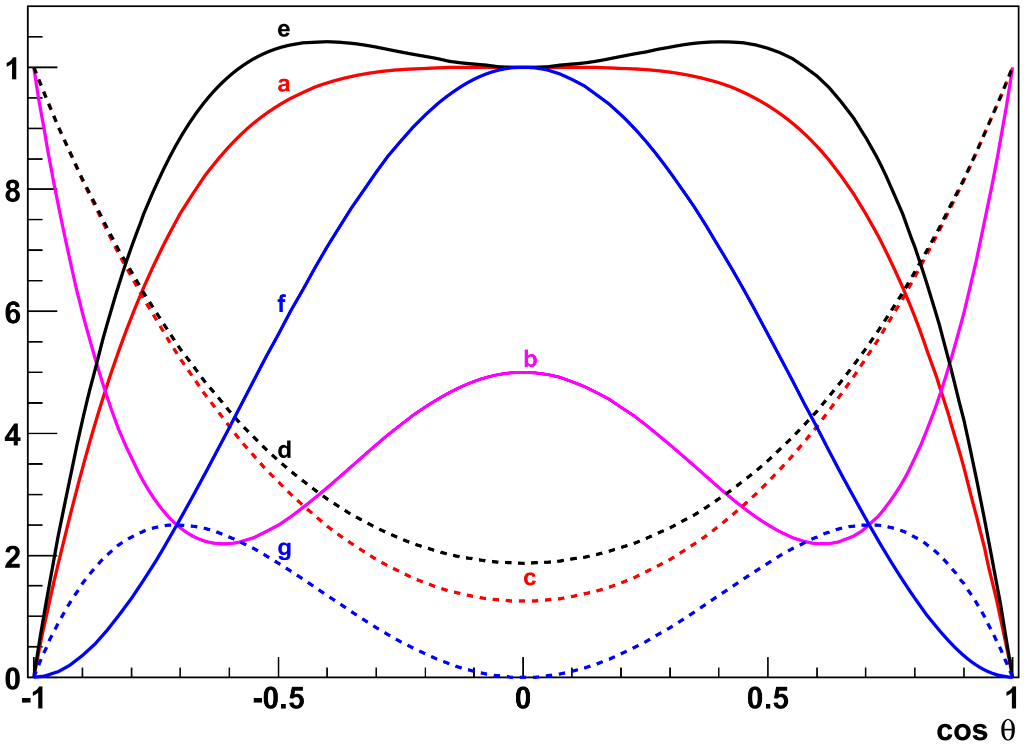
Coverage of parameter space

With one year at the LHC (high lumi) full coverage of parameter space



Spin determination of graviton resonance

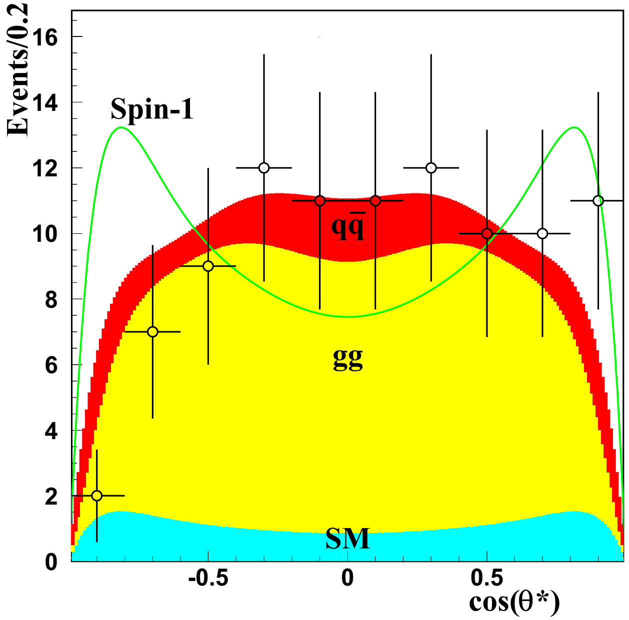
Graviton is spin-2 particle. Angular distribution of decay products depends on production mechanism, and on spin and mass of decay products



Process	Distribution	Plot
$gg \to G \to f\bar{f}$	$\sin^2\eta^*(2 \times \eta^2 \sin^2\eta^*)$	a
$q\bar{q} \to G \to f\bar{f}$	$1 + \cos^2\eta^* \times 4\eta^2 \sin^2\eta^* \cos^2\eta^*$	b
$gg \to G \to \eta\eta, gg$	$1 + 6\cos^2\eta^* + \cos^4\eta^*$	c
$q\bar{q} \to G \to \eta\eta, gg$	$1 \times \cos^4\eta^*$	a
$gg \to G \to WW, ZZ$	$1 \times \eta^2 \sin^2\eta^* + \frac{3}{16}\eta^4 \sin^4\eta^*$	d
$q\bar{q} \to G \to WW, ZZ$	$2 \times \eta^2(1 + \cos^2\eta^*) + \frac{3}{2}\eta^4 \sin^2\eta^* \cos^2\eta^*$	e
$gg \to G \to HH$	$\sin^4\eta^*$	f
$q\bar{q} \to G \to HH$	$\sin^2\eta^* \cos^2\eta^*$	g

η is v/c of decay products

Gluon fusion dominates, contribution from $q\bar{q}$ flattens distribution

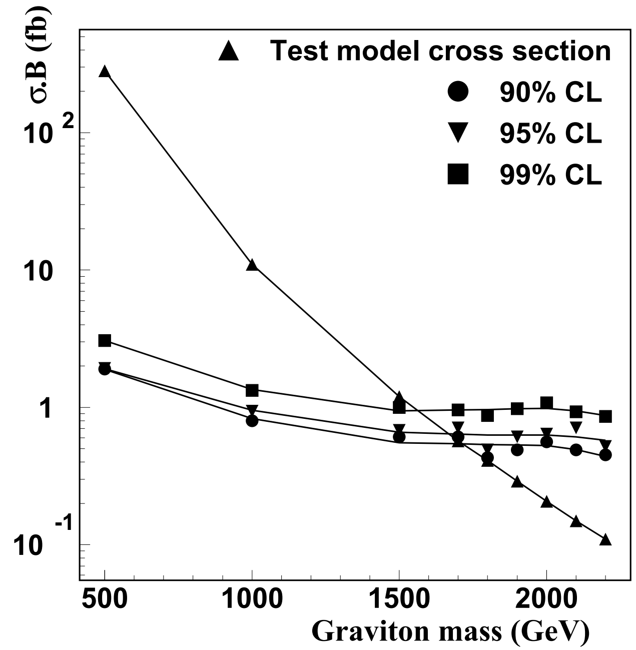


Polar angle distribution of $e^+e^\times$ after the acceptance cuts are applied

For $m_1 = 1500$ GeV and 100 fb$^{\times 1}$ can distinguish from spin 1 case

Test spin hypotheses with a likelihood technique

Spin-1 hypothesis can be ruled out at 90% CL up to $m_1 = 1720$ GeV



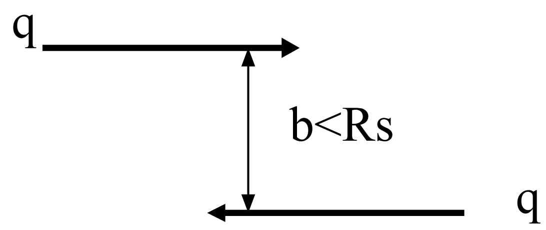
Black Holes

Geometrical semi-classical reasoning:

Possibility of black hole formation when two colliding partons have impact parameter smaller than the radius of a black hole

Consider two colliding partons with CMS energy $\sqrt{\hat{s}} = M_{\text{BH}}$

Dimensional analysis: partonic X-section for formation of black hole of mass M_{BH} is



$$\eta(\hat{s} = M_{BH}^2) \ll \eta R_s^2$$

Where R_S is Schwarzchild radius of black hole

$$R_S \ll \frac{1}{\sqrt{\eta} M_P}\left[\frac{M_{\text{BH}}}{M_P}\right]^{\frac{1}{n+1}}$$

In extra-dimension theories $M_P \ll$Tev $\Rightarrow$, for $M_{\text{BH}} \ll M_P$, $\eta \ll (\mathrm{TeV})^{\times 2} \ll 400$ pb

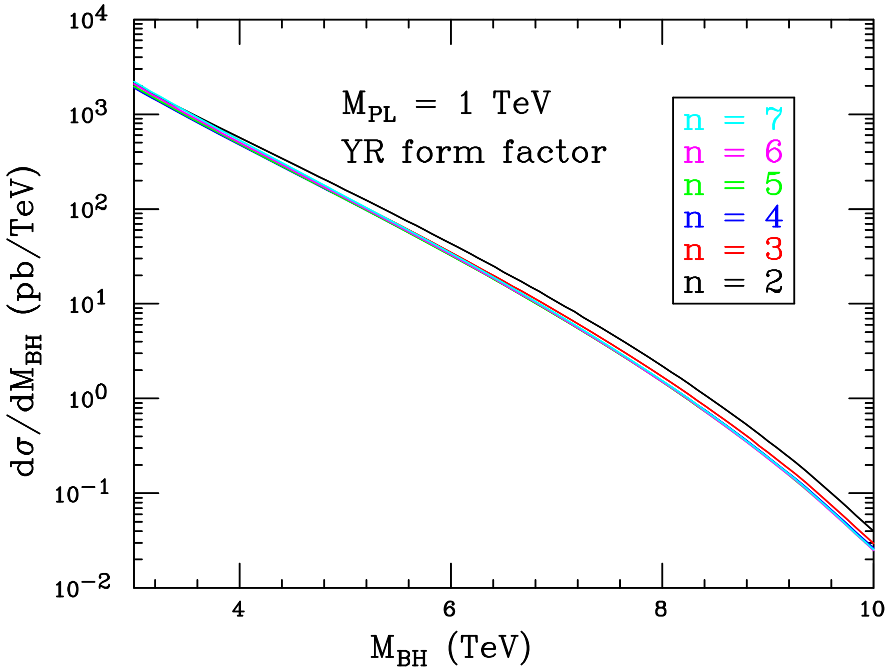
Potentially large production cross-section

Theoretical debate on geometrical formation factors. Possible big suppression

Black Hole production

Convolve the parton-level cross-section with parton distribution functions

For $n > 2$ dimensions little dependence on n because of assumed form of formation factor in CHARYBDIS generator (Cambridge group)



At high luminosity, > 1 black hole per second with $M_{BH} > 5$ TeV

Preliminary ATLAS study based on detailed simulation of different CHARYBDIS BH samples with $M_{BH} > 5$ TeV and various values of $n : 2, 4, 7$

Black Hole decay

Decay through Hawking radiation

Details of decay extremely model-dependent.

Simplifying assumptions: all partonic energy goes into BH formation, all Hawking radiation through SM Particles on the brane

Thermal radiation: black body energy spectrum

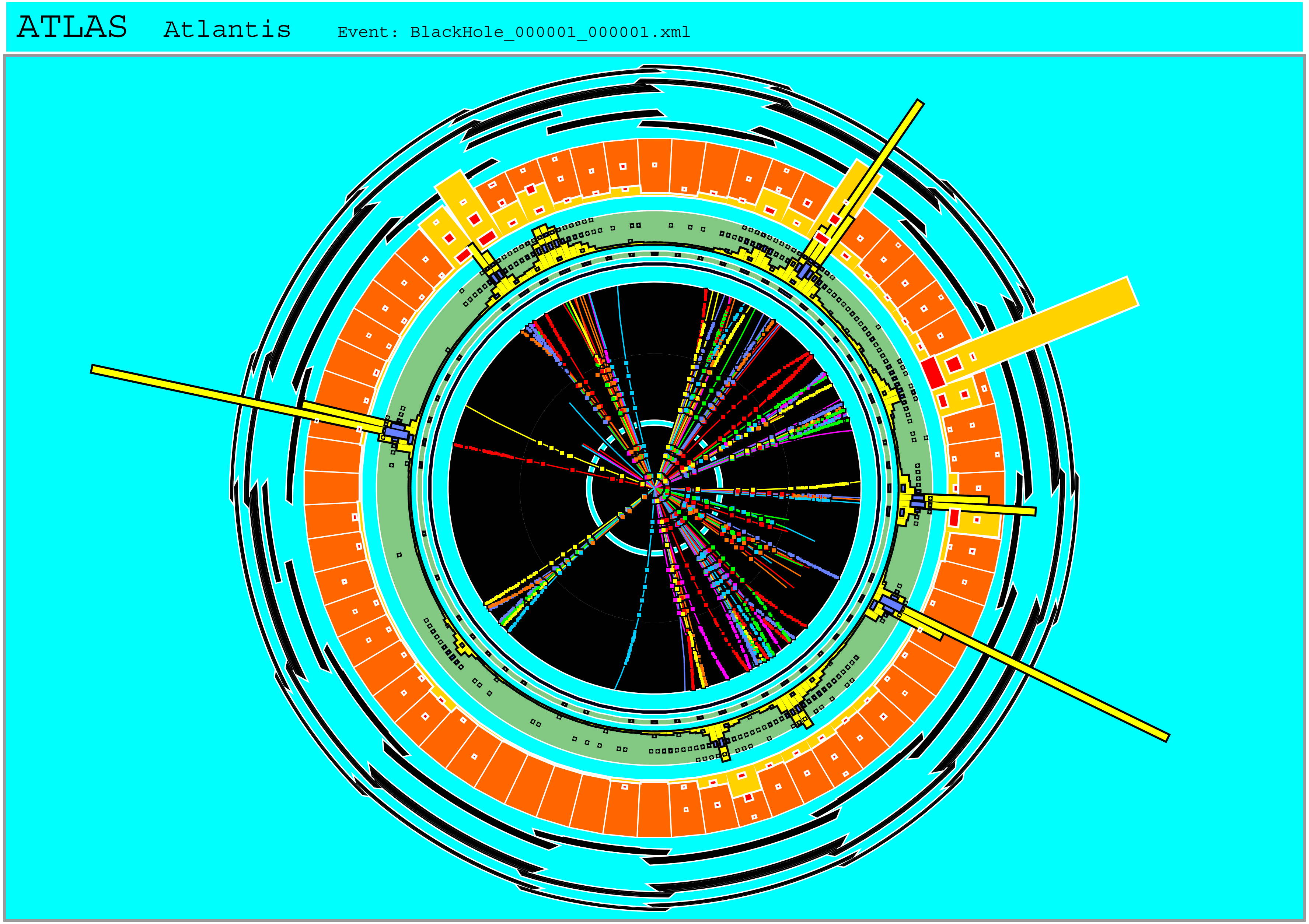
$$\frac{dN}{dE} \propto \frac{\eta E^2}{(e^{E/T_{\rm H}} \ll 1)} T_{\rm H}^{n+6} \tag{3}$$

$\ll$ applies to fermions and bosons, $T_{\rm H}$ is the Hawking temperature

$$T_{\rm H} = \frac{n+1}{4\eta r_{\rm s}} \propto M_{\rm BH}^{\times \frac{1}{n+1}} \tag{4}$$

η is *grey-body factor*: absorption factor from propagation in curved space

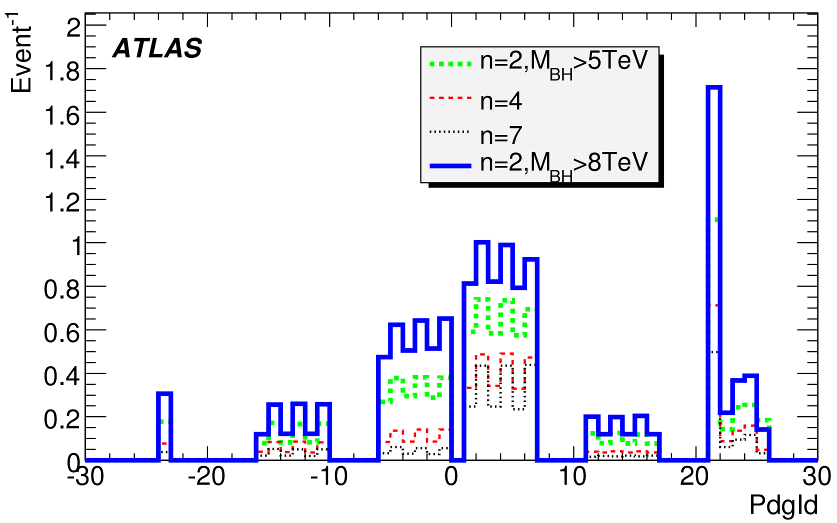
$T_{\rm H}$ increases with increasing n $\longrightarrow$ more energetic particles produced $\longrightarrow$ lower multiplicity for ffixed M_{BH}

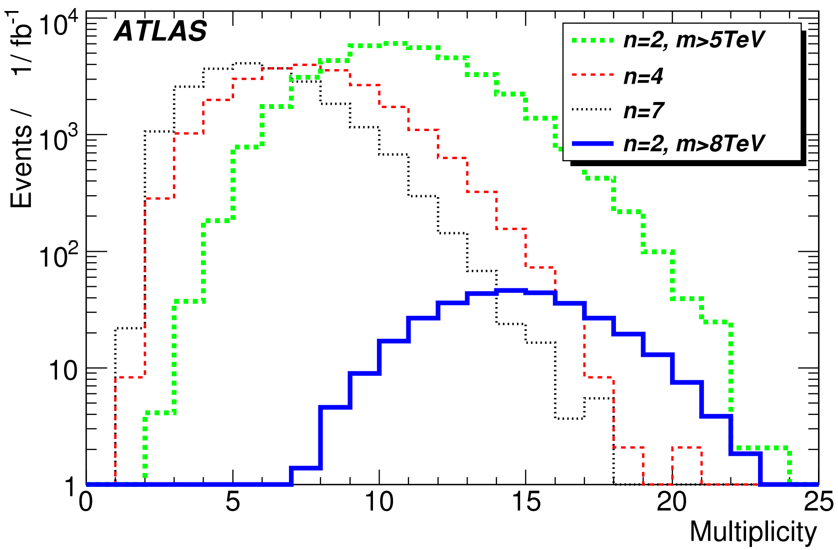

ATLAS
Atlantis
Event: BlackHole_000001_000001.xml

Event characteristics of BH decays

≪Approximately democratic decay in all types of particles, depending on the degrees of freedom (q=6, g=8), similar p_T spectrum for all types of particles

≪Large multiplicities of reconstructed objects (jets, electrons, muons, photons) in ffinal state, falling with n, as BH decays at higher temperature





$1 \le |PdgID| \le 6$: quarks, $11 \le |PdgID| \le 16$: leptons, $21 \le |PdgID| \le 25$: gauge bosons, higgs

In principle very spherical events, but shape of events strongly dependent on BH parameters

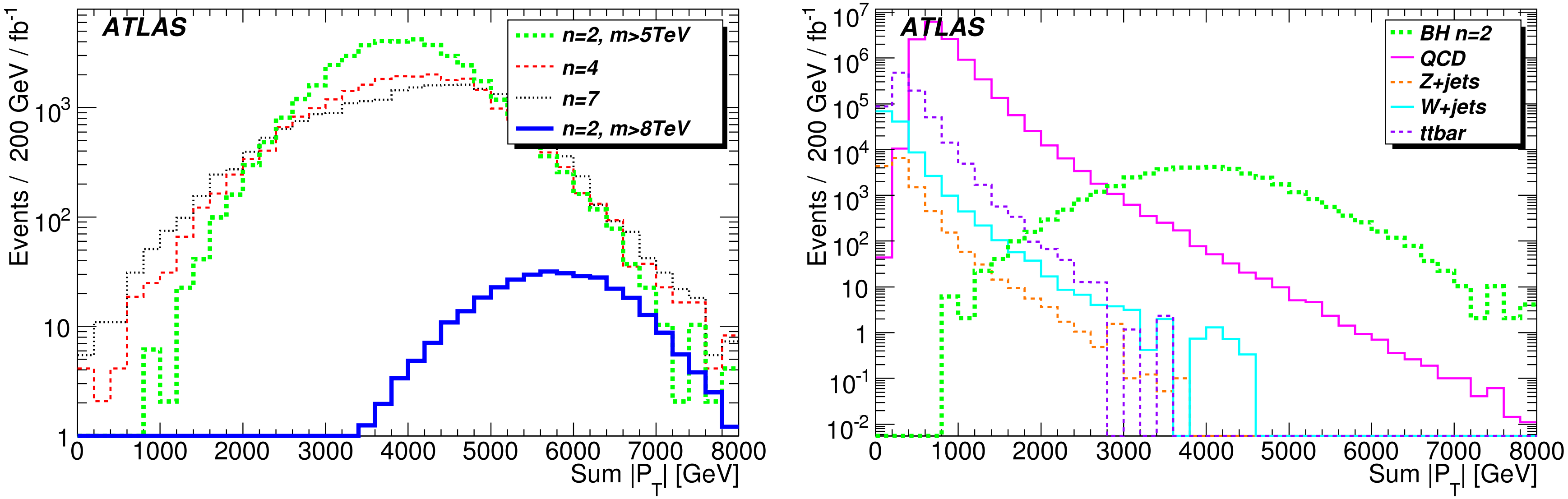
Event selection

First step is trigger. Given high mass of events, trigger request of one jet with $p_T > 400$ GeV has 99% for all generated samples

Backgrounds from QCD, $W + jets$, $Z + jets$, tt considered

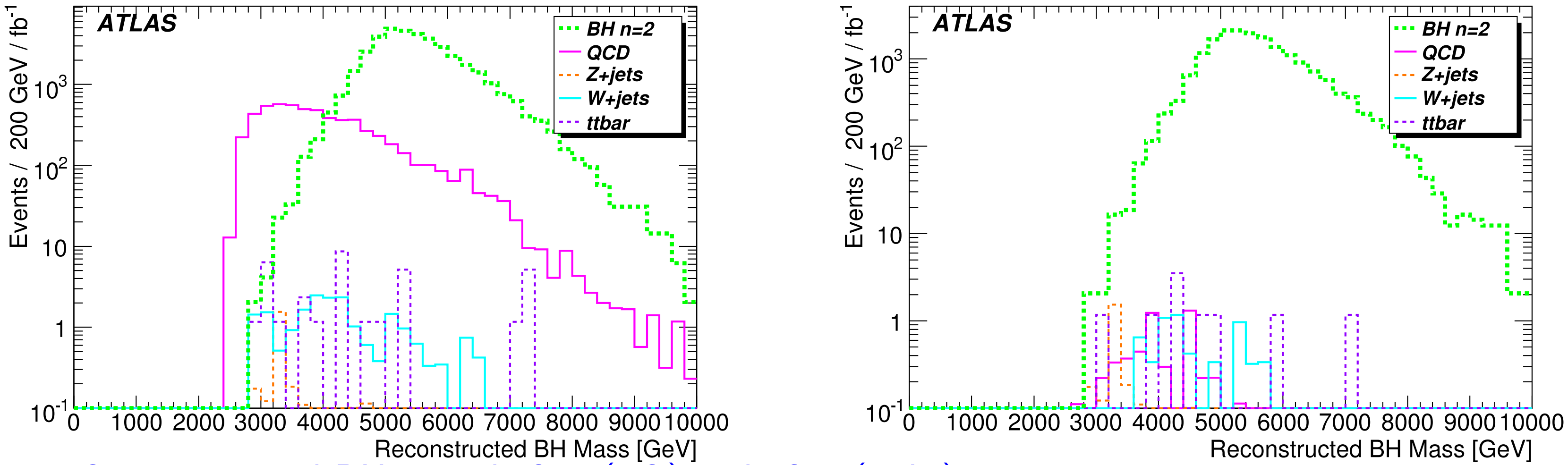
Rejection of SM background based on exploiting high mass of black holes

Use as discriminant variable $\Sigma |P_T|$, scalar sum of the P_T of objects in an event



Require $\Sigma |P_T| > 2.5$ TeV to separate signal from background

After cut on $\Sigma|P_T|$ significant QCD background. Require lepton with $P_T > 50$ GeV



Plot of reconstructed BH mass before (left) and after (right) lepton requirement

For $M_{BH} > 5$ TeV, efficiency for lepton cut $\leq 50(17)\%$ for $n = 2(7)$, Additional factor 1000 for rejection on QCD

Black holes can be discovered above the 5 TeV threshold with a few pb$^{\times 1}$ of data.

$\ll 1$ fb$^{\times 1}$ needed if production threshold is 8 TeV

Statement based on assumed correctness of the decay model and of the predicted tail of QCD at high $\Sigma|P_T|$. Needs to be substantiated by measurement with real data

Large uncertainties on acceptance from parameters of modelling of BH decay at high n

Parameter measurement

Consider the possibility of measuring the number of extra-dimensions n

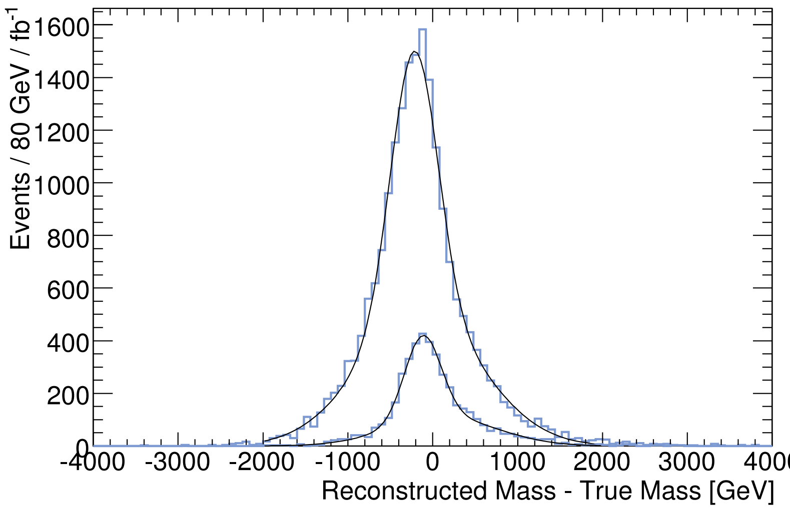
For given M_{BH} T_H depends on n

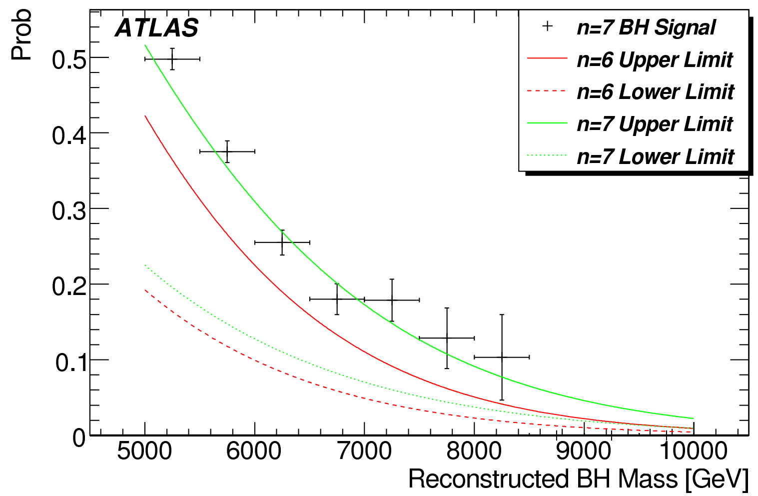
If we detect events with emissions near $M_{BH}/2$, the energy of the emission is a measure of T_H

For this measurement give up lepton requirement (bias), and ask $\Sigma|P_T| > 2.5$ TeV

Accurate mass resolution needed: require $\not{E}_T < 100$ GeV

Fit BH mass resolution with two gaussians. The width of the narrow gaussian goes from 276 to 215 GeV after $\not{E}_T$ requirement





Plot of emission probability as a function of BH shows sensitivity to n

Value of M_{Pl} needed for measurement should be measurable from production cross-section

Conclusions

Among many possible signatures for new physics concentrate on two signatures which can be discovered with early data

High mass lepton resonances as classical example

Detailed studies involving many different possible sources show good potential with the very ffirst data

In case of discovery necessary to measure couplings of Z' to understand underlying physics

Extra Dimension theories offer an attractive way of solving the hierarchy problem base don the space-time geometry of space

Among the most striking possibilities is the production of micro black holes

A detailed experimental study shows that few $pb^{\times 1}$ could be sufficient for the discovery of black holes

Backup

Kaluza-Klein towers

Features of compactified extra-dimensions, due to periodicity condition of fields in extra dimension: $\eta(y + 2n\eta R) = \eta(y)$ where y is extra dimension

Spacing of Kaluza-Klein states can be understood with heuristic considerations

Standing waves in box:

$\ll$Wavelengths η such as the size $L \ll 2\eta R$ of the box is a multiple of η

$\ll$The wave number k satisfies $k \ll 2\eta/\eta = n/R$ with n integer

$\ll$Energy is quantized $E = hk$

Compact dimensions can be assimilated to a finite box.

$\ll$Expect in compactified dimension particles with mass spectrum characteristic of standing waves, i.e. quantized in units of $1/R$

These oscillations are called Kaluza-Klein modes

Case of a single ED

Standard relativistic formula $E^2 = \mathbf{p}^2 + m_0^2$ reads:

$$E^2 = \mathbf{p}^2 + p_5^2 + m_0^2$$

Where p_5 is momentum in fifth dimension, quantised as $p_5 = hk_5 = nh/R$

Thus in center of mass $(\mathbf{p} = 0)$ one obtains the following energy spectrum:

$$E^2 = \left[m_0^2 + \frac{n^2 h^2}{R^2} \right]$$

A 5-dimensions field is identified in 4 dimensions to a tower of particles regularly spaced in mass squared, the gap being the inverse of the compact dimension size

$\Rightarrow$ For each field propagating in the bulk, with mass m_0, if $m_0 \ll 1/R$ in the theory will appear an infinite sequence of states with masses $1/R$, $2/R$, $3/R$.....

Study whether, for the different implementations of the model these KK states can be detected at the LHC