

Extra Dimensions at the LHC

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Introduction

Hierarchy problem: large separation between:

- weak interaction scale: W mass ~ 100 GeV
- gravitation scale: Plank mass $M_{pl} \equiv (G_F)^{-1/2} \sim 10^{19}$ GeV

Possible approach: exploit geometry of space-time:

Postulate that we live in 3-d "brane" embedded in higher dimensional space

Hierarchy is generated by geometry of extra dimensions (ED)

Possibility that matter and non-gravitational forces confined on 3-brane and gravity propagates through higher dimensional volume ("bulk")

Since we do not observe deviation from Newton's force at a distance \lesssim mm

extra-dimensions must be compactified with radius $R \lesssim$ mm

Number of perceived dimensions depends on whether observer can resolve compactification radius R

Two ways of establishing hierarchy through extra-dimension:

- Arkhani Ahmed, Dimopoulos, Dvali (ADD):

Trough "Large" flat extra-dimensions, compactified on torus.

- Gravitational strength diluted by volume of n extra dimensions: $M_P^2 = M_D^{n+2} R^n$ with M_D scale of gravity in the bulk
- To account for hierarchy: $M_D \sim 1 \text{ TeV} \Rightarrow R \gg 1/\text{TeV}$ "Large" ED
- EW measurements test SM gauge fields to distances $\sim 1/\text{TeV}$
 \Rightarrow SM fields localized on a brane

- Randall Sundrum (RS):

Through a curved geometry of the extra-dimension

- Only one extra dimension
- hierarchy from exponential warp factor in non factorizable geometry: $\Lambda_\pi = M_P e^{-k\pi r_c}$

In both cases, the presence of compactified dimensions gives rise to a Kaluza-Klein tower of excited states for the gravitons: Many striking signatures predicted at Colliders by these models

ED theories have emerged after design of detectors completed \Rightarrow ideal way of verifying robustness of detector for unforeseen signatures

Main phenomenologies under study at the LHC:

- Large Extra Dimensions (ADD): only gravity in bulk
 - KK Graviton Direct Production $\Rightarrow \cancel{E}_T$ signature
 - KK Graviton Virtual Exchange \Rightarrow Drell-Yan
 - TeV^{-1} Extra Dimensions: also gauge fields in bulk
 - KK Gauge Bosons \rightarrow multi-TeV resonances
 - Different α_S running
 - Universal Extra Dimensions: all SM fields in bulk
 - Through radiative corrections, spectrum of KK resonances: SUSY-like phenomenology
 - semi-stable KK resonances of quarks
 - Randall-Sundrum Model
 - KK Graviton \rightarrow TeV resonances
 - Radion \rightarrow Higgs-like signatures
 - Black Hole production
-

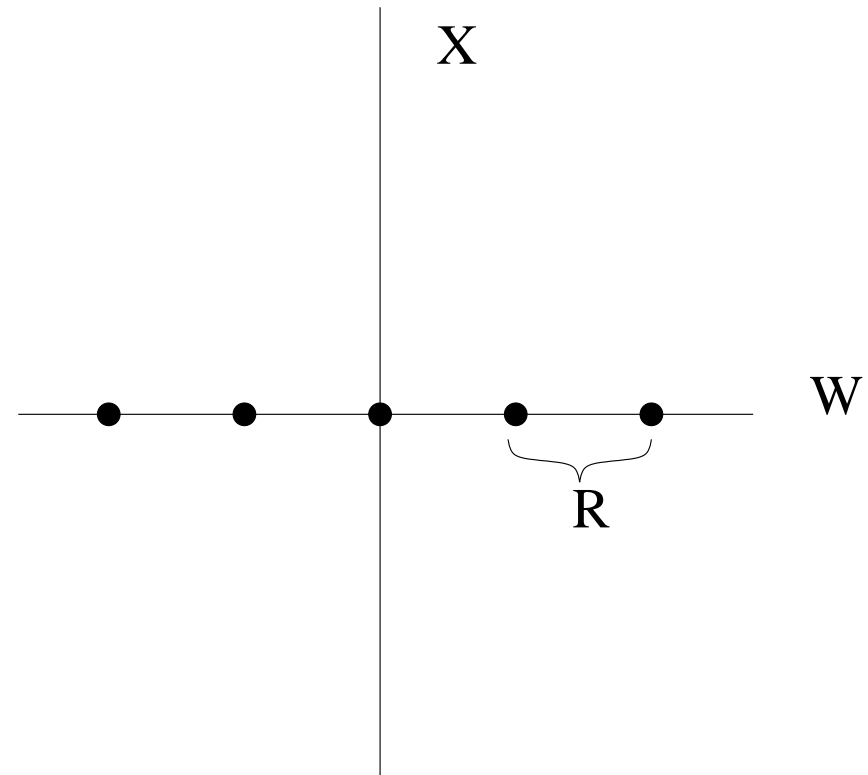
ADD: Lowering the scale of gravity

Consider single ED, compactified with periodicity R

Space variables are x, y, z and w .

For a field ϕ propagating in ED,
 $\phi(w) = \phi(w + R)$

A point mass at $w = 0$ will appear as a sequence of masses with spacing R along w



Calculate the gravitational force F felt by a unit mass at a distance r from the origin

Use of Gauss' law in n dimensions which can be written as:

$$\int F da = S_n G_n M_{enc}$$

Where S_n is the surface area of a unit n -sphere, M_{enc} is the mass enclosed in the Gaussian volume and G_n is the n -dimensional Newton's constant

Surface area of unit sphere:

$$S_n = \frac{2\pi^{n/2}}{\Gamma\left(\frac{n}{2}\right)}$$

$$S_3 = 4\pi \quad S_4 = 2\pi^2$$

Γ is gamma function:

$$\Gamma(n-1) = (n-1)\Gamma(n-2)$$

$$\Gamma(1) = 1 \quad \Gamma\left(\frac{1}{2}\right) = \sqrt{\pi}$$

$$\int F da = S_n G_n M_{enc}$$

Case 1: $r \ll R \Rightarrow$ only the mass at $W = 0$ contributes to the field

Using the fact that $F \equiv F(r)$, and $\int da = r^{n-1} S_n$

$$3 \text{ dimensions: } \int da = 4\pi r^2 \Rightarrow F = G_3 \frac{M}{r^2}$$

\Rightarrow Recover Newton's law

$$4 \text{ dimensions: } \int da = 2\pi^2 r^2 \rightarrow F = G_4 \frac{M}{r^3}$$

The form of Newton's law is modified at short distances

Short-distance experiments can in principle verify this

Case 2: $r \gg R$: mass source appears as a wire with uniform mass density M/R

Cylindrical geometry, for calculating field at distance r from the wire consider a 4-d cylinder with side length L and end caps composed of 3-d spheres of radius r .

In 4-d: $\int da = 4\pi r^2 L$, $S_4 = 2\pi^2$, $M_{enc} = M(L/R)$. Substituting into Gauss theorem:

$$F = G_4 M \frac{2\pi^2}{4\pi} \frac{1}{r^2 R}$$

At large distances we recover the $1/r^2$ dependence

For n space dimensions: $\int da = 4\pi r^2 L^{n-3}$, $M_{enc} = M(L/R)^{(n-3)}$

Identifying the n -dimensional formula to Newton's law with $G_N \equiv G_3$:

$$G_N = \frac{S_n}{4\pi} \frac{G_n}{V_{n-3}}$$

Where $V_{(n-3)} = R^{n-3}$ is the volume of the $(n-3)$ -dimensional compactified space

The strength of the gravitational interaction as felt at long distance (G_N) is equal to the strength in n dimension diluted by the extra dimension volume

Define $\delta \equiv n - 3$ of previous derivation, number of extra-dimensions

Define the characterisitc mass scales: $M_{pl} = (G_N)^{-1/2} \sim 10^{19}$ and

$$\hat{M}_D^{\delta+2} = \frac{G_\delta^{-1}}{S_{3+\delta}}$$

We obtain the reduction formula:

$$M_{pl}^2 = 8\pi R^\delta M_D^{2+\delta}$$

Assume now $M_D \sim 1$ TeV: solve hierarchy problem

$$R \sim 10^{32/\delta+3} \text{ Gev}^{-1} \Rightarrow R \sim 10^{32/\delta-16} \text{ mm}$$

$\delta = 1$ corresponds to astronomical distances: excluded

$\delta = 2$ at the limit of present tests of Newton's law

δ	R (mm)
1	10^{16}
2	1
3	5×10^{-6}
4	10^{-8}
5	10^{-10}

Experimental tests of Newton's law

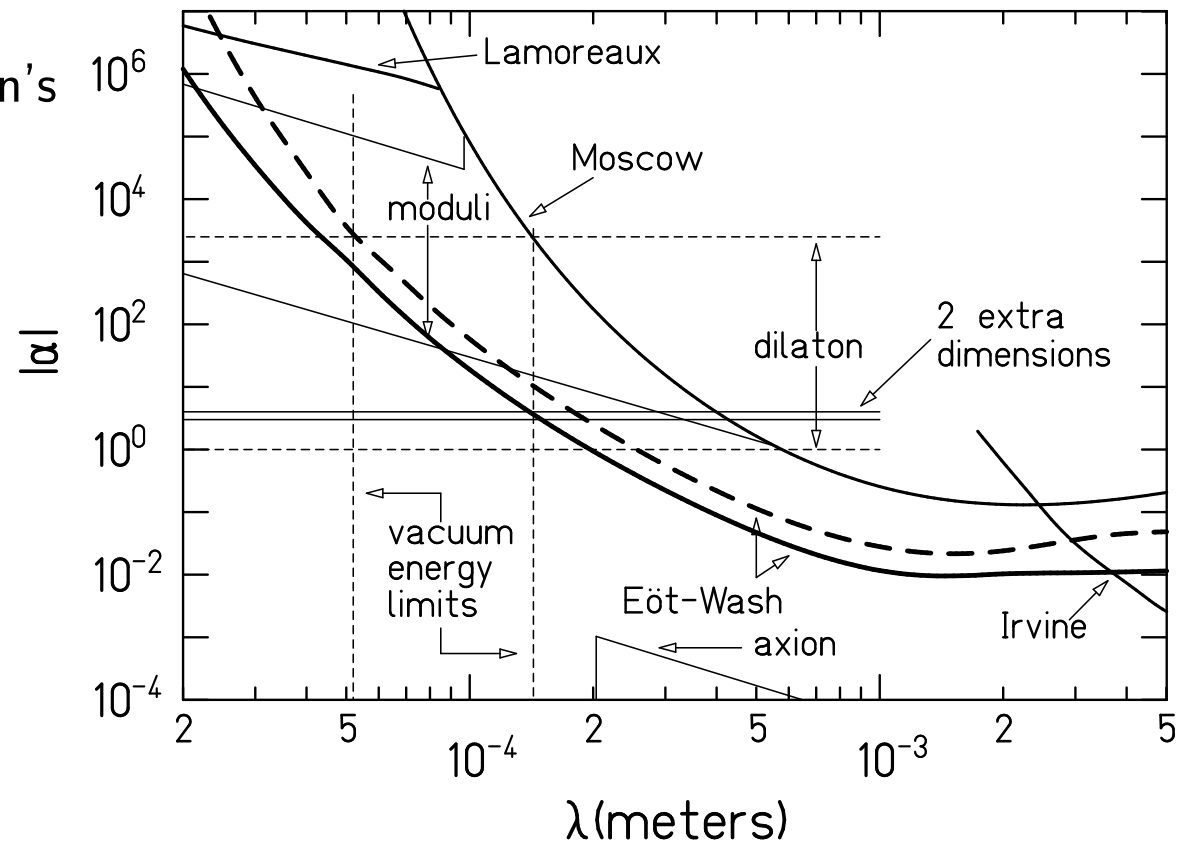
Cavendish-type experiments using torsion pendulum

Parametrize the deviation from Newton's potential with an exponential law

$$V(r) = -\frac{1}{M_{\text{Pl}}^2} \frac{m_1 m_2}{r} (1 + \alpha e^{-r/\lambda}) .$$

For ED compactified on torus:

$$V(r) = -\sim \frac{G_N M}{r} (1 + 2n e^{-r/R_c})$$



$\alpha = 4$ for 2 ED on torus $\Rightarrow R_c < 0.19 \text{ mm}$

Kaluza-Klein towers

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

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

Standing waves in box:

- Wavelengths λ such as the size $L \equiv 2\pi R$ of the box is a multiple of λ
- The wave number k satisfies $k \equiv 2\pi/\lambda = n/R$ with n integer
- Energy is quantized $E = \hbar k$

Compact dimensions can be assimilated to a finite box.

- 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

⇒ 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 $1/R, 2/R, 3/R, \dots$

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

ADD phenomenology

Two parameters defining the model: number of ED δ , compactification scale M_D

ED compactified with radius R_c connected to δ and M_D by reduction formula

$$M_{Pl}^2 = 8\pi R_c^\delta M_D^{2+\delta}$$

For $M_D \sim \text{TeV}$, Extra Dimensions "Large" $\text{mm} \lesssim R_c \lesssim \text{fm}$ for δ from 2 to 6

EW+strong forces tested down to 10^{-15} mm: SM fields confined on a 3-brane \Rightarrow only gravity probes existence of Extra Dimensions

Gravity propagates in bulk: KK tower of spin-2 graviton fields

- Equally spaced masses with $m_{\vec{n}} = \sqrt{\vec{n}^2}/R_c$, where $\vec{n} = (n_1, n_2, \dots, n_\delta)$ labels the KK excitation level
- Coupling to the Standard Model with universal strength M_{Pl}^{-1}

Two classes of possible collider signatures: real emission of KK gravitons, virtual graviton exchange

Direct graviton production

Graviton coupling strength $\sim 1/M_p^2$, but large number of accessible KK modes

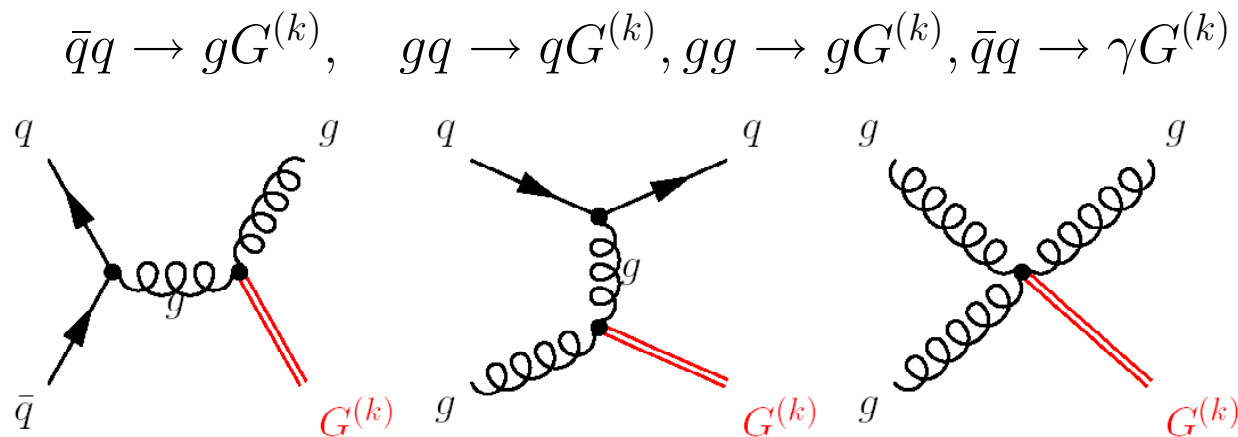
Spacing of modes $1/R_c$, for $\delta = 2, M_D = 1 \text{ TeV}, \Delta m_{KK} \ll eV$

In collider process with energy E , $(ER_c)^\delta$ massive KK modes accessible: For $\delta = 2$ and $E = 1 \text{ TeV}$ have 10^{30} modes

Using the reduction formula, sum over all modes exactly cancels $\sim 1/M_{pl}$ dependence

$$\sigma_{KK} \sim \frac{1}{M_{Pl}^2} (\sqrt{s} R_c)^\delta \sim \frac{1}{M_D^2} \left(\frac{\sqrt{s}}{M_D} \right)^\delta .$$

\Rightarrow Sizable cross-section for processes:



Direct graviton production analysis (ATLAS)

Directly produced $G^{(k)}$ interacts weakly with ordinary matter and goes undetected

Signature is large \cancel{E}_T from undetected graviton + a high P_T jet or photon

Single jet analysis requiring:

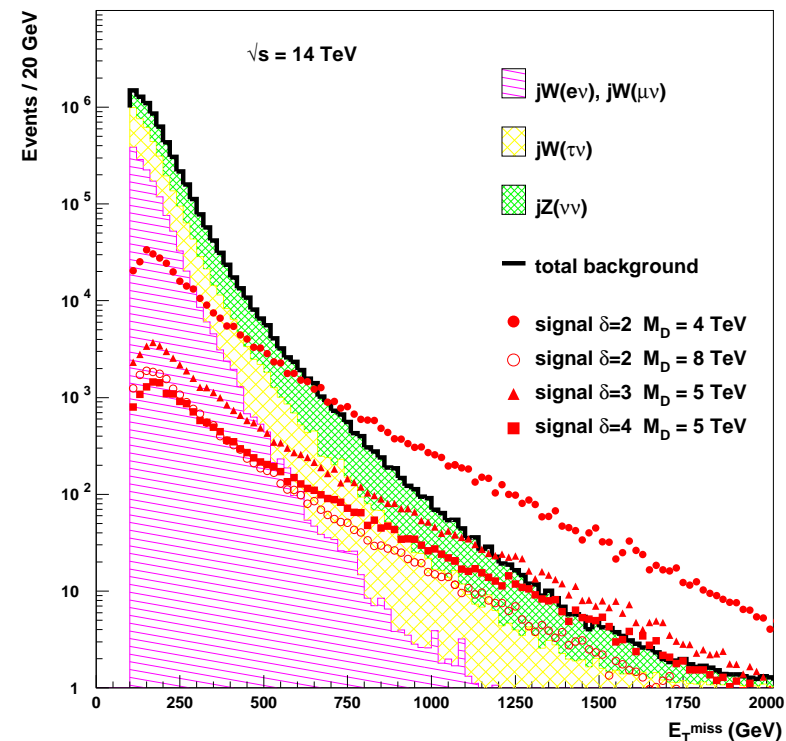
- $E_T^{jet} > 1 \text{ TeV}$, $|\eta_{jet}| < 2.5$
- Veto leptons
- Veto $\tau \rightarrow \text{hadrons}$

Signal emerges from background at

high \cancel{E}_T

Dominant SM contribution is

$Z \rightarrow \nu\nu + 1 \text{ jet}$



Apply standard cut at $\cancel{E}_T > 1 \text{ TeV}$ to evaluate discovery potential

Effective low-energy theory: valid up to M_D . Truncate cross-section when $\hat{s} > M_D^2$

Sensitivity evaluation

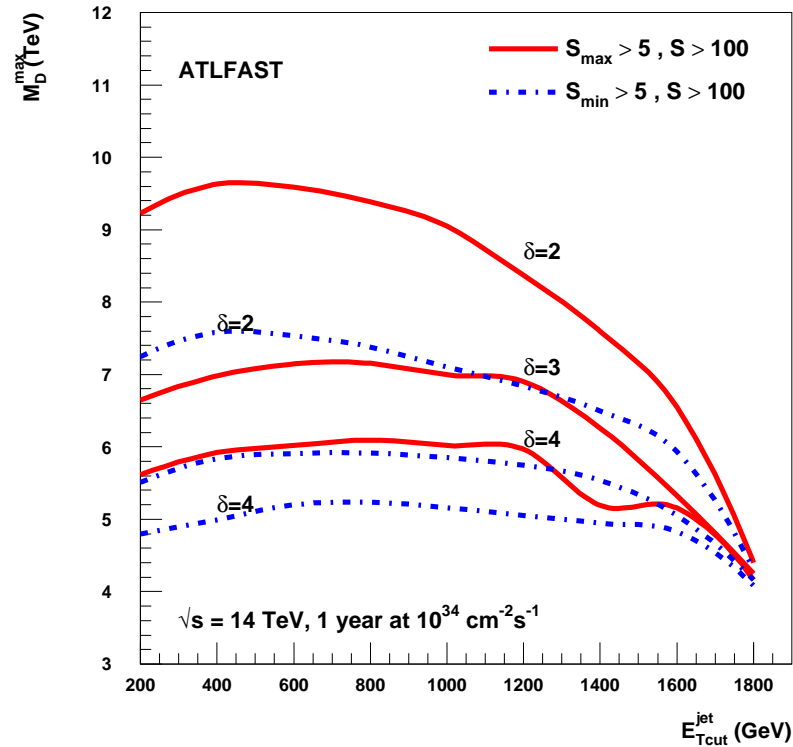
Significance for jG production

as a function of E_T^{jet} cut

$$S_{max} = S/\sqrt{B}$$

$$S_{min} = S/\sqrt{\alpha B} \text{ with } \alpha \sim 7, \text{ accounts}$$

for the fact that the background calibration sample $Z \rightarrow \ell\ell$ is smaller than the dominant $Z \rightarrow \nu\nu$ background.



Reach in M_D : $S_{max} > 5$, ≥ 100 signal events, $E_T^{jet} > 1$ TeV

δ	M_D^{max} (TeV) 100 fb^{-1}	M_D^{max} (TeV) 100 fb^{-1}	M_d^{min} (TeV)
2	7.7	9.1	~ 4
3	6.2	7.0	~ 4.5
4	5.2	6.0	~ 5

M_d^{min} is M_d below which analysis results not reliable, because high-scale physics affects results

Measurement of model parameters

Try to measure M_D and δ from the observed \cancel{E}_T distribution

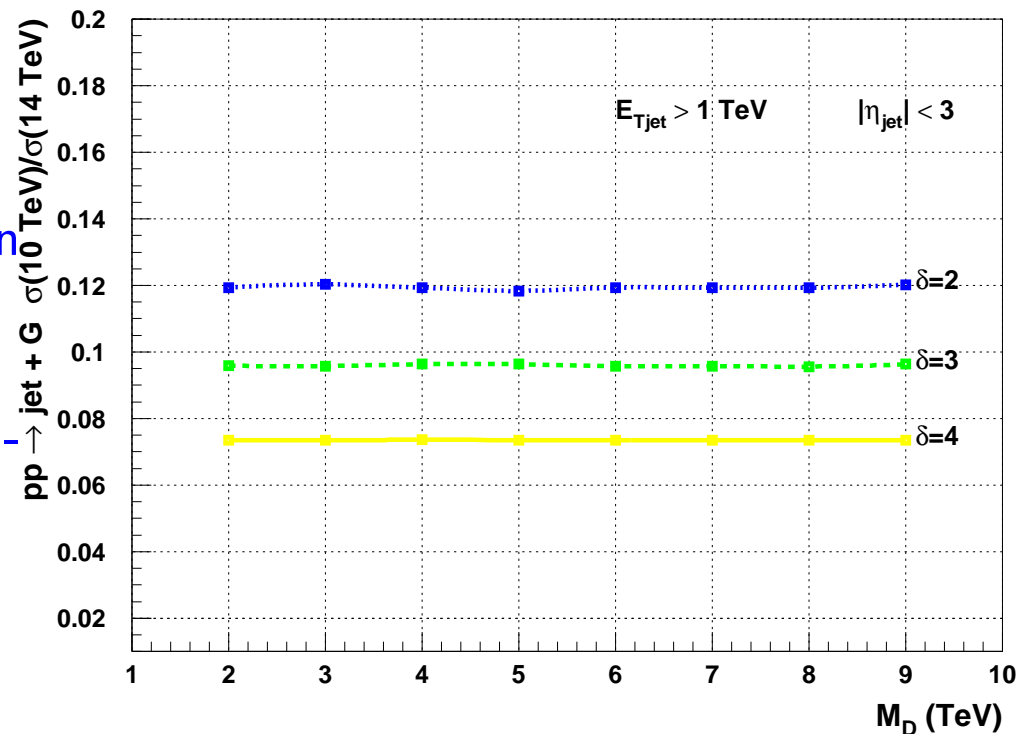
Very difficult to disentangle two effects: signal for $\delta = 2, M_D = 6$ very similar to the one for $\delta = 2, M_D = 5$

Exploit variation of cross-section with LHC energy

Kinematic limit on partonic subprocess

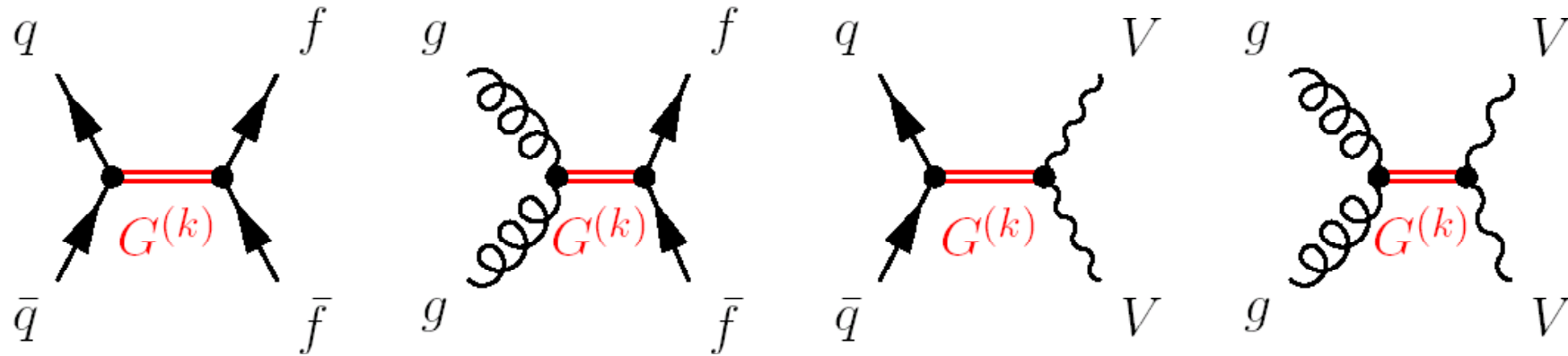
\Rightarrow limit on largest value of emitted graviton mass

Little dependence on M_D , strong dependence on δ



Virtual graviton exchange

Exchange of a virtual gravitons alters the cross section for particle pair production



Most promising channels $pp \rightarrow G^* \rightarrow \ell^+ \ell^-$, $pp \rightarrow G^* \rightarrow \gamma\gamma$

Interference with SM: effect parametrized in terms of $\eta = \frac{F}{M_s^4}$

$$\frac{d\sigma_\eta}{dM d\cos\theta^*} = \frac{d\sigma_{SM}}{dM d\cos\theta^*} + \eta f_{int}(M, \cos\theta) + \eta^2 f_{KK}(M, \cos\theta^*)$$

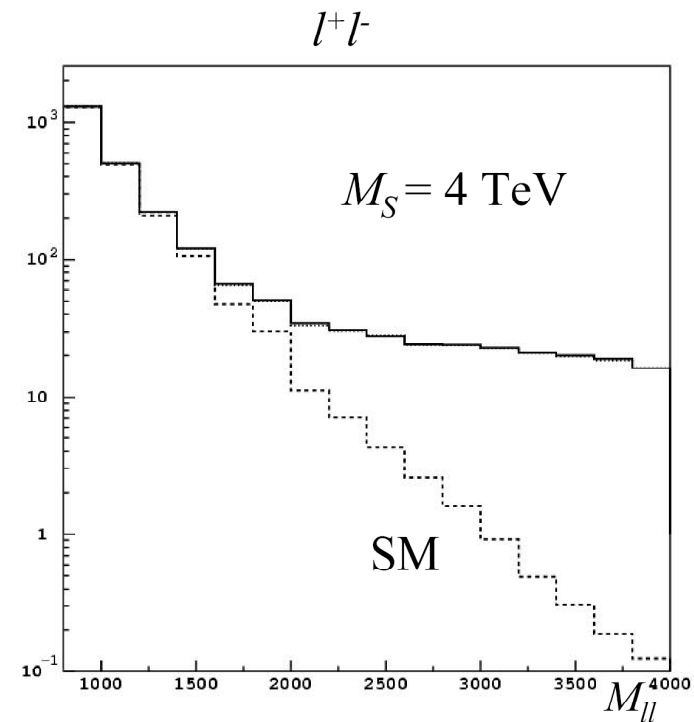
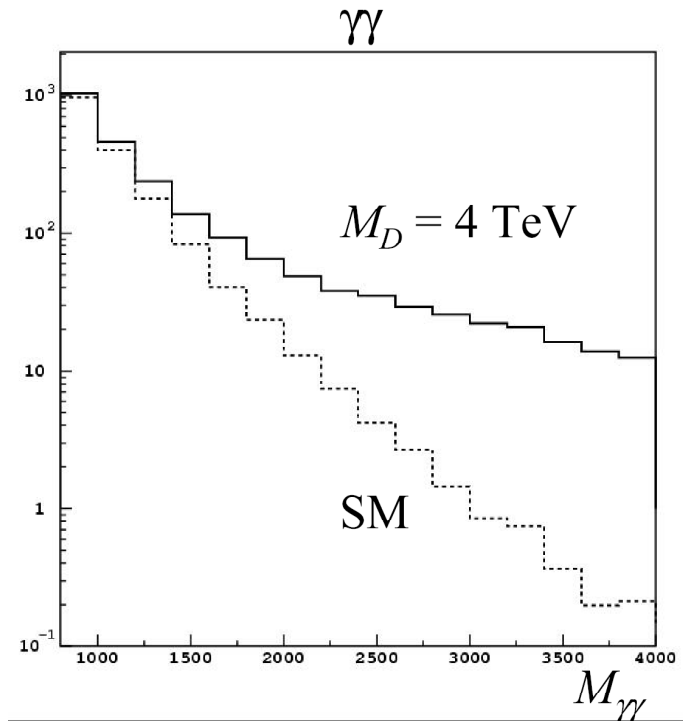
Sum over graviton states divergent, assume cut-off at M_s .

Explicit form of F depends on (unknown) quantum gravity theory, perturbative approach no more valid when $\hat{s} \sim M_s^2$

Gluon-gluon initial state contributes to f_{KK} for leptons

In convention where $F = 1$, independent from number of extra-dimensions:

Study invariant mass spectrum for both ll and $\gamma\gamma$, $M_{\gamma\gamma, ll} < 0.9M_S$ (regularization)



Establish minimal cut on $M_{\gamma\gamma, ll}$ to optimize sensitivity

For 10 (100) fb^{-1} :

$M_S > 5.1(6.7)$ TeV ($\gamma\gamma$) $M_S > 5.4(7.0)$ TeV (ll) $M_S > 5.7(7.4)$ TeV (combined)

Reach depends crucially on systematic control of $m_{\gamma\gamma}$ and m_{ll} at high masses

TeV⁻¹ Extra Dimensions

Standard ADD model:

EW precision measurement test SM gauge fields to distances $\sim 1/\text{TeV} \Rightarrow$ 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" ($R \sim 1/\text{TeV}$) 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 model possibilities, depending on which SM fields propagate in the bulk:

- Only gauge fields \Rightarrow This analysis
- 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 determined by compactification scheme and number of ED

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

- Excitations equally spaced with masses:

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

- Couplings equal to $\sqrt{2} \times$ gauge couplings

Minimum excitation mass compatible with EW precision measurement: 4 TeV

Consider excitations for all SM bosons:

- Z/γ , discovery channel: decay into $\ell^+\ell^-$
- W , discovery channel: decay into $\ell\nu$
- gluon, width $\sim 2\alpha_s M(g^{(n)})$, difficult to observe above QCD background

Excitations of all gauge bosons approximately degenerate \Rightarrow for decay into $\bar{q}q$ consider peak from all three together

Production cross section is the sum of an infinite series of terms identical to SM gauge boson production:

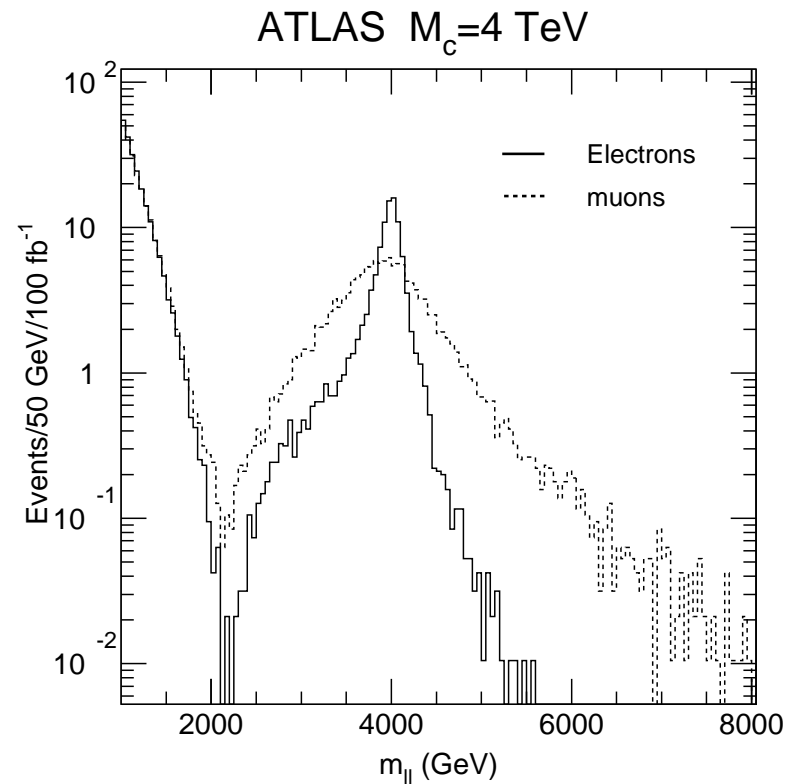
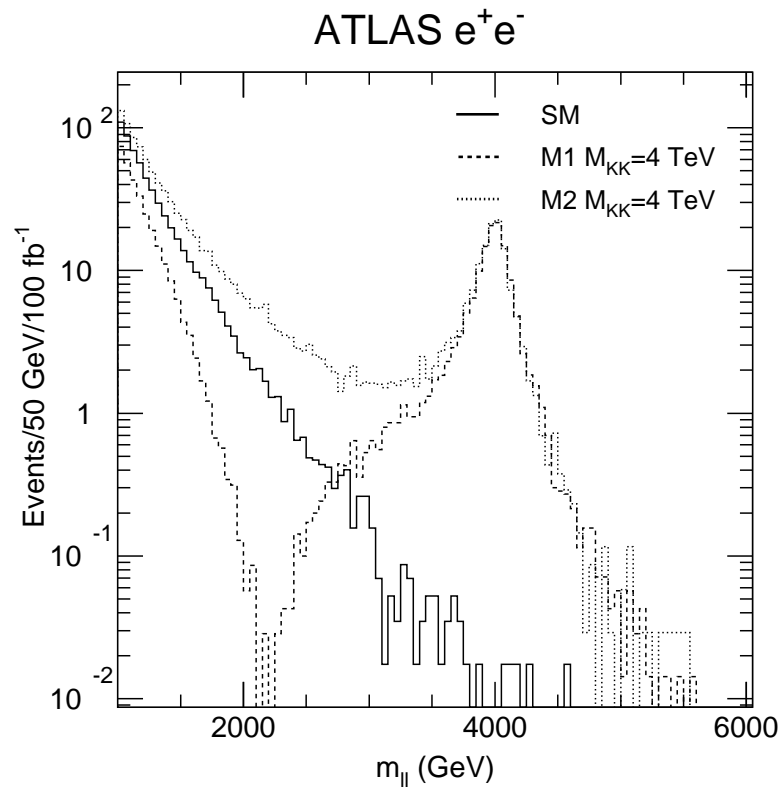
- For Z/γ matrix elements from T. Rizzo implemented into PYTHIA
- For W , calculation patterned on Z/γ
- For gluon, modify gluon propagator in PYTHIA according to prescriptions of hep-ph/0015259 (Dicus, McMullen, Nandi)

Events processed through ATLFAST, taking nominal resolutions for e (0.7% at 2 TeV) and μ (20%) .

Need to validate e measurement at high p_T

Minimum excitation mass considered: 4 TeV: natural width

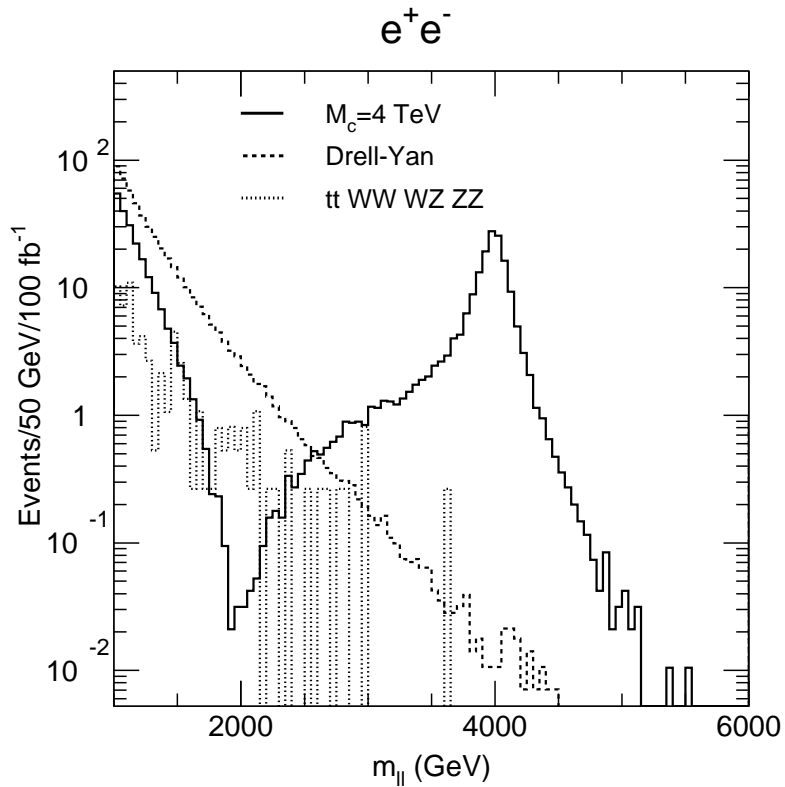
$$\sim 2 \times \Gamma(W) \times (M_c/100) \text{ GeV} \sim 200 \text{ GeV}$$



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

Experimental width dominates for $\mu^+\mu^- \Rightarrow$ use muons only for discovery, nt for measurements

Data analysis: Z/γ



Analysis requirements:

- Two leptons with $P_t > 20$ GeV in $|\eta| < 2.5$
- $m_{ll} > 1$ TeV

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

For $m(e^+e^-) > 1000$ GeV ~ 60 background events

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

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

Data analysis: W

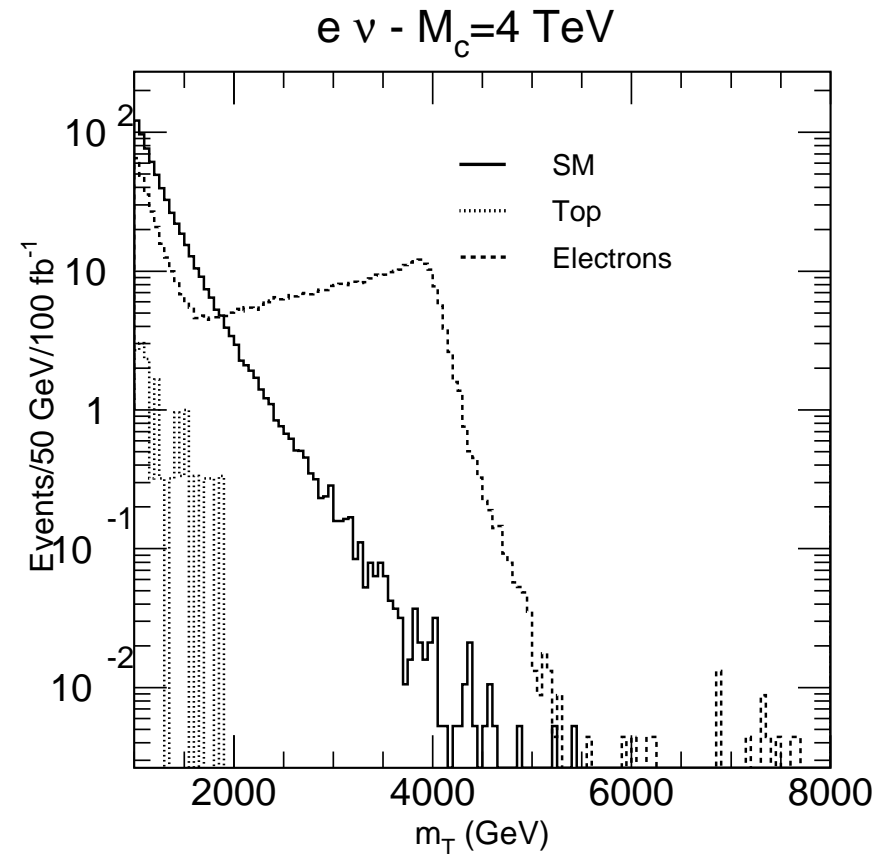
Analysis requirements:

- One lepton with $P_t > 200$ GeV in $|\eta| < 2.5$
- $\cancel{E}_T > 200$ GeV
- $m_T(\ell\nu) > 1$ TeV

Where $m_T = \sqrt{2p_T^\ell p_T^\nu (1 - \cos \Delta\phi)}$

If no new physics 500 events from off-shell

SM W (100 fb^{-1})

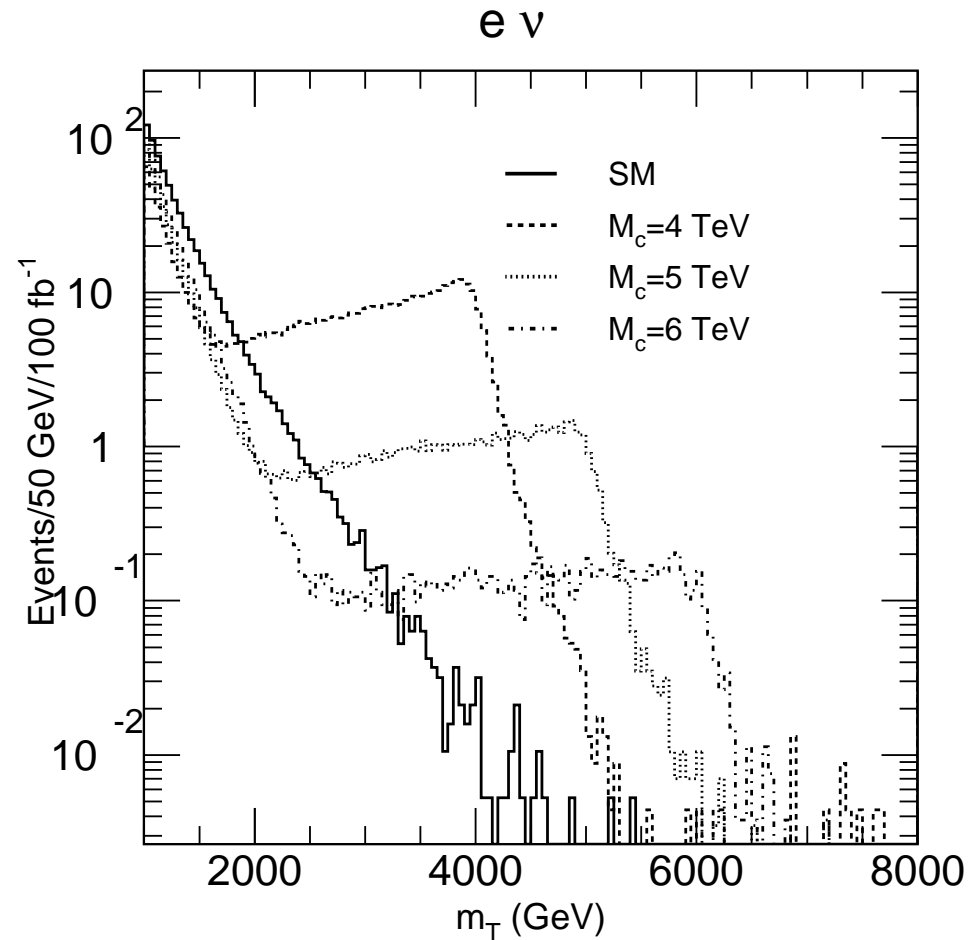


Reducible backgrounds considered: $\bar{t}t, WW, ZZ$

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

With moderate jet veto at 100 GeV, background reduced to ~ 20 events

For both Z/γ evaluate number of events in peak as a function of mass of first excitation (M_{kk})

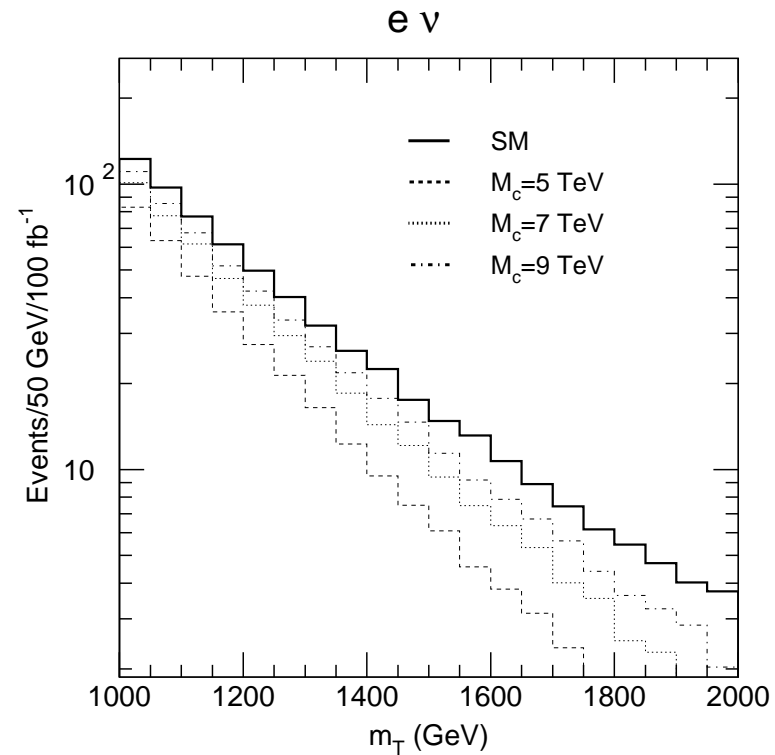
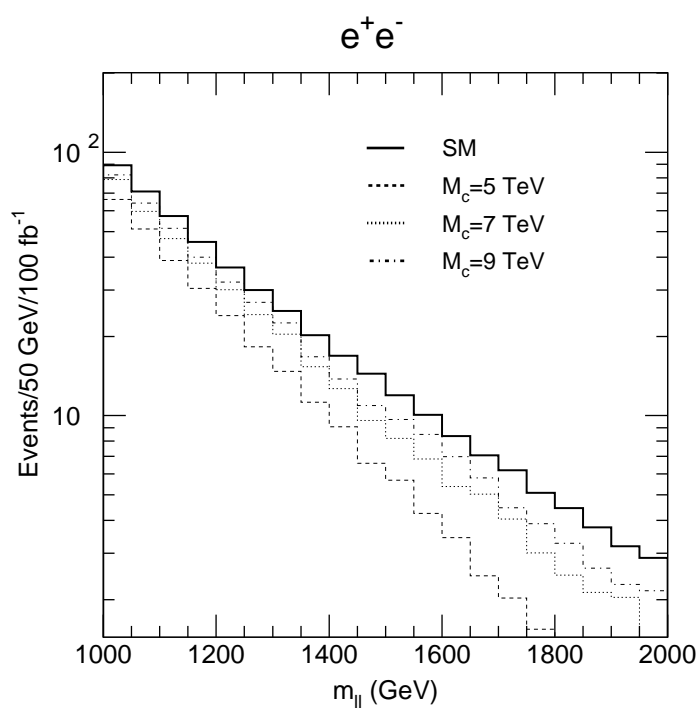


Require: $S/\sqrt{B} > 5$ and > 10 events in peak, summed over two lepton flavours

Reach for 100 fb⁻¹: ~ 5.8 TeV for Z/γ , ~ 6 TeV for W

Even for lowest considered M_c second resonance not observable

Even if no events in peak, can observe depletion in invariant (transverse) mass distribution off-peak



Count events with respectively: $1000 < M_{\ell\ell} < 2500 \text{ GeV}$ (Z/γ)

$1000 < M_T < 2500 \text{ GeV}$ (W)

Require: $(N(M_c) - N(SM))/\sqrt{N(SM)} > 5$ (two lepton flavours)

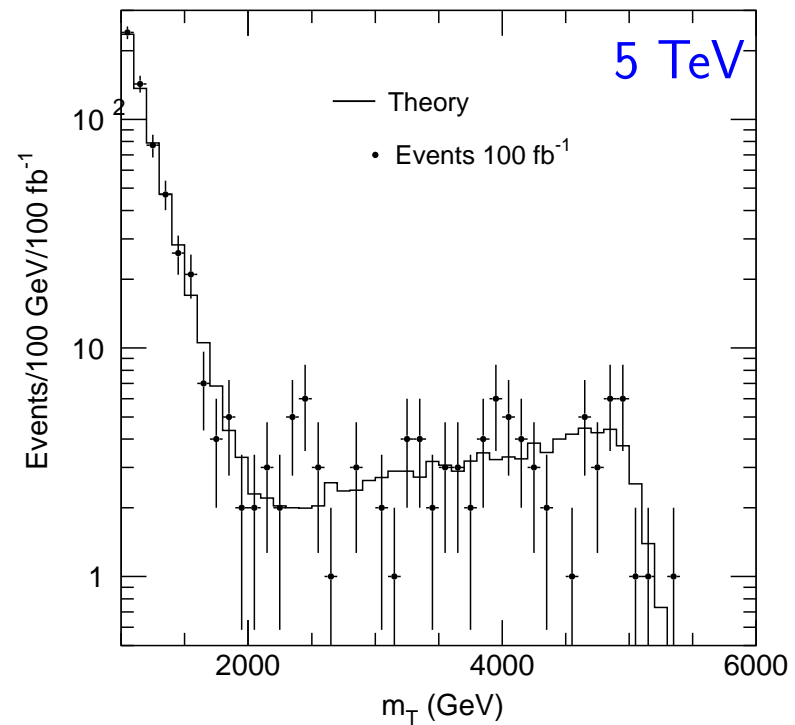
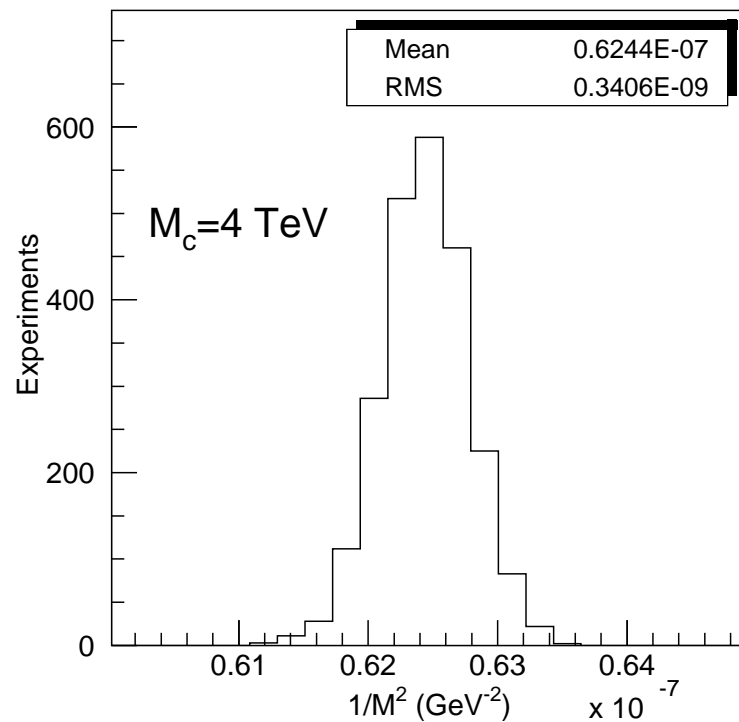
Reach for 100 fb^{-1} : $\sim 8 \text{ TeV}$ for Z/γ , $\sim 9 \text{ TeV}$ for W

Deviation from SM at sensitivity limit: $\sim 15\% \Rightarrow$ need systematic control on DY

Model-dependent likelihood fit

Method for precise measurement of M_c , and ultimate sensitivity evaluation.

For Z/γ completely fit event kinematics, for W , only m_T distribution



M_c for both Z and W at the 1-2 percent level as long as events detected in the peak

Off-peak 95% sensitivity for 1 lepton flavour (100 fb⁻¹):

~ 9.5 TeV for Z/γ , ~ 11.5 TeV for W

Only statistical error, need to further address systematics

Likelihood fit very sensitive to our ability to model correctly the SM lepton-lepton production.

Need to consider effects which can distort the the tails of the lepton distributions, both theoretical and experimental

- Structure functions: studied using different sets, reduce sensitivity by $\sim 0.2(0.4)\text{TeV}$ for Z (W). Need to study uncertainties on SF fits
- Electroweak higher order corrections
- Electron energy scale and non linearities in electron energy measurement: reduce sensitivity by 2% for each percent of uncertainty on energy calibration at 2 TeV
- \cancel{E}_T modeling effects for W , can extrapolate from studies for SM W , should be dominated by energy scale uncertainty

Effect of QCD corrections should be minor, tested switching off initial state radiation.

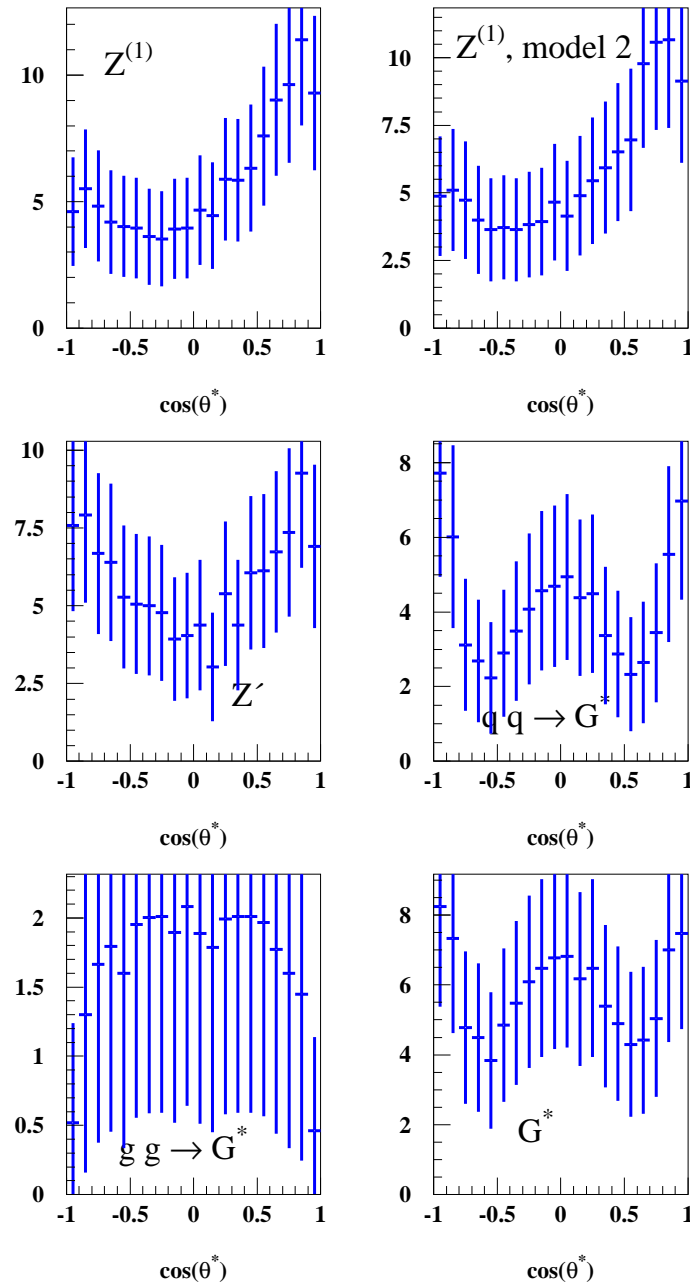
If $Z^{(1)}/\gamma^{(1)}$ observed, study distribution of polar angle $\cos\theta^*$ for $M(Z^{(1)}) = 4$ TeV and different models:

- Alternative $Z^{(1)}$ model
- Z' model with Standard Model couplings
- Graviton exchange with $G^* \rightarrow e^+e^-$

Trough Kolmogorov test study discrimination power:

Reject Z' hypothesis at 95% CL in 52% of cases

Reject $G^* \rightarrow e^+e^-$ hypothesis at 95% CL in 94% of cases



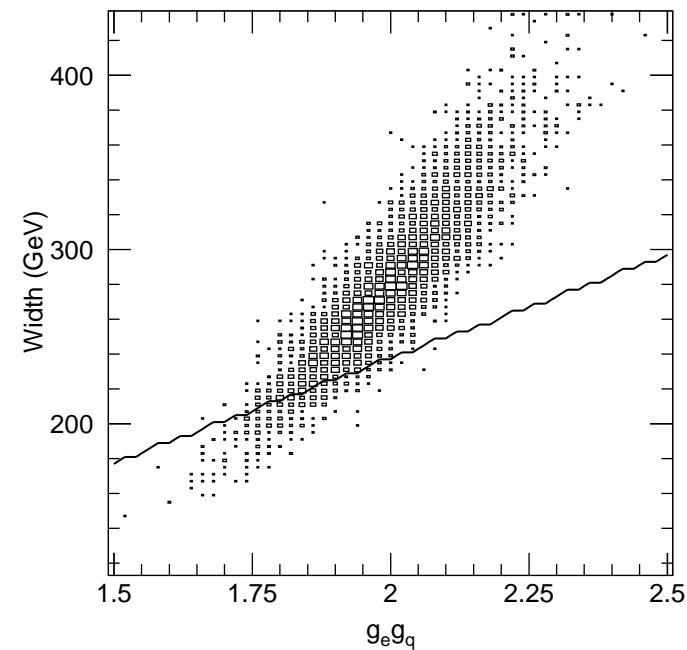
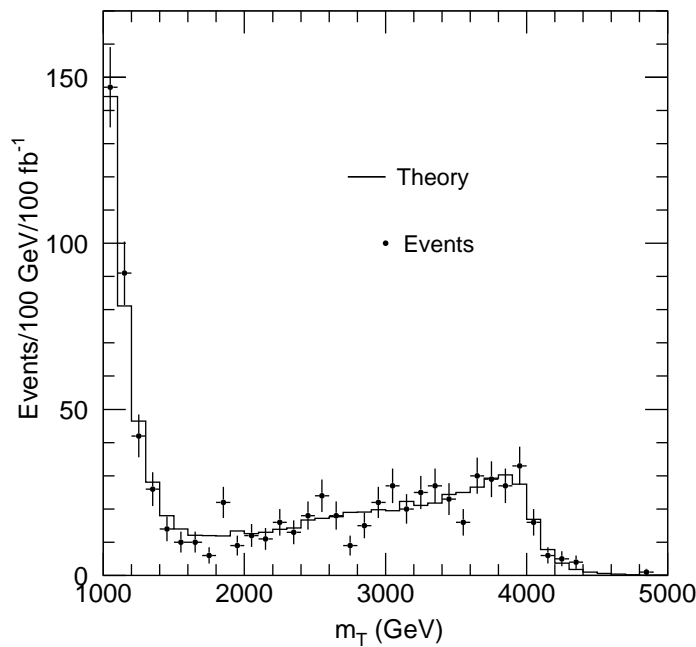
Measurement of $W^{(1)}$ couplings

$W^{(1)}$ has only flavour-universal left-handed couplings \Rightarrow production and decay only determined by:

- g^e : coupling to lepton SU(2) doublet
- g^q : coupling to quark SU(2) doublet

Measurable quantities from m_T distribution: normalization w.r.t SM ($P = g^e \times g^q$), and $W^{(1)}$ width (Γ)

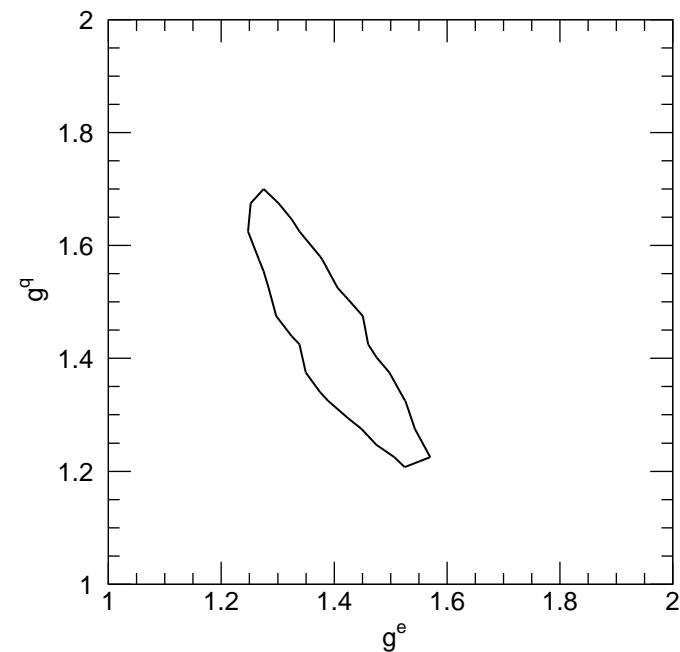
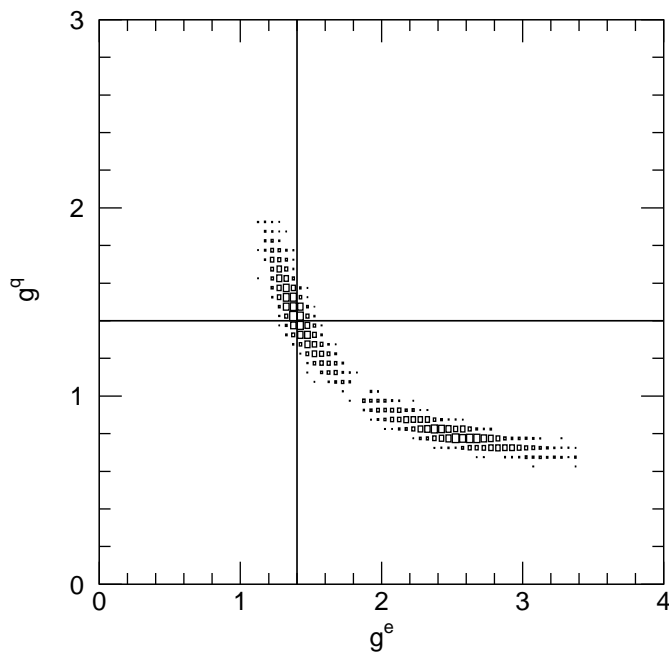
Perform likelihood fit to m_T for $m(W^{(1)}) = 4$ TeV, as a function of P and Γ for a set of MC experiments



Values of couplings related to P and Γ by expressions:

$$\begin{cases} P = g^e(n) g^q(n) \\ \Gamma \propto a g^e(n)^2 + b g^q(n)^2 \end{cases}$$

Solve fit results for couplings:



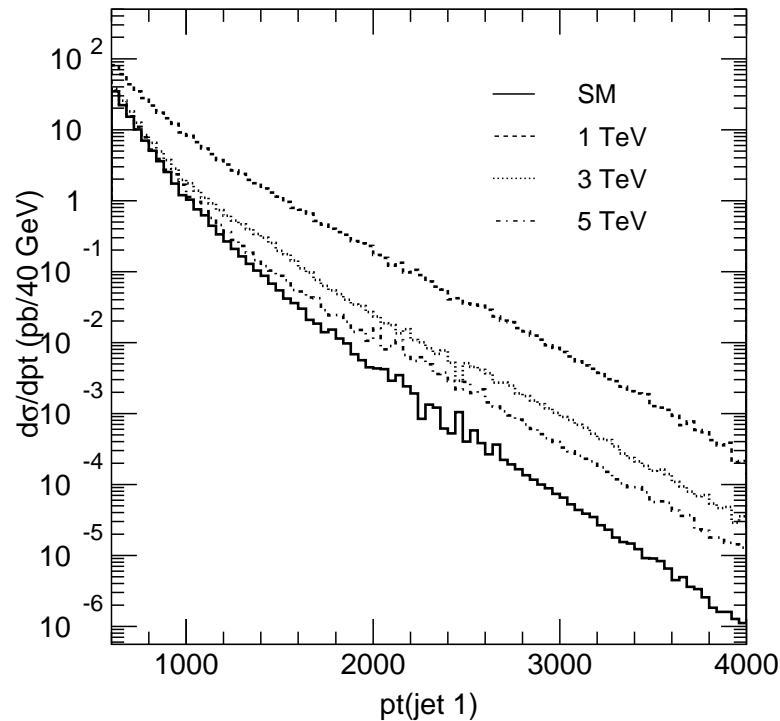
Two solutions: $W^{(1)} \rightarrow \bar{q}q$ to choose the correct one

For solution with $g^e = g^q$, 68% ellipse: $1.25 < g^e < 1.55$, $1.2 < g^q < 1.7$.

For 8% of experiments no statistical sensitivity to width: no solution for (g^e, g^q)

KK excitations of the gluon

Require no third jet with P_T above 100 GeV



Large deviation from SM QCD spectrum,

but

Need to understand how well we know jet

p_T spectrum:

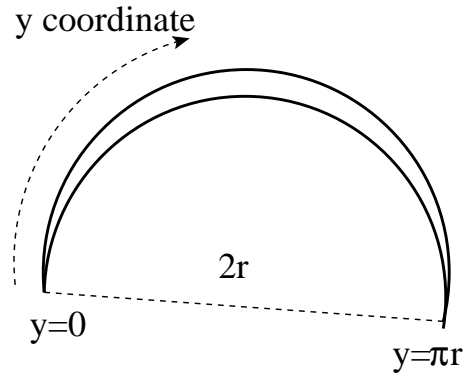
- PDF uncertainties
- NLO corrections
- Detector linearity at high p_T

Also need to study if peak from s-channel g^* exchange can be seen above smooth

SM+KK background

Difficult due to large width of resonances and complex multi-resonance pattern

Randall-Sundrum model



One additional dimension in which gravity propagates
ED compactified on S^1/Z_2 (circle folded on itself)

Two branes at extremal values of compactification:

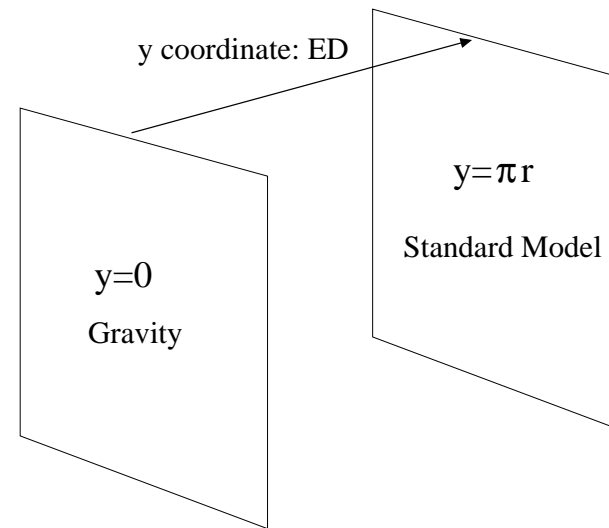
- Planck brane: $y=0$, where gravity localized
- Tev-brane where SM fields (us) constrained

Metric for this scenario is non-factorizable:

$$ds^2 = e^{-2ky} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \quad (1)$$

Exponential term: "warp factor". Parameter k of order Planck scale governs curvature of space

Consistency of low energy theory: $k/\overline{M}_{\text{Pl}} \lesssim 0.1$ with $\overline{M}_{\text{Pl}} = M_{\text{Pl}}/\sqrt{8\pi} = 2.4 \times 10^{18}$ being the reduced 4-d Planck scale.



Write action for gravitational field in 4-d effective theory (like it was done for ADD),
 obtain form for 5-dim fundamental scale \overline{M}_5

$$\overline{M}_{Pl}^2 = \frac{\overline{M}_5^3}{k} \quad (2)$$

Scale of all physical processes on the TeV brane described by:

$$\Lambda_\pi \equiv \overline{M}_{Pl} e^{-kR_c\pi}$$

$\Lambda_\pi \sim 1\text{TeV}$ provided that $kR = 10$.

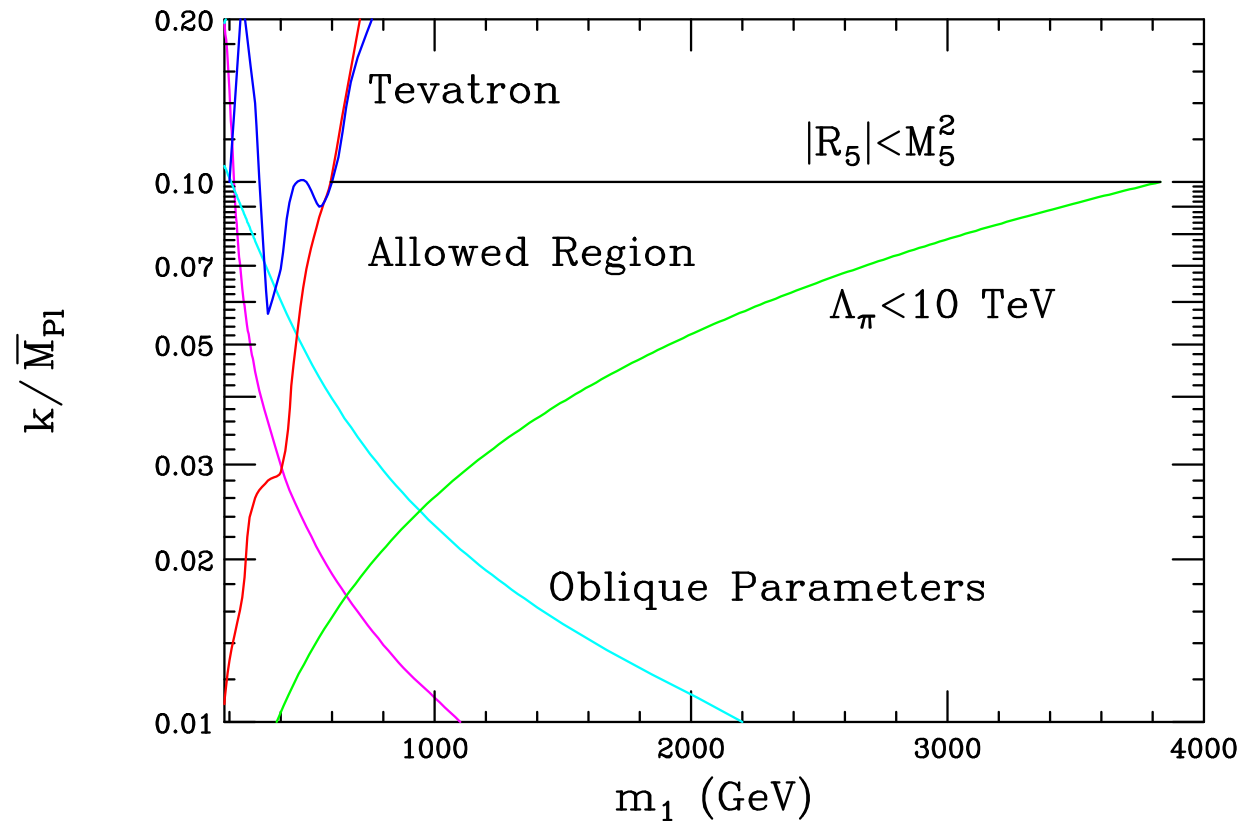
Two parameters define the model:

- Λ_π
- ratio k/\overline{M}_{Pl}

If require $\Lambda_\pi < 10\text{ TeV}$ (hierarchy)

closed region in parameter space

$$(m_1 = 3.83 \frac{k}{\overline{M}_{Pl}} \Lambda_\pi)$$



Randall-Sundrum: 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:

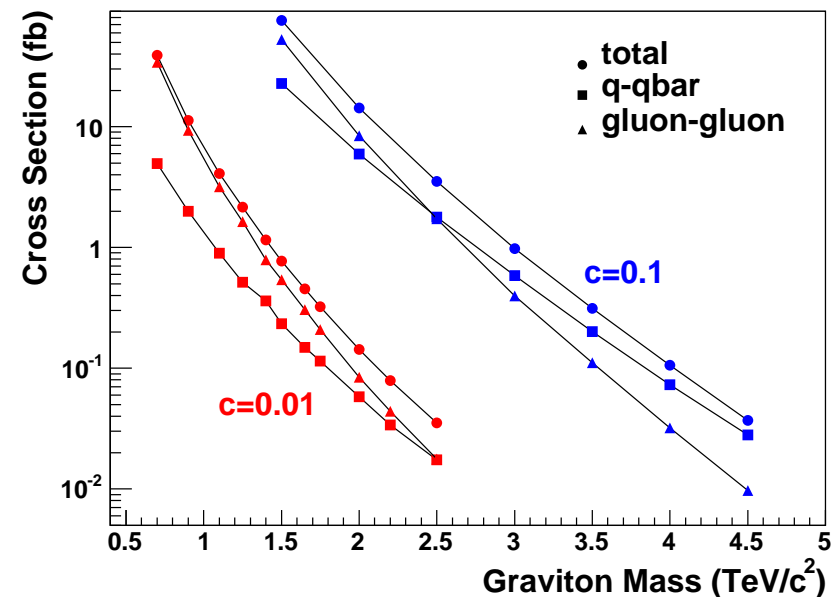
$$m_n = x_n k e^{-k\pi r_c} = x_n \frac{k}{M_{Pl}} \Lambda_\pi$$

where x_n are the roots of the first order Bessel function. $x_1 = 3.83 \Rightarrow \sim TeV$ scale
for mass of first excitation

Couplings of $G^{(n)}$ to SM fields $\sim 1/\Lambda_\pi \Rightarrow$

- sizable cross-section at the LHC
- Narrow resonances

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



$G(1) \rightarrow e^+e^-$ in CMS (full simulation)

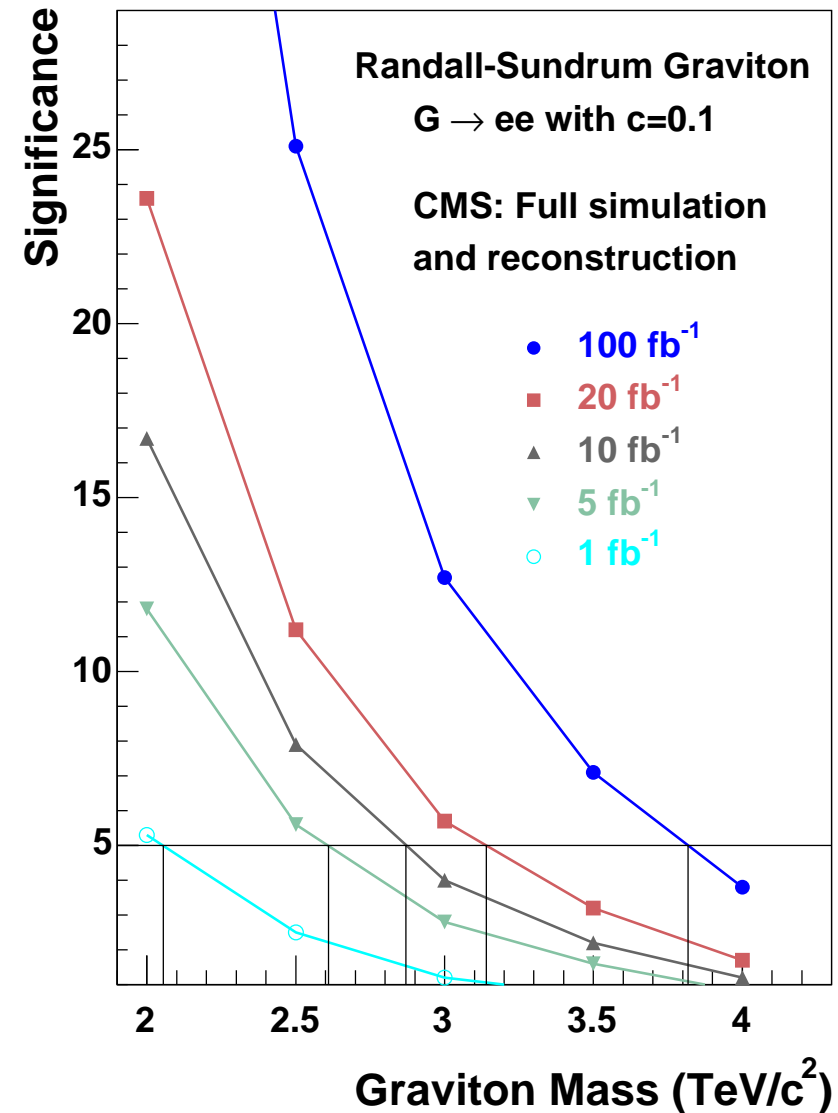
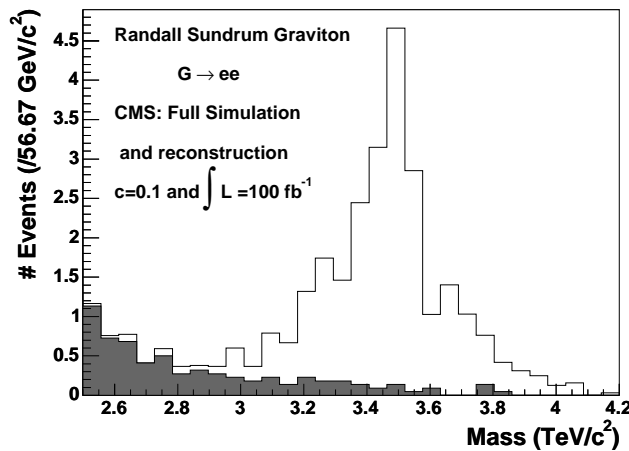
Graviton couples to all SM particles

Most favourable channel $G(1) \rightarrow e^+e^-$:

- Optimal experimental resolution
- Minimal background

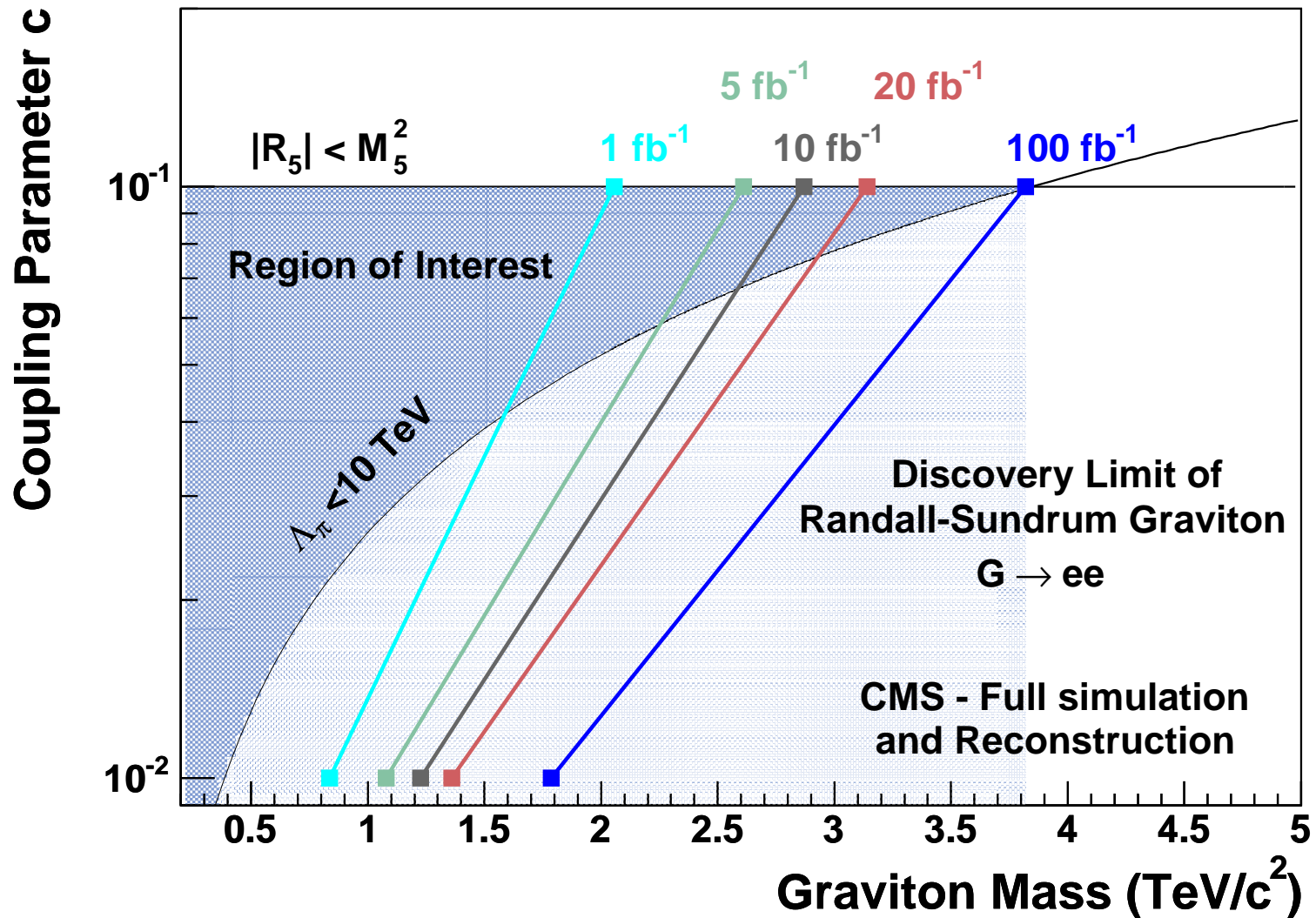
Study achievable significance as a function of mass of first excited state

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



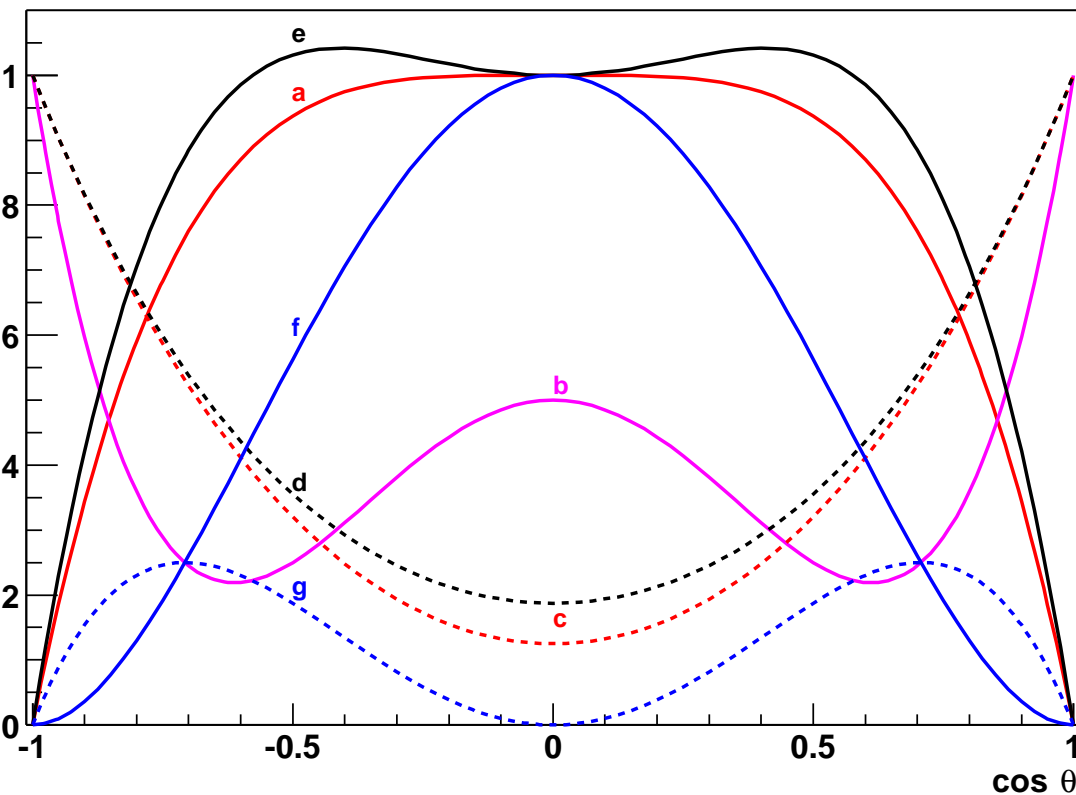
Coverage of parameter space

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



Spin determination of graviton resonance

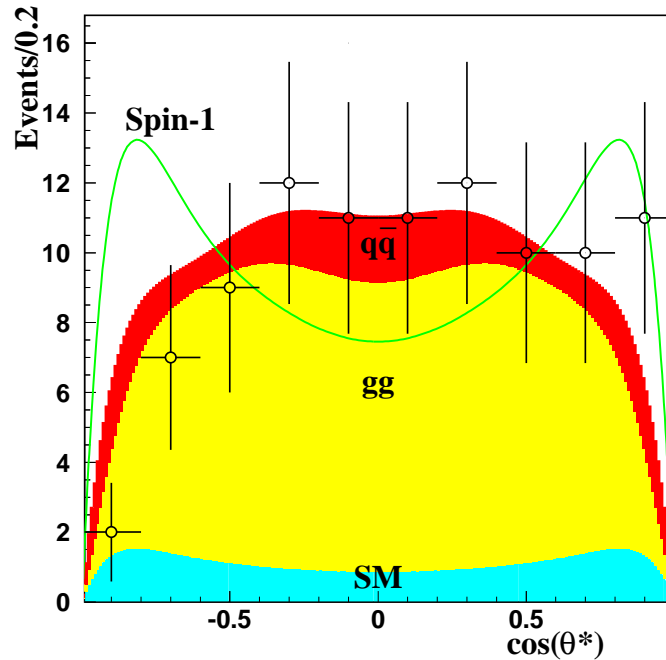
Graviton is spin-2 particle. Angular distribution of decay products depends on production mechanism, and on spin and mass of decay products



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

β is v/c of decay products

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

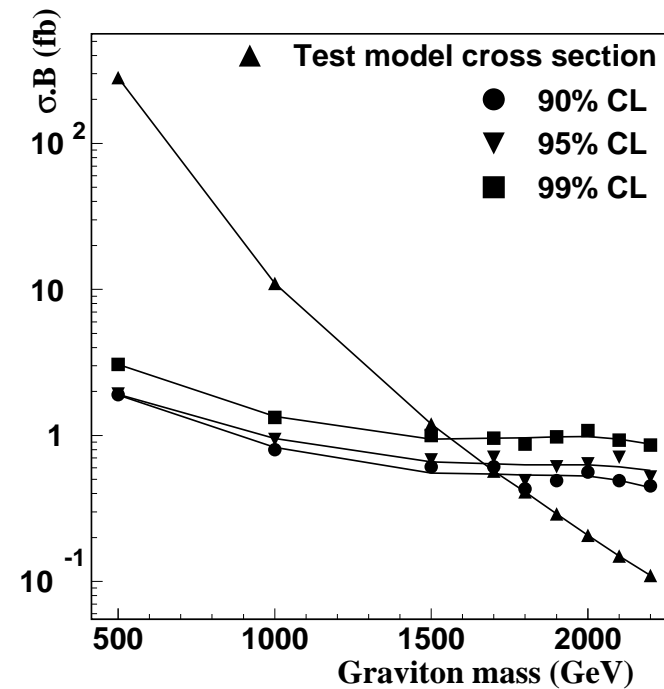


Polar angle distribution of e^+e^- after the acceptance cuts are applied

For $m_1 = 1500$ GeV and 100 fb^{-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

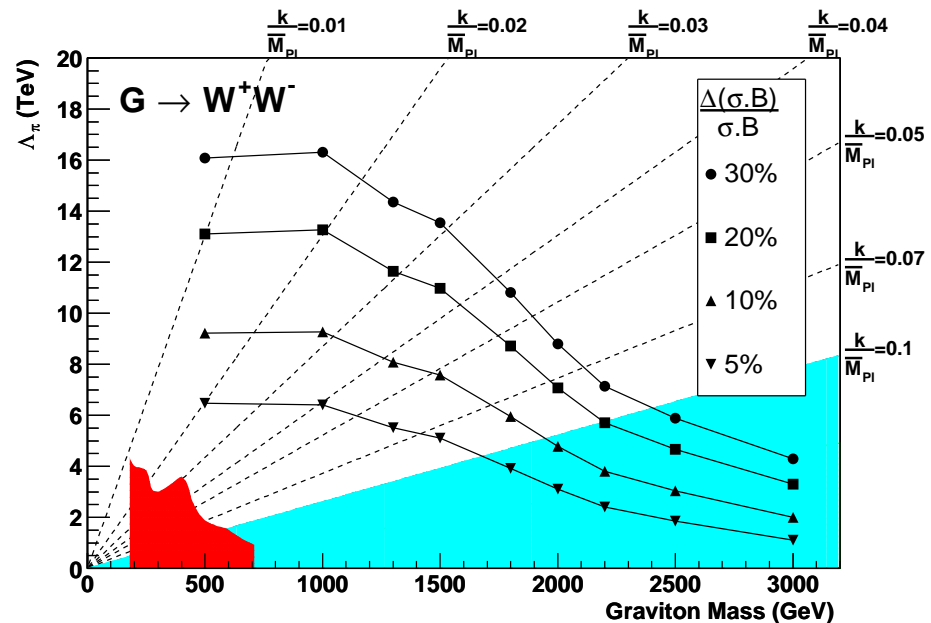
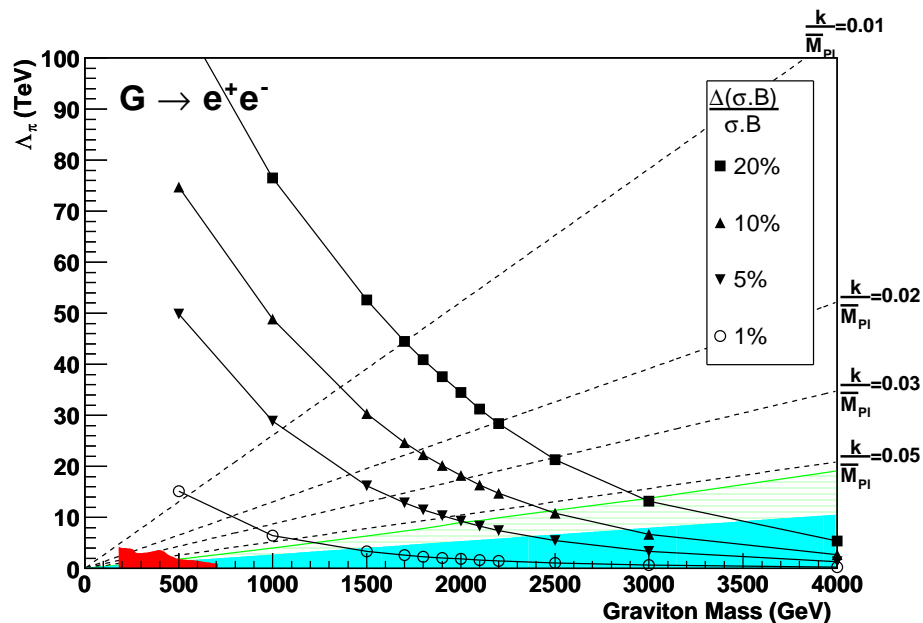


Measurement of model parameters

Graviton couples to SM particles democratically, BR determined by number of states for each particle

Possible to detect graviton decay in e^+e^- , $\mu^+\mu^-$, $\gamma\gamma$, WW , ZZ and possibly jet-jet

For each channel possible to measure σBR with a certain precision \rightarrow from mass and σBR extract model parameters



Radion in RS theories

Need to stabilize distance between branes r_c such that $kr_c\pi \sim 35$

Mechanism devised by Goldberger and Wise:

- introduce radion: a bulk scalar field representing fluctuations of the distance between branes
- Radion acquires mass $m_\phi < m(KK = 2)$

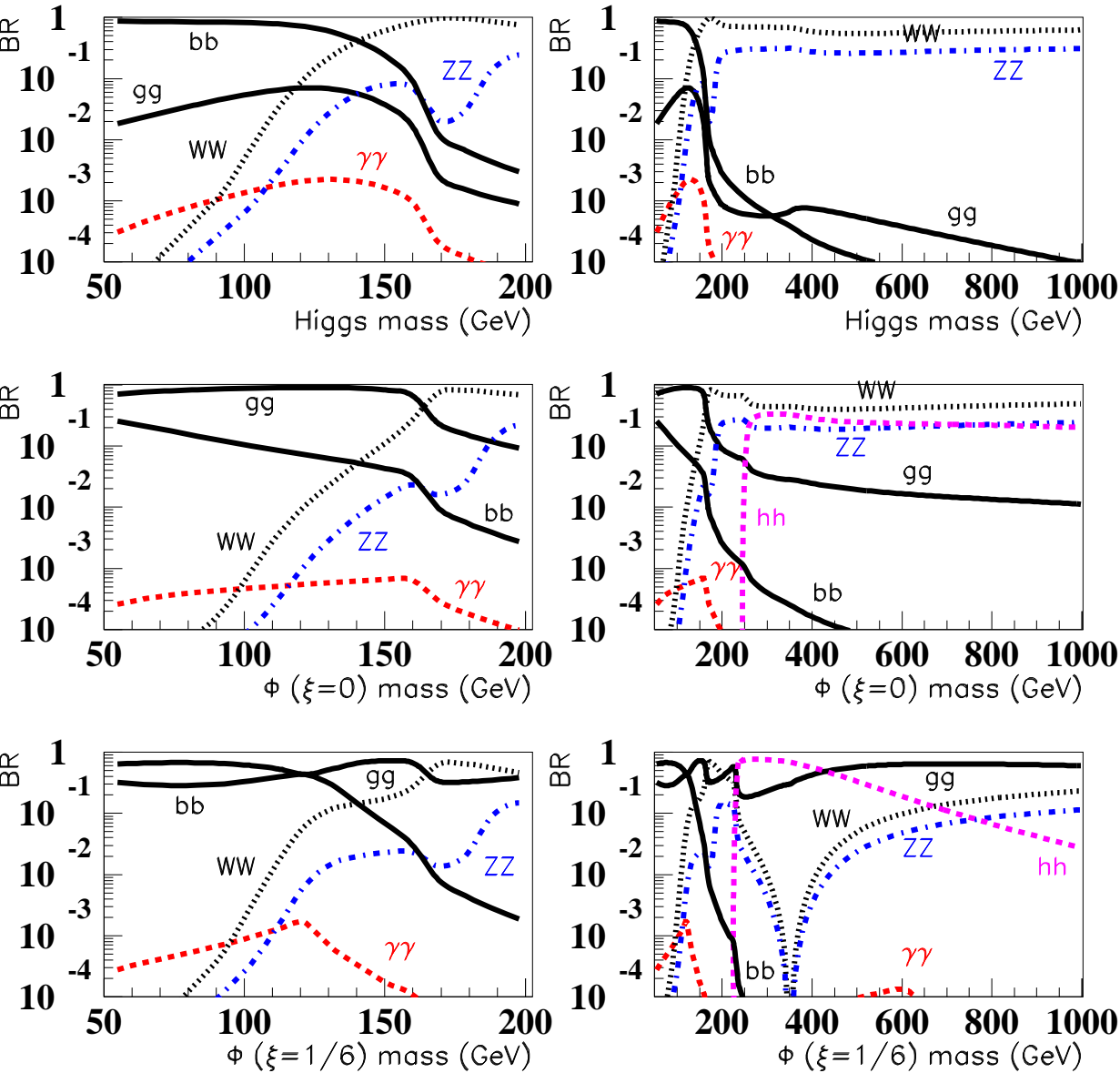
Radion properties determined by three parameters:

$$m(\phi), \quad \Lambda_\phi: \text{scale}, \quad \xi: \phi - H \text{ mixing}$$

Radion properties:

- Narrow resonance
 - Coupling to gg enhanced, other couplings modified
 - May mix with higgs
 - Partial width w.r.t. Higgs scale like Λ^2
-

Radion decays



Higgs-like resonance

Partial width determined by Λ_ϕ and ξ

Decay pattern similar to Higgs

Can rescale results of higgs studies

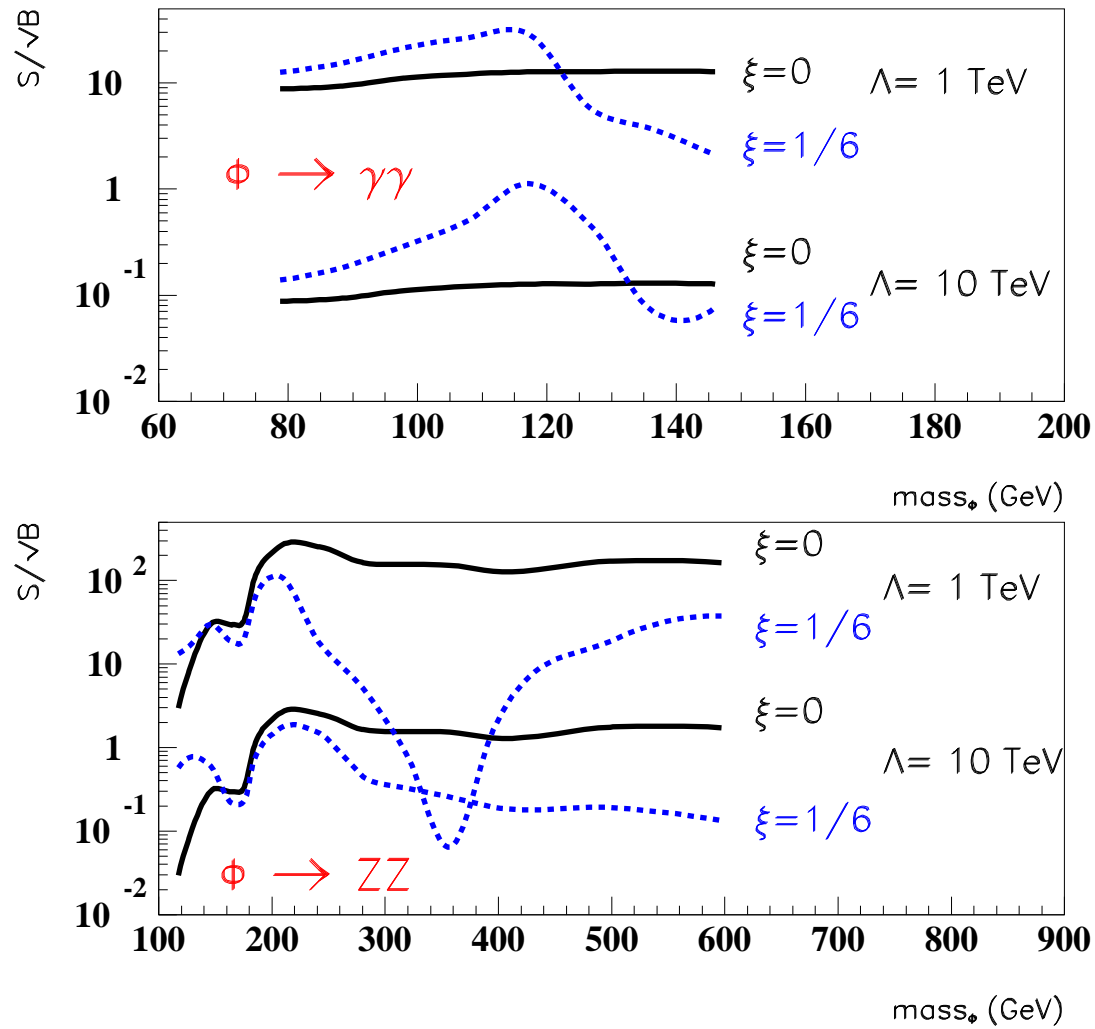
Additional signature: $\phi \rightarrow hh$

Most promising channels:

$\phi \rightarrow hh \rightarrow bb\gamma\gamma$

$\phi \rightarrow hh \rightarrow bb\tau\tau$

Radion reach in $\gamma\gamma$ and ZZ modes: extrapolate from SM Higgs searches (ATLAS)



$$\frac{S/\sqrt{B}(\phi)}{S/\sqrt{B}(h)} = \frac{\Gamma(\phi \rightarrow gg)BR(\phi \rightarrow \gamma\gamma, ZZ)}{\Gamma(h \rightarrow gg)BR(h \rightarrow \gamma\gamma, ZZ)} \sqrt{\frac{\max(\Gamma_{\text{tot}}^h, \sigma_m)}{\max(\Gamma_{\text{tot}}^\phi, \sigma_m)}}$$

$\phi \rightarrow hh \rightarrow \gamma\gamma bb$: ATLAS analysis

Fast simulation ATLAS study. Full simulation CMS study \sim available

Final state with two photons and (1)2 b -tagged jets

Fix $\Lambda_\phi = 1$ TeV, $\xi = 0$. Consider $m_\phi = 300, 600$ GeV, $m_h = 125$ GeV

Require $m_{\gamma\gamma}(m_{bj})$ compatible with Higgs mass within respectively 2(20) GeV

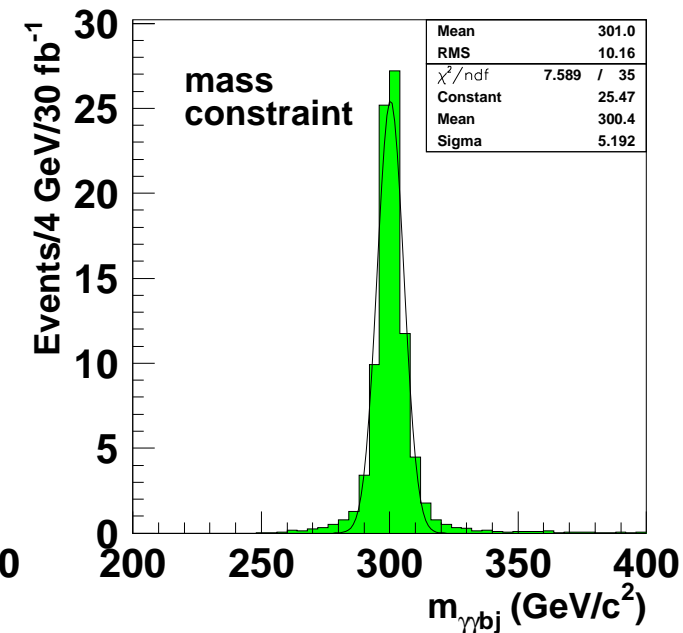
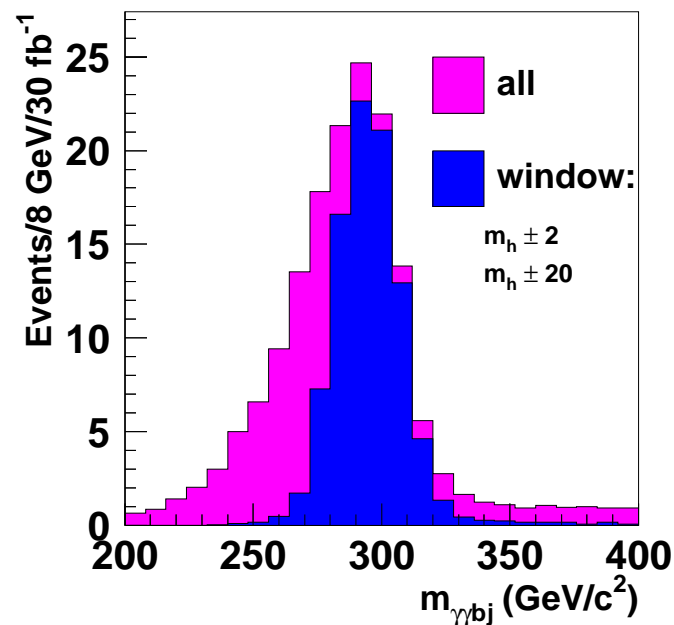
Reconstruct $\gamma\gamma bj$ invariant mass.

Sharp peak by constraining $m_{\gamma\gamma}$
and m_{bj} to m_h

Negligible SM backgrounds

95% reach for $\xi = 0$:

- $\Lambda_\phi \sim 2.2$ TeV for $m_\phi = 300$ GeV with 30 fb^1
- $\Lambda_\phi \sim 0.6$ TeV for $m_\phi = 600$ GeV with 30 fb^1

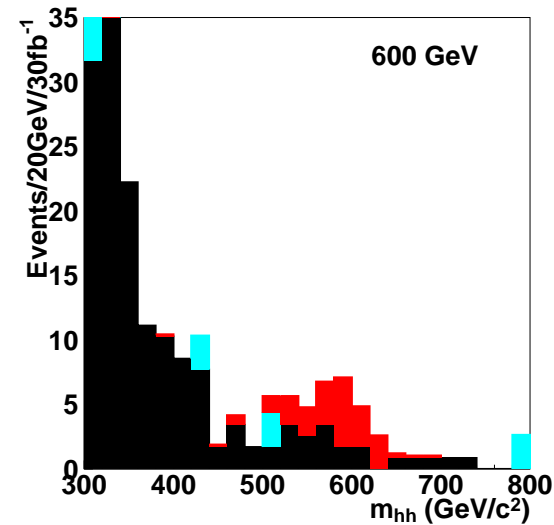
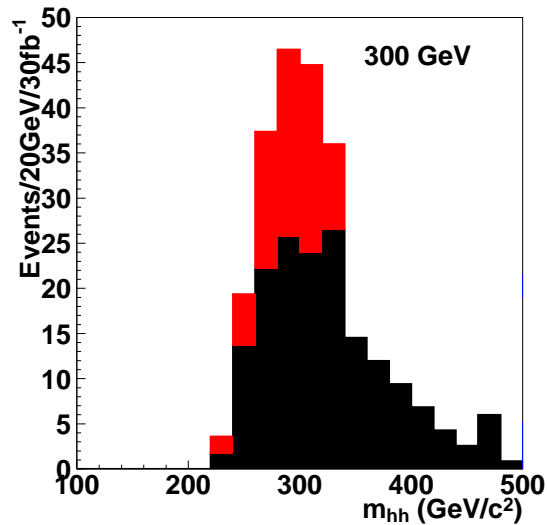


$\phi \rightarrow hh \rightarrow \tau\tau bb$: ATLAS analysis

Signal $\phi \rightarrow hh \rightarrow \tau\tau bb$: require two b -tagged jets, one τ decaying hadronically, one τ decaying leptonically

High background levels: $\bar{t}t$, Z +jets, W +jets

Study case: $\xi = 0$, $\Lambda_\phi = 1 \text{ TeV}$, 30 fb^{-1}



Reach: $\Lambda_\phi \sim 1.0 \text{ TeV}$ for $m_\phi = 600 \text{ GeV}$ with 30 fb^{-1}

Uncertainties in background evaluation considerably affect signal observability for $m_\phi = 300 \text{ GeV}$

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 $\sqrt{\hat{s}} = M_{BH}$

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

$$\sigma(\hat{s} = M_{BH}^2) \sim \pi R_s^2$$

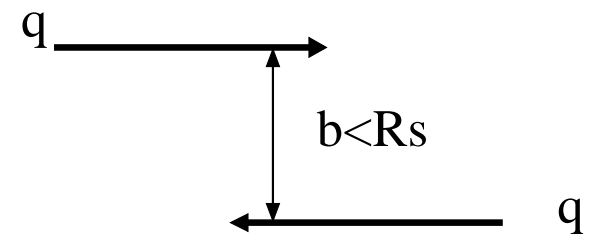
Where R_S is Schwarzschild radius of black hole

$$R_S \sim \frac{1}{\sqrt{\pi} M_P} \left[\frac{M_{BH}}{M_P} \right]^{\frac{1}{n+1}}$$

In extra-dimension theories $M_P \sim \text{TeV} \Rightarrow$, for $M_{BH} \sim M_P$, $\sigma \sim (\text{TeV})^{-2} \sim 400 \text{ pb}$

Potentially large production cross-section

Theoretical debate on geometrical formation factors. Possible big suppression

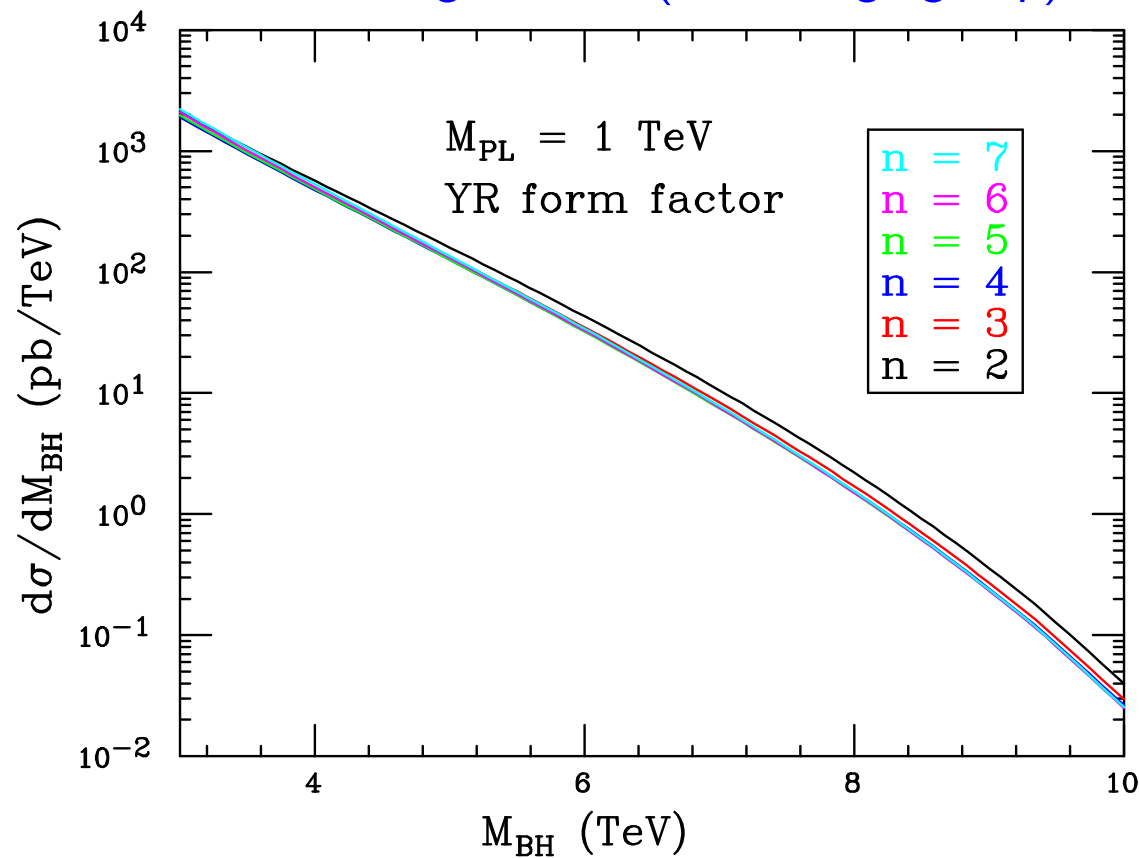


Black Hole production

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

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

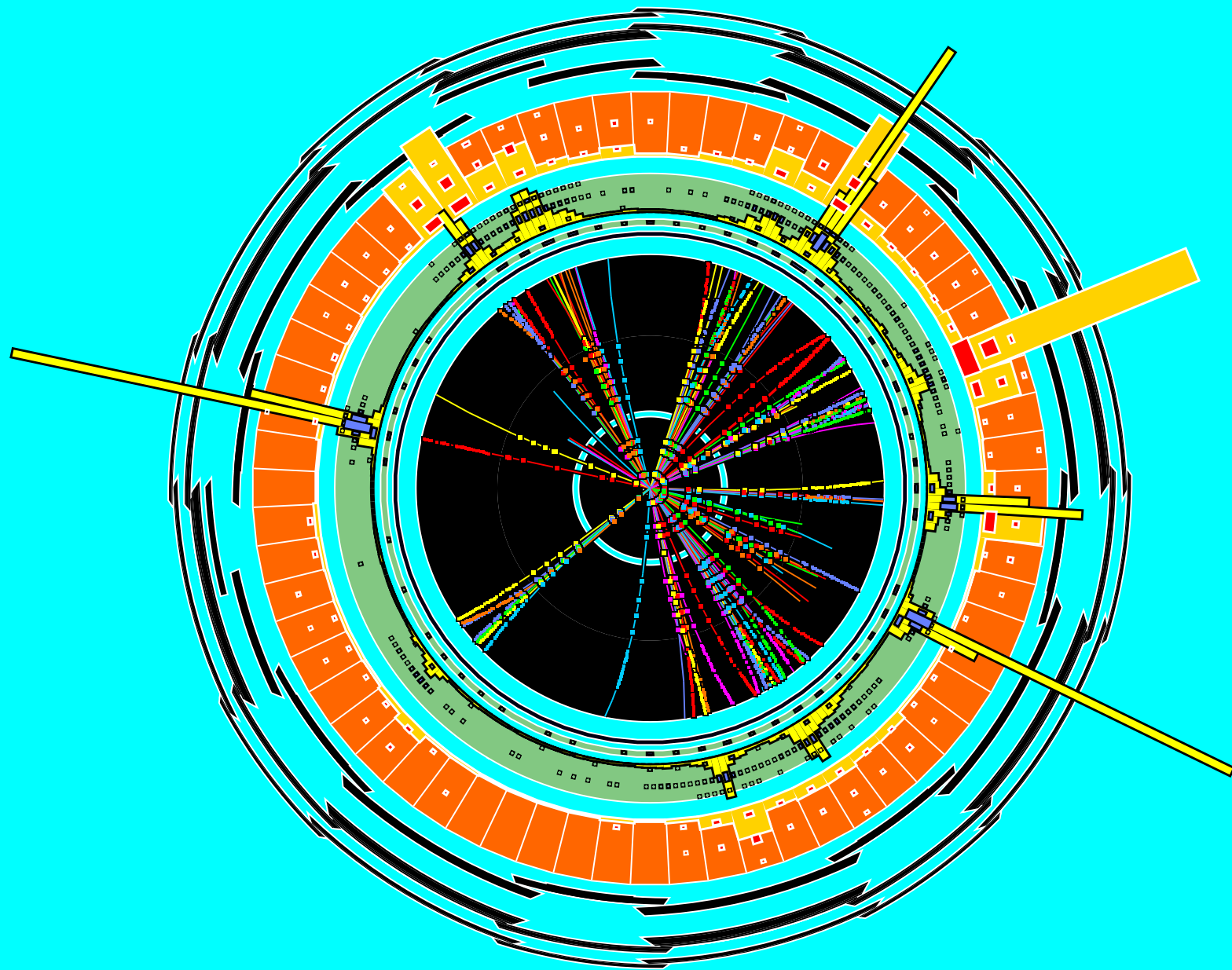
Thermal radiation: black body energy spectrum

$$\frac{dN}{dE} \propto \frac{\gamma E^2}{(e^{E/T_H} \pm 1)} T_H^{n+6} \quad (3)$$

\pm applies to fermions and bosons, T_H is the Hawking temperature

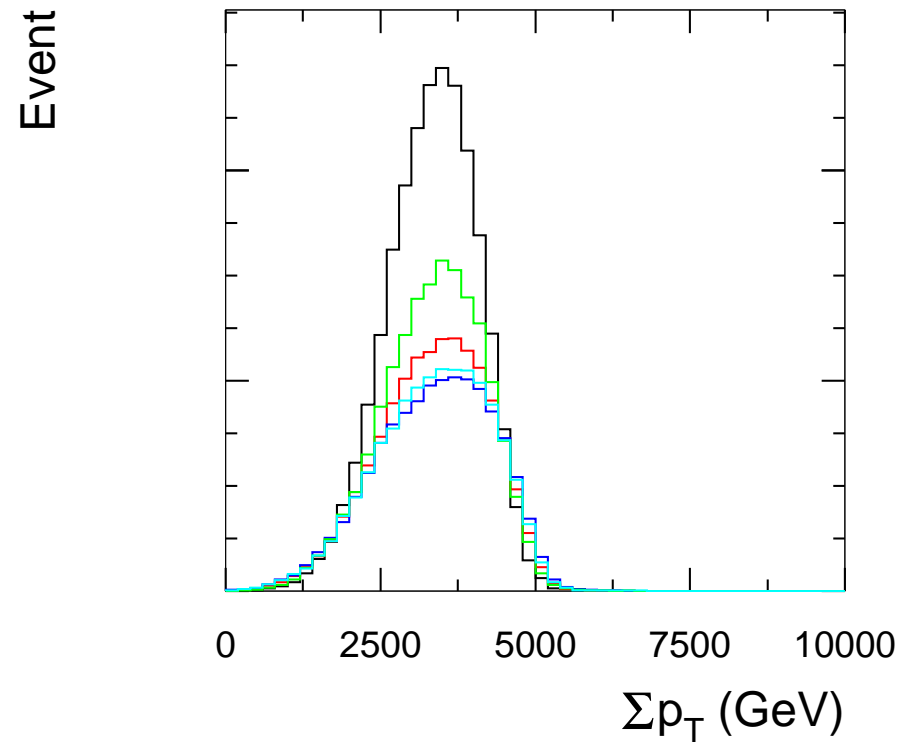
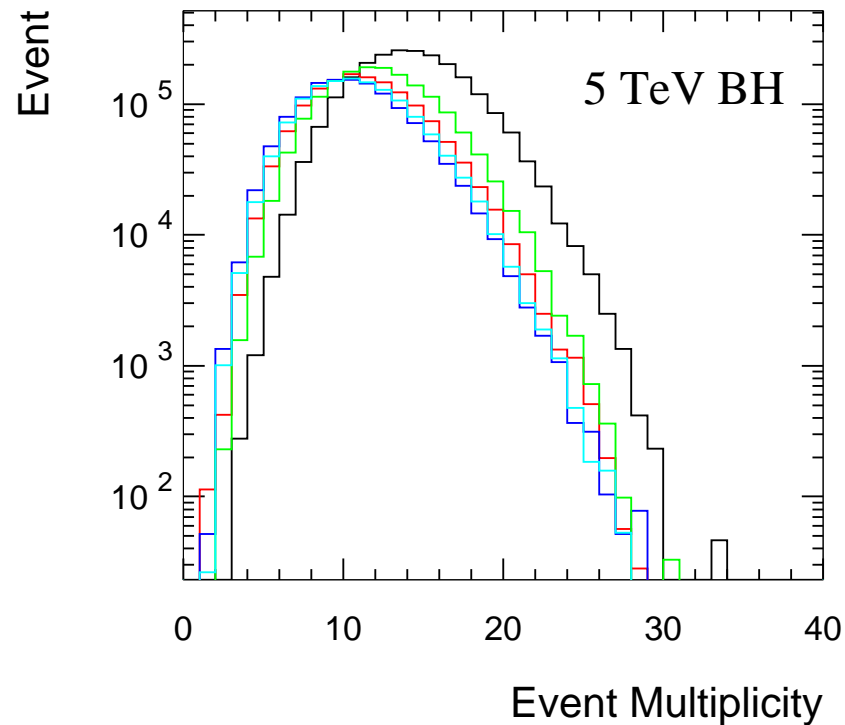
$$T_H = \frac{n+1}{4\pi r_s} \propto M_{\text{BH}}^{-\frac{1}{n+1}} \quad (4)$$

γ is a $(4+n)$ -dimensional *grey-body factor*: absorption factor from propagation in curved space



Event characteristics of BH decays

- From integrating flux: large multiplicities of particles in final state
- Hawking decay isotropic: spherical events (more spherical than SUSY)
- High mass: High Σp_T of final state particles



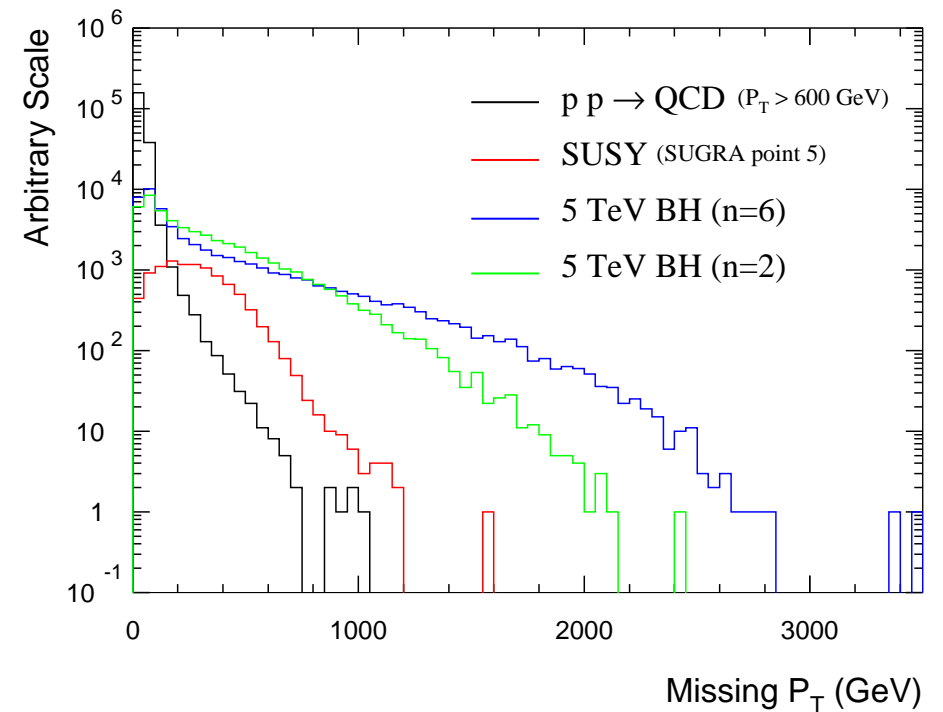
No significant SM background !

Democratic decay of BH into all types of SM particles

Large number of events containing a high- P_T neutrino

\cancel{E}_T distribution even in excess of SUSY

Particle type	Particle emissivity (%)
Quarks	61.8
Gluons	12.2
Charged leptons	10.3
Neutrinos	5.2
Photon	1.5
Z^0	2.6
W^+ and W^-	5.3
Higgs boson	1.1



Also large production of gauge bosons and higgses, BH decay even be privileged
production mode for higgs boson

Black hole mass measurement

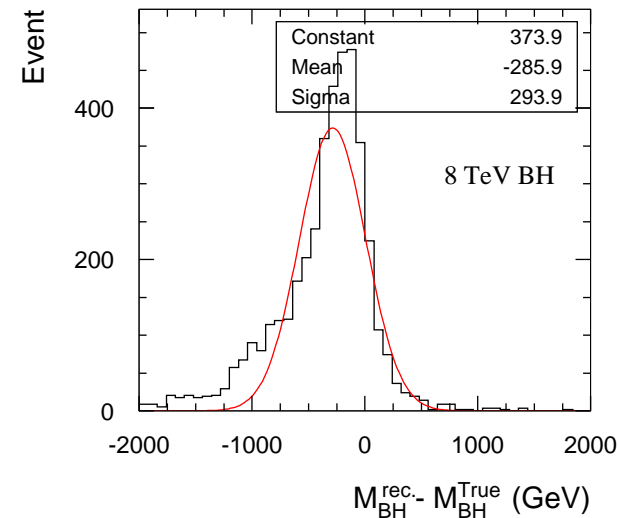
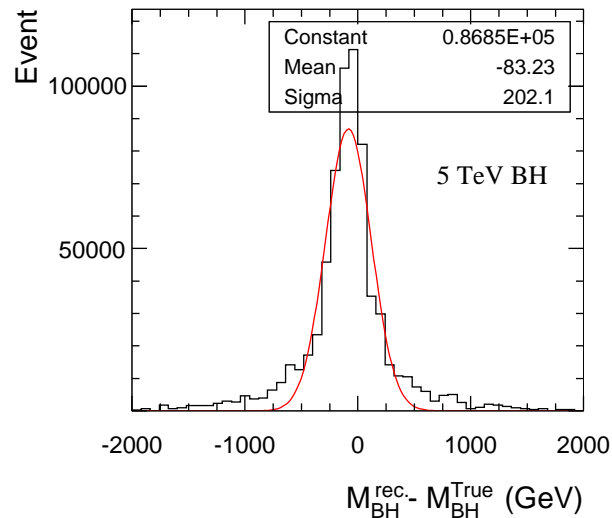
Simply sum the 4-momentum of all reconstructed particles in the event

Test procedure on two BH mass ranges around 5 and 8 TeV for n between 2 and 6

Require at least 4 jets with respectively $PT > 500, 400, 300$ GeV

To improve mass reconstruction, reject events with $\cancel{E}_T > 100$ GeV

Efficiency between 15 and 30% depending on mass and n



Achieve mass resolution of 3-5%

m_{BH} correlated to T_H , but large theoretical uncertainties

Useful benchmark process for study of high multiplicities and energies in the detector

Vigorous full simulation effort ongoing in ATLAS to verify these results

Conclusions

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

The presence of fields propagating in the extra-dimensions produces Kaluza Klein towers of particles

The mass scale of the lowest lying of the KK towers is typically approximately in the range of LHC

The details of the KK fields depend on the specific model implementation. For the main models available, detailed studies performed to test the LHC potential

In general the LHC will be sensitive to the new phenomenologies arising from ED theories for scales up to a few TeV
