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 $M_{\mathsf{Pl}} \equiv (G_F)^{-1/2} \sim 10^{19}$ 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: $M_{\mathrm{Pl}}^2 = M_D^{n+2} R^n$ with M_D scale of gravity in the bulk
  - To account for hierarchy: $M_D \sim 1$ TeV $\Rightarrow R \gg 1/$TeV "Large" ED
  - EW measurements test SM gauge fields to distances $\sim 1/$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

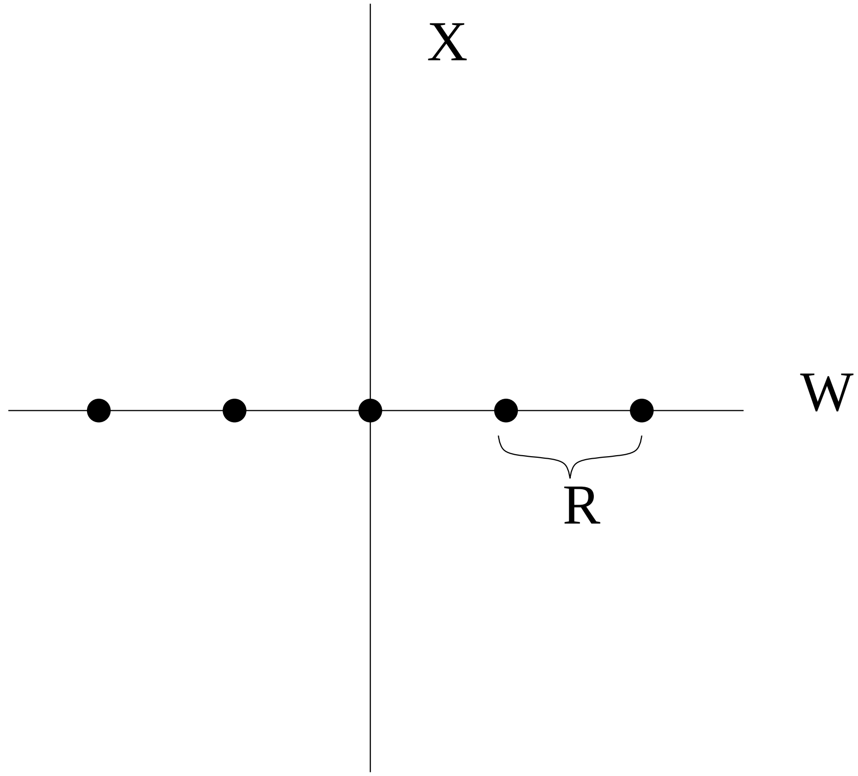
ADD: Lowering the scale of gravity

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:

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

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

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

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 $\int da = r^{n-1} S_n$

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

$\Rightarrow$ Recover Newton's law

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

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:

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

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

Generalising to n space dimensions:

$$\int da = 4\pi r^2 L^{n-3} \;\; M_{enc} = M(L/R)^{(n-3)} \quad \Rightarrow \quad F = \frac{S_n}{4\pi} \frac{G_n}{R^{n-3}} \frac{M}{r^2}$$

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

$$\frac{S_n}{4\pi} \frac{G_n}{R^{n-3}} \frac{M}{r^2} = G_N \frac{M}{r^2} \quad \Rightarrow \quad G_N = \frac{S_n}{4\pi} \frac{G_n}{V_{n-3}}$$

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 characteristic mass scales: $M_{\mathrm{Pl}} = (G_N)^{-1/2} \sim 10^{19}$ GeV and

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

We obtain the reduction formula:

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

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

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

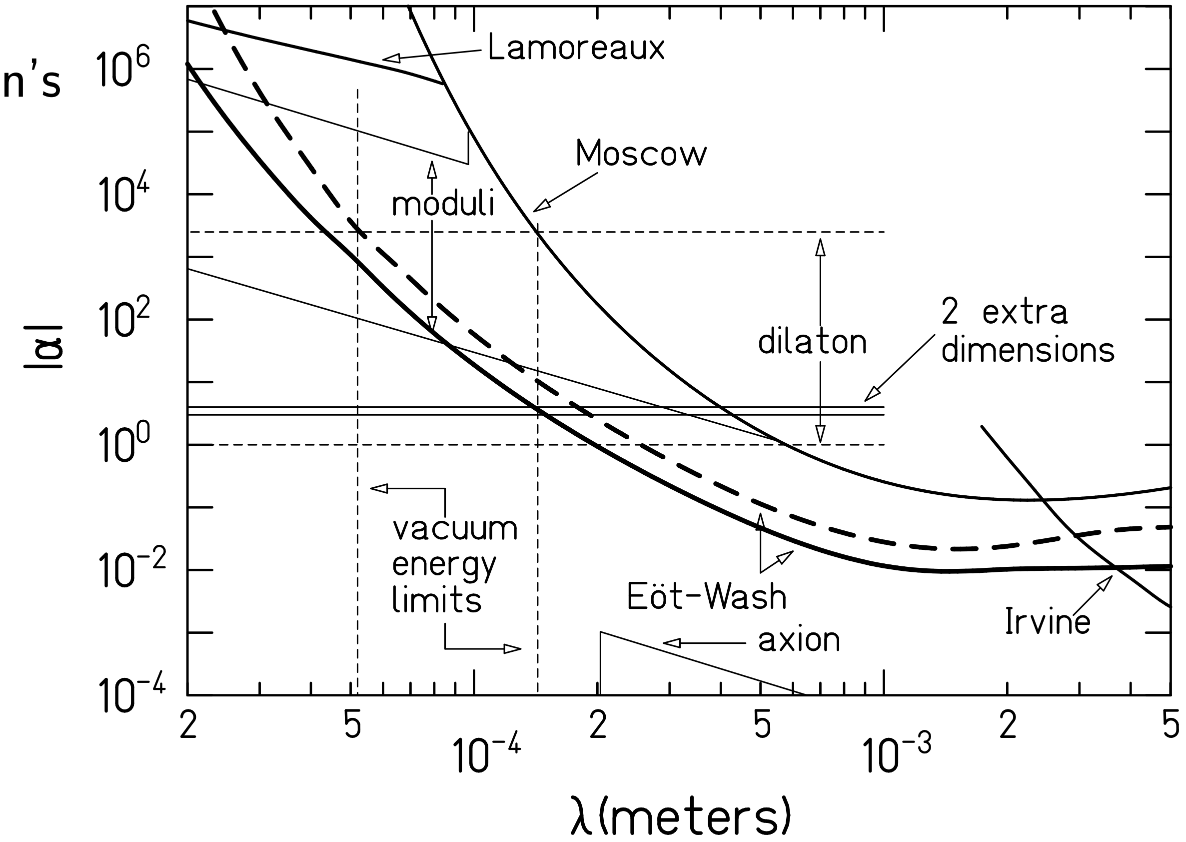
Cavendish-type experiments using torsion pendulum

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

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

For ED compactified on torus:

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



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

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 $E = hk$

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

$\Rightarrow$ 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

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

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

For $M_D \sim$TeV, Extra Dimensions "Large" mm $\lesssim R_c \lesssim$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 $m_{\vec{n}} = \sqrt{\vec{n}^2/R_c^2}$, where $\vec{n} = (n_1, n_2, ...n_\delta)$ 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 $\delta = 2, M_D = 1$ TeV, $\Delta m_{KK} \ll$eV

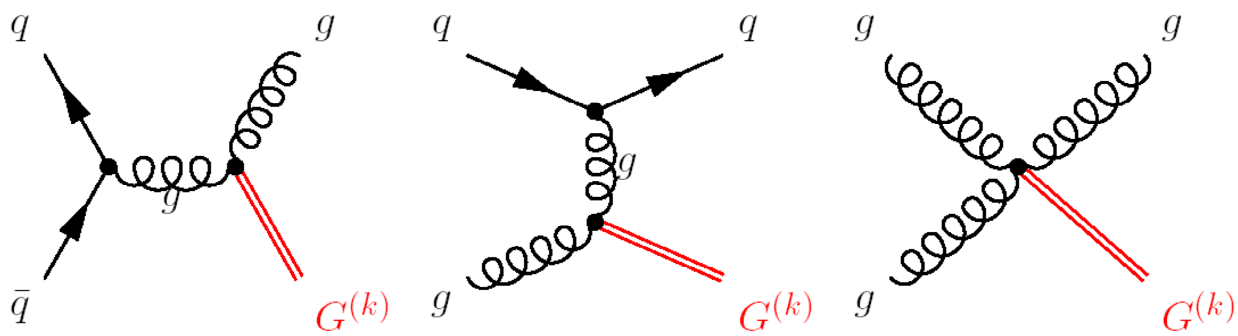
In collider process with energy E, $(ER_c)^\delta$ massive KK modes accessible: For $\delta = 2$ and $E = 1$ TeV have 10^{30} modes

Using the reduction formula, sum over all modes exactly cancels $\sim 1/M_pl$ dependence

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

$\Rightarrow$ Sizable cross-section for processes:

$$\bar{q}q \to gG^{(k)}, \quad gq \to qG^{(k)}, gg \to gG^{(k)}, \bar{q}q \to \gamma G^{(k)}$$



Direct graviton production analysis (ATLAS)

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

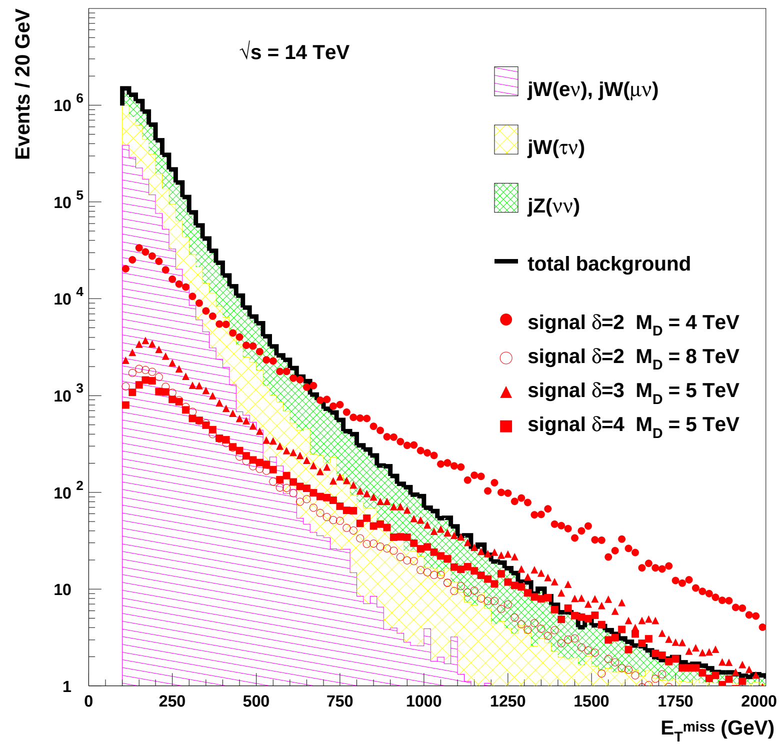
Signature is large $\not{E}_T$ from undetected graviton + a high P_T jet or photon

Single jet analysis requiring:

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

Signal emerges from background at high $\not{E}_T$

Dominant SM contribution is $Z \rightarrow \nu\nu$+1 jet



Apply standard cut at $\not{E}_T > 1$ TeV to evaluate discovery potential

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

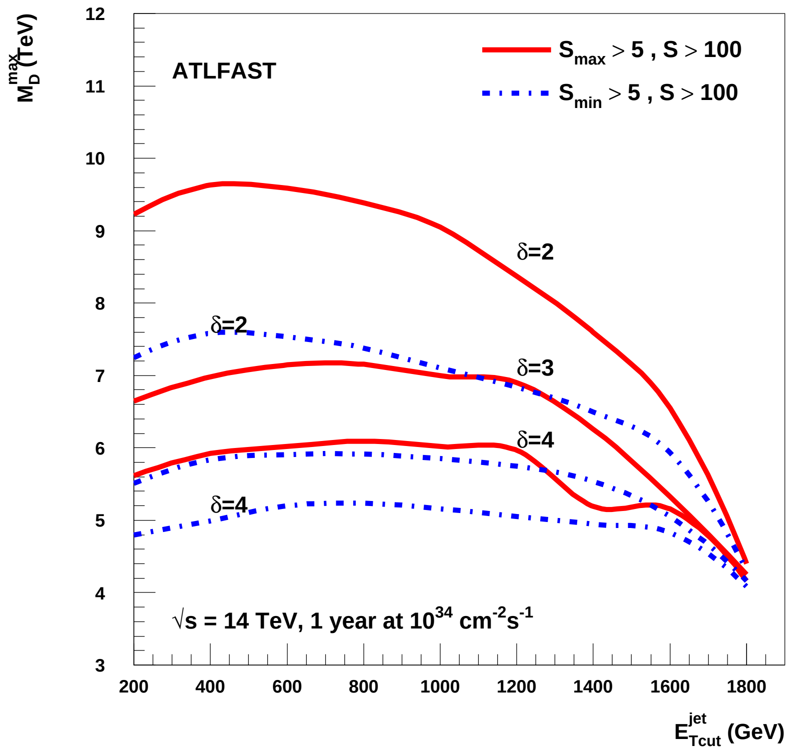
Sensitivity evaluation

Significance for jG production

as a function of E_T^{jet} cut

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

$S_{min} = S/\sqrt{\alpha B}$ with $\alpha \sim 7$, accounts for the fact that the background calibration sample $Z \to \ell\ell$ is smaller than the dominant $Z \to \nu\nu$ background.



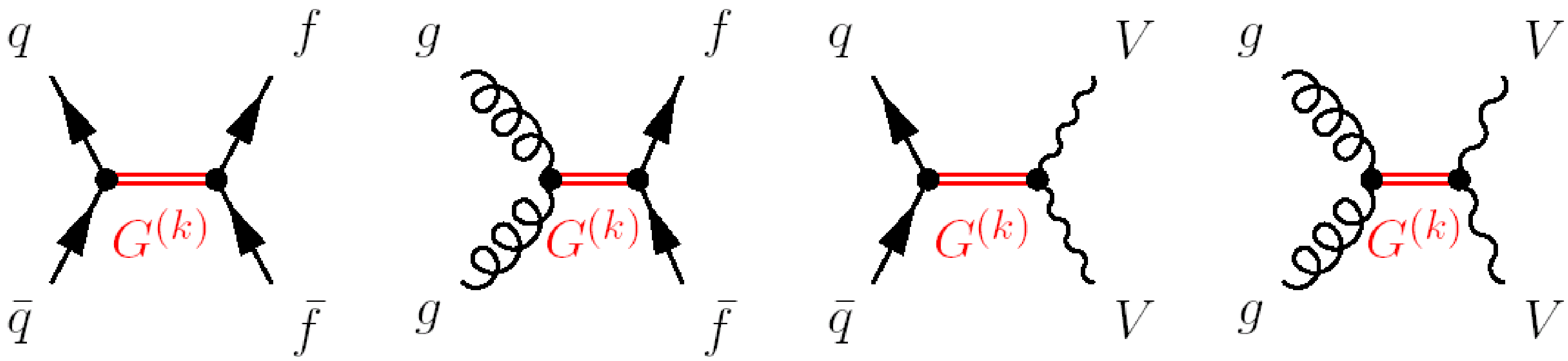
Reach in M_D: $S_{max} > 5$, ≥ 100 signal events, E_T^{jet} >1 TeV

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

Virtual graviton exchange

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



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

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

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

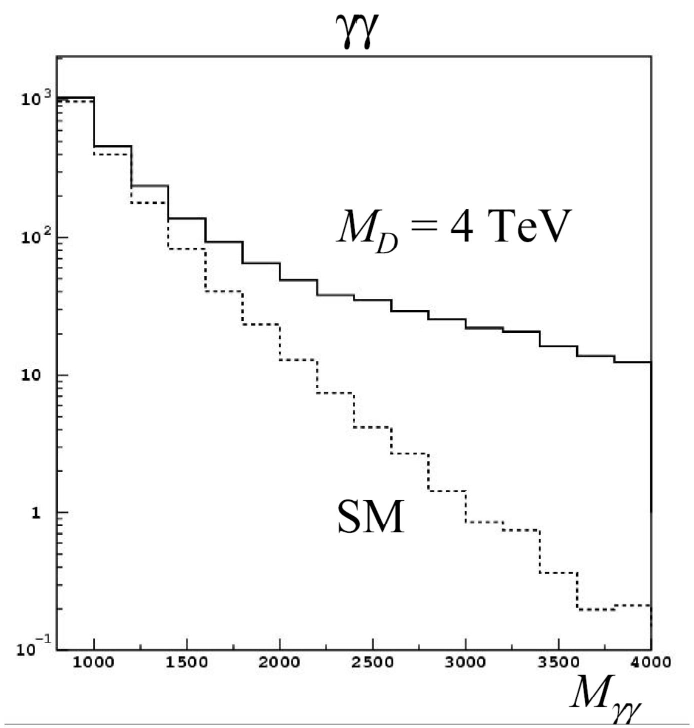
Sum over graviton states divergent, assume cut-off at M_s.

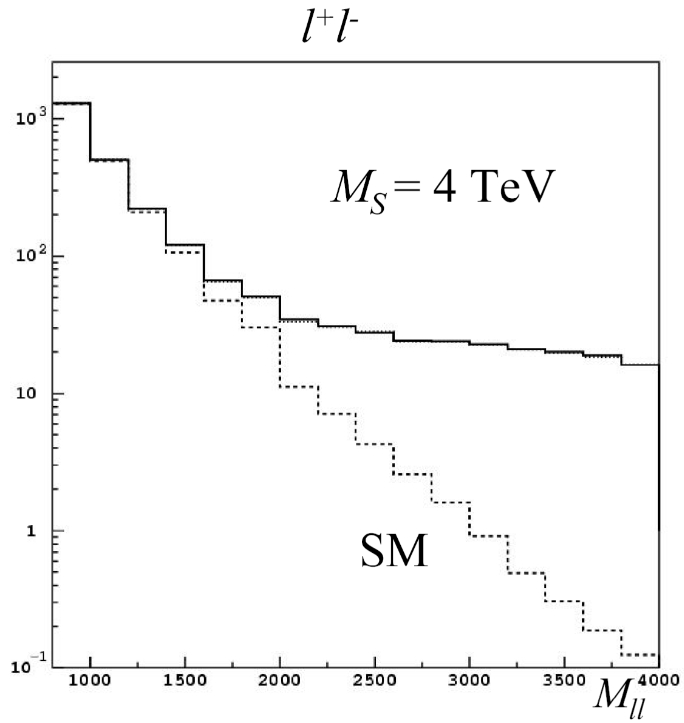
Explicit form of F depends on (unknown) quantum gravity theory, perturbative approach no more valid when $\hat{s} \sim M_s^2$

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 $\ell\ell$ and $\gamma\gamma$, $M_{\gamma\gamma,\ell\ell} < 0.9 M_S$ (regularization)





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

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

$M_s > 5.1(6.7)$ TeV ($\gamma\gamma$) $M_s > 5.4(7.0)$ TeV ($\ell\ell$) $M_s > 5.7(7.4)$ TeV (combined)

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

TeV^{-1} Extra Dimensions

Standard ADD model:

EW precision measurement test SM gauge fields to distances $\sim 1/$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" ($R \sim 1/$ 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 $R_c \equiv 1/M_c$:

- Excitations equally spaced with masses:

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

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

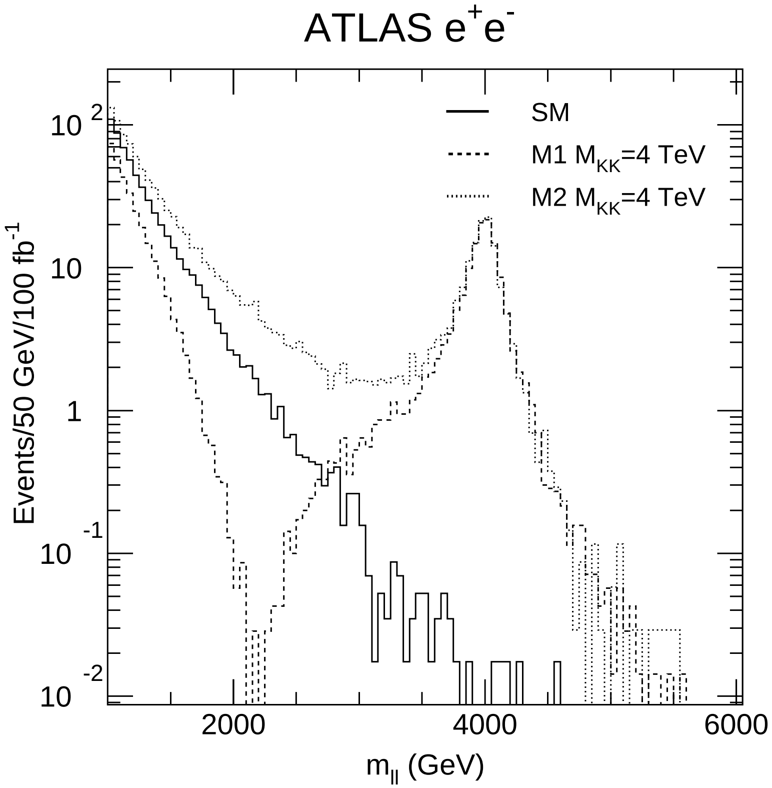
Minimum excitation mass compatible with EW precision measurement: 4 TeV

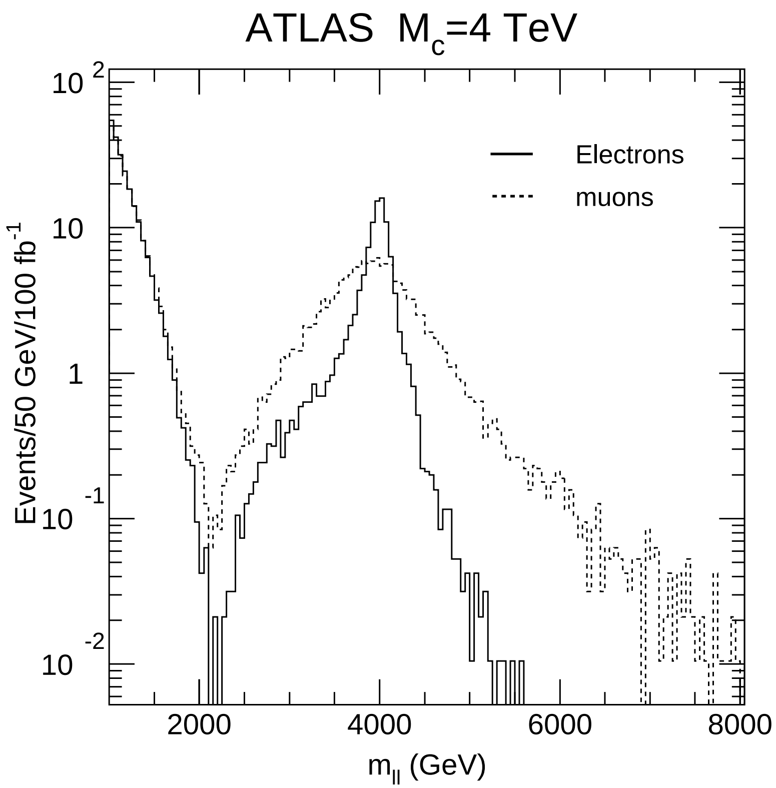
Consider excitations for all SM bosons:

- 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

Minimum excitation mass considered: 4 TeV: natural width

$\sim 2 \times \Gamma(W) \times (M_c/100)$ GeV~ 200 GeV

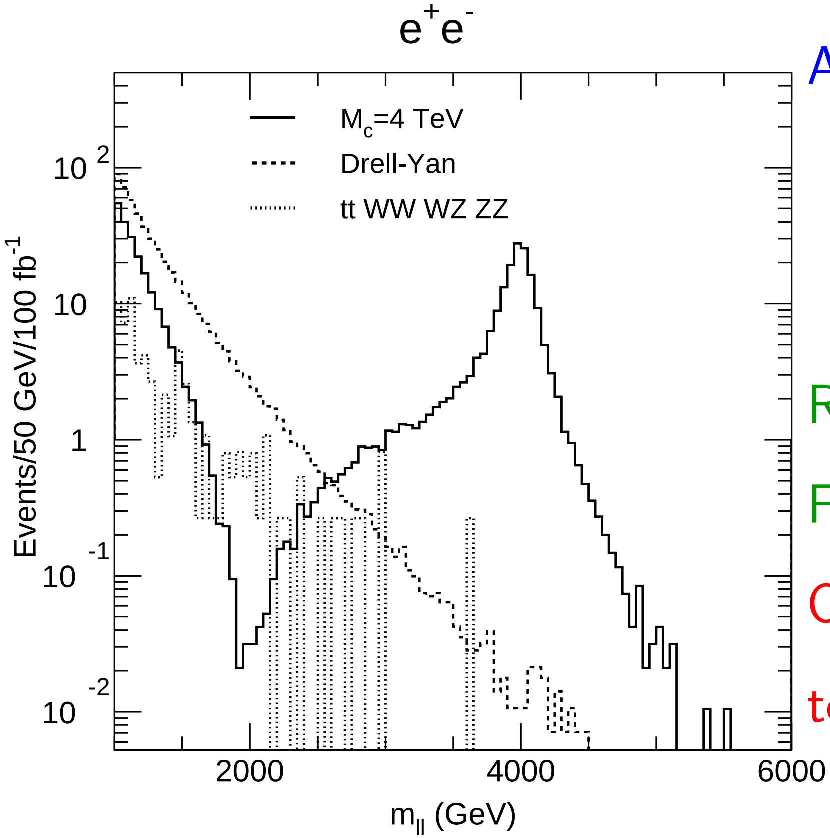




Natural width dominates for e^+e^-. Detailed knowledge of electron resolution not needed as long as $\sigma(E)/E$ better better than 2-3%.

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

Data analysis: Z/γ



Analysis requirements:

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

Reducible backgrounds: $\bar{t}t$, 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

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

In no case second KK peak observable

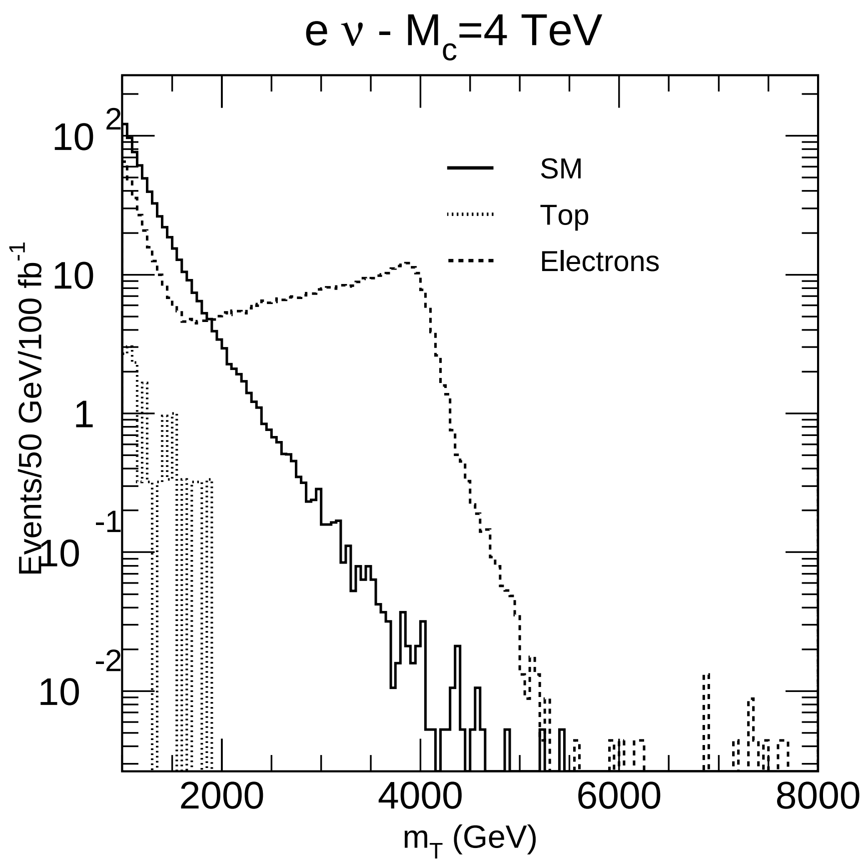
Data analysis: W

Analysis requirements:

- One lepton with $P_t > 200$ GeV in $|\eta| < 2.5$
- $\not{E}_T > 200$ 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})



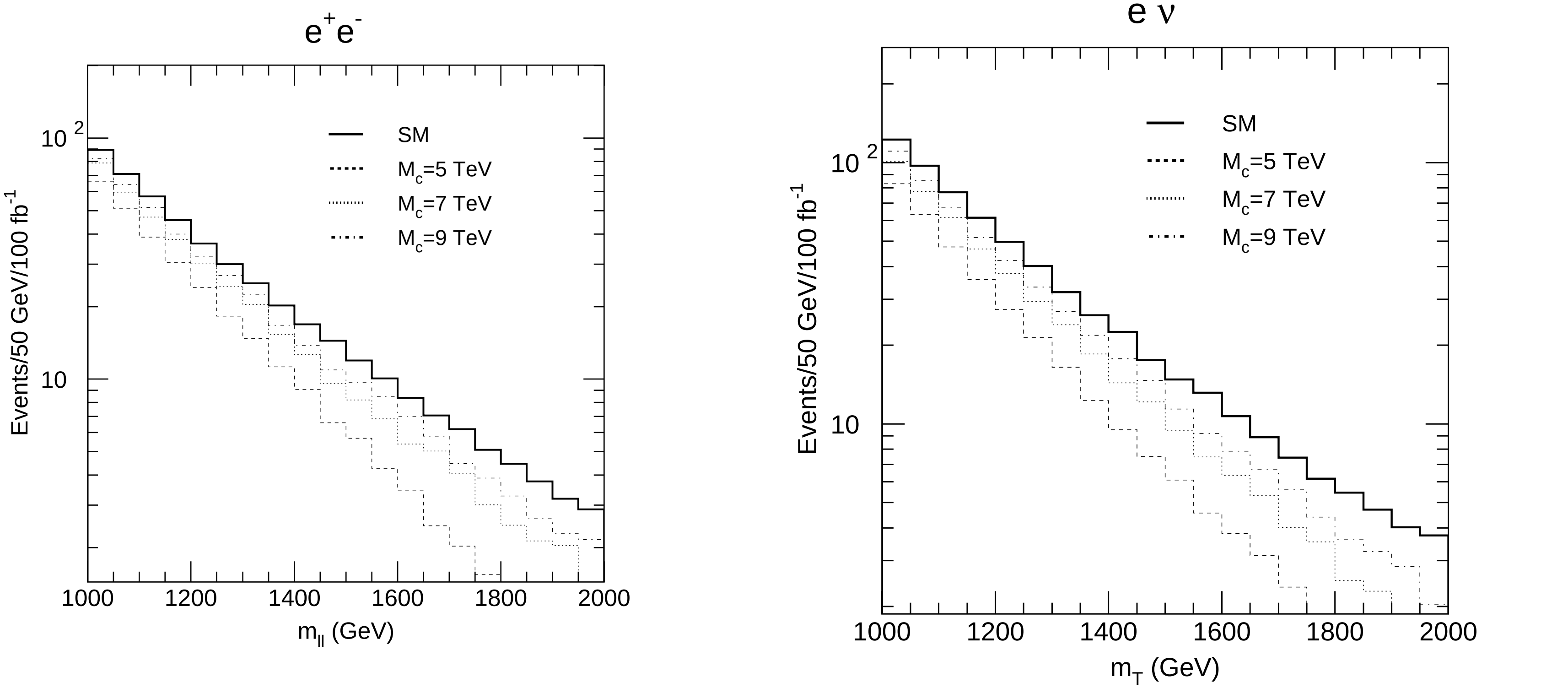
Reducible backgrounds considered: $\bar{t}t, WW, ZZ$

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, but bias for study of Jacobian shape

Reach for 100 fb^{-1}: ~ 5.8 TeV

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



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

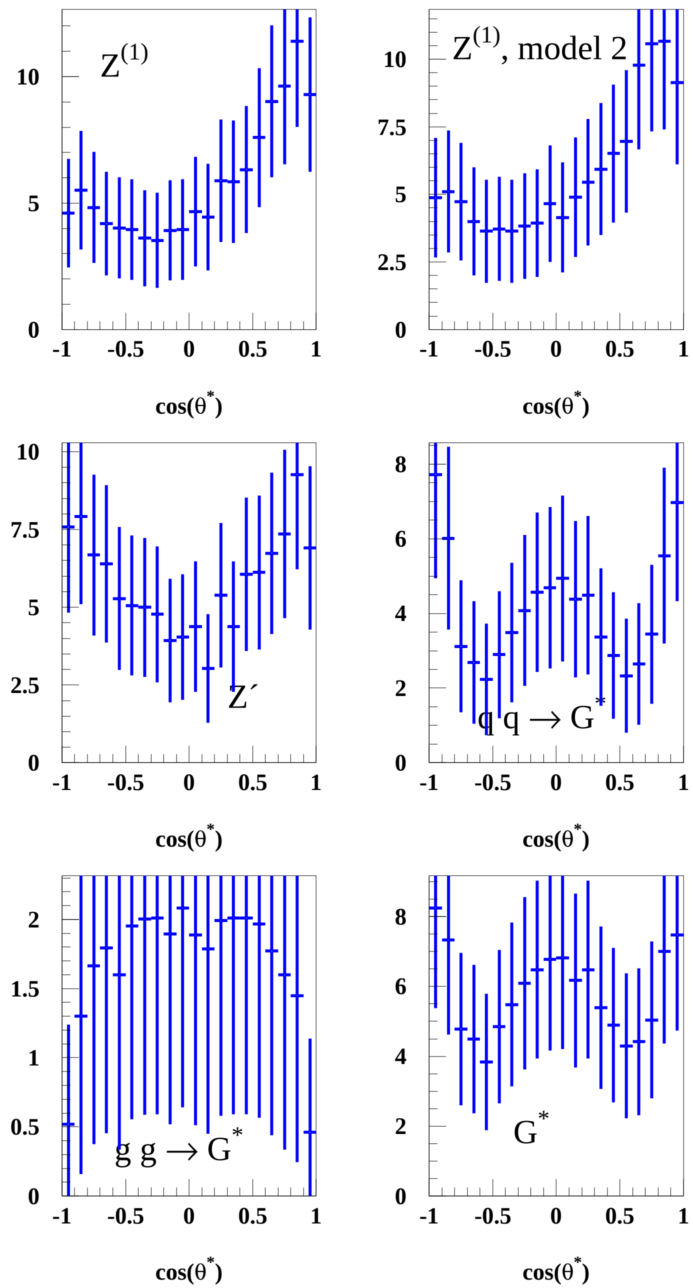
$1000 < M_T < 2500$ GeV (W)

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

Reach for 100 fb^{-1}: ~ 8 TeV for Z/γ, ~ 9 TeV for W

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

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 $G^* \to e^+e^-$

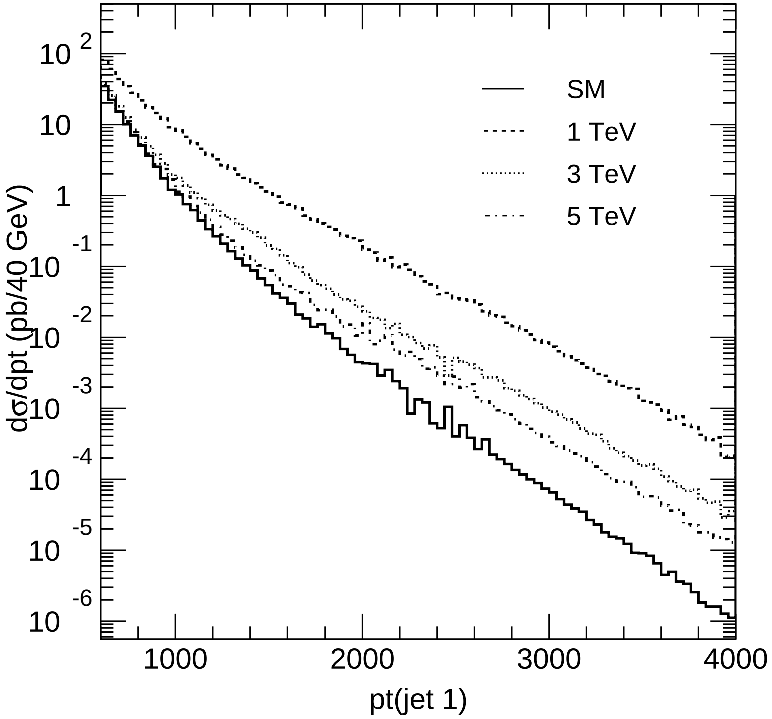
Trough Kolmogorov test study discrimination power:

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

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

KK excitations of the gluon

Require no third jet with P_T above 100 GeV



Large deviation from SM QCD spectrum,

but

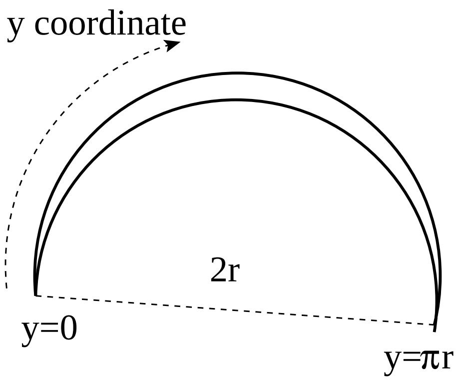
Need to understand how well we know jet p_T spectrum:

- PDF uncertainites
- 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

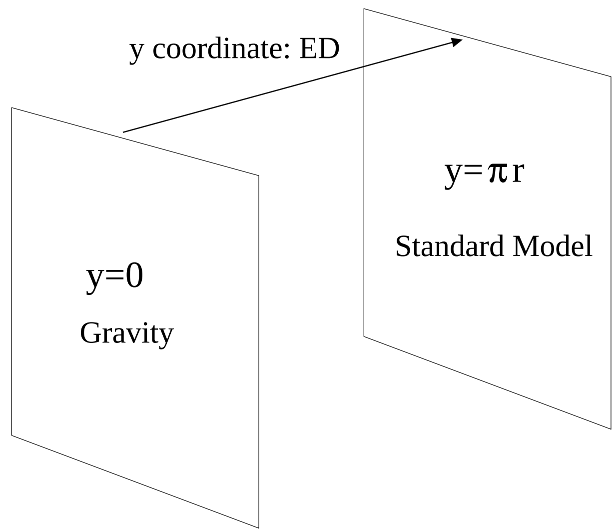


One additional dimension in which gravity propagates

ED compactified on S^1/Z_2 (circle folded on itself $\equiv$ 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:

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

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

Consistency of low energy theory: $k/\overline{M}_{\rm Pl} \lesssim 0.1$ with $\overline{M}_{\rm Pl} = M_{\rm Pl}/\sqrt{8\pi} = 2.4\times 10^{18}$ 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 $\overline{M}_5$

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

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

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

$\Lambda_\pi \sim 1$TeV provided thar $kR = 10$.

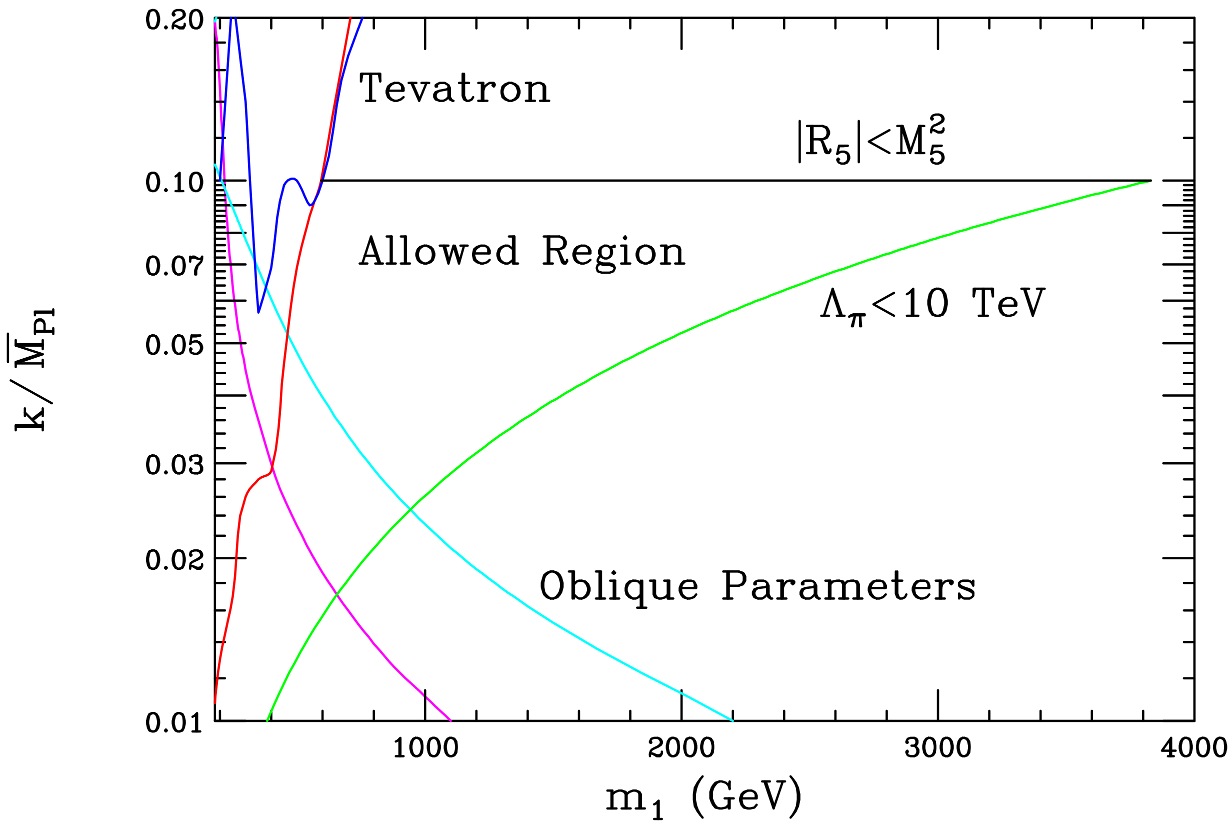
Two parameters define the model:

- Λ_π
- ratio $k/\overline{M}_{Pl}$

If require $\Lambda_\pi < 10$ 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:

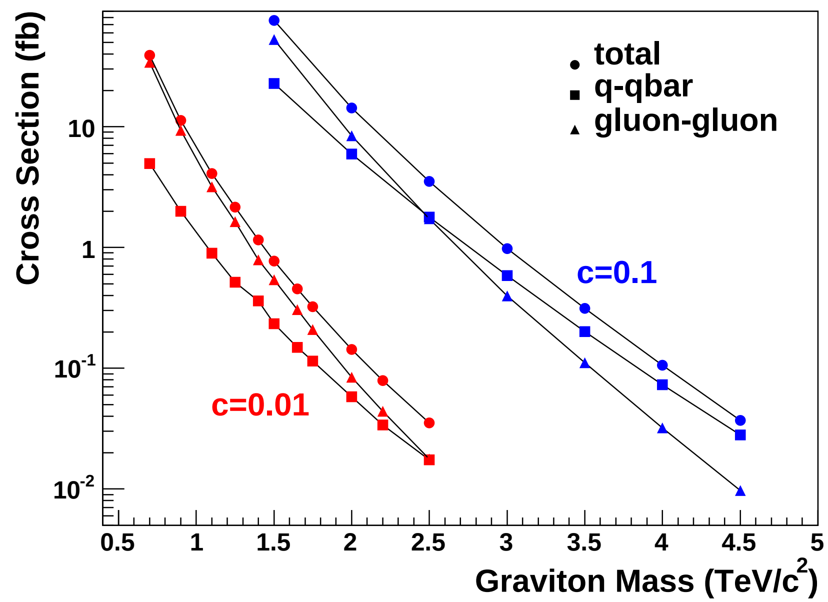
$$m_n = x_n k e^{-k\pi r_c} = x_n \frac{k}{M_{Pl}} \Lambda_\pi$$

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)

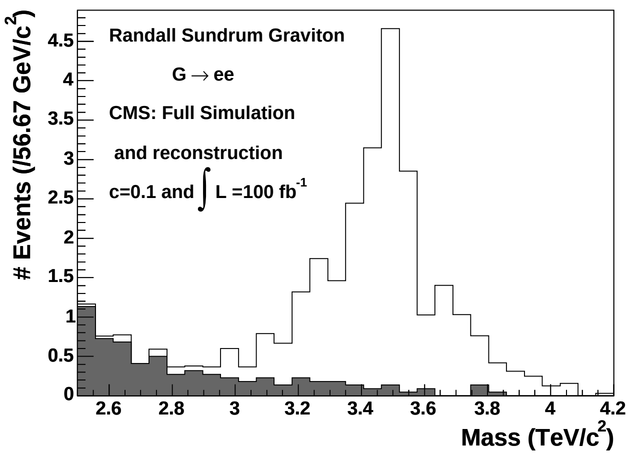
Graviton couples to all SM particles

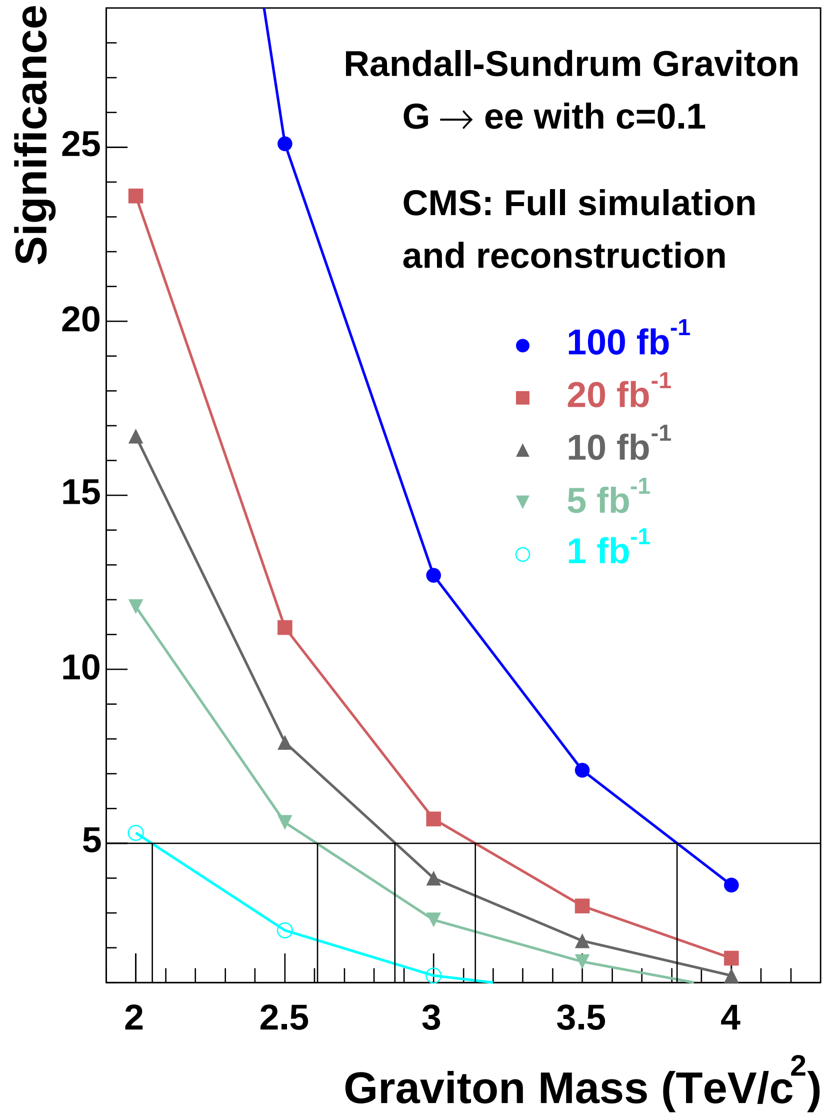
Most favourable channel $G(1) \rightarrow e^+e^-$:

- Optimal experimental resolution
- Minimal background

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

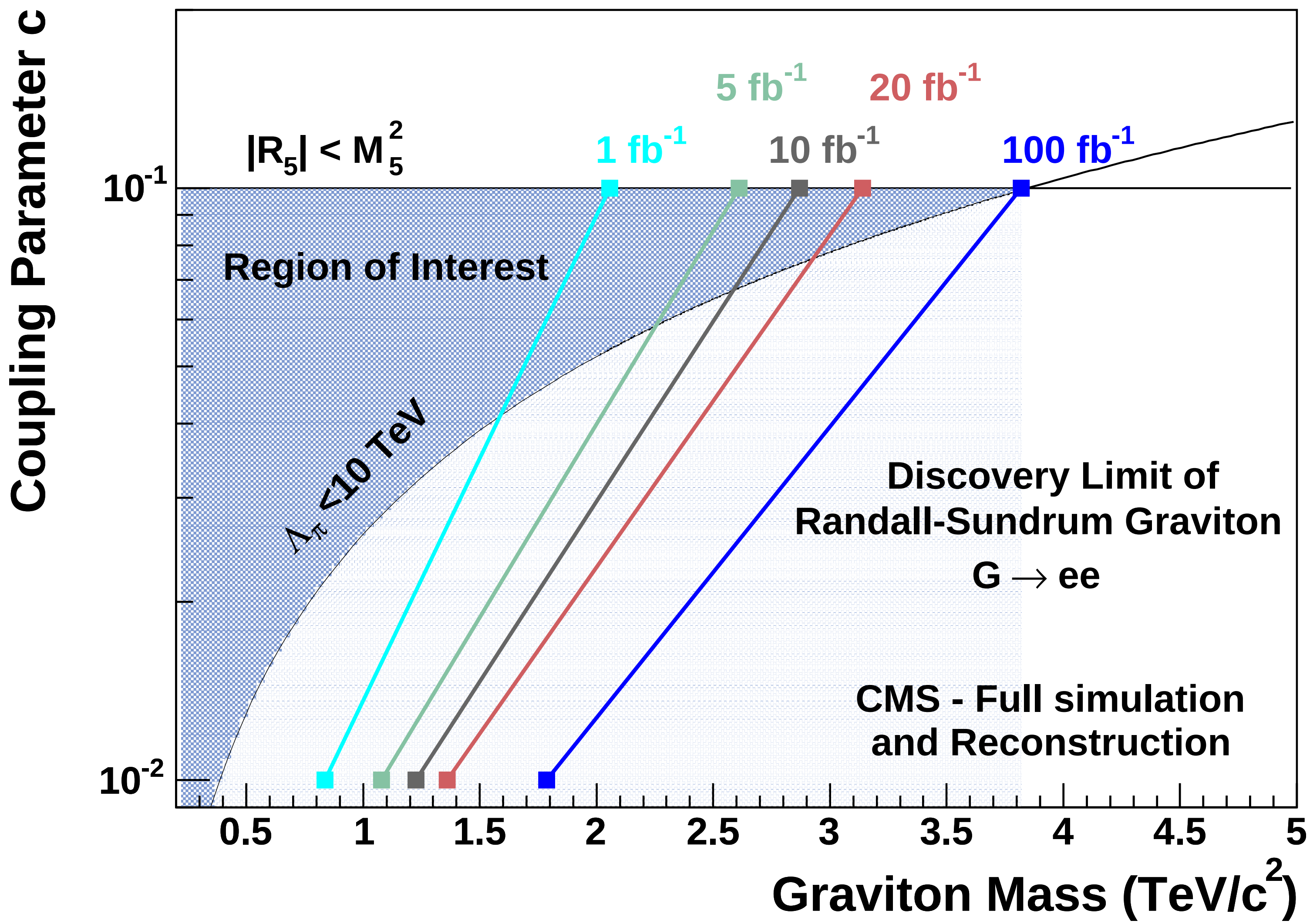
Use $c = 0.1$ and $c = 0.01$ for couplings





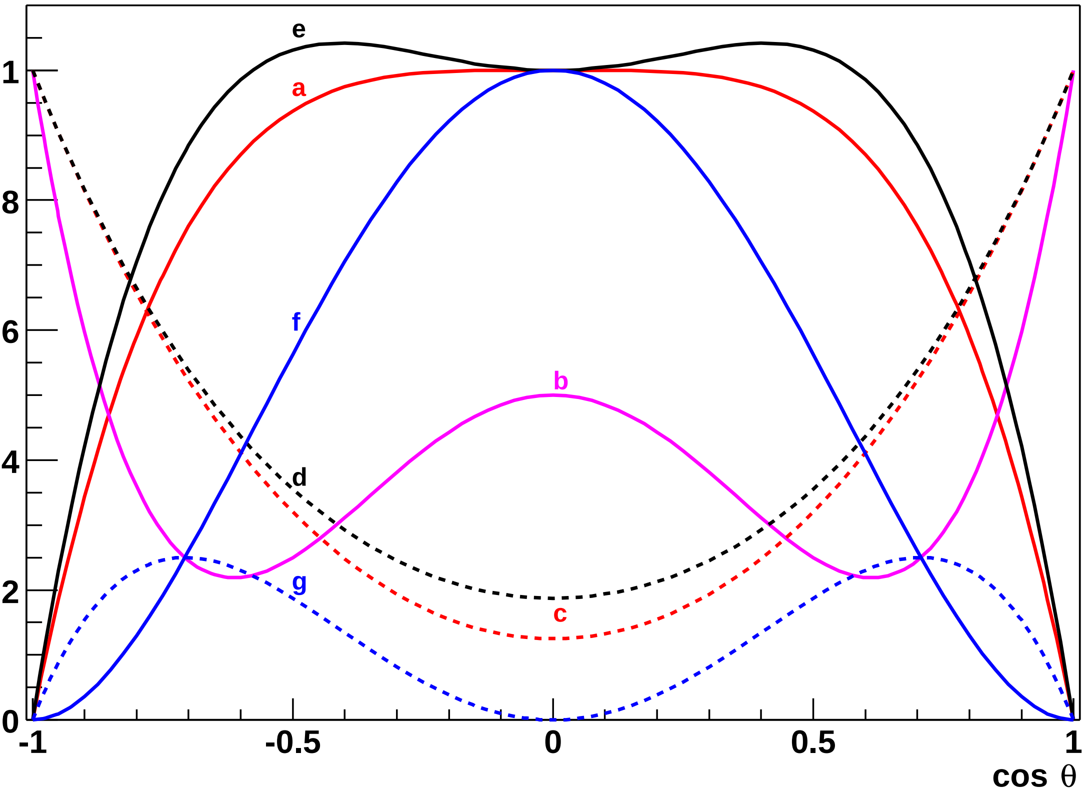
Coverage of parameter space

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



Spin determination of graviton resonance

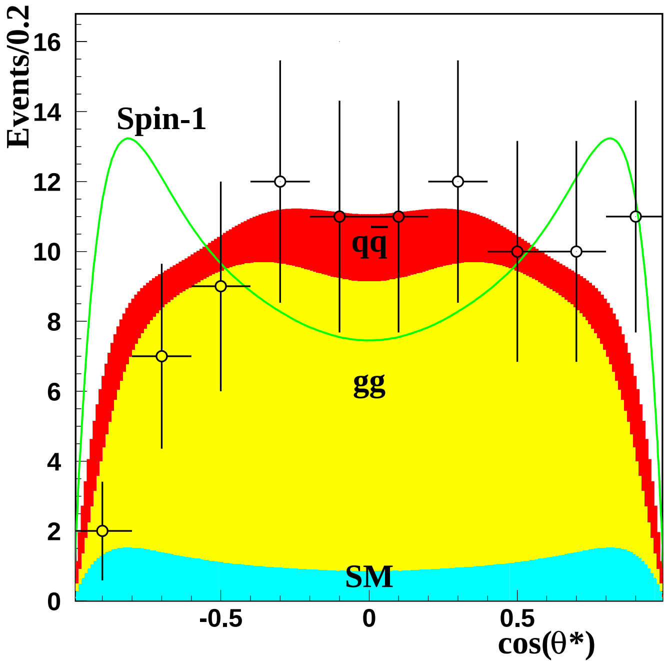
Graviton is spin-2 particle. Angular distribution of decay products depends on production mechanism, and on spin and mass of decay products



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

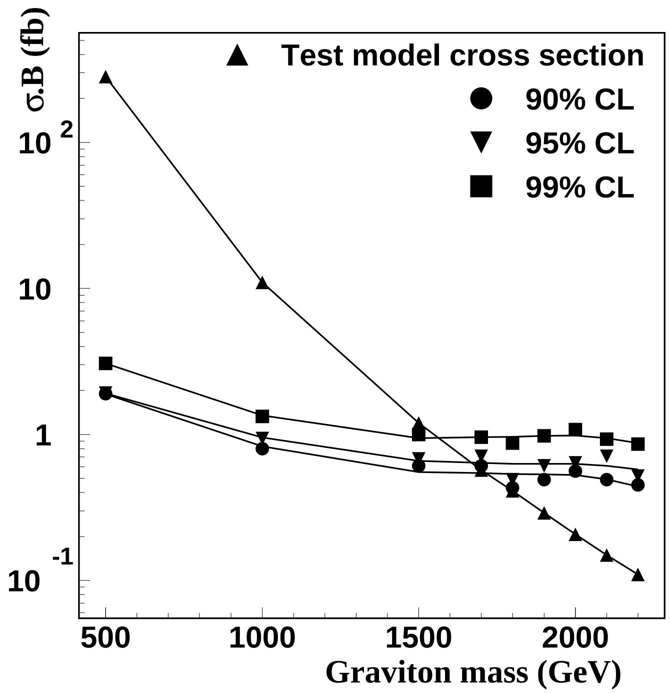
β is v/c of decay products

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

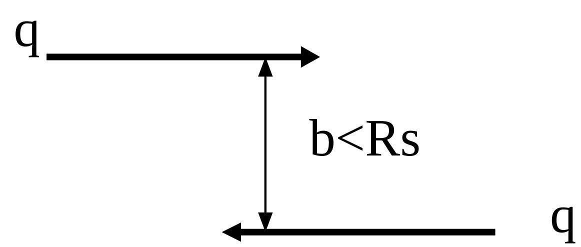
Spin-1 hypothesis can be ruled out at 90% CL up to $m_1 = 1720$ GeV

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



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 Schwarzchild radius of black hole

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

In extra-dimension theories M_P ~Tev ⇒, for $M_{\mathrm{BH}} \sim M_P$, $\sigma \sim (\mathrm{T}eV)^{-2} \sim 400$ pb

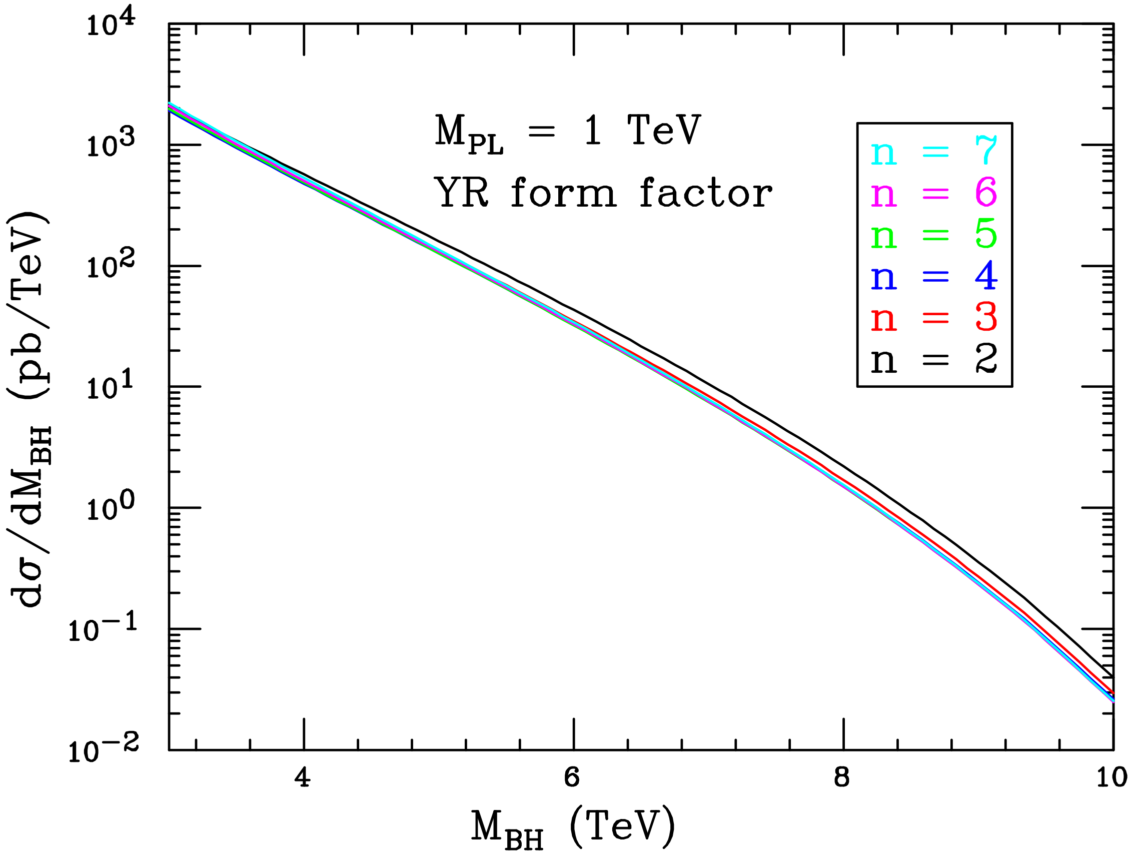
Potentially large production cross-section

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

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

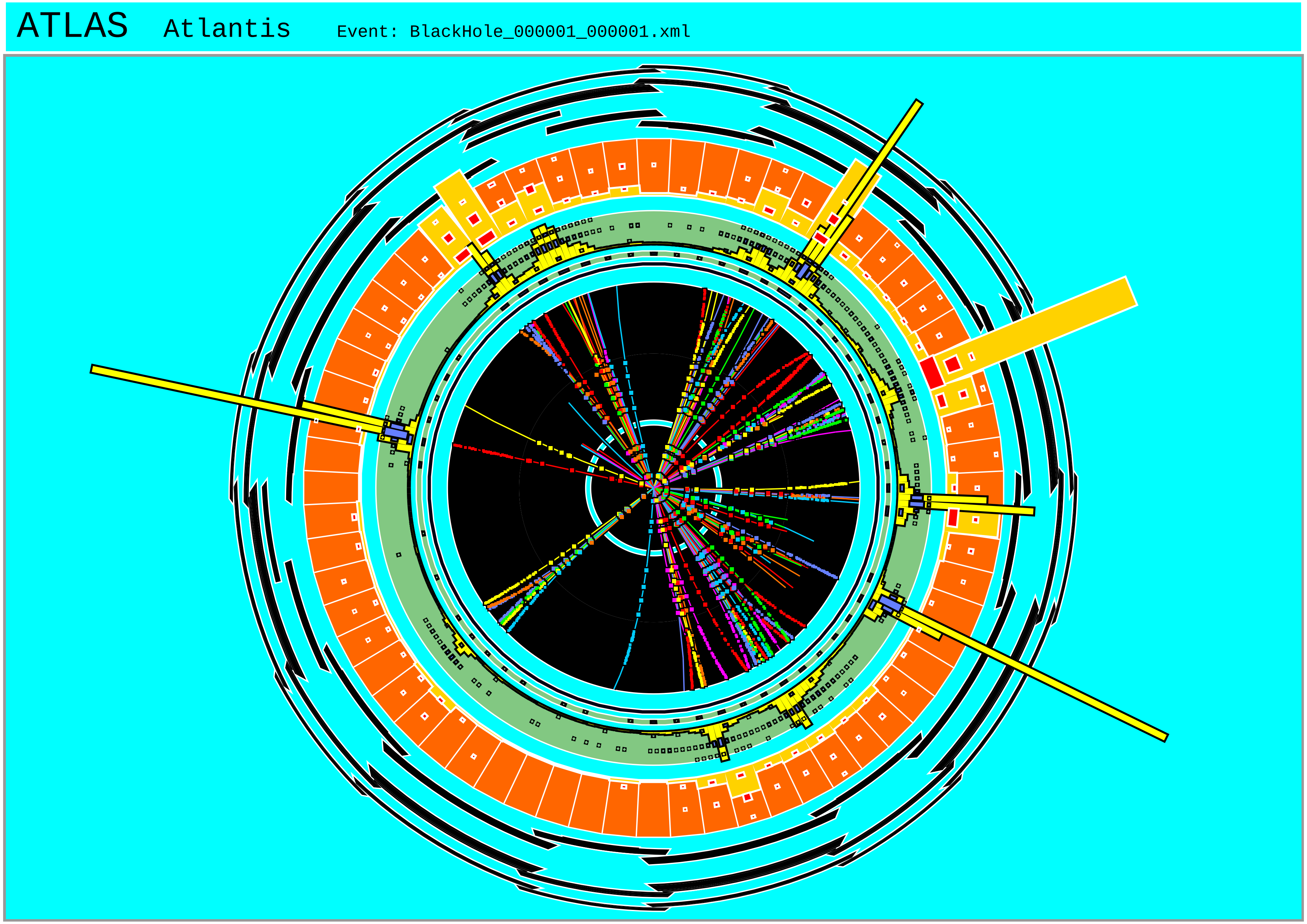
Thermal radiation: black body energy spectrum

$$\frac{dN}{dE} \propto \frac{\gamma E^2}{(e^{E/T_{\mathrm{H}}} \pm 1)} T_{\mathrm{H}}^{n+6} \tag{3}$$

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

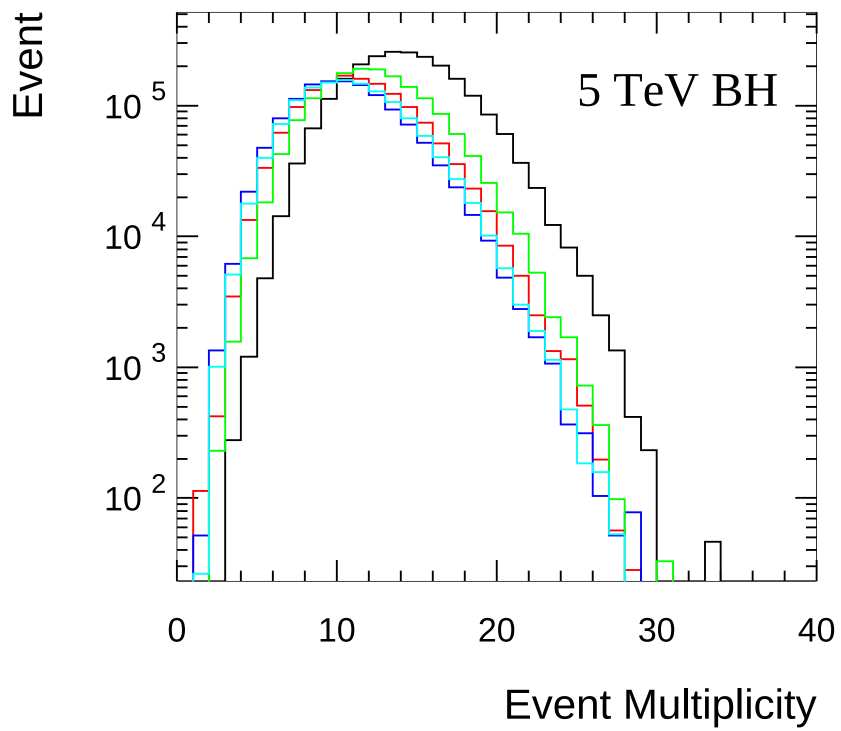
$$T_{\mathrm{H}} = \frac{n+1}{4\pi r_{\mathrm{s}}} \propto M_{\mathrm{BH}}^{-\frac{1}{n+1}} \tag{4}$$

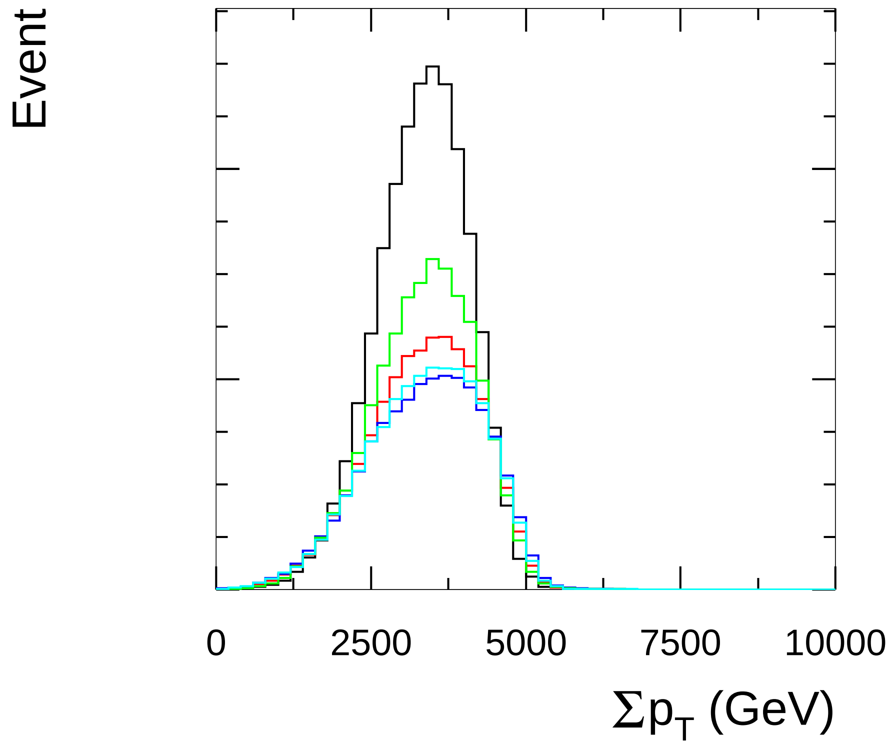
γ is a $(4+n)$-dimensional *grey-body factor*: absorption factor from propagation in curved space


ATLAS
Atlantis
Event: BlackHole_000001_000001.xml

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





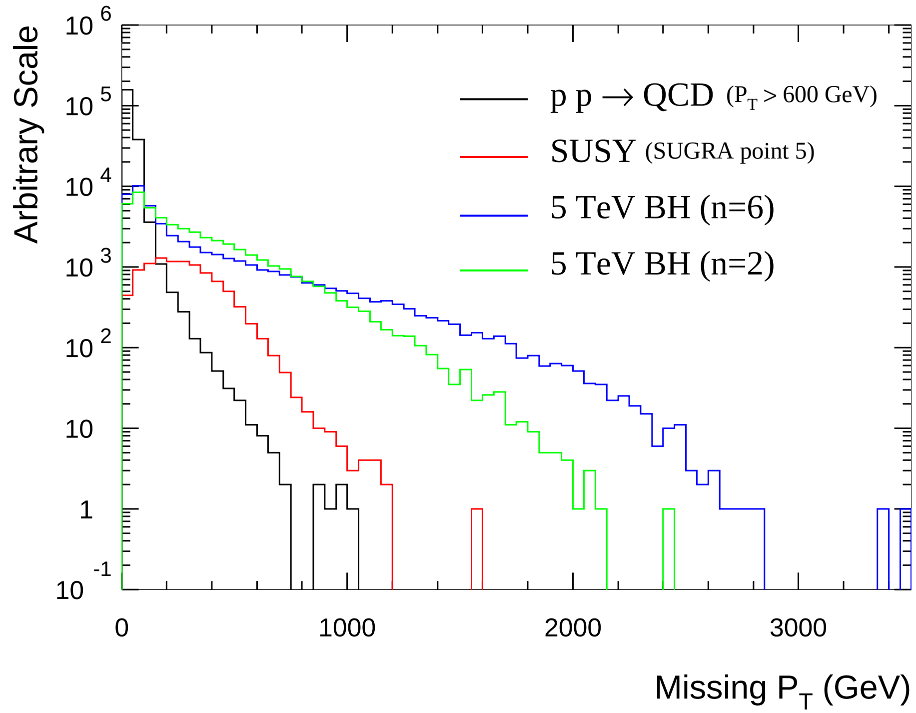
No significant SM background !

Democratic decay of BH into all types of SM particles

Large number of events containing a high-P_T neutrino

$\not{E}_T$ 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

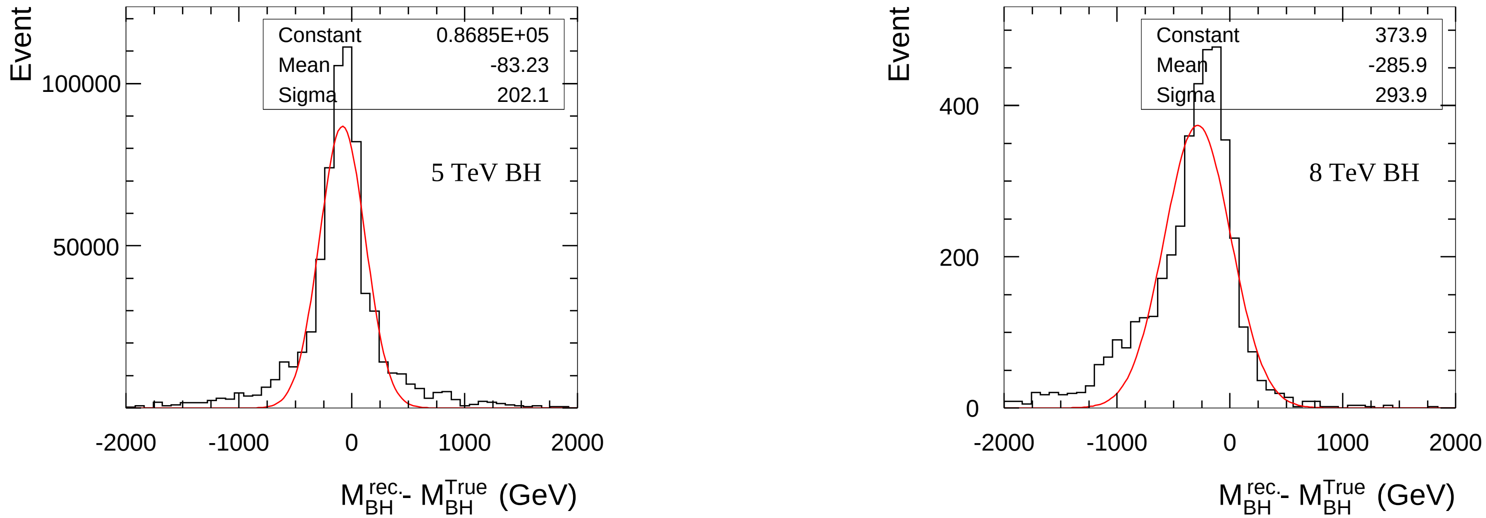
Simply sum the 4-momentum of all reconstructed particles in the event

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 $\not{E}_T > 100$ 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 simultion effort ongoing in ATLAS to verify these results

Conclusions

Extra Dimension theories offer an attractive way of solving the hierarchy problem basedon 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 th 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 nex phenomenologies arising from ED theories for scales up to a few TeV